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Effects of Stronach Dam removal on fluvial geomorphology in the Pine River, Michigan, United States

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ABSTRACT

Although dam removal has been increasingly used as an option in dam management, and as a river restoration tool, few studies provide detailed quantitative assessment of the geomorphological response of rivers to dam removal. In this study, we document the response of the Pine River, Michigan, to the gradual removal of Stronach Dam. In 1996, prior to the initiation of removal, 31 permanent cross-sectional transects were established in the 10-km study area. These transects were surveyed annually during the course of the removal (1996–2003) and for the three years following removal (2004–2006). Dam removal resulted in progressive headcutting of sediments in the former impoundment, extending upstream 3.89 km of the dam. Over the course of the 10 years since dam removal was initiated, a net total of 92 000 m^3 of sediment erosion occurred. The majority of sediments stored in the former reservoir remained in place, with only 12% of the estimated reservoir sediment fill being eroded. Approximately 14% of the net erosion was deposited within the stream channel 1 km downstream of the dam location, with the remainder being transported further downstream or deposited in the floodplain. Sediment fill incision resulted in a narrower and deeper channel upstream, with higher mean water velocity and somewhat coarser substrates. Downstream deposition resulted in a wider and shallower channel, with little change in substrate size composition. Counter-intuitively, water velocity also increased downstream because of the increased slope that developed. Prior to removal, bedforms in the former impoundment were dominated by runs but are showing signs of restoration toward reference conditions. Continuing changes in river geomorphology are evident even three years following removal and are likely to occur for years to come.

1. Introduction

Approximately 2.5 million dams have been built in the United States (National Research Council, 1992) on nearly every major river system in the lower 48 states (The Heinz Center, 2002). The period between 1950 and 1970 was marked by the most intensive dam construction efforts (The Heinz Center, 2002) with limited understanding of their impacts to rivers. Following this period, the body of scientific evidence documenting the drastic effects that dams have on river systems grew substantially. Today, a preponderance of evidence exists describing the multitude of ways dams alter river functioning, including alterations to the flow and temperature regimes; shifts in sediment, nutrient, and energy transport disruption; and numerous biological implications (e.g., Hammad, 1972; Petts, 1980; Williams and Wolman, 1984; Cushman, 1985; Bain et al., 1988; Ward and Stanford, 1989; Benke, 1990; Lessard and Hayes, 2003; Ligon et al., 1995; Collier et al., 1996; Shields et al., 2000).

Many dams continue to fulfill their intended purpose, providing social and economic benefits. However, as dams age they require maintenance to prolong their function and safety. Now, a large and growing number of dams exist 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 1.83 m or greater in height (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). The average design life expectancy of dams is ~50 years, implying 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 1960s to approximately 20 per year during the 1990s (Pohl, 2003). The abundance of aging dams and the increasing rate of dam removal indicate that removal of dams will become increasingly common in the future.

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Fig. 1. Photograph of Stronach Dam in 2001, during gradual removal.

Over 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 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, some researchers have developed general hypotheses of river ecosystem responses to dam removals (Doyle et al., 2002; Gregory et al., 2002; Pizzuto, 2002; Shafroth et al., 2002; Stanley and Doyle, 2002; Whitelaw and MacMullan, 2002), while others have hypothesized the outcomes of specific proposed dam removals (Shuman, 1995; Freeman et al., 2002; The Heinz Center, 2002). Despite an emerging conceptual basis for the effects of dam removals, this field continues to lack the empirical information that is needed to verify these hypotheses, calibrate preexisting models for use with dam removal, and generate novel insights into the effects of dam removal (Bushaw-Newton et al., 2002; Doyle et al., 2002; Graf, 2003; Hart et al., 2003). 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; Wildman and MacBroom, 2005), aquatic insects (Bushaw-Newton et al., 2002; Stanley et al., 2002), and fish (Hill et al., 1994; Kanehl et al., 1997; Bushaw-Newton et al., 2002). While these studies provide unique

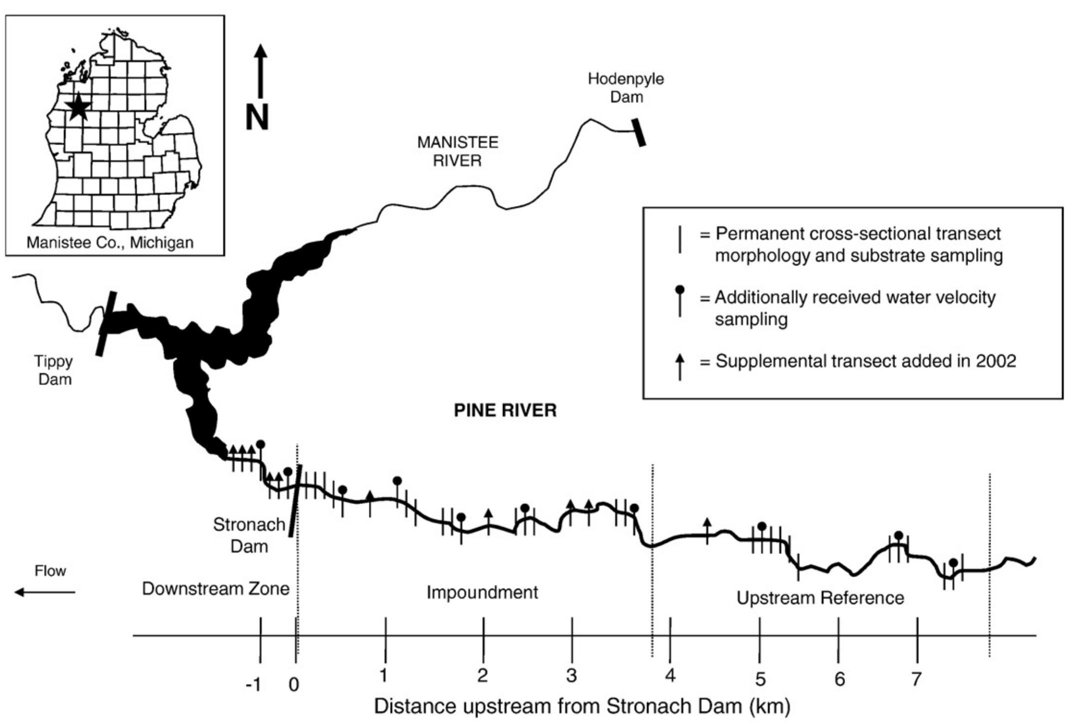

Fig. 2. Location of Stronach Dam and Pine River in relation to the state of Michigan, and the location of permanent cross-sectional surveying transects within the study area of Pine River.

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 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 is the spatial extent of change, 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 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 (i) document the spatial and temporal extent of sediment erosion, transport, and deposition that occurred because of the dam removal; and (ii) document the changes in river morphology attributes (i.e., slope, width, depth, water velocity, substrate composition, and bedform (riffle-pool) diversity) that occurred because of the sediment erosion, transport, and deposition. The 12 years of detailed quantitative monitoring of the outcomes of this dam removal provides a unique data set useful for validating and refining existing hypotheses about the geomorphologic effects of dam removals, generating novel hypotheses, and leading to improvements in the ongoing practice of removing dams.

2. Regional setting

Stronach Dam was located on the Pine River, a tributary to the Manistee River, in the northwestern Lower Peninsula of Michigan (Fig. 1). The Pine River is a 77-km-long, 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 (USGS) 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). The river carries a large bedload of sand because of the local geology and extensive logging operations of the late 1800s, which exacerbated bank instability along the river. Hansen (1971) estimated a mean annual sediment discharge of 50 000 tons at Stronach Dam from 1967 to 1970, which was 70–75% sand.

Stronach Dam was constructed from 1911 to 1912, 5.6 km upstream from the confluence of the Pine River and the Manistee River (Fig. 2). Stronach Dam was originally a hydroelectric dam with an earth embankment and concrete corewall, a 4.57-m fixed-concrete spillway section with 0.91 m of flashboards on top of the spillway and a concrete and brick powerhouse with two turbine bays (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 (Hansen, 1971; Consumers Power Company, 1994). Tippy Dam (17.07 m head height), also a hydroelectric dam, was constructed in 1918 immediately downstream of the confluence of the Pine and Manistee Rivers (Rozich, 1998) (Fig. 2), which created a 428-ha, 48 722 530-m^3 impoundment and impounded water upstream to Stronach Dam.

Because of the Pine River's large sediment load, the Stronach Dam reservoir quickly filled with sediment and problems arose with the operation of the dam's turbines. Attempts made in the 1930s to remove the accumulation of sediment behind the dam were only marginally successful and eventually became uneconomical (Consumers Power Company, 1994). In 1953, 41 years after construction, Stronach Dam was decommissioned as a hydroelectric dam and the river flow was directed over the spillway, shifting the location of the active river channel to the opposite side of the dam. The spillway flashboards were removed gradually over the following years with the last removed in 1983 (Consumers Power Company, 1994).

Table 1
Schedule of removal events during the staged removal of Stronach Dam on Pine River, Manistee County, Michigan.

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	

Stop logs are 15.24 cm diameter hollow metal pipes stacked on top of one another. Trash rack removal estimates are approximate. Cumulative meters removed are in parentheses (Dave Battige, Consumers Energy, personal communication 2003).

In the early 1990s, removal of Stronach Dam was negotiated as part of a Federal Energy Regulatory Commission (FERC) settlement agreement in the relicensing of Tippy Dam, owned by Consumers Power Company, the same company as Stronach Dam. A “staged,” or gradual, removal was decided upon in order to allow gradual river channel adjustments with the least amount of environmental impact risk, 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/year, over the course of six years (with corresponding trash-rack removal). This plan was altered because of recreational safety concerns, feasibility issues, and technical difficulties with removal (D.S. Battige, Consumer Power Company, personal communication, 2002). The actual sequence of the staged dam removal occurred between 1997 and 2003 and is shown in Table 1.

3. Materials and methods

In 1995, two years prior to the commencement of dam removal activities, Pine River was assessed to document the spatial extent of impoundment effects from 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). The assessment of stream bedforms 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

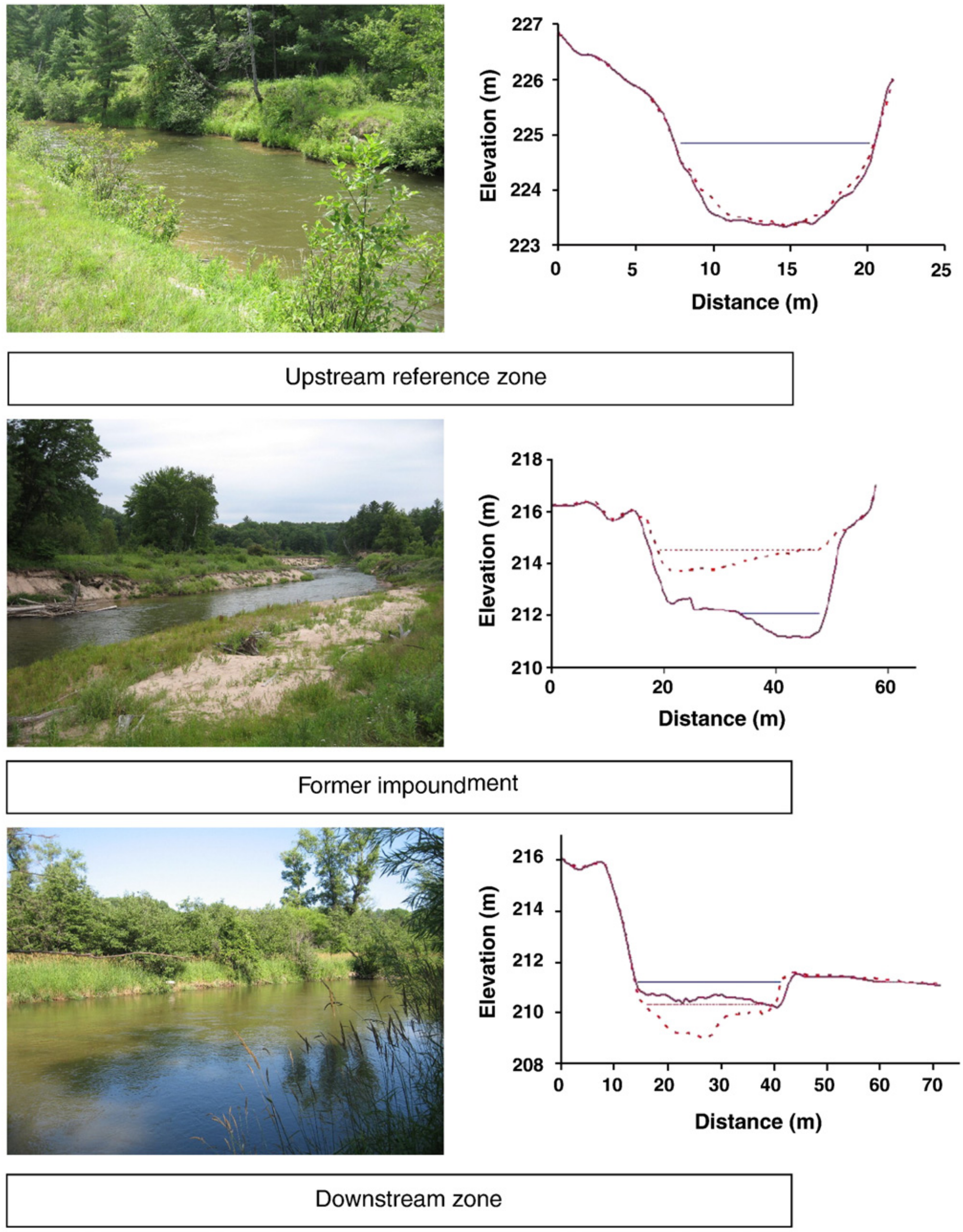

Fig. 3. Photographs and channel cross-section diagrams illustrating typical channel forms within each of the three study zones. Dashed lines indicate streambed and water surface level in 1996, prior to initiation of dam removal; solid lines represent post-dam removal, in 2006.

Stronach Dam and was typified as being relatively wide, slow-flowing, and sand-bottomed and generally consisted of only run bedform units.

A 3.7-km reach upstream from the impoundment, which exhibited no effects from the impoundment, was chosen as a reference zone. 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, and sand-bottomed and consisted entirely of run bedforms. Prior to the removal of Stronach Dam, water was impounded in this study zone by Tippy Dam Reservoir, and the study zone extended for only 0.63 km 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 to 2.55 km.

Thirty-one permanent cross-sectional transects were established in 1996 to document 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. The vertical and horizontal location of all cross-sectional transect endpoints were permanently referenced using rebar rods and spikes in witness trees. 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 (Fig. 2). Photographs, site descriptions, and latitude–longitude coordinates for all transects are archived at Michigan State University, Department of Fisheries and Wildlife. A typical photograph and stream cross-section for each of the study zones is provided in Fig. 3. All transects were linked to 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 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 slope change to document 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.

Channel geometries were expected to change following dam removal because of sediment incision or deposition processes. Therefore, at each cross-sectional transect we defined a constant baseline elevation above which no channel changes occurred (i.e., an arbitrary plane above the top of the bank prior to removal) in order to estimate overall changes in channel cross-sectional areas. The trapezoidal rule for numerical integration (Press et al., 1992) was used to estimate areas between each pair of cross-sectional points surveyed in a transect, 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 dam removal were calculated using the trapezoidal rule for integration (given the amounts of cross-sectional area change at transects) and the distances between transects. Water slope 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 bank toe, divided by the lateral distance between those two points (e.g., Duan, 2005). These points, including the top bank elevations, were allowed to change each year as channel profile changed. The change in bank slope, compared to the initial pre-dam removal slopes, was calculated and averaged for each transect.

Water velocity was measured at 10 of the permanent transects (Fig. 2) annually from 1996 to 2006. From 1996 to 2000 a Marsh–McBirney Model 201 portable current meter was used and from 2001 to 2006 water velocity was measured using a Global Flow Probe Model FP101. Water velocity was measured at 0.61-m intervals across the wetted width of the stream. If water depth was <0.75 m, water velocity was measured at 60% of the water depth from the water surface. If water depth was >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).

Water velocities were measured annually in June during transect surveying. In 1996, the average discharge during these measurements was 7.70 m^3/s. In 2006, because of continuing precipitation events, measurements were taken at an average discharge of 9.29 m^3/s, significantly higher than 1996. Because of 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) were used for comparison purposes.

The Kolmogorov–Smirnov (K–S) 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 10 additional sites from 2002 through 2006. A modified pebble count method was used (Wolman, 1954; Kondolf and Li, 1992) to determine substrate size composition. We sampled 100 streambed particles systematically 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 allowed linkage 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 that did not have corresponding size classes. The K–S two-sample test (Steel and Torrie, 1980) was used to test for differences in substrate size frequency distributions between years.

In 1995, two years prior to dam removal, bedforms (also commonly referred to as “mesohabitat” 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 width of each bedform were measured, as well as periodically recording latitude and longitude 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 low flow levels to aid in the delineation of bedform units.

4. Results

4.1. 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. Typical of a stable stream, the upstream reference reach experienced net erosion some years while net deposition occurred in others (Fig. 4). The average annual net sediment transport in the reference was 289 m^3 of erosion, with a standard deviation of 1946 m^3. This translates to only ~4 mm average 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 ~92 000 m^3. The annual volume of sediment eroded from the impoundment averaged 9159 m^3 and was quite variable with a standard deviation of 6947 m^3 and a range from ~0–21 000 m^3 (Fig. 4). In 2006, no net erosion occurred in the impoundment. Although the amount of mean annual sediment erosion was large, it was still 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 ~28 000 m^3 (using a density of 1.8 g/cm^3 for sand; Morris and Fan, 1998). This makes the total net amount of sediment erosion from the former impoundment over the 10 years during and post-dam removal 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

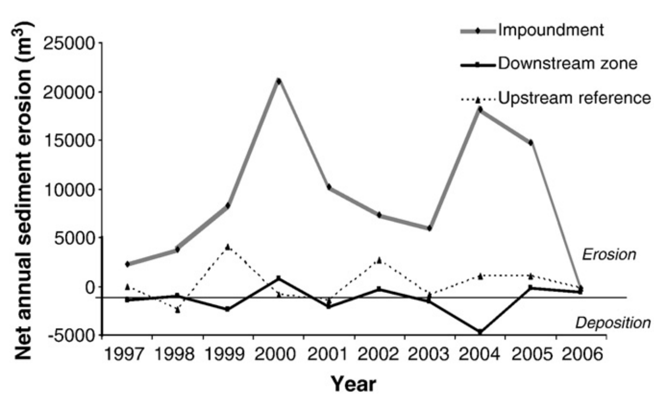

Fig. 4. Net annual sediment erosion or deposition volumes during and after the staged removal of Stronach Dam (1997–2003). Positive values correspond to net erosion; negative values correspond to net deposition.

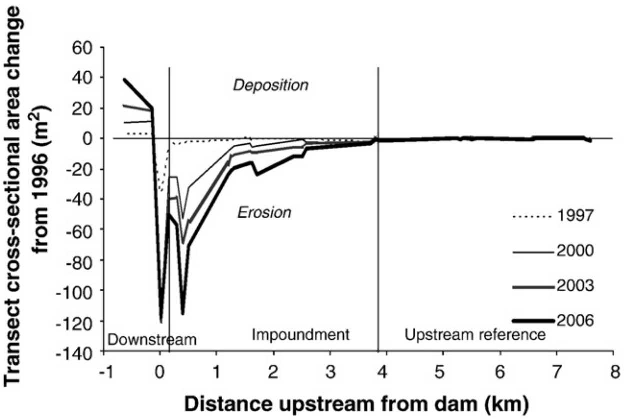

Fig. 5. Longitudinal pattern of change in cross-sectional area during the staged removal of Stronach Dam (1997–2003) compared to before dam removal (1996). Positive values correspond to deposition within a transect; negative values correspond to erosion at a transect.

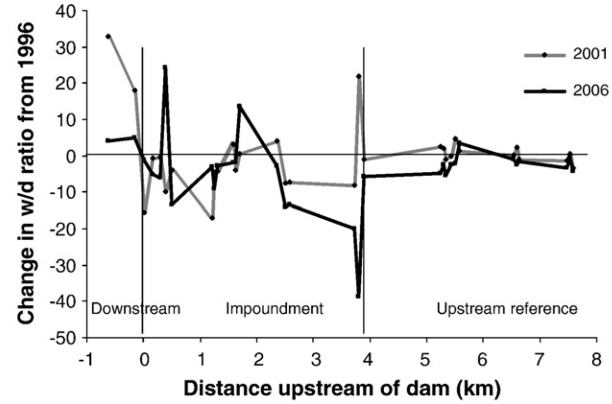

Fig. 7. Longitudinal pattern of change in wetted stream width to mean depth ratio (w/d) from pre-dam removal conditions in 1996. Only 2001 and 2006, 5 and 10 years after the beginning of dam removal, are shown for simplicity and clarity.

($R^2 = 0.00$), days at or above 1.5-year recurrence discharge ($R^2 = 0.01$), 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, or change in transect cross-sectional area that occurred in the impoundment varied spatially with distance from the dam (Fig. 5). 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 was not until 2001–2002 that net erosion was documented at the farthest upstream extent of the original 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 because of large amounts of lateral erosion in addition to 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 (Fig. 4). The volume of sediment that was retained and not transported farther downstream varied considerably between years (average = 1360 m^3, standard deviation = 1518 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 farther downstream in the river, eventually being deposited in Tippy Dam Reservoir or onto the floodplain downstream of the dam during high flow events.

4.2. Channel geometry

In the upstream reference reach, width and width-to-mean-depth ratio (w/d) of the wetted stream channel remained stable (Figs. 6 and 7). In the impoundment, the width of the wetted channel generally decreased (Fig. 6), with the magnitude of this narrowing generally corresponding to the amount of erosion that occurred at a transect (greatest closest to the dam and diminishing upstream through the impoundment). Localized differences in geology and slope influenced this general pattern at some transects, however. Change in the w/d ratio of the impoundment did not show any easily discernable patterns (Fig. 7). In the downstream reach, width and w/d ratio both increased (Figs. 6 and 7).

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 (Fig. 8). Because the streambed in this reach was stable during the study period, these changes are likely due to lateral erosion processes common to streams in this area. Bank slopes in the impoundment gradually increased during the dam removal, with the greatest increases seen closest to the dam (Fig. 8). In 2006, bank slopes farther upstream in the impoundment reach began to decrease, while those closer to the dam site remained steepened. In the downstream reach, bank slopes remained relatively stable (Fig. 8).

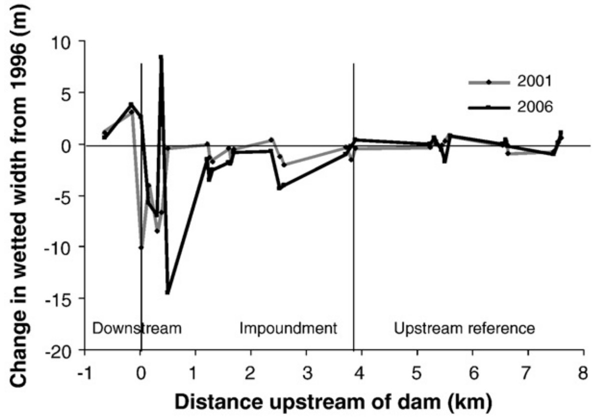

Fig. 6. Longitudinal pattern of change in wetted stream width from pre-dam removal conditions in 1996. Only 2001and 2006, 5 and 10 years after the beginning of dam removal, are shown for simplicity and clarity.

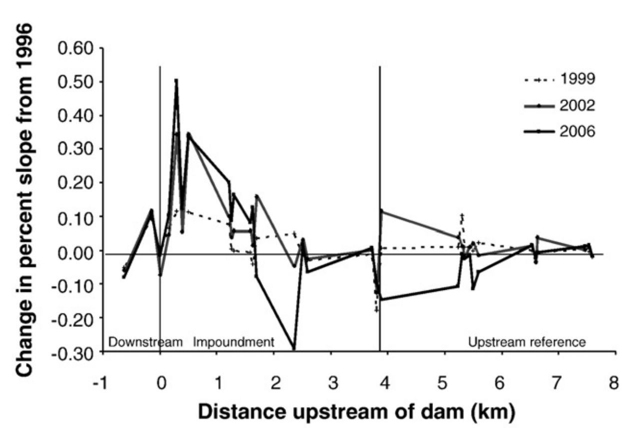

Fig. 8. Longitudinal pattern of change in bank slopes from pre-dam removal conditions in 1996.

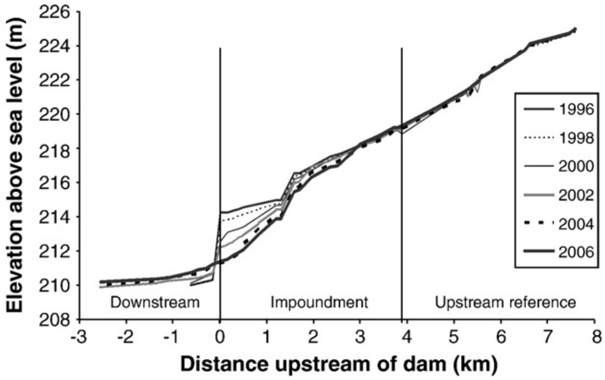

Fig. 9. Longitudinal profile of water slopes or gradients. Vertical scale exaggerated relative to horizontal scale.

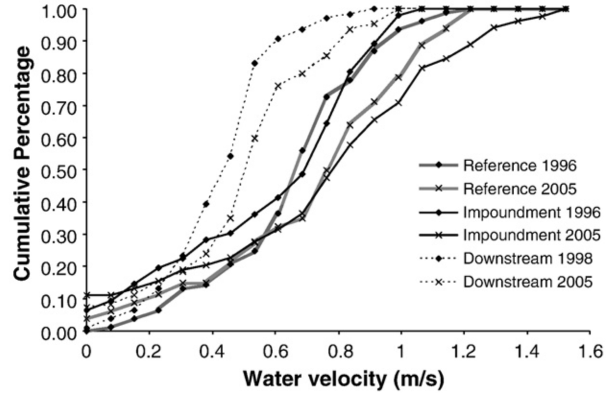

Fig. 11. Cumulative percent frequency distributions for water velocities in each study zone of Pine River.

4.3. 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 dam removal (Fig. 9). 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.

Prior to dam removal, mean water velocities generally decreased in a downstream direction through the impoundment and downstream zone (Fig. 10). With the dam removal and increased slope, mean water velocity generally increased in both the lower impoundment and the downstream zone, with some of the highest mean water velocities found in the impoundment after dam removal. Because of localized differences in slope and channel morphology, mean water velocities in the impoundment were more variable after dam removal compared to before dam removal.

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 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 $D_{\max}=0.247$, $n=137$, $p<0.01$). The water velocity frequency distribution for the downstream zone also was 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 <0.3 m/s were relatively unchanged (representing the slower water velocities found at the stream margins), while the magnitude of thalweg water velocities increased (Fig. 11). The former impoundment is now the only study reach to contain water velocities >1.2 m/s.

4.4. 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 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, substrate size composition in the Pine River showed considerable spatial variability and patchiness (Fig. 12). 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} 1997–1998 = 34.8 mm = "very coarse gravel," 2005–2006 = 29.5 mm = "coarse gravel"), but the overall substrate size frequency distribution did not change significantly (reference: *K–S* test $D_{\max}=0.063$, $n_1=989$, $n_2=1122$, $p>0.01$) (Fig. 13). Median substrate size increased slightly in the impoundment (Impoundment: D_{50} 1997–1998 = 7.9 mm = "fine gravel," 2005–2006 = 9.7 mm = "medium gravel") (Fig. 12). The substrate size frequency distribution for the impoundment was significantly coarser in 2005–2006 than for 1997–1998 (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) (Fig. 13). Median substrate size increased slightly in the downstream zone (downstream: D_{50} 1997–1998 = 1.0 mm = "sand," 2005–

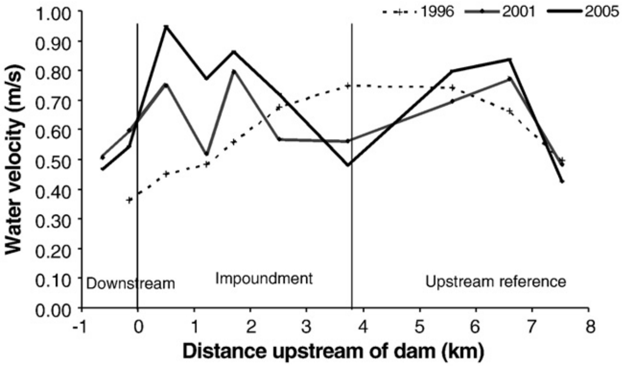

Fig. 10. Longitudinal pattern of mean water velocity (m/s) in Pine River.

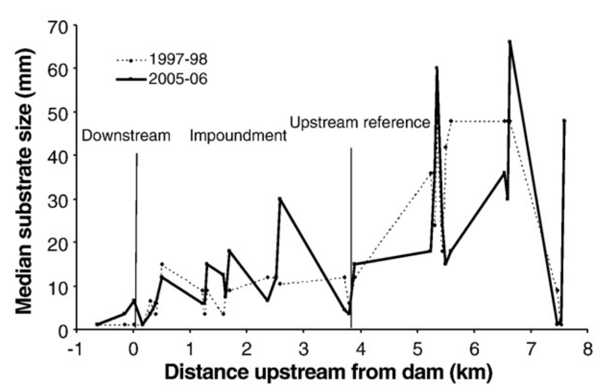

Fig. 12. Longitudinal pattern of median substrate size in Pine River, comparing 1997–1998 to 2005–2006.

2006 = 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 $D_{max} = 0.119$, $n_1 = 191$, $n_2 = 184$, $p > 0.01$) (Figs. 12 and 13).

4.5. Bedform

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 some differences in the percentages of the pool/complex and rapid designations and minor differences in the percentages of run bedforms occurred (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 had 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).

5. Discussion

5.1. Impoundment

The removal of each stop log during the dam removal process resulted in an abrupt increase in water slope and water velocity at the dam. The increase in shear stress created by stop log removal resulted in erosion of the impoundment sediments immediately upstream of the dam. As sediments were eroded adjacent to the dam and transported downstream, the process of sediment fill incision progressed upstream. Our onsite experience suggested that most of the sediment fill incision occurred rapidly, within hours to days, similar to observations by Wildman and MacBroom (2005). Each stage in the removal process pushed sediment fill incision progressively farther upstream, eventually reaching the upstream boundary of the original impoundment.

Relatively small amounts of sediment eroded during the first two years of the removal, likely because of the low slope of the impoundment during that period. 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

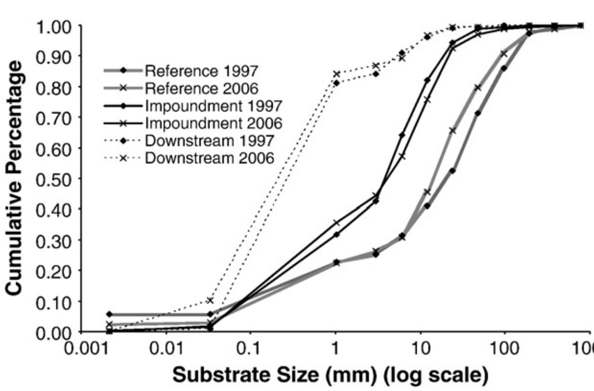

Fig. 13. Cumulative percent frequency distributions for substrate size compositions in each study zone of Pine River, comparing beginning size distribution to final size distribution.

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, the total volume of sediment that is likely to erode following a dam removal seems to be fairly easily estimated. Not all of the sediment in a reservoir will be mobilized. In 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 because of 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 (Fig. 14). For reservoirs such as Stronach Dam, where the reservoir was 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 bathymetric survey). To produce an area estimate for the triangular-shaped sediment fill, $H*L$ is divided by 2. 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, ~92 000 m^3 eroded from the impoundment with no new net erosion occurring during 2006. Assuming that no additional erosion will occur after 2006, this estimation method overpredicted the amount of sediment eroded, partly from the imperfect triangular shape of the impoundment and partly from the rectangular cross-sectional shape our approximation assumes (Fig. 14). However, this simple estimation method provides a useful and precautionary 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.

Prior to the removal of Stronach Dam, the former impoundment was estimated to contain approximately 789 000 m^3 of sediment. Of this stored sediment, we estimated a total of 92 000 m^3 was eroded in the 10 years since the initiation of dam removal. Thus, only 12% of the reservoir sediment was mobilized and transported downstream. Similarly small percentages of reservoir sediment fill 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, Wildman and MacBroom, 2005). 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, managing sediment transport downstream of a dam removal (e.g., through the use of sediment traps or collection devices) may be more cost effective than removing 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

Table 2
Percentages of bedform types found in each study zone in 1995 (prior to dam removal) and 2004 (after dam removal); pool and complex bedforms were aggregated to insure compatibility of complex bedform delineation.

Study zone and year		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

slope exerted greater influence on water depth at transects and led to large differences in w/d ratio changes between transects.

Changes in the slopes of stream banks following dam removal have been predicted to follow Channel Evolution Models (CEMs) (Simon, 1989; Pizzuto, 2002; Doyle et al., 2003; Doyle et al., 2005; Wildman and MacBroom, 2005). These models were developed from incising channels and predict that, following dam removal, bank slopes in former 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 and allowing for the development of equilibrium channel dimensions. In the Stronach Dam impoundment, bank slopes did increase gradually during dam removal, with the initial and greatest increases occurring closest to the dam. Bank slopes continued to increase during the last year of the study, and decreases in bank slopes were observed only at sites farther 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 Pine River may be naturally dynamic and variable. While some patterns consistent with the CEM seem discernible from these data, the natural variability in bank slopes makes interpreting the significance of those patterns difficult.

As stream slope increased in the impoundment following dam removal, so did mean water velocities. Comparison of water velocities across years is partially confounded with differences in discharge. Although we were able to sample during periods when differences in discharge were small (i.e., <5%), this still could have resulted in changes to mean water velocity. Of more interest, however, is how the frequencies of water velocities changed in the impoundment. The frequency of slower water velocities (i.e., <0.30 m/s), located primarily near the stream margins, did not change substantially despite increasing mean velocities and increased thalweg velocities. Water

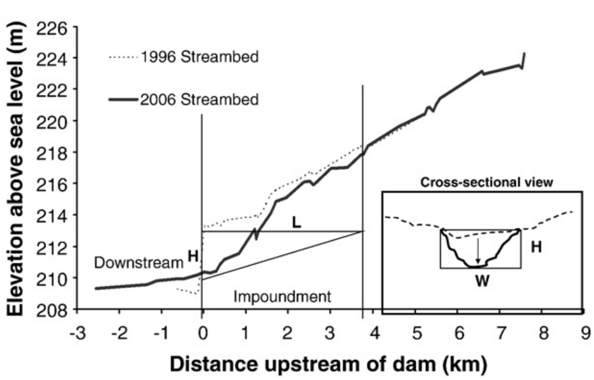

Fig. 14. Longitudinal profile of the Pine River streambed before and after dam removal. The triangle approximates the area of the sediment fill and, along with average stream width upstream of the impoundment, can be used to estimate the volume of sediment that can be mobilized at a dam removal.

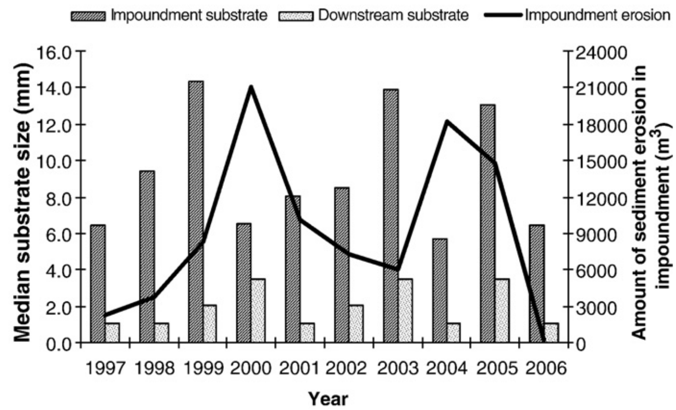

Fig. 15. Annual median substrate sizes in the impoundment and downstream study zones shown in relation to the annual amounts of sediment erosion occurring in the impoundment zone each year of the staged dam removal.

velocities therefore not only increased but became more diverse. Changes of this nature will have important implications for sediment 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. Larger transient changes in median substrate size were seen during dam removal, however. Apparently during years when less than roughly 15 000 m^3 of sediment eroded from the impoundment, substrate coarsening progressed in both the impoundment and downstream reaches (Fig. 15). However, during years when large volumes of sediment (>15 000 m^3) were eroded from the impoundment (1999–2000 and 2003–2004), fine sediment was transported through these reaches, covering up previously coarsened substrate and decreasing median substrate size (Fig. 15). An exception to this trend occurred in 2006, three years after the removal, when no net sediment erosion occurred and median substrate size still decreased.

Overall increases in the proportions of coarse substrate were similarly observed following the removal of Woolen Mills Dam on the Milwaukee River, Wisconsin, USA (Kanehl et al., 1997). However, substrate size frequencies also showed changes similar to those of water velocities. In the impoundment where substrates had been dominated by sand before dam removal, frequencies of sand decreased because of the dam removal, but frequencies of silt did not decrease. Similar changes were reported by Stanley et al. (2002) shortly after the removal of two low-head dams on the Baraboo River, Wisconsin, USA. 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 that were later replaced by larger size gravels. This shift corresponds with the thalweg velocities increasing in magnitude but not frequency. This also has important implications on stream biota because the homogenous sand substrate prior to dam removal was not replaced with 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, based on calculations of relative bed stability. 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 are 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 high flow events with recurrence intervals of roughly 5–20 years (Knighton, 1984; Petts and Foster, 1985; Beschta and Platts, 1986, as cited in Pizzuto, 2002; Gordon et al., 2004). 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-term empirical studies and laboratory flume experiments. Bushaw-Newton et al. (2002) also noted that riffle-pool bedforms had not reformed in the impoundment within 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, influences nutrient cycling, and is crucially important to the habitat suitability of stream biota (Gordon et al., 2004).

Based on the results we observed in Pine River that indicate restoration of bedform heterogeneity may take a long time to develop, we suggest that innovative ways of actively helping bedform reformation following dam removal may be valuable to restore river function. 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 bedform reformation may lead to a faster realization of the full benefits of stream rehabilitation achievable 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 correspond to the boundary of the formal reservoir where water widths would likely be very wide and water impoundment would be most noticeable. In the case of Stronach Dam, this corresponded to a point approximately 1.21 km upstream of the dam. However, through our method of delineating bedform types, low bedform diversity was apparent for a considerable distance upstream (3.89 km upstream of the dam) of the formal reservoir. In addition, the substrate in this area of low bedform diversity was largely sand-dominated. Therefore, the farthest upstream extent of this sandy run habitat became our upstream boundary of impoundment effects and the extent of where we expected to see changes from the dam removal. This method, along with the use of aerial photos, proved quite accurate in delineating the farthest 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 such as infrastructure concerns, mitigation measures, and landowner impact assessments.

5.2. 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 the dam created a situation where water velocities were extremely high and flow became supercritical. Transport of the sandy substrate proceeded with antidune formation. Farther 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 by increasing the slope of this section of stream downstream of the dam by nearly 100%, decreasing the water depth, and slightly increasing the stream width. These changes would have 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, ~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 farther downstream, forming a sediment delta at the confluence of Tippy Dam Reservoir, or deposited on 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 0.50 m at one of the transects.

The implications of these changes could be important in considering the impacts from dam removals. During the erosion process upstream of dams, the streambed is lowered reducing connectivity with adjacent floodplain wetlands. In some circumstances, regulatory agencies responsible for dam removal permitting may request remediation for any lost wetlands (even if the wetlands were created by 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 Pine River following dam removal and has been predicted to occur following the removal of other dams (Stoker and Harbor, 1991; Randle, 2003).

Sediment deposition in the downstream reach resulted in a substantial decrease in water depth and an increase in width, together greatly increasing the w/d ratio of this reach. This increase in w/d ratio reached a peak during the later stages of dam removal and began to decrease 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 and frequency distributions changed significantly. As with the impoundment, water velocity frequencies in the downstream zone increased in variability. Frequencies of slower water velocities (<0.3 m/s) increased as the stream channels became wider and shallower. At the same time, the fastest 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 than prior to dam removal, 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 overall may stay relatively sand dominated because of the close proximity of the next downstream reservoir and its impoundment effects.

Changes in bedform diversity downstream of Stronach Dam may never occur. This section is a much lower gradient because of the Tippy Dam impoundment, and even during high flows the stream may not have the power to scour pools. This section was all run bedform before dam removal and remained largely run bedform throughout the course of this study. Even if pools were scoured and 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.

6. Conclusions

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, changes are still occurring in Pine River because of the removal of Stronach Dam, even 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 Pine River for many years. Although dam removal has the potential to be an effective tool for stream rehabilitation, many of the outcomes may take years to decades to be fully realized. We hope that this research serves as a 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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