

# THE REHABILITATION POTENTIAL OF DAM REMOVAL: TEMPORAL PERSPECTIVE FROM MICHIGAN'S PAST DAM REMOVALS

Chapter Three of a 2007 Dissertation entitled:  
Effects of Dam Removal on Fluvial Geomorphology and Fish

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## INTRODUCTION

Dam removal has become a popular technique for stream restoration in the United States. The optimism for this technique to achieve restoration of stream ecosystems is based on the knowledge that dams critically alter the form and functioning of rivers. Often, the removal of dams is assumed to restore the original form and functioning of river systems, ameliorating the negative impacts of the dam's existence. To date, the strength of this assumption has largely overshadowed the need for evidence of the benefits of dam removals, as the rate of removing dams continues to increase and little empirical evidence of the benefits of dam removal exists. If the practice of removing dams is to be justified as a tool for stream improvement, and advances made in dam removal methods, then knowledge of the outcomes of dam removals needs to be documented.

Currently, only a few studies exist that document the outcomes of dam removals. The existing studies have focused on changes in river morphology, fish, aquatic insects, and nutrients, and have documented that substantial changes occur immediately following a dam removal (Hill et al. 1994, Kanehl et al. 1997, Evans et al. 2000, Bushaw-Newton et al. 2002, Stanley et al. 2002, Chaplin 2003, Burroughs 2007a, Burroughs 2007b). However, all of these studies have examined the effects of dam removal over relatively short time periods following removal. The financial commitment needed to study a dam removal for several years prior to removal, during the removal

phase, and for several years following a removal, can be large and limit the feasibility of evaluating long-term response (Doyle et al. 2002, Pizzuto 2002, Gordon et al. 2004).

Large changes in streams are expected to occur immediately following a dam removal. Many of these changes are expected to continue for long periods of time, acquiring knowledge about the eventual outcomes of dam removal and the time durations to achieve these outcomes, is a very challenging using conventional Before-After-Control-Impact (BACI) study design. Some of the important questions regarding dam removal may require decades to be answered. How long after a dam removal will sediment continue to be transported? Will the river channel in the formerly impounded area and downstream area ever resemble the original river channel? Will the dam removal be beneficial or detrimental for resident fishes? Knowledge of the eventual outcomes of dam removal, and the time required to achieve these outcomes is needed to develop realistic expectations and evaluate removal methods.

Dams have many different impacts to river systems. Upstream of dams, water is impounded, gradient is reduced, water velocity is slowed, river channels widen, and fine sediment is deposited (Petts 1980, Ward and Stanford 1989). Downstream of dams, temperature of water released is often warmer or colder than the normal river water temperature. Sediment supply downstream of dams is greatly reduced, often leading to channel degradation, a lowering of gradient and water velocity, narrowing of the river channel, and coarsening of the substrate (Williams and Wolman 1984, Cushman 1985, Ward and Stanford 1989, Ligon et al. 1995, Collier et al. 1996, Lessard 2000, Shields et al. 2000). Fish species respond in varying ways to the habitat alteration and fragmentation caused by dams (e.g., Holden 1979, Bain et al. 1988, Hayes et al. in press). Non-native species often flourish in modified habitats (Martinez et al. 1994) and overall species richness and diversity can decrease (Quinn and Kwak 2003). Native species often decrease in abundance due to loss of habitat, loss of access to habitat, or competition with non-native species (e.g., Benke 1990, Pringle et al. 2000).

In impoundments, sediment erosion occurs following dam removal, which increases gradient and water velocity, and leads to river channel narrowing, bank steepening, substrate coarsening, and some reformation of pools and riffles (Kanehl et al. 1997, Stanley et al. 2002, Burroughs 2007a). Downstream of dam removals, substantial amounts of sediment transport and deposition can occur, which increase gradient and water velocity, aggrade the streambed, increase stream width, decrease water depth and fill in pools and riffles (Burroughs 2007a). However, due to the relatively short periods of time post-dam removal that these changes have been studied, it is currently unknown how long they will take to reach an equilibrium, and what equilibrium conditions will be (Francisco 2004, Doyle et al. 2005).

Changes to river morphology, along with the opening of fish passage, will alter conditions for the fish community. Fish species will be able to access habitats not previously available to them, and interact with species they did not previously interact with. Changes in fish habitat conditions will alter the suitability of sections of the river to the benefit of some species and the detriment of others. With each stream possessing a unique fish species composition and unique habitat conditions, generalizations about the effects of dam removals on fish are difficult. Given this variability of fish communities among rivers, are there still some generalizations that will hold true for most dam removals? After a dam removal, a larger number of fish species will be able

to access all habitats within a river system. Burroughs (2007a) suggests that even within a few years after dam removal, habitat conditions will become more diverse and heterogeneous due to dam removal. Fish communities have been observed to become more diverse and overall productivity increased (Burroughs 2007b).

The difficulty of answering many of the crucial questions regarding dam removal lies in the relatively long periods of time that many of these changes may take to occur. Gathering this information could take scientists decades if not longer, using BACI experimental designs. However, the practice of removing dams continues to grow in frequency each year (Pohl 2003) despite the lack of this important information. These dam removals may have detrimental effects, or at least could be conducted more efficiently and effectively if more knowledge of the effects of dam removal was available. In this study we attempt to answer some of the crucial questions surrounding the eventual outcomes of dam removal, by surveying several past dam removals in Michigan that occurred from 2 - 39 years ago.

The goal of this study was to provide insight into the extent of the changes following dam removal and the duration of time required to realize those changes. Specifically, the study objectives were to:

- 1) document differences in water temperature, slope (gradient), width/depth, sinuosity, substrate size composition, and bedform frequencies, between upstream reference reaches and former impoundment and downstream reaches of dam removals, across a temporal scale of approximately 0 - 40 years post dam removal.
- 2) document differences in fish community composition and fish abundance between the reference reaches and former impoundments and downstream reaches, across a temporal scale of approximately 0 - 40 years post-dam removal.

## METHODS

### *Study Design*

At each past dam removal site, attributes of the fluvial geomorphology and fish community were surveyed in the former impoundment and downstream of the dam removal site. These were then compared to the same attributes surveyed in an upstream reference reach, outside of the influence of the dam on stream fluvial geomorphology. This upstream reference reach served as a surrogate for what the river in the former impoundment and downstream reaches would look like if the dam and the dam removal had not occurred. As such, we assume this provides a target for rehabilitation of river form and functioning. Natural differences between these three river reaches, not attributable to the presence of the dam or the occurrence of the dam removal might be expected (e.g., many dams were built on high gradient sections of stream to maximize storage potential and energy generation, and the underlying impoundment reach would have been higher gradient than an upstream reference reach). However, the reference reach conditions provide reasonable benchmarks for assessing how much rehabilitation was achieved in the two zones impacted by the dam and dam removal. If rehabilitation occurred in the area impacted by the dam and its subsequent removal, attributes of fluvial geomorphology in these zones would be expected to closely approach those seen in the reference reach of the river (Figure 1).

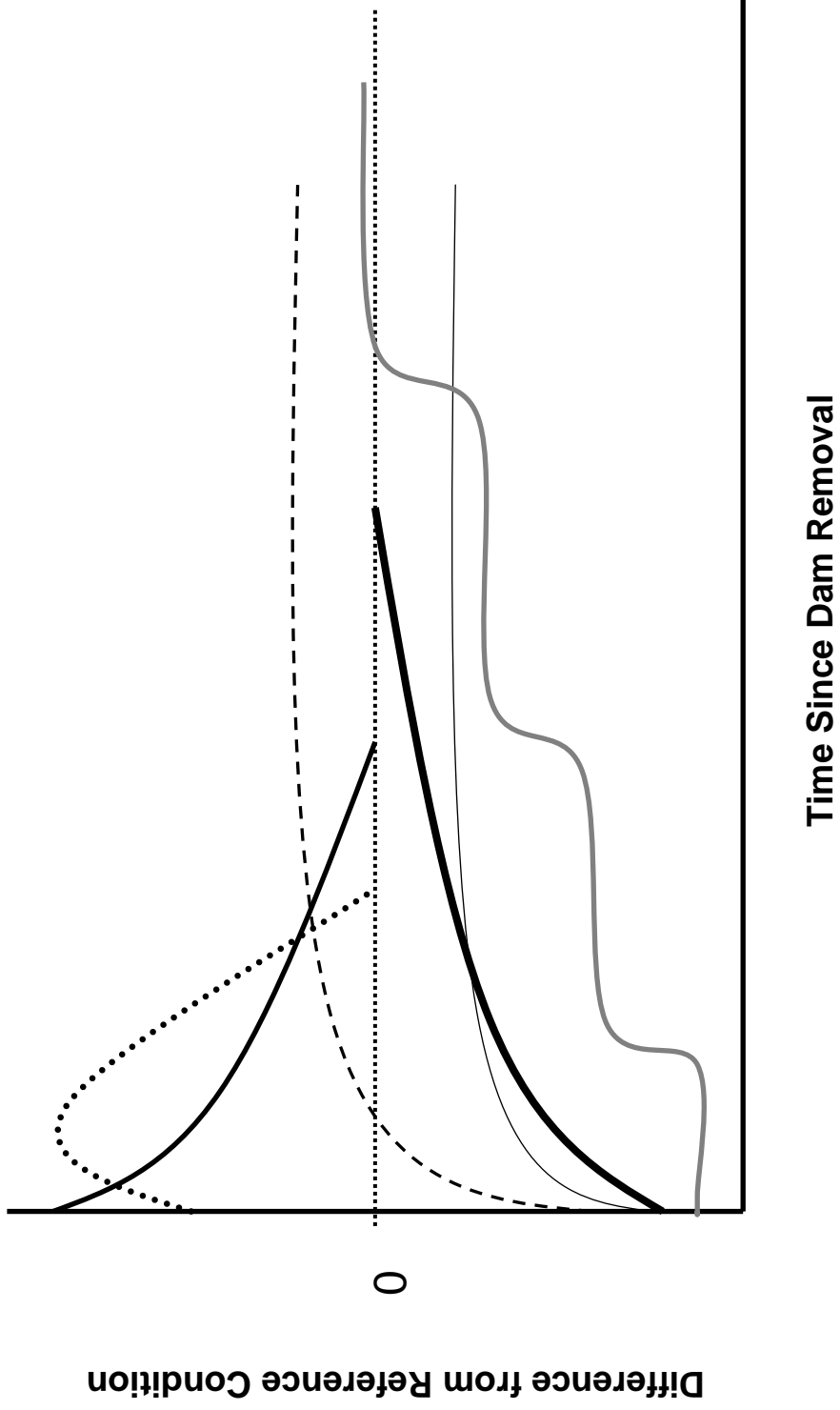


Figure 1. Hypothetical trajectories for rehabilitation of river attributes following dam removal.

Fish community attributes of a reference reach however, could not be considered rehabilitation benchmarks since with restored fish passage following dam removal, the fish community in the reference reach would also change. In this situation, differences in fish community attributes can only be compared between the three zones to assess whether any of these zones consistently ranks lower than the others, indicating impairment.

A list of all known dam removals that have occurred in the state of Michigan was obtained from the Michigan Department of Natural Resources, Fisheries Division. From this list of past dam removals, candidate study sites were selected to attain as wide and uniform of a temporal distribution possible. Additionally, sites were eliminated as candidates if the removal date was unknown or uncertain. Scouting trips were made to many of the remaining candidate sites, and final study site selections were made based on whether or not the former dam site could be located with certainty, logistic considerations, and the value of the dam removal to the temporal distribution of past dam removals (Table 1 Figure 2). Historic aerial photos were used to help identify former dam sites and the upstream extent of the historic impoundments. These photos were used in combination with the Delorme® digital topographic map program to determine latitude and longitude coordinates for pertinent landmarks, and to select study sites prior to sampling, to maximize the spatial distribution within each study zone and eliminate site selection bias.

Table 1. Past dam removal study site information.

Dam Name	Randall	Stronach	L'Anse	Salling	Smyrna	Wacousta
River Name	Coldwater	Pine	Falls	AuSable	Flat	Looking Glass
County	Branch	Manistee	Baraga	Crawford	Ionia	Clinton
Year Removed	2002	1997 - 2003	1998	1991	1973	1966
Dam Height	3.7 m	3.7 m	?	5.2 m	?	1.4 m
Constructed	1912	1912	?	1914	1908	1860

Each study stream was broken into three study zones; the former impoundment, the upstream reference, and a zone downstream of the dam site. The former impoundment was delineated through the use of historic aerial photos and maps, and confirmed in more recent dam removal sites, through use of on-ground visual cues (former impoundments length range 318 – 5869m). The upstream reference was chosen to start immediately adjacent to the former impoundment and extend upstream for as long a distance as logistically feasible (references length range 1155 – 5177m), in which the river maintained similar characteristics (e.g., it would not extend upstream of the confluence of significant tributaries). The downstream study zones extended from the former dam site downstream for as long as logistically feasible (downstreams length range 624 – 3286m), while still maintaining similar characteristics (e.g., not extending downstream of significant tributaries, or into downstream impoundments).

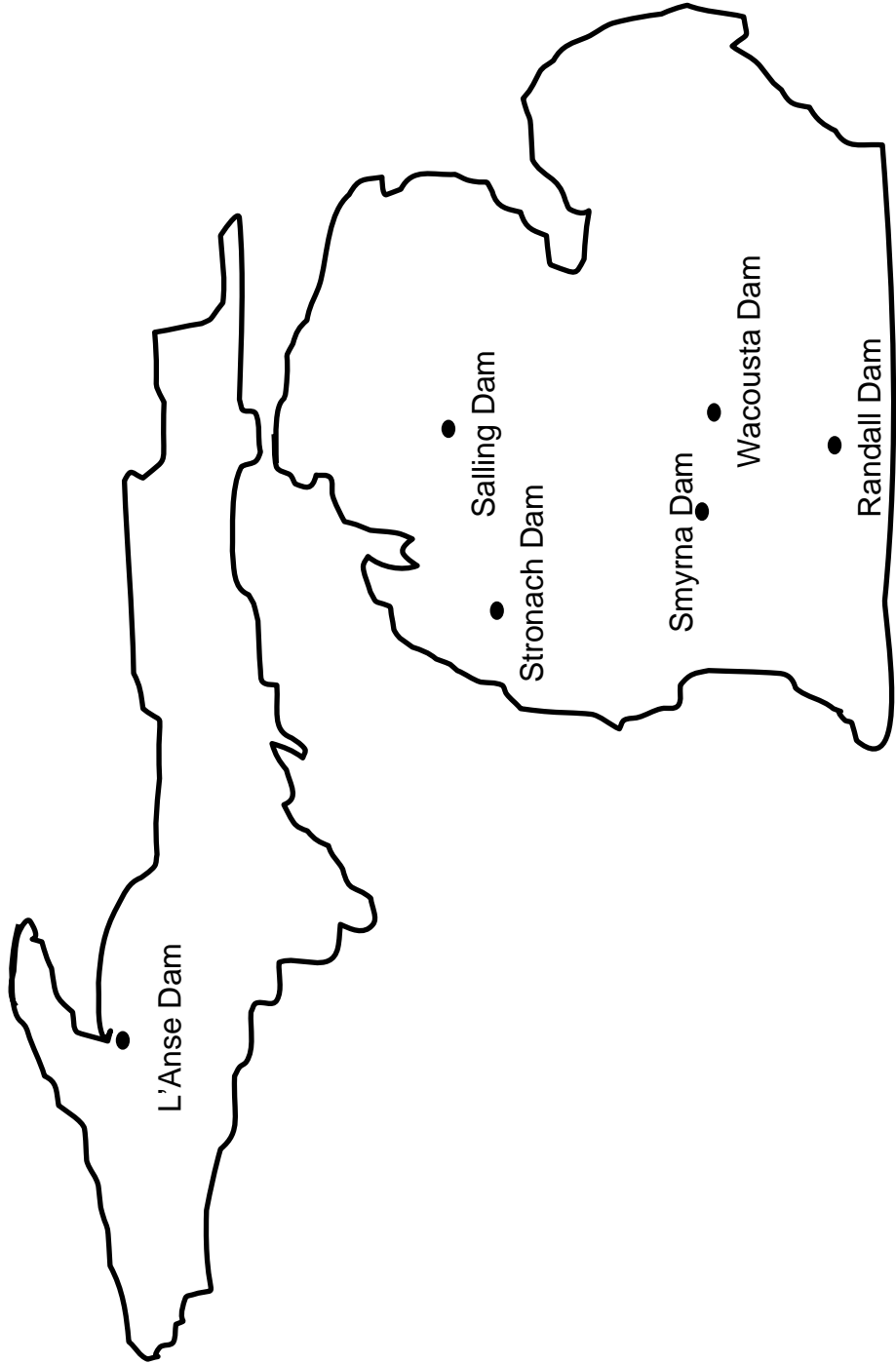


Figure 2. Location of study sites within the state of Michigan.

### *Data Collection & Analysis*

Bedforms (i.e., riffles, runs, and pools) were mapped throughout the entire study area of each river. Bedforms were delineated following the general guidelines of Hicks and Watson (1985), and were classified as runs, riffles, pools, rapids, waterfalls, or complexes (a designation where more than one bedform applied). Widths and length of each unit were measured using a Nikon® laser rangefinder (+/- 0.5m accuracy). Areas of rivers impacted by dams were expected to be relatively homogenous run bedforms compared to upstream reference conditions (Burroughs 2007a), and it was hypothesized that riffle and pool bedforms would be formed following dam removal. The diversity of bedforms in the former impoundment and downstream zones were compared to the diversity of bedforms in reference reaches. The Shannon-Weaver diversity index (H')(Shannon and Weaver 1949, Ricklefs 1990) was used to estimate the bedform diversity in each study zone. This index considers both the number of bedform types present and the evenness of the numerical proportions of each bedform, rewarding higher diversity values to study zones not numerically dominated by a just one bedform type (e.g., run).

Water temperature was recorded in each study zone using Onset® water temperature data recorders (HOBO Water Temp Pro, +/- 0.174° C). All water temperature recorders were placed at the downstream boundaries of each study zone (to reflect temperature effects of that zone), and recorded water temperature every 30 minutes, from July 29, 2005 through October 2, 2005.

Three sample sites, approximately 5-7 stream widths in length, were located within each study zone. River channel cross-sectional morphology was surveyed at both the upstream and downstream boundaries of each sample site, and the difference between the water surface elevations at each boundary cross-section was surveyed in order to calculate slope for the sample site. At each boundary cross section (n = 6 per zone), elevations were recorded to the nearest 3 mm, at 0.61 m intervals across the wetted width of the stream, and at points of inflection on the streambanks (appropriate for the accurate mapping of bank morphology), using a level and stadia rod. Width to depth ratio (W/D) was calculated for each cross section using the width and mean depth of the wetted channel.

Sinuosity of each study zone was estimated from aerial photos as the straight-line valley length of a section of river, divided by the actual length of the water flow through that section of river. River measurements were made with ARC MAP (by ESRI) software. Aerial photographs were compiled from the Michigan State University Remote Sensing and Geographic Information Science (RSGIS) Research and Outreach Services aerial imagery archive. If needed, photos were rectified using a Michigan roads shapefile from the Michigan center of geographic information website. Shapefiles of points were added to represent the three stretches of the river being measured; each stretch of the river was measured three times and averaged. For many of the older dam removal study sites, aerial photos had been taken in several different years since the dams were removed. In these cases, sinuosity was repeatedly measured at several points in time since dam removal, for individual study sites.

Substrate size composition was measured at each cross-section using a modified pebble count method (Wolman 1954, Kondolf and Li 1992, Burroughs 2007a). Systematically sampled 100 substrate particles, from water's edge to water's edge

across the wetted width of the channel. The substrate particles were measured along the intermediate axis and assigned a size class code (from a modified Wentworth scale) (Wentworth 1922, Cummins 1962). The median substrate size (D50) was calculated for each cross-section and averaged for each study zone.

Thorough one-pass sampling of the fish community was conducted of all habitats within each sampling site. The sites were unblocked, and effort (time actively sampling) was recorded. Backpack, tow barge, and boat electrofishing equipment were used as appropriate for each river, but the equipment used was constant within each river. All fish sampled were netted, identified to species, and released (with the exception of “voucher specimens” that were retained for further identification in the laboratory). Total species richness (number of fish species) and relative numeric abundance of all fish species were calculated for each study zone. The similarity of fish communities in each study zone of a river was evaluated using the Morista similarity index (Morista 1959). This index takes into account both the differences in which species are present and differences in the numeric proportions of those species present. An index value of 0.00 indicates complete dissimilarity, a value of 1.00 indicates complete similarity, and values greater than 0.60 are generally interpreted as “similar” (Angradi and Griffith 1990).

One of our study rivers, the Pine River, was part of a long-term investigation, and provided comparable but more detailed data. The data collection methods utilized were identical to those reported for this study (Burroughs 2007a, Burroughs 2007b). Data were selected from that dataset to match those acquired at that other past dam removals in this study (e.g., one pass fish sampling, matched cross-section sites), for both fluvial geomorphology and fish community characteristics. Repeated samples for each characteristic were drawn from the Pine River dataset from before and after the dam removal.

## RESULTS

### *Fluvial Geomorphology*

Only small differences in water temperature were observed between study zones following dam removal (Figure 3). Water temperatures in both the former impoundment zones and downstream zones showed very little deviation from water temperatures seen in the upstream references. This was observed for all past dam removals studied, indicating that once a dam and impoundment were removed, its effects on water temperature were almost immediately ameliorated.

In former impoundment reaches, slope was similar to or greater than reference levels, in all but one case, and this process appeared to occur within just a few years following dam removal (Figure 4). Differences in slope downstream of dam removals appeared more variable. Several downstream reaches had slopes greater than reference levels, while others had lower slopes than reference levels even 8 -15 years after dam removal. In the two oldest dam removals, greater than 30 years post-dam removal, slopes of both former impoundments and downstream reaches were similar or greater than reference reaches.

Width to mean depth of the wetted channel (W/D) is a unitless ratio describing the shape of the river channel cross-section morphology; higher W/D indicates a wide shallow river channel and a lower W/D indicates a narrow and deep river channel. Former impoundment zones generally had higher W/D than reference zones, but



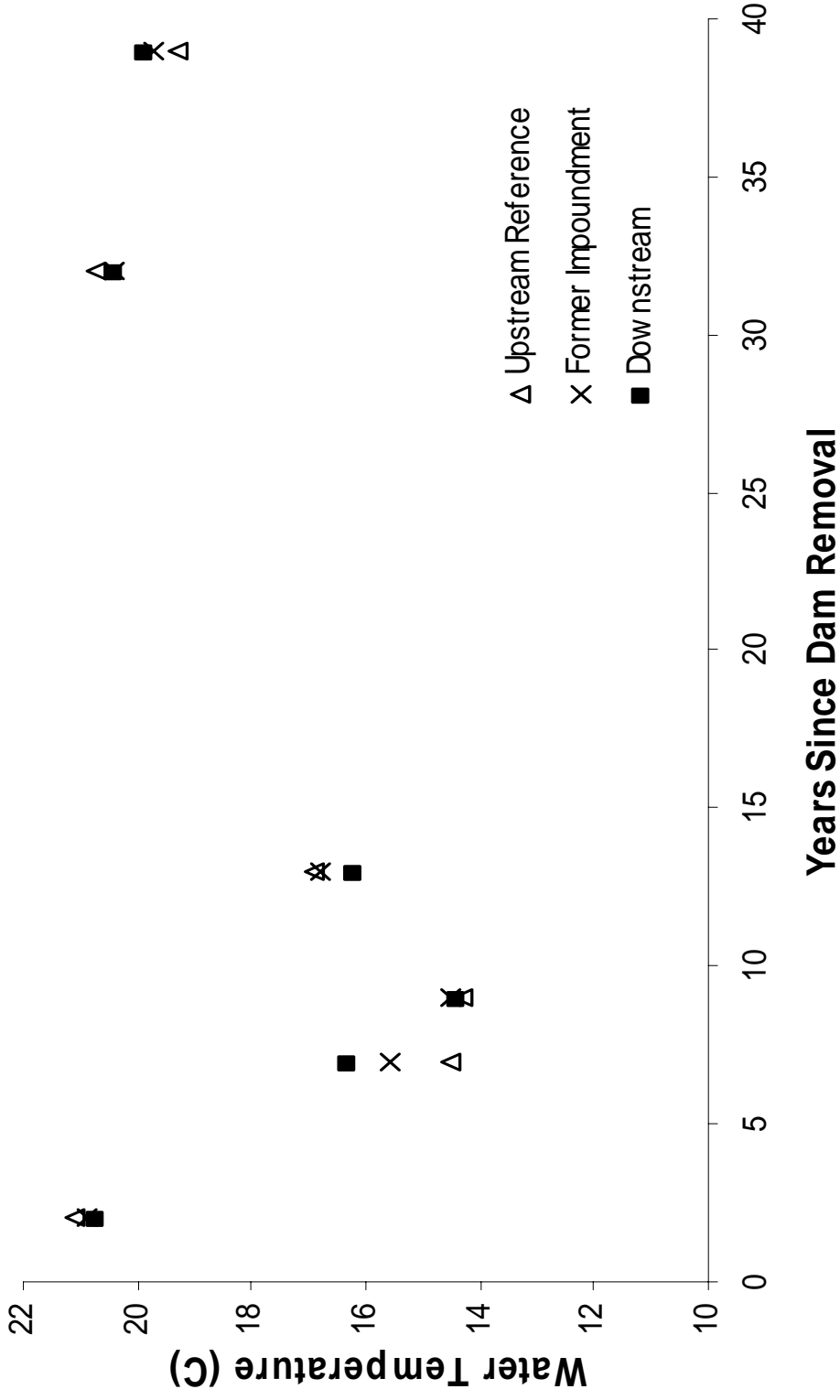


Figure 3. Mean water temperature for each study zone, recorded from 7/29/05 – 10/2/05.

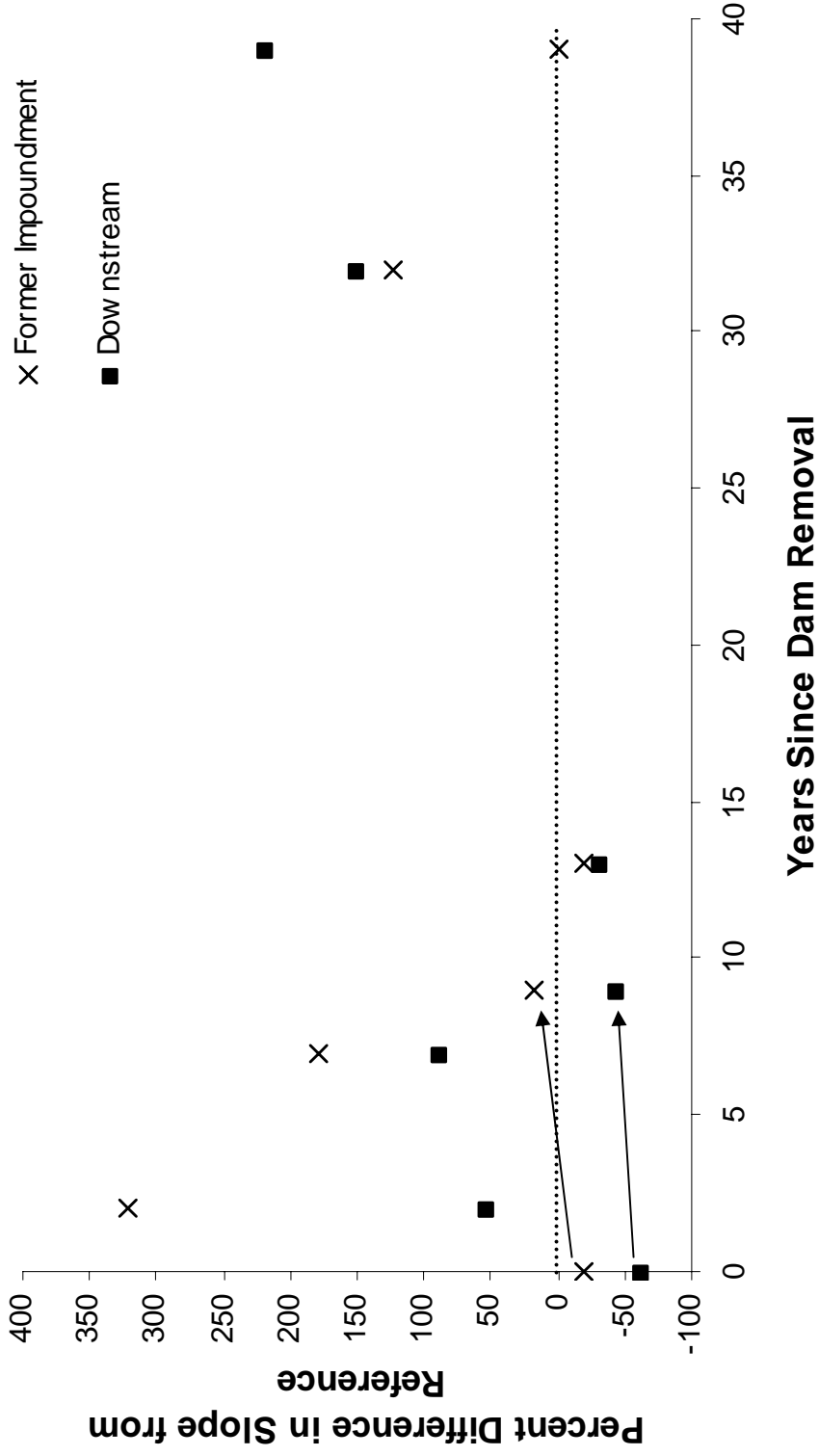


Figure 4. Percent difference in slope for former impoundment and downstream zones, compared to slope in reference zones. Arrows connect data points from the Pine River, indicating the trajectory observed before to after the removal of Stronach Dam.

appeared to decrease in W/D following dam removal, approaching reference level W/D by approximately 10 years (Figure 5). Downstream of dams, sediment transport and deposition appeared to increase W/D of the wetted channel immediately following dam removal, but eventually reference level W/D were achieved by 30 years post dam removal (Figure 5).

Sinuosity of the river channel in all three study zones was measured for multiple years at each dam removal site, and no changes were observed (Figure 6). At some rivers, both former impoundment and downstream zones were more sinuous than reference zones, and in other study rivers they were less sinuous. However, in all cases the sinuosity of the river channel in the former impoundment and downstream zones remained stable following dam removal.

Median substrate sizes in former impoundments and downstream zones were generally smaller than reference zones shortly following dam removal. One exception occurred where substrate in the former impoundment and downstream had coarsened to levels slightly higher than in the reference, just two years following dam removal, and in another case (excluded from graphical presentation) median substrate size was far greater than reference levels due to frequent boulders and bedrock in the waterfall-filled former impoundment and downstream zones. On average, substrate appears to begin coarsening slightly in the former impoundment immediately following dam removal, while the downstream zone shows very little substrate coarsening (Figure 7). The oldest dam removal cases studied, greater than 30 years post-removal, showed median substrates sizes in both former impoundments and downstream zones that were larger than those of the reference zones, indicating that restoration of substrate coarseness is possible following dam removal.

Bedform diversity was generally lower in the former impoundment than reference zones, following dam removal (Figure 8). The diversity of bedforms appears to increase following dam removal, with a greater rate of increase in the former impoundment zone than for the downstream zone. However, the diversity of bedforms in the former impoundment zones was still lower than reference zones even after 30 years post-dam removal. In the downstream zones, bedform diversity was more variable, with many of the sites attaining reference-level bedform diversity, while others remained less diverse. The seven-year post-dam removal study site, the Falls River, remained an exception to the general trends (excluded from graphical presentation). In this river, the reference zone was lower gradient and contained more run bedforms, while the impoundment and downstream zones were extremely high gradient, and contained extensive waterfall bedforms.

### *Fish Community Composition and Productivity*

Fish species richness differed between study zones for several years following dam removal, but by approximately 5 years post-dam removal fish species richness was similar between all three zones (Figure 9). Morista similarity index values also were similar for all zones within only a few years (Figure 10). The 7 year post-removal site remained an exception to fish community changes, due to waterfalls in the former impoundment and downstream zones which affected fish species distributions and prevented the influx of several species from Lake Superior.

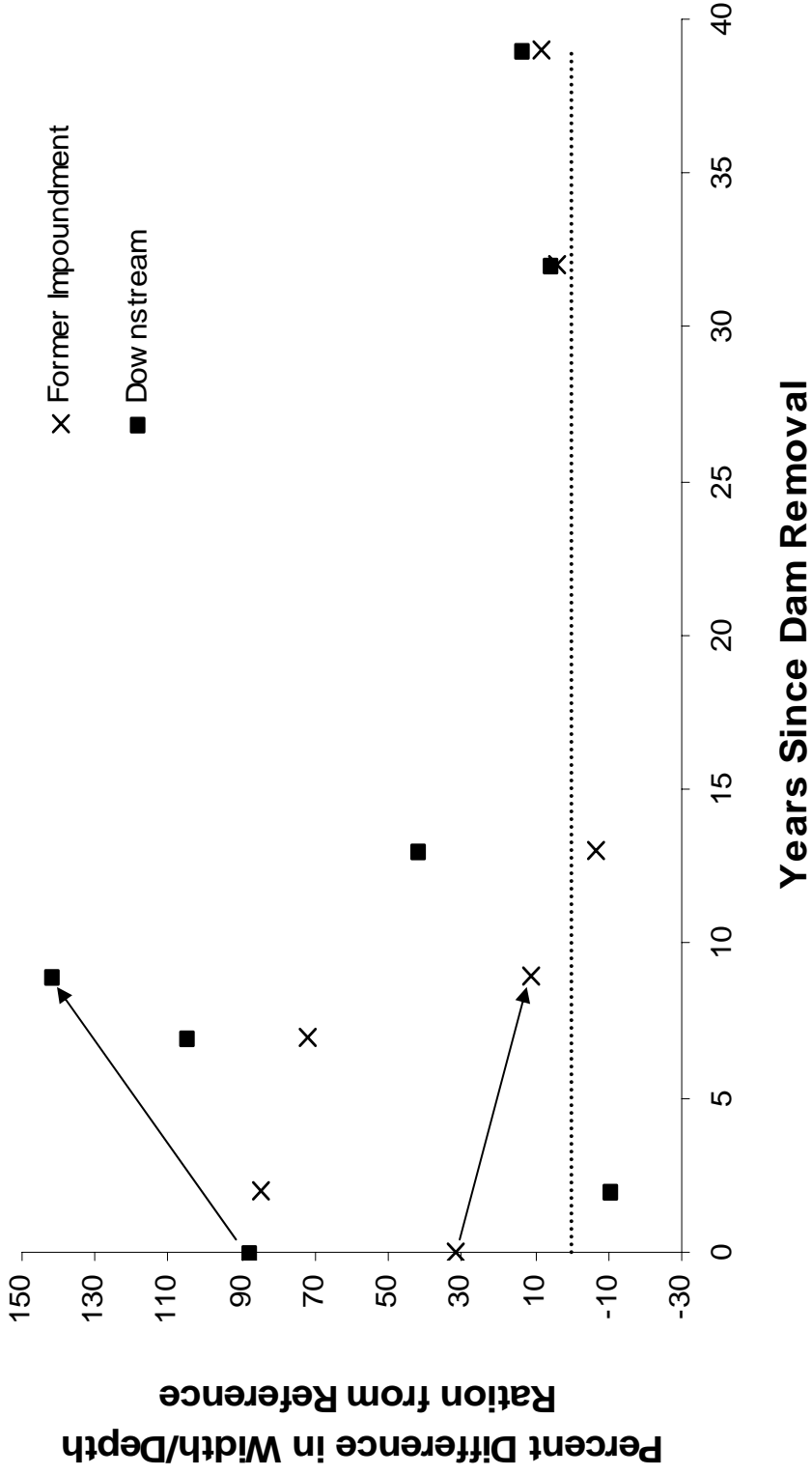


Figure 5. Percent difference in wetted width to depth ratio (w/d) for former impoundment and downstream zones, compared to w/d in reference zones. Arrows connect data points from the Pine River, indicating the trajectory observed before to after the removal of Stronach Dam.

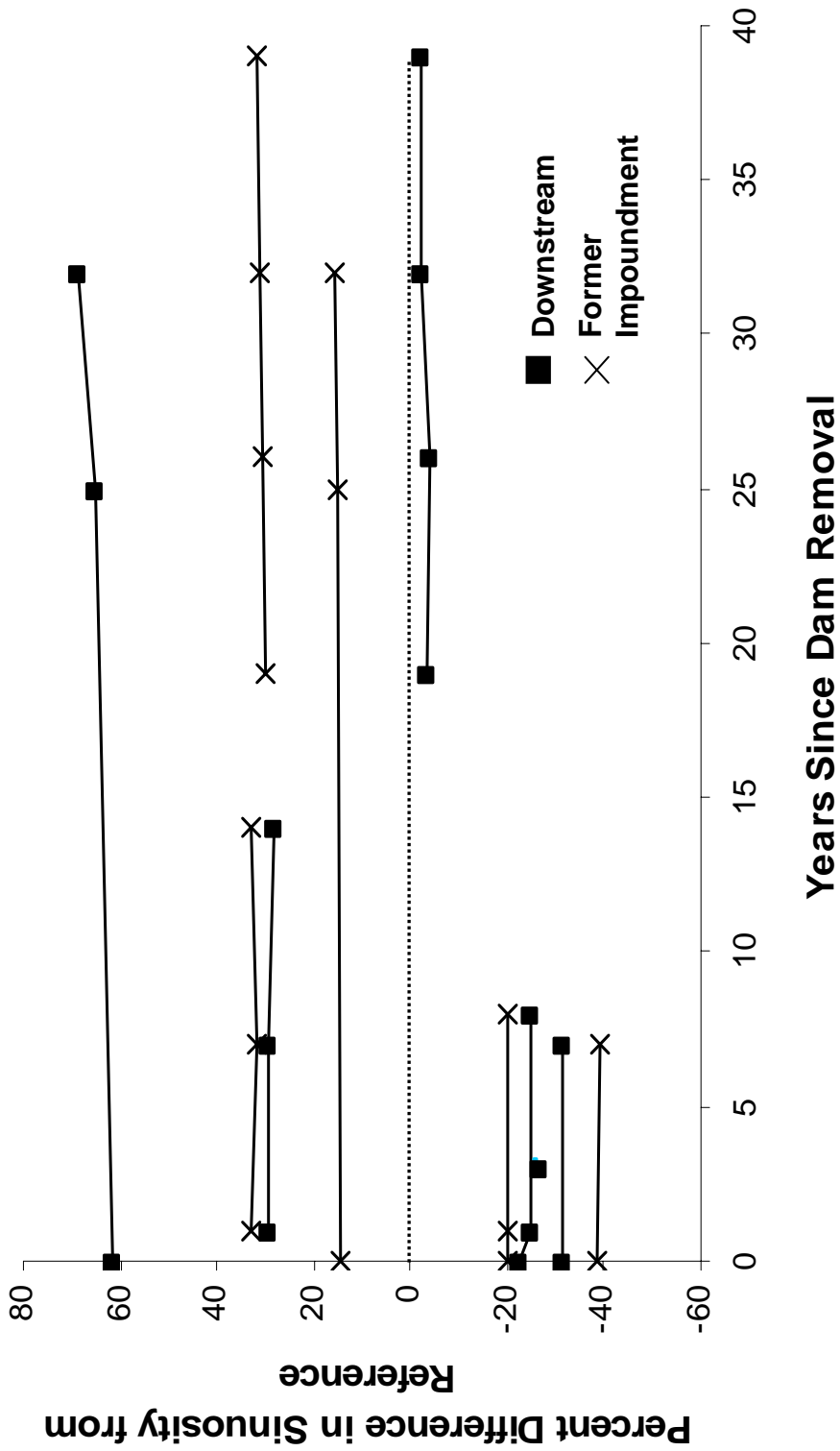


Figure 6. Percent difference in sinuosity for former impoundment and downstream zones, compared to sinuosity in reference zones. Connected data points indicate the sinuosity of the same study zone, measured at different dates through aerial photos.

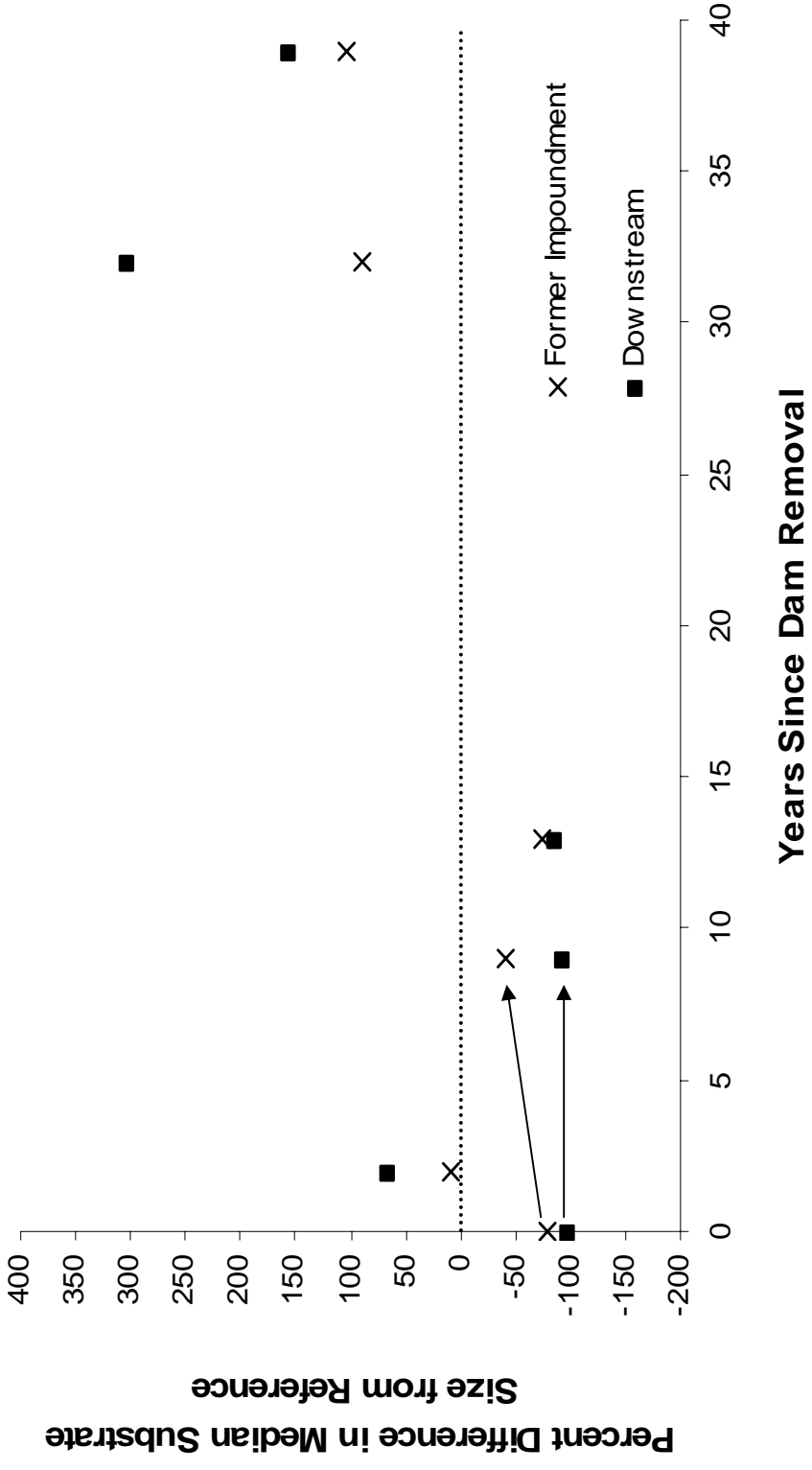


Figure 7. Percent difference in median substrate size for former impoundment and downstream zones, compared to median substrate size in reference zones. Arrows connect data points from the Pine River, indicating the trajectory observed before to after the removal of Stronach Dam.

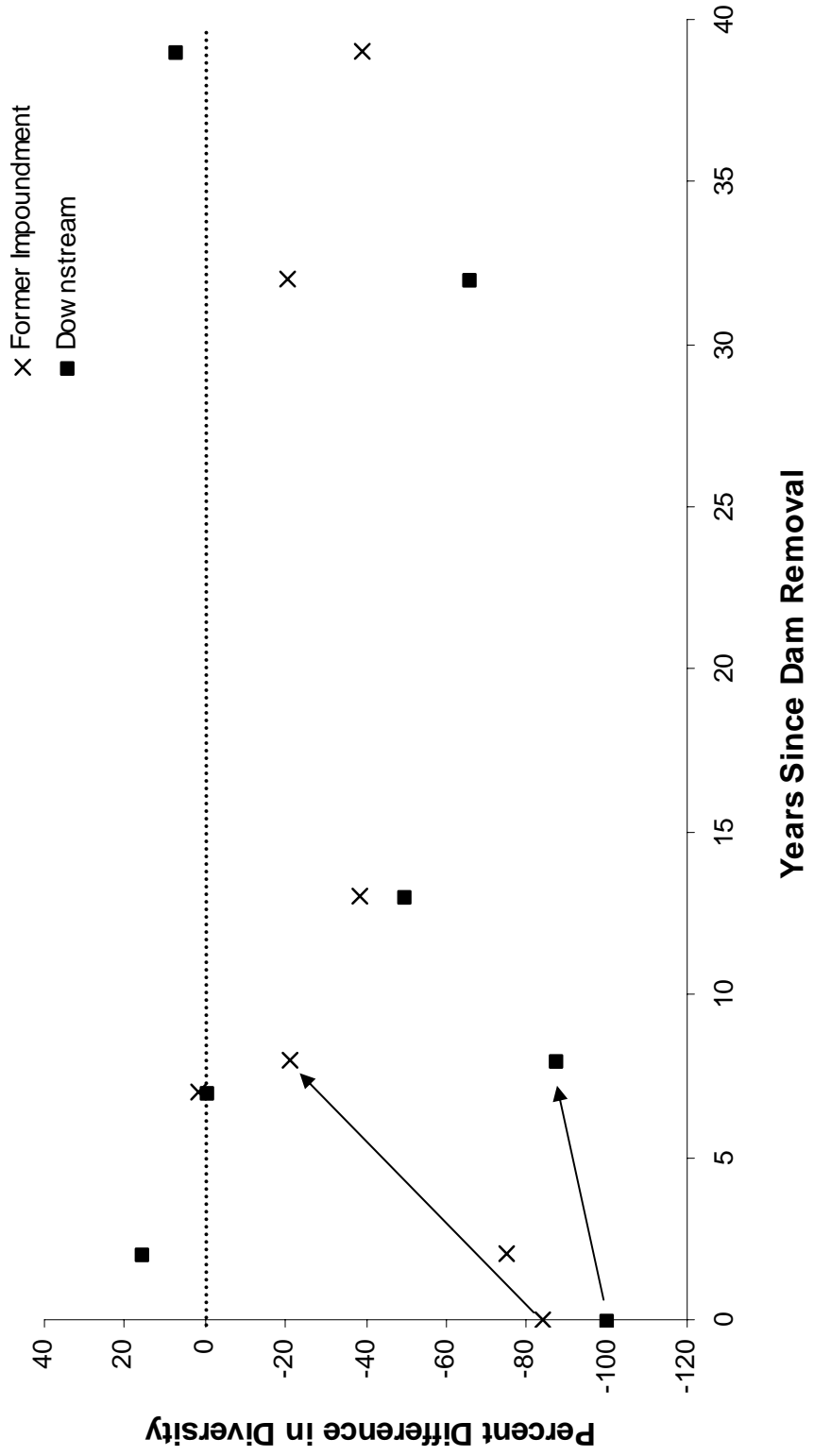


Figure 8. Percent difference in the diversity of bedforms for former impoundment and downstream zones, compared to reference zones. Arrows connect data points from the Pine River, indicating the trajectory observed before to after the removal of Stronach Dam. Shannon-Weaver diversity index used.

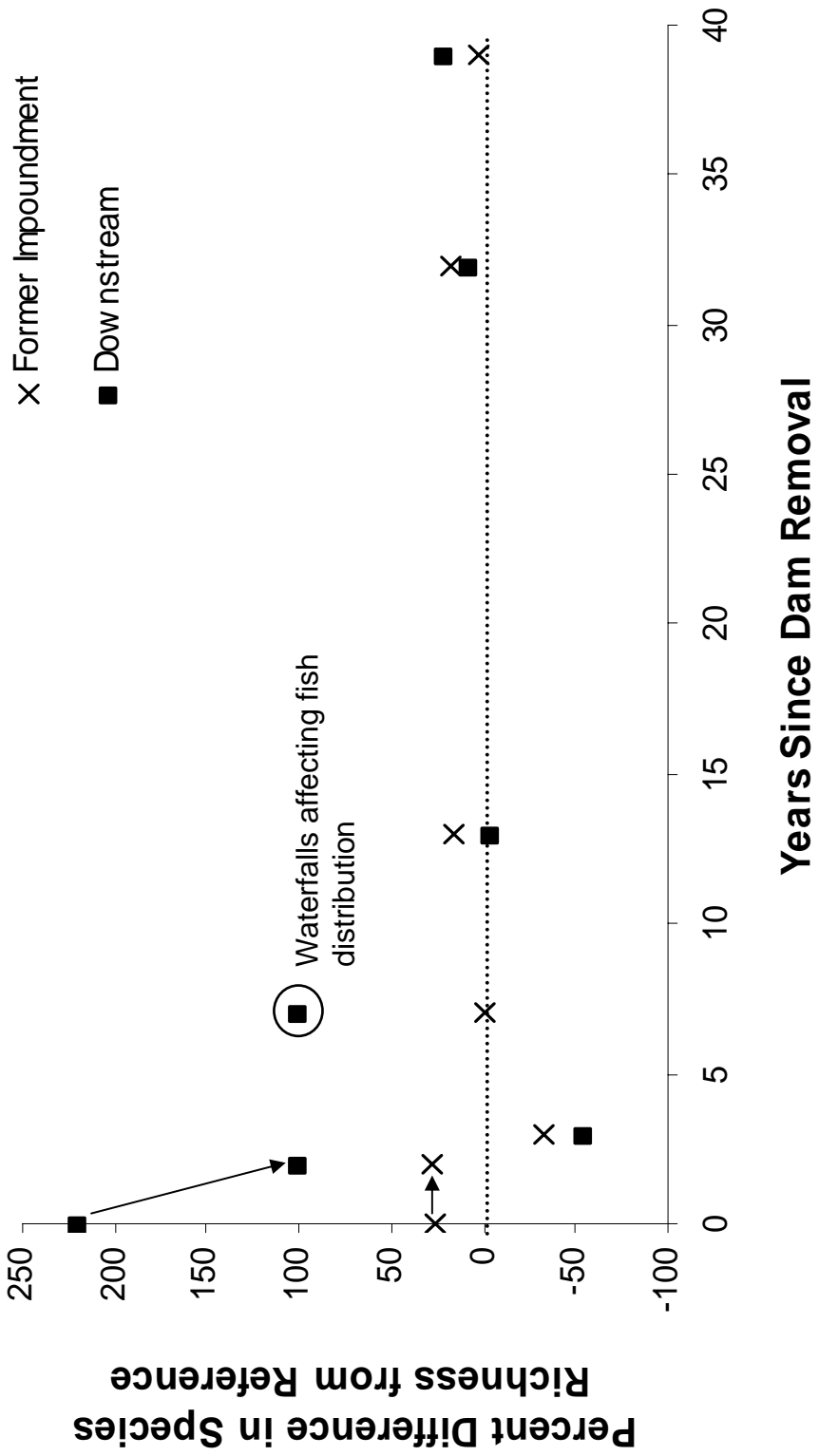


Figure 9. Percent difference in fish species richness for former impoundment and downstream zones, compared to fish species richness in reference zones. Arrows connect data points from the Pine River, indicating the trajectory observed before to after the removal of Stronach Dam.



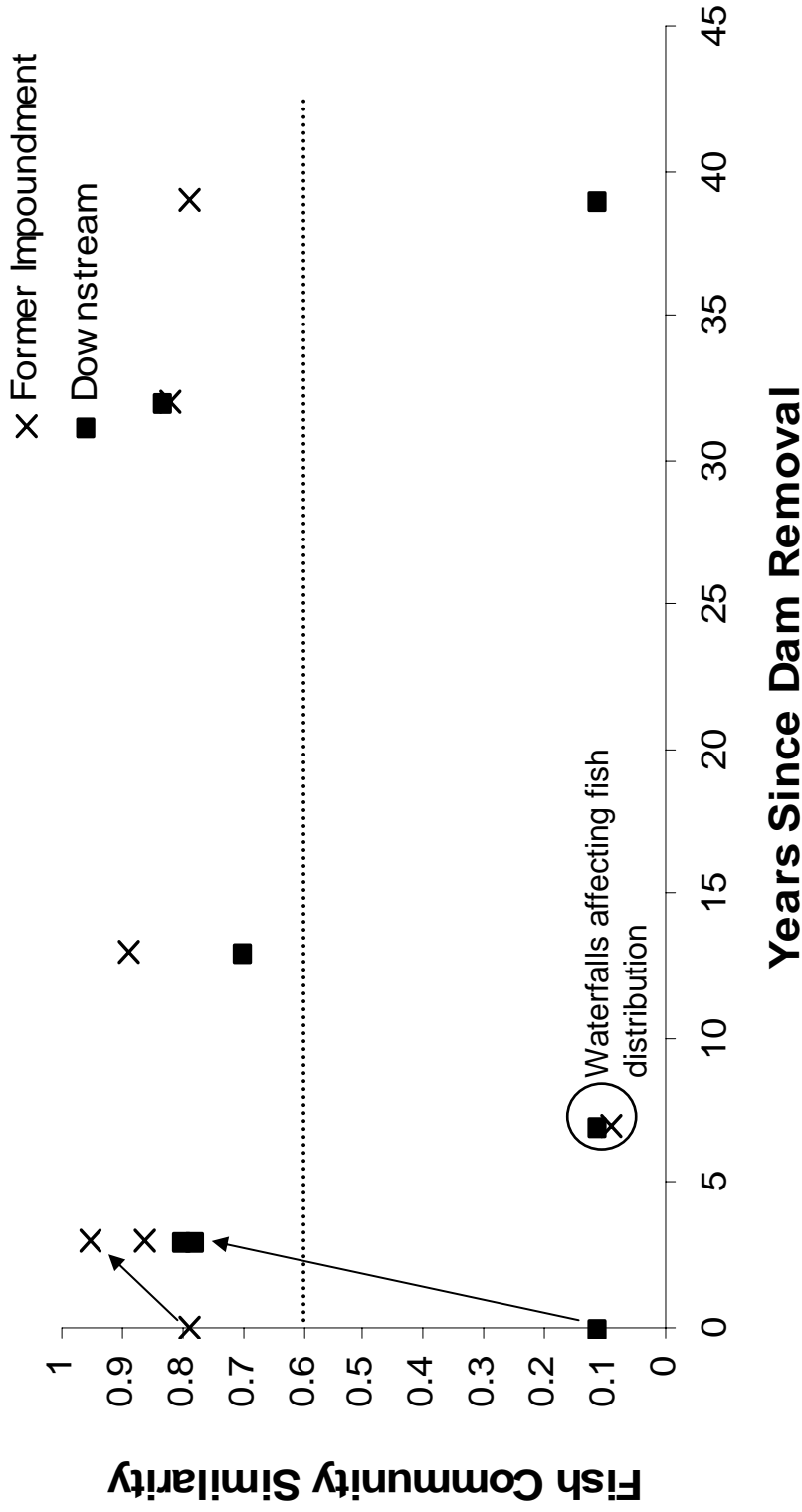


Figure 10. Morista similarity indices of fish community numeric composition, for former impoundment and downstream zones, compared to reference zones. Similarity indices of 0.00 denote complete dissimilarity, 1.00 denotes complete similarity, and indices greater than 0.60 indicate “similar” fish community compositions. Arrows connect data points from the Pine River, indicating the trajectory observed before to after the removal of Stronach Dam.

The total number of fish sampled in a study zone, adjusted for effort, was used as a surrogate for the productivity of the fish community. Total number of fish in former impoundment zones was relatively variable among rivers for the first 15 years or so, but across all rivers from 0 – 39 years post-removal, shows a gradual increasing trend, from slightly less fish than reference levels to slightly more than reference levels for the dam removals >30 years old (Figure 11). Downstream zones show a more distinct trend in lowered fish abundance immediately following dam removal, with lower fish abundances for approximately 15 years post-removal, and higher fish abundances than reference zones by >30 years post dam removal.

## DISCUSSION

### *Fluvial Geomorphology*

Dams can alter the river temperature in numerous ways (Ligon et al. 1995, Collier et al. 1996). Lessard and Hayes (2003) found that in Michigan coldwater streams, water temperature downstream of dams was on average, 2.7° C warmer than upstream reference zones. These effects were thought to be caused by the warming of water retained in the impoundment, and its subsequent release downstream. Dams can also release water from the hypolimnion of an impoundment, lowering water temperature substantially relative to upstream. The removal of a dam ameliorates effects on water temperature almost immediately, as only very small differences in water temperature were observed in any past dam removals in this study. The water temperature effects of dams can be a major motivation and consideration in deciding whether to remove dams. Dams can alter water temperatures in ways both detrimental and beneficial to fisheries management. In some cases, water temperature can be warmed by dams to levels that will not support coldwater fisheries resources (Lessard and Hayes 2003, Hayes et al. in press). In other cases, coldwater releases downstream of dams can create water temperatures cold enough to support coldwater fisheries not otherwise possible, but displace native fish species not adapted to the colder water temperatures (e.g., Martinez et al. 1994, Quinn and Kwak 2003). The results of this study suggest that dam removal will restore water temperatures in impoundments and downstream sections of rivers to levels similar to upstream references. Whether this outcome of dam removal is viewed as desirable will depend on the fish community goals, and will likely vary with the uniqueness of each river and its fish community.

Slope is a main variable driving many of the characteristics of a river channel and fish habitat. Slope directly affects water velocity, thereby influencing channel morphology and substrate size composition. Dams generally decrease water slope in reservoirs through the impoundment of water and aggradation of sediment (Lane 1955, Gordon et al. 2004). Sections of rivers downstream of dams also generally experience decreased slope, through the degradation of the streambed immediately downstream of dams. Following dam removal, slope increases through a reversal of these sediment processes, as sediment degradation (i.e., incision) occurs in former impoundments and sediment aggradation occurs downstream of dams (Figure 12). The recovery rate of slope following dam removal will depend on how much sedimentation occurred in a reservoir and how sediments are managed. In reservoirs with very little sediment fill, dewatering the impoundment during removal will restore the slope of the former impoundment nearly immediately. Reservoirs that contain large amounts of sediment

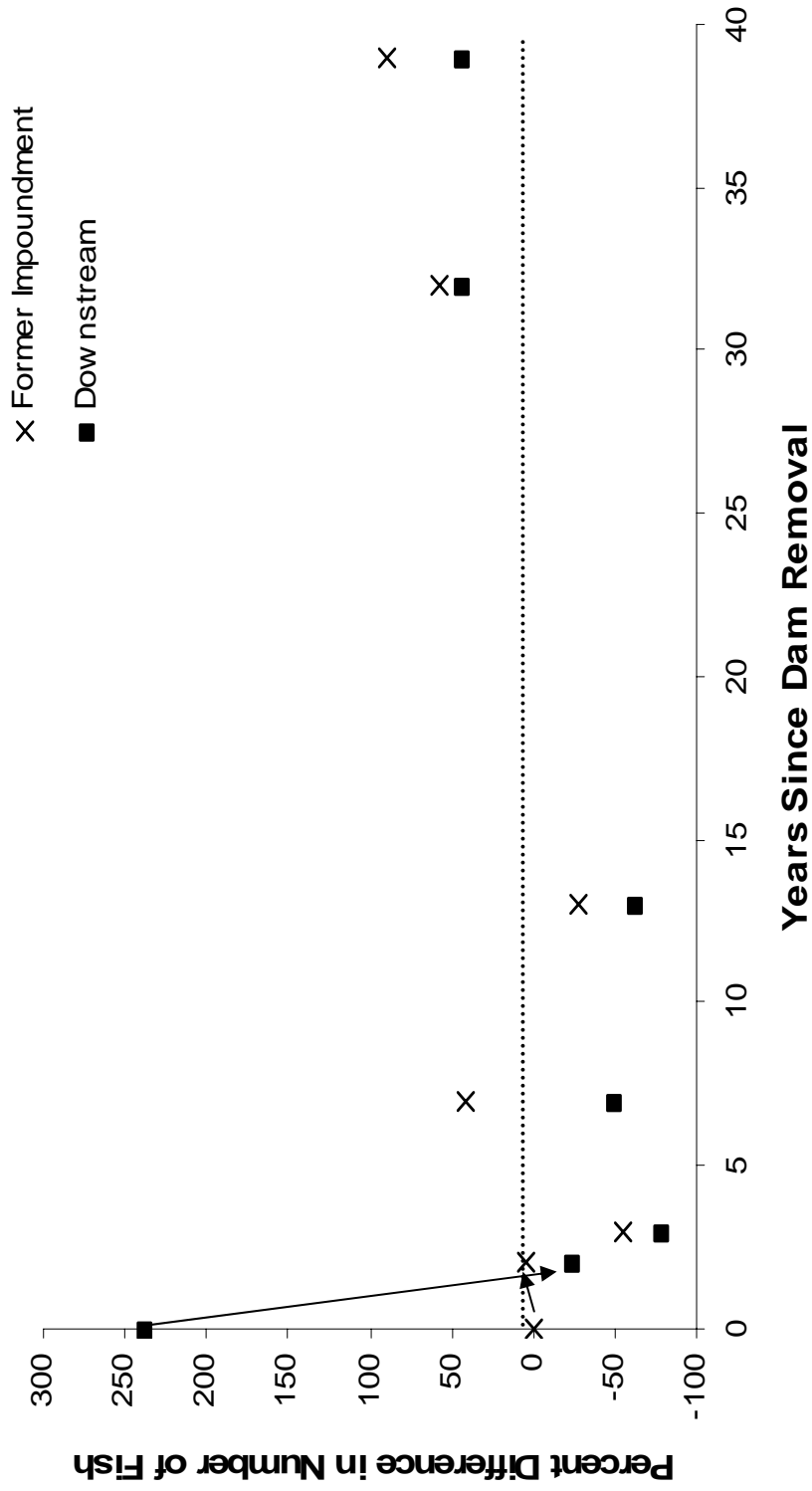


Figure 11. Percent difference in fish abundance (number of fish) for former impoundment and downstream zones, compared to fish abundance in reference zones. Arrows connect data points from the Pine River, indicating the trajectory observed before to after the removal of Stronach Dam.

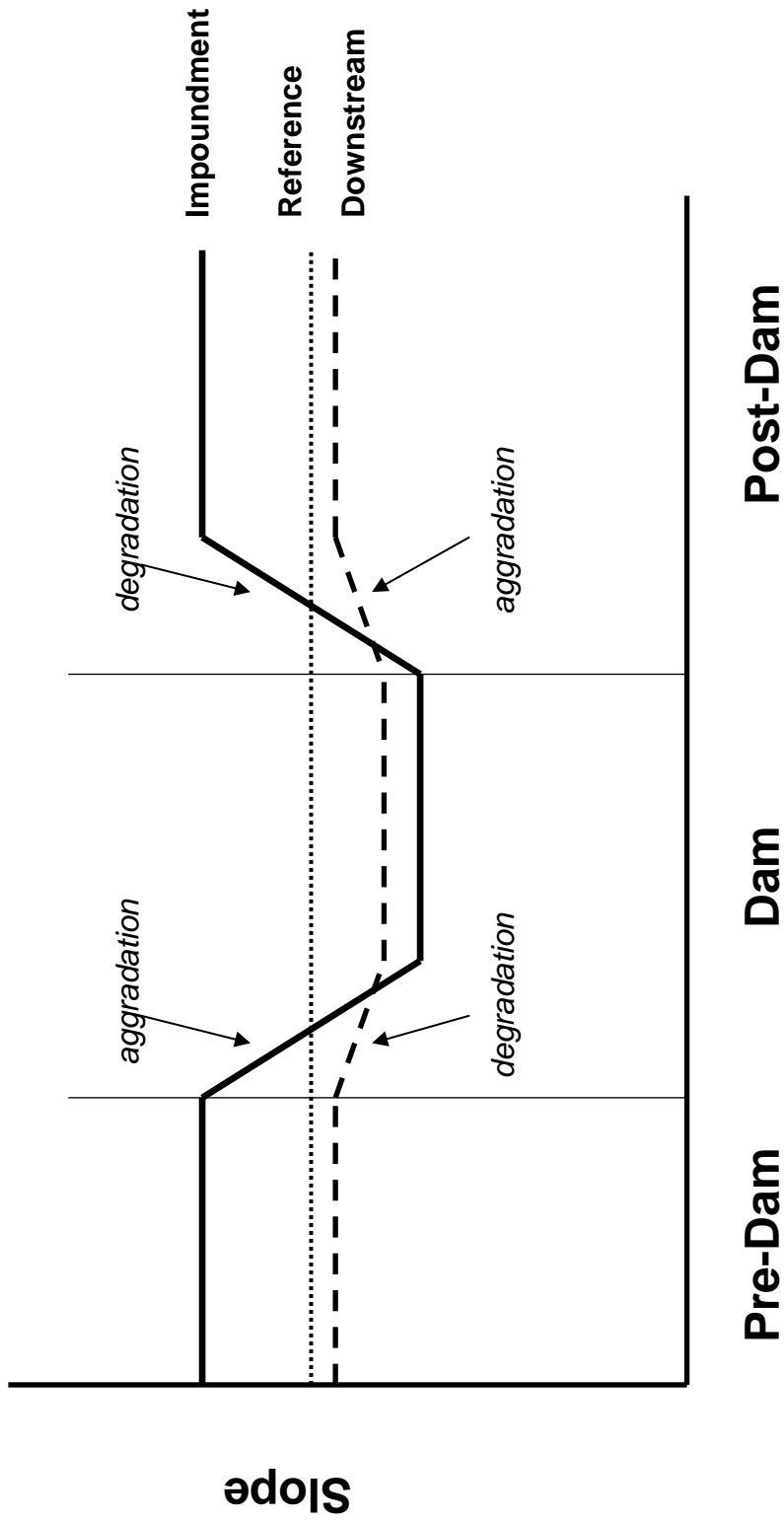


Figure 12. Hypothetical changes in the slope of sections of rivers affected by dams and dam removals, and the sediment processes causing the changes in slopes.

fill must undergo significant incision that could take several years to reach an equilibrium. In this study, we observed sites in which slope was restored quickly and others where slope recovered more slowly. These differences could be explained by the amount of sediment contained in the impoundments prior to dam removal, natural variation in the underlying slope of the river reaches the impoundments were constructed on, or possibly by the methods used to remove the dams (e.g., staged versus all-at-once dam removal). Understanding the influence of each possible explanation will be difficult given the lack of pre-dam removal information available for these past dam removal study sites. However, it appears that slope generally reaches reference levels within 2 to 5 years following dam removal.

Immediately following dam removal, the lack of water impoundment immediately decreases wetted width of the river channel and often the water depth. Further, in impoundments that contain significant amounts of sediment fill, incision occurs vertically downward through these sediments, forming a narrower river channel, and further decreasing the width of the river channel and the W/D ratio. The results of this study suggest that the equilibrium slope and W/D ratio will eventually become very similar to reference conditions, but may take more than a decade for this new equilibrium channel to form. Downstream of dams, increased sediment supply following dam removal generally aggrades the streambed and increases both slope and W/D of the river channel. So whereas the impoundment zones move toward restoration of channel form immediately following dam removal, the downstream zones often move away from reference conditions immediately following dam removal. The results of this study suggest that river channels downstream of dam removals eventually move toward reference conditions, but require more time to achieve these conditions, perhaps 20 years or more. Reference conditions were observed in the downstream zones for the dam removals >30 years old, indicating that restoration of channel form is possible. One notable exception occurred with implications for how dams are removed. The Randall Dam on the Coldwater River was removed in 2002, during which a sediment collection basin was operated immediately downstream of the dam (D. Zebell *personal communication*). This prevented large amounts of sediment from impacting the downstream zone of this river. Consequently, many of the negative impacts of sediment deposition, including increased W/D of the river channel were not observed.

Sinuosity in former impoundments and downstream zones did not change following dam removal. Despite large amounts of vertical incision observed at some dam removals (Stanley et al. 2002, Burroughs 2007a), substantial lateral erosion through the floodplain was not observed. Sinuosity of a river channel influences the slope and subsequently the equilibrium channel shape. Sinuosity also affects the formation of pool bedforms at the outside corners of meanders, and affects the rate of wood debris recruitment and retention in rivers. It still remains uncertain whether river channels will revert to pre-dam removal river channels or whether new river channels will form through accumulated reservoir sediment fill. Managers may decide upon desirable locations of new river channels formed following dam removal, and the equilibrium slope and sinuosity of these post-dam removal channels, based on various management objectives. However, it is important to realize that sinuosity does not seem to change significantly following dam removal, so desired sinuosity should be considered prior to dam removal as part of an integrated dam removal plan.

As slope increases in former impoundment and downstream zones, water velocity increases, and substrate size composition coarsens slightly. This begins soon after dam removal in the impoundment zone, and later in the downstream zone if the reservoir sediment fill is allowed to be transported and deposited downstream. However, the median substrate size of reference zones is reflective of higher, more infrequent flow events. Even as substrate size coarsens in impoundment and downstream zones, the median substrate size would not be expected to coarsen to reference levels for many years or decades, until several high flow events have occurred. Results from this study suggest that substrate in former impoundments and downstream zones can become as coarse as seen in reference zones following dam removal. This substrate coarsening could be achieved shortly after dam removal if active sediment management efforts are employed (i.e., dredging, or passive collection), or if a large, infrequent flow event happens to occur shortly after the dam removal. In most cases however, it appears as though several decades may be required in order to achieve the full restoration of substrate coarseness following dam removal.

Similar to substrate coarseness, the creation of bedforms is controlled by infrequent high flow events, often 5 -10 year recurrence interval floods, that possess sufficient energy to scour pools and transport and deposit large substrates, forming riffles (Petts and Foster 1985, Knighton 1984, and Beschta and Platts 1986, as cited in Gordon et al. 2004, and Pizzuto 2002). Bedforms can also be created secondarily by other localized structures or events such as wood debris or bank slumping. In this study we observed an increase in bedform diversity in former impoundment and downstream zones following dam removal, but full restoration of bedform frequency was inconsistent, even decades following dam removal.

In the case of the Stronach Dam removal on the Pine River, the former impoundment was almost entirely run bedform prior to dam removal (Burroughs 2007a). Eight years after the dam removal, the proportion of run bedform had decreased with increases in riffle and pool bedforms, but the diversity of bedforms was still less than observed in the reference zone. The results of this study suggest that while bedform diversity may improve in former impoundments following dam removal, the process will be slow, and reference-level bedform diversity may not be achieved. Several of the downstream zones in this study did attain reference-level bedform diversity. The two downstream study zones that remained low in bedform diversity were both low gradient and emptied into other impoundments. This situation may reduce sediment transport ability during high flows and slow or prevent the reformation of diverse bedforms downstream of dam removals.

Bedform diversity influences sediment transport and sorting, nutrient cycling, and is important to the habitat suitability of stream biota (Gordon et al. 2004). Given the lack of bedform restoration in impoundments following dam removal, managers may need to consider actively restoring bedforms following dam removal.

#### *Fish Community Composition and Productivity*

While many aspects of the fluvial geomorphology of rivers seem to be restored eventually following dam removal, changes that occur to the fish community can not necessarily be seen as restoration. With the initiation of fish passage following dam

removal, often quite different fish assemblages are allowed to intermix, and interact with varying habitat conditions. The result is a new and different fish community following dam removal, throughout all of the zones.

Hill et al. (1994) found that species richness increased in the Chipola River, Florida following dam removal. Kanehl et al. (1997) found index of biotic integrity scores increased in the Milwaukee River, Wisconsin following dam removal; and Burroughs (2007b) found fish species richness, diversity, and similarity of numeric community composition increased in all three zones (reference, former impoundment, and downstream) following the removal of Stronach Dam on the Pine River, Michigan. Results from this study support these other findings, in that the similarity of species richness and numeric composition between study zones increased very quickly, within just a few years following dam removal. Again, these changes are not necessarily interpreted as restoration of original “pre-dam” fish communities, but rather homogenization of fish assemblages within a river. Fisheries managers faced with potential dam removals will need to decide whether these changes are desirable for a specific river.

The trends in fish abundances after dam removal follow many of the changes in fish habitat observed in this study. Many aspects of fish habitat were observed to change immediately following dam removal, such as water temperature and slope. These changes will immediately alter the suitability of the habitat in former impoundment and downstream zones, leading to changes in the fish communities and fish abundances in each zone. These immediate changes alter the former impoundment to reflect more reference-like lotic conditions, while downstream zones are often inundated with sediment transport and deposition from the incision process in the former impoundment. This leads to wider and shallower river channels, and smaller sized, unstable substrates. Correspondingly, fish abundances in downstream zones were lowered to levels far below those of the reference zones, taking several decades to recover. Bushaw-Newton et al. (2002) also observed decreased fish abundance downstream of a dam removal in Pennsylvania immediately following dam removal.

Other important aspects of fish habitat were observed to take much longer amounts of time to recover after dam removal. The frequency of different bedforms such as riffles or pools are fundamentally important to the survival and feeding needs of different life stages of almost all stream fishes. Substrate coarseness is also related to the spawning requirements of many stream fishes, the survival needs of many juvenile fish as holding cover, and the productivity of macroinvertebrate communities which serve as food for many stream fishes. These important attributes of fish habitat were observed to require long periods of time post-dam removal to be improved or restored. It should not be surprising then, that fish community productivity as measured by fish abundance, also required a long period of time (~20 – 30 years) post-dam removal in order to reach levels seen in upstream reference habitat. Fisheries managers hoping to improve the productivity of a fish community through dam removal, may need to consider active restoration of key fish habitat attributes such as substrate composition and bedform diversity, if the full potential benefits of dam removal are to be achieved within short management timeframes.

## *Synthesis*

While the results of this study were derived from a limited number of dam removal case studies, they provide the first empirical estimates of the timeframes required for various attributes of rivers and their fish to recover or change following dam removal, and also generate novel insights into the trajectories these changes may follow. Many of the aspects of river form and function appear to be restored through dam removals. However, many of the most important aspects of fish habitat may take several decades to be restored, and the full benefits of dam removal won't be achieved until those aspects of fish habitat are recovered.

These results give guidance on where to best spend limited funds directed at dam removals and associated active restoration. Sinuosity did not change following dam removal, and bedform diversity and substrate coarseness took long amounts of time to improve or be restored. If active restoration is feasible following dam removal, efforts aimed at creating meanders, pool and riffle forming structures and coarsening substrate, could help to speed the restoration of these important habitat attributes and lead to a faster realization of the full potential benefits of dam removal.

Deciding on whether dam removal is good for a fish community will always require consideration of the uniqueness of the river, the fish assemblages surrounding the dam removal in question, and their preferred uses and states. Dam removal allows mixing of species from downstream and upstream of dams. This will allow all fish to access and sample all habitats available to them and select those that best fulfill their life history requirements. This appears to lead to higher species richness, higher similarity of fish communities upstream and downstream of dams, and higher diversity. While Hill et al. (1994), Kanehl et al. (1997) and Burroughs (2007b) all observed increases in abundances of desirable sportfishes, along with increased species richness following dam removal, changes in fish habitat and new species interactions could have detrimental effects for some desirable fish species. In order to make a decision on the desirability of suspected outcomes of potential dam removals, fisheries managers will need to consider the fish species present in the river, those fishes' habitat requirements, and the projected changes to habitat expected due to dam removal.

Surveying the outcomes of past dam removals, even with limited sample size, has revealed valuable insights, including the extent of restoration possible with dam removal, and the timeframes required for restoration. Pohl (2003) estimated that more than 400 dams have been removed in the U.S. to date. There is great potential for researchers to apply this methodology to the study of other past dam removals. As more of these past dam removals are studied, more reliable estimates of the timeframes of restoration of different attributes will be possible, the timeframes could be calibrated to specific geological or ecological regions, and the influence of starting conditions on time-to-restoration could be examined. For example, if particular starting conditions exist prior to dam removal, and they are known to lead to faster restoration times, decisions can be made whether to conduct active restoration or whether passive restoration would be sufficiently fast. Also, as more dams are removed in the future with active site restoration conducted (e.g., sediment collection and removal, natural channel design), the effectiveness of these efforts can be evaluated by whether or not they lead to faster restoration than average timeframes with just passive, natural restoration; and cost-effectiveness of dam removals can be improved.



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