EFFECTS OF THE STRONACH DAM REMOVAL ON FLUVIAL GEOMORPHOLOGY IN THE PINE RIVER, MANISTEE COUNTY, MICHIGAN

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

By Bryan A. Burroughs
Professor Daniel B. Hayes

Department of Fisheries & Wildlife
Michigan State University
13 Natural Resources, East Lansing, MI 48824-1222
www.fw.msu.edu
517-353-6697

INTRODUCTION

The intensive construction of dams in North America began in the 1800's (Petts 1980), reaching its peak from 1950 to 1970 (Heinz Center 2002). This resulted in approximately 2.5 million dams being built in the United States (National Resource Council 1992), on nearly every major and minor river system in the lower 48 states (Heinz Center 2002). These dams were built for a variety of purposes including (in order of prevalence); recreation, fire and farm ponds, flood control, municipal water supply, irrigation, tailings and waste containment, mechanical and hydroelectric energy generation, navigation, and wildlife management.

Dams alter the flow of water and fundamentally change the functioning of river ecosystems. From the earliest times of dam construction, people have recognized some of the inherent consequences of building dams. The first laws restricting dams on rivers, with the acknowledgement that they restrict crucial migrations of fish, were in the Magna Carta (Neilsen 1999). However it wasn't until after the peak period of dam construction ended in the 1970's that strong scientific proof for the multitude of ways dams impact river systems began to emerge. The effects that dams have on river ecosystems are now more fully understood (e.g., Hammad 1972, Petts 1980, Williams and Wolman 1984, Cushman 1985, Bain et al. 1988, Ward and Stanford 1989, Benke 1990, Ligon et al. 1995, Collier et al. 1996, Lessard and Hayes 2003, Shields et al. 2000), including interruption to the flow of water, sediment, energy, nutrients, biota, and associated indirect changes.

Many dams are still functioning and fulfilling their intended purpose, providing social and economic benefits. However, as dams age they require maintenance to prolong their function and safety. There are now, a large and growing number of dams that no longer fulfill their intended purpose and may not sustain sufficient benefits as to outweigh the negative ecological impacts they cause.

Of the estimated 2.5 million dams in the U.S., 76,000 are six feet or greater in height; a minimum size for dam safety regulatory concerns (Federal Emergency Management Agency (FEMA) and U.S. Army Corps of Engineers (USACE) 1996). Of these 76,000 dams, 80% or 60,000 are expected to be 50 years of age or older by the year 2020 (FEMA and USACE 1996). Given that the average design life expectancy of dams is approximately 50 years, this implies that a large number of dams in the U.S. will be in need of maintenance or considered for removal (River Alliance of Wisconsin and Trout Unlimited 2000). Over the last several decades, the rate at which dams have been removed in the U.S. has risen from approximately one per year during the 1960's to approximately 20 per year during the 1990's (Pohl 2003). Given all of these estimates, the practice of removing dams is likely to become increasingly common in the future.

At least 400 dams have been removed to date in the U.S. (Pohl 2003), but the scientific literature on the effects of dam removal is still sparse. Much of the existing dam removal literature focuses on the administrative, legal, and socioeconomic aspects of executing dam removals (Born et al. 1998, River Alliance of Wisconsin and Trout Unlimited 2000, Smith et al. 2000, Graber et al. 2001, Trout Unlimited 2001, Bowman 2002, Johnson and Graber 2002). Using analogies from various disciplines, other researchers have developed several hypotheses of river ecosystem responses to dam removals (Pizzuto 2002, Stanley and Doyle 2002, Shafroth et al. 2002, Gregory et al. 2002, Whitelaw and MacMullan 2002, Doyle et al. 2002), while others have hypothesized the outcomes of specific proposed dam removals (Shuman 1995, Freeman et al. 2002, Heinz Center 2002). Despite this emerging conceptual basis for the effects of dam removals, the field continues to lack the empirical information that is needed to verify these hypotheses, calibrate pre-existing models for use with dam removal, and generate novel insights into the effects of dam removal (Doyle et al. 2002, Bushaw-Newton et al. 2002, Graf 2003, Hart et al. 2003, Doyle et al. 2005). Qualitative observations on the effects of dam removal exist for several dam removal case studies (American Rivers et al. 1999, Smith et al. 2000), and several quantitative studies exist on the effects of dam removal on fluvial geomorphology (Evans et al. 2000, Wohl and Cenderelli 2000, Bushaw-Newton et al. 2002, Stanley et al. 2002, Chaplin 2003), aquatic insects (Bushaw-Newton et al. 2002, Stanley et al. 2002) and fish (Kanehl et al. 1997, Hill et al. 1994, Bushaw-Newton et al. 2002). While these studies provide unique insights into the outcomes of dam removals, many were relatively short in time duration (i.e., 1-2 years post dam removal), and the empirical information on the effects of dam removal is still considered very limited (e.g., Graf 2003, Doyle et al. 2005).

The goal of this study was to document the effects of dam removal on fluvial geomorphology. In particular, this study was designed to address questions such as; what types of changes occur in rivers following dam removal, what are the magnitudes of these changes, what are the spatial extents of the changes, and how long do these changes take to occur? Answers to questions such as these should lead to more informed decision making processes regarding dam removals, improved predictions on the outcomes of dam removal, and could lead to improvements in how dams are removed in the future.

To answer these questions, we monitored several aspects of fluvial geomorphology from 1995 through 2006, before, during and after the gradual removal of Stronach Dam, on the Pine River, Manistee County, Michigan. The specific objectives of this study were to: (1) document the spatial and temporal extent of sediment erosion, transport and deposition that occurred due to the dam removal; and (2) document the changes in river morphology attributes (i.e., slope, width, depth, water velocity, substrate composition, and bedform (riffle-pool) diversity) that occurred due to the sediment erosion, transport and deposition. The 12 years of detailed quantitative monitoring of the outcomes of this dam removal provide a unique dataset useful for validating and refining existing hypotheses about the effects of dam removals, generating novel hypotheses, leading to improvements in the ongoing practice of removing dams.

Site Description

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, 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). Mean daily discharge recorded at two U.S. Geological Survey gaging stations on the Pine River (8 and 13.7 km upstream from Stronach Dam) averaged 8.10 m^3/s during 34 years of record, with a minimum discharge of 4.56 m^3/s, a maximum of 69.09 m^3/s, and an average annual ratio of low to high mean monthly flows of 2.02, indicating “stable to very stable” flows (Rozich 1998). It carries a large bedload of sand due to the local geology and extensive logging operations of the late 1800’s, which created unstable banks along the river. Hansen (1971) estimated a mean annual sediment discharge of 50,000 tons at Stronach Dam from 1967 to 1970, 70 - 75% of which was sand.

Stronach Dam was constructed from 1911 to 1912, 5.6 km upstream from the confluence of the Pine River and the Manistee River (Figure 1). Stronach Dam was an earth embankment dam with a concrete corewall; a 4.57 m fixed-concrete spillway section with 0.91 m of flashboards on top of the spillway; a concrete and brick powerhouse with two turbine bays; and an upstream fish ladder (Consumers Power Company 1994). Stronach Dam, with 5.49 m of head height possible, was operated mostly around 5.18 m of head. This created a 26.7 ha reservoir with a 789,428 m^3 volume capacity (Consumers Power Company 1994, Hansen 1971). Tippy Dam (17.07 m head height) was constructed in 1918 immediately downstream of the confluence of the Pine and Manistee Rivers (Rozich 1998) (Figure 1). This created a 428 ha, 48,722,530 m^3, impoundment over the high gradient confluence area of the two rivers, blocked all upstream fish migration from Lake Michigan, and impounded water upstream to Stronach Dam.

Due to the Pine River’s large sediment load, the Stronach reservoir quickly filled with sediment and problems arose with the operation of the dam’s turbines. Attempts were made in the 1930’s to remove the accumulation of sediment behind the dam.

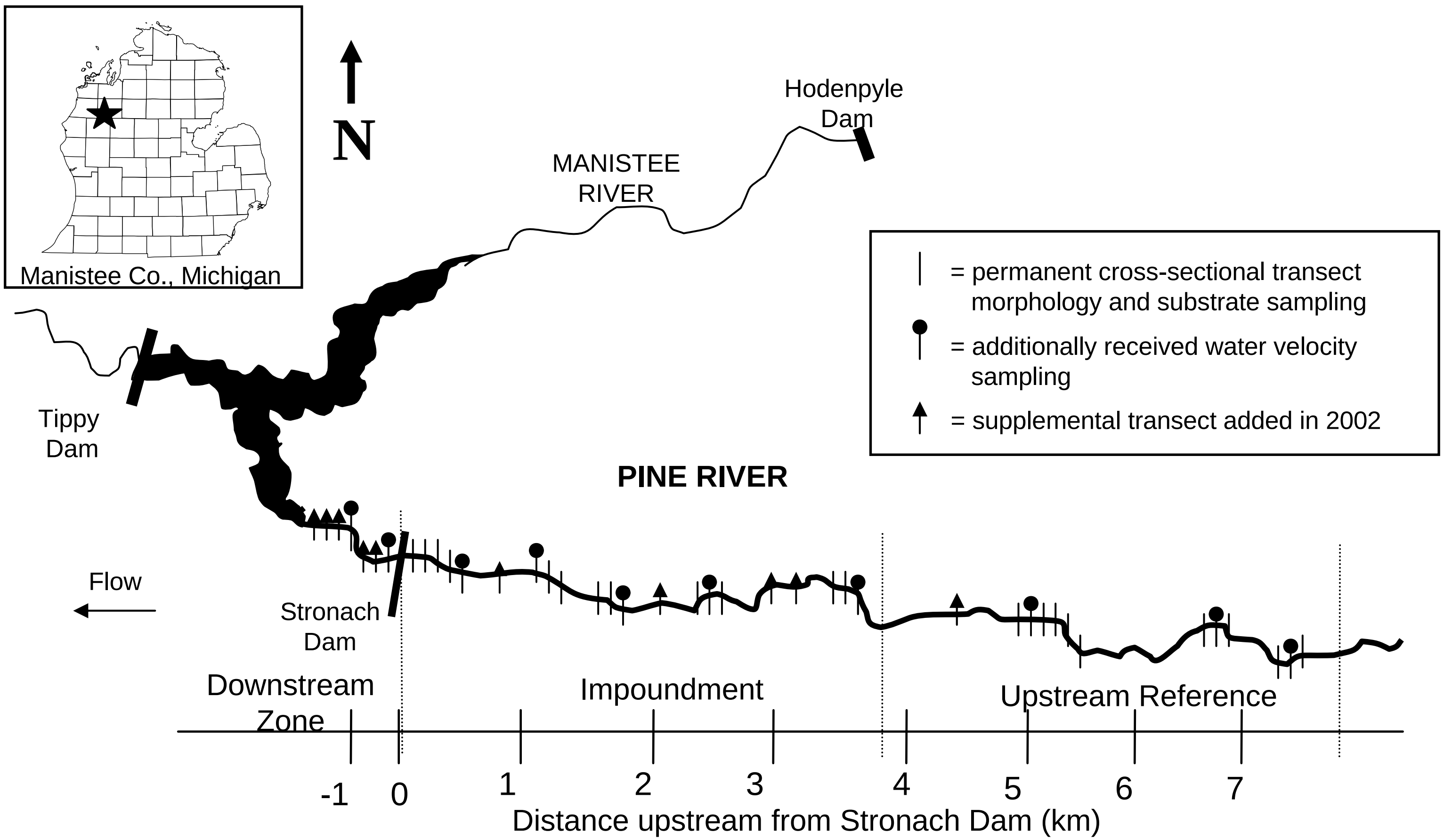

Figure 1. Locations of Stronach Dam and the Pine River in relation to the State of Michigan; and the location of permanent cross-sectional surveying transects within the study area of the Pine River.

These efforts were only marginally successful and dredging eventually became uneconomical (Consumers Power Company 1994). In 1953, 41 years after the dam's construction, Stronach Dam was decommissioned by the owner, Consumers Power Company. The generator rooms were demolished, the fish ladder was removed, and the river flow was directed over the spillway. The spillway flashboards were removed gradually over the following years; the last was removed in 1983 (Consumers Power Company 1994).

In the early 1990's, removal of Stronach Dam was negotiated as part of a Federal Energy Regulatory Commission (FERC) agreement in the relicensing of Tippy Dam. Removal of Stronach Dam began in the spring of 1997 and was completed in December of 2003. 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 impacting 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 three months, for a total of 0.60 m per year, over the course of six years; with corresponding trash-rack removal. This plan was altered due to recreational safety concerns, feasibility issues, and technical difficulties with removal (Table 1) (Battige personal communication 2002). The actual sequence of the staged dam removal is shown in Table 1.

METHODS

In 1995, two 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 surveying and description of physical characteristics, including categorization of the stream into bedform units of runs, riffles, pools, rapids, or complexes (a designation where more than one category applied), following the criteria developed by Hicks and Watson (1985). This survey method allowed detection of impoundment effects well upstream of the readily noticeable reservoir area. This "impoundment" area of the river extended for 3.89 km upstream of Stronach Dam and was typified as being relatively wide, slow-flowing, sand-bottomed, and generally consisted of only run bedform units. An upstream reference reach was chosen, extending for 3.70 km upstream from the upstream boundary of the impoundment. This study zone was chosen as a reference reach because no impoundment effects from the dam were evident. The river was narrower, faster-flowing, had coarser substrates, and showed high bedform heterogeneity. A third study zone was chosen downstream of Stronach Dam, where the river was wide, very slow-flowing, sand-bottomed, and consisted entirely of run bedforms. Prior to the removal of Stronach Dam, water was impounded in this study zone from Tippy Dam Reservoir downstream, and the zone extended for only 0.63km downstream of Stronach Dam. During the dam removal process, slope increased in this zone and the impoundment of water by Tippy Dam was not observed for 2.55 km downstream of Stronach Dam. In 2002, this downstream study zone was lengthened from 0.63 km to 2.55 km downstream of Stronach Dam.

Table 1. Schedule of removal events during the staged removal of Stronach Dam on the Pine River, Manistee County, Michigan. Stop-logs are 15.24 cm diameter hollolw 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 2003).

Date	**Number of Stop-logs removed**	**Meters of Trash-rack removed**
March 17, 1997	1 (0.15)	0 (0)
June 5, 1997	1 (0.30)	0 (0)
June 16, 1997	2 (0.61)	0 (0)
June 24, 1997	2 (0.91)	0 (0)
September 15, 1997	1 (1.07)	0 (0)
December 15, 1997	1 (1.22)	0 (0)
March 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)
June 15, 1998	1 (1.52)	0 (2.13)
September 8, 1998	1 (1.68)	0.30 (2.44)
December 14, 1998	1 (1.83)	0.30 (2.74)
March 15, 1999	1 (1.98)	0 (2.74)
May 11, 1999	1 (2.13)	0 (2.74)
September 13, 1999	2 (2.44)	0 (2.74)
September 16, 1999	0 (2.44)	0.61 (3.35)
April 17, 2000	2 (2.74)	0 (3.35)
October 2, 2000	2 (3.05)	0 (3.35)
October 5, 2000	0 (3.05)	0.61 (3.96)
May 8, 2001	2 (3.35)	0 (3.96)
September 8, 2001	2 (3.66)	0 (3.96)
November 11, 2002	0 (3.66)	1.52 (5.49)
December 2003	Remaining spillway and dam superstructure removed	

Thirty-one permanent cross-sectional transects were established in 1996 to allow for measurement of changes in river channel morphology over the course of dam removal. Ten additional transects were added in 2002 to fill in longitudinal gaps in areas of geomorphologic interest, and to extend the downstream zone. Thirteen transects were located in the upstream reference reach, 21 transects were located in the impoundment, and seven transects were placed in the downstream zone (Figure 1). Photographs, site descriptions, and latitude-longitude coordinates for all transects are archived at Michigan State University, Department of Fisheries and Wildlife. All transects were linked to real elevations above sea level based on a USGS monument. The distance of each transect from Stronach Dam was determined by floating the river in a canoe using the trip-log feature of several handheld Garmin® GPS units, on several occasions and averaging the results. All transects were surveyed annually from 1996 through 2006, during June to early-July of each year. At each transect, streambank elevations were recorded at points of inflection (appropriate for accurate documentation of streambank morphology). Streambed elevations were recorded every 0.61 m across the wetted width of the stream, and water surface elevation was measured once per transect. All measurements were taken at the same locations each subsequent year of the study. Elevations were recorded to the nearest 3 mm.

Top bank was delineated for each transect as the highest elevation during the entire time series in which water would just begin to overflow onto a floodplain. Cross-sectional areas, below top bank, were calculated for each transect in each year. The trapezoidal rule for numerical integration (Press et al. 1992) was used to estimate areas between each pair of cross-sectional points surveyed, and the sum of these was the transect cross-sectional area estimate. Change in transect cross-sectional area reflects the net amount of erosion or deposition that occurred between surveying events. Estimates of sediment volume transported during the dam removal were calculated using the trapezoidal rule for integration, given the amounts of cross-sectional area change at transects, and the distances between the transects. Gradient was calculated as the change in water surface elevation between two transects, over the river distance between those two transects. Width (w) and mean depth (d) were calculated for each transect, from the wetted channel dimensions. Bank slopes for each side of each transect were calculated as the difference in elevations from the top bank to the beginning of the streambed, divided by the lateral distance between those two points. The beginning of the streambed was determined to be the point, lower in elevation than the water surface, where bank slope was greatly diminished and the channel appeared to become mostly horizontal. These points, including the top bank elevations were allowed to change each year. The change in each bank slope at a transect, compared to the initial pre-dam removal slopes, were calculated and averaged for each transect.

Water velocity was measured at 10 of the permanent transects (Figure 1) annually from 1996 to 2006. From 1996 to 2000, a Marsh-McBirney Model 201 portable current meter was used. From 2001 to 2006, water velocity was measured using a Global Flow Probe Model FP101, impellor-style flow meter with a 4 cm diameter impellor. Water velocity was measured at 0.61 m intervals, starting at the water's edge on one stream bank and ending at the water's edge on the opposite stream bank. If water depth was less than 0.75 m, water velocity was measured at 60% of the water depth from the water surface. If water depth was greater than 0.75 m, water velocity was measured at 20% and 80% of the water depth from the water surface, and the two measurements were averaged (Gallagher and Stevenson 1999). Mean water velocities were calculated for each transect in each year. All point measurements of water velocity at each transect were aggregated for all transects in each study zone to examine changes in the distributions of all water velocities in a study zone. The Kolmogorov - Smirnov two sample test (Steel and Torrie 1980) was used to test for differences between water velocity frequency distributions between years. The K-S test was used because it evaluates the observed difference between two distributions, not just differences in means.

Streambed substrate size composition was measured at 10 of the permanent transects in 1996, at each of the 31 original permanent transect sites annually from 1997 – 2006, and also at the ten newer additional sites from 2002 through 2006 (Figure 1). A modified pebble count method was used (Wolman 1954, Kondolf and Li 1992) to determine substrate size composition. We sampled 100 streambed particles systematically (instead of randomly) along each transect, measuring the intermediate axis, and assigning a size class code to each particle (from a modified Wentworth scale) (Wentworth 1922, Cummins 1962). Systematically sampling the substrate and recording the transect side started on, and the approximate distance between samples, allows linkage of the information gathered to other morphological data (e.g., size of substrate at places of erosion or deposition within a transect cross-section) in addition to providing a measurement of the size structure of the substrate. Median substrate size (D_{50}) for a transect was calculated after excluding "organic" or "trash" designations which did not have corresponding size classes. The Kolomogorov-Smirnov two sample test (Steel and Torrie 1980) was used to test for differences between substrate size frequency distributions between years.

In 1995, two years prior to the dam removal, bedforms (also commonly referred to as "meso-habitat" or "channel unit types") were mapped for all three study zones. This assessment involved the categorization of the stream into bedforms following the criteria developed by Hicks and Watson (1985). The length (along the thalweg), and widths of each bedform were measured, as well as periodically recording latitude and longitudes of selected bedforms for mapping purposes. In 2004, the year following complete removal of the dam, this assessment was repeated to document changes in the frequencies of bedforms in each study zone. This assessment was conducted at base flow levels.

RESULTS

Sediment Transport

During and following the staged removal of Stronach Dam, significant sediment transport occurred in both the impoundment and the downstream zones, while the upstream reference reach remained remarkably stable. In the upstream reference reach, net erosion occurred in some years while net deposition occurred in others (Figure 2). The average annual net sediment transport in this reach was 289 m^3 of erosion, with a standard deviation of 1,946 m^3. This translates to only ~4 mm average

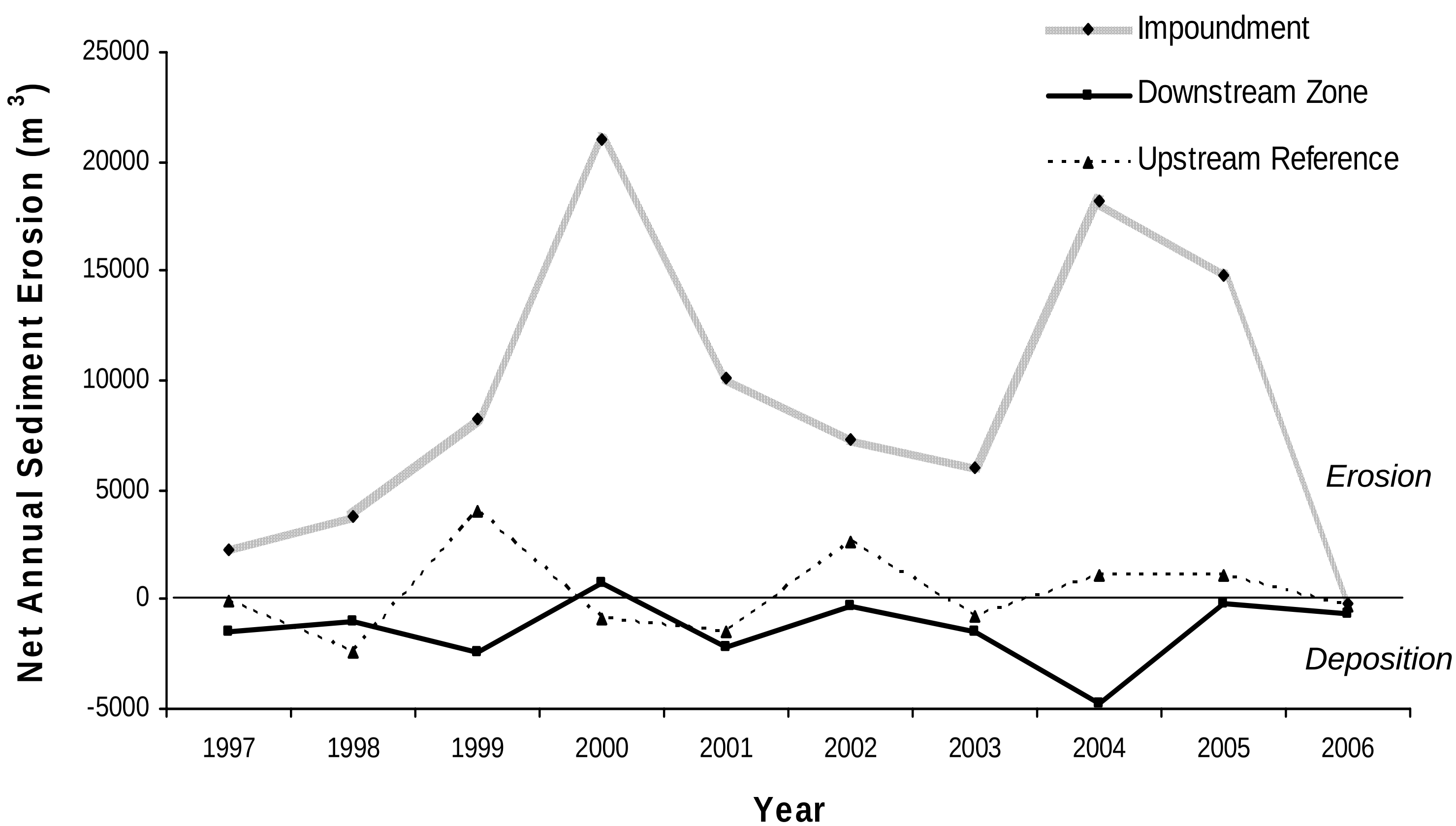

Figure 2. Net annual sediment erosion or deposition volumes during and after the staged removal of Stronach Dam (1997 – 2003). Positive values correspond to net erosion, negative values correspond to net deposition.

annual vertical change for each square meter of streambed in the upstream reference reach.

The total volume of sediment eroded from the impoundment during the staged removal through three years post removal was approximately 92,000 m^3. The annual volume of sediment eroded from the impoundment averaged 9,159 m^3 and was quite variable with a standard deviation of 6,947 m^3 and a range from approximately 0 – 21,000 m^3 (Figure 2). In 2006, no net erosion occurred in the impoundment. This volume of sediment, while large, is substantially less than the mean annual bedload estimated by Hansen in 1971 at the Stronach dam site. Hansen estimated that over three years, the mean annual bedload was 50,000 tons or approximately 28,000 m^3 (using a density of 1.8 g/cm^3 for sand (Morris and Fan 1998)). This makes the net total amount of sediment erosion from the former impoundment over ten years, roughly equivalent to about 3.5 years of annual sediment bedload during the time of Hansen's estimates.

The annual volume of sediment eroded from the impoundment was not correlated to the amount of dam removed between sampling events ($R^2 = 0.04$), annual mean flows ($R^2 = 0.07$), annual peak flows ($R^2 = 0.00$), days at or above bankfull discharge (1.5 year recurrence flood) ($R^2 = 0.01$), or approximate stream power in the impoundment reach (factoring in cumulative mean flows and changing stream slopes) ($R^2 = 0.12$).

The amount of erosion that occurred in the impoundment varied spatially with distance from the dam (Figure 3). In general, greater amounts of erosion occurred closer to the dam site, with the magnitude of erosion attenuating upstream. During the first several years of the removal, erosion progressed upstream only through the easily recognizable former reservoir (1.21 km), and it wasn't until approximately 2001 – 2002 when net erosion was documented at the furthest upstream extent of the impoundment, 3.89 km from the dam. A pair of transects, 0.39 and 0.50 km upstream of the dam, provide an exception to the longitudinal pattern of diminishing erosion with distance upstream of the dam. These two sites experienced greater amounts of erosion than other sites closer to the dam due to large amounts of lateral erosion in addition to the typical vertical erosion.

Each year of the dam removal, with the exception of 2000, some amount of sediment moving downstream from the impoundment was deposited and retained in the first 0.63 km downstream of the dam (Figure 2). The volume of sediment that was retained and not transported further downstream varied considerably between years (average = 1,360 m^3, standard deviation = 1,518 m^3), totaling 13,599 m^3 by 2006. The remainder of the 92,000 m^3 of sediment eroded from the impoundment was either transported further downstream in the river, eventually being deposited out of the study area in Tippy Dam reservoir, or onto the floodplain downstream of the dam during high flow periods.

Channel Geometry

In the upstream reference reach, width and width to mean depth ratio (w/d) of the wetted stream channel remained stable (Figures 4 and 5). In the impoundment, the width of the wetted channel generally decreased (Figure 4), with the magnitude of this narrowing generally corresponding to the amount of erosion that occurred at a transect

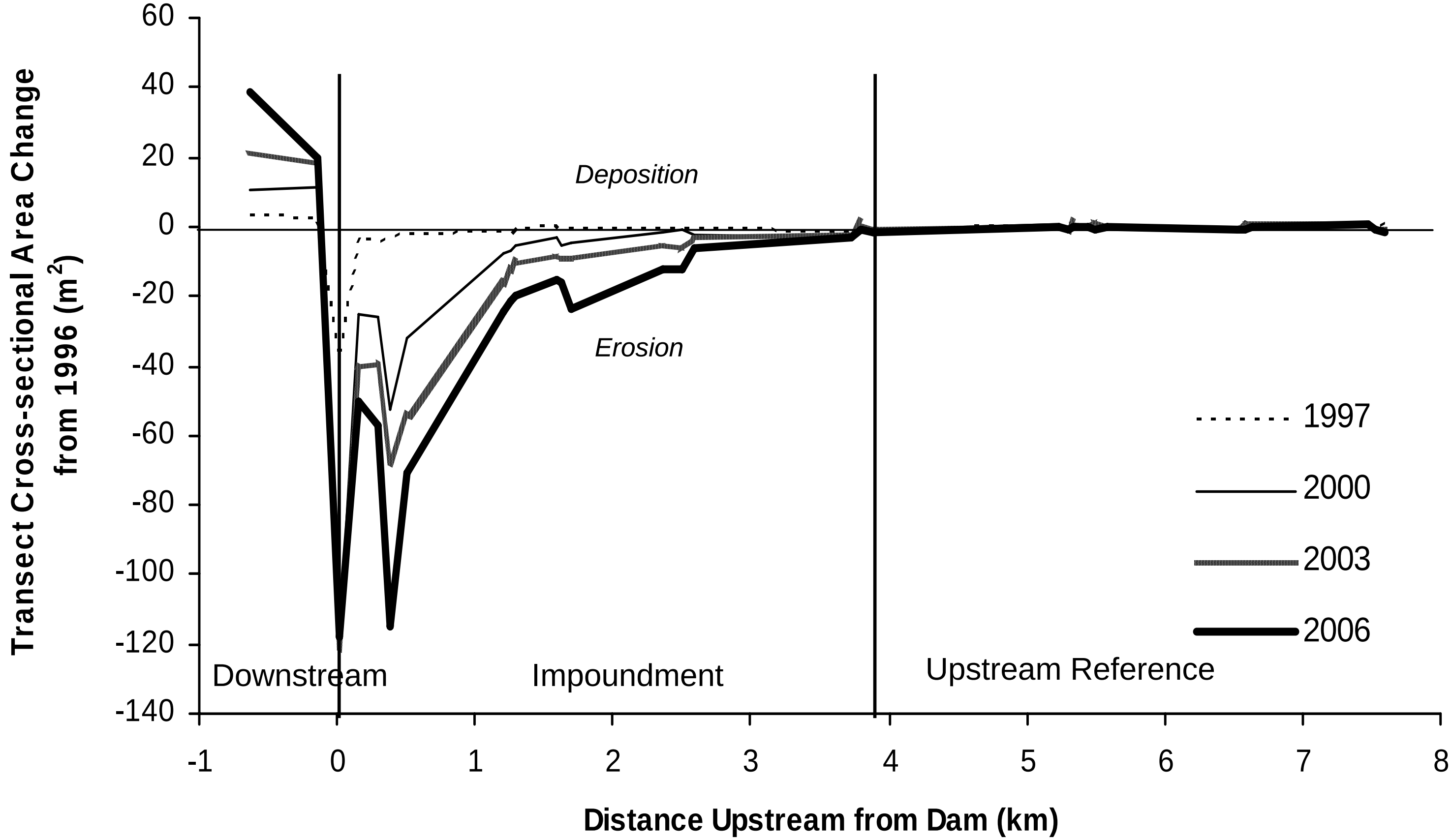

Figure 3. Longitudinal pattern of change in cross-sectional area, during the staged removal of Stronach Dam (1997 – 2003), compared to before dam removal (1996). Positive values correspond to deposition within a transect and negative values correspond to erosion at a transect.

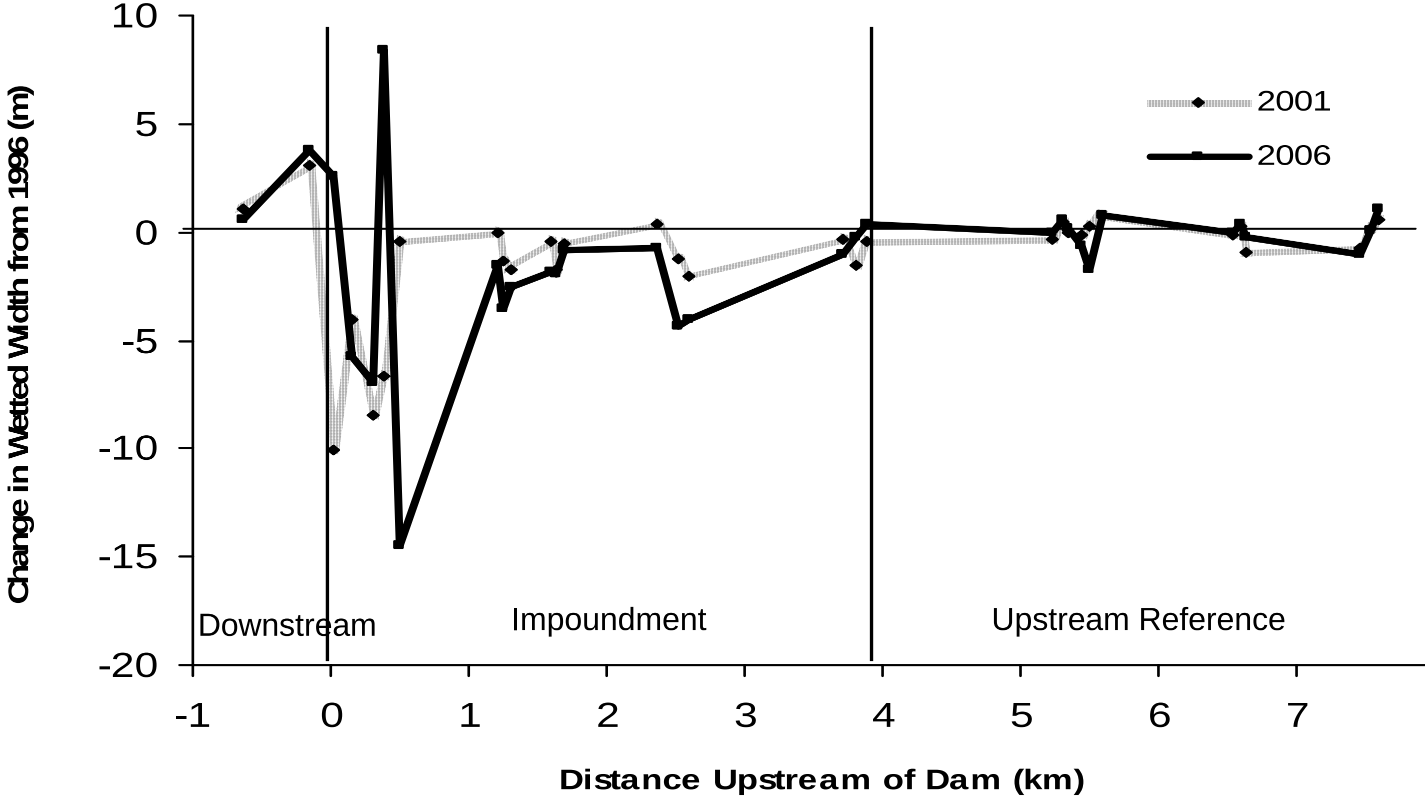

Figure 4. Longitudinal pattern of change in wetted stream width from pre-dam removal conditions in 1996. Only 2001 and 2006, five and 10 years after the beginning of the dam removal are shown for simplicity and clarity.

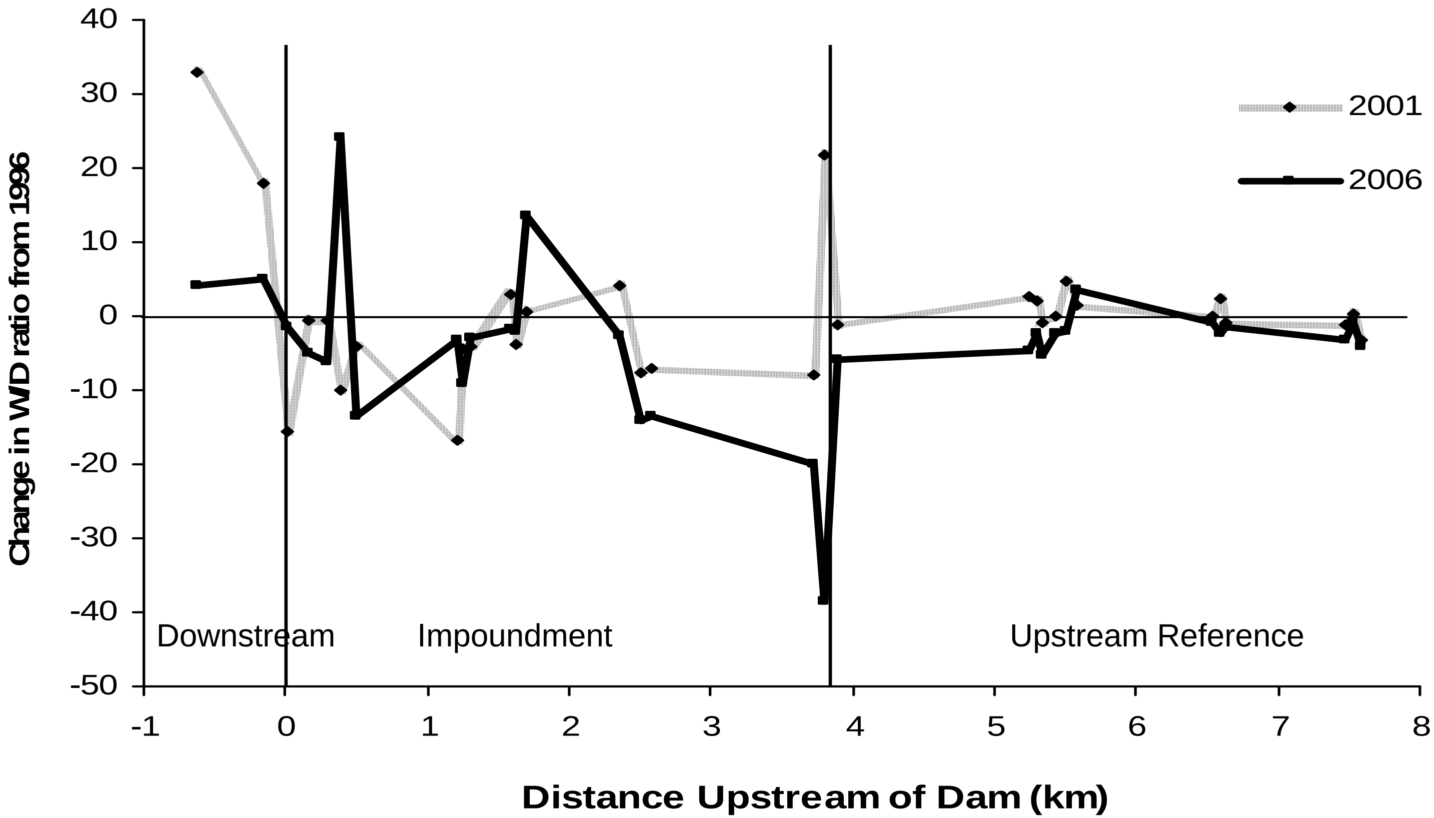

Figure 5. Longitudinal pattern of change in wetted stream width to mean depth ratio (w/d) from pre-dam removal conditions in 1996.

(greatest closest to the dam and diminishing upstream through the impoundment). Localized differences in geology and slope did alter this general pattern at some transects. Change in the w/d ratio of the impoundment did not show any easily discernable patterns (Figure 5). In the downstream reach, width and w/d ratio both increased (Figures 4 and 5).

In the upstream reference reach, bank slopes at some transects remained stable, while several others were quite dynamic; showing both increases and decreases in slope (Figure 6). Since the streambed in this reach was remarkably stable during the study period, these changes are most likely due to lateral erosion processes, and are common to many streams in this area. Bank slopes in the impoundment gradually increased during the dam removal, with the greatest increases seen closest to the dam (Figure 6). In 2006, bank slopes further upstream in the impoundment reach began to decrease in slope, while those closer to the dam site remained steepened. In the downstream reach, bank slopes remained relatively stable (Figure 6).

Water Slope and Velocity

As a result of the sediment erosion and deposition processes that occurred, water slope in the impoundment and downstream reaches increased during the dam removal (Figure 7). Increases in slope were greatest in the first 1.59 km upstream of the dam removal, but were observed to a lesser degree in most of the former impoundment. Slope increased in the entire impoundment from 0.13% in 1996, to 0.21% in 2006 (with 0.26% slope in the first 1.59 km upstream of the dam site in 2006). The slope in the downstream zone also increased from 0.06% in 1996 to 0.10% in 2006. Slope in the upstream reference reach remained at 0.16% in both 1996 and 2006.

Water velocities were measured each year during transect surveying, during the month of June. In 1996, the average discharge during these measurements was 7.70 m^3/s. In 2006, due to continuing precipitation events, the measurements were taken at an average discharge of 9.29 m^3/s, significantly higher than 1996. Due to the influence of discharge on water velocity, we chose to use measurements taken in 2005, when discharge was 8.07 m^3/s, for comparison with 1996 data. Water velocity was not surveyed in all downstream zone transects in 1996 or 1997, so data from 1998, when discharge was 6.94 m^3/s, where used for comparison purposes for the downstream zone.

Prior to dam removal, mean water velocities generally decreased in a downstream direction through the impoundment and downstream zone (Figure 8). With the dam removal and consequent increased slopes, mean water velocities generally increased in both the lower impoundment and the downstream zone, with some of the highest mean water velocities found in the impoundment after the dam removal. Due to localized differences in slope and channel morphologies, there is more variability in the mean water velocities in the impoundment than previously observed.

The frequency distributions of water velocities were compared for each zone, in both the first and last year of sampling. The water velocity frequency distribution for the upstream reference reach was not significantly different in 2005 as compared with 1996 (Reference: K-S test $D_{max} = 0.227$, $n = 77$, $p>0.01$). Water velocity frequencies in the impoundment were significantly faster in 2005 than in 1996 (Impoundment: K-S test

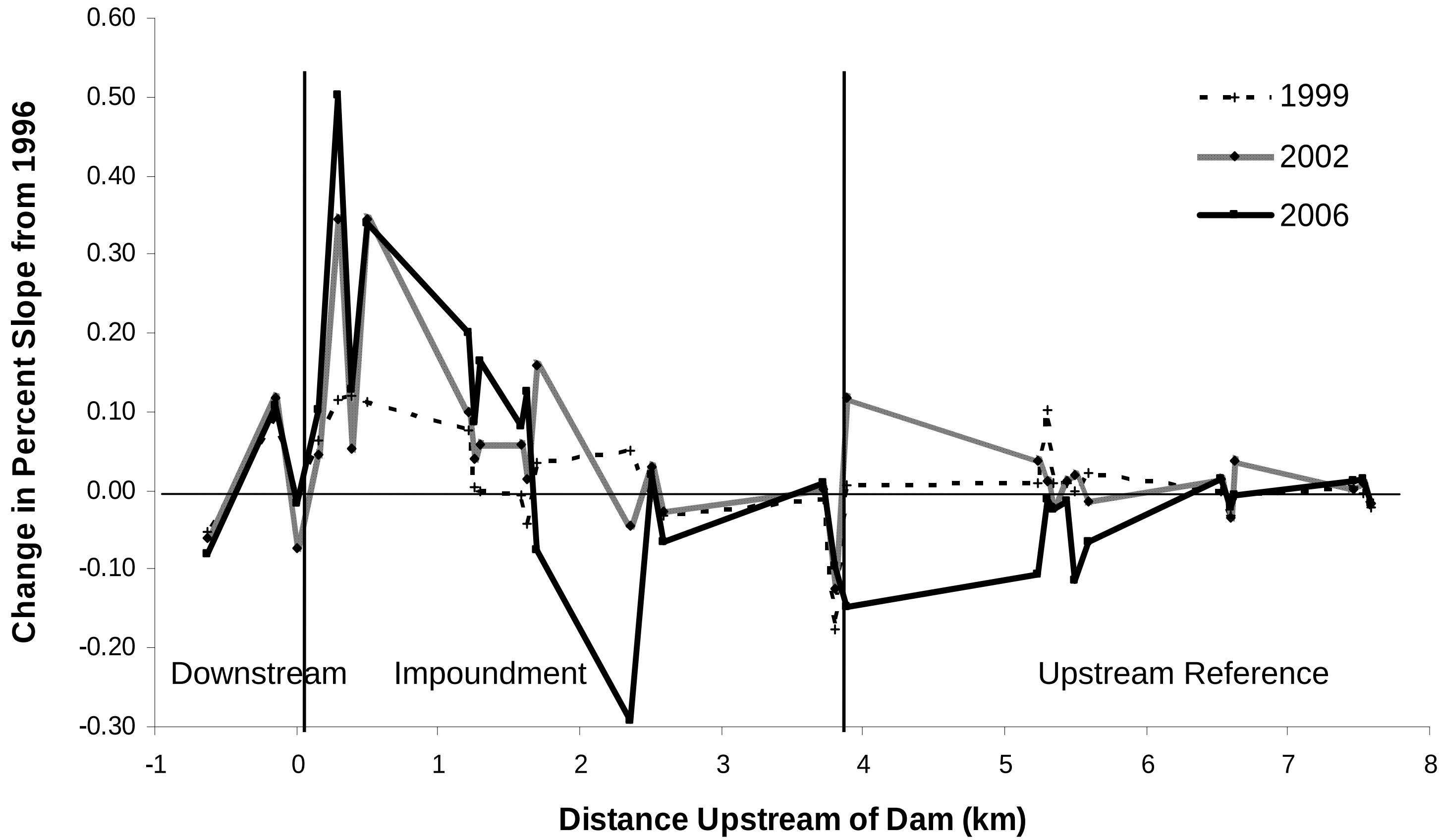

Figure 6. Longitudinal pattern of change in bank slopes from pre-dam removal conditions in 1996.

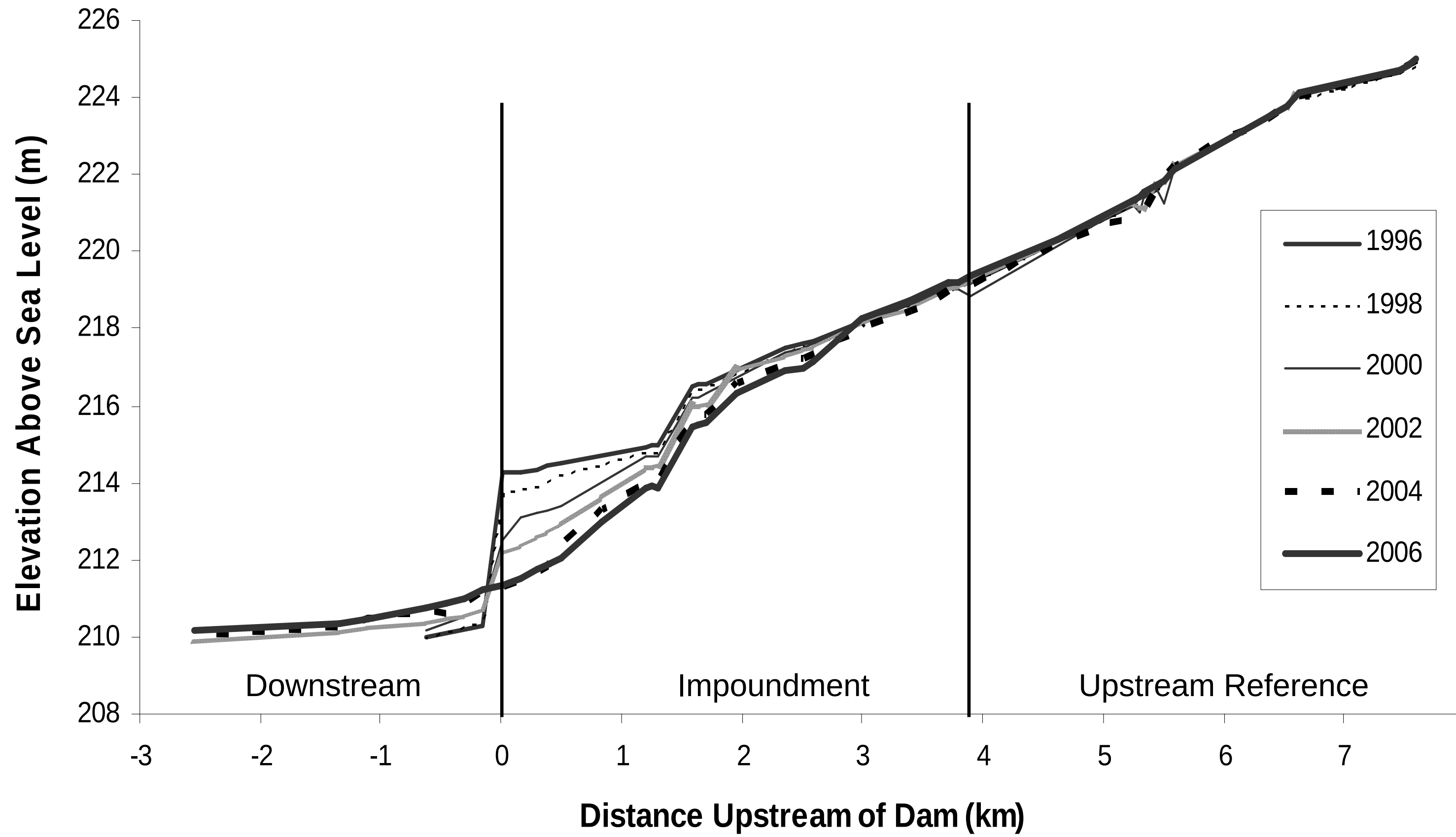

Figure 7. Longitudinal profile of water slopes or gradients. Vertical scale exaggerated relative to horizontal scale.

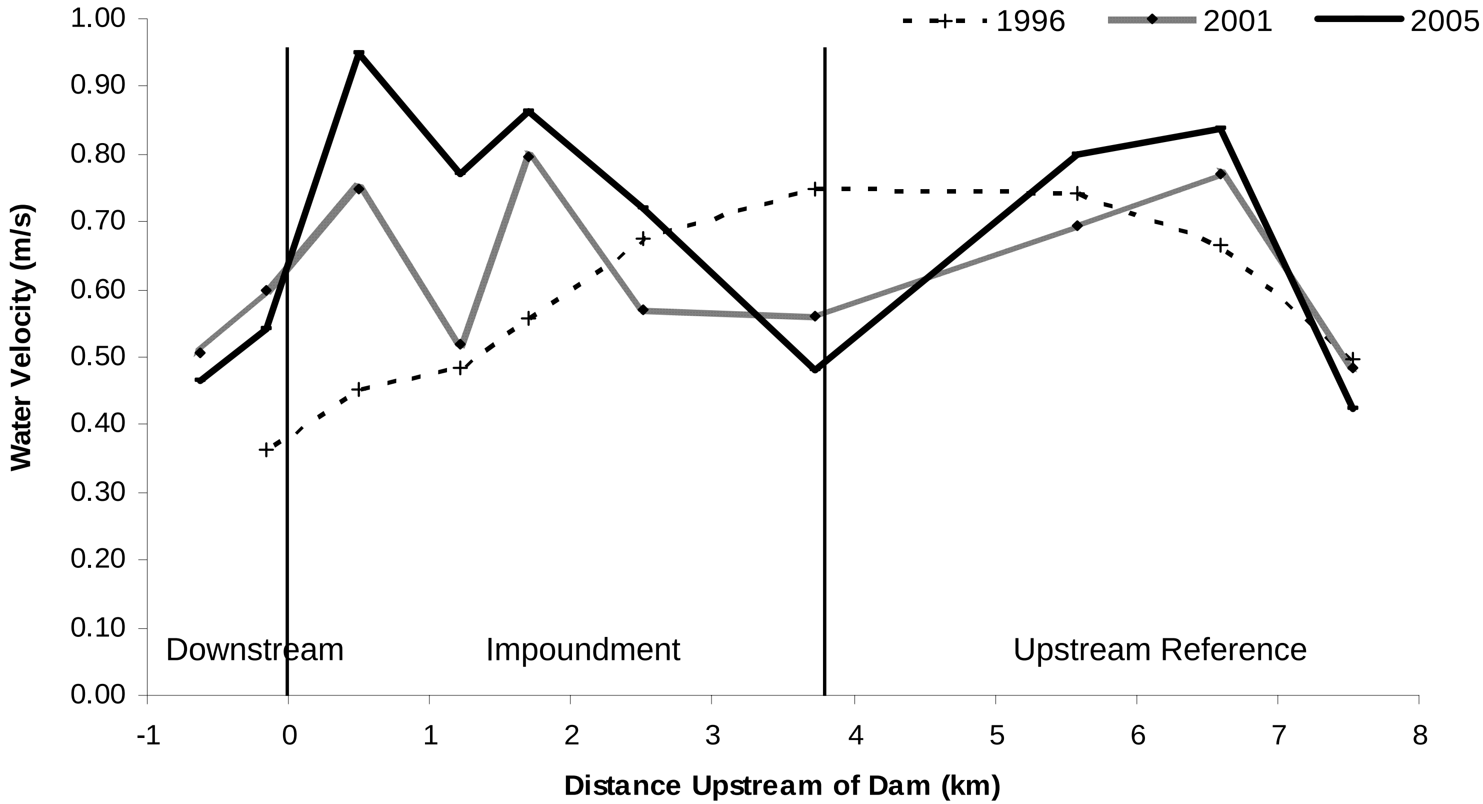

Figure 8. Longitudinal pattern of mean water velocity (m/s) in the Pine River.

D_{max} = 0.247, n = 137, p<0.01). The water velocity frequency distribution for the downstream zone became significantly faster in 2005 than in 1998 (Downstream: K-S test D_{max} = 0.235, n = 107, p<0.01). In the impoundment and downstream zones, frequencies of water velocities less than 0.3 m/s were relatively unchanged (representing the slower water velocities found at the stream margins), while thalweg water velocities increased in magnitude, with the highest water velocities increasing (Figure 9). The former impoundment is now the only study reach to contain water velocities greater than 1.2 m/s.

Substrate

Median (D_{50}) substrate sizes and substrate size frequency distributions were compared for each zone, in both 1997 – 1998 and 2005 - 2006, the first two years and last two years of sampling. The first and last two years were averaged to reduce the influence of annual variability in substrate composition measurements in comparisons. Before, during and after the removal of Stronach Dam, there was considerable spatial variability or patchiness in substrate size compositions in the Pine River (Figure 10). Prior to removing the dam, substrates were generally coarser and more heterogeneous in the upstream reference reach than in the impoundment and downstream. The impoundment was mostly fine sediments such as sand, with a few patches of small gravel, while the downstream zone was almost totally dominated by sand. During the dam removal process, median substrate size in the reference decreased slightly (Reference: D_{50} 1997-98 = 34.8 mm = "very coarse gravel", 2005-06 = 29.5 mm = "coarse gravel") but the overall substrate size frequency distribution did not change significantly (Reference: K-S test D_{max} = 0.063, n_1 = 989 n_2 = 1122, p > 0.01) (Figure 11). Median substrate size increased slightly in the impoundment (Impoundment: D_{50} 1997-98 = 7.9 mm = "fine gravel", 2005-06 = 9.7 mm = "medium gravel") (Figure 10). The substrate size frequency distribution for the impoundment was significantly coarser in 2005-06 than for 1997-98 (Impoundment: K-S test D_{max} = 0.087, n_1 = 1574 n_2 = 1567, p < 0.01), with increased frequencies of large gravel (12 – 48 mm) (Figure 11). Median substrate size increased slightly in the downstream zone (Downstream D_{50} 1997-98 = 1.0 mm = "sand", 2005-06 = 2.3 mm = "very fine gravel") but the overall substrate size frequency distribution for the downstream zone did not change significantly (Downstream: K-S test D_{max} = 0.119, n_1 = 191 n_2 = 184, p > 0.01) (Figures 10 and 11).

Larger transient changes in median substrate size were seen during the dam removal. It appeared as though during years when less than roughly 15,000 m^3 of sediment were eroded from the impoundment, substrate coarsening progressed in both the impoundment and downstream reaches (Figure 12). However, during years when large volumes of sediment (>15,000 m^3) were eroded from the impoundment (1999-2000 and 2003-2004), this sediment (mostly sand), was transported through these reaches, covering up previously coarsened substrate, and decreasing median substrate size (Figure 12). An exception to this trend occurred in 2006, three years after the removal, when no net sediment erosion occurred but median substrate size still decreased.

Bedform

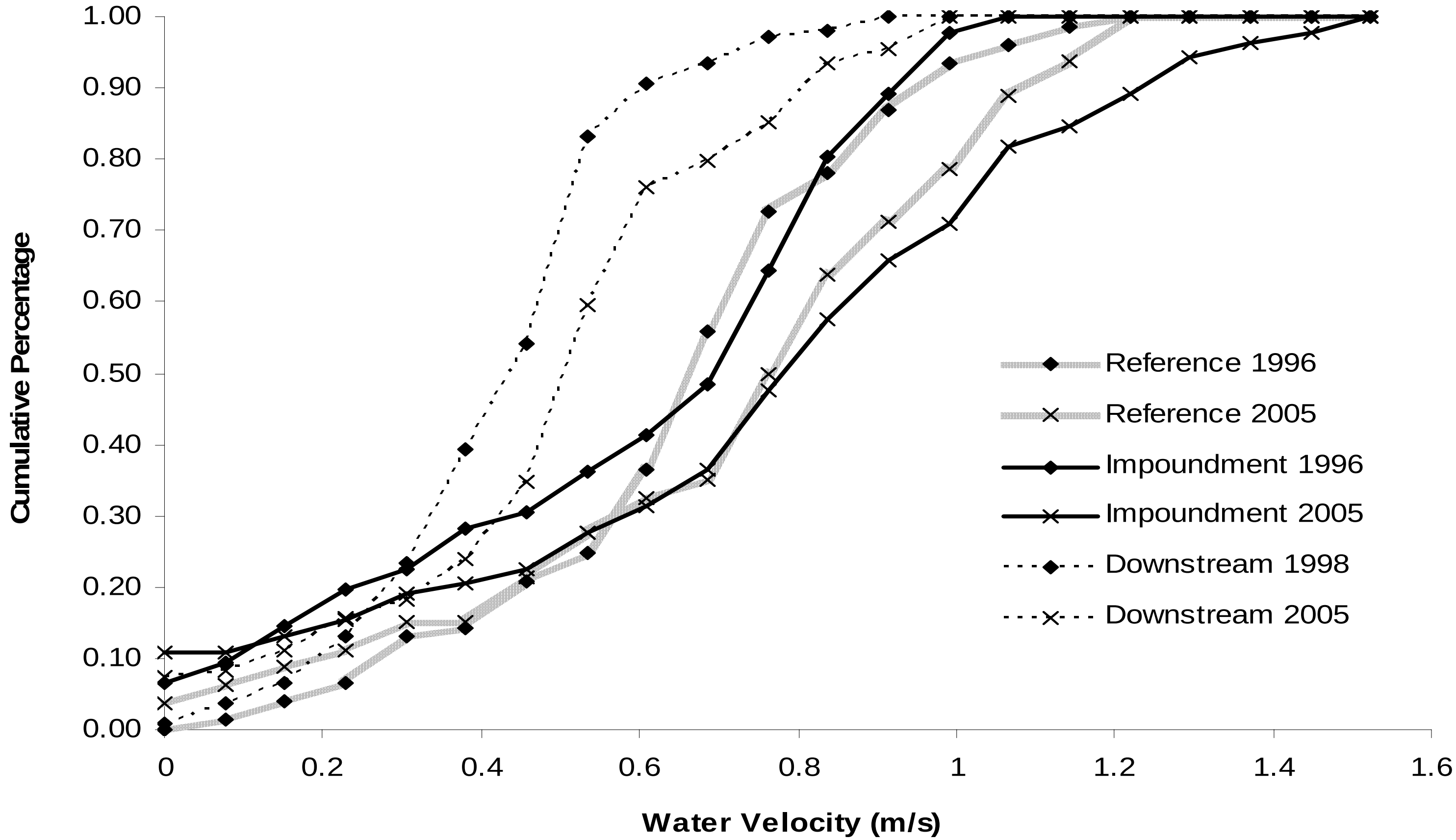

Figure 9. Cumulative percent frequency distributions for water velocities in each study zone of the Pine River.

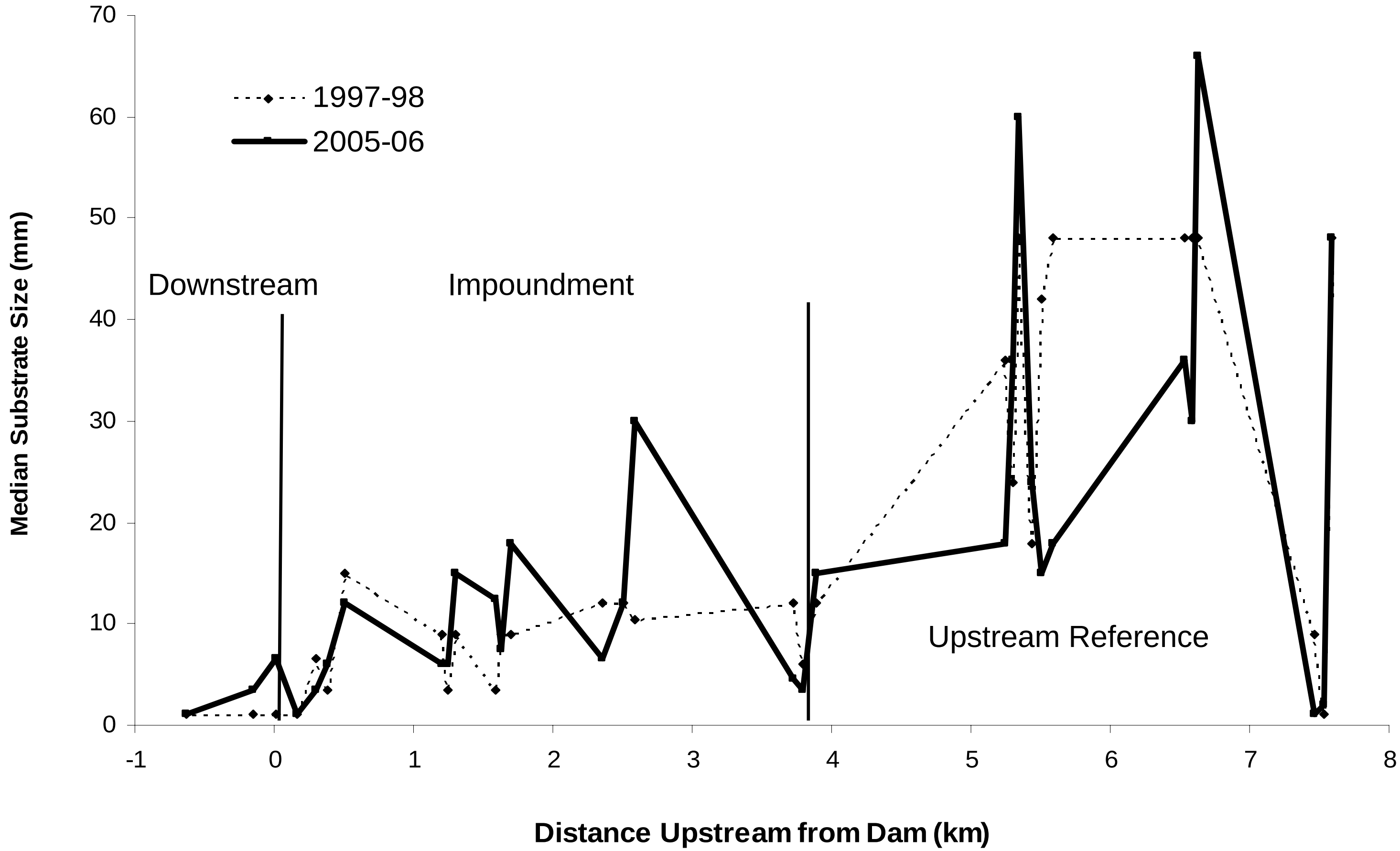

Figure 10. Longitudinal pattern of median substrate size.

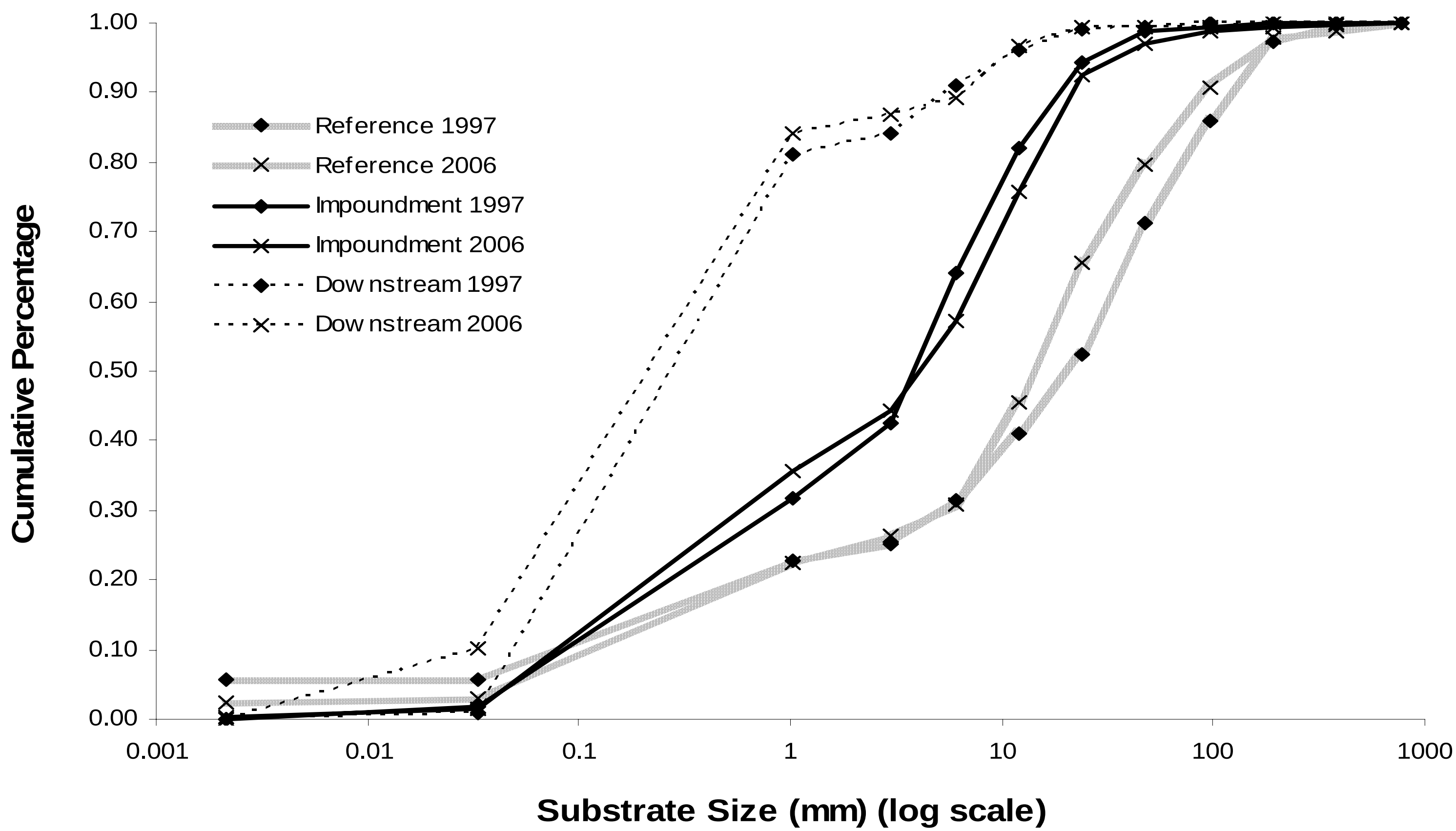

Figure 11. Cumulative percent frequency distributions for substrate size compositions in each study zone of the Pine River.

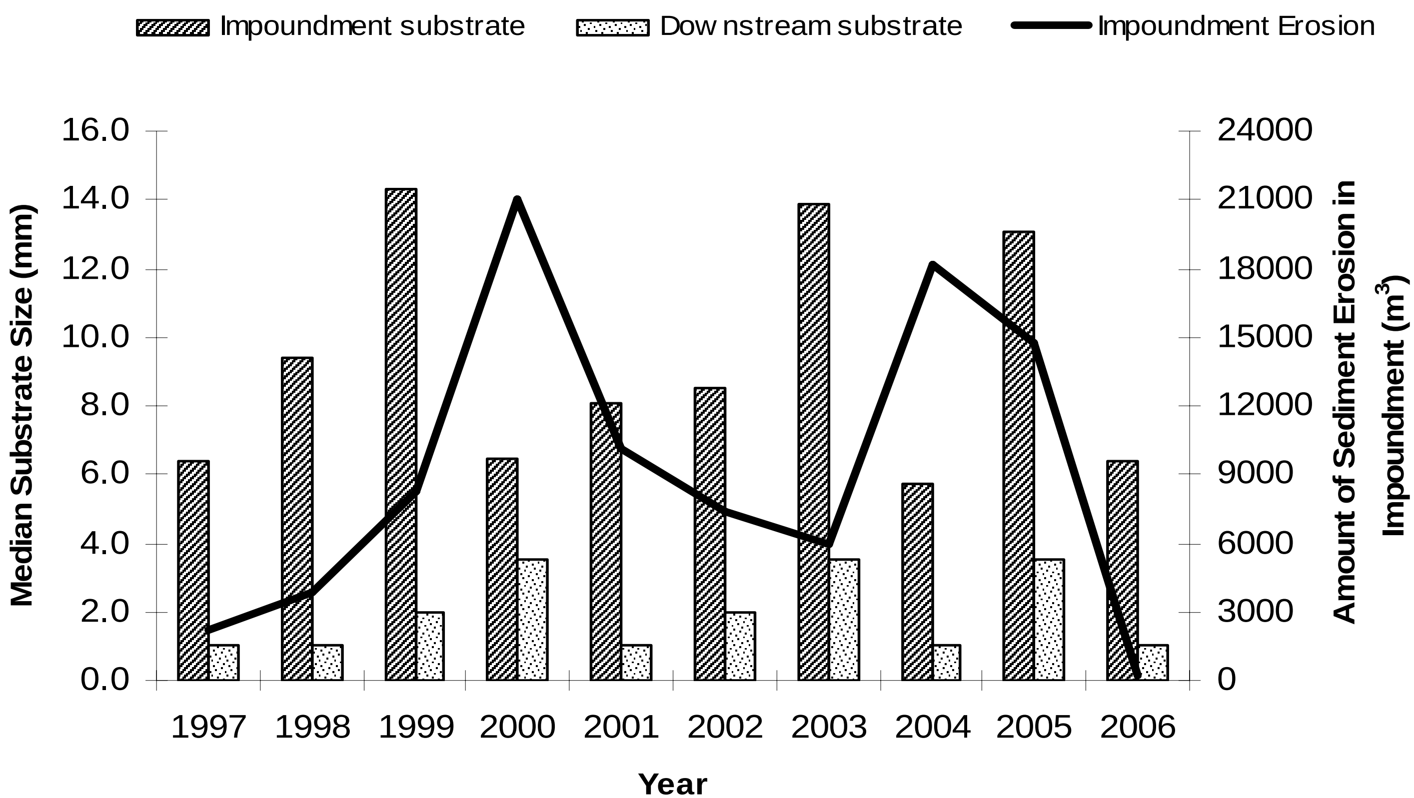

Figure 12. Annual median substrate sizes in the impoundment and downstream study zones shown in relation to the annual amounts of sediment erosion occurring in the impoundment zone each year of the staged dam removal.

In 1995, the upstream reference reach contained the highest heterogeneity of bedforms, and both the impoundment and downstream zones were comprised almost exclusively of run bedforms. In 2004, the reference reach had changed little from the 1995 survey but there were some differences in the percentages of the pool/complex and rapid designations, and minor differences in the percentages of run bedforms (Table 2). These changes were most likely due to differences between sampling crews in the designations of complex bedforms versus run or pool bedforms, and do not likely represent any real changes. In 2004, the impoundment had higher percentages of riffles and pools, and lower percentages of runs than in 1995 (Table 2). The downstream zone remained overwhelmingly run bedform in the 2004 survey, gaining only one pool unit (Table 2).

Table 2. Percentages of bedforms types found in each study zone in 1995 - prior to dam removal, and 2004 - after dam removal. Pool and complex bedforms were aggregated due to issues in the repeatability of complex bedform delineation.

Study Zone		**Run**	**Riffle**	**Pool / Complex**	**Rapid**
Upstream Reference	1995	44.0	32.9	16.3	6.8
	2004	41.5	32.8	23.6	2.1
Impoundment	1995	96.4	1.4	2.2	0
	2004	68.3	13.8	17.9	0
Downstream	1995	100	0	0	0
	2004	96.9	0	3.1	0

DISCUSSION

Impoundment

Each stage of the removal of Stronach Dam increased slope in the area immediately adjacent to the dam, leading to high water velocities over the downstream edge of the reservoir sediment fill at the site of the dam. The fine-sized sediments deposited in the impoundment and held by the dam were then subjected to increased shear stress and stream power, and were subsequently eroded. As this sediment erosion progressed upstream, it led to a dissipation of the slope difference caused by the dam removal, distributing increased slope upstream over longer sections of stream. Erosion continued due to this section of stream having increased slope, increased water velocity, and higher stream power, but still flowing over a channel of fine sediment that had accumulated in the slow water of the impoundment. This process should have continued to occur until the stream came into equilibrium with the new slope, sediment discharge from upstream, and coarsened substrate (Lane 1955). In the case of the staged removal of Stronach Dam, this equilibrium was not likely reached before successive stages of the removal occurred. An implication of this is that sediment erosion will continue to occur upstream of a dam removal, not only due to headcutting and immediate slope differences, but also at mean flows, until the stream channel reaches an equilibrium with its new slopes, substrate sizes, and increased sediment discharges coming from upstream eroding sites.

Relatively small amounts of sediment eroded during the first two years of the removal, likely due to the low slope of the impoundment at that time. As the removal progressed, the slope increased in the impoundment and on average more sediment erosion resulted each year, with the second and third highest amounts of erosion coming in the first two years following completion of the dam removal. These amounts did not correlate well with simple mean flows, peak flows, time duration over bankfull flow, approximate stream power (discharge and slope) or even the height of dam removed during each stage. Further explanation of the temporal variability of sediment erosion would likely require a site-specific approach, incorporating transect level differences both in space and time.

Despite the variability and complexity in estimating yearly amounts of erosion that will occur in impoundments behind dam removals, the total amount of erosion that is likely to occur following a dam removal seems to be fairly easily estimated. Not all of the sediment in a reservoir will be mobilized. In the Pine River the size of the reservoir that was filled with sediment was 789,428 m^3. However, as the stream channel eroded vertically through this sediment fill, the width of the wetted channel decreased and became very close to the average width of the upstream reference. The underlying slope of the reservoir was only slightly higher than the upstream reference, and consequently the mean width of the stream channel in the impoundment (17.6 m) became similar to the mean width of the stream in the reference (16.9 m). Therefore, the volume of sediment to be eroded due to dam removal could be estimated by (H*L/2)*W where; H is maximum height of the sediment fill, L is the longitudinal distance of the sediment fill, and W is the average width of stream immediately upstream of impoundment effects (Figure 13). For reservoirs such as Stronach Dam, where the reservoir is completely filled with sediment, H would equal the dam height and L would equal the length of the impoundment (delineated with a bedform survey). For reservoirs not completely filled with sediment, H would equal the maximum height of the sediment fill, usually at the downstream or leading edge of the sediment delta, and L would equal the length of the sediment fill (upstream extent delineated with bedform survey and downstream extent with a bathimetric survey). H*L is divided by 2 to produce an area estimate for the triangular shaped sediment fill or delta. In the case of Stronach Dam, this yields an estimate of (3.66 m*3800 m/2)*16.9 m = 117,522 m^3. Through 2006, approximately 92,000 m^3 eroded from the impoundment, with no new net erosion occurring during 2006. This estimation method over-predicted the amount of sediment eroded, due in part to the upper portion of the Stronach Dam impoundment not approximating a perfect triangle or sediment wedge, and partly due to the rectangular cross-sectional shape our approximation assumes (Figure 13). However, this simple estimation method allows for a conservative (in regards to pre-cautionary management) and useful pre-dam removal estimate of the volume of sediment that is likely to erode. If significant tributaries entered the impoundment, this method would have to be applied to these as well, and the results combined with the estimates from the main river channel.

In the case of Stronach Dam, only about 12% of the reservoir sediment was mobilized and transported. Similarly small percentages of reservoir sediment fill

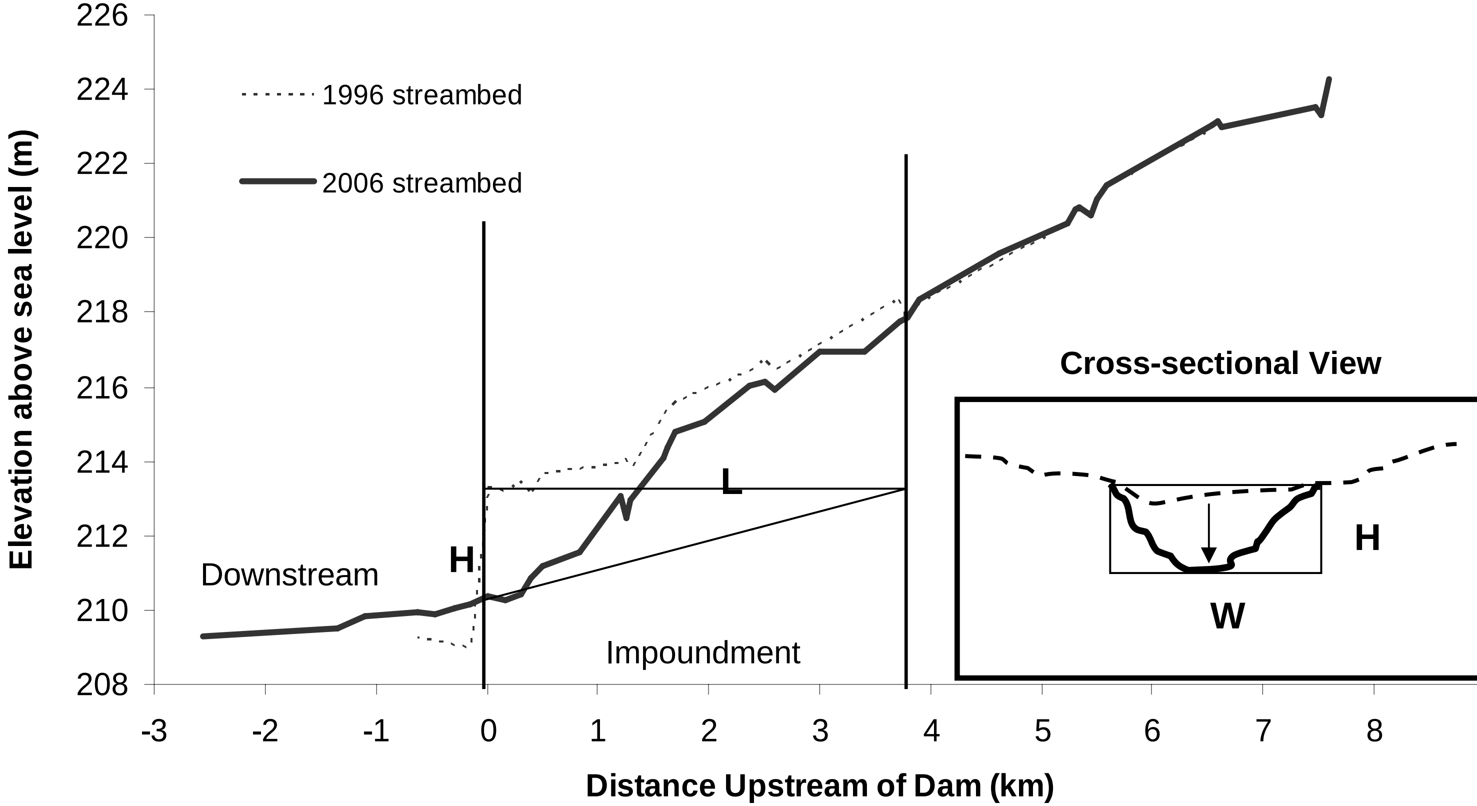

Figure 13. Longitudinal profile of the Pine River streambed before and after dam removal. The triangle approximates the area of the sediment fill, and along with average stream width upstream of the impoundment, can be used to estimate the volume of sediment that can be mobilized at a dam removal.

mobilization were found by Evans et al. (2000) in an Ohio dam failure (9 – 13 %) and Doyle et al. (2003) in a Wisconsin dam removal (8 – 14%). The amount of sediment to be mobilized with a dam removal is an important consideration during the planning and decision making process in removing dams (Doyle et al. 2002, Randle 2003, Rathburn and Wohl 2003). In situations where sediment transport downstream from dam removals is undesirable, sediment removal or management can add considerably to the expense of removing dams. Given the small percentage of the reservoir sediment fill that will likely be transported following a dam removal, it should be more cost-effective to manage sediment transport downstream of a dam removal (e.g., through the use of sediment traps or collection devices) than to remove larger amounts of sediment from the impoundment prior to dam removal (e.g., through dredging).

As the streambed incised in the impoundment and slope increased, the wetted width of the stream also generally decreased. Differences in the localized geology and slope between transects affected how much stream width decreased, but the average stream width in the impoundment became remarkably similar to the average stream width of the reference. These localized differences in geology and slope exerted greater influence on water depth at transects, and led to large differences in w/d ratio changes between transects due to the dam removal.

Changes in the slopes of stream banks following dam removal have been predicted to follow Channel Evolution Models (CEM's) (Pizzuto 2002, Doyle et al. 2002). These models were developed from incising channels and predict that following dam removal, bank slopes in impoundments should increase along with vertical incision (and so should be steeper, initially, closest to the dam). Banks should continue to steepen with further incision, until a point is reached where the slope is too great for the cohesive forces of the sediment or vegetation to continue holding it together, causing slumping and a reduction in bank slope, allowing for the development of equilibrium channel dimensions. In the Stronach Dam impoundment, bank slopes did increase gradually during the dam removal, with the first and greatest increases occurring closest to the dam. Bank slopes continued to increase and during the last year of the study decreases in bank slopes were observed only at sites further upstream in the impoundment, where streambed erosion had ceased. However, bank slopes in the reference reach also exhibited changes of similar magnitude (albeit different direction) during the study, indicating bank slopes in the Pine River may be naturally dynamic and variable. While some patterns consistent with the CEM seem discernable from this data, the natural variability in bank slopes makes interpreting the significance of those patterns difficult.

As the stream channel slope increased in the impoundment following the dam removal, so did the mean water velocities. This is not surprising, but perhaps more interesting is how the frequencies of water velocities changed in the impoundment. The frequency of slower water velocities, (i.e., less than 0.30 m/s) did not change substantially. These slower water velocities primarily occurred near the stream margins. Despite mean velocities increasing, and increased thalweg velocities (e.g., as seen in the creation of faster velocities not previously observed in the impoundment), similar amounts of slower stream margin water velocities still exist. Water velocities therefore not only increased but became more diverse. Changes of this nature will have important implications for sediment and nutrient transport dynamics, and should be beneficial in providing diverse habitat conditions for different species and life stages of aquatic invertebrates and fish.

Average substrate size increased throughout most of the impoundment in response to higher slope and water velocities. Overall increases in the proportions of rocky substrate were similarly observed following the removal of the Woolen Mills Dam on the Milwaukee River (Kanehl et al. 1997). However, substrate frequencies also showed some changes similar to those of water velocities. In the impoundment, where substrates had been dominated by sand before dam removal, frequencies of sand decreased due to the dam removal, but frequencies of silt did not decrease. Similar results were reported by Stanley et al. (2002), shortly after the removal of two low-head dams on the Baraboo River, Wisconsin. The frequency of slower water velocities at the stream margins stayed constant, allowing the retention of finer substrates such as silt. As sand decreased in frequency, so did several size classes of the smaller gravels, and they were replaced by larger size gravels. This shift corresponds with the thalweg velocities increasing in magnitude, not becoming more frequent. Again, this has important implications on stream biota, because the homogenous sand substrate prior to dam removal was not replaced with equally homogenous larger substrate, but with a greater diversity of substrates. At the conclusion of this study, we predict substrate size composition will continue to coarsen in the impoundment area. While substrates are already somewhat coarser, they are still smaller than predicted to be stable, even under typical flows (Burroughs unpublished data). This means that while substrate is coarser, it is still considered unstable, and not as beneficial to stream biota as possible (Gordon et al. 2004).

The alternating patterns of riffles, runs, and pools in mixed gravel streams is seen as a way rivers self-adjust to regulate energy expenditure, and are very important to the biological productivity of streams (Gordon et al. 2004). These bedforms can be created by localized scour during normal flows, at river bends or by wood debris, but are normally formed by rare high flow events (Petts and Foster 1985, Knighton 1984, and Beschta and Platts 1986 as cited in Gordon et al. 2004, and Pizzuto 2002). During the period of the Stronach Dam removal, a 1 in 5 year flood occurred, but a 1 in 10 year flood did not. Despite this, some new riffle and pool bedforms formed in the impoundment reach. In 2004, the diversity of these bedforms was not as high as seen in the reference reach, and may not be realized in the impoundment until very high flows are experienced. Long time durations for the complete recovery of bedforms were predicted by Pizzuto (2002) based on short time duration empirical studies and laboratory flume experiments. Bushaw-Newton et al. (2002) also noted that riffle-pool bedforms had not reformed in the impoundment with one year of the removal of Manatawny Creek Dam. This has important implications for the functioning of streams as bedform diversity influences sediment transport and sorting, nutrient cycling, and is crucially important to the habitat suitability of stream biota (Gordon et al. 2004). Consideration of the long timeframe for bedform restoration may lead to innovative ways of actively helping stream rehabilitation following dam removals. For example, if another water control structure existed upstream of a dam removal site, water releases could be negotiated to allow pool-riffle forming flows; or various structures such as wood debris or gravel bars could be added to the stream to aid bedform formation. Managing for these bedforms may lead to a faster realization of benefits of stream rehabilitation through dam removal.

Another insight derived from the consideration of bedform diversity, concerns the delineation of the impoundment effects boundary. If the top height elevation of the dam was followed upstream, it would roughly show the boundary of the formal reservoir, where water widths would likely be very wide and water impoundment would be most noticeable. However, we used a simple means of delineating bedform types, and performed this mapping of bedforms for many kilometers upstream of the dam. Through this, it became apparent that bedform diversity was lacking for a considerable distance upstream of the formal reservoir. In addition, it was noticeably sand-dominated in this area of little bedform diversity. The furthest upstream extent of this sandy run habitat became our upstream boundary of impoundment effects, and the extent of where we expected to see changes due to the dam removal. This method, along with the use of aerial photos, proved quite accurate in delineating the furthest upstream extent of impoundment effects and changes from the dam removal. We recommend this as an easy, and cost-effective technique to predict how far upstream changes may take place following dam removal. This information can be important in the early dam removal planning process for assessing possible impacts (e.g., infrastructure concerns, mitigation measures, and landowner impact assessments).

Downstream

As each stage of the dam was removed, the drastic difference in elevation from the top of the sediment fill to the downstream side of it, created a situation where water velocities were extremely high and flow became supercritical. Transport of the sandy substrate proceeded with antidune formation. Further downstream where slope and water velocities decreased, sediment transport continued with dune and ripple formations (Gordon et al. 2004). The transport of this sediment aggraded the streambed, increasing the slope of this section of stream downstream of the dam, decreasing the water depth, and slightly increasing the stream width. These changes led to higher sediment transport ability, but the sediment eroded from the impoundment was in excess of the transport capacity of this stretch of stream. At the end of this study, approximately 14% of the sediment eroded from the impoundment was retained and stored in the first 1 km of river downstream from the dam. The rest of the sediment was either transported further downstream, forming a sediment delta at the confluence of the next reservoir downstream, or deposited on the the floodplain during high flows. As the stream channel downstream from the dam aggraded, the elevation difference between the stream and the floodplain decreased. During high flows, suspended sediments were deposited onto the floodplain, vertically raising the top bank by as much as a 0.50 m at one of the transects.

The implications of this could be important in considering the impacts from dam removals. During the erosion process upstream of dams, the streambed is lowered drastically, and can reduce connectivity with adjacent floodplain wetlands. With dam removal permitting, the removal of wetlands could be seen by permitting agencies as needing remediation (even if the wetlands were created by the dam construction). However, if a river valley downstream of a dam removal is not steep and narrowly confined, floodplain connection and recharge (frequent overbank flooding) in this stretch of stream could be enhanced, leading to the recharge of historic wetlands or the creation of new ones. Frequent overbank flooding was observed in the downstream reach of the Pine River following the dam removal, and has been predicted to occur following the removal of other dams (Stoker and Harbor 1991, Randle 2003).

The sediment deposition in this downstream reach resulted in a substantial decrease in water depth and an increase in width, together greatly increasing in the w/d ratio of this reach. This increase in w/d ratio reached a peak during the later stages of dam removal, and has begun to decrease during the last few years after the removal was completed. At the conclusion of this study, the w/d ratios were only slightly higher than pre-removal levels.

With the increased slope in the downstream zone, water velocities also increased. Average water velocities increased in this section as well as frequency distributions changing significantly. As with the impoundment, water velocity frequencies in the downstream zone, changed in a manner as to increase the variability of velocities. Frequencies of slower water velocities (<0.3 m/s) increased as the stream channels became wider and shallower. At the same time, faster water velocities became faster, leading to an overall greater diversity of water velocities.

Substrate size increased only slightly in the downstream zone. This section of stream, while having faster velocities and higher slopes, continued to receive sediment from the eroding impoundment. The median size of substrate increased very slightly but the frequencies of substrate did not change significantly. The substrate composition of this zone will likely stay dominated by sand until the former impoundment section reaches an equilibrium. At that time, the downstream reach should experience some substrate coarsening immediately downstream of the dam. However, this section may stay relatively sand dominated due to the close proximity of the next downstream reservoir and its impoundment effects.

Changes in bedform diversity downstream of Stronach Dam may never occur, or may take a very long time to happen. This section is much lower gradient due to the downstream impoundment behind the Tippy Dam, and even during rare high flows may not have the power to scour pools. This section was all run bedform before dam removal, and remained largely run bedform at the end of this study. Even if pools were scoured, until the substrate becomes more diverse, including more gravel and cobbles, those pools may not be easily maintained in a stretch of stream with easily movable sand.

Synthesis

This study achieved its objectives of documenting the spatial and temporal dynamics of sediment erosion, transport and deposition following the removal of Stronach Dam. These processes and the subsequent changes in river morphology, were spatially and temporally variable in magnitude and extent, but in general were clearly understandable using the principles of fluvial geomorphology. At the end of this study it is apparent that changes are still occurring in the Pine River due to the removal of Stronach Dam, 10 years after its initiation. While sediment incision in the impoundment seems to have finally slowed, three years after dam removal, lateral erosion, substrate coarsening, and bedform formation will likely continue in the Pine River for many years. It now appears that dam removal does have the potential to be an effective tool for stream rehabilitation, but many of the outcomes make take relatively long periods of time to be realized. It is our hope that this research serves as valuable starting point for future research on the effects of dam removal, and as a tool to improve the effectiveness and efficiency of future dam removals.

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