The Effects of Late Holocene Climate Changes on Flood Frequencies and Magnitudes in Central Appalachia

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of the requirements for the degree
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This thesis titled
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Central Appalachia

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Discerning the effect climate change has on flood frequencies and magnitudes is tremendously important; because of the devastating impact large floods have on communities. Slackwater sediments in Colonial Acres Cave (CAC) preserve a 4,000 year-long flood history for the Greenbrier River in West Virginia and the slackwater stratigraphy is correlated with changes in Holocene paleoclimate proxies ($\delta^{13}$C and $\delta^{18}$O), and indirectly with low-latitude sea surface temperatures (SSTs). However, a significant correlation was not found between historic SSTs and Greenbrier River flooding. Based on hydraulic modeling of the Greenbrier River, a 1,600 m$^3$ s$^{-1}$ discharge is needed to inundate and deposit sediments within CAC and few historic floods have met or exceeded this threshold. Therefore, the lack of modern correlations may reflect the quantity and quality of existing flood records rather than the long-term relationship between climate(s), local flooding, and sediment deposition in CAC.

Approved: _____________________________________________________________

Gregory S. Springer

Associate Professor of Geological Sciences
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1.0 Introduction

What characteristics define the dynamic relationships between climatic and earth surface processes? As we rapidly change landscapes to accommodate growing populations, it is imperative to gain an understanding of how climate change will affect processes such as stream erosion and sedimentation because these processes literally affect the foundations of society. Based on the average number of fatalities over 10 and 30 year time periods, heat waves, hurricanes and flood events resulted in the first, second and third highest number of fatalities in the United States, respectively (NOAA, 2009). Thus, discerning how climate change (warming) will affect the magnitude and frequency of future flood events is crucial. However, the frequencies of extreme floods and droughts may be underestimated in global-scale climate change models because climatic and hydrological responses vary regionally (Knox, 1993, 2000; Noren et al., 2002; Beasonen et al., 2008). Hence, there is great need for regional studies of flood and streamflow regimes.

1.1 Background

In humid, temperate regions paleoflood studies are complicated by rapid decay and erosion of surface deposits needed to reconstruct stream behaviors (Kochel and Baker, 1988; Springer and Kite, 1997; Kite et al., 2002; Springer, 2002). Thus, most paleoflood studies have been conducted in arid regions, where surface deposits are extensive and well preserved (Gillieson et al., 1991; Springer, 2002). Few paleoflood studies have been done in the Eastern Continental U.S. due to a poorly preserved and incomplete flood record (Kite et al., 2002). However, caves can serve as repositories of
geomorphic information and have been used by geomorphologists to reconstruct flood histories (Kochel and Baker, 1988; Gillieson et al., 1991; Springer et al., 1997; Kite et al., 2002; Springer, 2002; Springer et al., 2008, 2009), quantify long-term river incision rates, continental-scale changes in river networks, and to determine ancient climate fluctuations (Granger et al., 2001).

### 1.1.1 Flooding in Appalachia

Flood hazard assessment is often overlooked in rural Appalachia until a destructive flood occurs, partly because people are impoverished and population densities are low. In addition, most developable land in Appalachia is adjacent to rivers and streams (Knocke and Kolivras, 2007). The Cheat and Greenbrier Rivers in West Virginia severely flooded local communities in 1985 and 1996, but little flood mitigation has been done in the region. Determining the effect that global warming will have on stream hydrologies in Central Appalachia can help impoverished communities protect and prepare themselves from future climate changes.

### 1.1.2 Flooding of the Greenbrier River

The Greenbrier River watershed straddles the Appalachian Plateau and Valley and Ridge Physiographic Provinces and is the longest un-dammed river east of the Mississippi River. On January 25 and 26 of 2010, heavy rain combined with snow melt caused some of the worst flooding along the Greenbrier River since the purportedly 100-year flood in 1996. Hundreds of residents in Alderson and Ronceverte were asked to evacuate their homes and businesses due to the rising water (The Associated Press, 2010; West Virginia Media, 2010). On January 26, 2010, stage and discharge at Alderson
peaked at 5.71 and 1,528 m³ s⁻¹, respectively making this the sixth largest flood recorded since 1896 (http://waterwatch.usgs.gov/?m=mfr&r=us&ym=201001). One resident who has lived in Ronceverte, West Virginia for the last 40 years commented, "They say it's a 100-year flood, but it's happened three times in the past 15 years," (West Virginia Media, 2010). Based on the historical record, the actual recurrence interval of the 1985 and 1996 floods are 57 and 114 years, respectively. Both the 1985 and 1996 floods resulted in stream gage heights of 7.3 meters.

The third flood this resident may be referring to is a 5-year flood that occurred February 23, 2003 (http://waterdata.usgs.gov; The Charleston Gazette, 2003). It had a peak discharge 1,306 m³ s⁻¹ and reached a stream gage height of 5.2 meters. The flooding resulted from rain and snow-melt in combination with unusually warm temperatures (The Charleston Gazette, 2003). These conditions are the most common reason for the devastating floods that occur along the Greenbrier River and other rivers in the region, but as indicated by the affected resident’s comment about three 100-year floods in 15 years there is much uncertainty about flood frequencies (because of a lack of data).

The United States Senate recently approved almost $111 million dollars to aid flood mitigation efforts and studies in West Virginia (The Register-Herald, 2009). One of several projects to receive aid was the Marlinton flood protection project, which was given $1.42 million to build levees and floodwalls along the Greenbrier River (The Register-Herald, 2009). This is the most extensive effort to mitigate flooding issues along the Greenbrier River to date. Marlinton was one of the many towns along the Greenbrier River that experienced extensive damage during both the 1985 and 1996
floods. Marlinton lies 60 miles northeast of Alderson and Ronceverte, which were also devastated by the 1985 and 1996 floods.

The Greenbrier River has been monitored by the USGS since 1886. The largest flood events to date occurred in 1985 and 1996 with peak discharges of 2,567 and 2,664 m$^3$ s$^{-1}$, respectively. Due to the limited historical record, extremely large flood events skew estimates of flood recurrence intervals and probabilities. This makes the cost effectiveness of flood mitigation efforts difficult to estimate. Thus, more extensive paleoflood studies need to be conducted to calculate more accurate flood recurrence intervals and probabilities.

1.2 Paleoflood Reconstructions

The best locations for paleoflood studies are areas where slackwater deposits are well preserved, where flood discharges are large, and rivers are incised into bedrock (Gillieson et al., 1991). Slackwater deposits are formed by the deposition and accumulation of suspended sediments during floods, primarily in protected areas with significantly decreased flow velocities (Baker, 1987; Kochel and Baker, 1982). Slackwater sediments are generally well sorted, fine grained sand and silt, and often contain flotsam, which is woody and man-made debris, and other materials capable of being transported by a flood. Undisturbed slackwater sediments can be used to recognize individual flood events and the presence of modern detritus can be used to distinguish recent from possibly ancient flood deposits. Other slackwater deposits, such as silt lines, similar to bathtub rings, establish minimum flood stages (Baker, 1987; Springer, 2002),
where stage is height of water surface above an arbitrary datum, but are unlikely to persist as long as inorganic sediments.

**1.2.1 North American Case Studies**

Small changes in climate can cause large and sometimes abrupt changes to the magnitudes and frequencies of floods, such as occurred during the Holocene of the Upper Mississippi Valley (Knox, 1993). The climatically sensitive region lies on the boundary where slow moving cold fronts collide with moist tropical air masses coming up from the Gulf of Mexico to cause large floods. Knox (1993) used cobbles and boulders in overbank sediment deposits to estimate flood magnitudes by calculating the minimum flood depth capable of transporting the largest cobbles and boulders. He then compared the flood reconstruction to climatic records and found that small scale changes in climate resulted in large scale changes in the magnitude and frequencies of flood events in the Upper Mississippi river valley (Knox, 1993).

A similar study conducted by Carson et al. (2007) in the Uinta Mountains in northeastern Utah, employed the same methodology as Knox (1993). A relationship was found between the magnitudes of flood events in the Uinta Mountains and the Upper Mississippi river valley. Prior to 7,000 calendar years B.P., bankfull floods were 10%-15% larger in the Uinta Mountains and 15%-30% smaller in the Upper Mississippi river valley (Knox, 1993; Carson et al., 2007). This evidence suggests a relationship between bankfull floods in the Uinta Mountains and the Upper Mississippi river valley, which coincides with changes in atmospheric circulation and storm tracks over North America (Carson et al., 2007).
The most significant use of caves in a paleoflood study was by Gillieson et al. (1991) in the Kimberley region in Western Australia. The Kimberley region is semi-arid and has good preservation of slackwater deposits in the Windjana Gorge. Downstream of the Windjana Gorge numerous slackwater deposits composed of dense woody debris were identified in the entrances of caves. These slackwater deposits were used to help extend the flood record in the Kimberley region, which has major problems with flood mitigation costs and difficulties estimating probable maximum flood discharges. Windjana Gorge was surveyed at points where slackwater deposits were identified, as well as, other points along the gorge to create accurate gorge cross-sections. Then small pits were excavated from which sediment samples were taken and stratigraphy was recorded. Using their field measurements and a computer-modeling program, the authors reconstructed the flooding history of the Windjana Gorge, which they were able to use to help solve mitigation problems in the Kimberley region of Western Australia. I have employed methodology similar to Gillieson et al. using slackwater sediments from Colonial Acres Cave (CAC), a cave adjacent to the Greenbrier River, for the purpose of refining estimates of flood frequencies and magnitudes.

1.2.2 Eastern United States Case Studies

Caves have been used to reconstruct flood histories in the central Appalachian Mountains, where surficial flood deposits are quickly destroyed by weathering and erosion (Kite et al., 2002; Springer, 2002). However, not all caves provide the conditions necessary for preserving flood sediments and organic material (Springer and Kite, 1997). For instance, Springer and Kite (1997) explored ten caves, six of which contained
slackwater sediments, in the Cheat River Canyon of northern West Virginia. The slackwater sediments were attributed to the catastrophic flood of 1985, which claimed many lives and created an estimated $1.4 billion dollars in damage, devastating the surrounding communities. However, only two of the caves contained fined-grained slackwater sediments from the 1985 flood and these were unsuitable for a paleoflood reconstruction due to their poor preservation (Springer and Kite, 1997).

Springer (2002) evaluated the usefulness of slackwater sediments deposited in caves along the Greenbrier River for paleoflood reconstruction in West Virginia, including Greenbrier River Cave (GRC). The anastomotic maze cave formed as floodwaters enlarged many flow paths simultaneously along sub-horizontal bedding planes where joint control is weak. GRC has nine entrances, four of which are ~4 m high and 2 m wide, which lie along a 30 m wide cliff-face adjacent to the Greenbrier River. Flow enters the cave via upstream stream entrances that directly point into the Greenbrier River and exits through entrances in the downstream direction (Figure 1) (Springer, 2002).

GRC contains evidence of the 1985 and 1996 floods. However, the only recognizable deposit from the 1985 flood was found in a wall niche and is composed of silt and macerated organics that have been heavily decomposed and lack sedimentary structures. A deposit attributed to the 1996 flood lies at a similar elevation, but is minimally weathered compared to the 1985 deposit. The 1996 flood deposits are mud-cracked and bioturbated, which destroyed some sedimentary structures. Some deposits are capped with earthworm mounds (Springer, 2002). Due to a lack of good preservation
of flood deposits, GRC is not the ideal cave for a paleoflood reconstruction; however, the study demonstrated the potential that slackwater deposits found in local floodwater injection caves can be used to extend the flood record.

Colonial Acres Cave (CAC), lies 140 meters downstream of GRC and contains clastic slackwater sediments deposited by the Greenbrier River (Figure 1). Thus, CAC contains a sedimentological record of Greenbrier River hydrology (Springer et al., 2009). CAC lies ~4 m above the Greenbrier River low-water surface and records low to intermediate sized floods. The sediments deposited within CAC are excellently preserved. The most extensive deposit lies within the Trench Room and is composed of laminated silts and sands with very little to no bioturbation observed. The slackwater sediments can be divided into 3 main units: Upper Unit (0-47 cm), Middle Unit (47-78 cm), and Lower Unit (>78 cm) (Figure 2) (Springer et al., 2009).

Laminated silts and sandy silts dominate the Upper Unit and contain partially articulated bat bones and organic detritus. Based on radiocarbon dates obtained from the organics these sediments were deposited beginning ~3,500 years B.P. and has continued to present (Springer et al., 2009). These sediments are the focus of my research and they contain valuable information about Greenbrier River flood events in the recent past.

The Middle Unit consists of clayey silts deposited prior to ~3,500 years B.P. These sediments lack vertebrate bones and there is very little visible organic matter within the sediments. However, cm-scale bedrock chips from claystone (bedrock) dikes in the cave ceiling and Paleozoic, coarsely crystalline, marine fossils, such as blastoid thecas, from the host limestone can be found in the clayey silts (Springer et al., 2009).
The sedimentology records a time (prior to ~3,500 years B.P.) when the Greenbrier River low water surface was higher than the Trench Room and slow dissolution liberated low-solubility objects from the host limestone.

The third or Lower Unit consists of laminated and cross-bedded sands containing some visible organic detritus.

Presently, the floor of the first 100 m of the entrance passage consists of cross-bedded sands containing little organic material and is overlain by woody debris. This evidence suggests the sandy cross-bedded sediments beneath the clayey silts of unit two were deposited similarly to the modern sands, which were deposited during episodic flooding of the Greenbrier River. Thus, the Greenbrier River low water surface was below CAC during deposition of the lower sands, but aggraded above CAC and then re-incised below CAC ~3,500 years B.P. The river has remained below CAC to the present day (Springer et al., 2009).
Figure 1. Field research location: A.) Location of the Greenbrier River in West Virginia. B.) Location of Greenbrier River Cave and Colonial Acres Cave along the Greenbrier River.
Figure 2. Three main stratigraphic units of the trenched sediment in Colonial Acres Cave and their respective ages (Cocina, 2006; Springer et al., 2009).
1.2.3 Unresolved Questions

Previous research laid the foundation for my research (Gillieson et al., 1991; Carson et al., 2007; Knox, 1993; Springer et al., 2009), which led me ask the following questions:

- What is the minimum discharge required to flood the Trench Room in CAC?
- How does this discharge compare to the historical flood record?
- How often do floods large enough to inundate the Trench Room occur?
- How do changes in climate affect flood frequencies and magnitudes in Central Appalachia?

In order to determine how climate has affected the local flood regime, I used correlations between river discharges, Atlantic Multidecadal Oscillations (AMO) and Pacific Decadal Oscillations (PDO) as “modern” analogs. These analogs allowed me to interpret the relationships between low frequency (decadal to centennial scale) sea surface temperature anomalies (SSTA) in the equatorial Pacific and North Atlantic oceans and their effects on flood frequencies and magnitudes.
1.3 Holocene Climate Change in Central Appalachia

Speleothems from Buckeye Creek Cave (BCC) provide a 7,000-year climate record demonstrating strong correlations between karst paleohydrology in the central Appalachian Mountains and global climate fluctuations (Springer et al., 2008; Hardt et al., 2010). The speleothem record, which contains a history of relative wetness as trace element ratios (Sr/Ca) and stable isotopes (δ¹³C and δ¹⁸O), were compared to a published pollen record (Watts, 1979) obtained from a bog 56 km north of BCC and 5 km from the Greenbrier River watershed, known as Cranberry Glades (Figure 3). Stable isotopic values of δ¹⁸O and δ¹³C, and tree pollen abundances (spruce, pine, hickory, beech, oak) indicate that the Middle Holocene was warmer and drier than the Late Holocene (Springer et al., 2009).

This warmer, drier period is known as the Holocene Climatic Optimum (HCO) and began >6,500 years B.P. and ended at 4,200 years B.P. (Hardt et al., 2010). Springer et al. (2008, 2010) determined that the Greenbrier watershed has experienced centennial-scale droughts throughout the Mid- to Late Holocene. The speleothem record also provides evidence for seven droughts during the Middle Holocene, six of which correlate to the cooling of the Atlantic and Pacific Oceans during North Atlantic ice rafting events (Springer et al., 2008). These droughts coincide with mega-droughts reported throughout the upper Midwest of the USA, northern Africa, the Middle East and New Jersey, USA (Springer et al., 2008).

The droughts recorded in the paleoclimate record are linked to climatic conditions similar to negative phases of the Pacific Decadal Oscillation (PDO) and the Atlantic
Multidecadal Oscillation (AMO). Negative PDO states create warm north Pacific sea surface temperatures (SSTs) and cool equatorial Pacific SSTs, which create conditions similar to a La Niña that result in a northward migration of the Pacific jet stream and decreased precipitation in east-central North America (Springer et al., 2008). However, during the Little Ice Age and Maunder solar minimum, North Atlantic and tropical Atlantic Ocean SSTs were cooler, which resulted in decreased N-S pressure and temperature gradients and drier conditions in eastern North America (Springer et al., 2008). Presumably, positive PDO and negative AMO states would increase precipitation, thus the potential for floods to occur in east-central North America.
Figure 3. Stable isotopes $\delta^{18}O$ and $\delta^{13}C$ from Buckeye Creek Cave compared to the palynological record from Cranberry Glades (Springer et al., 2009).
1.4 Hypotheses and Questions

The primary question tested in this investigation was: Do sea surface temperature fluctuations affect flood frequencies and magnitudes in Central Appalachia? To thoroughly address this question a set of research hypotheses were tested. My null hypothesis is:

- \( H_0: \) Peak annual flood frequencies and magnitudes of the Greenbrier River in West Virginia are not correlated with changes in sea surface temperatures in the equatorial Pacific or North Atlantic oceans.

Rejection of my null hypothesis would be consistent with my research hypothesis that Greenbrier River flood regimes are influenced by changes in sea surface temperatures (SSTs), including SST anomalies (SSTA) such as, the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO). Previous studies (Springer et al., 2008, 2010) have shown a correlation between droughts in east-central North America and decreases in SSTs during the Mid- to Late Holocene. By comparing the historical SST record to the historical flood record we can create a paleoflood model that could potentially help interpret the effects of future climate change on floods regimes in Central Appalachia. I tested my research hypothesis using additional hypothesis tests:

- \( H_1: \) The flood history contained in CAC slackwater sediments deposited after \( \sim 3,500 \) years B.P. correlates with proxies of local and regional climate change.

Failure to reject \( H_1 \) is evidence that paleoclimatic changes, perhaps tied to changes in SST, influenced the Greenbrier River flooding responsible for the deposition
of slackwater sediments in CAC. A failure to reject $H_1$ validates testing $H_2$, which explores the relationship between ancient and modern flood events and climate change.

- **$H_2$:** Modern and ancient flood regimes have been affected by equatorial Pacific and North Atlantic Ocean SST fluctuations.

  A failure to reject $H_2$ would support my research hypothesis and provide the basis for interpreting the Late Holocene paleoflood record in CAC within a larger context and to predict extrapolate future flood regimes based on projected future changes in SSTs.
2.0 Field Research Area

My field research was conducted in and around Colonial Acres Cave (CAC) along the Greenbrier River in Greenbrier County, West Virginia (Figure 4). The town of Ronceverte, West Virginia is 11.5 km upstream of CAC. Ronceverte originates from the French word for Greenbrier (ronce-brier, vert-green), the river on which the town lies. Ronceverte was established in 1882 in Greenbrier County as a result of construction of the Chesapeake-Ohio railroad and partially lies on the Greenbrier River floodplain.

The town of Alderson, West Virginia is 8.2 km downstream of CAC. The town of Alderson was established in 1890 and is located along the Greenbrier River where it forms part of the Monroe-Greenbrier county line, near their shared corner with Summers County. Alderson was built on the floodplain and terraces of the Greenbrier River. The Greenbrier River has repeatedly flooded Ronceverte and Alderson since their establishment. The most devastating floods occurred in 1985 and 1996 and are the largest historic floods recorded by a stream gage in Alderson, having peak discharges of 2,567 and 2,664 m³ s⁻¹, respectively.
Figure 4. Location of the Greenbrier River and Colonial Acres Cave in West Virginia (Springer et al., 2009).
2.1 Physiographic Setting

The Appalachian Plateau and Valley and Ridge physiographic provinces bisect Greenbrier County (Figure 5). The Appalachian Plateau lies in the west-northwest section of the county and presents a much different landscape and drainage pattern than those of the Valley and Ridge Province. Many mountains bordering the Greenbrier watershed are ≥1,220 meters in elevation and are capped by resistant Pottsville sandstone. Locally, streams have cut deep V-shaped gorges into the elevated plateau and stream development is only weakly controlled by geological structures, such as folds, and an insequent or dendritic drainage pattern has developed (Price, 1939).

The Ridge and Valley Province lies in the eastern-southeastern section of the county and contains series of alternating parallel ridges and valleys (Price, 1939). In the Ridge and Valley Province the Greenbrier River flows parallel to the strike of the rocks, but has meandered over and threw rocks that are resistant to erosion. The stream drainage pattern in this part of the county is trellis or rectilinear, but is hard to distinguish where karst is well-developed upon the Greenbrier Limestone (Price, 1939).
Figure 5. Physiographic Provinces in West Virginia. The yellow star denotes Greenbrier County. (West Virginia Geological and Economic and Survey Web Page, http://www.wvgs.wvnet.edu).
2.2 Geology of Greenbrier County

Mississippian rocks outcrop in a broad band, trending in a northeast-southwest direction across the center of Greenbrier County (Figure 6) (Price, 1939). The Greenbrier Group, middle Mississippian in age, lies conformably below the Mauch Chunk Group, upper Mississippian in age, which comprises the valley walls above my study area. Generally, the Mauch Chunk Group is composed of red shales and sandstones with very thin beds of coal and thin limestones and shales at its base, while the Greenbrier Group is dominantly composed of massive limestones, which host many caves (Price, 1939). For the purposes of my research, I will focus on the limestones of the Greenbrier Group (Figure 7).

The Greenbrier Group has a total thickness ranging between 145 and 229 m in Greenbrier County (Price, 1939). The members of the Greenbrier Group, from youngest to oldest, are as follows: Alderson Limestone, Greenville Shale, Union, Pickaway, Taggard, Patton, Sinks Grove and the Hillsdale Limestones. The Alderson is a very hard, dark-gray, and sandy limestone with crystalline streaks and contains a wide variety of fossils such as, bryozoa, brachiopods, crinoids, corals and a few pelecypods (Price, 1939). The Alderson Limestone ranges in thickness from 15 to 46 m. The Greenville is brown to dark brown, fissile, and calcareous shale that ranges in thickness from is 15 to 20 m and contains marine fossils, especially the brachiopod, Chonetes (Price, 1939). The Union is the formation in which CAC has developed, thus is the most important member of the Greenbrier Group to my research. The Union is a light to dark gray oolitic
limestone that ranges in thickness from 30 to 83 m in thickness. It weathers white and becomes shaly near its contact with the overlying Greenville Shale.

The Union contains an abundance of marine fossils such as, blastoid echinoderms (Pentremites), bryozoa (Archimedes), and gastropods (Price, 1939). The Pickaway is a dark, hard and brittle limestone with some red streaks and containing few marine fossils (Price, 1939). The Taggard is a yellowish-gray to red, shaly, oolitic limestone and ranges in thickness from 3 to 11 m. The Patton is a hard limestone that weathers gray at its base and commonly contains 1.5 to 3 m of light gray oolite, marine fossils and nodules of black chert. Sinks Grove is a blue, siliceous limestone that weathers yellow at its top and gray at its base and ranges in thickness from 12 to 27 m. The Sinks Grove Limestone commonly contains nodules of black chert and marine fossils including, brachiopods, bryozoa, crinoids and gastropods. Lastly, the basal member of the Greenbrier Group, the Hillsdale, is a gray-blue, hard, massive, limestone that ranges in thickness from 9 to 30.5 m. The Hillsdale has an abundance of marine fossils and commonly contains nodules of gray and black chert (Price, 1939).
Figure 6. Northeast-southwest trending Mississippian Greenbrier Group (blue) in Greenbrier County, West Virginia (Modified from Cocina, 2006).
Figure 7. Stratigraphic column of Greenbrier Group in the vicinity of the field study area (Worthington, 1984; Springer, 2002; White, 2007). Colonial Acres Cave formed in the Union Formation.
2.3 Greenbrier River

Flowing in a south-southwest direction the Greenbrier River begins its course at the confluence of the East and West Forks. The headwaters of the West Fork lie east of Shavers Mountain, approximately two miles northeast of Wildell at an elevation of 1,105 meters. The headwaters of the East Fork originate at Blister Swamp on the west slope of Allegheny Mountain, at an elevation of 1,181 meters. The East Fork flows in southwest direction to its confluence, with the West Fork forming the Greenbrier River in Pocahontas County in the city of Durbin, West Virginia. The Greenbrier River continues its course, flowing over sandstones, shales and limestones, to the southwest in a relatively straight line through Pocahontas and Greenbrier Counties.

Just south of Lewisburg in Greenbrier County, the Greenbrier River meanders westward, forming part of the Greenbrier-Monroe County line. It meanders into Summers County where it ends its course at its confluence with the New River in Summers County in Bellepoint, West Virginia at an elevation of 419 meters. The watershed has a total drainage area of 4,290 km² (U.S. Geological Survey NWIS database, accessed 29 April 2010). The Greenbrier River is a major tributary of the New River, which acts as base level for the Greenbrier River (Price, 1939).

Springer et al. (2003) demonstrated that values of unit stream power ($\omega$) and $\tau$ are lowest where the Greenbrier River flows over soluble substrates versus insoluble substrates. The Greenbrier River is narrowest where it flows over sandstone and sandstone boulders obstruct the channel. It is widest where there is evidence of corrosion. Thus, the correlation between $\omega$ and $\tau$ with specific substrates demonstrates variations in
Greenbrier River channel geometries. The study determined channel geometries and hydraulics have adjusted so that incision of the Greenbrier River coincides with incision in nearby reaches that are being incised by quarrying, abrasion, or corrosion (Springer et al., 2003).

2.4 Greenbrier River at Acme Quarry

Acme Quarry is located upstream of Anvil Rock where a low limestone ridge prevents sandstone boulders from reaching the riverbed. The Greenbrier River has incised 17 m below a strath terrace on river right and into the massive, oolitic and micritic limestones of the Greenbrier Group. Here, the Greenbrier River has pool-riffle morphology and bedrock exposures in the pools are variable. Maximum low water pool depths average 1.5 m. No major tributaries enter the river, so flood discharge is relatively constant along this reach (Springer et al., 2003). Locally, the catchment area is 3380 km² and the river is incising at a rate of $\leq 40$ m Ma$^{-1}$ (Shank and Sasowsky, 2001; Springer et al., 2003).

2.5 Greenbrier River at Alderson, West Virginia

The U.S. Geological Survey established a gaging station on the Greenbrier River on August 1, 1895 (Price, 1939). The gage is designated USGS 03183500 (37° 43’ 27” N, 80° 38’ 30” W, 466 m) and is 15 km downstream of CAC and my study reach (37° 44’ 47” N, 80° 33’ 42” W). At the Alderson gage the Greenbrier River’s drainage area is 3,533 km² has a mean annual daily discharge of 57 m$^3$ s$^{-1}$. The close proximity of CAC to the gage makes CAC an excellent site to study flood recurrence intervals of the Greenbrier River because:
1. No large tributaries enter the river between the caves and stream gage.

2. Flood frequencies can be assumed to be approximately the same at the caves as the gage at Alderson.

3. CAC fits the criterion established by Gillieson et al. (1991); the best locations for paleoflood studies are areas where slackwater deposits are well preserved, where flood discharges are large, and rivers are incised into bedrock.

2.6 Colonial Acres Cave

CAC lies in a vertical cliff of the Union Limestone along the Greenbrier River. CAC is a branchwork cave containing anastomotic features formed by floodwaters simultaneously enlarging flow paths in sub-horizontal bedding planes in the channel bank. Elliptical and keyhole shaped passages indicate an initial period of phreatic growth followed by vadose modification. Surprisingly, phreatic sediments are largely absent from the cave, apparently due to vadose scour, and passage morphologies offer the best record of the cave’s phreatic origin. However, CAC contains a permanently flooded pool (sump) within which elliptical tubes and phreatic solution features are visible and presumably growing.

The Greenbrier River is the only source of water and sediment to CAC, which contains water only during floods. Floodwaters enter CAC via an upstream entrance, which is also the main entrance to the cave, and exits CAC through a very small passage at the back of the Trench Room where there is a voice connection to the surface (Figure 8) (Cocina, 2006). Floodwaters can also enter and exit CAC via the sump (Figure 8), which is hydrologically connected to the Greenbrier River. At present, CAC records low
and intermediate sized floods because most passages are approximately 4 to 5 m above the Greenbrier River. CAC essentially becomes an extension of the river during floods and presently contains floodwater-deposited sediments. The most extensive slackwater deposit lies in the Trench Room (Figure 9) and is >2 m thick (Springer et al., 2009). The stratigraphy consists of interbedded silts and fine sands containing macerated organic detritus, charcoal, and bat bones. The bat bones definitively show that sediments post-date the cave’s phreatic inception.
Figure 8. Flood waters enter Colonial Acres Cave from an upstream entrance and exit the cave via a downstream exit where there is a voice connection to the surface. The perennial sump is hydrologically connected to the Greenbrier River and serves as an entrance and exit (Modified from Colonial Acres Cave Map, Springer, 2009).
Figure 9. The original < 2 m trench dug in Colonial Acres Cave Cocina (2005).
3.0 Methodology

My research involved field and laboratory components. For the field component, I collected sedimentary and stratigraphic information from Colonial Acres Cave (CAC) and conducted elevation surveys of CAC and the Greenbrier River. The laboratory component involved processing and analyzing sediment samples collected from CAC, modeling Greenbrier River hydrology using the computer program HEC-RAS (Hydrologic Engineering Center, 1998 a,b), and performing time series analyses to characterize the behavior of the physical system (Kirby et al., 2002; Weedon, 2003; Springer et al., 2008; Sahu et al., 2009).

3.1 Sediment Sampling and Stratigraphy

Paleostage indicators (PSIs) are sediment and debris accumulations that record flood stages (Kochel and Baker, 1982). PSIs include “silt lines” composed of silt, macerated organics, and anthropomorphic debris clinging to channel surfaces in protecting settings (Figure 10) (Kochel and Baker, 1982, Springer and Kite, 1997; Springer, 2002). A previous study conducted by Cocina (2006) determined that slackwater sediments deposited in the Trench Room of CAC were viable sources of paleoflood information and were the basis of my study. Slackwater deposits in other parts of CAC such as, the Potato Room were also considered for this study. However, upon sampling the sediments using a soil probe and the digging of a shallow trench it was determined that the sediments had been reworked and are unusable.

A 70-cm long core was taken in the Trench Room in CAC using two 9.5 x 62 cm PVC pipes with rectangular cross sections (Figure 11). Stratigraphic and sedimentary
information of flood deposits, such as facies and textural changes, were collected following the methods of Springer and Kite (1997) and Springer et al. (1997). I identified and sampled 15 distinct lithological units on the basis of visual facies changes from exposed sediment within the trench. For each lithological unit, detailed descriptions and measurements of slackwater deposits including thickness, textural characteristics (grain size, sorting, and roundness), organic content, and presence/absence of sedimentary structures, were recorded (Appendix 1).
Figure 10. The top image depicts a flotsam deposit and the bottom image depicts a silt line deposit. Both are examples of paleostage indicators (PSIs), which record minimum flood stage.
Figure 11. Overlapping cores obtained from Colonial Acres Cave. Up is to the left.
3.2 Greenbrier River Survey

The Greenbrier River channel was surveyed outside of CAC using a Topcon total station, which has mm-scale horizontal and vertical accuracies. Riffles, formed by cobbles and small boulders, alternate with bedrock and cobble bottomed pools in the channel (Springer et al., 2003). Channel vegetation is fairly dense along channel margins during the spring and summer and consists of tall hardwood trees such as, white oak, red oak, poplar and black walnut (Price, 1939), tall grasses and shrubbery. In order to determine the elevation of the low water surface, trigonometric functions were applied to the northing, easting, and z values measured with the total station.

3.3 Colonial Acres Cave Survey

CAC was surveyed using a Disto; a handheld device that measures distances and angles using a laser. Unlike the Topcon total station, it cannot measure the relative geographic position of an object. However, we connected the surveys by using the total station, which allowed for the relative geographic position of CAC to the Greenbrier River to be determined. Similarly to the river survey, trigonometric functions were applied to the survey data to determine the elevation individual points, specifically PSIs, within the cave.
3.4 Laser Particle Size Analysis

I sampled the core for laser particle size (LPS). For LPS analysis approximately 3 cm$^3$ of sediment was taken from each lithological unit within the core. These samples were sent to Dr. Carl Sondergeld at Oklahoma University, who performed LPS analysis for this study. Dr. Sondergeld dried and disaggregated the samples prior to using a Beckman Coulter 13 320 laser diffraction particle size (LPS) analyzer to analyze the samples.

3.5 HEC-RAS

Flood flows in the Greenbrier River were modeled using a computer-modeling program HEC-RAS with the goal of estimating paleodischarges from observed PSIs (Springer, 2002; Springer et al., 2003). HEC-RAS is a one dimensional, open channel, step-back modeling program for PCs (Hydrologic Engineering Center, 1998 a, b). HEC-RAS uses the normal depth assumption, which equates channel gradients to energies lost by floodwaters. This assumption is necessary for HEC-RAS to commence computations when energy losses are unconstrained (Gillieson et al., 1991). In addition to the normal depth assumption, HEC-RAS requires knowledge of the roughness value (Manning’s $n$), which can be determined if water-surface elevation(s) and discharge are known for a flood event. If two of the three variables (roughness, discharge, and water-surface elevation) are known, the missing variable can be calculated using the HEC-RAS program.
Water-surface elevation (WSE) and roughness value \( (n) \) were the known variables in this study. Elevations calculated from river survey measurements and the known Manning’s \( n \) was entered into HEC-RAS. This provided the information HEC-RAS used to create the channel profiles (Figure 12). From the CAC survey I knew the minimum WSE needed to flood the cave. I varied discharge within the program using the steady flow analysis tool until the discharge I entered resulted in the water surface elevation measured in the CAC. This allowed me to determine the minimum discharge necessary to overcome the sills within CAC and flood the back passages and rooms of the cave.
Figure 12. A channel cross section of the Greenbrier River created in HEC-RAS from river survey measurements. This particular cross-section illustrates the discharge modeled for the surface of the trench within Colonial Acres Cave.
3.6 Time Series Analysis

In order to determine if a significant statistical relationship between Greenbrier River peakflow and low-frequency sea surface temperature anomalies exists, I applied univariate and bivariate statistical methods to the data. Peakflow data were obtained for USGS stream gage 03183500 at Alderson, West Virginia (http://waterdata.usgs.gov). Sea surface temperature anomaly data were obtained from the World Data Center for Paleoclimatology and the National Oceanic and Atmospheric Administration.

Spectral analysis is a statistical method that evaluates periodicity in a time series (Kirby et al., 2002; Weedon, 2003; Sahu et al., 2009). For each variable (peakflow, average annual discharge, Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO)) autocorrelation and spectral density functions were applied for the univariate analysis. The autocorrelation is a dimensionless function in the range [-1 to 1] that describes relationships among successive terms of a single time series and provides information about memory effect of the system such as, the duration of an event. Spectral density describes how the periodicity of the time series relates to frequency by showing the relative amplitude of different wave components as a function of the frequency (Sahu et al., 2009) and pertinent frequencies appear as high, sharp peaks in the spectral density plots.

The bivariate method of cross-correlation describes the relationship between input and output time series. The degree to which they are correlated is illustrated by the lag time between individual points in the series (Weedon, 2003; Sahu et al., 2009). The cross-spectral density function or the cross-spectrum provides information about the
strength of the dependence between two processes at each frequency (i.e., peakflow and AMO) (Weedon, 2003; Sahu, 2009). Autocorrelation and cross-correlation were performed using a FORTRAN computer program written by Dr. Dina Lopez (Personal Communication, 2009) while spectral analysis was performed using the NCAR (National Center for Atmospheric Research) command language courtesy of Dr. Ryan Fogt (Personal Communication, 2010).
4.0 Fieldwork Results

Some infilling and collapse has occurred since the trench in Colonial Acres Cave (CAC) was excavated in 2005 (Cocina, 2006). The original trench was ~2.5-m deep, but I had to re-excavate the trench to only 80 cm because the upper 70 cm of the trench spans the past 4,000 years B.P. (Figure 13) (Cocina, 2006) and sediments below 70 cm are not related to the modern flood regime (Springer et al., 2009). The trench exposes well-preserved, laminated, clays, silt, and sands (Figure 13). Upon examining the sedimentary column, I identified 16 stratigraphic units based on visually distinct textural differences. The units are listed below in Table 1 and additional information is available in the Appendix.

Sediment grain sizes range from medium sand to clay. Individual laminations fine upward and are generally less than 2 mm thick. Alternating layers of light yellow-brown clayey silt with medium brown silty clay are common throughout the stratigraphic column. There are also distinct layers and isolated bodies of yellow sand with diameters ranging from less than one millimeter to 20 mm. However, sand is only observable in Units 3, 5, 6, 11, 13 and 15. The remaining units are primarily clayey silt. Pieces of charcoal and clay balls are present in all units, but vary greatly in size and abundance between individual units. Most pieces of charcoal and clay balls are 1 to 2 mm in diameter; however, some clay balls have diameters in excess of 30 mm. These balls fell from wall ledges and the ceiling where clay was deposited after the river aggraded and flooded CAC (Springer et al., 2009). Exposures of Unit 7 were mottled due to the abundance of clay balls present and it contained a 3-mm x 9-mm piece of charcoal.
In the Potato Room, a small 43 cm deep trench was excavated (Figure 14) to
determine if the sediments would aid this investigation. A total five units were identified
based on distinct textural differences (Appendix): Unit 1 (1-6.5 cm), Unit 2 (6.7-17 cm),
Unit 3 (17-23 cm), Unit 4 (23-25 cm) and Unit (25-43 cm). The sediments are composed
of primarily weakly laminated, mottled, medium brown silty clays. Rust colored streaks
of clay were observed throughout the column indicating the sediments were unsaturated
for a long period.

A 19-cm deep cylindrical burrow was found while excavating the trench. The
burrow began at ~12-cm depth (Figure 15) and ended at a depth of 31 cm (Figure 16). It
appeared that the burrow may have been deeper, but had been in filled with sediment. In
addition to the burrow, roots are present in the sediments. In short, these sediments have
been reworked and bioturbated, are poorly preserved, and not suitable for this
investigation.

<p>| Table 1. Stratigraphic units of uppermost sediments in Trench Room. |
|---------------------------|--------------------------|-------------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Unit</th>
<th>Depth (cm)</th>
<th>Unit</th>
<th>Depth (cm)</th>
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<tr>
<td>2</td>
<td>3-6</td>
<td>10</td>
<td>48-56</td>
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<tr>
<td>3</td>
<td>6-12</td>
<td>11</td>
<td>56-59</td>
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<tr>
<td>4</td>
<td>12-17</td>
<td>12</td>
<td>59-65.5</td>
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<tr>
<td>5</td>
<td>17-20</td>
<td>13</td>
<td>65.5-67.5</td>
</tr>
<tr>
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<td>20-22</td>
<td>14</td>
<td>65.5-71</td>
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<tr>
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<td>22-34</td>
<td>15</td>
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</tr>
<tr>
<td>8</td>
<td>34-41</td>
<td>16</td>
<td>72-74</td>
</tr>
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</table>
Figure 13. Upper 70 cm of slackwater sediments deposited in the Trench Room of Colonial Acres Cave (August, 2009).
Figure 14. Small trench dug in slackwater sediments deposited in the Potato Room of Colonial Acres Cave (July, 2009).
Figure 15. Beginning of burrow found while digging trench in Potato Room sediments.
Figure 16. End of burrow found in sediments while digging the Potato Room Trench.
5.0 Laboratory Results

5.1 Laser Particle Size Analysis

The laser particle size analysis revealed that sediment grain size ranges from very coarse sand to colloid. A plot of $d_{10}$, $d_{50}$, and $d_{90}$ versus depth illustrates the vertical distribution of grain sizes throughout the upper 80 cm of the trench (Figure 17). The mean values for $d_{10}$, $d_{50}$, and $d_{90}$ are 0.01372 mm, 0.06493 mm, and 0.16961 mm, respectively; 10 percent of the sediments are smaller than silt grains (0.0039 - 0.0625 mm), 50 percent of the sediments are smaller than very fine sand grains (0.0625 - 0.125 mm) and 90 percent of the sediments are smaller than fine sand.

A ternary plot illustrating the total percent clay, silt and sand fractions of sampled CAC sediments shows that silty sands and clayey silts are the dominant textures (Figure 18). Of the sediment sampled, the clay-sized fraction comprises 1% to 29%, the silt-sized fraction composes 3% to 83% and the sand-sized fraction composes 53% to 96% of the sediments samples. Figure 19 illustrates the total percent sand and the combined percentage of clay and silt.
Figure 17. Vertical distribution of $d_{10}$, $d_{50}$, and $d_{90}$ versus depth.
Figure 18. Total percent of clay, silt and sand composing the sampled slackwater sediments.
Figure 19. Distribution of the total percent of clay, silt and sand fractions with depth. The yellow peaks represent the total % sand with depth (cm).
5.1.1 Climate Proxies

Stable isotope $\delta^{13}C$ abundance can be used to determine relative moisture abundance. Stable isotope $\delta^{13}C$ values are typically more negative when climate is relatively moist due to increased soil respiration and less negative when climate is relatively dry due to decreased soil respiration (Springer et al., 2008). Although $\delta^{13}C$ values from the organic material found within the sediment is not the best proxy for climate because the organic material found within the sediment could actually be much older than the actual sediments (Springer, 2002), it provides information about the watershed.

The sediment size, $d_{50}$, is the grain diameter at which 50 percent of the sediment sample is finer than. Figure 20 depicts $d_{50}$ values determined from grain size analysis as compared to stable isotope $\delta^{13}C$ obtained from organic material found within Trench sediments by Cocina (2006). Generally, $d_{50}$ values are smaller when $\delta^{13}C$ values are more negative and larger when $\delta^{13}C$ values are less negative. This indicates that grain size is larger during periods of relative dryness. Over all there is only a rough correlation between $d_{50}$ values and $\delta^{13}C$ values; however, there is good correlation between $d_{50}$ values and $\delta^{13}C$ values at 19 cm, which corresponds to ~1,270 calendar years B.P..

To further investigate whether or not grain size is correlated to climate, $d_{50}$ values were compared to Sr/Ca values and $\delta^{18}O$ values obtained from a stalagmite in Buckeye Creek Cave (BCC). Sr/Ca ratios are very good indicators of relative moisture abundance because during periods of relatively low moisture calcite precipitates in the vadose zone
(epikarst), which leaves the residual drip waters that feed the stalagmite enriched with δ^{13}C and Sr (Springer et al., 2008). Stable isotope δ^{18}O is also a good climate proxy because it can record mean atmospheric temperature and precipitation provenance (Springer et al., 2008).

Sr/Ca ratio values (Figure 21) are higher when $d_{50}$ values are larger, which indicates that larger grain sizes were deposited during periods of relative dryness. In order to have larger grain sizes deposited within CAC, a flood with a magnitude capable of transporting and depositing larger sediments would have to occur. This suggests that larger floods occurred during periods of relative dryness. In addition, stable isotope δ^{18}O values are less negative (Figure 22) when $d_{50}$ values are larger, indicating that larger grains were deposited when there was a relative increase in summer precipitation, suggesting a seasonal influence on the deposition of larger grain sizes.

Springer et al. (2008) demonstrated that δ^{13}C, δ^{18}O and Sr/Ca ratios correlated to seven periods of drought during the Mid- to Late Holocene. Six of these droughts were attributed to Bond Cycles (Figure 23), which is a climatic phenomenon occurring every 1,450± 500 years. During a Bond event there is an increase in ice rafted debris (IRD) in the North Atlantic, which is thought to be driven by fluctuations in solar irradiance. Cooler sea surface temperatures (SSTs) in the Atlantic and Pacific Oceans were found to typically occur during the solar minima and result in droughts in east-central North America (Springer et al., 2008). Although the correlation is indirect, it is plausible that the larger grain sizes found in CAC are the result of floods that occurred during periods of relative dryness caused by changes in SSTs.
Figure 20. $d_{50}$ of Trench sediments compared to $\delta^{13}C$ obtained from organic material within Trench sediments.
CAC Grain Size (μm) versus BCC-002 Sr/Ca

Figure 21. $d_{50}$ of Trench sediments compared to Sr/Ca from BCC-002 stalagmite.
Figure 22. $d_{50}$ of Trench sediments compared to $\delta^{18}O$ from BCC-002 stalagmite.
Figure 23. Climate proxies, $\delta^{13}$C, $\delta^{18}$O and Sr/Ca ratios, obtained from BCC stalagmite and Bond events. Six of the seven peaks highlighted in grey correlate to North Atlantic Ice Rafted Debris (IRD) events known as Bond Cycles recorded by hematite-stained grains (Springer et al., 2008).
5.2 HEC-RAS

HEC-RAS is a one dimensional, open channel, step-back modeling program for PCs (Hydrologic Engineering Center, 1998 a, b). HEC-RAS was used to model the discharges necessary to flood selected parts of the cave. HEC-RAS can be used to estimate the discharge associated with a particular water surface elevation (WSE). There are 3 main sills that floodwaters must rise above to flood and deposit sediments in CAC (Figure 24). Discharges were modeled for these sills by assuming they would be overtopped when WSEs in the surface channel exceeded the elevations of the sill crests. The sills have elevations of 105.79 m, 106.30 m, and 106.64 m (Figure 25). They yielded discharges of 1,370 m$^3$s$^{-1}$, 1600 m$^3$s$^{-1}$, and 1,770 m$^3$s$^{-1}$, respectively (Table 2). As shown in Table 2, a minimum discharge of 1,600 m$^3$s$^{-1}$ is required to flood the Trench Room, where I performed most of stratigraphic work and the site of the most extensive slackwater deposit in the cave.

The discharges (m$^3$s$^{-1}$) required to overcome the sills are minimum values because the true surface channel water surface elevation (WSE) would have to be greater to deposit sediment within CAC and water flowing through the cave would need to overcome resistance to flow. The latter would require a steeper WSE between the inside and outside of the cave.
Table 2. Q is the modeled discharge (m³ s⁻¹), Elevation in meters (field measurement) is referenced to an arbitrary datum and discharges were calculated by matching water surface elevations using HEC-RAS.

<table>
<thead>
<tr>
<th>Q (m³ s⁻¹)</th>
<th>Water Surface Elevation (m)</th>
<th>Modeled W.S. elevation (m)</th>
<th>Location in CAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>760</td>
<td>104.17</td>
<td>104.18</td>
<td>Datum</td>
</tr>
<tr>
<td>1,600</td>
<td>106.29</td>
<td>106.29</td>
<td>Sill-Main Entrance</td>
</tr>
<tr>
<td>1,540</td>
<td>106.16</td>
<td>106.16</td>
<td>Permanent Marker 2</td>
</tr>
<tr>
<td>1,370</td>
<td>105.79</td>
<td>105.79</td>
<td>Sill-to Trench Room</td>
</tr>
<tr>
<td>1,360</td>
<td>105.76</td>
<td>105.76</td>
<td>Mouth to Sump</td>
</tr>
<tr>
<td>1,355</td>
<td>105.76</td>
<td>105.76</td>
<td>Sill-Trench to Sump</td>
</tr>
<tr>
<td>1,070</td>
<td>105.05</td>
<td>105.05</td>
<td>Surface of Trench</td>
</tr>
<tr>
<td>1,630</td>
<td>106.36</td>
<td>106.36</td>
<td>End Cave-Sol. Ceiling</td>
</tr>
<tr>
<td>1,920</td>
<td>106.95</td>
<td>106.95</td>
<td>Sol. Ceiling-Potato Room</td>
</tr>
<tr>
<td>1,770</td>
<td>106.64</td>
<td>106.64</td>
<td>Floor-Potato Room</td>
</tr>
</tbody>
</table>
Figure 24. Approximate locations of sills within Colonial Acres Cave and the associated discharges modeled in HEC-RAS. Cumecs refers to m$^3$ s$^{-1}$. 
Greenbrier River
Channel Cross Section

Figure 25. Elevations (m) of sills within Colonial Acres Cave and the corresponding discharges \((Q)\) modeled in HEC-RAS.
5.2.1 Greenbrier River Paleoflood Events

The discharge values modeled in HEC-RAS were compared to the historical flood record for the Greenbrier River. Figure 26 illustrates the probabilities of the modeled floods as they compare to the probability of historical floods. Figure 27 illustrates the flood recurrence interval of the modeled floods as they compare to the recurrence intervals of historical floods. A flood with a discharge of 1,600 m$^3$ s$^{-1}$, which is the minimum discharge, required to flood the Trench Room with Colonial Acres Cave (CAC) has a 9% chance of occurring in any given year and has a recurrence interval of 12 years (Table 2). However, it is important to keep in mind that the floods actually responsible for the deposition of slackwater sediments within CAC, in reality, could have been much greater than 1,600 m$^3$ s$^{-1}$ and the discharge-recurrence interval relationship may not have been constant with time. Moreover, the estimated recurrence interval is based on a limited amount of data.

The errors associated with probability and recurrence interval calculations are a direct reflection of the number of records ($n$) available. Probability ($P$) is rank ($m$) divided by the total number of records ($n$) and recurrence interval ($T$) is the reciprocal of probability (Gordon et al., 2004). This is known as the Weibull plotting position where:

$$P = \frac{m}{N + 1} \quad \quad T = \frac{N + 1}{m}$$

thus, $P = \frac{1}{T}$

For example, the total number of records ($n$) available for the Greenbrier River is 113, which is not a large statistical population in comparison to the 4,000-year long history of flood occurrences, so if a greater number of records were available the rank of
a flood with a discharge of 1,600 m$^3$ s$^{-1}$ may be greater or smaller, as a rank of 1 is given to the largest value and so on. Thus, these values are only estimates of the probability of exceedence ($P$) based on the available historical flood record and are not actual values as an increase in the number of records would negatively or positively skew these values.

The three parameter Gumbel Extreme Value Distribution (GEV) method II was used to estimate the largest or smallest values possible for the Greenbrier River discharge based peakflow (m$^3$ s$^{-1}$) (Table 3). The second GEV method was used because it extends the GEV to 10,000 years. The GEV is widely used in flood-frequency analysis because the GEV has no upper or lower limit and has a constant skewness of 1.1396 (Ponce, 1989; Gordon et al., 2004).

\[
1 / T = 1 - e^{-e^{-y}} \\
y = - \ln \{ \ln [ T / T - 1 ] \} \\
x = \bar{x} + Ks \\
y = \bar{y}_n + K \sigma_n
\]

The frequency formula $x = \bar{x} + Ks$ is used to obtain discharge and $K$ is evaluated with the frequency formula $y = \bar{y}_n + K \sigma_n$ (Ponce, 1989). Where, $T$ is the recurrence interval or return period, $K$ is the frequency factor, $y$ is the Gumbel (reduced) variate, which is a function of recurrence interval, and $\bar{y}_n$ is the mean and $\sigma_n$ is the standard deviation of the Gumbel variate. Both $\bar{y}_n$ and $\sigma_n$ are a function of the number of records ($n$) (Ponce, 1989).

Assuming that a flood with a discharge of 1,600 m$^3$ s$^{-1}$ or greater occurred once every 12 years, approximately 292 floods would have occurred and deposited sediment in the Trench Room of Colonial Acres Cave (CAC) in the past 3,500 years. Using the 55-cm of sediment deposited after 3,500 years B.P., an average of ~1.9 mm of sediment per
flood would need to have been deposited in the Trench Room. Based on limited observations in CAC, individual floods do leave in excess of 0.5 mm of sediment per flood, although this is highly location dependent. For comparison, the thicknesses of individual laminae within the sediments, which are thought to reflect individual flood events, generally range from 1 to 10 mm.

Separately, I calculated the average annual sedimentation for the slackwater sediments using the equation:

\[ z = k \cdot T \]

Where, \( z \) is the thickness of sediments (550 mm), \( k \) is the sedimentation rate (mm yr\(^{-1}\)) (unknown variable) and \( T \) is the period of deposition (3,500 years). From this equation, I determined that the average sedimentation rate of the slackwater sediments in the Trench Room of CAC is 0.16 mm yr\(^{-1}\).
Table 2. Discharge, rank, probability and recurrence interval (R.I.) of modeled discharge as compared to the historical record.

<table>
<thead>
<tr>
<th>Discharge (m$^3$ s$^{-1}$)</th>
<th>Rank</th>
<th>Probability</th>
<th>R.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,370</td>
<td>20</td>
<td>0.17</td>
<td>6</td>
</tr>
<tr>
<td>1,600</td>
<td>10</td>
<td>0.09</td>
<td>12</td>
</tr>
<tr>
<td>1,770</td>
<td>6</td>
<td>0.05</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3. Gumbel Extreme Value (GEV) Distribution II for Greenbrier River peakflow (m3 s$^{-1}$). GEV II is a three parameter distribution and is a variation of the GEV. The GEV II is bounded on the lower end versus the GEV which has no upper or lower limits.

<table>
<thead>
<tr>
<th>Recurrence Interval T (yr)</th>
<th>Probability P (percent)</th>
<th>Gumbel variate $y$</th>
<th>Flood discharge Q (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.05</td>
<td>95.24</td>
<td>-1.113</td>
<td>466</td>
</tr>
<tr>
<td>1.11</td>
<td>90.09</td>
<td>-0.838</td>
<td>558</td>
</tr>
<tr>
<td>1.25</td>
<td>80</td>
<td>-0.476</td>
<td>679</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>0.367</td>
<td>960</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>1.5</td>
<td>1,339</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>2.25</td>
<td>1,590</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
<td>3.199</td>
<td>1,907</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>3.902</td>
<td>2,142</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>4.6</td>
<td>2,376</td>
</tr>
<tr>
<td>200</td>
<td>0.5</td>
<td>5.296</td>
<td>2,608</td>
</tr>
<tr>
<td>500</td>
<td>0.2</td>
<td>6.214</td>
<td>2,915</td>
</tr>
<tr>
<td>1000</td>
<td>0.1</td>
<td>6.907</td>
<td>3,147</td>
</tr>
<tr>
<td>2000</td>
<td>0.05</td>
<td>7.601</td>
<td>3,379</td>
</tr>
<tr>
<td>5000</td>
<td>0.02</td>
<td>8.517</td>
<td>3,685</td>
</tr>
<tr>
<td>10000</td>
<td>0.01</td>
<td>9.21</td>
<td>3,917</td>
</tr>
</tbody>
</table>
Figure 26. Probability of modeled and historical flood discharges \((Q)\). Cumecs refers to \(m^3\ \text{s}^{-1}\).
Figure 27. Flood recurrence interval for modeled and historical flood discharges \((Q)\). Cumecs refers to \(\text{m}^3\ \text{s}^{-1}\).
5.3 Time Series Analysis

Time series analysis allows for dynamic relationships in a physical system to be characterized and is commonly used predict future values (Jenkins and Watts, 1968; Sahu et al., 2009). I applied univariate and bivariate statistical tests to determine if there is a significant statistical relationship between changes in sea surface temperatures and Greenbrier River discharge. I applied simple correlation (autocorrelation) and spectral density functions for the univariate analysis. Cross-correlation and cross-spectral functions were applied for the bivariate analysis. The autocorrelation and cross-correlation statistical functions were calculated using a FORTRAN program written by Dr. Dina Lopez (Lopez, 2009). Spectral density functions were calculated using the NCAR (National Center for Atmospheric Research) command language. The data evaluated included the historical records of the Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), as well as Greenbrier River peak annual discharge (peakflow), mean monthly discharge, and mean annual discharge.
5.3.1 Simple Correlation

The autocorrelation coefficient (ACF) considers the relationship among successive terms of a single time series. The ACF plotted against lag $k$ is known as an autocorrelogram. The ACF always lies between $[-1, 1]$ and is dimensionless. If there is a long-term memory effect, the slope of the ACF decreases slowly with time and has nonzero values over a long lag time, which indicates inter-dependency within the system. Conversely, a short-term effect is indicated by a rapid decrease in the slope whereby the slope reaches zero over a short time lag. This indicates that the time series is not internally correlated.

Autocorrelograms (Figure 28 and Figure 29) for Greenbrier River discharge (peakflow, mean annual $Q$) show there is a rapid decrease in slope and rapid damping as lag time increases, which indicates a short-term memory effect in the system and a lack of internal correlation. This is to be expected because seasonal influences on discharge are not observed at the annual scale and climate regimes influencing discharge can persist for months or years. However, it is not likely that we would observe correlations on the scale of multiple years because stream discharge responds to changes in the system (i.e. climate) relatively quickly (flood events).

Figures illustrate the ACF for mean monthly Greenbrier River discharge. The months of January (Figure 33), April (Figure 34), August (Figure 35), and November (Figure 36) represent winter, spring, summer and fall, respectively. Better correlation at higher lags is seen in the monthly data in comparison to the annual data, which is expected because the monthly data are of higher resolution. The autocorrelograms for the
AMO (Figure 30) and PDO (Figure 31) show a long-term memory effect with gentle slopes over long time lags, which are expected because ocean-atmospheric phenomena operate on decadal-to multidecadal time scales. However, the autocorrelogram for NAO (Figure 32) shows short-term memory effect. This is to be expected because the NAO is phenomena governed by changes in atmospheric pressure between the sub-tropical Atlantic and Arctic oceans, which can occur at interannual time-scales (Hurrell, et al., 2009).
Figure 28. Autocorrelogram of Greenbrier River peakflow.
Figure 29. Autocorrelogram of Greenbrier River mean annual discharge.
Figure 30. Autocorrelogram of Atlantic Multidecadal Oscillation (AMO).
Figure 31. Autocorrelogram of Pacific Decadal Oscillation (PDO).
Figure 32. Autocorrelogram of North Atlantic Oscillation (NAO).
Figure 33. Autocorrelation Function of Greenbrier River mean discharge for the month of January. Any peaks above the green line are considered to be within the 95% confidence interval.
Figure 34. Autocorrelation Function of Greenbrier River mean discharge for the month of April. Any peaks above the green line are considered to be within the 95% confidence interval.
Figure 35. Autocorrelation Function of Greenbrier River mean discharge for the month of August. Any peaks above the green line are considered to be within the 95% confidence interval.
Figure 36. Autocorrelation Function of Greenbrier River mean discharge for the month of November. Any peaks above the green line are considered to be within the 95% confidence interval.
5.3.2 Simple Spectral Analysis

In addition to the ACF, the simple spectral density function was applied to the data to determine the frequency of periodicity illustrated in the autocorrelograms. The spectral density function is derived from the Fourier transformation of the ACF, from time (lag) to frequency. Spectral density provides information about the variance of a time series with respect to frequency. Frequency is the inverse of periodicity, so 1/frequency equals the periodicity of a cycle within the time series. Each spectral density plot shows a dashed and a solid line.

The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum. Red noise refers to the shape of the spectra and refers to time series whose spectral power decreases as frequency increases. It is given the name red noise because red light is dominated by low frequencies. Red noise spectral power values are typically much larger at one part of the spectrum and much smaller in another part (Weedon, 2003). The null continuum is an underlying spectrum produced by applying one or more filters for the purpose of smoothing spectrum. The null continuum allows for background noise to be filtered and provides a means to test confidence levels of spectral peaks.

The simple spectral density plot (Figure 37) of Greenbrier River peakflow (m$^3$ s$^{-1}$ or cumecs) shows there is only one peak above the 95% c.i. This peak has a value of 0.41 cycles per year, which corresponds to a period of 2.4 years. The simple spectral density plot for AMO data (Figure 38) has no peaks of statistical significance. The PDO simple spectral density plot (Figure 39) shows one peak at 0.2 cycles per year, which
corresponds to a period of 5 years. The simple spectral density plot of NAO (Figure 40) has no peaks of statistical significance.
Figure 37. Spectrum of Greenbrier River peakflow. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum. Discharge \((Q)\) is expressed in cumecs \((\text{m}^3 \text{ s}^{-1})\).
Atlantic Multidecadal Oscillation

Figure 38. Spectrum of AMO. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum.
Figure 39. Spectrum of PDO. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum.
Figure 40. Spectrum of NAO. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum.
5.3.3 Simple Spectral of Monthly Anomalies

The simple spectral density shows that monthly discharge anomalies (Figure 41) for Greenbrier River have four peaks above the 95% c.i.; however, the third peak is barely above the 95% c.i. The frequencies of the four peaks are 0.008, 0.23, 0.39, and 0.48 cycles per month, which correspond to periods of 125, 4.35, 2.56 and 2.08 months, respectively. The plot of monthly AMO anomalies (Figure 42) has four small peaks above the 95% c.i.; however, the last three peaks are barely above the 95% c.i. The frequency of the largest peak is 0.08 cycles per month, which corresponds to a period of 12.5 months, respectively.

The simple spectral density plot for PDO monthly anomalies (Figure 43) has five small peaks, the second of which is just above the 95% c.i.. The frequencies of these peaks are 0.17, 0.28, 0.32, 0.41 and 0.48 cycles per month, which corresponds to a period of 5.9, 3.6, 3.1, 2.4, and 2.1 months, respectively. The plot of NAO monthly anomalies (Figure 44) shows eleven peaks of statistical significance. The three most prominent peaks have frequency of 0.165, 0.245 and 0.309 cycles per month and correspond to periods of 6.06, 4.08 and 3.23 months. In summary, the frequencies at which these different systems operate individually over time are not the same at the annual or monthly scale.
Greenbrier River Discharge (Monthly Anomalies)

Figure 41. Spectrum of Greenbrier River monthly discharge anomalies. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum.
Figure 42. Spectrum of AMO monthly anomalies. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum.
Figure 43. Spectrum of PDO monthly anomalies. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum.
Figure 44. Spectrum of NAO monthly anomalies. The dashed line represents the 95% Markov red noise confidence interval (c.i.) and the solid line represents the null continuum.
5.3.4 Cross-correlation

The purpose of the cross-correlation function (CCF) is to indicate the degree to which two time series are correlated as a function of time (Sahu et al., 2009). The cross-correlation coefficient is plotted against lag $k$ to create a cross-correlogram. The cross-correlogram allows the response time between two time series to be identified (Sahu et al., 2009).

The cross-correlogram for peakflow versus mean annual discharge (Figure 45) shows a response time of 2 years indicated by the CCF reaching zero at lag 2 and peak correlation occurs at lag 0. This response time does correlate with the regulation time of 2.4 years determined from the spectral density function for peakflow. This is expected because mean annual discharge will have an effect on peakflow (i.e. antecedent moisture or drought). However, maximum correlation is low (0.413), indicating that the influence of mean annual discharge is highly attenuated.

The cross-correlogram for peakflow versus AMO (Figure 46) shows a response time of 7 years indicated by the CCF reaching zero at lag 7 and maximum correlation occurs at lag 34. This response time does not correlate with the regulation time of 2.4 years determined from the spectral density function for peakflow and maximum correlation is very low (0.18). This indicates that AMO does not uniquely influence peakflow. The cross-correlogram for peakflow versus PDO (Figure 47) shows a response time of 2 years indicated by the CCF reaching zero at lag 2 and peak correlation occurs at lag 22. This response time does correlate with the regulation time of 2.4 years determined from the spectral density function for peakflow; however maximum correlation is low
(-0.164). This suggests that PDO may influence peakflow; however, discharge does not operate on a multidecadal time scale, so it is highly unlikely that there is a relationship between peakflow and PDO at a 22-year lag time. The cross-correlogram for peakflow versus NAO (Figure 48) shows a response time of 4 years indicated by the CCF reaching zero at lag 4 and peak correlation occurs at 4 years. This response time does not correlate with the regulation time of 2.4 years determined from the spectral density function for peakflow and maximum correlation (0.257) is low.

The cross-correlogram for mean annual discharge versus AMO (Figure 49) shows a response time 12 years indicated by the CCF reaching zero at lag 12. This response time does not correlate with the regulation time of 5.98 years as determined by spectral density function for mean annual discharge. Maximum correlation for mean annual discharge versus AMO occurs at lag 34 and is low (0.184). The cross-correlogram for mean annual discharge versus NAO (Figure 50) shows a response time of 3 years indicated by the CCF reaching zero at lag 3. This response time does not correlate with the regulation time of 5.98 years as determined by the spectral density function for mean annual discharge. Maximum correlation for mean annual discharge versus NAO occurs at 29 and is low (0.253).

The response time of mean annual discharge versus PDO (Figure 51) is 6 years as indicated by the CCF reaching zero at lag 8. This response time does not correlate with the regulation time of 5.98 years as determined by the spectral density function for mean annual discharge. Maximum correlation between mean annual discharge and PDO is at lag 28 and is low (0.225). In summary, there is no significant cross-correlation between
Greenbrier River discharge (peakflow (m$^3$ s$^{-1}$), mean annual) and AMO, PDO or NAO. Since no significant peaks were identified by the CCF, there was no reason to perform cross-spectral analysis.
Figure 45. Cross-correlogram of peakflow ($m^3s^{-1}$) and mean annual discharge ($m^3s^{-1}$).
Figure 46. Cross-correlogram of peakflow (m$^3$/s$^{-1}$) and Atlantic Multidecadal Oscillation (AMO).
Figure 47. Cross-correlogram of peakflow (m$^3$s$^{-1}$) and Pacific Decadal Oscillation (PDO).
Figure 48. Cross-correlogram of peakflow (m³ s⁻¹) and North Atlantic Oscillation (NAO).
Figure 49. Cross-correlogram of mean annual discharge and Atlantic Multidecadal Oscillation (AMO).
Figure 50. Cross-correlogram of mean annual discharge and North Atlantic Oscillation (NAO).
Figure 51. Cross-correlogram of mean annual discharge and Pacific Decadal Oscillation (PDO).
6.0 Evaluation of Hypotheses

H₀: Peak annual flood frequencies and magnitudes of the Greenbrier River in West Virginia are not correlated with changes in sea surface temperatures in the equatorial Pacific or North Atlantic oceans.

A significant statistical relationship was not found between peakflow of the Greenbrier River and SSTs, thus we fail to reject the null hypothesis. However, published records of stable isotope $\delta^{13}$C obtained from Colonial Acres Cave (CAC) slackwater sediments (Cocina, 2006; Springer et al., 2009), as well as, stable isotope $\delta^{13}$C and $\delta^{18}$O obtained from a stalagmite from Buckeye Creek Cave (BCC) (Springer et al., 2009) have been shown to correlate to oceanic-atmospheric changes (i.e. sea surface temperatures). A previous study (Springer et al., 2008) showed that changes in sea surface temperature-pressure gradients affect the frequency of local precipitation and possibly storminess. Thus, the influence of oceanic-atmospheric changes on local climate is well established.

The lack of statistical correlation is possibly a result of the resolution of the data because a stream will respond quickly to changes in climate (i.e. storminess). Furthermore, the frequency landfalling tropical cyclones, which are caused by oceanic-atmospheric changes, affect a variety of flood generating mechanisms and display large spatial heterogeneity over the eastern United States (Villarini and Smith, 2010). An uneven distribution of precipitation will affect stream discharge, as well as, the longitudinal profile (Galster, 2007).
**H1**: The flood history contained in CAC slackwater sediments deposited after ~3,500 B.P. correlates with proxies of local and regional climate change.

Correlations between $d_{50}$ values obtained from grain size analysis of CAC sediments and stable isotope $\delta^{13}C$ obtained from organic material found within CAC sediments indicate that larger grains were deposited during dryer time periods. In addition, correlations between $d_{50}$ values and $\delta^{18}O$ and Sr/Ca obtained from a stalagmite collected from Buckeye Creek Cave (BCC) (Cocina, 2006; Springer et al., 2009) indicate that larger grain sizes were deposited during periods of decreased moisture. Based on this evidence, we fail to reject H1. These local climate proxies have been attributed to changes in ocean-atmospheric oscillations driven by solar insolation (Springer et al., 2008; Springer et al., 2009).

**H2**: Modern and ancient flood regimes have been affected by equatorial Pacific and North Atlantic Ocean SST fluctuations.

Although this investigation did not find a statistical correlation between Greenbrier River peakflow and equatorial Pacific and North Atlantic Ocean SSTs, the aforementioned studies have demonstrated that during the Mid-to Late Holocene equatorial Pacific and North Atlantic Ocean SSTs influenced regional precipitation (storminess) causing wetter-than-normal conditions or drought. This investigation did find that floods large enough to flood CAC are not common in the historical record. The lack of modern correlations may be a result of the quality or quantity of available flood records rather than lack of correlation to long-term climate changes. Based on this evidence, we fail to reject H2.
7.0 Discussion of Results

As demonstrated by HEC-RAS modeling the minimum discharge required to flood the Trench Room in Colonial Acres Cave (CAC) is 1,600 m$^3$ s$^{-1}$. When compared to the historical record, I found that a flood of this discharge has a 9% chance of occurring in any given year and a recurrence interval of ~12 years. Historically a flood of this magnitude is not common; however, during the last century the Greenbrier River has exceeded the minimum discharge required to flood the Trench Room in CAC eight times (Table 5). However, all but two floods (1901 and 1967) were capable of flooding the Trench Room and Potato Room, so in other words the whole cave. The shortest time between these large floods is three years and the greatest amount of time is 49 years.

Table 5. Historically, eight floods potentially flooded the Trench Room in Colonial Acres Cave based on the minimum discharge of 1,600 m$^3$s$^{-1}$ required to flood the Trench Room in Colonial Acres Cave.

<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>Discharge</th>
<th>Rank</th>
<th>Probability</th>
<th>Recurrence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1901</td>
<td>1610</td>
<td>8</td>
<td>0.07</td>
<td>14</td>
</tr>
<tr>
<td>1913</td>
<td>1814</td>
<td>4</td>
<td>0.04</td>
<td>29</td>
</tr>
<tr>
<td>1918</td>
<td>2196</td>
<td>3</td>
<td>0.03</td>
<td>38</td>
</tr>
<tr>
<td>1967</td>
<td>1717</td>
<td>6</td>
<td>0.05</td>
<td>19</td>
</tr>
<tr>
<td>1974</td>
<td>1800</td>
<td>5</td>
<td>0.04</td>
<td>23</td>
</tr>
<tr>
<td>1977</td>
<td>1697</td>
<td>7</td>
<td>0.06</td>
<td>16</td>
</tr>
<tr>
<td>1985</td>
<td>2567</td>
<td>2</td>
<td>0.02</td>
<td>57</td>
</tr>
<tr>
<td>1996</td>
<td>2664</td>
<td>1</td>
<td>0.01</td>
<td>114</td>
</tr>
</tbody>
</table>

The Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal oscillation (AMO) are known to affect precipitation (drought and storminess), which directly affects stream discharge (Springer et al., 2008). Considering that PDO and AMO operate on decadal time scales and the recurrence interval for a flood large enough to flood CAC is
12 years. It is possible that oscillations of PDO and AMO are the driving force behind these large flood events.

The time series of analysis of Greenbrier River peakflow and sea surface temperature anomalies (SSTAs) failed to demonstrate that SSTAs have a significant influence on peakflow. The response time of Greenbrier River discharge is much smaller than the response time of AMO, PDO and NAO sea surface temperature anomalies (SSTAs). Thus, no significant peaks of correlation were determined. This is expected because the Greenbrier River is going to respond to local changes in climate (i.e. increased storminess) rapidly. However, a lack of significant peaks of correlation does not mean that SSTAs do not affect Greenbrier River discharge.

The effect of equatorial Pacific and North Atlantic SST fluctuations on flood regimes during modern times is well documented. For example, the ENSO state, El Niño, which is the warm episode of the ENSO mode, is known to cause an increase in precipitation along the West Coast of tropical South America, Gulf Coast region of North America and from southern Brazil to central Argentina (Viles and Goudie, 2003). La Niña, which is the cool state of the ENSO mode, tends to result in opposite conditions. During La Niña states, winter temperatures are warmer than usual in the southeastern United States and cooler in the northwestern United States (Viles and Goudie, 2003). The Pacific Decadal Oscillation (PDO) creates conditions similar to El Niño, but operates over a much longer time period. The two largest historical floods have occurred during the last 25 years when the PDO was in its positive phase (El Niño-like) and ENSO was weakly in its negative phase (La Niña) (Viles and Goudie, 2003; Kousky and Bell, 2000).
Stable isotopes $\delta^{13}C$ obtained from organic material found in CAC slackwater sediments correlates to regional climate histories (White, 2007). In addition, aforementioned climate proxies (i.e., speleothems, pollen, etc.) have demonstrated that oceanic-atmospheric systems have influenced local climate (Springer et al., 2008; Springer et al., 2009). A study by Springer et al. (2008) demonstrated that AMO and PDO correlate to periods of drought when compared to Greenbrier River discharge. Although we cannot pinpoint an exact frequency at which these events have or will occur, it is well established that SSTAs are a driving force in local climate change (White, 2007; Springer et al., 2009).
8.0 Conclusions

This investigation demonstrated the complexities involved in determining the influence of extrinsic factors on a fluviokarst system. A significant statistical correlation was not found between Greenbrier River peakflow and sea surface temperature anomalies (SSTAs). However, the correlation between grain size of Colonial Acres Cave (CAC) slackwater sediments and local climate proxies provides persuasive evidence supporting the hypothesis that oceanic-atmospheric changes, such as SSTAs, influence the Greenbrier River flood regime, in particular, peakflows.

This investigation determined that a minimum discharge of 1,600 m$^3$ s$^{-1}$ is required to flood the Trench Room in CAC. Historically a flood with this minimum discharge is uncommon and has only occurred eight times during the last century. However, all but two floods (1901 and 1967) were capable of flooding the entire cave. The most severe of these flood events occurred in 1985 and 1996. In 1985 and 1996 the PDO was in its positive phase (Viles and Goudie, 2003); however, the AMO was in its negative phase in 1985 and in its positive phase in 1996 (http://www.aoml.noaa.gov/phod/amo_faq.php). The lack of modern correlations may reflect the quantity and quality of existing flood records rather than the long-term relationship between climate(s), local flooding, and sediment deposition in CAC.
9.0 Future Hydroclimate Studies in Central Appalachia

Determining how extrinsic forces, such as climate, tectonics and human activities affect the geomorphology of a landscape is difficult because these processes overlap each other and are entangled with internal thresholds that also control Earth’s processes. However, we can make this task less complicated by collecting more data. There is a wealth of paleoclimatological information available in the Greenbrier River watershed that still needs to be investigated. Future investigations in the Greenbrier River watershed and other Appalachian fluviokarst systems have the potential to expand our current knowledge of the interactions between geologic processes and climate changes in southeastern North America.

Understanding how fluviokarst systems respond to climate is a complex issue as there are many interconnected processes at work. Collecting new paleoclimatic data including new sediment data for the central Appalachian region, would aid any further attempts to reconstruct the flood history for the Greenbrier River. It is crucial to find more caves that have well-preserved slackwater sediments in which to compare Colonial Acres Cave (CAC) if we are to better reconstruct flood histories for the Greenbrier River watershed. Although several other caves in the area are known to possess slackwater sediments, they are poorly-preserved. However, there are potentially many more caves similar to Colonial Acres Cave that have yet to be discovered and could aid paleoflood reconstructions. More effort needs to be put into finding and mapping these caves. Many caves go unreported because they are considered small and insignificant, but in actuality they may contain valuable geologic, geomorphic and biological information.
Determining how flood regimes respond to climate change is crucial if we want to protect and prepare local communities. We may never be able to 100% accurately estimate the magnitude and frequencies of flood events; however, the expansion of data sets will undoubtedly lead to more accurate estimates of flood frequencies and magnitudes, which in turn will aid flood hazard and risk assessment.
References


Kirby, M.E., Mullins, H.T., Patterson, W.P., and Burnett, A.W., (2002) Late Glacial-Holocene Atmospheric Circulation and Precipitation in the Northeast United States


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Appendix

Colonial Acres Cave Sediment Descriptions

1.0 Trench Room

Unit 1
Depth: 0cm-3cm
Sediment Description: Very finely laminated clayey silt. Alternating layers of medium brown clay and light yellow-brown layers of silt. Laminae <1mm. Distinguishable yellow-brown silt layer <0.5mm thick at 2mm depth.
Clay balls: none visible
Charcoal: sparse; < 0.5- 2 mm in size.
Upper contact: Surface (top of stratigraphic column) abrupt
Lower contact: Not distinct
Depositional Environment: Very slow moving to stagnant water

Unit 2
Depth: 3cm-6cm
Sediment Description: Finely laminated, medium brown clayey silt. Laminae <1mm.
Clay balls: sparse; < 1 mm
Charcoal: sparse; < 1 mm
Upper Contact: Not distinct
Lower Contact: Distinct clay laminae
Depositional Environment: Very slow moving to stagnant water

Unit 3
Depth: 6cm-12cm
Sediment Description: Medium brown clayey silt laminae 1mm to 2mm alternating with thin < .05 mm fine quartz sand laminae. At 7 cm depth there is a distinct pocket/nodule of fine quartz sand 5mm in width and 10 mm in length. At 9 cm depth there is a distinct light yellow-brown, medium coarse silt layer 1mm to 2 mm thick.
Clay balls: sparse; <1mm
Charcoal: sparse; < 1mm
Upper Contact: Distinct Clay
Lower Contact: Not Distinct
Depositional Environment: Very slow moving to stagnant water
Unit 4
Depth: 12 cm-17 cm
Sediment Description: medium brown clayey silt 0.05-1mm thick laminae alternating with layers of yellow-brown silt ~ 1mm thick. Distinctly thicker silt layers at 12 cm and 15.3 cm of depth 4mm and 2mm respectively.
Clay balls: none visible
Charcoal: none visible
Upper Contact: Not Distinct
Lower Contact: distinct sand layer
Depositional Environment: Very slow moving to stagnant water

Unit 5
Depth: 17 cm- 20 cm
Sediment Description: Yellow-light brown sand ~ 0.5 cm thick at upper contact; medium brown clayey silt laminae ≤ 1 mm, alternating with yellow sand laminae ≤ 1 mm thick.
Clay balls: abundant- give unit a mottled-like appearance
Charcoal: none visible
Upper Contact: distinct sand layer
Lower Contact: distinct sand layer
Depositional Environment: Moderate to slow moving water

Unit 6
Depth: 20 cm- 22 cm
Sediment Description: Massive, loose, yellow-light brown sand
Clay balls: present at contacts; none visible within unit
Charcoal: none visible
Upper Contact: distinct medium brown silty clay
Lower Contact: distinct medium brown silty clay
Depositional Environment: Moderate to slow moving water

Unit 7
Depth: 22 cm- 34 cm
Sediment Description: Medium brown clayey silt laminae generally ≤ 1mm, alternating with silty laminae generally ≤ .05 mm. Distinctly thicker silty laminae at 24 cm, 27cm-28 cm and 32 cm.
Clay balls: Abundant at the top and bottom of unit generally ≤ 2 mm gives unit a “mottled-like” appearance; large clay ball (~ 6mm x 13 mm) at 26 cm of depth.
Charcoal: (~ 3 mm x 9 mm) at 33 cm of depth; overall sparse, only visible between 30 cm and 34 cm of depth.
Upper Contact: Distinct medium brown silty clay
Lower Contact: Distinct light yellowish brown silty sand
Depositional Environment: Stagnate water with pulses of moderate to slow moving water
**Unit 8**
Depth: 34 cm-41 cm
Sediment Description: Medium brown clayey silt laminae ~ \( \leq 1 \) mm interbedded with light yellowish brown silt laminae ~ 1 cm-2 cm.
Clay balls: Abundant throughout unit; most generally ~ 2-3 mm
Charcoal: Several small pieces throughout unit
Upper Contact: Distinct light yellowish brown clayey silt
Lower Contact: Distinct loose medium brown clayey silt
Depositional Environment: Stagnate water with pulses of slow moving water

**Unit 9**
Depth: 41 cm- 48 cm
Sediment Description: Medium brown clay silt laminae ~ 2 to 3 mm interbedded with very thin light yellowish brown silt laminae \( \leq 1 \) mm.
Clay balls: Sparse
Charcoal: Sparse
Upper Contact: Distinct loose medium brown clayey silt
Lower Contact: Not Distinct
Depositional Environment: Stagnate water with pulses of moderate to slow moving water

**Unit 10**
Depth: 48 cm- 56 cm
Sediment Description: Very finely laminated \( \leq 1 \) mm, medium brown clayey silt; distinct light yellowish-brown clayey silt laminae at 49 cm- 50 cm of depth.
Clay balls: Present, but sparse between 50 and 51 cm
Charcoal: Small pieces present at the top and bottom of the unit;
Upper Contact: Not Distinct
Lower Contact: Distinct light yellowish-brown silty sand
Depositional Environment: Very slow to stagnate water

**Unit 11**
Depth: 56 cm- 59 cm
Sediment Description: Light yellowish-brown silty sand laminae interbedded with very thin \( \leq 1 \) mm medium brown clayey silt laminae.
Clay balls: None visible
Charcoal: Present at top and bottom of unit
Upper Contact: Distinct medium brown clayey silt
Lower Contact: Distinct medium brown clayey silt
Depositional Environment: Moderate to slow moving water
**Unit 12**
Depth: 59 cm–65.5 cm
Sediment Description: Very finely laminated (≤ 1 mm) medium brown clayey silt interbedded with very finely laminated light yellowish-brown clayey silt laminae.
Clay balls: None visible
Charcoal: None visible
Upper Contact: Distinct medium brown clayey silt
Lower Contact: Distinct loose light brown silty sand
Depositional Environment: Slow to stagnate water

**Unit 13**
Depth: 65.5 cm–67.5 cm
Sediment Description: Loose light brown silty sand
Clay balls: None visible
Charcoal: None visible
Upper Contact: Distinct medium brown clayey silt
Lower Contact: Distinct medium brown clayey silt
Depositional Environment: Moderate to slow moving water

**Unit 14**
Depth: 67.5 cm–71 cm
Sediment Description: Very finely laminated (≤ 1 mm) medium brown clayey silt interbedded with very finely laminated light yellowish-brown clayey silt laminae.
Clay balls: None visible
Charcoal: Sparse small pieces
Upper Contact: Distinct medium brown clayey silt
Lower Contact: Distinct yellowish-brown silty sand
Depositional Environment: Slow to stagnate water

**Unit 15**
Depth: 71–72 cm
Sediment Description: Light yellowish-brown silty sand
Clay balls: None visible
Charcoal: None visible
Upper Contact: Distinct medium brown clayey silt
Lower Contact: Distinct medium brown clayey silt
Depositional Environment: Moderate to slow moving water
Unit 16
Depth: 72 cm- 74 cm
Sediment Description: Very finely laminated (≤ 1 mm) medium brown clayey silt interbedded with very finely laminated light yellowish-brown clayey silt laminae.
Clay balls: None visible
Charcoal: None visible
Upper Contact: Distinct yellowish-brown silty sand
Lower Contact: Bottom of Core
Depositional Environment: Slow to stagnate water
1.1 Potato Room

Unit 1
Depth: 1 cm-6.5 cm
Sediment Description: Weakly laminated, medium silty clay inter bedded with light yellowish brown sandy silt.
Clay balls: None
Charcoal: None
Upper Contact: surface
Lower Contact: Distinct
Depositional Environment: Modern, reworked slackwater deposits

Unit 2
Depth: 6.5 cm- 17 cm
Sediment Description: Mottled, medium brown silty clay; streaks of rusty orange throughout; vague remnants of lamination.
Clay balls: None
Charcoal: None
Upper Contact: Distinct
Lower Contact: Not distinct
Depositional Environment: Reworked, exposed slackwater deposits

Unit 3
Depth: 17 cm- 23 cm
Sediment Description: Mottled medium brown silty clay
Clay balls: Yes
Charcoal: None
Upper Contact: Not distinct
Lower Contact: Distinct
Depositional Environment: Bioturbated slackwater deposits

Unit 4
Depth: 23 cm- 25 cm
Sediment Description: Weakly laminated medium brown silty clay with distinct streaks of light yellowish brown sandy silt.
Clay balls: Yes
Charcoal: None
Upper Contact: Distinct
Lower Contact: Distinct
Depositional Environment: Reworked slackwater sediments; light bands possibly a weathering phenomena or evidence of bioturbation.
Unit 5
Depth: 25 cm- 43 cm
Sediment Description: Massive, mottled medium brown silty clay. Streaks of rusty orange throughout
Clay balls: Yes
Charcoal: None
Upper Contact: Distinct
Lower Contact: Bottom of trench
Depositional Environment: Reworked, exposed slackwater deposits.