Dam Removal

Removal is the most ecologically comprehensive and economical means of addressing dam related problems. Dam removal

- *eliminates maintenance costs and liability due to risk of failure and drowning and*
- *restores migratory pathways, nutrient and sediment regimes, and ecological and channel forming processes.*

However, removal of the structure alone may not immediately restore all damages caused by the structure. As discussed, sedimentation upstream and incision downstream can leave an unstable channel that may be in an adjustment phase for an extended period. Sudden release of significant sediments can overwhelm the channel's sediment transport capacity and effect downstream habitat and biota. Since channels downstream of dams have been sediment starved, some release of sediment may remediate this lack of sediment. There are at least four strategies for dealing with sediment associated with dam removal:

1) abrupt removal, letting the river transport reservoir sediments,

2) incremental removal over a period of years,

3) dredging sediments before removal,

4) removal with river restoration to stabilize sediments.

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1) Simple removal – no restoration or sediment management

Most dam removals across the country take this approach, as it is the least expensive and simply involves removing the structure. It works well where there is little accumulated sediment in the reservoir or channel recovery rates are likely to be rapid. Recovery rates are likely to depend on the type of sediment that would be released, stream gradient, and hydrology, as well as the rate at which vegetation is likely to become established on dewatered or deposited sediments. The advantages are that it is inexpensive and natural fluvial processes reestablish the river channel. The disadvantages are 1) where large volumes of sediment have accumulated, channel recovery to a new state of equilibrium may take an extended period of time - from a decade (Schumm et al. 1984) to 1,000 years in some situations (Brookes 1988), 2) sudden release of very large volumes of sediment can have adverse downstream effects on channel morphology and stability, habitat, benthic invertebrates, and fish. Channel recovery time is likely to depend on slope, sediment type, and the amount of sedimentation and incision present. The first case example discussed here is of this type.

2) Staged removal and release of sediments over a period of several years

This has been proposed as a means of releasing sediment over a period of time without overwhelming the downstream channel (Barr et al. 2000). In some cases, reservoirs have accumulated sediments over a period of 50 to 100 years or more so incremental release is still likely to be significantly greater than natural sediment transport. Ideally, sediment releases would match transport capacity of the downstream channel. Cui et al. (2006) suggest that benefits of a staged removal may be minimal where sediments are predominantly gravel but could be significant where fine sediments dominate. They further suggest that impacts of fine sediments are more significant due to rapid transport.

3) Dredging the reservoir prior to removal

A primary limitation of this approach is that dredging is costly. Dredging was initially proposed for the Marmot Dam removal (Stillwater Sciences, 2002). The presence of contaminated sediments may be cause for removing them by dredging. In some cases, dredged materials can be sold to offset dredging costs. However, the market for dredged sediment is likely to depend on the type of sediment and local demand. While dredging is a means of removing accumulated sediment and reducing downstream effects, it does not assure stable channel morphology within the dewatered reservoir.

4) Removal and river restoration to stabilize sediments

Natural channel design techniques can be used to establish a stable channel within the accumulated sediments. The accumulated sediment is allowed to consolidate and vegetate and the channel is designed to use this sediment elevation as the new floodplain. Constructed fieldstone riffles provide grade control to establish the new profile until bedload is transported into the former reservoir. Advantages of this approach are: 1) the sediments are stabilized in the former reservoir, 2) a stable channel with diverse habitat can be established, and 3) channel evolution recovery processes can be advanced.

There are at least four strategies for dealing with sediment associated with dam removal:
1) abrupt removal, letting the river transport reservoir sediments,
2) incremental removal over a period of years,
3) dredging sediments before removal,
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Case Examples

The Sandstone Dam – Simple removal with no restoration

This example is included for perspective on the most common form of dam removal with a sediment-filled reservoir. It is not an example of natural channel design since no channel restoration was done. While monitoring data of the downstream channel and mussels are presented, these data were collected for a specific purpose and are not a comprehensive assessment. The study was designed to assess effects of sudden sediment release on downstream mussels communities rather than the beneficial effects of restored fish passage, habitat, and connectivity.

The Sandstone Dam on the Kettle River in East-Central Minnesota was originally built in 1908 and generated electricity until 1963 (Figure 17). It was the only dam on the designated Wild and Scenic River and was located within Banning State Park (Figure 18). The 20-foot high dam was owned by the Department of Natural Resources. The Kettle River has a diverse fish and mussel assemblage and the dam blocked migration of lake sturgeon and other species, including mussel hosts, from upstream spawning habitat. Discussions about removal began in the early 1990s. Among issues evaluated were releases of sediment, effects on recreational opportunities, potential effects on mussels, and common carp *Cyprinus carpio* that were known to exist downstream of the structure but had not been observed upstream.

Figure 17. Sandstone Dam on the Kettle River.

Summary Statistics:

- » **Dam height:** 20 feet (16.1 ft maximum head-loss)
- » **Dam crest elevation:** 956.6
- » **River:** Kettle
- » **Average flow:** 693 cfs
- » **Drainage area:** 868 square miles
- » **Year built:** 1908
- » **Year removed:** 1995
- » **Removal cost:** $208,000
- » **Known drowning deaths:** 1
- » **River mile:** 22.4 upstream of confluence with the St. Croix River at river mile 106 from its confluence with the Mississippi at river mile 811.5 (1770.3 miles from the Gulf of Mexico)
- » **Upstream mainstem river length blocked:** 71 miles (to headwaters)
- » **Appendix:** Project Brief #36

The dam was located just downstream of some of the steepest reaches of the Kettle including Hell's Gate rapids (Figure 19). It is known as one of the best whitewater boating rivers in the Upper Midwest. The reservoir created by the dam inundated Sandstone Rapids on which the dam was built, Big Spring Falls, about a half mile upstream of the dam, and partially inundated Quarry Rapids about two miles upstream of the dam at the upper end of the reservoir.

My coworkers and I became involved with the project to assess potential impacts of released sediments on the downstream mussel community. Transects were established between 1,000 and 7,000 feet downstream of the

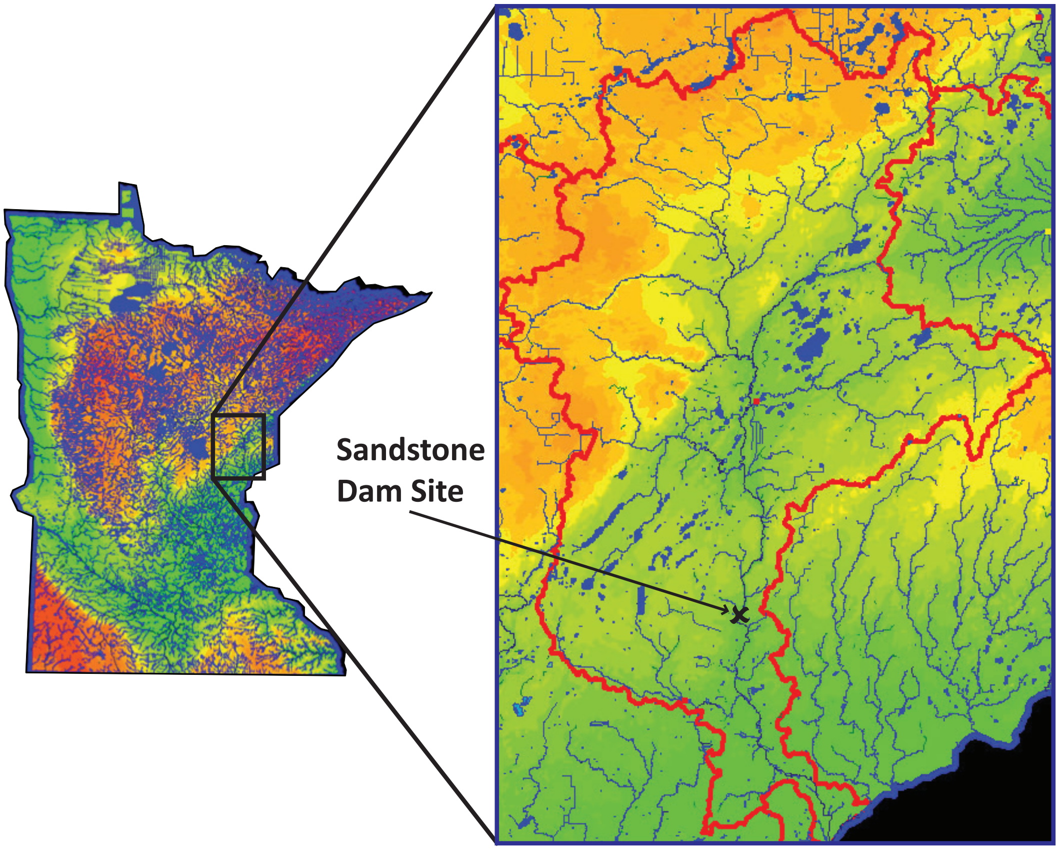


Figure 18. Kettle River shaded relief watershed map showing location of the Sandstone Dam.

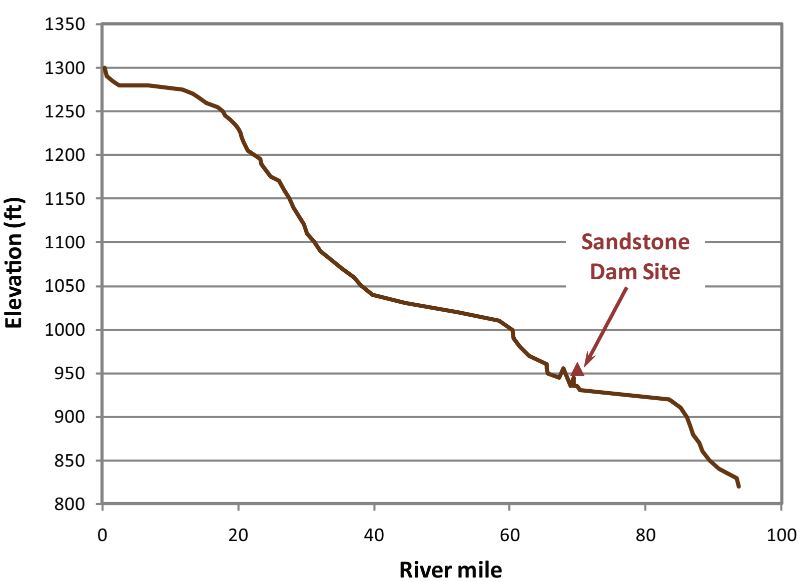


Figure 19. Elevation profile of the Kettle River showing the former dam site.

dam where substrate composition, depth, velocity, and mussel densities were recorded within 30 - four ft^2 quadrats randomly located along these transects using SCUBA (Figure 20).

Bankfull shear stress was calculated at each transect to predict where sediment deposition would likely occur. Slope was the primary variable driving shear stress differences among habitats. It was assumed that these facet slopes would be maintained at bankfull flow since this reach of the Kettle is relatively straight (sinuosity = 1.25) with bedrock or boulder rapids separated by lengthy pools or runs. The rationale was that deposition of fine sediments (predominantly sand) should be most extensive in habitats where shear stress is lowest. The lowest calculated bankfull shear stress was in a deep pool by Maple Island where no mussels were observed within the transect quadrats. The lack of mussels may have been due to the prevalence of silt and organic detritus that are not preferred substrates for most Minnesota mussel species (Aadland and Kuitunen 2006). Based on these observations, it was concluded that this large pool would be most prone to initial deposition of the released sediment and since mussel density was low in this habitat, effects of sediment deposition there would directly affect relatively few mussels. Effects of the elevated sediment loads passing through habitats on mussel survival were not specifically evaluated.

We recommended removing the dam incrementally to release sediment over a period of several years. However, there were concerns that a partially removed dam would be structurally unsound and would increase failure risk. Big Spring

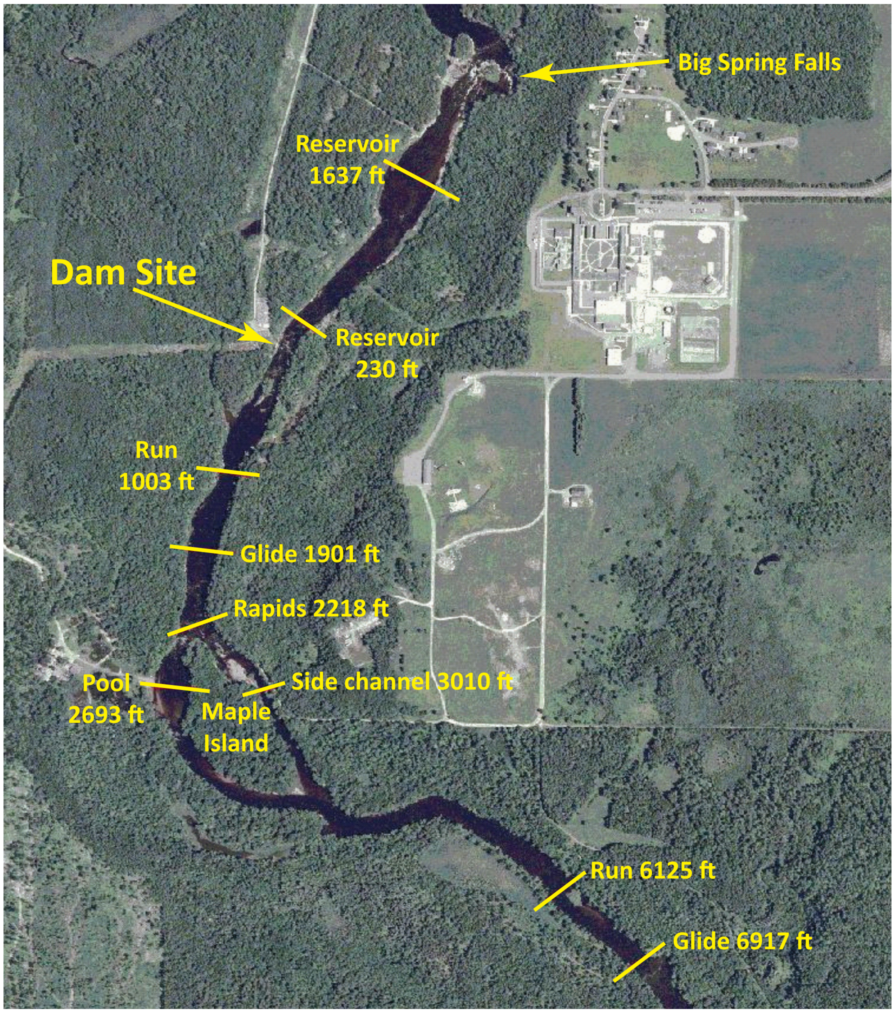


Figure 20. Aerial photo showing transect locations and distances from the dam site.

Falls bisects the reservoir and with the dam removed would have about eight feet of head so the reservoir upstream of the falls would only drop by about two feet.

While the pre-removal estimate (by others) of maximum sediment depth was seven feet, the reservoir had actually accumulated roughly 15 feet of sand that was released when the dam was removed in 1995 (based on a bathymetric lake map and post-removal surveys) (Figure 21). The pre-removal underestimate was apparently due to misidentification of firm sand as bedrock.

As predicted, the greatest sedimentation occurred in the deep pool by Maple Island. This pool was about 19 feet deep at bankfull prior to the removal. The pool initially filled with about 15 feet of sand that has subsequently scoured to a 12-foot bankfull depth in the 2007 survey. The greatest scour occurred between the 2000 and 2001 surveys when the pool deepened by about four feet to a depth of about 13 feet at bankfull. This was probably due to a 25-year flood (14,800 cfs) that occurred that spring. Subsequently, there have been relatively low flows and the pool actually lost about a foot of depth (Figure 22).

The proportion of substrates comprised by sand increased in most habitats after the removal but has approached pre-removal composition in some transects (Figure 23).

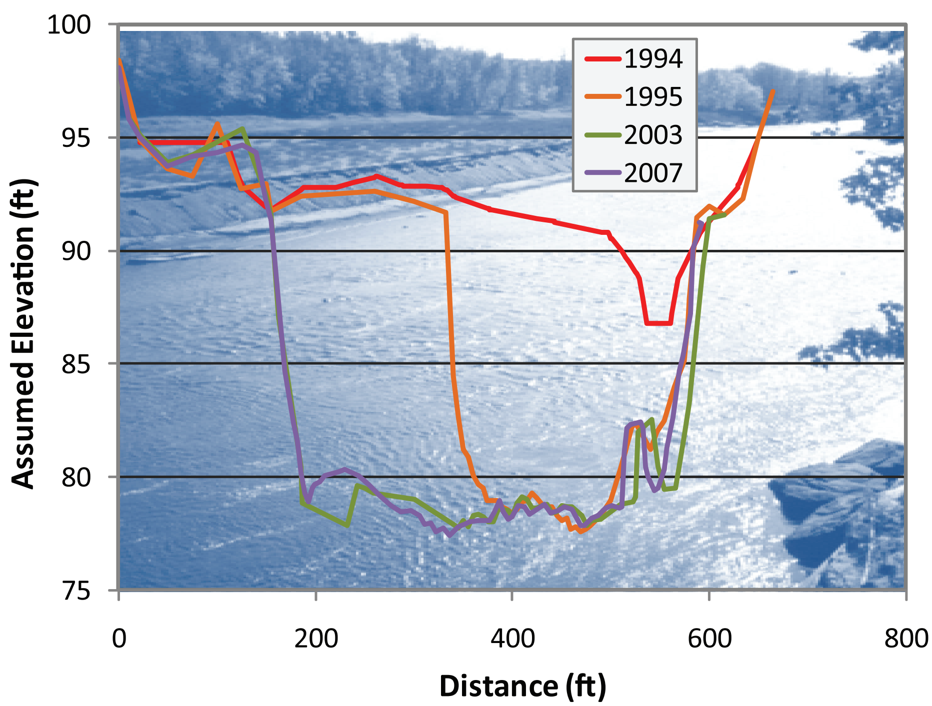


Figure 21. A cross-section within the reservoir 230 feet upstream of the dam, showing changes following removal.

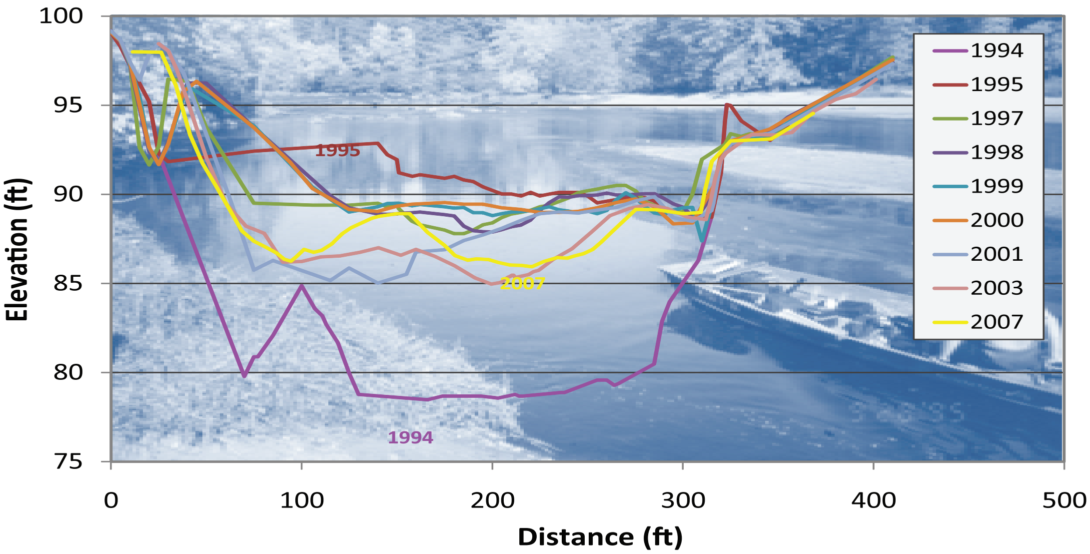


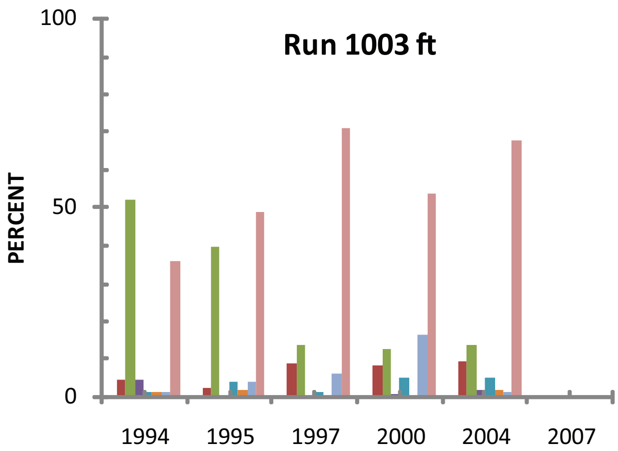
Figure 22. A pool cross-section, 2,693 ft downstream of the dam, showing sedimentation following removal. The background photo is looking upstream, cross-section stationing is left to right looking downstream.

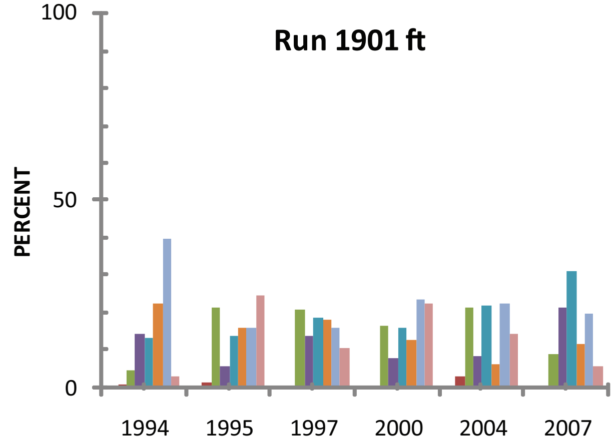
Substrates within the reservoir have also changed. While our sampling of sediments upstream of the dam did not begin until the dam had been removed, it is likely that it was almost entirely sand based on flats visible immediately after removal. Following removal, the river quickly downcut to bedrock and subsequently widened (Figure 24).

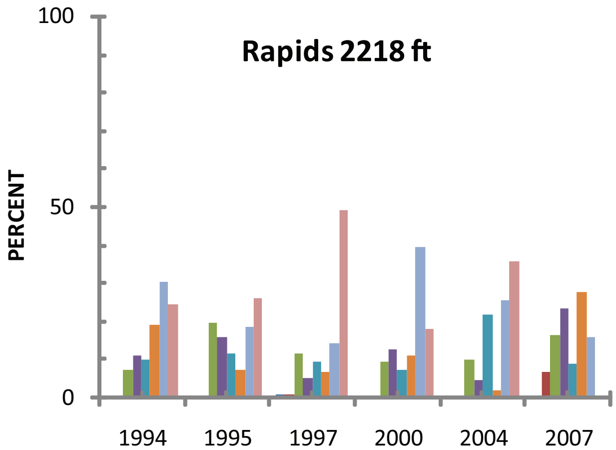
Mussel density observed along habitat transects declined in all habitats except for that in the deep pool where only one mussel was observed (Figure 25). It is unclear whether the reduction in mussel density was due to mortality from elevated sediment loads, being covered by sand, or habitat changes due to sedimentation or if the mussels were carried downstream with the sand load. Mussel surveys within the reservoir have shown no change in density as only one mussel has been collected along the two transects. This is probably due to predominance of bedrock and the lack of stable alluvial substrates.

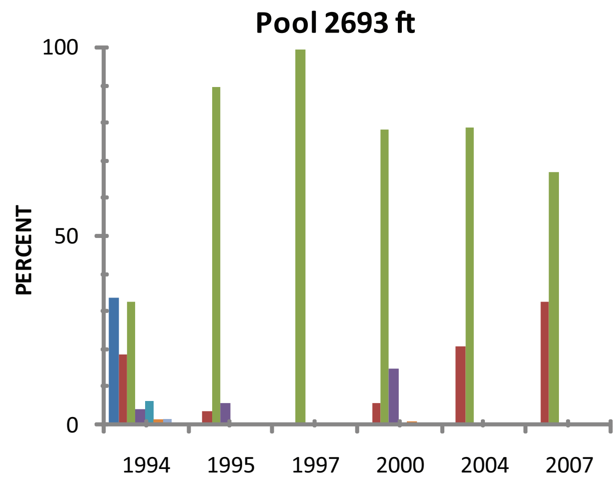
It is important to recognize that the data presented here focus on localized downstream effects on mussels over a short time period. We have not assessed upstream effects of restored host access on mussel communities or effects on the fish community. Tailwater mussel densities can be artificially high due to the concentration of host fishes during upstream migrations and the resulting localized release of larval mussels. These tailwater concentrations are at the expense of upstream habitats to which migrating hosts do not have access (Mike Davis, personal communications). Removal of the barrier may result in mussels being spread over a greater length of river. A full assessment of effects of the removal would include changes in more than 70 miles of reconnected habitat in the Kettle River mainstem and many more miles of tributary length. A suitable timeframe for mussel recovery would first include habitat recovery time plus the amount of time for juvenile mussels to become large enough to be collected in surveys. The pool and downstream channel are recovering as sediments are carried downstream. As microhabitat returns to pre-dam conditions, reestablishment of the mussel community may be expected. It is unclear whether mussel abundance will ultimately revert to that existing prior to the dam removal. Since the reservoir intercepted sediment and caused an artificial reduction of sediment supply downstream of the dam, the river may have a different substrate composition even after it has established a new equilibrium.

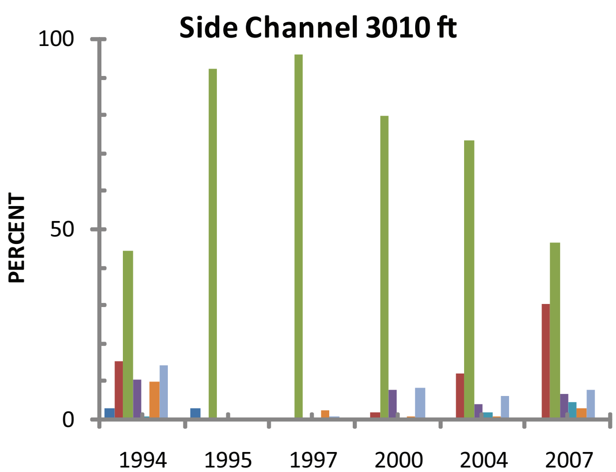
While sedimentation was considerable in the Maple Island pool, there has been no visual evidence of channel instability, significant channel migration, or change in pattern evident from aerial photos or ground observations following removal. Measurements taken by the USGS do not suggest significant changes in the stage: discharge relationship at the gage since

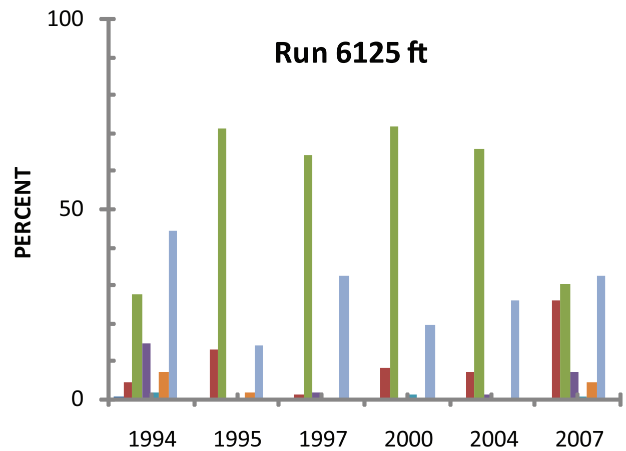


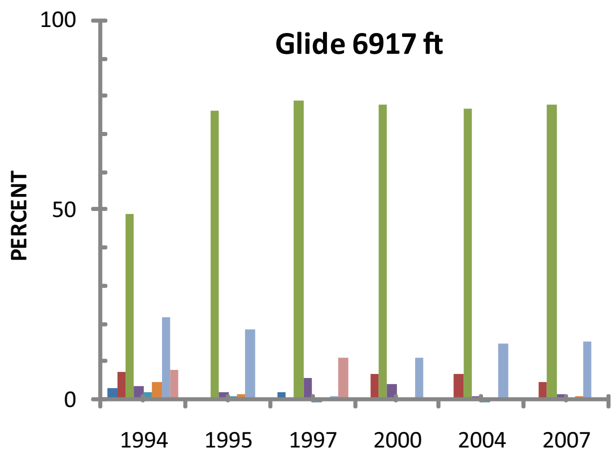












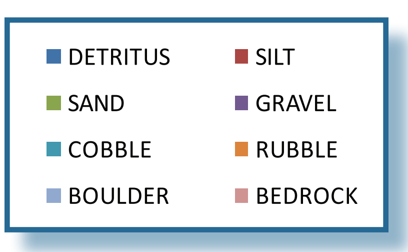


Figure 23. Substrate changes at transects and distance downstream of the dam site.

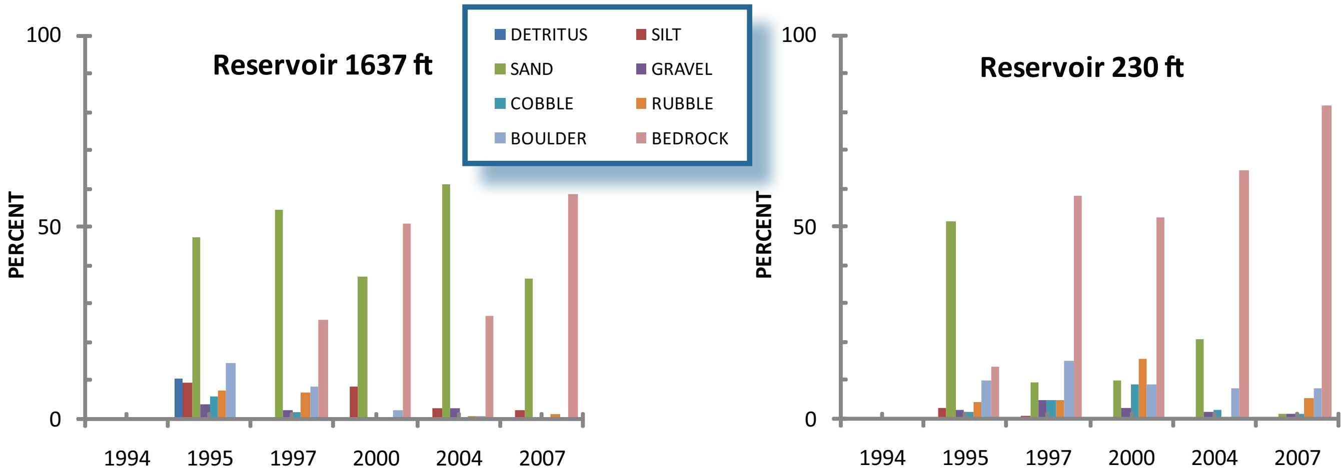


Figure 24. Substrate changes in the reservoir following removal and distance upstream. No data was collected prior to removal in 1994 but based on exposed flats it was likely near 100 percent sand.

the dam was removed (Figure 26). The gage is 850 feet downstream of the dam site. This indicates that the hydraulic control of the gage has remained at a similar elevation. While further downstream reaches may be different, substrate composition included boulder throughout the study timeframe suggesting that sand may have embedded larger substrates rather than changing hydraulic capacity of the channel. The banks have well-established riparian forest vegetation and appear stable.

The dominance of sand in the accumulated reservoir sediments may have increased downstream effects. Sand is more mobile than larger particles and lacks the cohesiveness of finer silts and clays. The high sand banks in the reservoir were also slow to vegetate. The findings here may differ from the effects of a dam removal where sediments are dominated by gravels or silt.

A different approach to the removal may have

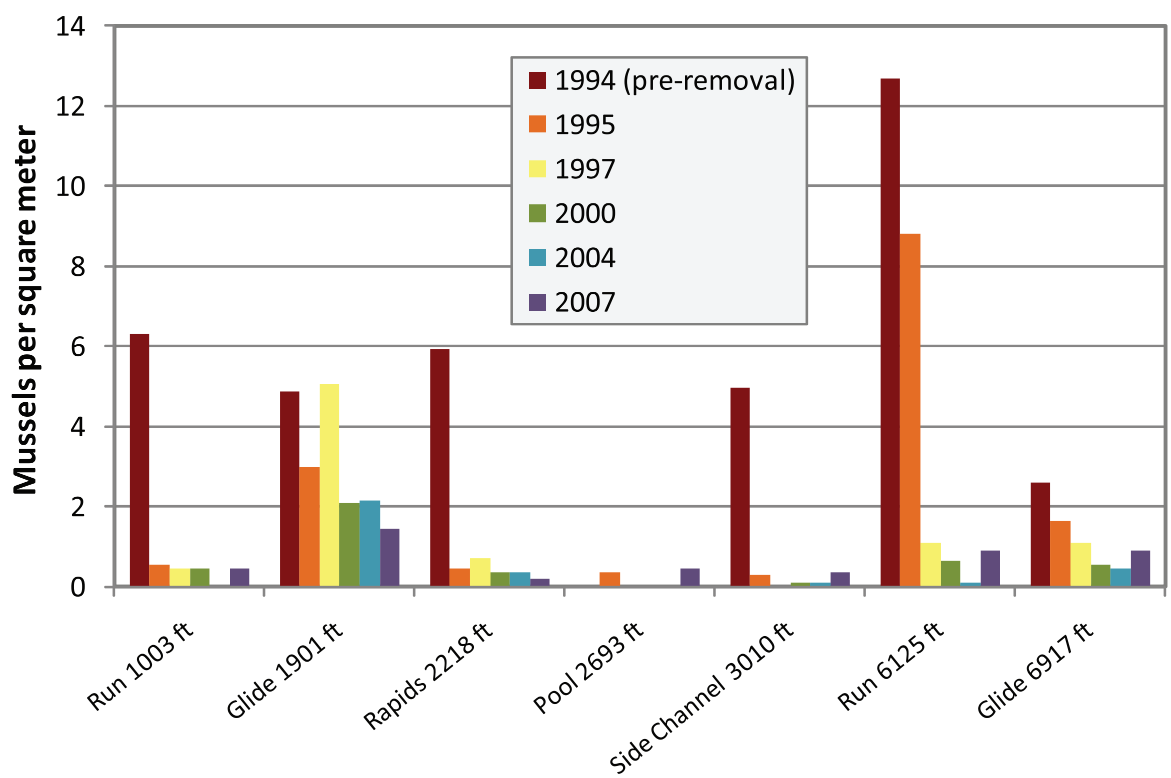


Figure 25. Mussel density along transects with distances downstream of the dam site.

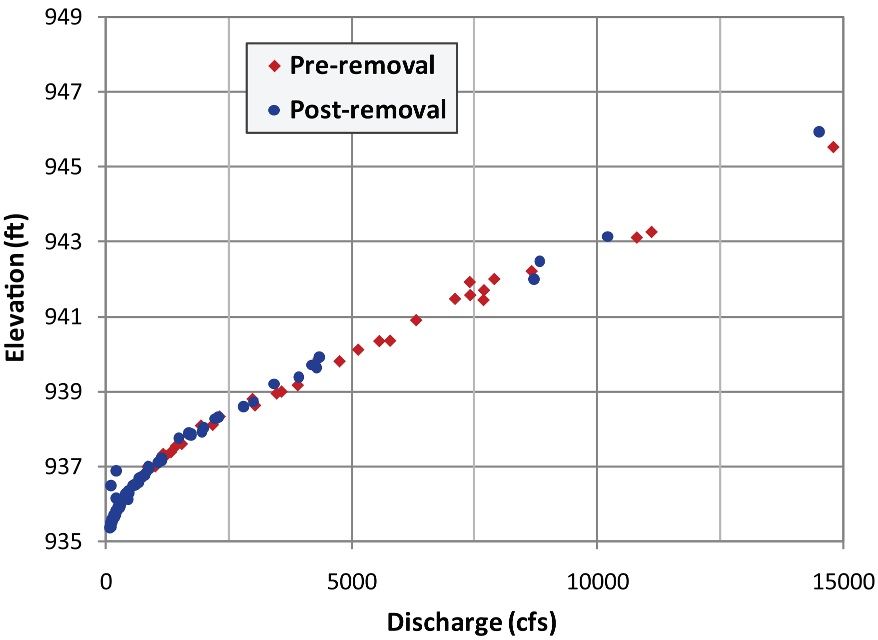


Figure 26. Measured stage and discharge values at the Kettle River gage before and after removal of the Sandstone Dam. The gage is 850 feet downstream of the dam site. Data from USGS gage 05336700.

reduced the short-term impacts. While a staged removal may have lessened immediate sedimentation effects, it would have extended the sediment release. Furthermore, sediment transport rates would still have depended on adequate flood flows. If an incremental lowering of the dam and sediment release coincided with low flows, sand accretion of the downstream channel may still have occurred. Channel stabilization and restoration within the reservoir could have stabilized sediments and reduced the amount passed downstream. However the channel was predominantly bedrock so the pre-dam form is likely similar to that which now exists. Native plantings and some grading of the banks within the reservoir may have helped retain sediment. Dredging of the reservoir prior to removal would also have reduced the sand carried downstream. All of these methods would have increased project costs.

Big Spring Falls, inundated by the reservoir, now provides potential spawning habitat for lake sturgeon (Figure 27). Tagged lake sturgeon have also been observed moving upstream of the dam site and through the falls. Numerous riffles, rapids, and falls upstream of the former dam are now accessible for sturgeon and other species.

The Kettle River is now free-flowing from its headwaters to its confluence with the St. Croix River. Implications of the Sandstone Dam removal may extend well beyond the vicinity of the dam. As discussed previously, fish, like lake sturgeon, and other species can migrate hundreds of miles to access suitable spawning habitat. Conceivably, fish populations in the St. Croix River may depend on habitat now accessible in the Kettle River. While full recovery of the Kettle River from the effects of the dam may take additional time, the processes for this recovery have been restored.

Figure 27. Big Spring Falls, inundated by the reservoir for 87 years, following removal of the Sandstone Dam.

Appleton Milldam, Pomme de Terre River – Dam Removal and River Restoration

Figure 28. The Appleton Milldam as it appeared in 1910. Photo courtesy of the Minnesota Historical Society.

The Appleton Milldam was originally built in 1872 (Figure 28). The dam had significant ties to the community. The mill provided the industrial roots for the small town of 2,871 people. An island in the reservoir was a popular site for weddings. An elderly resident talked of diving from the railroad bridge into a 15-foot deep pool.

The dam was located on the Pomme de Terre River in Western Minnesota (Figure 29). The Pomme de Terre River's headwaters are South Turtle Lake in the Central Lakes Region of Otter Tail County and flows predominantly through agricultural lands and remnant prairie to its confluence with the Upper Minnesota River. The French name, Pomme de Terre, literally "apple of the earth", is after the prairie turnip, *Pediomelum esculenta*, a native prairie plant that was an important food for Native Americans and early European settlers. The river's delta as it enters the Minnesota River formed Marsh Lake, an important wetland for waterfowl. The delta is now the site of another dam built by the Corp's of Engineers to raise the water level in Marsh Lake.

Summary Statistics:

- **Dam maximum head-loss:** 12.8 feet (may have historically been as much as 16 feet with flashboards)
- **Dam crest elevation:** 994 ft
- **Crest width:** 130 ft
- **Minimum tailwater elevation:** 981.2 ft
- **River:** Pomme de Terre
- **Average flow:** 136 cfs
- **Record flow:** 8,890 cfs in 1997
- **Drainage area:** 905 square miles
- **Year built:** 1872
- **Year removed:** 1998
- **Year restoration was completed:** 2001
- **Removal cost:** $117,000
- **River restoration cost:** $250,000
- **Excavation:** 24,410 cubic yards
- **River mile:** 9.2 upstream of the confluence with the Minnesota River at river mile 302 upstream of the confluence with the Mississippi River at river mile 844 (2,114 miles upstream of the Gulf of Mexico)
- **Upstream river miles reconnected:** 45.1 (including subsequent removal of a dam at river mile 15)
- **Contractors:** Dam breech: D&C Dozing, Dam removal: Landwehr Construction, River restoration: Sheryl's Construction
- **Project engineers:** Marty Rye, SEH (for removal), Shane Rustin and Eugene Redka, DNR (channel restoration)
- **Restoration design:** Luther Aadland
- **Appendix:** Project Brief #38

The dam's location, only nine miles from its confluence, was a complete barrier to fish migration (Figure 30). The dam was also situated in one of the steeper reaches of the river where it inundated gravel riffles important for spawning habitat of a number of fish species. Eleven dams were built on the Pomme de Terre River, most of which are at natural lake outlets. Appleton dam and another dam six miles upstream blocked over 45 miles of river.

The Appleton Dam became structurally

unsound and the city passed a resolution on December 14, 1994 to "examine all possibilities to remove and/or improve the Mill Pond Dam."

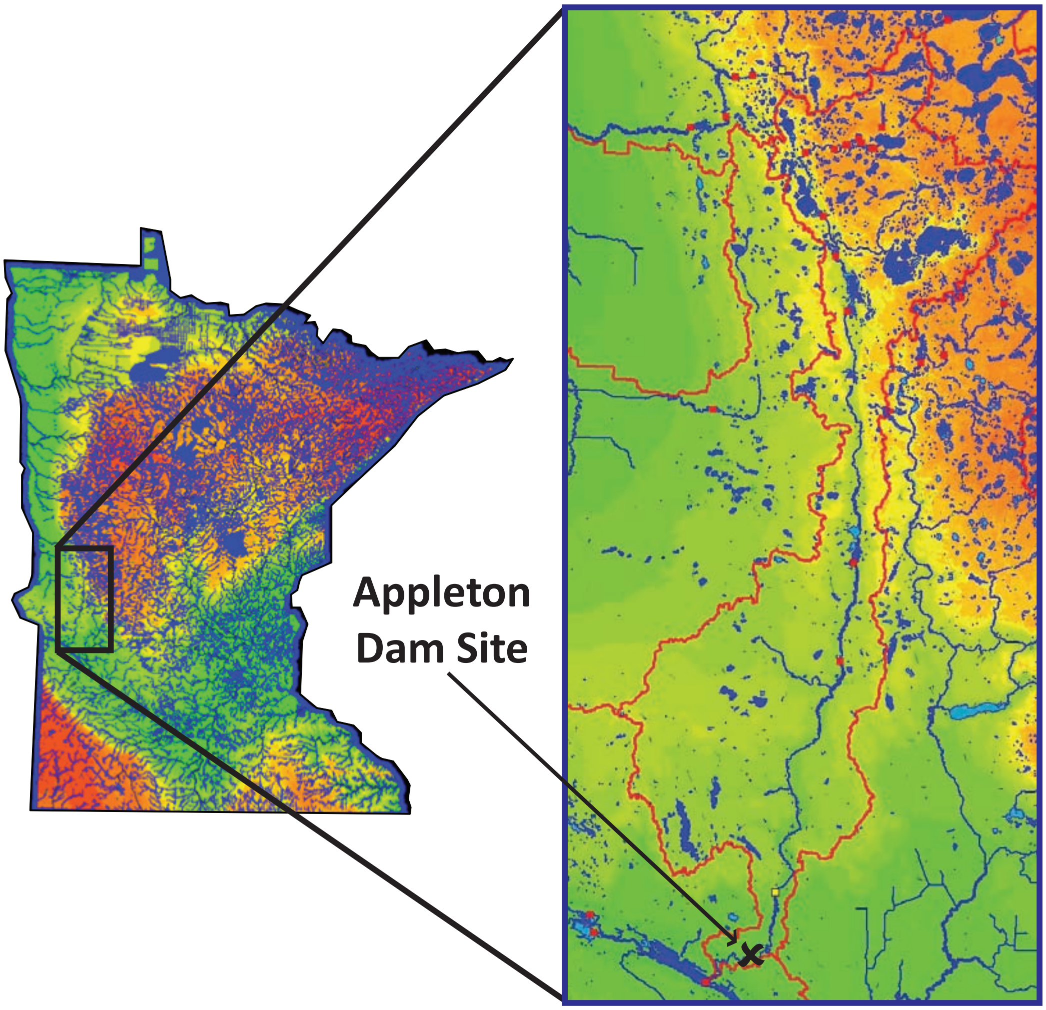


Figure 29. Shaded Relief map of the Pomme de Terre Watershed showing the Appleton Dam Site.

The Minnesota Department of Natural Resources worked with the City in the process that included a series of public meetings to discuss whether to repair or remove the structure. While some favored repairing the dam, the reservoir, once a popular swimming lake, had filled with up to 15 feet of sediment and no longer performed its original functions. The dam no longer powered a mill. The 1996 Minnesota Legislature provided $50,000 to study options. Cost of rebuilding the dam, would have been substantial leading the community to consider removal. The City of Appleton decided by January 9, 1997 to remove the dam. The dam spillway subsequently was undermined in the record April 1997 flood (Figure 31).

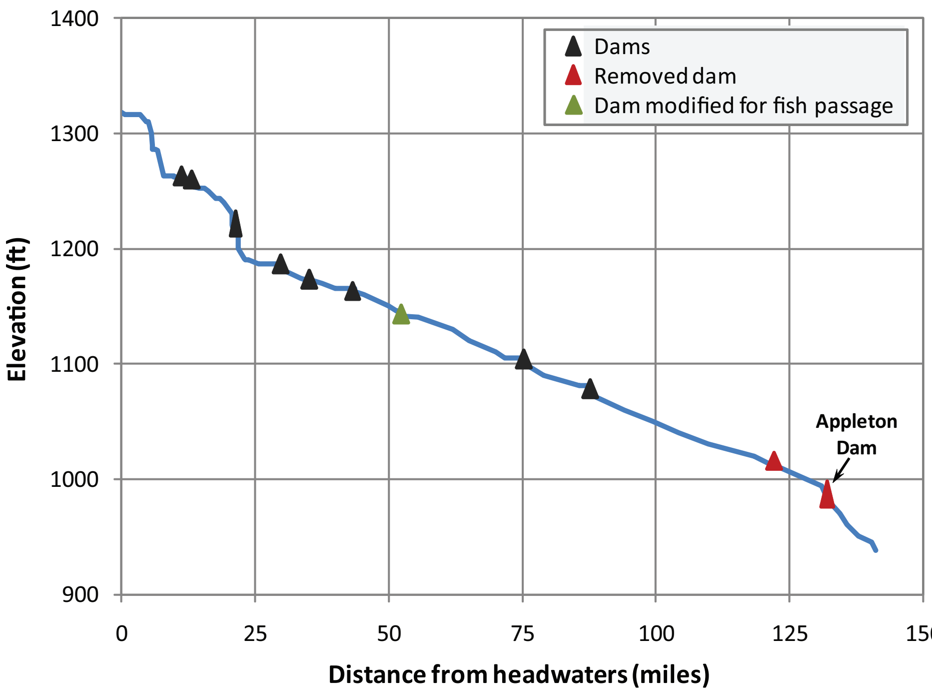


Figure 30. Elevation profile of the Pomme de Terre River showing dam locations.

Based on our experience with the Sandstone Dam, we were concerned about potential adverse effects of the accumulated reservoir sediments if released downstream. Sediments were collected from four sites in the reservoir and tested for a broad range of pesticides and heavy metals by MVTL Laboratories in New Ulm (SEH 1997). Contaminants were

Figure 31. Appleton Dam following the 1997 flood. A breech is apparent on the left side of the photo.

either non-detectable or below levels of concern. While contaminants were not a problem, potential downstream sedimentation and channel instability within the former reservoir were a concern. Unlike the Sandstone Reservoir that had filled with sand on a bedrock channel, Appleton Reservoir sediments were dominated by cohesive silt and clay with gravel in the upper portions of the reservoir.

Recovery of the river channel within the reservoir sediments was also a major factor in design. We concluded that removal of the dam without subsequent channel restoration would result in head cutting through the sediments followed by lateral migration as the channel evolved towards a stable form. The amount of time required for the channel to reach equilibrium was unknown, but the lack of pattern reestablishment in low gradient channels in Minnesota straightened in the late 1800s, suggested that recovery time could extend into centuries.

Design Approach

We concluded that the most effective means of stabilizing the sediments was to use natural channel design techniques to restore the river using the new sediment elevation as floodplain. This would also advance the channel evolution process and provide quality aquatic habitat and recreational opportunities. Channel design would be based on stable reference cross-sections transferred to the dam site using Manning's equation to adjust for slope and roughness. Quantifying channel morphology in reference sites was the first step in the design process.

Reference Sites

We canoed the lower Pomme de Terre River to find and survey reference cross-sections (Figure 32). The lower 30 miles of the river has a relatively small variation in drainage area due to the shape of the watershed. Surveys were conducted during a bankfull event of 500 cfs and a discharge measurement was taken in the upper site. This allowed back-calculation of roughness coefficients and assurance of discharge associated with bankfull. The bankfull indicator used was the elevation of the depositional flat at the point bar or the incipient point of flooding. A Kevlar tagline was used for support but surveying while wading was still challenging since the gravel bed materials were mobile. A canoe was attached to the tagline for surveying and for collecting discharge measurements in deeper cross-sections. A USGS gage is located directly downstream of the dam allowing determination of the bankfull recurrence interval.

Slope varied considerably among the reference sites but all riffle cross-sections were of the C4 type using Rosgen's stream classification (Figure 33). Slope and roughness differences explained differences in cross-sectional area.

Figure 32. Aerial photos of the reference reaches used in design of the Pomme de Terre River Restoration. Site Four is on the left, Site Five is in the middle, and the Gage Site is on the right. Red markers show riffle transect locations.

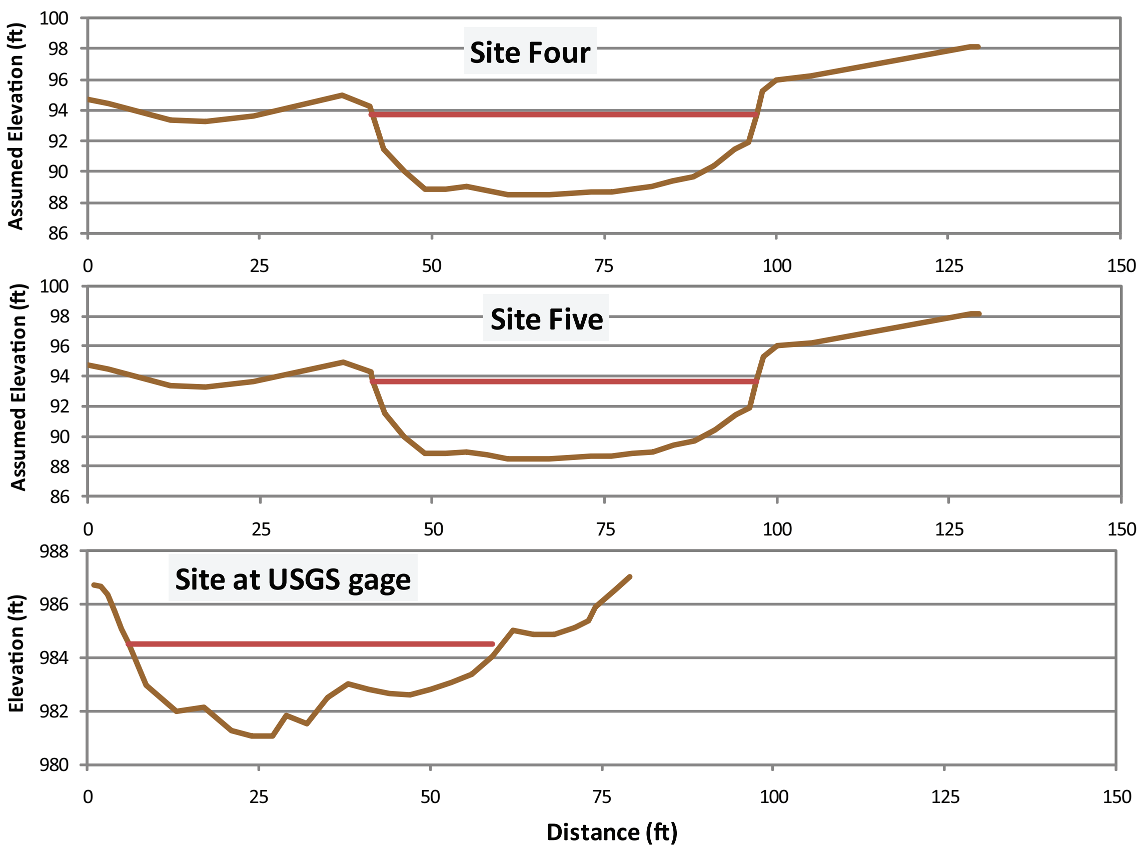


Figure 33. Riffle cross-sections at reference sites used for the design of the Pomme de Terre River.

Geomorphic data for three of the reference sites are shown in Table 1. Reference sites were selected for based on bank stability, presence of a healthy riparian corridor, and habitat. The narrowest riffle (hydraulic control) was chosen for cross-sectional survey. The hydraulic control for the USGS gage (05294000) was also surveyed to provide additional channel hydraulics and to allow back-calculation of Manning's N for a boulder weir. A discharge measurement was taken at the uppermost reach; discharge for Site Five and the Gage Site was taken from the USGS gage. Data were collected at Site Four on May 21, 1997 and at Site Five and the Gage Site on May 22, 1997.

A pebble count directly upstream of the reservoir at site five shows a median particle size of 24 mm (coarse gravel) (Figure 34).

Channel Design

The reference channels provided the basic geomorphic data for channel design. We assumed that since the reference channels were currently handling the water and sediment provided by the watershed and remaining stable, they would make appropriate templates for the restoration design. Slopes in the new channel; however, were a function of the floodplain established by the deposited sediments and the pattern of the design. Since slope affects both channel flow capacity and competence (shear stress), channel dimensions were adjusted with changes in pattern.

Two stream-reaches and four channel dimensions used in the restoration are shown in Table 2. The

Site	Four	Five	Gage
Location from dam	12 mi upstream	4.4 mi upstream	600 ft downstream
Wbf, Bankfull width (ft)	55.8	63.9	68.5
Dbf, Mean depth (ft)	4.4	2.3	2.5
Dmax, Max. depth (ft)	5.2	4.2	4.4
W/D	12.8	27.5	27.4
Cross-sectional area (ft^2)	243	148	171
Entrenchment ratio	27.8	21.9	3.1 (due to encroachment)
Floodprone width	1553	1399	209
Hydraulic control	Gravel riffle	Gravel riffle	Large boulder weir
Slope	0.018%	0.17%	0.7%
Back-calculated Manning's N	.026	.03	.077
P	58.8	67.3	70.1
R	4.1	2.2	2.4
Bankfull flow (cfs)	491	503	503
Bankfull shear stress (kg/m^2)	0.23	1.1	5.2
Drainage area (mi^2)	860	900	905
Sinuosity	1.8	2.3	1.6
Rc, Radius of curvature (ft)	128-218	150-308	144-331
Rc/Wbf	2.3 – 3.9	2.3 – 4.8	2.1 – 4.8
MBW, Meander belt width (ft)	1370	2134	1110
MBW /Wbf	24.6	33.4	16.2
Type	C5	C4	C4

Table 1. Geomorphic data for reference sites. Dimensions are for narrowest riffle cross-sections.

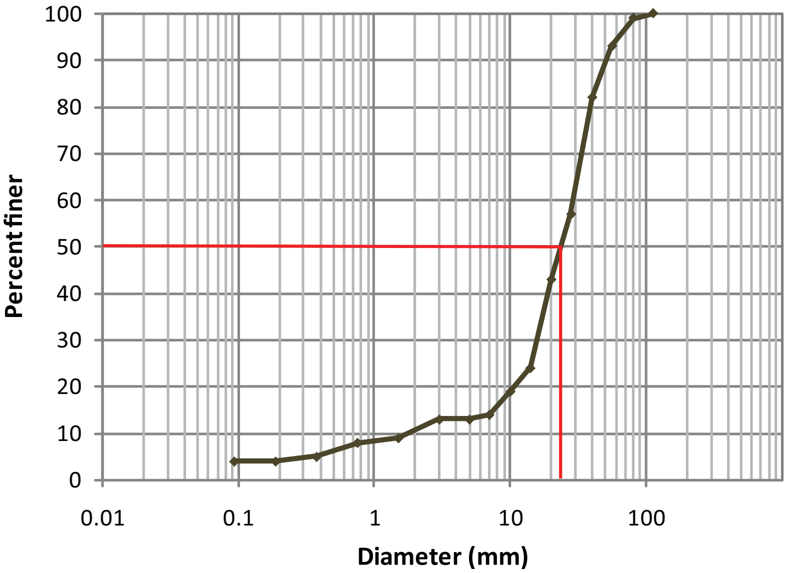


Figure 34. Pebble count from site five directly upstream of the Appleton Milldam Reservoir.

downstream reach, from the dam site to the bridge crossing, was designed with a steeper slope than the upstream reach to bring the channel up to the sediment level in a shorter distance. I also assumed a higher roughness coefficient for the downstream reach because boulder weirs and rougher riffles were to be used for grade control. The higher roughness compensated somewhat for the steeper slope but the downstream channel was slightly smaller than the flatter upstream reach. Both reaches used 2:1 side slopes in the riffles and the outside bank of the pool while a 4:1 side slope was used on the point bar of the pools. The channel was transitioned from riffle to pool cross-sections during construction.

Since existing sediments in the reservoir were dominated by silt, while the upstream bed materials were dominated by gravel, fieldstone riffles were incorporated into the design as grade control to assure channel competence until bedload was carried into the new channel. The riffle design used is a hybrid of the Newbury Weir (Newbury and Gaboury 1993) and structures used by Rosgen (1996), and was developed to: emulate natural riffles in Minnesota, create flow convergence patterns and pool scour, provide habitat, and remain stable when constructed on fine sediments (Figure 35). The fieldstone was sized based on shear stress calculations using large enough stone to remain stable.

The fieldstone riffles were used to bring the channel grade up at a steeper slope in the downstream end of the restoration to match bankfull with the sediment elevation so that it would become the new floodplain. A rock arch rapids (discussed in Chapter Two) would be built at the footprint of the dam with two additional rapids within the lower 1,000 feet of channel to raise the bed approximately three feet.

The pattern design process was iterative and was complicated by private land ownership. Abstracts for private lands used the water's edge as a boundary. With the dam removed, the water's edge became a function of the alignment of the constructed channel. Some residents wanted the river to meander near their homes while others, with fresh memories

Habitat	Width (ft)	Max. Depth (ft)	Side slopes	Area (ft^2)	W/D	N	Slope
Upstream Riffle	64.5	4.1	2:1	231	18	.04	0.077% (reach)
Upstream Pool	64.5	7.1	2:1 and 4:1	267			
Downstream Riffle	57	4.1	2:1	203	16	.07	0.026% (reach)
Downstream Pool	57	7.1	2:1 and 4:1	225			

Table 2. Basic riffle and pool cross-section design data used in the Pomme de Terre River restoration. The upstream and downstream reaches are separated by the North Hering Street bridge.

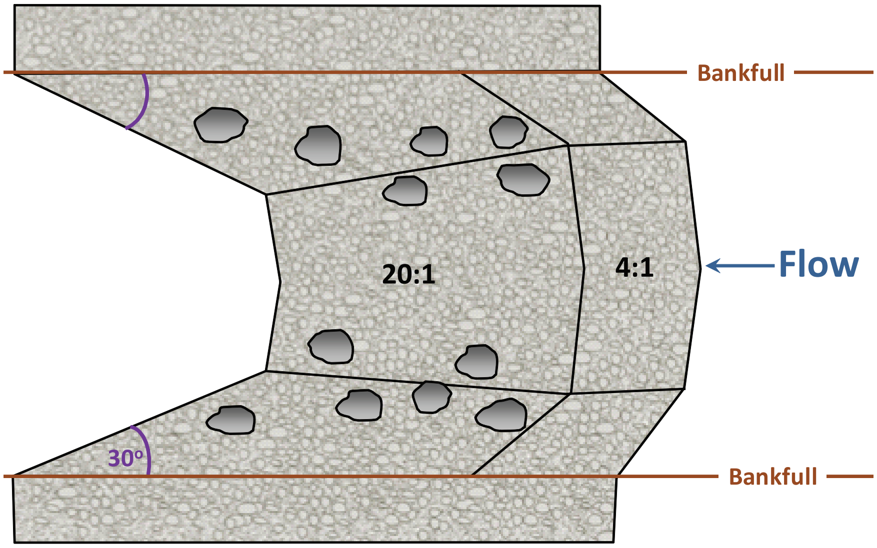


Figure 35. Riffle design used for grade control and habitat in the Pomme de Terre River restoration.

of the 1997 flood wanted the channel away from their homes even though the channel alignment would have no bearing on flood elevations. Several channel configuration alternatives were laid out using reference channel ranges for radius of curvature and other pattern statistics. The preferred design pattern that appeared to follow the historic channel became possible when the necessary land tract was donated to the city (Figure 36). The design channel included two main meanders on opposite sides of the gully that initially formed after the dam was removed.

The radius of curvature in the design channel varied within the range observed in the natural channel. Very tight meanders with radii of curvature as little as 70 feet (1.1 bankfull widths) were observed in the natural channel but were avoided since the constructed channel would not have the established vegetation and root density necessary to stabilize the banks with the associated centrifugal force. The tightest bends in the design had radii of curvature of about 131 feet or two bankfull widths. Root wad tree revetments, J-hook vanes (Rosgen 1996), and willow stakes, were used for bank protection on outside bends.

Root wad revetments included the root wad and 15-20 feet of trunk that were driven into the bank with an excavator so that the root wad faced into the current. A 20-foot footer log was set under and perpendicular to the root wad. Root wads were sized so that their crown diameter approximated the distance between the toe and the bankfull elevation to provide full protection of the active channel bank. Willow stakes were cut locally and primarily black willow *Salix nigra* cuttings were used.

The constructed channel was designed so that the estimated bankfull stage would approximately match the elevation of the reservoir sediments (Figure 37). Pre-dam channel elevations were approximated from thalweg elevations upstream and downstream of the reservoir. The channel slope was steeper downstream of the bridge.

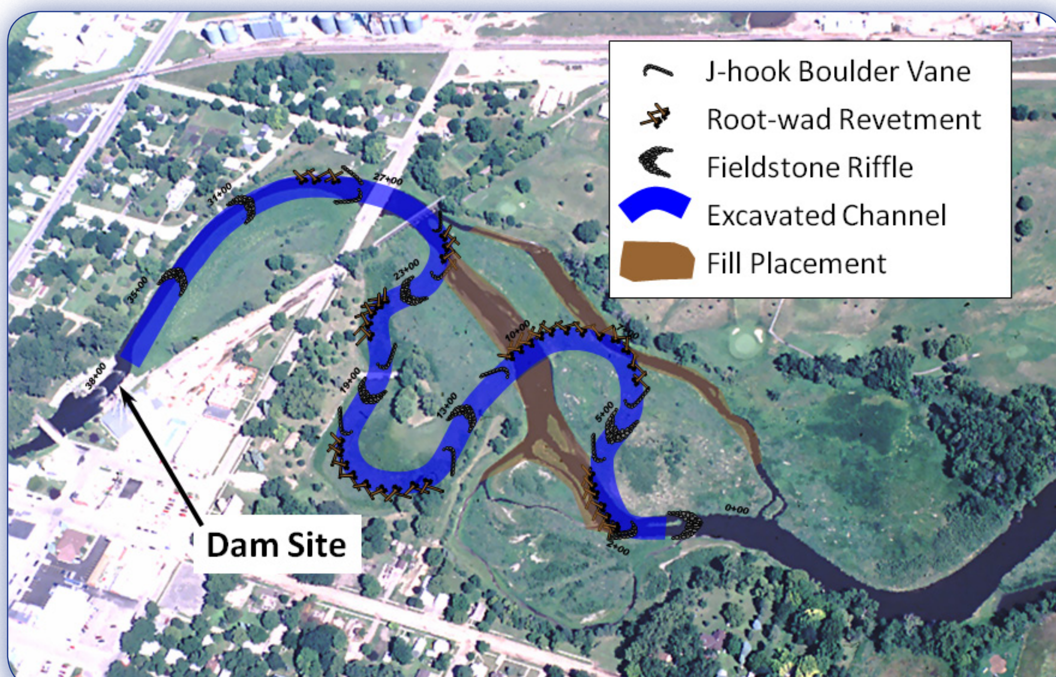


Figure 36. Planview of the Pomme de Terre River restoration in Appleton, Minnesota

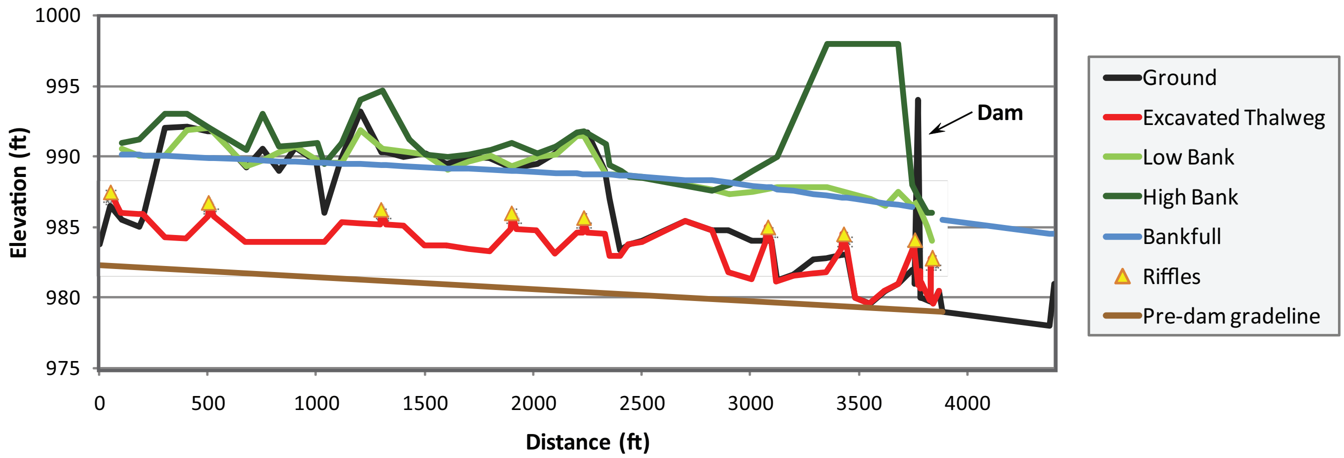


Figure 37. Profile of the Pomme de Terre River restoration showing pre-project sediment elevation at channel centerline, low and high banks, excavated channel thalweg, designed bankfull, and the approximate pre-dam grade-line.

Dam Removal and Project Construction

A 20-foot wide portion of the spillway was removed with a track excavator on July 9, 1998 during low flows to allow the reservoir to completely drain and the sediments to consolidate (Figure 38). The small opening allowed the dam to provide grade control in the event of a large flood. While flows on this date were 282 cfs, or a little over half bankfull, some head-cutting was initiated by the breach. Reservoir sediments contained resistant clays that slowed channel incision. The exposed sediments began to vegetate almost immediately and green ash *Fraxinus pennsylvanica*, eastern cottonwood *Populus deltoides*, and silver maple *Acer saccharinum* saplings were apparent by fall.

Figure 38. Partial removal of the dam spillway to allow the reservoir to drain (July 9,1998).

The dam was entirely removed by March 6, 1999 and replaced with a 2-foot high, 80-foot long, rock arch rapids for grade control and maintenance of the tailwater pool that was a popular fishing area (Figure 39). Two U-shaped boulder weirs were incorporated into the rapids to create flow convergence. Quarried boulders

Figure 39. Construction of rapids following removal of the dam, March 4, 1999.

were initially used for the weirs but these were later replaced with fieldstones due to the tendency of the sharp edges of the quarried stone to damage canoe hulls.

Two additional fieldstone riffles were constructed 300 and 700 feet upstream of the dam as an initial phase of the restoration in January 2000 (Figure 40). Cumulatively, the rapids and the two riffles raise the bed about four feet.

Excavation of the new channel was done in January 2001 (Figure 41). Winter construction was chosen because flows were low and stable without risk of sudden rains and the ground was frozen allowing trucks to access the work area. Most of the channel

Figure 40. Construction of a fieldstone riffle, January, 2000.

Figure 41. Excavation of the downstream meander, January 12, 2001.

excavation and placement of structures was separated from river flows and could be done in the dry (Figures 42 & 43).

Ideally, the channel would have been allowed to vegetate before flows were diverted into it but the 25,000 yards of excavated fill would have had to be hauled out of the floodway and then hauled back in to fill the gully and divert flows into the new channel. This would have significantly increased cost. We were also concerned that the gully would have further incised and mobilized more sediment if it were left in place through the spring flood. Flows were diverted into the downstream meander on January 29, 2001

Figure 42. Building a J-hook vane in the new channel, January 23, 2001.

Figure 43. Root-wad revetments in the new channel, January 26, 2001.

and into the upstream meander on February 13, 2001 (Figure 44 & 45). Final grading was finished on February 14, 2001.

The spring of 2001 brought the second largest flood of record (7,980 cfs), second only to the 1997 flood (8,890 cfs) that undermined the dam. Based on log Pearson analyses of the annual series, these two events were 350-y and 500-y recurrence floods respectively; the 100-year recurrence flood was estimated to be 5,520 cfs prior to inclusion of these events in calculations (Lorenz et al 1997). The 2001 flood was also very long duration and the river remained above bankfull for a month. Since the flood occurred prior

Figure 44. Diversion of flows into the downstream meander and simultaneous plugging of the straight gully, January 29, 2001.

Figure 45. Constructed riffle in the downstream meander just after flows were diverted into it on January 29, 2001.

to any re-vegetation of the disturbed area, the project was particularly vulnerable. The constructed channel survived this flood with few damages but significant fill was washed out of the plugged gully. Repairs were made the following August. While the damages were a setback, the flood also carried bed materials into the river channel through the former reservoir that had been dominated by silt. Gravel and cobble were deposited in the riffles and diversified the habitat.

Figure 46 shows the progression of the reservoir and river over time. In 1938 the reservoir was largely open water but had filled with sediment by 1997 and the river displayed a braided channel. After the dam was removed in 1999, the river incised a relatively straight channel through the accumulated sediments and started to isolate some of the channels. After the restoration in 2003, the river channel is similar to reaches not influenced by the dam. The most recent photo in 2008 shows the re-establishment of a floodplain forest in parts of the former reservoir. The restored channel has shown little apparent change since construction.

Sections of Fisheries surveys of the river upstream of the dam have shown a shift in the fish community since the dam was removed and the river restored towards native riverine species (Figure 47). Black bullheads *Amieurus melas* and common carp had dominated the silt-laden reservoir. Surveys subsequent to the dam removal have collected channel catfish, freshwater drum, stonecat, walleye, silver redhorse, golden redhorse, and other species not collected in pre-removal surveys (Data provided by Chris Domeirer, Section of Fisheries). These shifts are likely due to the combination of restored connections to the Minnesota River as well as habitat changes. The deepest areas of the reservoir were about four feet while the restored river has pools that have deepened to as much as eight feet during low flow conditions (10 ft bankfull depth). Substrates have shifted from predominantly silt in the reservoir to more diverse materials including gravel and cobble.

Figure 46. Aerial photos of the Appleton Reservoir in 1938, 1997, 2000 after dam removal, 2003 after river restoration, and 2008.

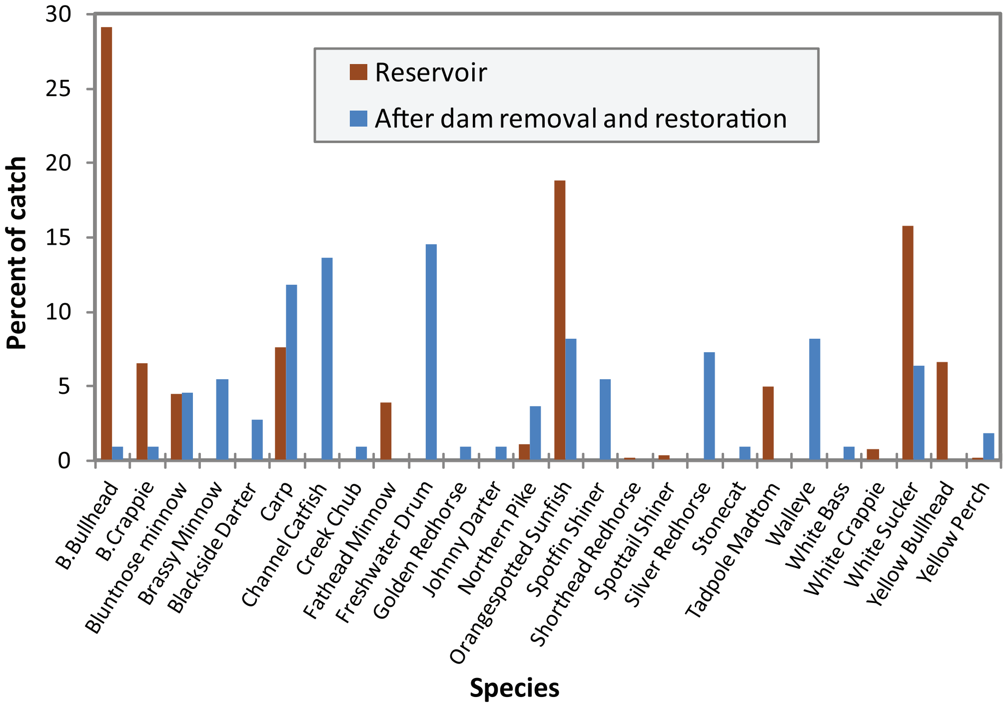


Figure 47. Relative abundance of fishes in the Lower Pomme de Terre River upstream of the dam site before (brown) and after (blue) removal of the dam. Fish were collected with trap-nets and electrofishing. Minnesota Section of Fisheries Data.

The city chose to allow the riparian zone of the river to revert to natural habitat. Native wildflowers, grasses, and trees have been planted in addition to those seeded naturally and they grew quickly in the fertile soils of the reservoir (Figure 48). Habitat created by the removal and restoration has also affected birds and mammals. River otter *Lutra canadensis* have been observed fishing near the fieldstone riffles and deer bed along the river. Wild turkeys *Meleagris gallopavo* move along the river corridor, and pheasant *Phasianus colchicus* are common in the new floodplain.

Attitudes about the dam removal have changed, as have recreational uses of the river. The river has become a popular canoe route and the pool below the rapids at the dam site is a well-used swimming hole for neighborhood children. Walleye fishing in pools of the restored channel can be excellent. Bob Hayes, a life-long resident who was born in the house where he lived on the reservoir, exemplified the shift in perspectives. He was initially opposed to the dam removal but later donated the land needed for the downstream meander to the city. After we diverted the river into the new channel he told me "it looked great", and that he planned to buy a kayak. Bob was 81 years old at the time and never got the chance to get his kayak as he died three years later, but his love of the river and his new appreciation of the restored channel were memorable.

Figure 48. A photo showing rapids at the former dam site as it looked on October 10, 2008.