

BIOGEOMORPHIC IMPACTS OF FRESHWATER MUSSELS ON
REACH-SCALE GEOMORPHOLOGY IN THE
SIPSEY RIVER OF ALABAMA

by

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A THESIS

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ABSTRACT

Freshwater mussels are burrowing, filter feeding organisms that were once widespread prior to river regulation but now face extinction or extirpation in many rivers of North America. The lifespan of some species can exceed a century and population densities have the potential to reach one hundred individuals per square meter in some rivers of Alabama. The functional traits of mussels, combined with their long lifespan and ability to occur in high-densities, suggest that they could impact reach-scale sediment processes, involving sediment transport and bank erosion, potentially leading to changes in channel morphology. Few studies, however, have examined ecosystem engineering by mussels and their potential effects on spatio-temporal changes in river morphology. We tested whether four, high-density mussel aggregations (> 14 ind/m²) influenced lateral river migration and bank erosion rates in a 48-km segment located in the Sipsey River of Alabama (USA). We digitized and compared riverbank positions of the study reach on georeferenced historical aerial images from 1965 and images from 2018. Above average rates of lateral migration (>0.2 cm per year) and bank erosion (>33 cm³ per year) occurred at all observed high-density mussel reaches. We observed the presence of mid-channel bars persisting for the duration of the 53-year study period immediately downstream of each high-density mussel location.

Additionally, we tested whether mussel population densities can be used to predict locations of reach-scale riverbank erosion. We quantified bank erosion, mussel density, median particle size distribution, and determined bank erosion hazard index (BEHI) scores at 44

transects located within three reaches. We created a stepwise, linear regression model to determine the effect of mussel population density on bank erosion. Mussel density was a stronger predictor ($r^2= 0.25$) of riverbank erosion than most BEHI metrics, including root depth ($r^2= 0.06$) and bank height/bank full ($r^2= 0.01$). The results of this study provide a critical step toward understanding reciprocal relationships between abiotic and biotic systems and new insights into the evolution of channel morphology not previously considered. Future river restoration projects should consider that many organisms, not just abiotic factors, can create biogeomorphic change of river geomorphology

DEDICATION

This thesis is dedicated to everyone who has believed I could accomplish this even when I didn't. I couldn't have done it without any of you.

LIST OF ABBREVIATIONS AND SYMBOLS

m^2	Meters squared
m^3	Cubic meters
ind/m^2	Individuals/meter squared
m	Meters
mm	Millimeters
km	Kilometers
yr^{-1}	Per year
GCP	Ground control point
RMSE	Root mean square error
x_s	X coordinate of base image
y_s	Y coordinate of base image
x_r	X coordinate of transformed image
y_r	Y coordinate of transformed image
ΔA	Area of polygon
L	Length of polygon

Δt Time interval

D_{50} Median particle size

B_0 Value of constant

B_1 Value of variable one

B_2 Value of variable two

Eq. 1 Equation one

Eq. 2 Equation two

Eq. 3 Equation three

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1.0 INTRODUCTION TO BIOGEOMORPHOLOGY AND FRESHWATER MUSSELS AS BIOGEOMORPHIC AGENTS

1.1 The Need for Biogenic Processes to be Included in Conceptual Frameworks of Fluvial Geomorphology

Prior to human influence, it is thought that many rivers maintained a state of equilibrium between discharge, sediment load and size, and slope, only altered by shifts in climate and geology (Lane 1955). The stream balance equation proposed by Lane (1955), states that an increase in flow volume or velocity must be offset by a subsequent increase in sediment load to balance the increase in river energy. The increased sediment supply can be sourced from either horizontal erosion of riverbanks or vertical erosion of the riverbed, the harder of the two to entrain will control river channel stability (Dunne and Jerolmack, 2018). Gravel dominated rivers balance the equilibrium equation by continuously reshaping their beds and banks (Parker, 1978; Phillips and Jerolmack, 2016; Pfeiffer et al., 2017), unless vertically resistant forces, such as a resistant bedrock formation (Cook et al., 2009), prevent this action. Channel adjustment has been widely validated as a result of a natural balance between fluid stress and the threshold of particle motion (Parker, 1978; Phillips and Jerolmack, 2016; Pfeiffer et al., 2017; Dunne and Jerolmack, 2018; Phillips and Jerolmack, 2019). Bed shear stress, which is required for particle entrainment,

can be affected by grain size sorting (Hammond et al., 1984) and the presence of an armoring layer (Lenzi, 2004). Larger grain sizes of riverbed particles require greater shear stresses to become entrained and, the presence of an armoring layer can prevent shear stresses from reaching movable bed particles. Since Lane's theory (1955) of stream equilibrium was introduced, results from many studies have detailed how anthropogenic activities influence this equilibrium (Ward, 1998; Wang, 2007; Gorney, 2011). Furthermore, these results strongly influence the design and planning of most river restoration projects. A growing body of research, however, provides evidence that animals, can also alter these processes, potentially influencing changes in channel adjustment (Zimmerman and de Szalay, 2007; Allen and Vaughn, 2011; Statzner, 2012; Atkinson et al., 2017; Fremier et al., 2018; Albertson et al, 2019).

Very little research exists on the biogeomorphic effects of freshwater mussels in freshwater systems. Thus, the aim of this paper is to detail the potential geomorphic implications of freshwater mussel activities and to identify their impacts in the Sipsey River, Alabama. In the following sections we discuss: 1) the discipline of biogeomorphology and research stemming from this field; 2) how ecosystems engineers can create a wide range of biogeomorphic impacts; 3) the potential for freshwater mussels, acting as biogeomorphic agents, to create geomorphic change; 4) potential implications of biogeomorphic research. We follow this review with two detailed studies describing how the biogeomorphic actions of freshwater mussels can create spatio-temporal changes in the Sipsey River.

1.2 What is Biogeomorphology?

Many studies provide evidence that fluvial and hydrogeomorphic processes drive biological processes within fluvial landscapes (Steiger et al., 2005; Florsheim et al., 2008; Stella et al., 2011; Stella et al., 2013). Conversely, other studies provide evidence that organisms are influential in controlling landscape change by modifying geomorphic processes (Tabacchi et al., 2000; Albertson et al., 2019). For decades, these approaches of understanding fluvial landscape dynamics operated independently of each other until recently. In the late 20th century, a new discipline called biogeomorphology emerged linking biologic and geomorphic processes (Viles, 1988) and suggests that a full understanding of earth surface processes cannot come without including the influence of biological processes (Fisher et al., 2007).

Studies developed from this subdiscipline describe how adjustments between biological and geomorphic processes are not unidirectional and may coevolve. Plants are widely accepted among geomorphologists to have a bi-directional relationship with geomorphic processes (Wynn and Mostaghimi, 2006; Corenblit et al., 2014; Corenblit et al., 2016; Atkinson et al., 2018).

Submerged and emergent macrophytes are plants that grow in the stream channel. Submerged macrophytes are generally more flexible and can withstand abrupt changes in flow while emergent macrophytes have stronger stems which propel them above the water surface (Puijalon et al., 2011). Dense populations of macrophytes are observed to adjust instream hydraulics by

altering flow velocity (Vaughn and Davis, 2015) and increasing localized sediment deposition (Barko et al., 1998). Depending on the nutrient content and the light reduction from the locally deposited sediments, loss of macrophyte communities or the transcendence to terrestrial communities can occur (Jones et al., 2011). Riparian plants grow outside the stream channel on riverbanks and can regulate stream channel size (Constantine et al., 2009) by increasing soil retention and reducing erosion (Julian and Torres, 2006). Communities of diverse riparian plants can generate more root biomass than single species (Schmid et al., 2009) leading to decreased bank erosion (Wynn and Mostaghimi, 2006). This has led to diverse communities of plants being used in many aquatic restoration projects to stabilize sediments and prevent erosion (Polvi and Sarneel, 2018). The stabilization of riparian areas can lead to channel adjustments (i.e. incision) and the formation of new habitat for additional riparian plant colonization (Corenblit et al., 2016).

Despite more biogeomorphic studies in recent years (Allen et al., 2018; Jerin, 2019; Mason et al., 2019), a mechanistic understanding of reciprocal relationships between fluvial geomorphic systems and aquatic organisms remain elusive for most aquatic organisms, likely because of the great number of aquatic organisms and the potential for biogenic processes to be organism and species dependent. Understanding the specific processes and cumulative effects of these two-way relationships in river systems through interdisciplinary research is needed to improve the management and conservation of freshwater systems.

1.3 Ecosystem Engineers

Physical earth surface processes drive biological processes; however, some organisms can alter geomorphic processes impacting landscape dynamics. Ecosystem engineers are organisms or a collective group of organisms that change or modify their surrounding habitat by physically altering properties of biotic or abiotic materials (Jones et al., 1994). Ecosystem engineers can alter habitat structures, leading to the success or decline of other species (Washko et al., 2020). Consequently, through the processes of altering their habitat, ecosystem engineers can have profound effects on the surrounding environment and associated stream function. For example, caddisflies are macroinvertebrates that spend their larval stages in aquatic environments and are typically less than 30mm in length. During the larval stage, caddisflies build cases by binding together fine sediments using high strength silk. As a result of case production, a greater shear stress may be required to initiate movement of the newly bound sediment particles (Statzner et al, 1999; Albertson et al., 2014). Although one caddisfly may not be significant in altering sediment entrainment properties, densities can occur in the thousands per square meter (Cardinale et al, 2004). Additionally, in lower reaches of a river, other species, such as salmon, can destabilize sediments. During yearly spawning events, female salmon excavate nests called 'redds' by undulating their tail fin mobilizing fine sediments. This nest building activity can contribute nearly 50% of the annual bedload yield of rivers (Statzner, 2012). Such large impacts to bedload sediments each year could have vast impacts on river form

and function over longer temporal scales. For example, findings from Fremier et al. (2018) suggest that the speciation of salmon in the western United States, which created a wider spatial range of impacts from nest building, may have altered the course of river channel evolution over geologic timescales.

1.4 Freshwater Mussels as Biogeomorphic Agents

Freshwater mussels are considered ecosystem engineers because of their ability to alter chemical and physical process in river systems (Strayer, 2007). Lifetimes of some freshwater mussel species can span a century (Strayer, 2007) and densities can exceed 100 ind/m² (Zettler and Jueg, 2007), dominating benthic river ecosystems worldwide. Mussels tend to occur across river systems in scattered patches called beds, often of high-densities and multiple species (Strayer, 2008). Further, mussels are sessile organisms with limited mobility, regulating them to reside in patchy aggregations for the entirety of their lives (Goodding et al., 2019).

Freshwater mussels are filter feeding bivalves with the potential to filter 100% of the water column when they occur in high densities (Strayer and Malcom, 2007). During filtration, mussels capture nutrients and sediment particles from the water column. Collected sediment particles are coated in mucus (Ward and McDonald, 1996), which increases cohesiveness (Grabkowski et al., 2011), ultimately leading to particles being more consolidated (Strayer et. al., 1999). Build-up of the consolidated particles can occur in the river substrate surrounding dense

mussel beds, increasing bed stability (Zimmerman and de Szalay, 2007). The consolidation of sediment particles into larger masses has the potential to increase the shear stress needed to entrain particles, as has been documented to occur with caddisfly cases (Albertson et al., 2014).

Mussels are also capable of bioturbation, leading to the destabilization of bed sediments. Mussels are aquatic animals, and burrow into the river substrate to avoid being moved by river currents (Thompson et al., 2016). Some mussel species burrow until they are fully submerged in the substrate while others only partially burrow (Allen and Vaughn, 2009). When mussels burrow, they disrupt the cohesive forces of bed sediments and introduce greater amounts of water content into the substrate (Allen and Vaughn, 2011). Mussel burrowing could result in decreased sediment shear strength, as a function of decreased sediment bulk density, and potentially, increased sediment entrainment in mussel communities with active burrowing species. For example, in a laboratory flume experiment testing the effects of mussels on sediment cohesion, Zimmerman and de Szalay (2007) found that when mussels initially position themselves in the river substrate, they destabilize bed sediments and significantly lower sediment shear strength. Conversely, individual mussels who remain imbedded can stabilize bed sediments. In the same experiment, Zimmerman and de Szalay (2007) found a significant increase in sediment compression ($p < 0.001$) once mussels had positioned themselves in the substrate, resulting in greater sediment shear strength. Because species burrowing techniques

differ, impacts on sediment stability may vary among species (Gutiérrez et al., 2003; Allen and Vaughn, 2007).

Alone, the ability of mussels to occur in extremely high densities, practically blanketing the riverbed, can prevent particle entrainment. Widdows et al. (2002) conducted a hybrid study in marine environments and through flume experiments and found suspended sediment concentrations to be significantly lower over high-density mussel aggregation relative to areas with no mussels. The authors attributed this finding to the continuous byssal connection between mussels across the entire bed. Additionally, mussels continue armoring river substrates after they die through the persistence of shells they leave behind (Atkinson et al., 2017). In a flume experiment, Commito et al. (2018) found fragments of mussel shells to have large impacts on sediment dispersal and attributed their findings to the ability of fragmented pieces of shells to fit closely together forming an armoring layer. Deposition of shells can accumulate in great amounts and persist for decades (Strayer and Malcom, 2007) further adding to the ability of live mussels to increase bed shear strength.

1.5 Implications of Biogeomorphic Research

Human activity over the past few centuries degraded many freshwater systems. Globally, rivers systems are impacted by increased sediment supply (Rutherford et al., 2019), channelization (Gregory, 2019), and reduced connectivity resulting from dams (Liu et al., 2020).

Numerous stream restoration and management efforts worldwide are racing to reduce these adverse impacts and preserve the river systems that are still intact. But, what if ongoing efforts to restore streams are not considering all variables needed to help ensure success? Many river restoration projects fall short of their intended goal or completely fail altogether (Kondolf, 1998). The cause of failure for many projects can be clearly identified, such as the failure of cross-veins or increased sediment deposition, yet, the in-stream mechanisms associated with artificial structures (i.e. bank and bed erosion) are poorly understood. In a study summarizing the outcomes of a stream restoration project in New York, Buchanan et al. (2010) detailed numerous modes of failure for portions of the project and linked them to a lack of understating of the complex mechanisms surrounding the failed restoration structures. River restoration is a \$1 billion per year industry (Bernhardt et al., 2015) supported by government agencies and various stakeholders attempting to reduce aquatic degradation. Yet many of these projects continue with a lack of understanding of river ecosystems and ecosystem processes (Wohl et al., 2005).

Dave Rosgen, a successful stream restoration consultant, has strongly influenced the river restoration community with the creation of his Natural Channel Design (NCD) method in the late 1990's (Rosgen, 1998). The NCD method still used today is based on "the field of dreams theory," which suggests that if a stream channel is restored to accommodate flow and sediment load flux, all other associated aquatic process will be restored (Palmer, 1997). Rosgen's method, however, was immediately met with intense opposition by university researchers and scientists

which created an ongoing rift among the stream restoration community known as the “Rosgen Wars” (Lave, 2016). Rosgen’s universally applicable 40-step NCD approach is strongly supported by government agencies because of its ability to address many different restoration goals. Additionally, Rosgen provides short courses covering his approach to stream restoration that are required by many government-backed restoration proposals. Because if this, most current stream restoration practitioners are trained by Rosgen, which has strengthened his dominance of the stream restoration industry.

The university- and research-based restoration community, however, believes there is no “one size fits all” approach to stream restoration and point to project failures that challenge the credibility of his approach. For example: Albertson et al. (2011) studied a restoration project where riverbed sediments were altered to promote suitable spawning habitat for Chinook salmon. They found a reduction in substrate heterogeneity led to a decrease in abundance and biomass of invertebrates, a known food source of salmon (Amundsen, 2001). Additional studies have found habitat heterogeneity and species richness to be positively correlated (Brown, 2003; Allen, 2004). A lack of systematic evaluation of restoration projects, however, limits the understanding of project outcomes and further prevents critics from discrediting Rosgen’s work (Kondolf et al., 2001; Lave, 2012). Some critics of Rosgen’s methods call for interdisciplinary collaboration and peer-reviewed science to further the understanding of river function and the development of a more comprehensive-based restoration plan (Wohl et al, 2005; Beechie et al., 2010; Palmer et al.,

2014). Such a comprehensive-based restoration plan, however, will be an evolving process requiring years of research and project development. Current conditions of many freshwater systems require immediate action to prevent further degradation and current restoration practices, such as Rosgen's methods, are addressing that need in present time. Many scholars agree with developing a deeper understanding of river function to holistically restore freshwater systems and moving away from current practices. Using an adaptive management approach by building upon current practices, as suggested by Buchanan et al. (2010), simultaneously addresses this need and allows for immediate disturbance mitigation. Furthermore, to prevent public disinterest and to ensure success of future projects, we must continue to eliminate the knowledge gap between river processes and restoration project design.

With numerous studies showing that organisms can alter physical processes (Cardinale et al., 2004; Zimmerman and de Szalay, 2007; Fremier et al., 2018; Albertson, 2019), and many restoration efforts (Palmer, 1997) based on a top down approach where abiotic processes drive biotic processes (Frissell et al., 1986), the unknown mechanisms causing the failure of restoration could be linked to the presence/absence of certain aquatic organisms. A fully comprehensive-based restoration plan would consider all possible mechanisms with potential to influence geomorphic and ecologic processes and will require detailed studies of aquatic organisms with this potential. Our study investigates the potential for freshwater mussels, acting

as biogeomorphic agents, to induce reach-scale geomorphic change. Our results will advance biogeomorphic research and aid in the progress to a comprehensive-based restoration plan.

2.0 UNDERSTANDING GEOMORPHIC CHANGE OVER DECADES IN RIVER REACHES WITH HIGH-DENSITY MUSSEL ASSEMBLAGES

2.1 Introduction

2.1.1 Overview of Mussels as Ecosystem Engineers

Freshwater mussels are ecosystem engineers. Through processes like filtering of water and burrowing, mussels can alter their surrounding ecosystem (Atkinson et al., 2013; Atkinson et al., 2015, Hopper et al., 2019) and habitat (Statzner, 2012; Atkinson et al., 2017). Effects of mussels as ecosystem engineers can also be species dependent as one species effect may counter act the other. A burrowing species of mussel can destabilize sediments causing fine sediment particles to become entrained, while sessile mussel species can blanket the riverbed, preventing mobilization of smaller sediments (Allen and Vaughn, 2011). High density beds of mussels can filter large portions of the water column (Strayer and Malcom, 2007). For example, in a study of eDNA detection in rivers, Friebertshauser et al. (2019) found large aggregations of mussels can be responsible for the complete removal of eDNA from the water column as a result of their filtration activities. While filtering the water, mussels ingest fine suspended sediment particles and digest them as mucus coated feces (Ward and McDonald, 1996). Buildup of these particles around the mussel bed can lead to increased sediment cohesion (Grabkowski et al., 2011) and

benthic algal biomass (Hopper et al., 2019). Although mussels can influence sediment properties in different ways, many beds consist of multiple species (Strayer, 2008) and could potentially magnify the effect on sediment transport processes.

The lifespan of mussels ranges from 6-100 years and is species dependent (Strayer, 2007). Because of the lifespan of some species can exceed a century, and the densities in which mussels can occur, the potential exists for mussels to greatly alter sediment transport properties in fluvial systems across multiple spatial and temporal scales. Furthermore, because sediment transport properties are widely associated with river form and function (Lane, 1955; Hammond et al., 1984; Dunne and Jerolmack, 2018; Pfeiffer et al., 2017), mussels could potentially be involved in the evolution of river geomorphology.

2.1.2 Purpose of Our Project and Questions

Researchers are becoming increasingly aware of how ecosystem engineers, such as mussels, impact geomorphic processes (Statzner, 1999; Zimmerman and de Szalay, 2007; Commito et al., 2018; Koerner et al, 2018). Although geomorphologists have a history of studying biotic and abiotic feedbacks on river processes at patch-scales (McCall et al., 1986; Zimmerman & de Szalay, 2007; Koerner et al., 2018), few studies have examined the significance of these feedbacks at reach or landscape-scales. In this study, we examined whether biogenic effects of mussels in riverbed sediments observed at the microscale have the potential to

influence spatial and temporal patterns of channel migration and bank erosion. Here we asked: (1) are river morphology changes across decades different at reaches containing high mussel densities relative to other reaches? (2) Are high-density mussel assemblages associated with different higher or lower rates of riverbank erosion? The findings of our study provide a better understanding of how mussels, operating as ecosystem engineers, can influence fluvial environments. Current literature lacks a full understanding of the relationships between most aquatic organisms and geomorphic processes. This knowledge gap limits our understanding of the mechanisms driving river planform change and may be responsible for the failure of river restoration projects. Because mussels occur in many freshwater systems worldwide, furthering our understanding of the reciprocal relationship between mussels and geomorphic processes could have widespread impacts on restoration and preservation efforts.

2.2 Study Area

2.2.1 Study Area

The world's highest biodiversity of freshwater mussel assemblages is found in North America and, some of the most biodiverse mussel populations in the United States are found in Alabama (Johnson et al., 2015). The Sipsey River is 148 km long, 5th order stream in west-central Alabama in the southeastern U.S. The Sipsey is an undammed, free-flowing river surrounded by frequently inundated bottomland forests making it worthy of federal protection

(Hopper et al., 2012) and, is considered a diversity hotspot for freshwater mussels (**Fig. 1**). The high degree of hydrologic connectivity of the Sipsey's floodplain, and the lack of human influence imposed on the river (Benke, 1990; Haag & Warren, 2010), make it the ideal location for this study. A total of 42 species have been observed in the mainstem portion of the river and, the highest densities concentrated in the lower reaches (McCullagh et al., 2003).

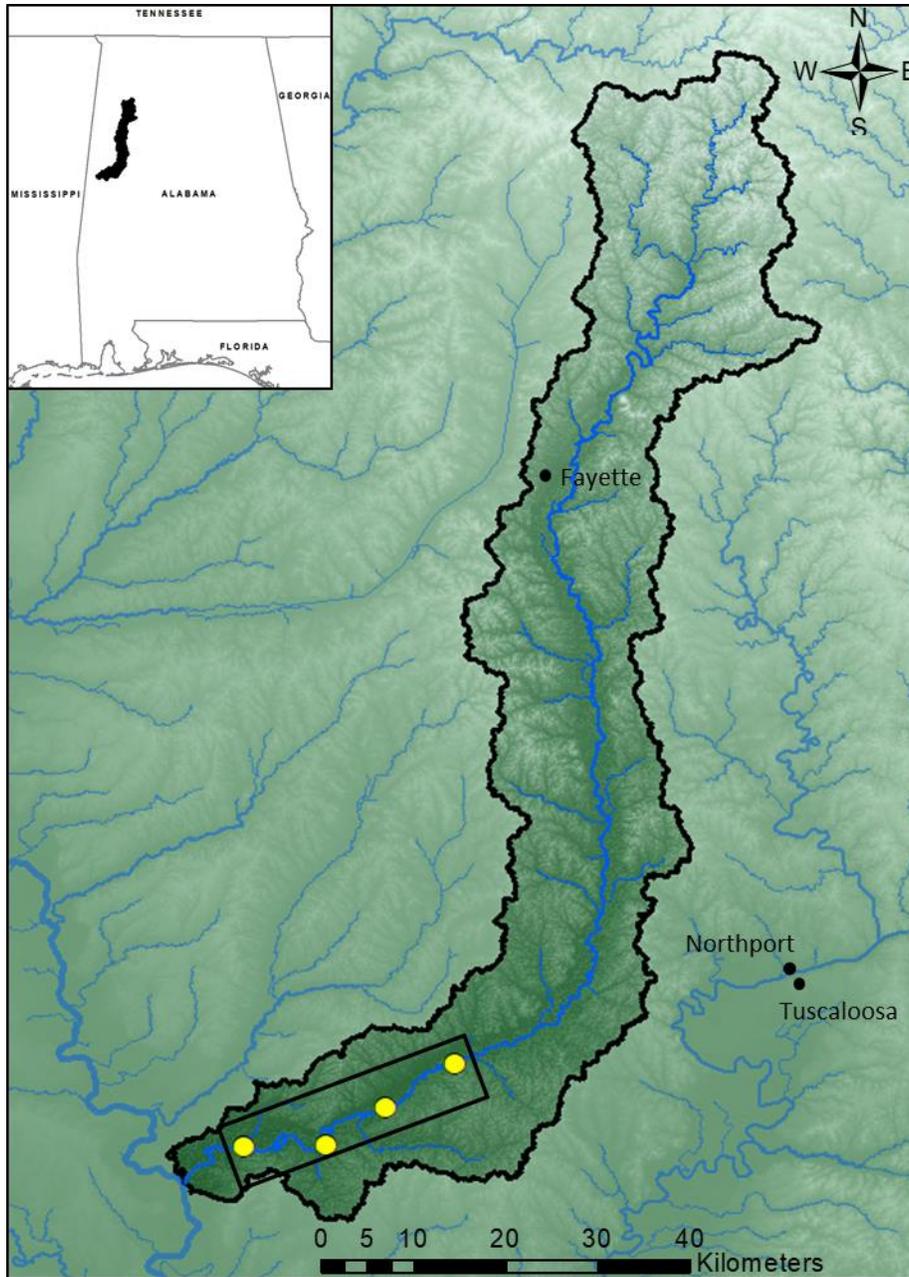


Fig. 1: Map of the Sipsey River watershed. Flow travels from northeast to southwest. High-density mussel locations are represented by yellow circles in the southwest corner of the watershed. The entire 48-km segment of the river analyzed in this study is encompassed by the black rectangle.

Land use in the watershed consists of mixed forest, agricultural land, and Fayette, AL as the only urban area. Most agricultural land is located near the headwaters of the river. Although agricultural use is not the foremost form of land use in the watershed, it dominates the mainstem riparian area due to the rich floodplain soils comprised of alluvium deposits produced by the major soil groups found within the watershed (USDA, 2019). Land use for agriculture in the lower reaches of the watershed has increased 6.8% since 2011 (Fry et al., 2011) and could impact river processes. The Sipseys wide floodplain contains numerous oxbow lakes, and as a result, the effects of land use practices on channel processes are mitigated by a large buffer created by the extensive bottomland forests surrounding it (Haag and Warren, 2010).

The Sipseys River is located in a humid subtropical climate where average annual precipitation exceeds 1,300 mm yr⁻¹ (Praskievicz and Luo, 2019). The river sustains strong seasonal high flows from November through May and lower sustained flow from May to November. Monthly precipitation totals are typically greatest in March (157 mm), although summer storms can lead to rapid increases in discharge. High flows during the winter months and intermittent high flows from summer rain events render the river inaccessible. High flows typically inundate the entire floodplain which, in some sections the floodplain is over 2-km wide.

2.2.2 Study Segment and Study Sites

We defined our study area as a 48-km segment of the lower mainstem of the Sipse River (**Fig. 1**) with the highest densities of mussels to occur in the lower reaches (Haag & Warren, 2010). Annual in-stream surveys have identified four reaches of high-density mussel aggregates (Haag & Warren, 2010). From the furthest upstream moving down, these reaches are named Wendell 6, Mussel Mania, Wendell 2, and Highway 14. Surveys of mussel aggregations in these reaches have occurred regularly since the 1990's, most recently in 2019 and, as far back as the 1910's. Results of these surveys show changes in species composition of assemblages over time, but a persistence of high population densities (Haag & Warren, 2010). Because the length of mussel population surveys has varied among studies, a standard length of 200-meters, encompassing all previous surveys, were used for this study.

2.3 Methods

2.3.1 Project Overview

We quantified changes in the river channel planform over five decades using a geographic information system-based (GIS) analysis of historical aerial photographs (**Fig. 2**). We digitized and georeferenced these historical aerial photos to a base image from 2018. Because our study area is 48-km in length, we relied on GIS-based methods previously identified as suitable for measuring large-scale planform change (O'Connor et al., 2003; Urban and Rhoads,

2003; Hughes et al., 2006; Rhodes et al., 2009; Lauer et al., 2017). Once the quantification of erosion totals was complete, we then compared rates of lateral migration and erosion at the four high-density mussels reaches to the rest of the study segment.

2.3.2 Aerial Photo Scanning

We acquired aerial photographs archived by Cartographic Research Lab at The University of Alabama covering the 48-km reach. Images were taken in 1965 at 1:24,000 scale and scanned in greyscale at 600 dots per inch (DPI) which, produced a pixel resolution of about 1-m. Because the 2018 imagery is registered in WGS 1984 Web Mercator Auxiliary Sphere, we used this projection for all unregistered imagery throughout the course of the study. The 2018 image had color display and a pixel resolution of 0.03-m at a scale of 1:1200.

2.3.3 Georeferencing

Proximity to the river, the number of hard or soft points, and distance from the center of the image controlled the distribution and placement of ground control points (GCP's). Because our area of interest is the river, we concentrated the location of GCP's near the portion of the photograph containing the river and the surrounding floodplain. This approach prevents the area of interest from being skewed by more topographically complex areas of the image (Hughes et al. 2006). We gave priority of placement of GCP's to hard points, locations that have maintained exact placement throughout the time spanning between each photograph (i.e. houses or road

intersections), rather than soft points, objects that have maintained the same location but may have changed in size over time (i.e. trees). Hard points allow for a more exact placement of GCP's and reduces error. Because the Sipsy River has such a vast floodplain, hard points were less common in some images, creating the need for more soft points. Each image contained a minimum of 12 GCP's although, most images had more.

We applied a second order polynomial transformation function to rectify each historical image with the base image. This curvilinear (quadratic) transformation function is commonly used when rectifying aerial photos because it can correct for associated errors related to the curvature of the earth or camera lens distortion (Rhodes et al., 2009). The transformation process can alter the proximal area of each GCP resulting in error (Hughes et al., 2006). This error, known as the Root Mean Square Error (RMSE), is the misalignment of GCP coordinates on the base layer and transformed images. The total RMSE for each image is represented by the sum of the RMSE of each coordinate pair calculated by **Eq. 1**

$$RMSE = [(x_s - x_r)^2 + (y_s - y_r)^2]^{1/2} \quad (\text{Eq. 1})$$

where x_s and y_s are coordinates on the base image; and x_r and y_r are coordinates of the transformed image (Slama et al., 1980). We adjusted the number of GCP's until the root mean square error RMSE associated with each photograph was < 1-m. RMSE values for individual images ranged from maximum of 0.97-m to a minimum of 0.61-m. Because second order

transformations can create variance in pixel size across images post-transformation (Hughes et al., 2006), we used a bilinear interpolation resampling method to equalize the pixel sizes of each image (Campbell, 2002).

2.3.4 Channel Planform Change

We traced and digitized stream-channel banks on the rectified images and base image (**Fig. 2B**). We maintained a constant scale of 1:1200 while riverbanks were traced on each image. We placed a minimum of 100 points per km while digitizing each shoreline (Rhodes et al., 2009). The riparian zone of the Sipsey River is heavily vegetated with thick bottomland forest, obstructing the view of the riverbank in some areas. In these areas, we interpolated bank traces towards the stream-channel side of the center of the impeding vegetation as outlined by Rhodes et al (2009). Although we minimized the associated error introduced during transformation, a small amount of error persisted. To account for this potential error, we placed a 2-m wide buffer, a value twice the highest measured RMSE, around the digitized channel banks (Urban and Rhoads, 2003; Rhodes et al., 2009). This assures that all subsequent measurements of the digitized lines represent planform change. Additionally, because of the buffers added to each digitized line, our results of planform change should be regarded as a minimum estimate.

To measure rates planform change, we overlaid digitized river-channel banks from the transformed historical images and the base image (**Fig. 2C**). We quantified lateral migration for

the 53-year study period by creating polygons in areas where buffered river-channel banks did not overlap (**Fig. 2D**). The rate of lateral migration for each polygon is expressed by **Eq: 2**

$$\textit{Lateral migration} = \Delta A / (L * \Delta t) \quad (\text{Eq: 2})$$

where ΔA is the area of the polygon, L is the length (represented by the longest line fit inside each polygon), and Δt is the time interval of the study (**Fig. 2E**).

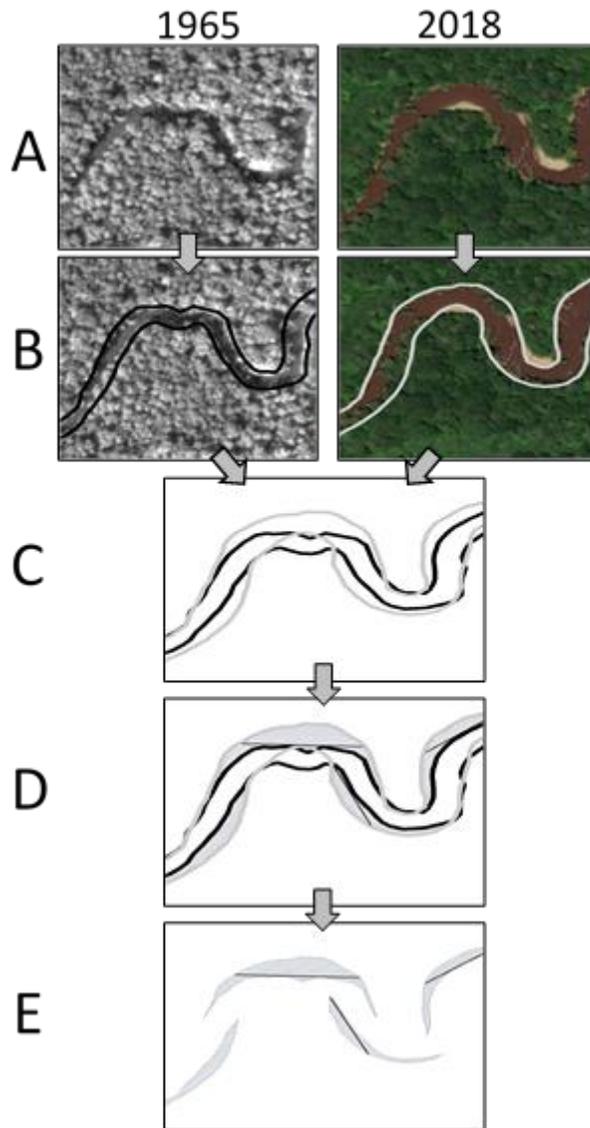


Fig. 2: Graphical representation of the georeferencing and digitization process. **A)** We georeferenced photos of the Sipsy River to images of the river form 2018; **B)** we digitized riverbanks form 1965 (black) and 2018 (gray); **C)** we visualized areas of erosion by overlaying the digitized banks from both images; **D)** We created polygons of areas where banks do not overlap to represent zones of erosion. Estimated area length is represented by the longest fit line with each polygon; **E)** We removed digitized banks leaving only zones of erosion for analysis.

2.3.5 Volumetric Bank Erosion

In this study, the polygons representing two-dimensional areas of channel displacement are combined with 1-m resolution LiDAR data published by the U.S. Geological Survey (USGS, 2019) to form a three-dimensional aspect of riverbank erosion. Because the Sipsey River has varying bank heights throughout its course, finding the bank height at each erosional area is more spatially accurate than defining an average bank height for the entire 48-km reach (Rhoades et al., 2009). Erosion volumes for each polygon are generated by subtracting the height of the water surface (minimum elevation) from the top of the riverbank (maximum elevation). The 2-m buffer applied to the digitized banks to reduce error from the transformation process likely removed the contact point between the riverbank and water surface at each polygon. This prevented the detection of maximum bank heights within each polygon. Therefore, we estimated the maximum bank height within the 2-m buffer on the eroding edge of each polygon (**Fig. 3**).

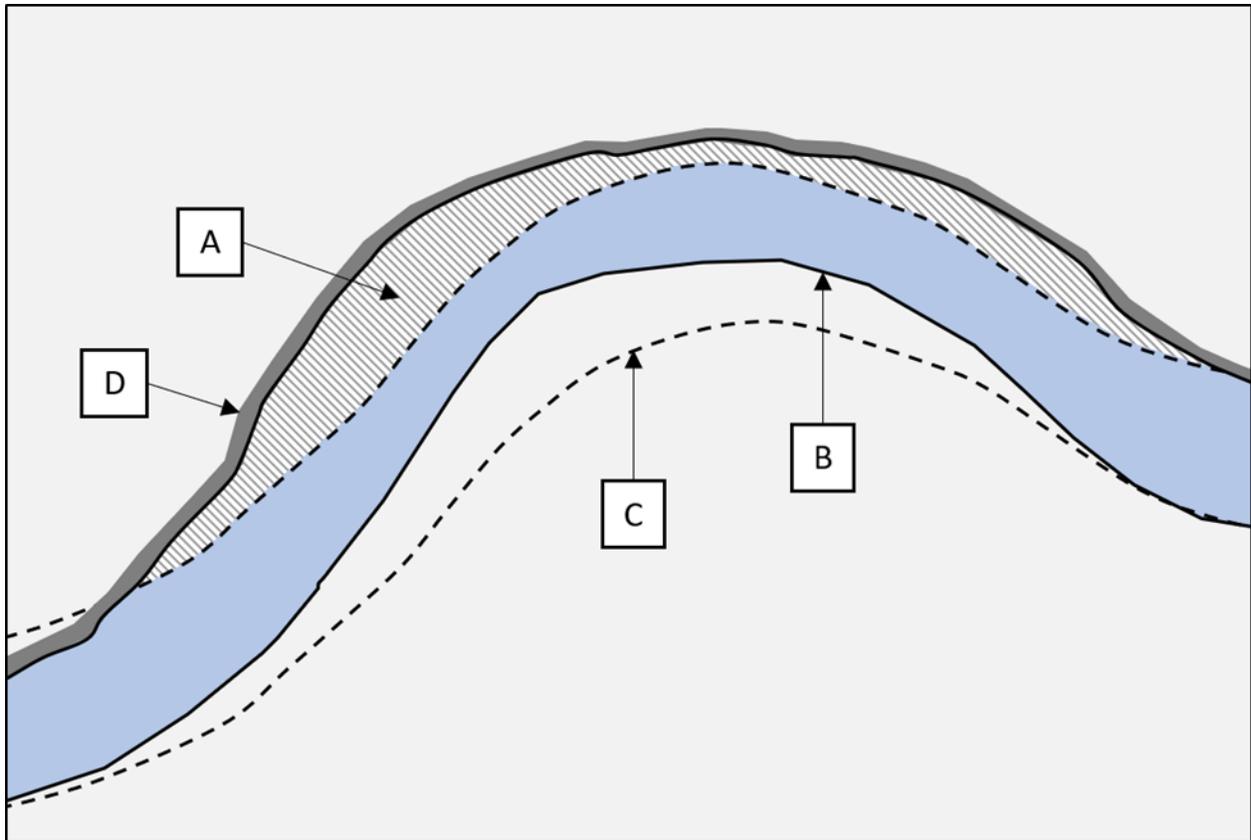


Fig. 3: Graphical representation of volumetric calculation process: A) polygon of 2-dimensional lateral migration; B) 2018 riverbank; C) 1965 riverbank; D) reapplied 2-m buffer encompassing water surface and riverbank contact point.

2.4 Results

2.4.1 Lateral Migration

A total of 444 zones of lateral migration were identified between 1965 and 2018 accounting for 24.5% of the total analyzed riverbank (**Fig. 4**). Measured areas of lateral migration ranged from 2.1 m² to 7339.8 m² and we observed a total net change of 228,722.1 m². Annual rate of lateral migration for the total 48-km reach ranged from 0.01 m yr⁻¹ to 0.68 m yr⁻¹ and averaged 0.15 m yr⁻¹. High-density mussel reaches exhibited a mean annual migration rate of 0.22 m yr⁻¹. Individual lateral migration rates for Wendell 6, Mussel Mania, Wendell 2, and Highway 14 were 0.14 m yr⁻¹, 0.20 m yr⁻¹, 0.20 m yr⁻¹, and 0.22 m yr⁻¹, respectively.

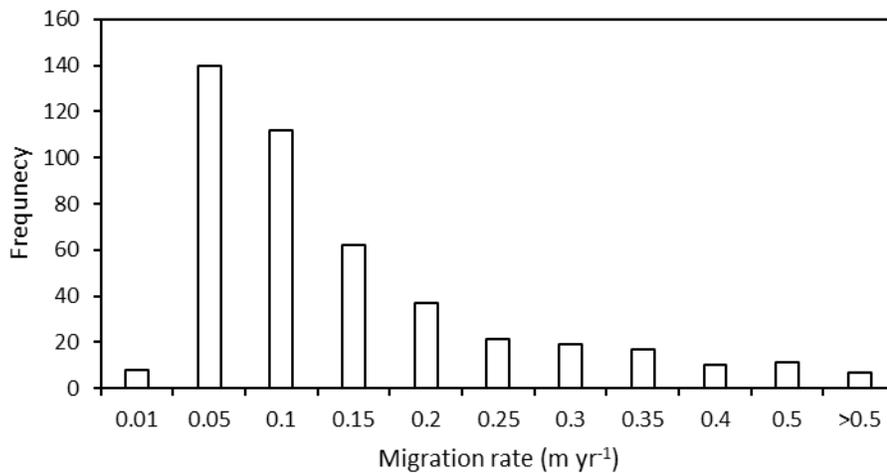


Fig. 4. Histogram of lateral migration rates of all zones.

Fig. 5 displays each zones of lateral migration categorized by one of five modes influencing the observed channel change. Most zones of lateral migration are attributed to the river meandering (n=226). This mode represented 51% of all modes observed and totaled 63% of total area change. Many instances of small lateral migration zones (< 20 m²), could not be attributed to a specific mode and were placed in the unknown category (n=97). These were primarily located on straight reaches of the river. Although the unknown category accounted for 22% of all identified modes, it only accounted for 9.4% of total area change. The 48-km study reach of the Sipsey River has a mean elevation drop of 0.34-m per downstream kilometer (**Fig. 6**). The flat nature of the land through which the Sipsey flows, and the gravel substrate consistent on the riverbed, leads to the river bifurcating in multiple locations. Bifurcation of the river channel at two locations produced the two largest areas of lateral migration (7339.8 m², 6004.1 m²). This category only represented 3% of the modes but, accounted for 10% of the of total area change. The formation of bank-attached bars and mid-channel bars is common throughout the Sipsey River. We observed 86 instances of this mode representing 19% of lateral migration modes and 15% of the total area change. Average migration for this mode was 0.08 m yr⁻¹.

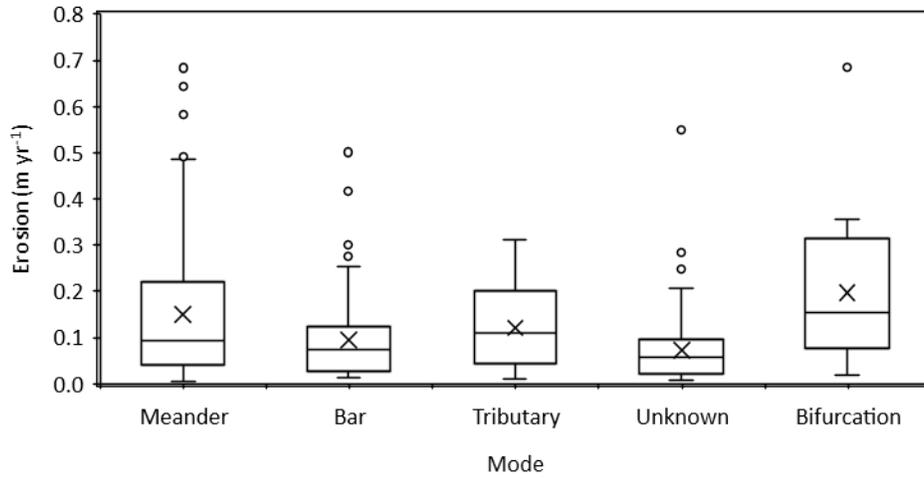


Fig. 5: Box and whisker plots of erosion rates for each mode.

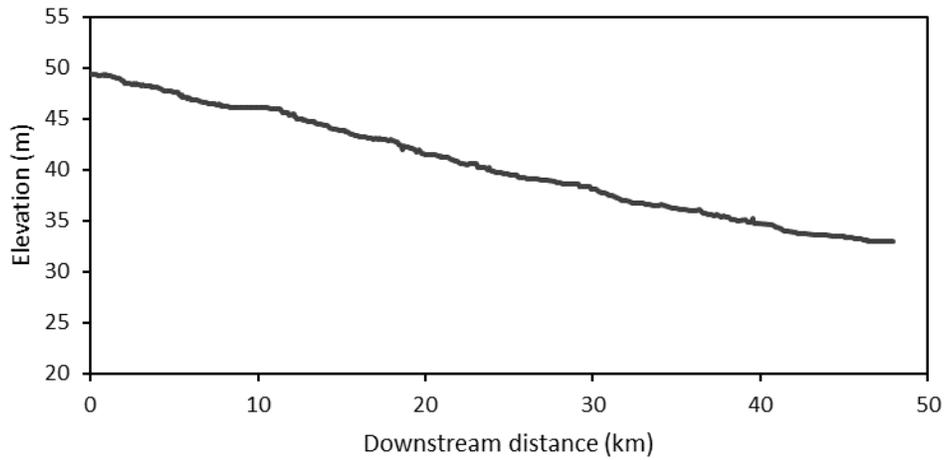


Fig. 6: Elevation profile of the 48-km study segment.

2.4.2 Volumetric Bank Erosion

Bank heights range from 0.02-m to 4.1-m with an average of bank height for the entire study segment of 1.9 m (**Fig. 7**). Bank heights at Wendell 6, Mussel Mania, Wendell 2, and Highway 14 were 2.0-m, 2.6-m, 2.93-m, and 3.2-m, respectively. Volumetric erosion rates range from less than $0.01 \text{ m}^3 \text{ yr}^{-1}$ to $387.95 \text{ m}^3 \text{ yr}^{-1}$ with a mean of $24.2 \text{ m}^3 \text{ yr}^{-1}$ for all erosional polygons (**Fig. 8**). Erosion rates for Wendell 6, Mussel Mania, Wendell 2, and Highway 14 were $13.24 \text{ m}^3 \text{ yr}^{-1}$, $33.56 \text{ m}^3 \text{ yr}^{-1}$, $72.97 \text{ m}^3 \text{ yr}^{-1}$, and $112.62 \text{ m}^3 \text{ yr}^{-1}$, respectively.

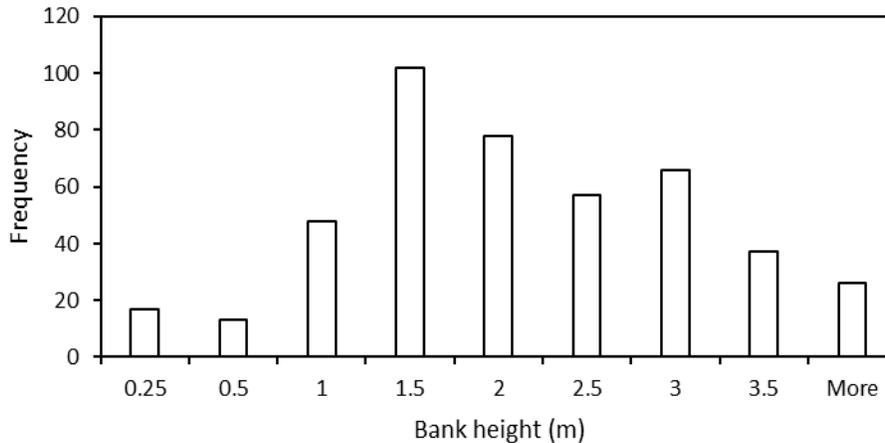


Fig. 7: Frequency of bank height observations for each zone.

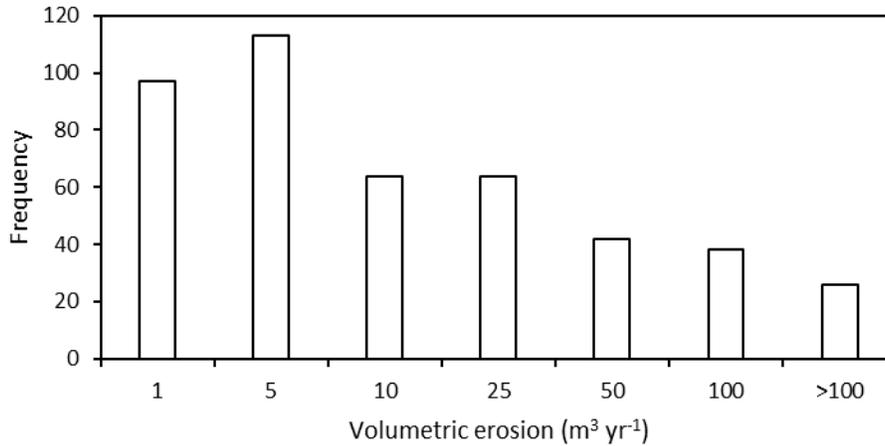


Fig. 8: Histogram of volumetric erosion rates per year at each zone.

2.5 Discussion and Conclusion

2.5.1 Methodology Performance

Lateral migration rates from our study are similar to those found by Rhoades et al (2009) for gravel-bed rivers but low in comparison to those found by other studies of gravel-bed rivers (Micheli et al., 2004). The difference is most likely explained by the process of digitization which, we followed from Rhodes et al. (2009). During digitization, we applied buffers to account for errors in the transformation process. These buffers likely covered some of the erosional zone edges lowering our overall estimate. Other previous studies digitized and compared differences in channel centerlines, as opposed to digitizing individual riverbanks (O'Connor et al., 2003; Urban and Rhoads, 2003; Gunalp and Rhoads, 2008). The method of digitizing the channel

centerlines, however, assumes the channel widths remain constant during migration (Rhodes et al, 2009). The Sipsy River has numerous instances of irregular patterns of erosion where channel width was not constant, which motivated our choice to follow methods set forth by Rhodes et al. (2009).

We found most lateral migration and bank erosion occurred at meander bend zones, which is characteristic of meandering rivers with high sinuosity (Nagata et al., 2000) like the Sipsy ($k = 2.14$). The magnitude of lateral migration and bank erosion, however, greatly depended on the height of the riverbank. Most two-dimensional zones of high lateral migration rates were in locations with low bank height, which, did not produce large bank erosion volumes. In few instances, there were above average rates of lateral migration in areas accompanied with above average bank heights. These rare combinations resulted in some of the largest zones of volumetric bank erosion observed in this study.

2.5.2 Mussel Density Sites

Rates of lateral migration at the high-density mussel locations were not considerably different from the average rate for the study area, although, three of the locations did experience rates higher than average. However, the volumetric rates of bank erosion at those reaches were as much as 5-times greater than the average for the study segment. Because areas with high lateral migration rates were not indicative of high erosion volumes, it is unusual that the locations of

high-density mussel aggregations simultaneously experienced greater than average lateral migration and volumetric erosion rates. Again, the lateral migration rate at the four studied mussel reaches was only slightly above the average, but the bank height at each location was also higher than average. The combination of the observed lateral migration rates and bank heights resulted in the increased bank erosion rates at the high-density mussel reaches. Additionally, because we defined the length of reaches containing high-density mussel aggregations as 200 m, lateral migration and volumetric erosion rates were not uniform across the total length of the reaches. All four reaches experienced most lateral migration and bank erosion in the lower parts of the reach. The upstream portions of all four reaches were relatively unchanged for the 53-year study period.

2.5.3 Mid-channel Bars

The presence of mid-channel bars, persisting for the 53-year study period characterized lower parts of each high mussel density reach (**Fig. 9**). The bars are responsible for directing flow toward the riverbank and were the observed mechanism of increased lateral migration within these reaches. Mid-channel bars are characteristic of active meandering gravel-bed rivers like the Sipsy (Hooke and Yorke, 2011), and can occur in two forms, migrating and non-migrating. The latter, also known as forced bars, are relatively fixed and are shown to result from changes in channel width (Wintenberger et al., 2015). Previous studies have modeled the

formation of forced bars using variables like width/depth ratio, slope, bed roughness and sediment characteristics (Crosato and Mosselman, 2009; Luchi et al., 2010), two of which, bed roughness and sediment characteristics, can be greatly altered by biogenic mussel activities. In the present study, changes in the size of the bars were consistent with changes in the density of the mussel aggregations. The mussel aggregations at Highway 14 and Mussel Mania contain the highest densities and, were associated with the largest bar formations.

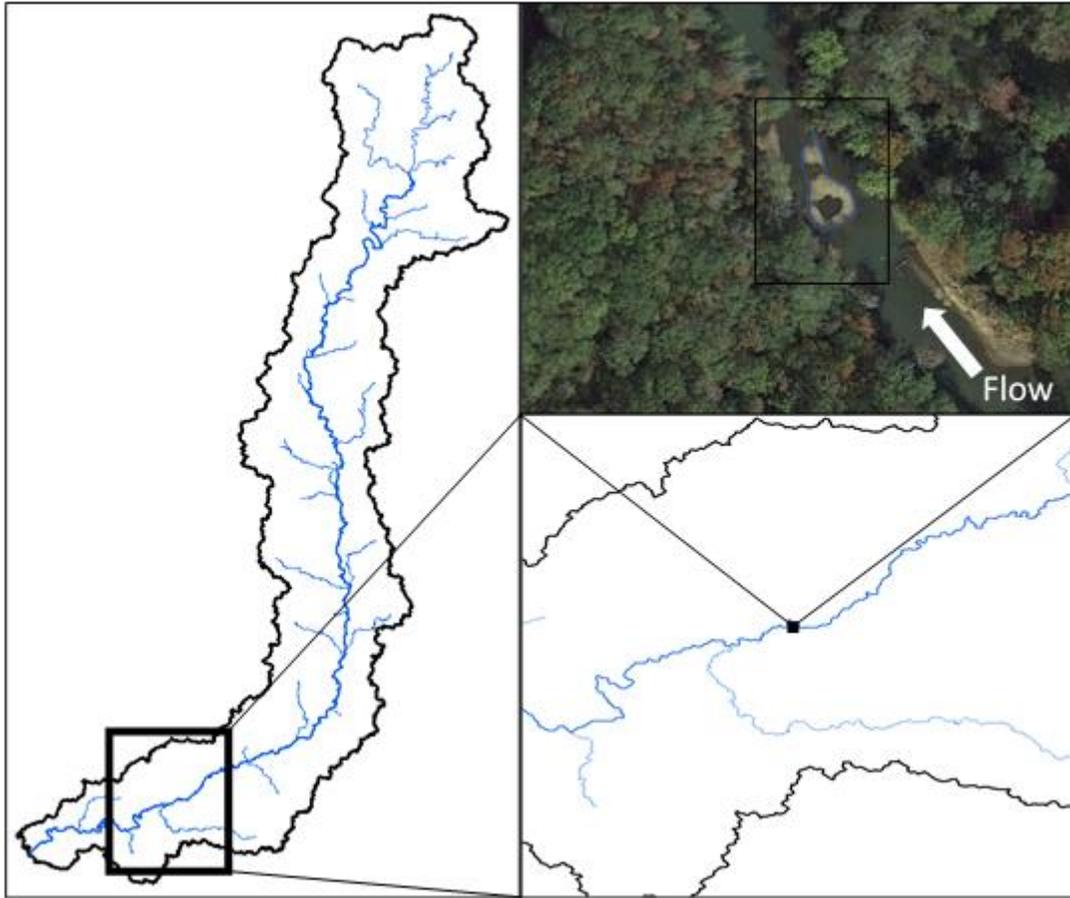


Fig. 9: Observed mid-channel bar at Mussel Mania study site located in the lower reaches of the Sipsey River. The mid-channel bar present immediately downstream of the survey high-density mussel bed is shown in the upper right image.

Lifecycle estimates of bars range from less than a decade (Hooke and Yorke, 2011) to upwards of a century (Church and Rice, 2009), and a common lifecycle for bars remains lacking in the literature. Hooke and Yorke (2011) derived their shorter lifecycle estimates from the Dane River in NW England which is subject to rapid change in flow accompanied with higher rates of sediment mobility, much like the Sipsy River. Church and Rice (2009) developed their bar lifecycle the much larger Frazier River in Canada which has lower relative rates of sediment mobility. Although we cannot identify the full lifecycle length of the observed bars in this study, we do find they persist for the duration of the 53-year study period. With the Sipsy River being subject to rapid changes in flow due to the high rainfall events in the region, we would expect the lifecycle of the midchannel bars to be similar to those found by Hooke and Yorke (2011). In an empirical study of the Loire River in France, Wintenberger et al. (2015) observed the head of the mid-channel bar being studied was stabilized by the presence of an armoring layer. The bar head was able to persist in shape and size through successive flooding events of various intensities. As previously discussed, studies have shown large aggregations of mussels can armor the riverbed and increase sediment stability. Additionally, mussels use their muscular foot to stabilize themselves increasing the shear stress need to mobilize them (Anand and Vardhanan, 2020). This allows them to withstand high flow events and avoid being moved by the increased flow. The patch-scale activities of (i.e. sorting of bed sediments) of these high-density mussel aggregations may help stabilize the upstream portions of the bars. Furthermore, the bars may be able to persist

for longer than expected lifecycle because mussels are able to anchor to the bottom and endure flooding events. Given that some mussels can live for over a century, and aggregations continue to be in the same locations for extended periods of time, they could easily influence sediment properties in one location for decades. The high-density mussel aggregation observed in this study could be the mechanism allowing these mid-channel bars to remain static, and indirectly causing the increased rates of lateral migration and erosion associated with the bars.

2.5.4 Limitations

It is important to consider the limitations and associated errors of our study before interpreting or expanding upon our results. Our measured results of lateral migration and erosion rates are only a minimum estimation of actual conditions because of the buffers used to account for errors in the digitization process. Additionally, we cannot determine if mussels are responsible for the formations of the four mid-channel bars or, if the mussels populated the area once the bar was formed. Furthermore, within the scope of this study, we can only speculate about what, if any, effect mussel activity has on influencing bar stabilization because no empirical analysis was conducted. All analysis was completed using a geographic information system (GIS) based platform. Future studies should consider an empirical approach to gather more precise measurements when investigating the impacts of freshwater mussels on reach-scale river form and processes. Because of the present immediate need to fully understand freshwater

mussel impacts to freshwater systems, a hybrid approach combining instream data measurements with reach- or watershed-scale modeling could be the most effective.

2.5.5 Study Implications

Our study has outlined pathways in which patch-scale activities of mussels could potentially alter reach-scale river form and processes. At minimum, the similarities in habitat conditions shared among all four high-density mussel reaches in this study warrants future research. Future studies on the ecosystem engineering effects of mussels in freshwater systems could use our findings to further develop their research methods and criteria. Only with the combination of present studies and future research can we eliminate the knowledge gap between these freshwater biotic and abiotic relationships.

Freshwater mussel populations are declining across North America. Because freshwater mussels are sessile organisms, they spend most, if not all, of their lives in one location. If the freshwater habitats which mussel populations currently occupy are altered, and conditions move outside their tolerance threshold, populations will likely perish. If watershed-scale changes occur, entire species of freshwater mussels could become extinct. As the human population continues to grow and urban development continues to encroach on our freshwater systems, the number of river restoration and management projects is likely to rise. The impacts that

ecosystem engineers have, such as freshwater mussels, must be considered to increase the effectiveness and success of current and future restoration and management projects.

3.0 UNDERSTANDING REACH-SCALE GEOMORPHIC CHANGES IN REACHES WITH HIGH-DENSITY MUSSEL ASSEMBLAGES

3.1 Introduction

3.1.1 Overview of Mussels as Biogeomorphic Agents

Freshwater mussels tend to occur in dense, patchy beds throughout the course of a river in reaches of low shear stress (Gangloff and Feminella, 2007; Allen and Vaughn, 2011). These patches, often of multiple species (Strayer, 2008), can blanket the riverbed and prevent the movement of smaller riverbed particles (Widdows et al, 2002). Throughout the course of their lifetime, mussels filter food from the water column (Vaughn et al., 2004; Strayer, 2008). During filtration, mussels ingest additional fine suspended sediment particles from the water column. These particles are consolidated and coated in mucus, then deposited back to the river (Ward and McDonald, 1996). Once coated in mucus, these particles can build up on the riverbed (Strayer et al., 1999) decreasing the erodibility of sediments (Grabkowski et al., 2011). Additionally, freshwater mussel can alter sediment properties through bioturbation by burrowing into the substrate (Allen and Vaughn, 2009). The bioturbation effect mussels have, however, is species

dependent and may alter sediment properties in different ways (Gutiérrez et al., 2003; Allen and Vaughn, 2007).

3.1.2 Linking Mussels to Biogeomorphology

Corenblit et al. (2007) established the fluvial biogeomorphic succession model which (**Table 1**) which has four phases. The first phase, called ‘Geomorphic’, consists of only abiotic process (i.e. erosion and deposition) altering landscapes. In the second phase, ‘Pioneer’, biological organisms begin to establish on the altered landforms. Once the organisms are established, phase three, ‘Biogeomorphic’, begins where biologic and geomorphic processes adjust to each other. The final phase, ‘Ecologic’, is the stabilization of the landform and the associated biologic and geomorphic processes or, the disconnection of the landform from hydrogeomorphic processes. For example, Corenblit et al. (2016) completed a biogeomorphic study testing the relationship between fluvial landform construction and vegetation establishment. They found the river created a point bar of suitable habitat for the rapid colonization of riparian trees. Once the trees colonized the bar, the natural meandering process of the river stopped. Because the river could not laterally migrate, it began to incise. The authors hypothesized that sediment will collect as midchannel bars separated from the colonized point bar by chute channels and will become colonized by riparian trees in the near future. This would cause the channel to shift and the process to start over.

Table 1: The fluvial biogeomorphic succession concept from Corenblit et al. (2007)

Biogeomorphic phase	Main biotic and abiotic processes	Duration in temperate context	Structure of interactions between hydrogeomorphic processes and vegetated dynamics
Geomorphic	Total destruction of vegetation; Diaspore dispersion; Fluvial landform erosion; Transitory channel deposition or alluvial and point bar formation	Few hours to a few months following a flood	Abiotic
Pioneer	Pioneer vegetation recruitment on bare sediment	Few hours to a few months	Abiotic controlling biotic
Biogeomorphic	Vegetation establishment; Secondary allogenic successions; Vegetated fluvial landform accretion	Few months to a few decades	Two-way feedbacks between Abiotic and Biotic
Ecologic	Vegetation autogenic successions; Vegetated fluvial landform stabilization and disconnection from hydrogeomorphic disturbances	Few decades to a few centuries	Biotic

While the fluvial biogeomorphic concept is novel in illustrating the two-way feedbacks between abiotic and biotic processes, it only suggests this type of relationship exists between vegetation and fluvial processes. We believe the geomorphic change created by pact-scale mussel actives can apply to the fluvial biodemographic concept.

3.1.3 Purpose of Our Project and Question

With the continued degradation of freshwater mussel species biodiversity and abundances in North America, a better understanding of how freshwater mussels, acting as ecosystem engineers, influence their surrounding environment is needed. Current research on the abilities of mussels to alter physical habitat characteristics is restricted to laboratory flume-based experiments (Folkard and Gascoigne, 2009; Jones et al., 2011; Capelle et al., 2019) or studies conducted in marine environments (Lathlean and McQuaid, 2017; Tang et al., 2020). While flume-based experiments allow for the isolation and measurement of ecosystem engineering effects in a controlled environment, they fail to represent the complex variation of stream conditions (e.g., flow conditions, sediment heterogeneity, organism density and composition) over time and space. No empirical research exists on the ability of freshwater mussels, which can persist in high densities and live nearly a century, to create reach-scale change in freshwater environments because of difficulties with conducting experiments during seasonal changes in river conditions.

The goal of our study was to determine if the modification of bed sediment properties by *in situ* high-density mussel aggregations at the micro (patch) scale can help determine reach-scale geomorphic changes. Because localized sediment properties function as one of the factors influencing river morphologic change (Parker, 1978; Pfeiffer et al., 2017; Dunne and Jerolmack, 2018; Phillips and Jerolmack, 2019), we hypothesized that the alteration of riverbed sediment properties by high-density mussel aggregations would indirectly influence riverbank erosion as a

consequence of mussels increasing sediment shear strength. Our study aimed to answer the following question: is mussel density a useful metric for predicting riverbank erosion? This in-stream study represents the first attempt to measure how freshwater mussels can affect reach-scale river processes outside of extrapolated results from laboratory flume experiments. The results from this study will help bridge the gap between river ecosystem processes and current stream restoration practices while broadening our understanding of feedbacks between biotic and abiotic processes.

3.2 Study Area

3.2.1 Study Sites

The Sipsey River is considered a “hot spot” of mussel species and abundance (McCullagh et al., 2002; Hopper et al., 2012). Surveys of mussel populations in the Sipsey River date as far back as the early 1900’s. Dense concentrations of mussels are commonly found in the lower reaches of the river where habitat conditions are favorable for facilitating large aggregations (Haag & Warren, 2010). We identified three reaches with high-density mussel aggregations in the lower segment of the river to be analyzed for this study (**Fig. 10**). From upstream to downstream, these reaches are named Wendell 6 (33.121551, -87.911287), Mussel Mania (33.077829, -87.977816), and Wendell 2 (33.041120, -88.035109). Mussel Mania and Wendell 2 are 80-m in length and Wendell 6 is 60-m in length. These three reaches were chosen

because of their geomorphic similarities. Each reach is situated within a single river meander, presenting a distinct point bar and opposing cutback. All three study sites begin with an upstream pool which, abruptly gives way to a riffle, features characteristic of suitable mussel habitat. A strong presence of large woody debris, a characteristic of the lower Sipsey River, exists in each reach with Wendell 2 experiencing slightly more than Wendell 6 and Mussel Mania.

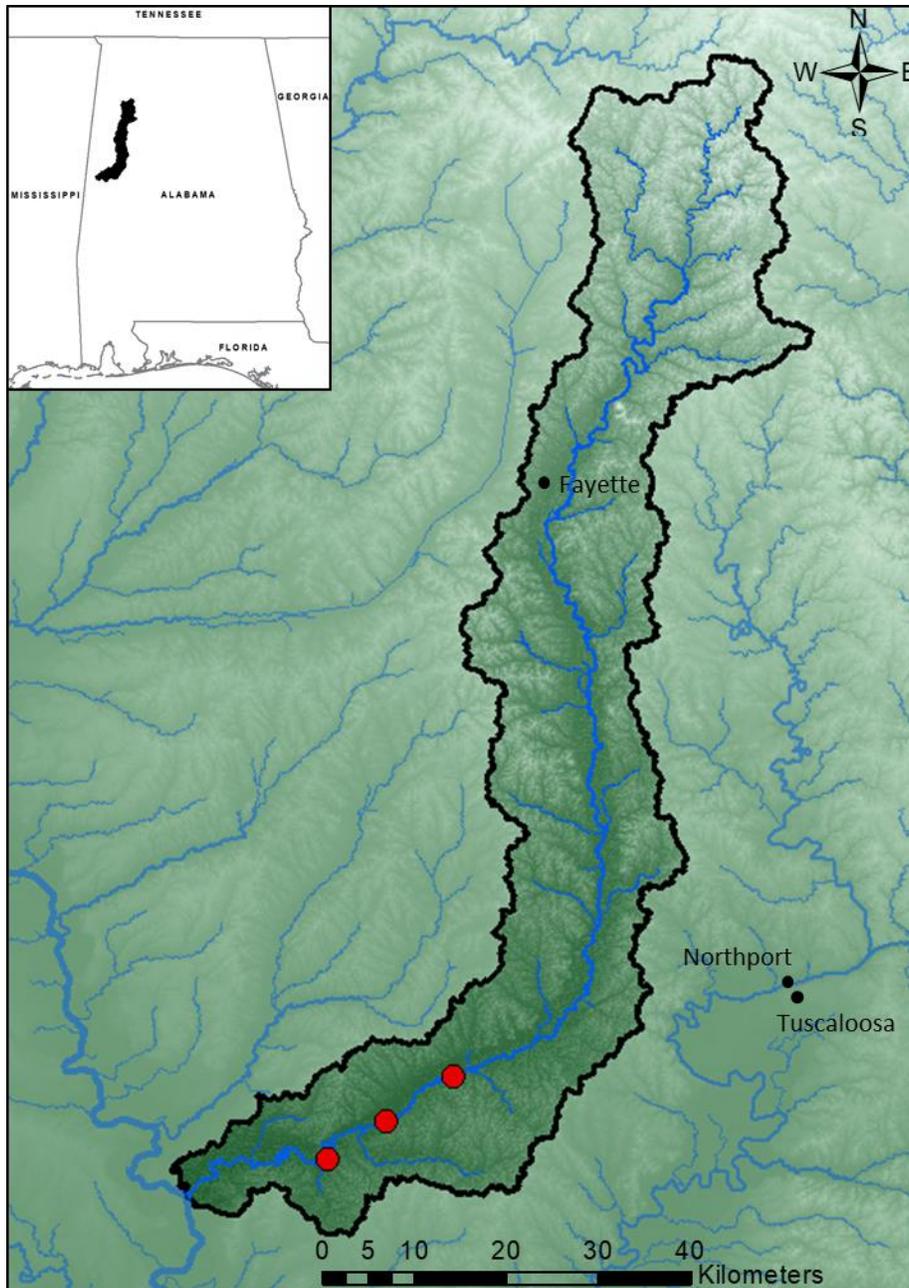


Fig. 10: Map of the Sipsey River watershed. Image in the upper left corner depict the location of the Sipsey River watershed in Alabama.

3.2.2 Study Design

To address the aim of this paper, we conducted an 11-week, instream experiment to develop a model to predict riverbank erosion (**Fig. 11**). We divided each high mussel density reach into 20-m sections. We randomly selected four transects perpendicular to flow within each 20-m section creating 44 transects total. At each transect, we measured rates of riverbank erosion, bank susceptibility to erosion, mussel density, D_{50} , woody debris, and distance from eroding bank to the thalweg. We used each of the measured variables to generate a model able to predict riverbank erosion.

The Sipsy River experiences sustained high flows between November and May and sustained low flows from May to November. During our sampling period, we experienced two high flow events, one in July and the other in August. The August high flow was a bankfull event.

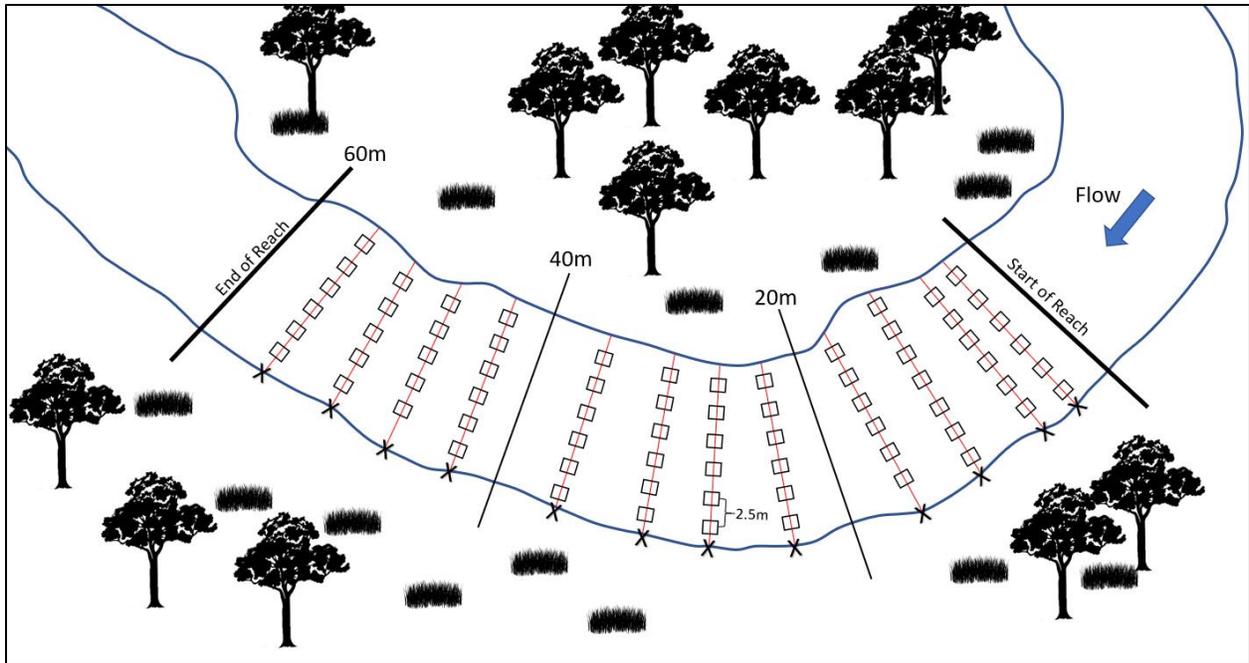


Fig. 11: Graphical representation of the study design at the 60-m reach (Wendell 6). Black lines perpendicular to flow separate the reach into 20-m sections. Red lines perpendicular to flow represent random transects selected for each section. Black squares on each transect represent spaced 2.5-m apart represent quadrats where mussel densities and D_{50} were quantified. The black X's on the cut bank side of the river represent the location of bank erosion surveys and erosion pins.



Fig. 12: Image of Wendell 6 study site. Picture taken at the start of the study reach (see **Fig. 11** for reference).

3.3 Methods

3.3.1 Erosion Pins

We installed 131 erosion pins at the three study reaches from July 9, 2019 to July 12, 2019 (**Fig. 13**). Erosion pin surveys are a widely used, low-cost method of measuring riverbank erosion (Wolman, 1959; Prosser et al., 2000; Lester and Wright, 2009; Kearney et al, 2018; Andrade and Maia, 2018; Arnold and Toran, 2018). Total change and average rates of change are established by measuring the amount of exposed pin protruding from the bank.

Erosion pins measuring 457 mm in length and 3 mm in diameter captured rates of erosion at each transect from July 12, 2019 to September 20, 2019. We placed three pins 0.3 m apart, vertically, on the eroding bank at each transect. On the date of installation, the placement of the bottom pin was just above the water line (**Fig. 14**). We inserted the pins into the bank leaving between 90 mm and 130 mm of the pin exposed. We did not use a uniform starting length to minimize bank disturbance. Once the pins were installed, we took a measurement of each pin from the tip to the streambank to establish an initial starting point. Return trips to calculate erosion were made following two high-flow events on August 1, 2019 and September 20, 2019, with the latter being the final measurement of the study. On three occasions, erosion exceeded the length of the pin. We reset these pins to the initial starting point between 90 mm and 130 mm to avoid losing the pin. During return sampling, we measured each pin individually, then averaged the three pin measurements at each transect to establish bank erosion totals and rates.

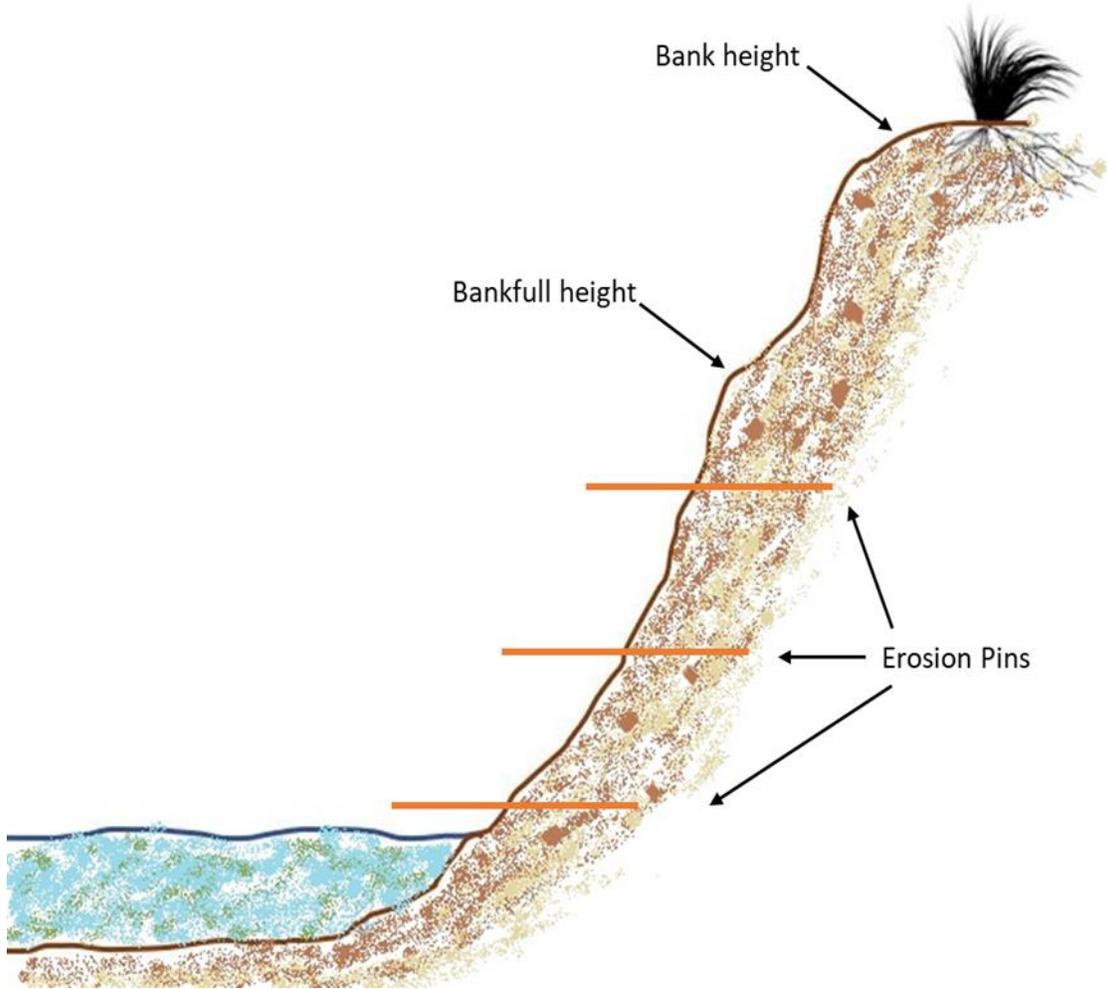


Fig. 13: Profile view of studied riverbank. Three erosion pins (orange lines) within bankfull and bank height.



Fig. 14: Image of one transect erosion pin placement at Wendell 6. Erosion pins are painted orange.

3.3.2 Bank Erosion Surveys

We used a modified version of the bank erosion hazard index (BEHI, Rosgen, 2001) to evaluate bank stability and potential erosion at each transect. Measurements for the BEHI include bank height/bankfull height ratio, root depth/bank height ratio, root density, surface protection, and bank angle. We directly measured bank height, bankfull height, and root depth using a Trimble Geo 7 Series handheld unit. Bankfull maximums were visually identified by topographic changes of the eroding bank. Identification of bankfull marks proved to be difficult in some locations because of water depth. In these instances, we obtained the measurement using

the laser feature of the Trimble from the opposite bank, where bankfull could be easily identified. We measured the bank angle at the location of each erosion pin, producing three measurements at each transect. We averaged the three measurements to generate a bank angle measurement for each transect. We placed an Abney level on a flat surface (i.e., clipboard) at each pin location to measure bank angle. We estimated percent of root density and surface protection relative to bank surface. We gave each measurement an index score based on the range of value in which they fell. A final BEHI score was then generated for each sample location by summing all the index scores and adjusting the summed score to reflect the underlying bank material and stratification of layers (**Table 2**).

Table 2: Modified version of BEHI measurement categories and transformation values from Rosgen, 2001.

Bank erosion risk category		Bank height/bankfull height	Root depth (% of bank height)	Root density %	Surface protraction %	Bank angle (degrees)
Very low	Value	1.0-1.1	90-100	80-100	80-100	0-20
	Index	1.45	1.45	1.45	1.45	1.45
Low	Value	1.11-1.19	50-89	55-79	55-79	21-60
	Index	2.95	2.95	2.95	2.95	2.95
Moderate	Value	1.2-1.5	30-49	30-54	30-54	61-80
	Index	4.95	4.95	4.95	4.95	4.95
High	Value	1.6-2.0	15-29	15-29	15-29	81-90
	Index	6.95	6.95	6.95	6.95	6.95
Very high	Value	2.1-2.8	5-14	5-14	10-14	91-119
	Index	8.5	8.5	8.5	8.5	8.5
Extreme	Value	>2.8	<5	<10	<10	>119
	Index	10	10	10	10	10

3.3.3 Mussel Density Surveys

We performed mussel density counts at each transect at Mussel Mania, Wendell 6, and Wendell 2 (see **Fig. 11** for an example). To complete the survey, a 0.5x0.5-m quadrat made of welded steel rebar was placed on the stream bed and, a total count of mussels within the quadrat was performed. We completed a quadrat every 2.5 meters across each transect, beginning on the

side of the river furthest from the study bank. The total number of surveys for each transect varied as a function of cross-sectional width. We averaged mussel density at each transect from the quadrat mussel density surveys.

3.3.4 Additional Habitat Measurements

We took additional habitat measurements, beyond those required for the BEHI, at each transect. During the mussel density counts, we determined a median particle size (D_{50}) using the Wolman Pebble Count Method (Wolman, 1954). We randomly chose 10 riverbed particles from within each quadrat and a minimum of 100 particles from each transect was measured for the pebble count.

During the acquisition of BEHI measurements, we located the river thalweg (Mossa & Konwinski, 1998), and surveyed the distance from it to the eroding bank at each transect. Additionally, we also surveyed the amount of woody debris at each transect and its proximity to the eroding bank of each piece. We walked the entire length of each transect until we identified the thalweg position and all woody debris. We used the laser range finder application of the Trimble to measure the distance from the thalweg and woody debris to the eroding bank.

3.3.5 Bank Erosion Prediction Model

The BEHI is used to evaluate potential riverbank erosion, however, we aim to identify if biotic factors, such as mussel density, can further aid metrics, such as the BEHI, in predicting

bank erosion. We formulated two stepwise multivariate linear regression models with one dependent variable (bank erosion) (**Eq. 3**):

$$\text{Bank Erosion} = \beta_0 + \beta_1x + \beta_2y \dots + \beta_n n + \epsilon \quad (\mathbf{Eq. 3})$$

The first model had five independent variables (total BEHI score, mussel density, D_{50} , distance from thalweg to bank, and distance from woody debris to bank). The second version of the model used 11 independent variables. Independent variables included mussel density, D_{50} , distance from thalweg to bank, distance from woody debris to bank, and each individual variable of the BEHI. Because the BEHI was used to determine bank erosion susceptibility, we broke down the index to determine which variables were the best predictor of bank erosion and evaluate how other variables, such as mussel density, compare to each BEHI variable.

Wendell 2 transect #3 had massive bank failure between the second and third sampling trips resulting in total loss of all three erosion pins. Because the pins were lost due to mass wasting, and not by hydraulic action we eliminated this transect from the data prior to statistical analyses as an outlier.

Prior to fitting the model, we tested to confirm if each dataset met all the assumptions of a linear regression model. Because we used a modified version of the BEHI that assigns a categorical value based on the instream measurement of each metric, individual BEHI indices failed to meet the assumption of normality. To fix this issue, we fitted the model with the raw measurements of each metric prior to being transformed into an index. Even with reverting back to the raw data, root density and root depth continued to fail the normality assumption, therefore,

required natural log transformation. Mussel density and total BEHI scores also failed the normality assumption. Mussel density was log transformed to meet the assumption but, total BEHI scores were left unchanged. A closer look at the distribution of data revealed that total BEHI scores could meet the assumption if the data were categorized by the material adjustment score. All other assumption of a linear regression was met by the data. **Fig. 15 & 16** show the distribution of data used for the regression analysis prior to transformation.

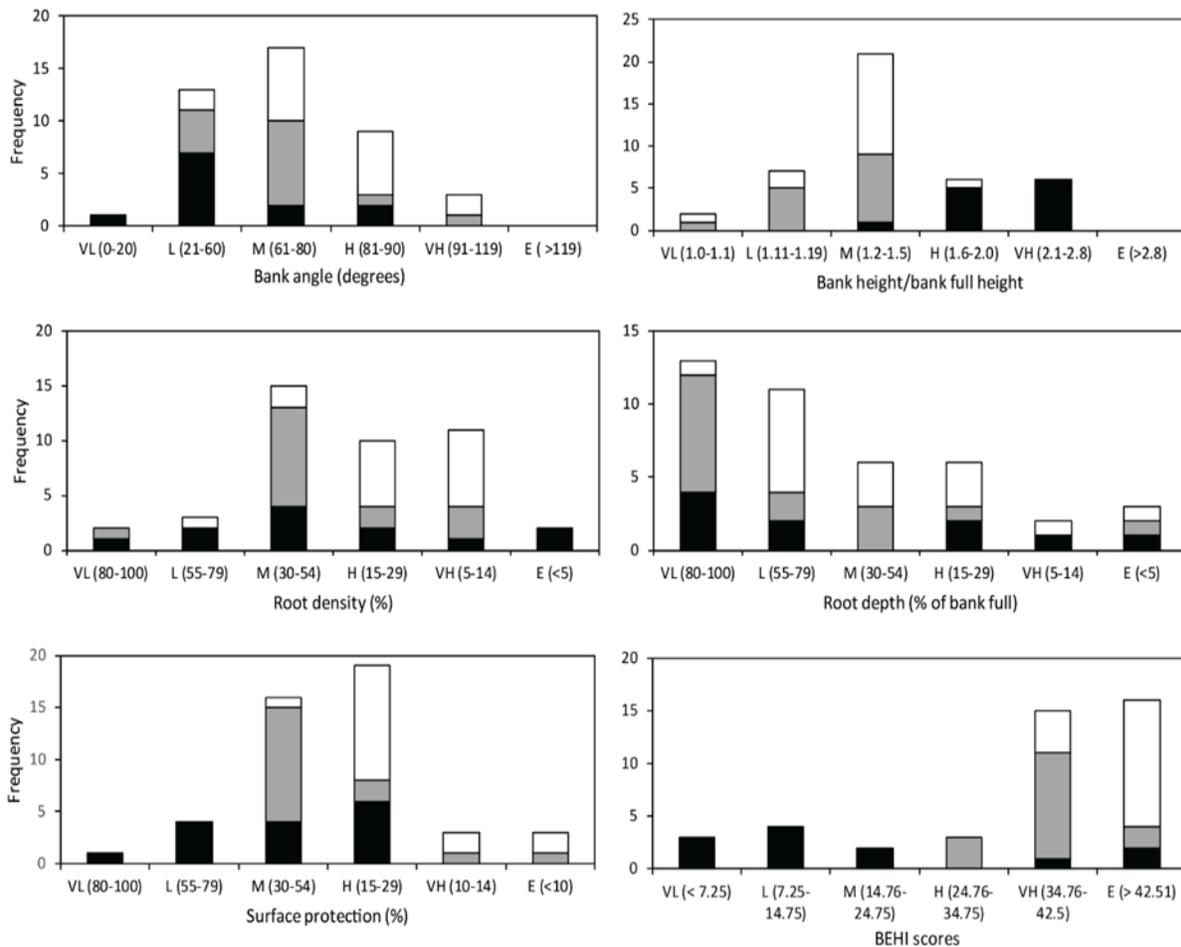


Fig. 15: Histograms of BEHI scores showing the distribution of individual BEHI measurements for each study reach: Wendell 6 is displayed in black; Wendell 2 in gray; Mussel Mania in white.

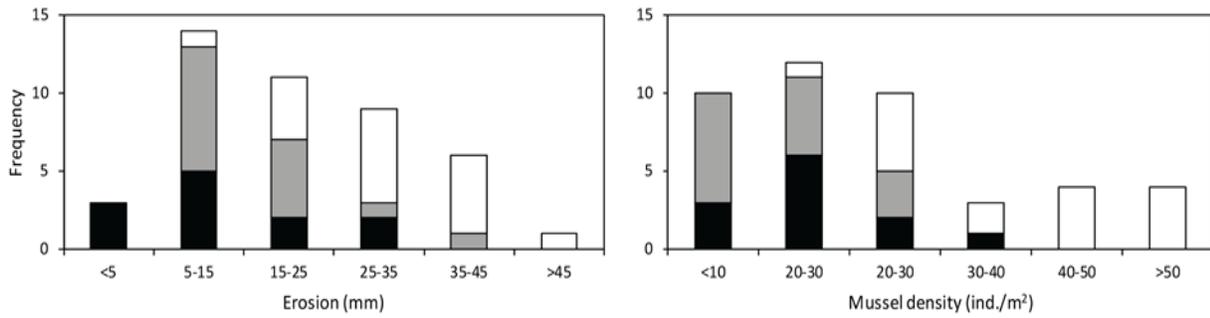


Fig. 16: Histograms of erosion rates and mussel density at each study reach: Wendell 6 is displayed in black; Wendell 2 in gray; and Mussel Mania in white.

3.4 Results

Bank erosion and mussel density at Mussel Mania were significantly different ($p = 0.01$ and $p < 0.01$, respectively) from Wendell 2 and Wendell 6 (**Fig. 17: A, B**).

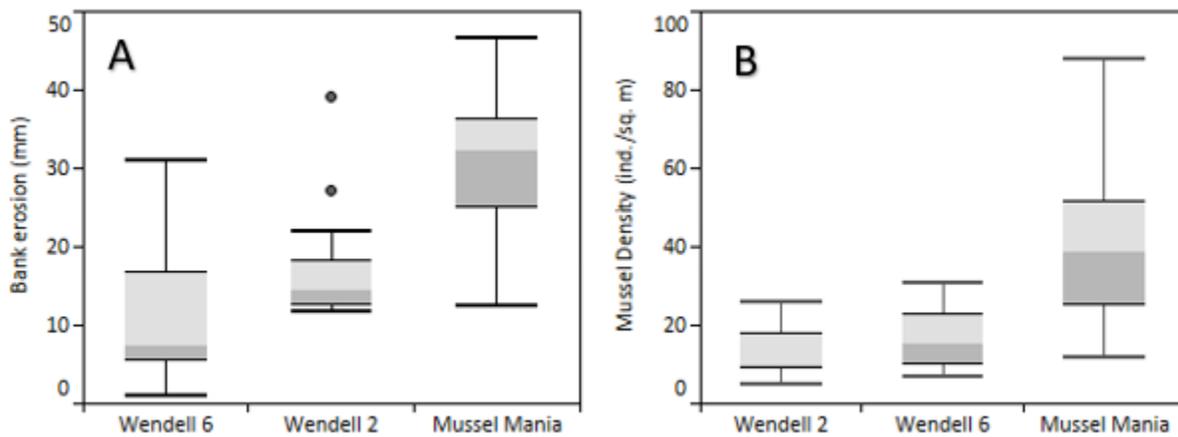


Fig. 17: A) Distribution of bank erosion rates; B) distribution of mussel densities at each study reach.

In the first linear regression model, total BEHI score ($p < 0.001$) and mussel density ($p = 0.010$) were the only significant predictors of bank erosion (**Table 3**). Total BEHI score

explained 64% ($R^2 = 0.638$) of the variance in bank erosion. Mussel density explained 25% ($R^2 = 0.252$) of the variance in bank erosion and was positively correlated ($r = 0.519$) with bank erosion. When applied together in the stepwise multiple linear regression (**Eq. 4**), total BEHI score and mussel density explained 69% (0.686) of the variance in bank erosion (**Fig. 18: A**).

$$\text{Bank Erosion} = -11.89 + (0.57 * \text{BEHI Total Score}) + (9.47 * \text{Log}_{10} \text{Mussel density}) \quad (\text{Eq: 4})$$

Table 3: Model 1; Multiple stepwise linear regression of BEHI totals and mussel density against bank erosion.

	Unstandardized coefficients		Standardized coefficients		<i>t</i>	<i>P</i> value	95% C.I.		Adjusted R Square		Collinearity Statistics	
	β	Standard error	β				R Square	R Square	Tol.	VIF		
(Constant)	15.314	6.173			-2.727	0.009						
BEHI Total	0.567	0.075	0.709		7.6	<0.001	30.99-39.99	0.646	0.638	0.922	1.085	
Log Mussel Density	9.465	3.499	0.252		2.705	0.01	1.18-1.37	0.701	0.686	0.858	1.166	

The second linear regression model found surface protection ($p = 0.000$), bank angle ($p = 0.001$), root density ($p = 0.002$) and mussel density ($p = 0.032$) to be significant predictors of riverbank erosion (**Table 4**). Surface protection explained 63% ($r^2 = 0.627$) and had a strong negative correlation ($r = -0.798$). Bank angle explained 51% ($r^2 = 0.513$) and was positively correlated ($r = 0.723$). Root density only explained 19% ($r^2 = 0.189$) and was negatively

correlated ($r = -0.455$). The regression model (**Eq: 5**) (**Fig. 18: B**), including all four variables, explained 81% of the variance in bank erosion ($r^2 = 0.807$).

$$\text{Bank Erosion} = 15.31 + (-0.31 * \text{Surface Protection}) + (0.19 * \text{Bank Angle}) + (-1.2$$

$$* \sqrt{\text{Root Density}} + (6.11 * \text{Log}_{10} \text{Mussel Density}) \tag{Eq: 5}$$

Table 4: Model 2; Multiple stepwise linear regression of individual BEHI variables and mussel density against bank erosion.

	Unstandardized coefficients		Standardized coefficients		t	P value	95% C.I.		Adjusted R Square		Collinearity Statistics	
	β	Standard error	β				R Square	R Square	Tol.	VIF		
(Constant)	15.314	6.173			2.481	0.018						
Surface Protection	-0.31	0.047	-0.531		-6.628	<0.001	27.39-39.58	0.636	0.627	0.818	1.223	
Bank Angle	0.196	0.053	0.307		3.721	0.001	62.92-74.10	0.761	0.75	0.719	1.392	
Sqrt Root Density	-1.195	0.366	-0.229		-3.268	0.002	4.22-5.58	0.813	0.798	0.966	1.036	
Log Mussel Density	6.115	2.749	0.163		2.224	0.032	1.18-1.37	0.834	0.817	0.857	1.167	

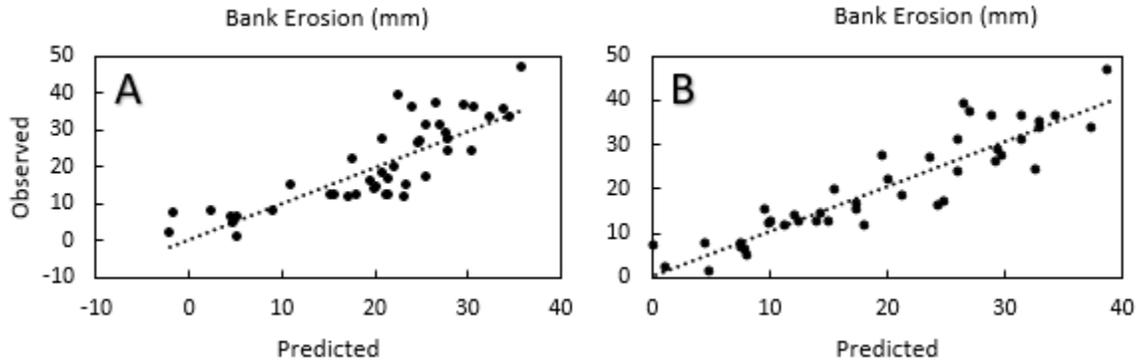


Fig. 18: Graphs of the relationships between observed data and the two multiple linear regression equations. Graph A represents the relationship between the predicted bank erosion and observed bank erosion using equation 1. Graph B represents the relationship between predicted bank erosion and observed bank erosion using equation 2.

3.5 Discussion

3.5.1 Interpretation of Results

We combined existing methods used to determine geomorphic changes in rivers with biological processes to further our understanding of the relationships between biotic and abiotic processes in rivers. This study provides new insights into the ability of patch-scale mussel activity and high-density aggregations of mussels to impact reach-scale river morphologic change. Mussel density was a significant predictor of riverbank erosion, suggesting the presence of mussels can potentially influence geomorphic processes at the reach scale. This is further supported by the relatively strong positive correlation between mussel density and particle D_{50} .

Greater mussel densities per quadrat were found with greater median grain sizes, supporting previous studies that have found patch scale mussel activities to have a coarsening effect of river substrates (Koerner et al., 2018). Other studies have found larger riverbed grain sizes are harder to entrain (Hammond et al., 1984), potentially limiting the ability of a river to incise, consequently diverting river energy and leading to increased bank erosion. Our finding of substrate coarsening by mussels could be leading to greater shear stress needed to entrain sediment particles. This would cause a diversion of the river's energy away from the riverbed creating the observed rates of bank erosion.

If mussel activity increasing D_{50} is creating increased bank erosion rates, we would expect D_{50} to be significant as well. Although mussel density was a significant predictor of bank erosion and, mussel density and median grain size were strongly correlated with each other, D_{50} was not a significant predictor of bank erosion ($p = 0.24$). We speculate the reason mussels were significant and D_{50} was not might result from other armoring effects that mussels can potentially create that would not affect the particle D_{50} measurement. Mussel biodeposition can facilitate the increase of benthic algae present which can increase the cohesion of sediments around mussel aggregations (Strayer et al., 1999). Additionally, mussels can increase sediment stability by remaining lodged in the substrate for extended periods of time (Zimmerman and de Szalay, 2007).

Bank erosion and mussel population densities differed significantly among study reaches. Significant differences in bank erosion ($p < 0.001$) and mussel density ($p = 0.01$) existed at Mussel Mania compared to Wendell 2 and Wendell 6. No significant differences were found between Wendell 2 and Wendell 6. The fact that a significant increase in mussel density at Mussel Mania was rivaled by a significant increase in bank erosion suggests that measured effects of mussels may be density dependent. In a flume study, Widdows et al. (2002) investigated the potential for bed erosion with varying mussel densities. Among all sample variations, the authors found the lowest amounts of bed erosion with high density mussel beds and localized increases in bed erosion with low-density patches of mussels. The high-density beds were able to bind together through byssal attachments preventing sediment resuspension. Erosion with low-density patches was attributed to scouring around small clumps of mussels. It is possible that mussel densities can reach a critical threshold where the population becomes large enough and prevents bed sediment entrainment. In the present study, we did not measure bank erosion rates for reaches of the river with low mussel densities, yet, observed significant difference between the population densities we did study.

3.5.2 Model Performance

The BEHI has shown to be a reliable tool when assessing the potential for bank erosion (Newton and Drenten, 2015; Ghosh et al., 2016; Allmanova et al., 2019) as was the case in this

study ($p < 0.001$), yet, it is merely an assessment of bank conditions and potential for erosion. The BEHI does not consider other variables outside of riverbank conditions such as riverbed settings. We applied other physical river conditions, along with the BEHI, to develop a model and determine if conditions outside the scope of the BEHI can predict bank erosion rates. The ability of the BEHI to predict bank erosion was slightly increased from 61% to 69% with the addition of mussel density as a metric. Although the BEHI totals were only able to predict 61% of the variance in bank erosion, breaking the BEHI down into individual metrics substantially increased the ability to predict bank erosion to 77%. Variables, such as bank height/bankfull ratio were unable to aid in predictability. Again, although breaking the BEHI down into individual metrics increased the predictability of bank erosion, the addition of the mussel density metric increased the predictability power of the BEHI from 77% to 81%. Mussel density consistently improved the BEHI's capability to predict bank erosion despite not being a relatively strong predictor of bank erosion ($r^2 = 0.252$).

3.5.3 Links to Biogeomorphology

The relationship we observed between mussel density and geomorphic change is most likely not cause and effect, but rather, the two variables coevolve. We believe a relationship similar to that found in Corenblit et al. (2016) is occurring between the fluvial process of the Sipsy River and the high-density aggregations of mussels. It is likely the mussels are currently

affecting the form and function of the river in some way but, at one point in time the river had to present conditions favorable for mussel to colonize the observed reaches. Once mussels were established, however, then began the relationship we between the mussel population dynamics and fluvial processes. First, the dynamic equilibrium of the river will present conditions favorable for mussels to inhabit and will begin adjusting as the mussel population grows. If mussels prevent the river from continuing its function at that location, the river will adjust accordingly, as our results suggest. This adjustment will likely cause the mussel habitat to degrade, ultimately causing the mussel bed to adjust to the new channel form, at which point, the cycle starts over. **Fig. 19** below details how we suggest mussels and river morphology coevolve.

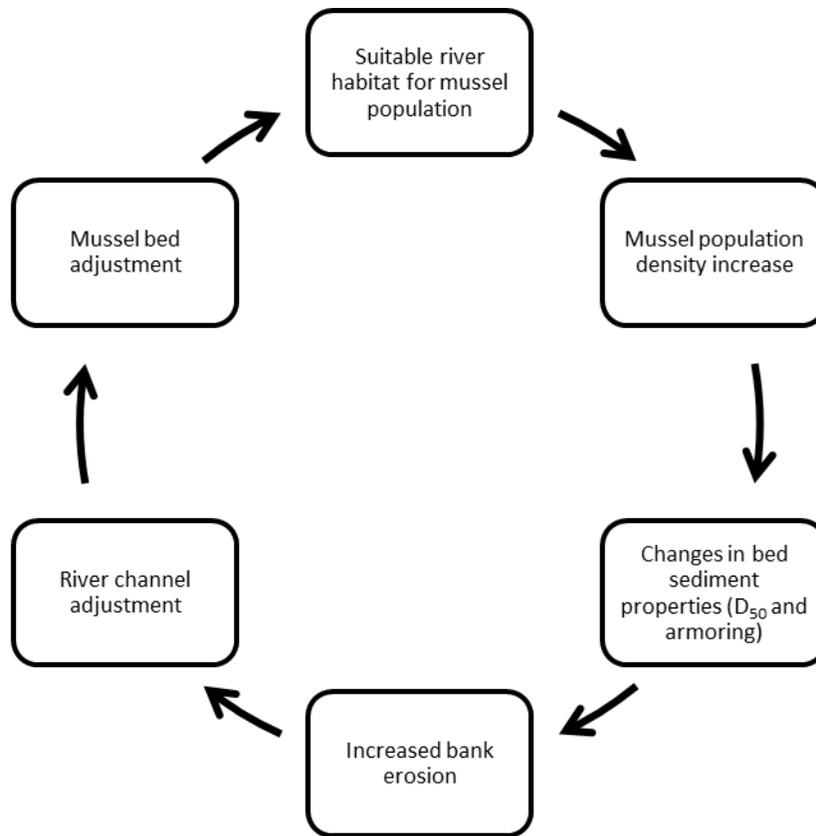


Fig. 19: Conceptual diagram of the coevolution of mussel populations and river morphology.

3.6 Conclusion

There are a few limitations of our study that should be considered. We assume the mussels are static with respect to their position in the river. Mussels are mobile organisms and will move if their needs are not met by conditions of their current location. This movement, however, is not of great distance and is usually confined within the mussel bed. We assume that, since the movement is usually contained within the mussel bed, the geomorphic impact individual mussels have will be contained within the study reaches. We assume that all bank erosion is a result from fluvial erosion only and do not consider mass failure. The one instance of mass failure was removed from the dataset and not used in any subsequent analysis. Finally, it is important to consider the design of our study when interpreting our results. Our method of using transects reduces the spatial resolution of our results making it difficult to determine the full extent to which mussels can alter erosional processes. Additionally, our study only spans 11 weeks. Future studies should consider a larger dataset, possibly from multiple river systems, and increasing spatial and temporal resolution.

Using field gathered data, this study demonstrates the first attempt in an uncontrolled environment to understand the effects of freshwater mussels on their surroundings. The results of this study not only demonstrate the potential impacts freshwater mussel can have on their surrounding environment, but that future research on freshwater mussel as geomorphic agents is

needed. Currently, much of the freshwater in the world are at a state a disequilibrium from human impact requiring intensive restoration efforts to restore balance to these systems. Our study provides evidence that consideration of animals as geomorphic agents is needed to holistically restore degraded river systems. We recommend a more in depth, empirical study to fully understand the scope at can alter reach-scale geomorphic processes.

4.0 SUMMARY AND CONCLUSIONS

4.1 Summary

Our studies suggest that there is the potential for spatio-temporal geomorphic adjustments in river systems to occur as a result of patch-scale biogenic activities of high-density mussel aggregations and that mussels may have a more substantial control over abiotic river processes than previously thought. Our studies found statistical associations between current mussel aggregations and rates of geomorphic processes. Additionally, we found common occurrences between mussel assemblages and geomorphic processes across a decadal time scale.

The fluvial biogeomorphic succession model established by Corenblit et al. (2007) presents the best framework explaining the observed relationship between mussel aggregations and geomorphic change. It demonstrates how the relationship began with habitat alteration by abiotic process and then the colonization of suitable habitat by mussels. Then, a two-way feedback between the hydrologic processes of the river and biologic processes of the mussels occurs. Although the biogeomorphic succession model can detail the bi-directional relationship between mussel activity and hydrologic processes, it only addresses the observed interactions between those two variables and fails to consider additional relationships that could influence

geomorphic change. For example, biodeposits from mussels can increase primary production around the mussel bed and affect algae assemblages (Atkinson et al., 2013). Algal mats can cover river substrates and prevent sediment from being entrained (Polvi and Sarneel, 2018). Additionally, the increase in primary production associated with mussel deposits can lead to greater macroinvertebrate abundance in the substrate (Spooner and Vaughn, 2006) and numerous studies show macroinvertebrates can alter bed sediment properties (Cardinale et al., 2004; Albertson et al., 2014; Albertson et al., 2019). Through the fluvial biogeomorphic succession model, any additional biogenic effects by organisms associated with mussel activity would be fully attributed to the mussels. Multiple species of mussels are commonly found in one bed (Strayer, 2008), and engineering activities of mussels are species dependent (Allen and Vaughn, 2009). This means the presences of organisms dependent on mussels to create habitat and the additional biogenic effects associated with these organisms should vary between mussel aggregations. This cannot be accounted for with the fluvial biogeomorphic succession model. The results from our studies suggest that a comprehensive-based restoration plan (Wohl et al, 2005; Beechie et al., 2010; Palmer et al., 2014) is needed to properly restore river form and function. A simple “one size fit all” approach to stream restoration is likely not considering the possibility that river processes could be controlled by biotic processes. We do not suggest abandoning current river restoration processes until a well-established, wide-ranging plan is formulated. We suggest gathering a complete understanding of all current and historic biotic and

abiotic processes at future restoration sites and implementing the best management plan with available resources while considering these processes.

Even with an understanding of past and present processes, restoration attempts may still fail for reasons unknown. An adaptive management approach to stream restoration (Buchanan et al., 2010) should be considered to combat this issue. Stream restoration professionals should assess each project thoroughly before and after project implementation. This approach would need to be accompanied with several years of systematic evaluation post-project construction. Stream restoration researchers have voiced concerns that restoration projects implemented by consultants in the restoration businesses has resulted in the privatization of the field (Lave, 2010; Palmer et al., 2014). Thus, because stream restoration has become a \$1 billion per year business (Bernhardt et al., 2015), companies are unlikely to report on project failures and risk reducing credibility. This leads to a lack of highly needed post-project analysis (Kondolf et al., 2001) on failed restoration plans and greatly reduces the effectiveness of an adaptive management approach.

4.1.1 Future Work

To help characterize the effect of mussels of geomorphic processes, future work should identify the mechanistic link between mussel aggregations and the presence and persistence of mid-channel bar. Because of our method of study used to identify the common occurrences

between mussel density and mid-channel bars, we could only speculate on the possibly mechanisms leading to the observed occurrence. If the biogenic activities of mussels are affecting the presences and persistence of mid-channel bars, the mechanistic link is most likely associated with the observed statistical association between mussel density and bank erosion. Additional studies explaining for our finding of associations between mussel should commence. Future studies attempting to understand how biogeomorphic systems should consider that all aquatic organisms are working as a functional whole to alter abiotic processes.

4.2 Conclusions

This research aimed to investigate links between mussel aggregation and geomorphic processes in the Sipse River, Alabama. Results from this study indicate there is a direct relationship between the observed biotic and abiotic processes. Mussel density was statically associated with bank erosion rates and mussel aggregations commonly occurred with the presence of a mid-channel bar. These results appear to support the fluvial biogeomorphic succession model as biological and geomorphic processes appear to possess a reciprocal relationship.

5.0 REFERENCES

- Albertson, L. K., Cardinale, B. J., Zeug, S. C., Harrison, L. R., Lenihan, H. S., & Wydzga, M. A. (2011). Impacts of channel reconstruction on invertebrate assemblages in a restored river. *Restoration Ecology*, *19*(5), 627-638.
- Albertson, L. K., Cardinale, B. J., & Sklar, L. S. (2014). Non-additive increases in sediment stability are generated by macroinvertebrate species interactions in laboratory streams. *Plos One*, *9*(8), 11.
- Albertson, L. K., Sklar, L. S., Cooper, S. D., & Cardinale, B. J. (2019). Aquatic macroinvertebrates stabilize gravel bed sediment: A test using silk net-spinning caddisflies in semi-natural river channels. *Plos One*, *14*(1), 17.
- Allen, D. C., & Vaughn, C. C. (2009). Burrowing behavior of freshwater mussels in experimentally manipulated communities. *Journal of the North American Benthological Society*, *28*(1), 93-100.
- Allen, D. C., & Vaughn, C. C. (2011). Density-dependent biodiversity effects on physical habitat modification by freshwater bivalves. *Ecology*, *92*(5), 1013-1019.
- Allen, D. C., Wynn-Thompson, T. M., Kopp, D. A., & Cardinale, B. J. (2018). Riparian plant biodiversity reduces stream channel migration rates in three rivers in Michigan, USA. *Ecohydrology*, *11*(4), e1972.
- Allan, J. D. (2004). Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics*, *35*, 257-284.
- Allmanova, Z., Vlckova, M., Jankovsky, M., Jakubis, M., & Allman, M. (2019). Bank erosion of the Trstie stream: BANCS model predictions vs. real bank erosion. *Journal of Hydrology and Hydromechanics*, *67*(2), 121-128.
- Amundsen, P. A., Gabler, H. M., & Riise, L. S. (2001). Intraspecific food resource partitioning in Atlantic salmon (*Salmo salar*) parr in a subarctic river. *Aquatic Living Resources*, *14*(4), 257-265.
- Anand, P.P., Vardhanan, S.Y. 2020. Computational modelling of wet adhesive mussel foot proteins (Bivalvia): Insights into the evolutionary convolution in diverse perspectives. *Sci Rep.* *10*, 2612.

- Andrade, J. H. R., & Maia, C. E. (2018a). Erosion of riverbank in semiarid rivers: study in the sub-basin of the Bass Jaguaribe - Ceara - Brazil. *Revista Brasileira De Geomorfologia*, 19(4), 859-870.
- Arnold, E., & Toran, L. (2018). Effects of bank vegetation and incision on erosion rates in an urban stream. *Water*, 10(4), 16.
- Atkinson, C.L., Vaughn, C.C., Forshay, K.J., & Cooper, J.T. (2013). Aggregated filter-feeding consumers alter nutrient limitation: consequences for ecosystem and community dynamics. *Ecology*. 94, 1359-1369.
- Atkinson, C.L., & Vaughn, C.C. (2015). Biogeochemical hot-spots: temporal and spatial scaling of the impact of freshwater mussels on ecosystem functions. *Freshwater Biology*. 60, 563-574.
- Atkinson, C.L., Allen, D.C., Davis, L., & Nickerson, Z.L. (2017). Incorporating ecogeomorphic feedbacks: A review and directions forward. *Geomorphology*. 305 (15), 123-140.
- Barko, J. W., & James, W. F. (1998). Effects of submerged aquatic macrophytes on nutrient dynamics, sedimentation, and resuspension. In *The structuring role of submerged macrophytes in lakes* (pp. 197-214). Springer, New York, NY.
- Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., . . . Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. *Bioscience*, 60(3), 209-222.
- Benke, A. C. (1990). A perspective on America's vanishing streams. *Journal of the North American Benthological Society*. (9), 77-88.
- Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., . . . Sudduth, E. (2005). Ecology - Synthesizing US river restoration efforts. *Science*, 308(5722), 636-637.
- Brown, B. L. (2003). Spatial heterogeneity reduces temporal variability in stream insect communities. *Ecology Letters*, 6(4), 316-325
- Buchanan, B. P., Walter, M. T., Nagle, G. N., & Schneider, R. L. (2012). Monitoring and assessment of a river restoration project in central New York. *River Research and Applications*, 28(2), 216-233.
- Campbell, J. B. (2002). Introduction to remote sensing. New York. *Guilford Press*.
- Capelle, J. J., Leuchter, L., de Wit, M., Hartog, E., & Bouma, T. J. (2019). Creating a window of opportunity for establishing ecosystem engineers by adding substratum: a case study on mussels. *Ecosphere*, 10(4), 15.
- Cardinale, B. J., Gelmann, E. R., & Palmer, M. A. (2004). Net spinning caddisflies as stream ecosystem engineers: the influence of *Hydropsyche* on benthic substrate stability. *Functional Ecology*, 18(3), 381-387.

- Church, M., Rice S. (2009). Form and growth of bars in a wandering gravel-bed river. *Earth Surface Processes and Landforms*, 34(10), 1422–1432.
- Commito, J. A., Jones, B. R., Jones, M. A., Winders, S. E., & Como, S. (2018). What happens after mussels die? Biogenic legacy effects on community structure and ecosystem processes. *Journal of Experimental Marine Biology and Ecology*, 506, 30-41.
- Constantine, C. R., Dunne, T., & Hanson, G. J. (2009). Examining the physical meaning of the bank erosion coefficient used in meander migration modeling. *Geomorphology*, 106(3-4), 242-252.
- Cook, K. L., Whipple, K. X., Heimsath, A. M., & Hanks, T. C. (2009). Rapid incision of the Colorado River in Glen Canyon - insights from channel profiles, local incision rates, and modeling of lithologic controls. *Earth Surface Processes and Landforms*, 34(7), 994-1010.
- Corenblit, D., Tabacchi, E., Steiger, J., & Gurnell, A. M. (2007). Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. *Earth-Science Reviews*, 84(1-2), 56-86.
- Corenblit, D., Steiger, J., González, E., Gurnell, A. M., Charrier, G., Darrozes, J., ... & Roussel, E. (2014). The biogeomorphological life cycle of poplars during the fluvial biogeomorphological succession: a special focus on *Populus nigra* L. *Earth Surface Processes and Landforms*, 39(4), 546-563.
- Corenblit, D., Davies, N. S., Steiger, J., Gibling, M. R., & Bornette, G. (2015). Considering river structure and stability in the light of evolution: feedbacks between riparian vegetation and hydrogeomorphology. *Earth Surface Processes and Landforms*, 40(2), 189-207.
- Corenblit, D., Steiger, J., Charrier, G., Darrozes, J., Garofano-Gomez, V., Garreau, A., . . . Voltaire, O. (2016). *Populus nigra* L. establishment and fluvial landform construction: biogeomorphic dynamics within a channelized river. *Earth Surface Processes and Landforms*, 41(9), 1276-1292.
- Crosato, A., & Mosselman, E. (2009). Simple physics-based predictor for the number of river bars and the transition between meandering and braiding. *Water resources research*, 45(3).
- Dunne, K. B. J., & Jerolmack, D. J. (2018). Evidence of, and a proposed explanation for, bimodal transport states in alluvial rivers. *Earth Surface Dynamics*, 6(3), 583-594.
- Folkard, A. M., & Gascoigne, J. C. (2009). Hydrodynamics of discontinuous mussel beds: Laboratory flume simulations. *Journal of Sea Research*, 62(4), 250-257.
- Friebertshauser, R., Shollenberger, K., Janosik, A., Garner, J.T., Johnston C. (2019). The effect of bivalve filtration on eDNA-based detection of aquatic organisms. *PLoS ONE* 14(11).

- Frissell, C. A., Liss, W. J., Warren, C. E., & Hurley, M. D. (1986). A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental management*, 10(2), 199-214.
- Fry, J. A., Xian, G., Jin, S. M., Dewitz, J. A., Homer, C. G., Yang, L. M., . . . Wickham, J. D. (2011). national land cover database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing*, 77(9), 859-864.
- Fisher, S. G., Heffernan, J. B., Sponseller, R. A., & Welter, J. R. (2007). Functional ecomorphology: Feedbacks between form and function in fluvial landscape ecosystems. *Geomorphology*, 89(1-2), 84-96.
- Florsheim, J. L., Mount, J. F., & Chin, A. (2008). Bank erosion as a desirable attribute of rivers. *Bioscience*, 58(6), 519-529.
- Fremier, A. K., Yanites, B. J., & Yager, E. M. (2018). Sex that moves mountains: The influence of spawning fish on river profiles over geologic timescales. *Geomorphology*, 305, 163-172.
- Gangloff, M.M., & Feminella, J.W. (2007). Stream channel geomorphology influences mussel abundance in southern Appalachian streams, U.S.A. *Freshwater Biology*. 52 (1), 64-71.
- Ghosh, K. G., Pal, S., & Mukhopadhyay, S. (2016). Validation of BANCS model for assessing stream bank erosion hazard potential (SBEHP) in Bakreshwar River of Rarh region, Eastern India. *Modeling Earth Systems and Environment*, 2(2), 15.
- Gorney, R. M., Ferris, D. R., Ward, A. D., & Williams, L. R. (2011). Assessing channel-forming characteristics of an impacted headwater stream in Ohio, USA. *Ecological Engineering*, 37(3), 418-430.
- Grabowski, R. C., Droppo, I. G., & Wharton, G. (2011). Erodibility of cohesive sediment: The importance of sediment properties. *Earth-Science Reviews*, 105(3-4), 101-120.
- Gregory, K. J. (2019). Human influence on the morphological adjustment of river channels: The evolution of pertinent concepts in river science. *River Research and Applications*, 35(8), 1097-1106.
- Generalp, I., & Rhoads, B. L. (2008). Continuous characterization of the planform geometry and curvature of meandering rivers. *Geographical Analysis*, 40(1), 1-25.
- Gutiérrez, J.L., Jones, C.G., Strayer, D.L., & Iribarne, O.O. (2003). Mollusks as ecosystem engineers: the role of shell production on aquatic habitats. *Synthesizing Ecology*. 101, 79- 90.
- Haag, W. R., & Warren, M. L. (2010). Diversity, abundance, and size structure of bivalve assemblages in the Sipse River, Alabama. *Aquatic Conservation-Marine and Freshwater Ecosystems*, 20(6), 655-667.
- Hammond, F. D. C., Heathershaw, A. D., & Langhorne, D. N. (1984). A comparison between shields threshold criterion and the movement of loosely packed gravel in a tidal channel. *Sedimentology*, 31(1), 51-62.

- Hooke, J. M., & Yorke, L. (2011). Channel bar dynamics on multi-decadal timescales in an active meandering river. *Earth Surface Processes and Landforms*, 36(14), 1910-1928.
- Hopper, G. W., DuBose, T. P., Gido, K. B., & Vaughn, C. C. (2019). Freshwater mussels alter fish distributions through habitat modifications at fine spatial scales. *Freshwater Science*, 38(4), 702-712.
- Hopper, J. D., Huryn, A. D., & Schuster, G. A. (2012). The Sipsey River, Alabama: A crayfish diversity "hotspot"? *Southeastern Naturalist*, 11(3), 405-414.
- Hopper, J. D., Huryn, A. D., & Schuster, G. A. (2012). The Sipsey River, Alabama: A crayfish diversity "hotspot"? *Southeastern Naturalist*, 11(3), 405-414.
- Hughes, M. L., McDowell, P. F., & Marcus, W. A. (2006). Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology*, 74(1-4), 1-16.
- Jerin, T. (2019). Biogeomorphic effects of woody vegetation on bedrock streams. *Progress in Physical Geography: Earth and Environment*, 43(6), 777-800.
- Johnson, P.D., Powell, J., Buntin, M.L., & Tarpley, T.A. (2015). Freshwater mussel reintroduction and recovery in Alabama. Conference paper: American Malacological Society.
- Jones, C. G., Lawton, J. H., & Shachak, M. (1994). Organisms as ecosystem engineers. *Oikos*, 69(3), 373-386.
- Jones, H. F. E., Pilditch, C. A., Bryan, K. R., & Hamilton, D. P. (2011). Effects of infaunal bivalve density and flow speed on clearance rates and near-bed hydrodynamics. *Journal of Experimental Marine Biology and Ecology*, 401(1-2), 20-28.
- Jones, J. I., Collins, A. L., Naden, P. S., & Sear, D. A. (2012). The relationship between fine sediment and macrophytes in rivers. *River Research and Applications*, 28(7), 1006-1018.
- Julian, J. P., & Torres, R. (2006). Hydraulic erosion of cohesive riverbanks. *Geomorphology*, 76(1-2), 193-2006.
- Kearney, S. P., Fonte, S. J., Garcia, E., & Smukler, S. M. (2018). Improving the utility of erosion pins: absolute value of pin height change as an indicator of relative erosion. *Catena*, 163, 427-432.
- Koerner, M., Davis, L., Atkinson, C., (2018). Biogenic modification of sediments by unionid mussels and their implications for sediment transport in the Sipsey River of Alabama. The University of Alabama, Masters Thesis.
- Kondolf, G. M. (1998). Lessons learned from river restoration projects in California. *Aquatic Conservation: marine and freshwater ecosystems*, 8(1), 39-52.

- Kondolf, G. M., Smeltzer, M. W., & Railsback, S. F. (2001). Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. *Environmental Management*, 28(6), 761-776.
- Lane, E.W. (1955). The importance of fluvial morphology in hydraulic engineering, *Proceedings of the American Society of Civil Engineers*, 81, 1-17.
- Lathlean, J. A., & McQuaid, C. D. (2017). Biogeographic variability in the value of mussel beds as ecosystem engineers on South African Rocky Shores. *Ecosystems*, 20(3), 568-582.
- Lauer, J. W., Echterling, C., Lenhart, C., Belmont, P., & Rausch, R. (2017). Air-photo based change in channel width in the Minnesota River basin: Modes of adjustment and implications for sediment budget. *Geomorphology*, 297, 170-184.
- Lave, R., Doyle, M., & Robertson, M. (2010). Privatizing stream restoration in the US. *Social Studies of Science*, 40(5), 677-703.
- Lave, R. (2012). Fields and streams: Stream restoration, neoliberalism, and the future of environmental science (Vol. 12). *University of Georgia Press*.
- Lave, R. (2016). Stream restoration and the surprisingly social dynamics of science. *Wiley Interdisciplinary Reviews-Water*, 3(1), 75-81.
- Lenzi, M. A. (2004). Displacement and transport of marked pebbles, cobbles and boulders during floods in a steep mountain stream. *Hydrological Processes*, 18(10), 1899-1914.
- Lester, R. E., & Wright, W. (2009). Reintroducing wood to streams in agricultural landscapes: changes in velocity profile, stage and erosion rates. *River Research and Applications*, 25(4), 376-392.
- Liu, X. J., Wu, R. W., Chen, X., Zhou, Y., Yang, L. M., Ouyang, S., & Wu, X. P. (2020). Effects of dams and their environmental impacts on the genetic diversity and connectivity of freshwater mussel populations in Poyang Lake Basin, China. *Freshwater Biology*, 65(2), 264-277.
- Luchi, R., Hooke, J. M., Zolezzi, G., & Bertoldi, W. (2010). Width variations and mid-channel bar inception in meanders: River Bollin (UK). *Geomorphology*, 119(1-2), 1-8.
- Mason, R. J., Rice, S. P., Wood, P. J., & Johnson, M. F. (2019). The zoogeomorphology of case-building caddisfly: Quantifying sediment use. *Earth Surface Processes and Landforms*, 44(12), 2510-2525.
- McCullagh, W. H., Williams, J. D., McGregor, S. W., Pierson, J. M., & Lydeard, C. (2002). The unionid (*Bivalvia*) fauna of the Sipsey River in northwestern Alabama, an aquatic hotspot. *American Malacological Bulletin*, 17(1-2), 1-15.
- Micheli, E. R., Kirchner, J. W., & Larsen, E. W. (2004). Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, Central Sacramento River, California, USA. *River Research and Applications*, 20(5), 537-548.
- Mossa, J., & Konwinski, J. (1998). Thalweg variability at bridges along a large karst river: the Suwannee River, Florida. *Engineering Geology*, 49(1), 15-30.

- Newton, S. E., & Drenten, D. M. (2015). Modifying the bank erosion hazard index (BEHI) protocol for rapid assessment of streambank erosion in Northeastern Ohio. *Jove-Journal of Visualized Experiments*(96), 14.
- O'Connor, J. E., Jones, M. A., & Haluska, T. L. (2003). Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. *Geomorphology*, 51(1-3), 31-59.
- Palmer, M. A., Ambrose, R. F., & Poff, N. L. (1997). Ecological theory and community restoration ecology. *Restoration Ecology*, 5(4), 291-300.
- Palmer, M. A., Hondula, K. L., & Koch, B. J. (2014). Ecological restoration of streams and rivers: shifting strategies and shifting goals. *Annual Review of Ecology, Evolution, and Systematics*, 45, 247.
- Parker, G. (1978). Self-formed straight rivers with equilibrium banks and mobile bed gravel river. *Journal of Fluid Mechanics*, 89(NOV), 127.
- Pfeiffer, A. M., Finnegan, N. J., & Willenbring, J. K. (2017). Sediment supply controls equilibrium channel geometry in gravel rivers. *Proceedings of the National Academy of Sciences of the United States of America*, 114(13), 3346-3351.
- Phillips, C. B., & Jerolmack, D. J. (2019). Bankfull transport capacity and the threshold of motion in coarse-grained rivers. *Water Resources Research*, 55(12), 11316-11330.
- Polvi, L. E., & Sarneel, J. M. (2018). Ecosystem engineers in rivers: An introduction to how and where organisms create positive biogeomorphic feedbacks. *Wiley Interdisciplinary Reviews: Water*, 5(2), e1271.
- Puijalon, S., Bouma, T. J., Douady, C. J., van Groenendael, J., Anten, N. P., Martel, E., & Bornette, G. (2011). Plant resistance to mechanical stress: evidence of an avoidance–tolerance trade-off. *New Phytologist*, 191(4), 1141-1149.
- Praskievicz, S., & Luo, C. H. (2019). Unsupervised hydrologic classification of rivers: Watershed controls on natural and anthropogenic flow regimes, Alabama, USA. *Hydrological Processes*, 33(8), 1231-1244.
- Prosser, I. P., Hughes, A. O., & Rutherford, I. D. (2000). Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. *Earth Surface Processes and Landforms*, 25(10), 1085-1101.
- Rhoades, E. L., O'Neal, M. A., & Pizzuto, J. E. (2009). Quantifying bank erosion on the South River from 1937 to 2005, and its importance in assessing Hg contamination. *Applied Geography*, 29(1), 125-134.
- Rosgen, D.L. (1998). Applied stream geomorphology. Pagoda Springs, CO. *Wildland Hydrol.*
- Rosgen, D.L. 2001. A practical method of computing streambank erosion rate. *Proceedings of the 7th Federal Interagency Sedimentation Conference*, Vol. 2, pp. 9-15.
- Rosgen D.L. (2006) A Watershed assessment for river stability and sediment supply (WARSSS). *Wildland Hydrology Books*, Fort Collins, Colorado.

- Rutherford, I. D., Kenyon, C., Thoms, M., Grove, J., Turnbull, J., Davies, P., & Lawrence, S. Human impacts on suspended sediment and turbidity in the River Murray, South Eastern Australia: Multiple lines of evidence. *River Research and Applications*, 20.
- Schmid, B., Pfisterer, A. B., & Balvanera, P. (2009). Effects of biodiversity on ecosystem, community, and population. *Ecology*, 90(3), 853.
- Slama, C.C., Theurer, C., Henriksen, S.W. (1980). Manual of photogrammetry, 4th edition. *American Society of Photogrammetry*, Falls Church, VA.
- Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Official Soil Series Descriptions. Available online. Accessed [12/01/2019].
- Spooner, D.E., & Vaughn, C.C. (2006). Context dependent effects of freshwater mussels on stream benthic communities. *Freshwater Biology*. 51 (6), 1016-1024.
- Statzner, B., Arens, M. F., Champagne, J. Y., Morel, R., & Herouin, E. (1999). Silk-producing stream insects and gravel erosion: Significant biological effects on critical shear stress. *Water Resources Research*, 35(11), 3495-3506.
- Statzner, B. (2012). Geomorphological implications of engineering bed sediments by lotic animals. *Geomorphology*. 157-158, 49-65.
- Steiger, J., Tabacchi, E., Dufour, S., Corenblit, D., & Peiry, J. L. (2005). Hydrogeomorphic processes affecting riparian habitat within alluvial channel-floodplain river systems: A review for the temperate zone. *River Research and Applications*, 21(7), 719-737.
- Stella, J., Hayden, M., Battles, J., Piegay, H., Dufour, S., & Fremier, A. K. (2011). The role of abandoned channels as refugia for sustaining pioneer riparian forest ecosystems. *Ecosystems*, 14(5), 776-790.
- Stella, J. C., Riddle, J., Piegay, H., Gagnage, M., & Tremelo, M. L. (2013). Climate and local geomorphic interactions drive patterns of riparian forest decline along a Mediterranean Basin river. *Geomorphology*, 202, 101-114.
- Strayer, D. L., Caraco, N. F., Cole, J. J., Findlay, S., & Pace, M. L. (1999). Transformation of freshwater ecosystems by bivalves - A case study of zebra mussels in the Hudson River. *Bioscience*, 49(1), 19-27.
- Strayer, D. L., & Malcom, H. M. (2007). Shell decay rates of native and alien freshwater bivalves and implications for habitat engineering. *Freshwater Biology*, 52(8), 1611-1617.
- Strayer, D. L. (2008). *Freshwater mussel ecology: a multifactor approach to distribution and abundance* (Vol. 1). Univ of California Press.
- Tabacchi, E., Lambs, L., Guilloy, H., Planty-Tabacchi, A. M., Muller, E., & Decamps, H. (2000). Impacts of riparian vegetation on hydrological processes. *Hydrological Processes*, 14(16-17), 2959-2976.
- Tang, F., Kemp, J. S., & Aldridge, D. C. (2020). Life on the edge: Compensatory growth and feeding rates at environmental extremes mediates potential ecosystem engineering by an invasive bivalve. *Science of the Total Environment*, 706, 10.

- Thompson, F., Gilvear, D., Tree, A., & Jeffries, R. (2016). Quantification of freshwater pearl mussel entrainment velocities and controlling factors; a flume study. *River Research and Applications*, 32(6), 1179-1186.
- Urban, M. A., & Rhoads, B. L. (2003). Catastrophic human-induced change in stream-channel planform and geometry in an agricultural watershed, Illinois, USA. *Annals of the Association of American Geographers*, 93(4), 783-796.
- Vaughn, C. C., Gido, K.B., & Spooner, D.E. (2004). Ecosystem processes performed by unionid mussels in stream meso-cosms: species roles and effects of abundance. *Hydrobiologia*, 527, 35-47.
- Vaughn, R. S., & Davis, L. (2015). Abiotic controls of emergent macrophyte density in a bedrock channel—The Cahaba River, AL (USA). *Geomorphology*, 246, 146-155.
- Viles, H. A. (1988). *Biogeomorphology*. Basil Blackwell, Oxford, UK.
- Wang, H. J., Yang, Z. S., Saito, Y., Liu, J. P., Sun, X. X., & Wang, Y. (2007). Stepwise decreases of the Huanghe (Yellow River) sediment load (1950-2005): Impacts of climate change and human activities. *Global and Planetary Change*, 57(3-4), 331-354.
- Ward, J. E., & MacDonald, B. A. (1996). Pre-ingestive feeding behaviors of two sub-tropical bivalves (*Pinctada imbricata* and *Arca zebra*): Responses to an acute increase in suspended sediment concentration. *Bulletin of Marine Science*, 59(2), 417-432.
- Ward, J. V. (1998). Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation*, 83(3), 269-278.
- Washko, S., Roper, B., & Atwood, T. B. (2020). Beavers alter stream macroinvertebrate communities in north-eastern Utah. *Freshwater Biology*, 65(3), 579-591.
- Widdows, J., Lucas, J. S., Brinsley, M. D., Salkeld, P. N., & Staff, F. J. (2002). Investigation of the effects of current velocity on mussel feeding and mussel bed stability using an annular flume. *Helgoland Marine Research*, 56(1), 3-12.
- Wintenberger, C. L., Rodrigues, S., Claude, N., Juge, P., Breheret, J. G., & Villar, M. (2015). Dynamics of nonmigrating mid-channel bar and superimposed dunes in a sandy-gravelly river (Loire River, France). *Geomorphology*, 248, 185-204.
- Wohl, E., Angermeier, P. L., Bledsoe, B., Kondolf, G. M., MacDonnell, L., Merritt, D. M., . . . Tarboton, D. (2005). River restoration. *Water Resources Research*, 41(10), 12.
- Wolman, M.G. (1954). A method of sampling coarse river-bed material. *Transactions, American Geophysical Union*. 35 (6), 951-956.
- Wolman, M. G. (1959). Factors influencing erosion of a cohesive river bank. *American Journal of Science*, 257(3), 2042-2216.
- Zettler, M. L., & Jueg, U. (2007). The situation of the freshwater mussel *Unio crassus* (Philipsson, 1788) in north-east Germany and its monitoring in terms of the EC Habitats Directive. *Mollusca*, 25(2), 165-174.

Zimmerman, G. F., & de Szalay, F. A. (2007). Influence of unionid mussels (Mollusca : Unionidae) on sediment stability: an artificial stream study. *Fundamental and Applied Limnology*, 168(4), 299-306.