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[Article]

The Effects of the Stronach Dam Removal on Fish in the Pine River, Manistee County, Michigan

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Abstract.—Although dam removal has been increasingly used as an option in dam management and as a river restoration tool, there are few studies providing detailed quantitative assessment of the response of fish populations to dam removal. In this study, we document the response of the fish community in the Pine River, Michigan, to the gradual removal of Stronach Dam. Ten sites were sampled annually during the course of the removal (1997–2003) and for 4 years following removal (2004–2007). Before the removal of Stronach Dam, 11 fish species were found only downstream of the dam, 1 species was found only upstream of the dam, and 19 species were captured both above and below the dam. Following removal, 8 species formerly found only below the dam utilized newly available portions of the river above the dam. Most fish species (18 of the 25 evaluated) showed an increase in abundance following removal, strongly supporting the idea that dam removal reduces multiple factors limiting riverine fishes. Brown trout *Salmo trutta* and rainbow trout *Oncorhynchus mykiss* were the primary sport fishes present in the river, and the abundance of both species increased by more than twofold over the course of the study. The abundance of white suckers *Catostomus commersonii* also increased significantly due to increased reproductive success. The results of this study illustrate how dam removal is a useful tool for restoration of habitat connectivity and habitat conditions and how the fish community in a coldwater stream responded to the removal.

Dams affect river systems in a myriad of ways, disrupting the flow of water, energy, sediment, nutrients, and biota (e.g., Petts 1980; Williams and Wolman 1984; Cushman 1985; Ward and Stanford 1989; Benke 1990; Ligon et al. 1995). These changes impact lotic fish communities through both habitat alteration and fragmentation (Hayes et al. 2008). Habitat alteration occurs upstream and downstream of dams, but in fundamentally different ways. Upstream from dams, the flow of water, sediment, and nutrients are slowed, creating impoundments and converting lotic habitat to lentic habitat (Petts 1980; Ward and Stanford 1989). This decreases habitat suitability for lotic species and often leads to the juxtaposition of lentic fish communities in impoundments with upstream resident lotic species. Downstream of dams, habitat is altered through a reduction in sediment supply and erosion due to "sediment starvation" (Phillips et al. 2004), water temperature changes, and changes in flow variability (Williams and Wolman 1984; Cushman 1985; Ligon et al. 1995; Collier et al. 1996). This often leads to the displacement of resident fish species and colonization of invasive or nonnative fish species (Martinez et al. 1994; Quinn and Kwak 2003). Changes in the fish community can be seen as being detrimental or beneficial, depending on the value placed on the fish species being lost or gained.

Dams also impact fish communities through habitat fragmentation. All fish species need access to habitats for reproduction, feeding, and survival. The placement of dams on rivers prevents or impedes movements for many fish species. For diadromous fishes, dams can block essential reproductive migrations and the migration of juveniles to feeding habitats, often with severe consequences (Benke 1990; Pringle et al. 2000). Many nondiadromous riverine fish species also make substantial migrations critical to their life histories and survival (Auer 1996; Northcote 1998; Burrell et al. 2000). These movements include downstream drift of juveniles, movements to and from overwintering habitat, movements to thermal refuges, migrations to preferred spawning habitat, and searching movements crucial for individual fish to locate optimal areas for feeding and holding.

Dam removal has been increasingly embraced as a restoration method for remedying both fish habitat alteration and fragmentation as well as rehabilitating overall river ecosystem form and function. However,

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despite the more than 700 dams removed in the United States (American Rivers 2008), there are still relatively few published studies documenting the effects of dam removal on fish populations. Among the studies published, several focus on the response of anadromous fishes, which would be expected to benefit greatly from removal of migration barriers. For example, Burdick and Hightower (2006) demonstrated the successful spawning of striped bass *Morone saxatilis*, American shad *Alosa sapidissima*, and hickory shad *A. mediocris* upstream of a dam following its removal. Along a similar line, Hill et al. (1994) found that the recruitment of largemouth bass *Micropterus salmoides* increased substantially following the removal of Chipola Dam in Florida, and that migratory striped bass were also seen using the river as thermal refuge. Further, the total number of species present in the river upstream of the dam increased from 34 to 61 following dam removal.

Only a handful of studies have documented changes in fishes following dam removal in the Upper Midwest of the United States. Among the earliest studies is that of Kanehl et al. (1997) who documented large increases in the recruitment and density of smallmouth bass *M. dolomieu* in the Milwaukee River upstream of the Woolen Mills Dam removal site, a decrease in the density of common carp *Cyprinus carpio*, and an increase in fish community biotic index scores. Similarly, Catalano et al. (2007) showed rapid species recolonization following the removal of four small dams from a low-gradient, warmwater Wisconsin river, and Maloney et al. (2008) documented partial recovery of a warmwater fish community in the former impoundment of an Illinois river. In contrast to these studies, Stanley et al. (2007) observed no change in a brook trout *Salvelinus fontinalis* population in a small Wisconsin stream 2 years after the removal of a dam.

While these studies provide valuable insight into the effects of dam removal on fish, our understanding of the outcomes of removing dams on fish remains limited. In particular, studies describing long-term responses with sufficient population-level detail are lacking. Given the current void in our understanding of this emerging and important topic, additional information on this subject is needed to inform future decision making regarding the removal of dams.

The "staged" or gradual removal of Stronach Dam on the Pine River in Manistee County, Michigan, created an opportunity to gain insight into both the effects of habitat alteration on a fish community following dam removal and the effects of restored connectivity and subsequent fish movements and species redistribution. This was possible because many years of habitat alteration occurred during the dam's removal before connectivity was finally restored during the final stage of dam removal.

The specific research objectives of this study were to document changes in (1) fish habitat that occurred due to dam removal, (2) the distributions of fish species in the Pine River following the dam's removal, (3) the density of fish during the course of dam removal, and (4) the size structure of selected fish species. Details on the changes in fish habitat due to dam removal are covered in Burroughs (2007) and Burroughs et al. (2009) and will only be summarized herein.

Study Area

Stronach Dam was located on the Pine River, a tributary to the Manistee River in the northwestern lower peninsula of Michigan (Figure 1). The Pine River is 77 km long, is a fourth-order stream, and drains a 68,635-ha watershed dominated by sandy glacial outwash plains, recessional moraines, and areas of consolidated clay (Hansen 1971; Rozich 1998). The river carries a high bed load of sand due to the local geology and extensive logging operations of the late 1800s, which created unstable banks along the river. Mean daily discharge recorded at two U.S. Geological Survey gauging stations on the Pine River averaged 8.10 m^3/s during 34 years of record keeping, with an average annual ratio of high to low mean monthly flows of 2.02:1, indicating "stable to very stable" flows (Rozich 1998). The Pine River is a coldwater stream, dominated by groundwater input, and rarely exceeds 21°C. The Pine River is a riffle–pool stream with an average gradient of 2.8 m/km. The section of river impounded by Stronach Dam historically had a gradient of 4.7 m/km and was reported to be the best fish-spawning area of the river (Rozich 1998). Self-sustaining populations of resident brown trout *Salmo trutta* and rainbow trout *Oncorhynchus mykiss* provide a valuable sport fishery upstream of the Stronach Dam site. Downstream of the dam a coolwater fish assemblage predominated.

Stronach Dam was constructed 5.6 km upstream from the confluence of the Pine River and the Manistee River (Figure 1) from 1911 to 1912. Stronach Dam was originally an earth-embankment hydroelectric dam with a concrete corewall, operated with about 5.18 m of head (Consumers Power 1994). This created a 26.7-ha reservoir with a 789,428-m^3 volume capacity (Hansen 1971; Consumers Power 1994). Tippy Dam (17.07 m head height), also a hydroelectric dam, was constructed in 1918 downstream of the confluence of the Pine and Manistee rivers (Rozich 1998). This dam created a 428-ha, 48,722,530-m^3 reservoir that impounded water upstream to Stronach Dam and blocked

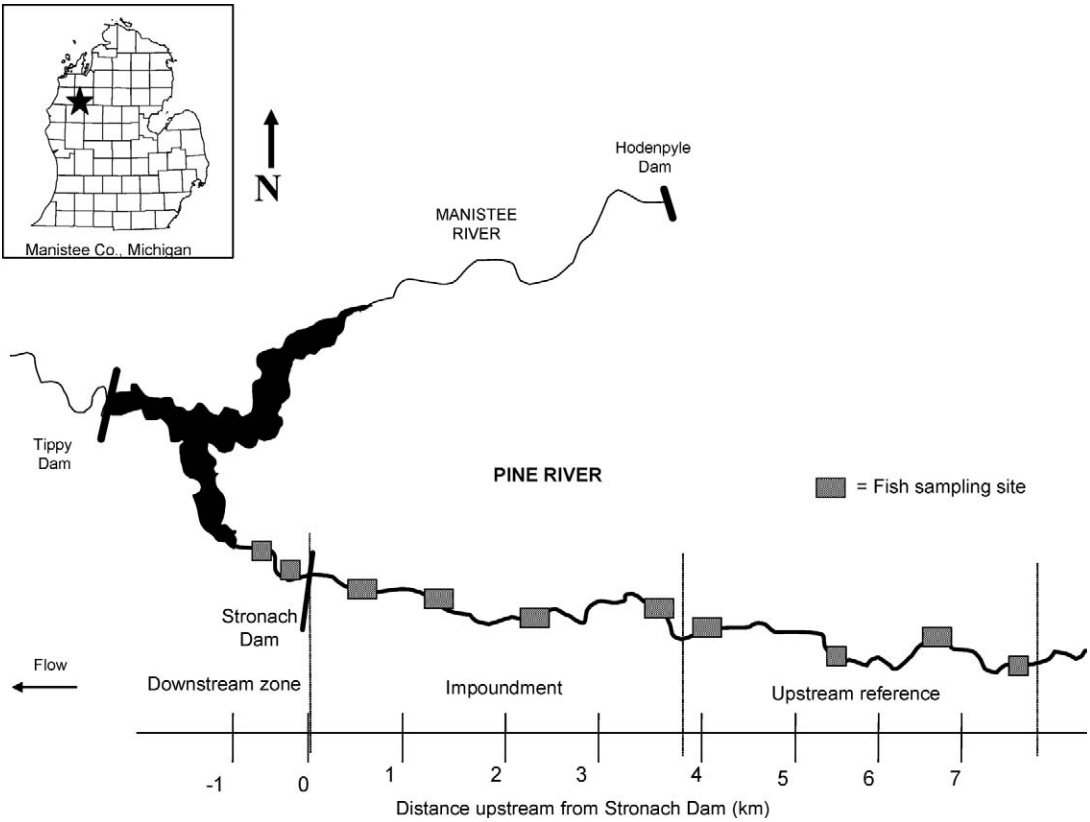

FIGURE 1.—Locations of Stronach Dam and the permanent fish sampling sites within the Pine River study area.

all upstream fish migration from Lake Michigan (Figure 1).

Due to the Pine River's large sediment load, the Stronach Dam reservoir quickly filled with sediment and problems arose with the operation of the dam's turbines. Attempts made in the 1930s to remove the accumulation of sediment at the dam were only marginally successful and eventually became uneconomical (Consumers Power 1994). In 1953, 41 years after construction, Stronach Dam was decommissioned as a hydroelectric dam by the owner, Consumers Power Company.

In the early 1990s, removal of Stronach Dam was negotiated as part of a Federal Energy Regulatory Commission settlement in the relicensing of Tippy Dam. A "staged" or gradual removal was decided upon in order to allow gradual river channel adjustments with the least amount of environmental impact, at the lowest cost, and without affecting the operation of Tippy Dam (Battige et al. 1997). In 1996, a 3.6-m-high "stop-log" structure was installed in the old powerhouse to allow a gradual drawdown of the river. The stop-log structure consisted of hollow metal pipes (15 cm diameter) stacked one on top of another, with a metal grate called a "trash-rack" immediately upstream to protect the stop-logs from debris impingement. The original removal schedule called for one stop-log to be removed every 3 months, for a total of 0.60 m/year, over the course of 6 years with corresponding trash-rack removal. This plan was altered due to recreational safety concerns, feasibility issues, and technical difficulties with removal (D. S. Battige, Consumers Power, personal communication). The actual sequence of the staged dam removal occurred between 1997 and 2003 (Table 1).

Methods

In 1995, 2 years prior to the commencement of dam removal activities, the Pine River was assessed to document the spatial extent of impoundment effects due to Stronach Dam. This assessment involved the survey and description of physical characteristics, including categorization of the stream into bedform units of runs, riffles, pools, or rapids, following the

TABLE 1.—Schedule of removal events during the staged removal of Stronach Dam on the Pine River. Stop-logs are 15.24-cm-diameter hollow metal pipes stacked on top of one another. Trash-rack removal estimates are approximate. Cumulative meters removed are in parentheses (Dave Battige, Consumers Energy, personal communication).

Date	Number of stop-logs removed	Meters of trash-rack removed
Mar 17, 1997	1 (0.15)	0 (0)
Jun 5, 1997	1 (0.30)	0 (0)
Jun 16, 1997	2 (0.61)	0 (0)
Jun 24, 1997	2 (0.91)	0 (0)
Sep 15, 1997	1 (1.07)	0 (0)
Dec 15, 1997	1 (1.22)	0 (0)
Mar 16, 1998	1 (1.37)	0 (0)
May 7, 1998	0 (1.37)	1.83 (1.83)
May 29, 1998	0 (1.37)	0.30 (2.13)
Jun 15, 1998	1 (1.52)	0 (2.13)
Sep 8, 1998	1 (1.68)	0.30 (2.44)
Dec 14, 1998	1 (1.83)	0.30 (2.74)
Mar 15, 1999	1 (1.98)	0 (2.74)
May 11, 1999	1 (2.13)	0 (2.74)
Sep 13, 1999	2 (2.44)	0 (2.74)
Sep 16, 1999	0 (2.44)	0.61 (3.35)
Apr 17, 2000	2 (2.74)	0 (3.35)
Oct 2, 2000	2 (3.05)	0 (3.35)
Oct 5, 2000	0 (3.05)	0.61 (3.96)
May 8, 2001	2 (3.35)	0 (3.96)
Sep 8, 2001	2 (3.66)	0 (3.96)
Nov 11, 2002	0 (3.66)	1.52 (5.49)
Dec 2003	Remaining spillway and dam superstructure removed	

criteria developed by Hicks and Watson (1985). Based on this assessment, we defined three habitat-based reaches within the Pine River. The river reach formerly occupied by the impoundment (which we refer to as the impoundment reach) extended 3.89 km upstream of Stronach Dam and was relatively wide, slow flowing, and sand-bottomed, and generally consisted of only run bedform units. It is important to emphasize that the impoundment had filled in completely, and no pool due to the dam remained. Thus, Stronach Dam effectively functioned as a waterfall on the Pine River. We designated an upstream reference reach extending 3.70 km beyond the upstream boundary of the former impoundment. In this reach, no effects of Stronach Dam on river morphology were evident, and the river was narrower and faster flowing, had coarser substrates, and showed high bedform heterogeneity. The third study reach was downstream of Stronach Dam, where the river was wide and slow flowing, sand-bottomed, and consisted entirely of run bedforms. The downstream reach extended down to the confluence of the Pine River with Tippy Dam Reservoir, located approximately 0.63 km downstream of Stronach Dam.

Bedform frequency, latitudinal and longitudinal channel morphology, water velocity, and substrate size composition were documented in the three study reaches annually from 1996 through 2006 (see Burroughs 2007 for complete details of the methodology used).

Fish were sampled in the Pine River from 1997 through 2007 with a 5.2-m (17-ft) Smith-Root Cataraft electrofishing boat to assess fish population response to the dam removal. The electrofishing boat was set to deliver pulsed DC (40% duty cycle) on low range (50–500 V) at 4–6 A. Fish were sampled annually at 10 sites along the river between mid-July and early August (Figure 1). Four sites were located in the upstream reach, four sites were located in the impoundment reach, and two sites were located in the downstream reach. Each site was enclosed with block nets and multiple-pass removal sampling was conducted to estimate fish population sizes (VanDeventer and Platts 1983) for selected large-bodied species including brook trout, brown trout, rainbow trout, white sucker *Catostomus commersonii*, and shorthead redhorse *Moxostoma macrolepidotum*. A minimum of three passes were made at each site; occasionally, additional passes were made in order to achieve a clear depletion pattern in catch. Fish captured were identified and total length (TL) was measured to the nearest millimeter.

For all other species, total catch across the three electrofishing passes within each reach, divided by the area of the sites within the reach, was used as an index of relative abundance (i.e., catch/ha). An index of the relative abundance for the entire study reach of the Pine River was calculated as the weighted mean of the reach-specific densities, multiplied by the total area of the study reach. In effect, this provided an estimate of the minimum total abundance for each species.

For the five species of fish for which depletion estimates were made, preliminary analyses based on depletion patterns by 25-mm size-groups, summed across all sampling events, suggested lower catchability for smaller fish. As such, abundance estimates were conducted by size-class to reduce bias due to unequal catchability (e.g., Al-Chokhachy and Budy 2008). The two size-classes were less than 130 mm and equal to or greater than 130 mm TL for brown trout, rainbow trout were less than or equal to 100 mm and greater than 100 mm, brook trout were less than or equal to 110 mm and greater than 110 mm, and white suckers were less than or equal to 100 mm and greater than 100 mm. One size-class was adequate for shorthead redhorses since few fish less than 300 mm were captured. Catch patterns were tabulated for each size-class for these species at each site, and abundance was calculated using the equations of Seber (1982) for triple-pass removal methods (Junge and Libosvarsky 1965; Seber 1982). Abundance for each length-group for each species was added to calculate total abundance at each site. Density within each study reach was calculated as total abundance at all sites within a zone (e.g., downstream of the dam) divided by total area sampled within a zone, and total abundance for the study site as a whole was calculated as mean density times total area.

For some sites and size-classes, low catches sometimes produced nondescending catch patterns, which did not allow direct estimation of abundance. In such situations, the average catchability for that species' size-class, for all sites in all years, was used to estimate the abundance, using the following formula:

$$Y[1 + (1 - q)^3],$$

where Y is the total catch across the three passes and q is the average catchability (Seber 1982).

Changes in the spatial distribution of each species over time were evaluated using a two-factor mixed-model analysis of variance (ANOVA). Analyses were performed only for species where the total catch was greater than 10 individuals for the study as a whole. We separated the study into three time periods (1997–2000, 2001–2003, 2004–2007), and three river reaches (upstream, impoundment, downstream). The time periods correspond to phases of the dam removal: (1) dam removal was underway, but habitat changes in the downstream zone and former impoundment were minimal; (2) dam removal was not yet complete, but extensive changes in habitat were observed both below the dam and in the former impoundment; and (3) dam removal was complete, so the barrier to movement was removed and the magnitude of habitat changes were decreasing (Burroughs et al. 2009). In this analysis, each year was treated as a replicate. Differences in time period are interpretable as general trends in abundance over the course of removal, differences in reaches are interpretable as mean differences in abundance across space, and significant interaction terms are interpretable as shifts in relative distribution over the course of time. Trends in total abundance over time were evaluated using a one-way mixed-model ANOVA using time period as a categorical main effect.

When implementing these analyses, we encountered two features of the data that did not meet the usual assumptions of the statistical model. As is common with fish abundance data, the data were not normally distributed, had nonhomogeneous variance, and had many observations of zero. The usual approach with such data is to take a logarithmic transformation of density + 1, but this proved to be ineffective because many of the observations of zero catch were grouped together (e.g., no shorthead redhorses were caught above the dam prior to removal) and, thus, the variance of these blocks of data were also zero regardless of the transformation. Our approach to this problem was to allow for group-specific variance (Littell et al. 1996), thereby focusing primarily on the problem of heterogeneous variance, which is viewed as a more critical violation of the assumptions than lack of normality (Lindman 1974).

The size structure of brown trout, rainbow trout, white suckers, and shorthead redhorses over time were examined for changes over time using the Kolmogorov–Smirnov (K–S) two-sample test (Steel and Torrie 1980). These analyses allowed us to assess whether changes in fish density occurred across all size-classes, or whether there was evidence of size-specific responses.

Brown trout density (estimated using mark–recapture methods) for several other Michigan trout streams was available as part of ongoing monitoring by the Michigan Department of Natural Resources. We selected streams with data covering the same time period as our sampling, and used trends from these streams as a basis for evaluating the trends we observed in the Pine River. Changes in density relative to 1997 were represented as

$$\text{Percent change} = \frac{\text{Density}_{\text{year}} - \text{Density}_{1997}}{\text{Density}_{1997}} \times 100.$$

Using this formula, declines in density are represented as negative percentages.

Results

Fish Habitat

From 1997 through 2005, substantial changes occurred to the morphology of the Pine River due to the removal of Stronach Dam. Those changes are described in detail by Burroughs (2007) and Burroughs et al. (2009), and are reviewed here briefly to provide context for understanding changes to the fish community mediated by habitat alteration following dam removal. In the upstream reference reach (above the former impoundment), no significant change in habitat conditions was observed for the reach as a whole. In the reach immediately upstream of Stronach Dam, progressive erosion, or incision, of the accumulated reservoir sediment fill occurred with each stage of dam removal. This erosion increased the gradient throughout the entire former impoundment (~4 km), increased water velocities, and eroded large volumes of sediment as a new channel was carved downward through the reservoir sediment fill. This resulted in a narrower river channel, with steepened banks, increased frequency of riffle and pool bedforms, and slightly increased median substrate particle size composition (Table 2). Large

TABLE 2.—Summary of key fish habitat changes that occurred during Stronach Dam removal (1997–2003). Fish passage past the dam site was not possible until 2003. Bedform frequencies were surveyed in 1995 and 2004.

Habitat characteristic	1996	2002	2006
Wetted stream width (mean, m)			
Reference	17.0	17.0	16.9
Impoundment	19.9	17.4	17.6
Downstream	32.7	34.9	34.8
Gradient (% slope)			
Reference	0.159	0.157	0.155
Impoundment	0.128	0.181	0.206
Downstream	0.061	0.074	0.104
Water velocity (mean, m/s)			
Reference	0.66	0.68	0.69
Impoundment	0.54	0.71	0.86
Downstream	0.15	0.63	0.57
Substrate size (median, mm)			
Reference	35.6	39.0	25.2
Impoundment	6.4	8.5	6.4
Downstream	1.0	2.0	1.0
Bedform frequency			
Reference	High diversity		No change
Impoundment	Run bedforms		More pools and riffles
Downstream	Run bedforms		No change

amounts of the reservoir sediment fill were transported downstream of the dam, eventually being deposited at the next impoundment downstream. Significant amounts of this sediment were also deposited in the river channel and a smaller portion was deposited onto the floodplain during high flow events. Sediment deposition downstream of the dam resulted in streambed aggradation, increased stream width, and decreased water depth. Gradient was increased downstream of the dam removal site through sediment deposition, water velocities increased slightly, and substrate size remained small (sand dominated). Bedform diversity did not increase in this reach during the study period and remains almost entirely as run bedforms (Table 2).

Response of Fish Distribution and Abundance to Dam Removal

A total of 14,623 fish were captured and 40 fish species were identified during sampling in the Pine River. Slimy sculpin *Cottus cognatus* and mottled sculpin *C. bairdii* were combined, however, into a single taxon due to difficulties in definitively identifying these species in the field, leading to a total of 39 taxa for our analysis (Table 3). Of the species encountered, only brown trout, rainbow trout, and redear sunfish are species not native to Michigan.

Prior to the removal of Stronach Dam, we captured a total of 31 species (Table 3). Eleven of these species were found only downstream of the dam, one species was found only upstream of the dam, and 19 species were captured both above and below the dam. Following dam removal, 37 species were captured, with three species being caught only below the dam, 10 species caught only above, and 24 species caught above and below. Of the 31 species caught prior to removal, all but two were also caught following removal. During the postremoval sampling, eight species were caught that had not been seen prior to removal (Table 3).

Most species showed significant differences in density across reaches for the study period as a whole (Table 4), indicative of distinct habitat preferences and the impact of the dam. The most abundant species below the dam were white sucker, shorthead redhorse, and logperch. Above the dam, brown trout, rainbow trout, slimy and mottled sculpin, and white sucker were the most abundant species.

Substantial shifts in the distribution of several fish species relative to the location of the dam were observed. Most dramatically, the distribution of eight species caught only below the dam prior to removal expanded to include river reaches above the former location of the dam following removal (Table 4). Of these species, significant time period by reach interactions were observed, however, for only the three most abundant: logperch, shorthead redhorse, and trout-perch (Table 4). Black bullhead, which was only caught upstream of the dam prior to removal was caught both upstream and downstream following removal. Among the 19 species that occurred above and below the dam prior to removal, five species were only caught above the dam following removal. These species were generally those with low catches, with the exception of brook trout (Table 4). The densities of four species (white sucker, brown trout, rainbow trout, and common shiner) showed significant time period by

TABLE 3.—Fish species captured in the Pine River prior to dam removal (1997–2003) and after removal (2004–2007) and their locations relative to the dam.

	Preremoval		Postremoval	
Species	Below	Above	Below	Above
Redear sunfish *Lepomis microlophus*	X			
Grass pickerel *Esox americanus*	X		X	
Silver redhorse *Moxostoma anisurum*	X		X	
Blackside darter *Percina maculata*	X		X	X
Johnny darter *Etheostoma nigrum*	X		X	X
Logperch *Percina caprodes*	X		X	X
Rock bass *Ambloplites rupestris*	X		X	X
Shorthead redhorse *Moxostoma macrolepidotum*	X		X	X
Smallmouth bass *Micropterus dolomieu*	X		X	X
Trout-perch *Percopsis omiscomaycus*	X		X	X
Walleye *Sander vitreus*	X		X	X
Spottail shiner *Notropis hudsonius*	X	X		
Bluegill *Lepomis macrochirus*	X	X		X
Emerald shiner *Notropis atherinoides*	X	X		X
Brook trout *Salvelinus fontinalis*	X	X		X
Central mudminnow *Umbra limi*	X	X		X
Black bullhead *Ameiurus melas*		X	X	X
Sand shiner *Notropis stramineus*			X	
Golden shiner *Notemigonus crysoleucas*			X	X
Banded killifish *Fundulus diaphanus*				X
Brook stickleback *Culaea inconstans*				X
Green sunfish *Lepomis cyanellus*				X
Hornyhead chub *Nocomis biguttatus*				X
Northern redbelly dace *Phoxinus eos*				X
Yellow bullhead *Ameiurus natalis*				X
American brook lamprey *Lampetra appendix*	X	X	X	X
Blacknose dace *Rhinichthys atratulus*	X	X	X	X
Brown trout *Salmo trutta*	X	X	X	X
Chestnut lamprey *Ichthyomyzon castaneus*	X	X	X	X
Common shiner *Luxilus cornutus*	X	X	X	X
Creek chub *Semotilus atromaculatus*	X	X	X	X
Largemouth bass *Micropterus salmoides*	X	X	X	X
Longnose dace *Rhinichthys cataractae*	X	X	X	X
Northern pike *Esox lucius*	X	X	X	X
Pumpkinseed *Lepomis gibbosus*	X	X	X	X
Rainbow trout *Oncorhynchus mykiss*	X	X	X	X
Slimy and mottled sculpins *Cottus cognatus* and *C. bairdii*	X	X	X	X
White sucker *Catostomus commersonii*	X	X	X	X
Yellow perch *Perca flavescens*	X	X	X	X

reach interactions, indicating detectable changes in their distribution over time (Table 4). These were also among the most abundant fishes in the Pine River.

Trends in total abundance for the river as a whole were evaluated for 25 taxa with catches greater than 10 over the entire study. Mean abundance from 2004 to 2007 was higher than in 1997–2000 for 18 species, with a significant difference detected for seven species (Table 5). For those species showing significant increases, the ratio of increase ranged from 2.36 for rainbow trout to 56.5 for pumpkinseed. Mean abundance in 2004–2007 was less for six species, but was not significantly lower for any of these (Table 5). One species (smallmouth bass) showed no change.

Changes in the abundance of brown trout in the Pine River were compared with trends in other Michigan trout streams. Many of the other streams also experienced increases in brown trout density during this study period, and due to the Pine River's relatively lower density of brown trout, the arithmetic increase in density in the Pine River was not unusual (Figure 2). However, when expressed as a rate of change, increases in brown trout density in the Pine River were substantially greater than those in the other trout streams, and this increase was greatest in the former impoundment reach (Figure 2).

Response of Fish Size Distribution to Dam Removal

Prior to dam removal, the size structure of brown trout did not differ significantly between the upstream and the impoundment reaches (Figure 3; K–S test: $D_{\max} = 0.18$, $P > 0.05$, $n = 78$ and 71, respectively). The downstream reach contained so few brown trout that annual estimates of the size structure were not reliable. The size structure of brown trout in the upstream reach in 1997 and 2006 was not significantly

TABLE 4.—Mean relative density (catch/ha) of fish in the Pine River, 1997–2007. Density for species marked with an asterisk is the estimated true density based on depletion sampling. *P*-values are reported from mixed-model ANOVA tests for period, reach, and period × reach effects. Cases where the model was nonestimable are indicated by "non-est," and cases where the analysis was not conducted due to small sample size are indicated by dashes (–).

	Downstream			Former impoundment			Upstream		
Species	1997–2000	2001–2003	2004–2007	1997–2000	2001–2003	2004–2007	1997–2000	2001–2003	2004–2007
Species caught only below dam									
Silver redhorse	9.1	0.8	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Sand shiner	0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0
Grass pickerel	0.6	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0
Redear sunfish	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Species caught only below dam preremoval, but caught above dam site postremoval									
Logperch	51.1	37.9	29.5	0.0	0.0	18.2	0.0	0.0	18.8
Shorthead redhorse*	85.2	43.9	25.0	0.0	0.0	5.3	0.0	0.0	3.3
Trout-perch	9.1	1.5	5.7	0.0	0.0	6.5	0.0	0.0	0.0
Rock bass	8.5	13.6	5.1	0.0	0.0	0.2	0.0	0.0	0.2
Smallmouth bass	9.1	9.1	2.8	0.0	0.0	0.3	0.0	0.0	0.2
Johnny darter	1.7	7.6	5.1	0.0	0.0	0.2	0.0	0.0	0.0
Blackside darter	1.7	3.8	1.1	0.0	0.0	0.1	0.0	0.0	0.4
Walleye	4.0	1.5	0.6	0.0	0.0	0.1	0.0	0.0	0.0
Species caught only above dam									
Banded killifish	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5
Green sunfish	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.2
Brook stickleback	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Hornyhead chub	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Northern redbelly dace	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Yellow bullhead	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Species caught only above dam preremoval, but caught below dam site postremoval									
Black bullhead	0.0	0.0	0.6	0.2	0.0	0.0	0.4	0.0	0.2
Species caught above and below dam either pre- or postremoval									
White sucker*	143.8	253.8	153.4	36.1	25.6	163.8	35.0	44.2	196.6
Brown trout*	13.1	13.6	58.0	49.7	113.6	142.6	68.0	126.4	113.8
Slimy and mottled sculpins	9.1	28.0	34.1	16.6	42.5	98.7	38.3	111.6	142.2
Rainbow trout*	1.7	4.5	7.4	33.8	38.7	92.6	59.6	51.1	102.0
Brook trout*	0.0	1.5	0.0	9.7	11.0	5.0	25.8	26.1	13.2
Longnose dace	8.5	6.8	2.3	1.5	15.1	14.8	10.3	9.6	14.6
American brook lamprey	16.5	11.4	10.2	7.2	6.0	2.5	11.7	22.0	8.2
Common shiner	23.9	7.6	0.6	0.2	1.4	0.1	0.6	0.3	0.0
Creek chub	6.8	1.5	1.1	1.3	2.9	1.6	0.6	0.3	0.4
Pumpkinseed	0.6	0.8	3.4	0.0	0.0	5.5	0.2	0.0	1.0
Northern pike	4.5	8.3	9.7	0.0	0.0	0.9	0.2	0.0	0.2
Yellow perch	2.3	10.6	5.1	0.0	0.1	1.0	0.0	0.0	1.6
Bluegill	0.0	0.8	0.0	0.6	0.1	0.4	0.0	1.4	4.1
Blacknose dace	0.6	0.0	3.4	0.1	0.1	0.4	0.0	1.9	1.4
Chestnut lamprey	3.4	6.1	1.7	0.0	0.1	0.4	0.0	0.0	0.4
Largemouth bass	0.6	0.8	5.1	0.0	0.1	0.6	0.0	0.0	0.0
Spottail shiner	5.1	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
Emerald shiner	2.3	0.0	0.0	0.0	0.0	0.2	0.6	0.0	0.2
Central mudminnow	0.6	1.5	0.0	0.0	0.1	0.1	0.0	0.0	0.2
Golden shiner	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.2

different (Figure 3; K–S test: $D_{max} = 0.18$, $P > 0.05$, $n = 78$ and 143), and neither was the size structure of brown trout in the impoundment reach in 1997 and 2006 (Figure 3; K–S test: $D_{max} = 0.15$, $P > 0.05$, $n = 71$ and 292). Although the size structure of both reaches did not change significantly over time, the difference in size structure between the upstream and impoundment reaches became significant by 2006 (Figure 3; K–S test: $D_{max} = 0.19$, $P < 0.01$, $n = 143$ and 292), indicating a smaller proportion of individuals over 200 mm in length in the upstream reach.

Rainbow trout in the upstream and impoundment reaches had a significantly different size structure prior to dam removal (Figure 4; K–S test: $D_{max} = 0.49$, $P < 0.01$, $n = 38$ and 51, respectively), but both reaches were characterized by having relatively few rainbow trout, and those present were mostly from 200 to 400 mm in length (Figure 4). The size structure of these

TABLE 4.—Extended.

	P		
Total catch	Period	Reach	Period × Reach
Species caught only below dam			
21	0.0377	0.0005	non-est
8	–	–	–
3	–	–	–
1	–	–	–
Species caught only below dam preremoval, but caught above dam site postremoval			
457	0.7788	<0.0001	0.0090
238	0.1252	<0.0001	0.0272
90	0.2590	0.0025	0.0252
45	0.2428	<0.0001	0.1460
37	0.2999	<0.0001	0.1678
24	0.1461	<0.0001	0.0891
13	0.3110	<0.0001	0.0666
11	0.3061	0.0177	0.2807
Species caught only above dam			
12	0.3471	0.3505	Non-est
2	–	–	–
1	–	–	–
1	–	–	–
1	–	–	–
1	–	–	–
Species caught only above dam preremoval, but caught below dam site postremoval			
6	–	–	–
Species caught above and below dam either pre- or postremoval			
3,687	0.0113	0.0053	0.0306
3,512	0.0240	<0.0001	0.0230
2,803	0.0090	<0.0001	0.1125
1,929	0.0324	<0.0001	0.0232
463	0.4331	<0.0001	0.6089
448	0.2138	<0.0001	0.3304
375	0.6098	0.0438	0.4752
70	0.0678	0.0032	0.0185
70	0.5635	0.1674	0.2400
67	0.1414	0.3871	0.3836
47	0.2138	<0.0001	0.3304
46	0.0833	<0.0001	0.0534
37	0.3094	0.1191	0.1500
27	0.3051	0.3015	0.2382
24	0.4866	0.0009	0.2776
18	0.1961	0.0832	0.2623
10	–	–	–
10	–	–	–
6	–	–	–
2	–	–	–

reaches was significantly different between 1997 and 2006, mainly due to much higher frequencies of rainbow trout less than 200 mm in length (Figure 4; upstream, K–S test: $D_{\max} = 0.49$, $P < 0.01$, $n = 38$ and 102; impoundment, K–S test: $D_{\max} = 0.58$, $P < 0.01$, $n = 51$ and 200). Few rainbow trout were captured in the downstream zone in either 1997 or 2006.

Large changes in the size structure of the white sucker population in the Pine River were observed. Prior to dam removal, the downstream reach had a relatively uniform size distribution from about 100 to 500 mm, the impoundment had relatively low frequencies of white suckers of intermediate lengths about 100–350 mm), and the upstream reach had few white suckers of any length (Figure 5). Following dam removal, the size structure downstream of the dam changed significantly (Figure 5; K–S test: $D_{\max} = 0.50$, $P < 0.01$, $n = 128$ and 56, respectively) and only contained individuals from about 100 to 200 mm in length. The size structure of white suckers upstream of the dam also changed significantly following removal, through the addition of large numbers of juvenile white suckers (about 75–200 mm) (upstream, K–S test: $D_{\max} = 0.58$, $P < 0.01$, $n = 33$ and 266; impoundment, K–S test: $D_{\max} = 0.55$, $P < 0.01$, $n = 140$ and 452).

Prior to 2003, shorthead redhorses were found only downstream of the dam. From 2003 through the end of the study in 2006, shorthead redhorses were found in relatively low densities throughout both the impoundment and reference zones. The few individuals that were sampled upstream of the dam were greater than 200 mm in length (Figure 6). Downstream of the dam, this species was more abundant than it was upstream, but was still relatively low in abundance. Here, the size structure changed significantly (K–S test: $D_{\max} = 0.63$, $P < 0.01$, $n = 28$ and 21, respectively) over time, with a higher proportion of larger fish present following dam removal (Figure 6).

Discussion

Fish Habitat

Fish habitat was altered greatly due to the dam removal. In the former impoundment, habitat quality generally improved for lotic fish species. Prior to the dam removal, this section of river was characterized by low gradient and wide, sand-dominated, run bedforms. During the removal process substantial amounts of sediment erosion occurred, leading to drastic changes in the habitat characteristics of this section of river. Gradient increased substantially, leading to faster and more diverse water velocities, narrower stream width, substrate coarsening, and a higher diversity of bedforms (i.e., more riffles and pools). While these changes represent significant improvements in the heterogeneity and quality of lotic habitat, this section of stream was not restored to habitat condition levels seen in the reference reach of the Pine River.

During the course of dam removal, erosion of sediments from the former impoundment led to increased sediment deposition in the downstream reach, thereby degrading habitat quality. Sediment deposition created unstable and shifting fine substrates and eliminated deeper water habitats. Throughout the

TABLE 5.—Mean total relative abundance of fish in the Pine River, by time period. Abundance for species marked with an asterisk is estimated true abundance based on depletion sampling. The P-value reported is for a mixed-model ANOVA test of differences between time periods, and the ratio is the mean abundance in 2004–2007 divided by the mean abundance in 1997–2000.

Species	1997–2000	2001–2003	2004–2007	P-value	Ratio
Brown trout*	1,362	2,912	3,415	0.0090	2.51
White sucker*	1,038	1,018	4,429	0.0010	4.27
Rainbow trout*	1,001	1,043	2,364	0.0184	2.36
Slimy and mottled sculpins	558	1,518	2,757	0.0003	4.94
Brook trout*	342	370	176	0.0750	0.51
American brook lamprey	225	261	109	0.4264	0.48
Longnose dace	101	346	369	0.0261	3.65
Shorthead redhorse*	89	46	146	0.0082	1.64
Logperch	53	40	486	0.3669	9.17
Creek chub	34	57	33	0.8707	0.97
Common shiner	33	35	3	0.1829	0.09
Bluegill	12	12	34	0.6559	2.83
Trout-perch	10	2	126	0.0745	12.60
Smallmouth bass	10	10	10	0.9960	1.00
Silver redhorse	10	1	2	0.1120	0.20
Rock bass	9	14	11	0.7269	1.22
Northern pike	6	9	29	0.0542	4.83
Chestnut lamprey	4	9	12	0.2629	3.00
Walleye	4	2	3	0.7290	0.75
Blacknose dace	3	15	20	0.1894	6.67
Pumpkinseed	2	1	113	0.3883	56.50
Yellow perch	2	14	35	0.0098	17.50
Johnny darter	2	8	9	0.1469	4.50
Blackside darter	2	4	6	0.4726	3.00
Largemouth bass	1	3	17	0.2759	17.00

study, the downstream reach of river was overly wide and shallow, sand-dominated, and consisted only of run habitat. Although the impact of excess sediment deposition should decline after sediment erosion in the former impoundment ceases, this was not observed during the duration of this study. The continued degraded habitat conditions encountered downstream are in line with Maloney et al. (2008) who showed depressed downstream fish metrics 3 years after a dam removal. One incidental benefit to the fish community in the downstream reach may result from the streambed aggradation that occurred. With a streambed higher in elevation, overbank flooding could occur more frequently, thereby recharging adjacent floodplain wetlands and ponds. These habitats contribute to overall system productivity (e.g., Dettmers et al. 2001), potentially enhancing fish production.

Fish Distribution

Prior to the removal of Stronach Dam, the three study reaches had distinctive fish communities. The species composition of the impoundment was intermediate to both the reference and the downstream zones, while the reference and downstream zones were highly dissimilar (Burroughs 2007). These differences were probably the result of both habitat differences between the zones and the effects of the dam on connectivity between the zones (Figure 7). The upstream and impoundment reaches differed in habitat conditions, but their connectivity allowed fish to move freely between the two zones. The impoundment and downstream zones had similar habitat conditions, but only possessed limited connectivity in the downstream direction. The upstream and downstream reaches possessed neither habitat similarities nor significant connectivity.

Dam removal resulted in habitat changes to the impoundment and downstream zones and restored connectivity between all three zones, leading to changes in the fish species composition of all three study zones. Most of the fish species (8 of 12) found only downstream of the dam prior to removal were found upstream of the dam following its removal. Catalano et al. (2007) witnessed a strikingly similar pattern with 10 of 11 species utilizing newly accessible habitat upstream from the site of dam removal. In the Pine River, many of the colonizing species remained in low abundance upstream of the dam due to differences in their habitat preferences and the habitat characteristics of the upstream zones. For example, logperch expanded their distribution above the former dam, but were not found in high abundance. Yellow perch and pumpkinseed abundance upstream increased, but they too were never found in high abundance. The distribution of these species following dam removal is consistent with known habitat preferences and a model of fish assemblage along an embayment-stream gradient by Singkran (2007). Blackside darter, johnny

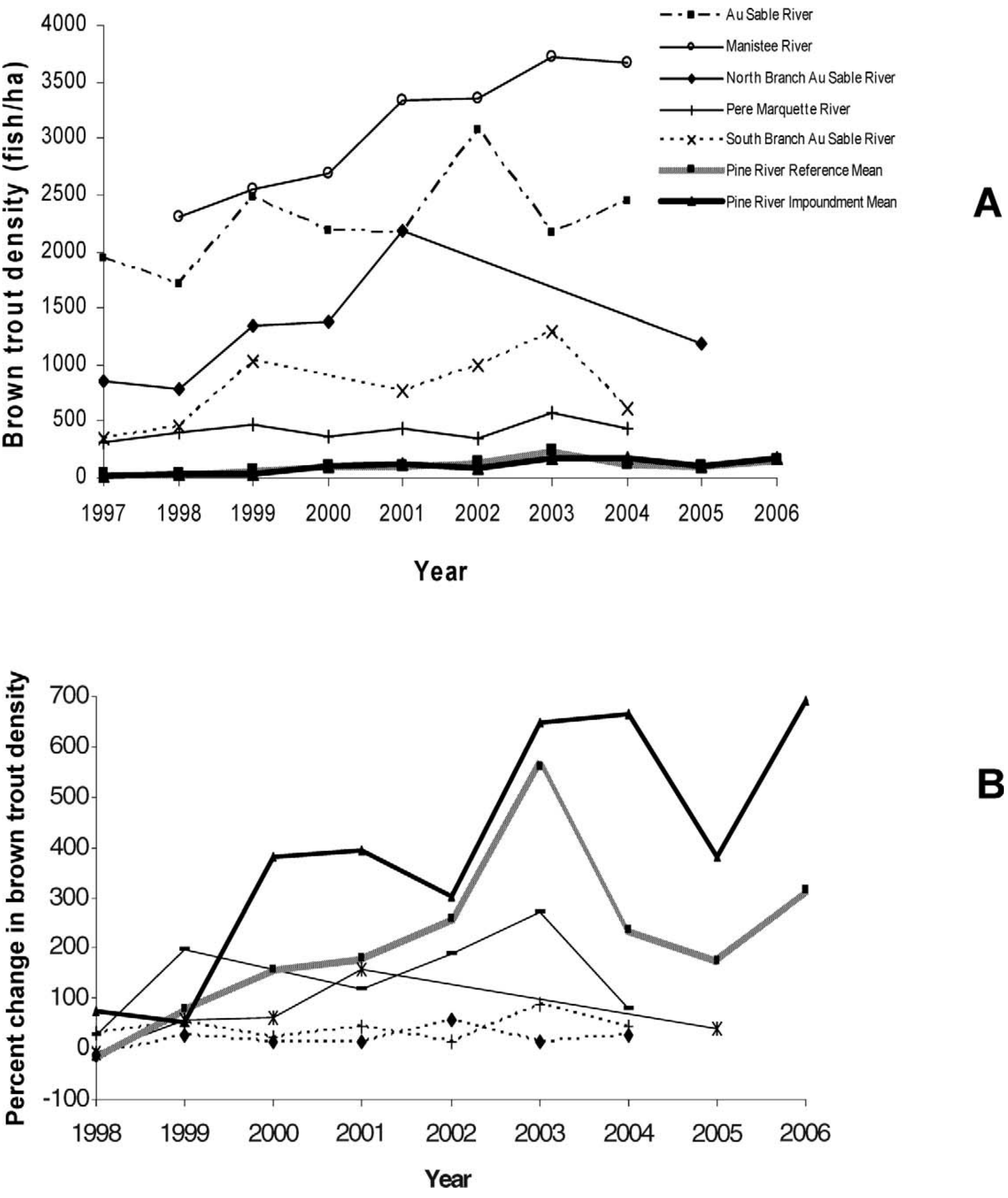

FIGURE 2.—**(A)** Density of brown trout and **(B)** relative change in density in several Michigan trout streams and the reference and impoundment study zones of the Pine River.

darter, and silver redhorses also expanded their distribution, but were not found in high numbers; these are also species that prefer large rivers habitats with modest current velocity (e.g., Scott and Crossman 1973; Weigel et al. 2006).

Only one species, black bullhead, was found above but not below the dam prior to removal. This species was found both above and below the dam following removal, but abundance of this species was very low.

White suckers, brown trout, and rainbow trout all showed significant shifts in their distribution during the process of dam removal. These species were among the

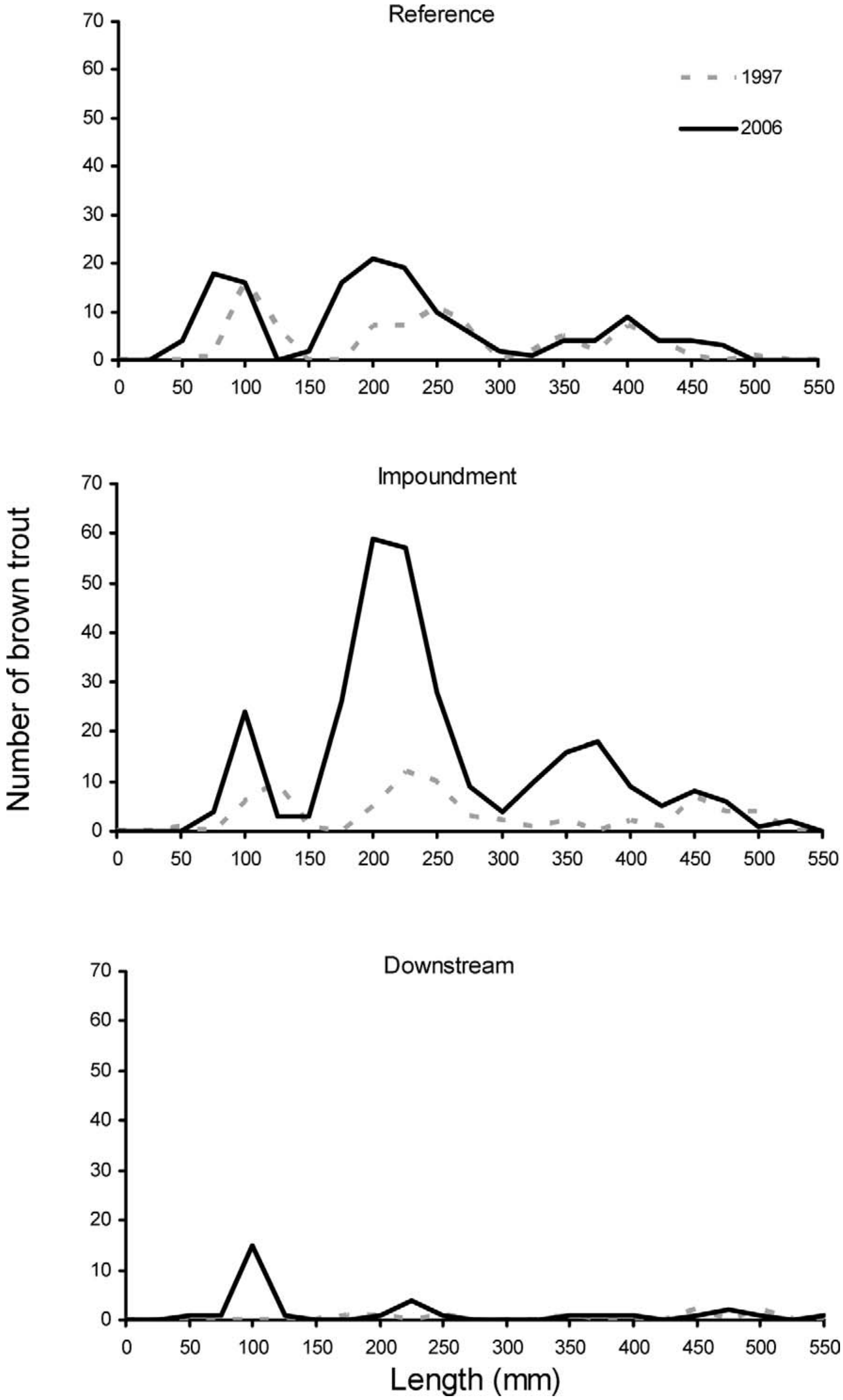

FIGURE 3.—Length frequency distributions for brown trout in the three study zones of the Pine River before (1997) and after (2006) the removal of Stronach Dam.

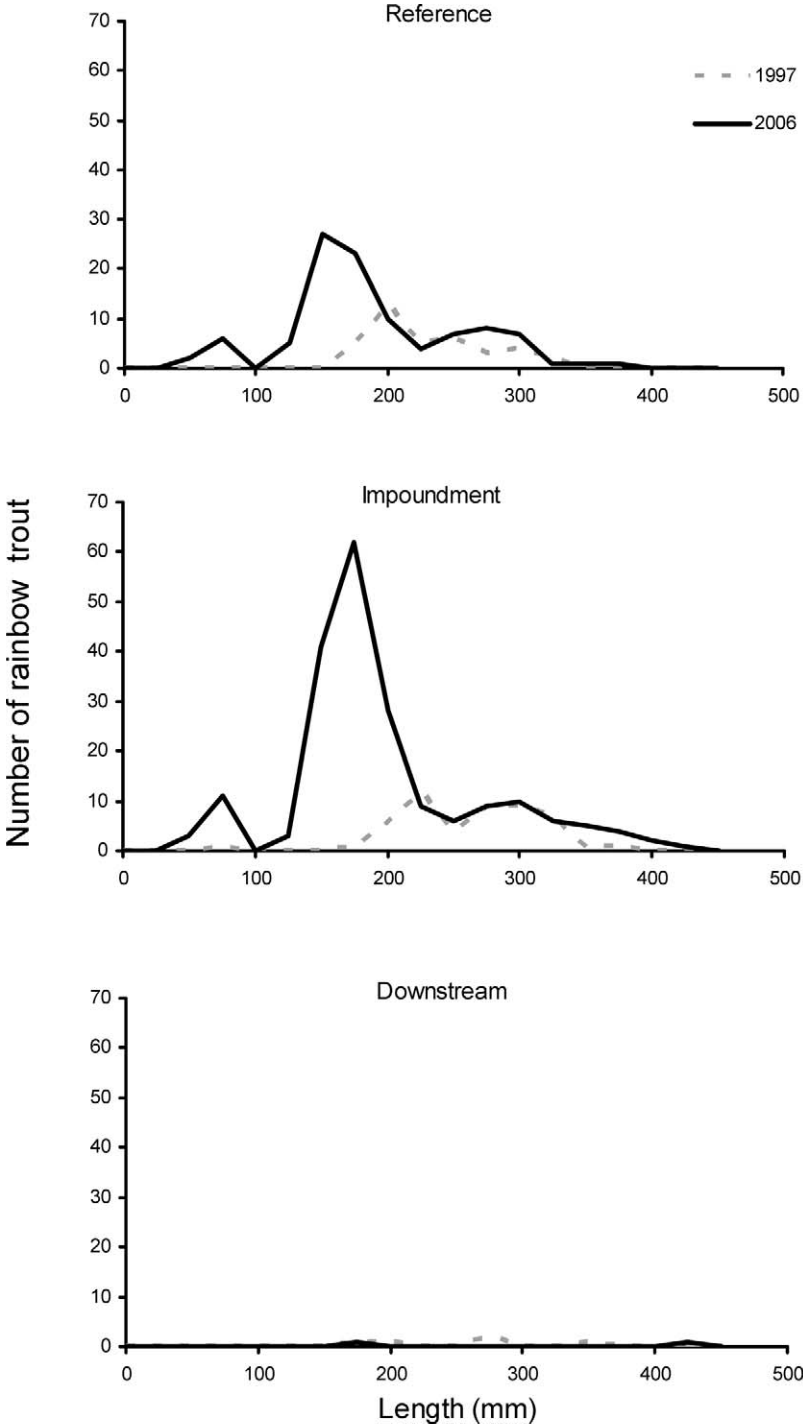

FIGURE 4.—Length frequency distributions for rainbow trout in the three study zones of the Pine River before (1997) and after (2006) the removal of Stronach Dam.

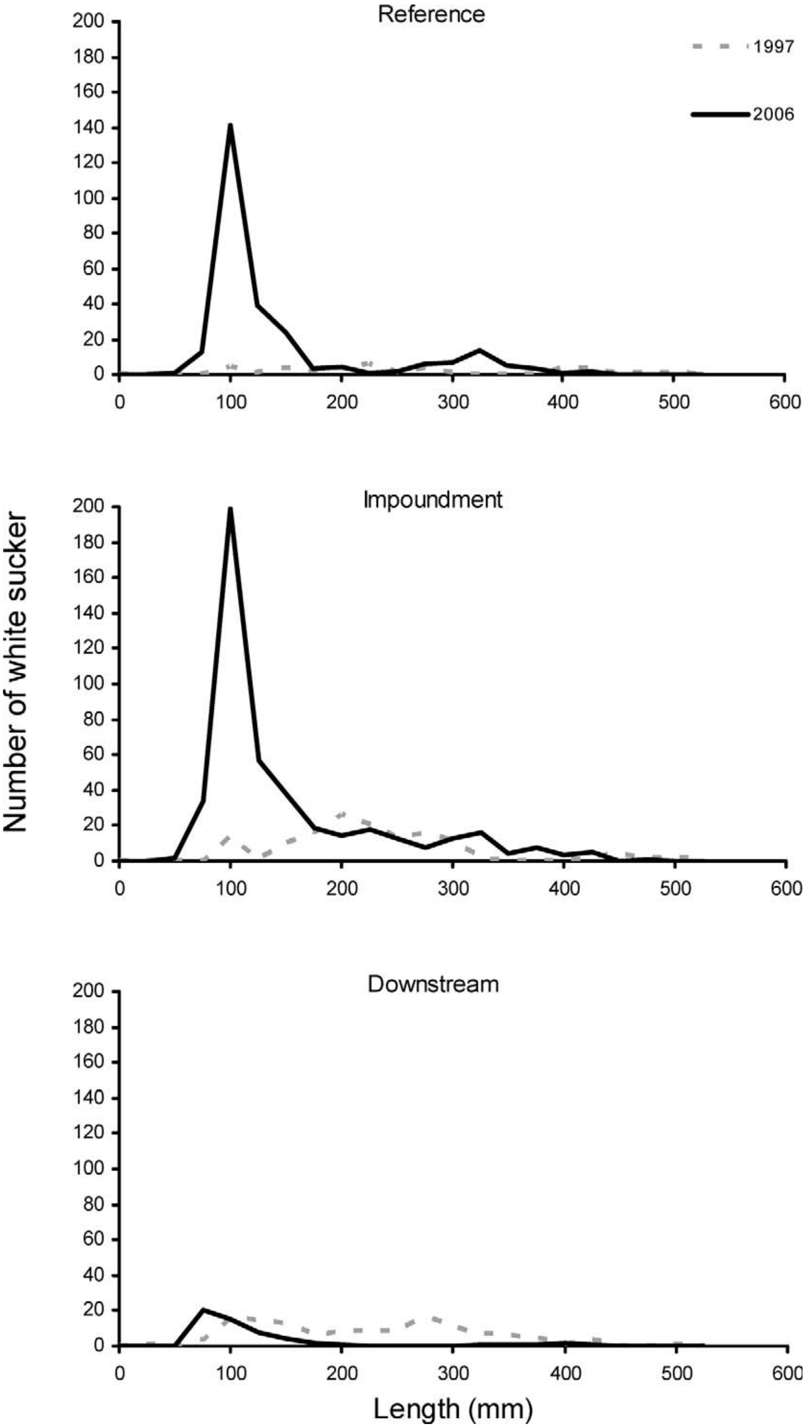

FIGURE 5.—Length frequency distributions for white suckers in the three study zones of the Pine River before (1997) and after (2006) the removal of Stronach Dam.

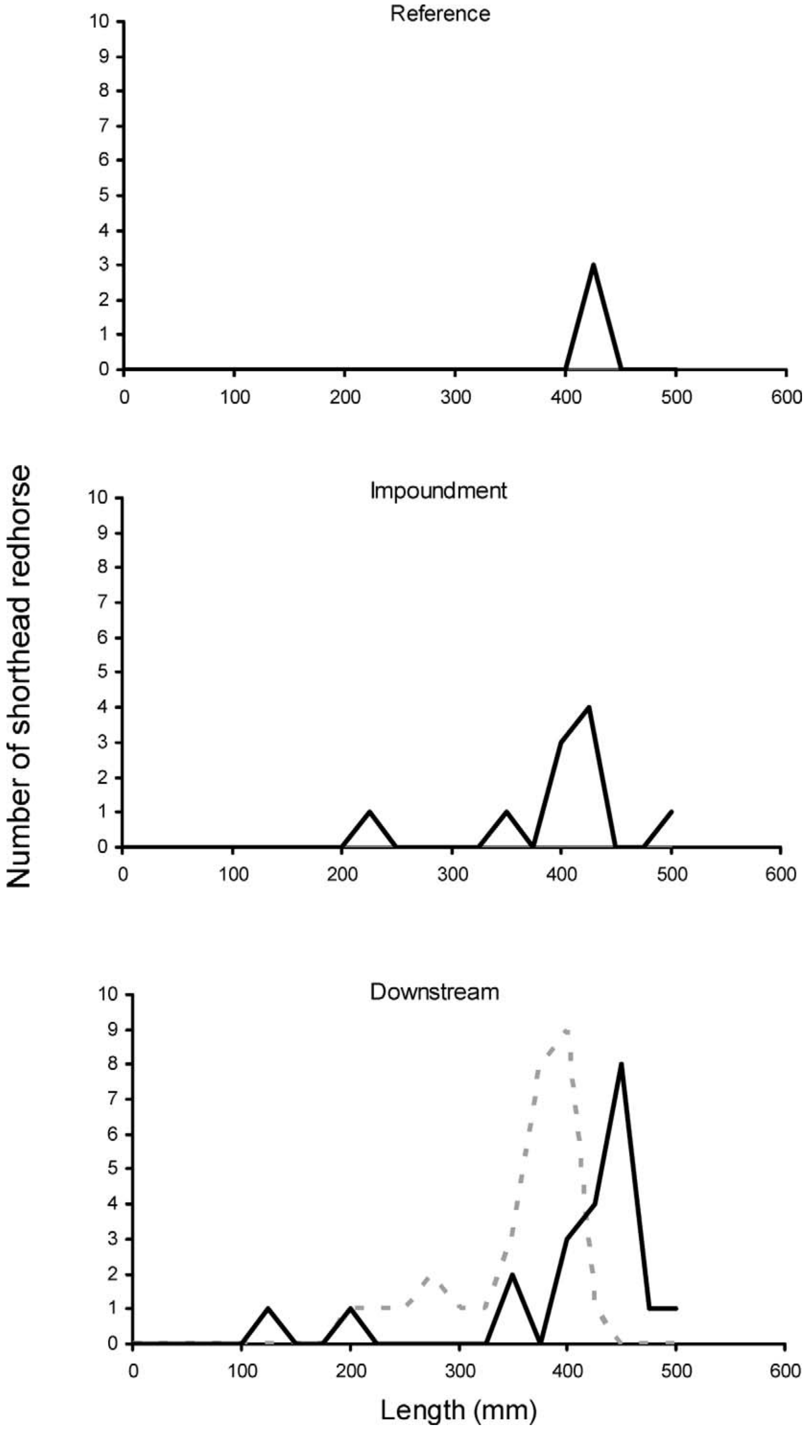

FIGURE 6.—Length frequency distributions for shorthead redhorses in the three study zones of the Pine River before (1997; dashed line) and after (2006; solid lines) the removal of Stronach Dam.

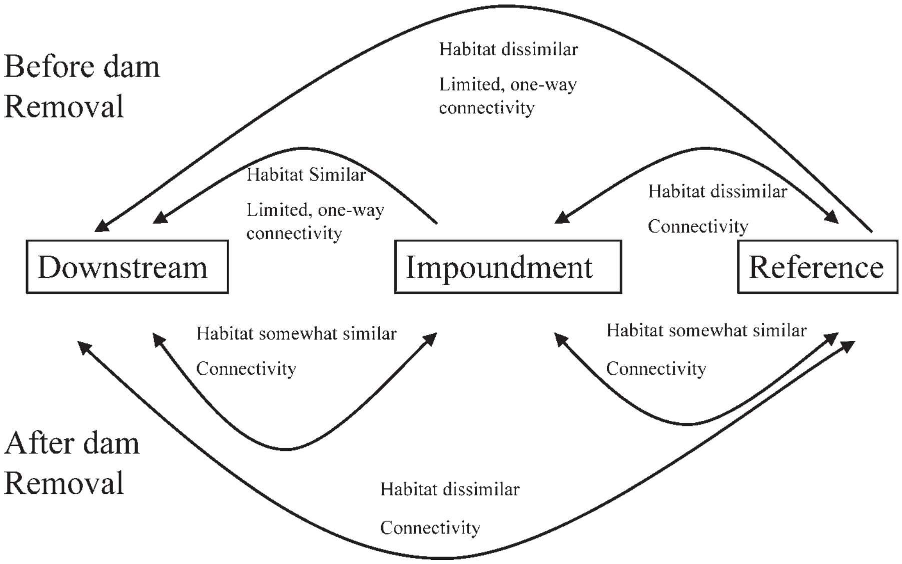

FIGURE 7.—Conceptual diagram depicting the changes in fish habitat and connectivity between reaches after the removal of Stronach Dam.

most abundant species throughout the river prior to the initiation of dam removal, and as such, their habitat preferences spanned the conditions present. All showed progressive increases in overall abundance, with the largest increases occurring in the impoundment and upstream reaches. The timing of changes in abundance and distribution of these species suggests that habitat changes in the former impoundment had an influence, but the final removal of the dam had the largest impact on these species.

Fish Populations

A critical finding was that the majority of species (19 of 25 species evaluated) showed an increase or no change in abundance following dam removal, and all of the populations with significant changes over time (seven species) were species with increasing abundance. This finding strongly indicates that the removal of the dam reduced habitat limitations present when the dam was in place. The abundance of only six species was lower in the final time period than in the initial time period, and none of these changes were statistically significant. Of the species declining, brook trout and American brook lamprey were the only two species that were relatively abundant prior to dam removal. Determining reasons for their apparent decline is not possible, however, given the numerous changes in the habitat as well as the fish community that occurred over time.

More detailed analysis of the dominant game fishes (brown trout and rainbow trout) revealed insights into potential factors limiting their abundance prior to dam removal. Focusing first on brown trout, their mean abundance increased more than 2.5-fold from the first to the final time block, and increased more than fourfold from the first year of the study to the last year (Burroughs 2007). The increase in density was evident across all size-classes, resulting in similar length distributions before and after dam removal. Thus, it appears that all size-classes benefited equally from the removal.

The increase in abundance observed in the upstream zone prior to full dam removal could be an indication that factors other than removal were also operating. Starting in the spring of 2000, trout harvest regulations were altered on many Michigan trout streams, including the portion of the Pine River encompassing the study area. From the beginning of the study through 1999, there was a 203-mm (8 in) minimum length limit and a creel limit of 10 fish per day on all three species of trout. In the spring of 2000, the regulations were changed to five fish per day, 203 mm minimum length, with no more than three fish over 381 mm (15 in) in length. In 2001, the regulations for trout harvest were changed to 254 mm (10 in) minimum length for brook trout, 305 mm (12 in) minimum length for brown trout and rainbow trout, and a creel limit of five fish per day, with no more than three fish over 381 mm in length. These regulation changes could have increased the survival and, subsequently, the abundance of large-sized brown trout in the study zones of the Pine River. However, if this had occurred, a significant shift in the proportion of fish over the regulatory minimum lengths would have been expected in the length frequency distributions. This was not observed, however, suggesting that the changes in harvest regulations were not the driving force in increasing brown trout abundance.

Another possible explanation for the increase in brown trout abundance is that environmental conditions were particularly favorable for brown trout during the study period. As a basis for comparison, we examined the dynamics of brown trout in similar Michigan trout streams where data were available as part of ongoing population monitoring by the Michigan Department of Natural Resources. These data suggested that abundance of brown trout generally increased during much of the study period in other Michigan trout streams. However, the population growth rate observed in the Pine River was substantially greater than all other populations. Therefore, there is evidence of a broader-scale set of influences on brown trout abundance, but the removal of Stronach Dam appears to have had an additional impact on brown trout in the Pine River.

Rainbow trout density had a pattern remarkably similar to that of brown trout. However, the steady increase in density of rainbow trout did not begin until almost 2003. At the end of the study in 2006, rainbow trout density had increased threefold relative to the density observed at the beginning of the dam removal (Burroughs 2007). Analysis of the size structure of the rainbow trout populations in both the impoundment and reference zones indicated that recruitment and the proportion of juvenile rainbow trout increased substantially, with the frequency of large rainbow trout increasing only slightly. Rainbow trout prefer spawning substrate between 15 and 60 mm (Raleigh and Hickman 1984), which was rare in the impoundment zone prior to dam removal, but significantly increased following the removal. This is likely to have improved spawning conditions for rainbow trout and contributed to improved recruitment. The lack of proportional increases in the abundance of large adult rainbow trout could result from the relatively recent increases in rainbow trout recruitment not yet carrying through to the older age groups.

Similar to brown trout and rainbow trout, white suckers were found upstream and downstream of the dam throughout the study period. However, the density of this species was relatively low and stable in both the upstream and impoundment reaches prior to full dam removal. Downstream of the dam, white sucker density was variable, but consistently higher than seen upstream of the dam. White suckers utilize both river and lake habitats (e.g., Scott and Crossman 1973), and the high abundance of this species below the dam was probably due to the connection of this river reach with Tippy Dam Reservoir. After dam removal, the distribution of adult white suckers shifted upstream. In addition to distributional shifts, a large increase in recruitment was observed, resulting in an increase in total density from 1997 to 2006. White suckers typically spawn in gravel reaches of streams (Scott and Crossman 1973), and the dam removal allowed this species to access habitats available in the river system that are beneficial to different life stages and resulted in higher productivity and abundance of this species. A similar type of response may also be expected from other fish species that make spawning migrations in streams but have been prevented from accessing suitable spawning habitat.

Prior to dam removal, shorthead redhorses were found only downstream of Stronach Dam and were probably individuals that remained in the river after spawning. In the spring, this species migrates out of large bodies of water into smaller rivers or streams to spawn (Scott and Crossman 1973). Meyer (1962) found that in Iowa shorthead redhorses became sexually mature at age 3, corresponding to approximately 300 mm in length. In the downstream zone of the Pine River, shorthead redhorses less than 300 mm in length were rarely sampled. After 2003, this species was found widely distributed throughout both the reference and impoundment zones, but in low densities. Juveniles of this species were not observed in the Pine River, suggesting that the lotic habitat of the Pine River is not their preferred habitat. This species represents other fishes where dam removal may benefit certain life history stages (e.g., spawning adults), but where the lotic habitats are only used for a portion of their life. Many of the other species of fish found only downstream of the dam prior to removal may have benefited from the dam removal in a similar way (e.g., northern pike, trout-perch, walleye).

Synthesis

Because the historic fish community composition of the Pine River is unknown, it is important to recognize that dam removal did not necessarily result in "restoration" of the fish community. Removal of the dam restored the ability of fishes to move upstream and increased fish diversity in each zone. Also, the abundance of fishes generally increased, indicating that the productivity of the fish community increased as fish were able to choose and access those habitats that best fulfill their life history requirements. As such, removal of Stronach Dam can be viewed as restoring some of the functionality of the fish community and some production potential that was limited because of the impacts of the dam.

Dams alter the habitat for lotic fish in streams. In the former impoundment zone of the Pine River we observed habitat conditions improved for brown trout and rainbow trout and documented improved reproductive success and significant increases in the density of these important sport fishes. With the dam removal, habitat conditions in the downstream zone worsened through the deposition and transport of large quantities of fine sediment, and the density of some fishes declined. However, 3 years after the dam removal was complete, habitat conditions were still changing. As suggested by Doyle et al. (2005), fish populations limited by habitat alterations in dammed rivers will be governed by the rates of geomorphic recovery following removal, compared with populations limited by connectivity. While conditions improved significantly in the former impoundment, they were not restored to reference levels. The second-to-last year of this study, 2006, was the first year in which no new net erosion occurred in the former impoundment (Burroughs et al. 2009). In the future, without this influx of sediment, habitat conditions in the downstream zone may also begin to improve. The extent to which these habitat characteristics will be restored to predam levels and the timeframes needed to realize these benefits of dam removal are still uncertain, but the potential for dam removal to be a useful tool for improving riverine fish communities appears strong.

Acknowledgments

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