FRESHWATER MUSSEL COMMUNITIES OF THE FLORIDA PARISHES, LOUISIANA: THE IMPORTANCE OF SPATIAL SCALE

A Thesis

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DEDICATION

I would like to dedicate this thesis to all of my friends and family who have supported and guided me through this experience. These individuals are: my parents John and Bettye Bambarger, my outstanding fiancé David Harlan, Kathy Sebastian, Kathy Berard, Jerry George, Andrea Kuns (and Kura), Barry Aronhime and Yasoma Hulathduwa. I would especially like to thank all of those who offered support and wisdom during hurricane Katrina; I will never be able to repay the strength given to me by the faculty and students of Louisiana State University during these past months. I have found a new place within myself that I never knew existed and I thank every one of these people for shedding light on that place.

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ABSTRACT

The Southeastern United States has the most diverse and imperiled freshwater mussel (Unionidae) fauna in the world. The community structure and decline of these organisms is the result of complex interactions between biotic and abiotic factors, but the limited spatial scale of most community studies has failed to elucidate the underlying mechanisms shaping community structure. Basing community assessments solely on microhabitat variables alone has lead to stark contradictions in management recommendations and opposing definitions of habitat requirements for these organisms. However, with the introduction of GIS technology into aquatic management, it is now feasible to include variables from larger spatial scales and investigate previously undetectable mechanisms influencing unionid community structure.

In my study, I tested the hypothesis that patterns of mussel species richness and abundance in the Tickfaw, Tangipahoa Bogue Chitto and West Pearl rivers in south-eastern Louisiana were related to a combination of local-scale habitat variables, riparian-scale land use and geology variables, and sub-segment scale land use and geology variables.

ANOVA results indicated a significant difference between the upper three sub-segments and lower three sub-segments of these rivers. The Principal Component Factor Analysis (PCFA) results revealed that geology, land-use and fine sediment are components working together across spatial scales to produce a hydrologic variability mechanism, and a simple regression model based on the factor scores of each site was successful in predicting abundance and species richness.

Through comparing the ANOVA results with the factor score results for each site, I conclude that hydrologic variability, defined by geology type and land-use as well as fine sediment, is influencing the pattern in freshwater mussel abundance and species richness found in the Florida Parishes of Louisiana.

INTRODUCTION

Freshwater mussels comprise one of the most diverse yet imperiled aquatic assemblages in the United States (Bogan 1993, Master 1990). Williams et al. (1993) identified native southeastern mussels (Unionidae) in particular as the most endangered assemblage of organisms in North America, with roughly 70% of the taxa threatened or endangered. More recently, Poole and Downing (2004) reported a species extinction rate of 1.2% per decade for freshwater mussels.

To understand and reverse this decline in abundance and diversity, aquatic ecologists focus on predicting how and why mussel communities are patterned as they are in nature. The key to predicting these patterns is detecting the mechanisms that determine the patterns (Raffaelli et al. 1992). However, the majority of freshwater mussel studies attempting to identify these mechanisms are based on data collected from a single spatial scale. Although most of these studies speculate that habitat loss, alteration of natural watershed processes and non-point source pollution are the major mechanisms contributing to the decline in unionid distribution (Neves et. al. 1998), little quantitative evidence statistically linking these factors to parameters measured at single spatial scales exists in the literature.

Studies conducted at the microhabitat spatial scale are most common in the literature. Many scientists have argued that sediment composition is a powerful determinant of mussel abundance and diversity (Harman 1972, Green 1971, Strayer 1981, Brown and Johnson 2000, Brown and Banks 2001), while others concluded that it poorly predicts these same responses (Downing et al 2000, Vaughn 1997, Michaelson and Neves 1995, Huehner 1987). Strayer and Ralley (1993) examined the distribution of six species of unionids in New York and found that sediment type did not predict mussel abundance. Strayer et al. (1994) also concluded that sediment type alone had no demonstrable impact on mussel assemblage structure. Other microhabitat descriptors such as dissolved oxygen, specific conductance, temperature and depth have also been used extensively in attempts to predict community structure. While intuitively appealing, quantitative studies indicate weak relationships between mussel distribution and most microhabitat scale descriptors (Arbuckle and Downing 2002, Poole and Downing 2004, McRae and Burch 2000, Layzer and Madison 1995, Salmon and Green 1985, Brim-Box et al 2002).

At the spatial scale of hundreds of meters, or the riparian scale, studies looking at the influence of vegetative cover, sheer stress, canopy cover, flow regime and stream size on freshwater insects and fish have also proven contradictory (Wang et al. 2003). Only a handful of freshwater mussel studies conducted at this spatial scale are present in the literature (Strayer 1993, Morris and Corkum 1996). Hornbach (2001) identified river gradient at the scale of several hundred meters as an important variable in predicting mussel distribution but also considered the presence of dams at transitional gradients as a possible cause for this relationship. Strayer (1999) linked mussel distribution to the presence of flow refuges at the riparian scale, but conceded that his results were only significant for specific flow conditions. DiMaio and Corkum (1995) identified flow regimes as influential to the distribution of specific mussel species but were unable to predict total abundance or species richness.

Landscape-scale studies using variables that describe land-use and geology over entire watersheds are becoming more prevalent in ecology with the introduction of GIS technology. Urbanization, logging and conversion of natural cover to agricultural crop and grazing land clearly degrade suitable aquatic macroinvertebrate habitat, but evidence of a strong statistical relationship between these changes and mussel distribution is lacking (Brim-Box and Mossa 1999, Arbuckle and Downing 2002). Richards et al. (1996) found that surficial geology at the watershed spatial scale influenced aquatic insect assemblage structure by shaping hydrologic processes and channel morphology. Arbuckle and Downing (2002), Poole and Downing (2004), and McRae and Burch (2000) found the underlying geology of a watershed to be an important predictor of mussel community structure, but were unable to statistically show any relationship between land use and mussel distribution.

The conflicting results reported from freshwater mussel studies conducted at single spatial scales have lead to contradictory state and federal management recommendations, poor conservation strategies and failed relocation efforts (Sheehan et al 1989, Burke 1991, Koch 1993, Layzer and Gordon 1993, Dunn et al. 1999). Few freshwater mussel studies have attempted to combine information from multiple scales into one statistical model to more accurately define the relative influence of landscape scale processes versus local scale processes on assemblage structure, and I argue that doing so is the only way to fully elucidate the complex components working together to form the mechanisms driving unionid community patterns.

In a seminal paper, Simon Levin (1992) addressed the lack of investigation into the influence of spatial scale on community structure. He argued that the mechanisms underlying community patterns operate at many spatial scales, some of which are different than that in which the pattern is observed. Levin stressed the importance of combining variables across small and large spatial scales to more precisely define the processes driving community structure. This study, inspired by Levin's suggestion, utilizes data collected over three spatial scales, microhabitat, riparian and sub-segment, to improve our ability to predict patterns in freshwater mussel abundance and diversity in Southeastern Louisiana coastal plain rivers.

The freshwater mussel communities in the Florida parishes of Southeastern Louisiana, in particular, are threatened by declining water quality and loss of quality riverine habitat (Hartfeild 1993). Poor water quality has plagued the Florida parishes for decades due to unregulated sewage disposal as well as agricultural and oil refining practices. Most rivers in this region are defined as impaired by the Louisiana Department of Environmental Quality and there are advisories against the consumption of fish and invertebrates from the rivers within this area (LADEQ 2004).

Silviculture and agriculture practices, unregulated gravel mining operations and urban development within the Florida Parishes have altered stream channels and created unstable flow regimes (Hartfeild 1993, Brown and Banks 2001). Mussels often become stranded during periods of low flow or dislodged during high flow in areas where the channel is altered and the riparian zone is destroyed. These same land-use practices introduce high levels of bacteria, pesticides and suspended sediment into the surrounding rivers, causing many invertebrates to suffer mortality due to hypoxia and the toxicity of the pesticides (DEQ 2004).

I hypothesize that unionid abundance and species richness in the coastal plain rivers of the Florida Parishes are influenced by mechanisms occurring at a combination of spatial scales. I examine this hypothesis by collecting data at the microhabitat scale, the riparian scale (defined in this study as a 1 km buffer around each site), and the sub-segment scale along the Tickfaw, Tangipahoa, Bogue Chitto and West Pearl rivers in southeast Louisiana. I utilize principal component factor analysis to combine these data into one statistical model and identify underlying mechanisms that are structuring mussel abundance and species richness patterns.

At the microhabitat scale, I sampled unionid species richness and abundance along with several water quality parameters, sediment type, stream width, stream depth, and flow. The percentages of surrounding area uniquely represented by four geological categories and seven land-use categories were estimated at both the riparian spatial scale, and the sub-segment spatial scale. My main objectives were to: (1) identify species richness and abundance patterns throughout the study region, (2) use a single, comprehensive statistical model to identify what mechanisms at what spatial scales are influencing the patterns and assess the relative influence of each mechanism on species richness and total abundance, and (3) discuss how community composition changes along these rivers.

METHODS

Site Description

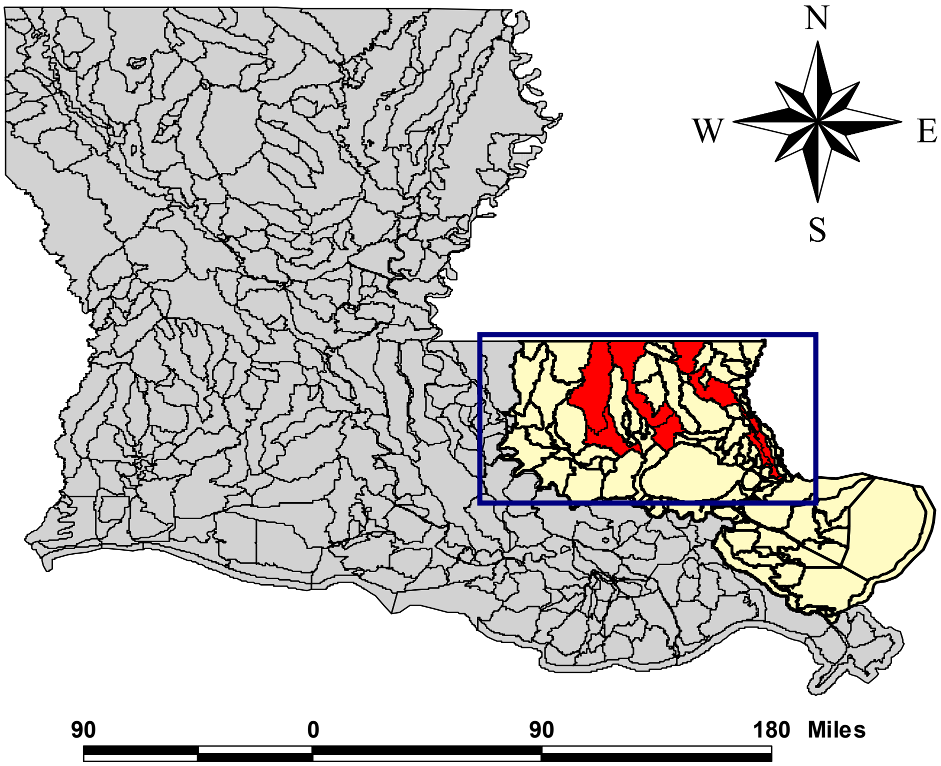
The four rivers included in the study are located in the Florida parishes of southeast Louisiana, which extend east from the Mississippi River to the Mississippi state line and north from Lakes Pontchartrain and Maurepas to the Mississippi state line. All study sites are located within the USGS-delineated Lake Pontchartrain watershed (Figure 1).

The northern portions of the watershed have the highest elevations found in the lower Mississippi Valley, where summits are roughly 152 meters above sea level, though the lakes are only 70 kilometers to the south (Russell 1940). The average gradient in this area exceeds 1.5 meters per kilometer, and has no equivalent elsewhere in Louisiana. The landscape in these upper segments has been historically characterized by rolling hills, pine forests and moderate to fast flowing streams and rivers of relatively low turbidity (Douglas 1974).

In the southern portion of the study area, stream gradients decrease markedly and elevations are less than 1 meter above sea level (Saucier 1963). The rivers become "bayou-like" with slower flowing water, numerous input tributaries, and higher turbidity. Historically, the landscape here has been characterized by mixed-hardwood bottomlands and Cypress (*Taxodium distichum)* swamps. During low water stages, tidal variations in Lakes Pontchartrain and Maurepas may result in salt water intrusion into the lower reaches of these rivers (Stern 1976).

Between April 2004 and August 2005, we sampled 50 sites along the Tickfaw, Tangipahoa, Bogue Chitto and lower West Pearl Rivers. GPS locations were taken at each site with a Garmin 12XL handheld unit and are presented in decimal degrees (NAD27) in Appendix 1. These rivers flow through six USGS-delineated sub-segments (Figure 2). The Tickfaw River flows through an upper sub-segment and a lower sub-segment as does the Tangipahoa River just 8 kilometers to the east. Twenty-four kilometers east of the Tangipahoa, the Bogue Chitto River flows through a single sub-segment located in the upper region of the watershed, and flows into the lower West Pearl River. The West Pearl river flows through a single sub-segment located in the lower region of the watershed.

Along the Tickfaw River, we sampled 15 sites from the Mississippi state line to the mouth of Lake Maurepas. Eleven sites fell within the upper sub-segment and 4 sites within the lower sub-segment. Thirteen sites were sampled along the Tangipahoa River from the

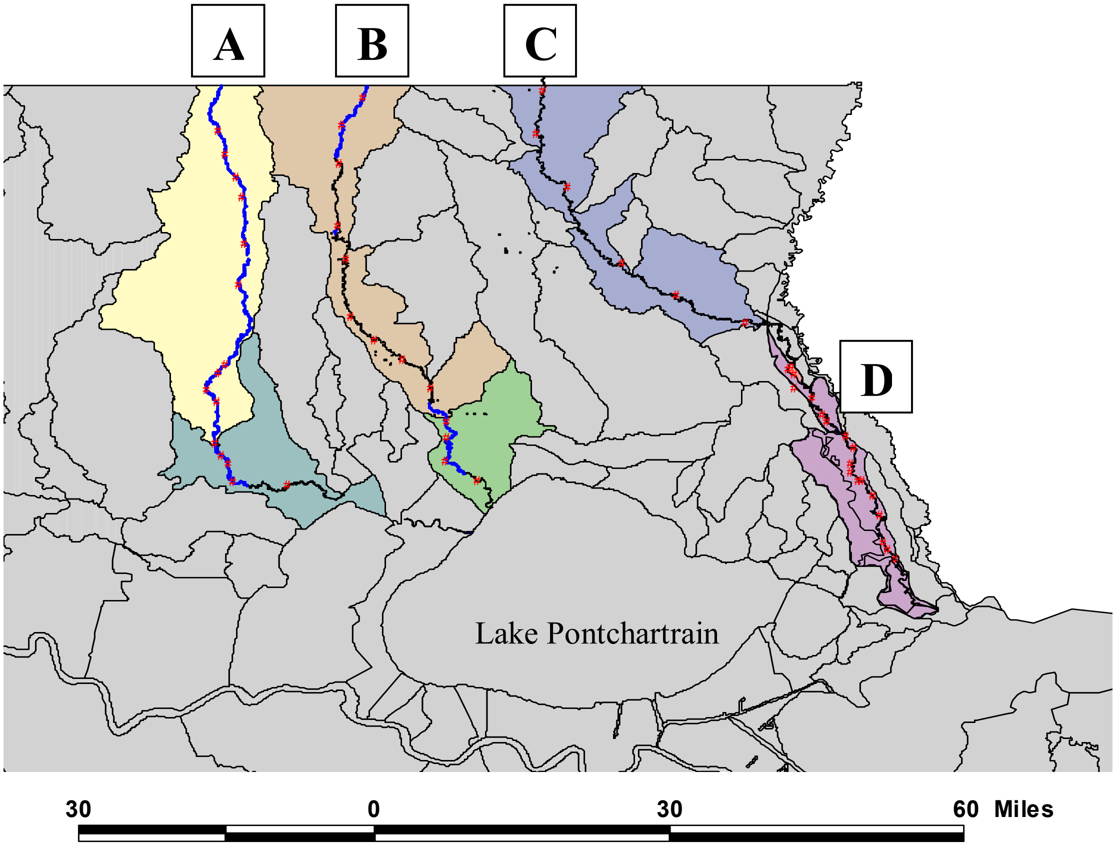


□ = Florida Parishes

🟨 = Pontchartrain Watershed

🟥 = Sub-segments in study

Figure 1: Graphical representation of the study area. The blue box indicates the area known as the Florida Parishes of Louisiana. The yellow area indicates the USGS delineated Lake Pontchartrain watershed. The red areas indicate the six USGS delineated sub-segments through which the four study rivers flow.



● = Sites

A = Tickfaw River

🟨 = Upper Tickfaw sub-segment

🟦 = Lower Tickfaw sub-segment

C = Bogue Chitto River

🟪 = Bogue Chitto sub-segment

B = Tangipahoa River

🟧 = Upper Tangipahoa sub-segment

🟩 = Lower Tangipahoa sub-segment

D = West Pearl River

🟪 = West Pearl sub-segment

Figure 2: Close-up of the six USGS delineated sub-segments involved in this study. Rivers are denoted by capital letters A-D. Each sub-segment is indicated by the appropriate coloration. Individual sample sites are indicated by red dots.

Mississippi state line to the mouth of Lake Pontchartrain, with 9 in the upper sub-segment and 4 in the lower. A total of 4 sites were sampled along the Bogue Chitto River from the Mississippi state line to the confluence of the West Pearl River and 18 sites were sampled from the convergence of the Bogue Chitto south to Lake Pontchartrain.

Mussel Assemblage Sampling

At each of the 50 sites, a two-person team conducted visual and tactile searches for mussels along the littoral zones over a period of 45 minutes with snorkel gear. This method provided a catch per unit effort (CPUE) estimate of abundance for each site. Several studies have compared qualitative versus semi-quantitative mussel sampling and found no statistical difference in estimates of diversity or abundance (Obermeyer 1998, Miller and Payne 1993). Although timed searches are considered semi-quantitative in that they do not describe density, it is the best method for efficiently estimating abundance and species composition over a large area and it is the best technique for locating rare species (Green and Young 1993, Hornbach and Deneka 1996, Strayer et al. 1997, Vaughn et al 1997, Metcalfe-Smith et al. 2000, Strayer and Smith 2003). Species richness, defined as the number of species found per site, was recorded for each site also. In-field identification of mussel species was performed using the keys of Vidrine (1993) and Stern (1976), and all nomenclature is based on Turgeon et al. (1998).

Microhabitat Variables

We collected 12 microhabitat variables at each site. Water temperature (˚ C), dissolved oxygen (mg/L) and specific conductance (μMHOS/cm) were collected at each site with a YSI-85 dissolved oxygen meter. Alkalinity ($CaCO_3$mg/l), pH, and total organic carbon (mg/L) were obtained through Louisiana Department of Environmental Quality databases (Louisiana Department of Environmental Quality 2004). Percent cover of cobble (>64.0mm), gravel (2.0-4.0mm), sand (0.06-2.0mm), and silt (<0.06mm) sediment types were estimated for each site following Brim-Box and Mossa (1999). We also measured stream depth (m) and width (m) for each site.

Land-use and Geology Variables

All landscape variables were estimated using ArcView 3.2 and Spatial Analyst (Environmental Systems Research Institute, www.esri.com). Percent area coverage (km^2) of seven land use categories was estimated from USGS LAGAP shapefiles (United States Geological Survey, Louisiana GAP shapefile). These seven categories were: (1) cropland, (2) evergreen forest, (3) forested wetland, (4) mixed forest, (5) deciduous forest, (6) urban and (7) gravel mining. These coverage's were estimated within a 1 km^2 circular area around each site, hereafter referred to as the riparian-buffer spatial scale, and within each USGS delineated sub-segment, hereafter referred to as the sub-segment spatial scale. We also estimated percent area coverage of four geological categories from USGS geology shapefiles (United States Geological Survey, Louisiana geology shapefile). These four categories included: (1) high terrace, (2) intermediate terrace, (3) prairie terrace and (4) alluvium. These categories were estimated within both the riparian and sub-segment spatial scale.

Statistical Analysis

To reveal statistical patterns in mussel assemblage structure, one-way analyses of variance were performed to compare abundance and species richness values among the four rivers, among 10 reaches defined as river fragments between major tributaries, and among the six USGS delineated sub-segments (ANOVA; PROC MIXED, SAS vers. 9.0, SAS Institute, Cary, NC). When significant differences were found, a subsequent Tukey's studentized range test was performed.

To find the relative influence of each original variable on species richness and total abundance, I initially performed a multiple regression analysis (Arbuckle and Downing 2002). However, the variables collected at the microhabitat spatial scale were highly correlated with the variables collected at the riparian and the sub-segment scale. I therefore employed Principal Component Factor Analysis (PCFA; PROC FACTOR, SAS vers. 9.0, SAS Institute, Cary, NC) to determine if the original variables could be explained largely or entirely in terms of a much smaller number of orthogonal variables called factors. These factors can in turn be defined based on correlations between the original variables and the new latent factors as well as the ecological significance of the variables associated with each factor.

I calculated a Pearson-Product moment correlation matrix from the original values of the microhabitat, riparian and sub-segment variables for each site and factored the correlation matrix using the common factor model. Based on the eigenvalues of the correlation matrix and the scree plot, I retained 3 factors for further analysis. Before interpreting the factor pattern, and in order to conduct subsequent multiple regression analysis, I orthogonally rotated the pattern using the varimax method.

The extent to which an original variable contributes to a factor is equal to its loading or factor pattern correlation coefficient. This can be a negative coefficient or a positive one. A common approach to interpreting this portion of the output is to use all coefficients greater than 0.30 or less than -0.30 to define each factor. To be ecologically conservative, I retained variables with factor loadings > 0.60 or < -0.60 (Stevens 2000). A factor should generate correlations among some but not all of the original variables, and variables loading significantly on one factor should have insignificant loadings on the other factors. Since I rotated the factor pattern orthogonally, individual factors describe statistically separate ecological processes.

Factor scores were calculated for each original variable and used to plot sample sites in multivariate space. If the factors represent the ecological mechanisms responsible for the patterns detected in abundance and richness, the sites should cluster together, based on their factor scores, in the same manner as seen in the abundance and species richness ANOVA and Tukey test output.

Once the sites were plotted in multivariate space, the factor scores for each sample site were input into a multiple regression model and the relative influence and predictive power of the latent factors on both total abundance and species richness were obtained (PROC REG, SAS vers. 9.0, SAS Institute, Cary, NC).

RESULTS

Abundance

Total Abundance ranged from 0 – 193 individuals per site, with the greatest abundance at site 12 in the lower Tickfaw sub-segment. The ANOVA results reveal a significant difference in the abundance data among the sub-segments (Figure 3). The sites within the upper Tickfaw, upper Tangipahoa, and the Bogue Chitto sub-segments as a group have significantly lower abundance than the sites within the lower Tickfaw, lower Tangipahoa and West Pearl sub-segments ($F = 13.12$, $p < 0.0001$).

The abundances in the upper Tickfaw sub-segment averaged 6.5 individuals per unit effort, the upper Tangipahoa sub-segment 3.0 and the Bogue Chitto 6.3. The lower Tickfaw sub-segment averaged 131 individuals per unit effort, the lower Tangipahoa sub-segment averaged 70 and the West Pearl sub-segment averaged 50 individuals per unit effort.

Species Richness

Species richness ranged from 0- 14 species per site, with the greatest richness at site 11 in the lower Tangipahoa sub-segment. The ANOVA indicated that sites within the upper Tickfaw, Tangipahoa and Bogue Chitto sub-segments had significantly lower species richness than the sites within the lower Tickfaw, Tangipahoa and West Pearl sub-segments, and Tukey's test placed the sub-segments in the same "upper" and "lower" groupings as seen in the abundance data (Figure 4, $F = 19.68$, $p < 0.0001$).

The upper Tickfaw sub-segment averaged 2 species per site, the upper Tangipahoa 1.3 species per site and the Bogue Chitto sub-segment 1.5 species per site (Figure 4, group A). The lower Tickfaw sub-segment averaged 9 species per site, the lower Tangipahoa averaged 9 species per site and the West Pearl sub-segment averaged 8 species per site (Figure 4, group B).

The microhabitat spatial scale ANOVA results were less obvious than the abundance and richness results. The only microhabitat variable statistically different among sub-segments, and displaying the same "upper" and "lower" Tukey groupings, was the percent of fine sediment at each site. The upper Tickfaw, upper Tangipahoa and Bogue Chitto sub-segments have statistically lower percentages of fine sediment than the lower Tickfaw, lower Tangipahoa and the West Pearl sub-segments ($F = 8.54$, $p < .0001$).

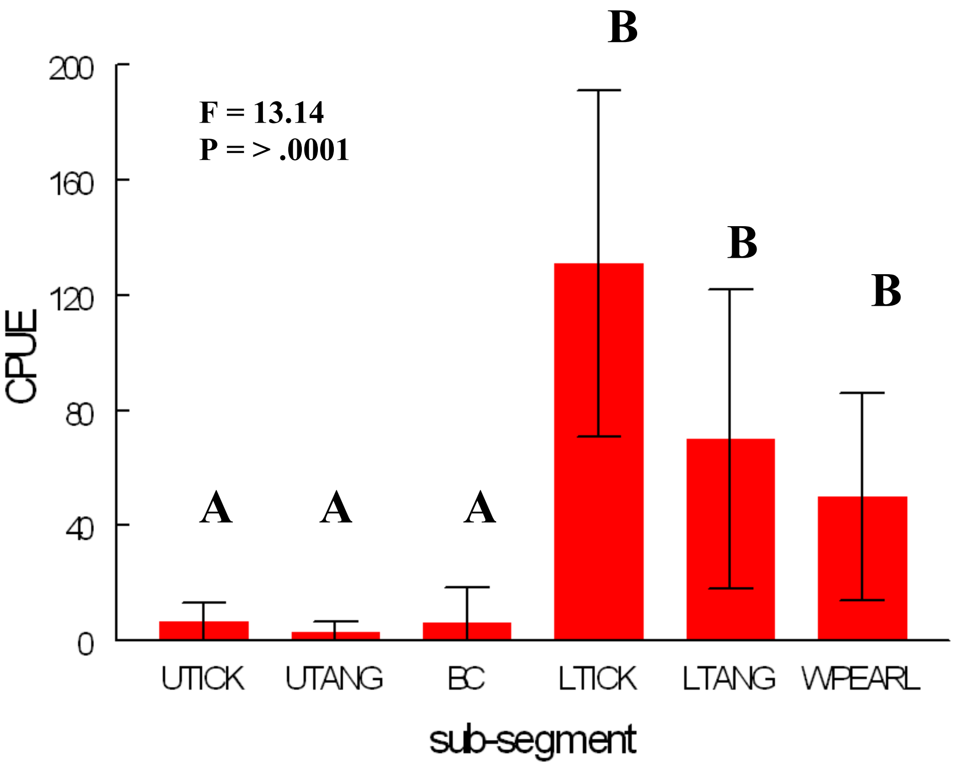


Figure 3: Average catch per unit effort estimates for each sub-segment and Tukey's *a posteriori* results indicating two separate groups. A indicates the low abundance, upper sub-segments and B indicates the higher abundance, lower sub-segments. UTICK = upper Tickfaw sub-segment, UTANG = upper Tangipahoa, BC = Bogue Chitto, LTICK = lower Tickfaw, LTANG = lower Tangipahoa, WPEARL = West Pearl River.

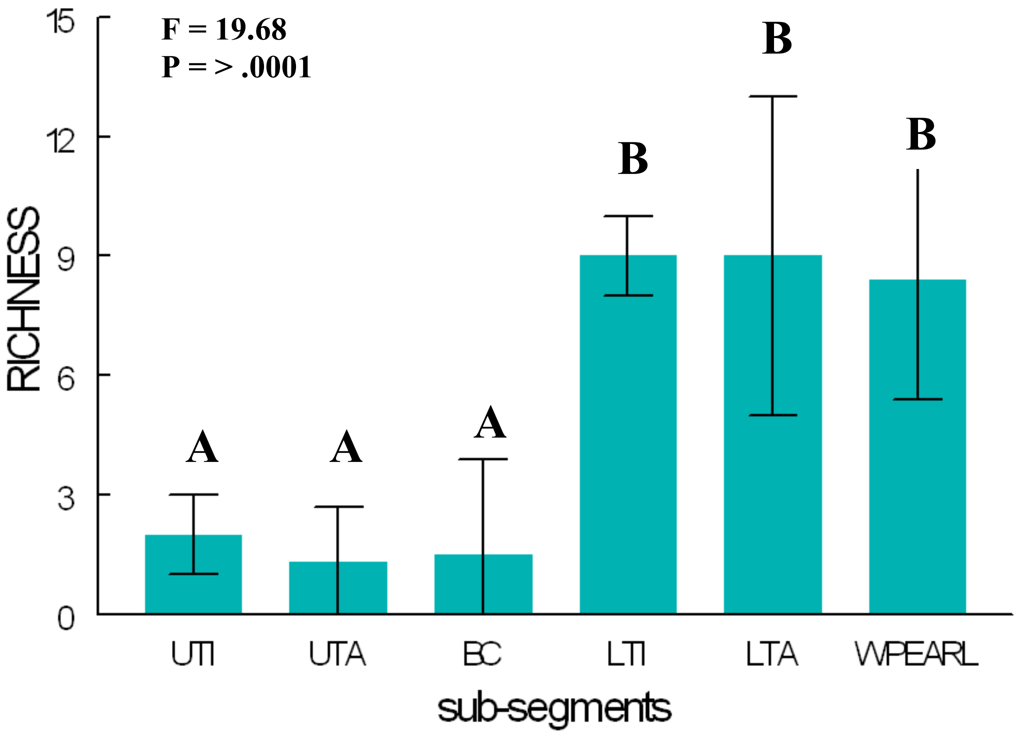


Figure 4: Average species richness estimates for each sub-segment and Tukey's *a posteriori* results indicating two separate groups of species richness. A indicates the low richness, upper sub-segments and B indicates the higher richness, lower sub-segments. Acronyms given in Figure 3.

The riparian spatial scale ANOVA indicated that percent coverage of cropland and forested wetland were both significantly different among sub-segments. The upper Tickfaw, upper Tangipahoa and Bogue Chitto sub-segments had significantly higher coverage of cropland ($F = 8.65$, $p < .0001$) and significantly lower coverage of forested wetland ($F = 39.47$, $p < .0001$) than the lower Tickfaw, Tangipahoa and West Pearl sub-segments.

Principal Component Factor Analysis

Three principal factor axes cumulatively accounted for 75 percent of the covariance in the original data (Table 1). The first factor accounted for 49 percent of the total covariance, the second factor accounted for 18 percent and the third accounted for an additional 8 percent.

The loadings of the original variables on the three rotated factors differed noticeably (e.g. variables loading significantly on one factor were absent in the other factors) as seen in Table 2. Variables loading positively on the first factor are associated with mechanisms functioning in the upper sub-segments, and variables loading negatively were associated with mechanisms functioning in the lower sub-segments. Specifically, for factor 1, percent fine sediment, percent forested wetland at both the riparian and sub-segment scales, and percent prairie terrace at the sub-segment scale are associated with the lower sub-segments. Percent coverage of agriculture at both the riparian scale and sub-segment scale and percent coverage of high terrace geology at the sub-segment scale are associated with the upper sub-segments.

Only percent area covered by prairie terrace geology and percent evergreen forest at the riparian spatial scale load positively on factor 2, but the ecological mechanism causing the association of these original variables is unclear. Percent evergreen forest at the sub-segment scale loads positively on the third factor, but the mechanism behind this association is even less clear since this factor only accounts for 8 percent of the cumulative variance with in the original data set.

When the sites are plotted based on their factor scores against principal component factors one and two (Figure 5), the importance of the first factor becomes clear. Sites in the high-diversity, lower sub-segments plotted to the left (negatively), and the lower-density, upper sub-segments plotted to the right (positively) on the first factor axis. The second and third factors do not group the sites in any pattern, as stated earlier, and do not seem to define any ecologically important mechanisms.

Table 1: Eigenvalues associated with each factor as well as the proportional and cumulative contribution of each factor to total variance with in the Correlation Matrix.

Factor	Eigenvalue	Proportion	Cumulative
1	5.89877	0.49	0.49
2	2.10148	0.18	0.67
3	0.99258	0.08	0.75

Table 2: Varimax rotated principal component factor loadings for the three factors which explain 75% of the variance in the data. The coefficients listed below indicate the loadings of the original variables on the principal components. Shading indicates loadings greater than 0.30.

Variable	Factor1	Factor2	Factor3
MICROHABITAT			
conductivity	-51	-48	21
% fine sediment	-79 *	-8	-9
RIPARIAN			
High terrace	58	-54	23
Prairie terrace	-1	81 *	35
Agriculture	75 *	-8	34
Evergreen forest	14	78 *	16
Forested wetland	-76 *	-21	-38
SUB-SEGMENT			
High terrace	96 *	7	7
Prairie terrace	-81 *	12	33
Agriculture	94 *	9	3
Evergreen forest	15	24	81 *
Forested wetland	-87 *	-21	-35

Multiple Regression

Factor 1, when considered alone, is significant in predicting the abundance of mussels (Figure 6) and to a greater extent, the species richness of mussels among sites (Figure 7). Thirty-five percent of the variation in CPUE abundance among sites was explained, versus 59 percent for species richness. Factors 2 and 3 alone were insignificant in predicting abundance and species richness values, which is not surprising since these factors accounted for 17% and 8% of the total variance in the original variable dataset, and did not aid in discriminating sites into any interpretable pattern.

Mussel Assemblage Structure

We identified 1,815 individuals from all 50 sites. Pooling the data from all six rivers, *Quadrula rufulgens* and *Quadrula quadrula* were the most abundant species, accounting for 15 and 12 percent of all individuals collected, respectively. These species were only found in the lower Tickfaw, lower Tangipahoa and West Pearl sub-segments. Other common species were *Plectomerous dombeyanus*, *Lampsilis teres* and *Leptoidea fragilis.* These species were only found in the lower Tickfaw, lower Tangipahoa and West Pearl sub-segments as well. The rarest species were *Pleurobema beadleana* found only in the upper Tickfaw sub-segment, *Toxolasma texasensis*, found only in the West Pearl sub-segment, *Strophitus radiata*, *Uniomerus declivu*s, found only in the Bogue Chitto sub-segment, and *Villosa vibex*. Each of these rare species was represented by fewer than 3 individuals at 2 or fewer sites.

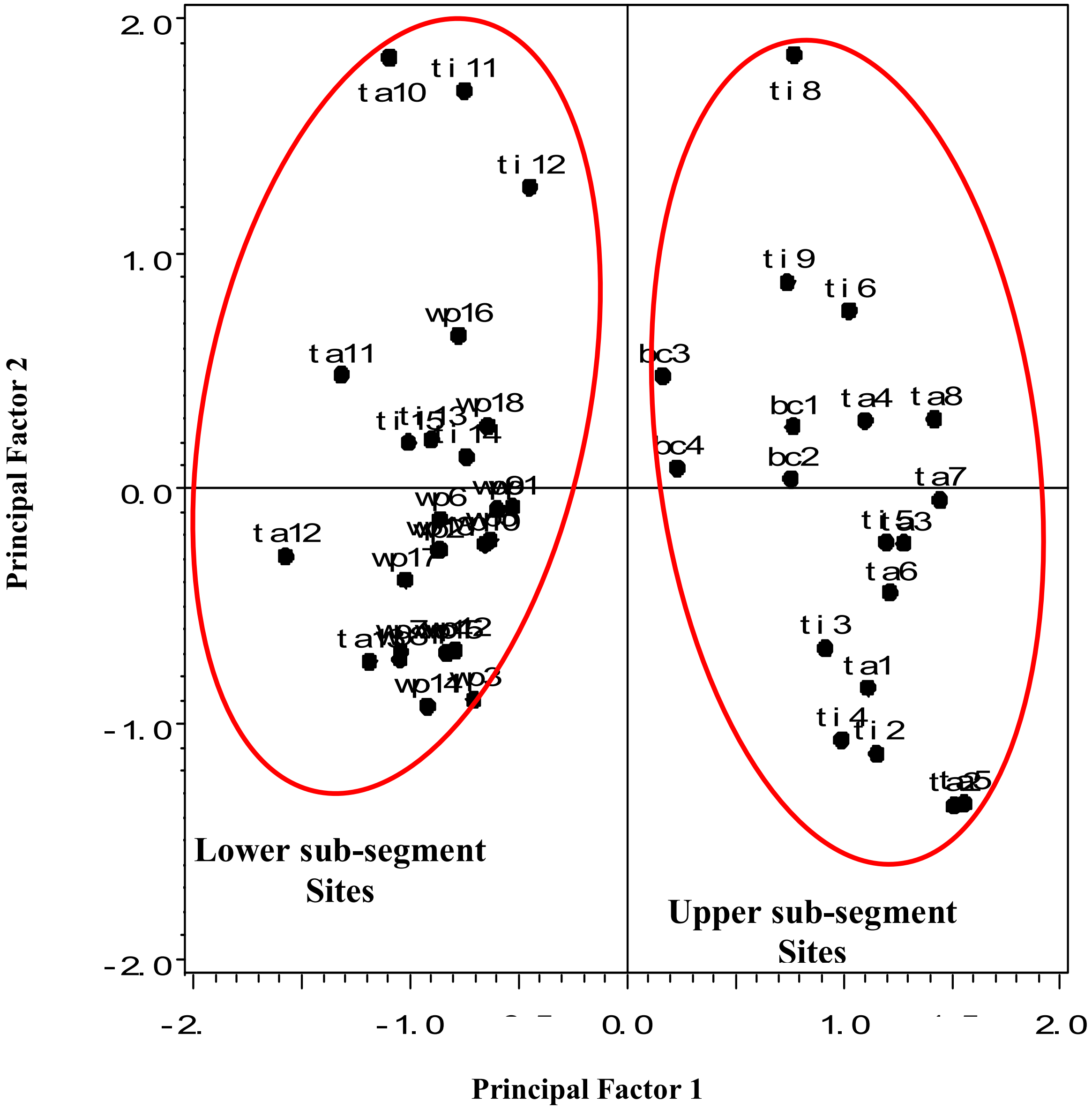


Figure 5: Sites in upper and lower sub-segments of four rivers plotted against principal component one and two. Red ovals discriminate upper from lower sub-segments sites.

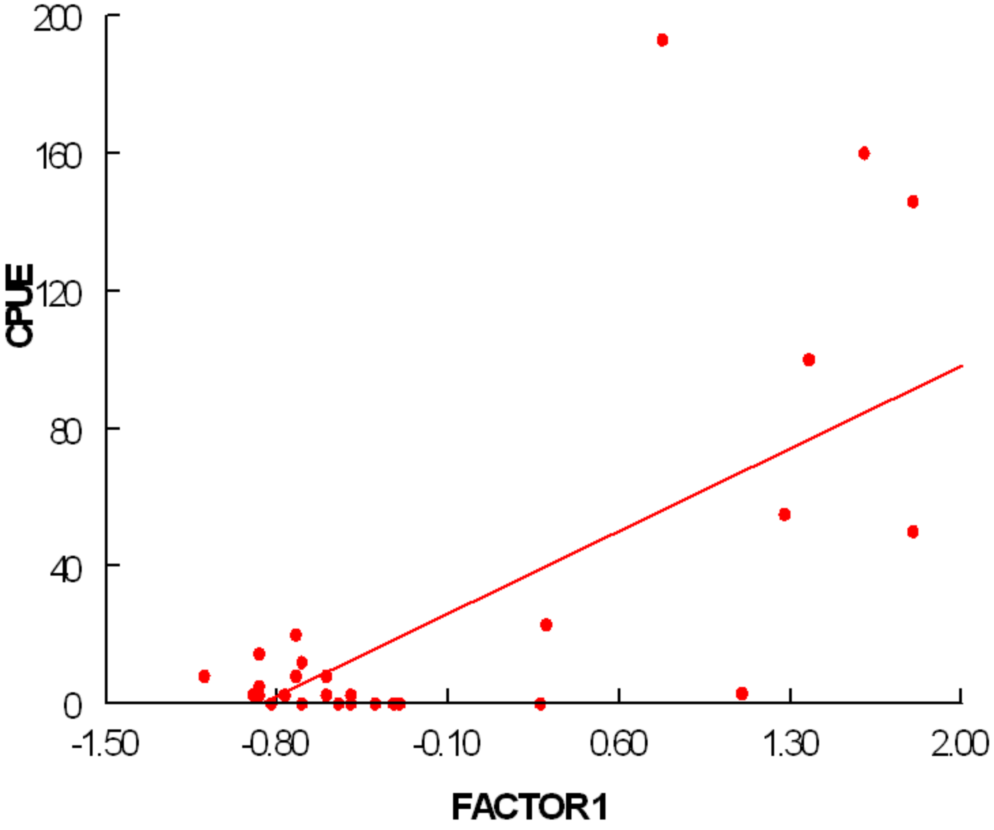


Figure 6: Simple linear regression of catch per unit effort against the factor one scores (R-square = 0.33)

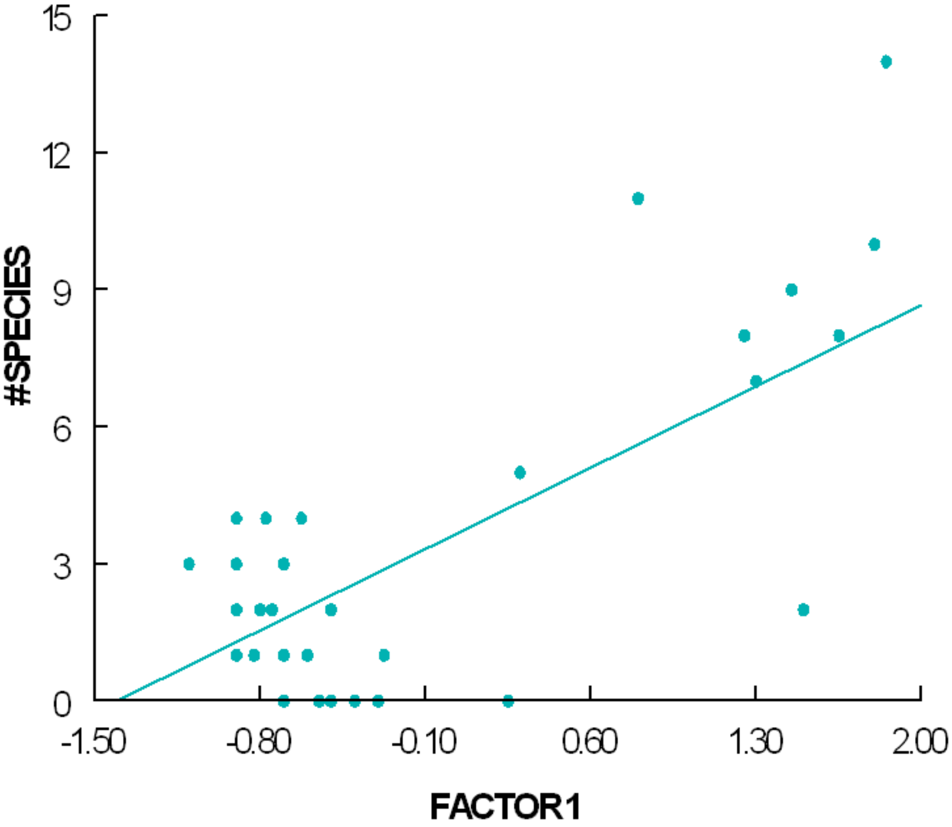


Figure 7: Simple linear regression of species richness against factor one scores. (R-square = 0.58)

DISCUSSION

My results indicate a distinct spatial pattern in freshwater mussel abundance and species richness, with higher mussel abundance and diversity occurring in the lower three sub-segments than in the upper three sub-segments. Individual ANOVA results for the microhabitat, riparian and sub-segment scale variables suggest that percent sediment type, land-use and geology all may explain this spatial trend, but to identify the mechanisms working across a combination of spatial scales, and to investigate the relative contribution of the original variables, I used Principal Components Factor Analysis.

The PCFA successfully combined multiple spatial scales into one model, and elucidated multi-scale mechanisms correlated to mussel assemblage patterns. Factor 1 appears to describe how geology type at the sub-basin scale, coupled with land-use with in both the riparian buffer and sub-segment scales, affects hydrological variability. The plot of sample sites along Factor 1 shows that the PCFA discriminates “upper” and “lower” sub-segments as in the abundance and richness ANOVA results and after investigating how the original variables significantly load on Factor 1, I argue that differences in hydrologic variability between the upper and lower portions of the study area are strongly correlated to the pattern of mussel abundance and species richness with in these four rivers. No clear ecological relationships could be surmised for variables loading significantly on Factors 2 and 3, nor were those factors significant in the regression analysis. Therefore, those factors will not be considered further.

The most highly correlated original variables on Factor 1 are percent coverage of high terrace geology and agricultural land-use at the sub-segment spatial scale. High terrace coverage and agricultural land-use both load positively on Factor 1 and contribute the most to defining the hydrological variability with in the upper sub-segments. Sites that plot positively along Factor 1 are all from the upper three sub-segments which have significantly lower abundance and richness averages than the lower three sub-segments indicating that the hydrologic variability in the upper portion of the study area is correlated to a relatively depressed freshwater mussel community.

High terraces are topographically the highest and oldest geological formations within the Florida Parishes. This formation consist of relatively larger sediment types such as sand and gravel deposits and tends to have an erosional topography with relatively steep stream gradients (Mossa and Autin 1986). This topography results in naturally variable hydrologic regimes. Water is quickly removed from the landscape, which results in soil erosion, bank failures, flashy stream flow, and high rates of sediment transport. This type of hydrological response to rain events greatly increases the potential for dislodgement of mussels from the substrate (Arbuckle and Downing 2002). Dislodged mussels, unable to maintain a suitable upright position for oxygen and food consumption as well as reproduction, are unlikely to survive. Agricultural practices in High Terrace geology formations compound these problems by escalating the rate of channelization within the rivers, which in turn increases annual flow variability, sediment transport rates and mussel dislodgment (DiMaio and Corkum, 1995, Hartfield 1993, Holland-Bartels 1990, Layzer and Madison 1995, Arbuckle and Downing 2002). Channelization has also been shown to greatly decrease instream habitat heterogeneity via scouring processes (Frothingham et al. 2001). This flow regime and resulting unpredictability of channel morphology, combined with disturbance from agricultural land-use, apparently reduces mussel abundance and species richness in the upper sub-segments.

Prairie Terrace geomorphology along with forested wetland land-use, on the other hand, load negatively on Factor 1 and contribute most in defining the hydrological variability within the lower sub-segments. Sites that plot negatively along Factor 1 are all within the lower three sub-segments and have significantly higher abundance and richness averages than the upper three sub-segments, indicating that the hydrologic variability in the lower portion of the study area is correlated to a relatively diverse and abundant mussel community

Prairie Terrace formation is the lowest and the youngest geological formation in the Florida Parishes, and consists of silt and sandy silt deposits. Prairie Terraces have a depositional topography with relatively flat stream gradients and poor drainage and result in naturally stable hydrological regimes (Mossa and Autin 1986). Water is slowly removed from the landscape due to low stream gradients, which results in decreased soil erosion, low sediment transport rates, and stable flow velocities annually. Dislodgement is less likely during spate events allowing mussels to maintain their upright positions for efficient filtration and reproduction. Although low-relief sub-segments have less run-off on average, they are prone to high sedimentation, which can be detrimental to mussels (Brim-Box and Mossa 1999). In the case of the lower sub-segments of the Florida Parishes, the large area of forested wetland acts as a buffer, filtering the run-off and deposition of sediment. The topography of the Prairie Terrace formation, combined with less land disturbance and more forested wetlands, appears to be facilitating freshwater mussel abundance and species richness in the lower sub-segments.

At the riparian buffer scale, only land-use appears to be significantly contributing to the hydrological variability of these sub-segments. Agricultural land-use loads positively, and percent cover of forested wetland loads negatively at this scale on Factor 1. These factor loadings again suggest that riparian agricultural land use negatively affects mussel abundance and species richness by increasing hydrological variability, while riparian zones containing forested wetlands increase abundance and species richness by decreasing hydrological variability

These results agree with several recent publications suggesting that intermediate levels of scale between large geographic range and the microhabitat scale are most important to mussel distribution. Strayer (1993), showed that stream size, stream gradient, and hydrologic variability had predictive power, and many have argued that the removal of riparian vegetation is detrimental to aquatic invertebrates (Brim-Box and Mossa 1999, Frimpong et al. 2005, Brooks et al. 2003, Morris and Corkum 1996). Riparian areas are the river's final defense against erosion acting as buffer zones, slowing water flow, stabilizing bank and channel structure, decreasing sedimentation and adding to habitat heterogeneity. During low flow events, the loss of riparian cover also increases mussel mortality due to excessive sedimentation and desiccation when individuals are stranded without the refuge of large woody debris (Golladay et al. 2005).

The only original microhabitat scale variable significantly correlated with Factor 1 is percent fine sediment. This variable has a negative coefficient, suggesting it is involved with hydrology in the lower sub-segments. Sediment type, as discussed in the introduction, is often debated as an important predictor of mussel assemblage structure, but I argue here that the debate stems from the use of microhabitat sediment type at too small a scale to explain unionid distributions in statistical models predicting abundance and species richness. In this study I combined geomorphology, land-use and microhabitat variables and found that at larger spatial scales, Prairie Terrace geology and forested wetland land-use produce a stable hydrological regime, resulting in a greater coverage of fine sediment. This link between hydrological variability and the dominant sediment type is well known (Brim-Box and Mossa 1999, Vaughn 1997, Morris and Corkum 1996), but here I am able to substantiate this relationship based on statistically driven multivariate methods that combined information across several spatial scales. In doing so, I more precisely define the mechanisms occurring in nature that are correlated to freshwater mussel assemblage structure with in the Florida Parishes.

Using Factor 1 scores as the sole independent variable in both the abundance and species richness regression models, I obtained an R-square value indicating the predictive power of Factor 1 (hydrological variability) on the unionid mussel community. The regression analysis resulted in mixed success. The abundance regression analysis yielded an R-square of 0.33, not a great improvement over most microhabitat regression models dealing with mussel abundance (Strayer and Ralley 1993). This may be explained because the CPUE data set has a greater inherent variance than the species richness data set.

On the other hand, regression of species richness on Factor 1 yielded an R-square of 0.75, a much higher value than most in the literature (Strayer and Ralley 1993). As the hydrologic regime of a river becomes more variable, species richness decreases. I argue that sediment type is inherently linked to hydrologic stability, but at the microhabitat scale, fine sediments could indicate more stable hydraulic habitat such as an eddy or backwater zones. Brim- Box and Mossa (1999) along with Brown and Banks (2001) found similar correlations between fine sediments and increased richness, and hypothesized these habitats were more stable, but were not able to substantiate this relationship by utilizing data across spatial scales.

The abundance and species richness of these freshwater mussels could be explained by factors not considered in this analysis. Although the PCFA explained 75 percent of the variance, 25 percent is unaccounted for. Dispersal constraints are a possible factor influencing patterns in mussel abundance and species richness that I do not discuss in this study (Haag and Warren 1998, Watters 1992, Vaughn and Taylor 2000). Unionid mussels often require a fish host during early life history stages, and presence of fish hosts could be a powerful addition to any model predicting mussel assemblage structure. Long-term declines in species richness in fish assemblages are occurring in the Bogue Chitto River (Stewart et al. 2005), suggesting that surveys including fish assemblage structure is a legitimate idea for future work in these rivers. We also did not test for nutrients, fecal coliforms or pesticides although these substances are present in the system according to the Department of Environmental Quality (2004), so we can not speculate on the extent to which these parameters are contributing to declines in mussel assemblages.

Although we successfully combined variables across spatial scales to predict mussel assemblage structure in the Florida Parishes, the analysis is correlative, not experimental. We can only say which of the original variables strongly correlate with each other to form Factor 1.

Although I argue that my definition of Factor 1 is ecologically correct, I can not prove that factor 1 is a surrogate for hydrologic stability. Therefore, we can not prove for certain that hydrologic stability, as described by the variables loading on to factor 1, influences mussel assemblage structure.

However, I consider that PCFA is an excellent tool for adaptive management of freshwater mussel habitat in the Florida Parishes. PCFA is capable of combining land use and habitat data from several spatial scales into one model, and the results can be orthogonally transformed for subsequent regression analysis. Currently, Louisiana manages the freshwater mussels of the Florida Parishes at the watershed spatial scale. This study suggests that management recommendations be tailored to the geology *within* the watershed, more specifically to the hydrologic variability generated naturally by the geology type with in a watershed.

For example, in this study, portions of the watershed dominated by High Terrace geology and erosional topography should be managed to conserve top soil and decrease sediment transport, bank failures and scouring events. Best management practices for agricultural activities as well as silvicultural activities should be employed whenever possible. Riparian zones should be protected in this portion of the watershed to maintain channel structure, heterogeneous habitat along the stream bed and decrease localized run-off. Mussels in the upper sub-segments should be monitored every 2-3 years.

River stretches in Prairie Terrace geology should be managed to prevent siltation. Riparian zones should also be conserved in the lower watershed, to filter sediment during rain events, and lessen input into the river. Currently, the lower portions of the Pontchartrain watershed are experiencing large amounts of disturbance. Hurricane Katrina has reportedly destroyed 70% of the riparian cover along the Pearl River and large woody debris is being removed by large, heavy equipment. Future research on the effects of a catastrophic hurricane and fish assemblage surveys would add vital information on the response of a healthy mussel community to extreme, natural habitat alteration.

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APPENDIX: GPS SITE LOCATIONS

GPS LOCATIONS IN DECIMAL DEGREE FORMAT (NAD27).UTI = Upper Tickfaw sites, LTI = Lower Ticfaw sites, UTA = Upper Tangipahoa sites, LTA = Lower Tangipahoa sites, BC = Bogue Chitto sites, WP = West Pearl sites.

site	long(x)	latt(y)	river
UTI 1	-90.67325	30.92912	tickfaw
UTI 2	-90.66	30.89	tickfaw
UTI 3	-90.65	30.85	tickfaw
UTI 4	-90.63763	30.82423	tickfaw
UTI 5	-90.63315	30.74972	tickfaw
UTI 6	-90.6428	30.68522	tickfaw
UTI 7	-90.66178	30.56008	tickfaw
UTI 8	-90.67418	30.5467	tickfaw
UTI 9	-90.69062	30.521167	tickfaw
UTI 10	-90.67625	30.50183	tickfaw
UTI 11	-90.68	30.44	tickfaw
LTI 12	-90.67	30.42	tickfaw
LTI 13	-90.66	30.4	tickfaw
LTI 14	-90.65	30.38	tickfaw
LTI 15	-90.57	30.37	tickfaw
UTA 1	-90.4607	30.98	tangipahoa
UTA 2	-90.4905	30.9376	tangipahoa
UTA 3	-90.4962	30.8768	tangipahoa
UTA 4	-90.4977	30.7781	tangipahoa
UTA 5	-90.48385	30.72712	tangipahoa
UTA 6	-90.4788	30.6356	tangipahoa
UTA 7	-90.43	30.66	tangipahoa
UTA 8	-90.4	30.57	tangipahoa
UTA 9	-90.36	30.52	tangipahoa
LTA 10	-90.34	30.47	tangipahoa
LTA 11	-90.34	30.45	tangipahoa
LTA 12	-90.345	30.41	tangipahoa
LTA 13	-90.29	30.38	tangipahoa
BC 1	-90.19525	30.990361	Bogue chitto
BC 2	-90.204861	30.923194	Bogue chitto
BC 3	-90.000013	30.67	Bogue chitto
BC 4	-90.897111	30.627611	Bogue chitto
WP 1	-89.8291	30.5584	West pearl
WP 2	-89.834	30.5531	West pearl
WP 3	-89.8256	30.5445	West pearl
WP 4	-89.8256	30.5229	West pearl
WP 5	-89.8001	30.5074	West pearl
WP 6	-89.7849	30.4812	West pearl

WP 7	-89.7782	30.472	West pearl
WP 8	-89.7507	30.4463	West pearl
WP 9	-89.7389	30.4294	West pearl
WP 10	-89.7435	30.4032	West pearl
WP 11	-89.7435	30.391	West pearl
WP 12	-89.7334	30.3786	West pearl
WP 13	-89.7255	30.3783	West pearl
WP 14	-89.7118	30.3547	West pearl
WP 15	-89.7006	30.3233	West pearl
WP 16	-89.6959	30.2805	West pearl
WP 17	-89.6898	30.269	West pearl
WP 18	-89.6787	30.2536	West pearl

VITA

Raynie Bambarger was born in Northport, Alabama on January 20th 1977. She attended Tuscaloosa County High School and graduated in 1995. Raynie attended Auburn University where she received a Bachelor of Science degree in Fisheries and Allied Aquaculture in 2000. For the next year, she worked as an Environmental Technician for Tuscaloosa Testing Lab, Incorporated located in Montgomery, Alabama testing drinking water, industrial waste water and Underground Storage Tank (UST) sites. In the spring of 2001, she moved to Newton, Georgia and began working at Joseph W. Jones Ecological Research Center as a Biological Technician. She worked in the aquatic ecology lab under Dr. Steve Golladay, where she became interested in freshwater mussels. In 2003, she enrolled in Louisiana State University as a graduate student in Dr. Kenneth Brown's laboratory and began her work with Louisiana freshwater mussels.

Since being at Louisiana State University, she has written and received two grants from the Louisiana Natural Heritage Program and was able to fully support herself for three years. She presented her findings at the 2005 annual North American Benthological Society meeting in New Orleans, Louisiana and also at the 2005 annual BioGrads symposium at Louisiana State University. In her final semester at Louisiana State University, she taught an introductory biology laboratory where she led exercises in ecology, systematics, genetics, dissection and spectrophotometry. She specializes in Southeastern freshwater mussel ecology and taxonomy as well as invertebrate and water sampling. She has experience with Global Positioning Satellite technology as well as univariate and multivariate statistics.