Verification of and Expansion Upon the Use of Cave Scallops in Recreating
Hydrogeologic Conditions in Karst Aquifers

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Andrew W. Hall

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This thesis titled
Verification of and Expansion Upon the Use of Cave Scallops in Recreating
Hydrogeologic Conditions in Karst Aquifers

by
ANDREW W. HALL

has been approved for
the Department of Geological Sciences
and the College of Arts and Sciences by

Gregory S. Springer
Associate Professor of Geological Sciences

Joseph Shields
Interim Dean, College of Arts and Sciences

ABSTRACT

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Hydrogeologic Conditions in Karst Aquifers

Director of Thesis: Gregory S. Springer

Turbulent flow across soluble bedrock can form concave dissolution features known as scallops. Scallops have been used to recreate paleoflow conditions in caves by deriving floodwater velocities and discharge from scallop lengths. The goal of this study was to verify and extend the application of scallops in recreating hydrogeologic conditions. We tested for the constancy of flow rates throughout a given passage (continuity), uniform vs. non-uniform flow, the effect on scallop lengths due to vertical position in a cave passage, correlations between sediment grain size and scallop-derived shear stresses in passages, and finally the effect of comparatively large scallop lengths (~outliers) on the derived discharge values. In order to test these hypotheses, we measured scallops and sediments from a multitude of caves in Greenbrier County, West Virginia, and by performing statistical analyses on the measurements. We attempted to replicate previous findings of continuity and were partially successful in doing so. We looked for a difference in the variances of scallops in curving and straight passages, which could be used to identify non-uniform flow, and concluded that variance is not able to be used as such. We then compared scallop lengths at various heights in a given passage cross-section and found that their derived specific discharges vary randomly with height with no upward increase of specific discharge. Sediment-derived and scallop-

derived floodwater velocities were similar to each other and may represent the same flow conditions. Monte Carlo simulations of the effect of extreme scallop lengths for varied sample sizes revealed that the comparatively large scallop lengths significantly impact the Sauter mean when using smaller sample sizes. The standard deviation of Sauter means nearly doubled from sample sizes of 30 to 10 scallop lengths. Taken together, this study's findings confirmed and expanded the use of scallops in recreating paleoflow conditions but shows more work is needed to understand the complexity of cave specific paleoflow conditions.

DEDICATION

Dedicated to my dad, Wes Hall and my pops, John Hall, who instilled within me a passion for science, and have always been supportive of my endeavors.

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CHAPTER 1: INTRODUCTION

Data collected from fieldwork comes with uncertainties but the magnitude and degree of those uncertainties are commonly unaddressed. The assumptions made while collecting data are the foundation of interpretation and the conclusions drawn forth. If the impact of certain assumptions is not tested then the accuracy of the interpretations is uncertain and the conclusions lose their support.

Cave scallops are erosional features commonly carved on soluble substrates (e.g., limestone) and are formed from turbulent flow associated with the ~95th percentile of flood discharges (Goodchild and Ford 1971; Lauritzen 1982). They resemble the depression of a scallop shell and the crests between these depressions are steeper on their downstream faces (Curl 1966, 1974). Scallops form in response to flow of water along walls that detaches and creates sublaminal jets that, after separating from the wall, destabilize and impact the wall. This forms an eddy that over time will erode a depression (i.e., scallop; Blumberg and Curl 1974). See figure 1 for the hydrodynamics of scallop formation in cross-section. This scalloping process moves downstream with the flow of the water (Curl 1974). It was discovered that the velocity of the formative water is inversely related to the length (L) between the scallop crests (Blumberg and Curl 1974). Thus, the velocity and discharge of the flow that formed the scallops can be deduced if the passage cross-section dimensions are measured in the field (Curl 1974).

Figure 1: Cross-section of cave scallop. At step 1, the water flow separates at the crest as a sublaminal jet. At step 2, the jet becomes turbulent. At step 3, the jet reattaches to the wall. At step 4, some flow becomes trapped and recirculates in a lee eddy. L is the length of a cave scallop and is the measurement used to derive discharge. Diagram adapted by G.S. Springer from Blumberg and Curl (1974).

The two main theories regarding the dominant force that erodes scallops are abrasion by sediments in fast-moving floodwaters and dissolution by carbonic acid in water. The 95th percentile discharge, which forms scallops, carries the highest sediment loads so abrasion may come into play (Newson 1971; Lauritzen 1982). However, scallops are known to form in slowly flowing water, which shows that abrasion does not always play an important role (Goodchild and Ford 1971). Thus, the conclusion is that both processes are at work but with solution being the dominant force under most circumstances (Goodchild and Ford 1971). This is not to be confused with the scalloping process itself which is purely hydrodynamic (Curl 1974; Lauritzen 1986).

Lauritzen (1985, 1989) found that the 95th percentile of flood discharges is the scallop dominant discharge. Higher discharges are correlated with greater rates of wall retreat, thus making the higher discharges the dominant scalloping discharge (Lauritzen 1989; Huang et al. 2015); in the larger discharge events, the amount of dissolution on the cave walls is proportionally much greater than during smaller discharges.

In the literature, scallops have been used to successfully reconstruct paleoflow conditions, especially in combination with sediment analyses. The applications of scallop length measurements are many but little has been done with the assumptions and methodology. Hence, it is important to test the assumptions and understand the limits of current practices. The effect of uniform and non-uniform flow and vertical variation are previously unaddressed and will be investigated in this thesis. Sample size has also not been addressed and an in-depth analysis should shed light on the most efficient number of scallop lengths to measure for accurate paleoflow reconstruction.

CHAPTER 2: PREVIOUS WORK

Scallop length (L) is inversely correlated with formative water velocities (Blumberg and Curl 1974; Curl 1974). Discharge can be derived by multiplying passage cross-sectional area by the average velocity calculated using scallops. The calculations are performed using the Sauter mean (L_{32}) of scallops measured in the field. Utilizing the Sauter mean of the scallop lengths dampens the effect of smaller length measurements (Curl 1974). The Sauter mean is calculated as:

$$L_{32} = \frac{\sum L_i^3}{\sum L_i^2}$$

Average water velocities ($\bar{v}$) are found using equations for elliptical and parallel walled (rectangular shaped) passage cross-sections, as formulated by Curl (1974) and Blumberg and Curl (1974). The average velocity equations are derived from Prandtl's universal velocity distribution law, which describes the velocity profile of velocity near a rough wall (Curl 1974). The equations for parallel walls and elliptical shaped passages given by Blumberg and Curl (1974) and Curl (1974) are respectively:

$$\bar{v} = \frac{\mu}{L_{32}} Re^* \left[2.5 \left(\ln \frac{w}{2L_{32}} - 1 \right) + B_L \right]$$

$$\bar{v} = \frac{\mu}{L_{32}} Re^* \left[2.5 \left(\ln \frac{D}{2L_{32}} - \frac{3}{2} \right) + B_L \right]$$

where D is the hydraulic diameter of the passage's cross-section, w is the width of the passage cross section, L_{32} is the Sauter mean of scallop lengths (as measured from crest to crest parallel to the direction of flow), μ is fluid viscosity, Re^* is the Reynolds

number based on friction velocity and L_{32} , and B_L is the roughness function. Re^* and B_L were found to be 2200 and 9.4, respectively, by Blumberg and Curl (1974). Since the equations were derived from experiments with steady flow on an artificially roughened plaster of Paris blocks, they are only accurate in determining velocity in passages of that are long and straight enough to develop uniform flow (Curl 1974).

Applications of Scallop-Derived Discharges

Scallop derived discharges can be used to recreate paleoflow conditions in caves. Blumberg and Curl (1974) developed the methods of using scallop lengths to deduce paleoflow conditions, but did not fully evaluate of the effects of uniform and non-uniform flow on scallops. Lauritzen (1982) successfully used scallop derived discharges to recreate flow conditions in the Pikhåggrottene cave system in Norway using an equation that combined the average velocity equations of Blumberg and Curl (1974) and Curl (1974). Lauritzen tested the continuity equation that states that the water discharge flowing through a tube must equal the discharge flowing out of the tube, and that discharge at any cross-section of the tube must be the same. He used field-measured scallop lengths to test the equation in a cave system lacking tributaries. However, cave passages are not always perfect “tubes” and can have numerous possibilities for the water to escape, such as fractures or branching passages. Passages could also be dammed which could suppress scallop formation. So, Lauritzen (1982) used the best unbranched passages he could find. He used scallop data from at least five different cross-sections in each passage to test the continuity equation and reported a flow-rate precision of $\pm 5.8\%$. He also tested the cave system as a whole with the continuity equation by analyzing the

scallop-derived discharges in each cave passage against discharges measured at a spring fed by the cave. He concluded that the flow rates throughout the whole system agree with the continuity equation. This study was designed to analyze and try to reproduce his continuity findings and extend the applications of scallop-derived data to other aspects of paleoflow conditions.

The effects of uniform and non-uniform flow on scallop measurements is a previously unstudied and novel idea presented in this thesis. Hypothetically, scallop lengths and statistical distributions created by uniform and non-uniform flows should be different. “In curving conduits, the velocity is greatest near the inner wall at the beginning of the turn and near the outer wall at the end of the turn (there also may be reversed flow on the inner wall near the end of the turn)” (Curl 1974, p. 4). Curl (1974) also stated that the equations of average velocity are made for passages of straight uniform flow and would be inaccurate in non-straight or curved passages. When deriving discharge from scallops in a straight passage one would expect the flow to be uniform, but if this is this not the case then the scallop measurements will not give an accurate velocity. Perhaps a characteristic of scallops developed in curving passages can be used to recognize non-uniform flow in straight passages.

Scallop length has been reported to vary at different heights within a cave passage (Palmer 2007). The scallop dominant discharge, logically, would not change while a cave is actively incising a canyon unless climate changes. Assuming a steady climate, vertical changes in scallop lengths might be attributed to scallops closer to the floor being subjected to more frequent low flows (Palmer 2007). Presumably, deeper flows have

higher discharges, so I tested whether scallop lengths do indeed show increasing discharge with elevation in a cave passage and will discuss this in more detail in the methods section.

Assumptions and Sample Size of Scallop Derived Discharges

Ever since Curl (1974) produced the equations to derive discharge from scallop measurements and Lauritzen (1982) implemented them in a natural setting, authors have used scallops alone or in conjunction with other discharge measurements in research regarding paleodischarge of karst aquifers. An investigation of the literature reveals a wide range of different assumptions—such as whether they used L_{32} or average L and sample sizes used when measuring and analyzing scallops (Table 1).

Table 1

Reported sample size for scallop measurement sets

Authors	L_{32} or Mean L	Sample Size
Gale (1984)	Mean L	25
González-Lemos, Jiménez-Sánchez, and Stoll (2015)	L_{32}	19-25
Springer et al. (2003)	L_{32}	30
Despain and Stock (2005, 2016)	Mean L	“Selected based on abundance”
Checkley and Faulkner (2014)	L_{32} and Mean L	3-17
Harman (2012)	L_{32}	2-21
Lauritzen (1982)	L_{32}	24-102

The majority of studies made using scallops either do not specify their sample size(s) or report using varying sample sizes (Table 1). This lack of a consistent sample size creates uncertainty in the use of scallops as indicators of discharge. Especially since the issue of sampling bias has not been addressed in the scallop literature. Relatively large scallops or even small scallops (~outliers) could have a noticeable effect on the accuracy of the Sauter mean and thus the average velocity. Hypothetically, Lauritzen's (1982) precision rate of $\pm 5.8\%$ may be significantly changed by the inclusion or exclusion of outlier scallop lengths. This will be addressed further in the methods section.

Sediment-based Estimation of Streamflow Properties

Sediments that are transported and deposited by water in cave passages can be used to indirectly calculate the flow of the water that deposited them (Gale 1984). Sediments have been used often in conjunction with scallop derived discharges to more accurately recreate paleoflow conditions. Gale (1984) combined scallop-derived discharges with sediment analyses to produce a clearer interpretation of the hydraulics of passage flow in karst aquifers. He calculated the boundary-shear stress of the water that carried sediments whose sizes he measured, and then derived the velocity (Gale 1984). He found that both the sediments and scallops correspond to high discharges. Jeaninn (2001) used pebble size and scallop length to recreate paleo-velocity conditions. He found that scallops formed at roughly half of the highest annual flow velocities, whereas the pebbles represent the highest annual flow velocities. Despain et al. (2016) used both cobble measurements and scallop lengths to estimate paleodischarge and compare that value to modern discharge measurements to help construct a history of Hurricane Crawl

Cave in Sequoia National Park, California. They used the stream cobbles to deduce critical shear stress which can be derived to produce velocity. They found that both cobbles and scallops are representative of the moderate to highest paleo-flow velocities, but cobble sizes represent comparatively greater flows than scallops.

CHAPTER 3: HYPOTHESES

H_1 : Scallop-derived specific discharges (q_s) are the same in three, widely-spaced reaches of the stream passages in multiple caves ($q_{s1} = q_{s2} = q_{s3}$).

The specific discharges derived from scallops on passage walls should be approximately equal to each other at three different reaches along a passage, based the continuity equation (*cf.* Lauritzen 1982). Specific discharge is the product of the scallop-derived velocity and the passage width at that specific height. Specific discharge, rather than velocity, was used to take into account the varied widths at different heights in a cross section. Velocities must be different for different widths if specific discharge is the same at each height, but specific discharge may not be the same everywhere due to blocked or dammed passages and discharge may be different if a tributary is between reaches. The ideal measurement locations will be in straight reaches far enough away from curved reaches. This hypothesis, if not disproved, would give researchers more confidence in using scallop measurements as means of reconstructing cave hydrogeologies and confirm the findings of Lauritzen (1982).

H_2 : Areas of uniform and non-uniform flow can be differentiated purely on the statistical distributions and non-dimensional variances of scallop lengths.

As stated earlier, scallop lengths measured in areas of uniform and non-uniform flow are presumed to be different. An analysis of these curved (non-uniform) passages may reveal statistical characteristics that can be used to differentiate them from uniform flow reaches regardless of passage shape. This might apply to finding non-uniform flow in straight passages. The statistical distributions and non-dimensional variances of scallop

lengths were compared in multiple curved passages to test whether there is a common characteristic that can identify a set of scallop lengths as having non-uniform flow.

H₃: The vertical position of scallop's in a passage affects calculated velocities and discharges.

Flow at different heights above a cave floor may be different in a given passage cross-section and should will be evident in the scallop sizes and geometries. This is because the scallops in the lower section of the passage are presumably subjected to more frequent low flows and the upper section scallops are formed by high intensity, less frequent flows (Palmer 2007). An analysis of these scallops in both the upper and lower regions of a cave passage should assist in determining the precision of velocity and discharge estimates based on channel (wall) position.

H₄: Sediment grain sizes are correlated with scallop derived shear stresses.

Streambed sediments were sampled with Wolman pebble counts at multiple locations within each cave to determine grain size and sorting. The shear stress values derived from the scallop measurements were tested to see if they correlate with sediment grain sizes. The latter are known to be correlated with bed shear stresses (Lauritzen 1982; Gale 1984). However, not all sediments found on a cave streambed are necessarily deposited from the same flow conditions responsible for scallop formation, especially if the flow conditions in the cave have changed since scallops formed; the sediments might not have been carried by the scallop-forming discharge and the dominant sediment transport discharge might not be in the 95th percentile of all flows. Thus, an analysis of grain size will shed light on whether the two are correlated. Velocities calculated from

median clast sizes (d_{50}) and scallop lengths were compared to test if the sediment is indicative of the discharge that formed the scallops.

H₅: The largest and smallest scallops (~outliers) significantly affect derived discharge values and influence accuracy.

The equations used to derive discharge from scallops utilize the Sauter mean, which is distorted by the inclusion of extreme values (outliers). Sampling methods affect how sensitive calculated discharges are to the inclusion of extremes. The statistically significant effect of the inclusion of extreme scallop lengths on the scallop-derived specific discharges was tested. Repeated subsampling and outlier tests were performed to investigate sampling bias and Monte Carlo simulations were run to learn how sampling bias effects the calculated specific discharges.

CHAPTER 4: GEOLOGIC SETTING

All caves used in this research are located in the karst landscape of Greenbrier County, West Virginia, USA (38°N, 80.4°W). Cave maps and locations are provided but should not be visited without assistance and guidance of an experienced caver and permission from landowners and WVACS (West Virginia Association of Cave Studies). The caves are located in a temperate climate at moderate latitude with a year-round average annual precipitation (rain or snow) of 1000mm (Hardt et al., 2010). Baseflow is during winter and spring but flooding events are possible year-round due to large storm-systems, remnant tropical storms, and snow-melt or rain-snow interaction. The flooding events are often rapid, large, and short-lived (1-10 hours), with most described as being “walls of water” recorded by pressure transducers. Some of these flooding events are longer-lived either due to caves with drainage areas larger than 20 km² or from back flooding caused by constrictions due to cave morphology.

Scallops were measured in 7.5km long Buckeye Creek Cave in an epiphreatic elliptical tube (The Watergate) and parallel-wall canyon (Gray canyon) (Dasher and Balfour, 1994). Buckeye creek cave drains a watershed of 14km² with 1km² thought to be captured by an adjacent watershed. Flood debris found near canyon ceiling (height of 15km) indicate pipe-full conditions and large hydraulic head during large flooding events.

Scallops were also measured in an epiphreatic inactive elliptical tube in Boarhole Cave, part of the 17km long Boarhole-Portal Cave System. The tube is 4-m wide and 2-m tall, phreatic in origin and located at the beginning of the k-survey.

The rest of the scallops were measured in Death Canyon and Fullers Cave of the 34-km long Culverson Creek Cave System (Figure 2, 3, 4, and 5). Death Canyon drains an area of 70 km² but during the largest flooding events an unknown amount of flow bypasses the canyon. Pipe-full conditions are frequently achieved due to a constriction at the upstream entrance known as Dread Pool. Dread Pool is 1.5-m high and 4-m wide and during pipe-full conditions, generates 30-m of head in Death Canyon. Fullers Cave drains an area of 2 km² and can achieve pipe-full conditions during the largest floods as shown by flood debris near the ceilings.

Figure 2: Culverson Creek Cave System. Shown above is the entire surveyed extent of the Culverson Creek Cave System. Fullers Cave is the eastern extent of the cave system while Culverson Cave proper is the rest of the system. Map from Lucas et al. (2018).

Figure 3: Culverson Creek Cave. Shown above is the Wildcat entrance to Culverson Creek Cave. Death canyon is the location of all scallops measured and is shown in its entirety. Map from Lucas et al. (2018).

Figure 4: Death Canyon of Culverson Creek Cave. Shown above are the locations (red dots) of scallop length measurement sites in the parallel wall shaped canyon. It is to be noted that Wolman pebble counts were conducted at Sites 1, 2, and 3 along with the scallop measurements. Map from Lucas et al. (2018).

Figure 5: Fuller's Cave. Shown above are the locations (red dots) of all scallop length measurement sites in Fullers Cave of the Culverson Creek Cave System. Wolman pebble counts were conducted at Sites 1, 2.5 and 3 along with scallop measurements. Map from Lucas et al. (2018).

CHAPTER 5: METHODOLOGY

Scallop Measurements

Scallops were measured crest to crest with a ruler to the nearest millimeter while an assistant recorded each value. To reduce sampling bias, all scallops studied in this project were measured by the same person. A minimum of 30 scallops were measured at each locality. Only scallops on uniform substrates were measured; calcite veins or secondary mineral growths that might have affected the scallops were avoided. Areas of reverse flow, based on scallop geometries, were noted and avoided. Scallops were measured in a line parallel to the passage trend and then measured down a 'row' of scallops and backwards parallel to the passage trend. If necessary, measured scallops were marked with a removable or washable marker to avoid repeat measurements. Also, each measurement locality was from a different region in a passage to get a more representative sample.

Scallops were measured at multiple straight reaches in three caves where flow is believed to be uniform and well developed (Table 2). Cross-sectional area and location in the passage was measured with a DistoX2 laser range finder. Scallops were also measured on the inner and outer walls of multiple curved passages, and at various heights above cave streams within multiple specific cross-sections (Table 2).

Table 2

Scallop and sediment data

Cave	Straight Reaches	Curved Reaches	Vertical Sections	Wolman Counts	Total Scallops Measured
Buckeye Creek	4	2	1	-	394
Culverson Creek	3	2	-	3	440
Fuller's	5	3	5	3	720
Boarhole	1	-	-	-	130
					1756

Shown above are the number of scallop length measurement sets in straight and curved reaches and vertical sections in all caves visited for this research. Also shown are the number of Wolman counts performed. All caves visited are located in the karst of Greenbrier County West Virginia.

Scallop Length Measurement Analysis and Statistics

Smaller sample sizes of scallop lengths are typically either normal or log-normal but large sets of scallop lengths ($n=100$) are log-normal (Table 3 and Figure 6).

Therefore, a $\log_{10}$ transformation of the scallop length sets was used to obtain a normal distribution for statistical analyses. $\log_{10}$ was chosen instead of $\ln$ for ease of interpretation. After transformation, the t (means), f (variances), and Bartlett (variances) tests can be performed to further analyze the scalloping process, such as. For a given cave, these statistical tests were used to test the hypotheses presented previously.

Table 3

Scallop length measurements normality test

Cave	Sample Size	Shapiro-Wilk Normality Test <i>p</i> -value	
		Untransformed Scallop Lengths	Log ₁₀ -transformed Scallop Lengths
Boarhole Cave Set 1 and Set 2 combined	100	<<0.001	0.062

Shown above are the results of the Shapiro-Wilk Normality Test for the raw scallop length measurement data and the log transformed scallop lengths for a sample of one hundred scallop lengths. Notice that the log-transformed scallop lengths are not statistically different from the normal distribution.

Figure 6: Histograms of untransformed and $\log_{10}$ -transformed scallop length measurement sets. A set of one hundred scallop length measurements taken in Boarhole Cave are used for the histograms. The top histogram is the scallop length measurements untransformed and note how they are not normally distributed. The bottom histogram is the $\log_{10}$ -transformed scallop length measurements and note how they are approximately normally distributed.

The Sauter mean of scallop lengths (L_{32}) was taken and the average velocity derived using the equations derived by Blumberg and Curl (1974) and Curl (1974). Specific discharge was calculated by multiplying the average velocity by the width of the passage. Then these specific discharges were tested against the continuity equation.

The scallops on the inner and outer wall of curved passages were compared with scallops in nearby straight reaches to ascertain if a difference in variances was present. *T*-tests were performed on the scallops measured on the inner and outer wall to determine if lengths were statistically different. Then, Bartlett tests were performed in R to compare the variances of scallop measurement sets in curved conduits and straight reaches in close proximity to each other (R Core Team 2018). These tests were used because they can determine if the variances of the scallop sets are statistically equal. This would potentially identify differences in variance related to differences in flow fields.

The ANOVA test of transformed lengths was used to compare the scallop sets at different heights to each other and see whether they record the same flow. The scallop lengths were $\log_{10}$ transformed so that the data was normal and the sample means comparable (R Core Team 2018). Therefore, we could see if flows are indeed varying with height in a passage, potentially recording different scallop dominant discharges.

Wolman Pebble Counts and Sediment Analysis

Wolman pebble counts were performed in the same straight reaches where scallops were measured to obtain the median clast sizes (d_{50}) (Wolman 1954). Herman et al. (2012) provided a method to calculate velocity from sediment compared to the other authors even though they didn't compare with or use scallop derived velocities. Hence,

we utilized their equations in this paper to provide sediment derived velocities for comparison with scallop derived velocities as a means to extrapolate and compare formative flow conditions. d_{50} was used to obtain critical boundary shear stresses which could be used to derive velocity using the methods of Herman et al. (2012). The critical boundary shear stress for sediments (cobbles) between 0.5 to 100mm in size is:

$$\tau_c = 0.68d_{50}^{1.08}$$

Where τ_c is critical boundary shear stress, d_{50} is the median clast size in meters. Once τ_c is found, mean velocity (V) is obtained using a rearranged formula presented by Herman et al. (2012):

$$V = \sqrt{\frac{\rho f}{8\tau_c}}$$

Where ρ is the fluid density (1000 kg m^{-3}), and f is the Darcy-Weisbach friction factor. f was found to be ~ 0.41 by Springer (2004) in Buckeye Creek Cave, so we assumed the same value in the nearby Culverson Creek Cave and Fullers Cave.

The sediment-derived velocities were then compared to the velocities derived from scallops in the same passages. This was done to see if the flow conditions that carried and deposited the sediments are the same that formed the scallops.

Subsampling and Outlier Tests

Multiple sets of scallop measurements were analyzed utilizing repeated subsampling and the outlier test. Z-scores were calculated for every scallop length in a set of 100 scallop lengths from Boarhole Cave to identify scallop measurements that were unusually large or small. Next, subsamples of varying sample sizes from 10 to 30

measurements were used to determine the effect of sample sizes on Sauter means and the average velocities. The subsampling used Monte Carlo simulations to vary sample sizes. All testing of the scallop measurements was performed in R and Monte Carlo simulations generated the Sauter means, velocities, and discharges for the tests.

CHAPTER 6: RESULTS

Hypothesis 1 Results: Test of Continuity

The testing of the first hypothesis yielded varied results between the three caves. Scallop-derived specific discharges were compared against each other at different points in a given cave passage to see if they were reasonably similar and thus if scallops are useful in determining paleo discharge conditions. It is to be noted that scallop derived specific discharges are only reported to one decimal place since the results of the fifth hypothesis show how sensitive these scallop-derived values are to extreme values. In Culverson Creek Cave two of the specific discharges are the same, but the third downstream site has a significantly different value (Site 3) (Table 4). Fullers Cave specific discharges all remain relatively similar to each other. For Buckeye Creek Cave, we calculated the actual discharge based off of the passages cross-cross-sectional area. Specific discharges calculated for elliptical cross-sections is not realistic and the passages showed evidence of flooding to the ceiling (pipe-full conditions). Buckeye Creek Cave's discharge varies between discharges in the canyon where Q_2 and Q_3 were measured and discharges for the elliptical-shaped entrance (Q_1) and Watergate near-siphon (Q_4) beyond the canyon. It is also to be noted that the maximum height of the canyon was used to calculate the cross-sectional area of flow. This was decided due to the presence of visible flood debris at ceiling-level.

Table 4

Scallop derived specific discharges

Cave	L_{32} (m)	Width (m)	Hydraulic Radius (m)	Height (m)	Cross-Sectional Area (m ²)	Velocity (m/sec)	Specific Discharge (m ² /sec)	Discharge (m ³ /sec)
Buckeye Creek Cave								
Site 1 (elliptical)	.13	-	.60	2.07	4.8	.21	-	1.0
Site 2 (parallel walls)	.06	1.4	-	5.58	7.7	.76	-	5.8
Site 3 (parallel walls)	.06	1.4	-	6.97	9.7	.69	-	6.7
Site 4 (elliptical)	.28	-	.84	2.29	16	.15	-	2.4
Culverson Creek Cave								
Site 1 (parallel walls)	.05	1.4	-	7.44	10	.94	1.3	-
Site 2 (parallel walls)	.05	1.5	-	7.65	11	.83	1.2	-
Site 3 (parallel walls)	.05	2.0	-	10.61	21	1.0	2.0	-
Fullers Cave								
Site 1: A (parallel walls)	.09	1.5	-	11.59	6.1	.49	0.7	-
Site 2: D (parallel walls)	.03	.56	-	12.26	2.3	1.4	0.8	-
Site 2.5 (parallel walls)	.03	.70	-	11.26	2.8	1.3	0.9	-
Site 3: A (parallel walls)	.05	.89	-	13.78	3.6	.88	0.8	-
Site 4: A (parallel walls)	.06	.91	-	3.68	3.6	.72	0.7	-
Site 5 (parallel walls)	.03	.91	-	3.85	3.7	1.3	1.2	-

Shown above are the results of the first hypothesis. The necessary variables and components needed to calculate the discharge for each site are provided. It is to be noted that we only calculated discharge for passages in Buckeye Creek Cave, see text for details. It is also to be noted that the sites for Culverson Creek Cave and Fullers Cave Site 2.5 and 5 are averaged from the velocities of the two sets of scallop length measurements on each side of the passage (river right and river left).

Hypothesis 2 Results: Variance of Scallops in Curved Passages

The second hypothesis is whether there is a difference in variance between scallops in curved and straight passages that could be used to differentiate uniform from non-uniform flow. Testing of the second hypothesis provided statistically significant results for t-tests of scallop length measurement sets in curved passages and mostly insignificant results for the Bartlett tests of variance (Table 5). *T*-tests performed on scallops on the inner and outer walls in curved passages all had statistically significant *p*-values except for one site, and the outer walls tend to have a smaller $\log_{10}$ means than the inner walls. The results of the Bartlett tests throughout the three caves have yielded mixed results. Only one Bartlett test in Culverson Creek Cave and one in Fullers Cave yielded statistically different variances (with *p*-values of 0.03 and $<<0.001$, respectively) out of the 6 tests.

Table 5

T-Tests and Bartlett tests of scallops in curved passages

Cave	<i>t</i> -test: Curved conduit			
	Log ₁₀ Mean: Inside Wall	Log ₁₀ Mean: Outside Wall	<i>p</i> -value	Bartlett Test <i>p</i> -value
Buckeye Creek Cave: Site 7 and Site 8	1.55	1.38	$<<0.001$	0.42
Culverson Creek Cave: 1	2.02	1.71	$<<0.001$	0.40
	1.91	1.68	$<<0.001$	
Culverson Creek Cave: 2	1.83	1.67	$<<0.001$	0.03
Fullers Cave: 1	1.36	1.36	.99	0.25
Fullers Cave: 2	1.36	1.47	0.0001	0.28
Fullers Cave: 3	1.39	1.30	$<<0.001$	$<<0.001$

Shown above are the means of scallop length measurement sets in curved passages on both the inside and outside wall of the curve. The *p*-value for the t-tests comparing the two sets of the inner and outer wall are provided. *p*-values of the Bartlett test of both the scallop sets in the curved passage and two additional scallop sets in the nearest straight passage are also shown. It is to be noted for the first site in Culverson Creek Cave, two different scallop length measurement sets were measured on both the inside and outside

wall. Thus, two t-tests were performed on the four sets as upstream and downstream pairs but only one Bartlett test on all four scallop measurement sets in the curved reach and two in the nearest straight reach. Also, to be noted is that Site 7 and 8 are the inner and outer wall respectively of the same curved passage.

Hypothesis 3 Results: Scallop Means at Different Heights

For the third hypothesis, we tested whether or not scallops at different heights in a passage had statistically different means. Testing of the third hypothesis yielded significant results for the ANOVA test of the transformed length measurements at varying heights. All sites in Fullers Cave and Buckeye Creek Cave except for Fullers site 3 yielded statistically different means, revealing that one or more of the scallop measurement sets at a particular height is different than the rest (Table 6). The specific discharges calculated in both caves from the scallop length measurements showed variation at the various heights above the floor, some with different patterns of increase or decrease with height than the others. The specific discharges at Site 1 stayed relatively consistent except for set D, which was lower and at a greater height than the rest. At Site 2 the specific discharges seemed to be consistent at the lower heights and then slightly larger at the greater heights. At Site 3 the specific discharges were the same at the two heights measured. At Site 4 the specific discharges interestingly were the same at the lowest and highest height recorded but were slightly different from the middle height. At Site 5 the two lower sets across from each other had the same specific discharge while the higher set was lower. At Buckeye Creek Cave Site 11, the specific discharge was greatest at the lowest and highest point measured, with the middle height discharge at B being lower than the two.

Table 6

ANOVA Tests and discharge of scallop measurements at different heights within cross-section

Cave and Location	Height (m)	Width (m)	Specific Discharge (m ² /s)	ANOVA <i>p</i> -Value
Fullers Site 1	Total: 11.59	-	-	<<0.001
Fullers Site 1: A	.914	1.52	0.7	-
Fullers Site 1: B	2.13	0.63	0.5	-
Fullers Site 1: C	2.74	0.86	0.7	-
Fullers Site 1: D	3.06	1.01	0.4	-
Fullers Site 2	Total: 12.26	-	-	<<0.001
Fullers Site 2: D	.75	0.56	0.8	-
Fullers Site 2: A	2.17	1.26	0.8	-
Fullers Site 2: B	3.49	1.32	1.3	-
Fullers Site 2: C	4.82	0.99	1.2	-
Fullers Site 3	Total: 13.73	-	-	.288
Fullers Site 3: A	1.05	0.89	0.8	-
Fullers Site 3: B	2.49	0.58	0.8	-
Fullers Site 4	Total: 3.68	-	-	.0527
Fullers Site 4: A	.695	0.91	0.7	-
Fullers Site 4: B	1.37	0.56	0.4	-
Fullers Site 4: C	2.13	0.91	0.7	-
Fullers Site 5	Total: 3.85	-	-	<<0.001
Fullers Site 5: A (left)	1.82	0.91	1.2	-
Fullers Site 5: B (right)	1.82	0.91	1.2	-
Fullers Site 5: C	2.23	0.70	0.6	-
Buckeye Creek Site 11	Total: 6.28	-	-	0.004
Buckeye Creek Site 11: A	1.02	1.32	1.7	-
Buckeye Creek Site 11: B	3.38	1.30	1.3	-
Buckeye Creek Site 11: C	4.43	1.19	1.5	-

Shown above are the results for the testing of the third hypothesis where scallop length measurement sets of varying height within a site were analyzed with the ANOVA test and *p*-values were provided. Also shown are the specific discharge values calculated from the scallops at each height above the passage floor. The specific discharges at each site were calculated at each height from the product of the scallop derived velocity and passage width.

Hypothesis 4 Results: Sediment and Scallop Derived Velocities

Our fourth hypothesis compares velocities derived from sediment grain sizes and scallops. Testing of the fourth hypothesis showed that velocity derived from sediments and scallops are roughly similar to each other with the exception of Site 1 in Fullers Cave. d_{50} values stayed roughly similar to each other in both caves.

Table 7

Sediment and scallop derived velocities

Cave	d_{50} (mm)	τ_c (N m ⁻²)	Sediment Derived Velocity (m/sec)	Scallop Derived Velocity (m/sec)
Fullers Cave				
Site 1	77	74.1	.83	.49
Site 2.5	82.5	79.9	.80	1.30
Site 3	79.5	76.7	.82	.88
Culverson Creek Cave				
Site 1	57	53.6	.98	.94
Site 2	51	47.5	1.03	.83
Site 3	49.5	46.0	1.06	1.00

Shown above are the results of the fourth hypothesis where velocity was calculated from cobble size (d_{50}) measured with the Wolman count (Wolman 1954). Note that for Site 2.5 in fullers cave the scallop derived velocity is the average of the velocity calculated from a river right and river left measurement sets directly across from each other.

Hypothesis 5 Results: Outlier Tests and Monte Carlo Simulations

Testing of the fifth hypothesis for the effect of sample size on the Sauter mean and identification of outliers showed significant results. Z-scores were calculated for each scallop length in a set of 100 scallops and then we identified any that were greater than ± 3 , which would make those lengths outliers. None of the scallop lengths z-scores were greater than ± 3 and deemed significant as outliers. Only one z-score came close at 2.945.

In addition to the z-scores calculated, Greg Springer compiled a graph (Figure 3) that shows how scallop length measurements fell on a normal distribution (after being log10-transformed). It is worth noting that a greater number of very large scallop lengths rather than very small scallop lengths were found to fall outside of 2 standard deviations.

For the Monte Carlo simulations, the larger sample sizes showed smaller ranges of L_{32} values in contrast to the smaller sample sizes showing larger ranges of L_{32} values (Figure 4). Also, the interquartile range (IQR) and maximum and minimum values showed a tighter spread of L_{32} values for the larger sample sizes and a wider spread for the smaller sample sizes. The median L_{32} values stayed around 0.06 m with little variation. The mean L_{32} values also stayed around 0.06 m with little variation (Table 8). The standard deviation of the L_{32} values decreased with greater sample size and a sample size of 10 had nearly double the standard deviation of a sample size of 30. (Table 8). The range of L_{32} values decreased with greater sample size. The difference in range between a sample size of 10 and 30 was about 0.02 m (Table 8).

Figure 7: The distribution of a 100 scallop length measurements. Shown above is the scallop length measurements and their log-transformed values from a set of 100 scallops in Boarhole Cave. The scallop lengths are plotted against the normal curve represented by the s-shaped faint dotted line. The area between and outside of the vertical dotted lines represents data that falls within or outside respectively of 2 standard deviations (± 2 s.d.). It is to be noted that this is the same set used to previously demonstrate log-normality of scallop length set data. This figure was compiled by G.S. Springer and is used here to help further demonstrate the results of hypothesis 5.

Figure 8: Monte Carlo simulation of varying scallop length set sample size. Shown above is the Monte Carlo simulation data displayed as boxplots. Each sample size from 10 to 30 are shown with their corresponding boxplot showing the distribution of L_{32} (Sauter mean) values from 1000 runs of random selection of scallop lengths from a set of 100 scallops. The dark line in the center of the boxplots is the median, with the lower and upper ends of the boxes being the first and third quartiles (interquartile range or IQR). The ends of the whiskers or dotted lines represents quartile plus or minus $1.5 * \text{IQR}$. The circles represent outliers.

Table 8

Monte Carlo simulation sample size mean and standard deviation of Sauter mean

Sample size	Mean of Sauter Means (meters)	Standard Deviation of Sauter Means (m)	Range of Sauter Means (m)
10	0.060	0.011	0.048
15	0.061	0.009	0.042
20	0.061	0.008	0.037
25	0.061	0.007	0.032
30	0.062	0.006	0.030

Shown above are the mean, standard deviation and range of the 1000 Sauter means calculated by the Monte Carlo simulations from the set of 100 scallop lengths from Boarhole Cave.

CHAPTER 7: DISCUSSION

The testing for continuity (first hypothesis) yielded conclusive results between the three caves with some discrepancies in Culverson Creek Cave from other factors. Culverson Creek Cave yielded similar discharges except at the most downstream location. The cross-sectional area of the downstream passage is wider than the other two locations (q_{s1} and q_{s2}), yet the velocities are all similar. Thus, the same flow being recorded by scallops at q_{s1} and q_{s2} , would have a lower flow depth in a wider passage and be shown at a lower height on the wall at q_{s3} . Fullers Cave discharges remain relatively consistent and compatible with continuity. Buckeye Creek Cave's discharge varies between discharges in the canyon where Q_2 and Q_3 were measured and discharges for the elliptical-shaped entrance (Q_1) and Watergate near-siphon (Q_4) beyond the canyon. The maximum height of the canyon was used to calculate the cross-sectional area of flow because of flood debris at ceiling-level, but flows rarely fill the canyon, so it is possible the scallops we measured are typical of flows that do not fill the canyon to the ceiling. If so, our discharge estimates for Q_2 and Q_3 are too high. Using specific discharges for the canyon would have provided more representative values for the flow depicted by the elliptical passages but we could not compare specific discharge to the discharge calculated at the two elliptical passages. The goal of this hypothesis was to attempt to replicate and confirm Lauritzen's findings of continuity and we were partially successful in doing so. We were only able to prove continuity for one of the passages and at least partial continuity in another passage, out of the three passages tested. This could be due to using actual discharges and specific discharges to find continuity in contrast to

Lauritzen (1982) who used only the actual discharges for the whole cross-section since he was measuring scallops in phreatic passages. He also used a single combined equation of passage shape (elliptical and parallel wall) whereas we discriminated passage shape and used the relevant Curl (1974) equations. It is also to be noted that Lauritzen's work with scallops was in caves affected by annual snow melt while the caves used in this thesis are not in the same climatic regime and lack an annual flood cycle. In conclusion, my work with the continuity equation partially replicates Lauritzen et al. (1982) probably due to use of slightly different procedures, and shows that more work is required to understand the complex specifics of individual caves.

Testing of the second hypothesis for a potential variance difference between curved and straight passages provided proof of predicted flow dynamics in curved and non-uniform passage in cave conduits, yet the analysis of the scallop variances yielded inconclusive results (Table 6). The identification of a characteristic difference in variance between scallops formed in uniform vs non-uniform flow is a novel and previously unaddressed in the literature. T-tests performed on scallop measurement sets on the inner and outer wall of curved conduits show that the outer walls tend to have smaller scallops on average than the inner walls. This was expected as the momentum of high velocity waters would cause flow to strike the outside of the bend. The results of the Bartlett tests throughout the three caves have yielded mixed results. Only one Bartlett test in Culverson Creek Cave and one in Fullers Cave yielded statistically different variances (with p -values of 0.03 and $<<0.001$ respectively) out of the 6 tests we performed. In conclusion, the results of the Bartlett tests are null because there isn't consistent data to show that

variances of scallops in straight and curved reaches are different. Thus, variance cannot be used to identify a characteristic of non-uniform flow at this time.

Testing of the third hypothesis for vertical variation in mean of scallops yielded significant results and the specific discharges tended to vary with height proving that there can be variation in scallop lengths in the same cross-section at different heights. All sites in Fullers Cave and Buckeye Creek Cave except for Fullers site 3 yielded statistically different means and thus one or more of the scallop measurement sets at a particular height is different than the rest. However, this could be due to changing widths at different heights, which would change the velocity and thus influence scallop sizes. A smaller width at a particular height would have greater water velocity than at other heights in the passage where width is larger, if flow is evenly distributed through the whole passage cross-section. These discharges at various heights within the passage should be relatively equal to each other if the scallops are indeed recording the same 95th percentile of flood discharges. However, we could not calculate discharge since we have no way of knowing the flow depth of the discharge that formed the scallops. So, we instead calculated the specific discharge at each height of scallop lengths measured by multiplying the width at each height and the scallop-derived velocity at each height. It was to be expected that the specific discharges (and discharge) would increase slightly with height in a passage because the flood discharge required to fill up to the higher regions in a passage would be greater than the lower portions. The results showed that the calculated specific discharges did indeed tend to vary with height. Yet they did not display the expected trend of increasing discharge with height. Hence, there is indeed a

vertical variation of scallop lengths independent of velocity fluctuations from changing cross-sectional dimensions (width) but other extraneous variables must be acting on the system separate from the expected increase in discharge during floods with increasing height and depth. Local flow conditions could be responsible for different specific discharges with height, such as active incision on the channel and changing of the 95th percentile of flood discharges from climate changes. But more research needs to be done to show this.

The findings of this test have major implications for the reliability and accuracy of using scallop length measurements to determine paleoflow conditions, especially when finding continuity as done previously in the first hypothesis. The varying of scallop lengths and their derived paleoflow estimates with height has been briefly speculated upon by Palmer (2007) but otherwise unaddressed in the literature. Regardless of how the scallop lengths vary vertically it is shown that they do indeed vary vertically. So, scallops at different heights are representing varying specific discharges but between the various measurement sites, as seen in Fullers Cave, the specific discharges are reasonably similar to each other. So, in order to accurately measure scallop lengths for proving continuity like we did for our first hypothesis, they should be measured at a relatively uniform height throughout a cave passage which will ideally allow derivation of the same scallop dominant discharge. Following this scenario, any outlier discharge value calculated for the first hypothesis (where continuity was tested) could be potentially explained by using an incorrect height above the floor for scallop length measuring in a given passage, which recorded a different scallop dominant discharge. In conclusion, it is now demonstrated

that scallop lengths have the potential to vary vertically in a given passage and not necessarily as expected.

Testing of the fourth hypothesis for sediment derived velocities showed that velocity derived from sediments are similar to velocities derived from scallops. Our goal was to compare the flow conditions that formed or deposited each. However, we couldn't calculate discharge from the sediments because we lack a known flow depth, but we do know that scallops are formed from high discharge events. Hence, the scallop lengths and the sediment grain size are probably representative of similar high discharges, since the velocities calculated from each are similar to each other. This agrees with the findings of Gale (1984). It disagrees however with the conclusions of Jeaninn (2001), Despain and Stock (2005) and Despain et al. (2016) that scallops and sediments represent high discharges but sediments represent the highest discharges. The sediment velocities we calculated were not significantly higher than the scallop velocities and in some sites, were actually lower with the exception of the first site in Fullers Cave (Table 7), where the sediment velocity is significantly larger than the scallop velocity. This could be due to the effect of a relatively large or small scallop length that significantly affected the Sauter mean, which is addressed by the discussion of the fifth hypothesis. In conclusion, the sediment and scallop derived velocities are similar to each other, and most likely indicate the same higher discharge events in the cave (95th percentile), but data from water probes are needed to provide a flow depth for discharge calculation.

Testing of the fifth hypothesis for outliers present in scallop length sets and Monte Carlo simulations of varying sample size, yielded very significant results.

Especially in regards to the assumptions and previous work done using scallop lengths. The assumptions of using scallop lengths have been not been addressed in the literature. The outlier tests show that scallop length sets can have a wide spread of values, some very close to being considered outliers. As was the case for the results of our outlier test of the Boarhole sample, where we got a z -score of 2.945 which is just short of the cutoff of 3 standard deviations. This was shown graphically by the comparison of the scallop lengths to the normal curve and what data fell within and outside of 2 standard deviations (Figure 4). It was shown that a greater number of scallop lengths too large in size rather than too small in size, fell outside of 2 standard deviations. Thus, proving that even though these large or small scallop length values aren't outliers and are from the same population as shown by the z -scores, they may still have a disproportionate effect on Sauter mean values. These very large or very small scallop lengths are not outliers but they are close enough to being such that we knew they were still having an effect on the distribution and most importantly discharges calculated from scallop lengths.

The Monte Carlo simulations showed the effect of these extreme scallop lengths and sample size on the Sauter mean (Figure 4). The larger sample sizes showed less variation and range of Sauter mean values and less outliers out of the 1000 randomly sampled scallop length measurement sets from 10 to 30 scallop lengths in size (Figure 4 and Table 8). A sample size of 10 had nearly twice the standard deviation and 0.02 m more range of Sauter mean values than a sample size of 30. This makes inherent sense for the larger sample sizes had more values which diminished the effect of extreme scallop lengths (~outliers). Hence the smaller scallop length measurement sets are more

vulnerable to drastic variability in Sauter mean from extreme scallop length values (Figure 4). The increasingly wider range and variation of Sauter mean values would also create an increasingly wider range of scallop-derived velocities, which would result in inaccurate paleoflow conditions. The sensitivity of the Sauter means and their derived velocities illustrates that they are only accurate to about 0.1 m/s (or one decimal place), and should be reported as such.

The outliers that were present in the smaller sample sizes were always very large Sauter means rather than very small Sauter means. Which lends credit to the reason why we use the Sauter mean, for it is used to suppress the effect of small depressions that may be mistakenly measured as scallops (Blumberg and Curl 1974). It does seem to suppress the effect of the very small lengths but is highly influenced with smaller sample sizes. This is because the equation for the Sauter mean is the sum of scallop lengths cubed over the sum of scallop lengths squared. This skews the Sauter mean toward larger values since the very large numbers get exponentially bigger by cubing them than by cubing the very small numbers. This affect is suppressed by taking a larger sample size as shown by the Monte Carlo simulations.

The larger the sample size the less variability in Sauter mean and thus the more accurate the derived paleoflow conditions. So, in order to acquire scallop lengths most representative for interpretation of paleoflow conditions, a larger sample size is required to diminish the effect of the extreme lengths. Authors who have used or are using any sample size less than 30 will undoubtedly run the risk of unrepresentative scallop length sets and Sauter means of paleoflow conditions. The risk of unrepresentative scallop

length sets and their Sauter means increases with fewer scallop lengths in a set. For example, in Lauritzen (1982), the lack of a consistent sample size (from 24-102) would create a different range of error in Sauter mean for every site along a passage he used to find continuity. Which would lend a doubt to the comparison between sites and thus his findings of continuity, especially the site where he only used 24 scallops. Gale (1984) also had inconsistent sample size of scallop length sets but did state that a minimum of 25 lengths should be measured. He also did not use the Sauter mean of scallop lengths but instead used the mean for use in Blumberg and Curl's (1974) equation for scallop derived velocity. This creates multiple levels of error that lend extreme doubt on the accuracy credibility of his scallop derived velocities. Another example would be the work on scallops done by Checkley and Faulkner (2014) as they extrapolated and derived a vast number of conclusions from their scallop length measurements, but they only measured sample sizes of 3 to 17, which casts huge doubt on the reliability of the data they derived. It is not only another example of inconsistent sample size use but those small size sample sizes are proven by our Monte Carlo simulations to vary greatly compared to larger sample sizes. Thus, it is advised for future authors to use at minimum a sample size of 30 when using scallop lengths to recreate paleoflow conditions and report velocities with few significant digits. Anything smaller than 30 runs the risk of drastically increased variability and range of Sauter mean and derived velocities. In conclusion, larger sample sizes of scallop length sets vary significantly less than smaller sample sizes.

CHAPTER 8: CONCLUSIONS

The testing of the five hypotheses confirmed and revealed some new discoveries, some with major implications for the use of cave scallops in determining paleoflow conditions. The testing of scallop length-derived discharges at multiple sites within a given passage for continuity for the first hypothesis was only partially successful in replicating the work of Lauritzen (1982). We could only prove continuity and partial continuity in two of the three cave passages tested. Showing that scallop derived discharges are indeed able to accurately provide consistent paleoflow conditions but further research into the hydrodynamics and hydrogeology of specific caves is needed to account for discrepancies. The testing of the second hypothesis attempted to reveal a difference in variance between scallop lengths found in curved and straight passages that could potentially reveal non-uniform flow in a passage where uniform flow would be otherwise assumed. The tests could not find a conclusive difference and thus variance cannot be used as a characteristic of uniform and non-uniform flow derived from scallops.

The testing of the third hypothesis for the presence of a variation of scallop lengths and discharge with height in a passage provided mixed results but very important revelations. Scallop lengths and discharges were indeed found to vary with height in a passage but not in the expected trend of increasing discharge with increasing height in a passage. Instead the scallops and derived specific discharge showed variation with height but with no conclusive trend in variation. This proves that scallop lengths used to find continuity or discharge throughout a cave passage or system, must be measured at similar

heights in order to derive the same 95th percentile of discharge. Although, much work is to be done here to explore why and how these scallop-derived discharges are varying with height. Perhaps a thorough investigation of local flow conditions would shed light on the random variation of specific discharges with height as shown.

The comparison between velocities from both scallops and sediments for the fourth hypothesis revealed that they are similar to each other and both represent the higher discharge events, although actual flow depths from water probes are needed to confirm this. Also, the velocities did not conclusively show that one or the other represented a higher or lower percentile of discharge event as previously found by multiple authors.

The testing of the fifth hypothesis for potential outliers and their effect on varying sample size and the Sauter mean with the use of Monte Carlo simulations, produced very revealing results. Very large and small scallop lengths relative to the majority of scallops are not outliers but still have significant influence on the Sauter mean. The effect of these relatively large or small scallop lengths was diminished with increasing sample size. The difference in range of Sauter mean values between sample sizes of 10 and 30 scallop lengths was 0.02 m. The standard deviation of Sauter means nearly doubled from a sample sizes of 30 to 10 scallop lengths. Which lends doubt to Sauter means and derived velocities and discharges from any sample of scallop lengths smaller than 30. In conclusion, the results of these five tests both verified previous findings and expanded the applications of using scallops in recreating paleoflow conditions, but more work is needed to understand the specific and local flow conditions of individual caves.

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APPENDIX: SCALLOP LENGTH MEASUREMENTS AND WOLMAN PEBBLE COUNTS

Supplemental Table: Buckeye Creek Cave scallop length measurements (mm)

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11: A	Site 11: B	Site 11: C
(RR)			(ceiling)	(RR)	(RR)	(curved)	(curved)	(RL)	(RL)	(RR)	(RR)	(RR)
						(RR)(inside wall)	(RL)(outside wall)					
129	35	57	175	75	36	58	22	65	33	34	26	34
105	73	45	174	54	34	22	21	57	32	36	25	31
67	44	42	195	44	38	39	20	38	26	56	32	20
86	47	44	152	54	46	24	19	40	21	41	29	28
150	55	46	378	86	57	37	27	82	52	24	39	32
113	65	56	305	79	53	40	17	68	20	38	54	53
112	67	39	372	48	32	66	29	71	24	44	35	28
124	60	69	187	102	67	27	30	76	33	26	37	28
101	65	80	220	64	42	28	32	55	24	27	24	34
73	57	70	124	58	39	35	20	37	56	23	29	35
105	56	53	132	62	48	39	25	42	72	36	25	32
55	76	95	194	55	49	36	22	93	31	25	29	40
56	53	63	153	64	44	33	25	83	28	24	33	35
72	42	81	210	40	38	29	26	68	39	28	40	30
190	55	41	310	49	42	27	24	63	40	34	49	29
81	64	44	218	50	42	26	25	61	23	34	43	50
35	43	44	197	59	46	34	25	62	24	34	59	40
55	51	36	190	49	48	24	26	64	53	33	58	43
97	42	45	283	68	39	37	44	64	43	31	49	36
90	62	40	293	72	40	52	30	69	57	39	42	31

Supplemental Table: Buckeye Creek Cave scallop length measurements (mm) (continued)

[illegible]

Supplemental Table: Culverson Creek Cave scallop length measurements (mm)

Site 1		Site 2		Site 3		Site 4		CCC-1 (curved)				CCC-2 (curved)	
A (RL)	B (RR)	A (RL)	B (RR)	A (RR)	B (RL)	Ceiling	Floor	Set 1-a (outside wall)	Set 1-b (outside wall)	Set 2-a (inside wall)	Set 2-b (inside wall)	Set 1 (inside wall)	Set 2 (outside wall)
77	53	58	46	44	73	59	45	56	60	127	100	60	45
37	35	66	46	38	40	47	50	52	50	117	48	41	33
42	42	52	60	27	47	39	37	85	60	106	107	73	46
36	50	47	66	34	32	44	54	77	44	92	160	50	34
40	41	47	80	30	60	65	66	51	31	145	74	49	60
59	53	40	63	31	59	49	52	36	66	74	80	66	87
39	46	48	41	32	56	45	51	41	55	90	72	61	33
28	47	54	31	26	51	69	50	30	48	99	73	200	35
56	32	37	70	25	59	57	67	48	34	74	102	55	33
34	25	48	62	38	32	31	45	44	42	115	96	90	36
36	30	64	54	40	51	30	37	61	72	65	72	107	31
48	52	66	32	32	42	51	40	49	51	128	140	53	54
45	46	49	47	24	49	46	46	50	34	107	55	50	48
48	47	60	56	74	47	47	55	47	37	90	75	40	42
50	44	56	58	42	36	40	56	64	64	125	52	35	52
60	24	46	42	40	38	45	41	103	36	136	55	49	46
44	43	59	43	50	51	50	48	42	60	167	45	64	86
59	35	48	68	49	43	60	47	60	50	138	65	51	42
74	34	90	45	49	65	34	61	46	46	155	95	34	35
31	39	71	64	44	47	48	70	65	45	176	104	56	44
48	29	55	50	45	56	82	63	36	64	109	74	85	38
48	36	59	40	72	38	52	52	42	43	116	82	79	54
49	28	53	42	50	41	28	76	72	32	51	64	55	74

Supplemental Table: Culverson Creek Cave scallop length measurements (mm) (continued)

[illegible]

Supplemental Table: Fullers Cave scallop length measurements (mm)

Site	Site	Site	Site	Site	Site	Site	Site	Site	Site	Site	Site	Site
1:A	1:B	1:C	1:D	2:A	2:B	2:C	2:D	3:A	3:B	4:A	4:B	4:C
(RR)	(RR)	(RR)	(RR)	(RL)	(RL)	(RL)	(RL)	(RL)	(RL)	(RL)	(RL)	(RL)
84	59	47	117	74	33	40	42	44	42	82	33	59
89	66	55	77	79	24	39	36	42	34	70	26	70
77	29	35	67	84	32	50	24	30	29	64	23	63
89	42	46	34	30	55	39	35	21	40	36	22	52
103	50	40	112	65	49	27	33	39	43	55	60	61
67	39	40	49	54	25	27	29	31	33	68	42	64
59	37	55	84	37	44	37	25	44	37	77	48	52
40	35	35	80	56	49	29	24	27	52	50	39	56
60	24	33	54	72	40	31	19	45	54	41	32	49
59	38	36	103	64	40	35	20	24	45	50	41	42
43	34	39	111	60	45	45	18	37	39	48	26	47
70	39	32	70	60	32	37	20	68	35	38	42	42
63	67	30	81	47	30	36	20	50	22	35	68	44
92	40	34	109	44	57	35	15	51	22	50	41	43
130	29	66	65	45	39	28	19	43	42	39	38	46
104	24	76	73	79	52	33	25	55	41	52	32	40
56	50	64	104	44	30	43	21	48	34	37	43	48
99	34	40	72	64	37	43	20	27	32	34	55	34
55	54	35	84	69	44	46	23	44	32	42	40	26
62	45	40	64	67	50	47	22	52	29	45	40	34
95	39	55	115	69	24	40	21	50	32	46	50	31
86	50	30	160	88	51	33	19	58	63	44	51	60
50	35	35	90	35	37	30	24	43	34	52	39	61
50	45	18	78	37	43	35	29	35	35	71	65	43
59	32	30	64	37	36	29	30	44	44	47	25	51
72	32	29	69	39	45	36	36	63	37	45	50	50
77	35	27	70	64	53	32	27	34	32	39	59	60
82	44	40	80	64	41	37	25	25	25	37	43	54
77	44	25	110	79	50	33	34	29	36	23	42	52
78	27	28	75	50	40	33	40	21	35	22	54	51

Supplemental Table: Fuller's Cave scallop length measurements (mm) (continued)

Site 5:A (RL)	Site 5:B (RR)	Site 5:C (RL)	Curve1:RL (outside wall)	Curve1:RR (inside wall)	Curve 2:RL (outside wall)	Curve 2:RR (inside wall)	Curve3:RL (outside wall)	Curve3:RR (inside wall)	Site 2.5 RL	Site 2.5 RR
31	30	65	30	30	33	24	20	28	46	30
38	30	52	30	25	29	17	24	30	17	25
26	29	49	34	27	18	28	14	27	20	27
36	30	64	30	30	26	32	16	22	39	40
31	36	38	20	27	26	22	17	24	15	21
29	30	55	20	16	40	21	25	29	28	24
21	35	40	20	17	34	21	22	23	15	25
33	31	28	33	17	22	27	21	22	16	22
24	41	26	23	25	25	20	22	31	17	43
31	31	50	23	26	50	24	24	24	30	38
41	31	52	24	17	23	28	20	26	30	40
40	30	35	21	24	32	33	25	20	40	42
24	39	44	24	19	22	21	22	22	30	27
27	31	50	20	27	28	22	22	21	27	37
35	32	27	22	20	27	22	21	20	30	34
39	36	29	27	21	25	30	17	30	25	25
34	35	21	21	26	30	22	20	22	28	23
38	44	35	17	29	31	27	23	22	22	23
37	37	38	22	24	27	19	24	27	25	39
28	37	32	20	29	27	23	22	24	22	38
25	27	22	8	28	22	28	19	23	30	21
41	38	37	19	21	29	34	20	21	41	24
32	31	70	20	29	37	23	15	31	31	32
34	45	43	27	24	34	18	15	34	31	35
46	34	44	24	22	43	17	16	24	32	24
27	28	51	29	17	22	21	15	25	34	24

Supplemental Table: Fuller's Cave scallop length measurements (mm) (continued)

Site 5:A (RL)	Site 5:B (RR)	Site 5:C (RL)	Curve1:RL (outside wall)	Curve1:RR (inside wall)	Curve 2:RL (outside wall)	Curve 2:RR (inside wall)	Curve3:RL (outside wall)	Curve3:RR (inside wall)	Site 2.5 RL	Site 2.5 RR
29	32	53	22	20	29	25	17	28	25	30
39	26	41	25	20	27	18	23	29	24	43
35	32	50	22	17	55	17	21	28	29	39
31	25	24	32	27	37	24	29	24	32	33

Supplemental Table: Boarhole Cave scallop length measurements (millimeters)

Set 1	Set 2	Set 3
89	54	69
67	63	30
55	57	32
94	45	60
53	46	62
42	41	55
29	46	50
83	42	56
63	42	35
30	37	41
63	45	39
60	41	46
56	47	55
78	46	54
40	44	63
41	65	42
36	46	49
37	41	57
45	35	36
57	39	74
25	42	32
59	42	33
39	61	46
40	34	44
44	49	34
48	43	60
61	56	43
26	51	43
38	41	54
44	39	35
58	36	
49	39	
69	69	
51	61	
49	91	
49	119	
37	47	
24	69	

Supplemental Table: Boarhole Cave scallop length measurements (continued)

Set 1	Set 2	Set 3
29	94	
30	40	
45	51	
43	46	
23	49	
54	49	
23	45	
30	40	
30	95	
34	39	
41	49	
31	49	

Supplemental Table: Wolman Pebble Counts (millimeters)

Culverson Creek Cave			Fuller's Cave		
Site 1	Site 2	Site 3	Site 1	Site 2.5	Site 3
67	58	44	62	94	102
28	50	68	99	144	100
45	83	34	90	99	50
57	93	39	102	64	90
82	41	80	75	87	48
53	21	71	58	82	89
67	76	67	105	126	170
82	37	29	63	118	80
74	56	49	109	90	60
76	55	67	150	84	37
80	60	30	96	109	96
80	54	51	130	76	190
66	81	70	80	70	20
57	69	41	200	59	90
66	37	58	132	70	65
82	35	43	137	65	105
48	98	27	135	70	75

Supplemental Table: Wolman Pebble Counts (continued)

Culverson Creek Cave			Fuller's Cave		
Site 1	Site 2	Site 3	Site 1	Site 2.5	Site 3
34	88	16	60	84	132
46	66	76	156	72	115
84	50	45	62	53	175
62	57	47	51	79	87
43	40	59	110	78	137
64	39	78	34	112	22
70	62	69	109	160	119
37	60	57	22	129	107
71	49	56	72	113	50
27	57	62	38	114	104
70	42	52	77	191	95
56	23	61	96	65	62
37	36	24	71	101	60
84	26	34	145	80	47
65	44	57	100	112	86
51	50	46	130	102	195
51	58	45	108	205	39
43	20	32	52	83	178
68	63	47	45	97	74
39	66	52	68	62	85
61	54	78	42	109	63
67	67	26	240	63	77
54	53	43	45	54	135
52	39	44	63	47	75
50	65	52	43	42	125
99	73	40	125	84	79
55	75	43	105	57	139
59	42	103	48	117	60
44	62	53	135	47	135
100	17	78	80	84	39
49	56	32	150	70	110
30	20	32	37	59	87
79	39	36	77	95	64
46	69	39	121	52	70
54	61	56	70	118	82
58	52	26	115	105	66
54	44	75	54	35	66
46	64	72	92	115	91
34	31	41	96	84	71
56	40	68	100	57	63
40	85	34	50	72	99
38	36	67	39	82	110

Supplemental Table: Wolman Pebble Counts (continued)

Culverson Creek Cave			Fuller's Cave		
Site 1	Site 2	Site 3	Site 1	Site 2.5	Site 3
64	65	54	94	94	49
51	42	42	42	59	105
64	37	66	123	100	67
74	47	50	67	40	70
69	22	33	48	72	62
56	65	54	83	100	85
49	38	68	170	54	90
66	49	53	89	73	170
53	44	32	75	120	86
42	46	53	109	44	93
73	44	37	57	49	57
59	41	54	58	45	74
52	54	35	41	145	57
78	43	30	59	54	112
63	50	67	130	59	45
89	57	64	49	77	69
47	26	32	63	112	82
77	54	50	67	152	122
52	34	76	70	104	99
77	78	33	152	58	49
55	29	37	164	134	135
66	91	56	72	70	88
53	46	30	99	49	46
93	49	44	98	85	39
61	68	34	28	89	34
48	86	30	137	58	96
38	65	65	50	68	40
85	73	39	69	64	66
117	40	71	54	32	73
46	53	36	47	230	39
71	30	54	72	139	50
29	59	38	57	185	66
47	53	27	85	107	51
31	26	26	148	134	83
78	34	78	93	163	83
39	50	22	114	101	94
44	59	73	54	64	50
97	47	59	32	48	126
63	84	73	67	39	40
42	50	62	40	69	72

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