Final Report
Unionid Mussel Habitat Construction/Creation Summary

Prepared for:

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St. Louis District
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February 2014
(ESI Project no. 12-027)

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1.0 Introduction

The St. Louis District (SLD) 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. Additionally, the SLD constructs smaller projects in and around waterways for flood management and environmental restoration. These projects involve dredging and the placement of rock structures; activities that have the potential to either negatively or positively impact freshwater unionid mussel species (unionids). The SLD 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 SLD contracted Ecological Specialists, Inc. (ESI) to compile a list of published literature on mussel habitat, with emphasis on the Upper Mississippi River Basin (UMRB) (ESI, 2013). Literature is summarized in this report with the objective of providing a non-scientific educated reader sufficient information to gain an understanding of mussel habitat construction and creation techniques and theory. Ideas for habitat construction were provided in a draft report. The draft was presented and habitat construction ideas discussed at a workshop in Alton, IL. This document provides a summary of literature, personal communications, personal knowledge of mussel habitat, and ideas discussed in the workshop. This information was used to develop a plan that may lead toward creating or enhancing mussel habitat in the SLD.

2.0 Methods

Literature was reviewed to obtain an understanding of variables that seem to define unionid habitat. Although this literature review facilitated a general understanding of unionid habitat, none of the published studies or reports was specific to the SLD portion of the UMRB. Dr. Teresa Newton and Dr. Steve Zigler at the U. S. Geological Survey (USGS) Upper Midwest Environmental Science Center (UMESC) in LaCrosse, WI, Dr. Craig Just at the University of Iowa IIHR-Hydroscience & Engineering (IIHR), and Mr. Jeff Janvrin of Wisconsin Department of Natural Resources (WDNR) were contacted to discuss mussel habitat models and on-going mussel habitat projects in the UMRB. Dr. Andrew Miller and Dr. Barry Payne (USACE-Environmental Research and Development Center [ERDC]; retired) were also contacted with respect to ERDC's mussel habitat projects that were constructed in the 1980's.

To assess unionid habitat conditions within the SLD, Mr. Travis Moore (Missouri Department of Conservation [MDC]), Mr. Elmer (Butch) Atwood (Illinois Department of Natural Resources [IDNR]), and Mr. Dean Corgiat (IDNR) were contacted for information on mussel distribution in the Mississippi and Illinois rivers. Illinois Natural History Survey (INHS) was also contacted for records of unionid species within the SLD. ESI unionid survey reports within the SLD were also reviewed. Mussel survey information from these sources was compiled in ArcGIS for a visual representation of mussel distribution in Pools 24, 25, and 26 of the Upper Mississippi River (SLD-UMR) and Alton Pool of the Illinois River (SLD-IR). These maps were evaluated to detect patterns in unionid community distribution and facilitate discussions on potential areas for habitat creation projects. Since unionids require a fish host to complete their life cycle, a table was prepared comparing fish species known to occur in the SLD with known hosts of unionid species in the SLD. Fish records were obtained from Stueck et al. (2010). Host fish records were obtained from the Ohio State Museum of Diversity Molluscs Division host database.

Following the compilation of unionid habitat and unionid distribution in the SLD, ESI presented the information at a workshop held on August 9, 2013 at the Melvin Price Lock and Dam Museum in Alton, IL. Participants included hydraulic engineers and project managers from the USACE SLD, and USACE biologists from SLD, Rock Island, and St. Paul Districts. Biologists from IDNR and MDC also attended (Appendix A). Ideas from this workshop were compiled to outline a plan for obtaining data toward habitat creation in the SLD and possibly improving habitat during maintenance and future construction.

3.0 Mussel habitat requirements and creation

The information gathered from literature and mussel researchers presented herein provides a basis for evaluating unionid habitat within the SLD. The factors that define unionid habitat are complex and are not consistent among watersheds or even within a river reach. However, the general concepts have been used in the past to successfully create mussel habitat and can be applied to SLD river training structures.

3.1 General mussel habitat requirements

Freshwater unionid mussel (Bivalvia: Unionoida) distribution and abundance is dependent on a complex suite of conditions due to their complex life history, which differentiates this group from other freshwater bivalves (see Strayer et al., 2004; Strayer, 2008; Haag, 2012 and references therein). In general, males release sperm into the water column. Females draw sperm in through their incurrent siphons, and fertilized eggs are brooded within the water tubes of the female's gills (marsupia). Glochidia (larval mussels) are released with a variety of strategies and must attach to a fish host. Those that do not attach to the proper host will die. Glochidia are frequently rejected by a host due to acquired fish immunity or host specificity of the glochidia. Once attached, the fish encapsulates the parasitic glochidia. Glochidia metamorphose into a juvenile during attachment and excyst from the fish. Those that are released on or drift into suitable habitat conditions may survive to become adults. Host attraction, glochidial release to the host, glochidial attachment, metamorphosis on the host, and juvenile behavior after release varies with species (Strayer et al., 2004; Haag, 2012). Unionid mussels tend to form aggregations (called mussel beds) in rivers. These beds generally have density much higher than the surrounding area; often 10 to 100x higher (Strayer et al., 2004), although lower density communities persist in the UMR and other rivers (Dunn, pers. obs). Most healthy beds in large rivers contain a variety of tribes, species, and age classes (Dunn et al., 2012) and are constrained to stable areas of the riverbed, which have physical boundaries that can generally be defined by changes in a combination of substrate, depth, and/or current velocity. The formation of these beds seems to be a function of biotic and abiotic variables. Strayer (2008) proposes the following list of functional characteristics of mussel habitat:

- Allows juveniles to settle (shears are not excessive during juvenile settlement)
- Provides support (soft enough for burrowing, firm enough for support)
- Is stable (stays in place during floods, no sudden scour or fill)
- Delivers food (sediment organic matter for juveniles, current provides suspended food to adults
- Delivers essential materials (oxygen, calcium, etc.)
- Provides favorable temperatures for growth and reproduction
- Provides protection from predators (interstitial juveniles)
- Contains no toxic materials.

These characteristics are a function of local to watershed influences. On a large scale, historic patterns of dispersal, host distribution, climate, physiography, stream size, hydrological variability, and land use are some of the factors controlling the distribution of mussels (Strayer, 1983 and 1993; Vaughn and Taylor, 2000; Strayer et al., 2004; Gagnon et al., 2006; Newton et al., 2008; Haag, 2012). On a reach to local scale, the physical habitat of unionids is generally constrained to stable areas of a river that have some current velocity during low discharge and are protected from high current velocity during high discharge (flow refugia) (Vannote and Minshall, 1982; Vaughn, 1997; Strayer et al., 2004; Gagnon et al., 2006; Strayer, 2008; Haag, 2012). Good mussel assemblages occur in low gradient streams with silt, sand, and clay substrates and in higher gradient streams in gravel, cobble, and sand substrate, but substrate must be stable during low and high flows (Haag, 2012). Additionally, all requirements of all life stages need to be met for a unionid mussel bed to persist (Strayer et al., 2004).

Quantifying this idea of physical habitat is problematic. Early habitat studies described physical mussel habitat in terms of stream size, gradient, location of tributaries, channel width, current speed, water or channel depth, substrate, and various channel and stream bank descriptors (Strayer, 1981; Holland-Bartels, 1990; Strayer and Ralley, 1993; Hart, 1995; Hastie et al., 2000; Johnson and Brown, 2000; Hornbach, 2001; Hastie et al., 2003). However, few studies attempted to quantify these variables (Strayer and Ralley, 1993; Strayer, 1999). Studies that did quantify simple variables met with limited success (Brim Box et al., 2002; Karatayev and Burlakova, 2008). Some studies did find correlations between these variables and unionid presence/absence or abundance, but variables that measured substrate stability, flow stability, and/or flow refugia were the most useful predictors (Hart, 1995; Hastie et al., 2000; Johnson and Brown, 2000; Hastie et al., 2003; McRae et al., 2004; Gagnon et al., 2006). As a result, researches began investigating the relationship of unionid presence and abundance with complex hydraulic parameters (e.g. shear stress [t], shear velocity [U_*], Froude number [Fr], Reynolds number [Re], bed roughness [k_s], boundary Reynolds number [Re_*], slope, substrate transport, hydrologic variability, relative substrate stability [RSS]; Di Maio and Corkum, 1995; Layzer and Madison, 1995; Strayer, 1999; Hardison and Layzer, 2001; Howard and Cuffey, 2003; Peck, 2005; Morales et al., 2006a and 2006b; Young, 2006; Gangloff and Feminella, 2007; Rahm, 2008; Steuer et al., 2008; Zigler et al., 2008; Randklev et al., 2009; Allen and Vaughn, 2010; Hornbach et al., 2010; Zigler et al., 2010).

Describing habitat with complex hydraulic variables in combination with other physical variables (e.g., depth, bank full depth and width, distance from the bank, substrate particle size [D_m, D_{16}, D_{50}, D_{84}], substrate heterogeneity, bed velocity, and depth averaged velocity [U]) has generally been more successful in predicting mussel presence and distribution, as most of these hydraulic functions combine substrate, depth, and current velocity. Holland-Bartels (1990) found substrate and current velocity correctly predicted unionid abundance 44% of the time: a reanalysis of this data using calculated complex hydraulic parameters at low and high flow explained 63% of the variability in total unionid abundance for the same dataset (Steuer et al., 2008).

Many studies have investigated these hydraulic variables on a catchment (Gangloff and Feminella, 2007; Randklev et al., 2009), reach (Strayer, 1999; Howard and Cuffey, 2003; Peck, 2005; Young, 2006; Morales et al., 2006a and b; Steuer et al., 2008; Zigler et al., 2008; Zigler et al., 2010; Goodding, 2012), and local scale (Layzer and Madison, 1995; Hardison and Layzer, 2001; Howard and Cuffey, 2003; Rahm, 2008; Allen and Vaughn, 2010; Hornbach et al., 2010; Goodding, 2012). Models developed with these variables have successfully explained much of the variability in unionid distribution and abundance within the respective study area, demonstrating that mussel distribution is affected by complex hydraulic factors on all of these scales. However, the variables and magnitude of these variables explaining variance in presence, absence, and abundance of unionids in general and for specific species varied among studies due to differences in physiographic region, river size and geomorphology, scale of the study (catchment, reach, or microhabitat), and species composition. Differences were also due to study design (habitat within a mussel aggregation, between aggregations, or between areas with and without mussels; discharge frequency at the time of study; method of obtaining data [measured or modeled], and formula used in calculations). A common conclusion, however, is that unionid beds are constrained by complex hydraulic variables at the extremes of low and high flow.

Low hydraulic variation also appears to be important. Rahm (2008) found unionids to be more abundant in areas where shear stress varied less with increased discharge. Peck (2005) found unionids were in areas protected from core flow. Lateral scour pools along outside bends had lower mean velocity, bed velocity, Froude number and stream power, and acted as flow refugia in the White River, Arkansas. These lateral scour pools were upstream of the inflection point where core flow migrated from the inner to the outer bank. They also noted that this inflection point migrated downstream and expanded during high flow events, and that the boundaries of the mussel communities tended to coincide with these inflection points. Thus, flow in the lateral scour pool remained fairly constant in comparison to the core flow. Other studies have also related unionid abundance/presence with flow stability (less fluctuation in flow levels; Di Maio and Corkum, 1995; McRae et al., 2004; Gagnon et al., 2006)

Simply put, unionids are typically found under moderate conditions: moderate velocity, low fluctuation in velocity, heterogeneous substrate that is stable at high flow, but is loose enough for burrowing, and low amounts of smothering silt or sand. They require sufficient current velocity at low flow to prevent siltation and provide necessary food and oxygen, but require flow refugia during high discharge to prevent dislodgement. They are physically constrained to areas with some near bed turbulence or flow (typically measured as boundary Reynolds number, bed roughness, or current velocity) at low flow (typical measured at 95% exceedance). Current velocity or near bed turbulence at low flow allows exchange of nutrients and gases between the interstitial spaces in the substrate and water, prevents build up of waste products, and provides food and dissolved oxygen (Randklev et al., 2009; Zigler et al., 2010). However, turbulence or current velocity must be sufficiently low to allow juvenile settlement after they excyst from the host fish (Layzer and Madison, 1995; Hardison and Layzer, 2001), which occurs at various times of the year depending on species. Mussel presence also seems to be constrained by high discharge. Complex hydraulic variables such as shear stress and relative substrate stability (shear stress/critical shear stress) at bank full flow appear to be constraining in many studies (Howard and Cuffey, 2003; Morales et al., 2006a and 2006b; Gangloff and Feminella, 2007; Zigler et al., 2008; Allen and Vaughn, 2010), although variables at higher exceedance levels have been used to successfully explain mussel presence, absence, and abundance in some cases (Allen and Vaughn, 2010).

Bank full flow (1 to 2 year recurrence) is the primary channel shaping disturbance flow (references within Theiling et al., 2000). Hydraulic parameters measured at this flow are most likely to measure mussel habitat stability. Young (2006) found that complex hydraulic parameters measured at low (95% exceedance) and moderate flow (5% exceedance) were more highly correlated to mussel characteristics than at higher flows (1 or 2% exceedance), as these parameters varied more widely at low and moderate flows. Once flow exceeded bank full, little variation in hydraulic parameters was observed between habitats (Young, 2006).

3.2 Habitat Models

Although complex hydraulic variables have been used to explain existing unionid distribution, they have not yet been used to create mussel habitat. However, models have been developed that appear to explain much of the variance in unionid mussel presence/absence and abundance in Pools 8, 10, 16, and 18 of the UMR (Young, 2006; Morales-Chaves, 2004; Morales et al., 2006a and 2006b; Steuer et al., 2008; Zigler et al., 2008 and 2010; Daraio et al., 2010).

Young (2006) created a model using bathymetric data and velocity data measured throughout Pool 16 in the UMR. Five flow levels were simulated, 9000 cubic meters per second (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 relative 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.

Young's (2006) model had some discriminatory power with respect to species. Species separated into two groups; juveniles and smaller species (*Truncilla truncata* [deertoe], *Quadrula pustulosa* [pimpleback], and *Obliquaria reflexa* [three horned wartyback) 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 and were 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 (*Ellipsaria lineolata* [butterfly], *Lampsilis higginsii* [Higgins' eye pearly mussel], *Megalonaias nervosa* [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.

Young's (2006) model indicated that hydrodynamic parameters were most highly related to mussel characteristics at low to moderate discharge (bank full). This was likely due to the greater spatial heterogeneity in hydrodynamic variables at lower flows, creating greater contrast between different habitats. At higher flows (beyond bank full), 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. These features correspond to flow refugia and areas protected from core flow. Young's model was limited by the quantitative mussel data set and substrate data set only available for a small area that harbored mussels. Young (2006) provided values associated with unionid communities in his appendices.

Morales et al. (2006a and b) present 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). RSS (t_o/t_c; shear stress divided by critical shear stress, tangential force on the streambed necessary to move the substrate) is a dimensionless parameter that normalizes the effects of substrate and discharge on shear stress. Computation of RSS at different flow rates demonstrated how substrate stability varied over a range of discharge. The authors hypothesize that annual peak flows most often limit spatial distribution of unionid communities. RSS calculated at 1-year high flow for Pool 16 (3965 m^3/s) was used to predict habitat suitability and juvenile dispersal over a 10 km reach in Pool 16. (However, they did not explain what particle size was used for critical shear stress). RSS < 1 (shear stress not high enough to move substrate) was considered suitable habitat and RSS > 1 unsuitable. Results generally agreed with historic mussel distribution in this river reach (Appendix B). This model was built on Young's (2006) Pool 16 model.

Steuer et al. (2008) used complex hydraulic parameters to reanalyze Holland-Bartels (1990) Pool 10 data and developed a model of unionid distribution within the east channel of Prairie du Chien mussel bed. 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 (S_o) and bed roughness (k_s). 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 (D_m [mean grain size], S_o, and K_s) were calculated according to standard formulae.

This model found that unionid beds might be constrained at both ends of the hydraulic regime (see Appendix B). Under low flow, mussels may require a minimum hydraulic variable (Re_*, Fr) to transport nutrients, oxygen, and waste products; $Re_* > 2.1$ and 2.4 seemed to accurately predict presence/absence of some species. Re_* combines U (depth averaged velocity), d (depth), and k_s to describe near-bed turbulence and may reflect minimum turbulence needed to remove waste products and provide dissolved oxygen. It also describes exchange of surface and interstitial water. Six variables (Re_*, t, d, D_m, S_o, k_s) were the primary split variables in Classification and Regression Tree

(CART) analysis. Re_* and D_m were the most frequent primary split variables. However, difference species seem to be limited by different hydraulic parameters. Highest density of *Amblema plicata* (three ridge) at low flow was related to $Re_* > 2.1$, depth < 1.7 m and $t < 1.0$ dyne/cm^2. *Leptodea fragilis* (fragile heel splitter) at low flow was related to $Re_* > 2.4$ (present), if $Re_* < 2.4$ then depth > 4.1 (present). *Fusconaia flava* (Wabash pigtoe) was related to high flow $Re_* > 7.2$ (present), $k_s > 1.0$ (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. A summary of model results is provided in Table 3-1.

Zigler et al. (2008) developed a CART model to assess 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 models were constructed using data compiled from various sources and explanatory variables derived from GIS (geographic information systems) coverages (see Appendix B). 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 (discharge level exceeded 5% of the time; high flow), Q50 (average flow), and Q95 (low flow). 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 (Q95) were approximately 25% more predictive than variables measured at median discharge (Q50) with high discharge (Q5) intermediate, suggesting that droughts and floods are important in structuring mussel communities. Data were analyzed for various gear types and sampling methods. Data collected by divers was least biased. 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. 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 dynes/cm^2, then RSS (Q50) was ≤ 2.77 for mussel presence at 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 sites. 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, Fr, and RSS were the most important variables. None of the variables calculated at Q50 were important in the density model. Highest density sites were those with RSS (Q95) ≤ 0.10, depth > 1.8 m, and Fr (Q5) > 0.09. Most sites were low density (133 of 314), these had RSS (Q95) > 0.10 and slope ≤ 2.1% (see Table 3-1).

Zigler et al. (2010) used a 2D hydraulic model of Pool 18 and a poolwide mussel study, which included quantitative samples collected by divers 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 (see Appendix B). Mussel data were 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 current velocity model (HEC-RAS), was calculated for Q5, Q50 and Q95. 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.

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%, sites with Fr (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 and 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 (Fr > 0.08), but with a low slope (< 0.84%). In less turbulent areas (Fr Q50 ≤ 0.08), mussels required some flow (velocity Q5 > 0.03 m/sec). If Fr (Q5) > 0.12 then velocity (Q50) >0.35 m/sec. But mussels were also present at sites with Fr ≤0.12.

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 dynes/cm^2. 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%), few 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 bank full 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.

In summary of these models, one set of complex or simple hydraulic variables cannot be applied to all situations, nor are the values of these variables consistent among models (Table 3-1). Although the variables and the magnitude of the variables predicting mussel presence/absence or abundance in the UMR differ, in all studies mussels were less abundant in the main channel and side channels with high hydraulic energy and poorly connected backwaters, whereas, they tended to occur more frequently in smaller side channels, geomorphically complex channel borders, and tributary mouths (Young, 2006; Steuer et al., 2008; Zigler et al., 2008; Zigler et al, 2010). For Pool 18 mussel abundance, moderate to low shear stress may 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 channel border areas with rapidly changing hydraulic conditions at the sediment-water interface (Zigler et al., 2010).

Dr. Zigler (pers. comm., March 2013) suggested that most complex hydraulic parameters can be associated with unionid mussel habitat, as they all consider a combination of substrate characteristics, current velocity, and depth. His preference if he had to choose one or two variables to model habitat, would probably be shear stress and RSS since these were useful predictors in multiple studies in multiple systems. They also seemed most closely associated with ecological processes important to mussels. They also seem related to displacement of mussels during high flow and areas of flow separation and deposition of excysted juveniles, and identify areas that might be too lentic for most mussels. However, substrate data is required and can be a difficult to obtain.

Although complex hydraulic variables at high and low flow levels can be used to predict mussel presence and abundance, no one set of variables applied to all situations. The lack of consistency in the variables and magnitude of these variables that successfully predict mussel presence and abundance limits their usefulness in habitat creation. However, all of these models reinforce the idea that mussel beds form in areas with stable physical habitat that can be described as having:

- moderate velocity,
- refuge from high velocity,
- limited siltation,
- low hydrological variability,
- heterogeneous substrate,
- stable substrate for flow conditions, and
- substrate loose enough for interstitial flow.

Although complex hydraulic variables have not yet been applied to habitat creation, these concepts have been used in a few mussel habitat creation projects.

3.3 Habitat Creation Projects

Few projects have attempted to create physical mussel habitat. Only four attempts at mussel habitat creation were identified; the Tombigbee River gravel bar (Miller, 1982, 1983, 2006), lower Ohio River (Miller, 1988), Tennessee River Wolf Island side channel (Payne and Tippit, 1989), and Bertom and McCartney Lakes habitat rehabilitation and enhancement project (HREP) in Pool 11 of the UMR (USACE, 1989, 1995, 1996, 2002). All of these projects were created before complex hydraulic variables were considered in defining mussel habitat. These projects used a combination of substrate characteristics and current velocity at difference discharge levels in their design. Although shear stress or relative substrate stability was not directly used, these general concepts were considered, as shear stress and relative substrate stability are a function of substrate, current velocity, and depth at various discharge levels.

The Tombigbee project (near Columbus, Mississippi) was designed after studying a gravel bar that harbored invertebrates, mussels, and fish (Miller, 1982, 1983, 2006). 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 used 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." Conceptual drawings are provided in Appendix C.

The Tombigbee is a medium size river (average flow 6458 cfs), with extreme fluctuation (138 cfs to 194,000 cfs). The site of the gravel bar was 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. The design created a small fourth order pool-riffle system in an eighth order river. 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 flow release from the dam was restricted to 5.7 m^3/sec. The primary objective for the bar was habitat for fish and invertebrates, but the bar was also designed for mussels. Two 46 m long and 24 m wide gravel bars were created with slack water pools between gravel bars, although the original design was for four gravel bars. The upper most elevation of the bars was 1 ft (0.3 m) above minimum water levels for the pool, and a channel was cut through the bar to allow passage of water. Elevation within the channel varied from side to side, such that minimum pool varied from 1 (0.3 m) to 4 ft (1.2 m) deep. Low flow channels had a depth of 1.2 m and velocity of 50 cm/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. This flow was designed to move silt and clay particles but not the gravel or sand/gravel mixture. The monitoring components included hydrologic success, invertebrate colonization rates, and fish use. Hydrologic success would be measured by measuring depth, current velocity, and particle sizes at various times. Invertebrate colonization would include quantitative sampling of invertebrates at regular intervals for a year or more. Long-term monitoring was recommended for mussels (10 years or more).

This project was successful. The area remains stable, and unionids colonized the area. Dr. Miller monitored the area in 2001 and collected many mussels (Dr. Miller, retired, ERDC, pers. comm., April 2013). Miller (2006) summarized monitoring results. Sampling in the fall of 1985 (completion year) yielded 50 invertebrate 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). *Dorosoma cepedianum* (gizzard shad) and *Dorosoma petense* (threadfin shad) dominated the gravel bar, but minnows, shiners, and darters were abundant. *Aplodinotus grunniens* (freshwater drum), Ictaluridae (catfish), *Lepomis* sp. (sunfish), and *Pomoxis* sp. (crappie) were also collected. Immediately after construction, juvenile *O. reflexa* and *Corbicula fluminea* (Asian clams) 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* (bank climbers) were the dominant species. This project was designed to simulate shallow water gravel bar habitat that was present in the original Tombigbee River. Miller (2006) 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.

This concept of adding gravel to the substrate was used to create a submerged gravel bar within a dike field in the lower Ohio River to mitigate for inadvertent dredging of a mussel bed by a grain company (Miller, 1988). Construction was initiated in 1986 on the Kentucky side of the river. An exposed shoal existed between Ohio River Mile (ORM) 971.3 and 973.3 that was built with material from maintenance dredging. A submerged dike at the downstream end of the shoal deflected 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 clam shell dredge. Divers indicated gravel was 3 to 75 cm thick. The area was seeded with 100 marked *Fusconaia ebena* (ebony shell). Monitoring was to include evaluating the marked mussels, checking sediment traps for fine inorganic and organic sediments, and macroinvertebrates. However, no documentation of monitoring was found.

Dredged cobble and gravel was also used to create gravel shoals in an otherwise unstable sand side channel (Wolf Island) in the Tennessee River (Mile 192-194; Payne and Tippit, 1989). Sandy gravel was removed from the main channel and dumped using dump scows at an acute angle into the flow. Gravel and cobble 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 (15 cm/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 (2.4 m) depth, then coarser gravel and cobble riverward. The main mussel community was in the coarser gravel and cobble in the deeper portion of the side channel. The gravel mounds appear to have stabilized the sandy eroding bank and created a stable gravel shoal shoreward to the existing mussel community. 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. Payne and Tippit (1989) suggest that site selection should consider the present distribution of aquatic resources, and bathymetric and hydrologic conditions to ensure disposal mounds will neither be severely eroded nor covered by silt.

The only attempt at creating mussel habitat in the UMR was within the Bertom-McCartney Lakes HREP. This project consisted of creating a high velocity run with a gradation of substrate sizes and fish LUNKERS (Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids) (USACE, 1989, 1995, 1996). Conceptual drawings are provided in Appendix D. One of the project goals was to establish a mussel bed. No mussels occurred in the area pre-project. Fish and mussel habitat was enhanced by lining approximately 1500 ft (457 m) of an existing side channel adjacent to Coalpit Slough with rock. The channel was designed as a high velocity area to deter *Dreissena polymorpha* (zebra mussel) colonization. The selected side channel had a minimum bottom width of 50 ft (15 m). Rock 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 (0.6 m), and minimum depth over the rock was 4 ft (1.2 m). A total of 9000 tons (5625 CY) of quarry rock of different sizes were used. The channel was divided into seven discrete sections. The first section immediately following the partial closing structure was 300 ft (91 m) long; the remaining sections were 200 ft (61 m) long. 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 limestone 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 (10 to x 91 cm). 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 that was installed into a stream bank to provide resting, feeding, and escape cover for fish. Mussel surveys were planned every five years but never conducted.

Project dredging began in 1990 and was completed and inspected 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 indicated some scouring of the rock substrate, but the substrate was free of sedimentation. 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. Mussel monitoring has not been undertaken 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.

The Pool 8 HREP, Phase 3 considered mussel habitat, but mussel habitat was never constructed (J. Janvrin, pers. comm.). 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 (Appendix E). 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 (0.2 to x 0.5 m/sec) during "normal flow", and mid-depth velocity ≥ 2.5 ft/sec (0.8 m/sec) during bank full flow. They also recommended using a variety of sizes of river washed or rounded rock; 50% < 0.25 in (0.6 cm), 30% 0.25 to 0.5 in (0.6 to 1.3 cm), 15% 0.5 to 1 in (1.3 to 2.5 cm), 5% > 2 in (5 cm), 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. 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 access for host fish, WDNR suggested the channel should be continuous and maintain a depth of a least 6 ft (1.8 m). 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. However, this project was never funded.

A few mussel habitat creation projects are on-going. Dr. Newton and Dr. Zigler USGS-UMSC) are currently working with Jon Hendrickson of the St. Paul District USACE to apply these principles in Capoli Slough HREP in Pool 9. Dr. Just (IIHR) is currently working with Iowa Department of Natural Resources (IADNR) and City of Coralville to create mussel habitat in conjunction with floodwall creation in the Iowa River. However, these projects are in the conceptual phase.

From the above studies, it is clear that the concepts of some flow/turbulence at low discharge and substrate stability/flow refugia at high discharge can be engineered. However, they probably need to be based on local habitat conditions.

3.4 Mussel habitat within the St. Louis District

Since the hydraulic parameters and values of those parameters that define physical unionid habitat seem to be specific to a river reach, an understanding of the habitat unionids occupy within the SLD is essential. Existing unionid communities and habitat conditions are summarized below. Maps showing mussel beds and recent studies within SLD are provided in Appendix F and G. In general, mussel communities in the Illinois River and Mississippi River Pools are limited by suitable stable habitat, as substrate is primarily loose unstable sand or thick silt. Some beds persist in silt, sand, and clay substrate, but few areas with cobble, gravel, and sand substrate that seem to support the highest density and species richness still exist. Communities are low density ($<5/m^2$), and heavily dominated by thick-shelled Amblemini and Quadrulini. Although federally endangered species (*L. higginsii*, *Plethobasus cyphyus* [sheepnose], *Potamilus capax* [fat pocketbook], *Cumberlandia monodonta* [spectacle case]) once occurred in at least portions of the SLD, all but *C. monodonta* seem to be extirpated, and only a few individuals of *C. monodonta* have been found in the last few decades.

3.4.1 Pool 24

Pool 24 is perhaps the most studied pool with respect to mussels within the SLD. Most of the thalweg and channel borders were loose sand, which is unsuitable for unionids. However, 13 mussel beds are know to occur in the pool. In general, unionids were limited to small pockets (< 500 m long) within secondary or tertiary channels or in thin strips (< 100 m wide) along the channel borders in silt/sand/clay substrate, although a few larger mussel beds occur in the upper portions of the pool with cobble, gravel, and sand substrate. Beds contained a low density ($\leq 5/m^2$) of unionids and were dominated by either *M. nervosa* or *A. plicata*. The few larger beds in this pool have cobble, gravel, and sand substrate, better species richness, and higher density than the smaller beds with silt/sand/clay substrate. One federally endangered species (*C. monodonta*), one Missouri endangered species (*F. ebena*), and two Illinois threatened species (*E. lineolata*, *Ligumia recta* [black sandshell]) appear to be extant in Pool 24. This pool may be the best area to study the hydraulic characteristics associated with mussel beds, as a variety of conditions exist, and beds are dominated by different species. Mussel beds identified within this pool that have been sampled post 2000 include:
Fools Creek (MO, MRM 299-300)
Hadley-McCraney Bed (IL, MRM 296.9-297.3)
Blackbird Island (MO side channel, MRM 291.8-292.4)
Murphy Bed (IL side channel, MRM 289.6)
Fritz Is complex (IL, MRM 287-287.5)
Lower Hickory Chute (IL, MRM 284.7-285.5)
Blackburn Island (MO, MRM 284.9-285.5)
Louisiana Riverfront (MO, MRM 282.4 to 284.3)
Pencil Island (IL side channel, MRM 279.4 to 279.6)
Crider Island (IL side channel, MRM 279.0)
Crider Bend (MO bank, approximately MRM 278 to 281)
Cash Island (IL bank, MRM 276.5-277.8)
Reference Area (IL bank, MRM 273.5 to 275)

The best mussel bed in this reach was the Fool's Creek bed along the RDB downstream of Lock and Dam 22 (MRM 299-300). This bed was sampled by ESI (1994a), USACE (1988, 1989, 1991, and 1994 in Miller and Payne, 1996), MDC (1988, 1994, 2003 in Moore and Corgiat, 2007), and ESI (2008a). The 2007 sample yielded a density of $40.9/m^2$ and 23 species; however, little recruitment was apparent. Substrate was bedrock, boulder, cobble, gravel, and sand. Density in 2007 was greater than in 1994 ($26/m^2$); however, mean age in 1994 was 6 years old and most species were represented by individuals ≤5 years old. In 2003, MDC noted that cobble washed out of Fools Creek (MRM 300) was having a detrimental effect on the bed (Moore and Corgiat, 2007).

The area across the river from Fool's Creek was primarily loose sand in 2009. A small pocket of unionids was found in 2003 between dikes (Corgiat, 2008); however, this pocket did not exist in 2009 (ESI, 2011a). Likewise, substrate was unstable sand between 297.5 and 299, and only a few unionids were found in silt/sand/clay near the bank (ESI, 2010a).

A small bed was found along the Illinois bank, just upstream of the Hadley-McCraney canal (MRM 296.9-297.3). Substrate in this bed consisted of large cobble and sand, and 15 species were found in 2008 (Corgiat and Moore, 2008). Part of this area was sampled by ESI in 2002. Substrate was cobble, gravel, sand, and bedrock within 50 m of the bank where unionids were found (ESI, 2002).

Blackbird Island Bed (MRM 291.8-292.4; Corgiat, 2008) is also one of the best beds in the SLD-UMR. This bed was quantitatively sampled in 1989 (14.8/m^2) and in 2003 (3.9/m^2). Construction of an "L" dike upstream of the side channel in 1987 and/or a bullnose dike at the head of the island in 1996 may have caused the significant decline in density. These structures altered local hydraulic conditions, which resulted in changes in substrate characteristics, which could have affected mussel distribution and abundance. In 1989, gravel and sand substrate and unionid mussels extended across the side channel. In 2003, substrate in most of the side channel was loose sand. Gravel substrate and mussels were limited to the area along the Missouri bank. However, sampling further downstream in 2003 resulted in 16 species. In 2008, substrate was clay/silt with pockets of sand along the island edge and sand/gravel along the Missouri bank. *Obliquaria reflexa*, *Obovaria olivaria* (hickory nut), *A. plicata*, and *Q. pustulosa* dominated this community in 2008, but the Missouri endangered *F. ebena* was also collected (Corgiat, 2008). A few unionids were also found in the silt/clay substrate near the Missouri bank between MRM 290 and 291 downstream of Blackbird Island, but the majority of the sampled area was unstable sand (ESI, 2009).

Three Chevron Dikes were constructed between MRM 290 and 289 on the LDB in 1993 (ESI, 2012a). Most of the area on the exterior of dikes was loose sand in 1994 (ESI, 1994b) and 2012, but the sand between dikes had started to form a crust and stabilize in 2012 (ESI, 2012a). No live unionids were found in the area surrounding the dikes in either 1994 or 2012, but one shell of *C. monodonta* was recovered in 2012. The face of the dikes was investigated, but no live or additional shells of this species were 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-shelled unionids were found in 2012. One strip of unionids was found in silt, sand, clay substrate near the island upstream of the upstream most dike. Most of the unionids were *A. plicata*. It is not known where this strip of unionids was present in 1994 or whether the chevron dikes created this habitat.

Unionids have also been found in the Fritz Island complex side channels. A bed occurred in the southern end between MRM 287-287.5 and in a tertiary channel (Murphy Bed, 289.6; Corgiat, 2008).

The only bed containing federally endangered species within the SLD was the Lower Hickory Chute bed (MRM 284.7-285.5) (Corgiat, 2008). This bed was in deep water (40-50 ft) and was not sampled quantitatively, but qualitative sampling in 1999 and 2003 yielded *C. monodonta*. This bed was dominated by *M. nervosa* and *A. plicata*. 16 species were found in 1999 and 10 were found in 2003. Young unionids were collected for most species.

Unionids also occur within a 100 m of the bank along the edge of Blackburn Island. The river bottom was more gently sloping in this area. Substrate was a mix of silt, sand, and clay within 80 m of the bank, and became sandier further riverward. As substrate became sandier, the density of unionids declined (ESI, 2008b). 18 species (but no state or federal endangered species) were found in a relocation conducted along Blackburn Island in 2008. Only a few *M. nervosa* were found in this area, whereas *M. nervosa* were one of the most abundant species downstream of the Salt River.

Other smaller beds in this area were found along the side channel edge of Crider Island (MRM 279.0), and along the Illinois bank (Pencil Island, MRM 279.4-279.6; Gosline Island Access, MRM 280.6; Old Refuge Island Bed, MRM 281.8) (Corgiat, 2008).

Several studies have been conducted along the Missouri bank from Blackburn Island (MRM 285.5) downstream through Crider Bend (MRM 278) (Louisiana riverfront). This may all be one bed, divided by floodplain activity. From the mouth of the Salt River (MRM 284) downstream to MRM 278, a low density of unionids dominated by *M. nervosa*, *A. plicata*, and *Quadrula quadrula* (maple leaf) occurs within a few hundred meters of the bank (ESI, 2010b and 2011b). Substrate near the bank was fractured bedrock, boulder, silt, clay, and sand. A strip of bedrock forms the riverward edge of the bed, and substrate is unstable sand riverward of the bedrock.

Cash Island (MRM 276.5-277.8) was a fairly large bed between Cash and Pharr Islands. The upstream portion of this bed had a density of $< 1/m^2$ in 1999, but sampling further downstream in 2003 suggests a higher density (Corgiat, 2008).

In the lower part of the pool, a 100 m wide low density ($2.3/m^2$) strip of unionids was found in silt/sand/clay substrate downstream of Middleton and Pharr Islands (Reference Bed; ESI, 2007a).

3.4.2 Pool 25

Corgiat and Moore (Corgiat, 2008) investigated previously known mussel beds in 2003, and ESI investigated areas for SLD river structures (ESI, 2003a, 2003b, 2012a), lock and dam extension (ESI, 2007b), and Batchtown HREP (ESI, 2005a, 2006, 2007a). Much of the remaining channel consists of unstable sand substrate. However, at least 8 small (<500 m long or 100 m wide) low density ($\leq 5/m^2$) unionid beds are known to occur in this pool. As with Pool 24, unionids seem to be limited to areas near the banks with sand, silt, and clay substrates. Pool 25 mussel communities are heavily dominated by thicker shelled species (Amblemini and Quadrulini) and very little recruitment was observed.

Beds that were still extant in Pool 25 in 2003 include Clarksville Riverfront (MRM 271.8-273.0, MO bank), Sny and Carroll Island (MRM 267.6-269.1, IL bank; within a few meters of the bank), Coon Is (MRM 266.1-266.4, IL bank; within a few meters of the bank), Quiller Bed (MRM 259.0-260.2, IL channel border), Kelly Island backchannel (MRM 256.0-257.0, IL bank), Outer Stump dike field (MRM 250.5-250.9, IL bank; unionids mostly at tips of dikes), Maple Island backchannel (MRM 248-249, IL bank), and Batchtown Bed (MRM 241.5-243.5, IL bank). No recent density information was available for most of these areas.

The Clarksville bed was the only area that extended more than 10 m from the bank and had a sand/gravel rather than silt/sand/clay substrate. The bed was within a bank concavity that provides a flow refugia. *Amblema plicata*, *Q. quadrula*, and *O. reflexa* dominated this bed.

Four areas that were previously identified as mussel beds only yielded a few scattered mussels in 2003; Pecan Island (MRM 270.0-270.5), Rip rap Landing (MRM 265.4-265.7), Dead Man's Landing (MRM 263.7) and Channel side of Kelly Island (MRM 256.0-257.0).

Immediately upstream of Lock and Dam 25, unionids beds historically occurred within the Batchtown backwater area and along the Missouri bank. The Batchtown bed is limited by shallow water along the Illinois bank. In the downstream portion of the bed, the riverward limit coincides with a change from silt/sand/clay substrate to loose sand. In the upstream portion of the bed, shallow water limits unionids. Density within this bed has declined from 5.1 and $6.3/m^2$ in the upstream and downstream sections of the bed in 2003 to 2.7 and $3.7/m^2$ in 2007, respectively. Amblemini (*A. plicata*) and Quadrulini (*M. nervosa*, and *Q. quadrula*) heavily dominate both of these areas and few young animals were observed. Most of the unionids within the Batchtown area are either in the deeper thalweg that runs through the upstream area (most of the area other than the thalweg was dry in 2007) or in the downstream area, perhaps due to the wave action over this wide fetch.

Riverward of the Batchtown island complex, substrate was silt and sand within 200 m of the bank, and unstable sand riverward. Unionids were scattered throughout the area, but a small bed was found in a deeper area along the edge of a parallel dike (ESI, 2012a). Density in this area was 3.3/m^2 in 2011 and 1.7/m^2 in 2012 (not significantly different). *Amblema plicata* and *Q. quadrula* dominated this bed, and few Lampsilini were collected. Young unionids represented a very small portion (2.4%) of the unionids collected. Unionids in this area seem to be limited to an area with more flow that is a result of the parallel dike.

On the Missouri bank, unionids historically occurred from the L dike (approximately MRM 242.1) to MRM 244. Unionids were fairly abundant immediately upstream of the L dike (5.1/m^2; ESI, 2007b), and from MRM 243.5 to MRM 244.0 downstream of the point of land at MRM 244 (2.4/m^2; ESI, 2012a). A few were also found in a boulder pocket near a dike remnant, but most were within 100 m of the bank in silt/sand/clay substrate. The rest of this area was unstable sand. The point of land upstream of the MRM 244 bed seems to provide a hydraulic refugia.

No federally endangered species have been recently found in this pool, although *E. lineolata* (IL threatened) is fairly common and a few *L. recta* (IL threatened) were found within this pool.

3.4.3 Pool 26

Corgiat (Illinois DNR; Corgiat, 2008) and ESI (2003c, 2005b, and 2007b) conducted mussel studies in Pool 26. Twenty-four sites were sampled, but only a few of these areas had more than a few mussels. Most areas without mussels had substrate of unstable sand. Many sites had a pocket of heterogeneous substrate that contained a few unionids. Only two beds were found in this pool; Site 11 (MRM 206.0-207.8, IL bank) and Powder Mill Bed (MRM 216.0-216.6, IL bank). Both of these beds were in wide sections of river, along slight outside bends. Site 11 is downstream from an island, and the Powder Mill Bed is downstream of the Illinois River confluence. Substrate in both beds was sand and silt, with some gravel and cobble. Density in these beds was 13.0/m^2 and 3.8/m^2 in the Powder Mill Bed and Site 11, respectively. Both beds contained the Illinois threatened species *E. lineolata*. *Fusconaia ebena* (endangered in both Illinois and Missouri) was found at Site 11. Both beds were within 100 m of the bank. The beds differed however in dominant species. *Amblema plicata* and *Q. quadrula* co-dominated Site 11, while *M. nervosa* dominated the Powder Mill Bed (ESI, 2005b, unreported data).

Pockets of mussels were found at Martin Towhead (MRM 233.5-234.5, IL bank)), West Point Landing (MRM 238-241, IL bank), and downstream of Lock and Dam 25 (MRM 240.9-240.4 MO bank). Habitat information was not available for the first two of these sites. Downstream of Lock and Dam 25, unionids were found in a thin strip between substrate types (silt and sand in the upper area, and rip rap and sand in the downstream portion of this area).

Historically (D. Corgiat, IDNR, pers. comm.) mussels were found along the channel borders and in side channels throughout this pool. Based on the 2005 IDNR survey, few unionids remain except in small pockets. An analysis of habitat conditions (substrate characteristics, local hydraulics) would be needed to determine if habitat could be improved within this pool.

3.4.4 Middle River

This reach historically did not harbor unionid communities due to the influx of sand and turbidity from the Missouri River (Utterback, 1917). The only area recently sampled that harbored unionids was the reach between Mel Price Lock and Dam and the mouth of the Missouri River along the Illinois bank. The only known mussel bed in this reach is the Hartford bed between MRM 196.6 and 198.1, along a rip rapped outside bend that is heavily used by barges. Bill Fritz (IDNR) discovered this bed in the 1980's. The most recent data is from 2008 by N. L. Owens (INHS database). The Owens collection was heavily dominated by *M. nervosa*, but 16 species were recovered including *C. monodonta* (2 live). This area of the river is extremely swift and heavily commercialized. No substrate or depth information was available. A small area with high mussel density was found downstream of this bed near MRM 195 (ESI, 2012b). Mussels were limited to a strip along boulders placed in the river for old pilings. Shoreward of pilings substrate was too silty; riverward, substrate was unstable sand.

The area downstream of the Missouri River confluence near St. Louis, MO is primarily loose sand. Corgiat and Moore (2008) sampled a few spots within the Chain of Rocks area; however, no unionids were found (MRM 189.5, MRM 188, and MRM 186.9).

Habitat within the middle Mississippi River is more similar to the Missouri River than the pooled portion of the Mississippi River. Some mussel beds in the upper Mississippi River have persisted for at least decades (and some maybe for centuries) due to the permanence of stable habitat areas. These stable habitats do not persist in the Missouri River (Hoke, 2009), and likely do not persist in the middle Mississippi River. Few mussel species have been found in the Missouri River, primarily due to unstable nature of the substrate. Most of the species are thin shelled that mature at a young age, have high recruitment, are very mobile, and can burrow quickly after being dislodged (adaptations for dynamic conditions in this reach of river). Species reported from the channelized portion of the Missouri River (live or fresh shells) within Missouri include primarily thin shelled species in the Tribe Anodontini (*Anodonta suborbiculata* [flat floater], *Lasmigona complanata* [white heel splitter], *Pyganodon grandis* [giant floater], and *Utterbackia imbecillis* [paper pondshell), thinner shelled and small Lampsilini (*Lampsilis teres* [yellow sand shell, *L. fragilis*, *O. reflexa*, *O. olivaria*, *Potamilus alatus* [pink heel splitter], *Potamilus ohiensis* [pink papershell], *Toxolasma parvus* [lilliput], *Truncilla donaciformis* [fawns foot]), and the thicker shelled but ubiquitous Quadrulini, *Q. quadrula* (Hoke, 2009). Middle Mississippi River species composition is very similar. Species reported from the middle Mississippi River between the mouth of the Missouri River and the Ohio River include *L. fragilis*, *P. ohiensis*, *P. alatus and A. plicata* found within the dike fields (J. Tiemann, INHS, pers. comm., April 2013), and *O. olivaria*, *L. complanata*, *L. teres*, *L. fragilis*, *P. alatus*, *P. ohiensis*, and *Q. quadrula* near Thebes, IL (D. Ostendorf, MDC, personal communication). While unionids probably occur in stable substrate pockets in the middle river, no permanent mussel beds have ever been reported. Locations that might harbor mussels include head of Establishment Island, chevron dike at MRM 90.4 RDB, Fountain Bluff bar (MRM 84.3 to 85.0 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, and head of Santa Fe side channel (D. Ostendorf, MDC, personal communication).

3.4.5 Illinois River

Historically, the Illinois River supported numerous species rich mussel beds, and 49 species were historically known from the river, including the federally endangered *L. higginsii* and *P. cyphyus* (Whitney et al., 1997). Much of the unionid fauna in the Illinois River was decimated by pollution, but the Alton Pool was less affected than the upstream reaches (Starrett, 1971). However, Whitney et al. (1977) concluded that the upstream areas of the Illinois River may be improving with respect to species richness, while the lower reaches (including the Alton Pool) continue to decline.

Current mussel communities in the Alton Pool of the Illinois River varied with respect to habitat/hydraulic characteristics. Some concentrations were along outside bends, some on inside bends, some restricted to the sand, gravel, cobble riverward, and others to the silt, sand, clay near the bank. However, most of the mussel beds in the Alton Reach appear to be fairly small (< 0.5 RM upstream to downstream), and the best areas were along slight outside bends. Many small pockets of mussels were also found along the edges of islands. Most concentrations were limited by either deep silt or loose sand substrate. A few areas were sampled near the placement of rock structures (Moore's towhead [IRM 76], downstream of La Grange Lock and Dam [IRM 76.3-79.5], and islands between IRM 38 and 40) that could be used to investigate changes in unionid communities due to placement of rock structure.

IDNR (Corgiat, 2008) sampled several areas between 2001 and 2006. Samples were primarily spot dives conducted by commercial divers. Whitney et al. (1997) conducted quantitative samples in

several beds. ESI also sampled a few areas for SLD to investigate unionid distribution with respect to shoreline stabilization and chevron dike placement. Areas with density or substrate information are listed below.
IRM 3.0 LDB (slight outside bend), 7.75/m^2 (Whitney et al., 1997),
IRM 5.2-5.5 RDB (outside bend), 9.46/m^2 (Whitney et al., 1997)
IRM 10.4 RDB (slight outside bend), 7.6/m^2 (Whitney et al., 1997)
IRM 37.8 RDB (slight outside bend backchannel), Whitney et al (1997) found a bed with density of 15.3/m^2. This bed was just downstream of ESI samples in 2006 (ESI, 2007c) that indicated the back channel was mostly silt and clay, and scattered unionids only occur in the upper half.

RM 38-41 - ESI (2007c) found low-density pockets of mussels in areas with “cleaner” substrate (sand, clay, gravel) mostly > 20 m from bank.

RM 41.5- ESI (2003d) sampled this area in 2003. This appeared to be an old mussel bed, as weathered shells were abundant, and subfossil shells of both *P. cyphyus* and *L. higginsii* were found. The area may be recovering, as 12 species were found in 2003. Mussels were 30 to 50 m from the bank in sand, gravel, cobble, silt, and clay.

RM 50.1 RDB, Montezuma bed- Whitney et al (1997) sampled this bed and found 19.12/m^2. ESI (2005c) sampled this same area qualitatively in 2003. Unionids were still fairly abundant (estimated at 5-6/m^2) and young unionids were found. *Amblema plicata, Q. quadrula*, and *M. nervosa* dominated the bed. Substrate throughout this site was sand, silt, and clay, and unionids were most abundant in the downstream portion of the bed.

RM 55.7 to 56.4, Florence Bridge bed- Several points were sampled in this bed by IDNR between 2002 and 2005. ESI (2005c) also sampled the area in 2003. Unionids were more abundant in shallower water in sand, silt and clay, and less abundant in the cobble, gravel, and sand in deeper water. Unionid abundance was fairly high and young unionids were found.

RM 66.8 RDB (slight outside bend) - 4.97/m^2 (Whitney et al., 1997)
RM 67 LDB (slight inside bend-same as IDNR 2002) - 8.17/m^2 (Whitney et al., 1997)

RM 75.8-76.3 - ESI sampled this area in 2010 (ESI, 2010c). Unionids were found in a small pocket within 50 m of the bank downstream of an island (hydraulically protected area). Density averaged 2/m^2. Substrate was mostly sand riverward, and silt/clay near the bank. The area with unionids was heavily dominated by young unionids (80% ≤ 5 years old). This area was sampled to determine if bank stabilization would affect unionids. This may be an old bed, as shells of *P. cyphyus*, *Quadrula* *metanevra*, and *F. ebena* (species more typical of sand, gravel, cobble and flowing areas) were found.

RM 79.5-76.3 - This area was sampled by ESI (2011c) 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 than in other reaches.

3.5 Habitat requirements of protected species

Four federally endangered species (*C. monodonta*, *P. capax*, *L. higginsii*, *P. cyphyus*) and six species listed as either threatened or endangered in Illinois and/or Missouri (*Cyclonaias tuberculata* [purple wartyback], *Elliptio crassidens* [elephant ear], *Elliptio dilatata* [spike], *F. ebena*, *E. lineolata*, *L. recta*) historically occurred in the SLD. Most of these species occur in species rich unionid beds. Habitat preferences that are listed in the literature are of little use in habitat creation, as habitat is generally described in terms of "mud, sand, gravel", "large rivers", and "flowing water". Most studies conducted at a species level with simple substrate and current velocity descriptors found a great deal of overlap in species/habitat associations (Holland-Bartels, 1990). Success in separating species preferences has met with slightly better success using a combination of simple and complex variables. However, some species seem to have habitat preferences and others do not (Goodding, 2012). Young (2006) found smaller species preferred smaller substrates (but not fine substrates), substrate heterogeneity, shallower depths, and higher Froude number. Larger species, such as *E. lineolata*, *L. higginsii*, and *M. nervosa*, seemed to prefer higher energy environments (high velocity, Reynolds number, and bed shear stress; Young, 2006). Hornbach et al. (2010) found very little difference in simple habitat variables when comparing *Quadrula fragosa* (winged mapleleaf) and *L. higginsii* habitat to other species in the St. Croix River. However, Froude number, shear stress, and shear velocity were higher at sites with *Q. fragosa* than without, but no differences were significant for *L. higginsii* (Hornbach et al., 2010). A few species (*C. monodonta* and *P. capax*) are habitat specialists, but specific hydraulic conditions that define their habitat are unknown. The sites where each species has been collected within the SLD-UMR and SLD-IR are listed under each species. Substrate and flow conditions are listed where available.

3.5.1 Cumberlandia monodonta

Cumberlandia monodonta historically occurred throughout the SLD (Table 3-2). Recent (last 20 years) records of live individuals; however, are restricted to Lower Hickory Chute, Pool 24 (Corgiat,

2008) and Hartford, IL bed, middle river (INHS database, 2008 record). Both of these areas are deep (40-50 ft; 12-15 m) with swift current velocity. Substrate information was not available for the Hartford bed, but Moore (T. Moore, MDC, pers. comm.) indicated that mussels were found among the boulders that had fallen from the bank riprap at the Lower Hickory Chute bed. This may also be the case in the Hartford bed. Only a few *C. monodonta* were found at either of these sites, and several of the *C. monodonta* collected at Lower Hickory Chute were within a large mussel shell (T. Moore, MDC, pers. comm.). This species tends to be found in dense aggregations with few other species in most locations where it occurs. They are generally found wedged between or under boulders on the edge of swift currents (Cummings and Cordeiro, 2012). This type of habitat is seemingly available within a number of dike fields and on the exterior of Chevron dikes in the SLD; however, it has not been found within any of these areas. A shell was found near the chevron dikes in Pool 24 (ESI, 2012a). The dikes were searched, but no live individuals or additional shells were found. However, a more intensive search could be conducted. The lack of this species within the SLD could be a host fish habitat issue; however, the host for this species is unknown. Natural infestations of glochidia have been found on shorthead redhorse (*Moxostoma macrolepidotum*) (OSU database), but laboratory transformation of glochidia has not been successful (Baird, 2000; Hove et al., 2009).

3.5.2 Potamilus capax

Potamilus capax also historically occurred throughout the SLD (Table 3-2). This species is also a habitat specialist, but prefers slacker water areas with fine sand/silt substrate or silt/clay substrate near the bank (Cordeiro and Cummings, 2012). Although seemingly suitable habitat occurs in many areas within the SLD, extensive searches have not revealed any live individuals (Corgiat, 2008). This species was reintroduced into Blackbird Island in 1989, but no evidence of the reintroduced individuals was found in 2003 (Corgiat, 2008). However, shells are occasionally recovered. A weathered shell was found near the Pool 24 dikes in 1994 and in 2012. It may still exist in SLD-UMR. U.S. Fish and Wildlife Service (USFWS) is currently investigating sites where it could be re-introduced in the UMR (J. Duyvejonck, USFWS, per. comm.).

3.5.3 Lampsilis higginsii

Lampsilis higginsii historically occurred within at least Pool 24 and within the SLD-IR (Table 3-2). This species tends to occur in high density, highly species rich mussel beds (USFWS, 2004). However, it has not been collected within the SLD for over 30 years (Kelner, 2011).

3.5.4 Plethobasus cyphyus

Plethobasus cyphyus also historically occurred within Pool 24 and 25 of the Mississippi River and within the SLD-IR (Table 3-2). However, no live individuals have been collected in Pool 24 since at least 1992 (Fools Creek bed; Moore and Corgiat, 2007) or in SLD-IR in over 30 years (Kelner, 2011). This species also tends to occur in high density, species rich unionid beds.

3.5.5 Cyclonaias tuberculata (IL T), Elliptio crassidens (MO E, IL T), and Elliptio dilatata (IL T)

All of these species historically occurred within the SLD, but have not been found in over 30 years (Table 3-2). These species also tend to occur in high density, species rich unionid beds.

3.5.6 Fusconaia ebena

Fusconaia ebena was a common inhabitant of UMR beds in the past, but has been all but extirpated (Kelner and Sietman, 2000). Recent (past 25 years) records in the SLD include isolated old individuals in the Fools Creek bed (Pool 24; ESI, 1994a), Blackbird Island Bed (Pool 24; Moore and Corgiat, 2007; Corgiat, 2008; Corgiat and Moore, 2008), Powder Mill Bed (Pool 26, ESI, 1998), and MRM 206-207 (Pool 26; ESI, 2005b). One *F. ebena* was also found in the Illinois River in the Griggsville Landing Bed (IRM 61.2, 2002; Corgiat, 2008). This species tends to occur in dense, species rich mussel beds in sand, gravel, and cobble substrate. It is extremely abundant in the lower Ohio River, but extremely rare in the UMR reportedly due to blockage of host fish (skipjack herring, *Alosa chrysochloris*) migration due to Lock and Dam 19 (Kelner and Sietman, 2000). However, this does not explain its rarity in the SLD.

3.5.7 Ellipsaria lineolata

Unlike other threatened and endangered species in SLD, *E. lineolata* is commonly found, but at a low frequency. It tends to occur in species rich unionid beds, and seems to prefer the riverward edge of the bed where flow is greater (Dunn, pers. obs). Although it has not recently been collected from SLD-IR, it has been collected consistently in Pools 24, 25, and 26, and in the upper portion of the Middle River in the past 10 years (Table 3-2).

3.5.8 Ligumia recta

Ligumia recta also occur in species rich unionid beds, although it tends to occur in sandier slower flowing areas (Dunn, pers. obs.). It is not as common as *E. lineolata*, but has recently been found at a low frequency throughout the SLD (Table 3-2).

4.0 Habitat Creation

In general, habitat within the SLD is poor compared to other areas of the UMR. Although creation of large mussel beds is likely beyond expectations, creating small areas attractive to mussels may be possible around existing or future river training structures. Modeling of complex hydraulic variables may be useful, however, this would require extensive data on bathymetric, velocity, substrate, and mussel distribution. These data sets are not readily available. However, best professional judgment of biologists and hydrologists can be used to identify physical conditions suitable for mussels (moderate velocity, refuge from high velocity, limited siltation, low hydrological variability, heterogeneous substrate, stable substrate for existing flow conditions) at existing structures and to identify modifications for future river training structure design that could result in mussel habitat. The probability of a successful habitat creation project would be enhanced by increasing fish attracting structure and by positioning the project near a source of juvenile mussels. Ideas for habitat creation were presented in the workshop held on August 9, 2014. Minutes of the workshop are provided in Appendix A. Information in this report and ideas from the workshop were used to identify actions SLD can use to potentially enhance and create mussel habitat.

Conditions that limit unionids throughout the SLD are unstable sand substrate that occurs throughout most of the channel and channel borders, and deep silt that occurs along some bank lines and back channels. Alleviating these conditions on a local scale may result in stable habitat that is suitable for unionid colonization. As stated by Dr. Miller “Any altered waterway likely has sites that could be improved by adding gravel or cobble substratum.”

River training structures are used throughout the SLD to divert flow into the main channel while promoting bathymetric and hydraulic diversity primarily for fish. A variety of structures have been developed to achieve this goal (Appendix H). The diversion of core flow seems to be associated with flow refugia (Peck, 2005) and is the goal in placement of river training structures. It therefore seems feasible that river training structures can be modified to create flow refugia or increase flow in depositional areas for the benefit of mussels.

For example, monitoring of the Chevron dikes placed in Pool 24 between MRM 289 and 290 (Cottonwood Island Chevrons) suggests that flow refugia occur between these dikes and substrate may be starting to stabilize (ESI, 2012a). However, these dikes were created in 1993 and substrate in 2012 was still homogeneous sand, although more stable than in the area surrounding dikes. Addition of coarser substrate in this area may promote stability and create the heterogeneous substrate conditions preferred by unionid mussels. Other modifications suggested at the August workshop included decreasing slope to reduce scour and deposition, widening notches to distribute flow more evenly, and creating stones mattresses in areas with suitable flow but lacking suitable substrate.

Although each of these ideas presents challenges that need to be resolved, workshop participants generally agreed that physical habitat could be created, but would need to be evaluated locally. Participants also agreed that habitat around existing structures should be evaluated to determine if some structures were providing suitable conditions for mussels. Structures in wider, flatter areas of the river may be more successful, as hydraulic variability may be less.

4.1 Preliminary Habitat Ideas

The following ideas were presented in the workshop to facilitate discussion among biologists and engineers on habitat creation using training structures.

Physical Habitat

Habitat could be created by configuring chevron, round point, or bullnose dikes in channel borders to create flow refugia in areas with unstable substrate or increase flow in depositional areas (Figure 4-1). Conditions that would divert the core flow (hydraulic refuge) yet have critical shear velocity sufficient to flush silt and fine sands from the substrate at low flows would need to be created. Placement of a heterogeneous mix of river rock sizes and sand within the refugia might also be necessary to stabilize the substrate. River structures could also be used to increase flow along a depositional bank line. Flow could be diverted into a channel between the structures and the bank. A mix of river rock and sand could be placed in the channel to provide stable substrate. A lower flow channel and/or a variety of depths could be created to increase habitat diversity similar to the Bertom-McCartney HREP and Tombigbee gravel bar. Wider flatter areas of the river may be the best areas to place these structures. Current velocity seems to vary less in these wider areas between low and high flow, particularly at the substrate/water interface.

Gravel bar habitat could also be created within the chevron dike structure (Figure 4-2). A few notches could be placed in key areas to provide flow. The structure could be filled in with a variety of river rock sizes and sand. A low flow channel could be engineered such that RSS prevents silt deposition but is sufficient to prevent scour of larger particle sizes similar to the Tombigbee gravel bar.

Workshop participants indicated that using medium to large rock and eliminating fine material would work better than round river rock. The fine material in the quarry rock is what causes the interlocking, not the jagged edges. Gilbert Island Chevrons were notched and could be evaluated to see if this idea worked. Rock mattresses between dikes and the bank to create stable substrate runs might also be possible.

Dikes along bank lines could also be modified for mussel habitat. Dike fields provide some flow refuge, but scour and deposition within the dike fields is not conducive to mussel colonization. However, mussels are often found downstream of gradually sloping points of land and within slight concavities in the bank lines (i.e., MRM 244; MRM 271 Clarksville riverfront). Dikes could be configured with more gradual slopes to create more of a concavity in the bank (Figure 4-3). Another possible alternative for longer dikes might be to enlarge the dike tips with a gradually sloping pile of rock. Dikes would need to be notched to provide some flow within the field (Figure 4-4). Various sizes of river rock may be needed to provide substrate stability between dikes.

These ideas also seemed feasible with some modifications. Larger rock would work better. It would allow river substrate to accumulate for mussel colonization. Multiple notches in dikes was the idea behind the multiple round point structures (MRS's). These structures should be evaluated to determine if they are providing habitat. Gradual slopes might be possible, but would require more rock. Several other good ideas were suggested and discussed (see Appendix A). Design/modification suggestions are summarized in Section 4.2.

Fish hosts

Physical hydraulic parameters such as shear stress, boundary Reynolds number, Froude number, and relative substrate stability appear to define a threshold of substrate and flow stability that unionids need to form a bed or aggregation. However, density, recruitment, species richness and other community parameters vary considerably within these aggregations, indicating that these processes are due to other habitat factors such as host fish abundance, food quality/quantity, water quality, water temperature, and dissolved oxygen (Strayer, 2008; Newton et al., 2008). Host fish distribution and abundance affects unionid abundance (Strayer, 1999; Hornbach, 2001; Strayer, 2008, Newton et al., 2008, Haag, 2012; Cao et al., 2013). Fish species richness may also affect unionid species richness (Vaughn and Taylor, 2000). Models of mussel distribution compiled by Young (2006) and Daraio et al. (2010) include juvenile settlement, which is a function of where juveniles are released from their fish hosts, hydraulic conditions within the river reach, and discharge at the time of juvenile release.

Fish host habitat was created along with mussel habitat projects in the Tombigbee River and Bertom-McCartney gravel bars and should be considered in habitat creation projects in the SLD. Positioning created habitat in areas that are within juvenile settlement range of existing beds and/or adding host fish attraction features to created mussel habitat would enhance the probability of success.

Daraio et al. (2010) provides a model for predicting the area of juvenile settlement from the area of glochidial release at various flows in Pool 16. In general, they found that the sources of juveniles are most likely to be within or just upstream of the settlement area. Janvrin (pers. communication) suggested that creating habitat in areas near tributary mouths or in narrower channels where fish were "forced" to travel may enhance the probability of juvenile settlement, particularly for species that use pelagic and migratory fish hosts such as *Aplodinotus grunniens* (freshwater drum), *Sanders canadense* (sauger), or *Sanders vitreum* (walleye). Many of the unionid species that are abundant in the SLD-UMR use either Centrarchidae (sunfish) or Ictaluridae (catfish) for hosts (Table 4-1). Many of these fish species are fairly sedentary. Creating slack water areas with cover for these species within any created mussel habitat would increase the likelihood of juvenile excystment.

LUNKERS were used to provide fish habitat in the Bertom-McCartney gravel bar. These structures might be difficult to include in projects such as river training structures, but might be possible within bank concavities or dike fields. Providing cover with anchored large woody debris and/or strategically placed large rocks might be a simpler solution.

Mussel colonization vs. seeding

Once habitat is created, some mussels (adults and juveniles) may colonize the area from nearby mussel beds. Unionid mussels, particularly juveniles, are present in the bedload in some areas of the UMR (Dunn, pers. obs., Pool 18). If unionids are deposited in suitable substrate they should survive. A few unionids have successfully colonized the Bertom-McCartney gravel bar (USACE, 2002), and the Tombigbee gravel bar was also naturally colonized (Miller, 2006). The site of a mussel kill in the Ohio River also recolonized with some adult mussels within 10 years of the kill even though the nearest mussel bed was a few miles upstream (P. Morrison, FMCS 2013 presentation). Some natural colonization in created habitat would be expected if conditions are suitable. However, it might require decades for a functional species rich community to form. Seeding the area with mussels that are relocated from other areas or with propagated mussels would enhance colonization. Unionids could be marked and placed such that they could be monitored for survival, growth, and movement.

4.2 Next Steps for Habitat Creation

Discussion of the above ideas led to ideas on how to create and enhance mussel habitat within the St. Louis District. Although details on regulatory authority, costs, and safety need to be addressed, workshop participants generally agreed that river training structures could be used to enhance habitat. In general the key ingredients needed include:

- Gradual flow changes
- Substrate heterogeneity
- Prevention of extreme scour and depositional velocities
- Prevention of substrate deposition

- Host fish source
- Mussel seed source

These ideas could be used in the design of future structures and in maintaining existing structures. However, the major question that requires investigation is whether existing structures provide conditions suitable for mussels. If so, what data is needed to model mussel habitat and engineer it into future design. If not, what modifications would be necessary to create habitat.

Steps needed to improve habitat include:

- Considering mussel habitat in design of future structures,
- Improving habitat in any river training structure maintenance,
- Determining if existing structures are providing habitat, and
- Using data from successful current designs in future engineering, construction, and maintenance

Design Ideas

Several design ideas were discussed that may improve conditions for mussels.

General

- Allow voids in structures to allow material to settle in those areas, add some cobble size stone in toes of structures which would spread out, leaving areas for heterogeneous substrate to form, possibly expanding the flow refugia that often occurs at the toes of these structures
- Use smaller size stone on revetments and allow some stone to settle to the bottom
- On dikes, make flow changes more subtle
- Put raised gravel/cobble beds on stable substrate areas
- Put out clusters of cobble within weir or other fields, let the river put the rock where it wants it. Come back and see how it settles out. Create rock aprons in these areas.
- Identify flow refugia, put substrate in and see if it stays

Weir fields

- Scatter some rock downstream and between weirs and see what happens
- Create more slope on both sides
- Notch structures to create a secondary flow channel

Chevrons

- Create a rock riffle between chevrons and bank
- Use blunt noses to reduce extremes in flow

- Put rock on either side of round nose and in refugia between chevrons

Wing dikes

- Create several wide shallow notches rather than one deep notch
- Spread material from notch downstream of the notch

Revetment

- Use more sorted medium sized boulders
- Continue rock placement further riverward, but scattered allowing substrate to accumulate between rocks

Maintenance Ideas

- Incorporate the above ideas where possible
- Spread or allow medium sized rock to scatter around structures

Monitoring of existing structures

The monitoring of existing structures needs to include selection of sites, determining biological and physical data needs, sampling to gather needed data, and evaluating data to determine whether existing structures provide or could provide mussel habitat.

Site selection and determination of data needs would best be accomplished through a meeting of key biologists, hydrologists, and river engineers. At least 5 sites with existing structures should be selected. Sites should be within Pools 24 and 25 of the UMR, as these areas appear to support the best unionid mussel communities within the SLD. Sites should be in wider, flatter river reaches as these areas have less hydraulic variability. Sites should also be near existing unionid communities, as these areas would have the highest probability of unionid colonization. Areas with current fisheries data would also have high priority, as fish hosts are necessary for unionid colonization. A variety of structure types should be investigated. Sites that were discussed in the workshop include:

- Gilbert Island Chevrons (MRM 300, LDB)
- MRM 290 W dikes (RDB)
- Multiple Round Point Dikes (MRS's; MRM 267 to 270 LDB and MRM 257 LDB)

A scope of work for investigating each site should be developed during this meeting. The biological field investigation should include sampling for mussels within areas most likely to provide hydraulic refugia identified by hydrologists and biologists, delineating areas of flow refugia and any mussel communities with GPS, and collecting preliminary hydraulic information on depth, velocity, and substrate within and outside of "flow refugia". Areas with fish habitat should also be identified and delineated.

In areas where mussels are found or where flow refugia exist, physical data should be collected to support numeric or physical hydraulic and hydrologic modeling. The physical data field collection should include collection of sufficient depth, velocity, and substrate information to detect differences in hydraulic parameters between areas with and without mussels or within and outside of hydraulic refugia.

The results of the biological and physical field investigations should be used to generate GIS maps and/or physical flow models of potential habitat and hydraulic conditions. Models should be discussed with the team to determine if existing structures are providing habitat and why, and to assess what information would be most useful in future engineering designs. Physical models of training structures could be modified in an attempt to create suitable habitat and determine what modifications might better provide habitat and/or facilitate unionid colonization.

Monitoring and modeling results should be applied to future structure engineering and maintenance of existing structures. Any future designs and modifications should also be monitored.

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6.0 Glossary

CART-Classification and Regression Tree analysis

Current velocity – measure of rate of flowing water typically measured in meters (or centimeters) per second

d- depth

D_x- Sediment particle size at which x% of the particles in the sample are smaller

D_{16}-Sediment particle size at which 16% of the particles in the samples are smaller

D_{50}-Sediment particle size at which 50% of the particles in the samples are smaller

D_{84}-Sediment particle size at which 84% of the particles in the samples are smaller

D_m-Mean particle size; typically $(D_{16} + D_{50} + D_{84})/3$, however different authors used different grain sizes in this calculation

Discharge – measure of volume of water in the channel, measured in cubic feet, meters or centimeters/second

ERDC-Engineer Research and Development Center

ESI- Ecological Specialists, Inc.

Freshwater unionid mussels- Freshwater bivalves (Bivalvia) in the order Unionoida. In North America this includes species in the families Unionidae and Margaritiferidae. Other freshwater mussels in North America include those in the order Veneroida (Corbiculidae [introduced Asiatic clam], Sphaeriidae [native fingernail clams], and Dreissenidae [introduced zebra and quagga mussels]). Only unionid mussels are considered in this paper.

Flow – often used in referring to velocity or discharge.

Flow exceedance – percentage of time discharge is exceeded. Q95 (95% exceedance) refers to a low volume of water that is exceeded 95% of the time. Q5 (5% exceedance) refers to a high volume of water that is infrequently exceeded.

Flow refugia – Area of river protected from high scouring current velocity during high discharge events

Fr-Froude number-ratio of inertial:gravitational force sqrt(U^2/gd)

g-gravitational force (9.81m/sec)

GIS-Geographic information system

Glochidia-Larval stage of unionid mussels

HREP- Habitat rehabilitation and enhancement project

IADNR-Iowa Department of Natural Resources

IDNR-Illinois Department of Natural Resources

IIHR- University of Iowa IIHR-Hydroscience & Engineering

INHS-Illinois Natural History Survey

k_s-bed roughness or topographical variation in stream bed (3.5 x D_x)

L-Laminar layer, viscous sub layer thickness (11.5v/ U_*)

LUNKERS- Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids

Marsupia-portion of female unionid gills used for brooding glochidia (larva)

MDC-Missouri Department of Conservation

MDM- Mussels Dynamics Model

MRS-Multiple Round Point Structure

Mussel beds – aggregations of unionids, where density is higher than the surrounding area, and several species and age classes are present. Aggregations generally occur in areas with stable heterogeneous substrate and have physical limits with respect to changes in depth, substrate, or current velocity.

p-density of water ($0.998 g/cm^3$)

PCA-Principal Components Analysis

Q(x)- discharge exceeded x% of the time

Re-Reynolds number-Ratio of inertial to viscous forces, indication of whether flow is laminar or turbulent (Ud/v)

Re_*-Boundary Reynolds number-roughness of flow near the stream bed ($U_* k_s / v$)

S_o-Trask sorting coefficient, measure of substrate homogeneity (sqrt(D_{50}/D_{16})

SLD-St. Louis District

SLD-IR- St. Louis District portion of the Illinois River (Alton Pool)

SLD-UMR-St. Louis District portion of the Upper Mississippi River (Pools 24, 25, 26, and middle river)

Substrate heterogeneity-measure of the diversity of particle sizes in the substrate. Calculated as a visual estimate of substrate classes with fractions that constituted more than 10% of the visual estimate (Zigler et. al, 2010), Trask sorting coefficient (Steuer et al., 2008)

t-Shear stress- tangential or frictional force acting on a stream bed ($p U_*^2$)

U-Depth averaged current velocity

U_*-Shear velocity- Friction velocity; proportional to inverse of vertical velocity log profile ($U/[5.75 \log(12d/k_s)]$)

UMESC- Upper Mississippi Environmental Science Center

UMR-Upper Mississippi River

UMRB-Upper Mississippi River Basin

USACE-U.S. Army Corps of Engineers

USFWS-U.S. Fish and Wildlife Service

USGS- U.S. Geological Survey

v-kinematic viscosity of water (0.01cm^2/sec)

WDNR- Wisconsin Department of Natural Resources

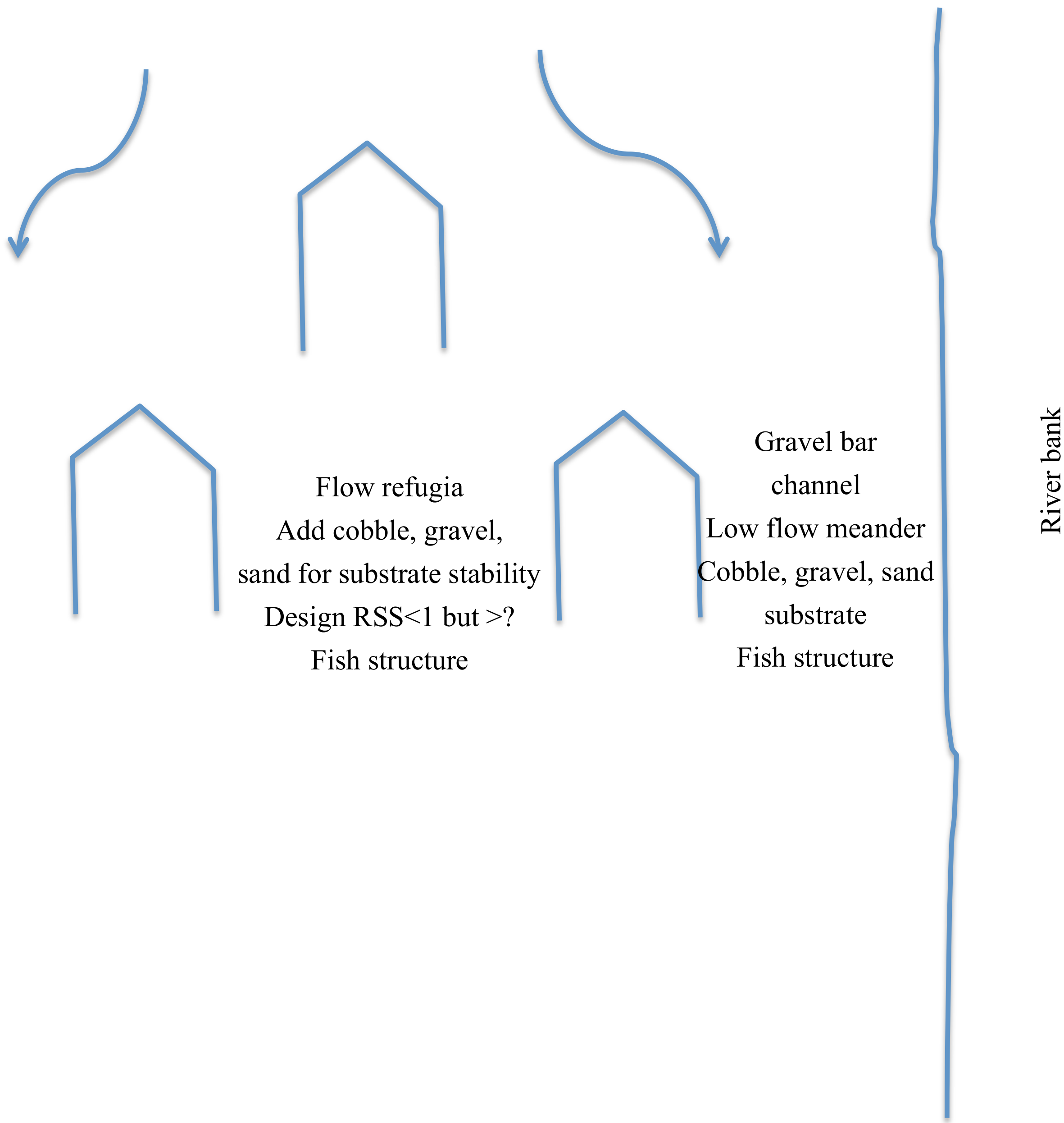


Figure 4-1. Conceptual drawing of flow refugia and gravel bar near chevron dikes.

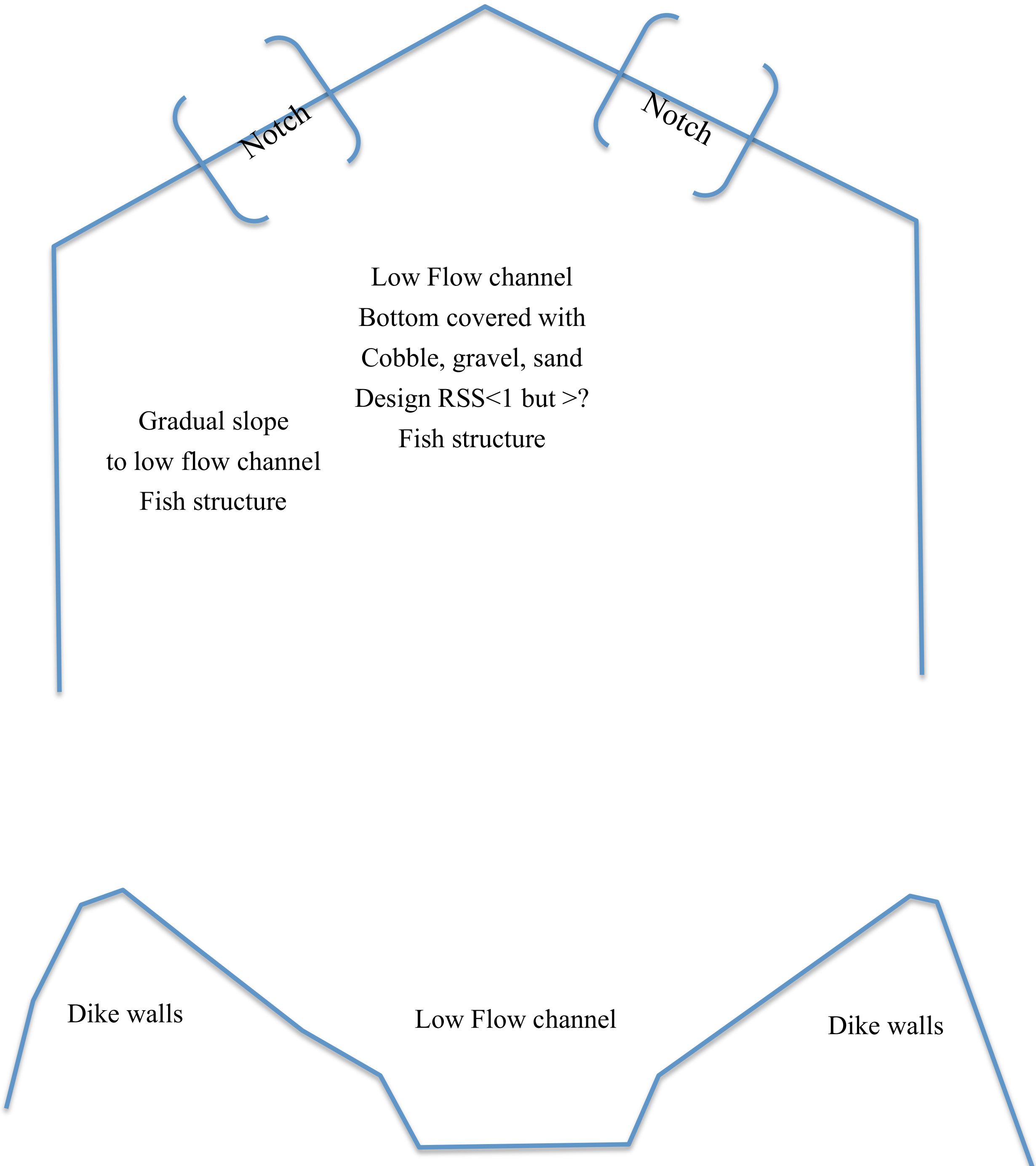


Figure 4-2. Conceptual drawing of a Chevron Dike gravel bar.

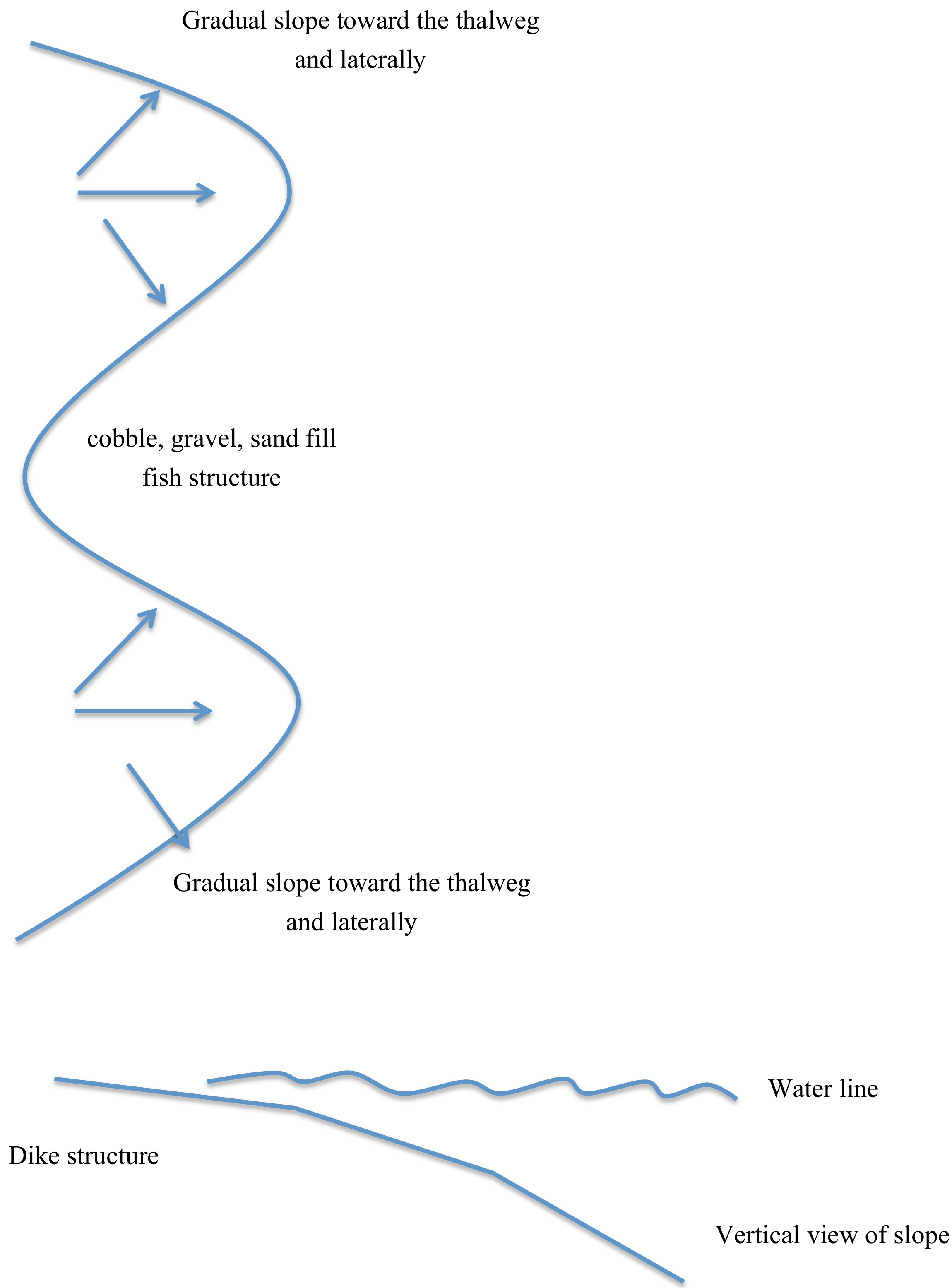


Figure 4-3. Conceptual drawing of bank concavities created with dikes.

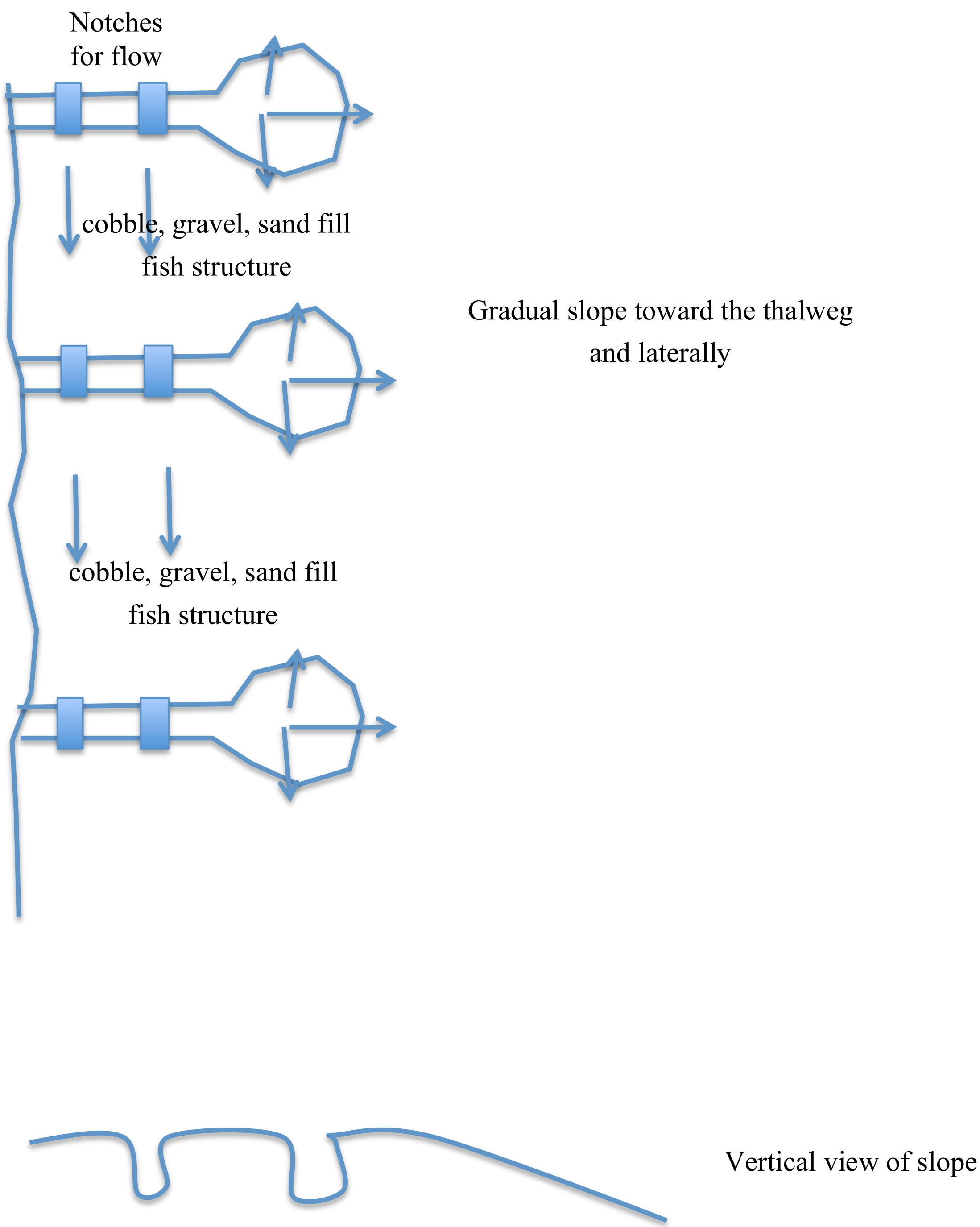


Figure 4-4. Conceptual drawing of modified dike tips within a dike field.

Table 3-1. Summary of UMR mussel model results (page 1 of 2).

River-Reach	Flow exceedance	Variables used	Predictive variables
Zigler et al. (2008)			
UMR-Pool 8 (38 km reach)	Q5	Pool 3rd	Presence dive data (165 of 223 present)
Within and outside of	Q50	Aquatic Area (i.e. nav channel, border)	*t* Q95 ≤0.18
mussel beds	Q95	Substrate-visual dominance	t Q50 >0.48
Presence/absence (total)		Depth (flat pool)	t Q5 ≤7.8
Density (total)		Slope-Difference in depth over 5 m	
		Velocity (depth averaged) *U* (m/sec)	Other positive sites
		Shear stress (dynes/cm^2) $t=pU^{*2}$	Slope
		Froude number Fr=SQRT(U^2/gd)	RSS
		RSS=t/t_c	
			Abundance
			RSS Q95≤0.10
			Fr Q5 ≤0.09
			if Slope >4.4
			then Depth >2.6
			if slope ≤4.4
			then RSS Q5 ≤11.0
Steuer et al. (2008)			
UMR-Pool 10 (6 km reach)	Q20	Mean grain size $(D_{50}+D_{16})/2$	Presence/absent Q50
Within East Channel	Q50	Trask sorting coefficient (heterogeneity)	Re_*>2.1 (*t*,Fr secondary split variables)
mussel bed		So= SQRT$(D_{50}+D_{16})$	Species varied
Presence/absence		Bed roughness (mm) $k_s=3.5 \times D_{16}$	
(total, by species)		Froude number Fr=SQRT(U^2/gd)	Density (Q50 and Q29)
		Reynolds number Re=(*U*d/v)	d, *t* (values not provided in text)
		Shear velocity (cm/sec) $U_*=U/[5.75\log(12d/k_s)]$	Species varied
		Boundary Reynolds no. $Re_*=U^*k_s/v$	
		Shear stress (dynes/cm^2) $t=pU^{*2}$	
		Laminar layer (cm) L=11.5 v/U^*	

Table 3-1. Summary of UMR mussel model results (page 2 of 2).

River-Reach	Flow exceedance	Variables used	Predictive variables
Zigler et al. (2010)		Pool 3rd	
UMR-Pool 18 (42 km reach)	Q5	Aquatic Area (i.e. nav channel, border)	Presence/absence with substrate
Poolwide survey	Q50	Substrate-visual dominance	(173 of 377 present)
Presence/absence (total)	Q95	Substrate-visual %	Depth Q5 ≤3.23m
Density (total)		Substrate heterogeneity (no. of classes >10%)	Velocity Q95 >0 (79 present, 29 absent)
		Slope-Difference in depth over 10 m	Velocity Q95 ≤0 (0 present)
		Velocity (depth averaged) U	
		Depth	Depth Q5 >3.23m
		Froude number Fr=SQRT(U^2/gd)	Perc. gravel >1.25 (28 present, 7 absent)
		Shear velocity (cm/sec) $U_*=U/[5.75\log(12d/k_s)]$	Perc gravel <1.25
		Boundary Reynolds no. $Re_*=U^*k_s/v$	Froude no. Q5≤0.12 and Vel Q5 >0.03m/sec
		Shear stress (dynes/cm^2) $t=pU^{*2}$	(27present, 20 absent)
		Critical shear stress (dynes/cm2) $t_c=\Theta gpD50(ps-p)$	
		Relative substrate stability (RSS) $=t/t_c$	
			Abundance
			Middle/Upper Pool
			Re* Q5 >662.24 and t Q95 ≤1.02 (20/m^2)
			Lower Pool- combination of
			Slope >17.29%,
			Depth ≤4.9m (25/m^2)
			Depth >4.9m (10/m^2)
			Slope ≤17.29%
			Velocity (Q5) ≤1.04m/sec
			Re_*>67.44 (30+/m^2)
			Re_*≤67.44, t (Q50)≤0.69, t (Q95)>0.08 (20/m^2)

D_{50} and D_{16}=50% and 16% quantile of substrate mass
g=gravitational force (9.81m/s^2)
d=water depth
v=kinematic viscosity (0.01cm^2/s)
p=density of water (0.998 g/cm^3)
ps=density of substrate (2.65g/cm^3)

Table 3-2. Distribution of unionid species in the SLD (page 1 of 2).

Species[1]	Status[2]	Pool 24		Pool 25		Pool 26	
		Kelner[3]	1997-2006 [4]	Kelner[3]	1997-2006 [4]	Kelner[3]	1997-2006 [4]
Cumberlandia monodonta	FE, IL E	R	0.1	-	-	R	-
Amblema plicata	-	A	42.9	A	32.4	A	28.3
Cyclonaias tuberculata	IL T	H	SF	R	-	H	-
Elliptio crassidens	MO E, IL T	H	-	H	-	H	-
Elliptio dilatata	IL T	H	-	-	-	H	SF
Fusconaia ebena	MO E, IL T	R	L	R	-	R	0.1
Fusconaia flava	-	R	1.6	C	0.7	C	0.4
Megalonaias nervosa	-	A	7.9	C	4.9	A	17.6
Plethobasus cyphyus	FE, MO E, IL E	R	-	H	-	-	-
Pleurobema sintoxia	-	R	WD	R	L	R	SF
Quadrula metanevra	-	R	0.1	R	0.6	R	WD
Quadrula nodulata	-	C	1.6	R	1.1	R	1.8
Quadrula pustulosa	-	C	3.7	C	2.9	C	6.7
Quadrula quadrula	-	C	7.6	C	21.6	C	23.1
Tritogonia verrucosa	-	R	L	H	-	H	WD
Uniomerus tetralasmus	-	-	-	-	-	-	-
Anodonta suborbiculata	-	H	-	R	0.0	R	-
Arcidens confragosus	-	R	0.2	R	0.3	R	0.2
Lasmigona complanata	-	R	0.5	R	0.3	R	0.1
Lasmigona compressa	-	-	-	-	-	-	WD
Lasmigona costata	-	-	-	-	-	-	-
Pyganodon grandis	-	R	1.3	R	2.1	C	2.2
Simpsonaias ambigua	-	-	-	-	-	H	-
Strophitus undulatus	-	R	-	-	-	-	-
Utterbackia imbecillis	-	R	0.0	R	0.0	R	0.1
Actinonaias ligamentina	-	R	0.0	H	0.1	R	WD
Ellipsaria lineolata	Il T	A	1.6	C	4.9	C	0.8
Lampsilis cardium	-	C	1.6	C	1.3	R	0.4
Lampsilis higginsii	FE, MO E, IL E	H	-	-	-	-	-
Lampsilis siliquoidea	-	H	WD	-	-	-	-
Lampsilis teres	-	R	1.3	C	1.5	C	2.5
Leptodea fragilis	-	C	1.0	C	0.6	C	1.6
Ligumia recta	IL T	R	0.2	R	0.2	R	0.1
Obliquaria reflexa	-	A	19.6	C	17.7	A	11.5
Obovaria olivaria	-	C	5.3	C	6.0	C	1.9
Potamilus alatus	-	R	0.2	C	0.2	C	0.1
Potamilus capax	FE, MO E, IL E	R	-	H	-	H	-
Potamilus ohiensis	-	R	0.4	R	0.1	R	0.2
Toxolasma parvus	-	-	-	R	0.1	H	-
Toxolasma texasense	-	-	-	-	-	-	-
Truncilla donaciformis	-	C	0.3	R	0.1	R	0.2
Truncilla truncata	-	A	0.8	C	0.2	C	0.4
Total live		30	26	27	25	27	22
Historic		6	3	5		7	6

Table 3-2. Distribution of unionid species in the SLD (page 2 of 2).

		Middle River		Illinois River-Alton Pool	
Species[1]	Status[2]	Kelner[3]	INHS/ESI [5]	Kelner[3]	1997-2006 [4]
Cumberlandia monodonta	FE, IL E	-	L	H	-
Amblema plicata	-	C	L	A	57.3
Cyclonaias tuberculata	IL T	-	-	H	-
Elliptio crassidens	MO E, IL T	-	-	H	-
Elliptio dilatata	IL T	H	-	H	WD
Fusconaia ebena	MO E, IL T	H	-	R	0.0
Fusconaia flava	-	R	L	R	0.0
Megalonaias nervosa	-	R	L	C	7.0
Plethobasus cyphyus	FE, MO E, IL E	-	-	H	WD
Pleurobema sintoxia	-	-	-	H	WD
Quadrula metanevra	-	R	-	H	WD
Quadrula nodulata	-	R	L	R	1.0
Quadrula pustulosa	-	R	L	C	1.7
Quadrula quadrula	-	C	L	A	18.0
Tritogonia verrucosa	-	-	-	H	WD
Uniomerus tetralasmus	-	R	-	H	-
Anodonta suborbiculata	-	R	-	R	-
Arcidens confragosus	-	R	L	C	2.2
Lasmigona complanata	-	R	L	R	2.1
Lasmigona compressa	-	-	-	-	-
Lasmigona costata	-	-	-	H	-
Pyganodon grandis	-	R	L	C	2.6
Simpsonaias ambigua	-	-	-	-	-
Strophitus undulatus	-	-	-	H	-
Utterbackia imbecillis	-	R	-	R	L
Actinonaias ligamentina	-	-	L	R	0.1
Ellipsaria lineolata	Il T	R	L	R	WD
Lampsilis cardium	-	R	L	R	0.0
Lampsilis higginsii	FE, MO E, IL E	-	-	H	SF
Lampsilis siliquoidea	-	-	-	H	L
Lampsilis teres	-	C	L	R	0.3
Leptodea fragilis	-	A	L	C	4.7
Ligumia recta	IL T	-	L	R	0.0
Obliquaria reflexa	-	C	L	C	2.6
Obovaria olivaria	-	C	L	R	0.0
Potamilus alatus	-	R	L	R	0.2
Potamilus capax	FE, MO E, IL E	H	-	H	-
Potamilus ohiensis	-	R	-	R	0.2
Toxolasma parvus	-	R	-	H	-
Toxolasma texasense	-	H	-	-	-
Truncilla donaciformis	-	R	-	R	L
Truncilla truncata	-	R	L	C	0.1
Total live		24	20	24	23
Historic		4		15	7

[1]Nomenclature follows Turgeon et al. (1998)

[2]FE = Federally listed endangered species (USFWS, 2012); MO E=Missouri endangered species (MDC, 2013);species (IDNR, 2011) IL E=Illinois endangered species, IL T=Illinois threatened

[3]Kelner (2011)

H = Records of occurrence but no live collections have been documented in the past ~25 years.

R = Rare, populations are small either naturally or have declined and may or may not be near extirpation.

C = Commonly taken in most samples; can make up a large portion of some samples.

A = Abundantly taken in most samples.

[4]Relative abundance based on cumulative studies in Corgiat (2008); L=live, FD=fresh shell, WD=weathered shell, SF=subfossil, species found by ESI or Corgiat and Moore (2008) in additional studies but not represented in Corgiat (2008)

[5]INHS database record or ESI (2012b)

Table 4-1. Fish and mussel species within the SLD and host relationships (page 1 of 6).

		Ambleminae														Anodontinae						
SPECIES	*Cumberlandia monodonta*	*Amblema plicata*	*Cyclonaias tuberculata*	*Elliptio crassidens*	*Elliptio dilatata*	*Fusconaia ebena*	*Fusconaia flava*	*Megalonaias nervosa*	*Plethobasus cyphyus*	*Pleurobema sintoxia*	*Quadrula metanevra*	*Quadrula nodulata*	*Quadrula pustulosa*	*Quadrula quadrula*	*Tritogonia verrucosa*	*Anodonta suborbiculata*	*Arcidens confragosus*	*Lasmigona complanata*	*Pyganodon grandis*	*Simpsonaias ambigua*	*Strophitus undulatus*	*Utterbackia imbecillis*
ACIPENSERIDAE																						
Lake sturgeon (Acipenser fulvescens)																						
Shovelnose sturgeon (Scaphirhynchus platorynchus)								LT					NI									
LEPISOSTEIDAE																						
Longnose gar (Lepisosteus osseus)								NI										NI	LT			
Shortnose gar (Lepisosteus platostomus)		LT,LI																				
Alligator gar (Lepisosteus spatula)																						
AMIIDAE																						
Bowfin (Amia calva)								NI														
HIODONTIDAE																						
Goldeye (Hiodon alosoides)																						
Mooneye (Hiodon tergisus)		NI																				
ANGUILLIDAE																						
American eel (Arguilla rostrata)								NI									NI					
CLUPEIDAE																						
Skipjack herring (Alosa chrysochloris)				x		NI,LI		NI											NI			
Gizzard shad (Dorosoma cepedianum)					NI			NI									NI	NI	NI			
Threadfin shad (Dorosoma petenense)																						
CYPRINIDAE																						
Central stoneroller (Campostoma anomalum)									LT	LT									NI,LT		LT	
Common carp (Cyprinus carpio)																	LT	LI,LT	NS,NI			
Goldfish (Carassius auratus)																			LT			LT
Grass carp (Ctenopharyngodon idella)																						
Mississippi silvery minnow (Hybognathus nuchalis)																						
Bighead carp (Hypophthalmichthys nobilis)																						
Speckled chub (Macrhybopsis aestivalis)																						
Silver chub (Macrhybopsis storeriana)																						
Golden shiner (Notemigonus crysoleucas)								LT								LT	LT		LT			LT
Emerald shiner (Notropis atherinoides)		NI																				
River shiner (Notropis blennius)																						
Ghost shiner (Notropis buchanani)																						
Bigmouth shiner (Notropis dorsalis)																						
Spottail shiner (Notropis hudsonius)																						
Red shiner (Cyprinella lutrensis)																						
Silverband shiner (Notropis shumardi)																						
Spotfin shiner (Cyprinella spiloptera)		NI								LT	LT										LT	LT
Sand shiner (Notropis stramineus)																						
Mimic shiner (Notropis volucellus)																						
Channel shiner (Notropis wickliffi)																						
Suckermouth minnow (Phenacobius mirabilis)																						
Bluntnose minnow (Pimephales notatus)										LT	LT								NI,LT		LT	
Fathead minnow (Pimephales promelas)																					LT	

Table 4-1. Fish and mussel species within the SLD and host relationships (page 3 of 6).

		Ambleminae														Anodontinae						
SPECIES	*Cumberlandia monodonta*	*Amblema plicata*	*Cyclonaias tuberculata*	*Elliptio crassidens*	*Elliptio dilatata*	*Fusconaia ebena*	*Fusconaia flava*	*Megalonaias nervosa*	*Plethobasus cyphyus*	*Pleurobema sintoxia*	*Quadrula metanevra*	*Quadrula nodulata*	*Quadrula pustulosa*	*Quadrula quadrula*	*Tritogonia verrucosa*	*Anodonta suborbiculata*	*Arcidens confragosus*	*Lasmigona complanata*	*Pyganodon grandis*	*Simpsonaias ambigua*	*Strophitus undulatus*	*Utterbackia imbecillis*
Bullhead minnow (Pimephales vigilax)																						
Creek chub (Semotilus atromaculatus)							LT				LT						LT		LT		LT	NI
CATOSTOMIDAE																						
River carpsucker (Carpiodes carpio)																			NS			
Quillback (Carpiodes cyprinus)																	LT					
Highfin carpsucker (Carpiodes velifer)								LI														
White sucker (Catostomus commersoni)																	LT		NS			
Blue sucker (Cycleptus elongatus)																						
Smallmouth buffalo (Ictiobus bubalus)																	LT					
Bigmouth buffalo (Ictiobus cyprinellus)																						
Black buffalo (Ictiobus niger)																						
Spotted sucker (Minytrema melanops)																						
Silver redhorse (Moxostoma anisurum)																						
Golden redhorse (Moxostoma erythrurum)		NI																				
Shorthead redhorse (Moxostoma macrolepidotum)	NI																LT					
ICTALURIDAE																						
Blue catfish (Ictalurus furcatus)																						
Black bullhead (Ameiurus melas)			LT					LI,LT					NI,LT								LT	
Yellow bullhead (Ameiurus natalis)			LT					LT							LT				NI		LT	
Brown bullhead (Ameiurus nebulosus)								LT					LT		LT							
Channel catfish (Ictalurus punctatus)		NI	LT					LI,LT				NI		LT		LT	LT				LT	LT
Stonecat (Noturus flavus)																						
Tadpole madtom (Noturus gyrinus)								NI														
Freckled madtom (Noturus nocturnus)																						
Flathead catfish (Pylodictis olivaris)		x	LT		x			NI,LT				NI	NI,LT	NI	LT							
ESOCIDAE																						
Grass pickeral (Esox americanus vermiculatus)																						
Northern pike (Esox lucius)		NI																				
APHREDODERIDAE																						
Pirate perch (Aphredoderus sayanus)																						
GADIDAE																						
Burbot (Lota lota)																					LT	
CYPRINODONTIDAE																						
Starhead topminnow (Fundulus dispar)																						
Blackstripe topminnow (Fundulus notatus)																						
POECILIIDAE																						
Western mosquitofish (Gambusia affinis)																						NI
ATHERINIDAE																						
Brook silverside (Labidesthes sicculus)																			NI,LT			
COTTIDAE																						
Banded sculpin (Cottus carolinae)																						

Table 4-1. Fish and mussel species within the SLD and host relationships (page 5 of 6).

	Ambleminae															Anodontinae						
SPECIES	*Cumberlandia monodonta*	*Amblema plicata*	*Cyclonaias tuberculata*	*Elliptio crassidens*	*Elliptio dilatata*	*Fusconaia ebena*	*Fusconaia flava*	*Megalonaias nervosa*	*Plethobasus cyphyus*	*Pleurobema sintoxia*	*Quadrula metanevra*	*Quadrula nodulata*	*Quadrula pustulosa*	*Quadrula quadrula*	*Tritogonia verrucosa*	*Anodonta suborbiculata*	*Arcidens confragosus*	*Lasmigona complanata*	*Pyganodon grandis*	*Simpsonaias ambigua*	*Strophitus undulatus*	*Utterbackia imbecillis*
PERCICHTHYIDAE																						
White bass (Morone chrysops)		NI						NI,LT											NI			
Yellow bass (Morone mississippiensis)																						
Striped bass (Morone saxatilis)																						
Hybrid striped bass																						
CENTRARCHIDAE																						
Rock bass (Ambliplites rupestris)		LT															NI,NT		NI,LT		LT	LT
Green sunfish (Lepomis cyanellus)		LT						LT			NI					LT	LT	LT	NI,LT		LI,LT	LT
Warmouth (Lepomis gulosus)		NI						NI								LT						NI
Orangespotted sunfish (Lepomis humilis)																	LT	LT	LT			
Bluegill (Lepomis macrochirus)		NI,LT					LI,NS	LI,NT		NI,LT	NI	LI							NI,LT		LT	NI,LT
Longear sunfish (Lepomis megalotis)								LT								LT			LT		LT	LT
Redear sunfish (Lepomis microlophus)																						
Smallmouth bass (Micropterus dolomieu)																					LT	
Largemouth bass (Micropterus salmoides)		NI,LT				x		LI,LT				LI				LT		LT	NI,LT		LT	LT
White crappie (Pomoxis annularis)		NI,LT			NI	x	NI	NI,LT				NI	NI			LT	NI	LT	NI,LT		LT	
Black crappie (Pomoxis nigromaculatus)		NI,LT			NS	x	NI	LI,LT				LI							NI,LT		LT	LT
PERCIDAE																						
Western sand darter (Ammocrypta clara)																						
Mud darter (Etheostoma asprigene)																						
Rainbow darter (Etheostoma caeruleum)																			NI,LT		LT	
Fantail darter (Etheostoma flabellare)																					LT	
Johnny darter (Etheostoma nigrum)																			NI,LT		LT	
Orangethroat darter (Etheostoma spectabile)																						
Yellow perch (Perca flavescens)		NI,LT			NS			LT									LT		NI,LT		LT	LT
Logperch (Percina caprodes)		NI						LT													LT	
Blackside darter (Percina maculata)																					LT	
Slenderhead darter (Percina phoxocephala)								LT													LT	
River darter (Percina shumardi)																						
Sauger (Sanders canadense)		NI			X			LI	NI		NI							NI				
Walleye (Sanders vitreum)																	LT				LT	
SCIAENIDAE																						
Freshwater drum (Aplodinotus grunniens)		NI						NT, LT									NI		NI			

Table 4-1. Fish and mussel species within the SLD and host relationships (page 2 of 6).

	Lampsilinae															
SPECIES	*Actinonaias ligamentina*	*Ellipsaria lineolata*	*Lampsilis cardium*	*Lampsilis higginsii*	*Lampsilis siliquoidea*	*Lampsilis teres*	*Leptodea fragilis*	*Ligumia recta*	*Obliquaria reflexa*	*Obovaria olivaria*	*Potamilus alatus*	*Potamilus capax*	*Potamilus ohiensis*	*Toxolasma parvus*	*Truncilla donaciformis*	*Truncilla truncata*	Total no. of species
ACIPENSERIDAE																	
Lake sturgeon (Acipenser fulvescens)										LT							2
Shovelnose sturgeon (Scaphirhynchus platorynchus)						NI				NI,LT							5
LEPISOSTEIDAE																	
Longnose gar (Lepisosteus osseus)						NI,LI,LT											5
Shortnose gar (Lepisosteus platostomus)						NI,LI,LT											3
Alligator gar (Lepisosteus spatula)						NI,LT											2
AMIIDAE																	
Bowfin (Amia calva)																	2
HIODONTIDAE																	
Goldeye (Hiodon alosoides)																	1
Mooneye (Hiodon tergisus)																	2
ANGUILLIDAE																	
American eel (Arguilla rostrata)	NI																4
CLUPEIDAE																	
Skipjack herring (Alosa chrysochloris)																	5
Gizzard shad (Dorosoma cepedianum)																	6
Threadfin shad (Dorosoma petenense)																	1
CYPRINIDAE																	
Central stoneroller (Campostoma anomalum)	LT							LT									7
Common carp (Cyprinus carpio)	LI							LI									6
Goldfish (Carassius auratus)																	3
Grass carp (Ctenopharyngodon idella)																	1
Mississippi silvery minnow (Hybognathus nuchalis)																	1
Bighead carp (Hypophthalmichthys nobilis)																	1
Speckled chub (Macrhybopsis aestivalis)																	1
Silver chub (Macrhybopsis storeriana)																	1
Golden shiner (Notemigonus crysoleucas)																	6
Emerald shiner (Notropis atherinoides)																	2
River shiner (Notropis blennius)																	1
Ghost shiner (Notropis buchanani)																	1
Bigmouth shiner (Notropis dorsalis)																	1
Spottail shiner (Notropis hudsonius)																	1
Red shiner (Cyprinella lutrensis)																	1
Silverband shiner (Notropis shumardi)																	1
Spotfin shiner (Cyprinella spiloptera)																	6
Sand shiner (Notropis stramineus)																	1
Mimic shiner (Notropis volucellus)																	1
Channel shiner (Notropis wickliffi)																	1
Suckermouth minnow (Phenacobius mirabilis)																	1
Bluntnose minnow (Pimephales notatus)					LT												6
Fathead minnow (Pimephales promelas)																	2

Table 4-1. Fish and mussel species within the SLD and host relationships (page 4 of 6).

	Lampsilinae																
SPECIES	*Actinonaias ligamentina*	*Ellipsaria lineolata*	*Lampsilis cardium*	*Lampsilis higginsii*	*Lampsilis siliquoidea*	*Lampsilis teres*	*Leptodea fragilis*	*Ligumia recta*	*Obliquaria reflexa*	*Obovaria olivaria*	*Potamilus alatus*	*Potamilus capax*	*Potamilus ohiensis*	*Toxolasma parvus*	*Truncilla donaciformis*	*Truncilla truncata*	Total no. of species
Bullhead minnow (Pimephales vigilax)																	1
Creek chub (Semotilus atromaculatus)																	7
CATOSTOMIDAE																	
River carpsucker (Carpiodes carpio)																	2
Quillback (Carpiodes cyprinus)																	2
Highfin carpsucker (Carpiodes velifer)																	2
White sucker (Catostomus commersoni)					NS												4
Blue sucker (Cycleptus elongatus)																	1
Smallmouth buffalo (Ictiobus bubalus)																	2
Bigmouth buffalo (Ictiobus cyprinellus)																	1
Black buffalo (Ictiobus niger)																	1
Spotted sucker (Minytrema melanops)																	1
Silver redhorse (Moxostoma anisurum)																	1
Golden redhorse (Moxostoma erythrurum)																	2
Shorthead redhorse (Moxostoma macrolepidotum)																	3
ICTALURIDAE																	
Blue catfish (Ictalurus furcatus)																	1
Black bullhead (Ameiurus melas)																	5
Yellow bullhead (Ameiurus natalis)																	6
Brown bullhead (Ameiurus nebulosus)																	4
Channel catfish (Ictalurus punctatus)																	10
Stonecat (Noturus flavus)																	1
Tadpole madtom (Noturus gyrinus)	NI				NI												4
Freckled madtom (Noturus nocturnus)																	1
Flathead catfish (Pylodictis olivaris)																	9
ESOCIDAE																	
Grass pickeral (Esox americanus vermiculatus)																	1
Northern pike (Esox lucius)				LT													3
APHREDODERIDAE																	
Pirate perch (Aphredoderus sayanus)																	1
GADIDAE																	
Burbot (Lota lota)																	2
CYPRINODONTIDAE																	
Starhead topminnow (Fundulus dispar)																	1
Blackstripe topminnow (Fundulus notatus)																	1
POECILIIDAE																	
Western mosquitofish (Gambusia affinis)																	2
ATHERINIDAE																	
Brook silverside (Labidesthes sicculus)																	2
COTTIDAE																	
Banded sculpin (Cottus carolinae)																	1

Table 4-1. Fish and mussel species within the SLD and host relationships (page 6 of 6).

	Lampsilinae																
SPECIES	*Actinonaias ligamentina*	*Ellipsaria lineolata*	*Lampsilis cardium*	*Lampsilis higginsii*	*Lampsilis siliquoidea*	*Lampsilis teres*	*Leptodea fragilis*	*Ligumia recta*	*Obliquaria reflexa*	*Obovaria olivaria*	*Potamilus alatus*	*Potamilus capax*	*Potamilus ohiensis*	*Toxolasma parvus*	*Truncilla donaciformis*	*Truncilla truncata*	Total no. of species
PERCICHTHYIDAE																	
White bass (Morone chrysops)	NI,LT				NI,LT												6
Yellow bass (Morone mississippiensis)																	1
Striped bass (Morone saxatilis)																	1
Hybrid striped bass																	1
CENTRARCHIDAE																	
Rock bass (Ambliplites rupestris)	LI,LT				LI			LI,LT									9
Green sunfish (Lepomis cyanellus)	NI,LT	NI	LT	LT	LT	NI		LT						LT,NS			18
Warmouth (Lepomis gulosus)					NI	NI								NI,LT			8
Orangespotted sunfish (Lepomis humilis)	LT					NI		LT						LT,NS			8
Bluegill (Lepomis macrochirus)	NI,LI		LT	LT	NI,LI,LT	LI,LT		NI,LI,LT						LT			17
Longear sunfish (Lepomis megalotis)								LT									7
Redear sunfish (Lepomis microlophus)					LT	LT											3
Smallmouth bass (Micropterus dolomieu)	NT,NS		LT	LT	LT,NI												6
Largemouth bass (Micropterus salmoides)	NI,LT		LT	LT	NI,LT	NI		LI,LT									16
White crappie (Pomoxis annularis)	NI,LT		NI,LT		NI,LT	NI		NI,LT					NI	LT,NS			20
Black crappie (Pomoxis nigromaculatus)	LI,LT				NI,LT	NI		LT									14
PERCIDAE																	
Western sand darter (Ammocrypta clara)																	1
Mud darter (Etheostoma asprigene)																	1
Rainbow darter (Etheostoma caeruleum)																	3
Fantail darter (Etheostoma flabellare)																	2
Johnny darter (Etheostoma nigrum)														LT			4
Orangethroat darter (Etheostoma spectabile)																	1
Yellow perch (Perca flavescens)	NI,LI,LT		LT	LT	NI,LT	LI		LI,LT									14
Logperch (Percina caprodes)																	4
Blackside darter (Percina maculata)																	2
Slenderhead darter (Percina phoxocephala)																	3
River darter (Percina shumardi)																	1
Sauger (Sanders canadense)	LI,LT	NI	NI	NI	LT			NI,LT							NI	NI	15
Walleye (Sanders vitreum)			LT	LT	NI,LT			LT									7
SCIAENIDAE																	
Freshwater drum (Aplodinotus grunniens)		NI,LT		NI			NI				NI,NS	NI,LT	NI,LT		NI,NS	NI,NS	13

[1]Mussel/Host database, Molluscs Division of the Museum of Biological Diversity at the Ohio State University

X=no type listed

NI=natural infestation; parasite found on wild-caaught fish but metamorphosis not observed

NT=as above but metamorphosis observed

LI=Laboratory infestation; fish parasitized in experimental conditions, but metamorphosis not observed

LT=as above, but metamorphosis observed

NS=not stated in orignal source

Appendix A. Habitat Workshop minutes

Appendix A. Mussel habitat workshop participants, August 9, 2013.

Name	Affiliation	Address	
Heidi Dunn	Ecological Specialists, Inc.	O'Fallon, MO	Malacologist
Ryan Foley	Ecological Specialists, Inc.	O'Fallon, MO	Malacologist
Don Duncan	USACE-EC-H	St. Louis District	Acting Chief of Hydrology Branch
Dawn Lamm	USACE-EC-H	St. Louis District	Hydraulic engineer, Applied River Engineering
Ed Brauer	USACE-EC-H	St. Louis District	Hydraulic engineer, Applied River Engineering
Rob Davinroy	USACE-EC-H	St. Louis District	Hydraulic engineer, Applied River Engineering
Ashley Cox	USACE-EC-HR	St. Louis District	Hydraulic engineer, Applied River Engineering
Don Duncan	USACE-EC-H	St. Louis District	H&H engineer
Mike Rodgers	USACE	St. Louis District	Project Manager, A&M, BiOp and Regulating Works
Terri Allen	USACE-PD-C	St. Louis District	Biologist
Brandon Schneider	USACE	St. Louis District	Fisheries Biologist, Avoid and Minimize Coordinator
Brian Johnson	USACE	St. Louis District	Chief of Environmental Compliance
Dan Kelner	USACE-PD-E	St. Paul District	Fisheries Biologist
Joseph Jordon	USACE	Rock Island District	Endangered Species Coordinator
Matt Cosby	USACE-PM-F	St. Louis District	Project Manager
Katy Manar	USACE-Rivers Project	St. Louis District	
Elmer (Butch) Atwood	Illinois Department of Natural Resources	Greenwood, IL	Fisheries Biologist
Dean Corgiat	Illinois Department of Natural Resources	Pittsfield, IL	Endangered Species Biologist
Danny Brown	Misouri Department of Conservation	St. Charles, MO	Fisheries Biologist
Travis Moore	Misouri Department of Conservation	Hannibal, MO	Fisheries Biologist
Matt Mangan	U.S. Fish and Wildlife Service	Collinsville, IL	Ecological Services

St. Louis District Mussel Habitat Creation Workshop Minutes- August 9, 2013, Alton, IL

The objective of this workshop was to discuss and evaluate the characteristics of mussel habitat on the UMR, discuss past habitat creation efforts and their results, and determine how river engineering can be used to create or enhance mussel habitat.

Introductions

Participants introduced themselves and gave a brief summary of their experience with mussels and the Mississippi River.

Heidi Dunn, President Ecological Specialists, Inc., -introduced to mussels in 1978 with USFWS. Worked with mussels and fish for 10 years with Environmental Science and Engineering. Started ESI in 1990. About 80% of ESI's work is with freshwater mussels. Last 2 years she has been an instructor for the Mussel Conservation Biology course at USFWS, National Conservation Training Center (NCTC).

Ryan Foley, Malacologists, Ecological Specialists, Inc.- Graduate student with Dr. James Layzer, came to ESI Spring 2013.

Dan Kelner, St. Paul District Army Corps of Engineers, Fisheries Biology. First job with ESI in mid to late 1990s. Worked for MNDNR ACE in 2002. Mussel inventory work for O&M. Currently working with reintroduction efforts for *L. higginsii* and *Q. fragosa.* Also working with Ecosystem Restoration and Management (ERM). How can we build/manage these projects for freshwater mussels?

Joe Jordan, Rock Island District Endangered Species Coordinator. Has more of a regulatory background-operations and management, navigation, and training structures. Would like to gain information on optimizing training structures for mussel habitat.

Brian Johnson, St. Louis District, Chief of Environmental Compliance. Instigated this process when coordinating with Travis Moore (MDC) for Gilbert Island chevron construction. Started thinking about what can we do to enhance mussel habitat in areas where river engineering needs to occur under the Avoid and Minimize (A&M) Program. Had the idea of having Ms. Dunn put together a report on mussel habitat, then getting good biologists and engineers in the room to figure out what we can do to create habitat, which is why we are here.

Brandon Schneider, St. Louis District Fisheries Biologist. Coordinator on Avoid and Minimize.

Terri Allen, St. Louis District, Biologist with Environmental Branch. PhD in ecology with specialty in fish communities. Working on creating better fish habitat in river training structures, would like to incorporate mussels into that process.

Matt Cosby, St. Louis District, Project Management Branch. Big River ecosystem restoration. Five endangered species in the Big River. Lead mining area. Suffocating habitat and adding toxicity to mussels. That and other projects on-going to stop downstream movement of lead mine tailings. Engineers will be designing structures to contain tailings. Can they be used to enhance mussel habitat? Much smaller structures but same concept.

Rob Davinroy, St. Louis District, River Engineering. Responsible for the design of chevrons and other structures. Previously did some monitoring of mussels at Olmstead, IL. Curious as to why mussels are in the Ohio River but not in middle Mississippi River. Why don't we do more mussel work in the middle river? We have more money for structures in the middle river. Perhaps we can create mussel beds in the middle river.

Butch Atwood, Fisheries Biologist, Illinois DNR. Works with ACE frequently, would like to know where mussels are and make sure we don't cover them up.

Ed Bauer, St. Louis District, River Engineering. He works with Rob in designing river training structures. Excited to know there might be criteria they can use for enhancing mussels in designing structures.

Don Duncan, St. Louis District, Acting Chief of Hydrology Branch. Mainly works on hydraulic modeling. He would like to get a feel for how we can apply numbers in mussel hydraulic models to river training structures.

Ashley Cox, St. Louis District, River hydrologist.

Matt Mangan, USFWS, Ecological Services, Collinsville, IL. Hope there is opportunity to enhance habitat for state and federally endangered mussel species.

Mike Rogers, Project Manager for River Works. Would like to put real numbers to engineering structures and habitat modeling and would like to see where they might take us.

Dean Corgiat, ILDNR, Biologist. Spent a lot of time on the Illinois and Mississippi River looking for mussels with Travis and with commercial musselers.

Travis Moore, MDC, Fisheries Biologist. His predecessor did Mississippi River mussel work, which he continued when he took over in 1993. Coordinates with ACE on O&M features. Often end up moving mussels and harming habitat without creating any more habitat. Is there a way to modify construction to create habitat?

Katy Manar, St. Louis District, Biologist, Rivers Project Office.

Danny Brown, St. Louis Region MDC, works on Missouri River and middle Mississippi River. Would like to establish some kind of protocol for work on upper Miss River as to how to deal with mussel issues.

Power points were presented that summarize the habitat report. Below is an outline with questions and comments

Introduction to freshwater mussels (See Report Section 3.1)

What is a freshwater mussel?
Life cycle
Host fish strategies
Economic uses
Ecosystem services
Endangered status

Comments/Questions/Ideas

What is a flow refugia? (Discussed later)

Why do we care about mussels? (Discussed later)

How do they move, how fast do they move?

Discussion on movement and behavior. Different species adapted in different ways.

Why don't we see more mussels downstream of St. Louis? (Discussed later)

What are they eating?

Siphoning in water, eating algae and bacteria. Discussion on feeding behavior.

Do you sample down in deep water in the channel?

Yes, we sample in the channel if needed, but the thalweg is generally not good habitat

Why are they moving around?

Substrate moves, need to dig back in. May not have the right habitat. Not sure of microhabitat requirements for most species or triggers that make them move. In general, some species move in response to disturbance.

Mussel beds and mussel habitat characteristics (See Report Sections 3.1 and 3.2)

Mussel bed definition

Habitat attributes

Hydraulic characteristics

Existing models Mississippi River

Questions to consider

Comments/Questions/Ideas

On Ohio River, there is a bar with bathymetry that hasn't changed over time. It is a cobble bar, but not soft, why were they there?

Stable area, substrate probably had areas between cobbles where mussels could dig in.

Most of structures graded from fines to large rock. Can you move stones and look for mussels.

We cannot move those large stones. Rock currently used doesn't allow mussels to dig in-between

Is silt important?

Silt loosens up clay; animals cannot dig into hard packed clay. Silt also important to juveniles. But too much silt will bury animals. Buried for too long, they will die.

Situation changes in smaller streams.

In some areas, clean coarse sand on top, but solid substrate underneath with mussels.

Talked about stump field upstream of spillway in Pool 25.

Chevrons should be exciting, as they are creating more riverine conditions in low flow areas.

They are also creating flow refugia.

Pool 25 Chevrons should flush out some of the shifting sand in some areas, and create refugia in other areas

These chevrons should be monitored to see if these changes occur.

Small changes in hydraulics can have significant changes in habitat

Have model results from one pool been applied to another pool and successfully predicted mussel distribution?

I think Steve Zigler is working on that.

Kelner-this study design has now been applied to Pools 18, 5, 6 and 3.

Is this the best available substrate data?

A Wentworth scale observation is most of what is available. Substrate is qualitative data.

Pool areas on average are slow moving (<0.5 ft/sec). Where mussels seem to be is in even slower flowing areas.

Yes, mussels are primarily in very low flow areas. Even in low flowing areas, if substrate is moving, mussel cannot stage in place. There is a very narrow window for mussels. What is this window? How do we define that window? The values may not extrapolate from one pool to the other.

Have we found mussel beds in the MiddleRiver?

Shifting sand habitat throughout, similar to Missouri River (see report section 3.4.4 Middle River)

Dams often create mussel habitat that otherwise would not have been there

Dams create big river shoals that we destroyed when we put in the dams

Is it feasible to create mussel beds in the Middle River?

Historically this area had unstable habitat. If we are managing for Middle River species, then this is not conducive to mussels. Some modifications have made the area more conducive to mussels.

We should consider how things have changed and manage accordingly

Overview of existing habitat creation projects (see Report Section 3.3)

Tombigbee River
Lower Ohio River
Tennessee River Wolf Island
Bertom and McCartney Lakes HREP
Pool 8 Islands ideas

Comments/Questions/Ideas

<u>Tombigbee project</u>

Nothing natural about the Tombigbee project, similar to river training structure.

Yes, we can do this

What kind of material did they use?

Not sure, I will have to look into that.

How far was this from the reference area? If we are creating good habitat in the middle of a desert, how will they get there? Will the mussels come or should we add mussels?

Travis-If hydraulic variables are right. It might attract fish and a few mussels are there. Mussels continue to colonize, they stabilize substrate. We are increasing the probability of mussel bed formation

Do shells become substrate component and further stabilize substrate?

Yes, they do over time.

<u>Bertom and McCartney</u>

Joe Jordan/Dan Kelner-This year doing an evaluation report. They do monitor the structure, but the biological component is typically monitored by state resource agency.

Would you need 10 to 20 years of monitoring to determine if it worked?

Yes, need baseline, then quantitative sampling over time to determine success.

For areas such as Gilbert Island (RM 300) that have only been there a few years, we really don't know if they worked or not.

Catastrophic events occur (such as 93 flood)- do we design to these events?

These events are occurring more often, they should be considered

Is the focus to make existing structures more suitable for mussels or to design the structures to create flow regimes more suitable for mussels?

Yes to both

What do you mean by river rock vs. quarry rock?

River rock is rounder; edges do not interlock preventing the accumulation of fines that animals can burrow.

Doesn't need to be river rock. We can use quarry rock, but reduce the amount of smaller size stone that fills in the interstitial spaces, allowing for some natural substrate. Smaller stones are what interlock. River rock would be excessively expensive. Could put a ramp of larger stone downstream of structure with angular rock.

Good ideas. We would likely need to play around and see what works.

However, it could take 20 years to see what works

We could put native mussels in the area in mussel silos or grids that could easily be monitored. Could use common species to see whether they are growing

Have you been around Chevron structures and what did you find.

Not a lot (we will discuss that)

Have you been around the MRS's?

No, we have not looked at these

St. Louis District Mussels (See Report Section 3.4)

General
Pool 24
Pool 25
Pool 26
Middle River
Illinois River

Comments/Questions/Ideas

Blackbird Island

Travis-Bullnose dike at tip of island changed how flow was coming in. Area was sanded in. Assuming mussels were buried. Still a vein of mussels along Missouri bank and near the toe

Habitat changed, mussels gone

Do you think it was the bullnose?

Discussion on how bullnose might have affected flow and mussels.

Lower Hickory Chute

Finding mussels in 40 to 50ft of water? This is much different then most other areas we have been talking about

Travis-chunks of riprap fallen off the riprap bank. Mussels along the bank associated with rocks that have fallen out of the riprap bank. 6 of 7 Cumberlandia in a washboard shell

This area is very old. Different type of rock used.

Again, mussels occur in a variety of areas for different reasons. We may need to look at several situations. In this case, the type of rock may be a factor. Unionids not in the riprap, but fallen riprap left large stones with spaces in between (flow refugia)

Could there be fantastic mussel beds out there that we know nothing about?

Yes, definitely

Areas on outside bend, that is pretty stable with lots of flow that you may not necessarily be *able to sample.*

Discussion of Andy Peck's thesis (discussed in the habitat report); lateral scour pools, area along outside bends between core flow at low and high flow made good flow refugia

Are there areas you have not found mussels because you cant sample there?

Maybe, but high flowing areas under low discharge conditions probably have scoured substrate. But could find areas with boulder refugia

What are the main impacts of fleeting?

Depends on substrate, depth, type of tows used, and how the tow is moving around in the area. Even small tows maneuvering in shallow water can have a large effect. There are things you can do to mitigate impacts

Do mussels care if barges are parked weeks at a time?

Probably not, may block the sun and reducing siphoning. However, may attract fish. Really don't know could be positive or negative. No studies that I know of.

<u>Pool 25 Missouri bank</u>

Where did historical data come from?

Dean Corgiat-mostly from commercial musseler

Butch- these are areas that with some tweaks might be good mussel areas

How do you know these commercial clammers did not devastate these areas?

They might have in some areas

Even if they did, habitat should still be good

If this area it is now all shifting sand, it must have changed somehow

If they were all harvested, could substrate have changed due to removal of mussels?

If we put substrate back here, could mussels live there?

Within ACE authority, how would we justify this?

Travis-Musselers could only take 3 species and bigger shells, so they should not have devastated bed

The area has generally always been the same.

If so, there were mussels there, but now all shifting sand, so something must have changed

On the other hand, this is just anecdotal information; maybe mussels were not there.

Floods could have caused minor shifts in substrate that we can't detect that affects mussels

Could be old dredge material

Do we know affects of dredging?

Physically picking up substrate-anything there is destroyed

Dredge disposal burying animals

Also, destabilizes substrate upstream

Also, dependent on situation

Do we want to continue dredging or use training structures?

Discussion on dredging and disposal

Do we have any experience with mussels in the side channel at Kelly Island?

Riverward side- no mussels in 2013 but have not looked at the area since construction of dikes and round points

Four dredging areas- considered mussel monitoring in areas of structures but don't know where we should monitor

Can we use hydraulic monitoring to determine areas that might turn into flow refugia?

Loading Area across from Missouri River (MRM 195)
This area is within a dike field- 4 bendway weirs along here
Bendway weir field may be creating hydraulic refugia
Rock probably attracted fish
This might be similar to lower Ohio- they put rock within a weir field with suitable flow and mussels colonized

Illinois River
Most of this data came from commercial musselers. Where they said there were mussels, they were there.
Mussel habitat can change dramatically within a few feet
Have we tried sampling with side scan sonar?
We have not tried, but it is a promising technology
If we can identify stable substrate with side scan sonar, we could limit the areas we need to dive
Travis- We know results if we build structures the way we have. However, if we continue to build different configurations, we may eventually learn what works.

Gilbert Island
Have we sampled around Gilbert?
We did original survey but have not gone back
How do we know it hasn't worked?
We don't. It might have
Have we looked at enlarging existing beds?
Not sure whether augmenting works
Could look at improving habitat around bed to increase the area

Threatened and Endangered Species (See Report Section 3.5)
Habitat specialists
Habitat generalists

Comments/Questions/Ideas
Do we know host of P. capax
Drum
Don't know host of C. monodonta
No, this is one that has eluded us to date
What is range of C. monodonta?
Throughout interior basin
Range of P. capax
More southern, channelized ditches in Arkansas
In Wabash, along edges of islands
Paducah riverfront-deep silt
Range of L. higginsii
St. Louis District southern extent of range
Dean put some in Pool 24, probably covered up with sand
Fusconaia ebena
Travis- Chris Barnhart working on propagation but not real successful

Habitat Creation/Enhancement Ideas (See Report Section 4.1)

Is creating stable substrate areas suitable for mussels possible?
Different approaches needed for different areas
Pool 24 Chevrons
Could different configuration work that would cause gradual change in flow rather than abrupt change in flow
Can we add substrate?
Create low flow channels within the chevrons
Scalloped banks with addition of cobble and gravel
Gradual slopes on dikes
Key ingredients:
- Gradual flow changes
- Preventing substrate deposition
- Heterogeneous substrate
- Fish attraction
- Source of mussels
- What are the key engineering ideas?

Comments/Questions/Ideas

Downstream from middle chevron dike (MRM 290), there were many juvenile mussels in silty/sandy area, but they piled sand on top of it.
If we don't have the right substrate after 20 years in our system will we ever have it?
Can we manage flows to get sand, cobble substrates back?
Is it more environmentally friendly to dredge or build river training structures?
Is it the way we are managing rivers or managing the flood plain?
We need to deal with something that is in our control.
Lots of sand coming down the system from flooding the last few years
W dikes create low flow areas between dikes- can we add some substrate to these?
On Chevrons- build legs first and did not have front when flood came through, it resulted in a 40ft hole behind the Chevrons.
We did put some notches in Gilbert
What are A&M program goals in St. Louis? Increase mussels, maintain mussels?
- *To take advantage of opportunities for structures to create habitat and achieve navigation goals if they exist*
- *Not a goal to get 10 mussels, just see if we do something different will things change*

Anytime something is different, it will probably benefit something
If we build everything slightly different, we are bound to help something
Pool 24 Chevrons have reduced need for dredging in conjunction with other structures in the area (W dikes across from Pool 24 Chevrons)
If it isn't working to reduce dredging are there opportunities to change the structures to create habitat?
Are there opportunities to modify things?
- *At this site, we have fixed dredging problem*
- *We can add substrate, but not under O&M, need a source of authority*

W's have shallower and deeper areas
3 W dikes, 2 in pools, one in open area
W dikes provide diversity for fish- variance of flow

If you dove off the backside or channelward side of the dike, you might find good hydraulic conditions for mussels

<u>Next steps?</u>
Need to survey at Gilbert Island-haven't gone back to look. These have been in for about 2 years. Look to see if we have created a flow refugia
If it has, use some of those design ideas in future structures
Allow voids in structures to allow material to settle in those areas, add some cobble size stone in toes of structures
Design on going at Pool 25 approach.
Is there any benefit to doing these things in Open River?
Do Chevrons downtown St. Louis provide flow refugia
    Open River, dynamic sand bar to deal with
Often find slim line of mussels around dikes, we would like to create a larger hydraulic area
Look at revetments, using a smaller size stone
On dikes, make flow changes more subtle
Multiple round point structures should be ideal. Hodgepodge of flow conditions
Rocks fall down between dikes, create flow refugia
Expand zone of low flow and heterogeneous substrate that occurs at toe of some rock structures
Don-Create mussel habitat, what would you do
    Investigate weir field a little more
    Scatter some rock downstream and between weirs and see what happens
Are we more interested in up or downstream side?
    Hydraulic question- need more slope on both sides to create more laminar conditions
Increase areas by adding some cobbles at toe of structures
We will probably have to approach this on a site-specific basis
Look at areas where you have structures and see if there are any changes we can make that would improve habitat
    Has habitat improved?
    How can we make it better?
    Incorporate ideas in future designs
    Monitor
River training structures create bed diversity and have flexible dredge pipe; create ephemeral or permanent islands, could utilize that
Area between bank and chevron- put a rock riffle there, we have done this by accident
Can incorporate more slope, but this costs a lot of money.
If not as high, spread it out- same amount of rock
    Must be 2 ft above maximum pool for safety
    Top width is 6 ft due to rock size
Can we be 2 ft below low water for safety and still maintain purpose of dike?
    Need some height for navigation benefit
In areas where doing maintenance can we do that?
If degraded, can we go in and add rock?
Reduce fines for more porous areas- fines come with stones, cheaper product
    Reducing fines will cost more
Sides of old dikes are all over the place
    Most of these areas are completely sanded in, how do we get sorted material in there

Sides of chevrons are too hostile
Overall idea
Mussels prefer moderate conditions
Get rid of extreme flow conditions
Where we find mussels, velocity doesn't change between hi and lo flow. If we move out of the mussel area, flow changes with discharge
If gravel were going to be there, it would be there. If we throw gravel on reasonably stable area, would the gravel stay there or be covered up?
So many variables. It may be exposed, and then covered up depending on discharge conditions.
If we had a raised gravel area, would it be maintained? Sounds like a dike.
It may be buried occasionally, but mussels are adapted to that.
We probably need to engineer to the norm. 95% and 5% exceedance.
Capoli Slough armored some of the channel, then proposing cobble liner with the idea it would maintain itself clean and act like a riffle. 10 to 20 ft bands in 100 to 150ft wide channel. Experimental in a secondary channel. Just put in this year.
Place clusters of cobble and let river take it where it wants it. Come back and see where it settles out. That would be where we would want to continue to put rock.
Use the system rather than doing complete modeling
Notching wing dams, get a flowing secondary channel. Get some flow down of chevrons
Take material we are taking out of notching and spread it downstream on wing dams
However, don't want to make one narrow notch. Several wider notches rather than one deep notch
Several notches-end up with MRS
Need the rock out there- Even with right hydraulic conditions, still don't have the substrate. Need some substrate.
Try to keep things from blasting, slow the flow down.

<u>What is next step?</u>
Look at Gilbert, look at MRSs, see if substrate if stable and heterogeneous
Identify flow refugia, put some substrate in and see if it stays.
Don't have any numerical models other than Pool 25 approach
Use some engineering judgment, put some rock in, see where it goes and monitor
Put rock on either side of round nose, in area between chevrons
Use more bluntnose chevrons
Want the moderate area, not the real slow flow area
Go out and look to identify best areas for additional substrate
Amaranth Island might be a good place to look (MRM 269)
May need to collect some data
Build a chevron and place a rock apron between edge of chevron and the bank- that would still be within the navigation mission
Amaranth Island-look at putting cobble at head of island? Need to look at conditions and see what is there now.
Could you get in there with a barge- need 70ft of 9ft depth? They are doing it up north.

<u>Summary of next steps</u>
Monitoring around MRS's and Gilbert
Identify areas of few refugia

Talk about cobble structures
Look at areas to put cobble aprons/blankets

Above dam on LDB, look at weirs. Not as energized as other structures
Some of notched structures in open river, we have drug rock down from notch, may have created some riffle
Have we monitored at Pharrs?
Hydrologists need to get together and see where they think mussels would be. Then we can go out and look and see if mussels are there.
Talk to Steve Zigler and see if his model information would be beneficial
If we are going to go out and collect data for the model, we might as well go out and look for mussels
Look at chevrons, W's, MRS's, notched weirs- we should be able to look at the structures and determine where we should look for mussels
Pool 25 model probably doesn't have the data needed to run Zigler's model.
What about rock blankets downstream of dams?
  Tailwaters are too fast to support mussels within 500 ft of dams
Need to talk about Blackbird and see if we can recover what was there

Appendix B. Habitat models

Figures from Morales et al. 2006b

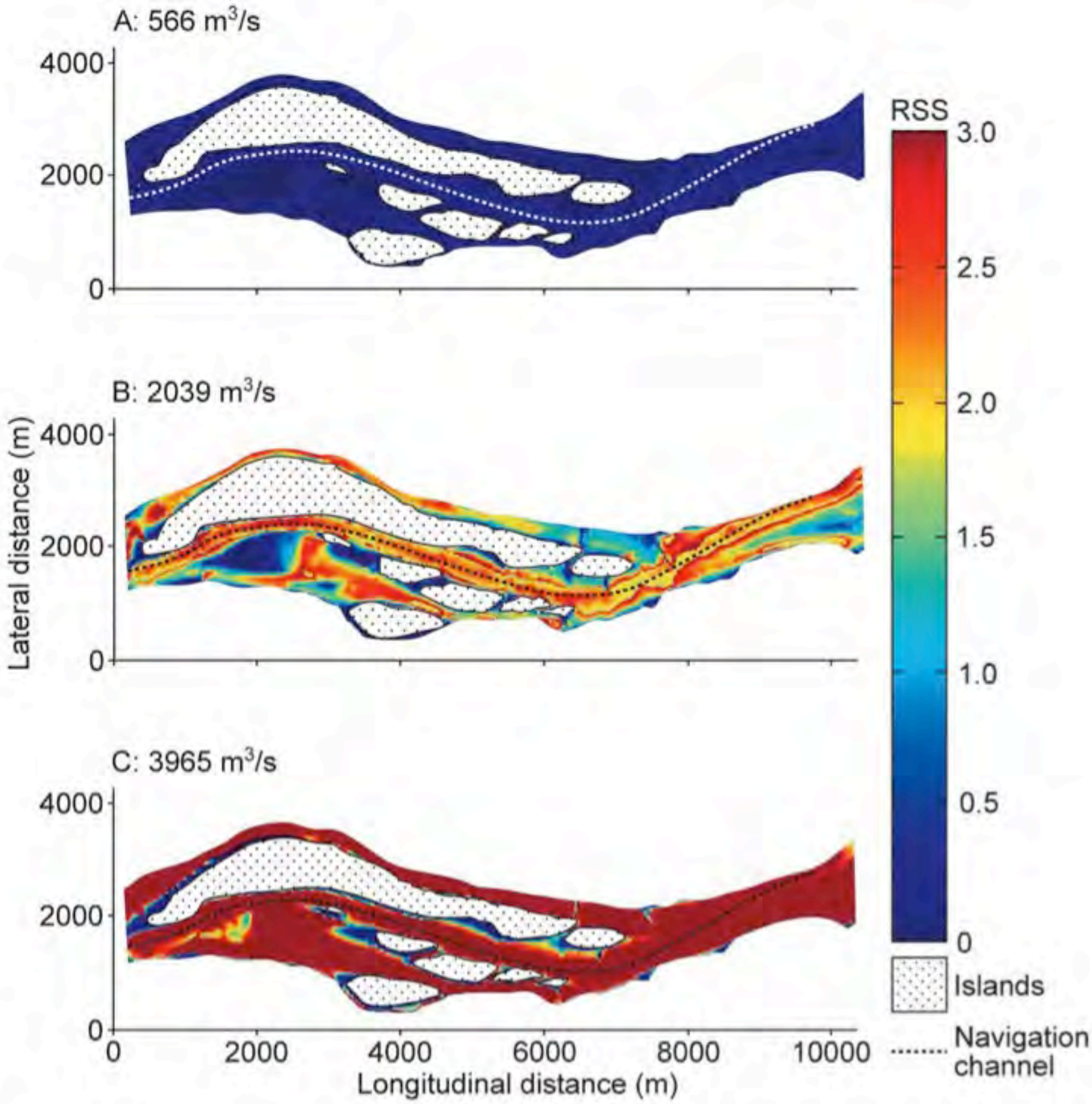


FIG. 3. Variation in shear stress ratio (RSS) in the study area across 3 flow regimes: 566 m^3/s (A), 2039 m^3/s (B), and 3965 m^3/s (C). An RSS > 1 indicates areas where the shear stress required to initiate sediment motion has been exceeded. Flow direction is from right to left.

Figures from Morales et al. 2006b (cont.)

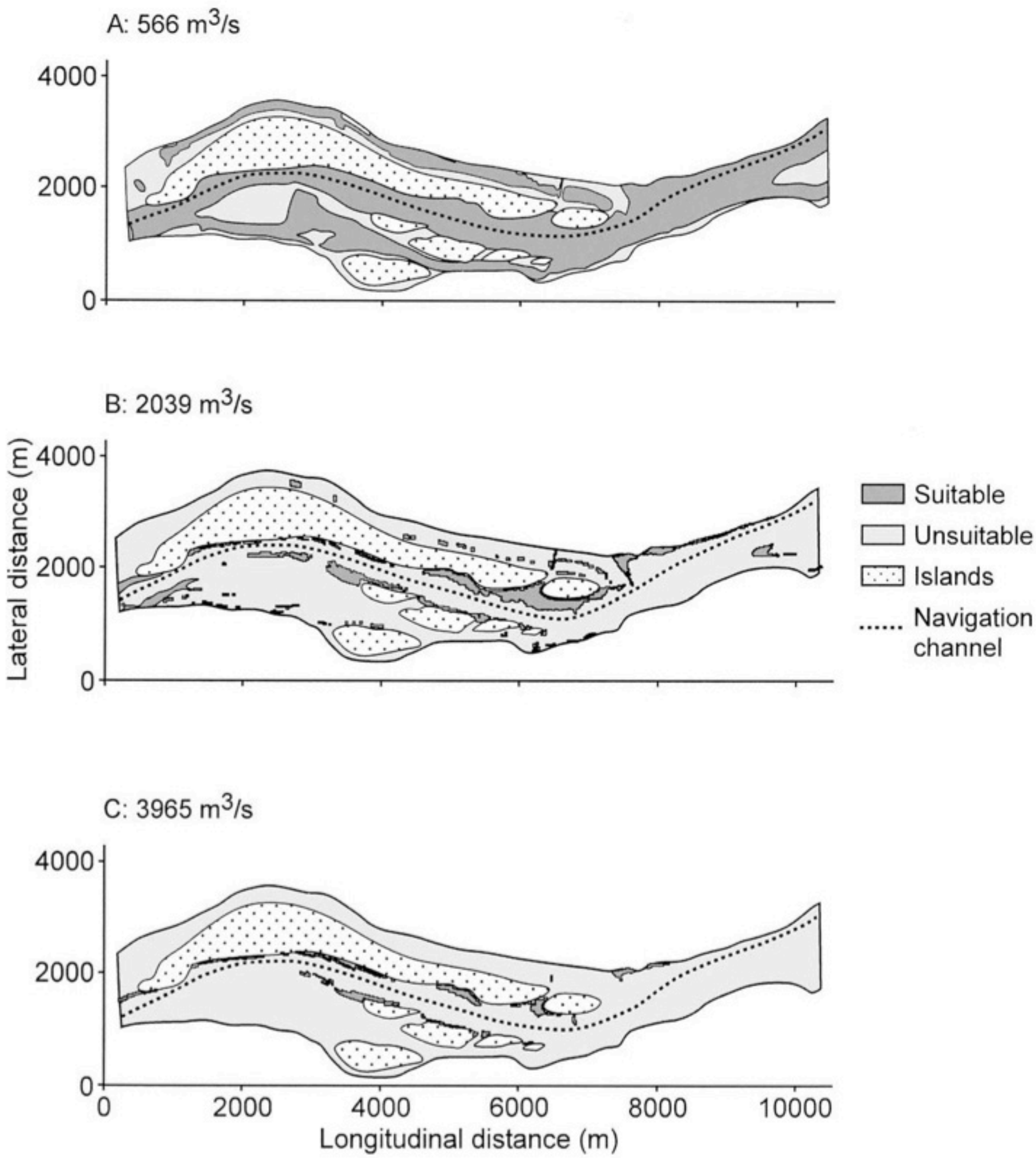


FIG. 4. Variation in habitat suitability in the study area across 3 flow regimes: 566 m^3/s (A), 2039 m^3/s (B), and 3965 m^3/s (C). Unsuitable areas are those with a habitat suitability score of 0, and suitable areas those with a habitat suitability score >0. Flow direction is from right to left.

Figures from Morales et al. 2006b (cont.)

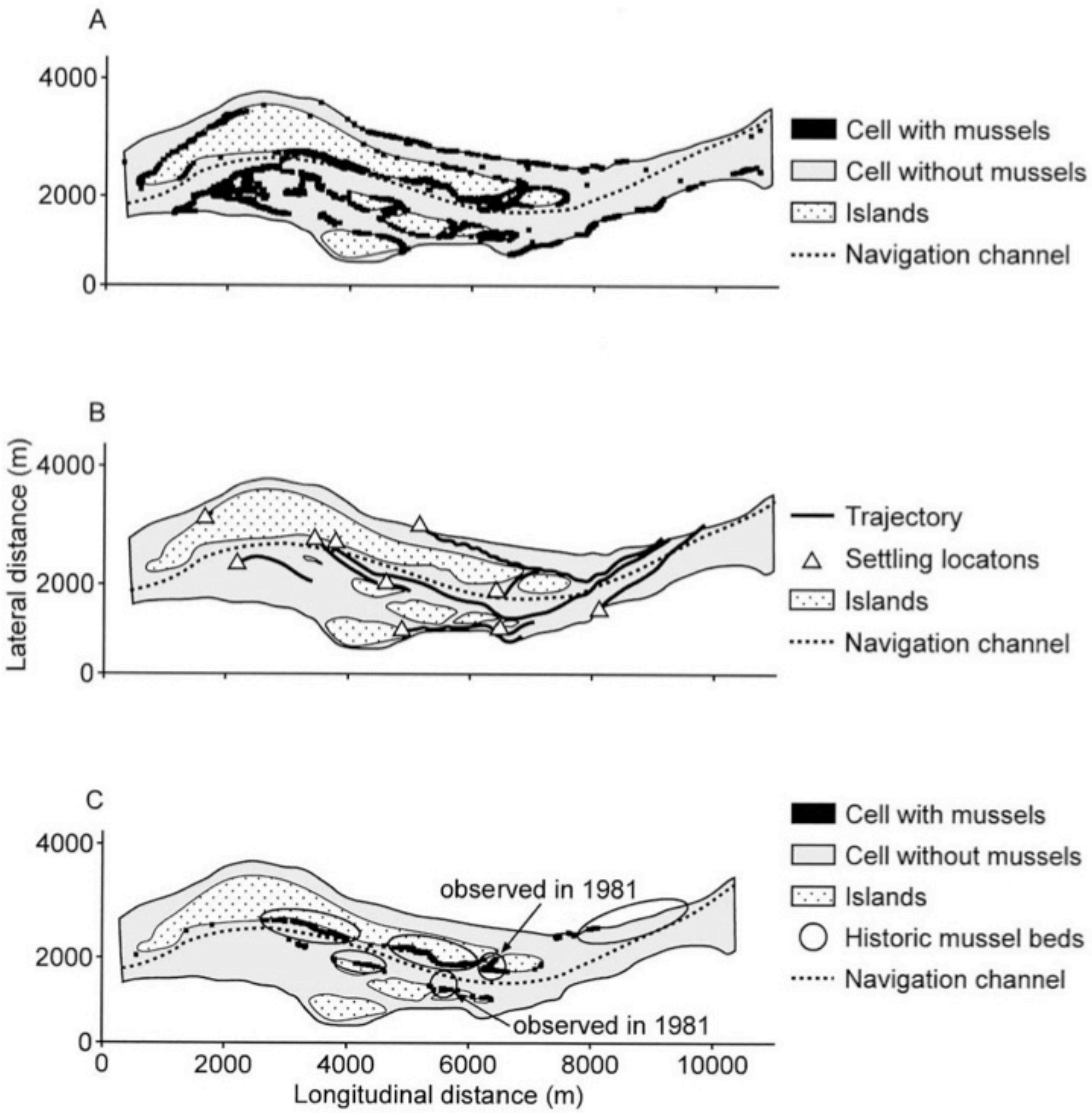


FIG. 5. Simulation results of the mussel dynamics model for estimating the spatial distribution of unionids in the study area. Flow direction is from right to left. A.—Predicted distribution of juvenile mussels settling in the river bottom. B.—Trajectory of 10 juveniles (length = 200 μm, settling velocity = 0.03 cm/s) between detaching from the host fish and settling in the river bottom. Distances shown correspond to the average flow (2039 m^3/s) and are likely to increase for higher flows and decrease for lower flows. C.—Correspondence between simulated areas of mussel accumulation and location of existing mussel beds in the study reach (USACE 1981, 1984). Simulated mussel accumulations occur at the conjunction of juvenile settlement locations and suitable habitats.

Tables and Figures from Steuer et al. 2008

Table 3 Results of regression tree modeling of mussel densities with simple and complex hydraulic variables at 167 sites under low flow (765–793 m^3/s) conditions in a 6-km reach of the Upper Mississippi River

Species	Sites present (%)	Density (no./0.25 m^2)	Simple variables (model 1)		Simple and complex variables (model 2)		Model improvement (%)
			Deviance	Primary split [secondary]	Deviance	Primary split [secondary]	
Total fauna	90	14.6	109.2	$D_m > 2.8$ [d]	100.0	$Re_* > 2.1$ [τ, Fr]	8
Amblema plicata	85	7.3	32.8	$D_m > 0.1$ [d]	29.5	$Re_* > 2.1$ [d, τ, Fr]	11
Truncilla truncata	58	1.3	1.8	$D_m > 1.8$ [d]	1.7	$D_m > 1.8$ [Fr]	2
Leptodea fragilis	56	1.0	1.2	$D_m > 5.6$ [d]	1.2	$D_m > 5.6$ [d]	0
Megalonaias nervosa	49	0.7	0.69	$d > 3.1$ [D_m]	0.69	d > 3.1 [D_m]	0
Fusconaia flava	51	0.6	0.40	$U > 16$ [d]	0.38	$\tau > 0.5$ [S_o, Re, U]	5
Potamilus alatus	44	0.5	0.48	$D_m > 5.6$ [U]	0.43	$S_o > 3.3$ [d, Re]	10
Obliquaria reflexa	43	0.4	0.32	$D_m > 0.2$ [U, d]	0.32	$D_m > 0.2$ [U, d]	0
Quadrula quadrula	44	0.4	0.23	$d > 3.1$ [D_m]	0.22	$D_m > 1.8$ [Re]	3
Lampsilis cardium	32	0.3	0.17	$D_m > 0.4$ [d]	0.16	$Re_* > 2.7$ [Re]	7
Quadrula pustulosa	31	0.3	0.13	$D_m > 0.3$ [d, U]	0.11	$Re_* > 2.7$ [Fr, S_o]	7
Truncilla donaciformis	36	0.3	0.19	$D > 0.7$	0.16	$k_s > 0.8$ [d, D_m, S_o, Fr, U]	16
Obovaria olivaria	31	0.2	0.12	$D_m > 5.6$ [d, U]	0.09	$k_s > 0.7$ [Fr, S_o]	26
Ligumia recta	25	0.2	0.09	$D_m > 0.2$ [d]	0.08	$D_m > 0.2$ [Fr, U]	14

Models were constructed with only the simple variables (model 1) and with simple and complex variables (model 2)

Variables are listed in order of importance with the primary split variable and split value listed first and secondary variables denoted in brackets. Model improvement is the percent change in deviance between the two models

D_m, grain size; d, water depth; U, mean current velocity; Re_*, Boundary Reynolds number; τ, Boundary shear stress; Fr, Froude number; S_o, Trask sorting coefficient; K_s, bed roughness; Re, Reynolds number

Tables and Figures from Steuer et al. 2008 (cont.)

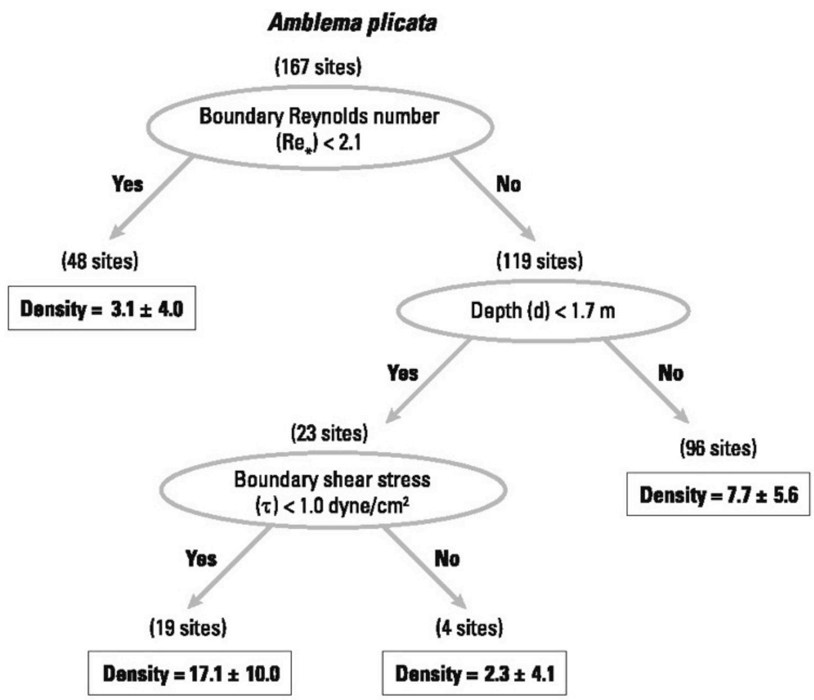
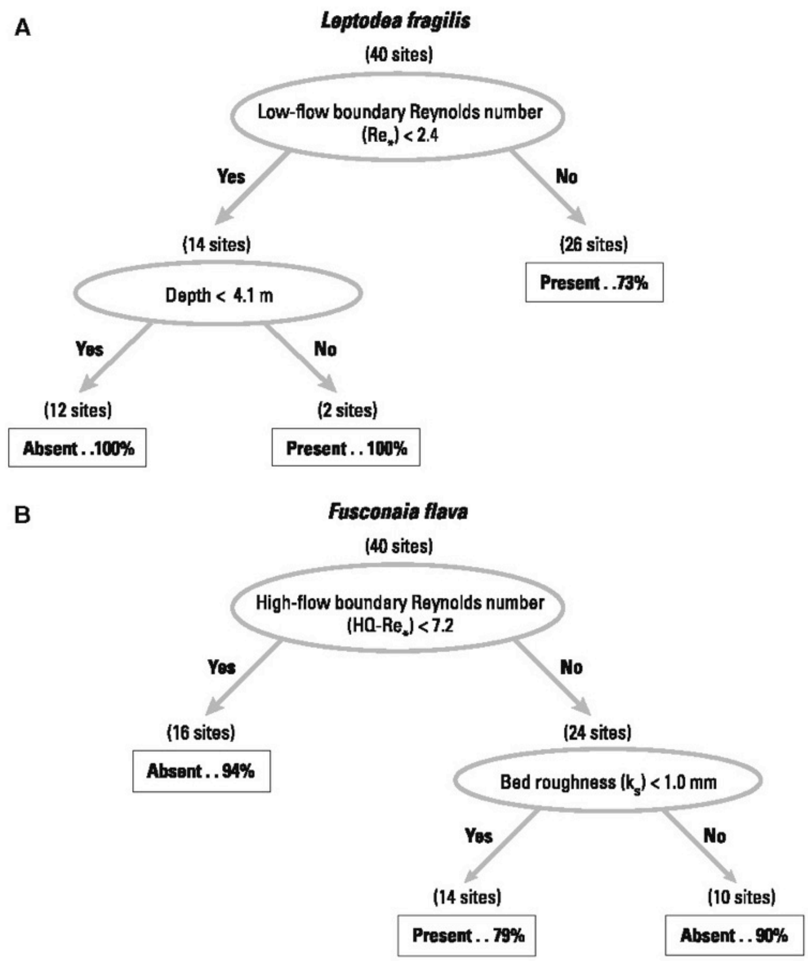


Fig. 2 Regression tree model of the influence of hydraulic and substrate variables on densities of *Amblema plicata* in a 6-km reach of the Upper Mississippi River during low flow (50% exceedence). The parentheses indicate the number of sites at an end node and below this is the density (no./0.25 $m^2 \pm 1$ SD). To read a model, start from the top and work down. For example, if $Re_* > 2.1$, $d < 1.7$ m, and τ is <1.0 dyne/cm^2–19 sites meet these criteria with a mean density of 17.1 mussels/0.25 m^2

Tables and Figures from Steuer et al. 2008 (cont.)

Fig. 4 Classification tree model of the influence of simple and complex hydraulic variables on the presence–absence of *Leptodea fragilis* (**A**) and *Fusconaia flava* (**B**) in a 6 km reach of the Upper Mississippi River during low (50% exceedence) and high (HQ; 20% exceedence) flows. The parentheses indicate the number of sites at an end node. For example, for *L. fragilis*, 26 sites had $Re_* > 2.4$ and 73% of these sites contained mussels



Tables and Figures from Zigler et al. 2010

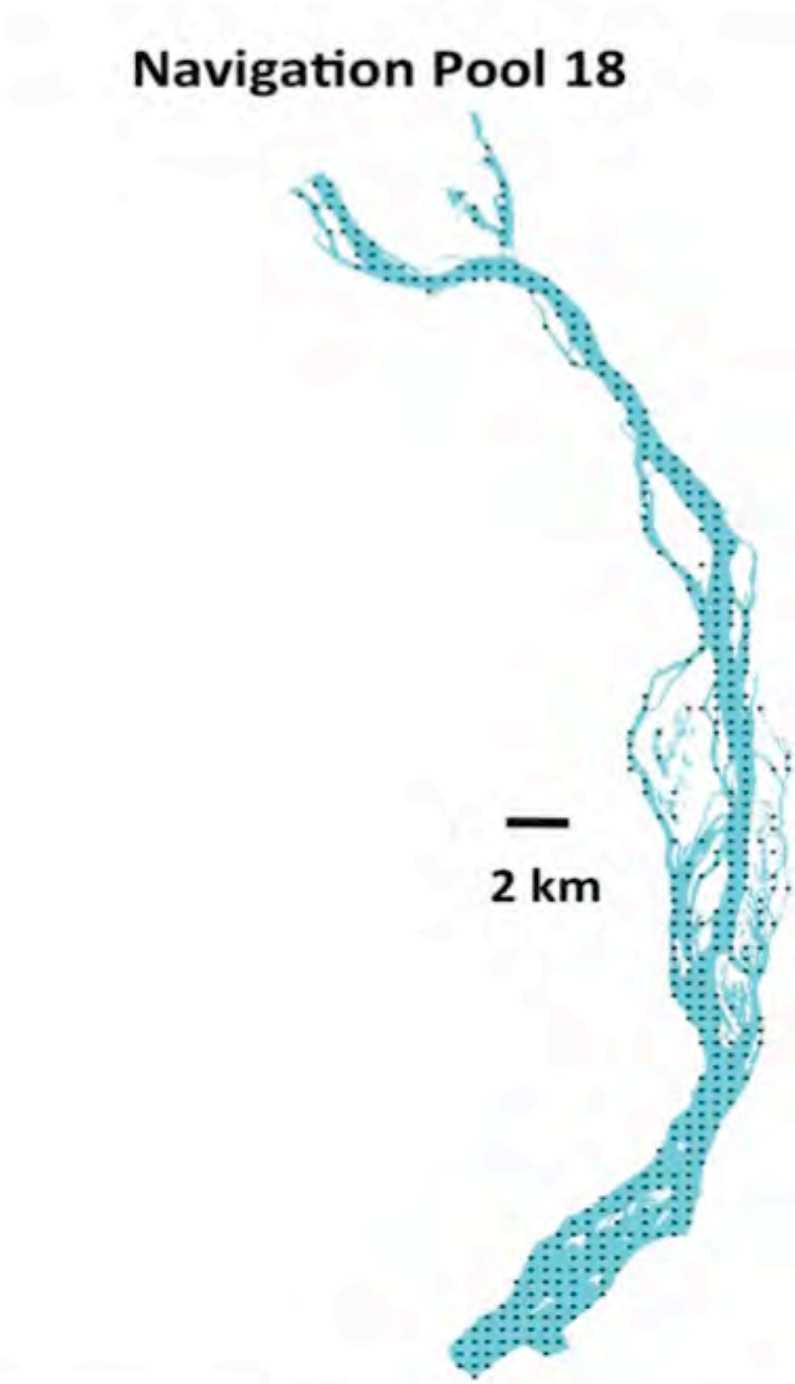


Figure 1. Sampling locations (dots) in Navigation Pool 18, Upper Mississippi River.

Tables and Figures from Zigler et al. 2010 (cont.)

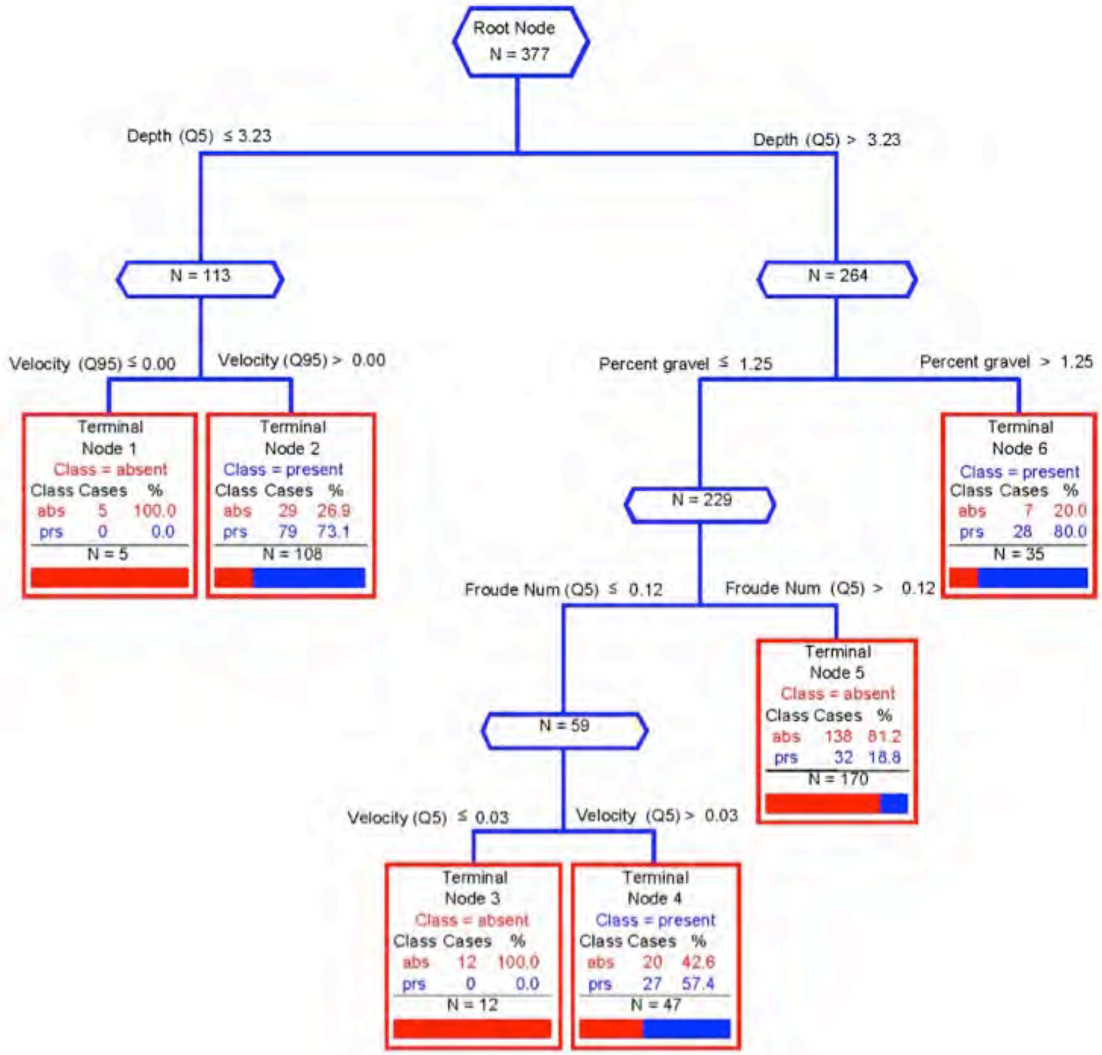


Figure 2. Classification tree model of mussel presence and absence in Pool 18. Models are read from the top down beginning at the root node, which contains all data. At each subsequent decision node, data that satisfy the splitting rule move into the branch below.

Tables and Figures from Zigler et al. 2010 (cont.)

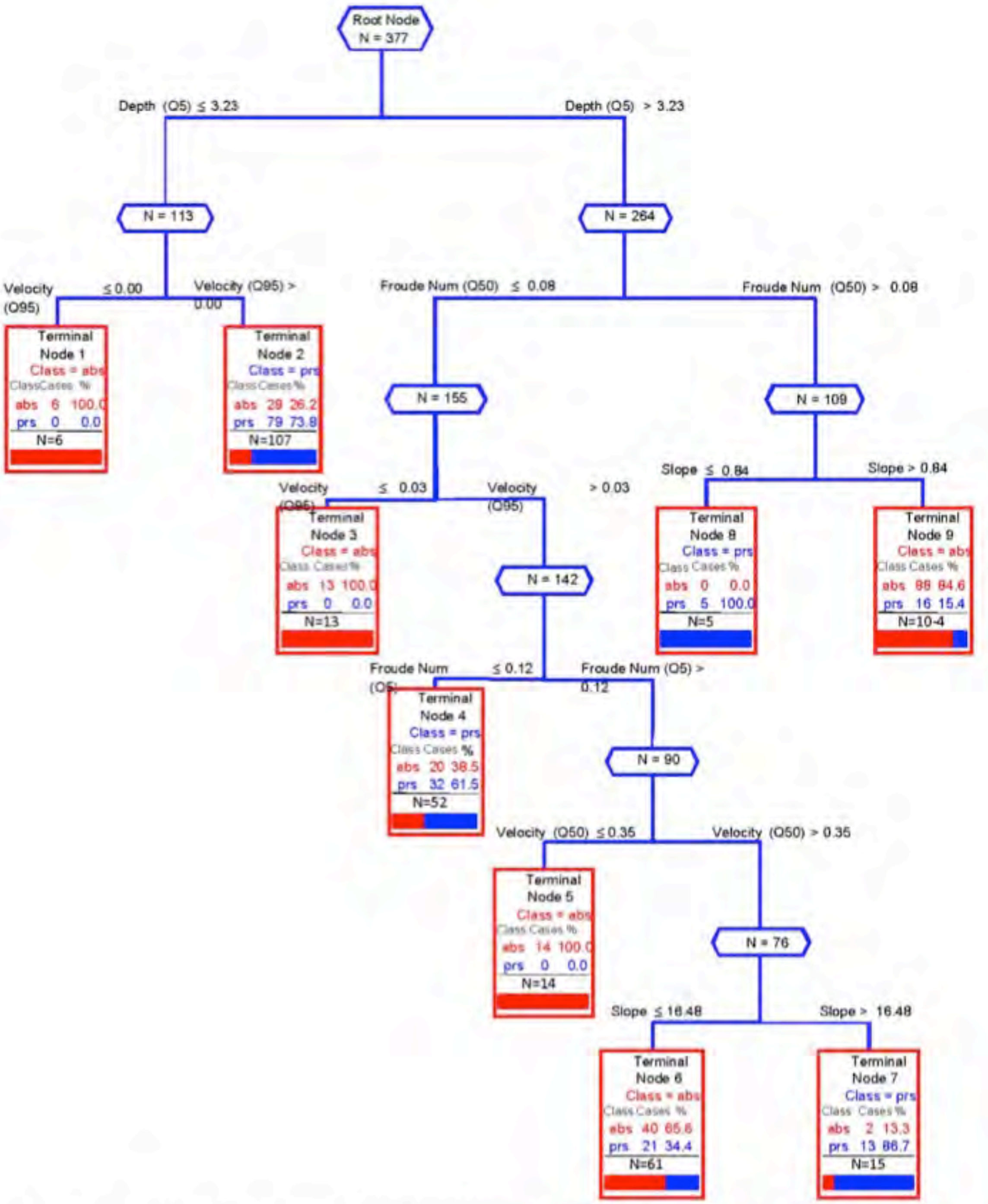


Figure 3. Classification tree model of mussel presence and absence in Pool 18 using variables independent of substrate. Models are read from the top down beginning at the root node, which contains all data. At each subsequent decision node, data that satisfy the splitting rule move into the branch below.

Tables and Figures from Zigler et al. 2010 (cont.)

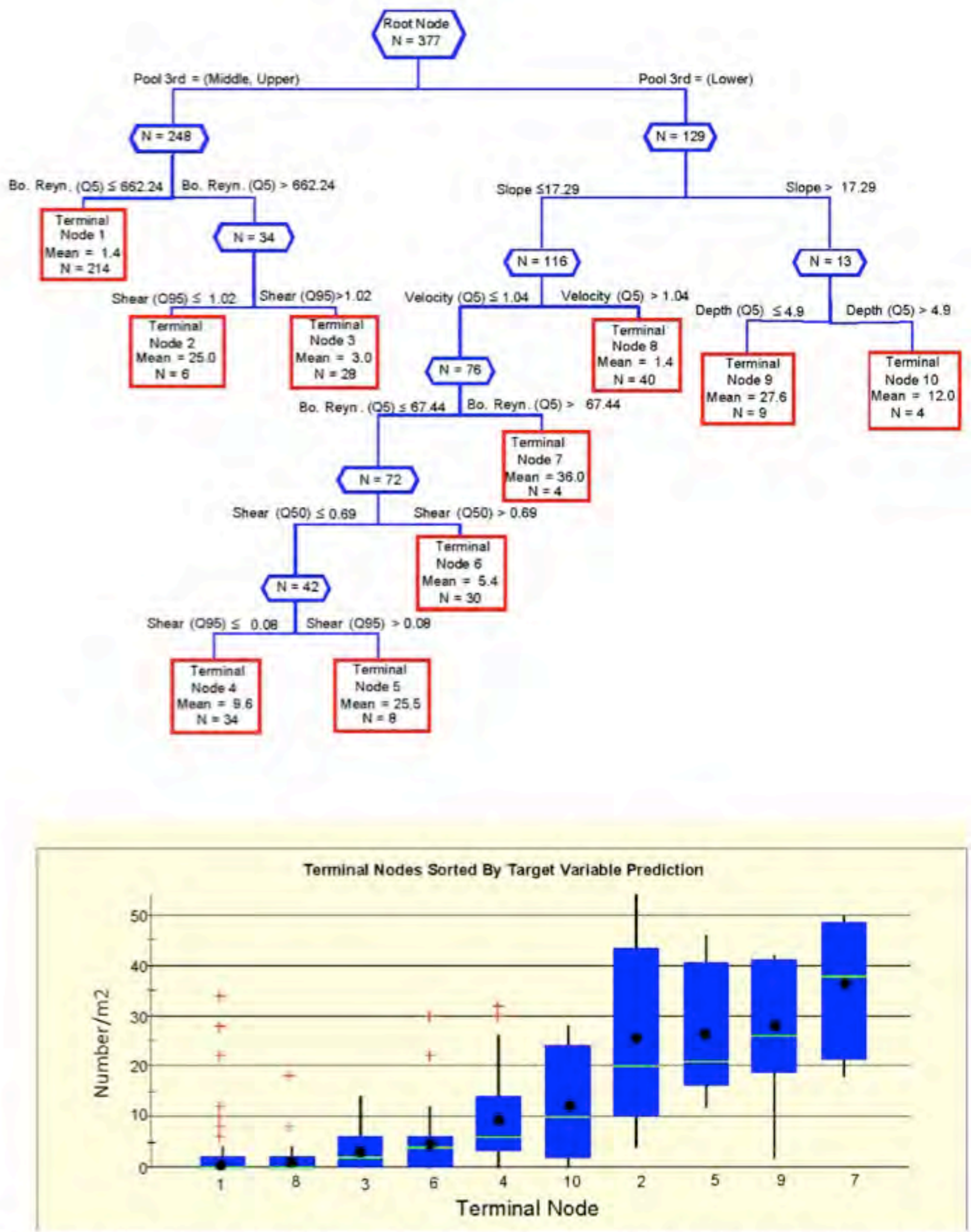


Figure 4. Regression tree model of mussel density in Pool 18. Models are read from the top down beginning at the root node, which contains all data. At each subsequent decision node, data that satisfy the splitting rule move into the branch below. Box and whisker plots are given for each terminal node of the model.

Tables and Figures from Zigler et al. 2010 (cont.)

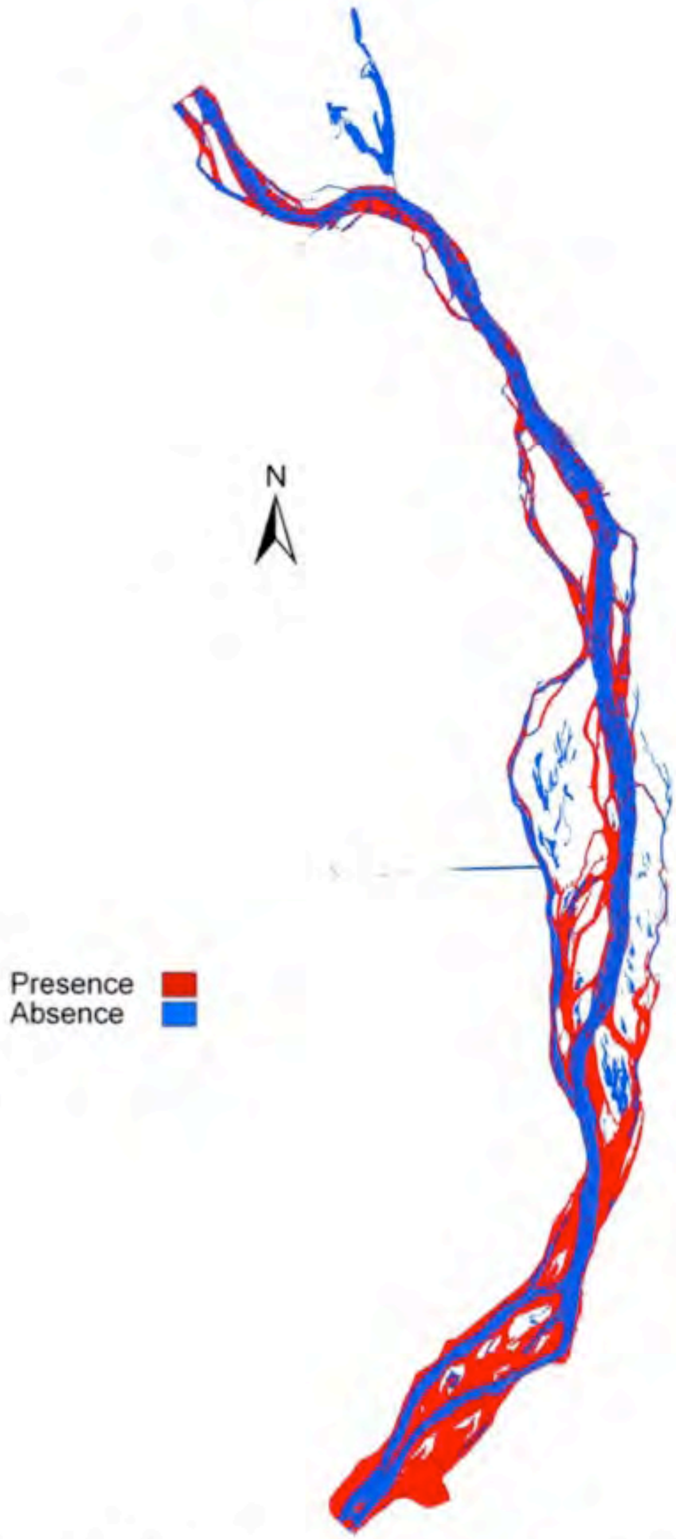


Figure 5. Geospatial model of the presence and absence of mussels in Pool 18, based on the classification tree model using only variables independent of substrate (Figure 1).

Tables and Figures from Zigler et al. 2010 (cont.)

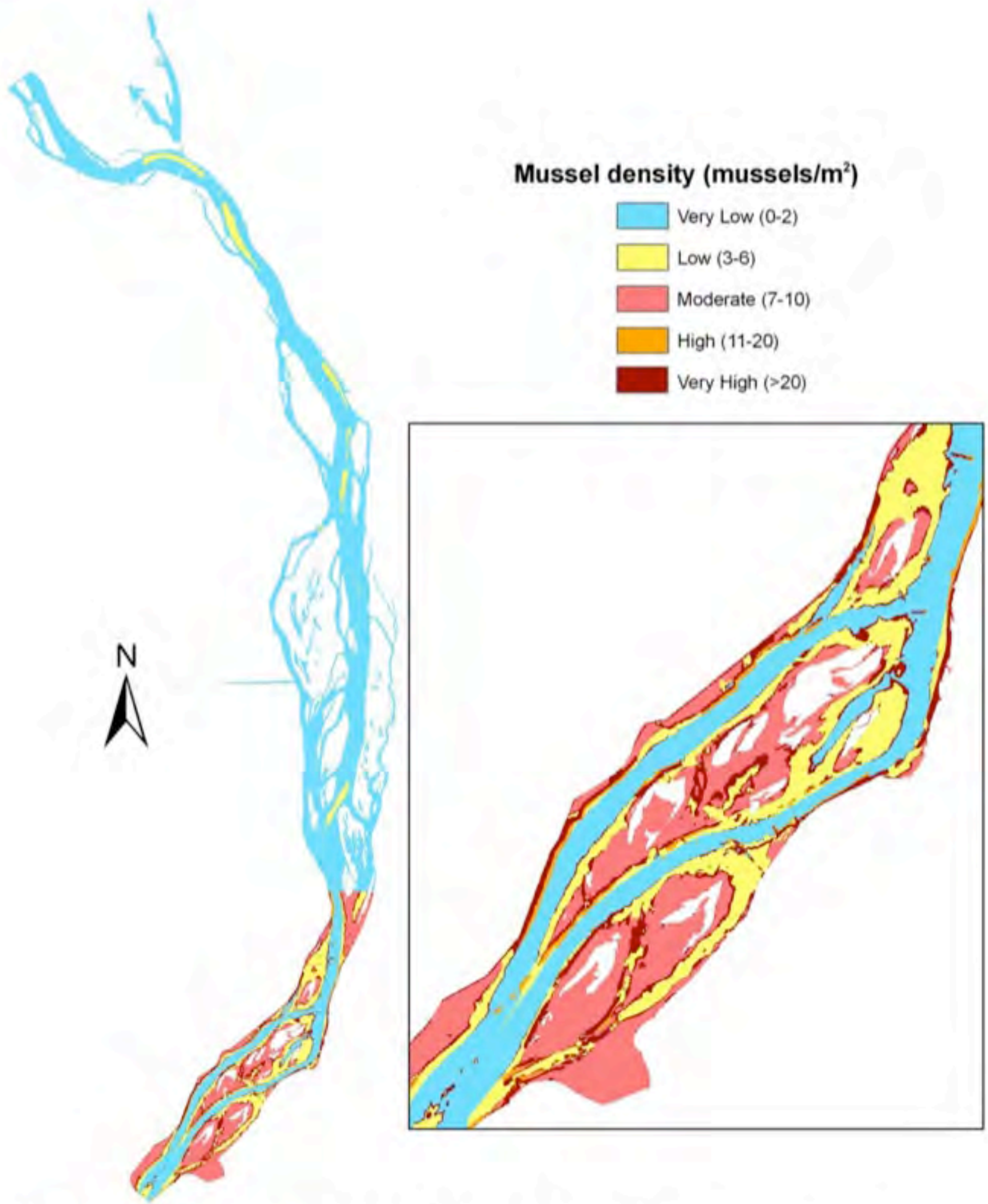


Figure 6. Geospatial model of the density of mussels in Pool 18, based on the regression tree model (Figure 4). Terminal nodes within each range are combined for visual clarity.

Appendix C. Tombigbee River gravel bar design (Miller, 1983).

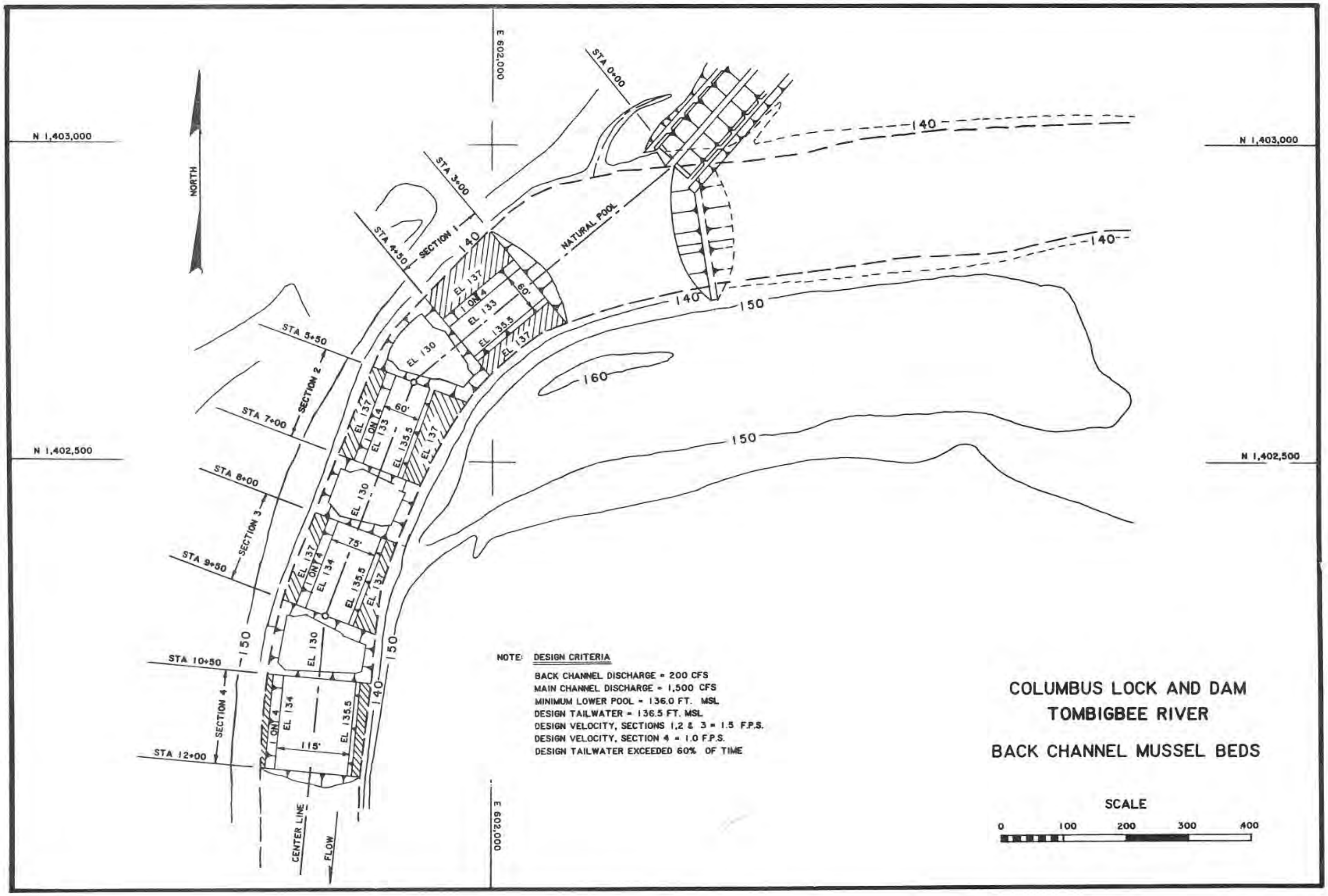


Figure 4. Design plans for proposed gravel bars, to be located at sections 1 through 4 of the bendway on the Tombigbee River

Table 1

Physical Characteristics of Proposed Gravel Bar Habitat

Parameter	Description			
	Bar I	Bar II	Bar III	Bar IV
Bar length, ft	150	150	150	150
Bar width, ft	175	175	175	175
Channel width, ft	60	60	75	115
Channel depth, ft	1.5-3.9	1.5-3.9	1.5-2.9	1.5-2.9
Gravel depth, in. (% composition)	1-5 (80)	1-3 (60)	1-3 (40)	1-3 (20)
Sand, % composition	20	40	60	80
Water velocity, fps	1.5	1.5	1.5	1.0

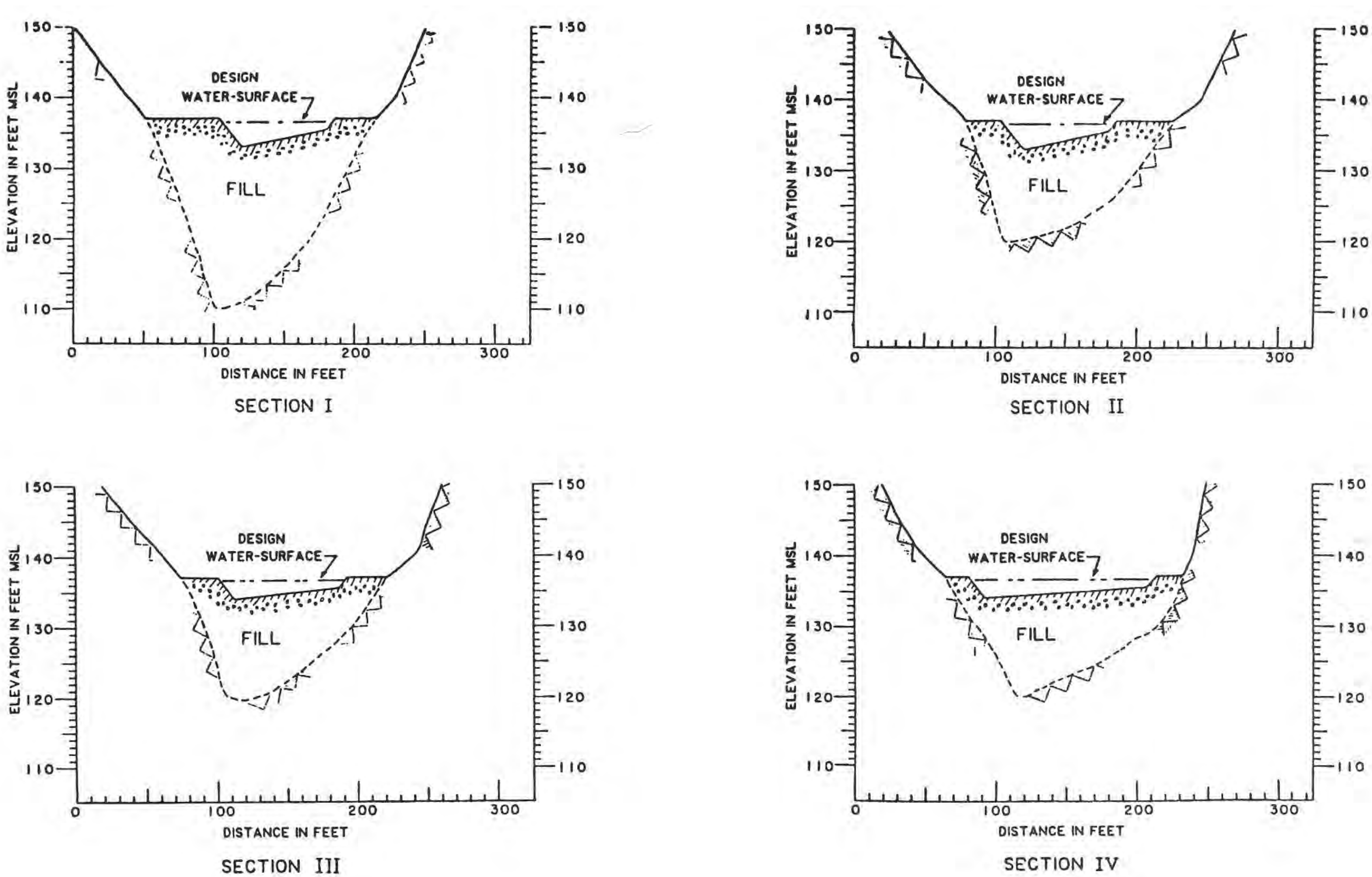


Figure 5. Transverse sections of proposed gravel bars

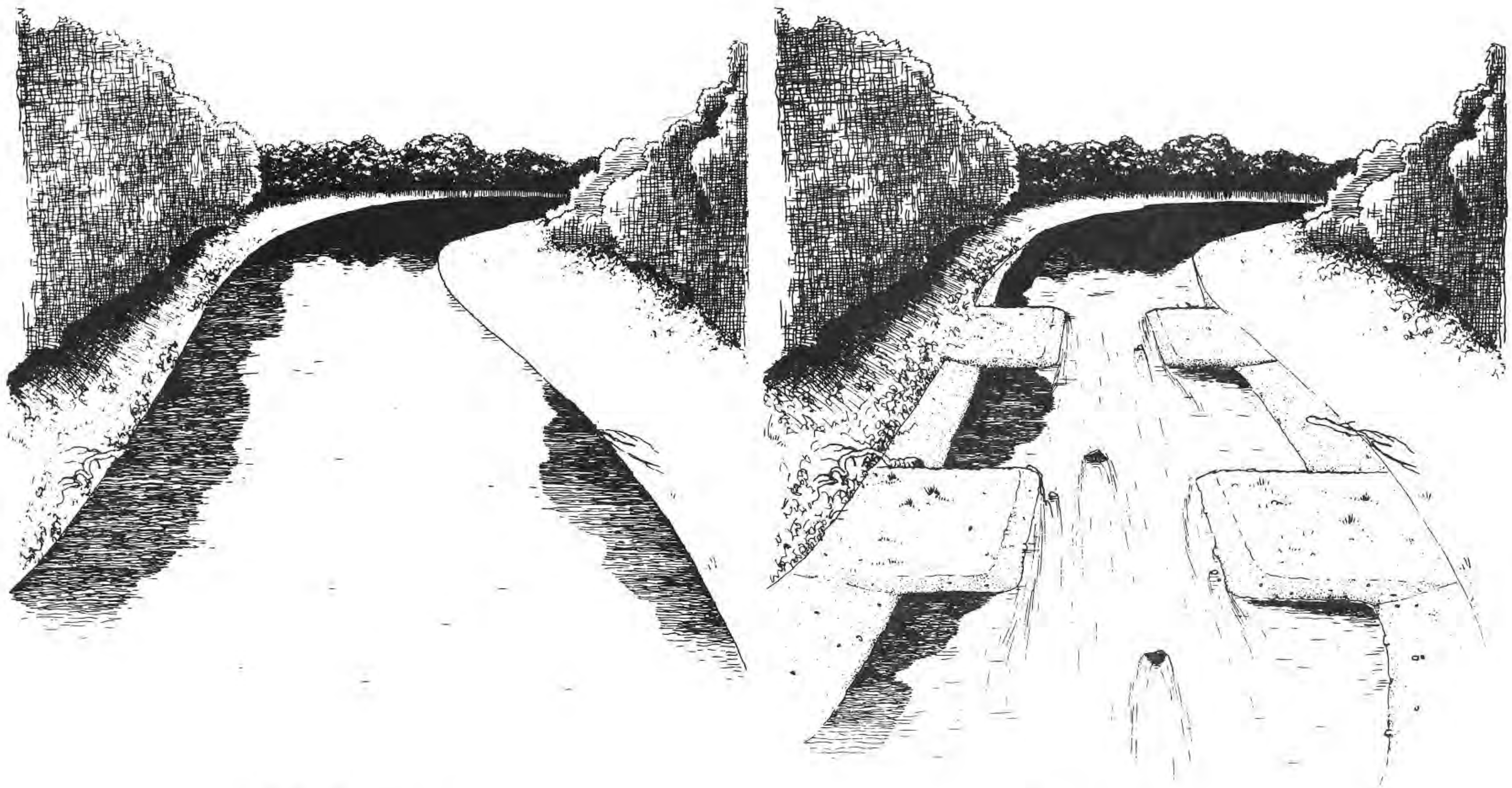
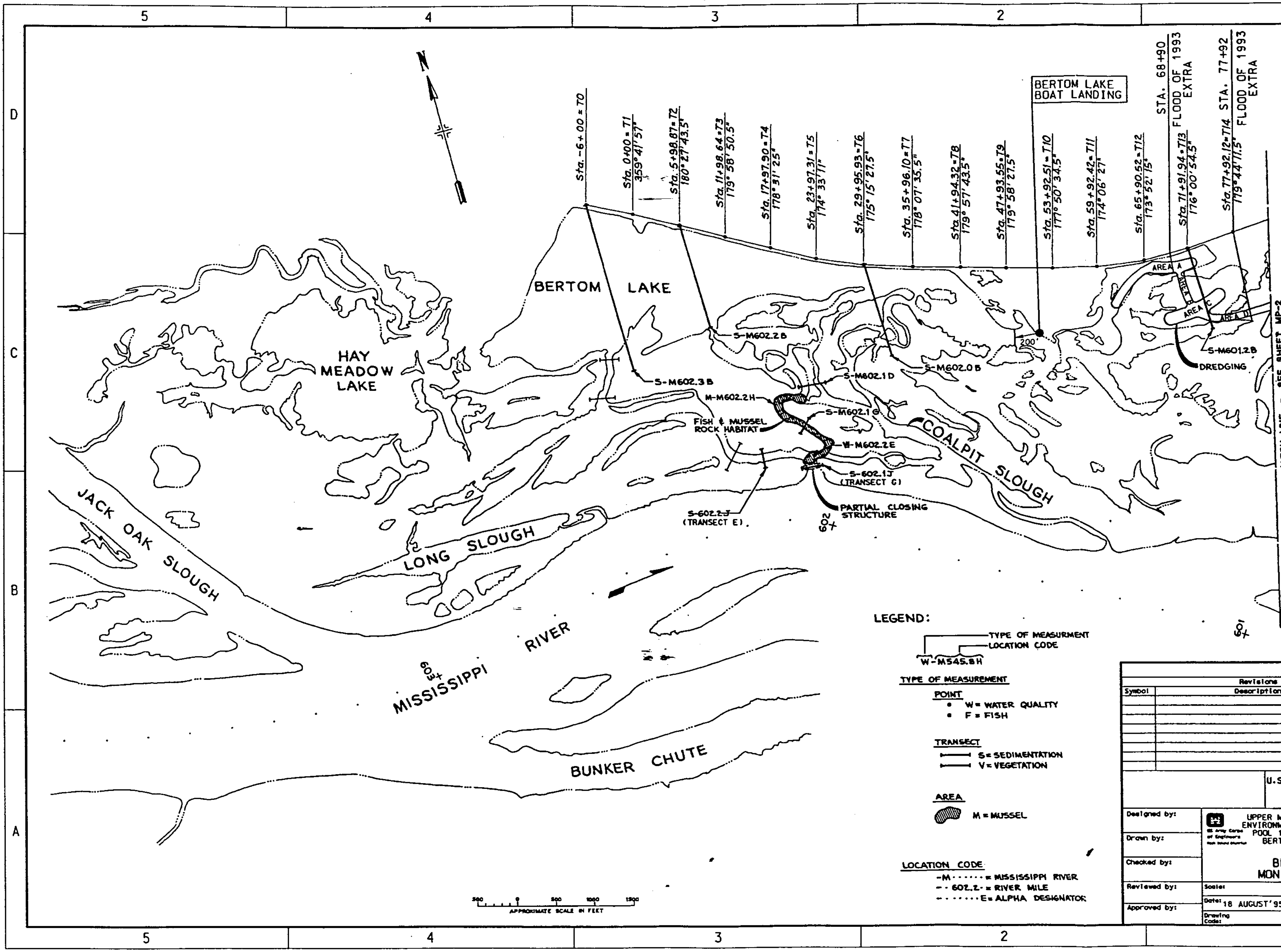


Figure 6. Artist's conception of the response of bars I and II to conditions of high water (little or no flow) and normal-to-low water (water restricted to the channel across the bar). Mussels and other nonmotile organisms will inhabit the channels (visible at low water) across the gravel bar

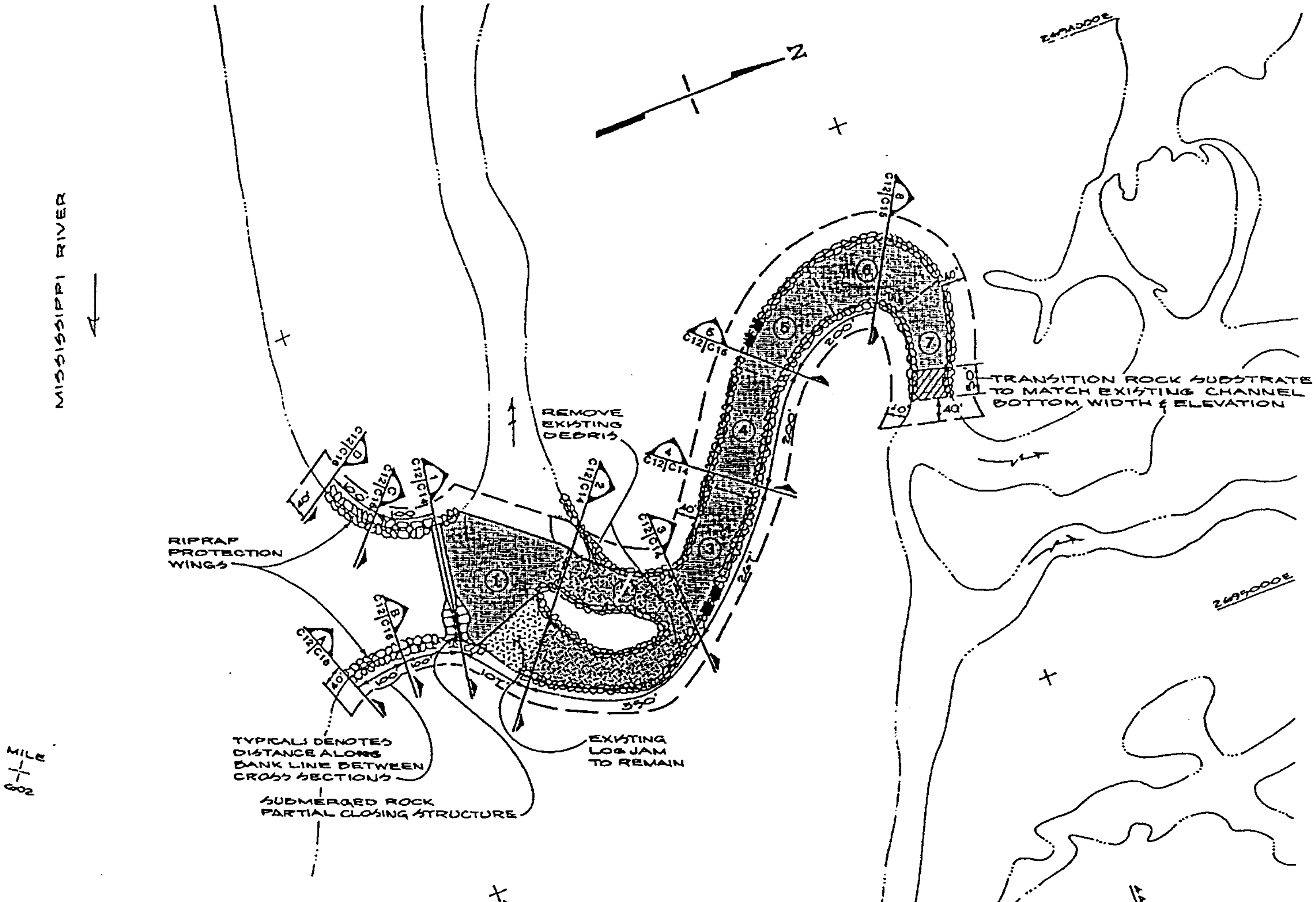
Figure 1. Gravel bar habitat in the upper end of an abandoned channel of the Tombigbee River, Mississippi, immediately after construction, 1985

Extracted from Miller (2006)

Appendix D. Bertom-McCartney Lakes HREP gravel bar design (USACE, 1996).



BERTOM LAKE BOAT LANDING
STA. 68+90
FLOOD OF 1993 EXTRA
STA. 77+92
FLOOD OF 1993 EXTRA
Sta. -6+00 = T0
Sta. 0+00 = T1 359° 41' 57"
Sta. 5+98.87 = T2 180° 27' 43.5"
Sta. 11+98.64 = T3 179° 58' 50.5"
Sta. 17+97.90 = T4 178° 31' 25"
Sta. 23+97.31 = T5 174° 33' 11"
Sta. 29+95.93 = T6 175° 15' 27.5"
Sta. 35+96.10 = T7 178° 07' 35.5"
Sta. 41+94.32 = T8 179° 57' 43.5"
Sta. 47+93.55 = T9 179° 58' 27.5"
Sta. 53+92.51 = T10 177° 50' 34.5"
Sta. 59+92.42 = T11 174° 06' 27"
Sta. 65+90.52 = T12 173° 52' 15"
Sta. 71+91.94 = T13 176° 00' 54.5"
Sta. 77+92.12 = T14 179° 44' 11.5"
AREA A
AREA B
AREA C
AREA D
200'
S-M601.2B
DREDGING
BERTOM LAKE
HAY MEADOW LAKE
S-M602.2B
S-M602.3B
S-M602.0B
S-M602.1D
M-M602.2H
S-M602.1G
W-M602.2E
FISH & MUSSEL ROCK HABITAT
S-602.1J (TRANSECT G)
S-602.2J (TRANSECT E)
PARTIAL CLOSING STRUCTURE
COALPIT SLOUGH
JACK OAK SLOUGH
LONG SLOUGH
MISSISSIPPI RIVER
BUNKER CHUTE
601
602
603
LEGEND:
TYPE OF MEASURMENT
LOCATION CODE
W-M545.8H
TYPE OF MEASUREMENT
POINT
W = WATER QUALITY
F = FISH
TRANSECT
S = SEDIMENTATION
V = VEGETATION
AREA
M = MUSSEL
LOCATION CODE
-M- = MISSISSIPPI RIVER
602.2 = RIVER MILE
E = ALPHA DESIGNATOR
500 0 500 1000 1500
APPROXIMATE SCALE IN FEET
Revisions
Symbol
Description
Designed by:
Drawn by:
Checked by:
Reviewed by:
Approved by:
US Army Corps of Engineers
Scale:
Date: 18 AUGUST'95
Drawing Code:
D
C
B
A
5
4
3
2



SITE PLAN

SCALE: 100 0' 100 200

LEGEND:

- ② CHANNEL SEGMENT NO. 2
- ROCK SUBSTRATE MATERIAL
- EXISTING LOG JAM AND DEBRIS (LOCATION APPROXIMATE)
- BANK PROTECTION MATERIAL
- ■ SUBMERGED TIMBER HABITAT STRUCTURE
- — — CONTRACTOR WORK LIMITS

CONCRETE PIPE SCHEDULE

QUANTITY	DIAMETER	LENGTH
8	12"	6'
8	24"	6'
8	36"	6'

SEE SHEET C-13 FOR INSTALLATION DETAIL OF CONCRETE PIPE FISH HABITAT STRUCTURES.

ROCK HABITAT CHANNEL CONSTRUCT

CHANNEL SEGMENT NUMBER	MINIMUM EXCAVATION ELEVATION	ROCK SUBSTRATE GRADATION	ROCK SUBSTRATE THICKNESS	BANK PROTECTION GRADATION
1	597.0	A	24"	A
2	596.0	F	12"	B
3	598.0	C	12"	B
4	596.0	D	12"	B
5	596.0	E1	12"	B
6	596.0	E2	12"	B
7	597.5	B	18"	B

NOTES:

1. CHANNEL SEGMENT LENGTH IS AS M ALONG THE LONGITUDINAL CENTE THE SEGMENT.
2. LOCATIONS FOR THE CONCRETE PI HABITAT STRUCTURES WILL BE AS DI BY THE C.O.R.
3. ALL CONCRETE PIPE WILL BE FU BY THE GOVERNMENT.

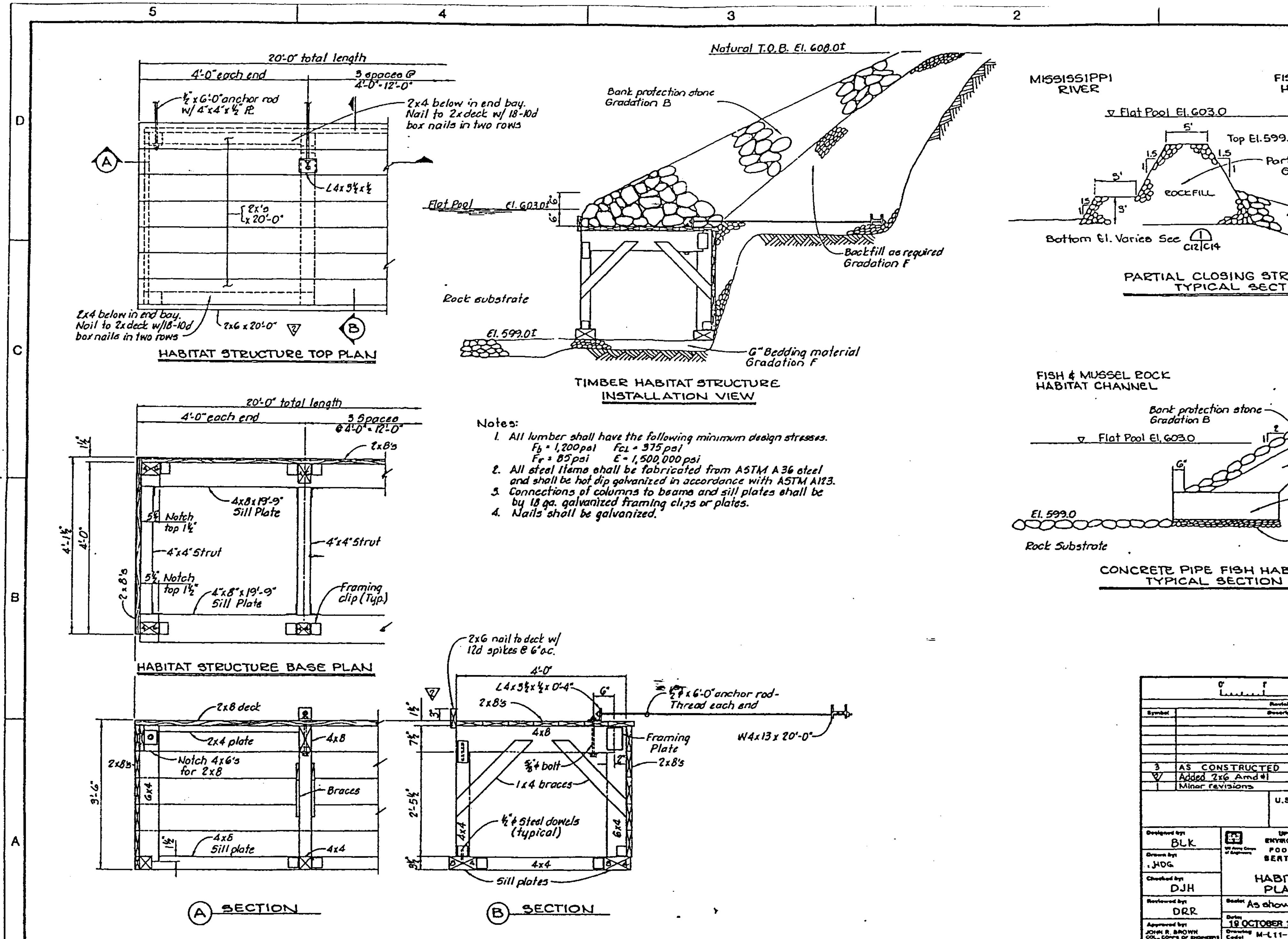
Symbol	Description
2	REVISED AS CONSTRU
1	MINOR REVISIONS

U.S.

Designed by: BLK
Drawn by: bly
Checked by: DJH
Reviewed by: DRR
Approved by: JOHN R. BROWN COL., CORPS OF ENGINEERS

UP ENVIRO POO BERT
ROCK

Scale: AS SHOWN
Date: 19 OCTOBER 19
Drawing Code: M-L11-1



Notes:

1. All lumber shall have the following minimum design stresses.
   F_b = 1,200 psi $F_{c\perp}$ = 375 psi
   F_v = 85 psi E = 1,500,000 psi
2. All steel items shall be fabricated from ASTM A 36 steel and shall be hot dip galvanized in accordance with ASTM A123.
3. Connections of columns to beams and sill plates shall be by 18 ga. galvanized framing clips or plates.
4. Nails shall be galvanized.

Appendix E. Pool 8 HREP mussel habitat design (WDNR).

Figure 1. Proposed features and locations for enhancement/creation of freshwater mussel habitat in the Pool 8 Islands Phase III West area, Mississippi River, Pool 8.

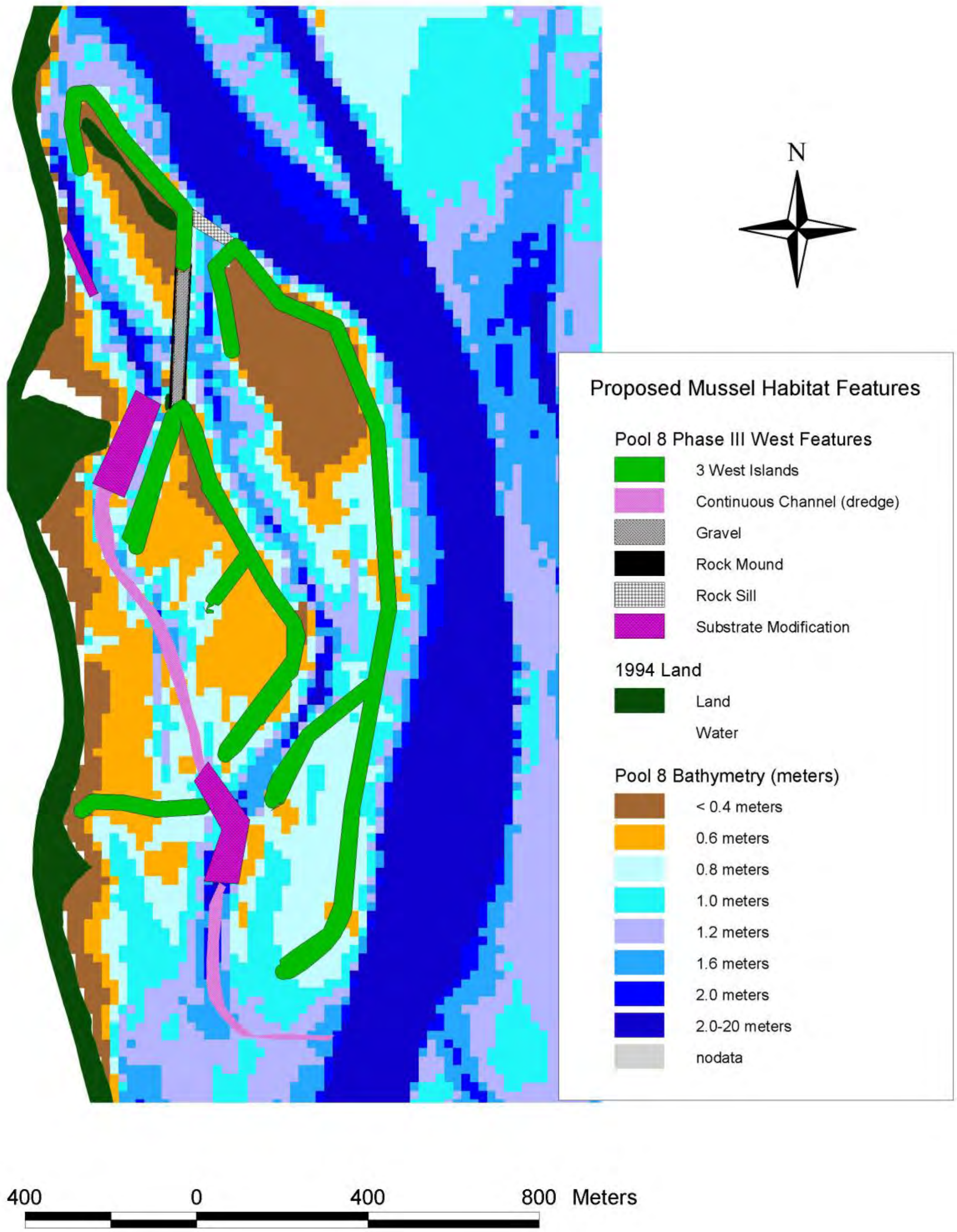


Figure 2. Gravel Comma, cross section view.

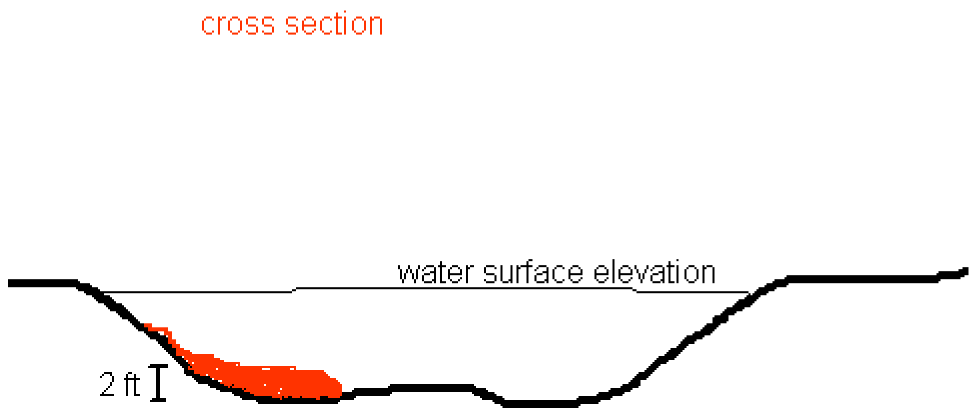
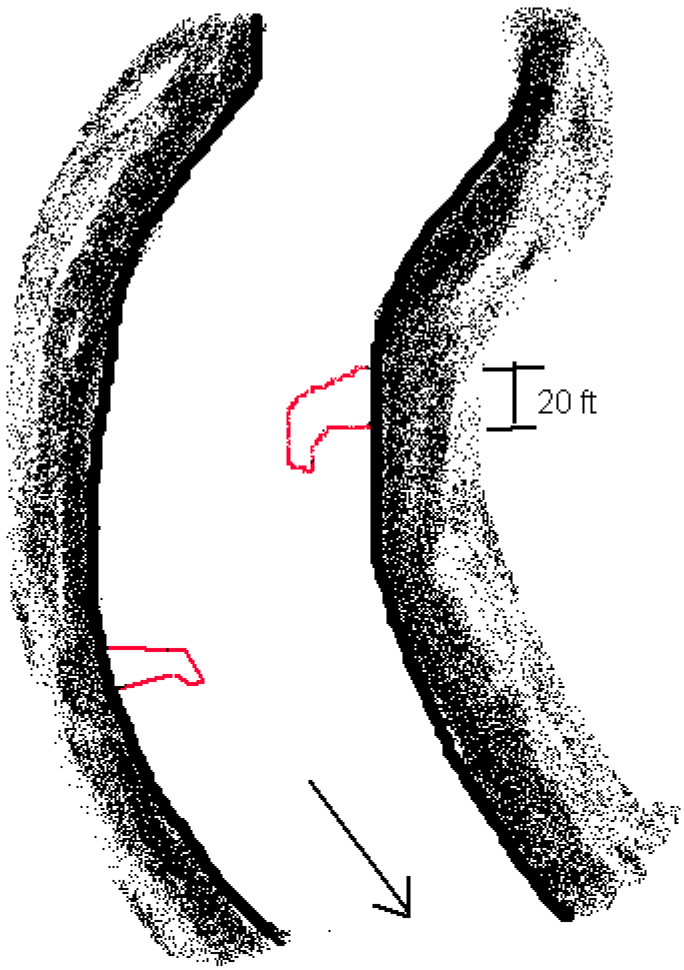
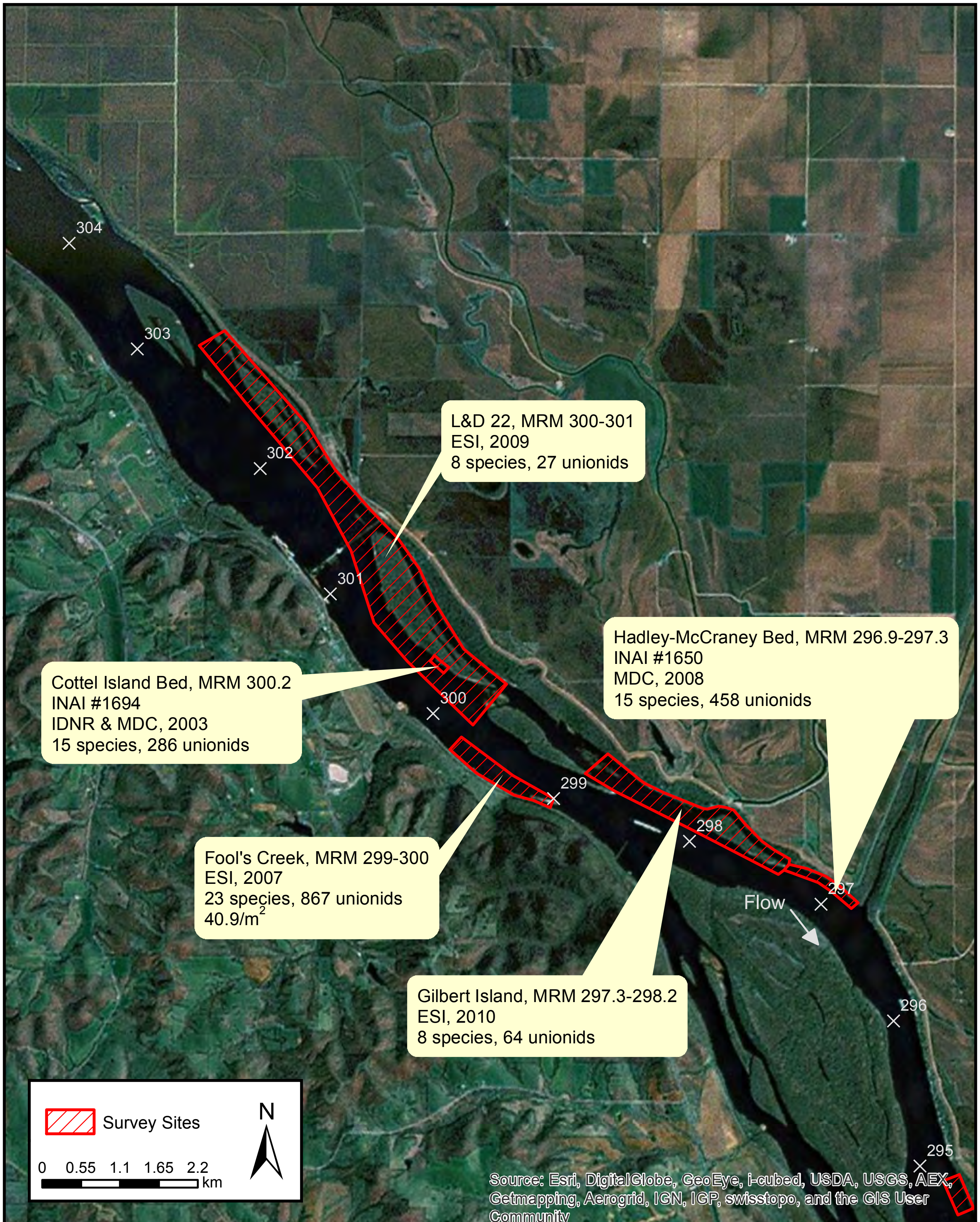


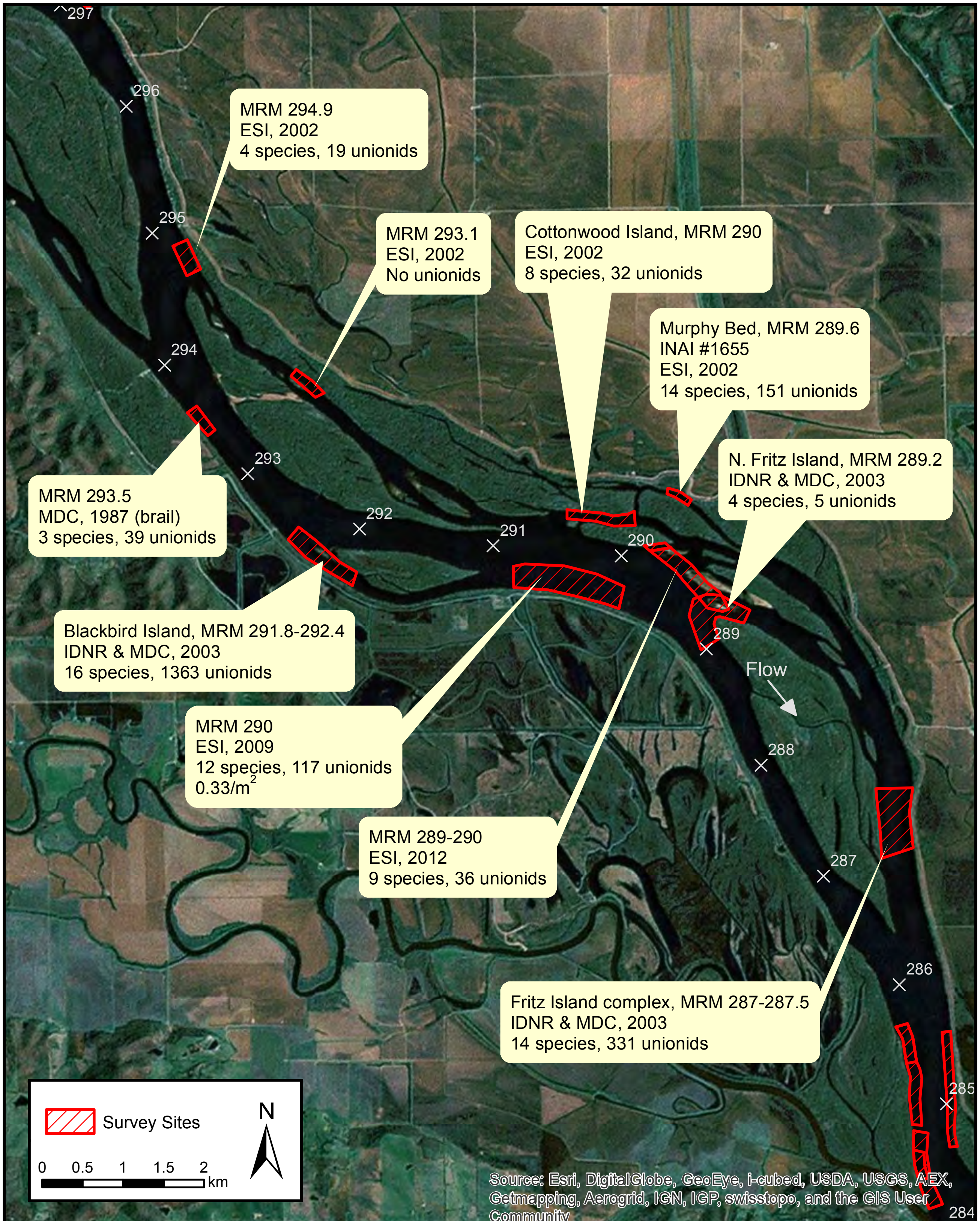
Figure 3. Gravel Comma, top view.



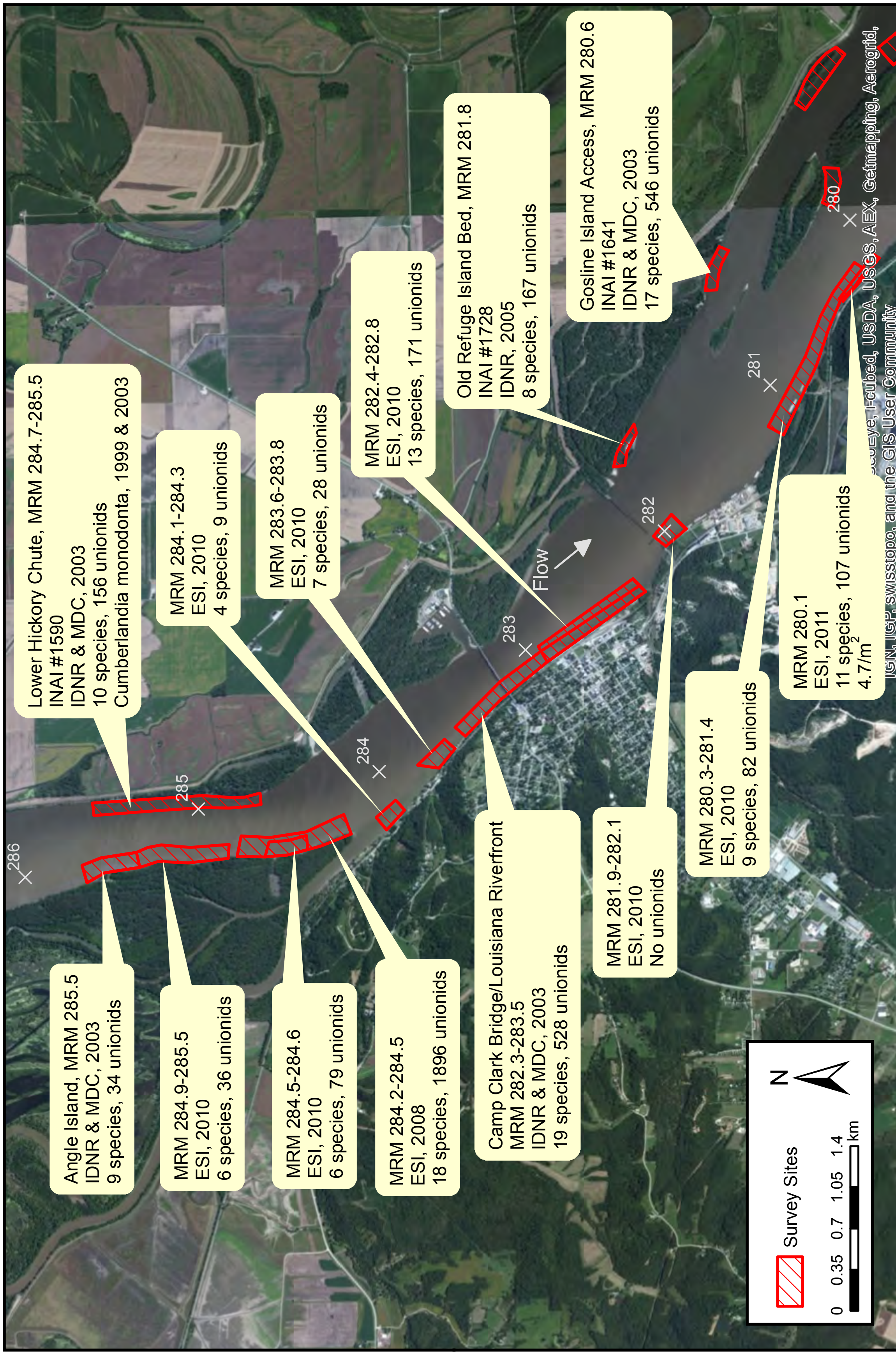
Appendix F. Post 2000 unionid abundance in SLD-UMR.



ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Mississippi River miles 295-305, 2000 to 2012.	ESI



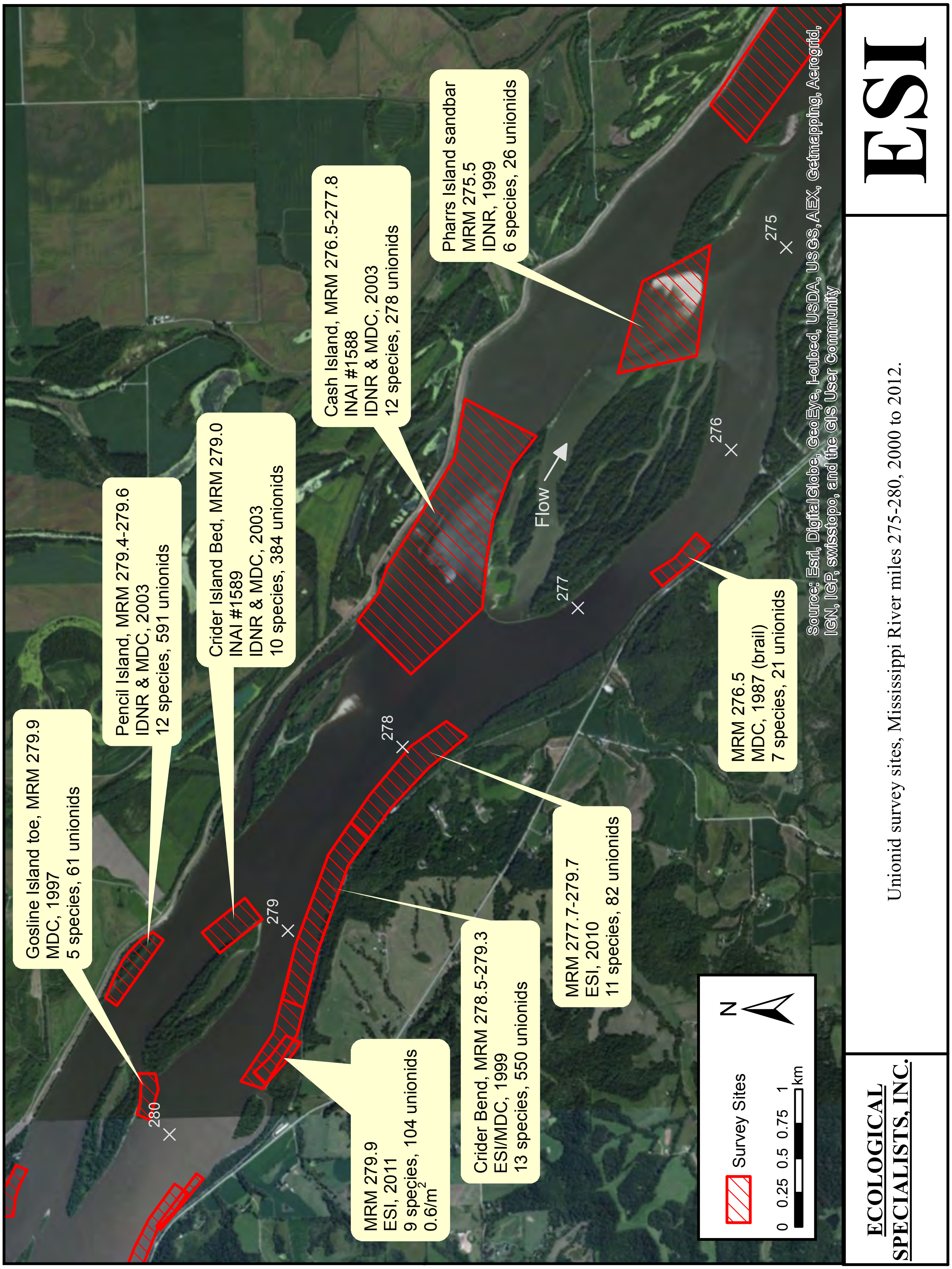
ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Mississippi River miles 285-295, 2000 to 2012.	ESI



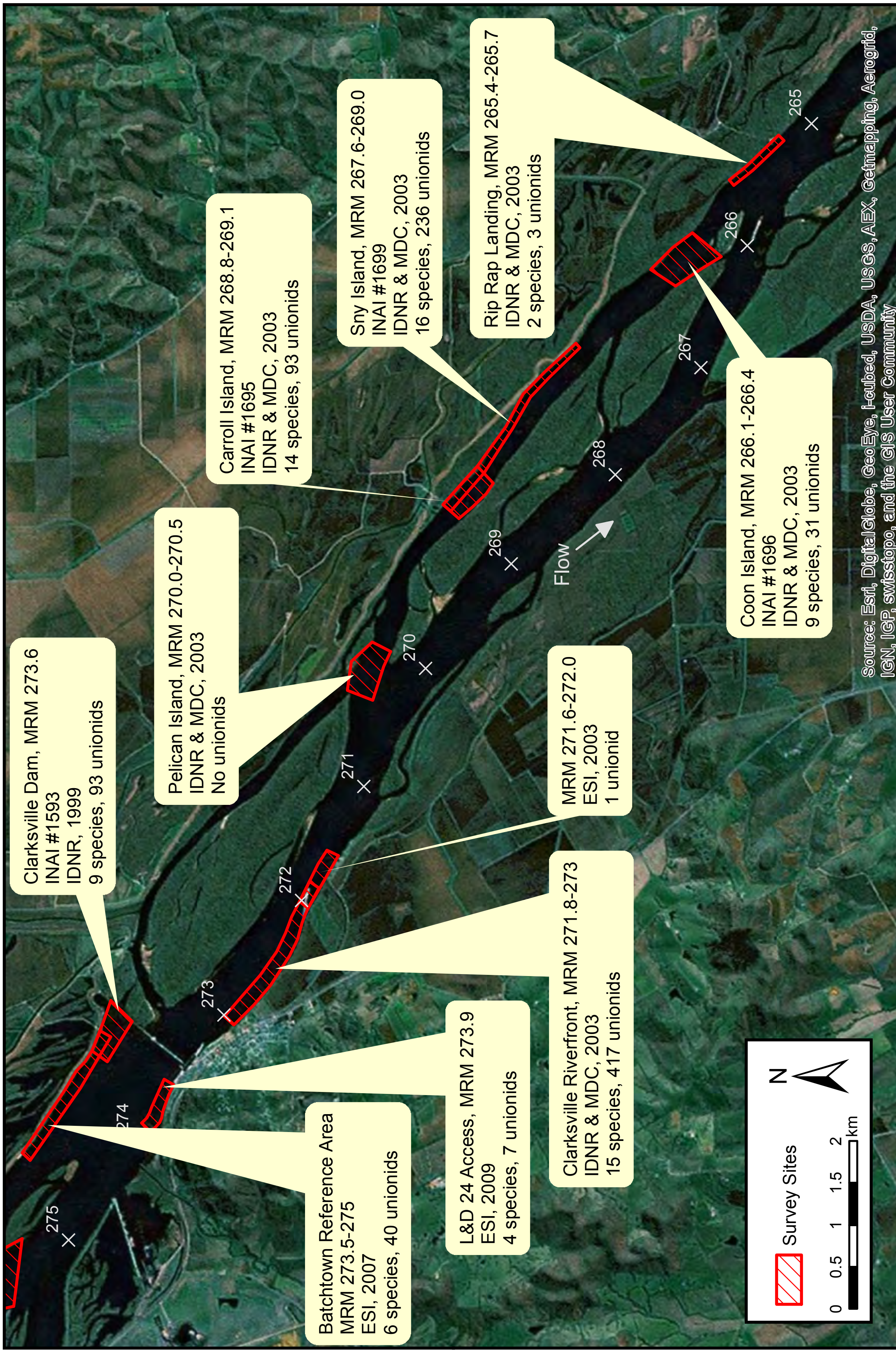
Unionid survey sites, Mississippi River miles 280-285, 2000 to 2012.

ESI

ECOLOGICAL SPECIALISTS, INC.



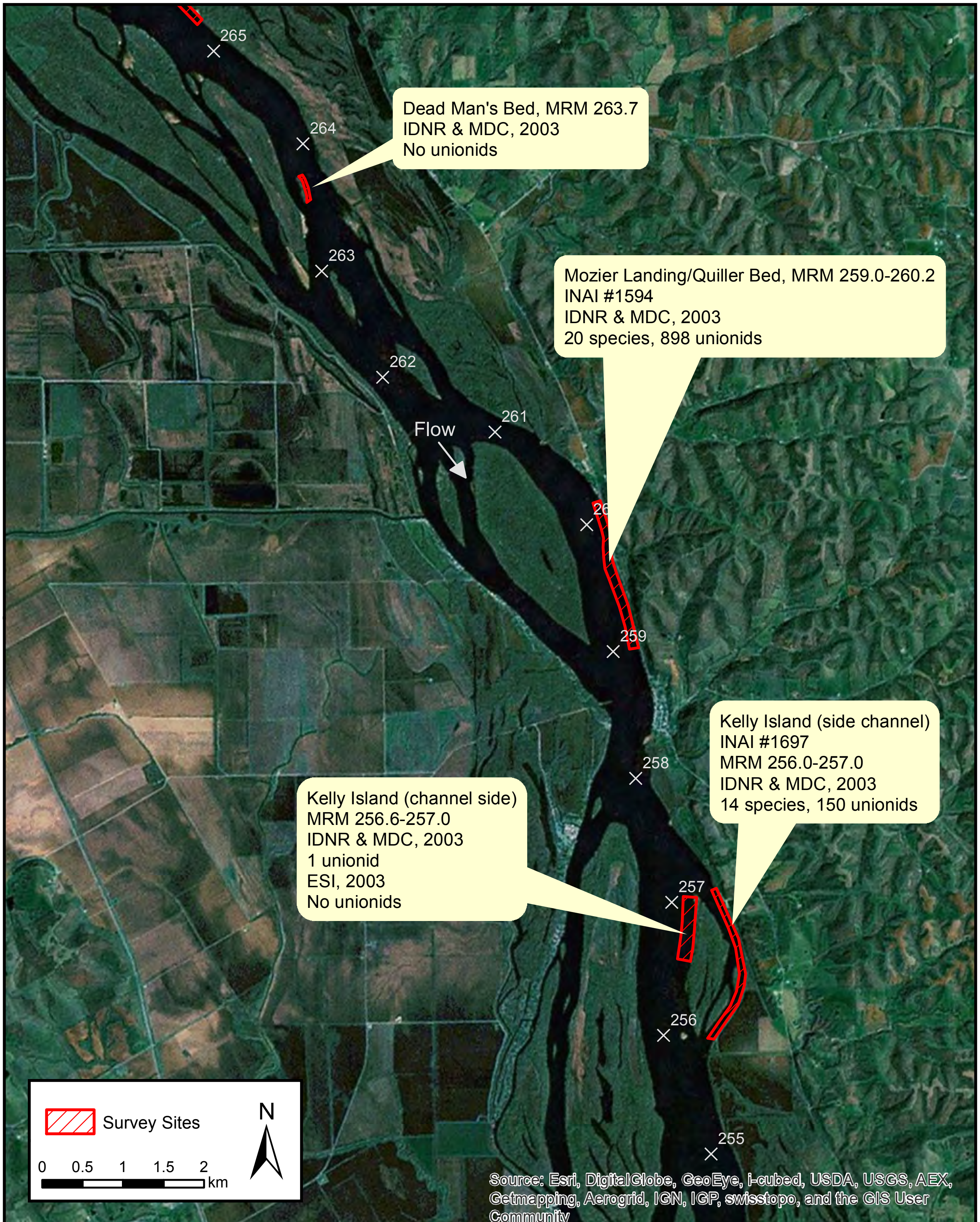
Unionid survey sites, Mississippi River miles 275-280, 2000 to 2012.



ECOLOGICAL SPECIALISTS, INC.

Unionid survey sites, Mississippi River miles 265-275, 2000 to 2012.

ESI



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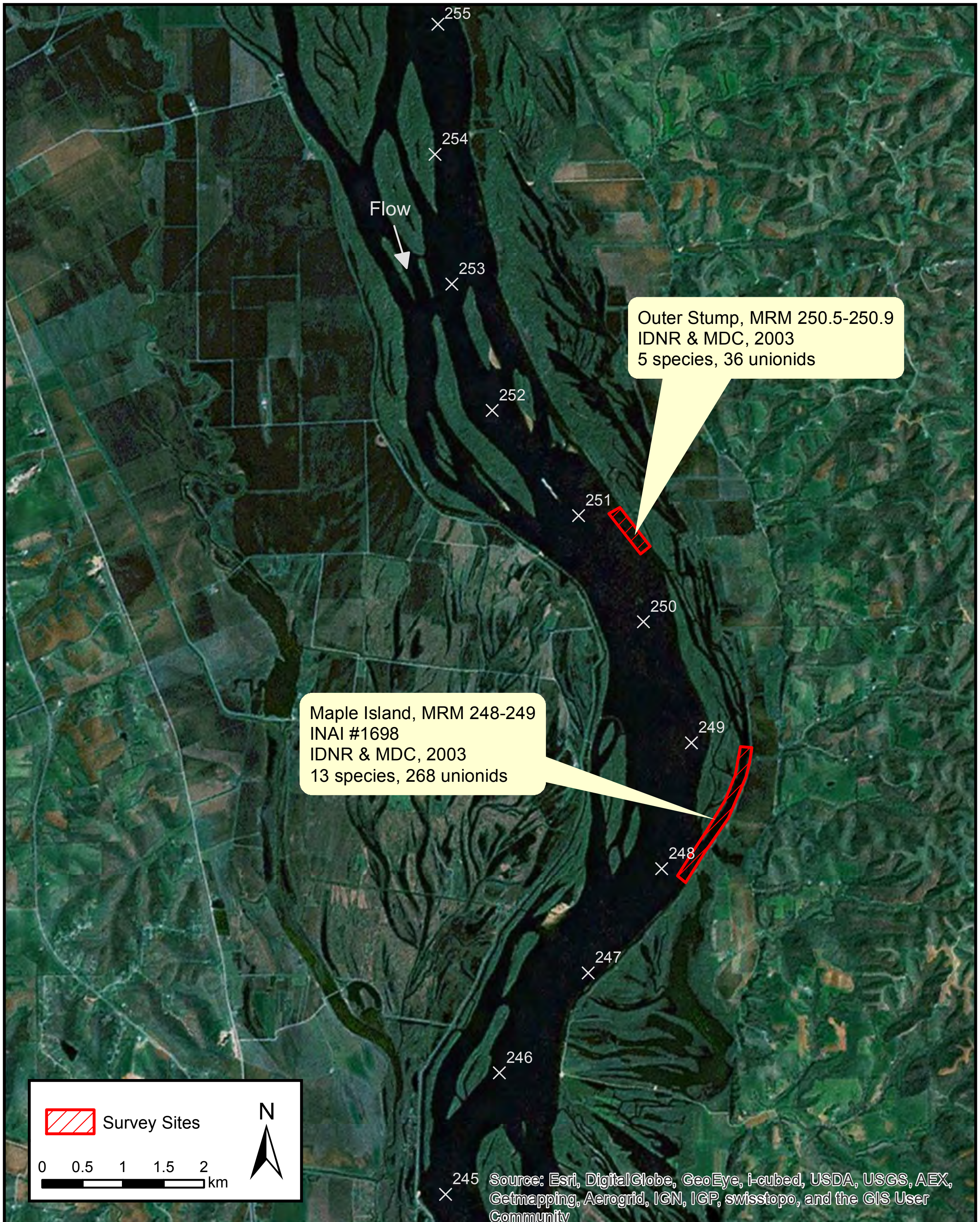

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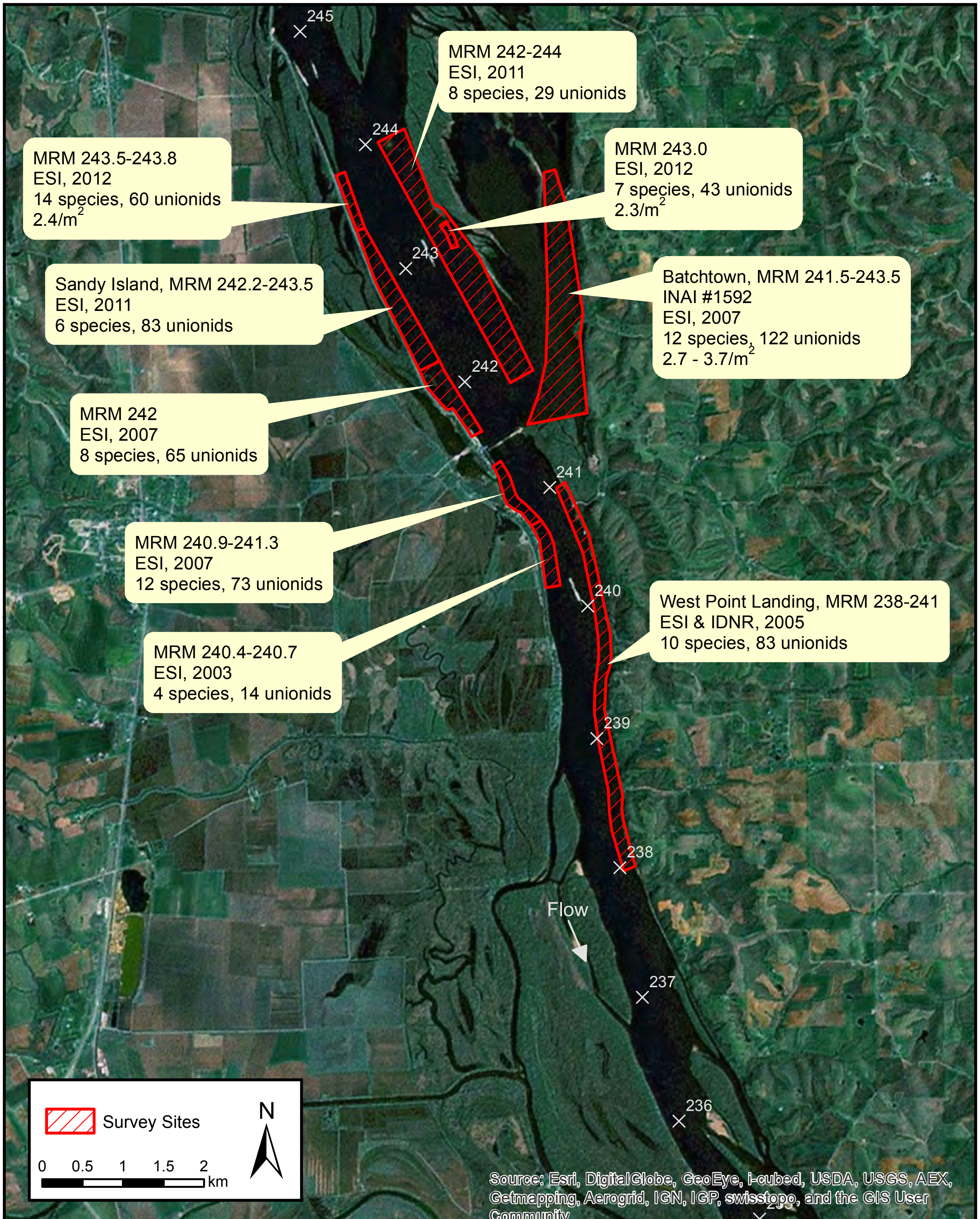

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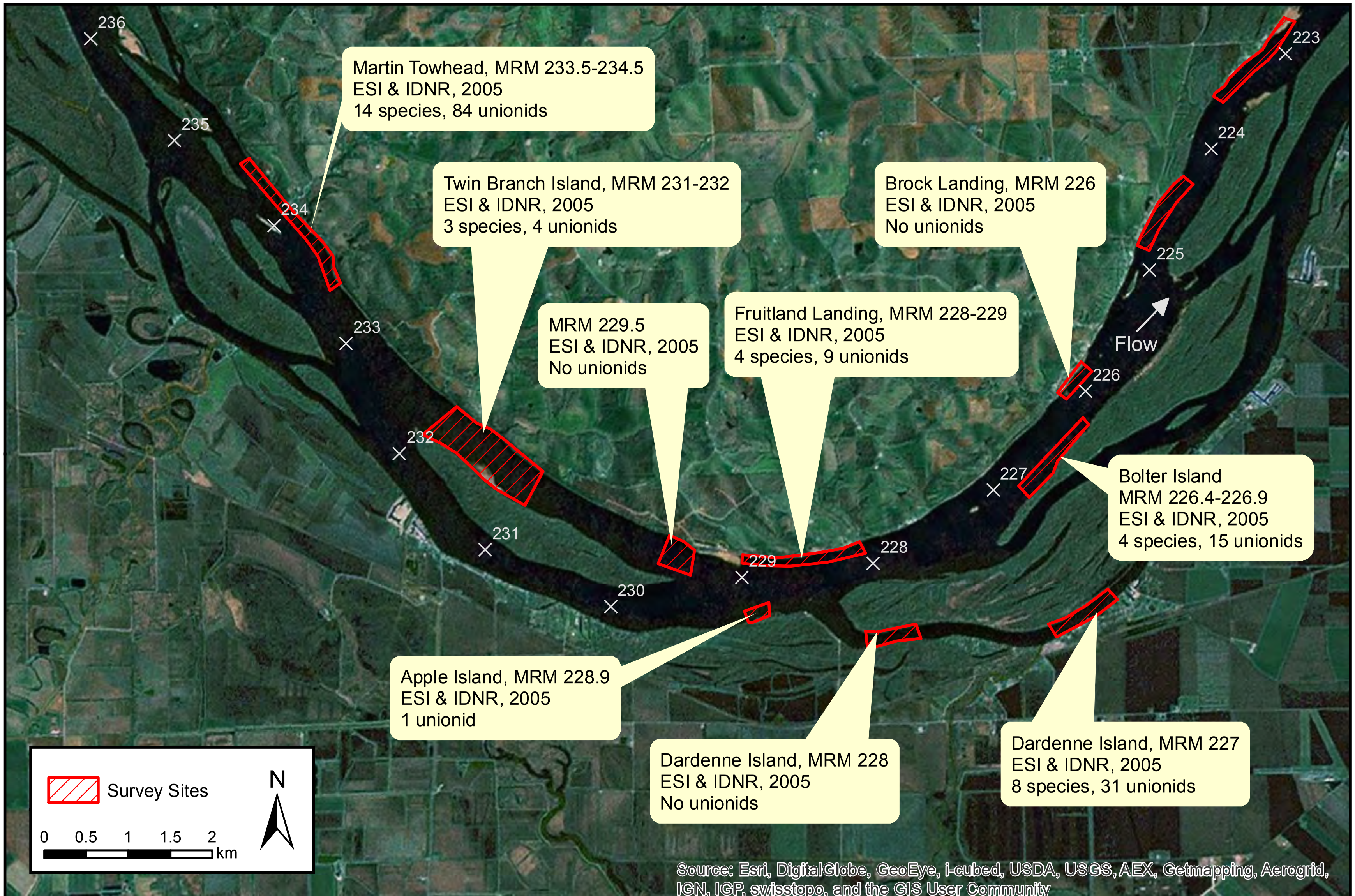
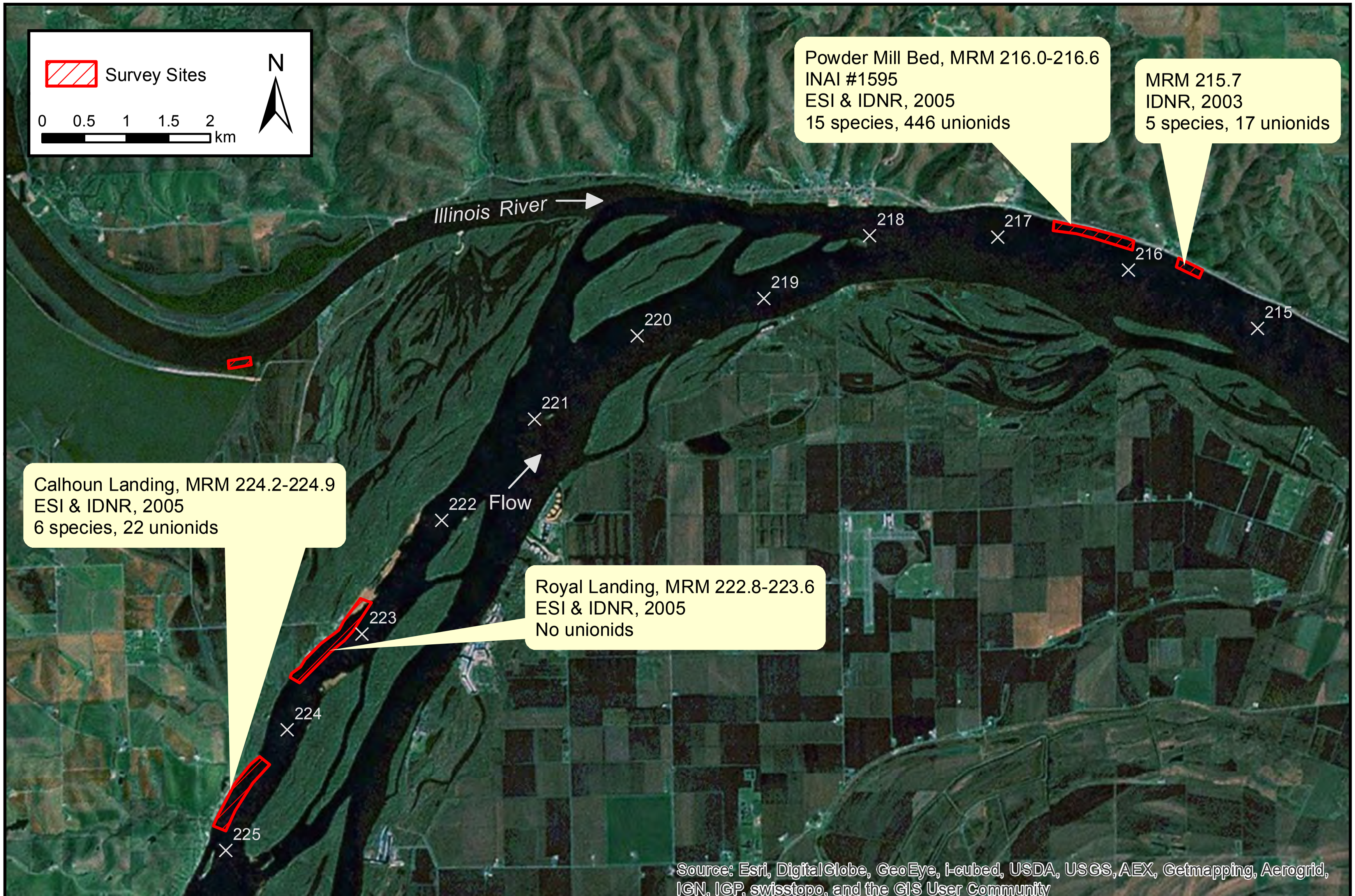


ECOLOGICAL SPECIALISTS, INC.

Unionid survey sites, Mississippi River miles 225-235, 2000 to 2012.

ESI



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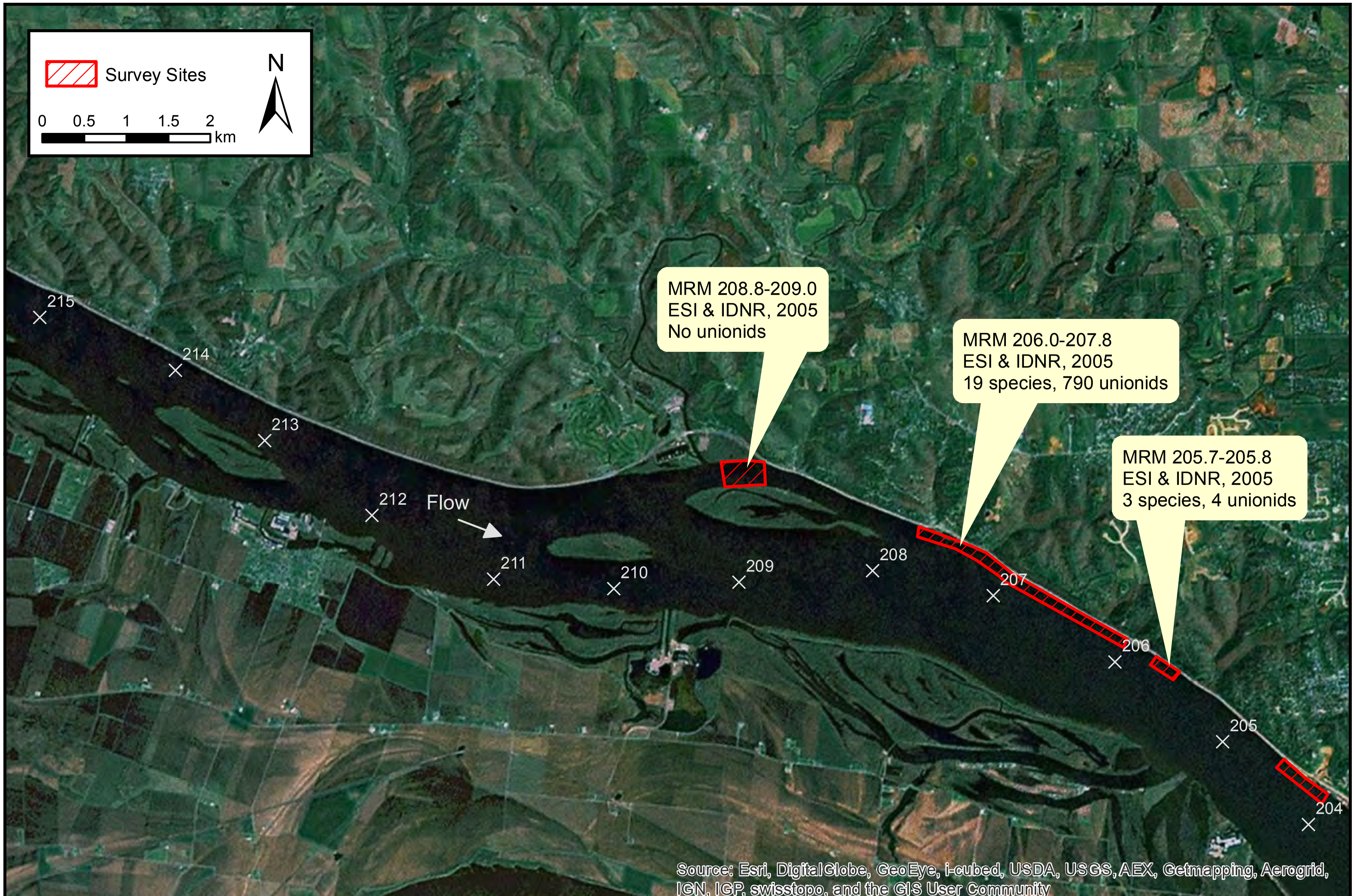
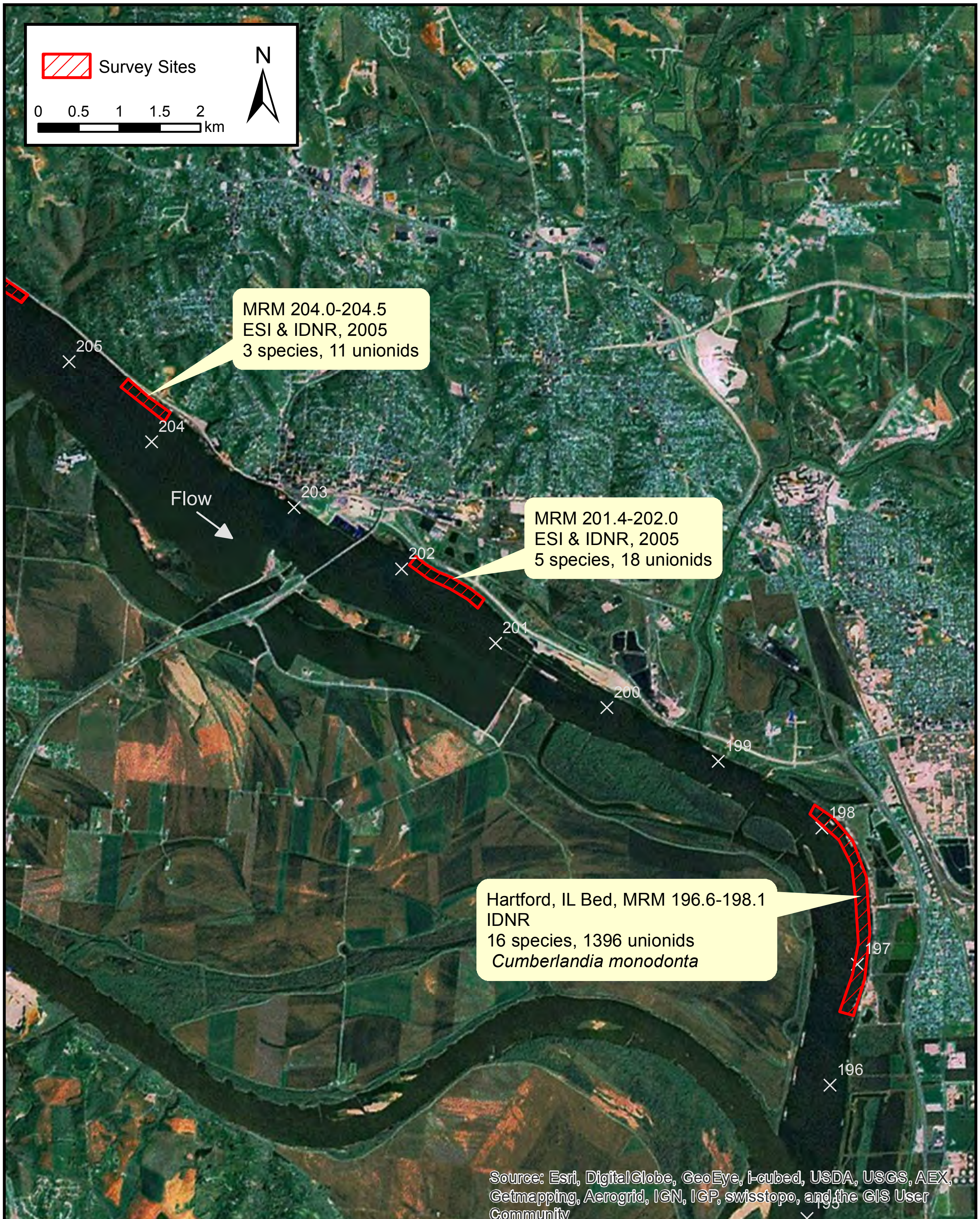


ECOLOGICAL SPECIALISTS, INC.

Unionid survey sites, Mississippi River miles 205-215, 2000 to 2012.

ESI



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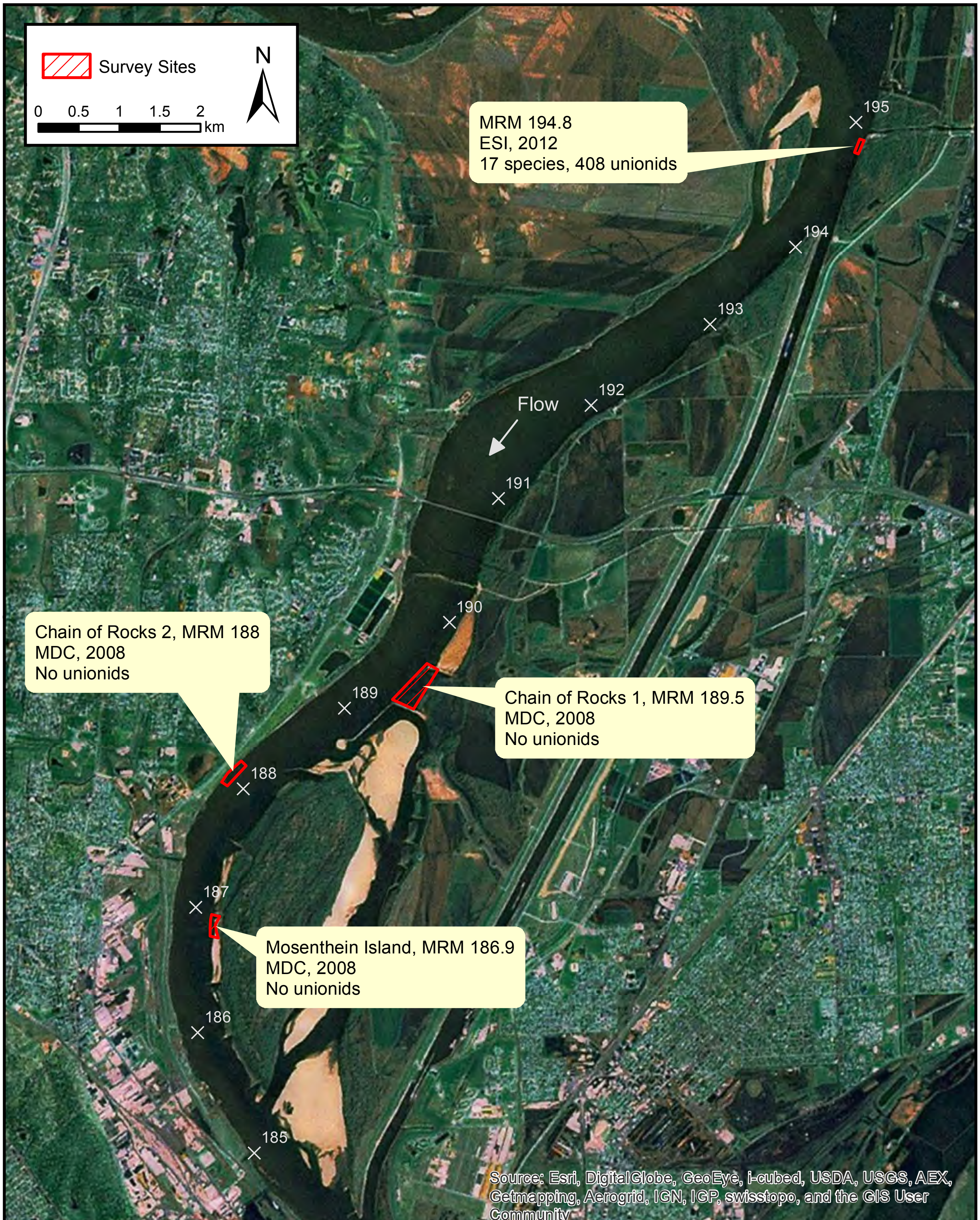
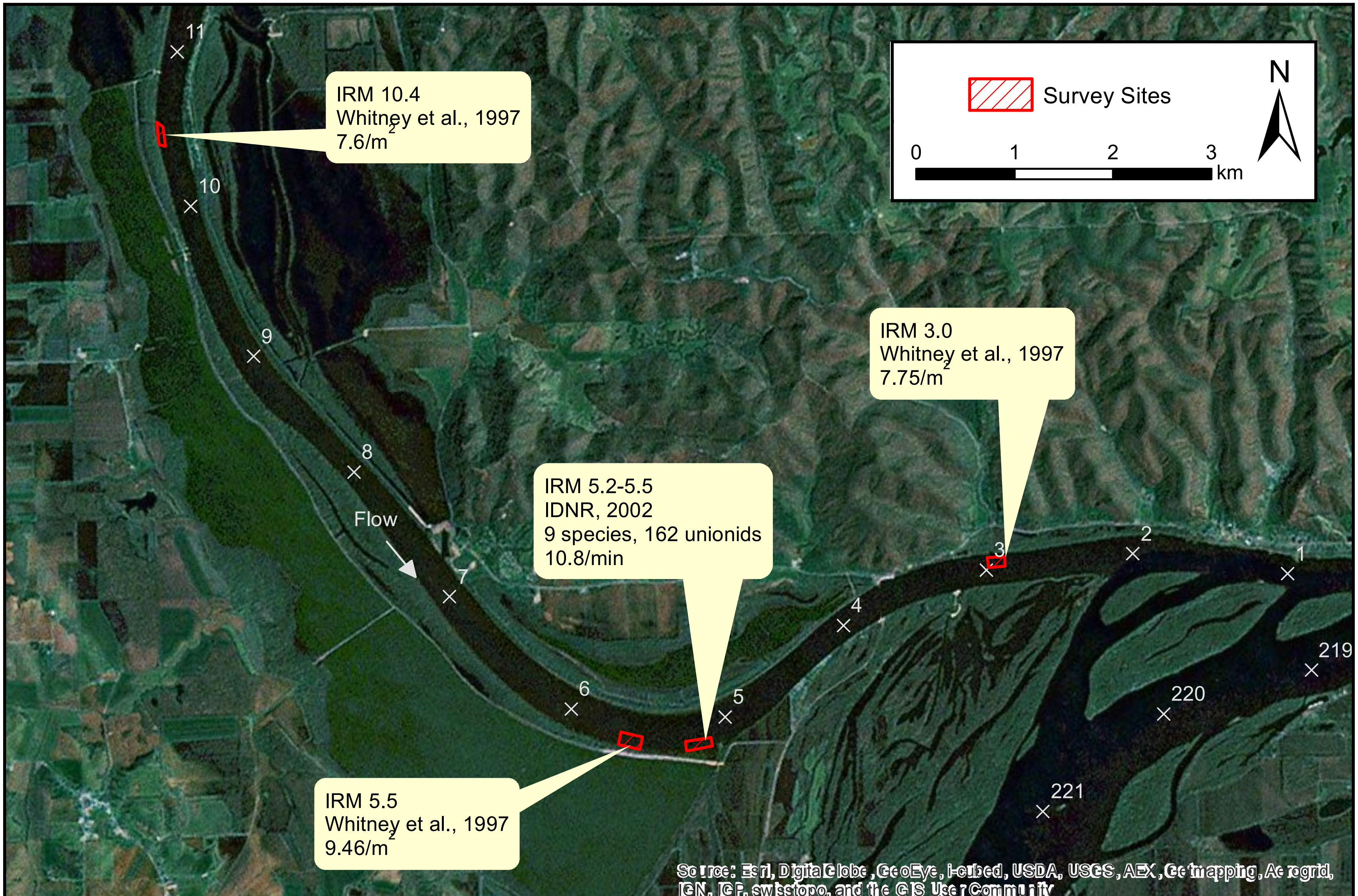


ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Mississippi River miles 185-195, 2000 to 2012.	ESI

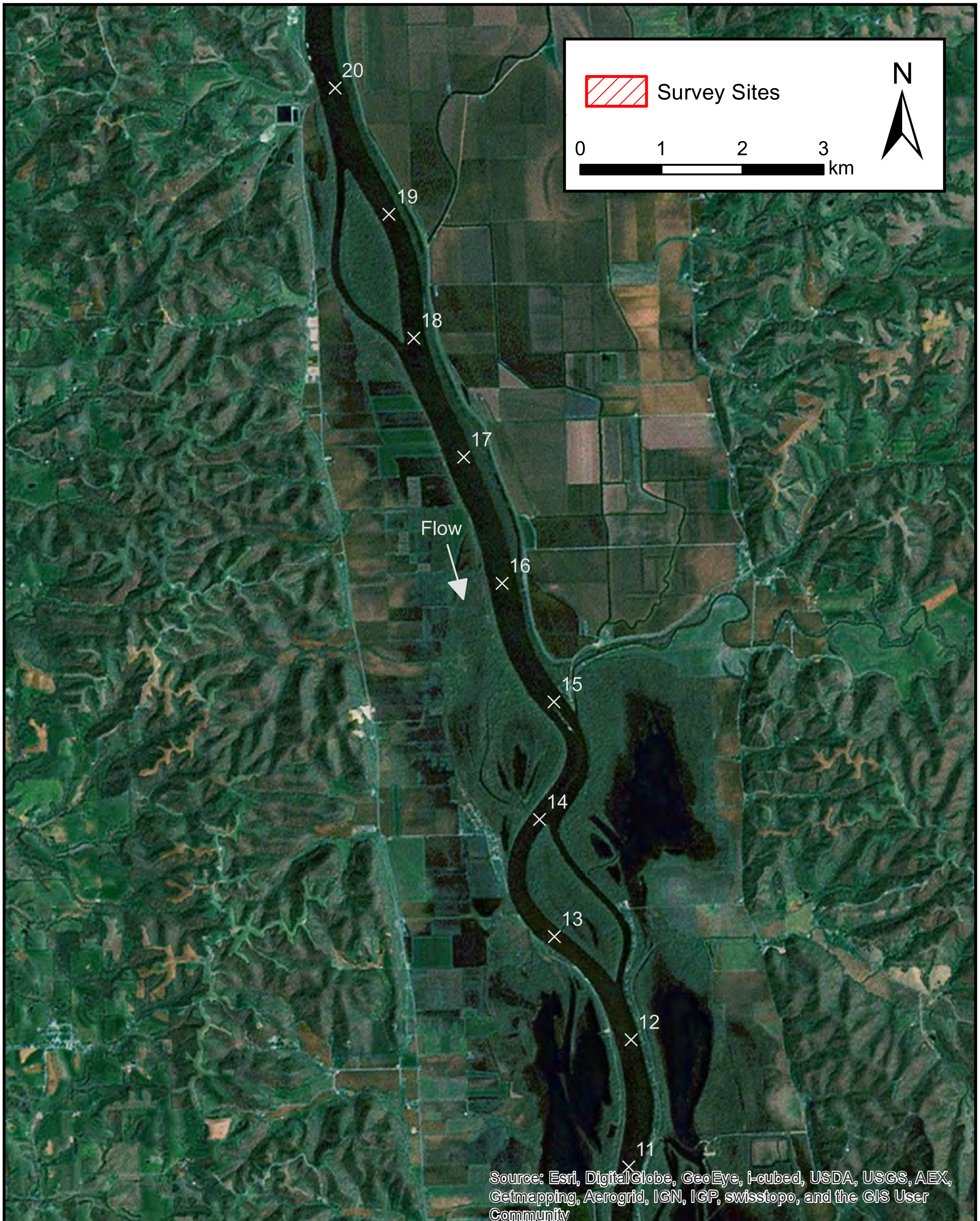
Appendix G. Unionid abundance in SLD-IR.



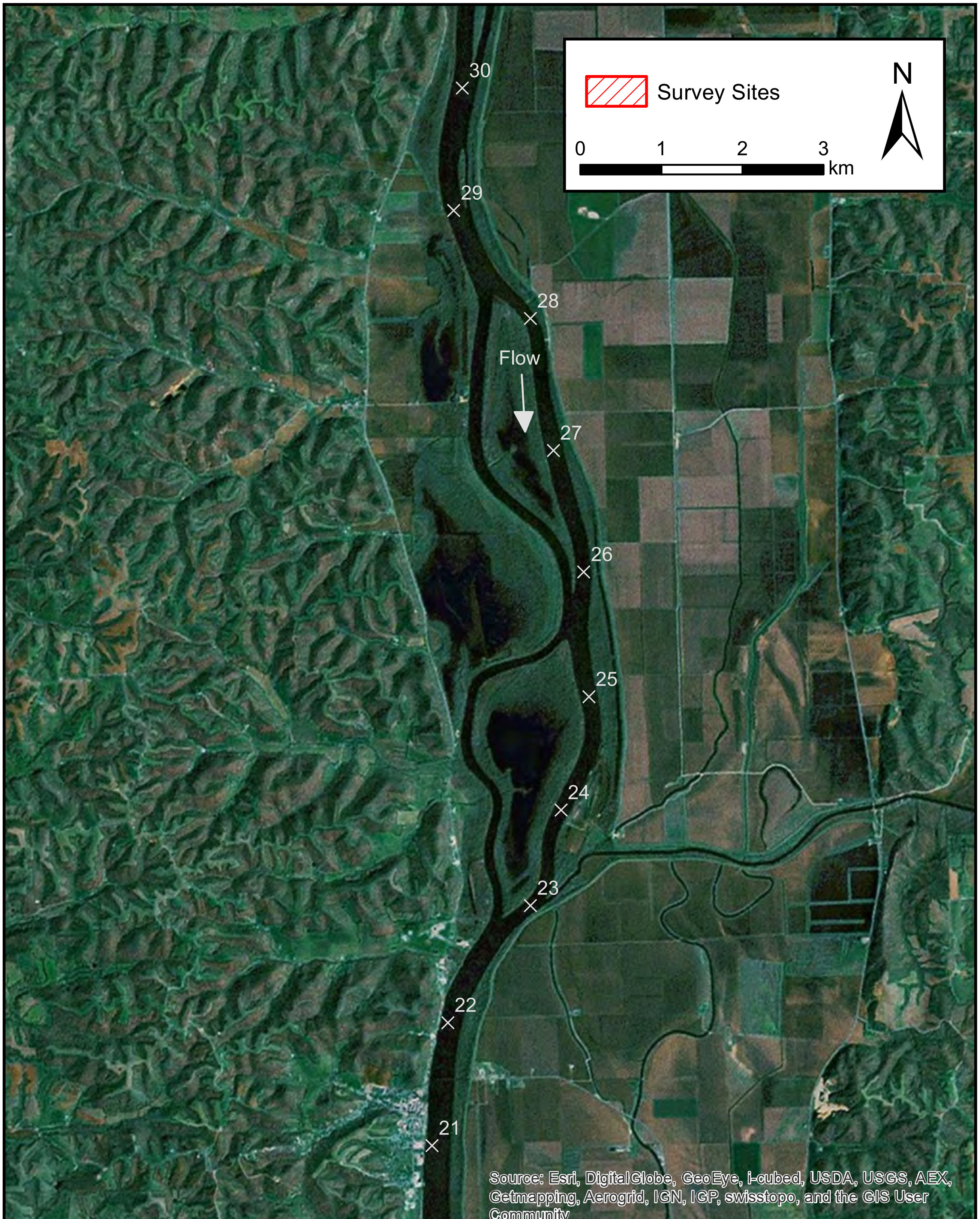
ECOLOGICAL SPECIALISTS, INC.

Unionid survey sites, Illinois River miles 0-10, 1997 to 2012.

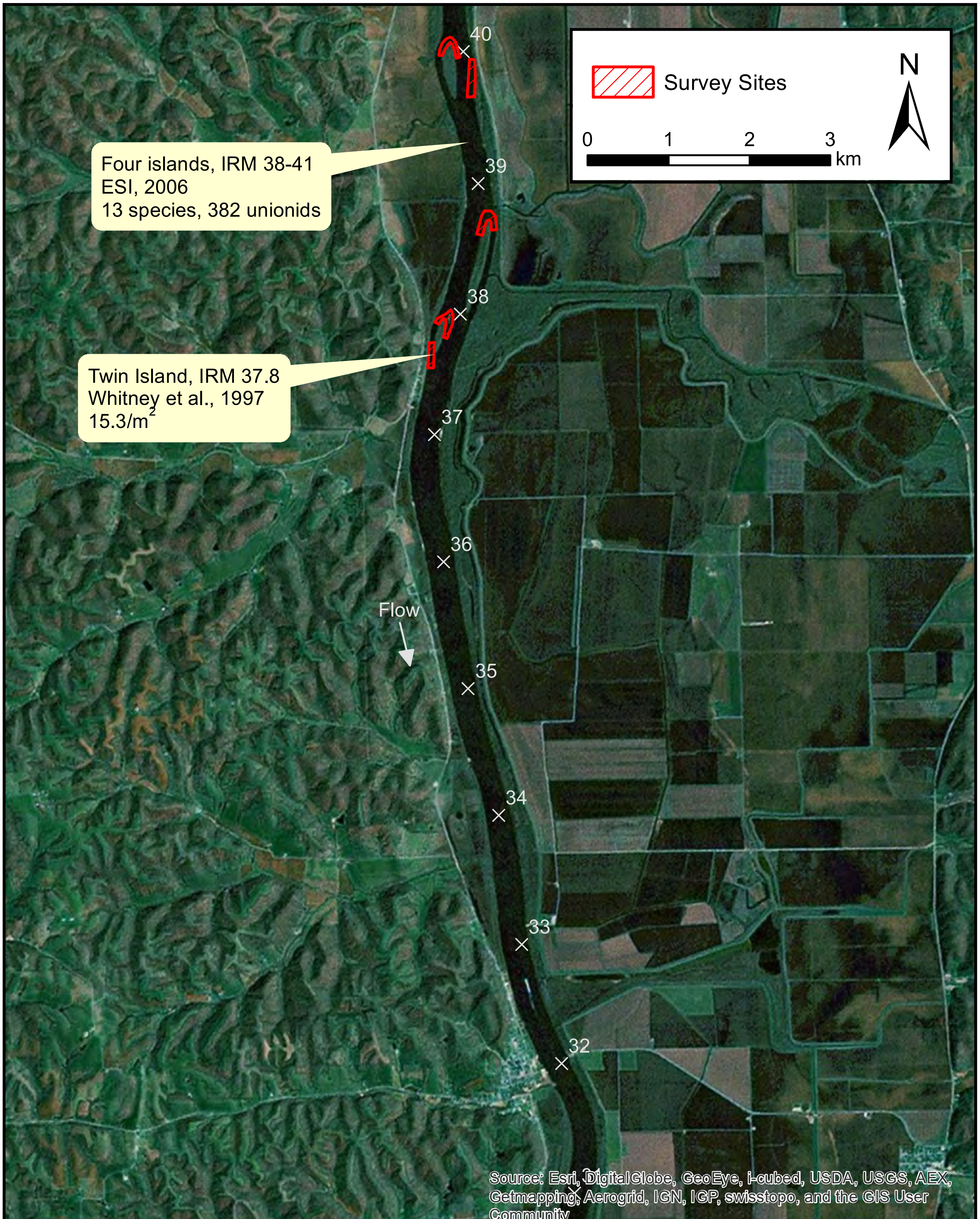
ESI



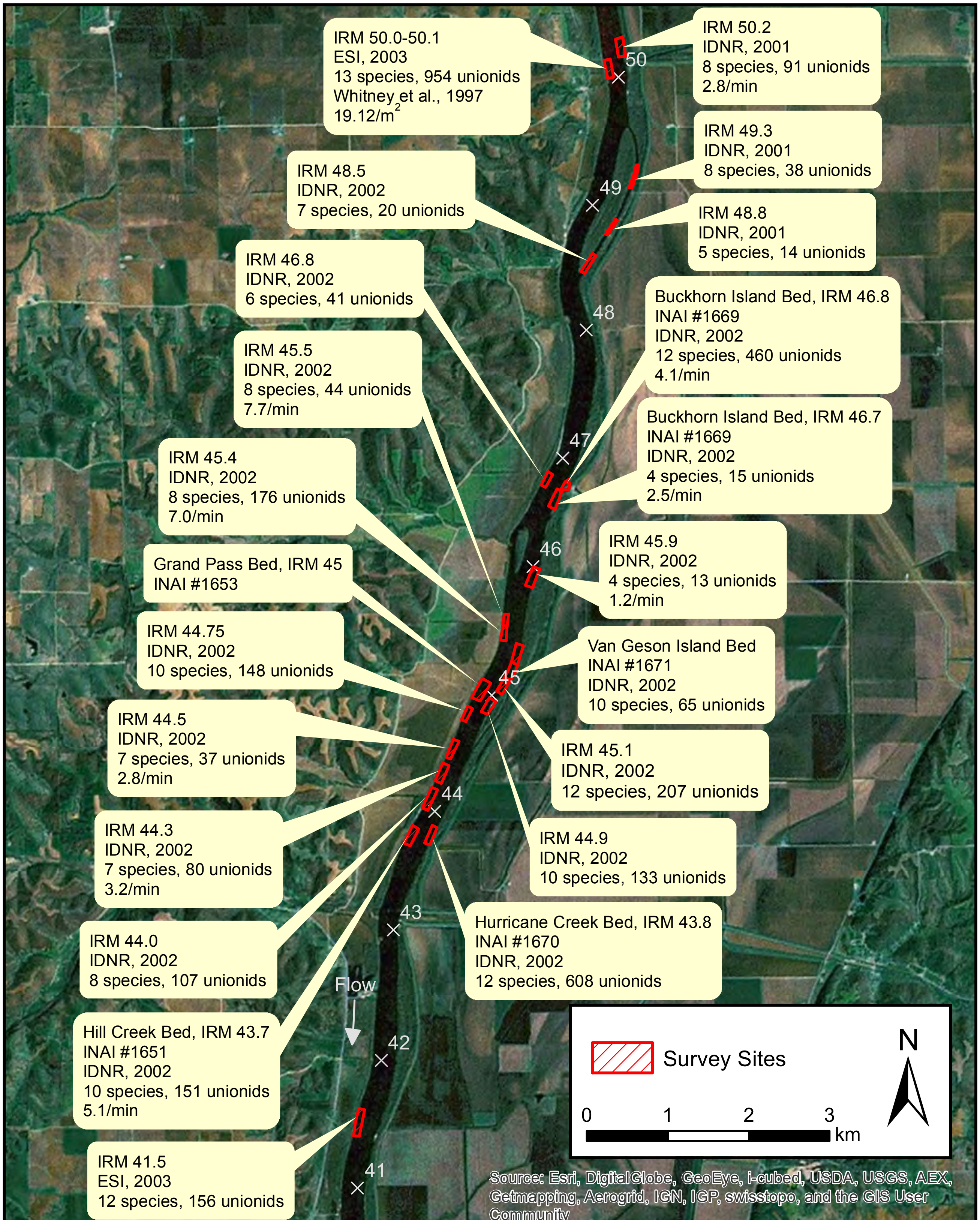
ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Illinois River miles 11-20, 1997 to 2012.	ESI



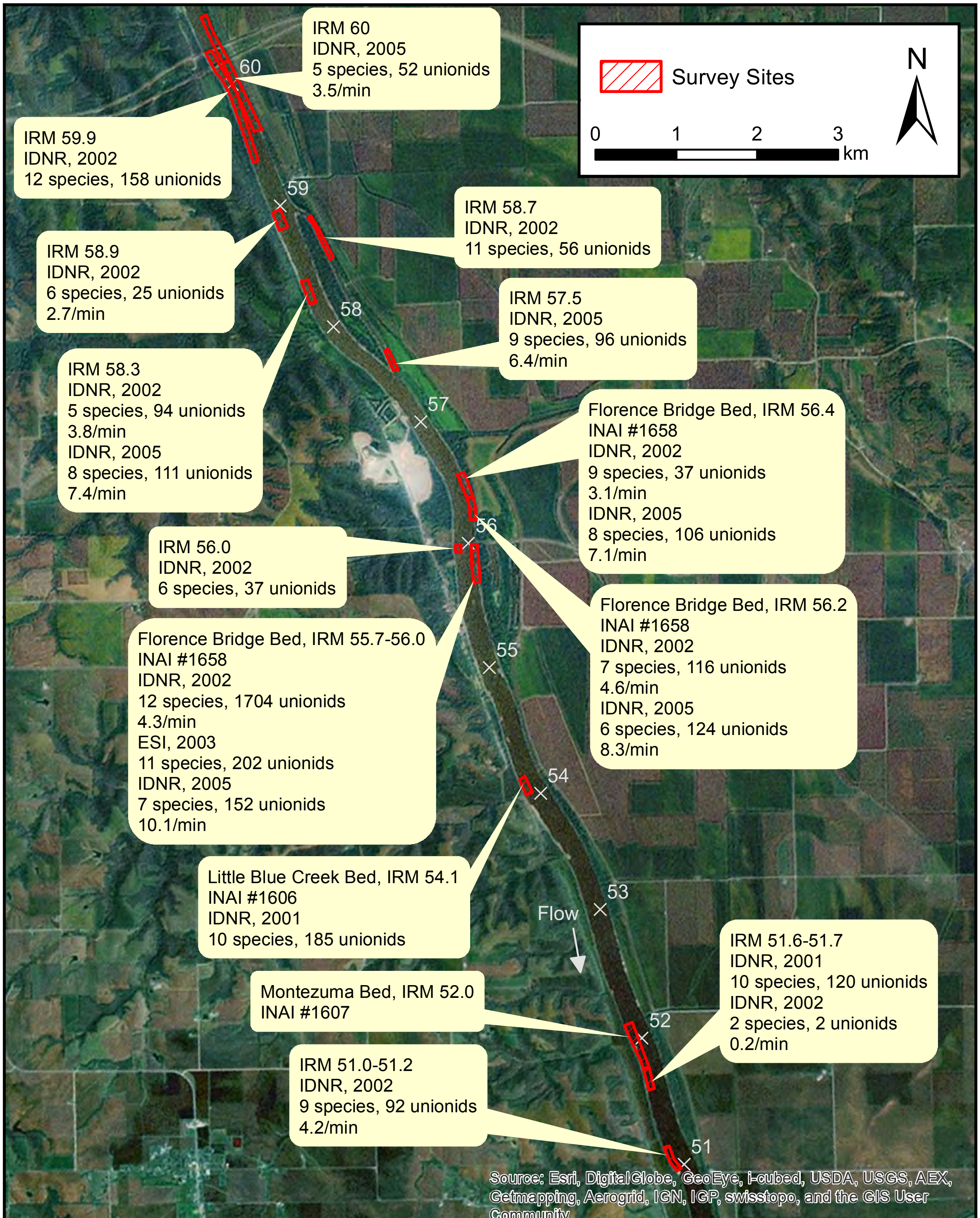
ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Illinois River miles 21-30, 1997 to 2012.	ESI



ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Illinois River miles 31-40, 1997 to 2012.	ESI



ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Illinois River miles 41-50, 1997 to 2012.	ESI



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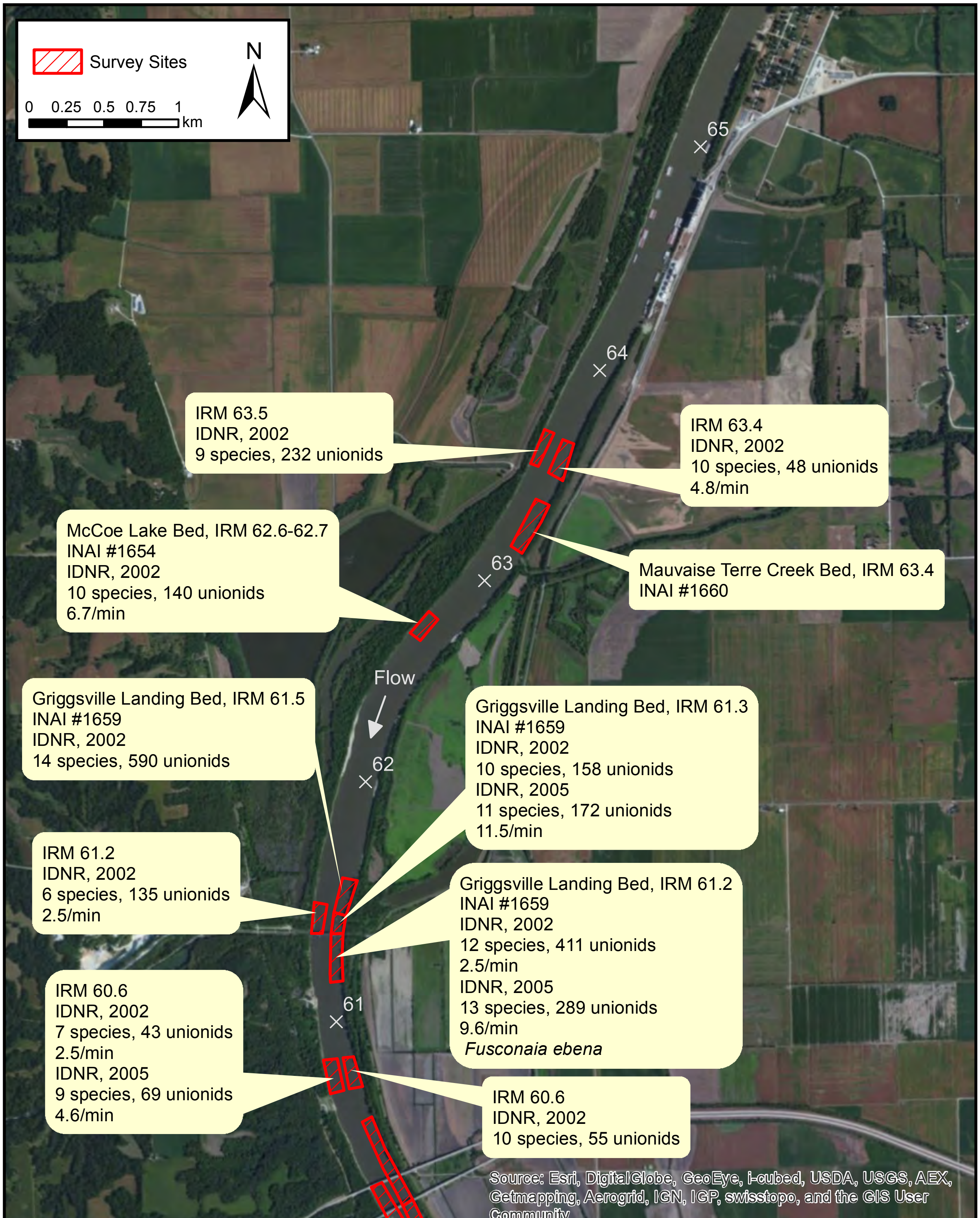

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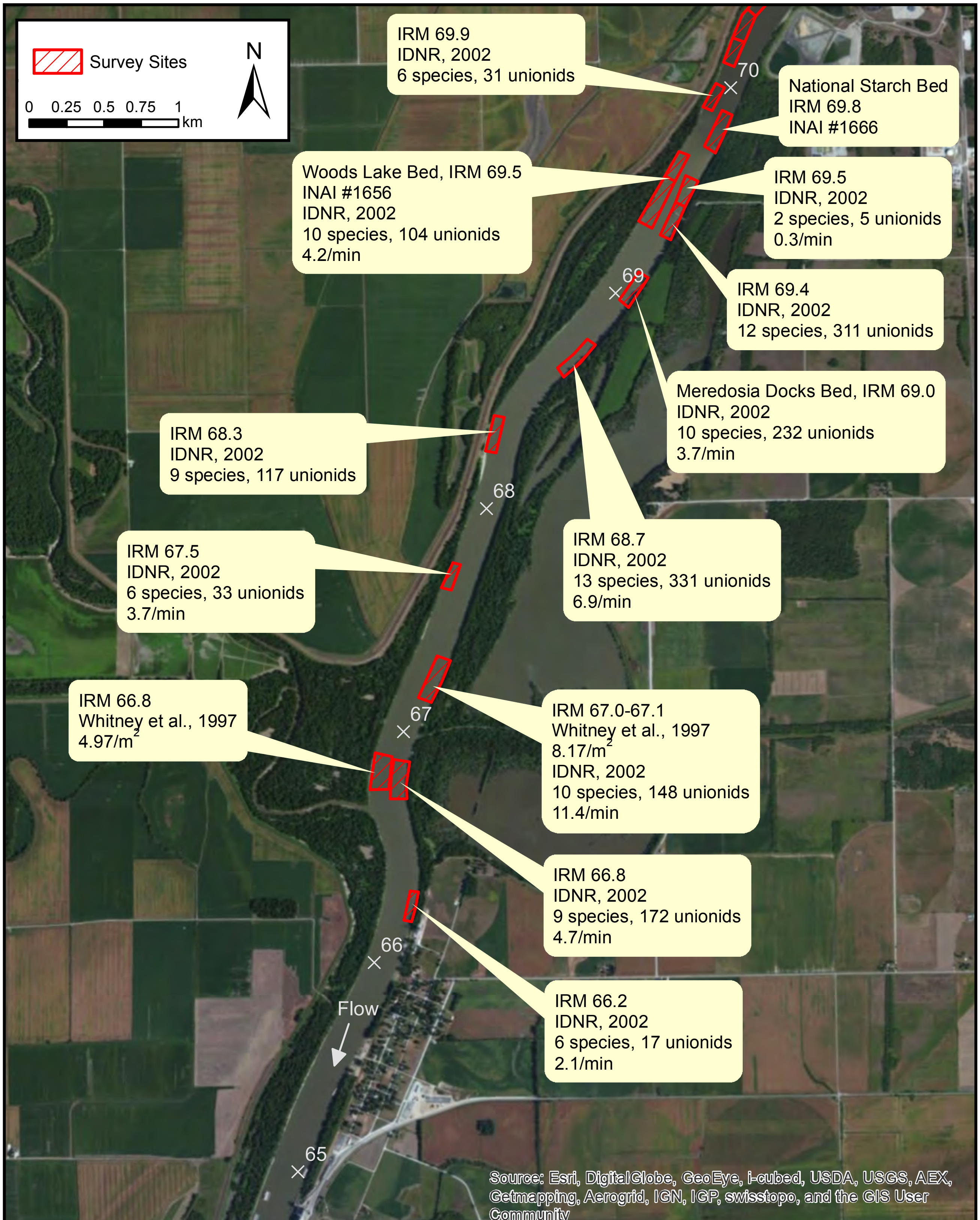

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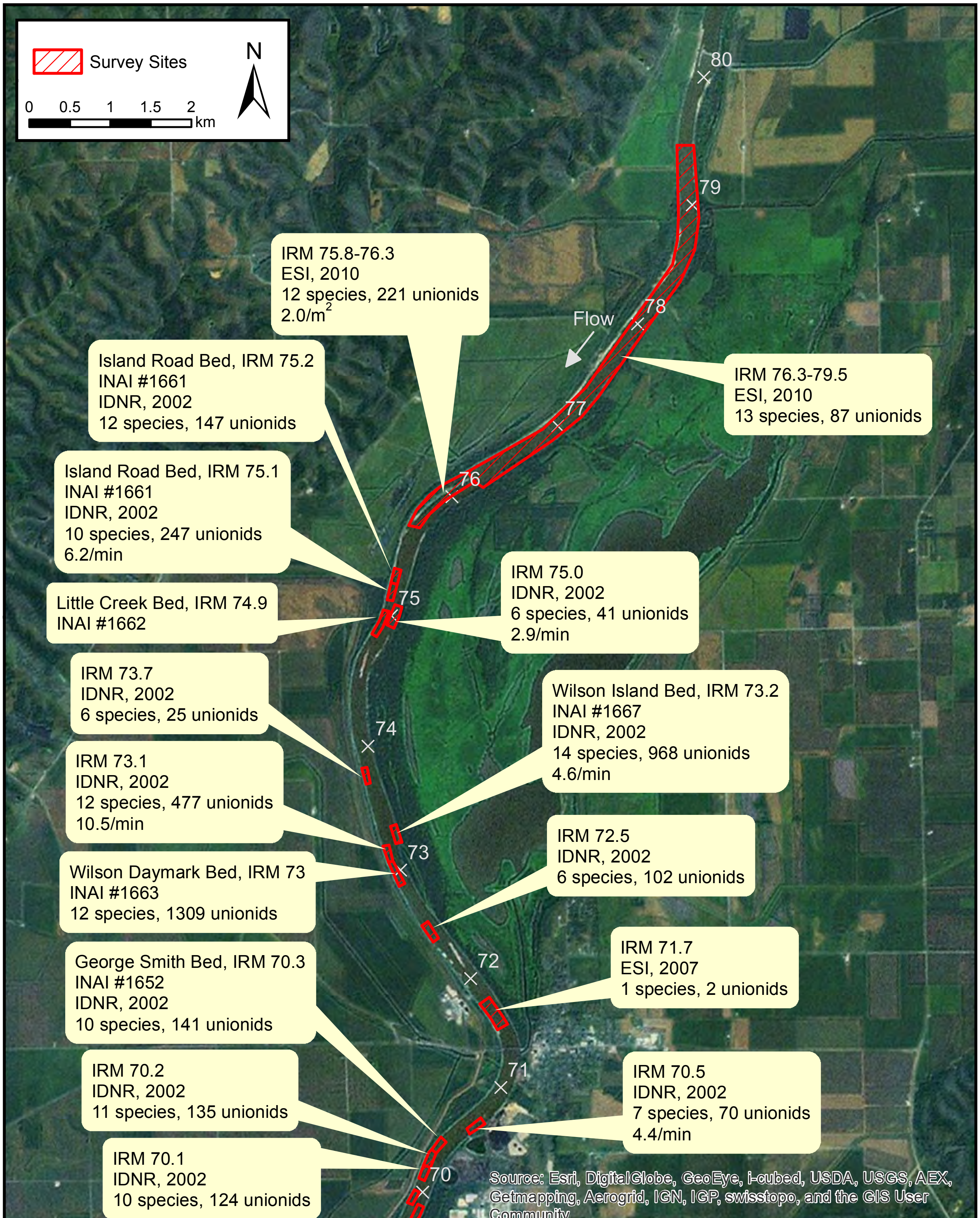


ECOLOGICAL SPECIALISTS, INC.	Unionid survey sites, Illinois River miles 71-80, 1997 to 2012.	ESI

Appendix H. River Engineering Structures for Navigation

River Engineering Structures for Navigation

The Corps designs its river training structures for navigation in a manner that also tries to improve river habitat diversity. Four primary habitats important to the river ecosystem that are enhanced through innovative design modifications of navigation structures include:

- Fast Water: Water moving quickly, usually the current in the main river channel.
- Slow Water/Quiet Water: Water outside of the main river channel moving slower than the primary river current.
- Wetted Edge: Land which is constantly getting wet and then dry again as the river rises and falls. This area is in a continual state of change. This habitat is very important, as there is a constant exchange of nutrients from the land to the aquatic environment.
- Terrestrial: Land separated from the shore is especially important because it is away from humans and other predators.

STRUCTURE DESCRIPTIONS

The following descriptions outline the structures currently employed by St. Louis District staff to attempt to meet the navigational and environmental components of the Corps's mission on the Mississippi.

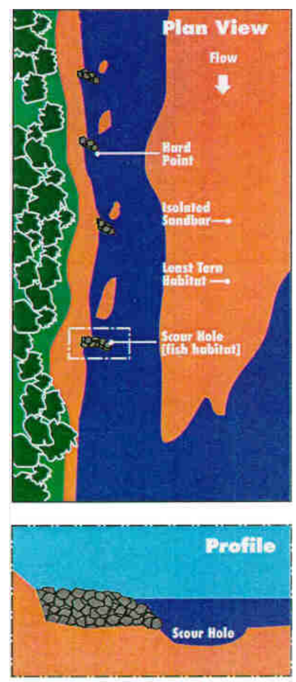
Bendway Weirs - The Bendway Weir is a low level, totally submerged rock structure that is positioned from the outside bankline of the riverbend and angled upstream toward the flow. These underwater structures extend directly into the navigation channel underneath passing tows. Their unique position and alignment alter the river's spiraling, secondary currents in a manner which shifts the currents away from the outside bankline. This controls excessive channel deepening and reduces adjacent riverbank erosion on the outside bendway. Because excessive river depths are controlled, the opposite side of the riverbank is widened naturally. This results in a wider and safer navigation channel through the bend without the need for periodic maintenance dredging. The Bendway Weir also eliminates the need for dikes to be constructed on the inside of the bendway, protecting bend interior sandbar habitat. There had been concern that bendway weir construction was leading to increased bend-interior slopes; analysis of pre- to post-construction data found that slope changes were largely within the expected natural deviation[1].

Bullnoses – Bullnoses redirect flows around islands protecting the islands from erosion. Without the rounded upstream rock structures, island heads can be exposed to high-velocity flows that hit head-on

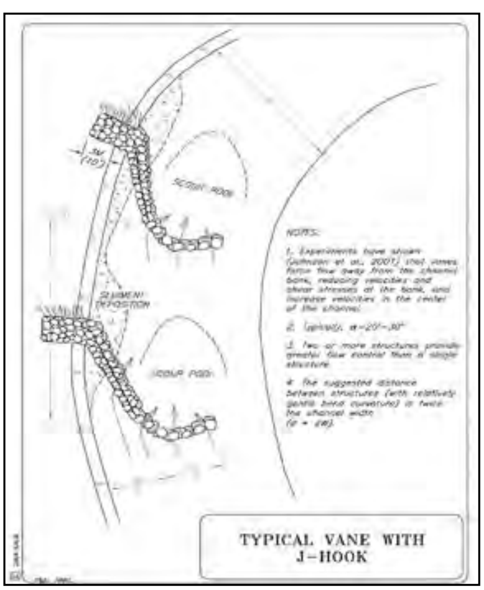
[1] Lauth et. al., "Analysis of the Effects of Bendway Weir Construction on Channel Cross-Sectional Geometry", 2011

and mobilize sediment, eroding an island away. The bullnose locks in the island's upstream geometry, rendering the island, and the aquatic and terrestrial habitat it forms, largely permanent.

Chevrons – Chevrons are "U"- or "V"-shaped rock structures with their apexes oriented upstream that divide flow smoothly so that a portion of the flow can be redirected without a significant undesired scour area forming. Dividing the flow in this manner can increase energy and decrease sedimentation in both side channels and the main channel. Besides redirecting flow along the front of the chevron, chevrons are designed with intent of periodic overtopping of the apex occurring. This overtopping results in the formation of a plunge pool within the chevron. The lower-velocity flow exiting the plunge pool can no longer maintain its sediment load and deposits sediment downstream of the chevron. This deposition can lead to the development of ephemeral or permanent islands downstream of chevrons. The bathymetric diversity presented by a plunge pool and downstream depositional area have been found to be favorable habitat for a variety of fish species. In the case of two or more chevrons, deposition behind the chevrons and side channel depth both increased with the number of chevrons. Use of multiple chevrons in a field can be used to either maintain a split flow situation or direct a split flow to a particular location (such as an area prone to a lower energy level). The disadvantage to the construction of chevrons is that they obstruct far less flow than a typical dike of equivalent length. Chevrons can be constructed with rootless trails extending the effective length of the chevron legs with regards to splitting flow while allowing for some flow behind the chevron. They can also be constructed with notches, with the intent of decreasing the depth of the plunge pool; these effects are still being studied. A third option for chevron construction is the shortening of one leg and the extension of the other. This J-shape can be used to further maintain a split flow.

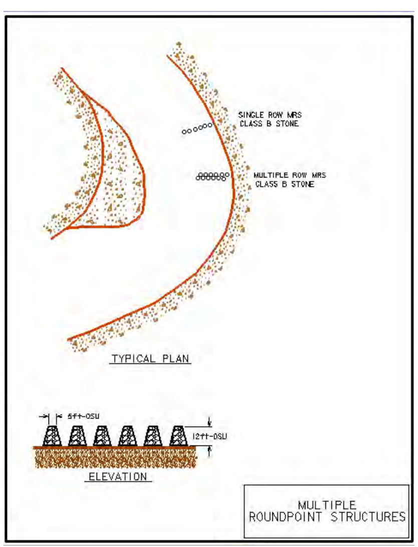


Hard Points - Hard points are very short rock dikes that are used to stabilize side channel river banks. The structures extend from the bank into the side channel and do not cause a significant buildup of sediment. Their contribution to habitat improvement is the creation of scour holes behind the hard points. These plunge holes attract fish that flourish in this environment. Effective hardpoint placement requires a relatively active side channel with little ongoing sedimentation.



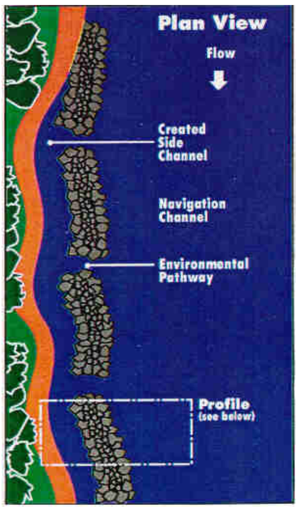
J-Hooks – J-Hook Rock Vanes are structures designed to re-direct velocity distribution and high velocity gradient in the near-bank region, stabilize stream-banks, dissipate energy in deep, wide, and long pools created below the structure, and create holding cover for fish and spawning habitat in the tail-out of the structure. The basic function of the structure utilizes the principle that water will flow over immoveable objects at right angles (90° angles). The device is constructed of large stone that is tied into the streambank. The stone is trenched into two rows at an upstream angle of 20° to 30° at a distance of 1/3 stream width. The stone is then formed into a hook shape to cover a distance of 1/3 stream width. The downstream row of rock is trenched into the stream bottom so that the top of the rock is approximately level with the stream bottom. The second row of rock is then placed just upstream of that row of rock slightly overlapping it so that as the water flows over the top of the upstream line of rock it will flow onto the downstream line of rock. This creates a stable surface on which the energy of the stream can be dissipated without completely scouring the stream bottom. As the stream dissipates its energy, it will scour the stream bottom slightly, creating a small scour pool immediately downstream of the device that serves as a source of aquatic habitat.

L-Dike – L-Dikes consist of a normal dike that has a trail dike constructed parallel to the flow from the tip. The constructed trail dike continues the constriction of the channel further along the main channel to increase main channel energy and decrease deposition. The area behind the L-Dike becomes a slack water area with beneficial habitat characteristics. This area can be prone to deposition due to the low energy level within the dikes, but such deposition can be reduced by notching the trail dike so that periodic sediment flushing occurs. Some disadvantages of L-Dikes are that they isolate the bankline from the river channel and that they don't promote new bathymetric diversity.

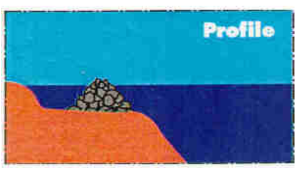


Multiple Roundpoint Structures (MRS) – Multiple Roundpoint Structures induce scouring off the tips of the structures and create depositional areas with the increased roughness generated by the structures. The MRS can also act as a primitive bank stabilization technique by creating depositional zones near the banks of the structures. The structures are generally built to 2/3 bankfull and the grade of stone needed is channel dependent. The spacing of the MRS is dependent of the height of the structure and natural angle of repose of the rock used. A rule of thumb with the spacing between the structures is to space them no less than 2/3 of the height. MRSs can be designed as a single row or in multiple rows. Preliminary data shows that incorporating more rows generates increased bathymetric changes. MRSs are not recommended as a bank stabilization technique but can be incorporated with other forms of bank stabilization such as revetment. The data collected suggest that MRS are providing useful and valuable habitat for a variety of riverine fishes. Collection of blue suckers may indicate these structures are providing a unique habitat type, once more common in the river.

Notched Dikes – Many rock dikes with notches in them can continue to have the same effect on navigation dimensions as un-notched dikes while also promoting increased bathymetric variation. Notches in the center or bank side of dikes achieve this variation by promoting scour downstream of the notch leading to a diversity of habitat. Varying notch depth is one factor that can be used to alter the depth of scour and thus the diversity. Low energy areas behind the un-notched portions of dikes can lead to deposition, supporting the creation of islands or side channels when used in a series. Notching is not always recommended; notching does remove a portion of the dike that may be necessary for the dike to have its intended effect, and a notch may have little effect without the proper flow depth and frequency through the notch.

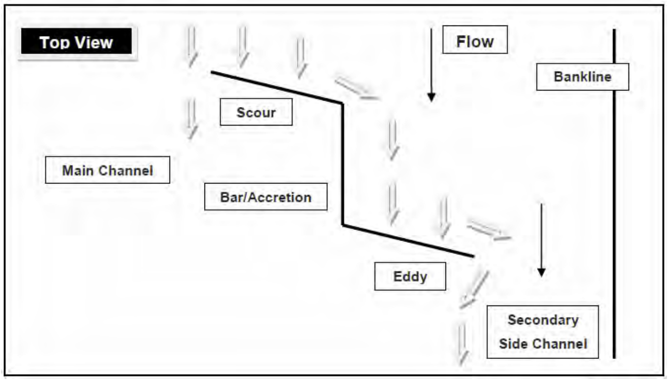


Off-Bankline Revetment – Off-Bankline Revetment reduces erosion on the shallow side of a river. By constructing a stone structure parallel to the bankline, a small side channel area is formed that is largely cut off from the energy of the main channel, producing a slow water habitat area. There is little critical bathymetric effect as the revetment is placed in shallow areas. However, the use of off-bankline revetment does not guarantee the same level of protection as normal revetment and leaves the bankline exposed at higher flow events.

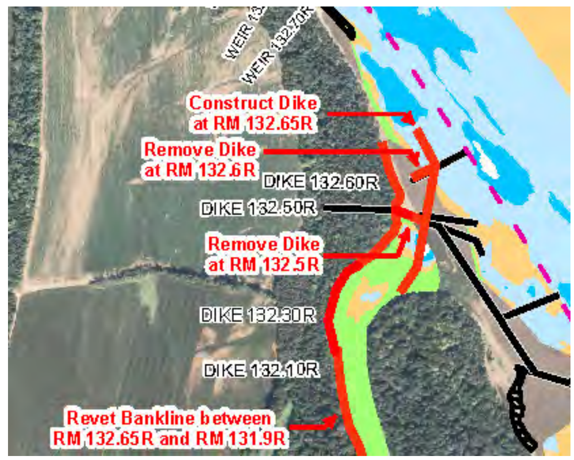


Offset Dike Extensions – Offset dike extensions expand upon the increased bathymetric diversity caused by notching dikes by extending the notch down to the structure base. This leads to a scour hole developing downstream of the offset area with the potential of the scoured material depositing downstream of the hole. These elevation changes are considered positive habitat areas. Offset extensions, unlike notches, require additional channel width so they can be constructed without having a negative effect on the navigation channel.

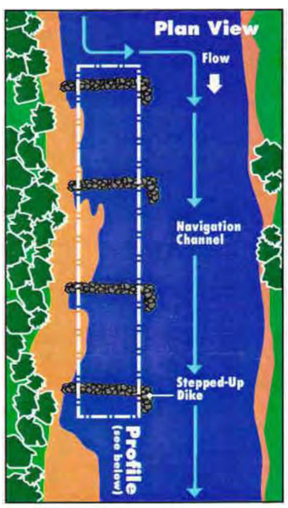
Rootless Dikes – Rootless dikes function much like notched dikes; they can have the intended effect of redirecting flow in beneficial directions while promoting bathymetric and habitat diversity in the space between the dike and the bank. Rootless dikes are also like notched dikes in that they need to obstruct enough of the flow to have their desired effect, they need to cause a constriction of the flow, and they need the gap between the dike and the bankline to experience the proper flow depth and frequency to have an effect.

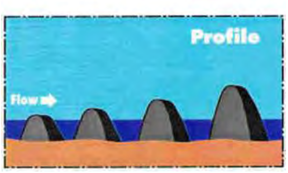


Diverter Dikes – Diverter Dikes, or "S-Dikes" due to their shape, are used to create secondary side channels because they angle upstream to capture water from the main channel and direct it towards the area of interest, while providing enough roughness and constriction to maintain a navigable channel. The S-dike showed that it will cause minimal erosion along the bankline because an eddy was formed at the tip. As flow and sediment hit the structure, depending on the orientation of the dike, a portion of the flow and sediment will be taken from the main source of flow towards a lower energy area on the opposite side of the dike.



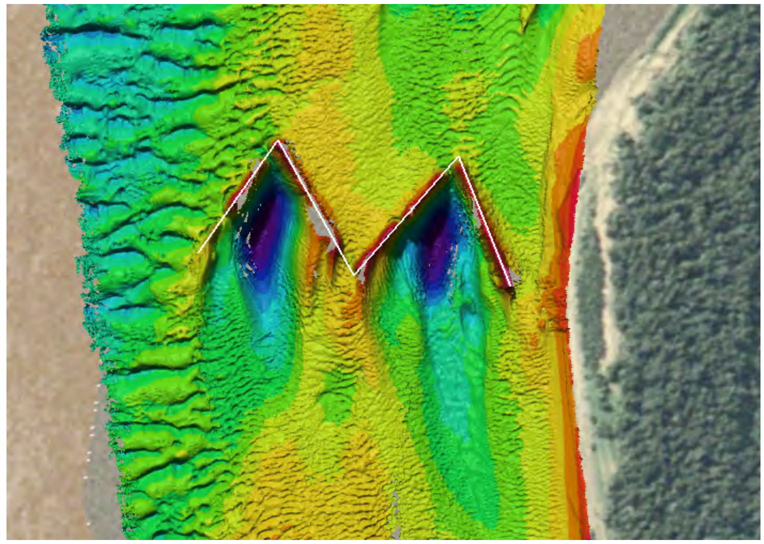
Side Channel Enhancement Dikes – Side Channel Enhancement Dikes (SCEDs) are a special class of L-Dikes with the trail oriented upstream from a spur dike constructed on the island side of a side channel entrance. With the upstream-oriented trail, the SCED captures flow from the main channel and redirects it down a side channel, increasing the energy in the side channel, scouring out deposited sediment, and preventing further sedimentation in the side channel. Under the right conditions, the installation of a SCED can reopen closed side channels, once again providing aquatic habitat in areas it had previously existed. The construction of a SCED does require certain conditions to be met for a higher likelihood of success: 1) a SCED works best when it can be constructed on the channel-dominant bank, and 2) SCED design requires a careful balance of flow capture between the side channel and main channel to avoid sedimentation in either channel.

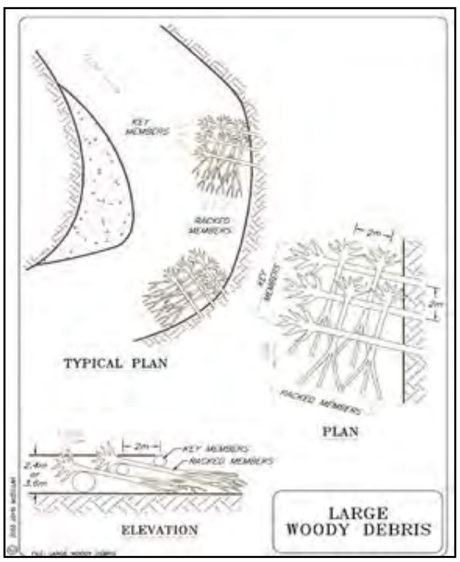




Stepped-Up Dikes - Stepped-Up dike fields of various elevations were developed to provide an additional element of diversity. They counteract sediment deposition, thereby preventing the conversion of aquatic environment into terrestrial. In the stepped-up dike configuration, each dike in sequence rises two feet higher than the previous one. This approach utilizes the river's energy to change the sediment deposits as the water level rises and falls. When the river's current hits the first dike it is propelled toward the main channel. As the river level rises, it moves over the first dike and hits the second dike, once again moving back into the main channel. This process repeats itself as the river rises and falls. The river's current, moving over each submerged dike, allows the sediment buildup to be redistributed back into the main channel and carried downstream.

W-Dikes – W-Dikes function in a manner very similar to chevrons, but are constructed to act over a larger width of the channel. By using a W-Dike instead of a chevron, two plunge pools are created between the inside and outside legs of the W, with deposition typically occurring downstream of the center of the W. Disadvantages of W-Dike construction include the cost of construction (as they require 2-3 times the stone), the difficulty in construction, and the channel width and depth needed.





Woody Debris - Naturally occurring large woody debris (LWD) (i.e., >10 cm diameter and 2 m in length) is an important component of many lotic systems. It provides roughness, reducing velocities and providing overhead cover for fishes, substrate for aquatic invertebrates, and can be an important source of particulate organic matter adding to primary productivity of a river. Large woody debris dissipates flow energy, resulting in channel stability and improved fish migration. It also provides basking and perching sites for reptiles and birds. Placing LWD into streams is an increasingly popular technique to improve fish and wildlife habitat. Large woody debris projects can be divided into two categories: improving the habitat by increasing the amount of LWD in the stream, and using LWD to alter flow in some way to improve aquatic habitat. Some specific objectives that can be accomplished by using LWD are the following: create pool habitat, generate scour, increase depths through shallow reaches, divert flows away from the bank to reduce erosion, armor stream banks to reduce erosion, promote bar formation through induced sediment deposition, and increase instream cover and refugia. Large woody debris commonly placed into the streams can be categorized as three types: whole trees, logs, and root wads. The use of woody bundles is more common in side channel rehabilitation and streambank stabilization, but can be implemented in dike structures in river environments. A primary concern with the installation of woody debris is that it can have a short life in the field.

Wood Pile Structures - Prior to the 1960's almost all of the structures placed in the Middle Mississippi River were of the woody pile type. Logs were driven into the river bed to create roughness and formed into a river training structure. Due to the higher maintenance of these woody structures, river training structures began to be constructed from stone during the 1960s. There is currently a push to start bringing back the woody pile structures because of their benefit to the micro- and macro-invertebrate species.

While wood pile structures promote bathymetric diversity, they are not as effective as stone dike structures for maintaining the navigation channel.

Summary

Biological Studies on the various river navigation structures described above have found an increase in diversity and numbers of micro-invertebrates. To a lesser degree, fish communities are also found to have greater diversity. In addition, the larger problem of aquatic environment becoming terrestrial is reduced, the river channel is maintained, structures are basically self-maintained and biological diversity is increased.

Isolated sandbars created by the various navigational structures provide suitable nesting sites for the endangered Interior Least tern. These sandbars are usually away from human encroachment which helps aid their development. In addition, the easy access from slow water to fast water is important for fisheries habitat.

Each structure is a piece of a giant jigsaw puzzle, having to “fit” exactly to create a safe and dependable navigation channel and at the same time, stimulate the rivers biological diversity.