# GEOMORPHIC RESPONSE TO TORNADO IMPACT IN ABRAMS CREEK, SMOKY MOUNTAINS NATIONAL PARK, TENNESSEE

by

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# ABSTRACT

Tornadoes have the potential to alter river geomorphology. Considering the frequency and intensity of tornado events in the U.S., it is likely that tornadoes are an unaccounted source of natural disturbance in fluvial systems. This study reviews the potential effects of tornado impact on rivers and presents findings from a study of tornado impacts conducted in Abrams Creek located in the Great Smoky Mountains National Park, Tennessee. In April 2011, an EF4 tornado touched down in Abrams Creek watershed. The National Parks Service left all the damage untouched. I studied two ~1 km stream reaches: an upstream reach directly impacted by the tornado and a downstream reach which was not. I measured the morphology of pools, including maximum length, average width, and residual pool depth, under base flow conditions (July-October 2015) in both study reaches and compared them using a *t*-test. Statistical differences in residual pool depth existed between the upstream and downstream reach (*p* value = .027). This difference is likely the result of increased hydraulic erosion in the upstream reach and an influx of sediment in the downstream reach. The results of this study suggest tornadoes can and do affect river geomorphology, with their effects persisting years after the event. The geomorphic disturbance initiated by tornadoes have short and long-term implications for in-stream ecological functions. A better understanding of the geomorphic and ecological implications following a tornado could help guide management strategies and decisions for river conservation and restoration efforts.

# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| % | Percent |
| > | Greater than |
| ≥ | Greater than or equal to |
| cm | Centimeter |
| km | Kilometer |
| m | Meter |
| mph | Miles per hour |
| kmph | Kilometer per hour |
| SPSS | Copyrighted by IBM. Statistical Package for the Social Sciences |
| $n$ | Sample size |
| $p$ | Significance (statistical significance) |
| °C | Degrees Celsius |
| EF | Enhanced Fujita Scale |

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I thank my family and friends for their unwavering support throughout my studies. I thank Lisa Davis, Cindy Taylor, and Ryan Vaughn for their time and energy assisting me with fieldwork. I thank my thesis committee, Dr. Lisa Davis, Dr. Doug Sherman, and Dr. Martin Lafrenz for their guidance and expertise. I thank the National Park Service for allowing me to sample within the GSMNP. I am extremely grateful for the research funds provided by the following that made my research possible: the Graduate School, the College of Arts and Sciences, the Department of Geography at the University of Alabama, the Geomorphology Specialty Group of the American Association of Geographers (Reds Wolman Research Award).

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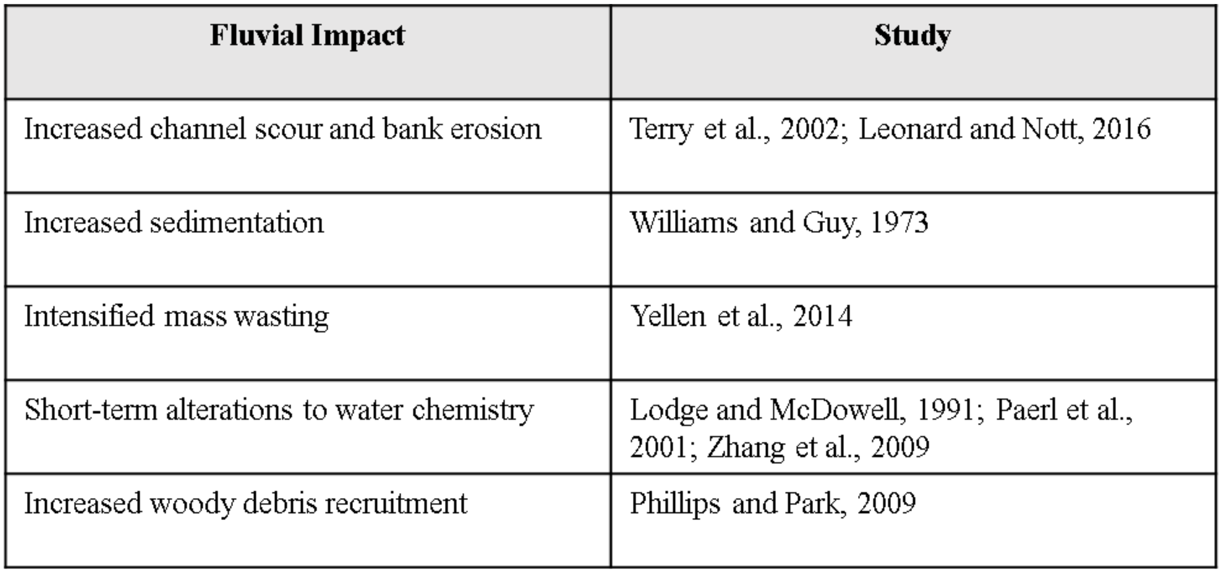
## I. Introduction

Meteorological disturbance plays a significant role in the evolution of North American Rivers. Extreme wind disturbance, such as tropical cyclones, can significantly alter rivers (Table 1).



| Fluvial Impact | Study |
|---|---|
| Increased channel scour and bank erosion | Terry et al., 2002; Leonard and Nott, 2016 |
| Increased sedimentation | Williams and Guy, 1973 |
| Intensified mass wasting | Yellen et al., 2014 |
| Short-term alterations to water chemistry | Lodge and McDowell, 1991; Paerl et al., 2001; Zhang et al., 2009 |
| Increased woody debris recruitment | Phillips and Park, 2009 |

Table 1. Summary table of the observed effects of tropical cyclones on fluvial systems.

Prior to this research, the fluvial geomorphic impacts of tornadoes have not been examined, which is somewhat surprising given their frequency in North America. For example, the United States experiences approximately 1,000 tornadoes per year; the highest worldwide (NOAA, 2014a). Extreme wind events studied for their geomorphic impact, such as tropical cyclones, are isolated to the east coast and the Gulf of Mexico in North America, and are limited by seasonality and climatic trends. While tornadoes do have a peak season and are certainly more common in some areas rather than in others, they are not uncommon in large sections of North America. Every major river east of the Rockies has been impacted by a significant tornado (NSSL, 2016). Extreme winds associated with tornadoes can input a significant amount of coarse woody debris (CWD) to the fluvial system and remove riparian vegetation, both of which directly and indirectly alter fluvial geomorphology and could potentially alter other stream processes such as temperature regime. These highly frequent, destructive phenomena are an unaccounted source of disturbance in fluvial systems that should be examined.

The potential for tornadoes to alter fluvial geomorphology is high. Substantial input of CWD and sediment as well as increased stream energy following a tornado can significantly alter in-stream morphological units. Pool units are highly responsive to disturbance events, responding with changes in pool width, length, and depth, to changes in flow velocities and sediment supply (Buffington et al., 2002), and as such, this study focused on pools. I measured and compared pool characteristics (length, width, and depth) between two reaches — a 1 km reach located in the tornado impact zone and a 1 km reach located roughly 1.5 km downstream of the impact zone — to determine if changes to pool morphology owing to the tornado's occurrence could be detected. Tornadoes have the potential to directly and indirectly modify pools, as well as initiate future disturbance within the fluvial system. Modifications to pool characteristics (deepening and shallowing) can have positive and negative effects on in-stream ecosystem processes and biological communities. A better understanding of the effect of tornadoes on rivers will help river managers and planners charged with river restoration efforts, maintaining ecological health, and overall monitoring of fluvial systems. As such, this thesis does the following: (1) reviews the potential impacts of tornadoes on fluvial systems and (2) presents findings of an investigation of the effects of a direct tornado impact on the channel morphology of a river located in the Great Smoky Mountains National Park, Tennessee.

## II. Potential Effects of Tornadoes

Tornadoes are considered one of the most intense and lethal wind related events in the world (Greenough et al., 2001), and yet, little is known about their significance as natural disturbance agents in fluvial systems. The frequency and destructive intensity of tornadoes in many regions of the North American continent, suggests they may be an overlooked mechanism of change in North American rivers, and perhaps, other parts of the world where tornadoes occur. The localized disturbance associated with a tornado event can lead to the introduction of coarse woody debris and the removal of riparian vegetation, resulting in changes in channel geomorphology, sediment distributions, and temperature regimes, all of which directly impact in-stream ecological processes.

### A. Introduction of CWD

The accumulation of CWD is a frequently studied topic because of its ability to directly modify morphological and ecosystem processes (Abbe and Montgomery, 1996). Woody debris, commonly referred to as coarse woody debris (Sass, 2009), large woody debris (Kraft and Warren, 2003), and large organic debris (Thompson, 1995), typically refers to any woody material >10 cm in diameter and >1 meter in length (Swanson and Lienkaemper, 1978; Faustini and Jones, 2003). The presence of CWD within a fluvial system initiates flow deflection that causes morphological changes, including, but not limited to, increased erosion (Daniels and Rhoads, 2003), increased formation of morphological units, particularly pools (Keller and Swanson, 1979), and increased sediment and nutrient storage (Thompson, 1995). The severity of flow deflection is determined by factors, such as location within the stream, size of the log(s), and the orientation of the log(s) (Bergmeier et al., 2013). The size of the log jams (Bergmeier et al., 2013) and their orientation relative to flow determines log jam potential to affect channel morphology (Magilligan, 2008). The impacts of in-stream CWD vary greatly from one system to the next, depending on factors, such as reach gradient and geographic location (Gurnell, et al., 2002).

Little research exists on the effects of CWD in the southern Appalachian region, but CWD has been studied within the GSMNP where this study took place. Hart (2003) analyzed the effects of CWD in upland, mountain streams in the GSMNP and found that a higher frequency of CWD obstructions significantly increased bankfull width and depth through localized erosion (Hart, 2003). His results are congruent with findings of the channel morphologic impacts of CWD made elsewhere. Daniels and Rhoads (2003) found that CWD located on the outside of a meander bend resulted in flow deflection and accelerated erosion of the inside bend.  Keller and Swanson (1979) identified CWD obstructions as the underlying mechanism causing localized bank erosion, which ultimately caused the stream to migrate ~2 channel widths (Keller and Swanson, 1979).

Additionally, the presence of CWD can alter channel bedform morphology by creating step sequences (Thompson, 1995), thereby decreasing flow velocity, altering sediment storage, and reducing channel gradient between steps (Heede, 1975; Swanson et al., 1984; Hogan, 1987). In high gradient systems, areas upstream of CWD obstructions act as sinks for sediment accumulation (Gurnell and Gregory, 1995). Thompson (1995) observed that pools created upstream of these woody steps provided the most stable sites for the aggradation of fine-grained sediments because of backwater effects resulting from a newly established local base level. Steps created by CWD contribute to the formation of the majority of deep pools within a fluvial network (Lisle, 1987). Thompson (1995) found that the plunge pools downstream of CWD structures often store coarser-grained sediments. Steps created by CWD can store approximately ten to fifteen times a stream's annual sediment yield (Megahan and Nowlin, 1976; Swanson and Lienkaemper, 1978; Megahan, 1982; Swanson and Fredriksen, 1982), as well as provide temporary storage for pulses of newer sediments introduced to the system (Keller and Tally, 1979).

Because CWD has the potential to alter sediment deposition, initiate channel scour, help determine bankfull width and depth, and modify bedform spacing and type it has the potential to alter both micro and macromorphology and water chemistry in fluvial systems, leading to significant implications for habitat structure, ecosystem functionality, and sediment dynamics.

### B. Destruction of riparian vegetative cover

High wind speeds associated with tornadoes can destroy riparian canopy cover, removing shade cover vital to the regulation of maximum daily water temperatures (Rutherford et al., 2004). While factors such as topography, stream discharge, and streambed interactions certainly contribute to temperature regimes within a stream, the greatest influencing factor, in regards to temperature flux, is incoming solar radiation (Cassie, 2006). Webb and Zhang (1997) found net radiation (solar and net longwave radiation) to be the most influential component in temperature control, accounting for 56% of total heat gains within the stream. The results found by Webb and Zhang demonstrate how important riparian shade is to temperature regulation (Webb and Zhang, 1997). In addition to providing shade, riparian vegetation also dictates air temperature, humidity, and wind speed, all of which impact water temperature (Rutherford et al., 1999; Benner and Beschta, 2000). Riparian vegetation is more influential on smaller streams than larger rivers because total closure of the canopy over smaller streams is possible. Therefore, the presence of riparian vegetation in smaller streams plays a larger role in the regulation of stream temperatures (Cassie, 2006). Rutherford et al. (2004) found that the presence or absence of dense riparian vegetation in 2nd order headwater streams caused water temperature fluctuations of 4-5 °C. Graynoth (1979) found that complete removal of riparian vegetation resulted in an increase of maximum daily summer temperatures by 6.5 °C. Feller and Kimmins (1984) found that a 66% removal of riparian vegetation is capable of increasing mean daily water temperatures by 5°C. Depending on factors, such as magnitude of the storm or proximity to impact, riparian vegetation following a tornado may be completely or partially removed resulting in temperature variability throughout the system. Removal of riparian vegetation can alter a stream's thermal regime for 5-15 years (Johnson and Jones, 2000; Murray et al., 2000).

In addition to removing zones of shade, a key influence on maximum daily temperatures, the removal of riparian vegetation also results in increased sediment supply. The presence of riparian vegetation, particularly root masses, provides essential bank stabilization for many fluvial systems (Beschta, 1997; Pollen et al., 2004). A large influx of sediment to a fluvial system can greatly alter channel geometry, resulting in a shallower stream channel (Benda et al., 2003). In turn, shallow streams are more susceptible to temperature variations because the rate of temperature change is inversely proportional to depth (Rutherford et al., 2004), making them particularly prone to increased water temperatures due to further water shallowing by increased sedimentation and/or the influx of CWD.

Intense wind speeds associated with tornadoes create a high probability of partial or total removal of riparian vegetation. Riparian vegetation provides essential shade to streams, which intercepts incoming solar radiation. The loss of riparian vegetation initiates bank instability and accelerates the rate of recruitment of CWD into streams, decreasing channel gradient; a condition associated with increased water temperatures. Total or partial removal of riparian vegetation has significant implications on in-stream temperature regimes, ecological processes, and the overall biotic health of a stream.

### C. Ecological implications of riverine tornado impact

The input of CWD, as well as the removal of riparian vegetation, has profound impacts on the ecological health of a stream. The addition of CWD, as well as the removal of riparian vegetation, can affect a range of aquatic organism from invertebrates (Hawkins et al., 1997; Cox and Rutherford, 2000) to fish species (Lee and Rinne, 1980). Water temperatures can ultimately dictate an aquatic organism's distribution within the stream (Coutant, 1977; Wichert and Lin, 1996), growth rates (Crisp and Howson, 1982; Markarian, 1980), and timing of fish movements (Jensen et al., 1998). According to Van't Hoff's Law, for every 10°C increase in water temperature biotic activity doubles (Caissie, 2006). This can become detrimental as increased biological activity is associated with increased oxygen consumption; a problematic situation in systems experiencing already reduced amounts of dissolved oxygen due to increased water temperatures (Brown and Krygier, 1967).

While CWD can influence fluctuations in water temperatures, it can also create habitat in the form of regeneration sites for seedlings, as well as direct habitat for fish and invertebrates, and increases the complexity of geomorphic and biotic conditions; thus strengthening community structure (Collins et al., 2012). Hydrodynamic and bioenergetics models have found that the addition of CWD to a fluvial system could potentially quadruple the available growth area for some fishes, particularly in the formation of pools (Hafs et al., 2014). An increase in pool formation comes at the expense of depleting riffles and runs, which can be detrimental to particular fish species and invertebrates (Gurnell and Sweet, 1998). A better understanding of the morphological and temperature characteristics of a stream following a tornado will help river managers and planners make more informed decisions concerning stream management and restoration post-tornado impact.

## III. Case Study: Abrams Creek, Great Smoky Mountains National Park (GSMNP), Tennessee

### A. Introduction

The addition of CWD following a tornado may initiate substantial morphological changes to a fluvial system, which prior to this research, have been unstudied. The two stream reaches in Abrams Creek examined for this investigation have similar watershed, land use, and geologic characteristics. In April of 2011 an EF4 tornado, producing wind speeds in the range of 267-322 kmph (NOAA, 2014b) touched down in the southwestern region of GSMNP. The National Park Service did not remove any of the damage created by the tornado after the event occurred, providing an exceptional opportunity to study the unaltered effects of tornadoes in fluvial systems and their longevity on the fluvial landscape. One of the study reaches was in the direct path of the tornado, while the other was not and is being included as a reference reach. I used the following hypothesis to examine morphological impacts following a tornado:

**H1: In-stream pools within the upstream, directly impacted reach will differ in width, depth, and length from the pools within the downstream reach that was not directly impacted by the tornado.**

*H1 Prediction: As a result of localized erosion resulting from the presence of CWD, the pools within the upstream reach will be wider than the pools within the downstream reach. Additionally, the pools in the upstream reach will be deeper than the pools in the downstream reach as a result of scour pools associated with a greater frequency of CWD steps. Lastly, as a* *result of slack-water or back-pooling effects associated with CWD structures, pools within the upstream reach will be longer than the pools in the downstream reach.*

### B. Study Location

Abrams Creek lies within the Blue Ridge Physiographic Provence and flows through the remote southwestern corner of GSMNP. This area of the park was in the direct path of an EF4 tornado on April 27, 2011, which carved a path approximately 25 km long and 600 m wide through the park, including segments of Abrams Creek. Abrams Creek is a fourth order stream (Strahler classification) and drains approximately 230 square kilometers. Abrams Creek originates in the region of the GSMNP known as Cades Cove at the confluence of Anthony Creek and West Prong Anthony Creek. Abrams Creek flows west/southwest through the park before draining into Chilhowee Lake. Using remote sensing data, I selected a stream reach with evidence of direct tornado impact and a stream reach with little to no evidence of direct tornado impact (Figure 1).

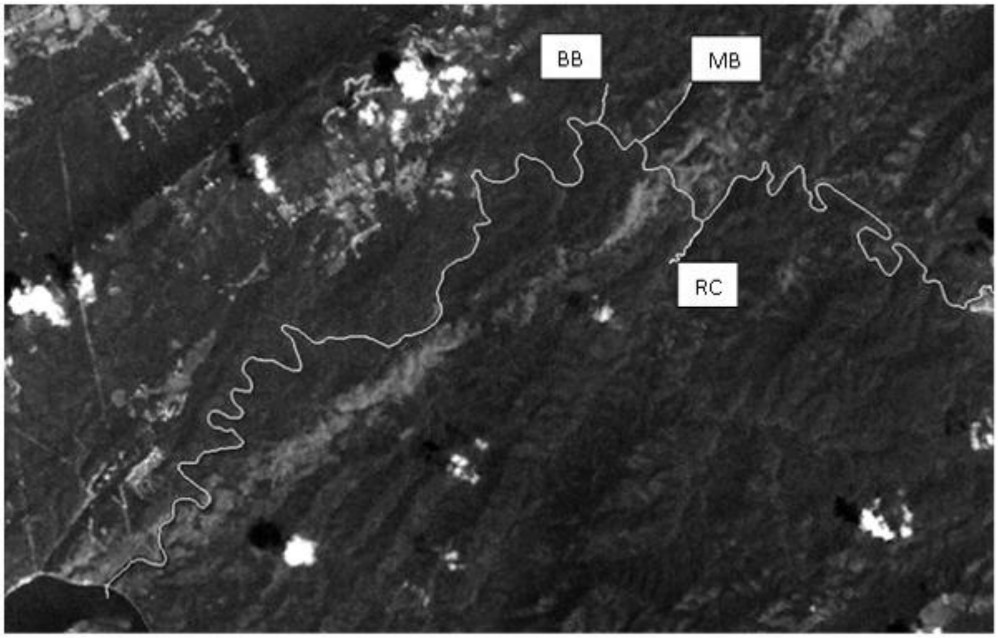


Figure 1. Aerial photograph of the EF4 tornado's path through the southwestern portion of GSMNP, TN (USGS, 2015), which spans ~25 km from the southwest to the northeast. The tornado path is visible in the image as a white strip and can be seen passing over Abrams Creek between Rabbit Creek (RC) and Mill Branch (MB).

The study sites for this research are mixed bed channels (bedrock channels with interspersed alluvial sections). A gauging station does not exist on Abrams Creek, but a gauging station does exists within the GSMNP on the nearby Little River, located near Townsend, Tennessee. The location of this USGS gauging station drains an area comparable to Abrams Creek and is used here to provide insight into Abrams Creek's hydrologic regime. Using mean annual discharge data provided by the USGS gauging station on Little River near Townsend, TN, I determined mean annual discharge to be approximately 8.03 cubic meters/second. Maximum rainfall typically occurs during July, while minimum rainfall typically occurs during September or October (Griess, 1987).

The upstream reach, which was directly impacted by the tornado, is located between two tributaries of Abrams Creek: Rabbit Creek (RC) and Mill Branch (MB). The downstream reach, which was not directly impacted by the tornado, begins downstream of Buckshank Branch (BB), a tributary to Abrams Creek. Both reaches are approximately 1 km long and are separated by an approximately 1 km "buffer zone" located between Mill Branch and Buckshank Branch (Figure 2).

Both reaches possess similar forest structure and are comprised of evergreen and deciduous tree species. Land use in the GSMNP, prior to park establishment in 1934, outlined by Pyle (1985) in a special report for the National Park Service, mapped the occurrence of human-induced disturbance throughout the park. The digital version of this report included 5 mapped categories including settled, heavily disturbed, lightly disturbed, selective cutting, and undisturbed. Lafrenz (2005) redefined portions of the original mapped areas within the park and reclassified the five categories into pristine, lightly disturbed, heavily disturbed, and settled. The location of the

Abrams Creek study sites, in the western portion of the park, is located within the pristine classification (Figure 3).

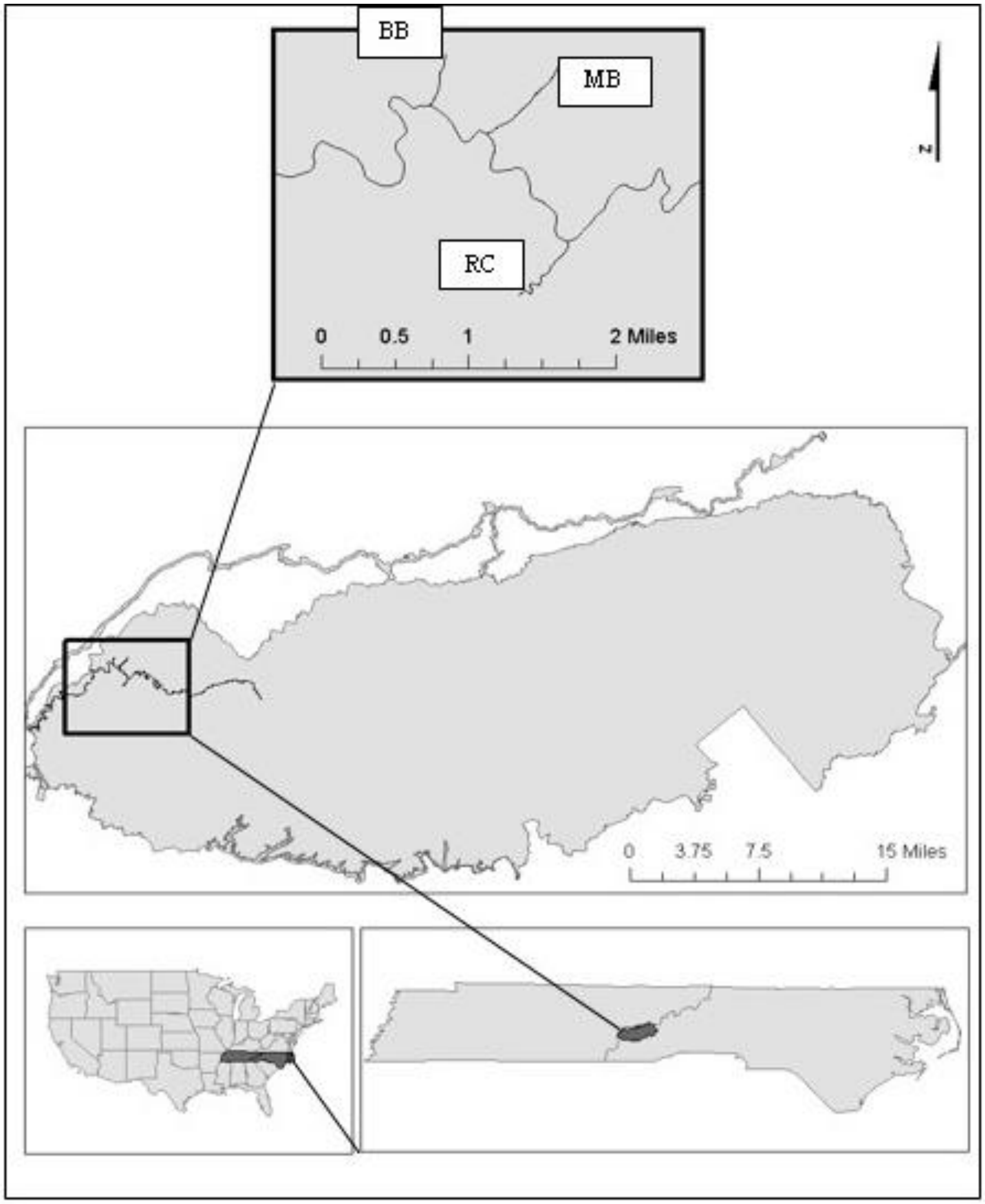


Figure 2. Location of the upstream and downstream reach within the GSMNP. The upstream reach (~1 km) is located between Rabbit Creek (RC) and Mill Branch (MB). The downstream reach (~1 km) begins downstream of Buckshank Branch (BB).

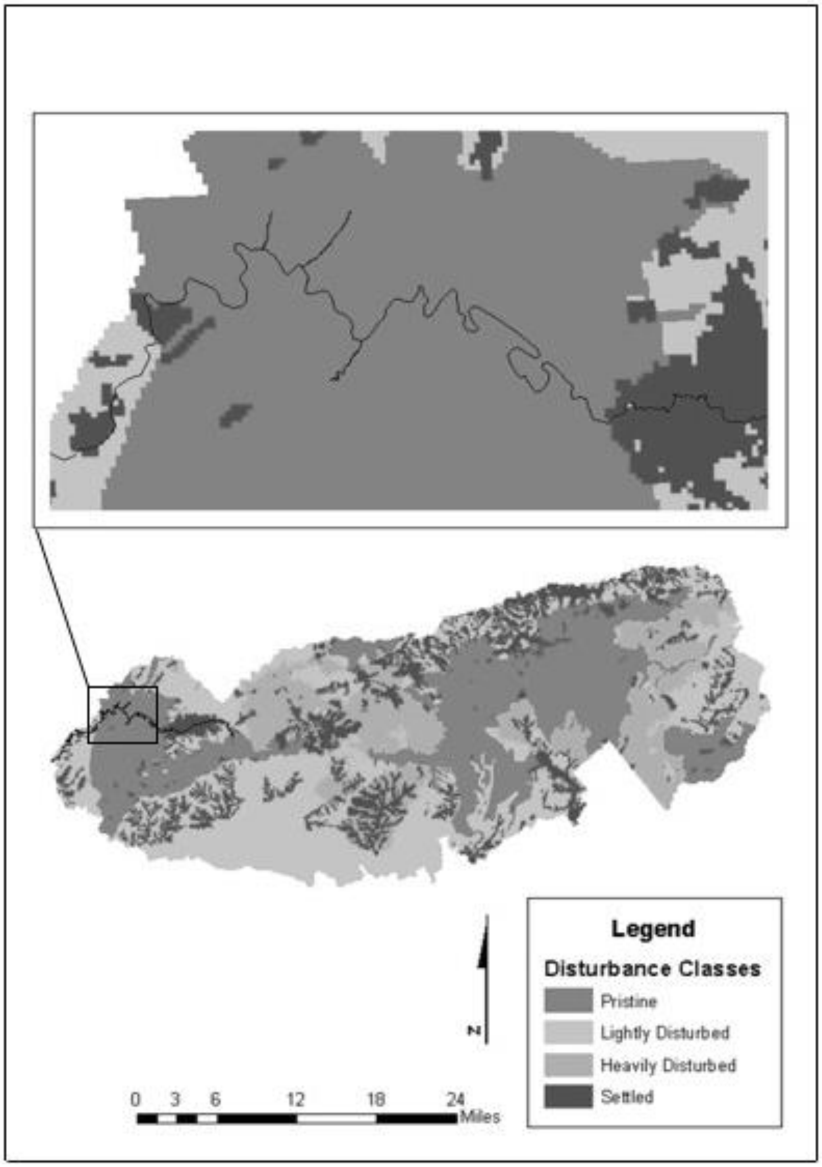


Figure 3. Map of the disturbance history throughout the GSMNP. Both study reaches are located within the pristine classification.

This area was originally classified as selectively cut because it was devastated by a previous chestnut blight and reported as "lacking in a wholly undisturbed appearance" (Pyle, 1985). Due to lack of anthropogenic disturbance in this area, Lafrenz (2005) reclassified this area as pristine. Both reaches are situated within the Walden Creek Geologic Group. Within this classification, the upstream reach is found within the Shields Formation; a conglomerate consisting of polymict pebbles and cobbles interbedded with pebbly sandstone. The downstream reach is located within the Wilhite formation, in a unit characterized by laminated metasiltstone, fine-grained sandstone, conglomerate, and carbonate rocks. The conglomerates within this geologic formation closely resemble the rocks of the Shield Formation; they are graded and contain roughly 80 percent vein quartz clasts (Southworth et. al, 2012). While the underlying geologies of these reaches are not identical, they are comparable in terms of their erodibility. I conducted strength of hardness tests, as per Compton (1985), on rock outcroppings within each reach. The results of these tests indicated similar hardness, suggesting similar erodibility. Both reaches are ideal locations for this study not only because they have very similar disturbance history, hydrologic, geomorphic, land use, and geologic characteristics but also because none of the CWD accumulated following the tornado has been removed.

## C. Methods

For this study, I determined the effects of tornado impact on channel morphology, specifically width, depth, and length characteristics of pools. For this study CWD is defined as woody material ≥ 10 cm in diameter and ≥ 1 m in length (Hart, 2003; Magilligan et al., 2008). Pools are widely defined as deep areas with slow velocities at low stage (Thompson, 2002). I identified pools for measurement based on visual assessments of flow and geomorphic assessments of the channel bed. Areas with increased depth, determined by wading the stream, and slow velocities were considered for measurement. I surveyed all pools within both reaches that met this criteria (i.e. deep areas with slow velocities), whether CWD was present or absent. I measured pool width, depth, and length, for each pool within both the upstream and downstream reaches. I surveyed the upstream reach during July 2015 and the downstream reach during October 2015. July’s mean daily discharge data, provided by the USGS gauging station on Little River near Townsend, TN, indicated below average discharges for 5 days prior to sampling. October’s mean daily discharge data, per the USGS gauging station on Little River near Townsend, TN, indicated above average discharges, associated with precipitation events, for 5 days prior to sampling. Because of elevated water levels, pools were not determined by water depth or height, but rather by geomorphic parameters, specifically transitions (increases and decreases) in channel bed slope. I conducted a standard *t*-test for hypothesis testing purposes, specifically to determine if any differences exist between the pool morphology associated with the two different study reaches.

### 1. Length

To determine the influence of tornado impact on pool length, I calculated the maximum length (ML) of each pool within the upstream and downstream reach (Figure 4). After wading the pool unit to delineate the start and end locations of the pool based on perceived decreases (start of pool) and increases (end of pool) of bed slope, I used a laser range finder to determine the furthest extent of the pool unit. The minimum distance calculated by the laser range finder used in this study is 10 meters. All pools measured ≥10 meters at maximum length. I recorded measurements for each pool within both the upstream and downstream reach.

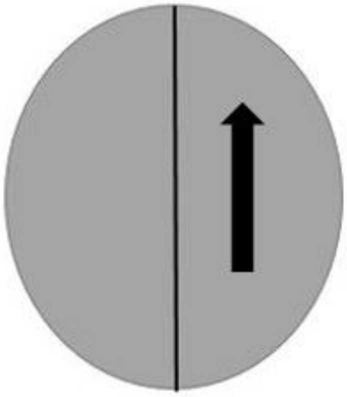


Figure 4. Diagram illustrating how I measured maximum length (ML) for this study. The grey polygon represents the shape of the pool while the black line indicates where I measured maximum length for this study. The black arrow indicates the direction of flow.

## 2. Width

To assess the influence of tornado impact on pool width, I calculated an average width (AW) measurement for each pool within the upstream and downstream reach. I waded the edges of each pool and based on perceived increases and decreases in bed slope, I determined the left and right edges of each pool at approximately the ¼, ½, and ¾ lengths of the pool (Figure 5) and measured pool width at each of these locations using a laser range finder. Because some pools measured less than 10 meters (the laser range finder's minimum), I laid a rod, measuring 1 meter in length, end over end to determine the width of the pool. I calculated an average of these three measurements to determine an average width for each pool within each reach.

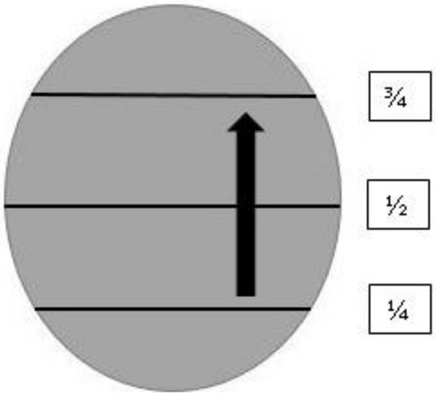


Figure 5. Diagram illustrating how I measured width for this study. The grey polygon represents the shape of the pool while the black lines indicate where I took width measurements. I averaged the three measurements to calculate width for this study. The black arrow indicates the direction of flow.

## 3. Depth

To better understand the influence of tornado impact on pool depth, I calculated residual pool depth (RPD) for each pool within the upstream and downstream reaches (Figure 6). The metric of RPD provides a depth measurement independent of discharge, which this study required since sampling of the two study reaches occurred during two different months. I determined RPD using methods outlined by Lisle (1987). The calculation is as follows:

RPD = maximum pool depth (MPD) – depth at riffle crest (DRC) (Equation 1)

I measured MPD and DRC using a standard folding ruler. I determined MPD, the deepest area within the pool, by wading the pool and taking depth measurements until I discovered the deepest area. Because the depth at downstream riffles is rarely uniform, and often varies in depth, I measured the DRC at an area best representative of the depth at the downstream riffle. I identified riffles based on changes in bed slope and particle size. I calculated RPD for each pool within the upstream and downstream reach.

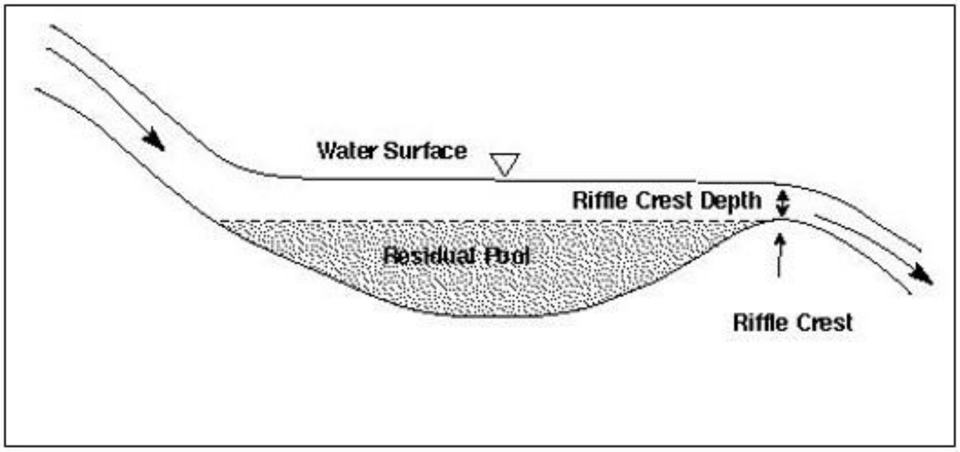


Figure 6. Diagram illustrating the Residual Pool Depth (RPD) method (Hilton and Lisle, 1993), outlined by Lisle (1987), I used to calculate pool depth for this study.

### 4. Hypothesis testing

I used a *t*-test to compare each group of data (i.e. length, width, and depth) to the same group within the other reach to determine if pools differ between the upstream and downstream reaches.

## D. Results

Qualitative surveys of the study sites revealed obvious differences between the two reaches. Within the upstream reach, the surrounding valleys and riparian zone still displayed evidence from the 2011 tornado impact, including severely damaged branches and snapped trees, (Figure 7).

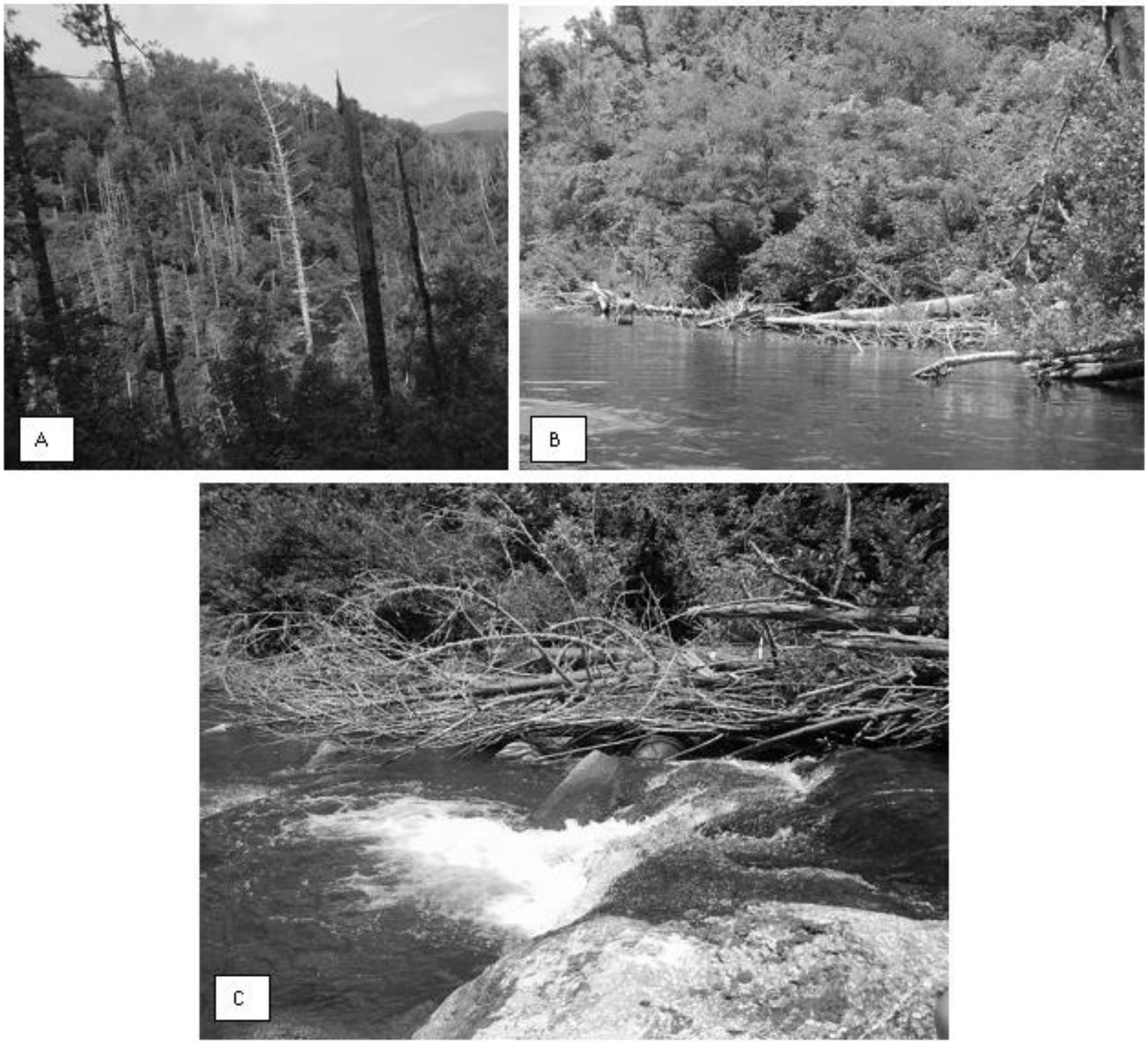


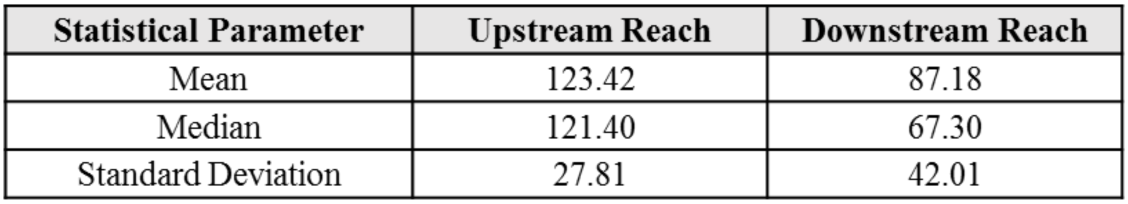
Figure 7. View of Abrams Creek's surrounding valley in the upstream reach which was directly impacted by the tornado. Severely damaged branches and snapped trees are evident (A). Evidence of large quantities of woody debris along the banks and in the riparian zone of the upstream reach (B and C).

I observed little wind damage in the downstream reach, but I did see some evidence of disease and/or pests damage to trees in this reach. Within the upstream reach, debris completely filled tributaries draining into Abrams Creek (Figure 8). Tributaries in the downstream reach showed little evidence of disturbance. Despite a relatively wide channel width, two CWD structures spanned the entire channel in the upstream reach (Figure 9).

Figure 8. Debris dams in Abrams Creek tributaries, within the upstream reach. Image was taken at the mouth of the tributary looking upstream.

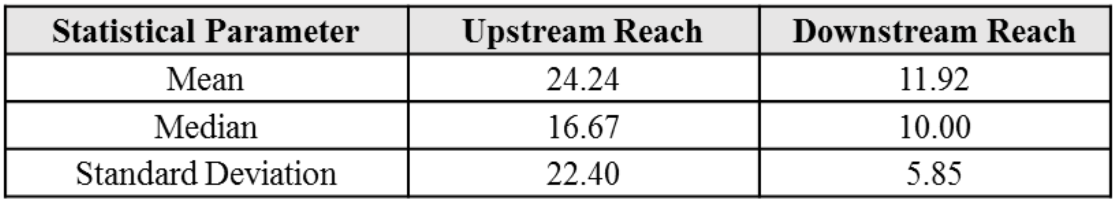
Figure 9. CWD structure in the upstream reach, spanning the entire width of the channel. Image was taken upstream of the single log jam, facing downstream.

The downstream reach had one CWD structure spanning nearly the entire channel, but this tree appeared to be the result of disease and/or pests rather than wind damage associated with the tornado. Other visually identified differences included a shift in sediment particle size with more fine sediment observed in the downstream reach. In total, I sampled 11 pools in each kilometer-long reach. Descriptive statistics for residual pool depth (Table 2), average width (Table 3), and maximum length (Table 4) measurements for each pool within the upstream and downstream reaches are illustrated below.



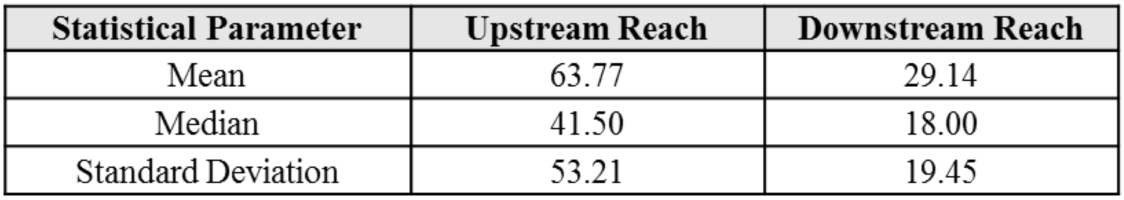
| Statistical Parameter | Upstream Reach | Downstream Reach |
|---|---|---|
| Mean | 123.42 | 87.18 |
| Median | 121.40 | 67.30 |
| Standard Deviation | 27.81 | 42.01 |

Table 2. Descriptive statistics for residual pool depth in the upstream and downstream reaches.



| Statistical Parameter | Upstream Reach | Downstream Reach |
|---|---|---|
| Mean | 24.24 | 11.92 |
| Median | 16.67 | 10.00 |
| Standard Deviation | 22.40 | 5.85 |

Table 3. Descriptive statistics for average width in the upstream and downstream reaches.



| Statistical Parameter | Upstream Reach | Downstream Reach |
|---|---|---|
| Mean | 63.77 | 29.14 |
| Median | 41.50 | 18.00 |
| Standard Deviation | 53.21 | 19.45 |

Table 4. Descriptive statistics for maximum length in the upstream and downstream reaches.

The number of pools counted in each reach, did not differ between the upstream and downstream reaches. The results of the *t*-test showed increased depths of pools within the upstream versus the downstream reach, indicated by a *p* value = .027. Statistical results for the width and length of pools fell outside of the 95% confidence bounds set for this study, indicated by a *p* value = .093 for width and .056 for length.

## E. Discussion

This study aimed to measure the geomorphological effects, if any, of a tornado impact on a fluvial system. Because pools are highly responsive to disturbance events, this study focused on pools.

Pools in the upstream reach are deeper than the downstream reach (*p* value = .027). Discharge and velocity increase downstream, as does shear stress, and because of this pool depth should also increase downstream.  Despite this, the deepest pools in this study occurred in the upstream reach. To eliminate the possibility that the difference in residual pool depth resulted from an increase in channel confinement, I calculated an average channel width from GoogleEarth imagery for the locations of the four deepest pools within each reach. The average channel width for the deepest pools measured approximately 19 m in the upstream reach and 21 m in the downstream reach. Similarities in average channel width at the deepest pools in both the upstream and downstream reach, suggests the significantly deeper pools in the upstream reach are not a result of channel confinement, but rather, differences created by the tornado.

The deeper pools within the upstream reach and shallower pools occurring downstream are likely a result of increased stream energy initiating hydraulic erosion and an increase in supply of sediment to the downstream reach. The extreme winds associated with a tornado event can remove riparian vegetation, resulting in an increase in runoff during subsequent storm events. Increased runoff can provide a pulse of energy capable of increasing channel scour and deepening stream pools. In addition to directly modifying channel morphology in river channels located within their impact zones (the upstream reach in this study), it appears tornado impacts also can be translated to downstream reaches via sediment connectivity evidenced in this study by decreased pool depth downstream.

The initial input of CWD following a tornado can initiate CWD jams which increase sediment storage. Following CWD jam failure initiated by subsequent storm flows, a pulse of sediment may be released downstream where it can alter channel bedform morphology by in-filling pools downstream. The uprooting of trees by tornadoes greatly increases bioturbation and soil displacement, presenting a viable source of sediment to be introduced to fluvial systems as run-off and/or sheet-wash. Phillips et al. (2015) found that uprooting, associated with an EF2 tornado, resulted in a mean bioturbation rate of 205 $m^3$ $ha^{-1}$ (about 240 t $ha^{-1}$). Increased bioturbation is particularly significant on hillslopes as it presents a readily available source of sediment to fluvial systems during subsequent rain events. As sediment load increases, more fine sediment becomes available to fill in pools and can potentially reduce residual pool volume by up to one-half (Lisle and Hilton, 1992). CWD structures which previously resided in the upstream reach may have acted as storage sites for sediment. High flow events likely caused CWD jam failure resulting in a pulse of fine sediment to the downstream reach. Brambrick (2013) reported woody debris, in a coastal Oregon alluvial bedrock stream, ranging from .1 m-1.7 m in diameter and 1.0 m-9.87 m in length is capable of being mobilized during a 2-year flood event. I estimated potential recurrence intervals for Abrams Creek using 50 years of nearly continuous annual peak stream flow data (1964-2014, 1994 was excluded due to erroneous data) from a nearby USGS gauging station on Little River near Townsend, TN. Since 2011, two events have exceeded the 2-year recurrence interval, outlined by Brambrick (2013) as capable of moving significant amounts of CWD, including the 3.19 year event in 2013 and the 2.43 year event in 2014. These events present a likely explanation for the lack of CWD structures within the study reaches and the distinct increase in fine sediment accumulation (changed from cobble and gravel to gravel and coarse sand) observed in the downstream reach. The increase in sediment in the downstream reach is likely responsible for the decrease in pool depth.

Pool width fell outside the 95% confidence bounds set by this study (*p* value = .093). Flow deflection associated with CWD has been observed to accelerate localized erosion (Hart, 2003; Daniels and Rhoads, 2003; Keller and Swanson, 1979), but I observed the majority of CWD in Abrams Creek positioned along the banks where its primary function is bank armoring, which prevents bank erosion and the development of wider pools. Localized erosion from the presence of CWD is not as severe likely because of the combined effects of bank armoring by large caliber sediment/bedrock and CWD and the relatively large width of Abrams Creek. Modifications to pool width would likely be more prominent in a narrower stream channel because CWD is capable of establishing itself across the entire width of the channel, perpendicular to flow; conditions which have previously shown to initiate the most geomorphic change within a fluvial system (Bergmeier et al., 2013).

Pool length also fell outside the 95% confidence bounds set by this study (*p* value = .056). Increased pool length is largely a result of slack-water effects associated with back-pooling that occurs upstream of CWD structures (Heede, 1975; Swanson et al., 1984; Hogan, 1987). The lack of observed CWD structures suggests pool length could return to pre-tornado conditions providing no future influxes of CWD. But substantial debris residing in the tributaries draining into Abrams Creek has yet to reach the main channel, meaning additional CWD recruitment is likely and the potential for future geomorphic change to pools is high.

My findings suggest tornadoes are a viable source of disturbance in fluvial systems. Geomorphic disturbance can be assessed under Gares’ et al. (1994) framework, adapted from White (1974), in which changes to geomorphic systems are evaluated based on temporal characteristics, such as frequency, duration, speed of onset, and temporal spacing, as well as spatial aspects, including areal extent, and spatial dispersion, and magnitude. Under this framework, compared to other wind events, such as tropical cyclones, tornadoes can be generalized as spatially localized with concentrated intensities capable of greater geomorphic impacts per unit area (Phillips et al., 2008; Phillips et al., 2015). The rate law of fluvial geomorphology (Graf, 1977) describes a potential geomorphic response sequence to a disturbance event, including a, reaction time, a relaxation time, and the establishment of a new equilibrium. Reaction time is defined as the period in which changes following a disturbance are internalized by the system, and the relaxation time is defined as the period in which the system adjusts to new conditions onset by the disturbance. Evidence of significant differences in pool depth between upstream and downstream reaches, which contradict established longitudinal trends in pool depth as a function of increased discharge and in absence of land use differences, suggest that geomorphic adjustment is ongoing in Abrams Creek several years after the 2011 tornado event. Furthermore, additional pulses of CWD and sediment supplies, stored on the hillslopes and within Abrams Creek's tributaries, could initiate or perpetuate changes to in-stream morphological units, essentially prolonging the reaction period and meaning that ecological structure and function may continue to be altered into the future.

Disturbance is viewed by many through the scope of ecological impacts (Poff 1992; Stanley and Fisher, 1992; White and Pickett, 1985). The geomorphic disturbance in Abrams Creek associated with tornado impact that have yet to materialize in the main channel but could happen in the future because of the post-tornado condition of tributary streams, includes additional influx of CWD, increased suspended sediment loads from the bioturbation of hillslopes that occurred during the event, channel scour and pool deepening from CWD recruitment, have both positive and negative implications for ecosystem structure and biological communities. For example, increased suspended sediment loads and sediment deposition negatively affect stream producers, macroinvertebrates, and fish species (Wood, 1997). Impacts to primary producers associated with increased sediment loads include reducing light penetration that ultimately reduces photosynthesis (Van Nieuwenhuyse and LaPerriere, 1986) and preventing the establishment of algal colonies on the substrate (Brookes, 1986). Macroinvertebrates are also subject to impacts from increased sediment loads, including respiration complications (Lemly, 1982) and preventing filter feeding (Aldridge et al., 1987). Lastly, the effects of increased sediment loads on fish species include reducing habitat for spawning (Chapman, 1988; Moring, 1982), food availability (Bruton, 1985; Doeg and Koehn 1994; Gray and Ward 1982), and, in some species, efficiency of hunting (Bruton, 1985; Ryan 1991). Other geomorphic changes resulting from the tornado impact, such as the input of CWD and the formation of deep pools, increases geomorphic heterogeneity, providing complex habitat for fish species as well as creating water temperature stratification which provide cooler water temperatures for fish populations, such as trout, which are otherwise stressed by periods of elevated water temperature (Mathews et al., 1994). Understanding the geomorphic, ecological, and biological implications following an intense localized disturbance, such as a tornado, provides much needed information for making river management and conservation decisions after a tornado disturbance event occurs.

## IV. Conclusion

Much like tropical cyclones, tornadoes are a natural disturbance mechanism capable of significant modifications to river systems. Prior to this research, the effects of tornadoes on fluvial systems have been completely unstudied. Considering the frequency and severity of tornadoes as well as the research gap that exists in regards to the topic, this study sought to develop a better understanding of fluvial changes following tornado impact. Based on the results of the case study conducted in the GSMNP, Tennessee, tornadoes are responsible for geomorphic change within rivers, specifically increased pool depth in an upstream reach proximal to the impact zone and decreased pool depth in a downstream reach distal to the impact zone. Qualitative analysis of the study location revealed significant disturbance to the riparian zone and surrounding valleys within the upstream reach owing to the tornado's occurrence. Based on the modifications observed following other wind disturbance such as tropical cyclones it is to be expected tornadoes possess the potential to alter other aspects within the fluvial system such as temperature regime or chemical composition.

Tornadoes, localized in spatial extent and short in duration, have concentrated intensities capable of inputting substantial amounts of CWD and sediment into the fluvial system. Evidence of morphological changes to Abrams Creek several years after the study suggests the system is still trying to reach a new equilibrium. Qualitative assessments of the upstream reach suggest pulses of debris still residing on the hillslopes and in the tributaries draining into Abrams Creek may initiate or further perpetuate geomorphic changes within the system. The geomorphic changes observed in this study, as well as the potential modifications which remain unstudied, can have profound ecological implications in fluvial systems, affecting the entire food chain, from primary producers to macrovertebrates. This study contributes to the understanding of the impacts of tornadic events and offers insight into other potential sources of modification. A firmer understanding of both the geomorphic and ecological impacts of tornadoes on river systems benefits river managers and planners responsible for the ecological integrity, restoration, and general monitoring of fluvial systems.

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