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Title: Restoration of rapids habitat in a Great Lakes connecting channel, the St. Marys River, Michigan

Running head: Restoration of rapids habitat

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Abstract

Aquatic habitat has been extensively altered throughout the Laurentian Great Lakes to increase navigation connectivity. In particular, the St. Marys River, a Great Lakes connecting channel, lost >50% of its historic rapids habitat over the past century. In 2016, natural flow was restored to the Little Rapids area of the St. Marys River. The goal of our study was to evaluate physical and ecological responses to the restoration of the Little Rapids area. Extensive habitat and biological data were collected prior to restoration (2013 and 2014), and after restoration (2017 and 2018). Measured parameters included total suspended solids, current velocity, benthic macroinvertebrates, and larval, juvenile, and adult fishes. Total suspended solids stayed low (<4 mg/L) following restoration, with the exception of a single construction related event. Pre-restoration data indicated that all measured velocities were below the target flow rate of 0.24 m/s, whereas 70% of the measured habitat was above the target flow post-restoration. Abundance and richness of benthic macroinvertebrates were reduced following restoration (>90% reduction). We observed a 45% increase in richness of larval fish two years after restoration and a 131% increase in catch per unit effort. For adult fishes, the proportion of individuals with preference for fast-moving waters increased from 1.5% to 45% in the restored area, and from 7% to 15% upstream of the restored area; a similar response was observed for lithophilic spawners. The physical and biological conditions of the Little Rapids improved and resembled conditions typical of rapids habitat extant in other areas of the river and other systems.

Keywords: Connectivity, River Restoration, Ecological Responses, larval fish, benthic macroinvertebrates

Implications for Practice:

- Responses of biota to river restorations can take multiple years, thus, long-term evaluations are recommended to determine effectiveness
- Restoration of large, working rivers is challenging due to their size, complexity, and diverse stakeholder expectations and desires; thus evaluations of these large projects are necessary to improve effectiveness of large river restoration programs
- Recovering rapids can lead to the recovery of important lotic fish communities, especially in highly modified habitats

Introduction

Habitat heterogeneity provides more niches and diverse ways of exploiting the environmental resources, especially for species that require multiple habitats during their life-cycle. Because fishes often exhibit ontogenetic habitat preferences throughout their life cycle, the maintenance of different types of habitat (habitat heterogeneity), and the connectivity between those habitats is critical to sustaining populations (Schlosser 1991; Bazzaz 1975; MacArthur & Wilson 2001). Loss of connectivity among habitats and habitat loss adversely affect biodiversity by altering dispersal, reproduction, and survival of populations (Abell 2002; Loreau et al. 2003; Staddon et al. 2010). In freshwater ecosystems, loss of connectivity is generally associated with anthropogenic barriers that can alter water flow, sediment and nutrient dynamics, river morphology, and vegetation composition (Petts 1980; Choi et al. 2005; Santucci et al. 2005; Li et al. 2013). Impediments to connectivity can also disrupt movement and dispersal of individuals, limiting their access to quality spawning and rearing habitat and thereby disrupting the life cycle of migratory freshwater organisms (Sheldon 1988; Dunham et al. 1997; Sheer & Steel 2006; Rudnick et al. 2012; Mattocks et al. 2017). The loss of both habitat heterogeneity and connectivity can imperil populations and negatively affect freshwater community structure and diversity (Gido et al. 2016). Recovering and maintaining habitats and their connectivity is an essential step towards restoration of freshwater ecosystems and their biota (Jansson et al. 2007; Beechie et al. 2010), and restoration and habitat connectivity has had a positive effect in the restoration of freshwater communities in large rivers (Watson et al. 2018).

Research and conservation related to connectivity in freshwater ecosystems have historically focused on mitigating effects of physical barriers such as dams (Bednarek 2001; Day 2009; Magilligan et al. 2016) and culverts (O'Hanley & Tomberlin 2005; Sheer & Steel 2006; Bourne et al. 2011) to migratory fishes. Hydrological connectivity has been altered in other ways while having similar effects on the ecosystem. For example, in the Laurentian Great Lakes region, habitat has been extensively altered to facilitate navigational connectivity throughout the lakes. The Great Lakes Navigation System (GLNS) is a complex, deep-water navigation system spanning over 3,800 km through the five lakes and connecting waters which includes locks, ports, navigational channels, dredged areas, and navigation structures(Larson 1983). Dredging to create navigational channels for large, ocean-going vessels increases connectivity for navigation resulting in flow and depth alterations that alter critical habitat, and hydrological connectivity in these large, complex systems (Bennion & Manny 2011). Channelization reduces habitat heterogeneity, which is necessary for the survival and reproduction of fish in lotic ecosystems (Schlosser 1991). For example, fast flow velocities through rapids have been reduced resulting in reduced hydrological connectivity, increased sediment deposition, and ultimately lost habitat for many ecologically and economically valued fishes that depend on these habitats for spawning (Kondolf et al. 2008).

The St. Marys River is the connecting channel between Lake Superior and Lakes Huron-Michigan and an important working river. It has historically lost >50% of its rapids habitat over the past century due to hydropower generation and navigational alterations (Harris et al. 2009). . Efforts to restore hydrological connectivity, recover lost rapids habitat, and increase habitat heterogeneity could increase the availability of critical habitat and improve movement between critical habitats in the St. Marys River and adjoining lakes. Tthere is, however, very limited data on fish movement in this area (but see Gerig et al. 2011, Michigan Department of Natural Resources 2012). Furthermore, the St. Marys River supports a diverse fish community, including species of great regional importance such as Lake Sturgeon (*Acipenser fulvescens*), Walleye (*Sander vitreus*), Lake Whitefish (*Coregonus clupeaformis*), and Atlantic and (introduced) Pacific Salmon (*Salmo salar* and *Oncorhynchus spp*.; Schaeffer et al. 2011). Historically, diverse rapids habitat was present throughout the St. Marys River, with five distinct rapids areas, including the Main Rapids and the Little Rapids (Figure 1). However, by the 1950s, human alterations to river flow and morphology, along with intensive industrial and commercial use of the river over the past century, reduced the number of rapids to only one (Main Rapids), and degraded and fragmented remaining critical fisheries habitat (Duffy & Batterson 1987) . In 1987, the St. Marys River was designated as a Great Lakes Area of Concern (AOC; US EPA 2020) due to a legacy of industrial contamination and development that adversely affected important habitat and biota in the river.

The ecosystem conditions, heterogeneity and connectivity of this river are critical for the system's production and diversity (Great Lakes Fishery Commission 2006). Stakeholders (including island residents, anglers, road transportation authorities, state and federal agencies) determined that restoration of lost rapids habitat was a critical step in efforts to de-list the St. Marys River as an AOC. The Little Rapids, one of the historical rapids areas that had been lost as a result of navigational modification, was identified as a target for restoration (Michigan Department of Environmental Quality 2012). At Little Rapids, an earthen berm composed of dredge material restricted hydrological connectivity, resulting in the loss of rapids habitat. As part of a multi-stakeholder decision-making process that considered cost, area of habitat restored, disruption to local residents, ferry traffic, and fishing access, a 183 m bridge was proposed to replace the earthen berm along the south end of the causeway. Restoring hydrological connectivity, restoring rapids habitat, and increasing habitat heterogeneity will address the three beneficial use impairments (BUIs; US EPA 2015) identified as part of the AOC de-listing process: 1) loss of fish and wildlife habitat 2) degradation of fish populations, and 3) degradation of benthos (biological community living in the benthic zone). Despite the potential ecological benefits of this project, local residents were concerned about some of the consequences of the restoration, such as changes to the shoreline and downstream water quality. Additionally, ecological risks, such as use of the restored habitat by invasive Sea Lamprey (*Petromyzon marinus*), which had been controlled in the river for multiple years (Schleen et al. 2003) (Schleen et al. 2003), were considered.

The goal of our study was to evaluate ecological responses to restoration of the Little Rapids area, a critical habitat in a major ecological and economic corridor of the Great Lakes. This restoration project was unique in that it occurred in a large, working river with great navigational importance and diverse stakeholders. Restoration of large working river systems is occurring globally, and communicating the results and ecological responses to restoration across the scientific community can improve effectiveness of river restoration programs (Palmer et al. 2005; Kania & Kramer 2011; Roseman & DeBruyne 2015). Our results provide insight into restoration of a large, working river, including the challenges encountered and the importance of evaluating restoration actions in large rivers.

Methods

Study system

The St. Marys River is a highly modified working river that flows out of Lake Superior and into Lake Huron, a distance of ~120 river kilometers (rkm), and contains numerous embayments, islands, and wetlands (Duffy & Batterson 1987). The Little Rapids area is located on Sugar Island in the binational St. Marys River, ~35 rkm downstream of Lake Superior, and 77 rkm upstream of Lake Huron (Figure 1). In 2011, Great Lakes Restoration Initiative (GLRI) funds were administered to support an engineering and design study aimed at replacing the causeway that limited flow in the area. In 2013, additional funding was received for the replacement of the causeway and construction of a bridge began in June 2016, and was finished in November 2016. As a result, a 183 m multi-span bridge replaced the deteriorating causeway (Nelson 2016 ; Figure 2). The new bridge maintained the two traffic lanes and added fishing access to the area which was desired by local residents. The original causeway limited flow to under 0.24 m/s (through two culverts), and degraded rapids habitat (contributing to a reduction of >50% of rapids habitat in the St. Marys River; Figure 2). As the causeway limited fish access to the area from upstream, it forced fish to find alternative spawning habitat, or to find alternative routes to the Little Rapids (Figure 1).

Extensive habitat and biological data were collected pre-restoration in 2013 and 2014, and post-restoration in 2017 and 2018. Data were collected upstream and downstream of the location of the Little Rapids causeway/bridge (46°29’01’’N, 84°17’20’’W). Transects were used for the collection of the data, distance between transects was ~100m, with five transects downstream, and three transects upstream (Figure 1).

Habitat data collection and analysis

Water samples to measure concentration of total suspended solids (TSS) were collected once in July 2014 to determine background TSS, biweekly during the summer of 2016 (bridge under construction), and monthly during the summer of 2017 (post-restoration). For each transect, five samples (with three replicates each) were collected using an integrated water column PVC sampler. Samples were processed following the gravimetric method (EPA Method 160.2; US EPA 1983), and averages and confidence intervals were calculated.

Current velocities were measured in mid-July of 2014 and 2017 using an acoustic Doppler current profiler (ADCP) following USGS Techniques and Methods 3-A22 (Mueller et al. 2013). Three upstream and three downstream transects were surveyed (Figure1). ADCP configurations were selected based on depth and modeled velocities in the area. Data were processed using WinRiver2 software (RD Instruments) and then imported into USGS program Velocity Mapping Toolbox. For each transect, the proportion of the transect cross-sectional area with a velocity above 0.24 m/s was estimated, using the data obtained from the mapping toolbox.

Benthic Macroinvertebrates

Benthic macroinvertebrates were collected using a modified version of the Large River Bioassessment Protocol for Benthic Macroinvertebrate Sampling (Flotemersch et al. 2006) . This method is semi-quantitative and was used to sample transects upstream and downstream of the restoration area. Transect length was dictated by the width of the stream, and along each transect (Figure 1), the sampling zone extended 5 m on each side of it (i.e. 10 m sampling zone), and sample locations were distributed based on available habitat within the zone to ensure coverage of sub-habitats (rocks, logs, soft sediment, etc.), samples were pooled by transect group. If water was >1 m deep at the water's edge, sweeps were collected from a boat. Samples were stored in 70% ethanol, processed and identified to the lowest taxonomic level possible. All analyses were done at the family level.

Larval fish

Larval fish were collected in 2013, 2014, 2017, and 2018 using D-frame larval drift nets (76.2 cm wide, 53.3 cm high, 3.4 m long mesh bag, and 1.6 mm mesh) anchored to the bottom substrate. Nets were set overnight twice per week, starting in May through August in an attempt to target larval fish emerging after winter or spring spawning. A total of five to six nets were set prior to restoration, two to three nets were set on the upstream side of the causeway directly in front of the large culverts, and three nets were set downstream of the causeway. Sampling locations prior to restoration were limited because few areas possessed sufficient flow to open the nets for deployment. Eight nets were set post-restoration, with three upstream of the causeway, three downstream of the causeway, and two attached to the bridge but fishing downstream of the newly created habitat (the bridge and downstream nets were both treated as downstream). All nets fished overnight for ~12 hours. Samples were sorted in the lab, and fish were identified to species according to descriptions in Auer (1982) and Fuiman et al. (1983), and photos were sent to the USGS Great Lakes Environmental Research Laboratory (GLERL) for verification. Samples included both larval fish and post-larval (age-0) fish that had absorbed their yolk-sac. For purposes of this study, these two groups are referred to as “larval fish”.

Adult fish

Fyke nets, a common passive sampling gear (Hubert et al. 2012), were set twice per week in the Little Rapids from late July to late October in 2013, and from late July to mid-September in 2017 to capture adult fish. Fyke nets were set in slower velocity, nearshore locations, using the American Fisheries Society recommended standard fyke nets (Bonar et al. 2009). Two nets (1 large, 1 mini-fyke) were set upstream of the bridge, and five nets (3 large, 2 mini-fykes) were set downstream of the bridge. The nets were set by tying the lead line to a tree near the water’s edge and running the net perpendicular to the shoreline. The nets were held in place by a fyke net anchor with a float attached to the net to mark the location. Nets were set for 24 hours, and then captured fish were identified and counted. All fish identified in the field were released. Unidentified fishes were preserved in ethanol and identified in the laboratory.

Biological data analysis

All data were analyzed using program R (R Core Team 2019)(R Core Team 2019). Catches of larval fish were converted to catch per net per 12-hr set (CPUE), and relative abundance of benthic macroinvertebrates was calculated as abundance per transect. A zero-inflated Bray-Curtis dissimilarity index (Bray & Curtis 1957), was used to estimate changes in the community composition for larval fish and macroinvertebrates following restoration, and was estimated using package vegan version 2.5-6 (Oksanen et al. 2019). CPUE and richness were not estimated for adult fish, as the sampling conditions changed dramatically following the restoration project, and the efficiency of the fyke nets was reduced due to increased flows. However, we calculated the proportion of catch that was represented by lotic species (species that require moving water), and by lithophilic spawners (which require clean, coarse rocky substrate for reproduction). Fish were categorized as lotic, transition, or lentic based on the functional organization by Poff and Allan 1995)).

Results

Abiotic responses

Concentrations of TSS remained below 4 mg/L throughout construction of the bridge in 2016, except for a single event on June 22 when TSS in the downstream section approached 30 mg/L during a temporary breach of the sediment curtain surrounding the construction (Figure 3). The TSS estimates for the sampling period the year after construction were all under 1.2 mg/L, and they were either less than or equal to pre-restoration concentrations (Figure 3).

Pre-restoration ADCP measurements indicated that all measured velocities were below target flows of 0.24 m/s. Post-restoration mapping illustrated substantial increases in velocity (to or beyond target velocities) throughout the restored area. Over 90% of the water column in transects 3-6 exceeded the desired velocities (Figure 4), whereas 50% or less of the water column of the furthest upstream transects 7-8 met the desired velocity. Of the ~58,700 m^2 surveyed in the Little Rapids site, ~40,000 m^2 (nearly 70% of surveyed habitat) met or exceeded the desired velocity.

Biotic Responses: Macroinvertebrates

Benthic macroinvertebrates declined in abundance and richness post-restoration. There was a 75% reduction in abundance from pre-restoration values one year post-restoration, and a 97% reduction two years post-restoration, with a total abundance <50 organisms for upstream and downstream transects combined. The decline in abundance corresponded to an increase in flow due to the new bridge and higher water levels in the Great Lakes that may have reduced sampling efficiency. In addition to changes in abundance, we observed a potential change in composition, with pre-restoration assemblages dominated by Diptera (>50% of sampled individuals), followed by Basommatophora, while the post-restoration assemblage in 2017 was dominated by Ephemeroptera and Amphipoda (Figure 5). The Bray-Curtis dissimilarity index was 0.71, which illustrates that the assemblage found prior to the restoration may be different from the assemblage present after the restoration, as evidenced by differences in the relative abundance between pre- and post-restoration (Figure 5B).

Biotic responses: Larval Fishes

The Bray-Curtis dissimilarity index for larval fishes was high (0.918), which is typical of assemblages that are very different in both presence of species and relative abundance (Pontasch et al. 1989; Bray & Curtis 1957). The pre-restoration assemblage was dominated by cyprinids, while the post-restoration assemblage was dominated by smelts, sculpins, and suckers (Figure 6). White Sucker (*Catostomus commersonii*), Rainbow Trout (*Oncorhynchus mykiss*), Pink Salmon (*Oncorhynchus gorbuscha*), and Rainbow Smelt (*Osmerus mordax*) were uniquely collected post-restoration. Both richness and CPUE of larval fish differed between the pre- and post-restoration time period. One year post-restoration (2017), richness declined by 45% upstream of the bridge, but increased by 11% downstream of the bridge when compared to the pre-restoration values (2013 and 2014). In 2018, richness increased in upstream and downstream reaches when compared to the year prior. These 2018 values (two year post-restoration), represent a richness reduction of 15% in the upstream section compared to pre-restoration values, and an increase of 45% in the downstream section compared to pre-restoration values. A similar trend was observed in CPUE, with an upstream reduction of 80% and downstream reduction of 89% one year post-restoration (2017), whereas in 2018 there was an increase in CPUE both downstream and upstream compared to the previous year. However, just as observed with richness, CPUE values in 2018 represented a 15% reduction in the upstream area compared to pre-restoration values, and a 131% increase in the downstream area

Biotic Responses: Adult Fishes

We observed an increase in the proportion of lotic fishes from pre-restoration in 2013 to post-restoration in 2017. Upstream, only 7% of the adult catch was categorized as lotic in 2013, whereas it doubled in 2018 with 15% of the catch categorized as lotic. Downstream, only 1.5% of the adult catch was categorized as lotic in 2013, but in 2017 lotic fishes represented 44% of the catch. In 2013, the highest proportion of lotic fishes was observed in the autumn (between September 15 and the end of October), which is a period that was not sampled post-restoration in 2017 (Figure 7). There was also an increase in observed lithophilic spawners after restoration. While the proportion of lithophilic spawners was low in the upstream area in both 2013 (7%) and in 2017 (6%), there was an increase from 1.5% to ~50% of the total catch in the downstream reaches (Figure 8).

Discussion

The Little Rapids system changed following restoration, with changes observed in the four assessed groups: habitat, benthic macroinvertebrates, larval fishes, adult fishes (Figure 9). However, magnitude and direction of change differed among groups. Velocity increased >450%, and the percentage of area in which the velocity exceeded the threshold went from 0% to 99% in the downstream sections. Macroinvertebrate abundance and richness declined sharply (>60%) in both upstream and downstream sections. Larval fishes exhibited a lagged response, with richness and CPUE increasing from 1 year to 2 years post-restoration. Richness increased by 50% downstream, and CPUE increased two-fold downstream. In adult fishes, we observed a >2,000% increase in the proportion of both lotic species and lithophilic spawners in the downstream section (Figure 9).

Our 5-year evaluation of a novel habitat restoration project in the St. Marys River documented progress towards physical and biological recovery in this major navigational and ecological corridor. “Our results suggest hydrological connectivity and habitat heterogeneity increased within the system, as increased flows suggest the recovery of habitat that resembles the historically lost rapids. Although river restoration projects are becoming increasingly more common (Bernhardt et al. 2005; Wohl et al.

2005), projects focused on restoring hydrological connectivity in large, working rivers are challenging due to their size, complexity, and diverse stakeholder expectations and desires (Schiemer et al. 2007).

The Little Rapids Restoration Project focused on increasing hydrological connectivity and restoring rapids habitat by restoring flow to one of the five historical rapids areas in the St. Marys River. The Little Rapids now represents the downstream-most rapids in the river, therefore serving as the first available rapids habitat for individuals moving upstream. While lotic habitat is abundant in the system, shallow rapids habitat with increased velocities was limited, The Little Rapids now represent one of only two rapids areas in the river. In only two years after the large-scale habitat restoration, we observed changes in the larval and adult fish assemblages that are consistent with a shift to lotic habitat. As multiple fish species undergo migrations for wintering, spawning, and feeding (Harden-Jones 1968; Secor 2015), the availability and connectedness of all necessary habitats is critical for the survival and reproduction of these species. Access to rapids habitat is especially important for lithophilic spawning species (Aarts & Nienhuis 2003; Freedman et al. 2013) ; therefore, an increase in lotic and lithophilic spawners was expected in the Little Rapids area following restoration of flow. The post-restoration assemblage was dominated by lotic species, and had a higher proportion of salmonids, sculpins, and Rainbow Smelt, while it also had a high abundance of suckers (*Catostomidae*), which had not been collected in this area prior to restoration. For adult fishes, we also observed a higher proportion of lotic species post-restoration. Restoration of flow in the Little Rapids area is the most likely cause of the observed changes in the fish assemblage.

Despite changes in fish assemblages, many target species (e.g., Lake Sturgeon), have not yet been documented using the restored habitat. However, habitat conditions including depth, current velocity, and substrate size are within the range of preferred habitat for these species (Cech & Doroshov 2004; Johnson et al. 2006). Thus, it may be that additional time is needed to evaluate the effects of the restoration on these target species. Responses of fishes to river restorations tend to be slower than other taxonomic groups and can require multiple years or even decades (Moerke et al. 2004; Pierce et al. 2013; Shirey et al. 2016). Therefore, the fish assemblages and populations in the Little Rapids may be in a transition period. Different life history and behavioral attributes can result in a lagged response, and species with long life cycles, like migratory fishes, may respond slowly, potentially over many years (Thompson et al. 2018). For example, Lake Sturgeon, may be slower to respond to new habitat than many other species inhabiting the river. Only recently has there been evidence of Lake Sturgeon spawning in the St. Marys River near the Main Rapids (Roseman et al. In. Press). Their population size was estimated to be <500 individuals (Bauman et al. 2011) in the river and individuals spawn every 4-5 years, which suggests that perhaps as few as 100 individuals may be spawning in any given year. Additionally, Lake Sturgeon may be limited by connectivity to this habitat since they have not been observed using the shipping channel (Gerig et al. 2011).

In contrast to the response of fishes to the restoration of flow in the Little Rapids area, we observed reduced macroinvertebrate abundance and richness. The response of macroinvertebrates was surprising because macroinvertebrate communities tend to respond quickly to restoration due to their shorter life cycles and diverse colonization abilities (Thompson et al. 2018) . However, improvements to diversity of macroinvertebrates may be delayed by simplified source populations or the slow development of secondary substrate structures (e.g., consolidation of organic compounds; Jähnig & Lorenz 2008) , or the restoration activities constituted a disturbance to the established invertebrate populations, resulting in reduced richness and abundance (Swamy et al. 2002; Pétillon & Garbutt 2008). Furthermore, the changes we observed in macroinvertebrates might be explained by the presence of the diatom, Didymo (*Didymosphenia geminata*) post-restoration. While Didymo was absent in the rapids pre-restoration, it was abundant post-restoration (A. Moerke, unpublished data). The presence of Didymo can disrupt food web structure, hampering the survival of larger invertebrates and changing community composition from large-bodied taxa to small bodied-taxa (Anderson et al. 2014; Ladrera et al. 2018), however, the role of Didymo in the Little Rapids requires additional investigation.

There are multiple challenges in the restoration of large, working rivers that go beyond recovering the ecology. These challenges include socio-economics, balancing the working function of the river (e.g. navigation) with the ecological goals of the restoration, and considering ecological risks. Historically, freshwater ecosystem restoration most commonly focused on smaller streams (Bernhardt et al. 2005), with a limited number of stakeholders involved in comparison to large river systems. Although, work in large-working rivers has increased in recent years (Bowron et al. 2018; Schaeffer et al. 2011; Rubin et al. 2017), the costs and the number and diversity of stakeholders in such projects are higher than when working in smaller streams. In the Little Rapids Restoration Project, stakeholders voiced concerns regarding disruption to road and ferry traffic, changes in ice formation in the navigational channel, changes in flow and water quality to downstream residents, and availability of boating and fishing access. As a result, this project had an extended timespan beginning in 1992, when the project was first proposed by a local sportsmen's group, to 1997 when the first feasibility study was published, to 2013 when the funding was awarded, and finally, to 2016 when it was constructed. Commitment and buy-in from diverse stakeholders were necessary to complete this project. Projects with timelines spanning multiple decades might be at risk of non-completion due to changes to funding or loss of stakeholder interest and engagement. Furthermore, there are ecological risks associated with restoration of dynamic, large rivers. One of the main concerns with the Little Rapids Restoration

Project was the potential for the invasive Sea Lamprey (*Petromyzon marinus*) to spawn in the newly created habitat, as Sea Lamprey typically spawn in rapids habitat and pose a risk to native and commercially-important fish populations (Lawrie 1970; Christie & Goddard 2003; Schleen et al. 2003). No evidence of sea lampreys in the restored Little Rapids was observed.

The Little Rapids Restoration Project is one of many projects funded through the Great Lakes Restoration Initiative (GLRI), and it is an example of a unique opportunity to improve our ecological understanding of complex ecosystems, as well as explore the cultural, social, and economic drivers of large-scale restoration projects. Since 2010, the GLRI has funded >5,000 total projects, and >2,000 projects focused on habitat and species restoration. These projects have increasingly modified the system in an effort to restore multiple habitats. As part of the habitat and species focus area, >$580 million has or will be spent on ongoing projects (GLRI 2019). These projects, similar to the Little Rapids Restoration Project, provide an ideal opportunity to evaluate the response of large systems to restoration projects, thereby advancing our understanding of restoration ecology and the resilience of Great Lakes ecosystems.

The Little Rapids Restoration Project attempted to build resilience in a working river, where important rapids habitat had been lost and fragmented. It recovered a historically lost rapids habitat and correspondingly, increasing connectivity and heterogeneity in the system. As a result, the physical and biological conditions of the area changed to conditions typical of rapids habitat, but long-term evaluations are necessary to document species expected to have long recovery timelines. The Little Rapids Restoration Project, and other GLRI projects, are unprecedented opportunities to evaluate restoration actions that are occurring in working rivers, or in complex environments that are often tangled within other social and economic constraints.

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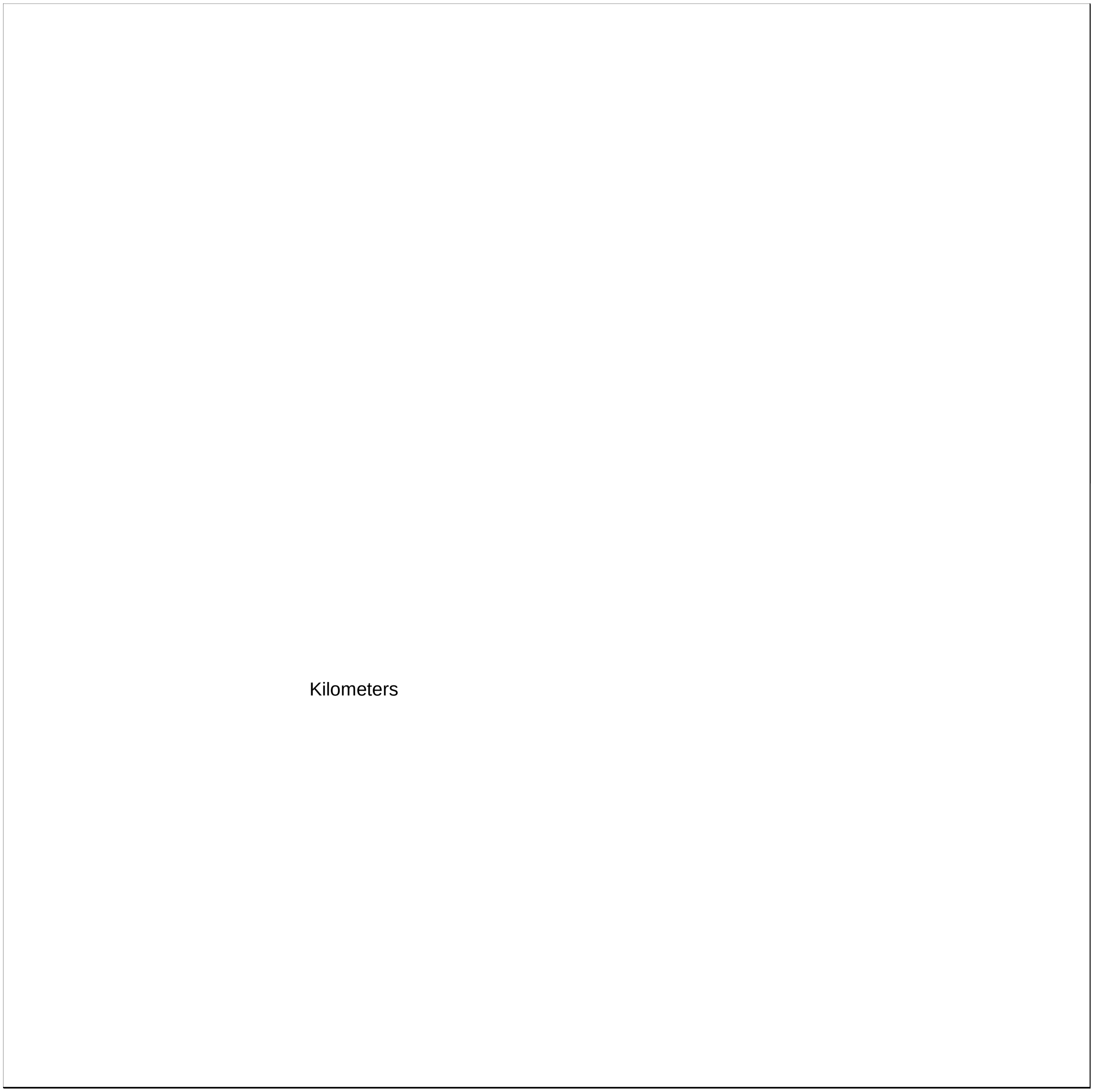

Figure 1. Location of the Little Rapids (LR) in the St. Marys River, MI. The insert in the bottom left hand corner represents the Laurentian Great Lakes. The single fill black square represents the diminished Main Rapids (MR), while the hatch pattern polygons represent historical rapids areas that have been lost: East Neebish Rapids (EN), Middle Neebish Rapids (MN), and West Neebish Rapids. The grey

polygon inside the river represents the navigational channel. The eight lines represent transects upstream and downstream of the bridge.

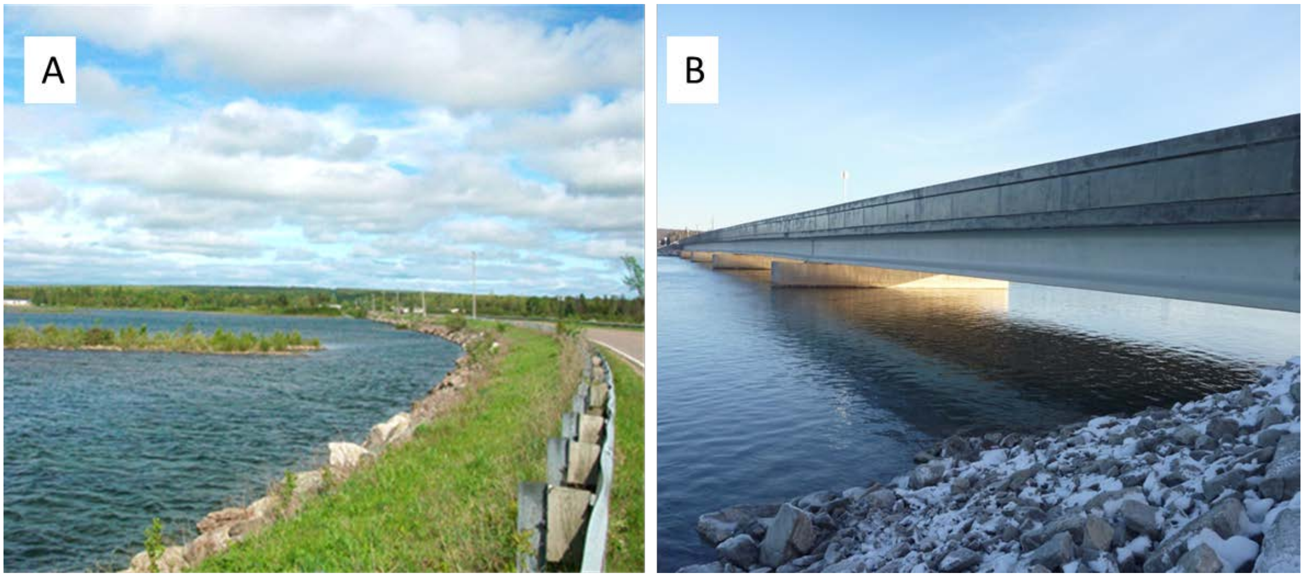

Figure 2. The Little Rapids A) causeway with earthen bern prior to restoration, and B) bridge following the restoration project in 2016.

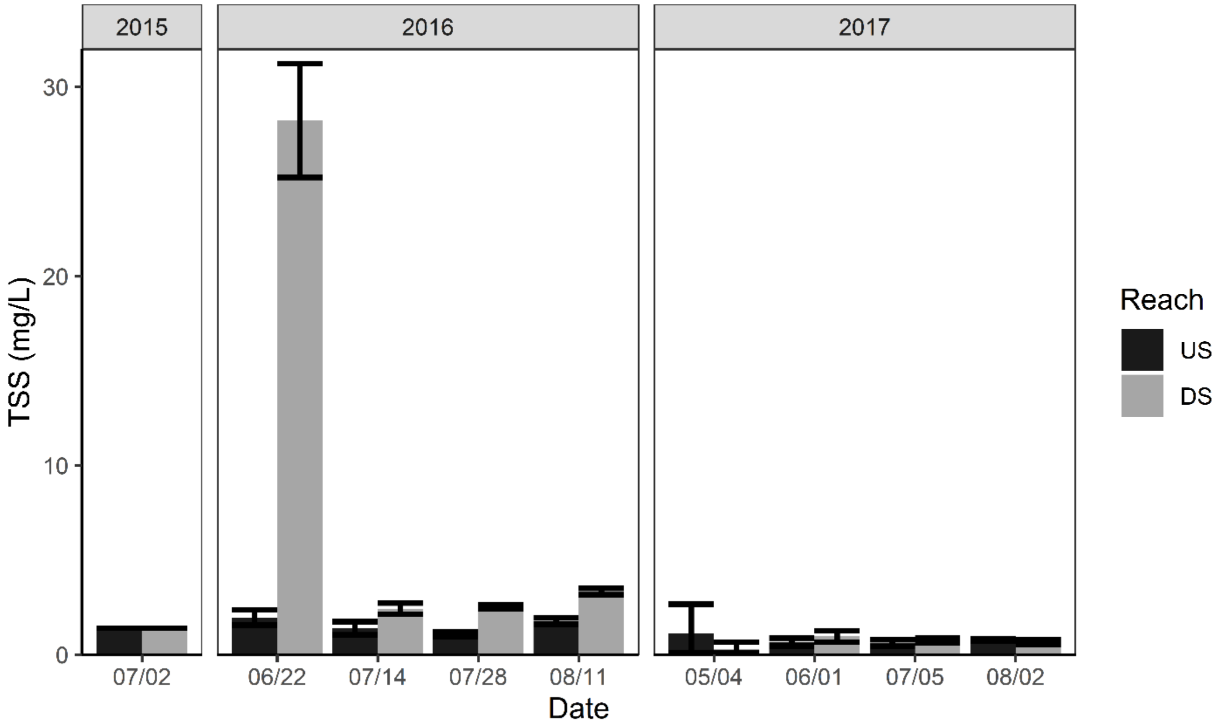

Figure 3. **Means of total suspended solids (TSS) and confidence intervals measured for 2015 (one occasion), and 2016 and 2017 (four occasions per year) for downstreas (DS), and upstream (US) reaches. TSS estimates in 2015 represent pre-restoration values, estimates in 2016 represent values during the construction of the bridge, and estimates in 2017 represent post-restoration values. Error bars represent ±SE.**

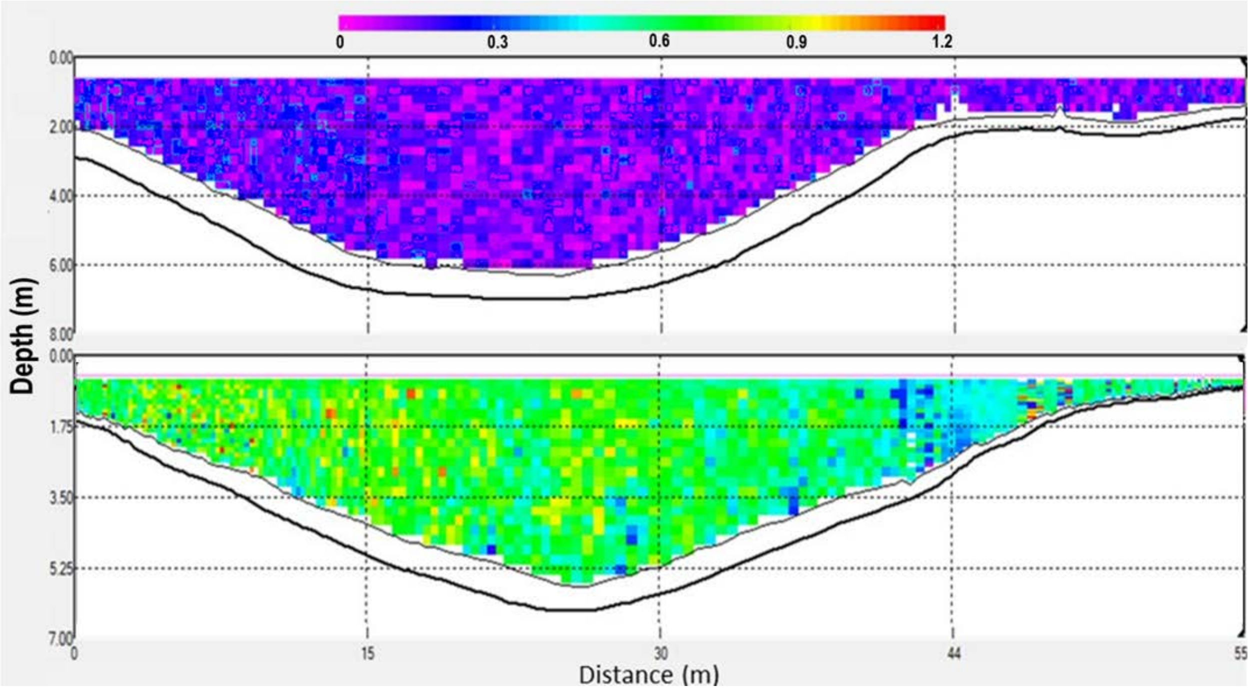

Figure 4. Modeled water velocities in a transect downstream of the restoration area based on ADCP. Upper panel represents pre-restoration estimates, while lower panel represents the post-restoration estimates. Pixel color represents velocity in m/s.

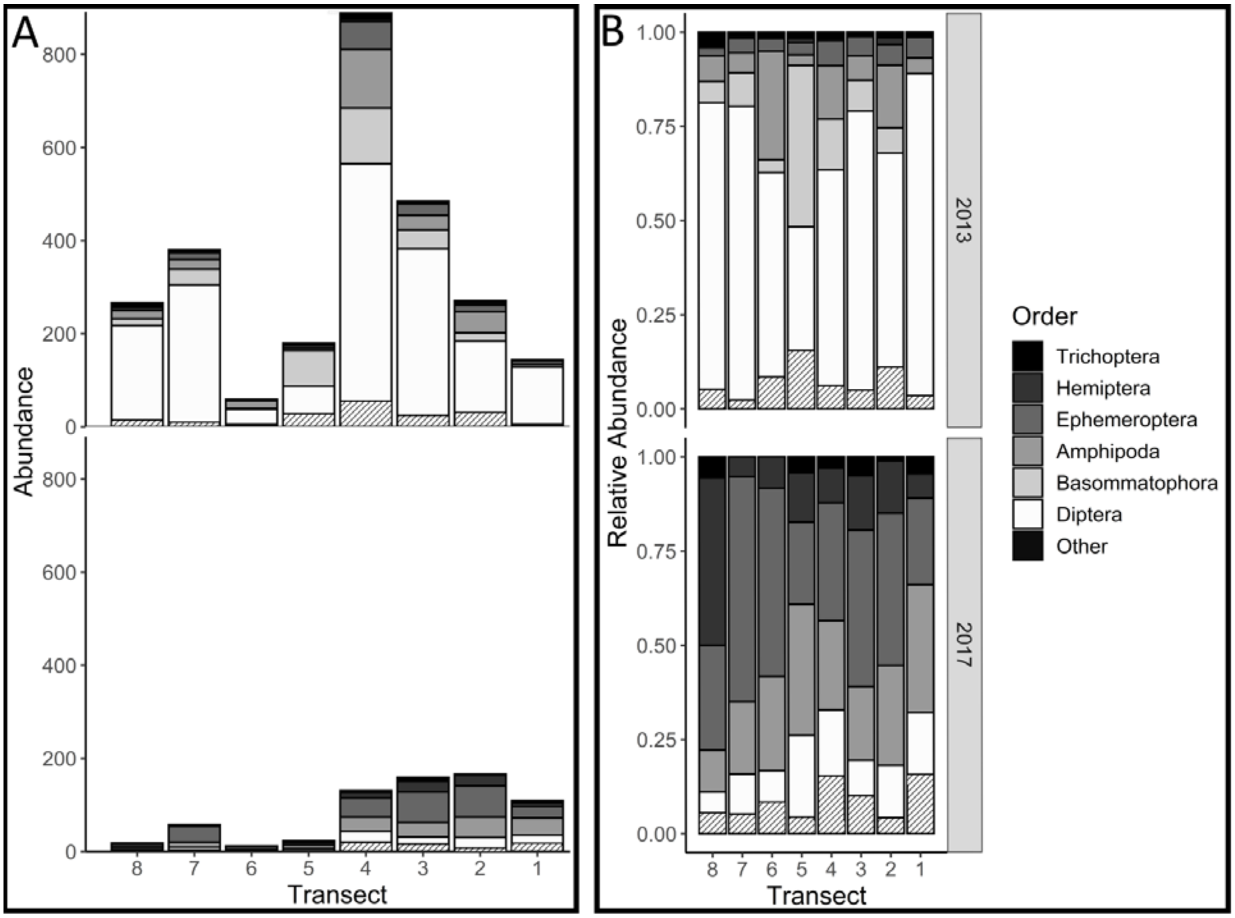

Figure 5. **Benthic invertebrates' A) abundance (number per 100 m transect) and B) relative abundance in 2013 (top panel) and 2017 (bottom panel). Transects are represented from upstream (8-6) to downstream (5-1). Others includes: Coleoptera, Decapoda, Isopoda, Megaloptera, and Odonata.**

Figure 6. CPUE (catch per net per 12 hour set) of larval fishes sampled by drift nets from mid-April to late-August, for pre-restoration sampling (2013, 2014), and post-restoration sampling (2017, 2018) for both upstream (US), and downstream (DS).___

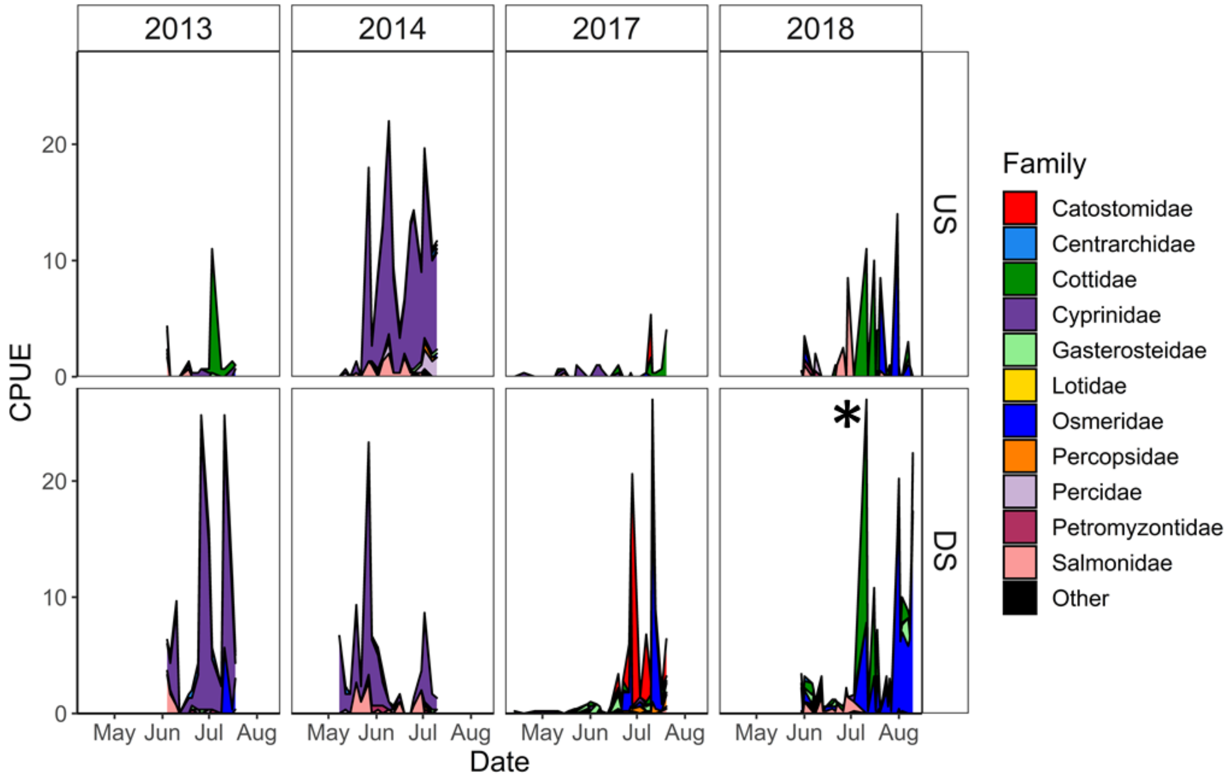

Figure 6. Total CPUE (catch per net per 12 hour set) of larval fishes sampled by drift nets from mid-April to late-August, for pre-restoration sampling (2013, 2014), and post-restoration sampling (2017, 2018) for both upstream (US), and downstream (DS). Cottidae in 2018 had an event with a CPUE of 67, which is represented by an asterisk (*), as it couldn't be represented using the current Y-axis scale. Other represents Others include Esocidae, Fundulidae, Atherinopsidae, and Umbridae.___

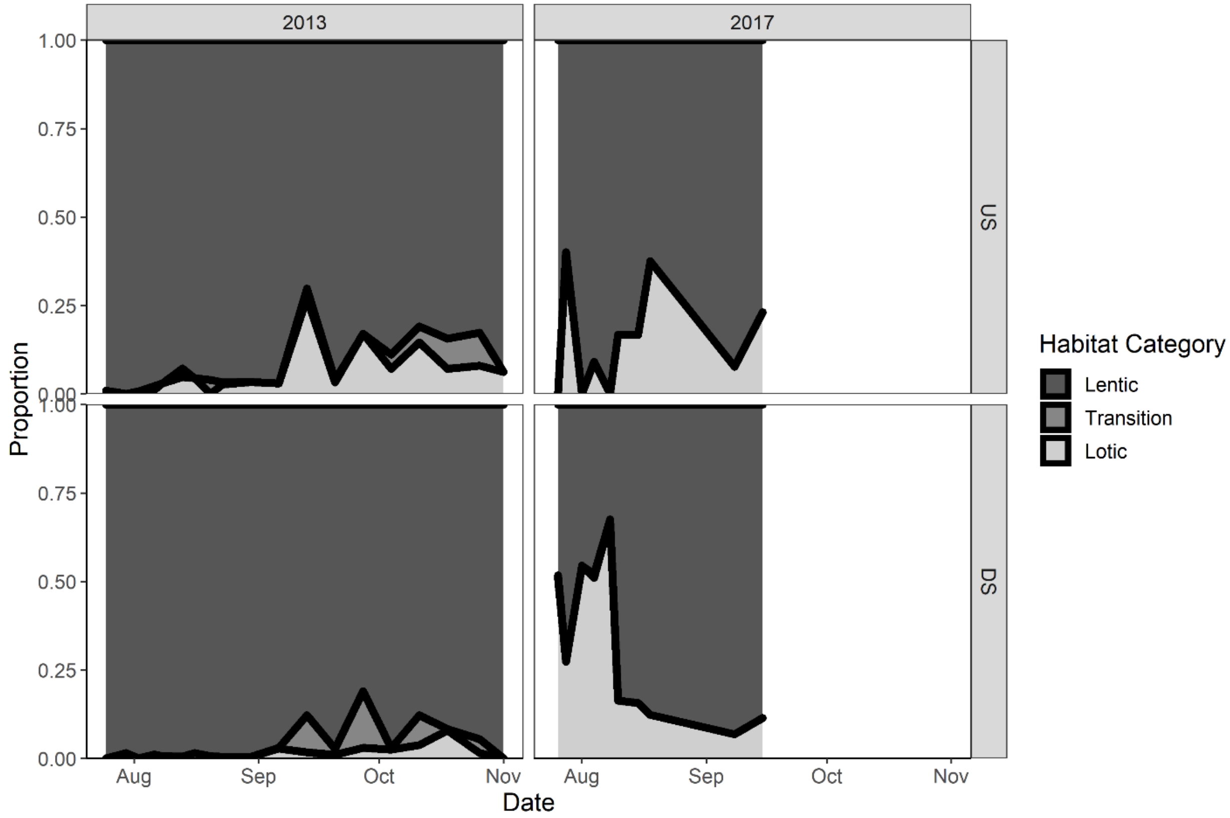

Figure 7. Proportion of adult fishes caught in fyke nets, representing each habitat category in 2013 and 2017 for the upstream (US) and downstream (DS) reaches.

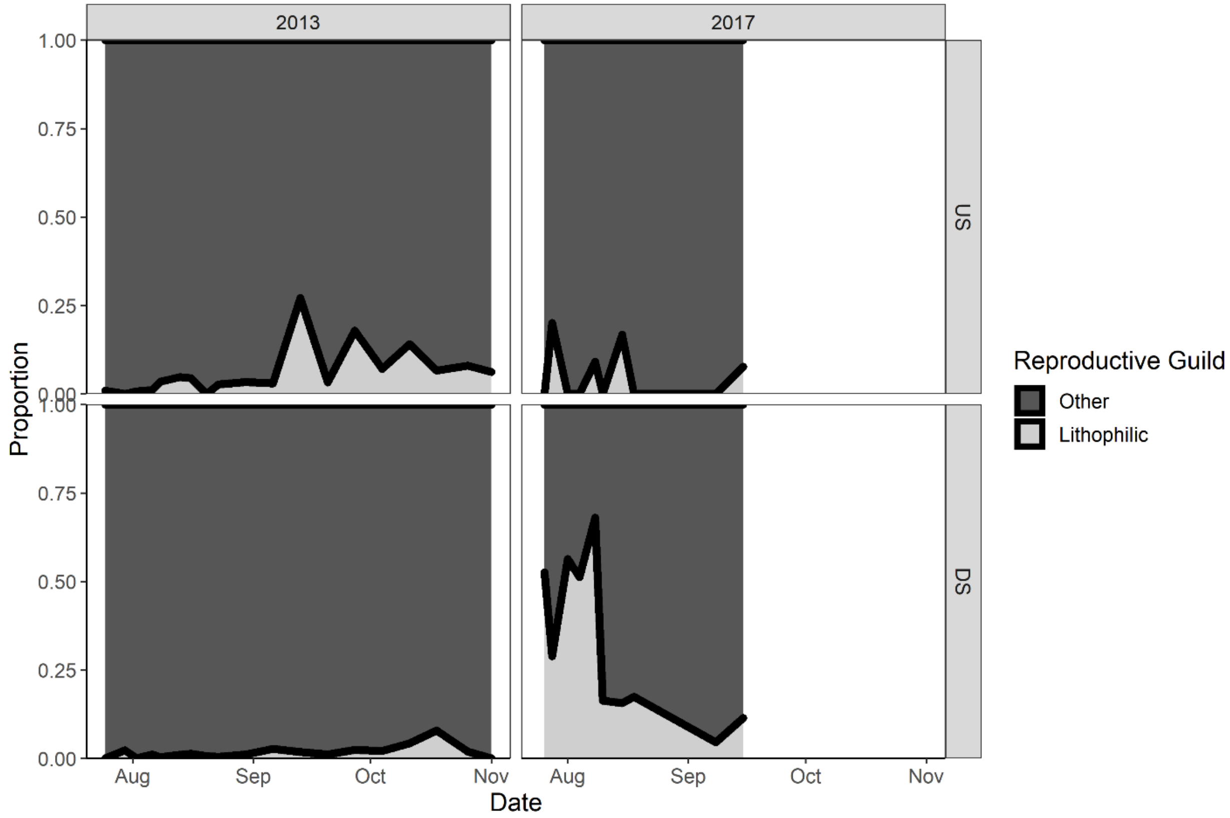

Figure 8. Proportion of adult fishes caught in fyke nets that were classified as either lithophilic or other reproductive guild in 2013 and 2017 for the upstream (US) and downstream (DS) reaches.

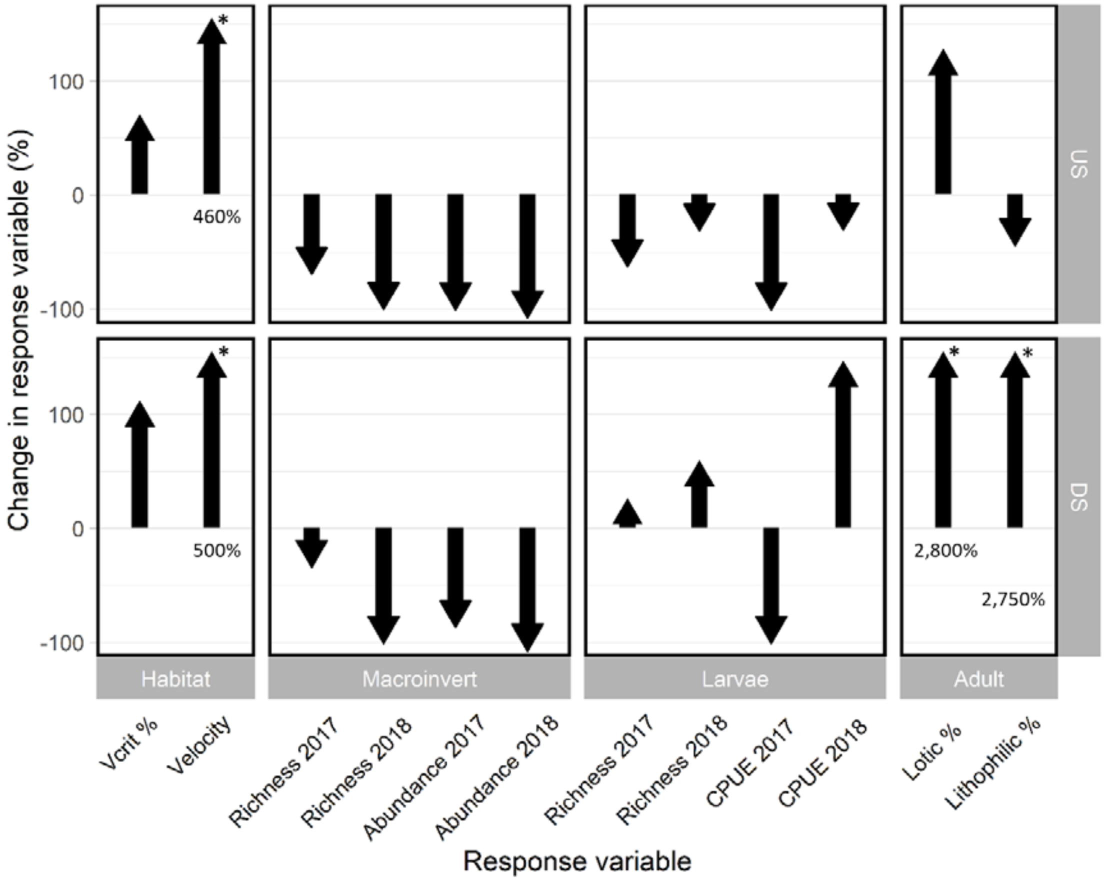

Figure 9. Changes in the Little Rapids following the restoration project. Changes are presented for the four main groups assessed: Habitat, Macroinvertebrates, Larval Fishes, and Adult Fishes, for Upstream (US) and Downstream (DS) reaches. The direction of the arrow represents the direction of the change. For Habitat VCrit%, the Y axis represents absolute change, as the percentage prior to restoration was 0. For factors in X that include year, the value presented represents changes between post-restoration and the year (2017 or 2018). Values with an asterisk (*) represents changes of over 150%, and the magnitude of the change is presented under the arrow.