Final
Unionid Habitat Literature Review

Prepared for:

U.S. Army Corps of Engineers
St. Louis District
St. Louis Missouri

Prepared by:

Ecological Specialists, Inc.
O'Fallon, Missouri

November 2013
(ESI Project no. 12-027)

Table of Contents

1.0 Introduction.....1
2.0 Methods.....2
3.0 Results.....3
 3.1 General life history, habitat requirements, and habitat review papers.....4
 3.2 Unionid mussel habitat studies outside the UMRB.....8
  3.2.1 Simple microhabitat variables-microscale.....9
  3.2.2 Simple habitat variables-macroscale.....14
  3.2.3 Complex hydraulic variables.....22
  3.2.4 Laboratory studies.....34
  3.2.5 River management for Freshwater mussels.....36
 3.3 Upper Mississippi River Basin Habitat Studies and Models.....36
  3.3.1 General Mississippi River habitat rehabilitation.....37
  3.3.2 Simple habitat variables.....40
  3.3.3 Complex hydraulic variables.....42
 3.4 Attempts to create mussel habitat and habitat ideas.....50
  3.4.1 Mussel habitat creation outside the UMRB.....51
  3.4.2 Mussel habitat creation within UMRB.....54
 3.5 Recent unionid mussel studies within the St. Louis District.....61
  3.5.1 Pool 24.....61
  3.5.2 Pool 25.....66
  3.5.3 Pool 26.....70
  3.5.4 Middle River.....71
  3.5.5 Illinois River.....72
4.0 Literature Index.....76

1.0 Introduction

The St. Louis District, U.S. Army Corps of Engineers (USACE) maintains a navigation channel on the lower 80 miles of the Illinois River, 300 miles of the Mississippi River from Saverton, Missouri to Cairo, Illinois, and the lower 36 miles of the Kaskaskia River. They also construct smaller projects in and around waterways throughout the district for flood management and environmental restoration. These projects involve dredging and the placement of rock structures, which have the potential to either negatively or positively impact freshwater unionid mussel species (unionids). The USACE is interested in developing a greater understanding of unionid mussel habitat requirements within its waterways and ascertaining whether habitat can be enhanced or created during channel maintenance and rock structure placement activities. The USACE contracted Ecological Specialists, Inc. (ESI) to compile a list of published literature on mussel habitat, with emphasis on the Upper Mississippi River Basin (UMRB). Literature will be summarized in a report that will allow a non-scientific educated reader to gain an understanding of mussel habitat construction and creation techniques and theory. ESI will then facilitate and document a meeting that will provide the St. Louis District (SLD) with an understanding of agency knowledge and opinions on mussel habitat construction and creation. This document provides an annotated bibliography of the literature that was compiled and reviewed toward this objective.

2.0 Methods

Literature was obtained through searches of ESI's in-house library, and on-line searches of Google Scholar and JSTOR. Additional literature was identified from the literature cited within the reviewed literature and discussions with UMRB resource managers. The list of literature herein encompasses the major literature associated with unionid habitat, habitat creation projects, unionid habitat within the SLD, and habitat requirements of threatened and endangered species that occur in the SLD. Most of the habitat papers attempt to describe unionid habitat either qualitatively or quantitatively using habitat parameters measured in the field or modeled with complex hydraulic models. The summary following the citation includes information on what was collected/measured/modeled, how it was collected/measured/modeled, and the results of the study. More detail is provided in cases where defining specific ranges of habitat variables might be used in engineering of unionid habitat or where the author provides a good summary of unionid habitat or life history characteristics that will assist the reader in understanding the complexities associated with defining "suitable habitat" for these unique animals. Literature is organized by studies conducted outside and within the UMRB. A chronology exists with respect to habitat investigations; therefore papers are listed chronologically within both sections. Studies also seem to relate to either microhabitat or macrohabitat and simple vs. complex variables. Where possible, papers are organized as such. UMRB researchers involved in habitat modeling and agency personnel within the SLD involved in mussel conservation were contacted to identify any on-going unpublished work with respect to mussel habitat creation. Notes from these conversations are included in this review. Most of the information on mussel beds within the SLD was found in unpublished reports. Some of these reports summarized all studies within the SLD, while others were for individual sites. Where possible, studies were organized within their respective river reaches and by river mile.

3.0 Results

Several papers reviewed ideas of what constitutes mussel habitat and how mussel habitat has been affected. Recent relevant work is listed in Section 3.1. Many studies were reviewed that investigate what habitat variables determine mussel distribution and abundance both outside and within the UMRB. Studies conducted outside the basin are in Section 3.2 and those within the UMRB are in Section 3.3. Papers ranged from observational to in-depth data collection and statistical analysis and model development. Preliminary work (1980's and early 1990's) focused on simple variables, whereas most recent work focuses on more complex hydraulic variables.

Although many studies have demonstrated that these complex hydraulic variables successfully predict mussel presence and abundance, designing mussel habitat using these variables has been considered but not realized. Restoration of mussel habitat has primarily focused on restoring more natural flow, temperature, and dissolved oxygen (DO) levels below dams or removal of dams to restore connectivity between mussels and their fish hosts. Section 3.4 presents the few identified projects on physical habitat creation outside (3.4.1) and within (3.4.2) the UMRB. Reports from an early attempt at mussel habitat creation in Pool 11 of the Mississippi River and discussions with researchers and agency personnel regarding current work on mussel habitat creation are included. Several Habitat Rehabilitation Projects (HREPs) have been built throughout the Mississippi River. Only one (Pool 11, Bertom and McCartney Lakes) of these HREPs attempted to construct mussel habitat. However, this project was designed and constructed in the early 1990's before researches began investigating complex hydraulic variables and monitoring has not been conducted to determine its success. Including mussel habitat in the Pool 8 islands HREP was discussed, but never realized.

In general, unionid mussels occur in areas with moderate flow and moderate hydrological variation. However, the hydraulic parameters and magnitude of those parameters seems to vary among rivers and among river reaches. An understanding of where unionid mussels occur within the SLD is therefore necessary for habitat creation in these river reaches. Recent unionid mussel surveys within the SLD are presented in Section 3.5. A few threatened and endangered (T&E) species occur in the SLD. The habitat requirements of these species should be considered in habitat creation. Information on T&E species is provided in Section 3.6.

An evaluation of the information provided in this document is discussed with respect to habitat creation in the St. Louis District in a separate report.

3.1 General life history, habitat requirements, and habitat review papers

Watters, G. T. 2000. Freshwater mussels and water quality: a review of the effects of hydrologic and in stream habitat alterations. Proceedings of the First Freshwater Mollusk Conservation Society Symposium 261-274.

This paper summarizes the effects of various hydraulic impacts on freshwater mussel habitat. The most common impact is that of impoundments, which alters depth and flow patterns in the main river, results in sedimentation upstream, scouring in the tailwaters, and altered temperature, dissolved oxygen (DO), and nutrient levels. Unionid loss and changes in species composition due to impoundment are well documented. Indigenous species are typically lost and are replaced by softer substrate adapted species. Some new habitats are created, such as overbank area, which are typically dominated by softer substrate adapted species and some species of *Quadrula*. Embayments and coves are also created, but they often experience the same siltation problems. Beaches may also be created, but these areas are typically not good habitat due to water level fluctuation that can leave newly deposited juveniles exposed. Dams are also barriers to host fish. Turbidity, anoxic water, and altered habitat may also restrict fish movement through reservoirs. Tailwaters may also have hostile habitat due to fluctuating discharges, fluctuating water temperature and DO, cold water discharge, and dramatic changes in water velocity. Scour immediately downstream of dams usually leaves unsuitable substrate in the form of either rock or unstable sand. Land use practices also affect mussels. Logging, mining, construction, farming, livestock, and other land use practices generally release runoff of sediments, salt, and other pollutants into streams and increase water volume. Bank stabilization practices can also affect mussels. Mussel density in one study in Belgium showed mussel abundance was highest in natural substrate of mud, sand and fine gravel, and lowest by several orders of magnitude on man-made reinforcements of riprap, gabions, concrete, and open stone pitching. Grassy vs. forested banks can also make a difference in water quality, temperature fluctuation, and hydraulic variability, which can affect species composition. Vessels operating in shallow water can also disturb substrate, resuspend sediments, and cause shore erosion. Other habitat altering activities discussed include trampling of mussels in shallow water fords, channelization, dredging, and snagging, headcutting, and canals.

All of the habitat alterations discussed in this paper result in hydraulic changes, changes in substrate composition, changes in flow, changes in water quality, or changes in fish host accessibility. All of these changes can affect unionid communities. Of particular interest was mention of a bank stabilization, where unionids did not colonize the riprap, but rather were more abundant in adjacent “natural substrates”.

Strayer, D. L., J. A. Downing, W. R. Haag, T. L. King, J. B. Layzer, T. J. Newton, and S. J. Nichols. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. BioScience 54:429-439.

This paper summarizes much of what is known about unionids to date. Unionids appear to eat more than just plankton. Bacteria and dissolved organic matter may also be important food items. Unionids were thought to be filter feeders, but recent studies indicate juveniles pedal feed, and that this behavior may continue into adulthood for some species. Diet may consist of a mixture of algae, bacteria, detritus, and small animals, and at least some algae and bacteria are required as a source of essential biochemicals. Food may be a limiting factor, as condition declines at high population densities and with dense zebra mussel competition. Mussel feeding seems to be a complicated, dynamic process that may vary across habitats, species, and life stages and have important consequences for mussel populations. Mussels have a variety of behavioral and morphological adaptations that allow transfer of glochidia to host fish. Three general strategies are known; lures that mimic fish or invertebrates that elicit an attack from a fish, glochidial packets (conglutinates) that mimic worms, insect larvae, larval fish or fish eggs that attract specific hosts, and release of large mucous webs that entangle fish less discriminately. Sexuality may also not be fixed. Some mussels can change from males to females with age or turn into hermaphrodites in low density situations. One species also transforms glochidia in its gills and by-passes the host fish stage. A few generalizations about host fish are apparent. First, host specificity varies greatly among species, ranging from wide generalists to strict specialists. Second, host compatibility may be temperature dependent (fish may only accept glochidia within a specific temperature range), and third, fish may acquire temporary immunity suggesting competition for hosts could be important. (Not mentioned in this paper is that a fish species may be a suitable host in one drainage but not in another). Unionid mussels are thought to be long lived animals, with many species living decades. However, the demographics (survival, recruitment, fecundity, mortality, live span, frequency of successful reproduction) of most species are largely unknown. Many communities may be declining at a slow rate. Others may be recolonizing with improvements in habitat and water quality, but species composition may be altered from the original community composition. The patchiness of unionid communities is well known, but the factors controlling patchiness are less known. Large scale patterns seem to be a result of historical patterns of dispersal, host distribution, and climate. Mussel beds (densities 10 to 100x greater than outside the bed) seem to occur where shear stresses are low and sediments are stable during floods. However, these factors only partially explain mussel distribution. The requirements of all life stages and species must be met for a mussel bed to persist. Factors such as food quality and quantity, local distribution of fish hosts during the season of glochidial release, well oxygenated sediments for juvenile survival and growth, and refuge from predators may all affect mussels on a local scale. The question of how mussel beds form also needs further study. Mussel beds could form as a result of negative factors (unionids cannot occur in areas where they are crushed, washed out, suffocated, starved, or heavily preyed upon). Alternately, juveniles and adults may choose favorable habitats, or fecundity may be higher in more favorable areas. It could also be that adults could stabilize an area, and sediment mixing by adults may increase pore space and dissolved oxygen and enhance conditions for buried juveniles and host fish. Some mussel beds may be relicts that formed under conditions that no longer exist. Interactions among unionids, between mussel populations, and between populations and their environments at the micro and macro scale are poorly understood. Reciprocal interactions between mussel populations and their environments occur over a range of spatial scales. Some of these neighborhoods of interaction are less than 1 meter in size (biodeposition), whereas others probably extend for tens of kilometers (effects of land use, dispersal of species with wide ranging hosts). Specifying the sizes of these different neighborhoods of interaction and understanding the functional consequences of unionacean patchiness are important challenges for ecologists in the coming years.

This paper is a great summary of general characteristics of mussels and where research is needed. It points out that many problems remain and that these animals are complex and answers will not be simple. However, the authors also conclude that we need to progress with conservation actions using an adaptive management approach.

Newton, T. J., Woolnough, D. A., and D. L. Strayer. 2008. Using landscape ecology to understand and manage freshwater mussel populations. JNABS 27:424-439.

Landscape ecology could be applied to management of freshwater mussels. Mussel beds could be equivalent to Patches (relatively homogeneous areas that differ from their surroundings in nature or appearance), river channels could be equivalent to Corridors (narrow elements of generally hospitable environment that facilitates movement among corridors), and the river bed could be considered the matrix (background cover in a landscape, which is generally less hospitable for the survival than the patches or corridors). The authors apply the landscape ecology approach to mussel habitat and suggest that this approach could be used to better understand the links between mussel communities and watershed characteristics. This approach has the potential to better focus the spatial scale of scientific studies and management activities. The authors agree with Strayer (2008) in his functional habitat approach. What does a mussel need from its habitat? Support – soft enough for burrowing, firm enough for support; Stability- stays in place during floods; Delivery of food and other essential materials; Favorable temperature for growth and reproduction; Protection from predators; Absence of toxicants; and Presence of fish host. This paper reiterates that hydraulic variables likely define habitat stability, but that mussel populations may not simply be limited by physical habitat, but habitat and another resource. Habitat restoration may not increase mussel densities, but only redistribute existing resources. Patch suitability might not be determined solely by habitat (hydraulics). Certain other features such as distribution of fish hosts, food resources, predation, competition, and dispersal patterns of early life stages, in conjunction with physical features may be needed to characterize suitable areas for mussels. Connectivity is also an important variable in a system where patches can be frequently created and destroyed. Connectivity is probably dependent on several variables; percentage of area composed of suitable habitat, spatial configuration of patches, identity of host fish, movement, abundance, and spatial structure of fish populations, nature of the habitat matrix, and the existence of barriers.

These items should all be considered in deciding if an area is a good candidate for habitat creation.

Haag, W. R. 2012. North American Freshwater Mussels. Natural History, Ecology, and Conservation. Cambridge University Press. New York, New York. 505pp.

Chapter 4, habitat

Several macro and micro physical factors affect unionid distribution. Macrofactors discussed include climate, salinity and tidal effects, physiography and water chemistry, physiography and physical habitat (including stability and disturbance on a macrohabitat scale, streams vs. lakes, upland vs. lowland, stream size). Microhabitat factors are important to microhabitat specialists (lentic habitats in streams) and generalists (stability and disturbance at the microhabitat scale). A few species are limited by temperature both at the northern extreme and southern extreme, one species is able to tolerate brackish water, and a few are tolerant of periodic inundation by brackish water. On a microscale, a few species are specialists with respect to lentic habitat or riverine lentic habitat, a few are almost exclusively riverine, a few prefer the stability of Justicia beds, some occur at the stream edges under large rocks, but most are generalists. However, one habitat characteristics they all have in common is habitat stability. Measures of habitat stability, particularly shear stress at high flow, are strongly correlated with and predictive of mussel occurrence from small to large rivers. Stable areas represent refugia from scour during floods and flow characteristics are important in determining habitats in which juveniles can settle. Good mussel assemblages occur in low gradient alluvial streams with silt/sand/clay substrate and in higher gradient glacial till streams but in gravel, cobble sand, as long as substrate is stable during low and high flows.

Chapter 11.3 Habitat restoration

Habitat restoration efforts are needed to save the fauna, however the cause of decline should be considered and rectified on a case by case basis. Restoration efforts to date that have been most successful include restoring natural flow, temperature, and DO regimes downstream of large dams such as those used for hydropower. Smaller dams in many cases provide the best habitat in some smaller systems, as they provide a flowing oxygenated water in an otherwise impounded situation. Removal of small dams can improve connectivity but should be done cautiously, as it could decimate existing communities upstream due to dewatering and downstream due to the release of toxicants and aggradation of the channel. The stream may require several years to restabilize. Restoring channelized streams has also met with some success, but generally requires more intensive construction efforts. Stream restoration is becoming more common, although no studies with restored streams and unionid restoration were presented.

Although restoration was discussed, restoring habitat patches as proposed by USACE was not discussed, nor were any successful case studies presented other than cases of restored flow, DO, and temperature below hydropower facilities.

<u>3.2 Unionid mussel habitat studies outside the UMRB</u>

Many habitat studies have been conducted within and outside of the UMRB in small to large rivers on a micro (1 m) to river basin scale. Studies conducted outside the UMRB are presented in this section. Studies are divided into those that attempt to predict unionid abundance, distribution, and/or species composition with simple habitat variables on a micro to reach scale (Section 3.2.1) and reach to watershed scale (Section 3.2.2), and those that use more complex hydraulic variables (Section 3.2.3). Depth, substrate constituents, instream cover, and current velocity were the most frequent simple variables measured. Distance from the bank, bank characteristics, canopy cover, adjacent land use, water quality variables, channel characteristics (width, depth, slope), sediment heterogeneity, substrate organic content, and sediment compaction were also considered. On a reach to watershed scale, studies considered bed structures (chutes, riffle, pools), geology of the surrounding landscape, stream size, stream gradient, hydrological variability, physiographic region, watershed land use, regional distribution and abundance of fish species, and dam use and condition. Studies using these simple variables provide some insight into mussel habitat, but studies using more complex variables are more applicable to habitat creation. Shear stress, shear velocity, Reynolds number, boundary Reynolds number, Froude number, substrate roughness, core flow, and bed stability in addition to the traditional depth, current velocity, and substrate characteristics have been used to explain unionid presence/absence and abundance. Most of these papers also considered these variables under various discharge levels. Some studies used data collected in the field, while others developed models to estimate variables at different discharge levels. A few laboratory studies were reviewed that investigated habitat parameters or ideas in a controlled setting (Section 3.2.4). These include a study investigating the influence of mussels on substrate stability and a study on the settling behavior of juvenile mussels. These studies provide insight into some of the common assumptions made in other studies. Section 3.2.5 includes a report on how manipulation on regulated rivers can affect unionid communities.

3.2.1 Simple microhabitat variables-microscale

Strayer, D. L. 1981. Notes on the microhabitats of unionid mussels in some Michigan streams. American Midland Naturalist 106:411-415.

This study looked at microhabitat (depth, substrate type [subjective mud, muddy sand, sand, sandy gravel, gravel, cobbles or bedrock], vegetation, proximity to shore [mid channel or near shore], and current speed [none, slow, moderate, fast or very fast]) of mussels in the Clinton River system (warm water, low gradient, small streams, with high bicarbonate content) in Michigan. The study was conducted under low water conditions. Three conclusions were apparent: 1. most species within a site had similar mean microhabitats (defined as the above variables), 2. species have broad microdistributions within a site, resulting in great interspecific overlaps, and 3. location of the mean microhabitat of a species is not consistent among sites. Some of this may be due to the broadcast dispersal of both glochidia and juveniles. Also, competition among species is likely low due to low density and abundant space.

This was one of the first studies to look at microhabitat variables for mussel species. The observation of mussels at different sites occupying different mean substrate/depth suggests factors other than these explain mussel distribution.

Strayer, D. L., and J. Ralley. 1993. Microhabitat use by an assemblage of stream-dwelling unionaceans (Bivalvia), including two rare species of *Alasmidonta.* JNABS 12:247-258.

The authors studied the microhabitat characteristics (water depth, current speed, bottom roughness, spatial variation in current speed, distance from shore, presence/absence of macrophytes, presence/absence of overhead canopy, patches of fine sediment, and sediment granulometry) within quadrats in the Neversink River, New York. The study area (Neversink River) was divided into 3 reaches (1.4 to 4.3 km long) based on gradient and stream position;

upstream high gradient, high gradient middle reach, and low-gradient downstream reach. They looked at three sites (100 m long) within each reach (riffle, pool, run). Mussels were highly clumped, and current speed (mussels most frequently found at moderate current speed) and spatial variation in current speed (mussels most frequent in areas with relatively uniform flow) were the most useful predictors of mussels. *Alasmidonta heterodon* was most frequently found at moderate current speeds with patches of fine sediment. *Alasmidonta varicosa* was most frequently found at moderate current speed with high proportion of medium sand. However predictive power of microhabitat variables was very low, and the authors question the use of traditional microhabitat variables in predicting freshwater mussel distribution in a stream. Unionid response to most values was non linear and typically peaked at intermediate values. One variable that this study considered was the availability of patches of finer sediment between rocks (measured as the number of successful core samples collected in a quadrat). This variable may be important in very rocky streams such as the Neversink. Although the effects of excessive sediment are often considered limiting, few studies have considered the limitations of reducing the sediment load. Another seldom looked at variable used in this study was the spatial variation in current speed. However, despite the extensive data set (270 quadrats and several measurements per quadrat), most of the variability in unionid abundance was unexplained by the measured variables.

This study looked at simple habitat variables on the reach and microhabitat scale within and outside of areas with mussels. Although some correlation of variables and unionid abundance were found, they had little predictive power. This suggests that more complex variables may be responsible for unionid distribution. This study does point out, however, that unionids prefer intermediate conditions with respect to depth, flow, and substrate, and that lack of fine substrate could be as detrimental to unionids as excessive sedimentation. Other than general principles, this study does not directly apply to habitat creation in the UMR.

Hart, R. A. 1995. Mussel (Bivalvia: Unionidae) Habitat Suitability Criteria for the Otter Tail River, Minnesota. Thesis: North Dakota State University.

The author investigated habitat suitability for 7 unionid species in the Ottertail River in Minnesota with the objective of developing criteria for Instream Flow Incremental Methodology (IFIM). The Ottertail is within the Hudson Bay drainage (Red River of the North), is 290 km long and has an overall gradient of 0.6 m/km. Sampling was conducted in July 1994. Habitats consisted of shallow riffles to deep pools and runs. Data (mussel density, water velocity, water depth, percent of each substrate category, and in stream cover) was collected within quadrats along transects within 5 sites. Water velocity was measured at 0.6 depth (sites < 76 cm), and 0.2

and 0.8 depth (> 76 cm). Even though benthic organisms do not encounter these velocities, they have been shown to be highly correlated with shear conditions and boundary layers. Four species *A. plicata*, *F. flava*, *L. costata*, and *S. undulatus* preferred velocity near 80 cm/s and depth near 150 cm, and avoided areas with velocity < 25 cm/s and depths < 60 cm. Mussels were most frequently found in run habitat with gravel substrates in areas with no in stream cover. *Anodonta (Pyganodon) grandis* preferred slow moving (< 10 cm/s), deep waters (135 cm) with aquatic vegetation.

This study was a good attempt to quantify mussel habitat preferences using the methods developed for IFIM. Habitat Suitability curves for unionid species were developed on a river wide scale. However, depth and flow criteria were measured under low flow conditions rather than over a series of flows. Despite this, preferences were found, with most of the riverine species avoiding shallow depths and slow current velocity. This is likely due to these areas drying out during low water and/or freezing during winter months rather than the animals actually moving into these areas. Likewise, the fewer mussels in higher flow areas is likely due to scour.

Sparks, B. L. and D. L. Strayer. 1998. Effects of low dissolved oxygen on juvenile *Elliptio complanata* (Bivalvia:Unionidae). JNABS 17:129-134.

Juvenile unionids of this very tolerant species exhibited distinct behavioral responses to low (< 2 mg/L) interstitial DO. This factor should be considered when reintroducing unionids or in management practices near unionid beds.

Sietman, B. E., Furman, M. A., and F. A. Pursell. 1999. Colonization of bedrock by freshwater mussels (Bivalvia: Unionidae). The American Midland Naturalist 141:209-211.

This study documents the presence of freshwater mussels under large rocks in an otherwise unsuitable bedrock habitat. Sediment accumulated under rocks provides an area for burrowing, and the rock provides a refugia from flow. As long as these substrates remain undisturbed, mussel communities can persist.

This study points out that mussels can survive in otherwise inhospitable conditions if flow refugia are available.

Hastie, L. C., Boon, P. J., and M. R. Young. 2000. Physical microhabitat requirements of freshwater pearl mussels, *Margaritifera margaritifera* (L.). Hydrobiologia 429:59-71.

This study investigates substrate particle size (1 to 10 m scale and < 1m scale), substrate diversity (using Simpsons Diversity index), depth and velocity as suitable habitat parameters for *Margaritifera margaritifera* in the Kerry River (Scotland). This species is limited to the lower few kilometers of the river, but this appears to be one of the largest populations of this species in Europe. Variables and mussel density were collected at low, medium, and high flow (did not give exceedance values). Based on habitat suitability curves, optimum water depth was 0.3 to 0.4 m and optimum velocity was 0.25 to 0.75 m/sec at intermediate water levels. However, river bed substrate seemed to be the best character for describing habitat, as it is a result of the various hydraulic conditions over time. Boulder stabilized refugia with interstitial sand for burrowing seemed to be ideal for juveniles and adults. Adults were also found in areas with some silt, suggesting they can tolerate siltation for an unknown period of time, but no juveniles were found in silt. Substratum discriminant models used Principle Component axis scores based on surface and subsurface particle sizes, substrate diversity index, and proportion of fine interstitial material. Velocity and depth did not appear to have any discriminant value. The discriminant model correctly predicted mussel presence/absence 76 to 92% of the time.

This study also points out that although velocity and depth preferences were found, they had no discriminating power. The use of substrate diversity in addition to particle size increased the predictive power of their model. Substrate diversity and stability were shown to be important for *M. margaritifera*. These attributes are also often cited as important for North American mussel communities.

Johnson, P. D., and K. M. Brown. 2000. The importance of microhabitat factors and habitat stability to the threatened Louisiana pearl shell, *Margaritifera hembeli* (Conrad). Canadian Journal of Zoology 78:271-277.

The authors investigated the microhabitat variables associated with the distribution of *M. hembeli* in second and third order streams in the Red River drainage in Louisiana. Streams were less than 5 m wide and 45 cm deep. Gradients ranged from 1.9 to 6.1 m/km, and discharge ranged from 0.12 to 0.65 m^3/s. They looked at high and medium density streams, as well as a site without mussels. Water quality (measured at several different times) included temperature, DO, conductivity, pH, redox, total hardness, and free carbon dioxide. Microhabitat variables were measured in 5 streams (at baseflow) with mussels and two streams without mussels that had similar habitat. They measured channel width, mean channel depth, geometric mean sediment size, percent organic content, mean sediment compaction, current velocity, and mussel density. Variables were measured at 11 locations at 100 m increments within 1 km of river, and specifically within mussel beds within the same kilometer. Bed stability was measured as the change in channel profile after 1 year. Streams with mussels had higher conductivity, hardness, pH, and free CO_2 than those without mussels. Channel width, current velocity, sediment compaction, and sediment size were all positively correlated with mussel abundance. Channel depth and organic matter were only weakly correlated. Change in stream bottom profile was significantly greater in channel areas without mussels than with mussels. In general, mussels were found in areas with higher calcium in the water, and in shallow, wide areas with well-compacted substrate, or in patches of larger gravel substrate, all with good flow. These mussels may be selecting habitat, as movement is frequently observed, and an entire bed in one stream moved 7 m upstream in one year after a spate reshaped the channel.

This study also indicates that channel stability is an important factor in mussel habitat. Shallow, wider areas of rivers also change less with increasing flow than more incised channels.

Brim Box, J., R. M Dorazio, and W. D. Liddell. 2002. Relationships between stream bed substrate characteristics and freshwater mussels (Bivalvia: Unionidae) in Coastal Plain streams. JNABS 21:253-260.

The authors looked at the association between 5 species in the Apalachicola, Chattahoochee, and Flint (ACF) river basins and substrate characteristics. Only one species *Villosa lienosa* was associated with well-sorted sediments that contained high proportions of fine particles, but it was unrelated to sediment porosity. Thirty sites were selected that represented 6 species richness categories. At each site, a 100 m reach was delineated and stratified by bank, slope, and channel habitat. Bank habitat extended from the bank to where depth rapidly increased, slope ended where depth leveled out, and channel was the deepest part of the river. Substrate changes were visible between these habitat types. 32 quadrats were randomly sampled in each habitat. Cores in the center of quadrats were used to collect sediment for porosity and particle size. Sediment was characterized in 19 particle size categories ranging from pebble to clay and corresponded to 0.5 phi intervals of the Wentworth scale. Sorting was defined as the ratio of mean/SD of particle sizes and was a measure of substrate heterogeneity. Equally spaced percentiles of each of 3 substrate characteristics (porosity, fraction of fine sediment, and sorting) were used to examine how substrate composition differed among the bank, slope, and mid-channel habitat. Although mussels in the ACF were more common in the bank habitat than in the channel habitat, the difference was unrelated to any systematic differences in the substrate characteristics of the three habitats across sites. Sediment composition varied among the three habitat types, but variation among sites within a habitat was generally much larger than variation among habitats. Thus, observed habitat specific differences could not be attributed to differences in substrate composition. Other factors such as shear stress may better explain variability in mussel distribution.

This study, along with others, indicates that substrate characteristics alone offer a poor explanation of mussel distribution. The authors suggest that the bank habitat, where most mussels were observed, likely provides an area of less shear stress during high flows.

Hastie, L. C., Cooksley, S. L., Scougall, F., Young, M. R., Boon, P. J., and M. J. Gaywood. 2003. Characterization of freshwater pearl mussel (*Margaritifera margaritifera*) riverine habitat using River Habitat Survey data. Aquatic Conservation: Marine and Freshwater Ecosystems 13:213-224.

Hastie et al. (2000) described *M. margaritifera* habitat on the microscale (< 10 m), but noted that larger scale habitat descriptors are also needed, as features of large river reaches or even catchments may be important determinants of mussel communities. River Habitat Survey (RHS) is a method designed for assessing physical habitat quality and impacts at the 50 to 500 m scale. It was developed to provide a semi-quantitative classification system for describing the physical state of British rivers. This study compares the physical components of RHS with *M. margaritifera* distribution in the River Spey, Scotland in 1999-2000. Surveyed sites were equally distributed and included areas with and without mussels. Optimum habitat had > $1/m^2$ and marginal habitat had < $1/m^2$, and 0 was coded as mussels absent. Mussels were positively associated with several RHS variables (boulder/cobble river bed substrates, broken/unbroken standing waves, aquatic liverworts/mosses/lichens, and broadleaf/mixed woodland/bankside tree cover). Negative associations included gravel-pebble/silt substrate and emergent reeds/sedges/herbs. Models developed using these variables had > 80% success rate in predicting mussel presence/absence and optimal mussel habitat.

This study reiterates that optimal *M. margaritifera* habitat includes swift flowing boulder areas, but also points out the associations with riparian habitat and steep banks not considered on a micro scale. Results of this study indicate that at least some of the macrohabitat parameters typically used to classify riverine habitat can be applied to mussels, and that macrohabitat features and microhabitat features are important in the distribution of unionids.

3.2.2 Simple habitat variables-macroscale

Vannote, R. L., and G. W. Minshall. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proceedings of the National Academy of Sciences of the United States of America 79:4103-4107.

This is one of the first papers to link flow refugia with mussel abundance. This study looked at the hypothesis that block-boulders prevent significant bed scour during major floods, and these boulder-sheltered mussel beds, although rare, may be critical for population recruitment elsewhere within the river, especially after periodic flood scour of less protected mussel habitat. The study was conducted in the Salmon River Canyon, Idaho and looked at *Margaritifera falcata*. Their study suggests that local lithology and fluvial geomorphic processes interact to regulate both population size structure and relative abundance of two dominant species *M. falcata* and *Gonidea angulata*. Fluvial bed structures (chutes, riffles, runs, pools, sand beaches, terraces) appear structurally controlled by external factors (large block boulders weathered from adjacent cliffs, outcrops of resistant bedrock, talus, and alluvial fans) in the vicinity of steep tributaries that constrict the river channel and provide debris at a rate or caliber that exceeds river competence. These factors regulate, in large part, the distribution of mussel habitats in the canyon. The study was conducted during summer low flow (60-90 m^3/s). Block boulders were defined as particles > 1 m in length of local origin. Cobble/gravel was measured by pebble count, and underlying sand/gravel was estimated by dry weight. Unionid beds were restricted to cobble/boulder runs connecting pools and riffles. Flow averaged about 1 m/s during low flow and 3-4 m/s during high flow. These areas had laminar flow. Mussels occupied gravel filled interstices of cobble pavement, or were clumped in series of large wave generated scour depressions or in smaller gravel-filled pockets behind large boulders. *M. falcata* dominated when interstitial sediment was gravel protected by block boulders. In this habitat they attained high density and large size and old age. They were absent from deep pools and riffles. *G. angulata* was dominant on stabilized sand gravel bars. In cobble runs without block boulders, *M. falcata* were mostly young. The authors suggest that periodic floods (50-100 yr events) may cause scouring and mussel mortality. Block boulders may dissipate the kinetic energy during floods through turbulence within the water column rather than bed shear. Changes in the watershed are resulting in sediment influx, changing the community from *M. falcata* to *G. angulata* where sand replaces or covers interstitial gravels. *G. angulata* was able to vertically migrate under both sudden and gradual burial by sediments, whereas *M. falcata* failed to migrate and died.

This study not only shows the need for flow refugia, but also points out how changes in habitat can shift species composition due to a species morphology and behavior. Also of interest is the suggestion that block boulders reduce bed turbulence, which later studies show to be related to Reynolds Bed Roughness, Froude no., and shear stress.

Strayer, D. L. 1983. The effects of surface geology and stream size on freshwater mussel (Bivalvia, Unionidae) distribution in southeastern Michigan, U.S.A. Freshwater Biology

13:253-264.

The author presents evidence that the distribution of species in southern Michigan is a function of variables at both the catchment and local levels. Stream size and surface geology (which regulates hydrology, slope, hydraulic variability, and turbidity) were found to explain much of the variance in species distribution.

This was one of the first papers to examine both catchment and local scales with respect to mussel distribution. It has little to do with creating habitat in the UMR, except to reiterate that what works in one area may not necessarily work in the lower portion of the UMR or in the Illinois River.

Strayer, D.L. 1993. Macrohabitats of freshwater mussels (Bivalvia: Unionacea) in streams of the northern Atlantic Slope. JNABS 12:236-246.

The study was one of the first to look at broad scale macrohabitat descriptors (stream size, stream gradient, hydrologic variability, calcium concentration, physiographic province, and the presence or absence of a tide) to predict mussel distribution. Stream size was significant for predicting species richness in non-tidal streams but accounted for little variability in data. Species distributions were affected by different factors. Five species groups were identified based on preferences to various factors or groups of factors. Group 1 were generalists, group 2 were associated with tidewaters, group 3 were more frequently found in large rivers, group 4 were more common in less hydrologically variable streams, and group 5 were influenced most by calcium content. Only stream gradient had limited predictive power. In Michigan, only stream size and surface geology were important in the variation in mussel communities.

This study suggests that macrohabitat variables are important, particularly hydrological variability, in predicting species assemblages on a 1 km scale. However, the variables that were useful predictors on the Atlantic slope were different from those found to be most predictive in Michigan. This study only looked at areas with mussels and did not compare variables between areas with and without mussels.

Vaughn, C. C. and C. M. Taylor. 2000. Macroecology of a host-parasite relationship. Ecography 23:11-20.

This study tested whether mussel assemblage attributes could be predicted from regional distribution and abundance of fishes in the Red River drainage (Oklahoma). Colonization of mussels is totally dependent on dispersal of fish hosts, a regional process, but growth and reproduction should be governed by local environmental conditions and processes. The authors predict that mussel distribution and abundance patterns should result from a hierarchy of constraints that includes historical effects, landscape-level influences, the availability of fish hosts, and local environmental conditions. These processes are intertwined, but they hypothesize that mussel assemblage attributes should be predicable across large spatial scales from the regional distribution and abundance of fishes, and that this effect is detectable above and beyond that due to spatial and environmental constraints. Mussels (species richness and abundance based on timed searches), fish (seining for 45 min up, within, and down of mussel beds), and environmental/spatial variables (distance form upstream tributaries, elevation, stream gradient, position with respect to impoundment, water temperature, pH, conductivity, DO, water depth, current velocity [means and Coefficient of Variation], calcium content, watershed area) were collected from 36 sites in the Red River. Mussel species richness and fish species richness were positively associated. Maximum mussel richness was limited by fish richness, but richness was variable beneath this constraint. Sites with high fish richness had a wide range of mussel species richness values, but sites with low fish species richness never had high mussel species richness. Measured environmental variables and local fish assemblages each significantly accounted for the regional variation in mussel assemblages. Combined 79.3% of variation in mussel assemblage matrix was accounted for. Fish alone accounted for 15.4%, space 16.1%, and environment 7.8%, fish + space 20.7%, space+environment 3.2%, fish+environment 4.9%, and fish+space+environment 11.2%.

This study points out the significance of fish habitat in association with mussel habitat. In the creation of physical habitat for mussels this should be strongly considered. However, like other habitat factors fish species richness seemed to be a limiting factor rather than a determining factor.

McRae, S. E., Allan, J. D., and J. B. Burch. 2004. Reach- and catchment-scale determinants of the distribution of freshwater mussels (Bivalvia: Unionidae) in south-eastern Michigan, U.S.A. Freshwater Biology 49:127-142.

This paper explores the hypothesis that unionid abundance, richness, and diversity is influenced by a combination of reach-scale (100 m) habitat variables (substratum, water chemistry, flow, channel shape measured in the field) and subcatchment-scale geology and land use variables (surficial geology and land use-1 km scale from GIS coverages). The study was conducted within the Raisin River basin in Michigan. Sites were throughout the mainstem and tributaries. Four mussel groupings, based on overall mussel diversity and abundance, were significantly associated with reach-scale variables. Best communities were at sites with overall higher habitat quality, greater flow stability, less fine substrate, and lower specific conductance. Measures of surficial geology were most effective catchment-scale variables. Spatial geology patterns (upper watershed higher gradient, more forested, less agriculture) are likely responsible for the higher quality unionid communities in the upper watershed. A combination of reach and catchment scale habitat variables accounted for a substantial amount of spatial variability in mussel distribution.

This paper substantiates others that mussel distribution is a function of catchment scale to micro scale habitat variables. At the reach scale, flow stability was important.

Gagnon, P., W. Michener, M. Freeman, and J. Brim Box. 2006. Unionid habitat and assemblage composition in Coastal Plain tributaries of Flint River (Georgia). Southeastern Naturalist 5:31-52.

The authors used macro (catchment scale variables such as stream size and drainage position, predominant catchment landcover, riparian landuse, and physiographic province type) and meso (stream gradient, channel depth, hydrological variability, stream ion content, substrate composition) habitat variables to assess habitat conditions that were associated with mussel species richness, abundance, and diversity (SW) in tributaries of the Flint River in Georgia. The study was conducted under base flow conditions during mid-June to late August 1999. Average mid-channel depth, drainage network position, riparian wetland cover, and catchment forest cover were the best predictors of richness, abundance, and diversity. Four species groups associated with various levels of these parameters separated in CCA. The slackwater species group (*Utterbackia peggyae*, *U. imbecillis*, *Villosa lienosa*, and *Pyganodon grandis*) was associated with small shallow streams, high conductivity, fine sediment cover, and detritus, pools, stream margins, backwaters, and headwaters. Large-river riffle species (*Elliptio arctata*, *Megalonaias nervosa*, *Elliptio crassidens*) were associated with large catchments, deeper flow, high levels of coarse woody debris, flow stability, and low levels of fine sediments and detritus; larger and deeper streams, more riffle habitat and lower amounts of detritus, fines, and coarse wood debris, and lower riparian forest and riparian wetland cover. The most abundant group were the generalists (*E. complanata/icterina*, *Villosa lienosa*, *Villosa vibex*, *Toxolasma paulus*, and *Uniomerus carolinianus*). These sites had few distinguishing characters but had more pool habitat and riparian wetland cover, but lower sediment bulk density than non-supporting sites. Stream-run species included federally endangered and state species of special concern (*Lampsilis subangulata*, *Medioniodus pencillatus*, *Pleurobema pyriforme*, *Elliptio purpurella*, *Lampsilis straminea claibornensis*, *Quincuncina infucata*, and *Strophitus subvexus*). These were found in larger streams (greater catchment area, greater drainage network, greater average depth) with significantly lower conductivity, greater flow stability, and greater catchment forest and riparian wetland. These habitats were between riffle and slack water, stream run species.

This study again demonstrated that variables on multiple scales contribute to mussel distribution and species composition. At the meso scale, flow stability (measured as the ratio of base flow/bankfull water level), average depth, and bulk density of substrate (dry mass of sediment/wet volume) were the best predictors of diversity, and Manning's n roughness and average depth were the best predictors of richness. These variables are not particularly useful in calculating hydraulic parameters to use for habitat creation, but reiterate that stability is an important component in mussel habitat, and that different species groups respond to different variables, some micro and some macro.

Haag, W. R., and M. L. Warren. 2007. Freshwater mussel assemblage structure in a regulated river in the Lower Mississippi River Alluvial Basin, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 17: 25-36.

This study looked at a small-regulated reach (2 to 3 km) of the Little Tallahatchie River in Mississippi. This reach was downstream of a large dam, Sardis Dam, but upstream of a small lowhead dam. Sardis Dam was the largest earthfill dam in the world when constructed in 1940. Because of the impounded nature of Lower Lake and the regulated input via Sardis Dam spillway, physical habitat conditions are relatively stable in the reach between these dams most of the year. Deviations from stability occur during high release periods associated with gradual reservoir drawdown in fall and periodic closure for dam maintenance and inspection. Differences in current velocity and substrate due to flow patterns in the lower lake have resulted in 4 distinct habitat types; riverine (strong current, sand/gravel substrate), open lake- with current (slight current, clean sand substrate), open lake- no current (no current, silty sand substrate), and lentic (no current, silt substrate). Density, species richness, and species composition varied among these habitat types, but all 4 habitat types supported mussels, and recruitment was evident in all of the communities. Density and species richness was highest in the most lotic situations. The presence of a diverse, healthy mussel community in this highly modified habitat suggested that a large component of the regional mussel fauna was relatively resilient and adaptable, but was limited by the lack of stable river reaches. Management actions that increase stream stability would likely result in the expansion of mussel fauna.

Although not intentional, the creation of a stable hydraulic environment in this river reach resulted in the creation of mussel habitat. In smaller upland streams, mussels need more flow refugia; in this lowland river, mussels require more flow and areas with stable coarser substrate. The hydraulic conditions necessary for habitat creation will differ depending on the geomorphic and hydrological conditions in the river basin.

Nicklin, L., and M. T. Balas. 2007. Correlation between unionid mussel density and EPA habitat-assessment parameters. Northeastern Naturalist 14: 225-234.

The authors looked at the correlation between EPA physical habitat parameters and mussel abundance in the middle Allegheny River. They looked at water quality parameters (pH, ammonium, nitrite, nitrate, sulfate, calcium, and phosphate), and physical parameters including in stream cover (boulder, cobble, submerged logs, undercut banks), embeddedness, velocity/depth regimes (slow-deep, slow-shallow, fast-deep, fast-shallow), and sediment deposition (point bars, percent of bottom with sediment deposition). No significant correlations were apparent with water quality parameters; however, all values were within the range considered acceptable to freshwater mussels. Significant positive correlations occurred with physical parameters (more in stream cover, lower embeddedness, higher habitat heterogeneity, lower sediment deposition). The authors concluded that these parameters could be used for assessing mussel habitat.

Although these parameters worked for this river, the authors did not appear to understand what they were actually measuring with respect to unionid habitat. Instream cover in this case likely measured the amount of coarse substrate or flow refugia in the river and lower embeddedness likely reflected the lack of siltation. They did not take into account that very low embeddedness would not be good for mussels, as mussels need areas for burrowing. Habitat heterogeneity is good for various species of fish, and mussels generally occur in run habitats or on the edges of riffles. Low sediment deposition however would be directly related to mussel habitat. This paper discusses habitat but does not provide any information that would be useful for creating habitat in the upper Mississippi River.

Karatayev, A.Y., and L.E. Burlakova. 2008. Distributional survey and habitat utilization of freshwater mussels. Report to the Texas Water Development Board.

The authors looked at macro and microhabitat factors affecting unionid distribution in the San Antonio, Brazos, and Sabine drainage basins in September 2006 and June 2007. They sampled 44 sites for mussels, and measured temperature, DO, pH, total dissolved solids, specific conductivity, and turbidity. Water velocity was measured at 60% and at 2" above the substrate. Substrate (visual observation) was recorded using 17 substrate types. The Lower Sabine River had lowest density and diversity, likely due to higher current velocity and sand substrate (unstable habitat). However, other factors such as massive fish kills could contribute. More than a snap shot of a small number of sites is needed to draw conclusions about lack of mussels. No mussels were found at water velocity > 30 cm/sec (60% of depth) and > 16 cm/s (2" from bottom). Most mussels were found at < 3 cm/s (2" from bottom). Optimum velocity for mussels corresponded to the velocities below the erosion line on the Hjulstrom's diagram (roughly equivalent to critical shear stress?). Current velocity was also the only significant factor in forward stepwise multiple linear Ridge regression. Correlation was negative (more mussels at lower velocity). Water velocity (along with a few other parameters pH, turbidity and TDS) affected mussel abundance, but the model had low explanatory power. Water velocity at 2" above the substrate was also the most important variable predicting presence and absence of mussels in an ANOVA of similarities. In PCA analysis, Factor 1 correlated with pH and conductivity (negative). Velocity (2"), substrate type, and percent organics in substrate correlated with Factor 2 (negative). Unionids were most abundant at sites with higher pH and conductivity, and lower velocity. However, relationship were not clear, as velocity was measured at different flow levels at different sites. Substrate was also important. Highest density and number of species were on substrates of silt/clay, silt/sand, sand/clay, and sand with the maximum abundance in silt/sand. Velocity at 2" above the substrate was more predictive than velocity at 60% when using only sites with velocity measured on the same date were considered. The authors also suggest that shear stress may be driving the community

This study, although conducted over a wide variety of river sizes, suggests that mussels cannot occupy areas with current velocity (measured at 2") > 16 cm/sec (measured at low flow). Although current velocity at 60% (standard measurement) had some predictive value, measurements at 2" were much better. However, they also indicate that velocity changes with discharge and that predictive velocity also likely changes with substrate types, and suggest shear stress is an important factor in unionid distribution in these rivers.

Galbraith, H. S., and C. C. Vaughn. 2010. Effects of reservoir management on abundance, condition, parasitism and reproductive traits of downstream mussels. River Research and Applications 27:193-201.

The authors examine the effects of a hydropower dam vs. a run of the river dam in the Little River, Oklahoma on mussel density, hermaphroditism, parasitism rates, reduced body condition, and sex ratio for *Quadrula pustulosa*, *Q. cylindrica*, and *Q. fragosa*. The hydropower dam had higher summer flow and lower summer temperature than the run of the river dam. Mussel density was lower, hermaphroditism and parasitism rates were higher, and body condition was reduced downstream of the hydropower dam. Alteration from natural flows can alter population dynamics of mussel species that may ultimately affect population viability.

This study does not directly relate to habitat creation in the UMR, but does point out some of the physiological and population processes that can be affected by altering flow regimes.

Gangloff, M. M., E. E. Hartfield, D. C. Werneke, and J.W. Feminella. 2011. Associations between small dams and mollusk assemblages in Alabama streams. JNABS 30:1107-1116.

The authors looked at mussel assemblages up and downstream of lowhead dams (< 10 m head) that were intact, relic (obstructed < 25% of the channel), and breached (obstructed 25 to 95% of the channel) in 3rd to 5th order streams in Alabama. Mussel abundance and species richness was greater at sites with intact dams, likely due to stability. Compared with historic fauna (post dam data), relic, breached, or intact/breached dams had lost 80% of their fauna compared to intact dams that lost only 8.4%. Breached and relic dams were probably disturbed in an uncontrolled manor that could have scoured mussel communities and those communities have not had time to recover. Overflow dams may stabilize substrates and increase suspended organic and inorganic matter export to downstream reaches, supplementing mussel food resources.

This study does not have direct relevance to habitat creation in the UMRB, other than to emphasize that rapid changes in hydraulic conditions can negatively affect freshwater mussel communities, and communities may require decades to recover.

3.2.3 Complex hydraulic variables

Di Maio, J., and L. D. Corkum. 1995. Relationship between the spatial distribution of freshwater mussels (Bivalvia: Unionidae) and the hydrological variability of rivers. Canadian Journal of Zoology 73:663-671.

The authors tested the hypothesis that unionid species composition is associated with hydrological features of a river on a drainage basin level. Thirteen event sites (hydrologically flashy) and 9 stable (hydrologically stable) sites were sampled in southwestern Ontario and southeastern Michigan (Great Lakes drainage) in 1993. Multivariate analysis revealed that distinct mussel communities were associated with each river type. *Amblema plicata*, *Pyganodon grandis*, and *Fusconaia flava* characterized event sites, and *Elliptio dilatata*, *Lampsilis radiata*, and *Lasmigona costata* characterized stables sites. Flashy and stable streams were defined using criteria in Richards (1990), who defined streams as event, variable, stable, and super stable based on variables associated with the frequency and magnitude of floods and droughts. All sites were wadable and supported mussels. Physical parameters measured included drainage basin, elevation, bankfull depth, slope, substrate in motion (%), and median particle size (D). *t* (tractive force) was calculated at 1000 (specific mass of water kg/m^2 x D (depth of flow) x S (slope m/m) at bankfull depth. Slope was measured using a pocket transit over a distance approximately 6x the width of the site. Percent of particles in motion was calculated by determining the size of randomly selected rocks, developing a frequency distribution curve, and determining the percentage of particles > t_c (critical shear stress) for the t at bankfull discharge. Slope was greater at stable sites, but bankfull depth was greater at event sites. Mean particle size was the same. Percent substrate in motion was slightly higher (but not significant) at event sites. Most hydrological variables, measured at the microhabitat scale were not significantly different suggesting that the differences in species at these sites was related to macro rather than microhabitat features. Both t and percent of sediment in motion did not differ between river types. Differences in species may be related to behavior, physiological processes, and/or fish community tolerance to flow.

This study points out that factors on the reach or river basin scale can influence the composition of mussel communities. It also demonstrates that the frequency and magnitude of hydrological events can affect unionids. This should also hold true on a smaller scale. Differences in species composition on a smaller scale (different beds within a river reach) may in part be determined by the frequency and magnitude of higher velocity events on a local level.

Layzer, J. B., and L. M. Madison. 1995. Microhabitat use by freshwater mussels and recommendations for determining their in stream flow needs. Regulated Rivers: Research & Management 10:329-345.

This study investigated the use of IFIM and PHABSIM (Physical habitat simulation model) for describing mussel habitat. Although this approach is useful for fish, mussels are not mobile and traditional simple hydraulic measures of depth and velocity change over a mussel bed with variation in discharge. The study was conducted in Horse Lick Creek, a fourth order stream in the upper Cumberland River drainage in Kentucky. Water depth and velocity were limiting at low discharge. Mussels at base flows more frequently used depths between 7 and 30 cm and areas with at least some velocity. However, complex hydraulic characteristics such as shear stress were significantly correlated with mussel abundance for flows ranging from 0.03 m^3/s (base flow) to 2.18 m^3/s, which are the range of flows during typical juvenile settlement. This relationship did not hold for higher flow levels (9.35 m^3/sec), due to the differences in channel morphology. These higher flows may prevent juvenile settlement. Froude number and Reynolds number were correlated at low flow, but not at higher stream discharges. Shear stress and stream power were negatively correlated with mussel densities for stream discharges 0.03 and 2.18 m^3/s. The authors recommend limiting shear stress to 50 dynes/cm^2 over existing mussel beds, based on the equations they used for calculation (formula in Statzner et al. [1988] used in calculations). The authors caution that other formula may result in different limits.

This was one of the first studies to use complex hydraulic variables in the description of mussel habitat and identify shear stress at higher flows as a limiting factor. They note that high shear stress was associated with low mussel densities, but that the relationship was more variable at shear stress < 40 dyne/cm^2. Even though Froude number and Reynolds numbers correlated at low flows, they did not investigate these numbers further due to the lack of correlation at higher flows. However, it may be that Froude and Reynolds numbers are the limiting variables at low flow, and shear stress at higher flows.

Strayer, D. L. 1999. Use of flow refuges by unionid mussels in rivers. JNABS 18:468-476.

The author explores the within-reach patchiness of mussels in two small rivers in New York (Neversink [drainage area 606 km^2] and Webatuck Creek [drainage area 215 km^2]). He tests the hypothesis that mussels are found chiefly in stable areas of the river bed where hydraulic stresses during floods are low. He suggests that refuges should be sufficient to protect unionids during flow intervals approximately equal to their life spans (decades). Mussels were found in flow refugia, but their location did not coincide with measures such as water depth, current speed, and sediment size. Persistent patches of mussel abundance were mapped in 1995 and 1996. Winter floods occurred in 1996 (5 to 6 yr frequency-above bankfull). In both rivers, mussels were found in areas where markers (made up of marked rocks of consistent sizes) moved less during high flows. Mussel density was 15x higher in flow refugia in the Neversink and 5x greater in the Webatuck. Results suggest that mussel beds occur in areas where flood shear stress was below some threshold value. No mussel beds were found outside of flow refugia, although some flow refugia were found that did not harbor mussels. Even when mussel density and microhabitat variables are well correlated at one site, they are often uncorrelated between sites. The same species may be in gravel at one site and mud at another due to differences in flow at higher discharge levels. He disagrees with Layzer and Madison (1995) that the distribution is a function of juvenile settling, as species settle at different times of year when shear stresses differ, yet all species are found in the same area. He also indicates that flow refugia do not explain all of mussel patchiness, as mussels were not found in all flow refugia. Uncolonized refugia could have other limiting factors, or the refuge has not existed long enough for mussels to colonize. These results raise the question of how mussels come to occupy these flow refugia. Perhaps beds are the product of differential survival. Juveniles settle evenly over the stream, but only survive in flow refugia. Alternately, host fish may remain close to the mussel beds where they are infected with glochidia and juveniles tend to settle within the beds.

Perhaps juveniles can sense existing mussel beds and settle as in some marine invertebrates.

This study, along with Layzer and Madison (1995) was one of the first to test the idea of shear stress as a factor in mussel distribution. As with later studies, this study points out that shear stress is likely a limiting factor (unionids found in flow refugia, but not all flow refugia contain unionids). The idea that juveniles could "select" to settle in these refugia is interesting and some evidence for altered juvenile behavior to induce settling (foot movement) was seen by Schwalb et al. (2011). Strayer suggests that some threshold shear stress value at flood frequencies of 3 to 30 yrs may be responsible for mussel patchiness. More recent studies suggest that shear stress is greatest at bankfull flows, rather than higher frequency floods.

Hardison, B. S., and J. B. Layzer. 2001. Relations between complex hydraulics and the localized distribution of mussels in three regulated rivers. Regulated Rivers: Research & Management 17:77-84.

These authors were among the first to look at the relationship of complex hydraulic variables and mussel abundance. They examined five sites on the Green, Licking, and Rough Rivers in Kentucky. All of these rivers had dams upstream of their sampling sites. These rivers had lower peak flows, but prolonged periods of moderately high discharge from fall to late spring or mid summer, a time of Lampsilini excystment from fish hosts. In all rivers, mussel density was negatively correlated with shear velocity and FST hemisphere number (a measure of shear stress). All sites were sampled during July 1995, a period when discharge was similar to pre dam conditions (presumably low flow). Depth and water velocity (0.6 of the water column) was measured in each quadrat. Substrate roughness *k* was measured with a 100 cm chain stretched to the substrate contours (*k*=100/linear distance of chain). Shear stress was estimated with FST hemispheres. Reynolds number (Re), Froude number (Fr), shear velocity (U_*) and Reynolds roughness number (Re_*) was calculated with standard formula. Mussels were present at all sites, but FST number, U (mean velocity), Fr, U_*, and Re_* were negatively correlated with mussel density in all rivers. This indicates that even at low flow, shear velocity can affect density. They attribute this to lack of juvenile settlement, as little to no recruitment was observed particularly for Lampsilini.

Howard, J. K., and K. M. Cuffey. 2003. Freshwater mussels in a California North Coast Range river: occurrence, distribution, and controls. JNABS 22:63-77.

This study was conducted in the South Fork Eel River, a high gradient stream in northern

California. This study looked at a continuous 8 km reach of river, and considered habitat variables at the macro (8 km), meso (within riffle/pools/runs), and micro scale (within areas harboring mussels). At the reach scale, mussels were limited to pools, where shear stress during 5 yr flood levels (modeled with HECRAS) averaged 5 Newtons/m^2 compared to riffles where shear stress averaged 80 N/m^2. Winter velocity in these areas ranges from 1 to 3 m/sec. Mussels were absent from locations of highest stress and velocity, but their occurrence was variable within low stress areas. Riffles were also stressed in summer by shallow depths, whereas pools provided sufficient depth. This is in contrast to Vannote and Minshall (1982) who found *M. falcata* in runs in the Salmon River. Pool areas in the Salmon River were severely aggraded by sand and gravel (may also be differences in gradient). Within pools (micro scale) *M. falcata* occurred almost exclusively within sedge root mats or in crevices in bedrock and cobble interstices.

This study does look at complex hydraulic factors at a reach scale within and outside of mussel beds. Shear stress limits unionids in this stream to pools, and within pools to only the most stable areas. Average shear stress for 5 yr flood levels within and outside of mussel beds is given. However, this study was in a small stream in a high gradient area and with species adapted to these high gradients.

Peck, A. J. 2005. A reach scale comparison of fluvial geomorphological conditions between current and historic freshwater mussel beds in the White River, Arkansas. M.S. Thesis – Arkansas State University.

This study looked at habitat variables on the reach scale in the lower White River, Arkansas. The flow regime, sediment transport regime, and channel geometry were compared between mussel beds with present day high mussel densities and with areas that historically had high mussel densities to determine if geomorphological conditions influence White River mussel beds. Mean velocity, bed velocity, Froude number, and stream power were all significantly lower in the area of the mussel bed than in other areas. Differences between present and historic mussel beds were less apparent with the exception of shear stress and marginally stream power. Shear stress was higher at historical beds than in current mussel beds. Mussel beds in the White River occur in velocity refuges, but also in sediment refuges. Energy, sediment, and biological regimes were clearly related in the lower White River. How these components shift in relation to each other is critical to maintaining system integrity. Five general components of aquatic systems are thought to influence aquatic communities; hydrologic, physical habitat, energy, chemical, and biological interaction regimes (TNC, 2000). These regimes and flow between regimes can be measured as micro and macro habitat variables. The first objective of this study was to quantify reach scale information relating to the physical energy regime associated with present and historic mussel beds in the lower White River. The second objective was to quantify reach scale information on sediment regime (sediment transport as both bedload and suspended sediment over multiple discharge events). They also analyzed size classes being transported to determine required flow thresholds and the frequency these thresholds occurred. The third objective was to look at the structural dimension of the river channel to determine if planform influences mussel presence and absence. Lateral scour pools (LSP) along outside bends have lower mean velocity, bed velocity, Froude number, and stream power, and serve as flow refugia. The region where the core flow migrates from the inner to the outer bank acts as a downstream boundary to the mussel bed. During high flow this inflection point migrates downstream. Future research should determine the dimensions and location of the core flow at multiple flow stages and at sustained moderate levels typically associated with regulated rivers. The core flow may also expand laterally during high flow, limiting the lateral expansion of a bed. Froude number also supports the refugia theory. LSP/outside cells were characterized by sub-critical flows, while other areas such as riffle/inside or glide/outside were critical to supercritical flows. Shear stress was higher in areas with historical beds (now lower in density) than in present beds, but differences in shear stress were not apparent among habitats within a reach. However, this could have been due to methods. Mapping stream power more precisely may also lead to presence/absence thresholds. LSP/outside bends were also areas of significantly less bedload transport than other cells. Many samples had no bedload. This appears to be largely controlled by strength and location of core flow pattern.

This study identified a range of several hydraulic parameters that could be used in considering values for mussel bed creation. It also points out the importance of core flow patterns in forming flow refugia, which appear to be areas of low to no bedload movement, lower current velocity, lower Froude number, and lower stream power than other areas within a meander. Since river training structures are designed to direct core flow, results of this study may be particularly applicable.

Feminella, J.W., and M.M. Gangloff. 2001. Analysis of relationships between unionid mussels and stream hydrology in tributaries of the Coosa and Talapoosa Rivers, Alabama. Prepared for Alabama Department of Conservation and Natural Resources, Division of Game and Fish. 24pp.

This is a report for a three-year study of unionids in Coosa and Tallapoosa River. The authors suggest that some of the differences were due to differences in hydraulic parameters. This data along with subsequent years and analysis is presented in Gangloff and Feminella 2007.

Gangloff, M. M., and J. W. Feminella. 2007. Stream channel geomorphology influences mussel abundance in southern Appalachian streams, U.S.A. Freshwater Biology 52:64-74.

The authors examined the association between freshwater mussel abundance and species richness and stream hydraulic parameters across eight Appalachian catchments in southeastern US. Mussels in these streams are now limited to highly localized reaches. Specifically, the authors examined the degree to which directly and indirectly measured physical habitat attributes predicted mussel abundance and species richness, and modeled site-specific nearbed shear stress and bed stability, at both baseflow and bankfull (spate-approximately yearly) conditions, to assess the importance of scouring flows and potential for streambed movement on mussel distribution and abundance. They quantified mussels and habitat at 8 Coosa tributaries, 3rd to 6th order, over several physiographic regions. Due to low unionid density, they used CPUE rather than quadrats. They searched a 50 m reach of each site for 1 hour. They measured water depth, mid-depth current velocity, and shear stress along six evenly spaced transects across the site during low flow. They also measured channel gradient and bankfull width and depth at 10 m intervals along the left and right banks, and mid channel. Substrate was quantified by measuring the maximum diameter of 20 randomly selected particles along each of the six transects. Shear stress was quantified using FST hemispheres. They also derived shear stress (*t*) from bankfull depth, mean slope and g (gravitational acceleration). Reynolds number (Re) and Froude number (Fr) and an index of bed stability (t/t_c for median particle size at baseflow and bankfull) were calculated. They tested the hypothesis that sites with higher mussel abundance and richness had lower shear stress, and that bankfull *t* was a better indicator of abundance and richness than baseflow *t*. They also predicted that sites with lower bedload movement (based on the bed stability index) would have higher abundance and richness, and that bankfull stability would be more important than baseflow stability. Results suggest that shear stress during high-flow periods was a critical factor affecting mussel distribution in southern Appalachian streams, as sites experiencing higher shear stresses during bankfull floods had fewer mussels than sites with lower bankfull shear stresses. Abundance was low at high shear stress sites, but variable at low shear stress sites; indicating shear stress is a limiting factor, but when bank full shear stress is low, other factors likely constrain abundance.

As with other studies, this study indicates that shear stress and bed stability at high flows limits unionid abundance. However, this study was also conducted within mussel communities rather than between areas with and without mussels. This study was also within smaller, high gradient streams. Although relationships were identified, no values for shear stress levels that limit abundance were given.

Rahm, E. J. 2008. Spatial distribution and microhabitat of adult and juvenile mussels (Bivalvia: Unionidae) within a bed. M.S. Thesis, Tennessee Technological University.

This study investigated complex microhabitat parameters at a microhabitat scale (100 m x 45 m) in the Green River, Kentucky. The objective was to determine the distribution of juvenile and adult mussels within a mussel bed and determine if distributions were related to simple and complex microhabitat variables. Distance from the bank was significant. Two peaks were apparent in adult abundance, one near the right descending bank (RDB) (7.5 m from the bank) and one 37.5 m from the bank (river was 45 m wide). Almost all juveniles were within 10 m of the RDB. Mean water column velocity explained much of the variation in adult distribution, but little of the juvenile distribution. Reynolds number (Re) was significant for both adults and juveniles. Except for substrate roughness (*k*), all variables were highest mid river, where mussel density was lowest. Adult density (with the exception of data from the left descending bank [LDB]) was negatively correlated with most habitat variables, but was positively correlated with substrate roughness. Juveniles were only negatively correlated with distance, depth, and Reynolds number. The left bank in this study appears to get scoured during high discharge, but had lower values for all hydraulic variables during sampling. The rather homogenous hydraulic conditions during low flow may become highly heterogeneous across the study site at high flow. The author also suggests that not only do these factors vary within a river reach with discharge, but that the factors affecting the spatial and temporal scales of hydraulic effects likely differ within a river and among river systems. No one factor consistently affects the recruitment and survival of unionids in all streams. Successful recruitment may require favorable conditions for a multitude of factors.

This study does give a range of values for hydraulic parameters and indicates that mussel density is negatively correlated with all but bed roughness. The author also suggests that the variables and values for those variables that are important to unionid distribution likely differ within a stream and between streams.

Randklev, C. R., Kennedy, J. H., and B. Lundeen. 2009. Distributional survey and habitat utilization of freshwater mussels (Family Unionidae) in the Lower Brazos and Sabine River basins. Prepared for the Texas Water Development Board.

This paper looks at the distribution of mussels with respect to their physical habitat in the lower Brazos and Sabine River basins in Texas. They looked at depth, velocity, shear stress, relative substrate stability [RSS (calculated slightly differently than Morales et al. (2006)], Froude number (Fr), Reynolds number (Re), and Boundary Reynolds number (Re_*). Lower Brazos River was sampled under low flow; Lower Sabine River was sampled under high and low flow. In the Lower Brazos River, boundary Reynolds number and Froude number were most predictive of mussel presence/absence. Highest occurrence of mussels was at Re* ≥ 11.01. If Re* was < 11.01, then Froude no ≥ 0.1503 was most predictive of mussel presence. This suggests a minimum Re* is needed under low flow conditions to meet physiological needs. However, in the lower Sabine River, RSS and water depth were most predictive. At low flow RSS < 0.6027 had higher occurrence of mussels. Where RSS was < 0.6027, water depth ≥ 0.335m was most predictive. Different mean grain sizes also affected mussel presence. Higher density occurred at sites with coarse sand and higher substrate stability.

This study reiterates that the factors limiting unionid presence/absence can differ among rivers. It also supports that a minimum Re* and Froude number is needed during low flow. This could be due to the need for incoming DO and food, and the washing out of wastes or for the exchange of pore water that could be important for juvenile survival. The Lower Brazos was not sampled at higher flow. RSS was most important in the Sabine at both high and low flow, possibly due to differences in substrate between the two rivers. Substrate in the Lower Brazos was coarser than in the Lower Sabine.

Allen, D. C., and C. C. Vaughn. 2010. Complex hydraulic and substrate variables limit freshwater mussel species richness and abundance. JNABS 29:383-394.

Several authors have suggested that excessive shear stresses limit unionid communities. Substrate stability also seems to be important but there is less evidence of this relationship due to lack of quantified substrate, lack of measurement of shear stress at both high and low flow, and use of models without ground truthing. While a relationship between substrate stability and mussel abundance and species richness is expected, as adults are less likely to be washed out and juvenile colonization and survival should increase, there is no empirical evidence. Further, these may only be some of the factors limiting unionid communities. Strayer (2008) suggests that fish host distribution, food quality and quantity, water quality, and temperature are also important. This study looked at shear stress and substrate stability as limiting factors rather than predictive factors. Substrate, depth and velocity were quantified in six mussel beds. Quantile regression models were used to analyze seven models as limiting unionid abundance and species richness in the Little River, Oklahoma. The Little River is a major tributary of the Red River that drains 10,720 m^2 in Oklahoma and Arkansas. Several models were investigated.

Substrate model (mean particle size [D] + substrate heterogeneity [sorting index]).

Low flow hydraulic model (low flow Reynolds number [Re] + shear stress (t) + relative substrate stability [RSS=t/t_c])

High flow hydraulic model (high flow Re + t +RSS)

Low flow substrate and hydraulic model (Re + t + RSS +D + substrate heterogeneity)

High flow substrate and hydraulic model (Re + t + RSS +D + substrate heterogeneity)

High flow substrate stability (high flow t + RSS)

Global model, all substrate and flow variables

Substrate stability at high flows is an important factor governing mussel distributions. High flow models were much more predictive than low flow models. Hydraulic variables related to substrate stability at high flows were most limiting for mussel species richness and abundance. Both substrate and hydraulic variables are important in estimating substrate movement for suitability of mussel habitat. Some substrate movement may be tolerated, as abundance and species richness were high when RSS > 1 (substrate movement). However, these metrics declined when RSS > 2. RSS used in the model may be biased, as it was calculated with D_{50} and larger substrates > 63.5 mm were excluded from samples. So RSS > 1 in this study indicates that some but not all substrate is in motion at high flows. Mussels were also not considered in particle size, and high mussel densities may increase substrate compaction and cohesion, decreasing the ability of substrate particles to become entrained.

This study empirically tests ideas of Young (2006), Morales et al (2006), Steuer et al. (2008), and Zigler et al. (2008), but in a smaller (but very species rich and high density) river. They also determined that hydraulic parameters were limiting factors, not determining factors. Mussels do not occur above thresholds, but abundance and species richness were variable below these thresholds.

Fulton, J. W., C. R. Wagner, M. E. Rogers, and G. F. Zimmerman. 2010. Hydraulic modeling of mussel habitat at a bridge-replacement site, Allegheny River, Pennsylvania, USA. Ecological Modelling 221:540-554.

The authors measured depth (bathymetry transects), velocity (depth averaged, acoustic Doppler current profiles), and mussel abundance (quantitative) at the East Brady bridge in the Allegheny River (drainage area 20,180 km^2) in 2004. Data were input to ArcGIS and a 4.9 m x 4.9 m mesh was created. Cell dimensions were selected so that a statistically significant analysis could be conducted using a sufficient number of samples based on n=z/2$^{\wedge 2}$ * variance$^{\wedge 2}$/tolerable error$^{\wedge 2}$. Shear stress and Froude number were based on interpolated depth and velocity data assigned to each cell by ArcGIS. Only a low flow event (145 m^3/s = 60% exceedance) was modeled, as time did not allow for collecting data during a high flow event. Results suggest that the greatest abundance of mussels occurs along the left bank and mid channel at the East Brady bridge, where depths were less than 3.6 m, mean vertical velocity ranged from 0.061 to 0.21 m/s, shear stresses ranged from 0.48 to 3.8 dynes/cm^2, and Froude number ranged from 0.006 to 0.04. These hydraulic boundaries were applied to the proposed Foxburg bridge upstream of the East Brady bridge. Existing conditions were measured (depth, velocity) at the existing Foxburg bridge, and changes in these parameters based on the new bridge design were modeled. Mussel distribution for the Foxburg bridge was not available at the time of this paper. The above hydraulic limits (based on the East Brady bridge) to mussel distribution were applied to the existing and proposed Foxburg bridge. Results indicated that the area of suitable mussel habitat would be increased by the new bridge design.

This approach could be used in creating mussel habitat in the UMRB. Depth, velocity, and mussel distribution could be measured in areas with and without mussels and models developed to determine the ranges of hydraulic parameters that appear to be limiting mussel distribution. These values could then be applied to design of river training structures. An email was sent to John Fulton to inquire whether any follow up monitoring was conducted to determine the success of his model (Feb 13, 2013 email). No monitoring has been conducted on this project to determine if areas predicted to provide habitat did provide habitat.

Goodding, D. 2012. Influence of substrate and hydraulic variables on habitat preferences of a sculptured and an unsculptured freshwater mussel. M.S. Thesis – University of Texas at Tyler.

Goodding tested the hypothesis that habitat preferences, as measured by hydraulic variables, differ for smooth and sculptured species. He conducted his study in the Sabine River in Texas, a medium sized river (average width 58 m, average flow 250 m^3/s), with *Lampsilis teres* and *Quadrula (Tritogonia) verrucosa*. He also looked at three scales for each of the variables; reach (4 km), transects, and quadrats. All variables were correlated at the reach scale, as averaging values loses variation. *Lampsilis teres* did not exhibit habitat preference on any scale, as this species appears to be a habitat generalist. *Q. verrucosa* abundance and density was positively correlated with shear stress, critical shear stress, Reynolds number, and average particle size, but negatively correlated with maximum depth and relative substrate stability (*t*/*tc*), suggesting that this species prefers areas with larger substrate that can tolerate higher shear stress, but as substrate stability declines so does this species. At the quadrat level, *Q. verrucosa* was positively correlated with average particle size, critical shear stress, and boundary Reynolds number. Larger mean particle size affects roughness of substrate. Disturbing the stream bed provides nutrients, gas exchange, and waste movement, but larger particles also provide flow refugia. Some of these results agree with other studies, but the correlation with shear stress, Reynolds number, and boundary Reynolds number differs from other studies. This could be due to species specific preferences rather than community tolerances. It could also be due to river size, as other studies were in higher gradient streams where higher shear stress would be detrimental. Lower slope of this river might lead to excessive siltation in areas of lower shear stress.

This study points out several important factors. Firstly, habitat preferences vary with species. Unfortunately, this type of study has not been conducted on most species in the UMRB. Secondly, hydraulic variables seem to be more important on a transect or small area scale, rather than the quadrat level. This suggests that designing for hydraulic conditions at a local scale such as a river training structure might be practical. Thirdly, response to increased shear stress may vary depending on the size and/or slope of the river. Unfortunately, this paper like others did not provide any guidance of the range of values for any of the parameters.

Parasiewicz, P, E. Castelli, J. N. Rogers, and E. Plunkett. 2012. Multiplex modeling of physical habitat for endangered freshwater mussels. Ecological Modelling 228:66-75.

This study combined several models at a variety of scales to define habitat preferences for *Alasmidonta heterodon*. In the end, suitability models indicated this species preferred hydraulically stable habitats. This study was conducted in the Upper Delaware River. They developed a concept of a multivariate, multi-scale, and multi-model (multiplex) habitat simulation through combining multivariate time-series analysis of complex hydraulics (CART and logistic regression), and micro-scale (River2D) and meso-scale (MesoHABSIM) habitat models to develop macro-scale management criteria. The concept was applied and tested on the Upper Delaware River. The physical habitat conditions of an approximately 125 km reach of the Delaware River was described using digital aerial imagery and ground-based surveys. Temporal and spatial variability of complex hydraulics simulated by a River2D model at 1547 locations was statistically analyzed to select ranges of attributes that corresponded to mussel presence. These criteria were applied to select ranges of attributes that corresponded to mussel presence. These criteria were applied to the river's meso-scale hydromorphological unit mappings to identify suitable meso-habitats, which then served as a calibration data set for the coarser scale model. The final meso-scale habitat model's predictions were hydraulically validated offering encouraging results. The meso-scale habitat suitability criteria defined moderately deep, slow-flowing, and non-turbulent hydromorphologic units as providing good conditions for *A. heterodon*. Management of freshwater mussels requires consideration of temporal as well as spatial patterns. Ideal management tools need to capture the temporal variability of environmental factors that correspond with each animal's location (microhabitat) as well as with their overall spatial distribution in the river (macrohabitats). River2D serves as a support tool for the development of microhabitat suitability criteria, while MesoHABSIM serves here as a vehicle to transfer the habitat characteristics from the scale of meters to many kilometers. Microhabitat suitability criteria were developed using temporal variability of complex hydraulics (shear stress, Reynolds number, etc) on a large sample of random points that included mussel locations. Temporal changes in hydraulic patterns caused by flow fluctuations during 2007 summer season were used. Suitable microhabitats with high probability of finding mussels were overlain on a detailed hydraulic survey of mesoscale hydromorphologic units to predict macroscale patterns. The HMUs with large proportions of surface area covered by the suitable microhabitats were considered suitable as a whole and served as calibration data for the mesoscale habitat model predicting suitability for the whole study area at different measured flows. Froude number (turbulence close to the surface), boundary Reynolds number (turbulence in the boundary close to the river bottom), and shear velocity were calculated for each point from depth, velocity and bed roughness, which were computed with River2D for each point at 15 flows from 0.11×10^{-3} m^3/s to 3.28 m^3/s. Bathymetry and velocity were measured using a variety of high resolution tools (LIDAR, RTK GPS AIRMAR and Acoustic Doppler current profiler unit) to create a dense grid of elevation points and velocity. Model input variables were depth, velocity, k (bed roughness), Froude number, shear velocity, and boundary Reynolds number based on Hardison and Layzer (2001) and Steuer et al. (2008).

Using the CART model, mussel habitat was predicted for sites with a max Re* < 6.725e+04 and depth < 70 cm, with Fr < 0.016 (slow water velocity). In deeper areas (> 70 cm), mussel habitat was predicted when velocity Coefficient of Variability > 0.2097. Models indicated presence/abundance of suitable location was positively correlated with depths between 75 and 100 cm, and Re* between 55×10^3 and 65×10^3. Unionids were limited by highly turbulent environments associated with high average Fr, high velocity and extremely low Re*, as well as boulders and rapids. Mapping optimum mesohabitats across flows indicated that some areas were sensitive to changes in flow and in some areas habitat suitability was stable across flows.

This study's results suggest that Re* is the best discriminating factor for a mussel site, with preference toward low values. These results corroborate with Steuer et al. (2008) that suggest high shear velocity (or boundary turbulence) may displace the mussels and that the temporally varying flow patterns in pools are necessary for food supply for the mussels. This study provides a method for assessing mussel habitat at micro to macro scales. It confirms that at least at low flow, low Re* and Fr numbers are important predictors of mussel habitat.

3.2.4 Laboratory studies

Zimmerman, G. F. and F. A de Szalay. 2007. Influence of unionid mussels (Mollusca:

Unionidae) on sediment stability: an artificial stream study. Archiv fur Hydrobiologie 168:299-306.

Mussels are thought to stabilize substrate within mussel beds. This study tested the hypotheses that unionid mussels influence the cohesion of the streambed sediments and that mussels affect the amount and types of sediments eroded during high flow events. The study was conducted in an artificial stream. Substrate was 27% small gravel, 25% large sand, 47% small sand, and 1% clay. Baseflow 10 cm above the sediment surface was 3.5 cm/sec. Shear strength was measured with a modified Torvane soil probe (probe measured the force required to twist a disk with tine embedded in the sediments). Compression was measured with a penetrometer with a 2.4 cm weak soil adapter. Sediment erosion was measured with a sediment trap at the bottom of each cell. Flow was increased to 15 cm/s for 2.75 hours to measure erosion at high flow. Substrates were initially destabilized (measured as decreased shear strength) when mussels were burrowing, but substrate was stabilized when mussels were sessile. Embedded mussels increased shear strength by 24% and compression by 31%. Mussel presence had no detectable effect on amount or grain size of sediments eroded during high flow events. These results suggest that mussels can affect the physical characteristics of a stream bed. Mussel are typically more abundant in areas with stable sediments than in nearby unstable substrate. However, it is unclear whether mussel survival is greater in these areas or if the mussels directly increase substrate stability.

This study successfully tested that the presence of mussels increases shear strength and cohesion; however, erosion was not reduced. This is somewhat puzzling as an increase in shear strength and cohesion should have reduced erosion, unless the velocity used produced shear stress high enough to erode particles from both areas. Also not addressed in this study is the possibility that fluctuating river and water quality conditions could cause more frequent vertical and horizontal migration, which could reduce the stability of substrates, rendering habitat less suitable. The effects of fluctuating conditions on mussels is implicated in several studies, but not empirically tested.

Schwalb, A. N. and J. D. Ackerman. 2011. Settling velocities of juvenile Lampsilini mussels (Mollusca:Unionidae): the influence of behavior. JNABS 30:702-709.

Previous studies have used Stokes Law to predict settling velocity of juveniles and determine distance traveled. This study looked at the settling velocity of 4 Lampsilini species to determine interspecific differences. Settling velocity of juveniles of smaller species was significantly lower than larger species, but considerable intraspecific variation was observed.

Observed settling velocities differed significantly from Stokes law and were affected by foot movement of the juvenile.

This study suggests that the assumptions for juvenile settlement in previous studies may be erroneous. Juveniles may settle more rapidly and may be able to alter behavior to select habitat. However, this has not been tested in the field. This suggests that host fish habitat (location of juvenile release) may need to be closer than previous models suggest.

3.2.5 River management for Freshwater mussels

Tippit, R.N., Brown, J.K., Sharber, J.F., and A.C. Miller. 1997. Modifying Cumberland River System Reservoir operations to improve mussel habitat. in Conservation and Management of Freshwater Mussels II: Proceeding of a UMRCC Symposium.

This paper describes how temperature was raised in the Cumberland River (Kentucky/Tennessee) to improve habitat conditions for freshwater mussels. At Wolf Creek Dam, fluctuating river levels and cold water releases from the dam were preventing reproduction, and 39 species found in 1964 had declined to a few remaining individuals in 1982. Similar declines were noted downstream of other dams. Depressed water temperatures induced physiological stress and eliminated many host fish species. Modeling was used to determine if temperature could be raised to a target level of 22°C for at least 3 consecutive weeks during June-September. A real time reservoir system model was used to determine impacts of reservoir operation on water quality hydropower production, intake temperatures at a fossil fuel plant, and outflow DO from two dams at critical points in the system. Five segments were considered. Upstream and tributary dam operations were considered to achieve desired results. The negative impacts of operation changes to power production, fisheries, recreation, and downstream waste capabilities were identified and considered.

This paper demonstrates how freshwater mussels can be affected by physical and water quality changes associated with regulated rivers. It also demonstrates that operation changes can be modeled to assess the impacts (both positive and negative) of operational changes.

3.3 Upper Mississippi River Basin Habitat Studies and Models

The following literature relates specifically to the UMRB; however, hydraulic models specific to St. Louis District Pools or the Illinois River were unavailable. Section 3.3.1 provides a general description of general habitat rehabilitation in the UMRB. Sections 3.3.2 and 3.3.3 review literature on mussel habitat studies in the UMRB using simple (Section 3.3.2) and complex hydraulic variables (Section 3.3.3).

3.3.1 General Mississippi River habitat rehabilitation

Theiling, C.H. 1995. Habitat rehabilitation on the upper Mississippi River. Regulated Rivers: Research & Management 11:227-238.

The author reviewed current Upper Mississippi River (UMR) restoration techniques and proposed drawdowns as an additional technique that could be used to restore ecosystem function on a larger scale than current projects. Current attempts at river rehabilitation are mostly local. Projects in the upper portions of the UMR are designed to reduce side channel and backwater sedimentation. These include 1) introduced flow to counteract oxygen depletion in backwaters or side channel isolation, 2) isolation of backwaters to reduce sediment inputs, and 3) island creation to reduce wave energy and sediment resuspension. Channel maintenance structures are used more often in the lower portions of the UMR, primarily south of the Missouri River. Off bank revetment is used to create lentic habitat; however, many of these areas have become silted in. Wing dikes (perpendicular to flow) divert water into the main channel during low flow. These dikes initially created lentic fish habitat, but sedimentation has resulted in the loss of this habitat. Chevron dikes are an alternative to side channel closing dikes. These dikes give the hydraulic appearance of a solid object, diverting water into the main channel, but allow some flow into the side channel. They also allow for dredge spoil behind the dikes, which can become bathymetrically diverse when overtopped by high water. Bendway weirs are an alternative to wing dikes along bends in the UMR downstream of the Missouri River. They prevent lateral scour along the outside bend and prevent the encroachment of point bars into the main channel. These structures should improve habitat diversity in the UMR; however, monitoring to determine effectiveness has been limited to a few cases.

This paper outlines some of the local approaches currently underway to improve river habitat while maintaining navigation in the UMR. It also points out the lack of monitoring to determine the success of these projects. These types of projects could be modified to attempt creation of mussel habitat.

Theiling, C.H., C. Korschgen, H. De Haan, T. Fox, J. Rohweder, and L. Robinson. 2000. Habitat Needs Assessment for the Upper Mississippi River System: Technical Report. U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, Wisconsin. Contract report prepared for U.S. Army Corps of Engineers, St. Louis District, St. Louis, Missouri. 248 pp. + Appendices A to AA.

This Habitat Needs Assessment (HNA) was developed to support the Upper Mississippi River System- Environmental Management Program (UMRS-EMP). Its purposes include:

describing historical and existing habitat conditions and identifying objectives for future habitat conditions; addressing a variety of habitat requirements including physical, chemical, and biological parameters; defining habitat needs at the system, reach, and pool scales; achieving a collaborative planning process that produces technically sound and consensus based results; identifying goals, objectives, and opportunities for habitat protection, enhancement, and restoration; and helping to guide the selection and design of HREPs at multiple scales.

Pools 24, 25, and 26 occur in Geomorphic Reach 8. The slope of the river in this reach decreases due to the hump of the Illinois and Missouri River alluvial fans. The modern river resembles the pre-development planform, but contains fewer shoals and sand bars. Upper reaches of the pools have numerous islands and simple single thread secondary channels. Lower reaches have smaller islands, and impoundment effects are noticeable. Agriculture is the predominant land use. 70% of pools 24 and 25 are levied. There is little urban development in the floodplain, but it is mostly privately owned.

Channel geomorphology is a function of flow, the quantity and character of the sediment in movement, and the character of the materials in the bed and banks. The greatest amount of sediment is conveyed when level of river discharge corresponds to the 1 to 2 year recurrence interval flood (Leopold et al., 1964). Bank full flood is therefore a primary shaping disturbance that sets the template of the river channel habitats and is an important factor in maintaining the ecological integrity of large floodplain rivers. Lower frequency but larger floods are responsible for forming the shape of the floodplain. The volume of water and sediment in the river depends on regional climate. Warming is usually accompanied by decreased floods; however, recent warming is an anomaly, due to the increase in precipitation due to rapid warming and unstable atmospheric conditions. A trend in gradually increasing discharge and an increase in the frequency and amplitude of multi-year fluctuations was apparent. Over the last 75 years Mississippi River discharge has been increasing coincident with increasing precipitation in the basin, and large floods are more common.

Human induced disturbances in the UMR include impoundment and river regulation; clearing, snagging, and dredging; channel training structures; commercial and recreational navigation traffic; levees; agriculture; logging; urban development; mining; parasites and diseases; and exotic species introductions. Natural ecological disturbances are predictable events that shaped the physical and evolutionary template of the UMRS. The pre-settlement channels and landscapes developed over thousands of years of seasonal and cyclical natural disturbance. Human development of the UMRS has permanently altered many important disturbance mechanisms. The river ecosystem is, in many ways, in dis-equilibrium and is responding to a new set of environmental controls. The cumulative impacts of human disturbance from basin to habitat scales have degraded habitat diversity and quality throughout the UMRS.

ArcGIS was used to classify aquatic and terrestrial habitats and biotic communities. An assessment of existing conditions on the UMRS was conducted at system, river, river reach, and pool scales. The analysis was rather extensive because 12 river reaches, 37 pools/reaches, and 33 land cover or geomorphic area classes were included. The greatest habitat diversity occurs north of Pool 14. The upper river reaches exhibit habitat degradation because of impoundment and development, but the large refuge system helps preserve river-floodplain connectivity and limited habitat fragmentation. Other river reaches have lower natural geomorphic diversity and have been more heavily impacted by agricultural development. Suspended sediment concentrations increase as the river moves through the corn belt. Backwater sedimentation in lower pooled reaches is a large problem impacting aquatic and marsh habitats. Channelization and agricultural development have greatly simplified habitats in the Open River reach. More than 80% of the Open River reach is leveed, and the only unfragmented areas occur along a narrow floodplain strip between the river and levees. Geomorphic conditions along the Illinois River are variable with some areas highly developed, large main channel lakes near Peoria, and numerous backwaters in the La Grange Reach. One commonality, however, is that water level regulation and sedimentation have degraded aquatic habitats. Connectivity is reduced throughout the UMR and habitats are fragmented by agriculture and urban development. Considering the entire UMR, agriculture, open water, and wet floodplain forests are the most abundant land cover classes. The amount and distribution of geomorphic area classes are quite variable among river reaches.

The geomorphic change model revealed that backwaters and secondary channel loss was the most prominent.

The assessment continues with a workshop of resource managers to present results of current conditions and assess what habitat conditions resources managers would like to achieve in the future. Resource managers did not feel data were adequate, but did agree in their concern for habitat loss and degradation. All resource managers want improved habitat quality, habitat diversity, and a hydrologic regime that is closer to the unregulated conditions and believe these factors are important in maintaining ecological integrity of the river. Deep backwater, floodplain prairies, hardwood forests, and marsh habitats were rated the most threatened habitats. River regulation, sedimentation, and floodplain development were rated as the primary stressors affecting river habitats. Information needs to better classify and analyze habitat. High resolution bathymetric data, system-wide bathymetric data, numerical hydraulic models, substrate characterization, habitat quality metrics, floodplain inundation models, floodplain geomorphic classification and survey, surveys of existing floodplain plant communities, characterization of the existing and pre-impoundment hydrologic regime, confirmation/validation of species-habitat models using stratified random sampling, development of refined life history information, development of refined species-habitat models, and analysis of and seasonal habitat availability are some of the information needs.

This report provides a good summary of what is known about the past and present condition of UMR habitats. It summarizes the factors affecting the river, including changes in flood frequency and their potential effects on the river. However, other than providing information on the general fluvial processes in various parts of the river, it provides little information that can be used in mussel habitat creation.

3.3.2 Simple habitat variables

Holland-Bartels, L.E. 1990. Physical factors and their influence on the mussel fauna of a main channel border habitat of the upper Mississippi River. JNABS 9:327-335.

The purpose of this study was to quantitatively determine habitat preferences of mussel fauna, particularly *L. higginsii*, in the east channel at Prairie du Chien, Pool 10, UMR. Substrate, near bottom current velocity, and mussel density were recorded at low (50% exceedance) and high discharge (29% exceedance), although sample size at high flow was small. Total mussel abundance varied significantly as a function of substrate and current, discriminate analysis models using these variables only correctly predicted abundance 44% of the time. Some minor differences in species preferences were noted, but most species overlapped considerably with respect to these habitat parameters.

This was one of the early attempts to define habitat preferences of UMR species. Although sampling was intensive and quantitative, little variability in data was explained with these microhabitat variables. This study also only looked at habitat within an area harboring mussels and not the differences between areas with and without mussels.

These data were reanalyzed by Steuer et al. (see below).

Tucker, J. K., Theiling, C. H., and J. B. Camerer. 1996. Utilization of backwater habitats by unionid mussels (Bivalvia: Unionidae) on the Lower Illinois River and in Pool 26 of the Upper Mississippi River. Transactions of the Illinois State Academy of Science 89:113-122.

Species composition differed between contiguous backwaters, which supported 7 to 14 species, and isolated backwaters of the Mississippi River in Pool 26. Species richness also decreased within the contiguous backwater. Although these backwater habitats are not typically considered good mussel habitat compared to the main stem Mississippi and Illinois Rivers, they may provide important refugia from zebra mussel infestation. HREPs are planned in some of these backwater area, and the effects of these projects on freshwater mussels should be considered. Riverine mussel fauna was present near the "exterior" of the backwater (close to its connection with the river), and fauna changed to lentic in the interior. Inflow and outflow currents and energy transport are likely important to this mussel fauna.

This study demonstrates that some flow is necessary to support a riverine mussel fauna, and that marginal quality habitat can support mussels if substrate is stable and flow is provided.

Straka, J.R., and J.A. Downing. 2000. Distribution and abundance of three freshwater mussel species (Bivalvia: Unionidae) correlated with physical habitat characteristics in an Iowa reservoir. Journal of the Iowa Academy of Science 107:25-33.

This study investigated the habitat preferences of three species (*P. grandis*, *P. alatus*, and *L. siliquoidea*) in an Iowa reservoir (Big Creek Lake), a eutrophic reservoir. Variables investigated included depth, slope, fetch, and sediment organic matter. *P. grandis* was most abundant on deeper shelves (3 m deep, slope < 0.15 m/m, fetch greater than 1 km) and low organic matter (3.5%). *L. siliquoidea* was in shallow (< 1.5 m), flat (< 0.10 m/m), sheltered areas (fetch < 0.4 km) on substrate with 1-3% organic matter. *P. alatus* was at all depths, but only on flats (< 0.01 m/m) where fetch was < 0.8 km. In general, all of these species required stable substrate with moderate levels of turbulence. Turbulence is necessary to provide food, oxygen, and to prevent siltation or mussel beds.

This study reiterates the need for stable substrate and some flow for mussel survival, and talks about the differences in habitat preferences of individual species.

Hornbach, D. J. 2001. Macrohabitat factors influencing the distribution of naiads in the St. Croix River, Minnesota and Wisconsin, USA. In Bauer, G., and K Wachtler (eds). Ecology and Evolution of the Freshwater Mussels Unionoida.

Hornbach looked at the distribution of unionid communities in the St. Croix River (6^{th} order stream in Wisconsin/Minnesota) with respect to macrohabitat variables such as location of tributaries and river gradient. The river was divided into 16 reaches based on stream gradient and the location of major tributaries. Distinct clusters of species were apparent at the kilometer scale. Species grouped by stream section and gradient in both correspondence and cluster analysis. The dam at St. Anthony Falls forms a distinct barrier, with more Lampsilinae species upstream and more Ambleminae species downstream. Groups from upstream of the dam clustered by high and low gradient. Below the dam, a distinct group was apparent immediately downstream of the dam, two transition groups occurred, and a group from the lake region at the lower end of the river clustered. However, river sections did not explain variation in diversity and evenness. Fish host distribution, microhabitat variables, and differences in reproductive strategies and burrowing strategies were plausible reasons given for the upstream to downstream differences.

As with other studies, this study focused on differences in species assemblages rather than differences between areas with and without mussels. But it does reiterate that mussel assemblages are influences by factors at several scales.

3.3.3 Complex hydraulic variables

Young, N. C. 2006. Physical characterization of freshwater mussel habitats in Upper Mississippi River Pool 16. Ph.D. dissertation – University of Iowa.

Young created a model using bathymetric data and velocity data measured throughout Pool 16 in the UMR. Five flow levels were simulated, 9000 cms (< 1% exceedance [1993]), 8000 cms (< 1% exceedance [peak 2001]), 5200 (2% exceedance [peak 2004]), 2300 cms (average discharge, 28% exceedance) and low flow 600 cms (98% exceedance). Raster data were created for the 5 flow conditions for depth, depth-averaged velocity magnitude, bed shear stress, and near-bed turbulent kinetic energy. Local Reynolds number and local Froude numbers were calculated. Substrate data and mussel data from existing studies were incorporated. Substrate variables (D_{16}, D_{50}, D_{84}), substrate heterogeneity (sqrt(D_{84}/D_{16})), and substrate stability t_0/t_c for D_{50} were calculated for each quadrat sample. Simple correlations, backward stepwise regression, and binary logistic regression were used to determine variables associated with mussel diversity and density and to create a probability of occurrence map. PCA (principle components analysis) was used to summarize species trends with respect to habitat variables. Species separated into two groups; juveniles and smaller species (deertoe, pimpleback, and threehorn waryback) were most strongly associated with substrate characteristics. These species showed a preference toward smaller substrates, but an aversion to extremely fine substrates. They also preferred substrate heterogeneity associated with a higher percentage of large material, likely related to habitat stability. They were negatively associated with depth (prefer shallower depths), and positively associated with Froude number. Larger species (butterfly, higginsii, washboard) were most highly associated with hydrodynamic parameters. These species had an affinity for high-energy environments and were highly correlated with velocity, Reynolds number, and bed shear stress. Hydrodynamic parameters were most highly related to mussel characteristics at low to moderate discharge. This was likely due to the greater spatial heterogeneity in hydrodynamic variables at lower flows, creating greater contrast between different habitats. At higher flows, little variation in hydrodynamic variables was observed. Binary logistic regression model predictions identified some geometric features associated with higher probabilities of mussel presence. Areas of high probability occur in shallow regions within the main channel border and secondary channels. Small deltas formed at the mouths of small tributary streams, and the concave bank line features at a larger scale appeared to be related to higher occurrence probabilities. This study was limited by the quantitative mussel data set and substrate data set only available for a small area that harbored mussels. Differences between areas with and without mussels at higher flows may have been more pronounced over larger areas.

Values for the substrate and hydrodynamic parameters (mean, SD, min, max) associated with mussel presence and with various species at different flow levels are available in the appendices. These values may helpful in determining conditions for habitat creation. However, similar values were not provided for areas without mussels.

Morales, Y., Weber, L. J., Mynett, A. E., and T. J. Newton. 2006a. Mussel dynamics model: a hydroinformatics tool for analyzing the effects of different stressors on the dynamics of freshwater mussel communities. Ecological Modelling 197:448-460.

This paper presents an individual-based configuration model that captures relevant mussel-environment interactions and simulates various processes of mussel dynamics, including intra- and inter-species food competition. The mussel dynamics model (MDM) developed by Morales-Chaves (2004) applies a dynamic approach (time-dependent) in a spatially distributed domain (two-dimensional). Environmental conditions that came from modules for water quality, hydrodynamics, and host fish distribution were given as input data. These modules run independently of MDM, and their formulation can be as general or as specific as desired or possible. A habitat suitability model estimates the quality of the habitat and becomes a forcing function driving individual mussel response. Given the initial population data, MDM computes the long-term dynamics of the population. Mussel behavior is represented in terms of mortality, life stage, food competition, growth, reproduction, larval and juvenile dispersion, and adult movement. The model simulates processes acting at the scale of meters that potentially affect the community distribution at the scales of 10-100s of meters.

The habitat suitability portion of the model used the parameter relative substrate stability (RSS). This was calculated at bed shear stress at average 1 year high flow for Pool 16 (3965 m^3/s)/critical shear stress. However, they did not explain what particle size was used for critical shear stress. RSS < 1 was considered suitable habitat and RSS > 1 unsuitable. Unionid distribution within a 10 km reach of Pool 16 was predicted using habitat suitability and juvenile dispersal. Results generally agreed with historic mussel distribution in this river reach. This model was built on Young's (2006) Pool 16 model. The habitat suitability criteria RSS was empirically tested by Allen and Vaughn (2010) in a smaller system.

Morales, Y., Weber, L .J., Mynett, A. E., and T. J. Newton. 2006b. Effects of substrate and hydrodynamic conditions on the formation of mussel beds in a large river. JNABS 25:664-676.

The model developed by Morales et al. (2006a) was used to predict distribution of unionids in a 10km reach of Pool 16 in the UMR. Habitat suitability (RSS < 1) and juvenile dispersal were used to predict areas of suitable habitat and which of the suitable habitat areas had potential for developing into mussel beds. Simulated areas of mussel accumulation coincided with the location of historical mussel bed locations, suggesting that these parameters influence the formation of mussel beds in large rivers. RSS (t_o/t_c) is a dimensionless parameter that normalizes the effects of substrate and discharge on shear stress. Computation of RSS at different flow rates showed how substrate stability varies over a range of discharge. The authors hypothesize that annual peak flows most often limit spatial distribution of unionid communities. RSS may also be useful for predicting areas where juveniles cannot settle. Juveniles are unlikely to settle if particles ≥ 0.25 mm are actively transported with the flow (However, juvenile settlement for most species occurs in June to August, typically lower flow conditions, and assumptions for juvenile settlement may not be valid- see Schwalb).

RSS may also be useful in creating mussel habitat. Creating conditions where RSS < 1 for a typical annual peak flow could result in conditions favorable to unionid colonization. However, the area would need within the range of a source of juveniles or seeded to facilitate unionid colonization. Providing nearby host fish habitat would also be important.

Steuer, J. J., Newton, T. J., and S. J. Zigler. 2008. Use of complex hydraulic variables to predict the distribution and density of unionids in a side channel of the Upper Mississippi River. Hydrobiologia 610:67-82.

This study was a retrospective analysis with unionid density, current velocity, and substrate particle size data from 1987 to 1988 in a 6 km reach of Pool 10 (reanalysis of Holland-Bartels, 1990 data). Simple and complex hydraulic variables were modeled under low (50% exceedance) and high flow (29% exceedance). D_{16} rather than D_{84} was used for grain size and to calculate Trask sorting coefficient (So) and bed roughness (ks). Reynolds number (Re), Froude number (Fr), shear velocity (U_*), boundary shear stress (t), boundary Reynolds number (Re_*), viscous sub layer thickness (L), and substrate variables (Dm [mean grain size], So, and Ks) were calculated according to standard formulae.

Unionid beds may be constrained at both ends of the hydraulic regime. Under low flow, mussels may require a minimum hydraulic variable (Re*, Fr) to transport nutrients, oxygen, and waste products; Rc* > 2.1 and 2.4 seemed to accurately predict presence/absence of some species. Re* combines U (mean velocity), d (depth), and ks to describe near-bed turbulence and may reflect minimum turbulence needed to remove waste products, etc. It also describes exchange of surface and interstitial water. Six variables (Re*, t, d, Dm, So, ks) were the primary split variables in CART analysis. Re* and Dm were the most frequent primary split variables. However, difference species seem to be limited by different hydraulic parameters. Highest density of *A. plicata* at low flow was related to Re* > 2.1, depth < 1.7 m and boundary shear stress < 1.0 dynes/cm. *L. fragilis* at low flow was related to Re* > 2.4 (present), if Re* < 2.4 then depth > 4.1 (present). *F. flava* was related to high flow Re* > 7.2 (present), ks > 1.0 mm (present). Under high flow, areas with relatively low boundary shear stress (t) may provide a hydraulic refuge. However, flows in this study may not have been high enough to identify flow refugia. Alternately, this study was done in a side channel, which may provide sufficient flow refuge at higher flows. t increased 8 fold from 0.3 to 2.5 dynes/cm^2 between low and high flow conditions.

This study does demonstrate that complex hydraulic parameters can limit unionid density and presence/absence of some species. However, this study looked at variability within a bed, rather than the difference between areas with and without mussels. Ranges of low and high flow values for parameters were given that might provide some guidance on the range of conditions that could be acceptable to unionids at these flow levels. This study also demonstrates that difference hydraulic parameters may be important for different species.

Zigler, S. J., Newton, T. J., Steuer, J. J., Bartsch, M. R., and J. S. Sauer. 2008. Importance of physical and hydraulic characteristics to unionid mussels: a retrospective analysis in a reach of large river. Hydrobiologia 598:343-360.

This paper assessed whether spatial distribution of unionids could be predicted with physical and hydraulic variables within Pool 8 of the UMR. Specific objectives included evaluating the role of discharge in structuring mussel distribution and abundance, and developing exploratory statistical and geospatial models of physical and hydraulic conditions that influence the presence and absence of mussels. CART (classification and regression tree) models were constructed using data compiled from various sources and explanatory variables derived from GIS coverages. Variables used included simple hydrophysical variables (predominant substrate type, water depth, aquatic area type, pool thirds, local slope, and current velocity), and complex hydraulic variables (shear stress, Froude number, and relative substrate stability). Complex variables were calculated for Q5, Q50, and Q95. Means and ranges of these variables are given in the text. Models were largely driven by shear stress and substrate stability, but slope also appeared important. Variables measured at low flow were about 25% more predictive than variables measured at median discharge with high discharge intermediate, suggesting that droughts and floods are important in structuring mussel communities. For dive data (presence/absence), shear stress (Q50), RSS (Q5), RSS (Q50), shear stress (Q95), shear stress (Q5) and slope were the most important variables in the model. Based on dive data most sites with mussels (165 of 223 [314 sites total]) had shear stress (Q95) ≤ 0.18 dynes/cm^2; shear stress (Q50) > 0.48 dynes/cm^2; and shear stress (Q5) ≤ 7.80 dynes/cm^2. If shear stress (Q5) was > 7.8, then RSS (Q50) was ≤ 2.77 for mussel presence for 23 additional sites. Only 19 sites with mussels had shear stress (Q95) > 0.18; slope was ≤ 5.7 for 11 and > 5.7 for 8. For the 11 sites with slope ≤ 5.7, slope was also > 1.5, and shear stress (Q5) was ≤ 8.88 dynes/cm^2. For density, depth, slope, Froude number, and RSS were the most important variables. None of the variables calculated at Q50 were important in the model. Highest density sites were those with RSS (Q95) ≤ 0.10, depth > 1.8 m, Froude (Q5) > 0.09. Most sites were low density (133 of 314), these had RSS (Q95) > 0.10 and slope ≤ 2.1.

This study, like others suggests that complex hydraulic characteristics are responsible for mussel distribution, and that high and low discharge levels determine the limits for mussel communities.

Daraio, J. A., Weber, L. J., Newton, T. J., and J. M. Nestler. 2010. A methodological framework for integrating computational fluid dynamics and ecological models applied to juvenile freshwater mussel dispersal in the Upper Mississippi River. Ecological Modeling 221:201-214.

Hydrologic processes affect water quality, timing and magnitude of floods, and flow rate. Flow rate affects river hydraulics. Hydraulics affects organisms on the reach to local scale. Location of fish host at time of juvenile excystment is affected by hydraulics, and settling point is dependent on point of juvenile release. A 3D model for juvenile mussel dispersal was developed for integration into the Mussel Dynamics Model (Young 2006; Morales et al. 2006b). Dispersal of juveniles was dependent on the source location (location of host fish at time of excystment), discharge rate at time of excystment, and local hydraulic conditions (impounded vs. channelized reach). The model used *Amblema plicata* in Pools 13 and 16 of the UMR and historical discharge levels during excystment time of June to August (low flow 600 m^3/s and average flow 2300 m^3/s). The model distributed host fish throughout the reach, except in the channel. Multiple simulations were used to determine the likelihood of settling in each grid cell and contours of likelihood of settling were used to create maps of spatial distribution. Dispersal distances at each flow rate were compared with multiple regression to identify relationships with bed shear stress, Froude number, water depth, and local bed slope. Simulations indicate that hydraulic conditions have a significant effect on settling of juveniles after release from fish host. Since juveniles are only slightly denser than water they follow the path of the water. Fluctuations and changes in water velocity are transferred directly to the juveniles. Settling of low density particles primarily occurs when vertical velocity near the river bed is near 0 m/s. An upward vertical velocity greater than fall velocity (10^{-6} m/s) will elevate juveniles higher into the water column, delay settling and result in drift further downstream. A 3D model is therefore more useful than a 2D model. Juveniles were most likely to settle around islands and in areas of reduced flow within the channel. Discharge affected settling. More juveniles settled in the impounded reach under average discharge. More juveniles settled along the edges of the channel under lower discharge. Dispersal distance varied with local hydraulic regime. Dispersal distances at low flow were 574 m within the upstream reach and 625 m impounded reach. These distances increased with higher discharge in the upstream reach to 634 m at 2300m^3/s (average discharge), 785 at 5200m^3/s (frequent moderate flood event), 784 at 8000m^3/sec (40yr flow), and 2105m at 9000m^3/s (100yr event). In the impounded reach, distance declined to 369 m and 486 m at 2300 m/s^3 and 5200 m/s^3; then increased slightly to 639 m and 789 m at higher flows. In both areas, the source of most juveniles was from less than 5 km upstream of high settlement areas; however, some were from as far as 30 km upstream. Patterns of juvenile dispersal as a result of this model were similar to spatial probability of presence of adult mussels based on habitat criteria in Young's (2006) model, and likelihood of settling was high in areas with known *Lampsilis higginsii* in Pool 16. Upstream hydraulics and juvenile source locations are likely to affect the local interaction of bed morphology and juvenile settling distribution. Juveniles settled on the same side of the river they were released, but features such as islands alter flow patterns and could transport juveniles to other parts of the channel. Upstream alteration of host fish habitat may impact juvenile settling locations. Through direct effects on local hydraulics in the water column, it is likely that river morphology affects mussel distributions at the juvenile dispersal stage. River hydraulics and flow patterns change with discharge. High discharge sets limits on mussel distribution most directly by bed mobilization, this also applies to settled juveniles. Low discharge can set limits on juvenile dispersal by reducing the area of river accessible for settlement and shorter transport distances by flow. Relationship between Froude number and juvenile settling distribution may be different in a reach of the river with different hydraulic regimes. In the impounded reach, greater concentrations of juveniles settled at a lower Froude number than in upper reach. Bulk parameters, such as Froude number, may be only indirectly related to the physical processes of settling.

Creation of mussel habitat should be within an area of high likelihood of juvenile settlement. Ideally habitat should be created within 1 km of good fish habitat. Habitat should consider hydraulic conditions that would be favorable to juvenile settlement.

Zigler, S. J., T. J. Newton, and D. A. Olsen. 2010. Final report: Development of habitat descriptors and models of mussel distribution in Pool 18 of the Upper Mississippi River. USGS Upper Midwest Science Center, LaCrosse, WI. 21pp.

Zigler et al. used 2D hydraulic model of Pool 18 and a poolwide mussel study, which included samples both within and outside of mussel communities, to develop potential descriptors of mussel habitat (bathymetric slope, shear stress, Froude number, relative substrate stability) and develop and test models of mussel distribution. Mussel data was collected in a systematic design with one random start at 340 m intervals. GIS data for bathymetry and current velocity were constructed from USACE models for Pool 18 and used to predict discharge specific depth and current velocities. Current velocity, based on a two-dimensional depth averaged (HEC-RAS) current velocity model, was calculated for 5, 50 and 95% exceedance. Substrate roughness was estimated from the standard formula in Statzner et al. (1988). Due to lack of quantitative substrate characteristics, D_{84} was based on percent of each substrate class visually estimated in the field. Substrate heterogeneity was calculated as the count of substrate classes with fractions greater than 10%. ArcGIS was used to develop poolwide datasets for shear stress, Froude number, boundary Reynolds number, relative substrate stability, and slope. Datasets for substrate classes were developed from a CART statistical model. Slope was calculated, based on a bathymetric GIS dataset, as the angle of change in depth over a plane fit to a 3 m x 3 m cell neighborhood around each 10 m processing cell in a moving window. For each cell, % slope was calculated irrespective of aspect. CART models were developed using presence/absence data and abundance data

Hydrophysical models seem to provide a good tool for assessing the distribution of mussels at large spatial scales. The model developed for Pool 18 yielded similar results as models developed for Pools 8 and 10. Mussels were less abundant in areas of the main channel and side channels with high hydraulic energy and in poorly connected backwaters, and more abundant in smaller side channels and geomorphically complex channel borders. The regression tree model for density indicated that moderate to low shear stress might identify flow refugia with stable substrate. Mussels seem to be constrained in areas of very low flow (low current velocity, shear stress and boundary Reynolds number) due to poor food delivery, sedimentation, low removal of waste products, and possibly low water quality. High bottom slope may also be important, as it represents areas of the channel border with rapidly changing hydraulic conditions at the sediment-water interface. For the presence/absence model variables used in order of relative importance were Q5 current velocity, Q50 shear stress, Q5 depth, Q95 shear stress, Q95 current velocity, percent gravel, Q50 current velocity, and Q95 shear stress. Depth at Q5 > 3.23 m was the first node. Sites with this depth and > 1.25% gravel tended to have mussels present. If percent gravel was ≤ 1.25%, Froude number (Q5) ≤ 0.12 and velocity at Q5 > 0.03 m/sec tended to have mussels present. If depth was < 3.23 m, then sites with Q95 velocity > 0 tended to have mussels. This indicates that mussels in shallow water require some flow during very low water conditions. In areas with sufficient depth, mussels prefer some gravel, lower turbulence at very high flow (Q5), but flow > 0.03 m/s at Q5. In the same model without substrate (as the distribution of gravel was difficult to ascertain with the existing data) the following variables differentiated sites with and without mussels: Q50 current velocity, Q50 Froude number, Q5 current velocity, Q95 current velocity, Q95 Froude number, Q5 depth, Q5 Froude number, and slope. Similar to the substrate model, depth of 3.23 m was the primary split. In shallow areas (< 3.23 m), mussels were present with velocity (Q95) > 0. In deeper areas (depth Q5 > 3.23 m) a few sites with mussels present had some turbulence at Q50 (Froude number > 0.08), but with a low slope (< 0.84). In less turbulent areas (Froude number Q50 ≤ 0.08) mussels required some flow (velocity Q5 > 0.03 m/sec), and most areas with mussels has Froude no. (Q5) > 0.12 or velocity (Q50) > 0.35 m/s and slope > 16.48%.

For abundance, mussels in the middle and upper pool were absent in areas with boundary Reynolds numbers (Q5) near bed turbulence ≤ 662.24. When boundary Reynolds no. was higher, density was highest when shear stress (Q95) was ≤ 1.02. In the lower third of the pool, most areas with high slope (> 17.29%) had mussels, but the greatest density was at depths ≤ 4.9 m at Q5 (20/m^2 vs. 10/m^2). In lower sloping areas (slope ≤ 17.29%), no mussels were present where velocity at Q5 > 1.04 (m/s). In slower flowing areas, (≤ 1.04 m/s), highest density occurred where near bed turbulence (Q5 Re_*) ≥ 67.44 (30+/m^2). In areas with lower Re_*, areas with shear stress (Q50) ≤ 0.69 and Q95> 0.08 had an average of 20/m^2, while other sites had lower density.

This model is an improvement over previous studies in that it includes data in all areas of the pool. Flow levels used in the model represent a good range of very low flow (Q95), average (Q50), and very high flow (Q5). Presence/absence may be misleading as many samples in this data set had 1 stray mussel that might have simply been part of the bedload (Dunn, pers. obs.). However, abundance was also used. The results of this model support the general hypothesis that mussels require some flow and near bed turbulence at low flow and refuge from high velocity and turbulence at high flows. It also points out, that these conditions are present with various combinations of shear stress, velocity, near bed turbulence, substrate type, and slope.

Hornbach, D. J., M. C. Hove, B. D. Dickinson, K. R. MacGregor, and J. R. Medland. 2010. Estimating population size and habitat associations of two federally endangered mussels in the St. Croix River, Minnesota and Wisconsin, USA. Aquatic Conservation: Marine and Freshwater Ecosystems 20:250-260.

Hornbach et al. used a two stage adaptive cluster sampling design to assess population size and habitat preferences for *Quadrula fragosa* and *Lampsilis higginsii* in the St. Croix downstream of the St. Anthony Falls Dam between 2005 and 2007. Their sampling concentrated on areas of high mussel density, determined in the first stage of sampling. They measured substrate (average particle size), volatile organic matter, soil compaction, depth, flow (substrate surface), and shear stress (FST spheres). Local hydraulic environment was also assessed at 20 randomly chosen sites. Water velocity was measured at 3 discharges (181, 239, and 628 m^3/s at Franconia and 162, 356, and 530 m^3/s at Interstate) with an Acoustic Doppler profiler. Velocity data was combined with substrate data to calculate Froude no, Reynolds no, Shear velocity, Roughness Reynolds number (Re*), shear stress and laminar layer. Simple habitat variables were compared to presence/absence data for *L. higginsii* and *Q. fragosa*. No differences were detected for depth, bottom velocity, FST spheres, or sediment organic matter. Sites with *Q. fragosa* and *L. higginsii* had coarser substrates and more force was required to compact substrate with *Q. fragosa*. For complex hydraulic measures, Froude number, shear stress and sheer velocity were higher at sites with *Q. fragosa* than without, but no differences were significant for *L. higginsii*. Both species were found in areas with significantly higher density and species richness.

This study does show that these species are more likely to occur in areas with higher density and species richness, and that *Q. fragosa* prefers areas within the bed that have higher shear stress. Values are given for measured variables, however as with other studies, all variables were measured within a high quality mussel bed.

3.4 Attempts to create mussel habitat and habitat ideas

USACE Army Waterways Experiment Station attempted creation of mussel habitat in the 1980's and 1990's in the Tombigbee, Ohio, and Tennessee Rivers. Although research on using complex hydraulic variables to describe habitat was not available at that time, the general concept of flow refugia, heterogeneous stable substrate, and preventing sedimentation were used to successfully create mussel habitat.

Mussel habitat creation was also attempted in the UMRB in the early 1990's in the Pool 11 Bertom and McCartney Lakes HREP using the understanding of mussel habitat at that time. However, no monitoring has been conducted to evaluate success. Reports on the design and implementation of the project are reviewed. Mr. Jeff Janvrin (WDNR's HREP fisheries biologist) has observed the Pool 11 site and offered some ideas to consider in future projects.

Some of these ideas were presented in a proposal for mussel habitat creation in the Pool 8 islands Phase 3 HREP project. Dr. Newton and Dr. Zigler (Upper Midwest Science Center [UMSC]) are currently working with St. Paul District on applying their model results to create mussel habitat in the Capoli Slough HREP. Dr. Craig Just and others at the University of Iowa IIHR Hydroscience & Engineering Department (IIHR) have also been working with hydraulic parameters and mussel habitat creation. Mr. Travis Moore (Missouri Department of Conservation [MDC]) had some ideas on how to create mussel habitat within the St. Louis District. Notes from conversations are provided in this section.

3.4.1 Mussel habitat creation outside the UMRB

Miller, A. C. 1982. Habitat development for freshwater mollusks in the Tombigbee River near Columbus, Mississippi. Pages 86-94 in U.S. Army Engineers Waterways Experiment Station, CE. “Report of freshwater mussels workshop”, Vicksburg, Miss.

Vicksburg (WES) began a project to create a gravel bar in the Tombigbee River near Columbus, MS near RM 232.9 for insects and mollusks. The study was divided into three phases: biological evaluation of the site, design of the bar or bars, and subsequent monitoring and possible seeding of the bar with mollusks. An existing bar was evaluated for habitat characteristics, water quality, and benthic invertebrates with the intention of using this data in the design of the gravel bar. The concept of enough flow at low flow but not too much flow at high flow was discussed as necessary for the design. “Preliminary indications are that some channel restrictions may be required to increase the flow in the river channel. These will have to have enough current above the substrate of the bar to adequately flush sediments deposited during high water. However, the habitat must be designed so that it is not eroded during high flow.” Monitoring was planned for twice a year. Monitoring was to include similar sampling to phase 1, sediment particle size, invertebrate colonization, water samples, and mussel sampling by brail. They planned to seed to area with mussels 2 years after construction and monitoring these mussels twice per year.

Miller, A. C. 1983. A gravel bar habitat for mussels on the Tombigbee River near Columbus, Mississippi. Pages 65-78 in U.S. Army Engineers Waterways Experiment Station, CE. “Report of freshwater mussels workshop; October 26-27 1982,” Vicksburg, Miss.

The Tombigbee is a medium size river (ave. flow 6458 cfs), with extreme fluctuation (138 cfs to 194,000 cfs). The site of the gravel bar would be in a bendway (river mile 232.9) directly downstream of the minimum flow release structure of the dam in an isolated channel downstream of Columbus Dam and upstream of the new lock and dam structure. This site was chosen such that minimum flow would be provided year round, but the site would be outside the thalweg, and the bendway would protect the site from high current velocities at high discharge. The primary objective for the bar was habitat for fish and invertebrates, but mussels could use the bar as well. Four distinct gravel bars 150 ft long x 170 ft wide were to be created with slack water pools between gravel bars. The upper most elevation of the bars were to be 1 ft above minimum water levels for the pool, and a channel was to be cut through the bar to allow passage of water. Elevation within the channel was to vary from side to side, such that minimum pool varied from 1 to 4 ft deep. Flow in gravel bars 1, 2, and 3 was designed for 1.5 ft/sec, and gravel bar 4 was designed for 1.0 ft/sec. At higher flow, water would overtop the low flow channel to the lateral portion of the gravel bar, and velocity would decrease in the channel. Some sedimentation would occur, but this would be scoured out during low flow. The 1.5 and 1.0 ft/sec was designed to move silt and clay particles but not the gravel or sand/gravel mixture. The monitoring components recommended included hydrologic success and invertebrate colonization rates. Hydrologic success should be measured by measuring depth, current velocity, and particle sizes at various times. Invertebrate colonization should include quantitative sampling of invertebrates at regular intervals for a year or more. Long-term monitoring is necessary for mussels (10 years or more).

Dr. Andrew Miller, personal communication, April 2013.

The gravel bar on the Tombigbee was a huge success. He monitored the area in 2002 and collected lots of mussels. Although it was a fourth order stream, it colonized with large river forms rather than pool-riffle species. Individuals were very large, likely due to the productivity of the upstream reservoir.

Miller, A. C. 2006. Experimental gravel bar habitat creation in the Tombigbee River, Mississippi. ERDC/TN EMRRP-ER-03.

The Tombigbee gravel bar involved transporting fill material (primarily sand) to the 80 m reach of the channel. The fill was capped with 24,000 m^3 of 2 to 80 mm coarse gravel obtained from an upland site. Construction was completed in March 1985. Two exposed gravel bars, with a channel running down the center of each, were created with the gravel. Each riffle was 46 m long and 24 m wide, with a depth of 1.2 m and velocity of 50 cm/sec. This design created a small fourth order pool-riffle system in an eighth-order river. Unlike lower order streams, there are no erosion flows or spates due to storm events, as the minimum flow release will not pass more than 5.7 m^3/sec. Velocity within the low flow channel is either 50 cm/sec at low flow or 0 at high flow. Colonization of the gravel bar was rapid. Three months after construction 30 invertebrate species were collected. Sampling in the fall of the same year yielded 50 species. Chironomidae dominated the samples the first year and diversity (H') was less than 1. However, diversity increased to 2.5 to 3.0 for the remainder of the study (1986-1988). Abundance was consistently greater than a nearby natural gravel bar. In 1985-1986, 39 species of fish were found in the gravel bar, 25 were found in the channel downriver of the habitat, and 16 were found in the flume (directly downstream of the minimum flow release). Gizzard shad and threadfin shad dominated the gravel bar, but minnows, shiners, and darters were abundant. Drum, catfish, sunfish, and crappie were also collected. Immediately after construction, juvenile *Obliquaria reflexa* and *Corbicula fluminea* were collected in benthic invertebrate samples. The first intensive mussel sample was in August 2001, 16 years after construction. At total of 360 unionids of 13 species were collected in the riffles. Density was estimated at 0.18/m^2. *Obliquaria reflexa* and *Plectomerus dombeyanus* were the dominant species. This project was designed to simulate shallow water gravel bar habitat that was present in the original Tombigbee River. The author suggests that this could be accomplished at similar sites. “Any altered waterway likely has sites that could be improved by adding gravel or cobble substratum.” In simple situations, gravel and cobble could be added to areas with adequate flow, but silt/clay substrate. Flow may need to be increased to prevent sedimentation. This could be accomplished with the addition of substrate or levees.

Miller, A. C. 1988. Construction of a submerged gravel bar habitat using dredged material. Environmental Effects of dredging Technical Note. U.S. Army Waterways Experiment Station, Vicksburg, MS.

Selected reaches of navigable waterways are frequently dredged. Gravel and cobble material could be used to create gravel bars, which are a natural feature of unaltered rivers and streams that provide habitat for invertebrates, fish spawning, and freshwater mussels. As mitigation for accidental dredging of a mussel bed, a grain company on the lower Ohio River agreed to construct a gravel bar. Construction was initiated in 1986 on the Kentucky side of the river. An exposed shoal existed between ORM 971.3 and 973.3 that was built with material from maintenance dredging. A submerged dike at the downstream end of the shoal deflects current into the main channel. Few unionid mussels occupied the shoal, as the shoal consisted mainly of coarse sand with less than 10% gravel. A site with appropriate depth and low flow current velocity of 20 to 33 cm/sec (removes settled silt but not larger particles) was selected near ORM 972.0. Material was obtained from the main channel by sieving dredged sand and gravel through a 9.5 mm screen. Since sand was already present, only gravel was added. Gravel was spread evenly across the site by slowly opening the clamshell dredge. Divers indicated gravel was 3 to 75 cm thick. The area was seeded with 100 marked *Fusconaia ebena*. Monitoring will include evaluating the marked mussels, checking sediment traps for fine inorganic and organic sediments, and macroinvertebrates.

Payne, B. S. and R. Tippit. 1989. The value of gravel disposal mounds in river side channels for freshwater mussels. Environmental effects of dredging, Technical Notes. EEDP-07-5. U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.

Dredge material was used to create gravel mounds in a side channel of Wolf Island, Tennessee River mile 192-194 in 1972, 1981, 1983, and 1988. Sandy gravel was removed from the main channel and dumped using dump scows at an acute angle into the flow. The dump scows were released from doors in the bottom of the dump scow as it slowly backed away from the bank line. Each load was 225 – 250 cu yds, and 29,000, 18,000, 28,000, and 10,000 cu yds were disposed in 1972, 1981, 1983, and 1988, respectively. Each disposal event was upstream of the previous event, creating a series of adjacent gravel mounds. No additional contouring was done. Most of the material was cobble and gravel. Current velocity in the disposal area was > 0.5 ft/sec preventing the accumulation of fine particles. In 1988, a reference site and the 4 disposal sites were sampled for mussels. Substrate in the reference site (upstream of the gravel mounds) was primarily sand near the bank, then gravel at 8 ft depth, then coarser gravel and cobble riverward. The gravel mounds appear to have stabilized the sandy eroding bank and created a stable gravel shoal. The main mussel community was in the deeper portion of the side channel. Sampling resulted in the collection of only 3 mussels at the reference site, but 29 mussels of 6 species at the 1972 disposal mound and 5 mussels of 3 species in the 1981 disposal mound. Placement of the gravel mounds near the bank avoided burial of the mussels in the deeper portion of the side channel and provided habitat closer to the bank and stabilized the bank. The authors suggest that site selection should consider the present distribution of aquatic resources. Site selection should also consider bathymetric and hydrologic conditions to ensure disposal mounds will neither be severely eroded nor covered by silt.

3.4.2 Mussel habitat creation within UMRB

Pool 11 Bertom and McCartney Lakes HREP (Rock Island District)

U.S. Army Corps of Engineers. 1989. Upper Mississippi River System Environmental management program definite project report with integrated environmental assessment (R-3). Bertom and McCartney Lakes rehabilitation and enhancement, Pool 11, Mississippi River miles 599 through 603, Grant County, Wisconsin.

Sedimentation was occurring in this backwater complex, decreasing aquatic habitat. This area, located mid Pool 11 had the areal extent, habitat characteristics, and land-use status necessary to meet habitat improvement objectives of Pool 11. Project objectives included: improving fish wintering habitat, establishing an aquatic vegetation bed for migratory waterfowl and fisheries benefit; reducing bedload sediment entry; and providing additional, diversified habitat for benthic and aquatic communities. One of the project goals was to establish a mussel bed. No mussels occurred in the area pre-project. Lining approximately 1500 ft of an existing side channel adjacent to Coalpit Slough with rock was used to enhanced fish and mussel habitat. The selected side channel had a minimum bottom width of 50 ft. Rock was of several different sizes, gradations, and types was used to further diversity the habitat. Side slopes were constructed as 1:2, rock depth averaged 2 ft, and minimum depth over the rock was 4 ft. A total of 9000 tons (5625 CY) of quarry rock of different sizes were used. Sketches of the mussel habitat and fish LUNKERS (Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids) were provided in the Attachment to Appendix B-Wisconsin Summary Reports.

The channel was divided into seven discrete sections. The first section immediately following the partial closing structure was 300 ft long; the remaining sections were 200 ft long. The channel design included a uniform bottom width of 50 ft (except in section 1 and existing areas wider than 50 ft) with 1 vertical on 2 relatively horizontal side slopes. The existing channel was excavated by dragline or clamshell as required to achieve the minimum bottom width and to provide for unrestricted channel flow. The excavated material was placed on the right bank of the channel and spread to prevent the creation of a berm. Each channel section had a different rock substrate material. The stone varied from section to section by size, gradation, and rock type. The rock was placed in descending order by size such that section 1, immediately adjacent to the partial closing structure, had the largest graded stone. Substrate was large grade limestones at the riverward entrance to the channel, intermediate grades in the middle section, followed by a gravel/cobble section. Rock sizes were 4 to 36 inches. The channel in which the rock habitat was constructed had stable banks and did not show signs of active erosion. Since bank armoring was required in the vicinity of the fish structures, bank protection was provided for the entire habitat channel to prevent migration of the channel. Conventional barge-mounted equipment was used for the construction of partial closing structure, fish and mussel rock habitat, and containment levee. The fish and mussel rock habitat also included habitat structures such as sections of reinforced concrete pipe and LUNKERS. These structures, originally designed as part of a trout habitat improvement program initiated by the WDNR, consisted of a submerged system of planking which was then installed into a stream bank to provide resting, feeding, and escape cover for fish. Mussel surveys were planned every five years. One post construction qualitative field observation was conducted, but no post monitoring has been conducted to date (J. Janvrin, WDNR, pers. comm., March 2013).

U.S. Army Corps of Engineers. 1996. Operation and Maintenance manual. Bertom and McCartney Lakes rehabilitation and enhancement,. Pool 11, Mississippi River miles 599 through 603, Grant County, Wisconsin.

This manual provides details for operation and maintenance of the HREP. No specific actions were required for the operation of the fish and mussel rock habitat. Maintenance included: Inspection for serviceability and accumulation of debris, which could affect the hydraulic capacity of the channel. Side slopes should also be inspected for movement and erosion. No maintenance was anticipated.

U.S. Army Corps of Engineers. 1995. Upper Mississippi River System Environmental management program post-construction performance evaluation report (PER3F). Bertom and McCartney Lakes rehabilitation and enhancement, Pool 11, Mississippi River miles 599 through 603, Grant County, Wisconsin.

Project dredging began in 1990 and was completed and final inspection made in 1992. Some sedimentation occurred due to bank sloughing rather than sediment influx. Sedimentation (even post 1993 flood) did not seem significant. Dredge channels provided an increase in fish habitat and a fish overwintering area. Monitoring of the rock channel indicates some scouring of the rock substrate, but the substrate was free of sedimentation. A mussel survey was scheduled for 1997.

U.S. Army Corps of Engineers. 2002. Upper Mississippi River System Environmental management program post-construction performance evaluation report (10-yrs after construction). Bertom and McCartney Lakes rehabilitation and enhancement, Pool 11, Mississippi River miles 599 through 603, Grant County, Wisconsin.

This report provided a summary of monitoring 10 yrs following construction (1994 to 2001). Sedimentation within the project was occurring at a rate of 3.9 acre feet per year vs. the planned 1 acre feet per year. Additional transect sampling was planned for 2002 to reevaluate sedimentation. Some damage to riprap occurred due to the 1993 flood. This was repaired in 1995. Additional damage was noted after the 2001 flood. WDNR reported some mussels in the rock channel. However, this was not yet declared a success due to the rock substrate gradations' inability to have a strong settlement of the desired native species of mussels. DNR and St. Paul Districts were looking into the best substrates for mussel habitats. Mussel monitoring has not been done to date, only periodic field observations. A dive on the rock substrate by WDNR was conducted August 31, 2000. New zebra mussel settlement was observed, but zebra mussels were not attached to any of the mussels found. The rock substrates gradations A, B, C, and D appeared to be too large for mussel colonization. However, native mussels were observed in depositional areas where these gradations were used. Gradations E1 and E2 appeared to offer better substrate conditions. Future projects should consider using similar gradations, but with "river washed" stones instead of crushed rock. No mussels were found in the Gradation F section, but this area should be sampled in the future. No mussel data was provided in this report.

U.S. Army Corps of Engineers. 2004a. Upper Mississippi River System Environmental management program 11-year (YR) post-construction addendum to the 10-YR post construction performance evaluation report (dated May 2002) for Bertom and McCartney Lakes rehabilitation and enhancement,. Pool 11, Mississippi River miles 599 through 603, Grant County, Wisconsin.

This report contains additional data and observations from January 2002 to December 2002. Mussel and vegetative surveys were still not conducted. They were scheduled for the next report in FY2004. Budget reductions and scheduling conflicts were the primary reasons for the delay. Bedload movement and sedimentation were concerns (but not in the mussel channel).

Note: Discussion with the Rock Island ACE and Wisconsin DNR indicate that no monitoring of the mussel habitat has occurred to date.

Pool 8 Islands (St. Paul District)

U.S. Army Corps of Engineers. 2004b. Final draft Pool 8 island construction – Phase I project completion report.

Construction of the Pool 8 Island Construction-Phase I project was initiated as an HREP in 1989 and completed in June 1993. This report summarized all available monitoring data, operation and maintenance information, and project observations made by USACE, USFWS, and WDNR between August 1990 and February 2001. The goal of this project was to preserve and enhance aquatic plant beds for fish and wildlife habitat between RM 681 to 688 (entire project Phases 1 through 5). Phase 1 extended from RM 685.3 to 687.8. The project was initiated in 1989 and completed in 1993. The project was transferred to USFWS in January 1994. Monitoring of terrestrial and aquatic vegetation and water quality was conducted 1991 to 2000.

The project seemed to attain its goals. Phase 1 did not mention mussels. No documents were available online for Phases II and III.

Wisconsin DNR. Mussel habitat enhancement for Pool 8 islands Phase III West. (personal communication with Jeff Janvrin, email and phone call Feb 18, 2013).

The original design of the Pool 8 island HREP Phase 3 did not include any enhancements for mussels. A proposal for mussel habitat was prepared by WDNR to enhance a moderate velocity tertiary channel habitat for lotic species such as fish, turtles, and mussels. The physical setting of the channel allowed for control of water velocities during normal river flows. The proposal included using a hydraulic model to approximate maximum velocities in the area. Mussel sampling near the area indicated sufficient mussel resources existed in the vicinity to promote establishment of mussels in the Phase 3 West area. Zebra mussels also seemed to be lower in this area.

They recommended mid-depth velocity 0.6 to 1.5 ft/sec during "normal flow", mid-depth velocity ≥ 2.5 ft/sec during bank full flow, and recommended using river washed or rounded rock with 50% < 0.25 in, 30% 0.25 to 0.5 in, 15% 0.5 to 1 in, 5% > 2 in, with larger rock scattered throughout for variation. River rock was suggested due to the lack of mussel habitat observed in the created channel in Pool 11 discussed above. The quarry rock wedged together and left no interstitial spaces for sediment accumulation, which is necessary for mussel burrowing (J. Janvrin, pers. comm.). To allow for access for host fish, the channel should be continuous and maintain a depth of a least 6 ft. The area should be parallel to the bluff line, similar to other mussel beds in this reach. The westerly channel would be best due to the small tributary streams and delta from the streams, which attract fish and provide a variety of substrates.

<u>Notes from conversations with researchers and agency personnel</u>

USGS, UMESC, Dr. Teresa Newton, pers. comm., February and March 2013

The models developed by Steve Zigler and others are published in Morales et al (2006a&b), Steuer et al. (2008), Zigler et al. (2008), and Zigler et al. (2010). The Pool 8 model was used to generate the hydraulic parameters for the Pool 8 islands proposal for mussel habitat, although it was never built. The model was originally developed for the upper section of the river. Boundary Reynolds number and Froude number seem to be the parameters that consistently correlate with mussels in all of these models. The Pool 18 model (Zigler et al., 2010) was developed using the poolwide mussel study, and some differences in the suitable values for mussels were noted between Pool 18 and the upper river sites. Dr. Newton believes the model could be used to generate hydraulic parameters values for the lower pools and Illinois River. However, she is not sure whether the model would need to be recalibrated to this section of the river. Dr. Newton and Dr. Zigler are currently working with John Hendricks (St. Paul District, USACE) to develop mussel habitat within the Capoli Slough HREP.

USGS, UMESC, Email from Dr. Steve Zigler, March 8, 2013

The models published in Morales et al. (2006), Steuer et al. (2008), Zigler et al. (2008) and Zigler et al. (2010) were built for specific areas and purposes. They are based on different strengths and weaknesses, but they all point in the same general direction with regard to relationships between observed patterns of mussels and hydraulic patterns. Areas with too much hydraulic energy are unsuitable for mussels. Some papers also show too little energy may also be detrimental. The question then becomes how to best identify suitable hydraulic habitat. A model can be built that has some predictive capability with most complex hydraulic variables (referring to shear stress, relative substrate stability, Froude number, and boundary Reynolds number), because these variables tend to be significantly correlated as the result of using the some of the same basic building blocks for computation (i.e., current velocity, depth and sometimes substrate particle size). Variables that adequately describe the high and low ends of the hydraulic pattern would work best, but of course the variables have different strengths. RSS does a really nice job of identifying areas that are stable at high flows, but does miss areas of clay that are stable due to particle adhesion, and might not adequately find areas that have too little hydraulic energy. Shear stress and Boundary Reynolds will both find areas of high and low hydraulic energy/forces on the river bottom, but do not account for substrate stability as well as RSS. Shear has a natural interpretation as far as displacement forces on the river bottom, and Boundary Reynolds has a natural interpretation for food delivery and waste removal. He also found that Boundary Reynolds sometimes serves as a marker for areas of gravel, which can be useful. Froude relates well to water column processes, overall hydraulic regimes (and mobility of substrates to a limited extent), especially with regard to substrate/juvenile deposition and finding areas with too low hydraulic energy; however it does ignores substrate type/stability. His preference if he had to choose one or two variables to model habitat, would probably be shear stress and RSS since these have been shown to be useful in multiple studies in multiple systems. They also seem most closely related to ecological processes that might be important to mussels. They also provide logical insight for displacement of mussels during high flow and areas of flow separation and deposition of excysted juveniles, and yet could still identify areas that might be too lentic for most mussels. However, they do require substrate data, which can be a difficult piece of information to obtain.

University of Iowa, IIHR, Dr. Craig Just, pers. comm. March 28, 2013

Dr. Tatsuaki Nakato started working with using complex hydraulic parameters to create mussel habitat, but never created any habitat before he retired. Dr. Just does not know of anyone successfully creating mussel habitat. He is currently working with Iowa DNR to attempt habitat creation in the Iowa River in conjunction with a flood protection levee.

Missouri Department of Conservation. Travis Moore, email to Scott Gritters and Paul Sleeper (Iowa DNR) concerning habitat creation on the Iowa River, April 20, 2012.

"The project I've always wanted to try in the Mississippi River is to build a submerged island (ring of rip rap), then fill it with pea gravel, and just wait to see what happens. I was originally thinking about 5 - 6 feet below normal minimum levels. I believe that fish would use it pretty quickly, then we would see early-successional mussels show up. Or we could use it as a destination site if we needed to relocate mussels.

There are some concerns about whether the pea gravel would stay in place. Personally, if the structure was filled to the top, I think it would. I think scour would be minimal.

On a small stream, I might be more inclined to try a boulder field, or W-dikes. I'm sure you've seen the same up there as we do down here. Anytime you get a larger object (boulder, fallen tree, etc), somewhere around it you get the right flow and substrate and the mussels are just packed in there. A boulder field would create similar miniature habitats like this. We tend to find the mussels in the stable substrates in the tail, oftentimes right next to the boulder. A field could be as big or small as you want it to be, and would be easy to make since you could get chunks of riprap pretty easily.

W-dikes are similar to boulder fields, but piles of rock. St. Louis COE has been doing some of these on the Mississippi. They're just alternating piles of rock that still act like a traditional dike, but because of the gaps, there is maintained flow moving through the whole structure. You'll get some scour, but some protection too. If the stream were big enough that a W-dike is preferred, then you may find the mussels in close to the piles, or further downstream where you get the right mix of flow and substrate again. I can't say for sure because we haven't gone back and looked for mussels around the W-dikes down here, but I'd bet there are some around them."

<u>3.5 Recent unionid mussel studies within the St. Louis District</u>

An understanding of the mussel resources and their distribution within the SLD is needed to evaluate what type of habitat is preferred in the SLD, and what the hydraulic conditions are where mussels currently occur. Unionid mussel surveys within the St. Louis District have primarily been conducted by Travis Moore (MDC), Dean Corgiat (IDNR), and ESI. Studies conducted after 2000 were reviewed. Some data was also available from the INHS database. Post- 2000 Illinois River data were mostly limited to qualitative sampling conducted by IDNR with the assistance of commercial musselers, and a few surveys conducted by ESI. INHS conducted a more intensive qualitative and quantitative study of the Illinois River in 1993 to 1995. Relevant data from that study is also included.

Corgiat, D. A. 2008. Mussel survey results of segments of the Mississippi and Illinois Rivers. 1977-2007. Natural Heritage Biologist, Illinois Department of Natural Resources.

This report is a summary of work Dean Corgiat (IDNR) and Travis Moore (MDC) conducted within Pools 26 to 20 of the Upper Mississippi River and Illinois Rivers for gathering baseline data for future trend analysis, and determining locations of endangered species, effects of harvest (Illinois River), or locating parent stock for future propagation studies. A summary of his data for each pool is provided within respective sections.

3.5.1 Pool 24

Moore, T. and D. Corgiat. 2007. Survey of freshwater mussel beds in pools 20, 22, 24, and 25 of the Upper Mississippi River, 2003. (summary limited to Pools 24 and 25)

Twenty-seven of the 36 known species from the Missouri section of the Mississippi River were found in this study. Most common species were *O. reflexa*, *A. plicata*, *Q. quadrula*, *O. olivaria*, *E. lineolata*, and *Q. pustulosa*. Pool 24 had the most diverse species assemblages. Louisiana Riverfront (Pool 24) and Quiller Bed (Pool 25) each had 19 species. Six species of conservation concern in Missouri or Illinois were found in Pool 24 (no *F. ebena*) and five were found in Pool 25 (no *C. monodonta*). *Quadrula metanevra*, although not a listed species, seems to be declining. *Megalonaias nervosa* had the highest commercial value. Over half of the *M. nervosa* were found at the Louisiana Riverfront in Pool 24. However, *M. nervosa* recruitment was very low, only 4 of 396 individuals was <80 mm and 1 <50 mm. *Amblema plicata* was the most abundant species and was fairly well represented in all beds. Sites with long-term data in Pool 24 include Fools Creek Bed (MO bank, 299-300; 1988, 1994, and 2003), Blackbird Island (MO bank, 291.8-292.4; 1989, 1995, 1998, 2003), Cash Island (IL bank, 276.5-277.8; 1999 and

2003), Lower Hickory Chute (IL bank, 284.7-285.5; 1999 and 2003), and Louisiana Riverfront (MO bank, 282.3-283.5; 1990, 1999, and 2003). Most of these beds appear to be stable. Habitat within Fools Creek Bed seems to have changed dramatically. Large cobble transported downstream from Fools Creek seems to be having a detrimental affect on mussels in this bed.

Corgiat, D. A. and T. Moore. 2008. Mississippi River-Pool 22, 24 and the Chain of Rocks-Ebonyshell mussel (*Fusconaia ebena*) survey. Funded by The Illinois Wildlife Preservation Fund Project.

The objectives of this project were to locate *F. ebena* and determine its status, provide data to develop a management plan for this species, and locate potential brood stock for propagation. A total of 3818 mussels of 22 species were collected at 7 sites in 2008. Four most common species were *O. reflexa* (24%), O. *obovaria* (17%), *Q. quadrula* (16%), and *E. lineolata* (12%). 20 *F. ebena* were found: 19 at Hadley Island (Pool 22), 1 at Orton Island (Pool 22), 98 at Fabius Island (Pool 22), and 1 at Blackbird Island (Pool 24).

Hadley-McCraney (MRM 296.9-297.3) was also sampled. 15 species were found, but no *F. ebena* were found. Substrate was large cobble/sand mix, and depth ranged from 13 to 22.5 ft. Samples were collected 50 to 100 m from the bank. *Amblema plicata*, *Q. pustulosa*, and *Q. quadrula* were the dominant species. *Ligumia recta* and *E. lineolata* were also found. Three sites were sampled downstream of the Chain of Rocks; Mosenthein Island (MRM 186.9), first dike down of Chain of Rocks at MRM 189.5 (LDB), and a stretch of old rip rap at MRM 188.0 (RDB), however no unionids were found.

Corgiat, D. A. 2008. Mussel survey results of segments of the Mississippi and Illinois Rivers. 1977-2007. Natural Heritage Biologist, Illinois Department of Natural Resources. Pool 24

Brailing was conducted at 10 sites throughout the pool from 1998-2000. If mussels were found, the area was determined to be a potential bed to be sampled at a later time. From 1997-1999, 2002-2004, and 2006 six beds were sampled via diving and 20 beds were sampled via grubbing.

Five beds were quantitatively and qualitatively sampled in 1999:

Blackbird Island (MO bank, 291.5-292)

Hickory Chute (IL bank, 284.7-285.5)

Champ Clark Bridge Site (MO bank, 283.0-283.5)

Crider Island Bend (MO bank, 278.5-279.3)

Cash Island (IL bank, 277.2-277.8)

Blackbird Island density significantly declined from 14.8/m^2 in 1989 to 3.9/m^2 in 1999, although species richness remained high (20 species). Most species aged showed some recruitment. This bed was dominated by *A. plicata*, *O. reflexa*, and *T. truncata*. *Fusconaia ebena*, Missouri endangered species, was collected in 1989 but not in 1999. Decline appears to be due to the placement of a closing structure. Much of the area around the structure was deep silt.

Lower Hickory Chute was only sampled qualitatively due to depth (40-50 ft). Sixteen species were found including *Cumberlandia monodonta* (5 individuals). *Cumberlandia monodonta* were 9 and 10 years old. This bed was dominated by *M. nervosa* and *A. plicata*. Individuals ≤5 years old were also found for most species in this bed.

Champ Clark Bridge historically harbored *F. ebena*. River bottom was bedrock and interspersed mounds of gravel. Unionids were found in fissures and gravel mounds. No live *F. ebena* were found, but relic shells were present. Weathered and subfossil shells were extremely abundant, suggesting this bed has existed for a long time. This bed was also dominated by *M. nervosa*; *A. plicata*, *O. reflexa*, and *Q. quadrula* were also common. All four of these species were represented by young unionids (≤5 years).

Crider Bend was overwhelmingly dominated by *M. nervosa* (1.72/m^2; total density 3.28/m^2). *Amblema plicata* (0.56/m^2) and *Q. quadrula* were also common (0.2/m^2). A few young *M. nervosa* and *Q. quadrula* were collected, but most individuals were > 5 years old.

Cash Island was a large bed, sparse at the upper end and increasing in density downstream. Density in the upper portion of the bed was only 0.8/m^2, but qualitative sampling further downstream suggested density was higher. This site was dominated by *A. plicata* (34%) and *O. reflexa* (30%); *Quadrula quadrula* (10%) and *M. nervosa* (7%) were also common.

Zebra mussels seemed to be declining at the time of this survey. Interesting was the difference in dominance of either *A. plicata* or *M. nervosa* in these beds, suggesting possible differences in fish host abundance, flow, or microhabitat variables.

Corgiat, D. A. 2008. Mussel survey results of segments of the Mississippi and Illinois Rivers. 1977-2007. Natural Heritage Biologist, Illinois Department of Natural Resources.
Population Status survey for the Fat Pocketbook mussel in Pools 20 and 24 (2003)

This study investigated South Fritz Is (IL, 287.0), North Fritz Is (IL, 289.2), both banks of Blackbird Is chute (MO bank, 291.1 to 292.1- previous *P. capax* reintroduction site), Cottel Island area (299.7-300.4), South Fritz Chute (right bank of the island 287), and Gosline access (IL, 280.6). All sites were sampled by timed dives in 2003. No live *P. capax* were found, but weathered shells were found at Cottel Island. A total of 286 unionids of 15 species were found, primarily within a small area between wing dikes. Substrate ranged from pure sand to equal mixture of sand, silt, clay, and detritus. Blackbird Is substrate was a clay/silt mix with pockets of sand along the island bank. The Missouri shoreline was gravel and sand. This is one of the best beds in Pool 24; 1363 unionids of 16 species were found in 4 hrs and 14 min. The 2003 survey was downstream of the 1999 survey. No *P. capax* were found in either survey. *Obliquaria reflexa* (31%), *O. olivaria* (20%), *A. plicata* (17%), and *Q. pustulosa* (10%) were the dominant species collected.

North Fritz Island tip was sampled based on records of live unionids from 1977. Substrate was clay/silt near the bank to sand/silt further from the bank. Only 5 unionids were found in approximately 1 hour of diving. No *P. capax* were found.

South Fritz Island near the shoreline was sampled for less than 1 hour. Substrate was silt/sand/clay. A fresh valve of *P. capax* was found in 1986, but none were found in this survey. A site further down the chute was also sampled. Water was only 2 to 4 ft deep and substrate was a firm sand/silt in the center and deep silt and clay near the banks (seemingly good *P. capax* habitat). Both sites harbored unionids but no *P. capax*.

Gosline Access water depth was 2 to 11 ft and substrate was a clay, silt, sand mix. Unionids were abundant (546 unionids of 17 species) and the Illinois threatened *L. recta* was present. The site was dominated by *A. plicata* (55%). *Obliquaria reflexa* (16%) and *Q. quadrula* (12%) were also common.

ESI. 2002. Unionid survey of proposed dredge sites, Mississippi River miles 290 to 297, July 2002. 02-013.

A unionid survey was conducted to determine if sand and gravel could be dredged from the river for levee repair. Six sites were investigated between MRM 290 and 297. Only a few scattered unionids were found at 4 or the sites; however, 14 species were found at the Murphy Bed site in the tertiary channel (MRM 289.6) in sand/clay substrate within 60 m of the IL bank, and in the silt/sand/clay substrate of the Hadley-McCraney Bed (MRM 296.9-297.3) within 30 m of the IL bank.

ESI. 2008a. Final report, Unionid survey Lock and Dam 22 new 1200-foot lock. 07-006.

A survey was conducted to determine if a staging area that could be used for construction at L&D 22 harbored unionids. This area was on the upstream edge of the Fools Creek bed that occurs between MRM 299 and 300. A total of 23 species were found and density averaged 40.9/m^2. Substrate was a combination of bedrock, boulder, cobble, gravel and sand. *Amblema* *plicata* and *O. reflexa* were the dominant species. However, very little recruitment was apparent, as only 3.8% of the community was ≤ 5 years old.

ESI. 2008b. Executive summary: addendum REX-East Pipeline Crossing-Missouri Unionid relocation Mississippi River Mile 284.9. 07-005.

A survey in 2007 indicated that a low density of unionids occurred within 100 m of the bank. Unionids were relocated from the construction area for the REX pipeline. A total of 1896 unionids of 18 species were removed from the area and placed just upstream of the downstream tip of the island. Banks were gently sloping and substrate was a mix of sand, silt, and clay within 80 m of the bank. Further riverward, substrate became sandier and unionid abundance declined.

ESI. 2009a. Assessment of unionids and habitat for proposed dike construction near Mississippi River mile 291. 09-013.

A unionid survey was conducted to determine if unionids would be affected by dike construction activities near MRM 291. Most of the area was unstable sand; however, a very low ($0.33/m^2$) of unionids was found in the silt/clay substrate near the bank.

ESI. 2009b. Final report: assessment of unionids and habitat for mooring cell G2 in Mississippi River Pool 24. 09-014.

A survey was conducted to determine if unionids would be affected by construction of a mooring cell upstream of Lock 24. Substrate was riprap, boulder, and cobble near the bank, and the bank sharply dropped off to >3 m. A dike was present at the upstream end of the site. This dike reduced current velocity, and silt and clay were the most prevalent substrate within 200 m of the dike. However, substrate within a scour hole downstream of the dike was boulder, cobble, and sand. Further downstream, loose sand was the predominant substrate. Only 7 unionids were collected, and these were found within the silt, clay substrate within 50 m of the bank, along the 2nd and 3rd transect downstream of the dike (shoreward and downstream of the scour hole).

ESI. 2010a. Final report: Assessment of unionids and habitat for proposed dike construction at the Gilbert Island Complex, Mississippi River mile 298.6 to 298.2. 10-023.

Most of this area was loose sand. A few unionids were found in the silt/sand/clay substrate near the bank.

ESI. 2010b. Final report: assessment of unionids and habitat at proposed dredge sites, Pool 24, Mississippi River. 10-008.

A survey was conducted within several alternative dredge sites between MRM 279.7 and 285.5. This area encompassed the Crider Bend and Louisiana Riverfront beds sampled by Moore and Corgiat in 2003 (Corgiat 2008). Downstream of the Salt River (284) a low density of unionids were within 100 m of the bank in silt, sand, clay, boulder, bedrock substrate. A strip of bedrock formed the riverward edge of the bed, and unstable sand occurred riverward of the bedrock. *Megalonaias nervosa*, *A. plicata*, and *Q. quadrula* were the dominant species. Upstream of the Salt River along Blackburn Island, substrate was silt, sand, clay and unionids were primarily within 50 m of the bank. *Amblema plicata*, *O. reflexa*, and *Q. quadrula* were the dominant species.

ESI. 2011a. Unionid mussel distribution upstream and downstream of Lock and Dam 22, Mississippi River miles 299.8 to 302.3, 2009. 09-001.

Habitat downstream of Lock and Dam 22 along the Illinois bank was primarily loose sand, with boulder, cobble, gravel near the dikes and silt/clay near the banks within the side channel. Only a few scattered unionids were collected throughout the area.

ESI. 2011b. Assessment of unionids and habitat for proposed operations and maintenance navigation features, Mississippi River miles 279.7 and 280.4. 11-023

Two small strips within 50 m of the bank were sampled to determine if placement of rip rap would affect unionids. This area was within the area sampled by ESI in 2010. Density averaged $3.7/m^2$ and $0.6/m^2$ near 280.1 and 279.9, respectively. *Amblema plicata*, *M. nervosa*, and *Q. quadrula* were the dominant species.

3.5.2 Pool 25

Corgiat, D. A., and T. Moore. 2004. The Illinois-Missouri Cooperative Mussel Project-Report of 2003 Mussel Surveys of Eight Beds on Mississippi River Pool 25; Clarksville, Quiller, Sny Island, Coon Island, Maple Island, Carroll Island, Outer Stump, and Kelly Island. 19pp.

Eight beds in the pool were sampled in 2003. All sites were sampled qualitatively. A total of 22 species were collected at these sites combined, and *A. plicata* (28%), *O. reflexa* (22%), and *Q. quadrula* (15%) were the dominant species. Several other sites were sampled that yielded only a few mussels.

Clarksville Bed is located along the Missouri bank MRM 271.8-273 just downstream of Lock and Dam 24. Quantitative and qualitative sampling methods were used. 15 species were found, and density averaged 2.76/m^2. *Obliquaria reflexa* was the dominant species, and *A. plicata*, *Q. quadrula*, and *O. olivaria* were common. Water depth was 5 to 13 ft, and substrate ranged from 80%gr/20%sd mix to 90%sd/10%gr mix.

Sny Island bed is located along the Illinois bank near MRM 267.6-269.0, just downstream of the Carroll Island bed in the side channel. This bed was limited to 5 to 10 m from the bank in 4-5 ft of water. Substrate was 60% sand, 20% silt, and 20% clay. Dominant species were *A. plicata*, *O. reflexa*, and *Q. quadrula*.

Coon Island bed is located near the tip of Coon Island at MRM 266.2-266.5. Unionids were limited to 3 to 7 m from the bank in water 4-5 ft deep. Substrate was sand, silt, and clay, with sand dominating. Dominant species were *A. plicata*, *O. reflexa*, and *Q. quadrula*, although several *P. grandis* were also found.

Quiller Bed is located along the Illinois bank at MRM 259.0-260.2. Quantitative and qualitative sampling yielded 20 species, and density averaged 4.93/m^2. *Obliquaria reflexa* also dominated the Quiller Bed. *Amblema plicata*, *Q. quadrula*, *O. obovaria*, and *E. lineolata* were also very common. Depth ranged from 3 to 26 ft and substrate was mostly sand with cobble, gravel, silt, and clay throughout the bed.

Carroll Island Bed is within the side channel along the Illinois bank at MRM 268.8-269.1. This was a shallow bed at 4 to 5 ft with a substrate of mostly clay mixed with silt and sand. 14 species were found, with *A. plicata*, *O. reflexa*, and *Q. quadrula* being dominant

Kelly Island bed is along with a side channel along the Illinois bank at MRM 255.9-256.9. All unionids were from 2 to 30 m from the bank in 5 to 8 ft of water. Clay and sand dominated the substrate. *Amblema plicata* and *Q. quadrula* were the dominant species.

Outer Stump Lake was along the Illinois bank at MRM 250.4-250.8. Unionids were primarily between dikes at the tips of the dikes. Depth averaged 10 ft and substrate was mostly sand. A 25 minute dive yielded only 36 unionids of 5 species, mostly *O. reflexa*, but also *P. grandis*, *Q. quadrula*, *Q. pustulosa*, and *A. plicata*.

Maple Island was along the Illinois bank at MRM 247.8-248.5. All samples were within 30 m of the bank. Substrate was silt and clay. *Amblema plicata* overwhelmingly dominated the community, but *O. reflexa* and *Q. quadrula* were also common. A total of 13 species were found.

Four sites that were previously classified as good beds were no longer in existence

Pecan Island MRM 270.0-270.5

Rip rap Landing MRM 265.4 to 265.7
Dead Man's Bed MRM 263.7
Channel side of Kelly Island MRM 256.6-257.0

ESI. 2003a. Letter report, Evaluation of unionid mussel colonization near a potential mooring site in Mississippi River Pool 25 (MRM 272.0 to 271.6). 03-032.

A survey was conducted to determine if unionids would be affected by the construction of mooring cells downstream of Lock and Dam 24. A unionid bed is known to occur upstream of this area and the mooring cells would prevent barges from nosing into the bank and disturbing this mussel bed. Substrate within the study area was riprap along the bank, and unstable sand riverward of the riprap. Only one live *P. alatus* was found in the study area.

ESI. 2003b. Letter report, Unionid survey near proposal round point construction on Kelly Island, MRM 257. 03-008.

Three 200 m transects were sampled on the riverward upstream edge of Kelly Island (MRM 256.6-257.0). Substrate was almost entirely sand and only one unionid was found.

ESI. 2008c. 2007 Monitoring of unionids and habitat for the Batchtown environmental management program- habitat rehabilitation and enhancement project in Mississippi River Pool 25. 07-008

This area was monitored to determine if the Batchtown HREP would affect the unionid communities in the Batchtown mussel bed, upstream of L&D 25. Monitoring was conducted pre-construction in 2003 and during construction in 2006 and 2007. An area immediately upstream of Dam 24 (LDB) was sampled as a reference. Density significantly declined within and downstream of the HREP between 2003 and 2006. Depths also declined in these areas, although substrate remained a mix of silt and clay. Unionids seemed to be more confined to the deeper thalweg in 2006 than in 2003, however, unionids were scattered throughout the area in 2007. Density in the reference area was also significantly less in 2007 than in 2006. This area was also shallower in 2007, and substrate was sandier than in 2006. Both of these beds were heavily dominated by Ambleminae and very little recruitment was observed. The Batchtown Bed is limited to the silt/sand/clay substrate, and ends where depth increases and sand becomes the dominant substrate type near the channel. The bed in the reference area was limited by shallow water near the bank, and the sand substrate riverward. All unionids in the reference area were

within 100 m of the bank.

ESI, 2007a. Final report: Unionid survey of the Mississippi River mile 241.5 Lock and Dam 25 addition. 07-007.

Unionid mussels were sampled upstream and downstream of the lock to determine unionid distribution and community characteristics. Only two small concentrations of unionids occur in the area, at the upstream and downstream ends of the study area, respectively. These are the only areas protected from flow, with stable heterogeneous substrate. The remaining area is affected by high current velocity and either substrate has been scoured or is mobile, which are conditions not conducive to unionids. Overall, 138 unionids representing 13 species were collected from the project area. Unionid density observed in the small concentrations upstream of and downstream of the lock was 5.1 unionids/m^2 and 1.6 unionids/m^2, respectively. The upstream concentration was upstream of the L dike where substrate was cobble, boulder and clay. The downstream concentration occurred in a narrow strip downstream of a silty area, but within a hydraulic refugia.

ESI. 2012a. Final report: unionid and habitat monitoring for pre-construction O&M navigation features, Mississippi River Mile 245.0 to 242.0. 12-003

ESI sampled areas along both banks between MRM 244 and 242 to determine if unionids would be affected by placement of chevron dikes. Three small mussel beds were found, one along the Missouri bank between MRM 243.5 and 243.8, and two along the Illinois bank near MRM 242 and MRM 243. The bed along the Missouri bank and the Illinois bed near MRM 242 were quantitatively sampled in both years to establish baseline conditions with the objective of determining how hydraulic changes due to the chevron dikes might affect unionids in these beds. The MO bed was limited to the silt, sand, and clay substrate within 100 m of the bank. The Illinois bed occurred within a deeper trough created by the presence of a parallel wing dike. Substrate was primarily sand/gravel with more silt/clay near the bank and upstream. Both areas were dominated by the Ambleminae *A. plicata* and *Q. quadrula*, both were also low density (1.7 to 3.3/m^2), and had <10% of their communities ≤5 years old.

A second aspect to this study was a qualitative investigation of the chevron dikes in Pool 24, between MRM 289 and 290 on the Illinois bank. These dikes were constructed in 1993 and previously sampled in 1994. Substrate throughout the area in 1994 was loose sand and not conducive to unionids. Most of the area on the exterior of dikes was also loose sand in 2012, but some of the area between dikes appeared to be stabilizing. No live unionids were found, but one shell of *C. monodonta* was recovered. The face of the dikes was investigated, but no live or additional shells of this species was found. A weathered *P. capax* shell was also recovered, but no evidence of live individuals was found. The area directly within the structures was deep silt and a few thin shell unionids were found. One strip of unionids was found in silt, sand, clay substrate near the island upstream of the upstream most dike. Most of the unionids found were *A. plicata*. It is not known where this strip of unionids was present in 1994.

3.5.3 Pool 26

Corgiat, D. A. 2008. Mussel survey results of segments of the Mississippi and Illinois Rivers. 1977-2007. Natural Heritage Biologist, Illinois Department of Natural Resources.

Pool 26

Most of this work was completed in 2005. Twenty-two (22) sites were sampled by timed dives and 2 sites were quantitatively sampled (including the Powder Mill Bed, an INAI site and Site 11 at MRM 206.0-205.8). A total of 1486 unionids of 20 species were found. Based on raw data (ESI database), most sites had a few scattered unionids. Sites 1 (238-241) and 2 (233.5-234.5) contained several species. Dominant species were *A. plicata*, *O. reflexa*, and *Q. quadrula*. The only sites with significant unionids was the Powder Mill Bed (216-216.6; just downstream of the Illinois River confluence) and Site 11 (206.0-207.8). Powder Mill Bed contained 15 species, and was dominated by *M. nervosa*. Substrate was sand and silt, with pockets of gravel and cobble. Density averaged 13.0/m^2 and 10.8 % of the unionids in quantitative samples were ≤5 years old. The Illinois threatened *E. lineolata* was collected in this bed. Site 11 contained 19 species, including *E. lineolata* and *F. ebena*, although density was only 3.8/m^2 and no juveniles were found. Site 11 was co-dominated by *A. plicata* and *Q. quadrula*. Substrate was also sand/silt with some gravel/cobble.

ESI. 2003c. Letter report, mussel survey for potential mooring buoy site in Mississippi River Pool 26. 03-022

A mussel survey was conducted between MRM 240.4 and 240.7 along the Missouri bank downstream of Lock and Dam 25 for placement of a potential mooring buoy. The survey included the area from 0 to 100 m from the bank. In general, substrate was boulder rip rap with 10 m of the bank along a sharply sloping bank, and sand riverward. The downstream most transect was somewhat protected from the flow coming from the dam and was less steep. 13 of the 14 unionids collected in this study were found at the toe the riprap in a small patch of cobble, sand, and silt. This small vein of unionids may benefit from substrate stability of this specific area and reduced shear stress provided by the bank at the bend in the river just upstream.

3.5.4 Middle River

Corgiat, D. A. and T. Moore. 2008. Mississippi River-Pool 22, 24 and the Chain of Rocks-Ebonyshell mussel (Fusconaia ebena) survey. Funded by The Illinois Wildlife Preservation Fund Project. (see summary under 3.4.1 Pool 24).

Illinois Natural History Survey/Illinois DNR. 2008. N.L. Owens NW edge Hartford, RM 197.5. Data from INHS database. 38.840887, -90.105374.

16 mussel species, 1396 mussels were collected, including *Cumberlandia monodonta* along the outside bend within the Hartford Bed.

ESI. 2012b. Unionid survey at Flint Hills Resources barge terminal Mississippi River mile 195. 12-020.

A small area downstream of the Missouri River and upstream of the Chain of Rocks canal along the Illinois bank was sampled in 2012. Unionids were limited to a strip of mussels riverward and shoreward of rip rap. 17 species were collected, including *E. lineolata*. In one area density averaged 16.7/m^2. Shoreward substrate was silt, riverward substrate was loose sand.

INHS, Jeremy Tiemann, personal communication. April 2013

Jeremy Tiemann and Kevin Cummings conducted shoreline searches for mussels in the Middle Mississippi River during the drought of 2012. They found mostly shells of thin shelled species (*L. fragilis*, *P. ohiensis*, and *P. alatus*) and *A. plicata* in dike field areas. They did not find any evidence of mussel beds.

MDC, David Ostendorf, personal communication, August and November 2013

A few areas with stable gravel bars are present in the middle Mississippi River that could harbor small areas with mussels. These areas include the head of Establishment Island, chevron dike at MRM 90.4 RDB, head of Fountain Bluff Bar MRM 85.0 to 84.3 RDB, head of Cottonwood side channel, mouth of Crawford Creek (MRM 73.1 RDB), mouth of Hanging Dog Creek (MRM 72.0 RDB), Thebes Gap area, and the head of Santa Fe side channel. These gravel bars have been present for years and have not changed much. Mussels are likely behind dikes or boulders, and in small pockets rather than in beds such as those in the upper pools. Species found near Thebes, IL include *O. olivaria*, *L. complanata*, *L. teres*, *L. fragilis*, *P. alatus*, *P. ohiensis*, and *Q. quadrula*

3.5.5 Illinois River

Corgiat, D. A. 2008. Mussel survey results of segments of the Mississippi and Illinois Rivers. 1977-2007. Natural Heritage Biologist, Illinois Department of Natural Resources.

Most of the Illinois River sites were sampled in conjunction with a commercial clammer. 87 timed dives (total 1944 minutes) were conducted from 2001 to 2006. A total of 12,789 individuals and 24 species were found. Areas sampled in the Alton Pool were ILR mile 5.2, 43.2 to 80.1. One site was at IRM 5.2, and the remaining 60 were between 43.2 and 80.1. In nine years of sampling only two Illinois T&E species were collected, one *L. recta* at IRM 5.2 and *F. ebena* at IRM 61.2. Unionids were primarily along the banks. Substrate was listed at mud, fine sand/silt, or sand/pea gravel. Substrate was not listed consistently enough to determine if catch per effort was greater in a particular substrate type. Approximately 23 Illinois Natural Area Inventory sites were proposal and accepted.

Hill Creek Bed (RDB, RM 43.7)
Hurricane Creek Bed (LDB, RM 43.8)
Van Geson Island Bed (LDB IRM 45)
Grand Pass Bed (RDB, RM 45)
Buckhorn Is Bed (LDB, RM 46.7)
Montezuma Bed (RDB, RM 52.0)
Little Blue Creek Bed (LDB, RM 54.1 to 56.4)
Griggsville landing Bed (LDB, RM 61.2-61.5)
McCoe Lake Bed (RDB, RM 62.6-62.7)
Mauvaise Terre Creek Bed (LBD, RM 63.4)
Meredosia Docks Bed (LDB, RM 69.0)
Woods Lake Bed (RDB, RM 69.5)
National Starch Bed (LDB, RM 69.8)
George Smith Bed (RDB, RM 70.3)
Wilson Daymark Bed (RBD, RM 73)
Wilson Island Bed (LDB, RM 73.2)
Little Creek Bed (RDB, RM 74.9)
Island Road Bed (RDB, RM 75.1-75.2)

ESI. 2003d. Unionid survey at a proposed dredge site on the Illinois River in Pike County, Illinois. 03-009.

This survey was conducted to determine if dredging near a power plant intake would affect unionid mussels. The survey was conducted along the right descending bank of the Illinois River near RM 41.5. Unionids were primarily found 30 to 50 m from the bank in the sand, silt, clay, cobble, gravel substrate. This appeared to be a historic bed, as 12 species were found in the survey and 9 additional species were collected as weathered or subfossil shells (including *L. higginsii* and *P. cyphyus*). Recruitment was also apparent. This site was also sampled by Danglade (1914) and Starrett (1971). The extent of the bed is unknown.

ESI. 2005. Final report: Qualitative surveys of unionids and associated habitats within the Rock, Illinois, and Kankakee Rivers, Illinois to identify potential relocation areas for the federally endangered Higgins' eye pearly mussel (*Lampsilis higginsii*). 03-020.

Five historical *Lampsilis higginsii* sites were investigated for the potential of relocating *L. higginsii* from the Mississippi River. Two sites were within the Alton Pool of the Illinois River, Florence bridge (RM 56.0) and Montezuma (RM 50.1). At the Florence bridge site, unionids were more abundant in shallower water in sand, silt, and clay, and less dense in the cobble, gravel, and sand in deeper water. Substrate throughout the Montezuma site was sand, silt, and clay, and unionids were more abundance in the downstream portion of the site. Recruitment was evident in both areas, and unionids were fairly abundant (estimated density 5-6/m^2). Florence was dominated by *Q. quadrula*, *A. plicata*, and *M. nervosa*. Montezuma was dominated by *A. plicata*, *Q. quadrula*, and *Q. pustulosa*.

ESI. 2007b. Unionid mussels and habitat at the heads of four islands in the Illinois River. 06-015.

This survey was conducted to determine if any unionids would be affected by shoreline protection structures near four islands on the Illinois River between RM 38.0 and 40.1. Unionids were found along the east edge of Twin Islands. Substrate around most of this island was sand, silt, and clay. Unionids were limited to the sand, clay, and small gravel substrate along the east bank in the upstream half of the island and between islands. This area seemed to have better substrate (less silt) and may be protected from higher flow by the small island. At Fisher Island unionids were limited by deeper silt in the back channel, and were primarily found in the sand substrate along the west side of this island. At Spar Island, substrate within 20 m of the bank was clay, and substrate further from the bank was sand, clay, and gravel. Unionid density was fairly low, with the exception of one 10 m section of transect. Wing Island may have been an old mussel bed site on the west side of the island, as 8 species were collected live and 15 were collected as shells. This side of the island dropped off abruptly, and substrate was sand, silt, and relic shells. East side of the island was primarily silt.

Mussels in this area seemed to be in areas with less silty substrate, which usually corresponds to higher flow. Even though mussels were found, recruitment was very low (5.8%).

ESI. 2007c. Letter report, IRM 71.5 to 72.0. 07-020.

This survey was conducted for a small construction site on the RDB along an inside bend. Substrate was silt/sand/clay near the bank, but 90 to 100% sand riverward. Only 2 unionids were found near the bank.

ESI. 2010c. Final report: freshwater mussel survey Illinois River (RDB, RM 75.8-76.3), Alton Reach Moore's Towhead bank stabilization project. 10-011.

This survey was conducted to determine if bank stabilization would affect unionid mussels. Substrate was primarily silt/clay near the banks and sand with some silt riverward. Unionids were scattered throughout the area, but a small concentration was found within 50 m of the bank downstream of the island. Within this area, density was $2.0/m^2$ and 80.0% of the unionids were ≤5 years old. *Amblema plicata* and *Q. quadrula* were the dominant species. Bank stabilization efforts may have affected the hydraulic characteristics of this area. This area could be considered for investigating the effects of stream bank stabilization. This area may be an old bed, as shells of *P. cyphyus*, *Q. metanevra*, *F. ebena*, and *Q. nodulata* were found.

ESI. 2011c. Final report: Illinois waterway dike and revetment Illinois River Reach (RM 79.5-76.3), Alton Reach. 10-021.

This survey was conducted in an area of frequent dredging, where training structure construction was proposed to reduce the need for dredging. Substrate throughout the area was sand, silt, and clay. Unionids were scattered throughout the area, but were primarily found near the bank along the slight inside bends. This suggests that areas of low energy are more suitable for unionids in this river reach rather than the typical outside bends typically associated with mussel habitat. This area was within a few miles of the dam, and flow may be higher here than in other reaches.

Whitney, S. D., K. D. Blodgett, and R. E. Sparks. 1997. A comprehensive mussel survey of the Illinois River, 1993-1995. Illinois Natural History Survey.

The Illinois River was once thought to be one of the most productive mussel rivers in the United States. 49 species historically occurred in the river. Starrett (1971) indicated over half of these species were extirpated in his survey between 1966 and 1969 due to pollution, siltation, over harvesting and destruction of mussel habitat A series of 5 locks and dams were completed during the 1930's that divided the river into 5 reaches. The upper river reaches, Marseilles and Starved Rock, have a steep gradient, with an average fall of 18 inches per mile. The lower three reaches (Peoria, LaGrange, and Alton) occupy the pre-glacial bed of the Mississippi River and have a lower gradient (1.8 inches/mile), and a river bottom of silt and sand. Sampling was conducted in all pools between 1993 and 1995 using brailing as an exploratory device, and quantitative and qualitative sampling. A few of the quantitative sites fell in the Alton Pool, IRM 5.5, 50.1, 66.8, 3.0, 10.4, 37.8, and 67.0. A total of 17 species were found in the Alton Pool. Density averaged

IRM 3.0 LDB	7.75/m^2
IRM 5.5RDB	9.46/m^2- same site sampled by IDNR 2002
IRM 10.4 RDB	7.6/m^2
IRM 37.8 RDB	15.3/m^2- downstream of ESI sample in the back channel
IRM 50.1 RDB	19.12/m^2- same area sampled by ESI in 2003
IRM 66.8 RDB	4.97/m^2
IRM 67.0 LDB	8.17/m^2

Zebra mussels significantly affected unionid mortality.

Species richness in the lower 3 reaches continued the trend of reduced species richness identified by Starrett, whereas species richness improved in the upper 2 reaches.

4.0 Literature Index

A

Allen and Vaughn (2010) 30

B

Brim Box et al. (2002) 13

C

Corgiat (2008) 61, 62, 64, 70, 72
Corgiat and Moore (2004) 67
Corgiat and Moore (2008) 62, 71

D

Daraio et al. (2010) 46
Di Maio and Corkum (1995) 22

E

ESI (2002) 64
ESI (2003a) 68
ESI (2003b) 68
ESI (2003c) 71
ESI (2003d) 73
ESI (2005) 73
ESI (2007a) 69
ESI (2007b) 73
ESI (2007c) 74
ESI (2008a) 65
ESI (2008b) 65
ESI (2008c) 68
ESI (2009a) 65
ESI (2009b) 65
ESI (2010a) 66
ESI (2010b) 66
ESI (2010c) 74
ESI (2011a) 66
ESI (2011b) 66
ESI (2011c) 74
ESI (2012a) 69
ESI (2012b) 71

F

Feminella and Gangloff (2001) 28
Fulton et al. (2010) 31

G

Gagnon et al. (2006) 18
Galbraith and Vaughn (2010) 21
Gangloff and Feminella (2007) 28
Gangloff et al. (2011) 22
Goodding (2012) 32

H

Haag (2012) 7
Haag and Warren (2007) 19
Hardison and Layzer (2001) 25
Hart (1995) 10
Hastie et al. (2000) 11
Hastie et al. (2003) 14
Holland-Bartels (1990) 40
Hornbach (2001) 41
Hornbach et al. (2010) 50
Howard and Cuffey (2003) 26

I

INHS/IDNR (2008) 71

J

Johnson and Brown (2000) 12
Just (personal communication) 60

K

Karatayev and Burlakova (2008).............. 20

L

Layzer and Madison (1995)...................... 23

M

McRae et al. (2004).................................. 17
Miller (1982).. 51
Miller (1983).. 52
Miller (1988).. 53
Miller (2006).. 53
Moore (personal communication)............. 60
Moore and Corgiat (2007) 61
Morales et al. (2006a) 43
Morales et al. (2006b).............................. 44

N

Newton (personal communication)........... 59
Newton et al. (2008) 6
Nicklin and Balas (2007) 20

O

Ostendorf (personal communication) 72

P

Parasiewicz et al. (2012)........................... 33
Payne and Tippit (1989)............................ 54
Peck (2005) 26

R

Rahm (2008) 29
Randklev et al. (2009)............................... 30

S

Schwalb and Ackerman (2011)................. 36
Sietman et al. (1999)................................. 11
Sparks and Strayer (1998)......................... 11
Steuer et al. (2008).................................... 44
Straka and Downing (2000)...................... 41
Strayer (1981) 9
Strayer (1983) 16
Strayer (1993) 16
Strayer (1999) 24
Strayer and Ralley (1993) 9
Strayer et al. (2004)..................................... 5

T

Theiling (1995) 37
Theiling et al. (2000)................................ 38
Tiemann (personal communication) 71
Tippit et al. (1997) 36
Tucker et al. (1996).................................. 41

U

U.S. Army Corps of Engineers (1989)...... 55
U.S. Army Corps of Engineers (1995)...... 56
U.S. Army Corps of Engineers (1996)...... 56
U.S. Army Corps of Engineers (2002)...... 57
U.S. Army Corps of Engineers (2004a).... 57
U.S. Army Corps of Engineers (2004b).... 58

V

Vannote and Minshall (1982) 14
Vaughn and Taylor (2000)........................ 16

W

Watters (2000) 4
Whitney et al. (1997) 75
Wisconsin DNR 58

Y

Young (2006).. 42

Z

Zigler (personal communication).............. 59

Zigler et al. (2008) 45
Zigler et al. (2010) 48
Zimmerman and de Szalay (2007)............ 35