Freshwater Mussel Surveys of Great Lakes Tributary Rivers in Michigan

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Left inset photo: *Elliptio crassidens* (elephant-ear) shell from the Grand River. Photo by Peter Badra
Right inset photo: Stephanie Carman and Peter Badra with a live *Obliquara reflexa* (threehorn wartyback) from the Huron River. Photo by Paul Marangelo.
Background photo: St. Joseph River near Berrien Springs. Photo by Reuben Goforth.

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Introduction

This project is part of an ongoing effort by Michigan Natural Features Inventory (MNFI) to assess Michigan's native freshwater biodiversity and investigate ecological factors affecting aquatic species and communities. The aim of this report is to present the results of freshwater mussel (unionidae) surveys conducted in 2002, to investigate the relationship between substrate characteristics and unionid abundance and diversity, and to identify issues with special relevance to the conservation of unionids and the aquatic ecosystems they inhabit. A similar study was conducted in 2001 (Badra and Goforth 2002) and our surveys continue through 2003-2004. This information is being incorporated into decision making tools (such as the MNFI and NatureServe databases) to assist in the management of aquatic ecosystems and provide information needed to evaluate the State of Michigan and global status and distribution of native freshwater species and communities. Survey results from the Galien, Grand, Red Cedar, Manistee, Au Sable, Pine, Belle, and Huron Rivers are included in this report.

Native freshwater mussels (Unionidae) are an important component of Michigan's aquatic ecosystems. They play a significant role in freshwater ecosystems, are useful indicators of water quality, and have historically been economically valuable. They also serve as umbrella taxa for the conservation of aquatic ecosystems because they are comparatively sensitive to habitat degradation and pollution, and are dependent on fish hosts to complete their life cycle. Although unionids inhabit streams and lakes in Central America, North America, Eurasia, and Africa (Bogan 1993), eastern North America is the region of highest diversity with 292 described species (Williams et al. 1993). Forty-five unionid species have been documented in Michigan's rivers and lakes.

Mussel communities in southern Michigan were once economically valuable. In the early 1900's, live unionids were harvested from these and other large rivers to support the button industry. In 1938, Henry van der Schalie, a noted malacologist, documented a rapid decline of unionid mussels during the 1930's due to harvest pressure. In response, The Michigan Department of Natural Resources, then known as the Michigan Conservation Commission, closed the harvest for a period of five years beginning in 1944 to allow the resource to recover. By the end of the 1940's, much of the demand for unionid shell had subsided due to increased use of plastics to manufacture buttons. Surveys of the Grand River later revealed that at least some of the mussel beds had recovered (van der Schalie 1948). Although unionid shells are now collected in some parts of the country for the cultured pearl industry, Michigan's unionid communities are not considered stable enough to allow a harvest, and it is illegal to possess or collect them without a permit.

Unionids are now recognized as useful water quality indicators and for their ecological value. Most species are long-lived, some with life spans up to 50 years and more (Badra and Goforth 2001). They are generally sessile, spending most of their lives within a particular stream reach. Unionids are sensitive to and tend to accumulate contaminants because they are filter feeders. Empty unionid shells can reveal historic community composition because they remain intact for many years *post mortem*. These characteristics make unionid mussels valuable indicators of water quality (Strayer 1999a). Chemical analysis of shell material can also reveal environmental information from years past (Mutvei and Westermark 2001).

Unionids also play significant ecological roles in rivers. The action of filter feeding can change the particle content of river water (Pusch et al. 2001). Both live individuals and empty shell provide habitat for aquatic insects, and empty shell also provides habitat for crayfish. Unionids play a substantial role in the flow of energy in stream ecosystems. They often comprise the highest percentage of biomass relative to other benthic stream organisms (Strayer et al. 1994), and are therefore a key link in the food chain from aquatic microorganisms to crayfish, muskrats, and other large predators. The status of unionids tends to be indicative of the biological integrity of river ecosystems as a whole.

The Unionidae rely upon fish hosts to complete their life cycle. Larvae called glochidia develop from fertilized eggs and live within the females' mantle tissues (i.e., marsupia). Glochidia are released into the water column and must attach to the gills or fins of a suitable fish host in order to survive. These parasitic glochidia transform into juvenile versions of the adult form and drop off the host after a 6-160 day period depending on the mussel species (Kat 1984). Some unionids are known to have only a few suitable host species, while others are generalists and utilize several species. The females of some taxa display mantle flaps or conglutinates that function as lures to fish hosts, thereby increasing the chances that larvae will successfully attach to an appropriate host (Kraemer 1970). Since adult mussels are relatively sessile (Amyot and Downing 1997), the transportation of glochidia by fish hosts is the primary mode of dispersal for the Unionidae (Kat 1984; Watters 1992). Gene flow, the exchange of genetic material among unionid populations is facilitated by fish hosts, allowing genetic diversity to be maintained.

Over the past century many factors have negatively impacted Michigan's river ecosystems. Increasing land use intensity within watersheds, point source pollution, direct habitat alteration (e.g. drain clean-outs and dredging), and non-native species introductions have impacted native mussel and fish communities (Bogan 1993; Fuller 1974; Strayer 1999b). Without the appropriate host species present in sufficient densities, the unionid life cycle cannot be completed. Threats to native fish communities can undermine the stability of unionid populations. Barriers to fish migration, such as dams and degraded habitat, are also barriers to the successful reproduction and dispersal of unionids (Watters 1995a). They can inhibit the re-colonization of suitable habitat, threaten genetic diversity through lack of gene flow, and prevent the recovery of unionid populations. The non-native *Dreissena polymorpha* (zebra mussel) has had drastic effects on unionid communities (Schloesser et al. 1998) and is continuing to spread throughout the surface waters of Michigan.

Over one-third (19) of Michigan's 45 unionids are state-listed as special concern, threatened, or endangered. A review of the status of U.S. and Canadian unionids by the American Fisheries Society found that 97 of the 292 species that occur in the U.S. are considered endangered (Williams et al. 1993). The decline of freshwater bivalves is occurring in other parts of the world as well (Bogan 1993). Goals for conserving unionid diversity in Michigan parallel those that exist on the national level. These include: prevent or minimize the continued degradation of high quality habitat; increase our fundamental knowledge of basic biology and habitat requirements; increase our knowledge of the current distribution and health of unionid populations; and understand how anthropogenic factors such as habitat alteration and water quality degradation impact unionids (National Native Mussel Conservation Committee 1998). A more complete understanding of the status, distribution, and ecology of the Uniondae in Michigan is needed to effectively manage this endangered group and can assist in the management of aquatic ecosystems.

Elevated input of fine particles has been widely identified as a contributing factor to the dramatic decline of unionids. Specific examples of the negative impact of sediment deposition are described in Box and Mossa (1999), along with laboratory experiments which document the potential for excessive fine particles to cause mortality in unionids. Is substrate composition a limiting factor for Michigan unionid communities? Should the increase of fine particles due to land use in watersheds be a high management priority? To address these questions the following hypotheses were posed and tested for unionid communities surveyed in eight Lower Peninsula rivers: unionid abundance and species richness are negatively correlated with fine particle sizes (i.e., silt), and unionid abundance and species richness is positively correlated with larger particle sizes (gravel and pebble). Unionid abundance and species richness was also compared to three indices developed by Wilhelm (2002) which provide measures of aquatic habitat quality, disturbance of riparian zones, and human disturbance in watersheds.

Methods

Sites were surveyed in the Galien, Grand, Red Cedar, Manistee, Au Sable, Pine, Belle, and Huron Rivers during the summer and fall of 2002. River reaches were selected for field visits based on availability of suitable unionid habitat and potential for occurrences of listed unionids. The Galien, Manistee, and Au Sable Rivers were chosen because of an almost complete lack of historical unionid surveys in these systems. Sites covering multiple watersheds allowed a general characterization of the habitat use of unionid species over a large portion of their range in Michigan. Survey sites on the Manistee and Au Sable Rivers, and four sites on the Grand River were deep enough to require the use of SCUBA. All other sites were in shallow and clear enough water to allow wading with glass bottomed buckets. In reaches where a boat and SCUBA were used, the nearest boat ramp to the reach was identified and used as an access point. Mussel habitat and signs of mussel beds, such as shells in muskrat middens, were identified from a boat within these reaches and were used as a basis for survey site selection. Handheld GPS units (Garmin 12XL) and topographic maps were used to document the position of SCUBA sites. Latitude and longitude were recorded at a point in the approximate center of the site. The use of a jet drive outboard motor made navigating in shallow areas much more time-efficient, and mechanical failure was far less likely than with a traditional propeller drive outboard motor (Figure 1).

The field crew typically consisted of two divers and a third person who recorded data, assisted divers with gear, and tended the boat while divers were in the water. Once signs of a mussel bed were identified, the boat was anchored and transects were set. Two transects were set side by side approximately 3 to 8m apart parallel to river flow. Transects were delineated using 10m lengths of 2.54cm nylon webbing with 4.5kg anchors fastened to each end. An arms-width (approx. 0.8m) on each side of each transect was searched by passing the hands over and through the substrate to a depth of approximately 5cm of substrate. A buoy was tied to each anchor to mark the endpoints of each transect. Divers started working each pair of transects at the same time, moving in an upstream direction. Searching in an upstream direction minimized increased turbidity due to disturbance of fine sediments during surveys. Divers searched a total of eight transects at each site (four transects per diver). Subsequent pairs of transects were placed directly upstream from the previous pair. Transects that were in water shallow enough to wade (approx. <70cm) allowed surveyors to kneel on the bottom and perform tactile searches without the use of SCUBA. Glass bottom buckets were also used at these sites to help detect mussels visually (Figure 2). When stream width was less than approximately 6m, the entire width of the stream was surveyed without transect lines for a reach length that would allow an area of 128m^2 to be covered (Figure 3).

Unionids buried up to approximately 5cm below the substrate surface and located within 0.8m on either side of transect lines were detectable. Due to low visibility underwater at most sites, mussels were primarily located by feel as divers passed their hands through the substrate adjacent to the transect lines. Relatively clear water and rocky substrate at a few of the sites made visual searches of transects a more reliable and time efficient method for detecting mussels. Rocks and live mussels were more easily distinguished visually than tactually at these sites. Live unionids were placed in mesh bags, brought to the surface, and identified after completing each transect. Length measurements of all individuals were taken (Figure 4). The presence of *D. polymorpha* within transects was recorded, and the number of *D. polymorpha* attached to each live unionid was determined. The exotic *Corbicula fluminea* (Asian clam) was generally too small to be detected reliably using the methods described above; however, the presence of shell or live *C. fluminea* was recorded when they were detected. Empty unionid shell found during transect searches was either identified underwater or brought to the surface for identification. Additional species represented only by empty shell were noted. After processing, live unionids were planted in the substrate, anterior end down, along transect lines in approximately the same density as they were found. Most empty shells were returned to the river, although approximately 50 shells were collected. The boat and outboard motor were either dried for several days or washed with a bleach solution to prevent the transportation of live *D. polymorpha* and other exotics between different river reaches. Substrate within each transect was characterized by estimating the percent composition by volume of each of the following six particle size classes (diameter); boulder (>256mm), cobble (256-64mm), pebble (64-16mm), gravel (16-2mm), sand (2-0.0625mm), silt/clay (<0.0625) (Hynes 1970).

To maximize diver safety three factors had to be addressed; water quality, current, and visibility. Bacteria counts in Lower Michigan rivers are often high enough that contact with river water should be avoided. Sediments in river substrates can also contain potentially hazardous substances. Reports of discharges into the river were monitored and no diving occurred downstream from points of discharge for at least a week after the event. Drysuits (D.U.I. ™) and full facemasks (Scubapro™) were used to minimize direct contact with river water and sediments. Current speeds at most of the sites made it necessary for divers to wear a much heavier weight belt than usual. Transect lines not only delineated the area to be searched, but were also used as a hand line to help divers stablize themselves in the current. Broken glass, scrap metal, zebra mussel shell, and other sharp debris was frequently encountered during tactile searches. Neoprene gloves (3mm) with kevlar reinforcement were worn to minimize the chance of injury. Visibility typically ranged from a few cm to greater than 3m in the rivers surveyed. Transect lines were essential for keeping divers oriented to sampling areas during surveys (Figure 5). The person on the boat also spotted divers to help them avoid hazards.

Pearson correlation coefficients and statistical significance values were calculated to determine whether unionid abundance and species richness were correlated with the proportion of each substrate particle size. The same calculations were performed to determine if unionid abundance and species richness were correlated to measures of river habitat quality and human disturbance from Wilhelm (2002). These statistics were calculated using the SPSS 11.5 software package (α=0.01).

Figure 1. Boat with jet drive outboard engine used during surveys. Photo by Pete Badra.

Figure 2. Transect searches with glass bottomed buckets in shallow water habitat. Photo by Eric Tobin.

Figure 3. Survey of shallow habitat in a small river (Pine River). Photo by Tamara Lipsey.

Figure 4. Taking length measurements of unionids. Photo by Pete Badra.

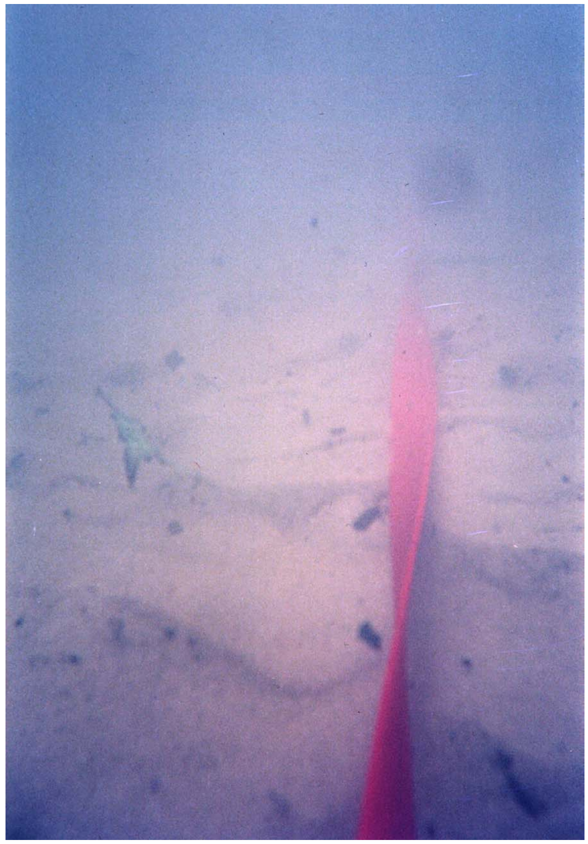


Figure 5. Underwater view of transect line and sand substrate. Photo by Pete Badra.

Results

Fifty-eight sites were surveyed in eight rivers for a total of 464 transect searches. Survey site locations are given in Figures 6-15. A relatively large number of sites were surveyed due to help from extra field workers and the fact that many sites did not require the use of a boat or SCUBA. Twelve sites in the Galien River watershed, nine sites in the Red Cedar River watershed, four sites on the main stem of the Pine River, and 11 sites on the main stem of the Belle River were surveyed with glass bottom buckets. Eight sites on the main stem of the Manistee River, four sites on the main stem of the Au Sable River, and two sites on the main stem of the Huron River were accessed by boat and surveyed using SCUBA. Four sites on the main stem of the Grand River were surveyed with glass bottom buckets, while four sites were accessed by boat and surveyed with SCUBA.

A total of 32 unionid species were found, including three state-listed as endangered in Michigan (*Epioblasma triquetra, Obovaria subrotunda,* and *Villosa fabalis*), one state-listed as threatened (*Lampsilis fasciola*), and six state-listed as special concern (*Alasmidonta marginata, Alasmidonta viridis, Cyclonaias tuberculata, Pleurobema sintoxia, Venustaconcha ellipsiformis,* and *Villosa iris*) (Table 1).

Several important new occurrences of state endangered species were documented, as well as updates of historic records. New occurrences of *E. triquetra* were recorded in the Grand River (D5 and D6) and Belle River (B2 and B3). Occurrences of *E. triquetra* in the Belle River at site B1, and Pine River at sites P1, P2, and P3 are updates of historic records. New occurrences of *O. subrotunda* were documented in the Belle River (B2 and B3) and Pine River (P1 and P4). Updates of historic records of *O. subrotunda* were made at sites B1, P2, and P3. Live individuals were found at sites B2 and P2. Live *O. subrotunda* had not been documented in the Belle River since 1965 or in the Pine River since 1986. A new occurrence of *V. fabalis* was recorded in the Belle River at site B2. Updated occurrences were documented in the Belle River at site B1 and in the Pine River at sites P1, P2, P3, and P4. Though several historic surveys had documented *V. fabalis* shell at site B1, no records for live individuals in the Belle River have been documented before this survey. Two new occurrences for the state listed as threatened *L.*

fasciola were recorded from the Belle River (B3 and B4). The following new occurrences were recorded for special concern species. *A. marginata*: 4-Grand River; *A. viridis*: 2-Galien, 2-Grand, 2-Red Cedar, and 4-Belle; *C. tuberculata*: 2-Grand; *P. sintoxia*: 2-Grand, 3-Pine, 3-Belle; *V. ellipsiformis*: 1-Grand, 1-Red Cedar; *V. iris*: 2-Grand, 2-Red Cedar, 4-Pine, 5-Belle.

Two species that are rare in Michigan but not currently listed in the State were also found. Two live *Obliquaria reflexa* were discovered at site H1 in the Huron River, a watershed that was not previously known to support this species. *Actinonaias ligamentina*, a species that may be declining in Michigan, was found at four sites in the Grand River and three sites in the Au Sable River. Live individuals were found at two sites on the Au Sable River, while the rest of the seven occurrences were represented by shell only. Of special note was the occurrence of three *Elliptio crassidens* valves in the Grand River (site D5) (See Discussion).

Density and relative abundance for each species at each site are given in Table 2. Relatively low species richness and abundance were recorded at sites in the Galien River watershed (maximum of 0.06 indvs/m^2), though a live individual of a special concern species (*Alasmidonta viridis*) were found. Very low unionid density was also recorded at two sites near the mouth of the Huron River (0.09 indvs/m^2). Sites in the Manistee and Au Sable Rivers ranked the next highest in maximum density (0.25 indvs/m^2 and 0.30 indvs/m^2 respectively). Sites in the Red Cedar and Pine Rivers had similar maximum densities (0.55 indvs/m^2 and 0.56 indvs/m^2, respectively). Sites in the Belle and Grand Rivers had the highest densities at 0.93 indvs/m^2 and 0.94 indvs/m^2 respectively.

Mean lengths for each species were calculated for each river system (Table 3). Though few very young individuals were found, we cannot rule out the possibility of recent reproduction. Specific methods targeting young unionids are needed to detect individuals less than approximately 2cm in length with consistency.

Dreissena polymorpha (zebra mussel) was found in the Grand, Manistee, Au Sable, and Huron Rivers. *Corbicula fluminea* (Asian clam) was found in the Grand and Manistee Rivers, though only shell was seen in the Manistee. The exotic fish, *Neogobius melanostomus* (Round goby), was found in the Grand, Manistee, and Au Sable Rivers (Table 4). *D. polymorpha* was attached to native unionid mussels at three sites in the Manistee River and two sites in the Au Sable River. The rate of colonization was high and affected at least eight unionid species in the Manistee River and six species in the Au Sable River (Tables 5a-b). Most of the *D. polymorpha* attached to unionids were large individuals (1.5-3cm in length).

Riparian zones in the Galien and Red Cedar watersheds typically consisted of trees and shrubs, were several meters wide, and were surrounded by agricultural fields. Many of the sites appeared to have been channelized or modified in the past (Figure 16). The riparian zone characteristics adjacent to Grand River sites varied widely and included forested buffers ranging from a few meters to >50m wide, interstate highway, mowed grass, and residential areas. The riparian zone towards the mouth of the Manistee (sites M1 and M2) included steel plate armoring the banks, urban areas, and forested areas. The channel has been dredged at these two sites to accommodate boat traffic. The riparian zone at sites M3-M6 was a combination of forested floodplain and agricultural fields. The two sites located furthest upstream (M7 and M8) were in National Forest and had very large forested riparian zones and wetlands. Riparian zones in the Au Sable ranged from seawalls and heavily developed residential areas at the two downstream sites (A1 and A2) to large forested floodplains in the two upstream sites (A3 and A4). Riparian zones in the Pine River consisted of wide forested buffers, moderately developed residential areas, and some agricultural areas (Figure 3). A beaver dam located between sites P3 and P4 strongly influenced stream morphology and flow characteristics immediately up and downstream of the dam. The four most downstream sites on the Belle River (B1-B4) had riparian zones consisting of a mix between forested, residential, and agricultural areas. Forested buffers usually ranged from 20m to 50m wide. Riparian zones at sites B5 and B6 were dominated by lawns from residential areas, and sites B7-B9 were dominated by agriculture with very narrow grass and shrub buffers. The two sites on the lower Huron River had narrow forested buffers with fairly intense residential development.

Substrate at sites in the Galien watershed was dominated by unstable sand. The Grand, Red Cedar, Manistee, and Au Sable Rivers also were dominated by sand but had higher percentages of gravel and pebble and tended to be more stable and than substrate in the Galien. Substrate at Pine River sites was dominated by gravel. Substrate at Belle and Huron River sites was dominated by silt (Table 6). The boulder size class was not included in all of the substrate analysis due to the fact that very few transects contained boulders.

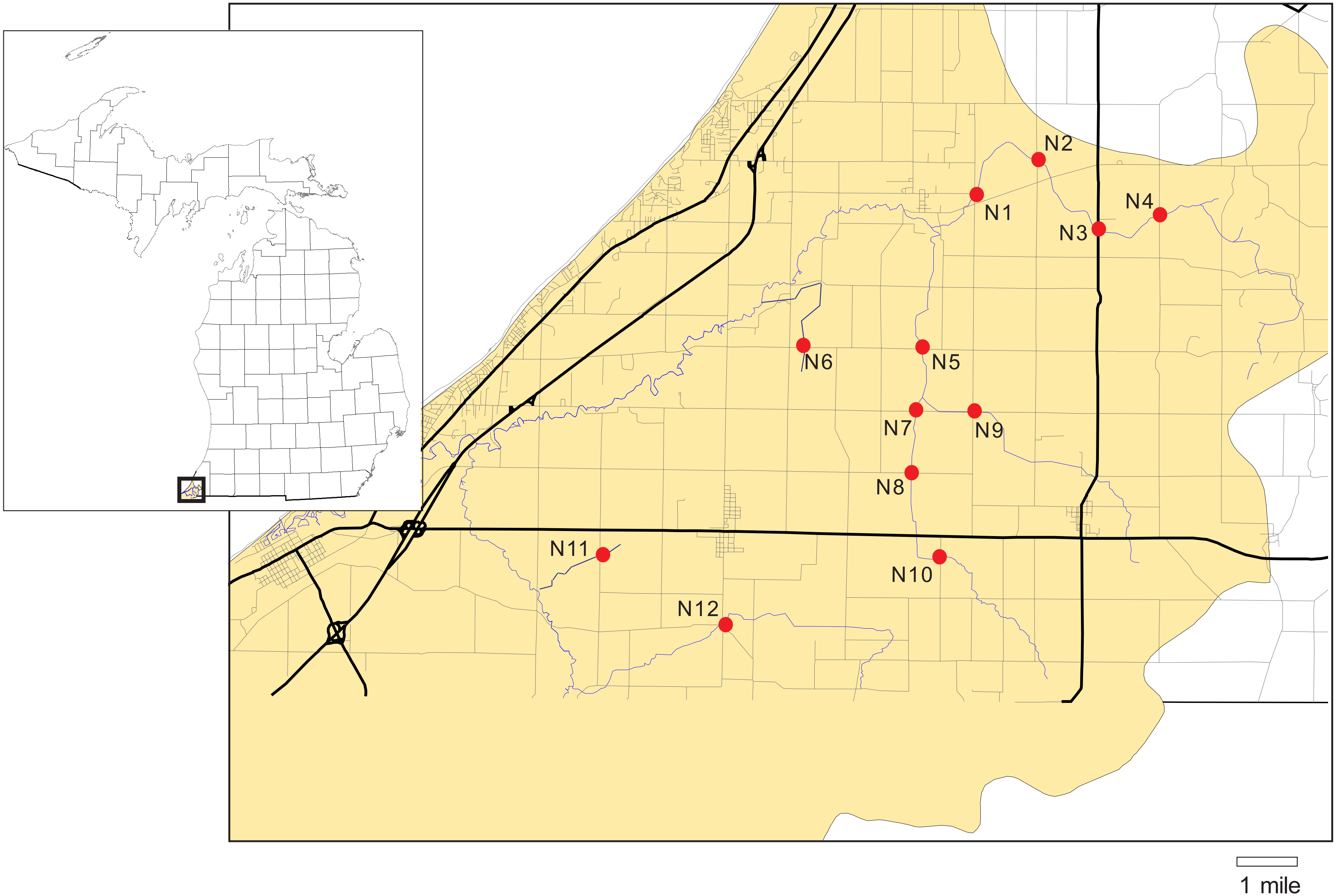


Figure 6. Survey sites on the Galien River (N1-N12).

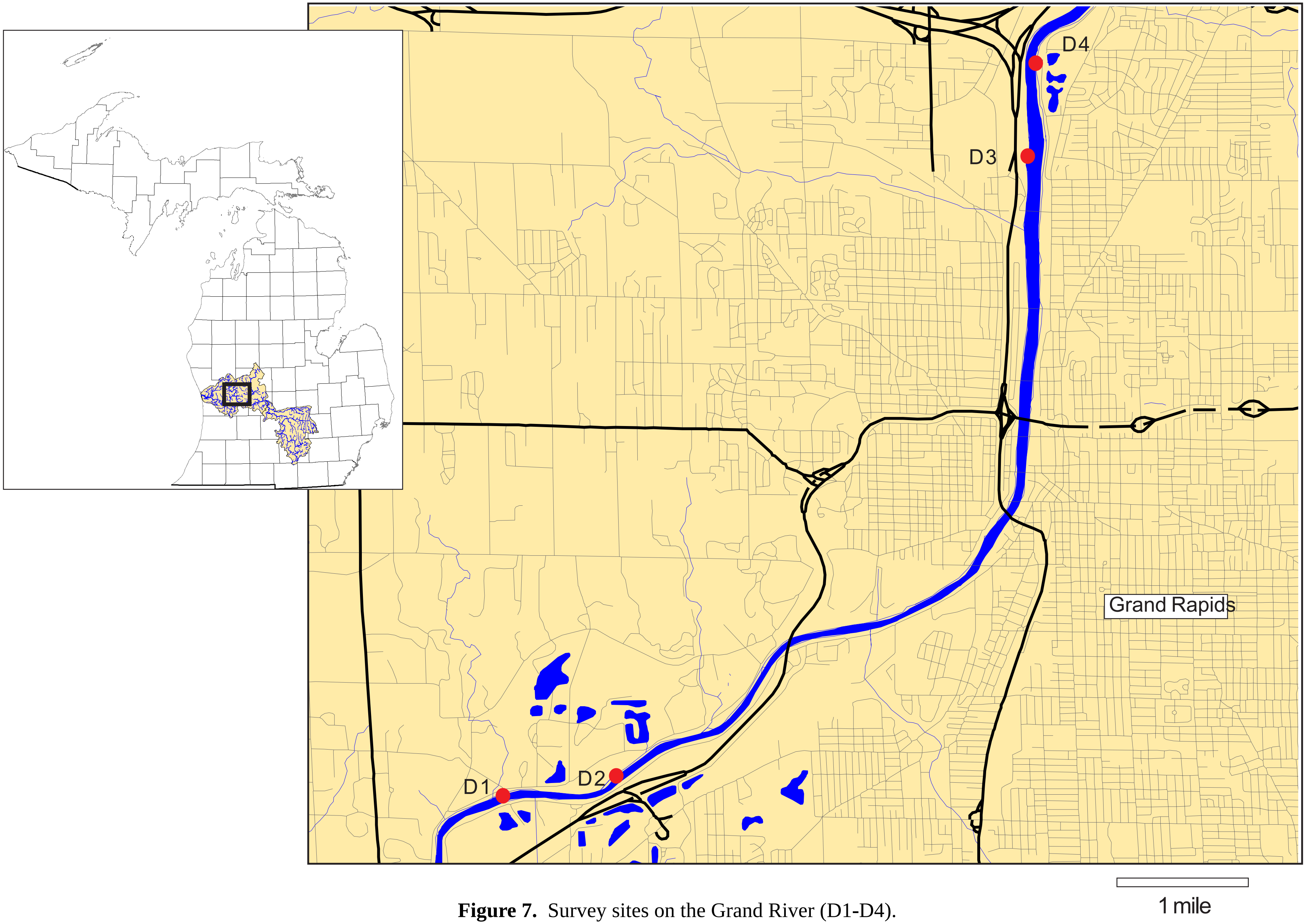


Figure 7. Survey sites on the Grand River (D1-D4).

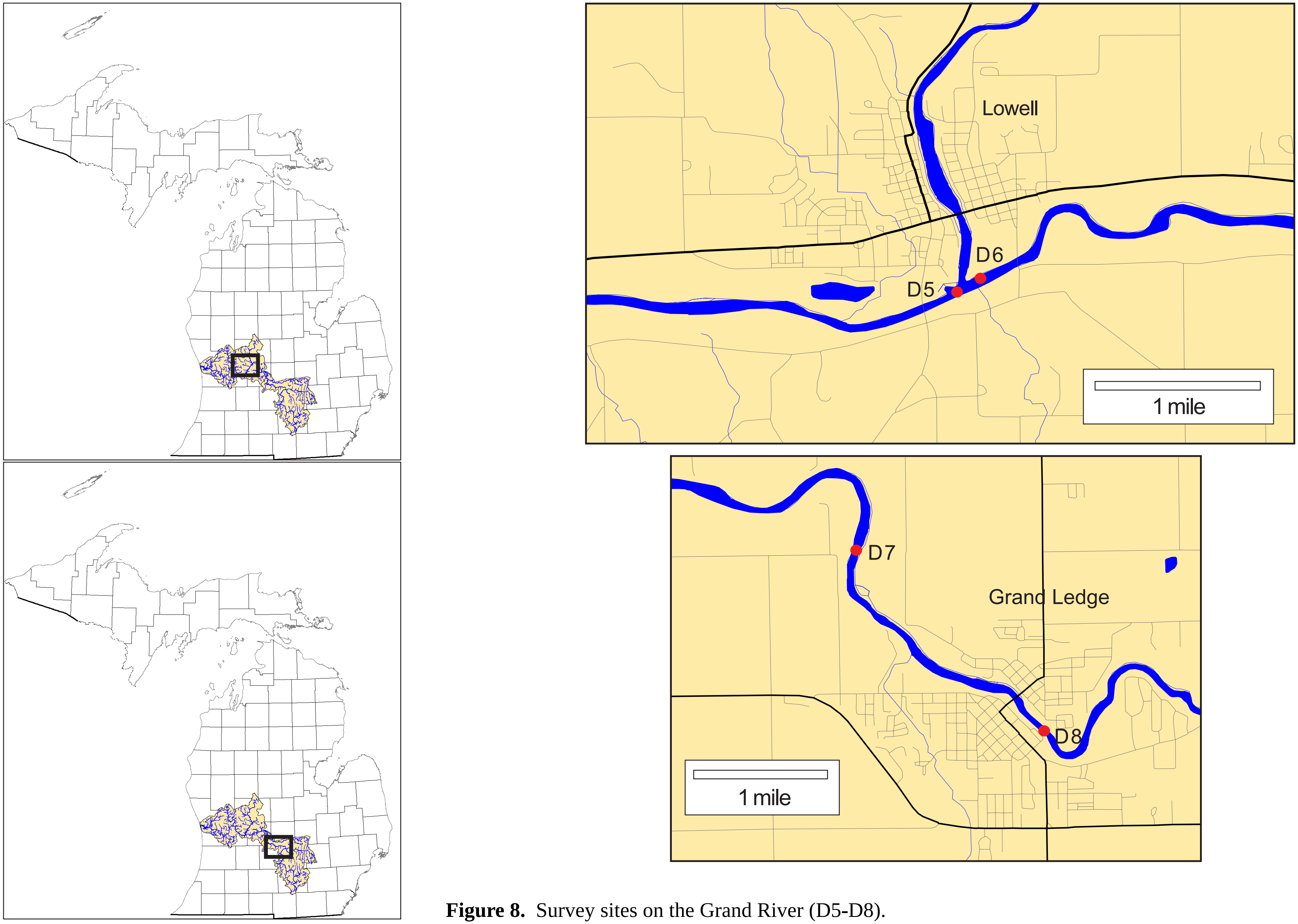


Figure 8. Survey sites on the Grand River (D5-D8).

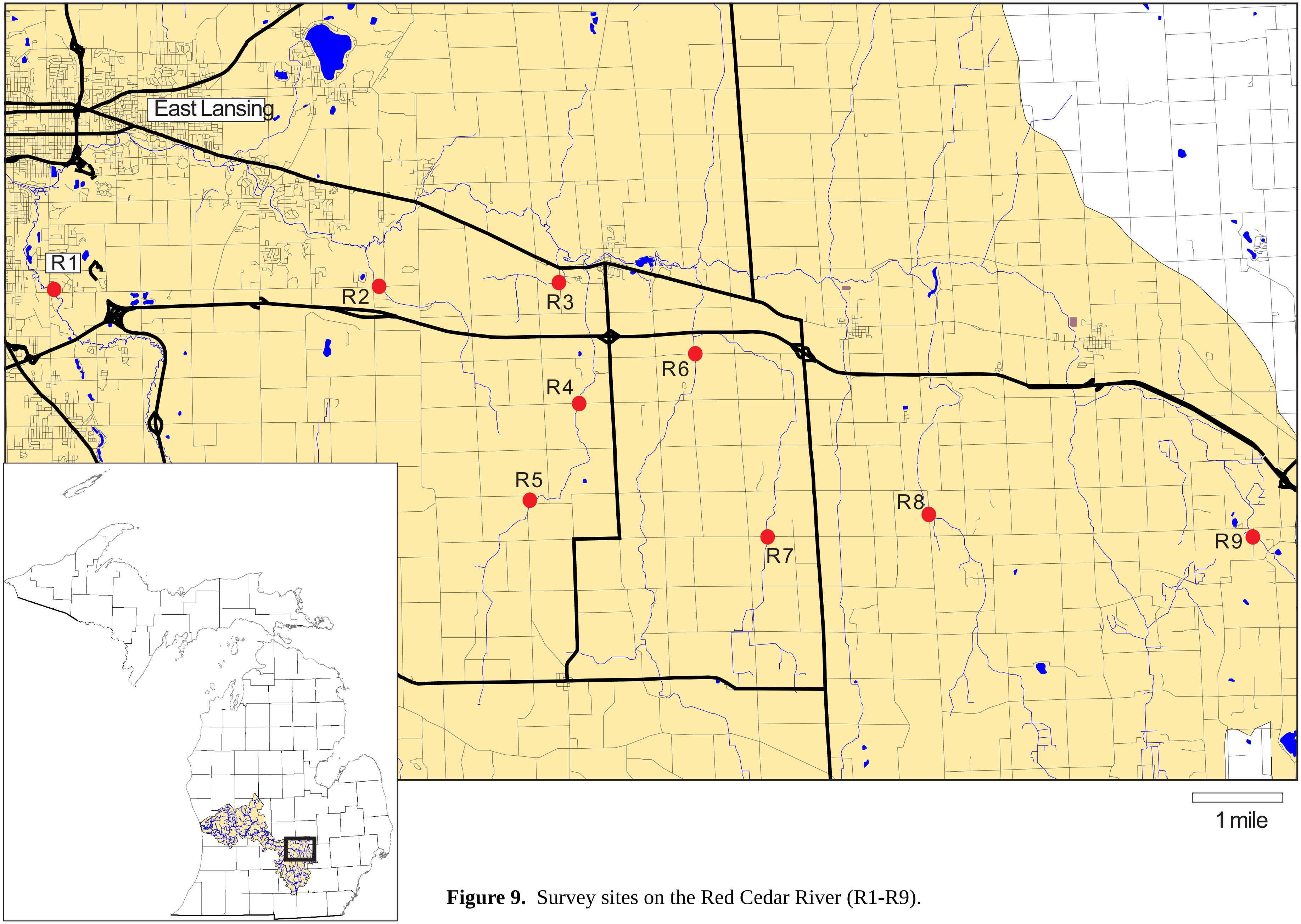
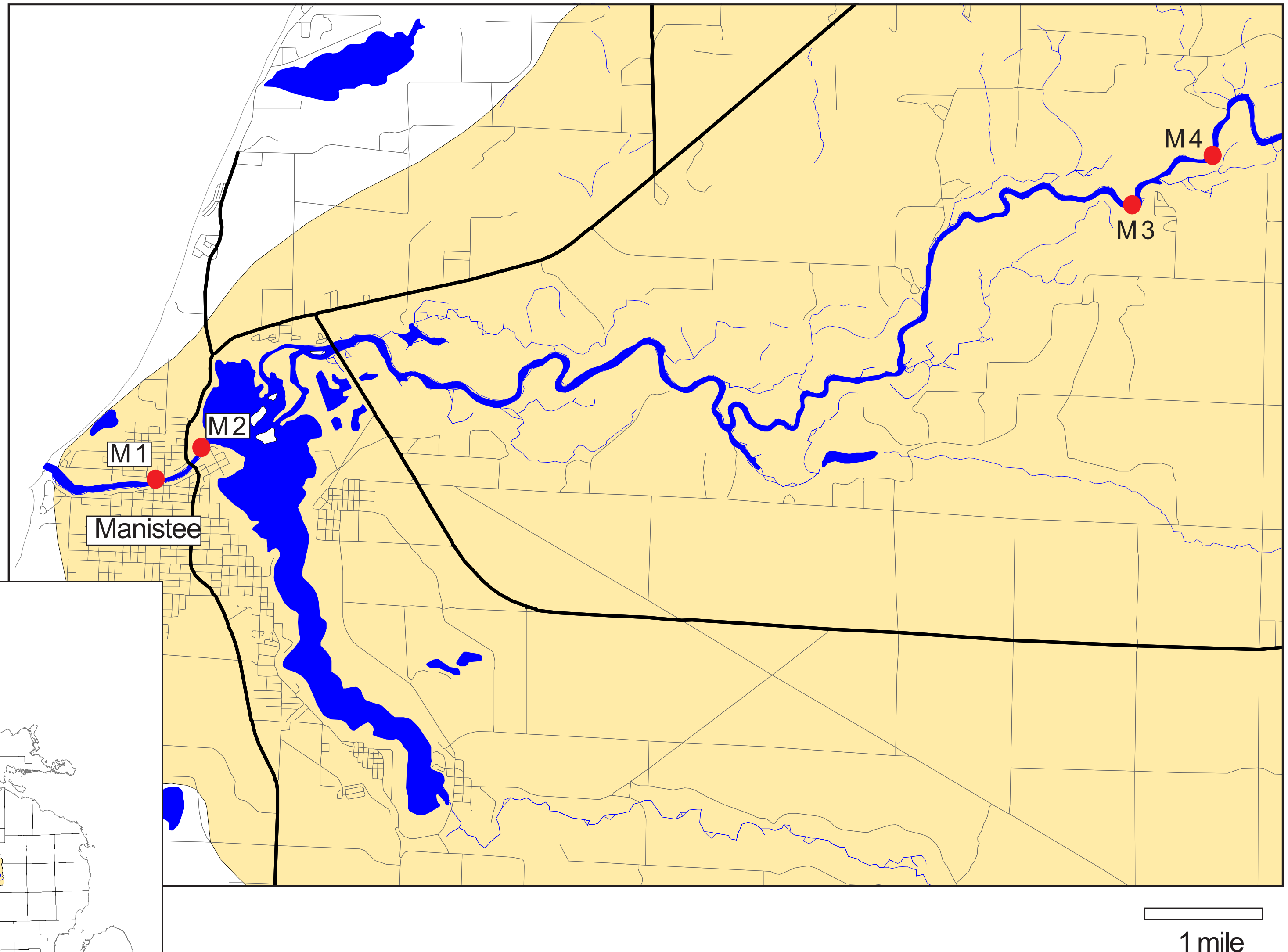


Figure 9. Survey sites on the Red Cedar River (R1-R9).



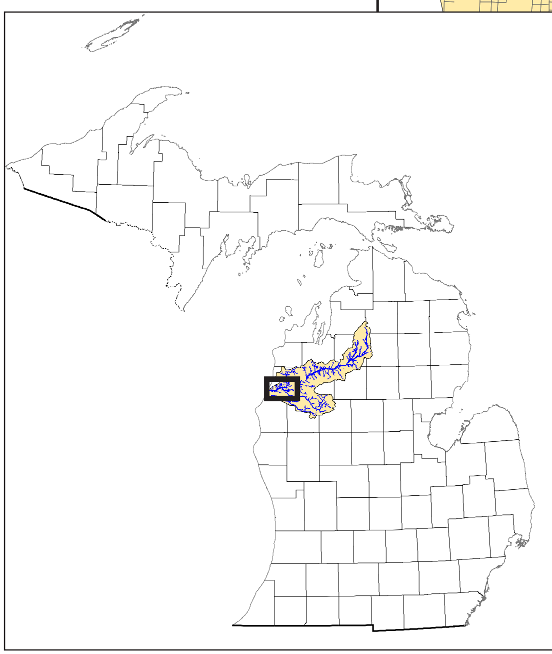


Figure 10. Survey sites on the Manistee River (M1-M4).

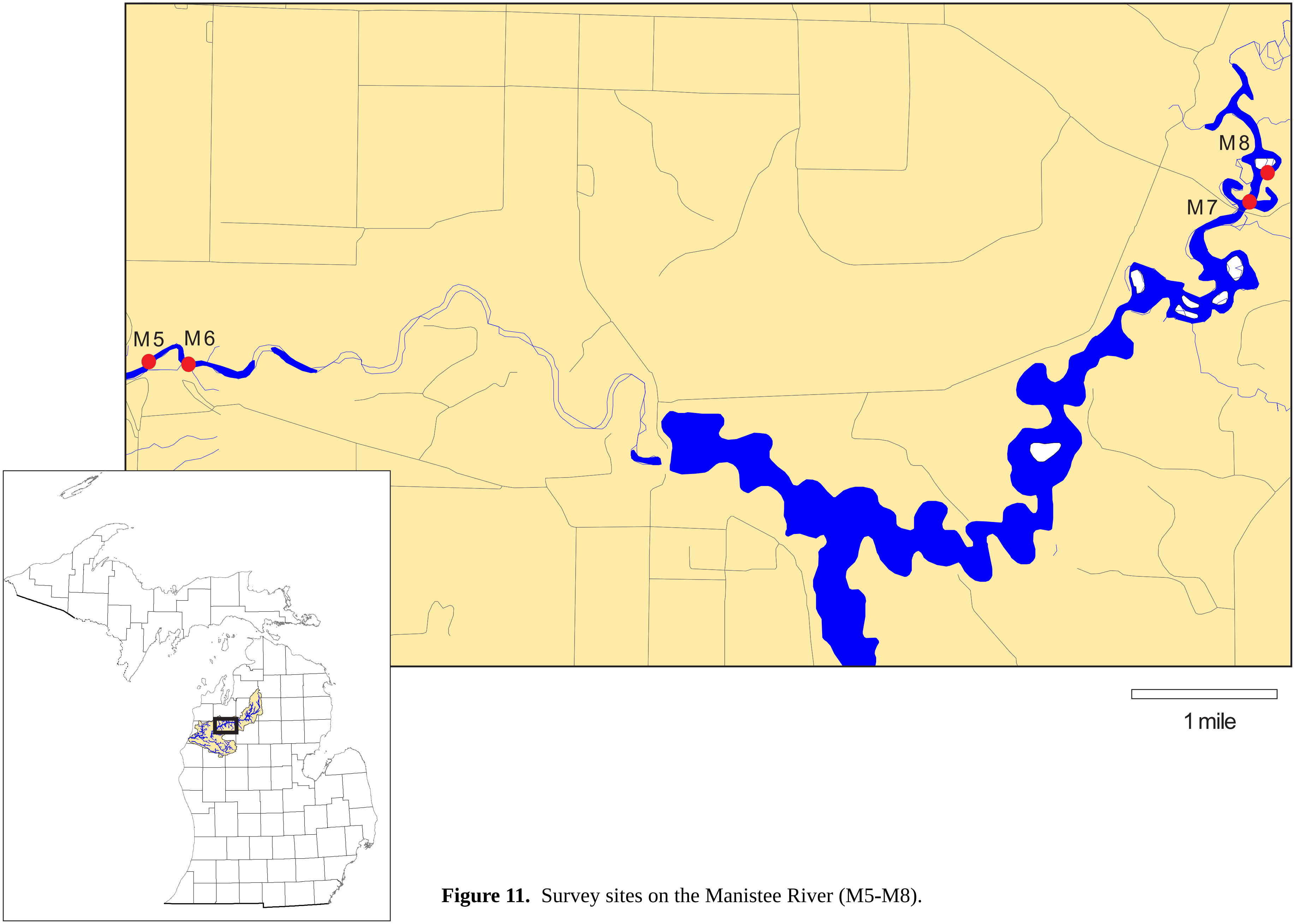


Figure 11. Survey sites on the Manistee River (M5-M8).

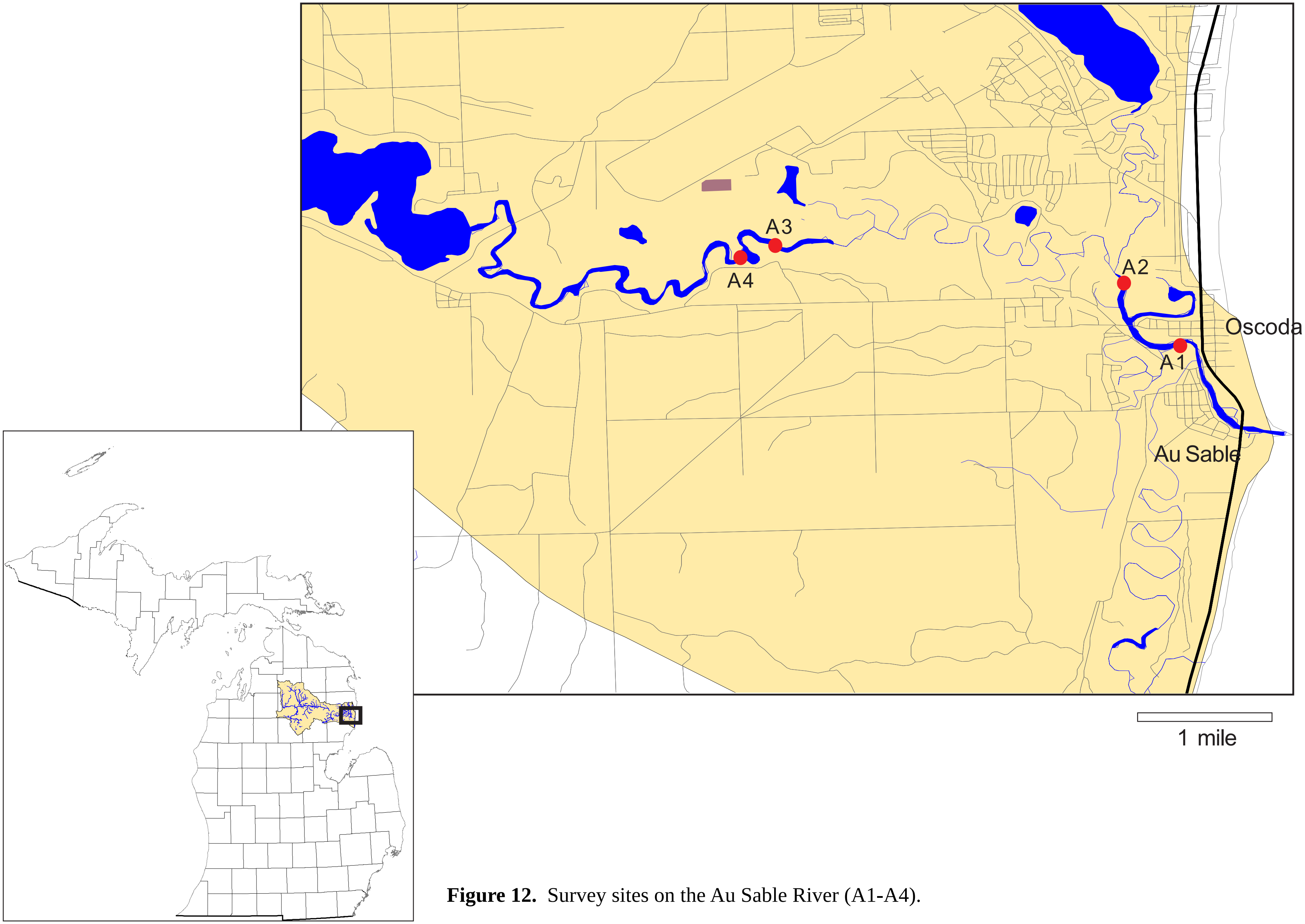


Figure 12. Survey sites on the Au Sable River (A1-A4).

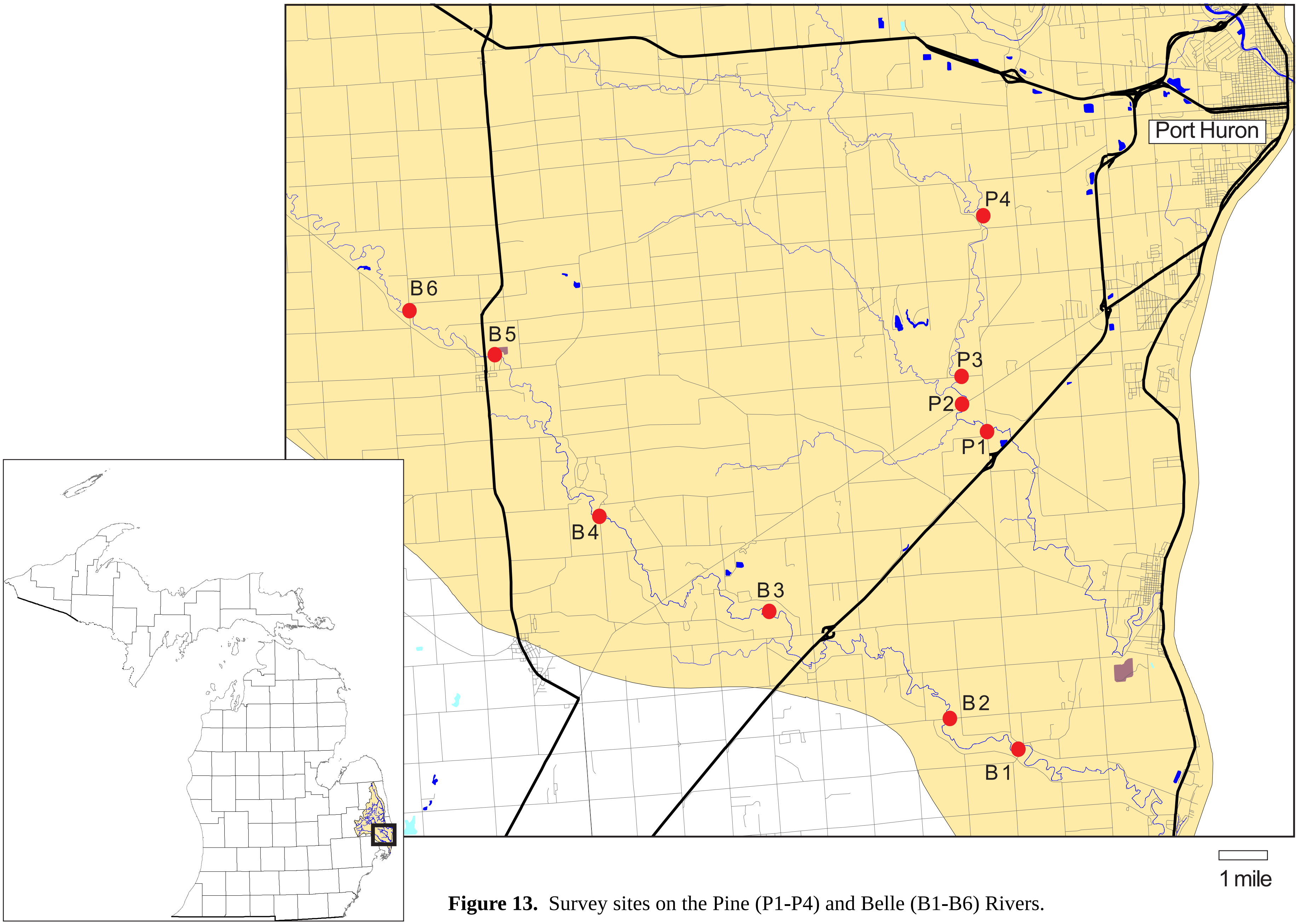


Figure 13. Survey sites on the Pine (P1-P4) and Belle (B1-B6) Rivers.

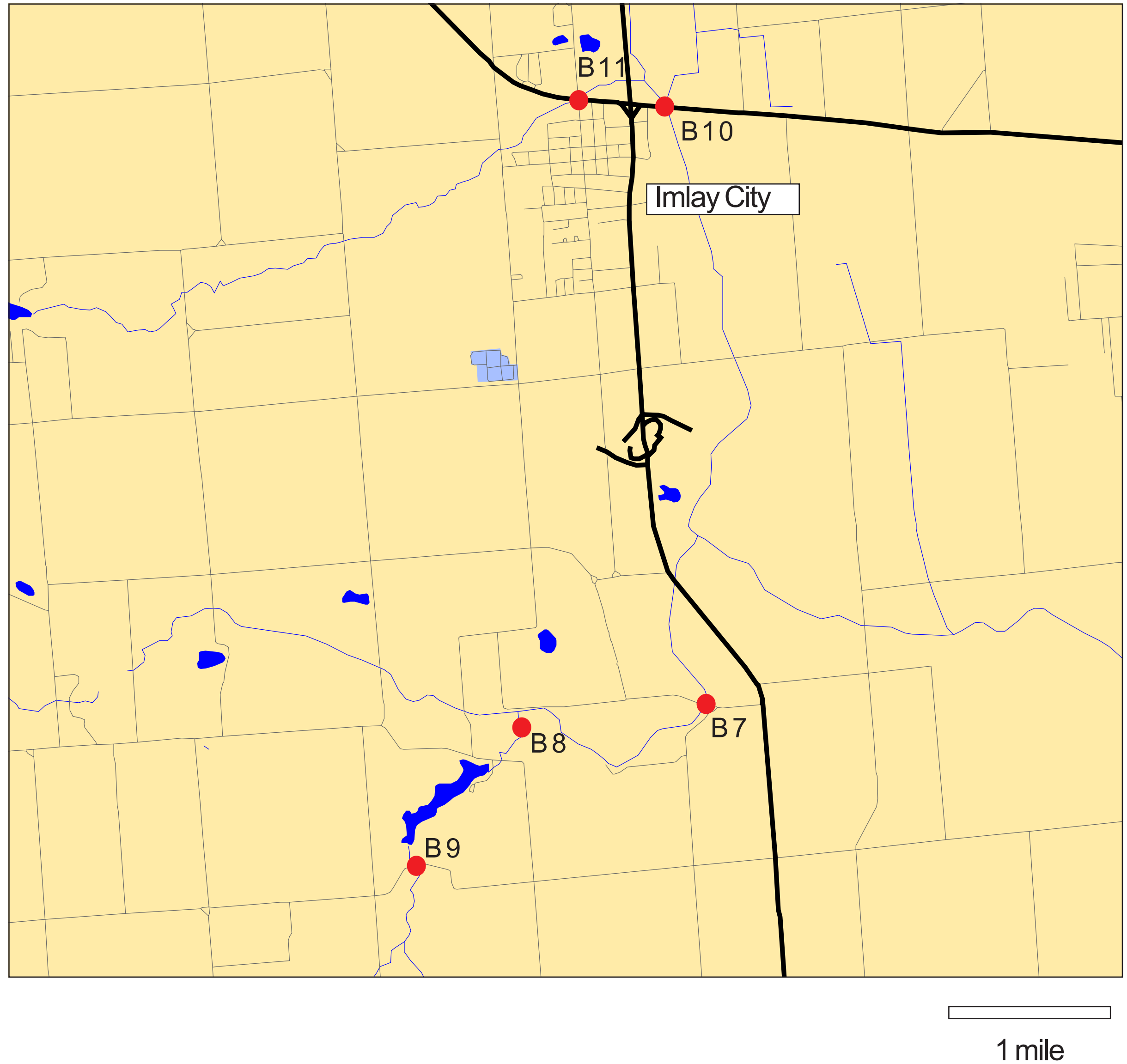


Figure 14. Survey sites on the Belle River (B7-B11).

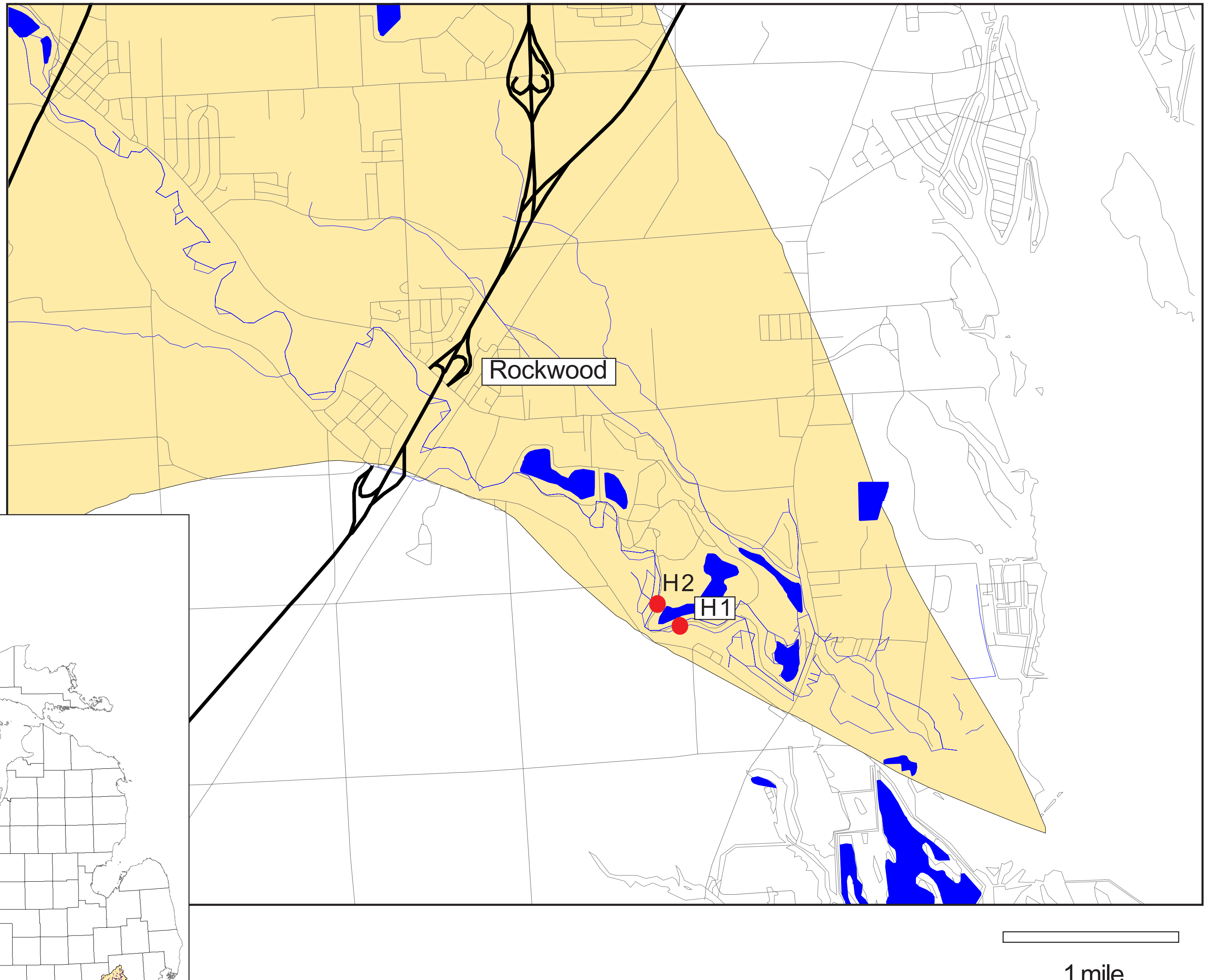


Figure 15. Survey sites on the Huron River (H1-H2).

Table 1. Scientific and common names of unionids found during surveys, summer 2002. (L=species represented by live individuals; S=species represented by shell only; E=state listed as endangered; T=state listed as threatened; SpC=state listed as special concern; *Elliptio crassidens* shell was found at site D5)

Species	Common Name	Galien	Grand	Red Cedar	Manistee	Au Sable	Pine	Belle	Huron
Actinonaias ligamentina	Mucket		S			L			
Alasmidonta marginata (SpC)	Elktoe		L					S	
Alasmidonta viridis (SpC)	Slippershell	L	S	S				L	
Amblema plicata	Threeridge		L				L	L	
Anodonta imbecillis	Paper pondshell				L			L	
Anodontoides ferussacianus	Cylindrical papershell	L	L	L	S			L	
Cyclonaias tuberculata (SpC)	Purple wartyback		S						
*Elliptio crassidens**	Elephant ear		S						
Elliptio dilatata	Spike	S	L	L	L	L	L	L	
Epioblasma triquetra (E)	Snuffbox		L				L	L	
Fusconaia flava	Wabash pigtoe		L	L	L	L	L	L	L
Lampsilis fasciola (T)	Wavy-rayed lampmussel							S	
Lampsilis siliquoidea	Fatmucket	S	S	L	L	L	L	L	
Lampsilis ventricosa	Pocketbook		L	L	L	L	L mdr, S	L	
Lasmigona complanata	White heelsplitter				L	S	L	L	
Lasmigona compressa	Creek heelsplitter		L				L mdr	L	
Lasmigona costata	Fluted-shell		L	L			L	L	
Leptodea fragilis	Fragile papershell		L			S	L	L	S
Ligumia recta	Black sandshell		L		L	L	L	S	
Obliquaria reflexa	Three-horned wartyback								L
Obovaria subrotunda (E)	Round hickorynut						L	L	
Pleurobema sintoxia (SpC)	Round pigtoe		S				L	S	
Potamilus alatus	Pink heelsplitter					L	L	L	L
Ptychobranchus fasciolaris	Kidney-shell						L	L	
Pyganodon grandis	Giant floater	L	L	L	L		L	L	S
Quadrula pustulosa	Pimpleback		L				L	L	L
Quadrula quadrula	Mapleleaf		L			L		L	L
Strophitus undulatus	Strange floater	L	L	S	L	S	L	L	
Truncilla truncata	Deertoe		L				S	L	L
Venustaconcha ellipsiformis (SpC)	Ellipse		L	L					
Villosa fabalis (E)	Rayed bean						L	L	
Villosa iris (SpC)	Rainbow		S	L			L	L	
	# species live	4	17	9	9	8	20	23	6
	# species live or shell	6	23	11	10	11	21	27	8
Corbicula fluminea (Exotic)	Asian clam		L		S				
Dreissena polymorpha (Exotic)	Zebra mussel		L		L	L			L
Neogobius melanostomus (Exotic)	Round goby		L		L	L			

Table 2. Numbers of unionids (#), relative abundance (RA), and density (D, individuals/m²) recorded at each site surveyed. (N=Galien River; D=Grand River; R=Red Cedar River; M=Manistee River; A=Au Sable River; P=Pine River; B=Belle River; H=Huron River; S=species represented by shell only; Lmdr=live individuals found outside of transect)

	N1	N2	N3			N4			N5	N6	N7	N8	N9	N10			N11	N12		
Species			#	RA	D	#	RA	D						#	RA	D		#	RA	D
Actinonaias ligamentina																				
Alasmidonta marginata (SpC)																				
Alasmidonta viridis (SpC)									S									1	1.00	0.01
Amblema plicata																				
Anodonta imbecillis																				
Anodontoides ferussacianus			6	0.75	0.05									1	1.00	0.01				
Cyclonaias tuberculata (SpC)																				
Elliptio dilatata									S											
Epioblasma triquetra (E)																				
Fusconaia flava																				
Lampsilis fasciola (T)																				
Lampsilis siliquoidea									S											
Lampsilis ventricosa																				
Lasmigona complanata																				
Lasmigona compressa																				
Lasmigona costata																				
Leptodea fragilis																				
Ligumia recta																				
Obliquaria reflexa																				
Obovaria olivaria (SpC)																				
Obovaria subrotunda (E)																				
Pleurobema sintoxia (SpC)																				
Potamilus alatus																				
Ptychobranchus fasciolaris																				
Pyganodon grandis			1	0.13	0.01	1	1.00	0.01												
Quadrula pustulosa																				
Quadrula quadrula																				
Strophitus undulatus			1	0.13	0.01															
Truncilla truncata																				
Venustaconcha ellipsiformis (SpC)																				
Villosa fabalis (E)																				
Villosa iris (SpC)																				
Total # individuals and density	0	0	8		0.06	1		0.01	0	0	0	0	0	1		0.01	0	1		0.01
# species live	0	0	3			1			0	0	0	0	0	1			0	1		
# species live or shell	0	0	3			1			3	0	0	0	0	1			0	1		

Table 2. (cont.)

	D1			D2			D3			D4			D5			D6			D7	D8		
Species	#	RA	D	#	RA	D	#	RA	D	#	RA	D	#	RA	D	#	RA	D	#	#	RA	D
Actinonaias ligamentina	S			S															S	S		
Alasmidonta marginata (SpC)	S												2	0.02	0.02				S	S		
Alasmidonta viridis (SpC)							S													S		
Amblema plicata				S			16	0.47	0.13	3	0.43	0.02	22	0.18	0.17	1	0.09	0.01				
Anodonta imbecillis																						
Anodontoides ferussacianus													1	0.01	0.01							
Cyclonaias tuberculata (SpC)				S												S						
Elliptio dilatata				S									1	0.01	0.01				S	S		
Epioblasma triquetra (E)													14	0.12	0.11	S						
Fusconaia flava	S						3	0.09	0.02				8	0.07	0.06	2	0.18	0.02	S	S		
Lampsilis fasciola (T)																						
Lampsilis siliquoidea	S																			S		
Lampsilis ventricosa	1	0.09	0.01	S			2	0.06	0.02	2	0.29	0.02	19	0.16	0.15	1	0.09	0.01	S	1	1.00	0.01
Lasmigona complanata																						
Lasmigona compressa													2	0.02	0.02							
Lasmigona costata	1	0.09	0.01	S			1	0.03	0.01				20	0.17	0.16	2	0.18	0.02	S	S		
Leptodea fragilis	3	0.27	0.02	4	0.50	0.03																
Ligumia recta							S						S			1	0.09	0.01				
Obliquaria reflexa																						
Obovaria olivaria (SpC)																						
Obovaria subrotunda (E)																						
Pleurobema sintoxia (SpC)	S																			S		
Potamilus alatus																						
Ptychobranchus fasciolaris																						
Pyganodon grandis							1	0.03	0.01				4	0.03	0.03							
Quadrula pustulosa	2	0.18	0.02	S			7	0.21	0.05	1	0.14	0.01	3	0.03	0.02	2	0.18	0.02				
Quadrula quadrula	3	0.27	0.02	4	0.50	0.03	4	0.12	0.03	1	0.14	0.01	3	0.03	0.02	2	0.18	0.02				
Strophitus undulatus				S									6	0.05	0.05				S	S		
Truncilla truncata	1	0.09	0.01	S									5	0.04	0.04							
Venustaconcha ellipsiformis (SpC)													10	0.08	0.08							
Villosa fabalis (E)																						
Villosa iris (SpC)																			S	S		
Total # individuals and density	11		0.09	8		0.06	34		0.27	7		0.05	120		0.94	11		0.09	0	1		0.01
# species live	6			2			7			4			15			7			0	1		
# species live or shell	11			11			9			4			16			9			8	10		

Table 2. (cont.)

Species	R1			R2	R3	R4	R5			R6			R7			R8			R9
	#	RA	D				#	RA	D	#	RA	D	#	RA	D	#	RA	D	
Actinonaias ligamentina																			
Alasmidonta marginata (SpC)																			
Alasmidonta viridis (SpC)	S															S			
Amblema plicata																			
Anodonta imbecillis																			
Anodontoides ferussacianus							1	0.50	0.01	S						S			
Cyclonaias tuberculata (SpC)																			
Elliptio dilatata	49	0.70	0.38																
Epioblasma triquetra (E)																			
Fusconaia flava	2	0.03	0.02				1	0.50	0.01	5	0.63	0.04							
Lampsilis fasciola (T)																			
Lampsilis siliquoidea	1	0.01	0.01							2	0.25	0.02				10	1.00	0.08	
Lampsilis ventricosa	7	0.10	0.05																
Lasmigona complanata																			
Lasmigona compressa																			
Lasmigona costata	5	0.07	0.04																
Leptodea fragilis																			
Ligumia recta																			
Obliquaria reflexa																			
Obovaria olivaria (SpC)																			
Obovaria subrotunda (E)																			
Pleurobema sintoxia (SpC)																			
Potamilus alatus																			
Ptychobranchus fasciolaris																			
Pyganodon grandis										S			1	1.00	0.01				
Quadrula pustulosa																			
Quadrula quadrula																			
Strophitus undulatus				S						S									
Truncilla truncata																			
Venustaconcha ellipsiformis (SpC)	1	0.01	0.01																
Villosa fabalis (E)																			
Villosa iris (SpC)	5	0.07	0.04							1	0.13	0.01							
Total # individuals and density	70		0.55	0	0	0	2		0.02	8		0.06	1		0.01	10		0.08	0
# species live	7			0	0	0	2			3			1			1			0
# species live or shell	8			1	0	0	2			6			1			3			0

Table 2. (cont.)

Species	M1	M2	M3	M4			M5			M6			M7	M8
				#	RA	D	#	RA	D	#	RA	D		
Actinonaias ligamentina														
Alasmidonta marginata (SpC)														
Alasmidonta viridis (SpC)														
Amblema plicata														
Anodonta imbecillis										1	0.04	0.01		
Anodontoides ferussacianus							S							
Cyclonaias tuberculata (SpC)														
Elliptio dilatata				1	1.00	0.01				2	0.08	0.02		
Epioblasma triquetra (E)														
Fusconaia flava							1	0.03	0.01	Lmdr				
Lampsilis fasciola (T)														
Lampsilis siliquoidea							4	0.13	0.03	2	0.08	0.02		S
Lampsilis ventricosa							11	0.34	0.09	9	0.36	0.07		
Lasmigona complanata							1	0.03	0.01					Lmdr
Lasmigona compressa														
Lasmigona costata														
Leptodea fragilis														
Ligumia recta							9	0.28	0.07	3	0.12	0.02		
Obliquaria reflexa														
Obovaria olivaria (SpC)														
Obovaria subrotunda (E)														
Pleurobema sintoxia (SpC)														
Potamilus alatus														
Ptychobranchus fasciolaris														
Pyganodon grandis							1	0.03	0.01	1	0.04	0.01		
Quadrula pustulosa														
Quadrula quadrula														
Strophitus undulatus			S				5	0.16	0.04	7	0.28	0.05		
Truncilla truncata														
Venustaconcha ellipsiformis (SpC)														
Villosa fabalis (E)														
Villosa iris (SpC)														
Total # individuals and density	0	0	0	1		0.01	32		0.25	25		0.20	0	0
# species live	0	0	0	1			7			8			0	1
# species live or shell	0	0	1	1			8			8			0	2

Table 2. (cont.)

Species	A1			A2			A3	A4	P1			P2			P3			P4		
	#	RA	D	#	RA	D			#	RA	D	#	RA	D	#	RA	D	#	RA	D
Actinonaias ligamentina	7	0.18	0.05	2	0.06	0.02	S													
Alasmidonta marginata (SpC)																				
Alasmidonta viridis (SpC)																				
Amblema plicata									Lmdr			2	0.03	0.02	5	0.07	0.04			
Anodonta imbecillis																				
Anodontoides ferussacianus																				
Cyclonaias tuberculata (SpC)																				
Elliptio dilatata	2	0.05	0.02						26	0.43	0.20	17	0.24	0.13	1	0.01	0.01			
Epioblasma triquetra (E)									Lmdr			2	0.03	0.02	Lmdr					
Fusconaia flava	11	0.28	0.09	12	0.38	0.09		S	12	0.20	0.09	17	0.24	0.13	4	0.06	0.03	1	0.33	0.01
Lampsilis fasciola (T)																				
Lampsilis siliquoidea				1	0.03	0.01			4	0.07	0.03	4	0.06	0.03	6	0.08	0.05	1	0.33	0.01
Lampsilis ventricosa	13	0.33	0.10	13	0.41	0.10	S	S	S									Lmdr		
Lasmigona complanata	S			S					1	0.02	0.01	2	0.03	0.02	2	0.03	0.02	Lmdr		
Lasmigona compressa																		Lmdr		
Lasmigona costata									7	0.11	0.05	4	0.06	0.03	10	0.14	0.08			
Leptodea fragilis				S			S					7	0.10	0.05	27	0.38	0.21	1	0.33	0.01
Ligumia recta	4	0.10	0.03	4	0.13	0.03			Lmdr			1	0.01	0.01						
Obliquaria reflexa																				
Obovaria olivaria (SpC)																				
Obovaria subrotunda (E)									S			1	0.01	0.01	S			S		
Pleurobema sintoxia (SpC)									S			4	0.06	0.03	7	0.10	0.05			
Potamilus alatus	1	0.03	0.01				S		Lmdr						8	0.11	0.06			
Ptychobranchus fasciolaris									3	0.05	0.02	3	0.04	0.02	1	0.01	0.01	Lmdr		
Pyganodon grandis									S			1	0.01	0.01	1	0.01	0.01	Lmdr		
Quadrula pustulosa												1	0.01	0.01						
Quadrula quadrula	1	0.03	0.01																	
Strophitus undulatus								S	5	0.08	0.04	2	0.03	0.02						
Truncilla truncata												S								
Venustaconcha ellipsiformis (SpC)																				
Villosa fabalis (E)									S			1	0.01	0.01	S			S		
Villosa iris (SpC)									3	0.05	0.02	1	0.01	0.01	Lmdr			S		
Total # individuals and density	39		0.30	32		0.25	0	0	61		0.48	70		0.55	72		0.56	3		0.02
# species live	7			5			0	0	12			17			13			8		
# species live or shell	8			7			4	3	17			18			15			11		

Table 2. (cont.)

	B1			B2			B3			B4			B5	B6			B7		
Species	#	RA	D	#	RA	D	#	RA	D	#	RA	D		#	RA	D	#	RA	D
Actinonaias ligamentina																			
Alasmidonta marginata (SpC)				S			S												
Alasmidonta viridis (SpC)							S			S				2	0.02	0.02			
Amblema plicata	2	0.04	0.02	S			16	0.16	0.13										
Anodonta imbecillis										1	0.50	0.01							
Anodontoides ferussacianus										S				4	0.03	0.03			
Cyclonaias tuberculata (SpC)																			
Elliptio dilatata	S						4	0.04	0.03					3	0.03	0.02			
Epioblasma triquetra (E)	1	0.02	0.01	S			S												
Fusconaia flava	2	0.04	0.02	1	0.03	0.01	7	0.07	0.05					3	0.03	0.02	S		
Lampsilis fasciola (T)							S			S									
Lampsilis siliquoidea	S			S			4	0.04	0.03	Lmdr			Lmdr	23	0.19	0.18	1	0.33	0.01
Lampsilis ventricosa	2	0.04	0.02	3	0.09	0.02	S			S									
Lasmigona complanata	8	0.15	0.06	15	0.47	0.12	10	0.10	0.08	1	0.50	0.01	Lmdr	19	0.16	0.15	2	0.66	0.02
Lasmigona compressa							5	0.05	0.04					4	0.03	0.03			
Lasmigona costata	19	0.37	0.15	3	0.09	0.02	7	0.07	0.05					6	0.05	0.05			
Leptodea fragilis	2	0.04	0.02	4	0.13	0.03	6	0.06	0.05	S				1	0.01	0.01			
Ligumia recta	S																		
Obliquaria reflexa																			
Obovaria olivaria (SpC)																			
Obovaria subrotunda (E)	S			1	0.03	0.01	S												
Pleurobema sintoxia (SpC)	S			S			S												
Potamilus alatus	2	0.04	0.02				5	0.05	0.04										
Ptychobranchus fasciolaris	S						25	0.26	0.20										
Pyganodon grandis	S			1	0.03	0.01	1	0.01	0.01	S				9	0.08	0.07	S		
Quadrula pustulosa	2	0.04	0.02																
Quadrula quadrula	S			2	0.06	0.02													
Strophitus undulatus	10	0.19	0.08	1	0.03	0.01	1	0.01	0.01	S			Lmdr	45	0.38	0.35			
Truncilla truncata	1	0.02	0.01																
Venustaconcha ellipsiformis (SpC)																			
Villosa fabalis (E)	1	0.02	0.01	1	0.03	0.01													
Villosa iris (SpC)	S			S			6	0.06	0.05	S			Lmdr						
Total # individuals and density	52		0.41	32		0.25	97		0.76	2		0.02	0	119		0.93	3		0.02
# species live	12			10			13			3			4	11			2		
# species live or shell	21			16			20			11			4	11			4		

Table 2. (cont.)

	B8			B9			B10	B11	H1			H2		
Species	#	RA	D	#	RA	D			#	RA	D	#	RA	D
Actinonaias ligamentina														
Alasmidonta marginata (SpC)														
Alasmidonta viridis (SpC)								S						
Amblema plicata														
Anodonta imbecillis														
Anodontoides ferussacianus	S							S						
Cyclonaias tuberculata (SpC)														
Elliptio dilatata														
Epioblasma triquetra (E)														
Fusconaia flava									1	0.17	0.01			
Lampsilis fasciola (T)														
Lampsilis siliquoidea				S				S						
Lampsilis ventricosa														
Lasmigona complanata	2	1.00	0.02	3	1.00	0.02		S						
Lasmigona compressa														
Lasmigona costata														
Leptodea fragilis												S		
Ligumia recta														
Obliquaria reflexa									2	0.33	0.02			
Obovaria olivaria (SpC)														
Obovaria subrotunda (E)														
Pleurobema sintoxia (SpC)														
Potamilus alatus												1	0.09	0.01
Ptychobranchus fasciolaris														
Pyganodon grandis									S			S		
Quadrula pustulosa												3	0.27	0.02
Quadrula quadrula									3	0.50	0.02	5	0.45	0.04
Strophitus undulatus														
Truncilla truncata												2	0.18	0.02
Venustaconcha ellipsiformis (SpC)														
Villosa fabalis (E)														
Villosa iris (SpC)														
Total # individuals and density	2		0.02	3		0.02	0	0	6		0.05	11		0.09
# species live	1			1			0	0	3			4		
# species live or shell	2			2			0	4	4			6		

Table 3. Mean length of unionid species found in each river with standard error (±SE) and sample size (N).

	Galien			Grand			Red Cedar			Manistee			Au Sable			Pine			Belle			Huron		
Species	Mean	±SE	N	Mean	±SE	N	Mean	±SE	N	Mean	±SE	N	Mean	±SE	N	Mean	±SE	N	Mean	±SE	N	Mean	±SE	N
A. ligamentina													81.4		9									
A. marginata (SpC)				51.5	7.5	2													53		1			
A. viridis (SpC)	40		1																31.5	1.5	2			
A. plicata				87.0	4.2	42										106.0	5.0	5	93.1	5.2	18			
A. imbecillis										47		1												
A. ferussacianus	66.4	5.0	7	56		1	51		1										51.4	3.8	5			
C. tuberculata (SpC)																								
E. dilatata				91		1	67.3	1.0	49	84.0	7.2	3	54.0	3.0	2	70		1	86.1	3.7	7			
E. triquetra (E)				55.9	3.5	14													49		1			
F. flava				61.2	4.5	13	61.3	4.6	8	81		1	55.6	3.2	23	72.4	5.9	5	68.3	3.5	13	75		1
L. fasciola (T)																								
L. siliquoidea							78.5	3.5	8	67.7	4.0	6	50		1	80.0	6.4	7	89.6	2.7	28			
L. ventricosa				87.3	5.2	26	103		1	107.6	3.4	21	83.3	4.2	26				109.0	6.1	5			
L. complanata										104		1				87.0	9.0	2	111.2	3.0	60			
L. compressa				58.5	7.5	2													75.0	3.7	9			
L. costata				91.8	6.7	24	98.4	2.4	5							105.4	5.4	10	94.1	2.8	35			
L. fragilis				150.4	2.3	7										91.7	3.4	28	78.2	4.8	13			
L. recta				140		1				136.3	6.7	12	100.9	11.5	8									
O. reflexa																						44.5	0.5	2
O. subrotunda (E)																			36		1			
P. sintoxia (SpC)																63.7	4.8	7						
P. alatus													126		1	92.8	7.6	8	121.1	6.1	7	113		1
P. fasciolaris																74		1	101.1	2.0	25			
P. grandis	102.5	8.5	2	79.6	20.1	5	98		1	82.0	5.0	2				72		1	57.7	4.8	11			
Q. pustulosa				58.3	4.5	16													72.0	8.0	2	67.7	14.0	3
Q. quadrula				92.2	6.1	14							73		1				80.5	4.5	2	74.8	5.6	8
S. undulatus	71		1	73.0	4.4	6				70.4	2.4	9							68.8	1.5	57			
T. truncata				36.3	3.7	6													49		1	41		1
V. ellipsiformis (SpC)				57.9	3.5	10	65		1															
V. fabalis (E)																			25.0	4.0	2			
V. iris (SpC)							48.7	1.9	6										57.3	3.6	6			

Table 4. Occurrence of *Corbicula fluminea* (Asian clam), *Dreissena polymorpha* (zebra mussel), and *Neogobius melanostomus* (round goby) by site. (L=species represented by live individuals; LA=*D. polymorpha* found attached to unionids; S=species represented by shell only)

Exotic species	D1	D5	D6	D7	D8	M1	M2	M3	M4	M5	M6	M7	M8	A1	A2	A3	A4	H1
Corbicula fluminea		L	L	L	L			S										
Dreissena polymorpha		L				L	L		LA	LA	LA	L	L	LA	LA	S	S	L
Neogobius melanostomus	L						L							L	L			

Tables 5a-b. *Dreissena polymorpha* (zebra mussel) colonization data, including the number of unionids colonized by *D. polymorpha* per site (UCZ), mean number of *D. polymorpha* per colonized unionid (ZM/U), and the percentage of individuals at a site colonized by *D. polymorpha* (%CU).

a.

	M4			M5			M6		
Species	UCZ	ZM/U	%CU	UCZ	ZM/U	%CU	UCZ	ZM/U	%CU
E. dilatata	1	12	100				1	2.0	50
F. flava				1	3.0	100			
L. siliquoidea				2	1.5	50	2	5.0	100
L. ventricosa				9	23.9	82	9	8.6	100
L. complanata				1	19.0	100			
L. recta				6	48.0	67	2	13.5	67
P. grandis				1	16.0	100	1	5.0	100
S. undulatus				4	19.3	80	7	6.4	100
Total	1	12	100	24	25.9	75	22	7.9	92

b.

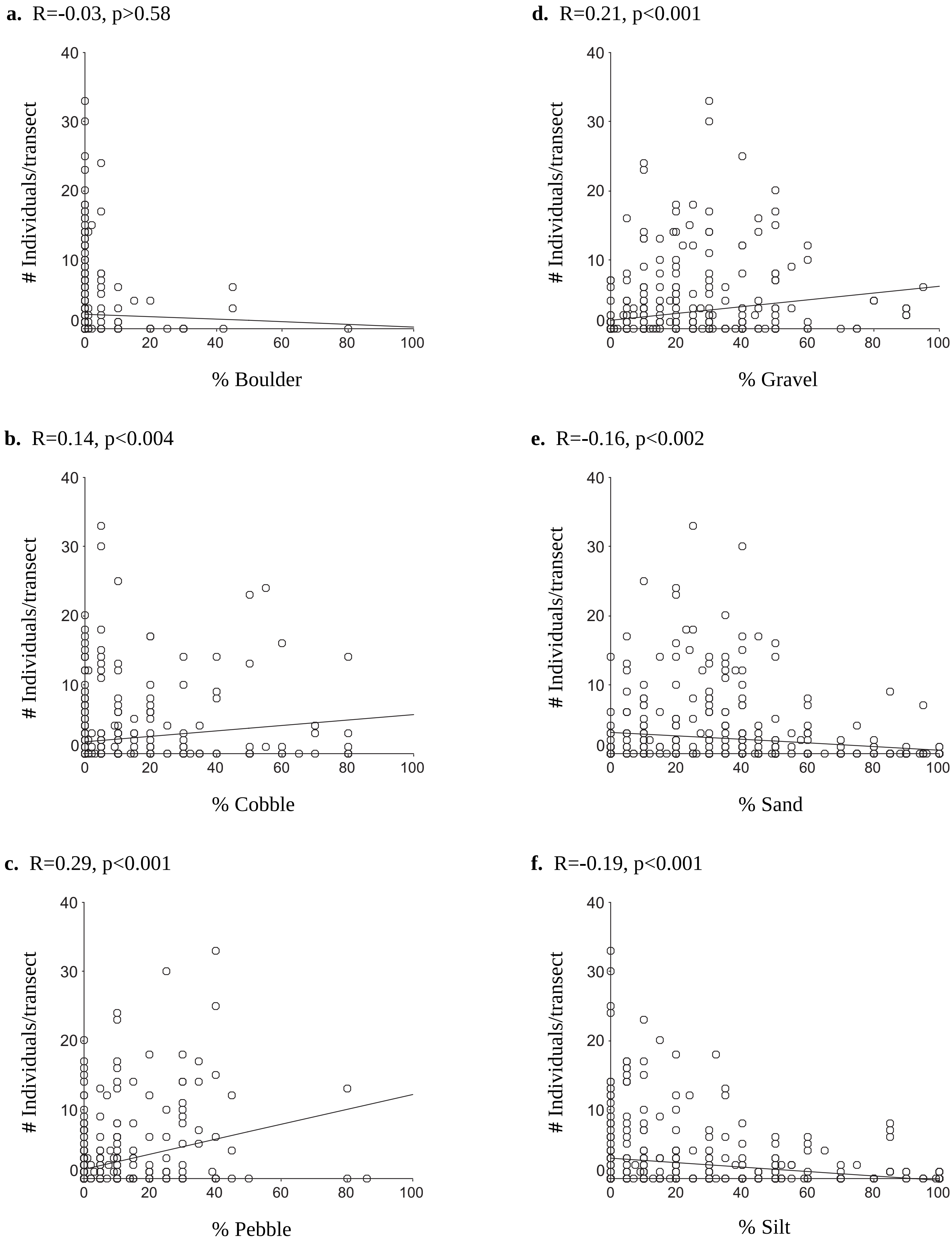
	A1			A2		
Species	UCZ	ZM/U	%CU	UCZ	ZM/U	%CU
A. ligamentina	2	1.0	29			
E. dilatata	1	1.0	50			
F. flava	2	1.0	18	2	1.0	17
L. ventricosa	5	2.8	39	4	1.5	31
L. recta	1	1.0	25	2	1.5	50
P. alatus	1	3.0	100			
Total	12	1.9	32	8	1.4	25

A significant positive correlation was detected between unionid abundance and the proportion of cobble, pebble, and gravel particle size classes (Figures 17b-17d). A significant negative correlation was detected between unionid abundance and the proportion of sand and silt particle size classes (Figures 17e-17f). A significant positive correlation was also detected between unionid species richness and the proportion of cobble, pebble, and gravel particle size classes (Figures 18b-18d), and a significant negative correlation was detected between unionid species richness and the proportion of sand and silt particle size classes (Figures 18e-18f). No significant correlation was detected between the proportion of boulder and unionid abundance or species richness (Figures 17a and 18a). Correlations between unionid abundance and five different size classes were calculated separately for each river, and the same was done for unionid species richness. Due to a large proportion of zero values in the boulder size class, results for this size class were omitted (Tables 7a-b). Correlations between abundance and all six different size classes were calculated separately for each species (Tables 8a and 8b). Mean substrate particle size composition was calculated for each river/watershed surveyed (Table 6).

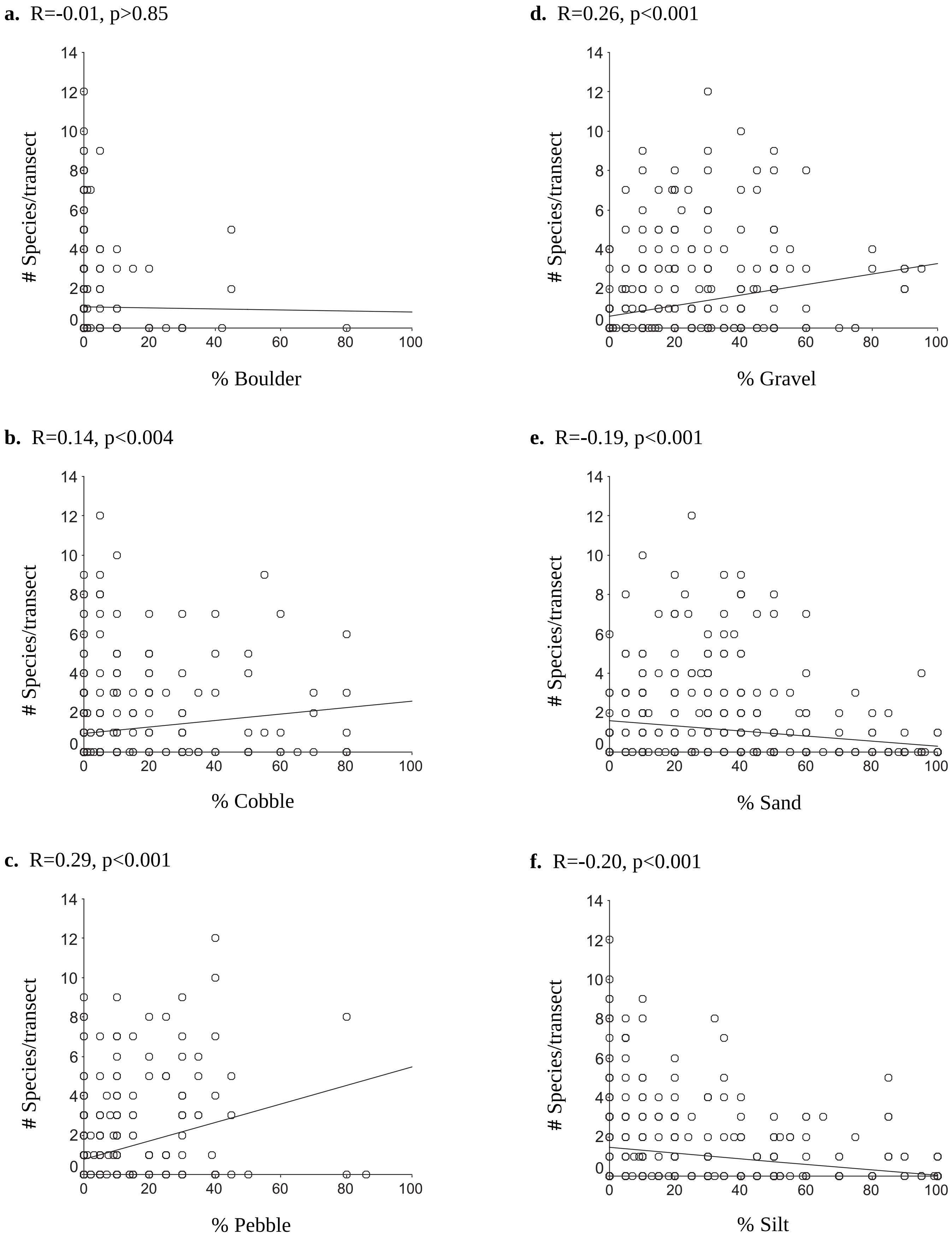
Figure 16. A modified stream channel surrounded by agriculture in the headwaters of the Red Cedar River. Photo by Pete Badra.

Table 6. Mean percentage composition for each substrate particle size class, mean abundance per transect, and mean species richness per transect for each river. (±SE=standard error; N=number of transects)

		Boulder	Cobble	Pebble	Gravel	Sand	Silt	Mean abundance /transect	Mean sp. Richness /transect	N
Galien River	mean %	0.4	1.0	3.7	9.6	47.3	38.0	0.11	0.08	96
	±SE	0.3	0.5	1.3	1.8	3.0	3.4	0.05	0.03	
Grand River	mean %	3.0	10.4	14.3	19.4	35.8	17.2	3.00	1.66	60
	±SE	0.8	2.0	2.1	1.6	3.3	3.4	0.76	0.30	
Red Cedar River	mean %	1.5	2.3	1.7	15.4	45.3	33.8	1.26	0.49	72
	±SE	1.1	0.8	0.6	2.1	2.6	2.2	0.42	0.11	
Manistee River	mean %	1.5	5.0	7.4	23.5	49.8	12.9	0.91	0.69	61
	±SE	0.8	1.3	1.8	3.7	4.5	2.1	0.25	0.18	
Au Sable River	mean %	0.0	5.2	8.6	23.9	56.6	5.6	2.22	1.16	31
	±SE	0.0	1.5	2.3	3.5	5.2	2.4	0.59	0.29	
Pine River	mean %	0.6	9.0	10.6	32.0	24.8	23.0	6.44	3.44	30
	±SE	0.3	2.0	2.2	2.5	3.5	3.3	1.00	0.46	
Belle River	mean %	1.9	22.5	7.3	18.4	22.3	27.8	3.52	1.75	86
	±SE	0.8	3.0	1.0	1.9	2.0	3.3	0.65	0.27	
Huron River	mean %	6.7	9.9	11.1	18.4	6.1	47.7	1.06	0.75	15
	±SE	3.2	3.0	2.6	2.7	2.7	7.1	0.40	0.27	
Total	mean %	1.5	8.2	7.0	18.2	38.8	26.3	2.06	1.09	451
	±SE	0.3	0.8	0.6	0.9	1.4	1.3	0.21	0.09	



Figures 17a-f. Unionid abundance versus estimated percent substrate composition for each particle size class (n=451 transects).



Figures 18a-f. Unionid species richness versus estimated percent substrate composition for each particle size class (n=451 transects).

Tables 7a-b. Correlations between unionid abundance and percent substrate composition of each particle size class for each river. Correlations between unionid species richness and percent composition of each substrate particle size class for each river. Significant correlations (p≤0.01) are in bold.

a.

		Galien		Grand		Red Cedar		Manistee	
Substrate		Abund.	Sp. rich	Abund.	Sp. rich	Abund.	Sp. rich	Abund.	Sp. rich
Cobble	Pearson Correlation	-0.01	-0.03	-0.10	-0.05	-0.12	-0.17	0.03	0.01
	Sig. (2-tailed)	0.890	0.781	0.448	0.699	0.324	0.145	0.790	0.951
	n	96	96	60	60	72	72	61	61
Pebble	Pearson Correlation	-0.05	-0.05	**0.40**	**0.44**	**0.39**	**0.38**	-0.18	-0.19
	Sig. (2-tailed)	0.623	0.625	**0.002**	**0.000**	**0.001**	**0.001**	0.159	0.133
	n	96	96	**60**	**60**	**72**	**72**	61	61
Gravel	Pearson Correlation	-0.09	-0.10	0.13	0.06	**0.32**	0.27	0.30	**0.38**
	Sig. (2-tailed)	0.394	0.337	0.313	0.657	**0.005**	0.022	0.019	**0.003**
	n	96	96	60	60	**72**	72	61	**61**
Sand	Pearson Correlation	0.01	0.02	-0.18	-0.25	-0.14	-0.10	-0.16	-0.19
	Sig. (2-tailed)	0.938	0.809	0.165	0.056	0.251	0.415	0.231	0.138
	n	96	96	60	60	72	72	61	61
Silt	Pearson Correlation	0.06	0.06	-0.01	0.04	-0.18	-0.14	-0.10	-0.13
	Sig. (2-tailed)	0.539	0.587	0.923	0.735	0.124	0.232	0.445	0.320
	n	96	96	60	60	72	72	61	61

b.

		Au Sable		Pine		Belle		Huron	
Substrate		Abund.	Sp. rich	Abund.	Sp. rich	Abund.	Sp. rich	Abund.	Sp. rich
Cobble	Pearson Correlation	0.26	**0.52**	0.07	-0.12	0.10	0.05	-0.42	-0.41
	Sig. (2-tailed)	0.153	**0.003**	0.716	0.525	0.365	0.661	0.118	0.130
	n	31	**31**	30	30	86	86	15	15
Pebble	Pearson Correlation	0.42	**0.64**	0.28	0.01	**0.42**	**0.43**	-0.05	-0.10
	Sig. (2-tailed)	0.020	**0.000**	0.141	0.967	**0.000**	**0.000**	0.849	0.730
	n	31	**31**	30	30	**86**	**86**	15	15
Gravel	Pearson Correlation	0.00	-0.04	0.03	0.18	0.21	**0.29**	0.02	-0.07
	Sig. (2-tailed)	0.994	0.834	0.856	0.337	0.055	**0.007**	0.951	0.793
	n	31	31	30	30	86	**86**	15	15
Sand	Pearson Correlation	**-0.46**	**-0.60**	0.14	0.36	0.10	0.12	0.02	-0.02
	Sig. (2-tailed)	**0.009**	**0.000**	0.475	0.048	0.367	0.289	0.933	0.936
	n	**31**	**31**	30	30	85	85	15	15
Silt	Pearson Correlation	0.44	0.43	-0.41	-0.45	**-0.41**	**-0.44**	0.36	0.44
	Sig. (2-tailed)	0.014	0.016	0.026	0.012	**0.000**	**0.000**	0.184	0.102
	n	31	31	30	30	**86**	**86**	15	15

Tables 8a-b. Correlations between abundance and percent substrate composition of each particle size class for each species. Significant correlations (p≤0.01) are in bold.

a.

Species		Boulder	Cobble	Pebble	Gravel	Sand	Silt
A_LIG	Pearson Correlation	-0.03	0.04	**0.17**	0.05	-0.06	-0.06
	Sig. (2-tailed)	0.517	0.455	**0.000**	0.337	0.206	0.202
	n	451	451	**451**	451	450	451
A_MAR	Pearson Correlation	-0.02	-0.01	**0.15**	0.04	-0.02	-0.06
	Sig. (2-tailed)	0.737	0.786	**0.001**	0.390	0.664	0.180
	n	451	451	**451**	451	450	451
A_VIR	Pearson Correlation	-0.02	0.09	0.02	-0.01	-0.06	0.02
	Sig. (2-tailed)	0.747	0.055	0.678	0.756	0.180	0.739
	n	451	451	451	451	450	451
A_PLI	Pearson Correlation	-0.02	-0.05	**0.26**	0.05	-0.10	-0.02
	Sig. (2-tailed)	0.722	0.334	**0.000**	0.271	0.039	0.625
	n	451	451	**451**	451	450	451
A_IMB	Pearson Correlation	0.04	0.12	0.00	-0.05	-0.05	0.01
	Sig. (2-tailed)	0.455	0.013	0.957	0.255	0.293	0.852
	n	451	451	451	451	450	451
A_FER	Pearson Correlation	-0.03	0.07	-0.01	-0.07	0.02	-0.01
	Sig. (2-tailed)	0.539	0.147	0.915	0.164	0.658	0.867
	n	451	451	451	451	450	451
E_DIL	Pearson Correlation	-0.02	0.01	0.10	**0.17**	-0.08	-0.08
	Sig. (2-tailed)	0.683	0.790	0.026	**0.000**	0.081	0.081
	n	451	451	451	**451**	450	451
E_TRI	Pearson Correlation	-0.02	0.00	**0.22**	0.08	-0.03	-0.11
	Sig. (2-tailed)	0.616	0.930	**0.000**	0.081	0.487	0.016
	n	451	451	**451**	451	450	451
F_FLA	Pearson Correlation	-0.02	-0.02	**0.18**	**0.18**	-0.06	-0.12
	Sig. (2-tailed)	0.633	0.652	**0.000**	**0.000**	0.173	0.011
	n	451	451	**451**	**451**	450	451
L_SIL	Pearson Correlation	-0.04	**0.13**	0.08	0.06	-0.04	-0.11
	Sig. (2-tailed)	0.403	**0.005**	0.101	0.176	0.427	0.018
	n	451	**451**	451	451	450	451
L_VEN	Pearson Correlation	0.00	-0.03	**0.17**	**0.15**	-0.04	**-0.12**
	Sig. (2-tailed)	0.988	0.523	**0.000**	**0.001**	0.378	**0.009**
	n	451	451	**451**	**451**	450	**451**
L_CML	Pearson Correlation	-0.02	**0.16**	0.03	0.11	-0.08	-0.10
	Sig. (2-tailed)	0.721	**0.001**	0.513	0.022	0.086	0.032
	n	451	**451**	451	451	450	451
L_CMR	Pearson Correlation	-0.02	**0.26**	**0.17**	-0.02	-0.10	-0.09
	Sig. (2-tailed)	0.660	**0.000**	**0.000**	0.633	0.034	0.055
	n	451	**451**	**451**	451	450	451
L_COS	Pearson Correlation	0.08	**0.12**	**0.25**	0.09	-0.11	-0.15
	Sig. (2-tailed)	0.109	**0.008**	**0.000**	0.059	0.016	0.001
	n	451	**451**	**451**	451	450	451
L_FRA	Pearson Correlation	-0.03	-0.01	0.06	0.09	-0.04	-0.03
	Sig. (2-tailed)	0.538	0.776	0.217	0.049	0.370	0.482
	n	451	451	451	451	450	451

Tables 8a-b. (cont.)

b.

Species		Boulder	Cobble	Pebble	Gravel	Sand	Silt
L_REC	Pearson Correlation	-0.04	-0.01	0.06	**0.28**	-0.06	**-0.14**
	Sig. (2-tailed)	0.427	0.756	0.184	**0.000**	0.211	**0.002**
	n	451	451	451	**451**	450	**451**
O_REF	Pearson Correlation	-0.01	-0.02	-0.03	0.00	-0.03	0.06
	Sig. (2-tailed)	0.813	0.623	0.572	0.925	0.512	0.226
	n	451	451	451	451	450	451
O_SUB	Pearson Correlation	-0.01	-0.02	-0.03	0.10	0.00	-0.04
	Sig. (2-tailed)	0.813	0.623	0.572	0.031	0.967	0.344
	n	451	451	451	451	450	451
P_SIN	Pearson Correlation	-0.02	-0.02	0.03	0.06	-0.04	0.00
	Sig. (2-tailed)	0.600	0.628	0.542	0.173	0.433	0.991
	n	451	451	451	451	450	451
P_ALA	Pearson Correlation	0.03	0.00	0.01	0.07	-0.03	-0.01
	Sig. (2-tailed)	0.539	0.957	0.868	0.128	0.485	0.777
	n	451	451	451	451	450	451
P_FAS	Pearson Correlation	-0.01	-0.01	**0.15**	0.12	-0.04	-0.10
	Sig. (2-tailed)	0.881	0.789	**0.002**	0.012	0.391	0.038
	n	451	451	**451**	451	450	451
P_GRA	Pearson Correlation	-0.02	**0.13**	0.11	0.03	-0.04	-0.10
	Sig. (2-tailed)	0.682	**0.005**	0.024	0.565	0.373	0.036
	n	451	**451**	451	451	450	451
Q_PUS	Pearson Correlation	-0.02	0.06	0.03	-0.02	**-0.13**	0.11
	Sig. (2-tailed)	0.697	0.238	0.501	0.691	**0.004**	0.023
	n	451	451	451	451	**450**	451
Q_QUA	Pearson Correlation	-0.04	0.01	0.10	0.01	-0.09	0.05
	Sig. (2-tailed)	0.367	0.905	0.030	0.874	0.051	0.290
	n	451	451	451	451	450	451
S_UND	Pearson Correlation	0.00	**0.32**	0.09	0.02	-0.10	**-0.14**
	Sig. (2-tailed)	0.966	**0.000**	0.056	0.646	0.033	**0.002**
	n	451	**451**	451	451	450	**451**
T_TRU	Pearson Correlation	0.00	-0.02	**0.15**	0.06	-0.07	-0.03
	Sig. (2-tailed)	0.972	0.744	**0.001**	0.218	0.148	0.519
	n	451	451	**451**	451	450	451
V_ELL	Pearson Correlation	-0.03	-0.02	**0.31**	0.05	-0.06	-0.10
	Sig. (2-tailed)	0.585	0.704	**0.000**	0.258	0.196	0.042
	n	451	451	**451**	451	450	451
V_FAB	Pearson Correlation	0.00	0.05	-0.02	0.08	-0.02	-0.06
	Sig. (2-tailed)	0.975	0.293	0.606	0.099	0.740	0.220
	n	451	451	451	451	450	451
V_IRI	Pearson Correlation	-0.03	0.07	0.06	0.11	-0.08	-0.06
	Sig. (2-tailed)	0.485	0.147	0.194	0.023	0.107	0.223
	n	451	451	451	451	450	451

Discussion

The rivers surveyed in this study range widely in their ability to support unionid species richness and abundance. The suitability of rivers for supporting mussel communities is determined by numerous factors including biogeography, local physical and chemical habitat characteristics, geology, chance events, and impacts from watershed land use and discharges. The positive correlation between both unionid abundance and species richness with large substrate particle sizes, and the negative correlation with small substrate particle sizes suggests that substrate composition can be one of the factors limiting unionids in Michigan. Correlations coefficients are fairly low (Figures 17a-f and 18a-f), meaning that a relatively small amount of the variation in abundance and species richness can be attributed to the variation in substrate composition. Considering the ecologically realistic environment the data were gathered from, these results are to be expected. Multiple abiotic and biotic factors affect abundance and species richness in addition to substrate suitability. Sites with higher proportions of sand and silt tend to have lower abundance and species richness. At these sites substrate composition can be a limiting factor for unionid abundance and species richness. Sites with lower proportions of sand and silt have other factors which limit unionid abundance and species richness (Figures 17e-f and 18e-f).

One explanation for the negative correlation observed is direct cause. Sites with substrate consisting of high proportions of sand may exclude unionids due to substrate instability. Unionids are typically oriented with the posterior end up and the anterior end buried in the substrate. The foot anchors the mussel in a position that allows the siphons to be opened in the water column and provides resistance to being transported downstream by current. A moving sand sheet, such as the substrate condition observed in the Galien River and parts of the Manistee and Au Sable Rivers, would presumably make maintaining a stable position difficult or impossible for mussels.

Changes in sediment levels can impact unionid communities by interfering with host fish-mussel interaction. This is thought to occur primarily by three mechanisms. The first is that increased sedimentation can reduce fish abundance, diversity, and reproduction. Second, lures present on many lampsiline unionids are colored and shaped in a way that resembles prey of fish hosts. Conglutinates (packets of glochidia) released by females as well as lures are effective only when visible to potential fish hosts. Third, some conglutinates that mimic aquatic insects and adhere to hard substrates may not be able to attach to silt cover substrate or may be buried by sediment accumulation (Box and Mossa 1999).

Correlation does not necessarily equate to causation. An alternative explanation is that a factor associated with elevated levels of fine particles may be the cause for low abundance and species richness. For example, intense agricultural land use may increase sand and silt, and increase levels of pesticides and herbicides (such as atrazine). While negatively correlated to a certain substrate type, low unionid abundance and species richness may actually be caused by negative effects of another pollutant associated with erosion from agriculture.

Some fairly pristine river ecosystems naturally have moderate levels of biodiversity. Different types of river ecosystems support different levels of biodiversity aside from impacts from people. Some rivers inherently have high levels of sand and/or silt, while others have elevated levels due to the effects of land use within the watershed. By comparing substrate data to the soil types and surface geology (from Albert 1995) of the watersheds surveyed it was found that substrates with high levels of sand tend to be related to sandy soil types and the geologic history of the watershed. High levels of silt appear to be related to erosion from agriculture and other land uses in the watershed (personal observation during this and past unionid surveys). Wilhelm (2002) calculated three indices describing aquatic habitat quality, disturbance of the riparian zone, and human disturbance in the watershed. Indices for eighteen sites corresponded to unionid survey sites (A1, A3, A4, D1, D2, D5, D6, D8, M1, M2, M4-8, H1, and H2). No significant correlations were detected between unionid abundance and species richness and these three factors. With a larger unionid sample size, distinct relationships may be detected. Further analysis of substrate, unionid, and land use data could elucidate the connection between unionid diversity, habitat quality, and land use.

From a conservation biology standpoint we are most interested in the relationship between a river's ability to support biodiversity and human impacts to the river. We are also interested in conserving representations of the different varieties of river systems or communities, although a classification system for Michigan's aquatic communities has not yet been fully developed and accepted. Unionid diversity is directly related to the diversity of the aquatic community as a whole. For example, a positive correlation between unionid species richness and fish species richness was found in the Ohio River drainage (Watters 1992) and in rivers in the lower peninsula of Michigan (Goforth et al. 2001). Since unionids are sensitive to environmental changes, have a life cycle that requires certain densities of fish hosts, and a unique and often large ecological role in the system, they can act as an umbrella species for the conservation of aquatic communities. Threats to unionid diversity are also threats to the entire aquatic community, which is sustained by complex relationships between interdependent taxa from microbes to vertebrates to trees, and abiotic factors. One approach to prioritizing conservation efforts for unionids (and rivers) in Michigan is to focus on areas of high diversity with high or potentially high levels of impact from human activity. Rivers with inherently low diversity and low potential for impacts would have lowest priority. Rivers with high diversity and greatest risk of loss due to impact would have the highest priority.

The Pine and Belle Rivers are great examples of watersheds where conservation efforts taken now have the potential to make great strides in the protection of aquatic biodiversity. Due to their biogeographic history and habitat characteristics, both rivers (the Belle in particular) support some of the most diverse unionid communities in Michigan. The Belle supports occurrences of three state endangered species, one state threatened species, and four special concern species. The two rivers contain two live occurrences each of *O. subrotunda*, a state-listed as endangered species which is close to being extirpated from Michigan. Outside of the Pine or Belle Rivers, the only records for live individuals of this species are a 1983 record from Belle Isle in the Detroit River and a 1965 record in the Clinton River (MNFI database 2003). *V. fabalis* also has very few live occurrences outside of the Pine and Belle Rivers. A beaver dam located at Dove Road between sites P3 and P4 strongly influenced stream morphology and flow characteristics up and downstream of the dam. Surveys of this site in 1982 revealed one live *V. fabalis* and one *O. subrotunda* shell (both state endangered in MI). Surveys in 1985 failed to find any individuals of either species. Beaver activity may have contributed to the extirpation of most of the unionid community at this site, including the listed species. The stream at this site was 2m+ deep with almost no current and was not surveyed during 2002. Land use in the watersheds is dominated by agriculture which has most likely increased silt levels in the rivers. No *D. polymorpha* were found in either river though they are well established in Lake St. Clair and numerous inland lakes in southeastern Michigan. Efforts to minimize the input of silt from agricultural land and keep *D. polymorpha* from entering the watersheds should be made to help prevent and reduce impacts to aquatic communities. Direct alteration of these rivers, such as dredging and channelization, would have severe negative effects on unionids and the aquatic ecosystem as a whole.

The Galien River is located in a region of Michigan where, biogeographically, unionids would be expected to occur in relatively high abundance and species richness. Unionid diversity tends to increase in a southern direction, and the Grand River, a very unionid rich system, is located less than 100 miles to the north. Poor habitat conditions (unstable sand) in this river have apparently kept unionid communities from establishing in most of the drainage. There is a large amount of agricultural land use in the watershed; however, further study of the watershed's soils, surface geology, and land use suggest that the dominance of unstable sand is an inherent part of the Galien River's substrate and not necessarily a result of land use in the watershed. The Galien watershed is in an area of sandy soils and fine-textured end and ground moraines (Albert 1995). Since human activities have probably not contributed to any substantial loss of unionids in this system, it has a lower priority for conservation efforts. Additional sites need to be surveyed in the downstream reaches to assess the complete potential of this river to support unionids.

The Grand River and its tributaries form a large system with very important unionid communities. Aquatic habitat in this system is impacted by a variety of land uses from agriculture to residential and urban. Agriculture has likely increased silt levels throughout the watershed. Point and non-point source discharges into this watershed also affect water quality. Conservation efforts would need to be coordinated with a wide range of land use interests over a large portion of Michigan, including a variety of state agencies, drain commissioners, and land use planners at city, county, and state levels.

Relatively high species richness and abundance was found in the Manistee and Au Sable Rivers considering the number of sites surveyed and that the northern location of the two rivers puts them far away from the center of unionid diversity in Michigan. The biggest threat to unionid communities in these systems has been the spread of *D. polymorpha* and alteration of hydrology from dams.

Dams also prevent the migration of unionids and gene flow among populations via host fish. The mean number of *D. polymorpha* attached per unionid was similar to that found in the Clinton River, Oakland County, MI, in 1995 (Hunter et al. 1997). Most attached *D. polymorpha* were large individuals (1.0-2.5 cm in length), that presumably have a greater impact per individual than small *D. polymorpha*. The unionid communities present at sites in the Manistee and Au Sable Rivers are at risk of extirpation by *D. polymorpha*. It is not known how much the unionid communities of these two river systems has already declined from the effects of this exotic. Though *D. polymorpha* is already well established in both systems, efforts to reduce the transport of this exotic into the rivers are needed to keep *D. polymorpha* density to a minimum. Without constant input of *D. polymorpha* to upstream sites, densities might actually decrease. Current in lotic systems carries the free-swimming veligers (larvae) downstream and may inhibit the establishment of *D. polymorpha* (Hunter et al. 1997). The designation of parts of these rivers as National Wild and Scenic Rivers and State Natural Rivers provides unionid communities some additional protection from impacts. Interest groups seeking to preserve or improve a river system's ability to support game fish have some common goals with those interested in maintaining aquatic biodiversity. These groups could be an ally in conservation efforts. Future surveys of these two rivers will likely reveal additional unionid species.

The occurrence of *Obliquaria reflexa* in the Huron River is one of very few live records of this species in Michigan in the past 30 years. It may also be the first record for the Huron watershed. Historic occurrences (>30 years) of *O. reflexa* are documented at the University of Michigan's Museum of Zoology from the Black, Grand, Kalamazoo, Raisin, Saginaw, and St. Joseph Rivers. In recent times the Black River is the only other river besides the Huron where live individuals have been found. The conservation rank of *O. reflexa* in Michigan is "unranked", however in Ontario, Canada it is "critically imperiled", in Ohio it is "imperiled", and in Indiana and Wisconsin it is "vulnerable". It is abundant in the Mississippi drainage in the southern U.S. (NatureServe 2003). This species needs to be reviewed for listed status in Michigan and should be considered for listing as state endangered.

The occurrence of *Elliptio crassidens* (Elephant ear) shell in the Grand River (site D5) presents an interesting puzzle. This species is listed as "critically imperiled" in Ohio and Wisconsin (NatureServe 2003) and has never been reported in Michigan. Its range is in the Ohio and Mississippi River drainages and is not thought to extend into the Great Lakes. The only known fish host for *E. crassidens* is *Alosa chrysochloris* (skipjack herring) (Howard 1914, cited in Watters 1994). Although reference has been made to *A. chrysochloris* occurring in the Great Lakes, Hubbs and Lagler (1947) believed that these were actually *Dorosoma cepedianum* (gizzard shad) and that the species does not occur in Michigan. The Michigan DNR does not consider *A. chrysochloris* to be native to Michigan (Bailey and Smith 1991). Determination of fish host species for unionids is done in the laboratory with a limited number of potential hosts. It is possible that fish species other than those tested in the lab could be viable hosts in natural stream environments. It is not known for sure whether or not a viable host for *E. crassidens* exists in Michigan. The habitat of *E. crassidens* is listed as "large rivers in mud, sand, or fine gravel" (Cummings and Mayer 1992); "Usually found in large streams and rivers, rarely straying into small streams. Occurs in sandy mud and gravel in a good current." (Watters 1995b); Oesch (1984) cites records of this species in Missouri from the Meramec River, "a medium sized river with a substrate ranging from fine gravel on some riffles to coarse gravel and cobbles to boulders in some areas." The Grand River at this site (D5) is a medium sized river with good current and substrate consisting of approximately 10% cobble, 40% pebble, 25% gravel, and 25% sand. Identification of the three shells was confirmed by comparing them to shells from The University of Michigan Museum of Zoology, and by two other malacologists (Dan Graf and Paul Marangelo, pers. com. 2003).

A March 27th, 1924, newspaper article from the Lowell Area Historical Museum states that a button factory employing 15-20 hands was in operation in Lowell, MI. (Judy Straub, pers. com. 2003). In 1995 two people from out of State were arrested for poaching unionids from the Grand River to be used in the cultured pearl industry. The shells were found in the water partially buried near the surface of the substrate. One of two explanations seems likely. *E. crassidens* shell could have been transported from outside Michigan to the button factory when it was in operation and discarded. Since it is unlikely that shells would remain intact and not be washed downstream away from Lowell in the 75 or so years since the factory was operation, they were probably discarded on land and more recently entered the river through erosion or someone moving them there. Another explanation could be that poachers transported *E. crassidens* shells in recent years and for some reason discarded them at the site. Additional surveys of the Grand River in this area and of the factory site should be done to rule out the possibility that there are live individuals present.

An outline of recommendations to mitigate cumulative impacts to aquatic habitats and water quality was produced by the North Carolina Wildlife Resources Commission. These focus on riparian buffer zones. Intact riparian zones are known to provide a buffer between land use impacts and aquatic habitats. The minimum width of riparian buffers to maintain all riparian processes has been estimated at 100-300 feet (Knutson and Naef 1997, May and Horner 2000, Martin *et al.* 2000, and others cited in NC Wildlife Resources Commission 2002). Minimum riparian buffer widths to retain certain riparian habitat functions, such as filtering nitrogen, erosion control, and water temperature control, have been estimated by various researchers and are also summarized by the NC Wildlife Resource Commission (2002). Removal of riparian forests has also been found to be associated with a decrease in fish abundance and changes in the fish community composition (Jones et al. 1999). Which in tern could have implications for unionids given their reliance on fish hosts.

To manage Michigan's rivers in a way that conserves diversity of aquatic life, we must address land use within watersheds that impacts aquatic habitats. The correlation between substrate composition and unionid abundance and species richness provides evidence that certain habitat types (sand and silt) can negatively impact or preclude unionid diversity. Other aquatic taxa such as fish and insects are known to be negatively impacted by increased input of fine particles as well (Henley et al. 2000, Waters 1995). Land uses that increase this habitat type need to be reviewed to identify ways to minimize their impact. Analysis of watershed land use and geology by Arbuckle and Downing (2002) provides evidence that agricultural watersheds with high slopes impact mussel abundance and richness through siltation and destabilization of stream substrate.

The Upper St. Joseph River Project of The Nature Conservancy (TNC) might be a conservation model that could be adapted to other watersheds. The St. Joseph River (Hillsdale Co., Maumee drainage) supports a diverse and very rare aquatic community, including a unionid that is Federally listed as endangered. Agriculture has been the main land use within the watershed for over a century. Excessive sediments and nutrient input related to this land use were identified as the top stressors to the river. Strategies were developed to make it economically feasible for landowners to make changes to their farming practices that would help reduce impact to aquatic habitats. Examples of these are reforestation of the floodplain with native tree species (a program which can be combined with the Conservation Reserve Program incentive payment), monetary assistance to purchase no-till farming equipment (with a conservation tillage risk protection program that protects the farmer from any economic loss caused by changing to no-till production), and creation of grass buffer strips along drains (Larry Clemons pers. com. 2002). These programs reduce fine particle and nutrient input to the river. A monitoring program was put in place to measure their success through biological, chemical, and physical parameters. Most landowners in the watershed grew up in the area and have a strong connection to the land as well as an appreciation for wildlife. Many were interested in minimizing impacts to their stream (pers. observation 2000-2001, Badra and Goforth 2001). Parallel strategies can be developed to address impacts associated with livestock operations, urban land use, and other non-point source threats which are cumulative in nature. The Nature Conservancy's Shiawassee River Conservation Tillage Project is also promoting incentives to make conservation tillage a more attractive option to farmers (Ken Algozin pers. com. 2003).

Management strategies for conserving unionid diversity differ depending on specific factors associated with each watershed. Biologists at MNFI and elsewhere are continuing to build a more complete base of information on the community composition, abundance, and distribution of unionids in Michigan. We are also developing a better understanding of the complex ecological interactions that support unionid diversity. A clear picture of unionid status and distribution combined with the knowledge of which factors are impacting unionid communities in specific watersheds, will lead to better informed decisions relating to the management of river ecosystems and the biodiversity they contain.

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