GEOMORPHIC AND GEOLOGIC CONTROLS ON BEDROCK-DOMINATED SHOALING: SPATIAL DISTRIBUTION AND CHARACTERISTICS OF SHOALS IN THE CAHABA RIVER

by

JEREMIAH BISHOP

LISA DAVIS, COMMITTEE CHAIR
SAGY COHEN
JENNIFER EDMONDS

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Geography in the Graduate School of the University of Alabama

TUSCALOOSA, ALABAMA

2013
ABSTRACT

Bedrock shoals are geomorphic features located in river systems throughout the world. They are commonly found in bedrock channels of the Eastern United States. Previous studies have identified the importance of these features showing that they are areas of high biologic complexity. Shoals can affect sediment transport dynamics and are capable of acting as nitrate sinks due to the vegetation that inhabits them. However, information regarding their distribution and formation is lacking. In this study, shoaled and non-shoaled reaches throughout the length of the Cahaba River, located in central Alabama, were analyzed to determine the factors responsible for their presence. Flow orientation (expressed and measured as perpendicularity), rock type, and confinement ratio were selected as possible contributing variables based on the existing literature on shoals and bedrock bedforms. Each variable was initially tested using exploratory statistical methods (Mann-Whitney U tests) to determine if there were differences between shoaled and non-shoaled sites. The results of the Mann Whitney U test showed that the all three variables were significantly different when located in a shoaled or non-shoaled reach. This information was then used to conduct a binary logistic regression analysis. Results of the logistic regression were in alignment with the Mann-Whitney U tests and suggested that perpendicularity as well as rock integrity, are significant predictors of shoal occurrence, with rock integrity being the most significant (p<.001) and strongest predictor. Confinement ratio, a variable often believed to be a major contributor to stream geometry, was found to be insignificant both as a consolidated variable (p=.727). A predictive equation was formulated based on the results of the logistic regression using the regression coefficients for flow perpendicularity and rock integrity and the y-intercept for the regression model. The resulting predictive equation was used to test several...
shoaled and non-shoaled sites that were not included in the original dataset. The equation predicted 8 of these sites with greater than 98% probability, one site at 76% and another at 28%. All but one non-shoaled site produced predictive probabilities under 35%, correctly predicting low possibility for shoal occurrence in these areas.
LIST OF ABBREVIATIONS

1. GIS……………………………………………Geographic information system
2. CW…………………………………………….Channel width
3. VW……………………………………………..Valley width
4. DEMs…………………………………………Digital elevation models
5. GSI…………………………………………….Geologic strength index
6. GSA…………………………………………..Geologic Survey of Alabama
7. SS……………………………………………..Sandstone
8. β………………………………………………Regression coefficient
9. P………………………………………………Probability of case
ACKNOWLEDGEMENTS

I would like to thank Mr. Lewis Dean for assistance in finding relevant literature throughout the course of this research. I also thank Ashley Ross for editing assistance and Nick Haney and Ryan Vaughn for their help with sample collections, fieldwork, model development and interpretation. I especially thank Lisa Davis, Sagy Cohen, and Jennifer Edmonds for their service on my thesis committee and their continued assistance and support throughout this entire process.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF EQUATIONS</td>
<td>x</td>
</tr>
<tr>
<td>1.0 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 SHOALS IN THE CAHABA RIVER</td>
<td>2</td>
</tr>
<tr>
<td>1.2 HABITAT CONSERVATION AND RESTORATION EFFORTS</td>
<td>3</td>
</tr>
<tr>
<td>1.3 CONTROLS ON BEDFORMS AND MORPHOLOGICAL UNITS IN BEDROCK CHANNELS</td>
<td>6</td>
</tr>
<tr>
<td>1.4 RESEARCH QUESTIONS</td>
<td>9</td>
</tr>
<tr>
<td>2.0 STUDY SITE</td>
<td>11</td>
</tr>
<tr>
<td>3.0 METHODS</td>
<td>14</td>
</tr>
<tr>
<td>3.1 ROCK AND FLOW ORIENTATION</td>
<td>14</td>
</tr>
<tr>
<td>3.2 CHANNEL CONFINEMENT</td>
<td>18</td>
</tr>
<tr>
<td>3.3 INTEGRITY OF ROCK AND EROSIONAL RESISTANCE</td>
<td>20</td>
</tr>
<tr>
<td>3.4 STATISTICAL ANALYSIS</td>
<td>22</td>
</tr>
<tr>
<td>4.0 RESULTS</td>
<td>24</td>
</tr>
<tr>
<td>4.1 EXPLORATORY DATA ANALYSIS</td>
<td>24</td>
</tr>
<tr>
<td>4.1.1 STRIKE ANALYSIS</td>
<td>24</td>
</tr>
<tr>
<td>4.1.2 CHANNEL CONFINEMENT AND SHOAL DISTRIBUTION</td>
<td>26</td>
</tr>
<tr>
<td>4.1.3 LITHOLOGICAL CHARACTERISTICS</td>
<td>28</td>
</tr>
</tbody>
</table>
LIST OF TABLES

1. Adapted GSI table for a typical sandstone 22
2. Adapted Spearman correlation matrix for selected variables 28
3. Results of binary logistic regression using model 1 31
4. Results of binary logistic regression model 2 32
5. Results of predictive equation 33
**LIST OF FIGURES**

1. Aerial and on-site photo of shoals in the Cahaba River 3

2. Map of the study area in the Cahaba River 12

3. Geology of region surrounding the Cahaba River 13

4. Reach distribution with background geology and structure 16

5. Example of confinement perpendicularity calculation 18

6. Example of confinement ratio calculation 20

7. Distribution of strike measurements for each reach type 24

8. Distribution of perpendicularity measurements for each reach type 24

9. Confinement values for shoaled and non-shoaled reaches 27

10. Channel width and valley width measurements for each reach type 27

11. Typical rock integrity values for rocks composing shoaled reaches 29

12. Rock types for shoaled reaches 29

13. Physiographic provinces of Alabama 39
LIST OF EQUATIONS

1. Equation used to calculate confinement ratio 19

2. Equation based on regression output to predict shoal occurrence 32

3. Equation based on regression output with logistic coefficients inserted 34
1.0 Introduction

Bedrock-dominated shoals are located in fluvial systems throughout the world and are important geomorphic features. However, their formation and evolution is not well understood (Goode and Wohl 2010). Bedrock shoals are best defined as channel bedforms that consist of a rocky, shallow area transecting the channel in an otherwise continuous stretch of deeper water, that are especially visible during periods of low water (Figure 1). Bedrock shoals provide habitats that have higher species richness than other areas of the associated river system (Robson and Chester 1999). Shoals in particular have been observed to be areas of high biologic complexity that have great impacts on a wide range of biota throughout the entire river ecosystem (Kennon 2007). In the latest National Rivers and Streams Assessment produced by the Environmental Protection Agency, it was shown that over 70% of rivers in the eastern United States were impaired by human influence. The most widespread problem was high levels of nutrient pollution, namely phosphorous and nitrogen (EPA 2013). In the Cahaba River, bedrock shoals provide habitat for plant life that have been identified as being responsible for decreases in these nitrates (Tatariw et al., 2012). Although bedrock shoals provide important aquatic habitat structure and through their habitat function may play a role in nutrient cycling in southeastern rivers, their formation and occurrence is poorly understood.
1.1 Shoals in the Cahaba River

Shoals in the Cahaba River appear as laterally extensive topographic discontinuities composed of bedrock with little to no overlying sediments (Figure 1a). They are often densely vegetated with a variety of aquatic plant species (Figure 1c). Shoals vary in size throughout the river ranging from a few meters in longitudinal width to several hundred. These features can occur as singular anomalies within the channel bordered on each side by non-shoaled reaches or as continuous bands that stretch for several hundred meters. Hardly any transition is seen between shoaled and non-shoaled reaches. The contact between these features is often abrupt and can lead to a “banded” appearance of the channel (Figure 1b) when aerially viewed, as a result of the sudden change in channel depth and vegetation patches that utilize the shoals as habitat. Shoals in the Cahaba extend from the headwaters near Leeds, Alabama to just below the boundary of the Valley and Ridge Province and East Gulf Coastal Plain near Centerville, Alabama, with the majority being located within the Valley and Ridge Province.
1.2 Habitat Conservation and Restoration Efforts

Existing research on alluvial and bedrock shoals found in fluvial systems is severely limited, and most of what does exist focuses on the ecological significance of shoals. Duncan (2008) noted that shoals are biologically diverse areas, harboring endemic and endangered species and that, given their biological relevance, should be...
better understood and protected. Duncan (2008) found that shoals increase habitat complexity and due to their lower erodibility can be immune to habitat degradation processes, such as channel incision, making them particularly significant features for stream restoration planning.

Kennon (2007) as well as Robson and Chester (1999) provide some insight into the impacts of shoals on associated biota. Kennon (2007) attempted to explain the occurrence of shoals and correlate their distribution and species richness throughout the Little Uchee, Wacooche and Halawakee rivers. He found that shoals in these systems were comprised of exposed and submerged bedrock formations, formed > 20% of the total habitat area, and created habitat for fishes and other organisms. Furthermore, he found in the Little Uchee, Wacooche and Halawakee there were six species exclusive to shoals and 18 that were shared between shoals and pools. It was also found that shoal volume significantly predicted species richness. This was seen in the cobbles and boulder shoals located in his study area that increased the streambed heterogeneity, which in turn contributed to higher species richness than in other shoal types. Overall, shoaled reaches were shown to have higher species richness than adjacent pool sequences. Likewise, Robson and Chester (1999) found that more structurally complex bedform resulted in higher species richness. In the spring, crevices in the bedrock comprising the bedforms were found to have higher species densities than other habitats of the same scale. They also found that areas containing not only bedrock, but also cobbles and boulders had higher species richness than bedrock habitats alone.

Other channel landforms have been shown to be essential to aquatic habitat, including bedrock and cobble riffles. Riffles have been found to have a mosaic of
smaller scale habitats, each of which contained species that were unable to colonize other habitats (Robson and Chester 1999). The physical complexity created by bedrock and cobble riffles were thus found to have increased potential for species richness. Duncan (2008) attempted to address the relationship between hydrogeomorphic factors and in-stream flora and fauna – specifically factors affecting shoal sediment composition and *Podostemum ceratophyllum* (riverweed) in the Etowah River, Georgia. *P. ceratophyllum* inhabited shoaled areas, predominantly rocky shoals throughout the study area. These “rocky shoals” varied widely in their sediment composition and channel dimensions. It was shown that altered hydrology, in the form of incision and channelization, reduced habitat complexity and changed sediment composition. An increase in coarse sediments, concentrated in shoaled reaches, was linked to increased biodiversity, while an increase in fine sedimentation led to habitat degradation. The proportion of bedrock shoaling and channel width accounted for 77% of variation in riverweed occurrence. Shoals in the Etowah River were locations that enabled coarse, stable sediment deposition, which led to growth by various aquatic macrophytes. Duncan (2008) concluded that landscape or shoal-scale restoration approaches that increase the proportion of coarse sediment in shoals are likely to increase the abundance of fish as well as the proliferation of *Podostemum ceratophyllum*. 
1.3 Controls of Bedforms and Morphological Units in Bedrock Channels

Bedrock channel processes have been studied, and some of the factors controlling sediment dynamics, reach geometry, and other channel characteristics are known. Harvey et al. (2008) studied the influence of rock type on reach-scale sedimentological and vegetation characteristics. In their research, rivers were divided into groups based on broad lithologic characteristics. Altitude and slope, both of which determined reach type, were found to be strongly correlated with rock type categories created using lithology, i.e., chalk, sand, limestone, etc. The relation of rock type to channel morphological characteristics, such as the spacing of pool riffle sequences, was explored, and it was found that the influence of rock type on morphology is likely to be more strongly manifested as differences in bedform types rather than distribution of a single reach class. Wohl and Legleiter (2003) examined the controls of pool characteristics, including pool spacing, pool dimensions, and geometry, in bedrock channels. They found that both flow energy and substrate appear to have an influence on pool geometries, wherein constricted areas of the river maximize stream power, leading to the development of longer and deeper pools. The joint density of bedrock located in the channel also corresponded with the occurrence of deeper pools. These studies demonstrate how the substrate that underlies a stream can influence the occurrence and development of channel morphological units.

Previous research in bedrock channels suggests that bedrock exposures and channel bedform development are controlled by erosion rates, lithology, gradient, geologic structure, or a combination of these factors. Wilson et al., (2012), studied upstream-facing convex surfaces (UFCS), a type of bedrock bedform. High erosion rates,
as a result of abrasion, were found to be the main influence responsible for the shape and size of these features. Wilson et al., (2008), observed solid particle impact abrasion and incision taking place in bedrock channels. Particle size as well as the number of particles striking a surface was found to be major contributor shaping bedrock channels and bedforms. Keen-Zebert and Curran (2009) observed the spatial distribution of bedrock in the Upper Guadalupe River, Texas. They found that interactions of the channel with valley sides, variations in lithology, and regional structure control, contribute to the distribution of bedrock reaches. They also hypothesized that the Upper Guadalupe River has changed over time from a largely alluvial river to a mixed, alluvial/ bedrock river due to changes in base level associated with regional fault zones. Wohl and Merritt (2001) classified bedrock reaches into stepped, plane-bed, inner-channel, and undulating wall based on their formational characteristics. Stepped channels are characterized by small knick-points, flutes and longitudinal grooves, and tend to be steep and form in either highly resistant or heterogeneous lithologies. Inner-channel bedrock reaches often have undulating walls and are suggested to have formed from the slow coalescence of potholes and longitudinal grooves (Wohl et al. 1999, Whipple et al. 2000, Wohl and Merrit 2001). Plane-bed bedrock reaches, similar to features in the Cahaba River, are often lower gradient features and are associated with sedimentary rocks (Wohl & Ikeda 1998, Pazzaglia & Brandon 2001).

Wohl and Merritt (2001) researched bedrock channel geometry in great depth and specifically studied characteristic differences between multiple channel types. Their research encompassed high gradient, mountain streams that are almost entirely composed of very highly resistive bedrock substrate. Their research concluded that step-pool
channel types, had significantly different hydraulic and geomorphic characteristics than plane-bed and pool-riffle sequences. It was concluded that step-pool channels occurred in areas of higher gradients and have very coarse substrate. As gradient decreases, both plane-bed and pool-riffle channels developed.

Goode and Wohl (2010) examined the impact of “bedrock ribs”, which appear to be similar features to the bedrock shoals observed in the Cahaba River, on sediment transport and channel incision in the Ocoee River of Georgia. Like bedrock shoals, bedrock ribs are bedrock features that transect the channel that have an “undulating rib-like” appearance. Goode and Wohl (2010) concluded that structural and lithologic features in the underlying bedrock units control the presence of bedrock ribs. They also stated that these features impact sediment dynamics but on a smaller scale than similar features located in alluvial channels. Previous researchers in the Cahaba river stated similar observations, suggesting that shoals form as a result of the presence of erosion-resistant sandstone where the Cahaba flows perpendicular to the strike of the strata and stream valleys have formed in less resistant units (Mink and Winstanley 1978). Bedrock ribs were found to have a strong influence on coarse sediment transport, but only when bedrock ribs were oriented across the channel at a high angle to flow. Duncan (2008) researched bedrock shoals in Georgia. The main purpose of the study was to research the geomorphic and hydrologic factors that control in-stream habitat features and distribution of plant life. The study examined whether the introduction of sediment resulting from stream confluences formed alluvial and bedrock shoals, which he determined was the case for only alluvial shoals. The location of stream confluences did not help explain the
occurrence of bedrock shoals. Tributary basin area and the ratio of tributary basin area to mainstem basin area was also tested and found to not predict shoal occurrence.

Flow energy and substrate have been noted as having an influence on stream geometry. Sections of the river with stronger lateral constrictions are deeper and have higher stream power (Wohl and Legleiter 2003) thus leading to more erosive power. Stronger constrictions are also associated with a stronger central jet, stronger recalculating flow, and shearing between the central and marginal flow areas, which leads to a greater potential for bed erosion and pool formation (Wohl and Legleiter 2003). Alternatively, areas where less constriction occurs can be assumed to have lower velocities and lower stream power.

Finally, substrate erodibility can influence channel bed gradient and flow energy, which in turn control reach types and bedforms (Wohl and Legleiter 2003; Harvey et al. 2008). Deeper sections of river systems have been associated with lateral constrictions produced by bedrock outcrops and it has been suggested that substrate resistance controls the distribution of varying stream geometries, such as pools and riffles (Wohl and Legleiter 2003). It was also suggested by Harvey et al. (2008) that lithology might be more responsible for bedform type rather than overall reach classification.

1.4 Research Questions

Previous researchers have identified the following factors to be significant to the formation of channel bedforms in bedrock or in mixed bed rivers: underlying geologic structure, degree of constriction, and substrate erodibility. Based on these findings, the
following hypotheses were used in this study to explain the factors that control the occurrence of bedrock shoals in the Cahaba River.

- **Hypothesis 1:** The trajectory of streamflow relative to strike (orientation) of underlying geologic strata affects the spatial distribution of channel bed erosion.
  - Where the rock is perpendicular to flow, areas of low erodibility are created, resulting in shoal formation.
  - Where streamflow is parallel to rock orientation, areas of low erodibility form, subsequently leading to the absence rocky shoals.

- **Hypothesis 2:** Changes in channel confinement of the river within its valley control confinement, which leads to shoal occurrence in less confined areas.
  - In less confined reaches, the increase in channel width and related decrease in channel depth facilitate shoal development by decreasing the unit stream power locally.

- **Hypothesis 3:** Physical changes in rock type and competency or integrity influence rock erodibility.
  - Areas where more easily erodible rock types are present form non-shoaling reaches and
  - Areas of more resistive rock result in shoaled reach formation.

Given the importance of shoals to aquatic habitats and the potential link between plant patches growing on shoals and nitrate reduction, a better understanding of the factors that explain shoal occurrence and distribution would improve our understanding of biologic and geomorphic feedback interactions, which should aid in preserving water quality. Identifying geologic and geomorphic controls on shoal location is the predominant goal for this research.
2.0 Study Site

The Cahaba River is a 5th order river, the longest free flowing of its type in Alabama. The river serves as a major tributary of the Alabama River and is part of the Mobile River basin. The river is 312 km long and drains an area of 4,800 km$^2$. One hundred and thirty-five fish species inhabit the river and its tributaries and several of these have been assigned special conservation status (Kaufmann and Wise 1979). The shoals are bedrock-dominated throughout the study area and form unique stream ecosystems on which a range of plants and animals rely. In addition to rare fishes the Cahaba ecosystem also includes various macrophyte species that are dependent on shoals (Figure 1c). One of these is the rare Spider lily, *hymenocallis coronaria*, which grows in shoaled reaches and is found only in Alabama, Georgia, and South Carolina. Other macrophytes, such as *Justicia americanum*, are also found predominantly in swift flowing reaches and take root directly on the bedrock that forms the shoals.

The study area (Figure 2) encompasses approximately 120 km of the Cahaba River, between Centreville in Bibb County and Leeds in Jefferson County. Within the study area, 100 shoaled reaches and 70 non-shoaled reaches have been selected based on their ease of access and viewing ability by aerial photography and satellite imagery. For the purposes of this research a "reach" was defined as a channel segment that has identifiable physical characteristics controlling channel function, formation, and the sustainability of habitat structure with only short disruptions of the controlling physical
characteristics, in keeping with the definition of a reach provided by Lyon and Maguire (2008). Boundaries of separate reach types are often located at natural constriction points, such as bedrock or large alluvial deposits that provide lateral and vertical limits to channel change (Lyon and Maguire 2008). In the Cahaba shoaled and non-shoaled reaches range in size from a few meters to several hundred meters.

Figure 2. Map of the study area in the Cahaba River.

The Cahaba River flows mainly over rocks deposited during the Carboniferous period (~359-299 million years ago). The vast majority of rock composing the channel throughout the river is part of a formation that extends from Pennsylvania to Alabama, known as the Pottsville Formation. The majority of the Pottsville is composed of fine to
coarse-grained sandstones as well as some conglomerates. Limestone, siltstone, and shale are not uncommon. The formation is best known, however, for its tremendous anthracite and bituminous coal deposits, which are responsible for the mining history of the region dating back to the 19th century.

The path of the Cahaba River is controlled by the geology that underlies the area. Most of the river is contained within the Cahaba Synclinorium, a large geologic feature regionally characterized as an expansive inward dipping fold. Within the synclinorium there are numerous secondary antiformal and synformal structures that further direct overall river direction. The Cahaba Synclinorium, as well as the structure of the entire region, is the result of deformation that took place during the Carboniferous and Permian, approximately 325 million to 260 million years ago, an event known as the Alleghanian orogeny. This event produced the folded and faulted nature of the region as well as the Appalachian and Allegheny Mountains, which parallel the eastern coast of the United States and extend from Alabama to Newfoundland.

Figure 3. Geology of the area surrounding the Cahaba River. Varying geologic units are represented by different colors.
3.0 Methods

This study focused on 100 shoaled reaches located within the 305 km length of the Cahaba River. Though the study area is defined as the full length of the river, the last observable shoal is located approximately 2 km north of the city of Centreville. Therefore, the main areas of focus are from this point northward to the headwaters, located near Springville, AL. Specific shoaled areas were selected by examining aerial photographs made available by Dr. Jennifer Edmonds from the Biological Sciences Department at the University of Alabama, as well as satellite imagery through resources such as Bing and GoogleEarth. When necessary, aerial photographs were georeferenced using key ground control points in each photograph, such as road intersections or unique landforms. From an aerial perspective shoals were most easily observed during periods of low river stage, and therefore satellite images from the months of June-September were used to aid in visual identification and location of bedrock shoals.

3.1 Rock and flow orientation

The large study area was possible due to extensive geologic map coverage provided by both private and public institutions and the use of GIS to visualize and analyze the large amount of spatial data. To address hypotheses 1 and 3, the influence of geology and rock orientation, geologic maps procured from the Alabama Geologic
Survey were input into an ArcGIS 10.1 database. These maps are ESRI map documents and can be fully integrated into the ArcGIS 10.1 software. Detailed maps by quadrangle are available and cover portions of the study area. Where these maps did not cover the study area, detailed coal and natural resource maps were used to gain highly detailed information on both structure and rock type. Viewing geologic background in combination with the aerial photographs allowed some of the influences behind shoal development to be understood. These influences include: overall strike of the catchment, rock type (sedimentary, metamorphic, igneous), broad geologic setting and any faulting or folding that occur, which might affect shoal formation.

To address hypotheses 1 and 3, it was necessary to characterize the geometric orientation of the bedrock units in relation to the orientation of flow at each shoaled and non-shoaled reach (figure 4). Rock strike was chosen for these purposes and strike measurements were taken in the field (Brunton compass readings of visible outcrops) and digitally using ArcGIS 10.1 and aerial photographs for both the shoal and non-shoal reaches.
Figure 4. Example of shoaled and non-shoaled reach distribution with background lithology and structure. Shoaled sites represented by circles and non-shoaled by crosses.

Strike is normally represented by an azimuthal angle where north is 0° as well as 360°, but this results in a large range of values that compromise statistical tests in which comparisons are made with observations from other variables whose observations have smaller ranges, as is the case in this study. Therefore, strike measurements were standardized prior to statistical analyses by converting any value over 180° into its
azimuthal antipode, e.g., 225 = 45. When strike was measured digitally, the ArcGIS 10.1 measure tool was used, which gives the user an azimuthal measurement of a line feature being drawn. For each shoal a line was traced that best represented the orientation of the feature and the strike of this line was recorded as the strike of its corresponding shoal.

To better represent the relationship between strike of the bedrock and direction of stream flow, a perpendicularity index was developed. This index is determined by using the angular difference between the strike and flow direction and represents both variables as one, more easily understood, representative variable. If the index is closer to 90 degrees, a more perpendicular relationship between stream flow and rock strike exists (Figure 3). Conversely, the closer the index is to 0 or 180 degrees, the more parallel the relationship. Flow direction was measured on aerial photos in ArcGIS 10.1 using the measure tool and the same technique used to digitally measure strike previously described.
To address hypothesis 2, the degree in which the river channel is confined/unconfined was measured both in the field and using GIS. Digital elevation models (DEMs) were created in the GIS and used to calculate confinement ratios for the river channel. Each shoaled and non-shoaled reach was analyzed to determine if changes in confinement and the resulting water depth and velocity changes produced or inhibited
shoal formation. Confinement was calculated using the following formula, which is the most commonly applied method for characterizing channel confinement:

\[ \text{Confinement Ratio} = \frac{CW}{VW} \quad \text{Equation 1} \]

where \( CW \) is channel width measured directly from aerial photographs or satellite imagery and \( VW \) is valley width measured from flood maps denoting the 100-year flood elevations (Figure 4). The ArcGIS 10.1 measure tool was used to measure both the width of the channel and the width of the valley. A laser rangefinder was used to check the accuracy of measurements taken in ArcGIS 10.1. The digital measurements were found to be accurate to within 3 meters when compared to actual field measurements. This procedure was applied for each reach type. Confinement was also examined by separately analyzing channel width and valley width since using this information as a ratio may obscure which of the variables, valley or channel width, were actually creating an effect on shoal occurrence and because of the possibility that the ratio would not accurately represent confinement. For example, at some sites the channel width and valley width were nearly the same, which produces a smaller confinement ratio and gives the impression that these locations are very confined. When, in fact, the channel is actually quite wide.
3.3 Integrity of rock and erosional resistance

To address Hypothesis 3, it was necessary to characterize rock resistance to hydraulic erosion and weathering processes by rock type. The Geological Strength Index (GSI) was modified for these purposes. The GSI is a classification system that presents an easy way to quantify a rock's overall integrity and acknowledges geological constraints that occur in nature, such as joints and other heterogeneities (Marinos and
Hoek 2000). GSI values vary based on rock type and properties and range in scale from 0 (weakest) to 100 (strongest). Detailed geologic data were acquired for the Cahaba River from geologic maps and publications (Mink and Winstanley 1978; Osborne 1995; Pashin and Carrol 1995; Osborne and Ward 1996, 2006; Rindsburg and Rheams 2007;) and used to determine a GSI index for each study location.

To determine the GSI for shoaled sites, rock outcroppings were visually observed in the field and using satellite imagery and aerial photos during periods of low flow to determine rock integrity, i.e. presence of joints and fractures. When field visits were not feasible detailed descriptions of the rock formations, obtained from multiple published sources ( Osborne 1991, Pashin et al. 1995, Pashin 1997) were used to describe structure and lithologic characteristics. Once all of the geologic characteristics for each site had been collected it was used to assign a GSI range for each site using the GSI table provided in Marinos and Hoek (2000) (Table 1). The GSI ranges for each site were averaged to simply these data in preparation for statistical analyses.
Most common GSI ranges for typical sandstone

<table>
<thead>
<tr>
<th>Structure</th>
<th>Surface conditions</th>
<th>Very Good</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
<th>Very Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact or massive</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Blocky</td>
<td>80</td>
<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Very Blocky</td>
<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Blocky/disturbed/seamy</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Disintegrated</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Laminated/Sheared</td>
<td>n/a</td>
<td>n/a</td>
<td>20</td>
<td>10</td>
<td>&lt;10</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. GSI table adapted from Marinos and Hoek (2000) showing typical GSI ranges for sandstone with various degrees of structure and surface conditions.

3.4 Statistical Analyses

Statistical analyses conducted for hypothesis testing purposes included exploratory data analyses using Mann-Whitney U tests to identify differences between shoaled and non-shoaled reaches in advance of binary logistic regression analysis. Data for rock strike, perpendicularity index, rock integrity, lithology, and channel confinement (expressed as ratio and channel width and valley width) were grouped based on shoal status (shoaled or non-shoaled) and compared using Mann-Whitney U tests to determine statistically significant differences. After the Mann-Whitney U tests revealed which variables were different between shoaled and non-shoaled sites, the variables that differed at a statistically significant level ($p = .05$ or better) were selected for use in the binary logistic regression analysis. Binary logistic regression was chosen to help develop a predictive equation for shoal occurrence. A binary logistic model was used because of the “yes or no” nature of the question being asked, i.e., “does a variable increase the likelihood of shoal occurrence?” The binary logistic model identifies which variable(s) have the highest probability of being responsible for shoal occurrence, in comparison to other variables, and provides an estimate of how accurately these variables predict the
occurrence of the phenomena of interest. Binary logistic regression has been used in a variety of fluvial-geomorphic research to accurately assess and predict the probabilities of independent variables having an influence on dependent variables (e.g., Chang et al., 2007; Eeckhaut et al., 2005; and Tolga et al., 2005). Bledsoe and Watson (2000) employed the logistic regression in a method similar to this research in which they developed a probabilistic statistical model to predict thresholds of varying channel patterns and instability. Their research suggested that logistic regression analysis was an appropriate and useful technique for linking fluvial processes with stream geometry and stream form (Bledsoe and Watson 2000).
4.0 Results

4.1 Exploratory Data Analysis

4.1.1 Strike

Azimuthal strike measurements (n=100) for the shoaled sites averaged 55.56 degrees, with a range of 6 to 175 degrees. Average strike measurements (n=70) for non-shoaled sites averaged 49.24 degrees, with a range of 1 to 171 degrees, though the outer limits of these ranges were not typical for the dataset (Figure 6). Average stream direction at shoaled sites was 103.42 degrees and stream direction at non-shoaled averaged 65.17 degrees. The relationship between strike and river direction is represented by the perpendicularity value and was calculated for each reach (Figure 7). For shoaled sites perpendicularity averaged 79.8 degrees and for non-shoaled sites the average was 29.4 degrees.
Figure 7. Distribution of strike measurements for shoaled and non-shoaled reaches.

Figure 8. Distribution of perpendicularity measurements for shoaled and non-shoaled reaches.
Strike values were first tested using a Kolmogorov-Smirnov test for normality. Strike measurements were found to be non-normal and therefore, non-parametric tests were chosen for statistical analysis used to detect a difference between shoal and non-shoal observations. Results of a Mann-Whitney U test show that shoaled and non-shoaled reaches were significantly different from one another (p=0.01). Perpendicularity was also tested using a Mann-Whitney U test because non-shoaled values were not normal. Results indicate that perpendicularity values for the two feature types are significantly different (p<0.001).

4.1.2 Channel Confinement and Shoal Distribution

Confinement ratio measurements for shoaled and non-shoaled reaches averaged 2.8 and 3.06, respectfully and had a total range of 1.33 to 8.24 for shoaled reaches and from 1.45 to 4.52 for non-shoaled reaches (Figure 8). Confinement ratio for each site was broken into its components, valley width and channel width, for further testing. Valley width for shoaled reaches averaged 115.74 meters and channel width averaged 45.74 meters. For non-shoaled reaches, the average valley width was measured at 102.06 meters and channel width averaged 34.83 meters (Figure 9).
Figure 9. Distribution of confinement measurements for shoaled and non-shoaled reaches.

Figure 10. Confinement component values for shoaled and non-shoaled reaches.
Confinement measurements were found to be non-normal therefore non-parametric tests were applied. Results of a Mann-Whitney U test show that shoaled and non-shoaled reaches were significantly different from one another (p = .04). Valley width and channel width for shoaled and non-shoaled reaches were also tested against one another using a Mann-Whitney U test and were found to be statistically significant (valley width p<=.019, channel width p<=.001). Analysis of a correlation matrix (Table 2) shows that confinement ratio does not correlate with any other variable, including the dependent variable (.003). There was a slight negative correlation present between confinement ratio and rock integrity (-.052).

<table>
<thead>
<tr>
<th>Spearman Correlation Variable</th>
<th>Shoal</th>
<th>Perpendicularity Value</th>
<th>Confinement Ratio</th>
<th>Rock Integrity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoal</td>
<td>1.000</td>
<td>.418</td>
<td>.003</td>
<td>.898</td>
</tr>
<tr>
<td>Perpendicularity Value</td>
<td>.418</td>
<td>1.00</td>
<td>.034</td>
<td>.337</td>
</tr>
<tr>
<td>Confinement Ratio</td>
<td>.003</td>
<td>.034</td>
<td>1.000</td>
<td>-.052</td>
</tr>
<tr>
<td>Rock Integrity</td>
<td>.898</td>
<td>.337</td>
<td>-.052</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 2. Adapted Spearman correlation matrix showing relationship between variables.

4.1.3 Lithological Characteristics

The average rock integrity value for shoaled reaches ranged from 65-75. For non-shoaled reaches the rock integrity average range was 30-45. The overall range for integrity values for shoaled reaches ranged from 60-90 and for non-shoaled reaches 15-
45. Nearly all shoaled reaches were composed of sandstone, with the exception of 10 reaches, which were conglomerate or limestone (Figure 10). Non-shoaled reaches were estimated to be composed primarily of weaker sandstones, shale, or sandstone-shale mixes, as interpreted by geologic map, cross-sections, and stratigraphic columns, with a few exceptions being unconsolidated conglomerates, dolomites, and silty/shaly limestones.

![Figure 11. Typical rock integrity values for rocks composing shoaled reaches in the Cahaba River.](image)

![Figure 12. General shoal composition graph.](image)
Results of a Mann-Whitney U test show that shoaled and non-shoaled reaches were significantly different from one another (p<.01) in terms of rock integrity.

Correlation analyses show that rock integrity is very strongly correlated with the dependent variable (p=.898) and slightly correlated with the perpendicularity variable (p = .337) (Table 2).

Based on the results of the exploratory data analyses, the independent variables of rock integrity, perpendicularity, and confinement were chosen for further analysis in the binary logistic regression model.

4.2 Binary logistic regression

IBM SPSS 19 statistics software was used to conduct a logistic regression analysis using perpendicularity, confinement ratio and rock integrity, which were found to be significant during the exploratory data analysis stage. The logistic regression was first used to predict shoal occurrence using all three of these independent variables (model 1) as predictors and then applied again (model 2) without confinement, which model 1 showed to be statistically insignificant.

Model 1 was tested against a constant-only model and was found to be statistically significant (chi square = 151.835, p<.000 with df = 3). A Cox and Snell $R^2$ value of .629 was produced by the model. This value can be treated as a typical $R^2$ that would be produced in a simple logistic regression that shows how well the data fits the model. The Hosmer and Lemeshow goodness-of-fit statistic, which compares the model prediction to the observed, was .324. Furthermore, the SPSS output demonstrated that
model 1 correctly predicted 91.8% of the cases as being shoaled or non-shoaled. The Wald criterion was highest for perpendicularity and rock integrity, 10.676 and 31.998 respectfully, and lowest for confinement (.122). Rock integrity and perpendicularity were shown to be significant predictors in the model (p = .000 and .001 respectfully), while confinement was shown to be insignificant (p = .727). Rock integrity produced the highest regression coefficient (β = .179). Perpendicularity followed rock integrity with the next highest values for β with a value of .052. (Table 3).

<table>
<thead>
<tr>
<th>Step 1a</th>
<th>B</th>
<th>S.E.</th>
<th>Wald</th>
<th>df</th>
<th>Sig.</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perpendicularity</td>
<td>.052</td>
<td>.016</td>
<td>10.767</td>
<td>1</td>
<td>.001</td>
<td>1.053</td>
</tr>
<tr>
<td>Rock Integrity</td>
<td>.179</td>
<td>.032</td>
<td>31.998</td>
<td>1</td>
<td>.000</td>
<td>1.195</td>
</tr>
<tr>
<td>Confinement Ratio</td>
<td>.061</td>
<td>.174</td>
<td>.122</td>
<td>1</td>
<td>.727</td>
<td>1.063</td>
</tr>
<tr>
<td>Constant</td>
<td>-11.908</td>
<td>2.233</td>
<td>28.432</td>
<td>1</td>
<td>.000</td>
<td>.000</td>
</tr>
</tbody>
</table>

Table 3. SPSS output of binary logistic regression analysis for model 1.

Based on the results of model 1, which showed channel confinement to be statistically insignificant in the determination of whether a location was shoaled or not, a second regression model was constructed (model 2) using only rock integrity and perpendicularity. Model 2 was statistically significant (chi square = 151.663, p < .000 with df = 2). A Cox and Snell $R^2$ value of .629 was produced by using this model. The Hosmer and Lemeshow goodness-of-fit statistic was .284. Furthermore, the SPSS output demonstrated that model 2 correctly predicted 92.8% of the sites as being shoaled or non-shoaled.

Further analysis of the output for model 2 showed that the Wald criterion for rock integrity and perpendicularity were 31.717 and 10.695, respectfully. Rock integrity and
perpendicularity were both statistically significant in model 2, \( p = .000 \) for rock integrity and \( p = .001 \) for perpendicularity. Rock integrity produced the highest regression coefficient (\( \beta = .179 \)). Perpendicularity produced a \( \beta \) value of .052 (Table 4).

<table>
<thead>
<tr>
<th>Step 1*</th>
<th>B</th>
<th>S.E.</th>
<th>Wald</th>
<th>df</th>
<th>Sig.</th>
<th>Exp(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perpendicularity</td>
<td>.052</td>
<td>.016</td>
<td>10.695</td>
<td>1</td>
<td>.001</td>
<td>1.053</td>
</tr>
<tr>
<td>Rock Integrity</td>
<td>.179</td>
<td>.032</td>
<td>31.717</td>
<td>1</td>
<td>.000</td>
<td>1.196</td>
</tr>
<tr>
<td>Constant</td>
<td>-11.712</td>
<td>2.150</td>
<td>29.667</td>
<td>1</td>
<td>.000</td>
<td>.000</td>
</tr>
</tbody>
</table>

Table 4. SPSS output of binary logistic regression model 2, which used only perpendicularity and rock integrity.

Both the model incorporating confinement and the model using only perpendicularity and rock integrity fit the data well, with only negligible differences in model significance. The manner in which confinement behaved in the model (i.e., poor significance and model statistics), however, led to decision to the use of only two variables in final predicative equation.

4.3 Predictive equation

The \( \beta \) values produced by the model are the logistic coefficients that can be used to create a predictive equation. This equation appears as the following:

\[
P = \frac{e^{(a+\beta_1X_1+\beta_2X_2)}}{1+e^{(a+\beta_1X_1+\beta_2X_2)}}
\]

Equation 2. Basic probability equation used with the binary logistic regression
In the equation, $P$ is the probability of the event (shoal occurrence), $\alpha$ is the Y intercept denoted by the “constant” in the model output and, as previously stated, the $\beta$s are the regression coefficients obtained from the model output. X1 and X2 are the predictor variables, in this case perpendicularity and rock integrity. Using this equation with output from the model, the probability of shoaled reaches occurring at a location, given values for perpendicularity and rock integrity can be determined.

10 shoaled and 5 non-shoaled sites throughout the Cahaba that were not in the original dataset used to create the logistic model were tested to gauge the reliability of the predictive equation. The values for each site as well as the results are shown in Table 5.

<table>
<thead>
<tr>
<th>Site</th>
<th>Perpendicularly</th>
<th>Rock Integrity</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1 (shoaled)</td>
<td>69.02</td>
<td>70</td>
<td>.987864</td>
</tr>
<tr>
<td>Site 2 (shoaled)</td>
<td>95.78</td>
<td>75</td>
<td>.99875</td>
</tr>
<tr>
<td>Site 3 (shoaled)</td>
<td>88.00</td>
<td>75</td>
<td>.99813</td>
</tr>
<tr>
<td>Site 4 (shoaled)</td>
<td>18.72</td>
<td>55</td>
<td>.28893</td>
</tr>
<tr>
<td>Site 5 (shoaled)</td>
<td>40.16</td>
<td>75</td>
<td>.97799</td>
</tr>
<tr>
<td>Site 6 (shoaled)</td>
<td>92.20</td>
<td>65</td>
<td>.99107</td>
</tr>
<tr>
<td>Site 7 (shoaled)</td>
<td>65.21</td>
<td>80</td>
<td>.99750</td>
</tr>
<tr>
<td>Site 8 (shoaled)</td>
<td>60.37</td>
<td>70</td>
<td>.98111</td>
</tr>
<tr>
<td>Site 9 (shoaled)</td>
<td>54.34</td>
<td>70</td>
<td>.97433</td>
</tr>
<tr>
<td>Site 10 (shoaled)</td>
<td>41.41</td>
<td>60</td>
<td>.76392</td>
</tr>
<tr>
<td>Site 11 (non-shoaled)</td>
<td>36.84</td>
<td>50</td>
<td>.289966</td>
</tr>
<tr>
<td>Site 12 (non-shoaled)</td>
<td>5.44</td>
<td>60</td>
<td>.332673</td>
</tr>
<tr>
<td>Site 13 (non-shoaled)</td>
<td>2.76</td>
<td>40</td>
<td>.011944</td>
</tr>
<tr>
<td>Site 14 (non-shoaled)</td>
<td>78.65</td>
<td>45</td>
<td>.596764</td>
</tr>
<tr>
<td>Site 15 (non-shoaled)</td>
<td>6.78</td>
<td>45</td>
<td>.035181</td>
</tr>
<tr>
<td>Logistic Coefficient (Perpendicularity)</td>
<td>.052</td>
<td>Logistic (coefficient (Rock Integrity)</td>
<td>.179</td>
</tr>
<tr>
<td>Alpha</td>
<td>-11.712</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Results of predictive equation using 15 sites not included in original data.
The probability results from table 5 were achieved by inserting the $\beta_1$ (logistic coefficient for perpendicularity), $\beta_2$ (logistic coefficient for rock integrity) and $\alpha$ values from the bottom of table 5. The resulting equation using these values appears below in equation 3. Once the logistic coefficients are established ($\beta_1$ and $\beta_2$) only values for $X_1$ and $X_2$ are needed. $X_1$ and $X_2$ represent the actual measurements of perpendicularity and rock integrity of the feature in question.

$$P = \frac{e^{(a+.052*X_1+.179*X_2)}}{1+e^{(a+.052*X_1+.179*X_2)}}$$  \textit{Equation 3. Basic probability equation used with the binary logistic regression showing proper coefficient substitution.}

The results of table 5 show how equation 3 reacts when values outside the training set are used. The results showed that as $\beta_1$ values approached threshold perpendicularity (90), and $\beta_2$ values increased, the probability of shoal occurrence increased. Conversely, when $\beta_1$ and $\beta_2$ values decreased the likelihood of shoaled sites dropped and non-shoaled reaches were predicted correctly. Rock integrity, the more significant of the two variables, accounted for the most variability in the equation. This is due to the nature of the $\beta$ value for Rock integrity, which is larger than that of perpendicularity. The results of the test show that the equation predicted all but two shoaled sites (sites 4 & 10) with probabilities above 90% and all sites above 75% except site 4. Likewise, the equation correctly predicted the presence of non-shoaled sites. Sites 11-15 all had lower percentages reflecting a lower probability of shoal presence. All but one non-shoaled site
(site 14) produced probabilities for shoal occurrence under 35%. The higher probability that results from site 15 is due to the high degree of perpendicularity in the area. These results show that the equation is reliable in predicting shoals in the Cahaba River, given the two necessary predictor variables.
5.0 Discussion

Perpendicularity and rock integrity were shown by Mann-Whitney U tests and binary logistic regression analyses to be the most significant controls on shoal presence in the Cahaba River. Confinement was found not to be a significant contributor based on the same tests. The angle at which the river interacts with the channel bedrock, i.e., perpendicularity, is a direct result of the underlying geology of the area. Where channel bedrock is oriented perpendicular to streamflow, shoaled reaches are often more likely to occur. Rock integrity also plays an important role and was shown to be the most significant variable in the study. Shoals were shown to be composed of lithologies more resistant to erosion, while non-shoaled areas were mostly comprised of weaker rock types. The combination of rock integrity and perpendicularity as predictor variables resulted in an accurate model that was capable of making reliable predictions on feature location.

5.1 Strike as a controlling factor

Strike of channel bedrock was different at shoaled reaches, where, on average it maintained a higher angle than in non-shoaled reaches. Strike throughout the study area is a direct function of orogenic events that took place during the late Paleozoic, beginning approximately 250 million years ago. This event formed the Appalachian Mountains and
faulted, folded, and titled the rocks in the study area into their current positions (Figure 5). The river likely now flows along its current path as a result of the underlying geology. Goode and Wohl (2010) observed similar structural controls on channel geometry and bedforms, specifically bedrock ribs, in their study of the Ocoee River, TN. In the Cahaba, stream valleys are formed in less resistant rock that is oriented parallel to stream direction. These stream valleys are often bounded by more resistant ridge-forming rocks striking in the same or nearly the same direction as each other, which helps to direct the river’s course, as has been previously noted by Mink and Winstanley (1978).

Perpendicularly values indicate that the river, on average, flows near perpendicular to strike of the underlying strata in shoaled reaches. This result suggests that the development of bedrock shoals occurs in areas where the river ultimately has to cross a resistant ridge-forming rock type, or perhaps, a secondary fold associated with larger structural features related to the Cahaba synclinorium, e.g., the Tacoa anticline or Belle Ellen syncline. Where water flowing through the river has to overcome these topographic highs formed by perpendicularly striking strata, it is forced up and over the rock causing a shallowing effect. As a result of having to overcome these features, the water loses much of its erosive power. A large percentage of the rock is sandstone with high structural integrity, which further prevents erosion in these areas. This in conjunction with the strike contributes to areas of low erosive power compared to other areas of the river.

Differences in the perpendicularity values between shoaled and non-shoaled sites further suggest non-shoaled reaches have formed in locations where lithological resistance is lower due to the underlying structure of the geology. In non-shoaled
reaches, perpendicularity values are much closer to parallel (nearer to 0 and 180). In these areas of the Cahaba River, called “strike valleys” or “stream valleys” by Mink and Winstanley (1978), the potential for hydraulic erosion is greater because the orientation of the underlying rock is parallel to flow, resulting in much less resistance. It was also noted that the river is deeper and narrower in these sections, which would contribute to faster stream velocities, thus more erosive power. It is important to note, however, that the results of this research indicate that it is the underlying geologic structure, not the confinement, which produces these strike valleys.

5.2 Confinement for Shoaled and Non-shoaled Reaches

Confinement ratio values had a low range throughout the study area for both shoaled and non-shoaled reaches. Though the average confinement ratio was larger on average for shoaled reaches, as supposed in hypothesis 1, the difference between shoaled and non-shoaled sites was not as large as originally hypothesized. In fact, several shoaled reaches exhibited smaller narrower confinement ratios than non-shoaled reaches. This misrepresentation of confinement may be a function of a few anomalous shoals located at the southern most section of the study area in areas of extreme non-confinement that drive up the average confinement ratio for shoaled reaches. While 97% of the shoaled reaches occur in the upper portion of the study area located within the valley and ridge province, a few appear in the transition zone between the valley and ridge and coastal plain province. In this region, the river leaves the more confined valley and ridge province and enters the beginnings of coastal plain (figure 13).
In the coastal plain the river maintains approximately the same channel width as in the valley and ridge, but the floodplain, or valley width, is significantly larger as a result of the much more gradual relief throughout the region. The dramatic increase in valley width, in combination with an insignificant change in channel width results in substantial increases in confinement ratio values. Though these anomalous confinement values are few, they appear to weight the overall average confinement ratio of shoaled reaches in such a way as to make these sites appear larger relative to non-shoaled sites, when the difference between the two reach types is actually negligible. After the anomalous values were removed, an additional Mann-Whitney U test showed that the confinement ratios for shoaled and non-shoaled reaches were not as different from one another as when the anomalous values were present.
The results of this research suggest that confinement, as related to surrounding topography, is not an important variable in controlling the distribution of shoals. Other researchers, however, have shown confinement to be important in shaping bedforms and channel geometry in bedrock and mix-bed streams like the Cahaba (Wohl and Legleiter, 2003; Wohl and Merrit, 2008; White et al., 2010). It appears any potential effects of channel confinement that could control shoal development are superseded by topographic controls created by the folded geology underlying the Cahaba River. The folding of the rocks that underlie the river directs it in such a way that it is forced to flow perpendicular to resistant rock units, regardless of the confinement. While certain sections of the river may be less confined in shoaled reaches and more constricted in non-shoaled, this is not the case for all reaches, and there does not seem to be a strong enough link between the two to constitute confinement as a controlling variable. This is best observed in confined sections of the river where shoals occur. In these areas, the river is more confined due to topographic and geomorphic influences. Though the topography may direct the river’s course, the underlying bedrock, controlled not by the topography but by the geology, is oriented near perpendicular to flow. This scenario creates areas with high perpendicularity and results in shoaled reaches in these portions of the river, a phenomenon noted multiple times throughout the course of the river.

The fact that the results of confinement ratio both as an intact variable and in component form were inconsequential suggests that stream geometry, in the form of confinement, is not linked to shoaled reach occurrence. Confinement appears to act independently of reach type and can result in shoaled reaches having stronger confinement or non-shoaled reaches being very non-confined.
5.3 Rock Integrity

Previous researchers stated that shoals form as a result of the presence of resistant sandstone where the Cahaba flows perpendicular to the strike of the strata and stream valleys have formed in less resistant units (Mink and Winstanley 1978). Rock type data for both shoaled and non-shoaled sites suggests that certain lithologies dominate the study area. In the Cahaba synclinorium, where the Cahaba River is located, sandstone constitutes 15 to 35 percent of the entire region. The sandstones are mostly very fine to fine-grained and are primarily litharenites and sublitharenites (Mack et al., 1991 in Osborne 1996). Nearly every shoaled reach was found to be composed of Pottsville Sandstone, which is part of a geologic formation of clastic rocks that was deposited near the end of the Paleozoic approximately 300-350 m.y.a. (Osborne 1996). Some of the sandstones of the Pottsville formation appear to have optimal lithologic characteristics for the formation of shoals. The combination of largely homogeneous size, well sorted, grains, supported by strong cementation makes the Pottsville sandstones resistant to weathering and erosion associated with the hydraulic forces of the river. Conversely, the interbedded shales and siltstones are often fissile or partially disintegrated, accommodating erosional forces such as abrasion or grain impacting which eventually leads to non-shoaled reaches.

Though sandstone was found to be the dominant lithology for the majority of the study area, the sandstones of the Pottsville formation are often interbedded with units of varying thickness, e.g., shale, dolomite, limestone, coal, etc. These facies represent periods of fluctuation, when the depositional environment of the formation as a whole was changing due to fluctuations in sea level. Non-shoaled reaches were on average
composed of rock that is more easily erodible, e.g., shale, siltstone, and sandy-shales. These rock types are more easily worked by the hydraulic power of the river and as a result tend to form deeper reaches, which lack shoals. It is important, however, to note that not all of the rock composing non-shoaled reaches is of weaker structural integrity or rock types more easily disposed to erosion. Non-shoaled reaches composed of rock that is normally resistant to erosion appear as anomalies when lithology alone is viewed as the only controlling variable. In these cases it seems that the orientation of the rock plays an important role in determining shoal status. In such reaches, the rock is oriented in the same direction as river trajectory and this seems to be of enough influence to facilitate the development of non-shoaled reaches due to the fact that the river does not have to overcome the orientation of rock. Though it does appear to play the largest role of all variables in this research, the fact that non-shoaled reaches can occur in rock units that are normally resistant to erosion may indicate that rock type alone is not always responsible for shoal occurrence and other variables such as perpendicularity need to be taken into account.

The possibility may exist that joints or fractures in the rock play a role in reach type development. The effects of joint patterns have been observed to have an impact on stream geometry in previous studies. Wohl and Legleiter (2003) concluded that increased density of joints corresponds to deeper pool sequences. Therefore, there may be a possibility that joints or fractures could be additional variables contributing to reach development. Joint density may play a key role in areas where anomalous reaches occur, i.e., non-shoaled reaches appearing where a shoaled reach should exist or vice versa.
This hypothesis was not tested and would need to be the focus of future research to analyze any effect joint density may have on shoal development.
6.0 Conclusions

Shoaled reaches in the Cahaba River occur based on two key variables, the relationship between strike of the channel bedrock and river flow direction (perpendicularity) and the lithologic characteristics of the rock composing the channel. Analysis of several possible variables revealed that both perpendicularity and rock characteristics were good predictors of shoal occurrence, while confinement ratio, valley width and channel width had little to no effect. These results make sense, given that the study area is dominated by the Pottsville sandstones, which have high structural integrity, making them more resistant to hydraulic erosion and weathering. Conversely, weaker rock units, commonly interbedded within the sandstone of the formation, constitute rock types for most of the non-shoaled reaches in the study area.

Geologic structure throughout the study area is comprised of a series of major anticlines and synclines with abundant secondary structures. The deformation associated with the Alleghenian Orogeny, which produced the Appalachian Mountains, is the main control on the structure of the region. In shoaled reaches, the trajectory of the river is on average near orthogonal to the strike of the channel bedrock. This relationship results in areas where the river flow is obstructed relative to its previous path. Alternatively, where flow trajectory and strike is oriented in the same direction, non-shoaled reaches form. In these sections of the river erosive potential is at its maximum due to the combination of
weaker rock and essential orientation. These segments were also seen to be narrower and
deeper on average, which contributes to higher velocity and further erosion potential.

Confinement ratio was treated as a singular variable and broken into its
components of valley width and channel width for analysis. The confinement ratio for
shoaled reaches was higher than that of non-shoaled reaches on average, but this is
misleading as a result of a few outlying measurements and the way in which confinement
ratio is calculated may not correctly weight differences in channel width and valley
width. Valley width and channel width were on average larger for shoaled reaches, but
results of several statistical tests indicate that the difference between the variables
between each reach type was not significant. Confinement in rivers such as the Cahaba
appears to be topographically controlled and while reach type is more dependent on local
geology.

A predictive binary logistic regression model developed to predict where shoals
should occur was shown to reliably predict the occurrence of shoals in the Cahaba River.
However, it is unclear whether this model is applicable in other river systems, and this
should be an area of future research. Also, it should be investigated if the models
performance could be improved by evaluating the importance of other variables not
tested in this study, such as joint density and stream power. Given the importance of
shoals to aquatic habitats and the other ecological issues, such as nitrate reduction, a
better understanding of the factors that explain shoal occurrence and distribution is
essential. This information would help improve our understanding of these features, aid
in preserving water quality, and provide useful information for habitat conservation.
7.0 References


Wohl, E.E., and D.M., Merritt (2008) Reach-scale channel geometry of mountain streams, Geomorphology, 93, 168-185