Reconnecting Rivers: Natural Channel Design in Dam Removal and Fish Passage

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Reconnecting Rivers:

Natural Channel Design in Dam Removals and Fish Passage

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Acknowledgements

The projects discussed here were the culmination of the hard work of many dedicated individuals. Dam removals and modifications are inherently controversial and breaking away from status quo often requires that those involved face resistance and skepticism. Special thanks to Ian Chisholm, Stream Habitat Program Supervisor, for providing the professional support and latitude to take on these projects, as well as his contributions to fieldwork, design, and funding acquisition. Thanks to coworkers, Ann Kuitunen, Shawn Johnson, Kevin Zytkovicz, Karen Terry, Neil Haugerud, and Amy Childers for field work, project assessment, and intellectual exchanges that made this possible. Thanks to Section of Fisheries staff, Arlin Schalekamp, Dave Friedl, Mike Larson, Dennis Topp, Chris Domeier, Henry Drewes, Henry Van Offelen, Kevin Stauffer, Tom Groshens, Roger Hugill, and others who acquired funding, conducted assessments, contributed to design, logistics, permitting, and worked with communities to bring projects to fruition. Thanks to Division of Waters staff, Bob Merritt, Chad Konickson, Julie Aadland, Terry Lejcher, Skip Wright, Rob Collett, and Dam Safety engineers, Craig Regalia and Jason Boyle for work on permitting. Thanks to Paul Stolen for his pivotal work in environmental review. Thanks to Amy Childers for her outstanding work in editing this publication. Finally, thanks to Julie Aadland, DNR Hydrologist, for her support, constructive criticism, and feedback.

Disclaimer

Every dam, fish passage project, and river has its own unique characteristics. State laws often require the oversight of a licensed professional engineer (P.E.) with dam related experience for projects of this type especially if the dam crest is altered. In addition, permits from multiple jurisdictions are often required for dam related projects. While the author developed the conceptual designs and design criteria as they pertain to river restoration and fish passage for the projects detailed here, many of the projects also had the involvement, final design responsibility and oversight of one or more licensed civil engineers. River projects, by nature, are most successful when they are designed through the collaboration of experts of different disciplines and, where possible, dam related projects should involve hydrologists, fluvial geomorphologists, ecologists, engineers, and biologists to assure that all site-specific issues are addressed. None of the design information or examples presented here replaces the design oversight and responsibilities of the project engineer.

Preface

The goal of this document is to provide an overview of issues relevant to dam removal and fish passage projects with case examples to illustrate problems that were encountered and how they were handled. Both the technical and social issues surrounding these projects have been included because controversy is inherent to dams and river management. Frequently, advancement of river restoration projects requires as much expertise in diplomacy as science. Opponents to such projects often have genuine concerns and my experience has been that these individuals can become valuable allies when their concerns are addressed and projects are successfully implemented. People are frequently fearful of change especially when there are numerous unknowns. Relatively new concepts are particularly subject to these unknowns and uncertainty. Hopefully this paper helps in addressing these concerns and provides a vision for some river management alternatives.

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Introduction

Dams have long been viewed as symbols of industrial productivity and icons of national pride credited with a key role in the early growth of industry in the U.S. and other countries. Dams have been built for a wide range of uses including mills (grist, flour, and lumber), flood control, water supply, hydropower, recreation, navigation, and irrigation. The U.S. has

- *6,575 large dams at least 15 m high (49 feet), second only to China (Figure 1),*
- *over 75,000 dams at least six ft high (1.8 m) (National Dam Inventory),*
- *and likely much greater numbers of non-inventoried smaller dams.*

From a strict economic view, dam and reservoir deterioration, failure risks, and costs of dealing with obsolete dams is a crisis that countries with large numbers of dams will need to face. In the past, environmental damages associated with dams have been largely ignored or excluded from benefit: cost analyses that are fundamental in decision-making. This is unfortunate because dams have severely altered our rivers and many of the consequences have been unanticipated or poorly understood. Research over the last 50 years has substantially increased the understanding of dam effects. The objectives of this manuscript are to provide an overview of dam related problems and issues followed by examples of alternatives that will hopefully lead to better-informed decisions.

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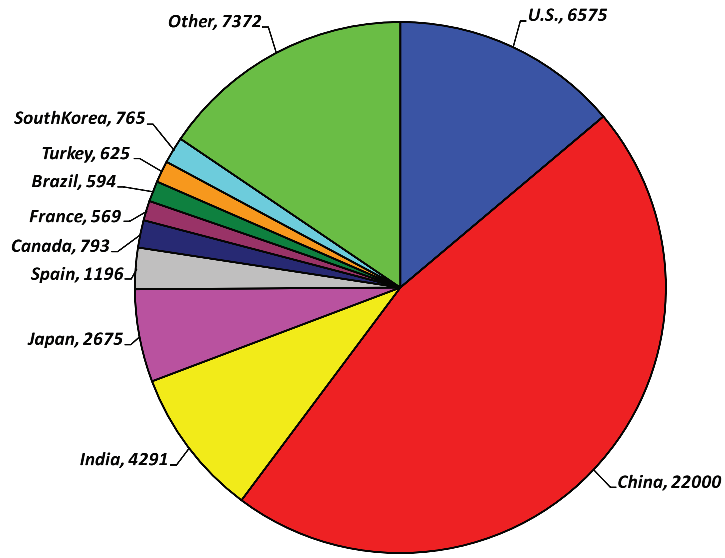

Figure 1. Number of large dams (≥15 m high) by country. Source: World Commission on Dams

Dam Problems

Structural Integrity and Dam Failure; Diminishing Functions, Growing Liabilities

As dams age, failure risks increase and loss of life and economic costs associated with failure can be substantial. Over 30% of U.S. dams are at least 50 years old, which is the design life of many dams (Powers 2005), so by 2018 85% of our dams will have exceeded their design life (FEMA 1999). The Natural Resources Conservation Service has constructed over 10,450 dams for flood control and other functions plus many additional dams designed for grade control at a cost of $14 billion. More than 2,400 of these dams are in need of repair, of which 1,800 of them will have reached the end of their life span by 2010 (NRCS 2000). While significant flood damage reductions are claimed by builders of flood control dams, these benefits must be weighed against negative impacts including environmental damages, attraction of floodplain development, resulting increased risk, potential damages, and loss of life from catastrophic dam failures.

From 1985 to 1994, there were more than 400 dam failures in the United States or about 40 per year (NRCS 2000). The number of unsafe U.S. dams rose by 33% between 1998 and 2005 to over 3,500 (ASCE 2005). The Johnstown Flood in Pennsylvania that killed 2,209 people in 1889 was due to failure of the South Fork Hunting and Fishing Club Dam that was rebuilt just eight years prior. This dam had serious design flaws and concerns over its stability had been expressed prior to its failure. Six dams failed during a flood in the same watershed in 1977 killing 85 and causing $300 million in damages (Hutcheson 1989, Frank 1988). While loss of structural integrity due to age and poor design increase failure risk, all dams have the potential to fail.

The most catastrophic and deadliest dam failure was that of the Banqiao Dam on the Ru River, China in 1975. The water released by the failure resulted in the failure of 61 additional dams and an estimated 235,000 fatalities from drowning and subsequent famines and other factors due to the dam failures. This dam was nicknamed the "Iron Dam" because it was thought to be unbreakable after Soviet engineers had rebuilt it to withstand a 1,000-year flood. The watershed received over a meter of rain during a monsoon prior to the failure (Yi Si 1998).

While loss of structural integrity due to age and poor design increase failure risk, all dams have the potential to fail.

The 2003 failure of the Silver Lake Dam on the Dead River, Michigan resulted in over $100 million in damages and failure of the downstream Tourist Park Dam. The dam had been equipped with an overflow spillway "fuse plug" to meet "probable maximum flood" (PMF) standards in 2001. A PMF rainfall for this site is a 16.6-inch 24-hour rain, or a 19.6-inch 3-day rain, but the fuse plug failed when 4.5 inches of rain fell over five days in the watershed (FERC 2003). Both the Banqiao and Silver Lake dams were designed to handle very large floods but failed none-the-less.

Dam failures also can result in long-term damages to channel stability, aquatic habitat, and water quality. The Silver Lake Dam failure released approximately one million yards of sediment into the Dead River burying the river channel and leveling thousands of trees (Mistak 2004, Figure 2).

Figure 2. The Dead River downstream of the Silver Lake Dam failure showing resulting hillside failure (upper right), buried tree in middle of river channel and widespread sedimentation.

Failure of the newly constructed City Dam in Fergus Falls, Minnesota and resulting failure of three downstream dams in 1909 resulted in severe channel incision still evident today (Figure 3).

Heiberg Dam on the Wild Rice River in Western Minnesota failed in 2002 by eroding through an embankment into a tributary and cutting off a 1.5 mile-long meander (Figure 4). This resulted in as much as 15 feet of incision of the streambed that nearly undermined the footings of an upstream state highway bridge. The dam was ultimately removed and replaced with rapids and the gully was plugged with a new embankment reconnecting the abandoned meander.

Like loss of structural integrity, sedimentation of reservoirs is becoming a national and world crisis. ...25% of the reservoirs in the U.S. are projected to be at least half full of sediment by 2018.

Figure 3. Floodwaters released by the failure of the Fergus Falls City Dam and the Wright Power Dam in 1909 (left) and remains of the City Dam (right) on the Otter Tail River, Minnesota.

Reservoir Sedimentation

The functional lifespan of all dams is also limited by inevitable sedimentation. Like loss of structural integrity, sedimentation of reservoirs is becoming a national and world crisis. The rate at which a reservoir fills with sediment is a function of sediment loads of the contributing watershed, percent of that sediment intercepted, and the volume of the reservoir. Despite reductions in cropland soil losses due to the Conservation Reserve Program, reservoir sedimentation rates are about six times that prior to 1930 (Figure 5) and 25% of the reservoirs in the U.S. are projected to be at least half full of sediment by 2018 (Bernard and Iivari 2000). This higher rate may be due to increased stream bank erosion resulting from aggraded valleys, agriculture practices, channel incision due to channelization, and removal of riparian vegetation. Palmieri et al. 2003 estimates that 21% of global reservoir storage has already been lost to sedimentation, 42% of the world's reservoir storage will be lost by 2050 and within 200 to 300 years virtually all of the world's reservoirs will be full.

The large reservoirs of the Missouri River are filling at a rate of 89,000 acre-feet (144 million yards) per year (ACOE 1998), and the most downstream

Figure 4. Failure of Heiberg Dam, Wild Rice River, Minnesota on June 12, 2002 (left) and an aerial photo of the meander cut off (orange oval) by the failure. Local residents are shown rescuing stranded fish on the Otter Tail River, Minnesota.

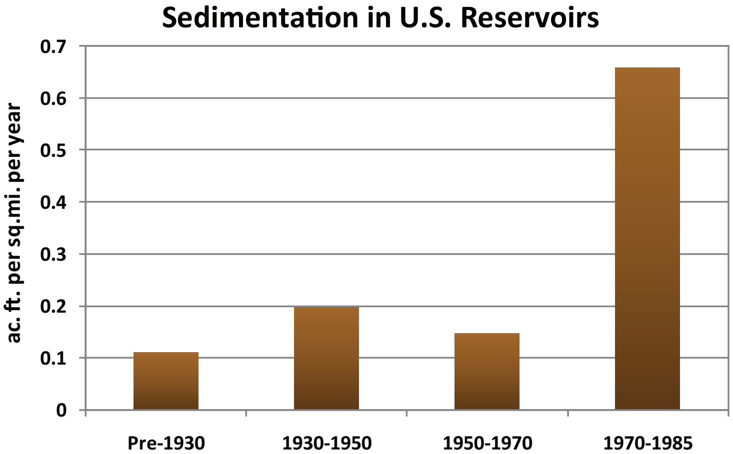

Figure 5. Sedimentation rates in acre-feet per square mile of drainage area per year. The lower rate in the 1950 to 1970 time period is due to addition of the large drainage reservoirs that have a lower sedimentation rate per drainage area. Data from Bernard and Iivari (2000).

reservoir, Gavin's Point, had already lost 23-24% of its original storage by 2007 (Boyd et al. 2008). The Sanmenxia Dam, built in 1960 on the Yellow River, China, created a reservoir that was initially about twice the volume of Lake Mead, the largest U.S. reservoir. The Yellow River has the highest sediment concentration of any major river in the world, which is about 60 times that of the Mississippi. Within the first four years after completion it lost roughly half of its storage capacity to sedimentation (Qinghua and Wenhao, 1989). The dam also caused retrogressive siltation in the Weihe River, an upstream tributary of the Yellow River, progressing upstream at a rate of 10 km/y and causing massive flooding (Wang et al. 2007). Rapidan Reservoir on the Blue Earth River in Southern Minnesota was almost 60 feet deep when it was built in 1910 but is now less than four feet deep since accumulating over 11 million yards of sediment, virtually filling it up to 55 feet deep (Barr, 2000, Figure 6). The dam is also structurally unsound and $2 million were spent on temporary emergency repairs in 2002 with additional emergency repairs in 2007 to fill voids under the buttresses.

Efforts to maintain the volume of reservoirs have had minimal success and have been costly. Removing sediments by dredging needs to be done continuously as new sediments continue to enter the reservoir. In 1998, the U.S. Army Corps of Engineers dredged 250 million yards from our rivers, harbors, and shallow reservoirs at a cost of $715 million or $2.86 per yard (Hilton, 1999). For perspective, Lake Sakakawea (Garrision Dam on the Missouri River) would cost about $118 million per year to maintain at this rate, and costs in current dollars would likely be much higher, if dredging is even possible, due to the depth of the reservoir. Flushing sediments by drawing down reservoir levels and creating riverine conditions has been used as a strategy at some sites but also has major drawbacks. The technique only works on narrow reservoirs, requires the reservoir to be drained for extended periods, and requires

Figure 6. Rapidan Reservoir on the Blue Earth River in 1939 (left) and 2003 (right) showing accumulation of over 11 million yards of sediment.

passage of large volumes of water (Atkinson 1996). The Sanmenxia Dam had been designed to produce 1,000 megawatts (MW) of hydropower but turbines had to be removed to pass sediment and most of the original functions of the dam were lost. Flushing of reservoirs can cause additional problems downstream of the dam. When Bilsby Reservoir on the Cannon River, Minnesota was flushed in 1985, the organic-rich, sediment-laden water leaving the reservoir caused anoxia and a significant fish kill (Dirk Peterson, Area Fisheries Manager, personal communications). Flushed sediments can also aggrade the river channel causing channel instability, fill interstitial spaces in the substrates, and cause mortality of mussels and other benthic invertebrates (Katapodis and Aadland, 2006).

Channel Degradation

The interception of sediment in reservoirs creates additional problems downstream of dams. Channel incision due to "sediment hungry" discharge is common. Channel incision separates the channel from its floodplain and creates high, erodible banks. Once a channel has downcut its bed, erosion rates accelerate as the channel rebuilds its floodplain through erosion and sedimentation processes. Red Rock Reservoir on the Des Moines River, Iowa intercepted about 65 million yards of sediment in the first eight years of its existence (Karim and Croley 1979) and caused six feet of channel incision downstream of the dam (Williams and Wolman 1984). Channel incision, primarily due to channelization, has caused over $1.1 billion in damages to roads, bridges, and cropland in Western Iowa (Hadish and Braster, 1994). Studies below 24 dams in Kansas found incision ranged from one to nine feet (Juracek, 2001). Williams and Wolman (1984) found up to 7.5 m (24.6 ft) of channel incision among sites below 21 dams studied.

While "check" dams have been widely used for grade control, they too can cause further downstream incision due to sediment interception. Four check dams were built on the Sand Hill River in western Minnesota. Since their construction, the riverbed has degraded seven feet (Eric Jones, Houston Engineering, data and personal communications, Figure 7).

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River Delta Effects

Another problem associated with sediment interception by dams is the effect on river deltas. Despite five- to ten- fold increases in sediment loads in the Ohio River from deforestation and row-crop agriculture, there has been a 70% reduction in sediment supply to the lower Mississippi due to dam construction on the Missouri and Mississippi Rivers. The reduction in sediment supply associated with the construction of Fort Randall Dam (1952), Garrison Dam (1953), and Gavin's Point Dam (1955) could be observed almost immediately at the mouth of the Mississippi River (Williams and Wolman, 1984; Meade, 1995; Julien and Vensel, 2005). The City of New Orleans and the Mississippi River Delta are

Figure 7. A check dam on the Sand Hill River where the river has degraded seven feet downstream of the structure since it was constructed.

sinking at a rate of 5 to 25 mm/y due to sediment compaction and tectonic subsidence (Dixon 2008). Lack of sediment to rebuild the delta, loss of coastal wetlands increasing vulnerability to hurricanes, and construction of levees that redirect sediment off the continental shelf have resulted in loss of land area of coastal Louisiana of 102 km^2 (66 mi^2) per year (Kesel, 1989). The sediment annually intercepted by the large Missouri River dams alone would be enough to cover 139 mi^2 with a foot of sediment per year.

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Hydraulic Undertows – The Drowning Machine

While most dam safety agencies have focused on assessments of structural integrity and failure risks, dam tailwater hydraulics are a more common cause of fatal incidents. Most of these fatalities occur below low-head dams with a low hazard rating. In Minnesota, there are no documented fatalities due to dam failure but dam related drowning deaths averaged 1.4 per year in the 1980s prior to the projects discussed here (Jason Boyle, Minnesota DNR Dam Safety Engineer, personal communications). This statistic may be understated since the cause of many drowning deaths in rivers is not established and a single dam discussed here (Midtown Dam) averaged one drowning death every two years.

One of the problems leading to these fatalities is that many of these dams do not look dangerous. I had the misfortune of seeing a dog drown below a low-head dam in Grand Forks, ND while taking a break from my graduate studies. The dog's owner threw a stick into the river upstream of the dam, obviously not aware of the danger. The retriever swam out to get the stick and was carried over the crest into the hydraulic roller. I felt compelled to jump in myself to try and save the helpless animal. Rescuers have, in fact, been frequent victims of hydraulic undertows. In Binghamton, New York, two firefighters died while trying to retrieve the body of a third firefighter in 1975 on the Susquehanna River. Three others nearly drowned as two rescue boats were capsized in the hydraulic roller. Similar incidents are common, but the disturbing event in Binghamton was videotaped.

Hydraulic undertows below low-head dams are caused by high velocity (supercritical) water flowing over the smooth concrete dam face at a steep slope (Figure 8). Supercritical velocity is flow that exceeds the wave velocity or where the Froude number exceeds one. The Froude number (**Fr**) is:

$$Fr = u/\sqrt{g*h}$$

where **u** = velocity, **g** = gravitational acceleration = 32.2 ft/s^2, and **h** = depth of flow.

It is analogous to supersonic velocities in gas. Supercritical velocities are rare in low gradient streams due to the roughness of the bed and gradual slope and are naturally found only in steep rapids and falls. As these flows enter the tailwater, flow vectors are directed into the streambed, while surface water is drawn towards the dam face. Debris and anyone unlucky enough to enter this roller is pulled under and, if they come back to the surface, they are likely to be drawn back again into the undertow near the dam face. Air bubbles are also drawn down by the undertows so the tailwater downstream

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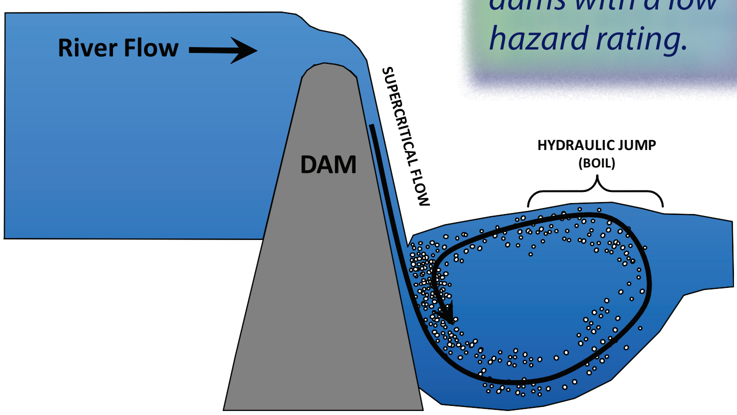

Figure 8. Formation of the hydraulic roller below low-head dams.

of the boil becomes so filled with these bubbles that buoyancy is reduced and boat motors cavitate and lack thrust.

Socioeconomic and Cultural Effects

All of the environmental effects associated with dams ultimately have socioeconomic effects as well. Dam benefits, quantified by their builders, have frequently excluded not only environmental costs but direct societal and cultural costs as well. This is particularly true of those affecting native peoples. Many of the large reservoirs in the United States required relocation of residents, often Native Americans. Garrison Dam, closed in 1953, flooded 152,360 acres of fertile reservation lands belonging to the Mandan, Hidatsa, and Arikara Indians and the required relocation of 325 families (Lawson, 1982). Ironically, the reservoir that flooded 94% of their agricultural lands was named Lake Sakakawea after the Shoshone woman that had been living with the Hidatsa and guided Louis and Clark. The remaining uplands lack the fertility of the productive river bottoms. Similarly, the large hydropower dams in northern Manitoba have required relocation of a number of native bands. In order to build the Grand Rapids Dam, natives of Chemawawinat living at the confluence of the Saskatchewan River and Cedar Lake were moved to a new town built at Easterville with promises of electricity, roads, running water, and a school. However, the project elevated the lake level causing mercury contamination in the fish requiring closure of the fishery. Furthermore, the higher reservoir levels flooded out habitat for beaver, muskrat, and moose that had been mainstays of the community while the new site lacked traditional means of subsistence. Residents of South Indian Lake met a similar fate when diversions of the Churchill River and dams on the Nelson River were built (Waldram 1988). The Three Gorges Dam on the Yangtze River, China, completed in 2008, has required relocation of more than 1.4 million residents but some estimate this could grow to as many as 5.3 million due to landslides and other environmental problems (Bezlova 2007). Hundreds of ancient archeological sites and the scenic gorge itself are submerged by the reservoir (Mufson 1997).

As a result, high gradient habitat, critical for many riverine species, has become rare.

Inundation of Critical Habitat

Dams were frequently built in high gradient river reaches to allow the greatest head, storage, and available power and to take advantage of bedrock outcroppings for solid footings for dams. As a result, high gradient habitat, critical for many riverine species, has become rare (Aadland et al. 2005). Many of the towns with “falls” or “rapids” in their name no longer have falls but rather a dam at the same site (Figure 9). In Minnesota, Thief River Falls, Fergus Falls, International Falls, Grand Rapids, Redwood Falls, Little Falls, Pelican Rapids, Taylor’s

Figure 9. International Falls before and after a dam was built at the site. Pre-dam photo courtesy of Bruce Wilson. The steamboat in the background belonged to Bruce’s grandfather and was able to pass the falls with the help of mules.

Falls, Granite Falls, and Minnesota Falls are examples of communities that had historic rapids or falls that have been inundated by dams. It is interesting that these communities often associate the dam with their heritage rather than the falls after which their town was named. The implication of this practice is that in many river systems few natural rapids remain and species that depend on rapids for spawning habitat are in decline.

Even the Mississippi, which is noted for its low gradient, had major rapids at St. Anthony Falls (flooded out by the Upper and Lower St. Anthony Falls and Ford Dams in Minneapolis), Rock Island Rapids (inundated by Dam 15), Keokuk Rapids (inundated by Dam 19), and the Chain of Rocks rapids that is still present but altered by Dam 27 near St. Louis (Figure 10). The Upper Mississippi river is now a series of reservoirs. The change from lotic (riverine) to lacustrine (lake-like) habitat often results in propagation of alien species and loss of native species (Holden and Stalnaker 1975). Alien species like silver and bighead carp and zebra mussels have benefited from this conversion.

In addition to the presence of critical habitat, some fish species may require lengthy reaches of free-flowing river to sustain populations. Observed migration distances, though impressive, are conservatively biased due to the presence of dams and other impediments to upstream migration (Figure 11). While the importance of migration to anadromous salmonids has long been known, it may be equally important to other species. Auer 1995 concluded that lake sturgeon populations need 155-186 miles of unrestricted habitat and may migrate up to 620 miles. American eel *Anguilla rostrata*, which spawn in the Sargasso Sea, have been collected in the headwaters of the Minnesota River, a distance of almost 3500 miles and even crossed the marshy continental divide into the Red River of the North where they were caught by anglers in Fargo, North Dakota (Aadland et al. 2006).

Flow Regulation

Regulation of flow is an intended effect of flood control, water supply, and many hydropower dams. The large reservoirs on the Missouri, Columbia, and

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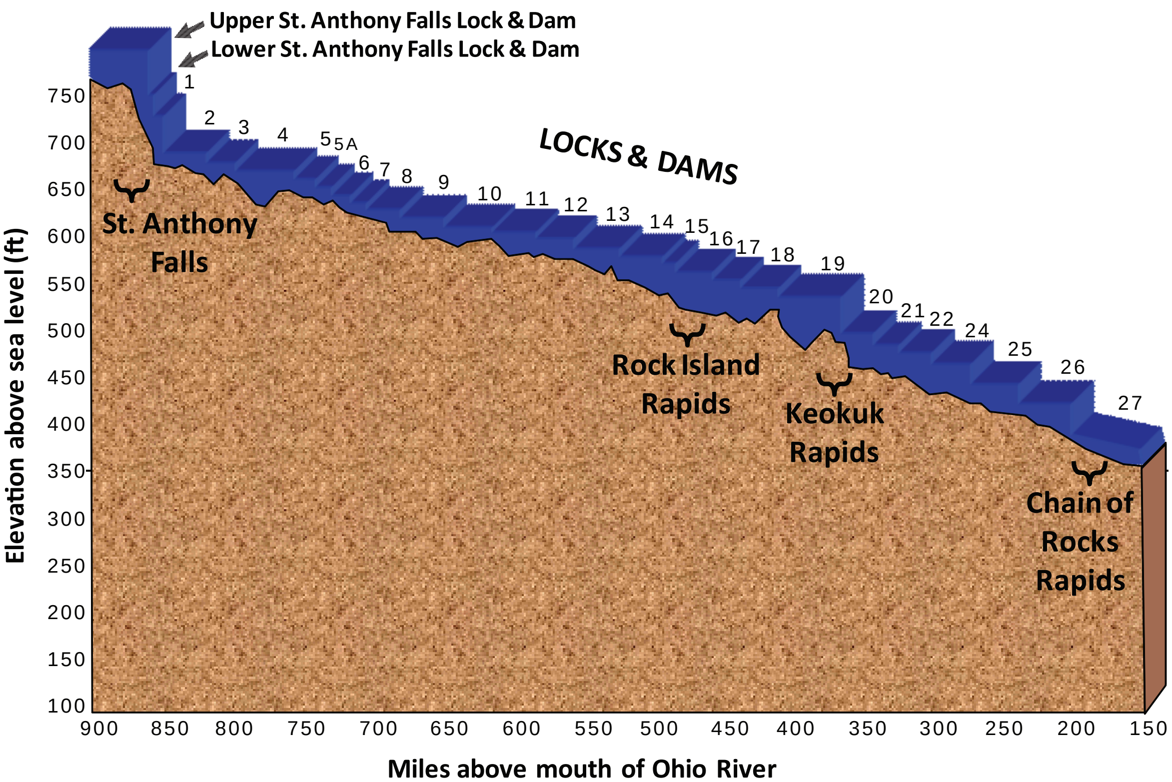

Figure 10. Profile of the Upper Mississippi River showing the dams and historic rapids.

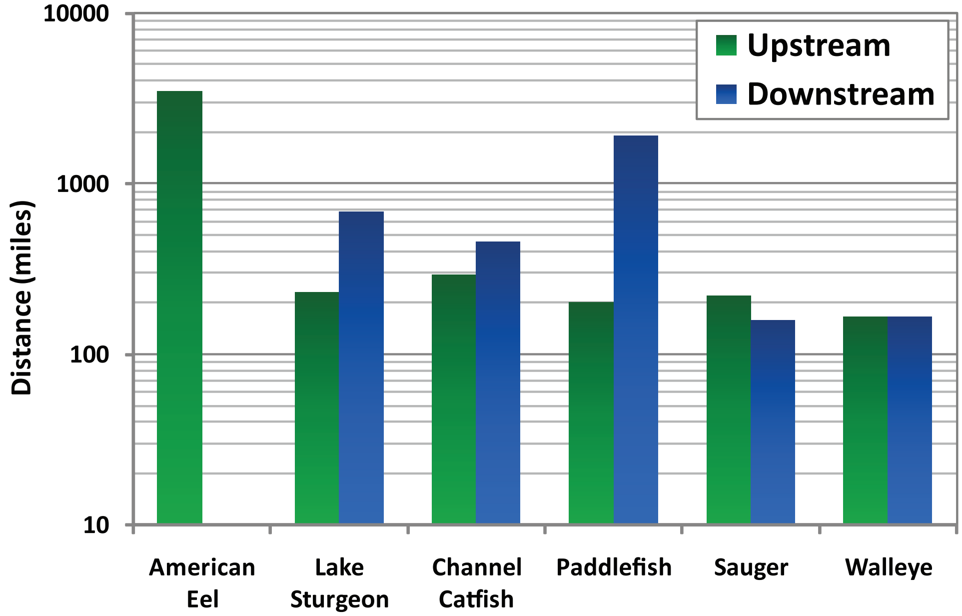

Figure 11. Observed migration distances of Minnesota fishes. References: Stancill et al. 2002, Mosindy and Rusak 1991, Bellgraph 2006, Ron Bruch, Wisconsin DNR, personal communications, Mike Larson, Minnesota DNR, personal communications, Jaeger 2004.

These changes in flow regime largely eliminate the seasonal flooding necessary for maintenance of

- *channels,*
- *riparian and floodplain vegetation,*
- *floodplain habitat, and*
- *the hydrologic cues that many species rely on for migration and reproduction.*

Colorado rivers have enough storage to completely alter the seasonal flow regime. Peak monthly flows on the Missouri and Yellowstone Rivers are naturally high in June. Regulation of flows by Fort Peck and Garrison Dams have resulted in essentially uniform seasonal flows with peaks in February and July (Figure 12). These changes in flow regime largely eliminate the seasonal flooding necessary for maintenance of channels, riparian and floodplain vegetation, floodplain habitat, and the hydrologic cues that many species rely on for migration and reproduction.

While dams tend to moderate seasonal variation in flow, they often increase daily variations. This is especially true of hydropower plants that maximize power production during peak demand and store water during off peak periods. Operation of these plants can create flood flows and drought flows within a 24-hour period (Figure 13). These fluctuations can strand fish or increase their vulnerability to predation and disease, dewater mussels and other benthic invertebrates, desiccate fish eggs, and reduce useable habitat (Figure 14).

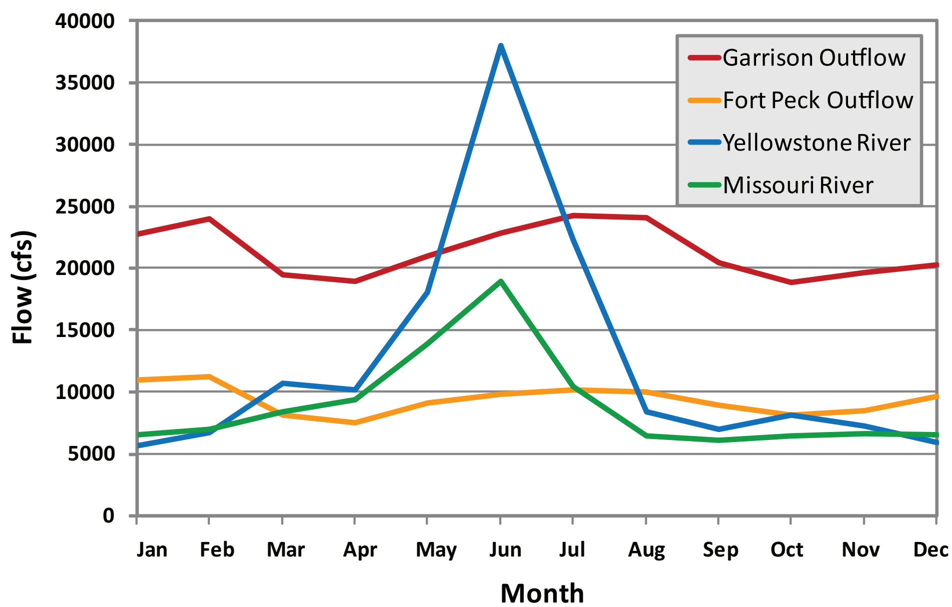

Figure 12. Average monthly outflows of Garrison and Fort Peck dams (1967-2008) and mean monthly unregulated flows of the Missouri River at Landusky, Montana (USGS gage number 06115200, 1934-2007) and the Yellowstone River at Sidney, Montana (USGS gage number 06329500, 1911-2007). Source: U.S. Army Corps of Engineers and U.S. Geological Survey.

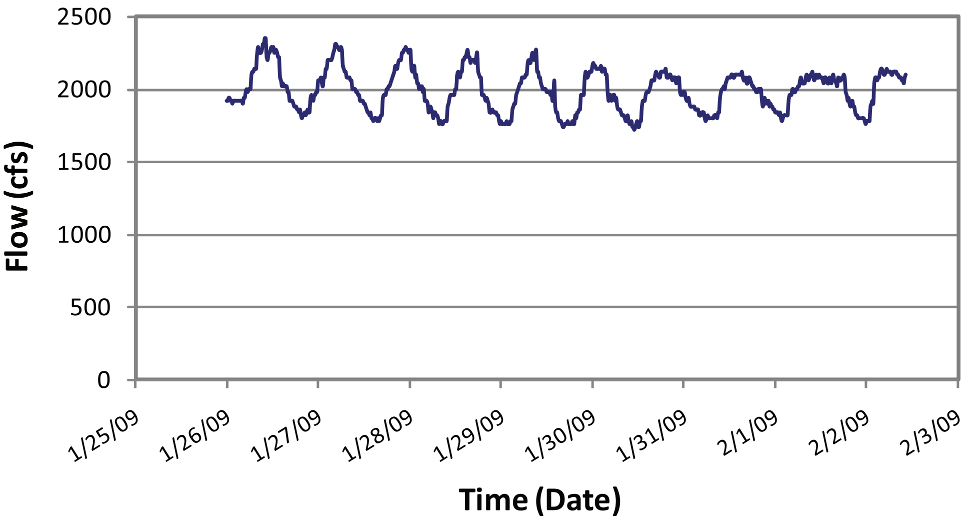

Figure 13. Daily flows fluctuations caused by a hydropower dam at Taylor's Falls, Minnesota on the St. Croix River. Flow fluctuations at this site were much greater prior to implementation of protected flows.

Water Quality Effects

Artificial impoundments created by dams can affect water quality in several ways. Reservoirs can act as both nutrient sources and as nutrient sinks (Al Bakri and Chodhury 2006). Newly impounded reservoirs leach nutrients from flooded sediments and organic matter. While conducting graduate research in 1983, my colleagues and I measured tailwater total phosphorus levels 285% and nitrate levels 479% of those measured upstream of the Larimore Reservoir on the Turtle River, North Dakota, that was dammed four years earlier. Reservoirs can also reduce river nutrients by intercepting and storing them in accumulating sediments and by blocking anadromous fish migrations. This is a problem in nutrient-poor upper reaches of the Columbia River where the productivity of Arrow Lake was reduced by 30% due to conversion of the lake to a reservoir and upstream dam construction (Matzinger et al. 2007).

Rivers can carry significant nutrient loads, especially in agricultural and urban watersheds, and reservoirs create low water velocity conditions that favor blue-green algae (cyanobacteria) blooms (Yoshinaga 2006). The frequency of cyanobacteria blooms in the impounded Barwon-Darling River, Australia was about double that of the natural undammed river (Mitrovic et al. 2006). Observed algae concentrations of the Mississippi River increased 40-fold after impoundment according to Baker and Baker 1981.

Mercury release from sediments, accelerated mercury methylation, and mercury contamination of fish have become significant concerns associated with impoundment and hydropower development in Canada and the Amazon watershed because of their adverse effects on the health of the native people (Rosenberg et al. 1997, Fearnside

Figure 14. A mussel trying to find water during an artificially low flow due to hydropower operation (above) and a northern pike with wounds from blue heron attacks while the pike was trapped in a shallow pool created by operation of a flood control dam (right).

1999). Fish downstream of a reservoir in French Guiana had mercury concentrations eight times higher than fish upstream of the reservoir attributable to anoxic conditions in the reservoir favoring mercury methylation (Boudou et al. 2005)

Temperature regimes can also be significantly altered by impoundments. Shallow and surface release reservoirs on cold-water streams tend to increase temperatures due to increased solar inputs associated with greater surface area and retention time of the reservoir. High head dams with hypolimnion release on warm-water streams tend to reduce downstream water temperatures due to temperature stratification in the reservoir. This drop in water temperature can shift a fish community from a warm or cool-water assemblage to a cold-water community (Tarzwell 1938).

Invasive Alien Species

The conditions and disturbance created by reservoirs makes them conducive to invasive, alien, and tolerant species. A study of five alien species (Eurasian water milfoil *Myriophyllum spicatum*, zebra mussel *Dreissena polymorpha*, spiny water flea *Bythotrephes longimanus*, rainbow smelt *Osmerus mordax*, and rusty crayfish *Orconectes rusticus*) in the Laurentian Great Lakes Region found that these non-indigenous species were 2.4 to 300 times more likely to occur in reservoirs than in natural lakes (Johnson et al. 2008). The study also suggested that reservoirs provide stepping stones for these species to access new waters.

Dam construction creates habitat that is a hybrid between that of a lake and that of a river. In many cases, introduced non-native species have been more successful in part, because native river fishes are not well suited to the altered environment and therefore cannot successfully compete. Many additional invasive species are brought in accidentally via bait buckets and live wells of anglers. Non-native fish now dominate the assemblage of the fragmented Colorado River with at least 67 species introductions. Meanwhile, the native assemblage has declined dramatically due to impoundment of the river and predation and competition by alien species (Mueller et al. 2005, Valdez and Muth 2005).

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Conversion of the Upper Mississippi River to a series of reservoirs has provided ideal conditions for Asian carp. Silver carp *Hypophthalmichthys molitrix* and bighead carp *Hypophthalmichthys nobilis* are planktivorous fish that were introduced in the United States by fish farmers to control algae (though studies have not supported this benefit) (Burke 1986, Bitterlich and Gnaiger 1984). Both species consume phytoplankton including cyanobacteria though stomach contents of bighead carp usually have greater percentages of zooplankton. Flow modifying features such as dams and the resulting low velocity habitat have been identified as important variables associated with the occurrence of Asian carp by Mississippi River scientists (Stainbrook et al. 2006). Silver and bighead carp move easily through the locks and dams on the Mississippi and Illinois Rivers and reproduce within the reservoirs (Mark Cornish and Kelly Baerwaldt, Corps of Engineers, personal communications, DeGrandchamp et al. 2008). While new migration barriers and retention of existing dams have been proposed as a means of impeding range expansion by these species, research on the role of reservoirs in the success of invasives and the decline of native species, contradicts the logic of this strategy.

Propagation of Parasites

Increases in the prevalence of parasites have been observed in reservoirs around the world. Impoundment affects the prevalence of parasites by inundating vegetation, altering habitat, and increasing the abundance of intermediate hosts.

Man-made reservoirs have been cited as a major cause of malaria outbreaks in India and Africa (Desowitz 2002). The presence of northern pike *Esox lucius* parasites increased significantly following impoundment of South Indian Lake on the Churchill River, Manitoba (Watson and Dick 1979).

Gas Supersaturation

Release of pressurized water from high head dams can create gas supersaturation and gas bubble disease in fish downstream of dams (Beeman et al. 2003). Gas bubble disease is due to expanding gases that cause embolisms in fish and has been compared to "the bends" in people. This has resulted in significant mortality of salmonids (*Oncorhynchus* spp.) below the large dams on the Colorado and Columbia rivers (Beiningen and Ebel 1970). It has also been documented below Red Rock and Salorville dams in Iowa (Lutz 1995). Gas bubbled disease is generally associated with high head dams since they develop greater hydrostatic pressure.

Hydropower Effects

While hydropower is often viewed as "green" or "clean" energy, hydropower has unseen detrimental impacts associated with the turbines in addition to general dam related effects discussed here. Recent studies have suggested that methane release from reservoirs may actually exceed greenhouse gas emissions from fossil fuels (Fearnside 1997, Lima et al. 2007). Methane is 20 times more potent than carbon dioxide as a greenhouse gas. Decaying organic matter in deep anoxic reservoirs favors methane formation. Sudden pressure decreases as water is discharged causes its release into the atmosphere.

Turbines can cause significant mortality in downstream migrating fish (Shoeneman et al. 1961). Fish can be killed by blade impacts, pressure changes, and other factors. In small turbines with high head, mortality may be near 100% (Cada, 2001). While close tolerance "fish friendly" tubines can reduce mortality to around 12% (Bickford and Skalsky, 2000), large bodied fish like sturgeon are less likely to avoid blade impacts or may impinge on intake screens.

Blockage of Fish Migrations

In the past, it was assumed that only the large-bodied fishes were migratory. This was likely because there was limited interest in small-bodied non-game species and research studies focused on commercially and recreationally important game fish. It is also more difficult to study small-bodied fishes since radio transmitters and other tags are too large to install in small fishes. It is logical to assume that all species migrate to some degree. The broad distribution of river-oriented species across river systems supports this contention. Streams are subject to drought, natural disasters, and, in northern latitudes, severe winters that can dramatically reduce or eliminate habitat.

Re-colonization of streams following perturbation depends on migration and passage. I first observed this in the stream (Dutch Charlie Creek) along which I grew up in southwestern Minnesota. The creek frequently had low or no winter flow and every spring I could catch as much bait as I needed at the downstream end of a perched box culvert. Creek chub *Semotilus atromaculatus*, johnny darter *Etheostoma nigrum*, central stoneroller *Campostoma anomalum*, brook stickleback *Culea inconstans*, and other species would congregate at the outlet and try to make it over the one-foot high falls. Re-colonization, spawning, and optimization of habitat all drive this behavior. Quantitative seasonal sampling using pre-positioned area samplers in the Otter Tail River in West Central Minnesota has shown emigration by most individuals and species out of the reach in mid-winter followed by a return of fish in spring (Figure 15).

Seasonal fish migrations are critical to mussels for both reproduction and dispersal as they use fish as hosts for larval glocidia. Since mussels are important filter feeders, they may have an important role in nutrient uptake and increasing water clarity (Mclvor 2004). Some mussel species have very specific host requirements and blockage of these host species will lead to the extirpation of the mussel species. For example, two species of mussels, the ebonyshell, *Fusconaia ebena* and the elephant ear *Elliptio crassidens*, were extirpated from the Upper Mississippi River when Lock and Dam 19 was built in 1914, which blocked migrations of their sole host, the skipjack herring *Alosa chrysochloris*. Sauger *Stizostedion canadense*, freshwater drum *Aplodinotus grunniens*, and channel catfish *Ictalurus punctatus* are important hosts to a number of mussel species (Figure 16) and are also species that frequently become extirpated upstream of dams on medium-sized rivers (Aadland et al. 2005).

Two species of mussels, the ebonyshell and the elephant ear were extirpated from the Upper Mississippi River when Lock and Dam 19 was built in 1914, which blocked migrations of their sole host, the skipjack herring.

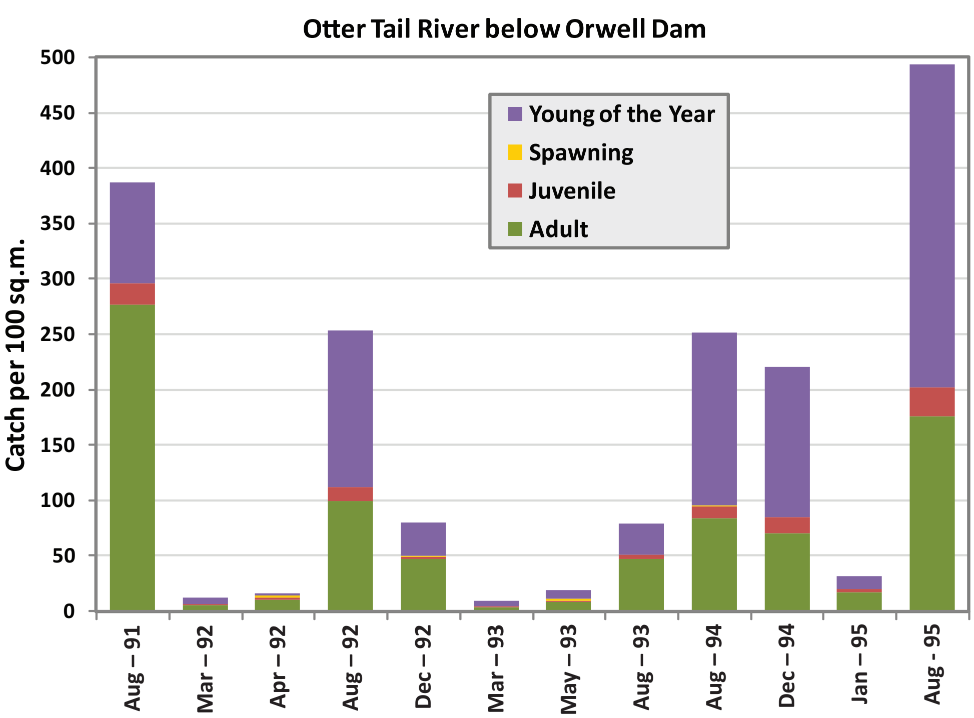

Figure 15. Seasonal changes in density (catch per 100 m^2 with prepositioned area samplers) of fish by life stage in the Otter Tail River, 1991-1995. Most of the species present spawn in spring (early April to June).

This was the case upstream of Hieberg Dam on the Wild Rice River in northwestern Minnesota. When the dam washed out after heavy rains, passage was restored to the river upstream of that point and 11 of 18 native species found downstream of the dam but missing from surveys upstream of the dam returned. By the following year, DNR Fisheries and our (Ecological Resources) surveys confirmed large numbers of channel catfish, smallmouth bass *Microptera dolomieu*, sauger, walleye *Sander vitreus*, freshwater drum *Aplodinotus grunniens*, shorthead redhorse *Moxostoma macrolepidotum*, pumpkinseed sunfish *Lepomis gibbosus*, goldeye *Hiodon alosoides*, spotfin shiner *Cyprinella spiloptera*, and pearl dace *Margariscus margarita*, had returned to upstream reaches as far as 75 miles upstream.

Fish passage is also important in nutrient processes. Given that nutrients spiral downstream with stream flow, they can be returned upstream through migrating fish. Downstream migrating fish are important in nutrient transport as well (Moore and Schindler, 2004). On the west coast, the contribution of Pacific salmon carcasses and gametes to the fertility of otherwise nutrient-poor streams is well documented (Gresh et al. 2000). While most warm- and cool-water species are not genetically programmed to die at the end of their spawning migration, a combination of mortality and deposition of spawn can still amount to a significant amount of nutrients. Blockages due to dams and road crossings eliminate upstream passage and consequently this upstream transport of nutrients.

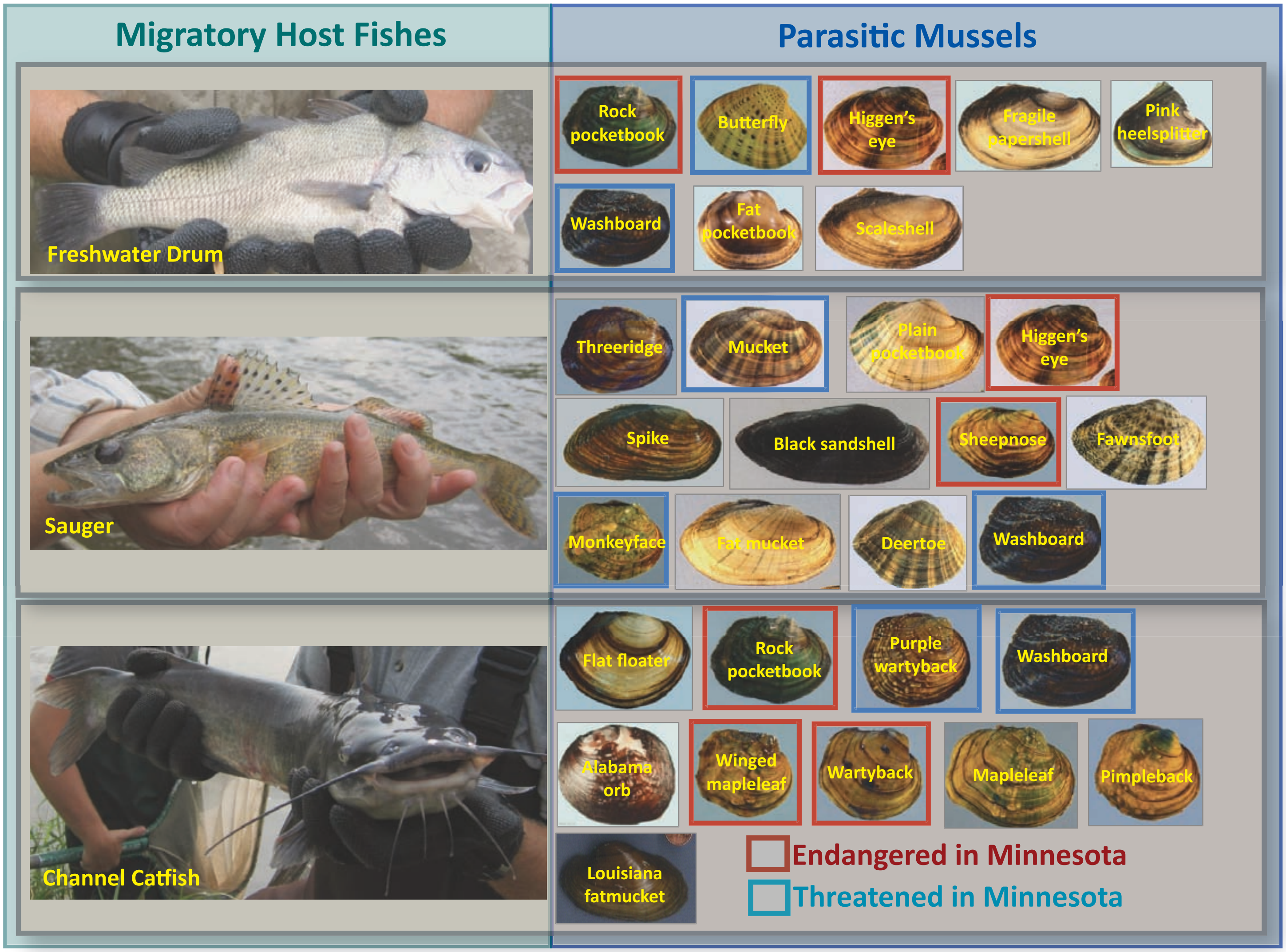

Figure 16. Mussel species that use freshwater drum *Aplodinotus gruniens*, sauger *Sander canadense*, and channel catfish *Ictalurus punctatus* (from Mollusk Division of the Museum of Biological Diversity at the Ohio State University data base).

River Restoration Philosophy and Definition

Restoring a river is analogous to healing a patient. One approach is to focus on symptoms such as treating a 400-pound smoker with experimental drugs for heart disease. While the drugs may lower the patient's blood pressure, the underlying problem is not addressed and the drugs may have damaging side-effects. The underlying cause may be obvious (lack of exercise, overeating, and smoking) or more cryptic (job stress leading to over-eating and smoking leading to high blood pressure) but identifying the cause ultimately leads to a more comprehensive and effective cure. The human body is comprised of interacting systems and organs that work collectively to determine the overall health of the individual. Like the human body, the health of a river is dependent on interacting systems. Hydrology, geomorphology, water quality, biology, and connectivity are components of rivers that work collectively to define rivers and their health (Annear et al. 2004). Each of these components is, in itself, a complex group of variables. Changes in one of these components can have a cascading effect on the other components.

River management practices have traditionally focused on symptoms rather than underlying causes. Many of the dams built in the United States have been built for flood damage reduction; however, watershed changes such as increases in impervious area, wetland drainage, channel straightening, and floodplain encroachment, that may be underlying causes of accentuated flood flows and flood damages, are rarely addressed. One result of this strategy is that a significant proportion of total flood damages are damages to dams and other flood control infrastructure. Some of the most damaging floods have been due to dam failures.

Restoring a river is analogous to healing a patient.

Identifying the cause ultimately leads to a more comprehensive and effective cure.

Fisheries management has centered on stocking hatchery-raised fish rather than restoring spawning habitat required for self-sustaining populations. Side effects of this approach have included disease transmission, loss of genetic integrity, loss of native species, and introduction of aggressive non-native species. While "habitat improvement" projects have been built, they have not always fit the geomorphology of the stream and some have incorporated extensive riprap that locks the channel in place, disrupts channel forming processes and resilience, replaces riparian vegetation, and bears little resemblance to a natural channel.

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Resource management based on specific products can also result in unanticipated costs, deficiencies, and adverse effects in complex ecosystems. For example, the Whitewater River in southeastern Minnesota was channelized in 1958 to allow the construction of waterfowl impoundments that could be manipulated to maximize waterfowl production. However, straightening the river caused channel incision that eliminated natural riparian wetlands and aquatic habitat in the river. The river's

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"Restoration is the act of relaxing human constraints on the development of natural patterns of diversity, where restoration measures should not focus on directly recreating natural structures or states but on identifying and reestablishing the conditions under which natural states create themselves."

floodplain was separated from the channel by levees produced by the excavation. Other levees constructed to contain the impoundments regularly fail during floods. The processes that created natural riparian wetlands were replaced with a high cost, high maintenance alternative.

Ironically, river restoration is often needed due to past efforts to "improve" the river. In my career, restoration efforts have included restoring hydrology where flows have been regulated; restoring channel morphology by re-meandering straightened rivers; and restoring connectivity by removing dams or providing passage. All three of these practices causing the impairment (flow manipulation, channelization, and dam construction) were originally done as means to improve the river. The practice of making a meandering river into a straight channel is still referred to as "channel improvement" by some but recognition of channel instability, loss of habitat, impairment of water quality, and increases in peak flow caused by these projects has grown. Like "channel improvement", the term, "habitat enhancement" has been used to identify projects. It is predicated on the presumption that we can improve on the pristine condition. The arrogance of past failed attempts to improve or enhance natural systems should be a lesson to everyone involved in river projects.

River restoration is a relatively new science and the term has been applied to a wide range of activities warranting some definition. The word, "restore" means literally, "to bring back to an original state" (Webster, 2001). In a dynamic river, this is rarely possible and would require further defining "original state" for an entity that is always changing. For the purposes of this document, "restoration is the act of relaxing human constraints on the development of natural patterns of diversity (Ebersole et al., 1997, and Frissell et al., 1997), where restoration measures should not focus on directly recreating natural structures or states but on identifying and reestablishing the conditions under which natural states create themselves" (Frissell and Ralph, 1998). This definition of restoration is virtually opposite of traditional river management. While there is job security in building rivers that require constant repair and manipulation, restoring natural processes and functions has the advantage of being self-sustaining. By reestablishing natural processes that shape habitat as well as form, the likelihood of unanticipated deficiencies is reduced.

Defining the cause or causes of impairment is a critical step in determining an appropriate restoration approach.

Defining the cause or causes of impairment is a critical step in determining an appropriate restoration approach. While dam-related problems have an obvious cause (the dam), damages do not necessarily disappear once the dam is removed. Reservoir sedimentation and subsequent channel incision after dam removal, channel instability and lack of quality habitat, and lack of riparian vegetation are examples of post-removal problems that are either left to recover through erosion, deposition, and succession processes or are accelerated through intervention (restoration). Similarly, restoration of fish passage does not necessarily address the disconnection caused by a dam. If spawning habitat that once existed prior to dam construction no longer exists due to the reservoir, fish passage will not fully address the problem. Furthermore, a misdiagnosis of the impairment can result in "restoration" measures that make the problem worse or create new problems.

Hard armoring has been a standard means of addressing bank erosion problems. This approach locked channels into a degraded condition and caused accelerated erosion downstream.

Natural Channel Design in River Restoration

The natural channel design approach involves the use of reference channel morphology as templates for design (Rosgen 2007). Reference channels are selected for their natural stability, habitat, and functions. Normally, these reference channels are least altered reaches found on the same river where the restoration is proposed. The logic of this approach is that reference reaches within the same watershed and with similar drainage area are handling the flows and sediment that the restored channel will need to carry. In addition, mimicking habitat characteristics in a natural reference channel is more likely to address habitat needs of the biota found there. In adapting reference channel morphology to restoration sites, slope differences, sediment differences, sediment transport capacity and competence, and flow capacity must be accounted for.

A useful measure of the success of a restoration project is the degree to which it looks like a project. Unfortunately, many "restorations" are very easy to identify with structures that bear little resemblance to natural features. If the channel form is different than that of natural channels, it is likely that the river processes and functions are also different. Ideally, a restoration should look like an unaltered stream...like we were never there.

Three different applications of natural channel design are discussed here:

- *dam removal and channel restoration in the reservoir,*
- *converting low-head dams to rapids, and*
- *by-pass fishways.*

Of these, dam removal and channel restoration is the most complete application of restoration and natural channel design while the latter two types are done with the constraint of leaving the dam in place. Since fish passage around or over dams involves slopes that are likely to be steeper than the natural river slope, channel morphology based on steeper natural channels must be applied. However, since dams are frequently built in relatively high gradient river reaches, the steeper gradient provided by these fishways may actually provide otherwise lacking habitat.

Ideally, a restoration should look like an unaltered stream…like we were never there.

Reference channels are selected for their natural stability, habitat, and functions.

In adapting reference channel morphology to restoration sites, slope differences, sediment differences, sediment transport capacity and competence, and flow capacity must be accounted for.

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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Dam removal

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- *restores migratory pathways, nutrient and sediment regimes, and ecological and channel forming processes.*

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,
4) removal with river restoration to stabilize sediments.

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

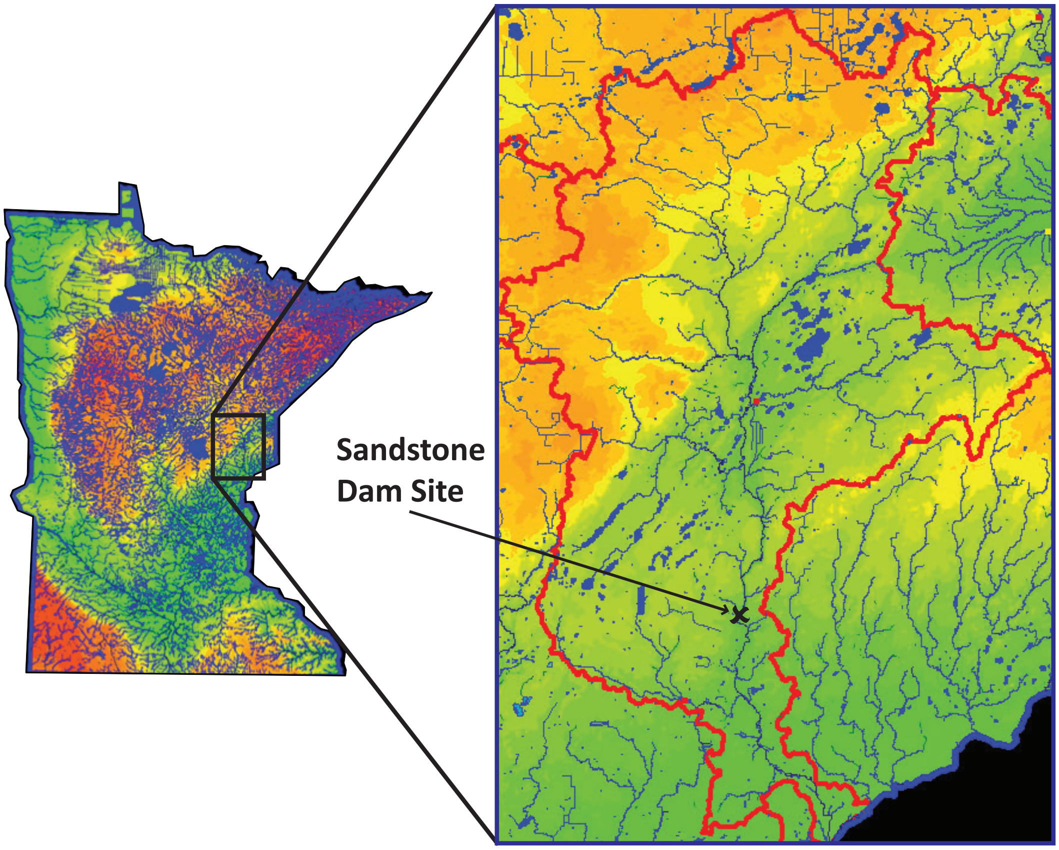


Figure 18. Kettle River shaded relief watershed map showing location of the Sandstone Dam.

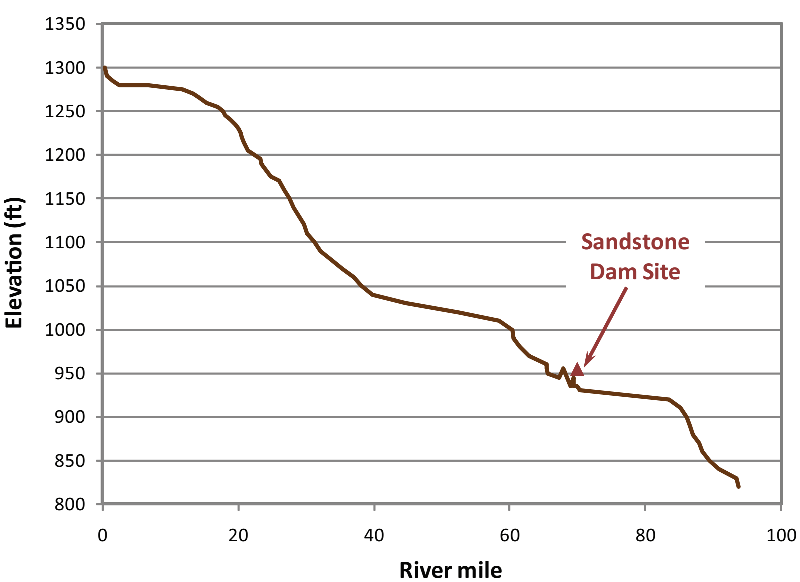


Figure 19. Elevation profile of the Kettle River showing the former dam site.

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

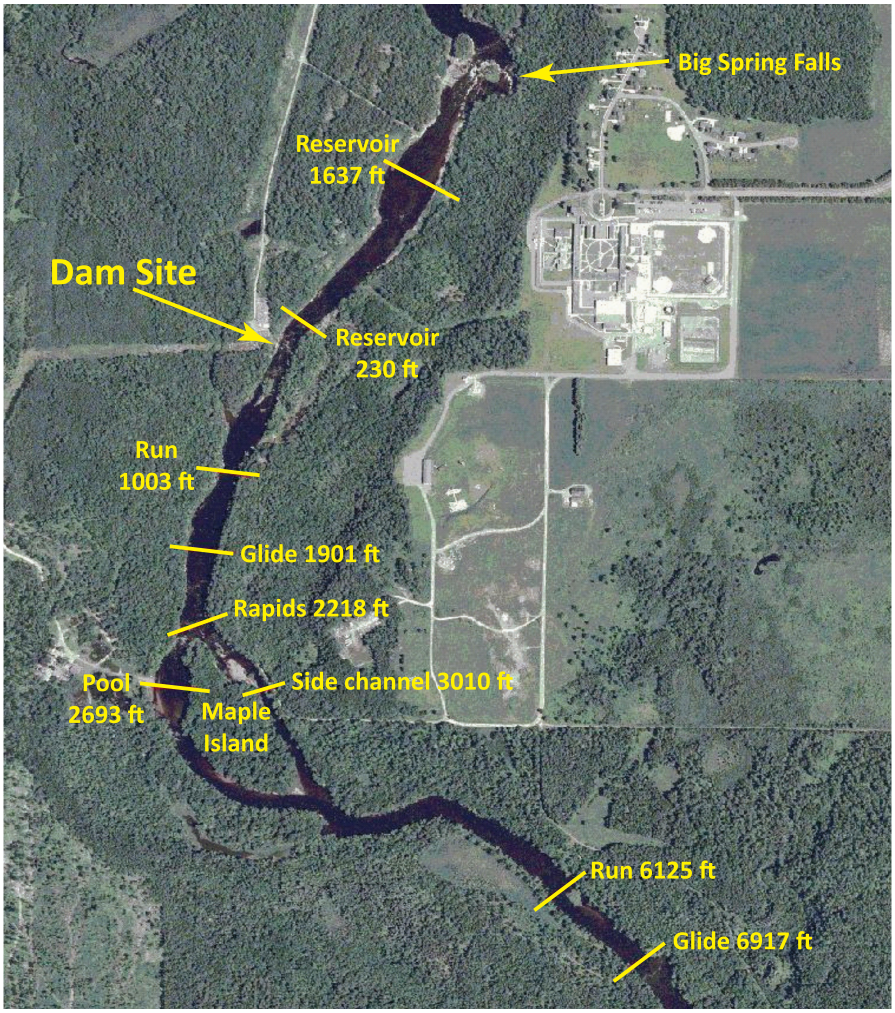


Figure 20. Aerial photo showing transect locations and distances from the dam site.

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).

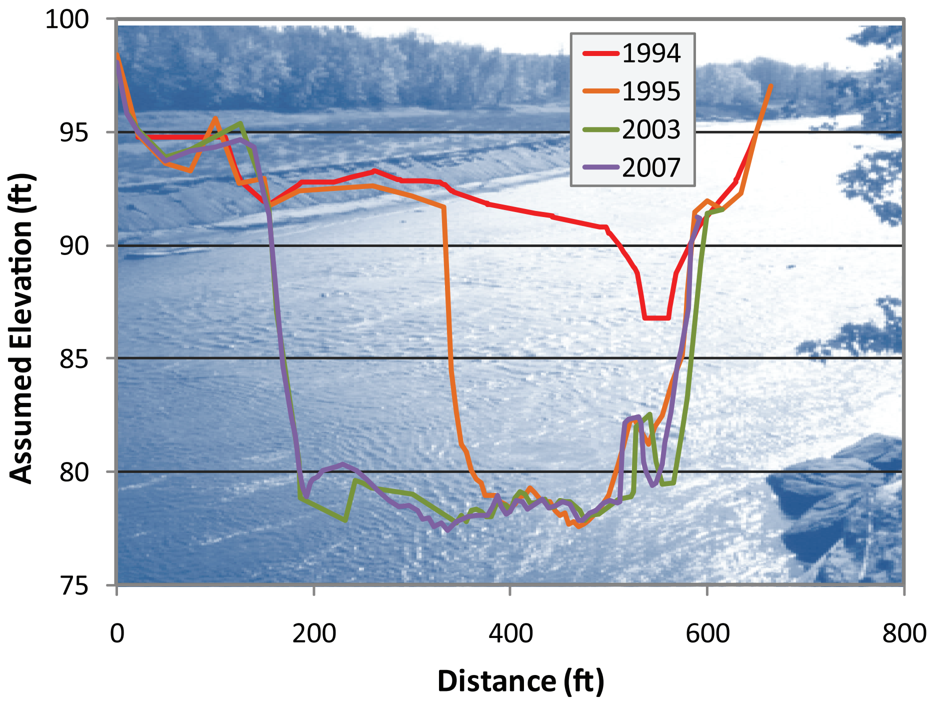


Figure 21. A cross-section within the reservoir 230 feet upstream of the dam, showing changes following removal.

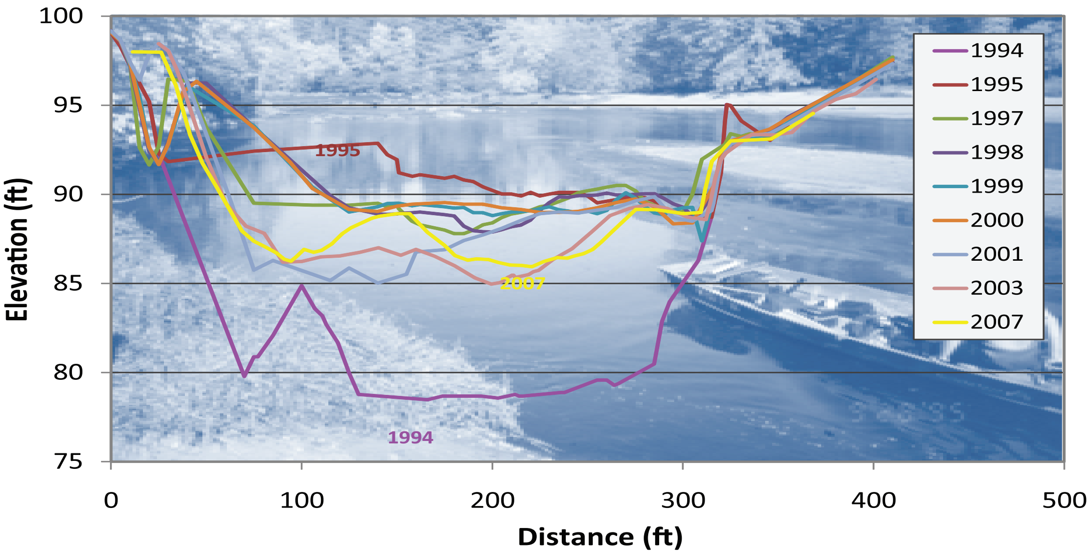


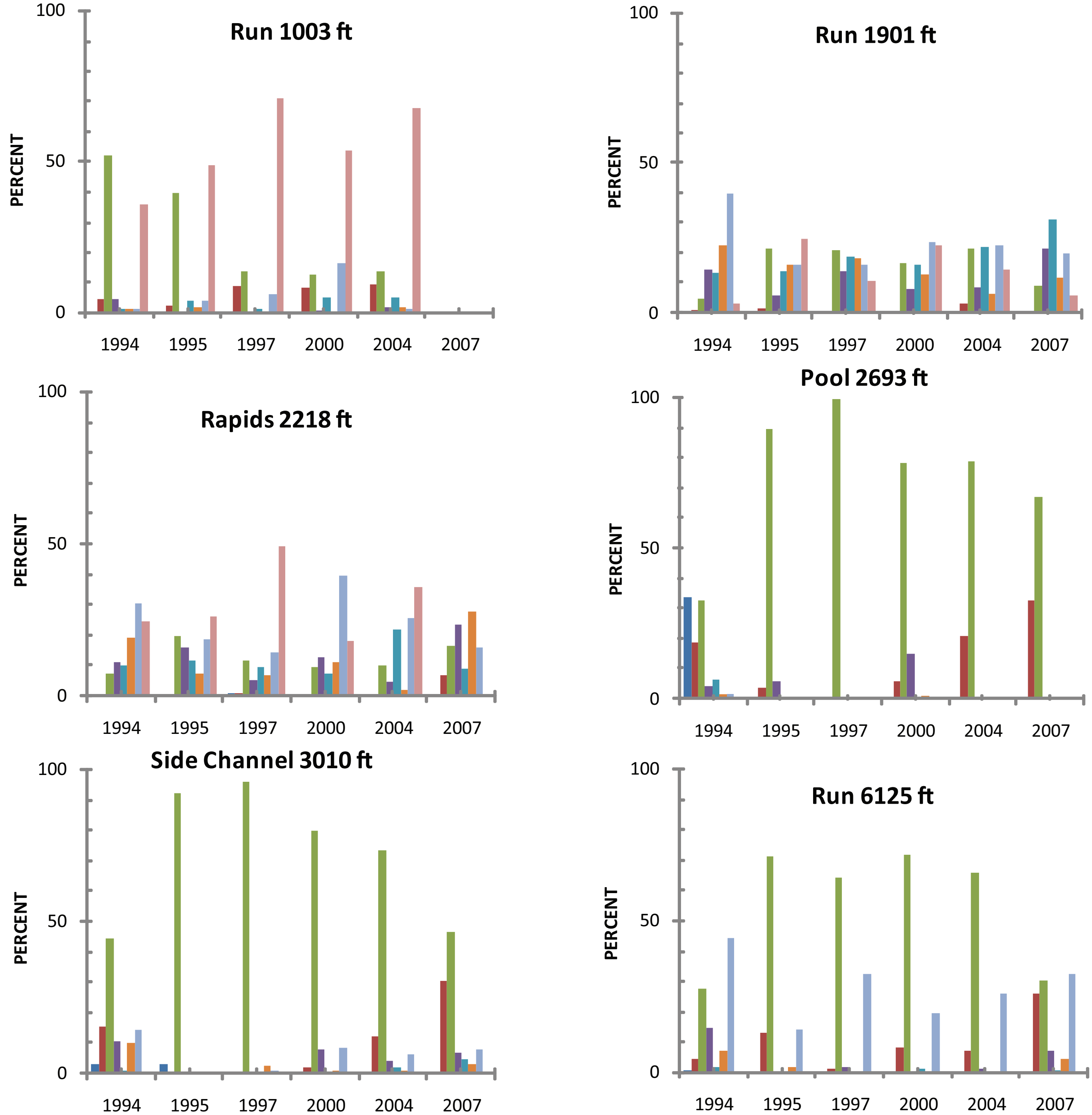
Figure 22. A pool cross-section, 2,693 ft downstream of the dam, showing sedimentation following removal. The background photo is looking upstream, cross-section stationing is left to right looking downstream.

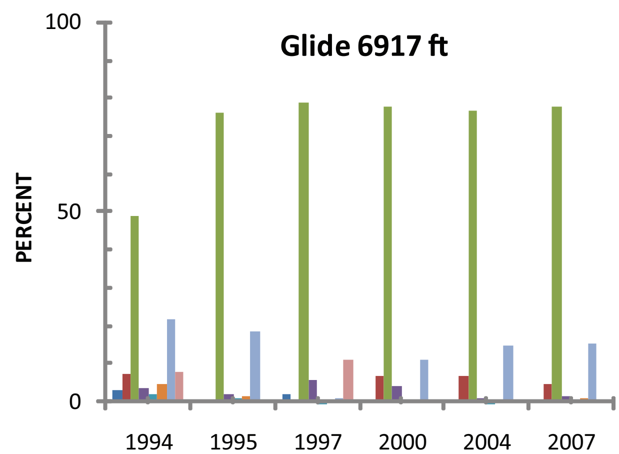
Substrates within the reservoir have also changed. While our sampling of sediments upstream of the dam did not begin until the dam had been removed, it is likely that it was almost entirely sand based on flats visible immediately after removal. Following removal, the river quickly downcut to bedrock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





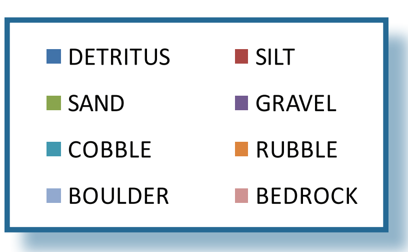


Figure 23. Substrate changes at transects and distance downstream of the dam site.

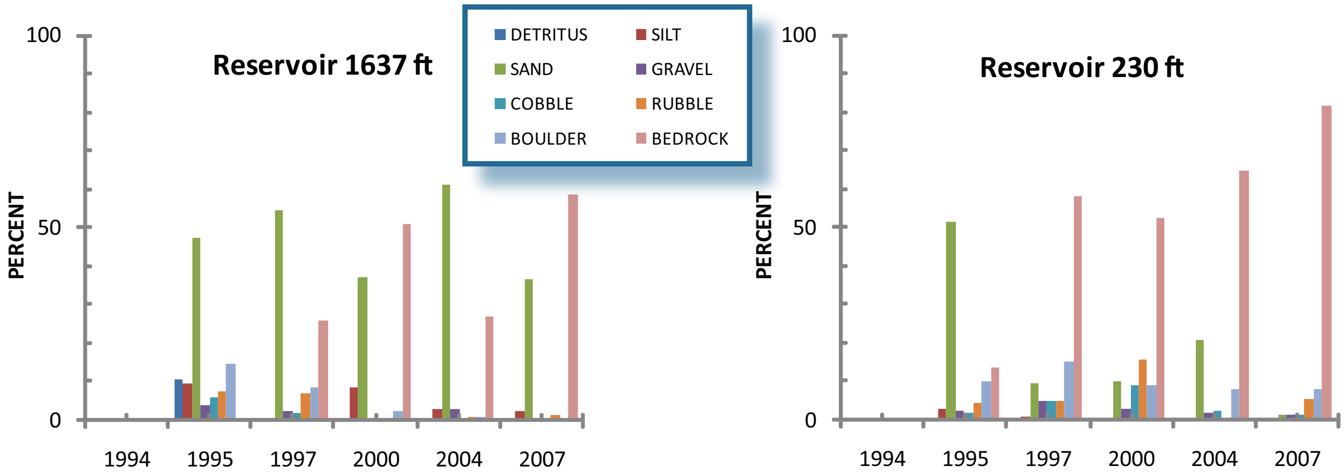


Figure 24. Substrate changes in the reservoir following removal and distance upstream. No data was collected prior to removal in 1994 but based on exposed flats it was likely near 100 percent sand.

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

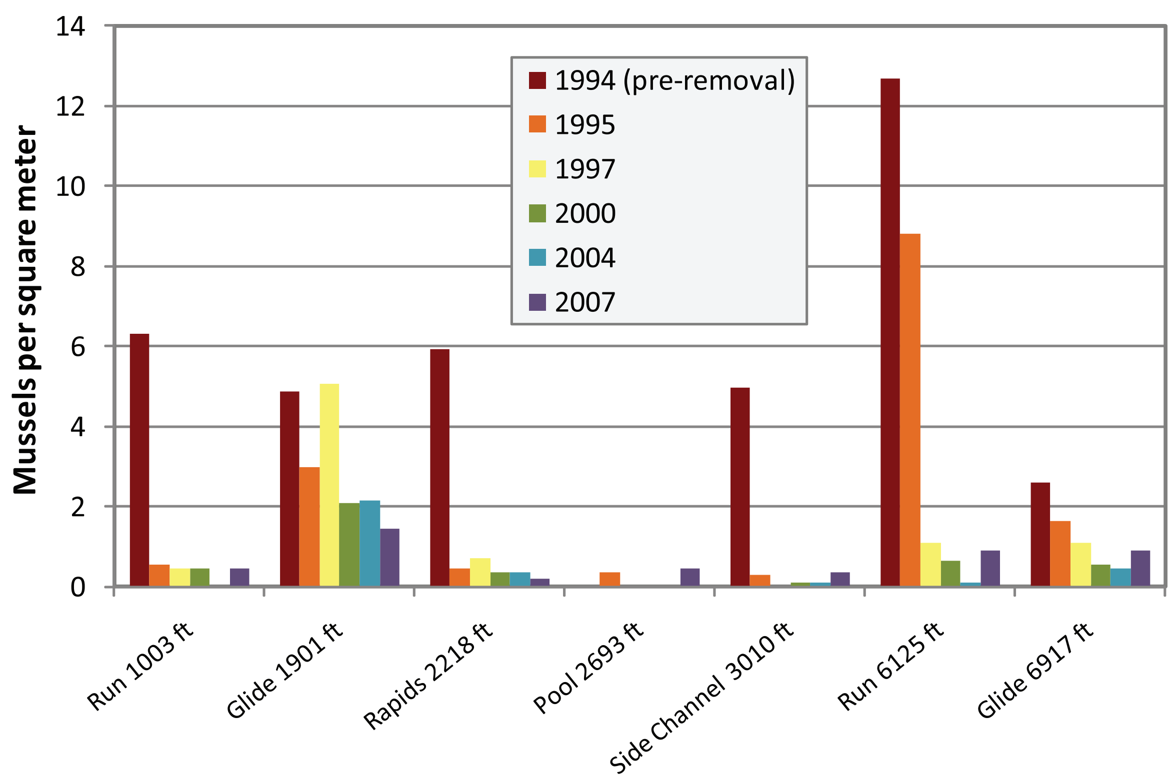


Figure 25. Mussel density along transects with distances downstream of the dam site.

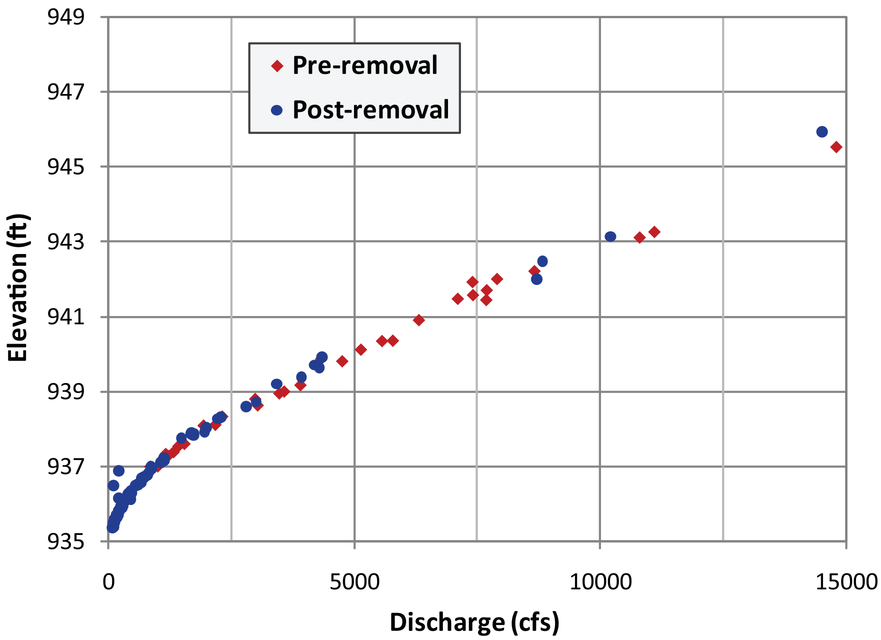


Figure 26. Measured stage and discharge values at the Kettle River gage before and after removal of the Sandstone Dam. The gage is 850 feet downstream of the dam site. Data from USGS gage 05336700.

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

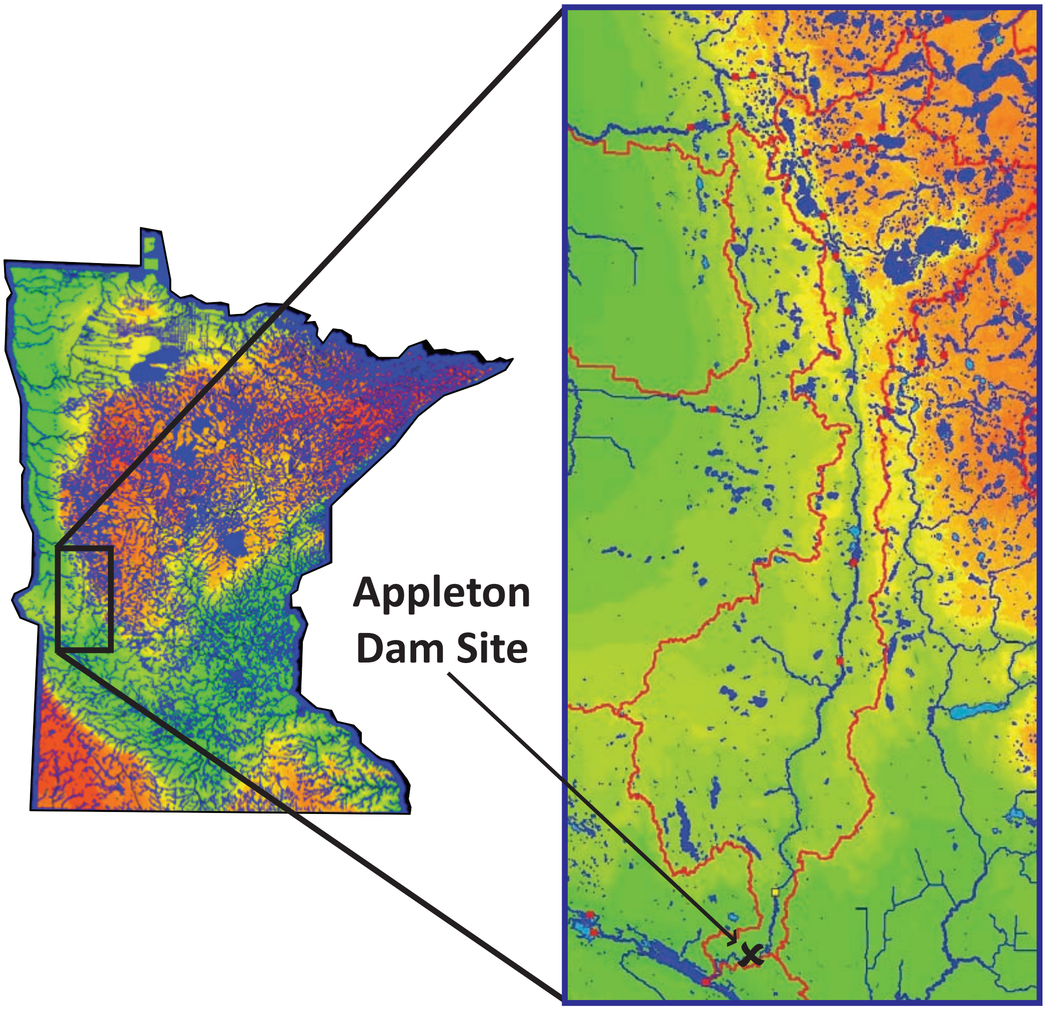


Figure 29. Shaded Relief map of the Pomme de Terre Watershed showing the Appleton Dam Site.

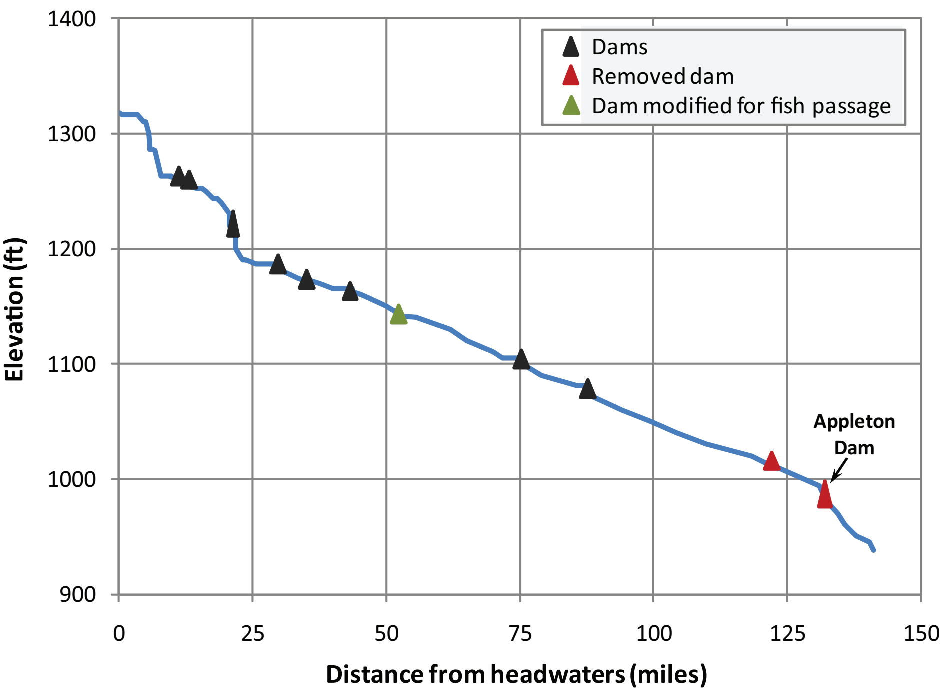


Figure 30. Elevation profile of the Pomme de Terre River showing dam locations.

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

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).

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.

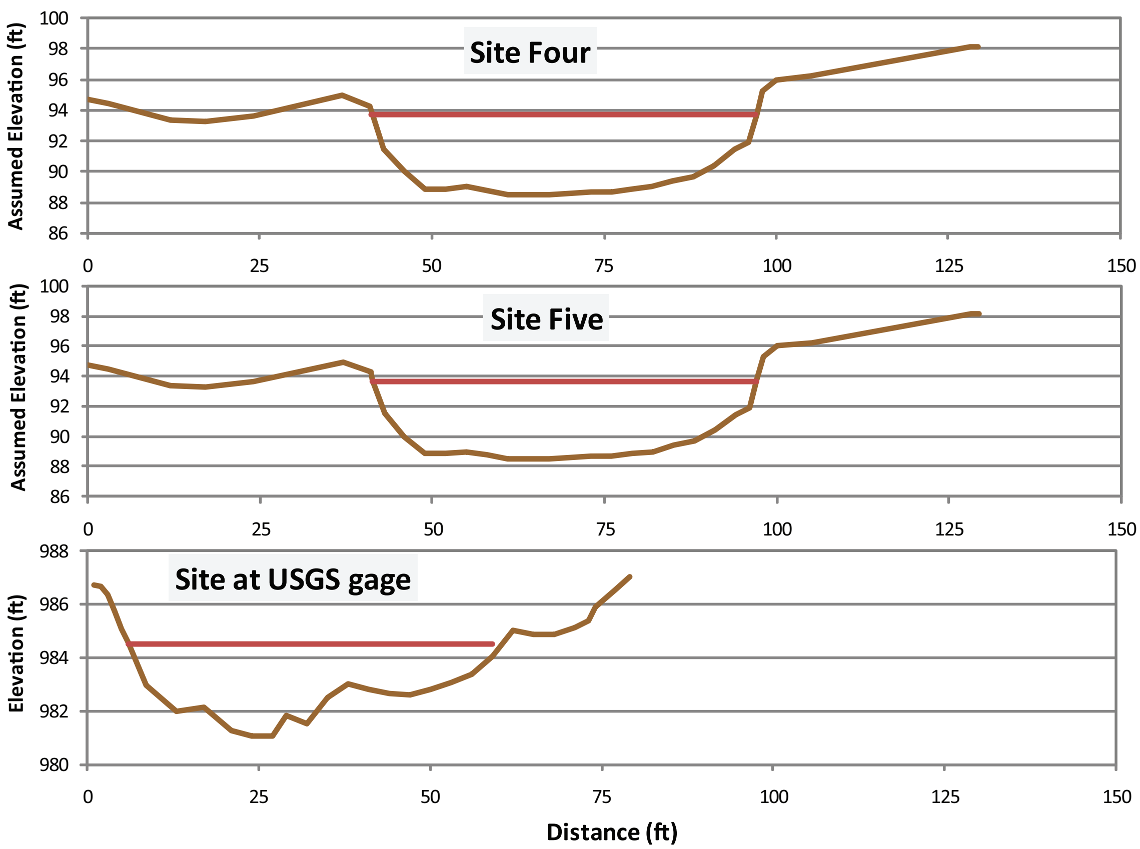


Figure 33. Riffle cross-sections at reference sites used for the design of the Pomme de Terre River.

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.

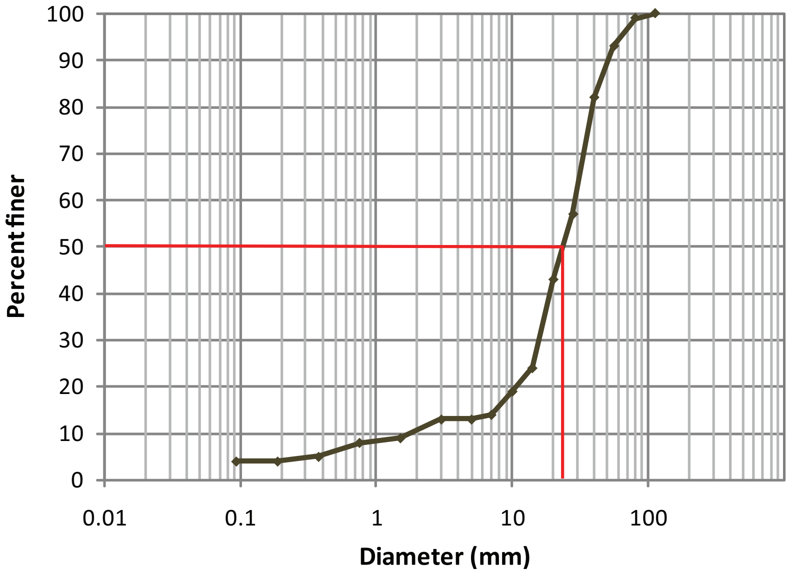


Figure 34. Pebble count from site five directly upstream of the Appleton Milldam Reservoir.

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.

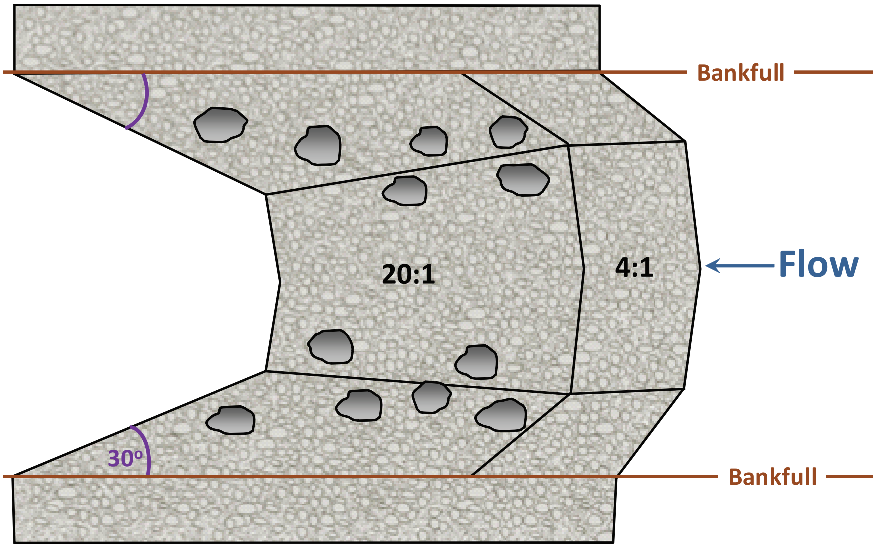


Figure 35. Riffle design used for grade control and habitat in the Pomme de Terre River restoration.

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.

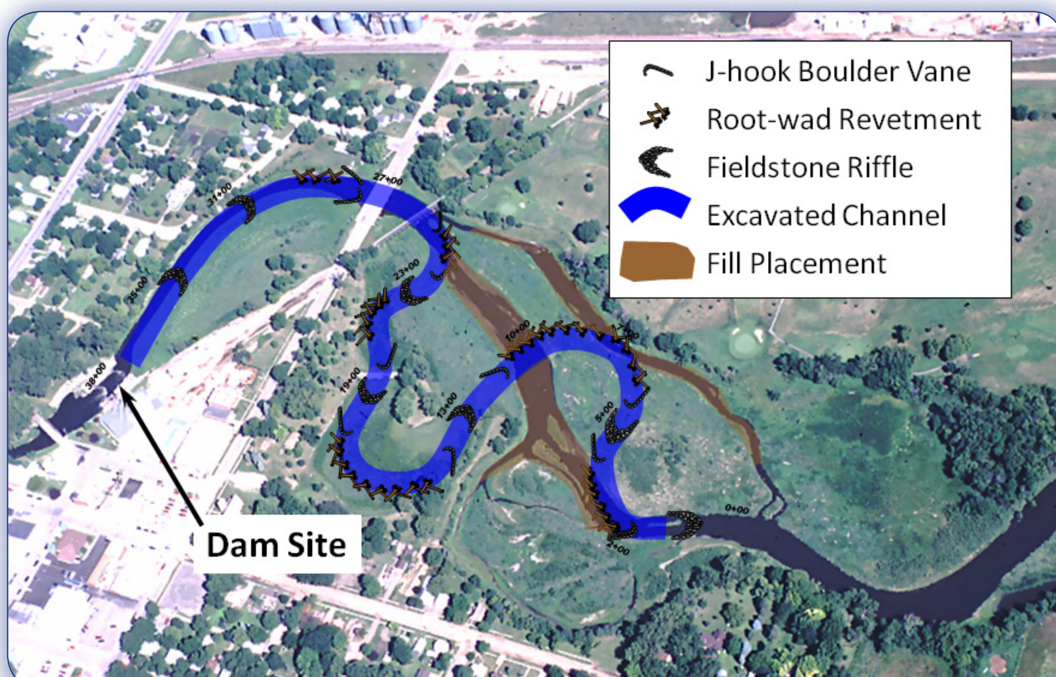


Figure 36. Planview of the Pomme de Terre River restoration in Appleton, Minnesota

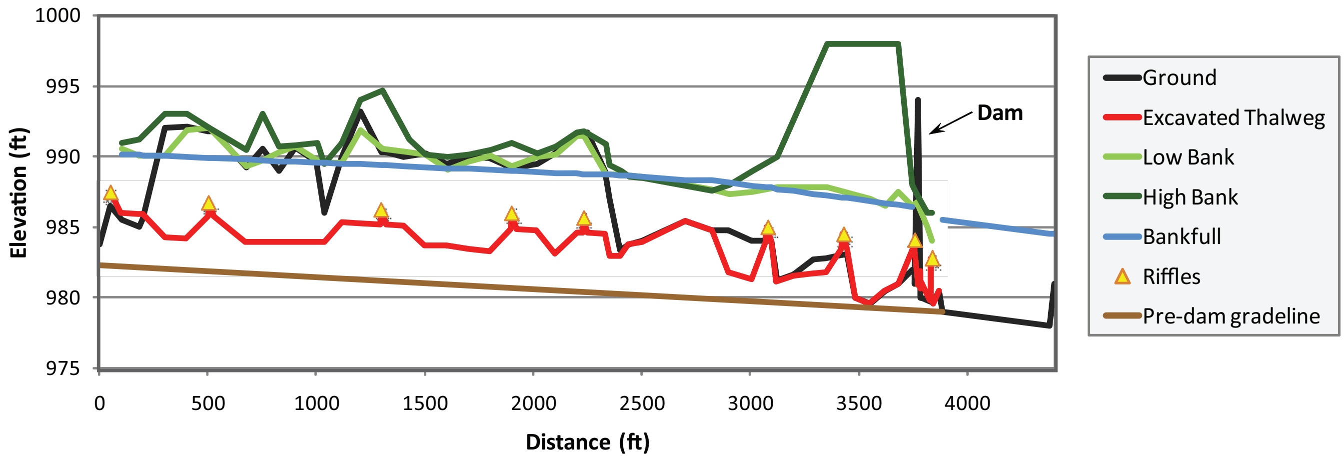


Figure 37. Profile of the Pomme de Terre River restoration showing pre-project sediment elevation at channel centerline, low and high banks, excavated channel thalweg, designed bankfull, and the approximate pre-dam grade-line.

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.

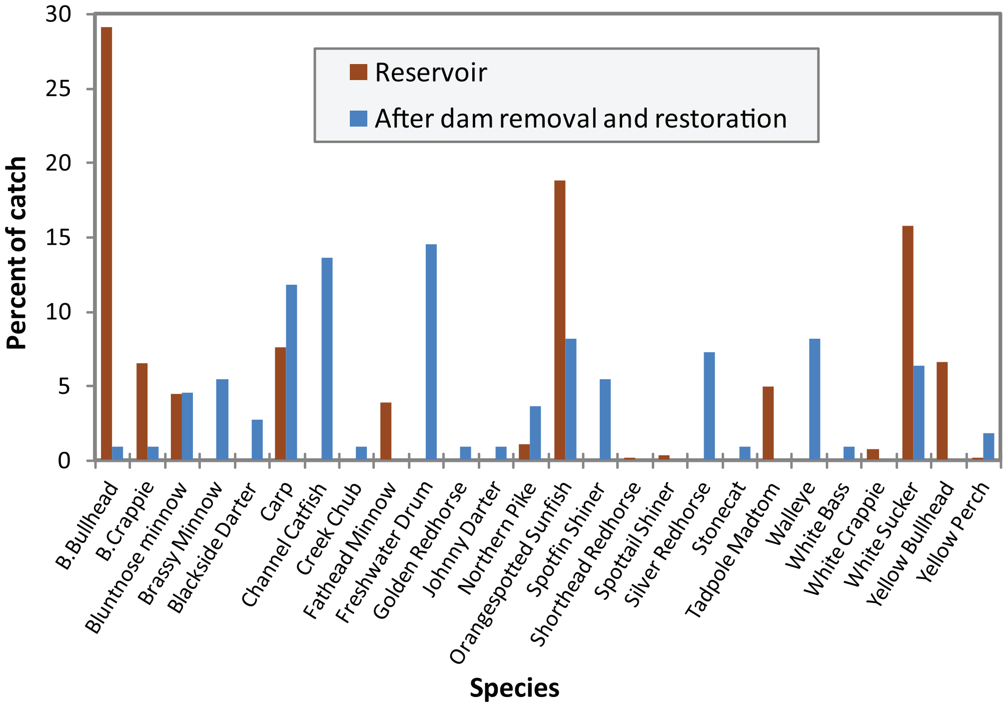


Figure 47. Relative abundance of fishes in the Lower Pomme de Terre River upstream of the dam site before (brown) and after (blue) removal of the dam. Fish were collected with trap-nets and electrofishing. Minnesota Section of Fisheries Data.

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.

Nature-like Fishways

Traditional approaches to fish passage involved the use of concrete baffles and compartments. Some of these designs required the fish to jump from one compartment to the next posing a problem for fish species that don't tend to jump. In other cases, the compartments are so small and the slope so steep that it is unlikely that any fish species is able to consistently pass them (Figure 49).

While some baffle type fish ladder designs are effective in passing a variety of species, they lack any habitat useful to the species. An alternative to structures designed only to pass fish, is to design fishways that emulate natural rapids. Such designs are not only more likely to pass a wider range of species, but also provide rapids habitat similar to that lost due to dam construction.

An alternative to structures designed only to pass fish, is to design fishways that emulate natural rapids. Such designs are not only more likely to pass a wider range of species, but also provide rapids habitat similar to that lost due to dam construction.

Figure 49. Traditional fish ladder built in 1929 on the Pelican River in west-central Minnesota. Lake sturgeon exceeding 100 pounds historically were found in this watershed and likely migrated past this site prior to construction of the dam. This fish ladder is not effective for any of the native species.

Fish Hydrodynamics

Many of our native warm and cool water fish species have comparable burst swimming speeds to that of the salmonids (Figure 50) but are generally less effective in passing barriers. Northern pike *Esox lucius* have high burst speeds as a result of their elongate sagittiform shape but lack maneuverability for the same reason and have difficulty with barriers that other species can pass.

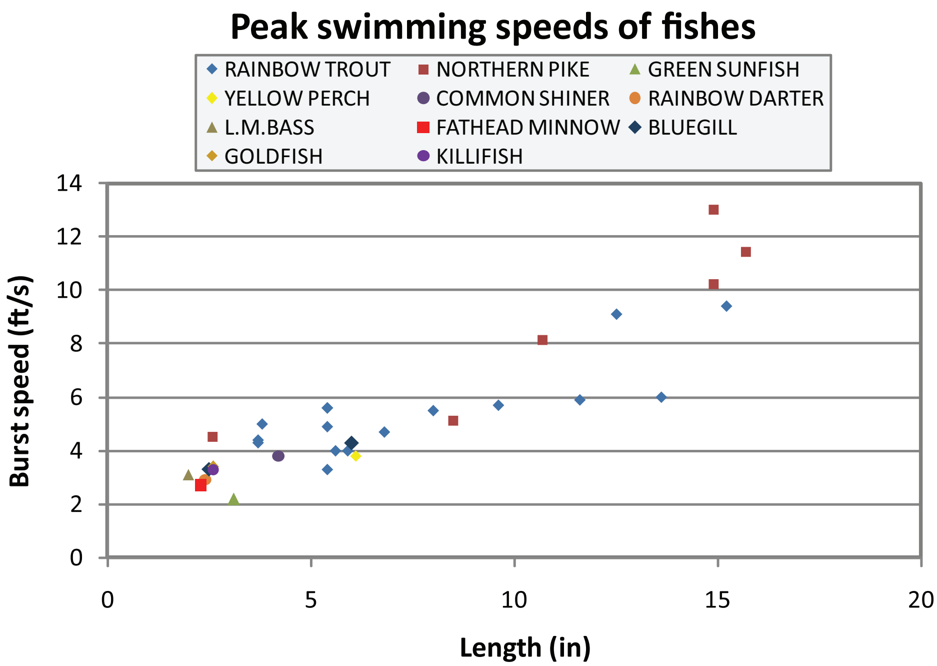


Figure 50. Burst swimming speeds of rainbow trout and some warm and cool water fishes (data from Domenici and Blake 1997).

Salmonids have probably evolved the ability to jump barriers because they needed to pass small waterfalls to reach suitable spawning habitat in the mountainous regions where they are found. Many of the fishes of the Northern Plains are found in streams that lack waterfalls so jumping is not a required trait.

Most fish have burst speeds that approximate ten body lengths per second but they cannot maintain this speed for more than a fraction of a second to a few seconds. Small fishes have proportionately slower burst speeds but have the advantage of moving closer to or within the substrates where velocities are slower (Figure 51). Some small riffle oriented species like the rainbow darter *Etheostoma caeruleum* shown, prefer habitats where mean column velocities are greater than their burst speed capability (Aadland 1993, Aadland and Kuitunen 2006). The use of interstitial space as a velocity refuge is not restricted to small fishes. I observed a walleye wedged between boulders in a constructed rapids fishway so only its caudal fin was exposed. Thinking it was stuck, I lifted the boulder and pulled it out only to watch it indignantly dart back into the crevice. Bed velocities are lower above large substrates due to the resistance they create. Velocity distributions near large substrates are also very complex resulting in small eddies that provide resting areas. The distribution of velocity is far more important than are mean column velocities. This limits the usefulness of hydraulic models in predicting fish passage. While more sophisticated two- and three-dimensional models are available, like all models, they are only as accurate as the data input into them. Accurate depictions of bed velocity require detailed surveys of the streambed.

Figure 51. A rainbow darter *Etheostoma caeruleum* using interstitial space in gravel. This species prefers mean column velocities near its maximum burst speed.

Concrete is smooth resulting in less resistance and high bed velocities (Figure 52). It also lacks interstitial space important to the passage of small-bodied species.

Emulating natural channel geomorphology and materials has several advantages. First, fish react to complex current and bathymetry cues, and channels similar to natural channels are less likely to cause disorientation than channels that are not. Second, natural channel design allows fishways to provide important habitat as well as passage. This is important because some species may not naturally migrate the distance necessary to reach suitable spawning habitat. A greater number of alternative spawning areas are also likely to provide greater reproductive success and resilience. Third, use of natural substrates, rather than concrete or other smooth materials, provides roughness and interstitial spaces that allow small fishes and benthic invertebrates to pass and, in many cases, colonize the fishway. Fourth, a fishway built with natural channel design techniques provides habitat that in some cases may be rare due to reservoir inundation.

Rapids are a habitat that has been largely eliminated on many rivers due to dam construction. This has been a major factor in the decline of sturgeon species across North America. Tagged lake sturgeon have been observed moving significant distances from one rapids to another (even to different tributaries) before spawning (Mosindy and Rusak 1991). We have documented sturgeon spawning in several specific geomorphic microhabitats in bedrock and boulder rapids (Figure 53). Some of the fishway designs presented here can provide this type of habitat.

Most fish have burst speeds that approximate ten body lengths per second but they cannot maintain this speed for more than a fraction of a second to a few seconds.

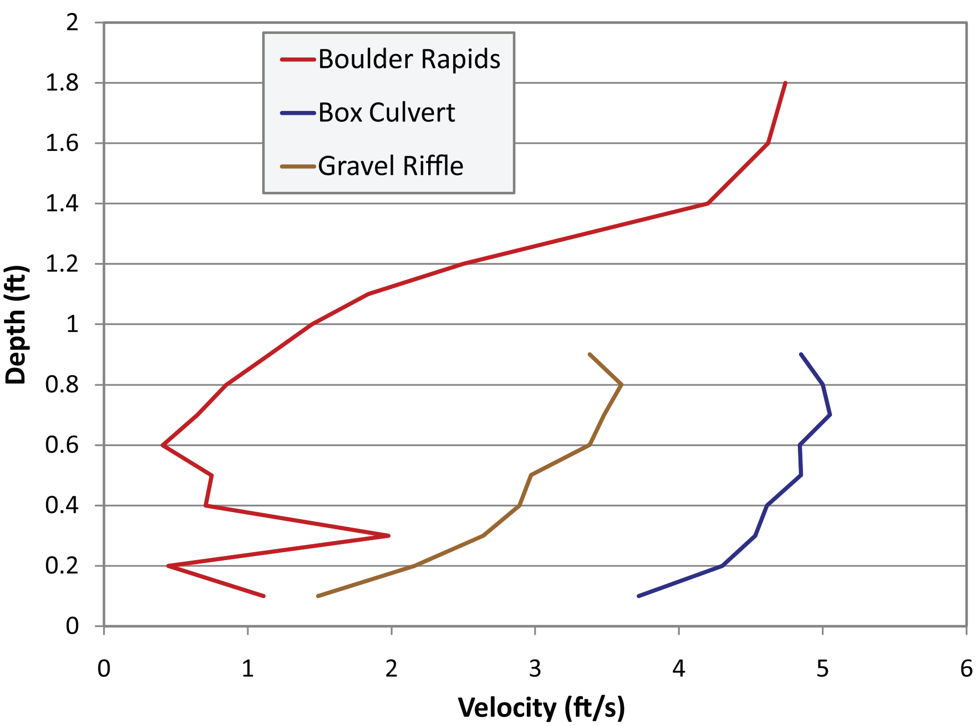


Figure 52. Velocity profiles over three different substrate types in the Otter Tail River. The rock rapids profile was from a constructed fishway.

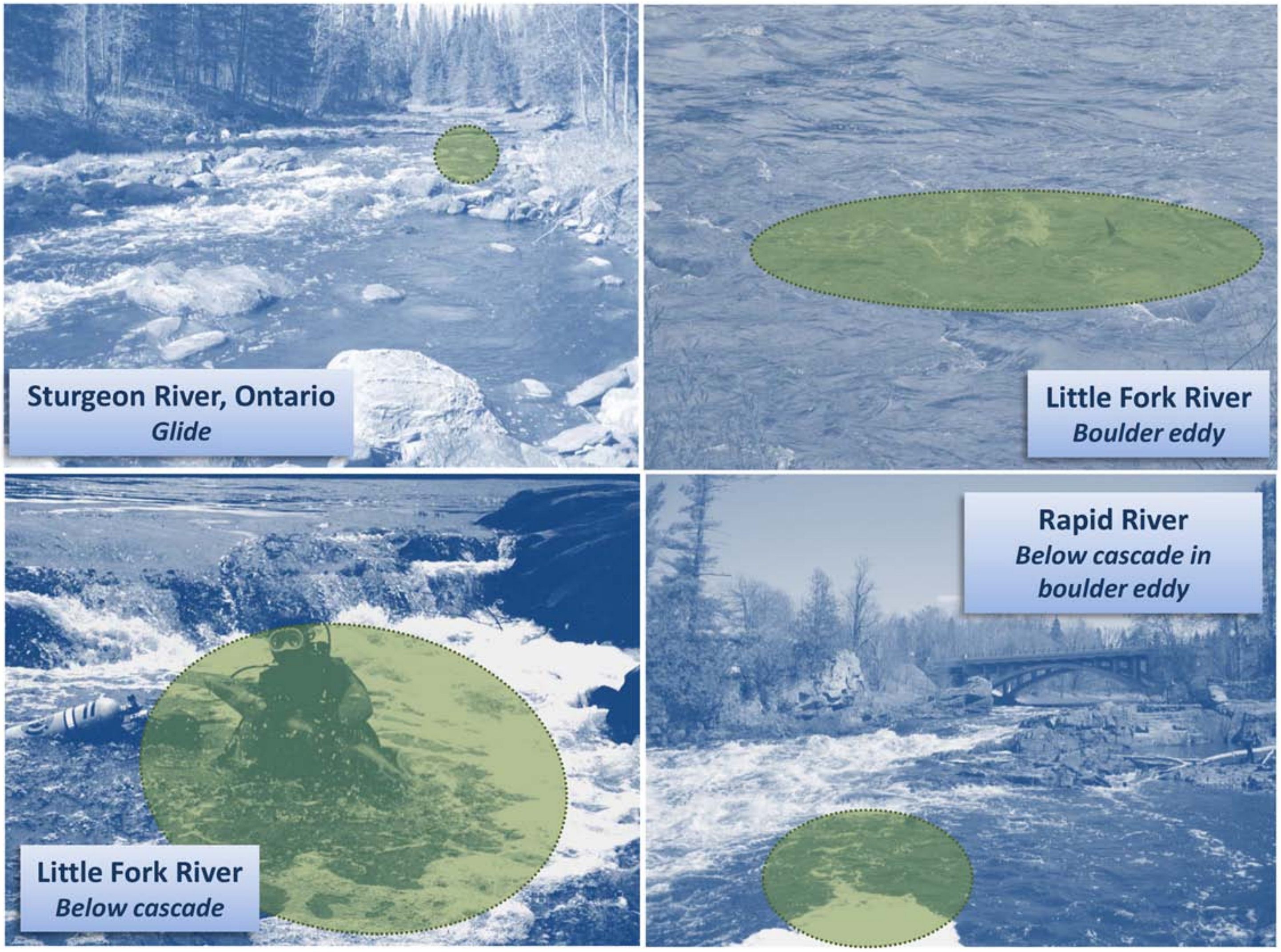


Figure 53. Lake sturgeon spawning areas in tributaries of the Rainy River.

Emulating natural channel geomorphology and materials has several advantages.

1. *Fish react to complex current and bathymetry cues, and channels similar to natural channels are less likely to cause disorientation than channels that are not.*
2. *Natural channel design allows fishways to provide important spawning habitat as well as passage.*
3. *Use of natural substrates, rather than concrete or other smooth materials, provides roughness and interstitial spaces that allow small fishes and benthic invertebrates to pass and, in many cases, colonize the fishway.*
4. *A fishway built with natural channel design techniques provides habitat that in some cases may be rare due to reservoir inundation.*

Design Approach

*Two primary means of providing fish passage using natural channel design techniques will be discussed here; **conversion of low-head dams to rapids or ramps**, and **construction of by-pass type fishways**. The rapids conversion has practical limits of dam height while the by-pass channel can be applied at higher dams as long as adequate room exists for building the channel.*

Conversion of a dam to rapids is best suited to low-head dams that become inundated during bankfull flows.

Rock Ramps: Converting a Dam to Rapids

The rock ramp, as its name implies, consists of constructing a wedge to create a passable slope over a dam. While the term has been applied to by-pass channels, for purposes here, ramps are defined as those built in the existing riverbed directly downstream of the dam crest. The approach works well on low-head dams but has practical limitations on higher head dams due to the quantity of fill material needed and stability issues.

Rock ramps have been built in Europe since the early 1970s and were originally applied as a means of stabilizing riverbeds. Some of these ramps had slopes too steep (10% or greater) to provide fish passage, while those specifically designed for fish passage were generally 7% or less (DVWK, 2002).

The widest rock ramp was completed on the Churchill River, Manitoba in 1999 by Manitoba Hydro. The ramp is 300 m (984 ft) long, 2.0 m (6.6 ft) high, and has a 3.3% slope. The weir is 2.3 km (1.4 mi) long and required 220,000 m^3 (288,000 yds) of rock and was built to impound water to offset diversion of 77% of the Churchill River's flow into the Nelson River for hydropower. The ramp has had considerable ice damage due to river ice that can reach two m thick resulting in reductions of the reservoir stage, but the project is generally viewed as a success (Fortin 2003).

Prior to projects detailed here, few rock ramps had been built in North America. The Eureka Dam on the Fox River in Wisconsin was converted to a "rock ramp" in 1988. Lake sturgeon have been observed spawning in this fishway (Ron Bruch, personal communications). A pool and riffle fishway was built on the Roseau River in Manitoba in 1992 (Gaboury et al. 1994). Work by Newbury and Gaboury (1993) and Rosgen (1994) provided insights into natural channel design techniques.

The Rock Arch Rapids

The Rock Arch Rapids is a design that evolved from early projects with several goals in mind (Figure 54). Low-head dams have a number of problems associated with them including blockage of fish migration, dangerous hydraulic undertows, and tail water erosion. In addition to addressing these problems, habitat similar to that found in natural rapids can be provided with the design. Some of these rapids have become popular with kayakers. Finally, aesthetics of the dam site can be improved.

Conversion of a dam to rapids is best suited to low-head dams that become inundated during bankfull flows. The application of this design at high dam sites is primarily limited by required stone quantities and cost. Dams that flood out during bankfull events usually have maximum shear stress at flows just below this point of inundation because

Figure 54. Generalized conceptual design of the Rock Arch Rapids developed by the author.

slope is reduced to overall river slope during larger flood events. High dams that do not submerge have maximum shear stress during record events requiring larger stone or reduced slope.

Two approaches have been used for sizing stone in the base of the rapids. Rapids designed using both techniques have endured numerous floods without apparent movement of stones. The Army Corps of Engineers (ACOE 1991) unit discharge technique is:

$$D_{30} = 1.95\ s^{0.555}q^{0.667}/g^{0.333} \quad \text{and} \quad D_{50} = D_{30}*1.22$$

where **s** = slope, **q** = unit discharge (cfs/ft), and **g** = gravitational constant (32.174 ft/s^2)

Engineers Manual EM 1110-2-1601 that gives this equation recommends use of angular stone or 25% larger diameters for rounded stone. Rock used in most of these projects has been fieldstone, which is more rounded than quarry stone but in the large gradations, is still somewhat angular and has been stable. Since canoeists and kayakers use these rapids, quarry stone presents problems due to sharp edges that can rip keels. Quarry stone also lacks the aesthetics of natural fieldstone. Engineers Manual EM 1110-2-1601 also recommends use of filter fabric under the stone. However, most applications of the Rock Arch Rapids have been built in flowing water and have not used filter fabric, as it would be very difficult to place in larger rivers like the Red River of the North and has not proven to be necessary or desirable.

The second approach to rock sizing is based on shear stress calculations and regressions of shear stress to incipient diameter of particle moved in rivers (Newbury et.al. 1993, Lane 1955):

tractive force in kg/m² = depth in mm × slope ≈ D_{50}

The tractive force method yields the approximate size of stone that could be moved in a stream so the base should include a significant proportion of stones that are larger than this value. However, the tractive force calculation often yields larger stone than the ACOE method, which is designed for sizing the actual D_{30} and D_{50} used in the spillway. This may be due to the fact that regressions of shear stress with particles moved in rivers include those with finer sub-pavement enabling the transport of larger bedload. Since spillways are generally constructed with more uniform materials than that found in natural streams, stability may be greater. Actual diameter of stones moved in a stream depends on the shape and density of the material and on the diameter of the sub-pavement. Applications of this approach for rock sizing use more uniform gradations in a thick layer to prevent instability associated with a finer sub-pavement.

Subsurface flows have been a concern at rock ramps where very low flows are typical of the river's hydrology. Equations that estimate subsurface flow through rock layers have been developed in laboratory flumes (Stephenson 1979; Abt et. al. 1987, Mooney et al. 2007). However, these equations are not presented here because observed subsurface flows in actual river applications have been much lower than these calculated values. There are several factors that limit subsurface flows in Rock Arch Fishways:

1) While the D_{30} and D_{50} are calculated, inclusion of gravel in rock gradations helps to fill voids and reduce subsurface flow. Gravel and pea gravel placed on the surface of the completed rapids are used to seal the rapids at sites prone to low flows. These materials are drawn into the voids and are very effective at reducing leakage.

2) Sediments supplied by the river fill interstitial spaces in the rock base. In rivers with narrow reservoirs and lowhead dams that are inundated at bankfull flows, these sediments can include bedload. In wide reservoirs where the dam does not submerge, sediments may be limited to suspended loads that may include sand. Interception of sediment by the reservoirs is a function of reservoir length, depth and width and the length of time that sediment of a given size stays in suspension.

3) Large amounts of organic matter including leaves, wood, and aquatic plants are annually carried by rivers, especially in the fall. These materials are drawn into voids where subsurface flows enter the rock base (Figure 55). Subsequent fine sediments collect on these organics and further plug subsurface flow.

Figure 55. Leaves and woody debris sealing void in a rock rapids fishway.

A series of surface flow measurements in a five-foot high, five percent slope Rock Arch Rapids on the Otter Tail River, Minnesota were taken to quantify subsurface flow (see Project Brief #28). In several respects, this was a worst case scenario for subsurface flow. The modified dam was at a lake outlet where it is likely that the lake intercepted most sediment before they could be supplied to the rapids. As a result, the ramp did not benefit from river sediments that would help to seal the interstitial spaces. Two of the five feet of the dam's height were originally controlled by flash boards. Half of the 80-foot crest width of the dam was missing these flash boards so pool stage was controlled by the rock ramp rather than the original dam. The rock ramp was 100 feet wide over most of its length. In addition, pools were constructed between weirs that shortened the length of the riffles (in the direction of flow) separating the pools and reducing flow resistance. The area between the dam crest and the first weir were sealed with gravel and pea gravel but the remainder of the ramp was not. A discharge measurement was taken at a riffle downstream of the rock ramp to establish full-river flows. The difference between the full-river flow and surface measurements taken on the rock ramp indicated subsurface flows at the corresponding cross-section (Figure 56). These measurements showed very little leakage in the upstream portion of the rapids where the rapids was sealed with gravel and the measurement taken four feet downstream of the crest matched full river flow while the difference between full river flow and a measurement 13 feet downstream of the crest was less than one cubic foot per seconds (cfs). The greatest leakage was 35 feet downstream of the crest where surface flows were 13 cfs less than full river flows.

Similar observations were made of an eight-foot

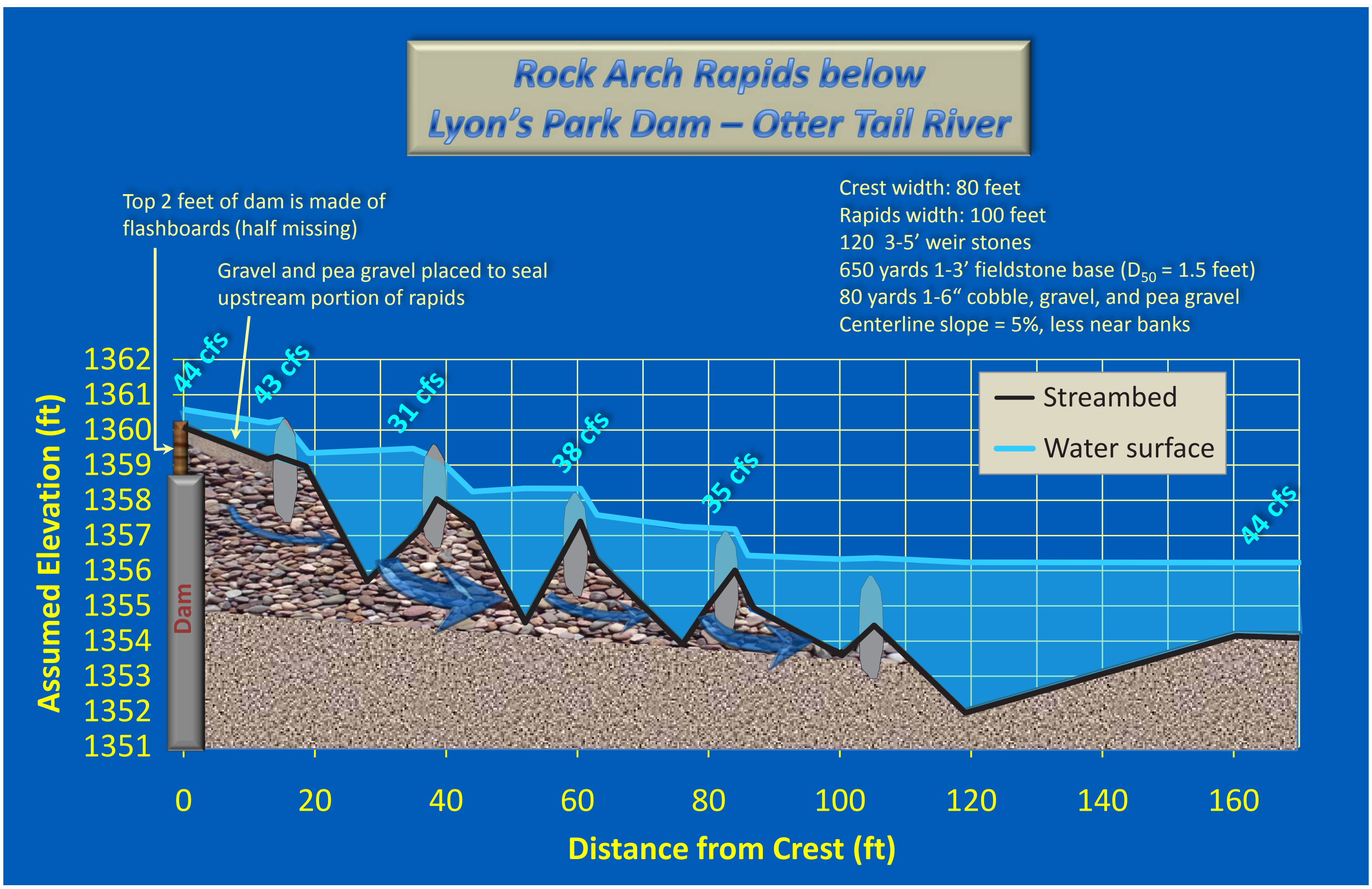


Figure 56. Centerline profile and surface discharge measurements in Lyon's Park Dam Rock Arch Rapids. Discharge measurementst were taken at 4, 13, 35, 60, 85, and 170 feet downstream of crest.

high Rock Arch Rapids on the Lac qui Parle River that replaced a dam (see Project Brief #37). Discharge measurements were taken on the rapids crest and at a natural channel cross-section 433 feet downstream. Flow measured on the crest was 132.2 cfs while the full river flow was 135.0 cfs suggesting subsurface flow (leakage) of 2.8 cfs. However, estimated error of the measurement was ±2.7 cfs. While a mix of sand, gravel and cobble had been used to seal the voids, these measurements were taken during construction before organic matter and sediment carried by the river could further seal pores in the rock. The rapids was built entirely of loose stone and aggregate with no sheet piling or other seepage barrier.

An understanding of site hydrology is critical to the design process.

An understanding of site hydrology is critical to the design process. Headwater and tail-water rating curves (stage: discharge relationships) should be developed. This defines the flow at which the dam submerges and the energy slope changes from the slope of the rapids to the slope of the river. Low gradient rivers generally have lower shear stress (due to low slope) during floods than rapids experience at pre-submergence flows. However, during large floods, energy slopes in these streams can be higher than bed slopes due to approaching flood crests, and shear stress calculations should be made for the entire range of flows.

In projects with deep scour holes and where large volumes are needed, an alternative material for sub-base is waste concrete that can be covered with a layer of fieldstone. Since waste concrete is angular, it makes a good base material and is often much less expensive than fieldstone. It is important to make sure the concrete is clean and free of rebar and, while exposed concrete is aesthetically unacceptable, the layer of fieldstone eliminates this problem. The fieldstone should be laid to a thickness of at least the D_{100} when a waste concrete sub-base is used.

Maximum base slope is 5% or 20:1 and, in sites with high shear stress (over 70 kg/m^2) slope should be reduced. A lower slope is preferable. European experiences have suggested a 3% maximum slope for similar structures (Ulrich Dumont, personal communications) although rock ramps with slopes of 5% have been successful in passing "weaker swimming" species (FAO 2002). This is consistent with the Rock Arch Rapids design, which typically has yielded a lower near-bank slope of about 3% when the center slope is 5% due to the weir configuration. Base should also be sloped from the banks to 1/3 of the distance across the channel. Since the rapids must match the existing crest, the base is parabolic with cross-sections flat near the crest and becoming concave downstream. Specific cross-section slopes will depend on river width and other factors.

Banks adjacent to the rapids should be armored with fieldstone (sized as described above) to an elevation that matches or exceeds the inundation stage of the dam. It should be laid to a thickness that exceeds the D_{100} or 1.5 times the D_{50}, whichever is greater. This is important because pre-inundation flows maintain the slope of the rapids and have high shear stress that would erode unprotected banks and potentially undermine the rapids. While this initially creates an austere and artificial looking bank, deposited sediments favor sprouting of trees and wildflowers between the stones, giving the rapids a more natural appearance. The riprap can also be covered with topsoil and seeded to improve aesthetics, accessibility, and riparian functions. Trees and their root systems also bind soils, reduce soil saturation, and add strength to the banks (Simon and Collison 2002).

Boulder weirs are built on the rock base to create a step-pool configuration and to further reduce near-bank slope. Weir stones are substantially larger than base D_{50} and add stability to the rapids. For most projects we have used stones 3.5 to 6.5 feet in diameter with weights ranging from about 3,600 to 23,000 pounds. While the weirs create locally higher velocities and shear stress directly downstream of the boulders, they reduce velocities and shear stress between the weirs by flattening the energy slope. Gravel placed between weirs for spawning habitat has generally remained in place even though average calculated shear stress on the rapids slope was far in excess of that needed to move gravel.

The weirs are built with a hemi-circular or U-shaped configuration with the center of the U pointing upstream. The individual weirs slope downward from the banks to the center or opposite the slope of the base. This creates flow convergence, as the energy slope and velocity vectors are perpendicular to the weir tangent. This configuration has been used with many variations in stream restoration projects (Rosgen 1996, Newbury et al. 1993) and it has several advantages. First, much of the energy is dissipated in the center of the rapids and near bank velocities are reduced. A deep pool is typically created or maintained (dams often have deep scour holes below them) while sediment often deposits along the banks. Second, boulders within the arch buttress against each other and add stability. This is particularly important for protection against ice and log impacts. Third, the configuration facilitates fish passage by creating low velocity eddies and passage is resilient to changing flow conditions. Slopes are reduced because the weirs lengthen the rapids near the banks. Passage routes are most suitable in mid-channel areas during low flows and near the banks as flows rise. Finally, the low velocities near the banks also improve safety for individuals who may slip into the water.

The hemi-circular weir configuration has several advantages:

1. *Much of the energy is dissipated in the center of the rapids and near bank velocities are reduced.*
2. *Boulders within the arch buttress against each other and add stability.*
3. *The configuration facilitates fish passage by creating low velocity eddies and passage is resilient to changing flow conditions.*
4. *The low velocities near the banks improve safety for individuals who may slip into the water.*

The downward weir slope from the banks to mid-channel is created by the concave cross-section of the base, by embedding the mid-channel weir stones in the base and by using the largest boulders at the toe of the bank. In small narrow rivers, the weirs can be a full semi-circle and still maintain proper slopes. In wide rivers, the radius of curvature of the weir must be increased or the weir arch must be truncated to maintain the proper invert slope along the weir. Otherwise the weirs would extend too far up the opposing base slope to compensate with the methods just described. Unfortunately, as the radius of curvature of the arch increases, the buttressing effect decreases. Staggering the boulders within the arch and embedding center boulders help to buttress them against ice and wood impacts.

More than one weir per foot of head-loss is used to assure that less than 0.8 foot of head loss exists over each weir. Even though the first weir matches the crest elevation, the gaps between the irregular boulders pass significant flow and will cause head loss between the crest and the weir. Gap width between boulders in the weirs can be adjusted to increase or decrease flow between boulders and head loss over each weir. This is a critical step to avoid excessive head loss and a fish-passage bottleneck due to differential head loss among weirs. Partial weirs or random boulder clusters can also be placed between the crest, first full weir, and riverbanks to further reduce velocities in the upper part of the rapids.

The By-pass Fishway

This approach involves the construction of a channel through the dam embankment that connects the reservoir to the immediate tailwater. The channel should be built with the dimensions, meander pattern, and profile of a natural channel. Observed norms of natural channel geometry by type have been summarized by Rosgen 1996. Bypass fishways are usually sized smaller than the natural river channel and are designed to carry a fraction of total river flows (Figure 57). Slopes of these channels can range from steep (up to 4%) to as gradual as the available land and topography allow. Since the channel is normally smaller with a steeper slope than the river's natural channel, design needs to emulate the morphology of a stream with similar characteristics.

Criteria have been developed in Europe to assure that fishways are appropriate for the ecological setting in which the fishway is built (Parasiewicz et al. 1998). This is a means to assure that passage and habitat conditions are appropriate for native biota. By-pass channels with low slopes are likely to be more effective in passing slow swimming fishes than steep slope channels. However, even low slope streams can have steep reaches due to bedrock outcroppings or glacial deposition of boulders. These steeper reaches are often important critical habitat for rheophilic (prefer flowing habitat) species. In many cases, dams have been built at these sites eliminating the habitat. Consequently, the habitat component needs to be considered in fishway slope and design.

Design of a bypass fishway differs from other stream channel restorations in the way channel competence is assessed and depends on the upstream connection of the fishway to the river. Main channel restoration projects can use stable reference channels for geometry and sediment analysis. Stable reference channels that handle the flows and sediment provided by their watershed can be used as templates for design geometry for these projects. If the fishway channel connects upstream of the reservoir, sediment supplied to the fishway is that of the main river channel and the channel competence problem is similar. However, if flows into a bypass fishway are drawn from the reservoir, they are likely to be low in sediment as most bedload and much of the suspended load are deposited in the reservoir. If the fishway connects at the downstream end of a sediment- filled reservoir, the sediment supply may contain less bedload and more fines since the reservoir slope and shear stress may be inadequate to carry larger particles and most bedload is deposited in the upper reaches of the reservoir.

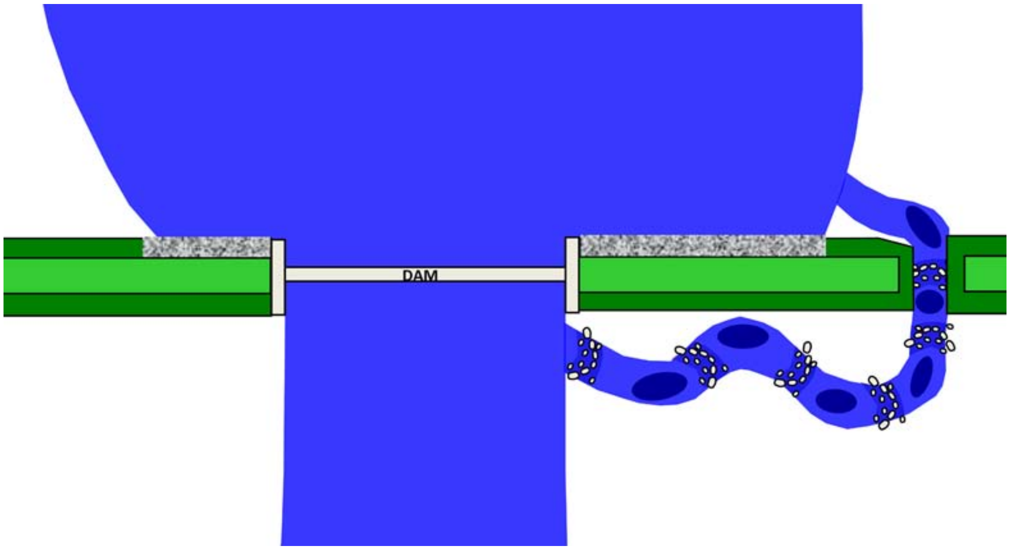


Figure 57. A generalized by-pass fishway.

Bypass fishways should be built with the dimensions, meander pattern, and profile of a natural channel.

Since the channel is normally smaller with a steeper slope than the river's natural channel, design needs to emulate the morphology of a stream with similar characteristics.

Since the fishway slope is typically steeper than the main river channel, bed degradation must be addressed. Constructed riffles or boulder weirs provide the necessary grade control and also create the hydraulics necessary for fish passage. Use of arching or U-shaped riffle or weir configurations like those presented in chapter one creates flow convergence and provides sediment transport superior to straight weirs based on physical model comparisons and *in situ* field observations. These structures also reduce bank stress and maintain downstream pool depth.

Steep (> 2%) natural channels tend to have a step-pool configuration (Figure 58). The pools provide

Figure 58. Hellroaring Creek, Montana, a steep, natural stream with a step-pool channel and the St. Louis River, Minnesota showing a large step-pool rapids.

resting habitat and areas that allow fish to position their bodies to launch through the step. Step spacing in these channels is often closer, 0.43 to 2.4 channel widths (Chin 2002) than riffle spacing found in low gradient streams of five to seven channel widths (Leopold et al. 1964).

However, even natural channels with excessively steep slopes can be impassable, especially for species not normally found in steep streams. Fishways with lower slopes are generally more likely to be passable for the full spectrum of species.

Sizing the channel is a function of the flows that it will need to carry and the size of river. Maximizing design flows will best assure that there is adequate capacity for passing migrating fish as well as attracting them to the entrance. Flows available for fishways are often constrained by the resulting reduction of flows available for consumptive withdrawals from the reservoir such as hydropower, irrigation, and municipal water supplies and construction costs. As a result, the question typically arises, "How much is enough". Inadequate flows in a bypass fishway will result in the lack of attraction to the fishway entrance. Where large numbers of passing fish are present, an undersized fishway may have inadequate capacity and be a bottleneck. High densities of fish may result in increased stress; disease; bird, mammal, and piscivorous fish predation; and mortality. Large fish such as sturgeon may be physically unable to swim through an undersized fishway.

Entrance position is critical in assuring that fish find the fishway. The best entrance location is in the immediate tailwater so fish impeded by the barrier will naturally enter the fishway. Entrances located significant distances downstream of the barrier may cause fish to swim past and become trapped below the dam by their natural instinct to swim upstream. While some fish are likely to ascend a downstream entrance, the proportion may be comparable to a tributary.

Entrance velocities may also be a factor in attraction efficiencies. Fish species with widely different body types and sizes have different swimming capabilities; therefore, the use of single target entrance velocities based on single target species will not provide suitable conditions for the diverse fish communities dependent on seasonal migrations. The solution is the use of riffles and boulder weirs that provide diverse velocity distributions similar to natural riffles. Use of an elliptical cross-section and variable gaps between boulders provides a wide range of depths and velocities. Figure 59 demonstrates the complex velocity distributions of a natural riffle and two different boulder weirs in fishways. I have observed schools of small-bodied minnow and darter species moving through lower velocity, shallow areas of the riffle near the banks while larger, faster swimming fish moved through the deeper, faster portion of the weir in the center of the channel.

While technical fishways have focused on optimizing conditions for single or a few target species, use of natural channel design techniques create complex and diverse conditions that provide for the full spectrum of conditions needed to pass the fish community.

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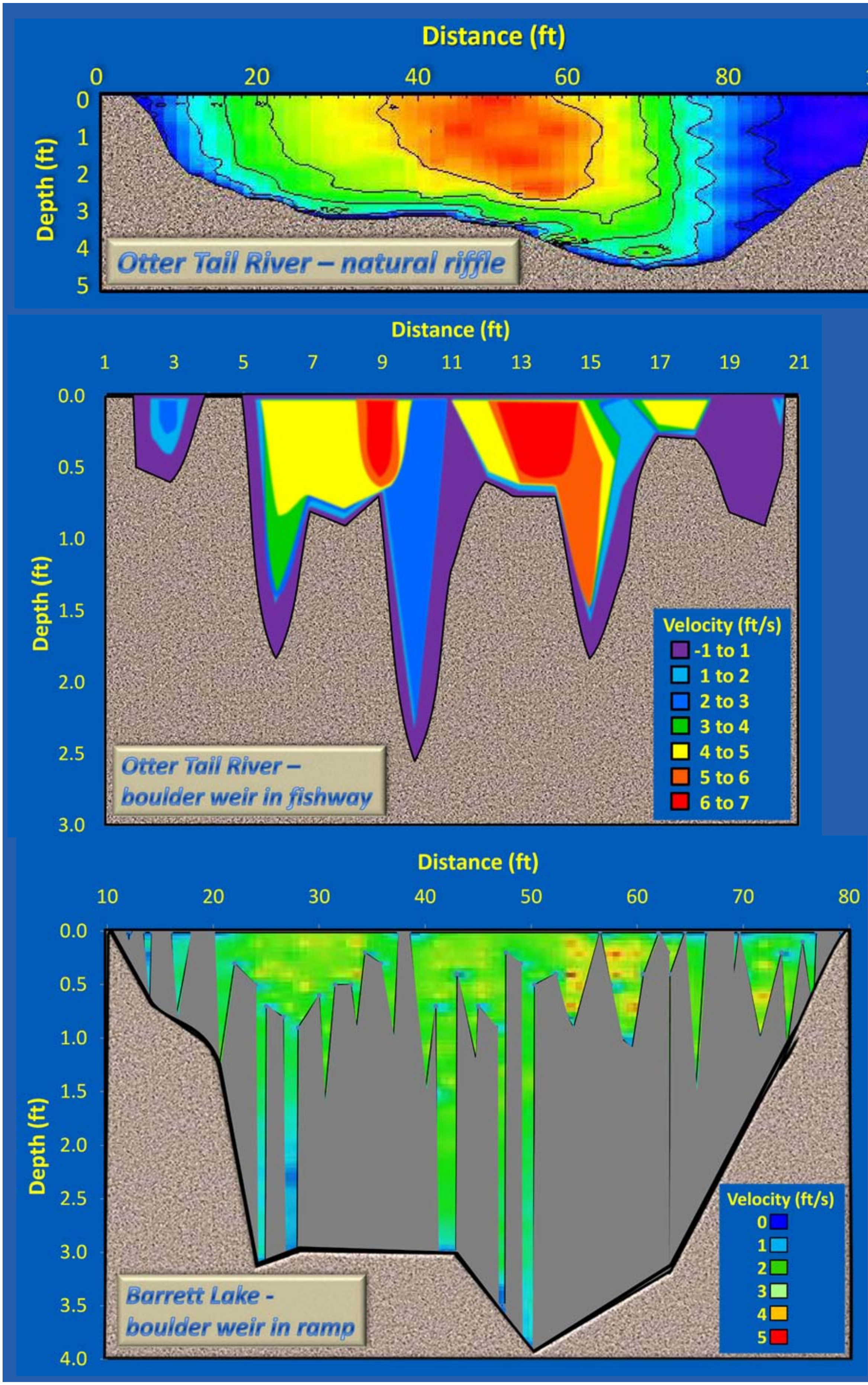

Figure 59. Velocity isovels across a natural riffle in the Otter Tail River, a boulder weir in the Diversion fishway, and a boulder weir in the Barrett Lake Dam fishway.

Case Examples

As with all aspects of rivers, restoration efforts need to be evaluated in the context of the system. This is particularly true with restoration of migratory pathways. The following are a series of projects that have specific aspects and importance but fit into a larger effort to reconnect a major river system. This underlying effort was tempered by the need to not only prioritize projects according to their potential benefits, but to be opportunistic. The benefits of restoring passage through a barrier may not be fully realized until other barriers are also addressed. This is particularly evident with the first fishways we built as they were bracketed by other dams. However, the early projects became pivotal in gaining support for later projects that have progressively worked towards the broader goal.

The early projects became pivotal in gaining support for later projects that have progressively worked towards the broader goal.

The Red River Basin – Reconnecting a System

The Red River of the North, part of the Nelson River System that flows into Hudson Bay, is among the lowest gradient rivers in the world (Figure 60). Its mainstem lies entirely in the bed of Glacial Lake Agassiz and drops only 240 feet in 545 miles for an average slope of 0.008%. As a result, riffles are largely absent and the channel is deep, narrow, and silt or sand bottomed. A total of 90 fish species are found in the watershed with 57 species observed in the Red River itself (Aadland et al 2005). Many of these mainstem species spawn in riffles or other habitats lacking in the Red River. These habitats are found in tributaries that pass through glacial till at the beach ridges of Lake Agassiz. Near these beach ridges the streams have steeper slopes with gravel, cobble, and boulder substrates. While these habitats were connected to the mainstem prior to European settlement, dam construction blocked historic migratory pathways. Steeper stream reaches were also preferred locations for dam construction and many of the key rapids were inundated by reservoirs.

While it is difficult to determine the extent to which dam construction changed the fish community, lake sturgeon were extirpated from the Red River Basin. Based on the detailed writings of Alexander Henry the Younger, sturgeon were abundant around 1800, and he reports catching up to 120 sturgeon per day in the Pembina River, a tributary to the Red flowing out of Manitoba and North Dakota (Gough 1988). Henry mentions various sturgeon habitats including spawning rapids at the confluence of the Red Lake and Clearwater rivers, over-wintering habitat at the confluence of the Red Lake and Red rivers in Grand Forks, ND-East Grand Forks, MN, and areas near the mouth of the Pembina River where juvenile sturgeon were abundant.

The fate of lake sturgeon in the Red River Basin was mirrored to a lesser degree by other species that were extirpated from reaches upstream of dams. While species like channel catfish, sauger, and others maintained populations in the mainstem of the Red, their distribution diminished as dams fragmented tributary habitat. The effect of this fragmentation and loss of connected spawning and nursery habitat on mainstem populations is unknown.

Efforts to reconnect the system began modestly and momentum grew with each successful project. Much of this was driven by site-specific problems including safety, erosion, loss of structural integrity, and dam failure. Detailed descriptions are provided in the main text with additional project briefs in the Appendix.

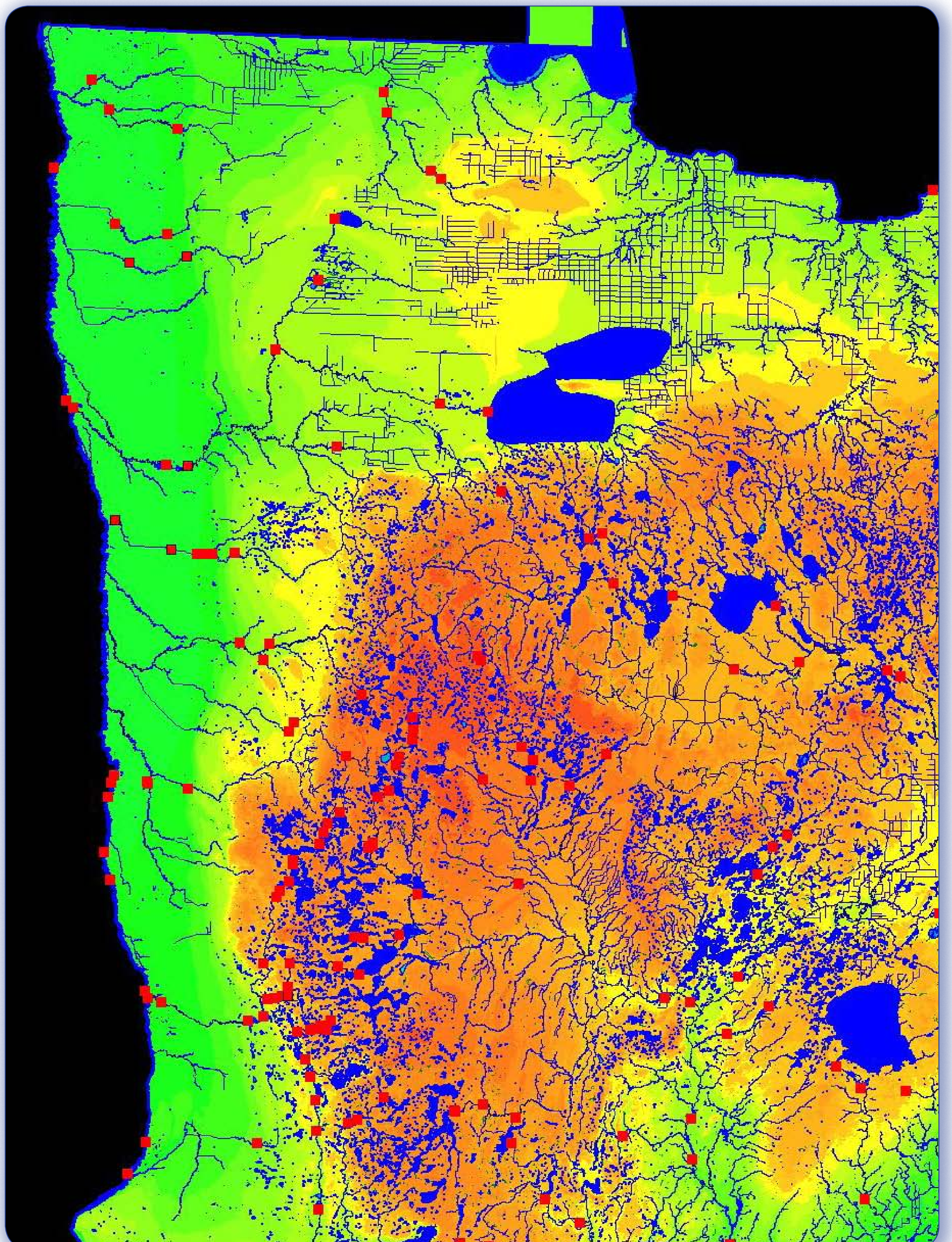

Figure 60. Map of Northwestern Minnesota showing the Red River of the North Basin and the location of barrier dams as they existed in 1993.

Steam Plant Dam

Location: The dam is on the east side of Fergus Falls, Minnesota on the Otter Tail River (Figure 61).

Historical and Political Context: This dam was located at the downstream end of a 12-mile long reach of the river from which water was diverted for hydropower and for cooling a steam plant (Figure 62).

The dam provided a pool for an emergency water supply for the steam plant if the primary intake failed. Following licensure of the plant in 1991 by the Federal Energy Regulatory Commission, improved protected flows were restored to the reach. We concluded that our efforts to restore the fish community in this reach were limited by the dam that prevented fish passage. The reach also had significant recreational canoeing potential but the dam presented a boating hazard. Following negotiations with Otter Tail Power in October 1994, it was agreed that the dam would be lowered and converted to a rapids. Some locals were

Dam Description

- **Hydraulic height:** Approximately 10 feet
- **Crest width:** 40 feet
- **Crest elevation** 1,189 ft MSL
- **Dam owner:** Otter Tail Power Company
- **Max head-loss:** 7 feet
- **River flow:** Regulated and diverted, Minimum flows: 30 cfs September to March, 110 cfs in April, 60 cfs May to August. Peak flows up to 850 cfs.
- **Appendix:** Project Brief #25a & 25b

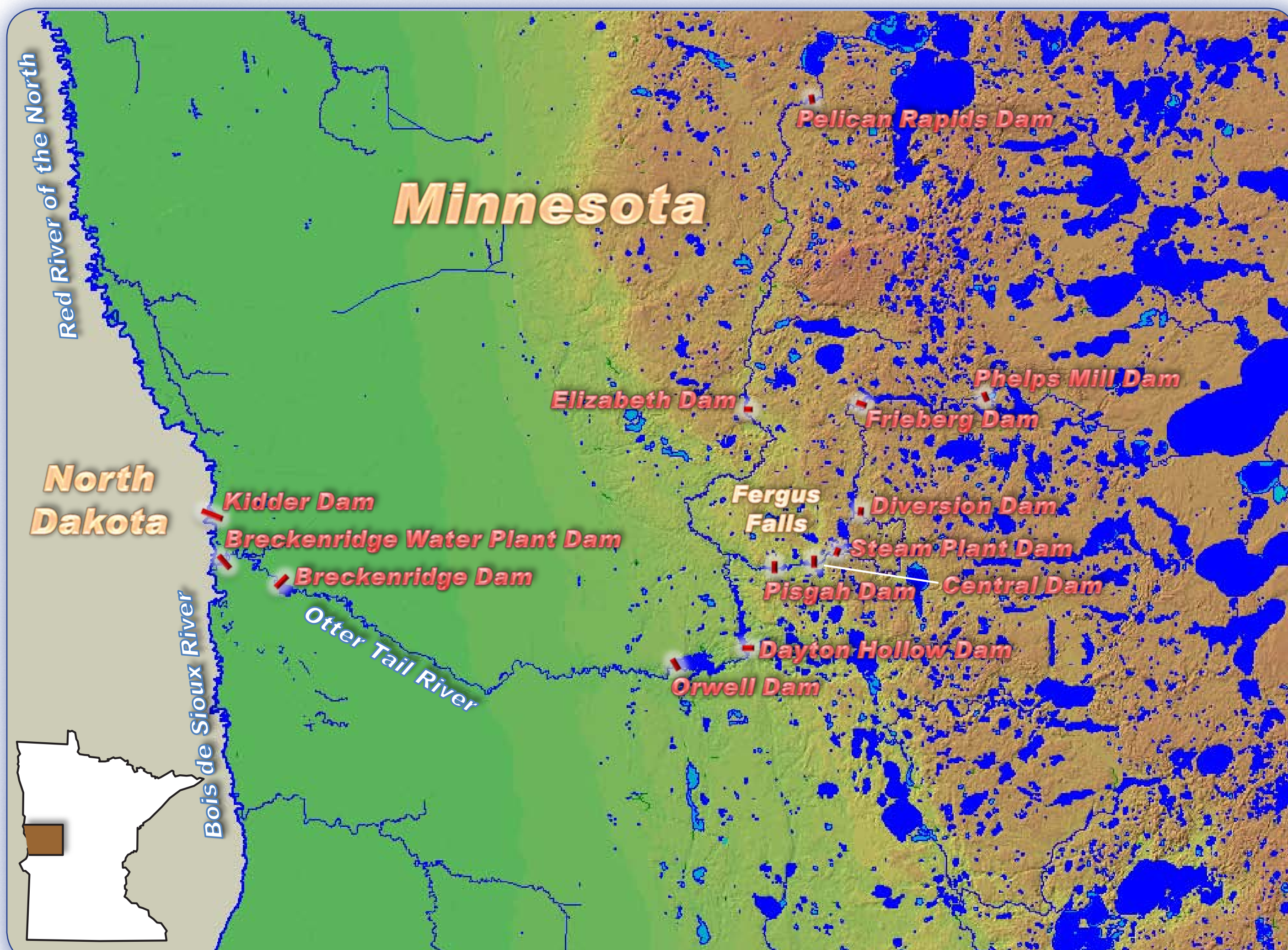

Figure 61. Topographic relief map showing the Otter Tail River and some of the barrier dams.

Figure 62. The Steam Plant Dam on the Otter Tail River. The dam was made of concrete and burlap bags filled with fly ash.

concerned that the project would allow carp to access upstream lakes. These concerns were alleviated by Fisheries records showing that carp had been present upstream of the dam for about 40 years.

Design

The project goal was to convert the dam to rapids as a means of providing both fish and canoe passage. Few projects of this type had been built in the United States. Staff from the Wisconsin Department of Natural Resources provided a videotape of construction of the Eureka fishway that helped sell the general concept as an alternative to a baffle type fish ladder.

The project would reduce the height of the dam by three feet and a series of rock riffles and pools would create a step pool channel (Figure 63). The original crest elevation was 1,189 MSL giving the dam a hydraulic height of approximately six feet. The plan would reduce that height to 1,186 and would still maintain adequate depth for the emergency pump without cavitation. One side of the channel was designed to be relatively smooth to accommodate canoes while the other side rough with additional step pools to provide fish passage.

The hydrology of the Otter Tail River is naturally regulated by thousands of lakes and wetlands in the watershed. The dam was on a reach from which up to 300 cubic feet per second (cfs) are diverted for hydropower. Record high flows at the U.S.G.S. gage five miles upstream of the diversion are 1,170 cfs or about 870 cfs at the dam site.

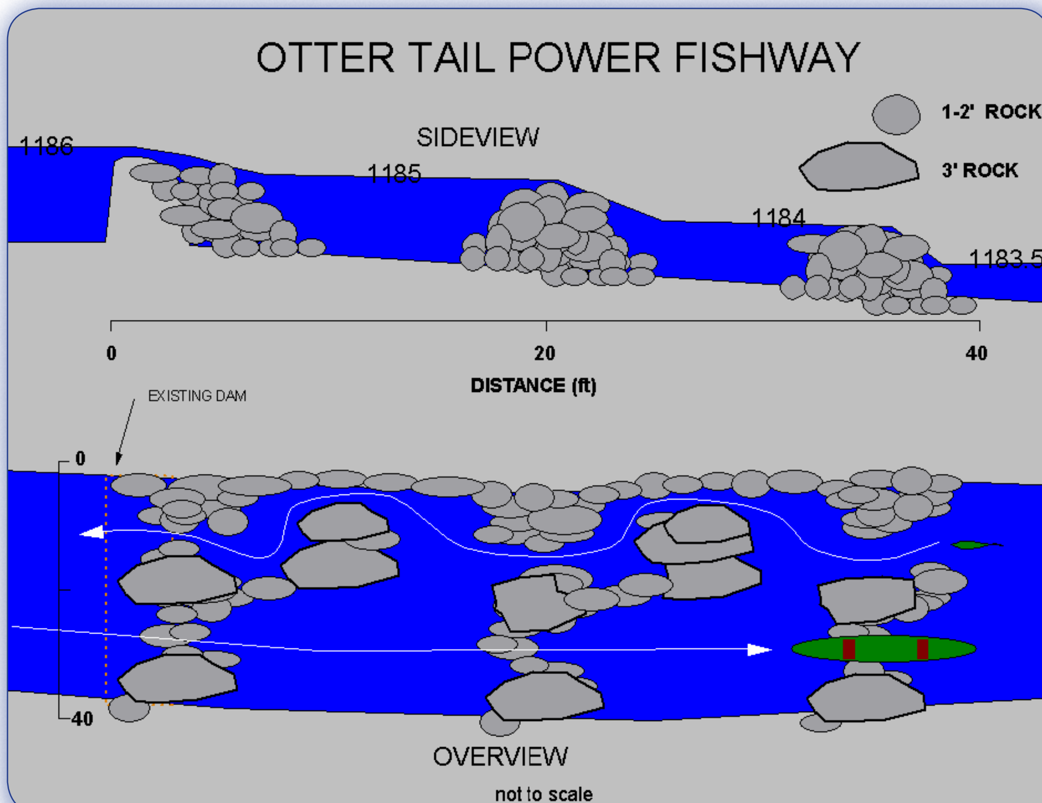

Figure 63. The Steam Plant Dam on the Otter Tail River. The dam was made of concrete and burlap bags filled with fly ash.

The stone used for construction was sized using relationships between shear stress and particles moved as applied by Newbury et al. 1993. Using Manning's equation, I estimated that 870 cfs would yield a depth of flow of about two feet (610 mm) over the dam crest resulting in a shear stress of 38.1 kg per m^2 or a particle diameter of 38 cm (1.25 feet). We used a gradation of one to two-foot stones for base and larger three-foot stones for added stability and weir construction.

Construction

The site was adjacent to a steam plant and high voltage transmission lines directly overhead limited the use of heavy machinery. Many of the smaller stones were hand placed (Figure 64).

The project wasn't constructed as designed initially because the excavator could not break age-hardened concrete in the dam. As a result, the dam was over a foot higher than specified, the overall slope was 10% rather than 6% and the velocities and slope over the dam crest were excessive. While the completed project provided fish passage and created rapids passable for kayakers, it was too steep for canoeists and passage for some fish species was likely limited (Figure 65). A portage was provided around the rapids but the steep banks and narrow confines in this industrial site made it a difficult take-out. Part of the problem with this project was a very limited budget. Total project cost was only $2,580 and 124 yards of fieldstone were used.

Our experience with other projects and the development of the Rock Arch Rapids design prompted Fisheries and Trails and Waterways staff to pursue funding to improve the project. The improvement involved the addition of two boulder weirs on the existing rock and two downstream riffles that would reduce the overall slope to 1% and each step to about a foot of head-loss (Figures 66 - 69). The downstream placement of the riffles avoided the deep pool immediately downstream of the existing rapids that would have required much more fieldstone.

Improvements used about 750 yards of fieldstone including about 80 three-foot plus stones. The rock cost was $20 per yard or $15,000 total. The work

Figure 64. Hand placement of fieldstone during the initial conversion of the Steam Plant Dam to rapids, October, 1994.

was done by the Section of Fisheries Construction Crew and used a small track hoe with a thumb and a front-end loader. Construction required four ten-hour days and was finished in September 2005. Total cost was approximately $30,000.

Monitoring

Schools of shiners and smallmouth bass fingerlings have been observed swimming through these rapids. Smallmouth bass have become established upstream of the fishway, which was a primary objective of the original project. Due to the difficulty of the site, no quantitative monitoring has been done for this project.

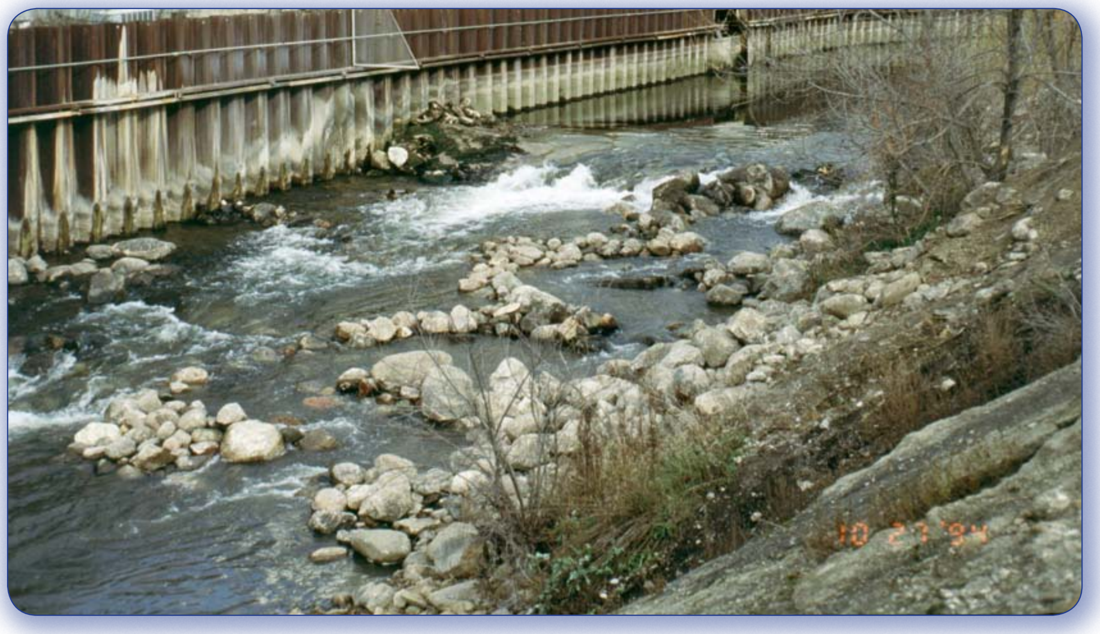

Figure 65. Steam Plant Rapids during low flows on the Otter Tail River in 1994.

Figure 66. Planview for improvements to the Steam Plant Rapids.

Figure 67. Plant Rapids after improvements in September, 2005.

Figure 68. Steam plant rapids viewed from downstream showing the constructed riffles.

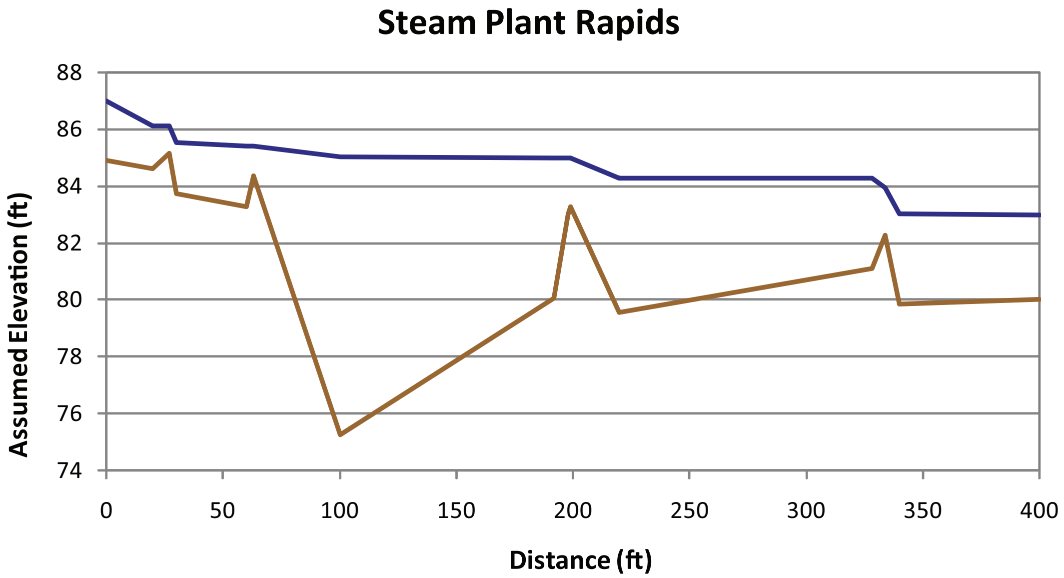

Figure 69. Center-line profile of the Steam Plant Rapids after improvements. Water surface elevations are shown in blue, the bed is shown in brown.

Midtown Dam

Location: The Midtown Dam is on the Red River of the North between Fargo, North Dakota and Moorhead, Minnesota.

Historical and Political Context: The U.S. Army Corps of Engineers, as part of a flood control project, originally built the Midtown Dam in 1961 when the channel was straightened and flood control levees were built (Figure 70). It replaced an earlier dam built in 1929. Between 1997 and its completion there were at least 19, and as many as 25, deaths by drowning at the site due to the hydraulic roller created by the dam crest.

The dam was also a barrier to fish migration. The Red River of the North has a diverse fish assemblage with at least 57 species (Aadland et al 2005). One tagged channel catfish had been observed migrating over 300 miles, from Fargo to Lake Winnipeg (Hegrenes 1992). While the dam was submerged and passable during floods, they were of short duration, inconsistent, and did not necessarily coincide with spawning migrations (Figure 71).

Local concerns over the safety issue leveraged funding for a Corps of Engineers study of alternatives in 1995. Several Department of Natural Resources staff, including myself, recommended removal of the structure as the preferred alternative, but since the intake for the Fargo water supply depended on the minimum pool maintained by the dam, this recommendation made little headway. As a secondary alternative, I recommended a 5% slope rapids as a means of eliminating the hydraulic roller and restoring fish passage. The previously constructed Steam Plant Rapids provided an image of the concept as well as criteria for design. This alternative was also met with little initial enthusiasm, as there was an interest by some parties to build a larger dam and use chain link fence to prevent access. The Rock Island District of the Corps of Engineers completed the Reconnaissance Report for Safety Modifications in March 1997. This study assessed various alternatives including

Dam Description

- **Year built:** 1961 (replaced a dam built in 1929)
- **Owner:** City of Fargo
- **Hydraulic height:** 9.7 feet
- **Maximum head:** 5.3 feet (tailwater is effected by the downstream North Dam)
- **Crest elevation:** 875.7 MSL (N.G.D.V. 1988)
- **Crest width:** 120 feet at 875.7, sloping from 190 feet width at approximately 877 MSL
- **River flow:** Average 681 cfs, record maximum 28,000 cfs, minimum 0 cfs
- **Project engineers:** Roger Less, P.E., ACOE, Mark Bitner, P.E., City of Fargo, Vern Tomanack, P.E., City of Fargo
- **Appendix:** Project Brief #18

Figure 70. The Midtown Dam on the Red River of the North between Fargo, North Dakota and Moorhead, Minnesota (photo courtesy of Robert Backman, River Keepers).

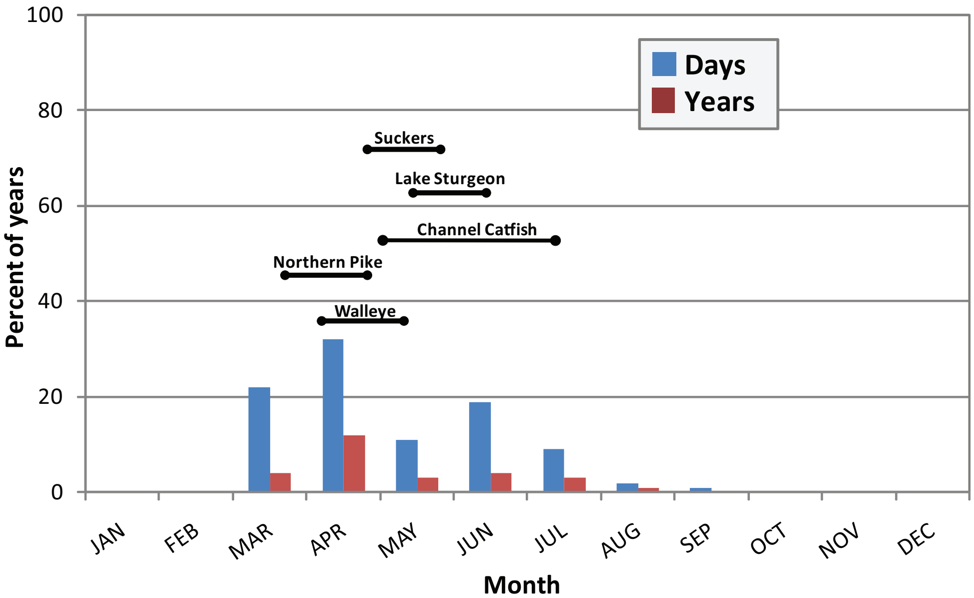

Figure 71. Percent of days and years that Midtown Dam was passable. Based on U.S.G.S gage 05054000 records from 1901 to 1997 and the assumption that the dam was passable at flows greater than 3000 cfs. Approximate migration periods are shown by lines for northern pike *Esox lucius*, walleye *Lucioperca vitrium*, suckers *Catastomus commersoni* and *Moxostoma sp.*, lake sturgeon *Acipenser fulvescens*, and channel catfish *Ictalurus punctatus*.

using pre-cast concrete blocks or concrete fabric bags on the downstream face of the dam to create stair steps, channel sidewalls to prevent access to the tailwater, a 25% rock slope to reduce the hydraulic roller, and my recommendation of a 5% slope rock rapids.

A January 1997 letter indicated that the Minnesota Department of Natural Resources would permit removal of the dam or conversion of the dam to rapids while the other alternatives would not be permitted. There was significant controversy surrounding the issue exacerbated by several features carried by a local television station featuring a city official and myself in a sort of point-counterpoint debate. Stated concerns by people opposed to the rapids alternative included the potential for individuals climbing boulders in the rapids and slipping off, potential for the rapids to collect trees and branches, and the desire to build a larger dam. After discussion and the support of several groups including River Keepers, upstream Wahpeton Parks Department, and the Fargo Parks Department, Fargo Mayor Bruce Furnace made a motion to recommend the 5% slope rapids and it carried.

Project funding was provided by: the cities of Fargo and Moorhead, the Minnesota Department of Natural Resources, the North Dakota Game and Fish Department, the North Dakota State Water Commission, Southeast Cass Water Resource District, the Buffalo-Red Watershed District, and the Fargo Park District.

This was the first project to use and develop the Arch Rock Rapids design previously discussed. A basic layout for the rapids was designed in collaboration with Roger Less, P.E. of the Rock Island District Corps of Engineers. The Corps had been involved in a project that created a 25% slope using 5-foot stones as a means of eliminating the hydraulic roller and included this alternative in the reconnaissance report. I advised a 5% slope based on experiences with previous fish passage projects and presented a conceptual design for the rapids. Plans were further refined and the specifications and bidding process was handled by City of Fargo Chief Engineer Mark Bitner, P.E. with the assistance of Vern Tomanack, P.E. also from the City of Fargo. Mark Bitner also signed the final plans.

A gage immediately upstream of the dam allowed estimation of shear stress by providing a stage: discharge relationship. I had observed that the dam was inundated at a flow of about 3,000 cfs. Above this flow, the energy slope was reduced to that of the river slope, in this case, the very low gradient Red River of the North. Since the slope of the rapids was 5% up to the point of inundation, shear stress was greatest at flows just below 3,000 cfs. At a flow of

3,000 cfs, the depth of flow at the dam crest was 3.0 feet or 910 mm. Shear stress in kg per m^2 = depth (mm) × slope so 910 × 0.05 = 45.6 kg/m^2. Regressions by Lane 1955 and applications by Newbury 1993 discussed earlier, suggest that this correlates to a diameter (D_{50}) of 45 cm or about 1.5 feet. Based on these calculations, rock gradations larger than 1.5 feet were recommended (Table 3). Smaller (one-foot) material was used to fill voids.

Material	Quantity	Placed Cost	Function
Riprap (D50 = 41 lbs.)	940 y	$26,371.66	Sub-base and downstream 50 feet of rapids
1-foot fieldstone	75 y	$3,450.00	Base
2-foot fieldstone	450 y	20,700.00	Base
3-foot fieldstone	510 y	$23,460.00	Base
5-foot fieldstone	330 y	$15,180.00	Weirs
Crushed rock: 1.25” and under	506.3 y	$14,682.18	Access causeway
Crushed rock: 6” and under	938.8 y	$43,171.10	Sub-base
Crushed rock: 4-12”	949 y	$43,654.00	Sub-base

Table 3. Materials used in the Midtown Dam Project. Total cost of $237,500.00 included $37,565.00 for a temporary water diversion.

The contract specified that boulder placement would be overseen by the author but didn’t include the configuration in the plans. The U-shaped weirs were used because they created converging flow conditions, a step-pool configuration that favored fish passage, habitat similar to natural rapids where lake sturgeon spawn, low velocity conditions near shore as an added safety benefit, and were structurally stable since the boulders buttressed against each other.

Figure 72. Temporary partial diversion using steel I-beams placed on the dam crest.

Construction

The bid was awarded to Industrial Builders, Incorporated of Fargo, North Dakota and construction began on February 9, 1998. Flows were partially diverted by placing a large double I-beam on the dam crest (Figure 72). This created slack water so small diameter sub-base could be placed.

However, even with this diversion, placement of the 1.25” and smaller crushed rock was difficult as material was lost where velocities increased near the center of the river, therefore larger crushed rock was substituted. As the center of the channel was approached, the larger base material was used exclusively since velocities were too high for placement of the smaller material (Figure 73). Work had to be suspended on February 24, and the I-beam diversion was removed as the first February flood in over 100 years of record occurred. A series of seven floods during the spring, summer, and fall prevented construction from resuming until January 1999.

Figure 73. A front-end loader using the rock causeway to supply fieldstone for placement by the excavator.

Once the base was laid, the 5-foot diameter boulders were placed with large excavators. These boulders weighed around five tons each. The use of two excavators accelerated boulder placement by employing a bucket-brigade technique (Figure 74). This allowed the excavators to keep their tracks stationary and swing boulders into place. Several large boulders were placed on the dam crest near each abutment. This reduced near-bank velocities and created eddies for fish passage.

The project was finished on February 3, 1999 (Figure 75). Required rock volumes exceeded initial design estimates and the funding partners covered an over-run of $38,890.30 from the original contract amount of $189,335.00 making the final contract total $228,225.30. Difficulty and inaccuracy of surveying in a dangerous tailwater area, annual variability in channel morphology due to scour and deposition, and increased scour due to flow redirection during construction all likely contributed to this over-run. As a result, allowances for over-runs should be made and anticipated for similar projects.

Monitoring

Following completion of the project we took a series of measurements in a line parallel to the current to determine the velocity distribution through the rapids. A distance weighted least squares function was used to develop velocity isovels (Figure 76). While several species were observed swimming through the rapids, floating debris, very low water clarity, the size of the rapids (180 feet wide), and high spring flows limited use of trap nets and other means of quantifying passage. The velocity distributions served as a surrogate for fish passage by referencing projects with similar velocity distributions where passage could be monitored (Breckenridge and Diversion fishways). While this type of inference falls far short of actual collections, scale limitations on monitoring are a reality of projects of this size. The velocity profile shows generally low velocities between weirs and higher velocities in and directly downstream of the gap between boulders in the weirs. Velocities of up to 6.5 feet per second were measured at points directly downstream of the weirs but even at these locations, velocities near the substrates remained significantly lower (generally four feet per second or lower, Figure 76).

Figure 74. Two excavators using a bucket-brigade technique for placing weir stones.

Figure 75. Midtown Rapids at flows of 405 cfs (upper photo), 1,640 cfs (middle photo), and 2,560 cfs (bottom photo).

While mean velocities through the weirs may exceed the burst speed capability of small bodied fishes, I have observed schools of two-inch sand shiners move through them by moving close to the substrates where velocities are much lower. High velocities are also present only over short distances and the lower velocities between the weirs provide resting areas. This design takes advantage of the high burst speed capabilities of fish while addressing the fact that they can sustain these high speeds for only short distances.

Radio telemetry is a viable means of monitoring passage of large fishes that would have potential for projects of this type, but is not applicable to the

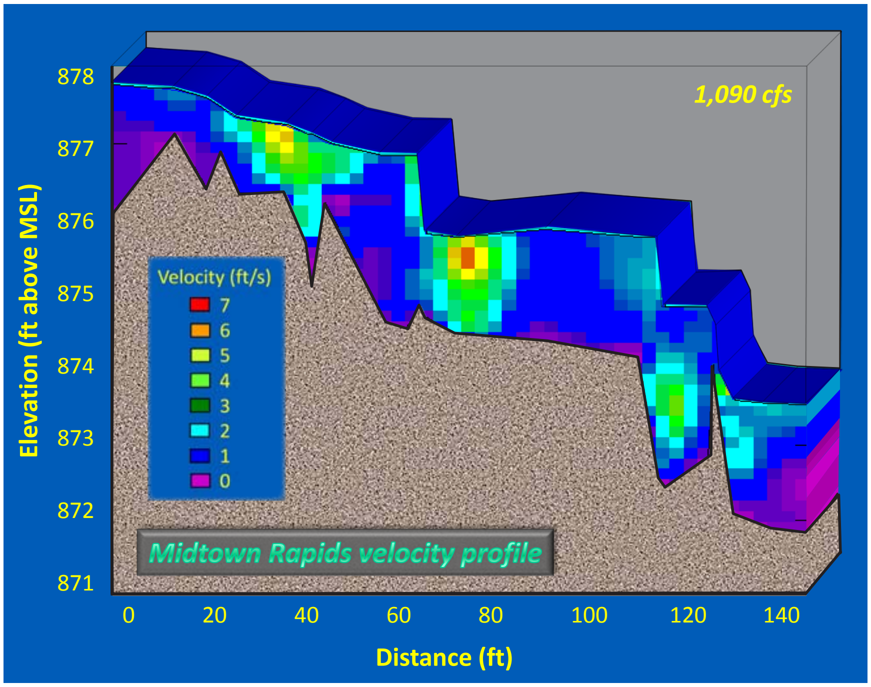

Figure 76. Longitudinal velocity distribution taken on August 3, 1999 at a flow of 1,090 cfs. This does not necessarily represent the best route for a migrating fish but is intended to show the velocity gradients one would encounter.

numerous small-bodied fish species. Various tagging methods allow recapture of tagged fish in new locations and provide some insight into movement but rarely do successive captures allow determination of timing of passage. This is a problem for projects like Midtown since large floods provide passage by inundation that would occur without the rapids conversion. Coded wire tags allow tagging of smaller-bodied fishes but recovery of tagged fish would require large numbers of tags and an extensive re-sampling effort to recover adequate numbers of tagged fish since the populations of these fishes may be very large.

The U.S.G.S. gage upstream of the dam presented the opportunity to determine effects of the project on upstream stage. This became pertinent in discussions and permitting of subsequent proposals for the remaining two dams in the Fargo-Moorhead city limits. There were concerns that flood stage for a given discharge could be raised as a result of the increased roughness of the dam's downstream face. Actual measured stage and discharge values collected by the U.S. Geological Survey did not show a measurable increase (Figure 77).

While it is logical that increased roughness of the weir and reduced cross-sectional area due to boulders placed on the crest would cause increased resistance and higher stage, these effects were apparently too small to be apparent at low flows and are compensated by elimination of the hydraulic roller and submergence at high flows. These empirical data were supported by numerical models done at the Waterways Experiment Station in Vicksburg, Mississippi that predicted no increases in upstream stage of the 100-year event resulting from a similar proposed project at the Fargo South Dam (Fuller and Bernard 2000). Record flows during the 1997 flood were 28,000 cfs at the site and had

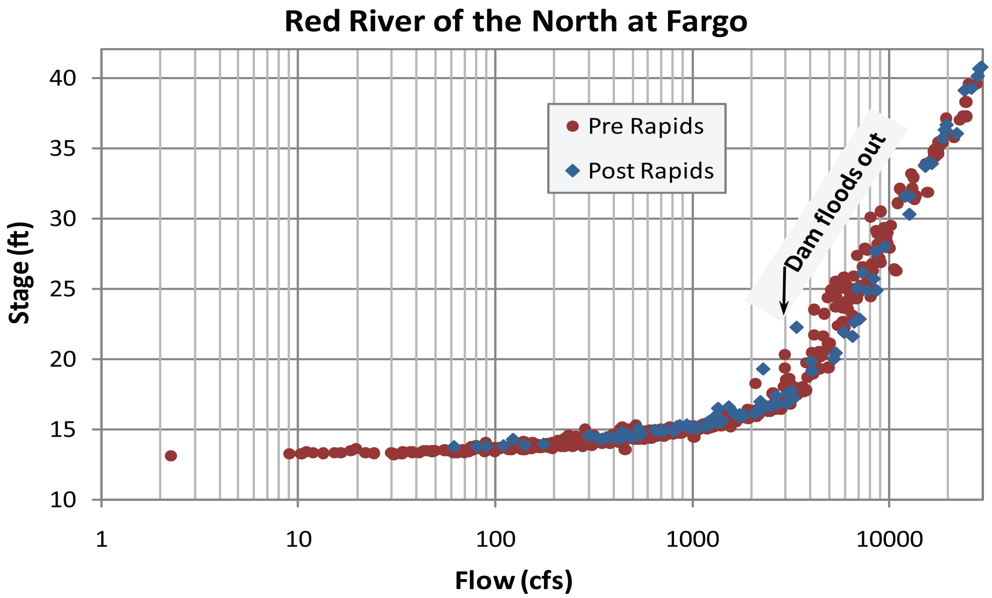

Figure 77. Stage and discharge measurements made by the U.S. Geological Survey at the gage (05054000) upstream of Midtown Dam before and after it was converted to rapids.

a stage of 901.52 or 25.82 feet above the Midtown Dam crest. The 100-year flood is presently calculated at 31,400 cfs. Observed head-loss over the dam and rapids is minimal (less than a tenth of a foot) at flows above 3,000 cfs (Figure 78).

In the six years since completion of the Midtown Rapids, no deaths have been reported at the site. Prior to conversion of the dam to rapids the site averaged a drowning every two years. Since people can drown anywhere there is water, there is no assurance that there will not be future deaths at the site, but it will not be a result of the deceptively dangerous hydraulic roller that had existed there. One result of the project has been its use for kayaking (Figure 79). Since there are no natural rapids in the community many of these kayakers are novices. While this use increases the potential for incidents, there have not been any serious injuries to date.

Midtown Rapids has not required maintenance since its construction despite the largest flood of record in 2009 (30,000 cfs) in addition to the fourth (20,300 cfs in 2001) and sixth (19,900 cfs in 2006) highest in 125 years of record.

Discussion

Despite controversial beginnings, the Midtown Rapids project has been widely viewed as a success. In the words of City of Fargo Engineer, Mark Bitner, “In my 25 years working for the City, I can’t remember any project of such small magnitude that has received such acclaim from the public.” The success of Midtown Rapids gave momentum to subsequent dam conversions that applied the same basic design.

Figure 78. Midtown Rapids at a flow of 3,430 cfs on April 4, 1999 showing minimal head-loss over the structure.

Figure 79. Recreational kayaking at Midtown Rapids. Photo courtesy of Dave Friedl.

Breckenridge Dam Fishway

Location: Breckenridge dam was located two miles east of Breckenridge, Minnesota on the Otter Tail River about seven river miles from its confluence with the Bois de Sioux River forming the Red River of the North. The dam was a complete barrier to fish passage (Figure 80).

Dam Description

- **Year built:** 1936
- **Owner:** City of Breckenridge
- **Hydraulic height**: approximately 13 feet
- **Maximum head-loss:** approximately 6 feet, 3 feet when stop-logs were removed
- **Crest elevation:** variable, operated with stop logs and a 3'x 3' gated orifice
- **Crest width:** 40 feet total in eight five-foot stop log bays
- **River flow:** Average 365 cfs, Maximum 2,040 cfs, Minimum 0.7 cfs due to Orwell Dam operation (flow statistics from gage 25 river miles upstream)
- **Appendix:** Project Brief #22a & 22b

Historical and Political Context: Breckenridge dam was built in 1936 for water storage. The dam created a complete fish barrier separating high quality upstream spawning habitat from the Red River of the North. Within about 50 years of construction the reservoir had almost entirely filled with sediment, largely eliminating storage and recreational functions (Figure 81). In 1995, the fishery and environmental problems associated with the dam led Arlin Schalekamp, the Area Fisheries Manager, and myself to discuss the idea of removing the dam with landowners, the Public Utilities Department (the dam owner), and other county and city officials. Primary concerns expressed regarding removal included the loss of potential water storage that would be available if the reservoir were dredged, loss of lake frontage for residents, and the effect on waterfowl hunting access. The Public Utilities Department rejected the removal option but supported fish passage. While removal was our preferred option, we decided to pursue a fishway because of the importance of fish passage at this site. The Wilkin County Highway Department and the County Engineer, Tom Rickles, agreed to oversee the project and provide the crew and equipment.

Figure 80. Breckenridge Dam on the Otter Tail River in West Central Minnesota. Stop-logs are not installed in this photo.

Project Goal

Restore fish passage for all species during all seasons and flow conditions.

Design

The design was developed collaboratively with the Wilkin County Engineer, Tom Rickles, P.E. and the Wilkin County Highway Department, who did the construction. The diverse fish community in the Otter Tail and Red River of the North dictated a design

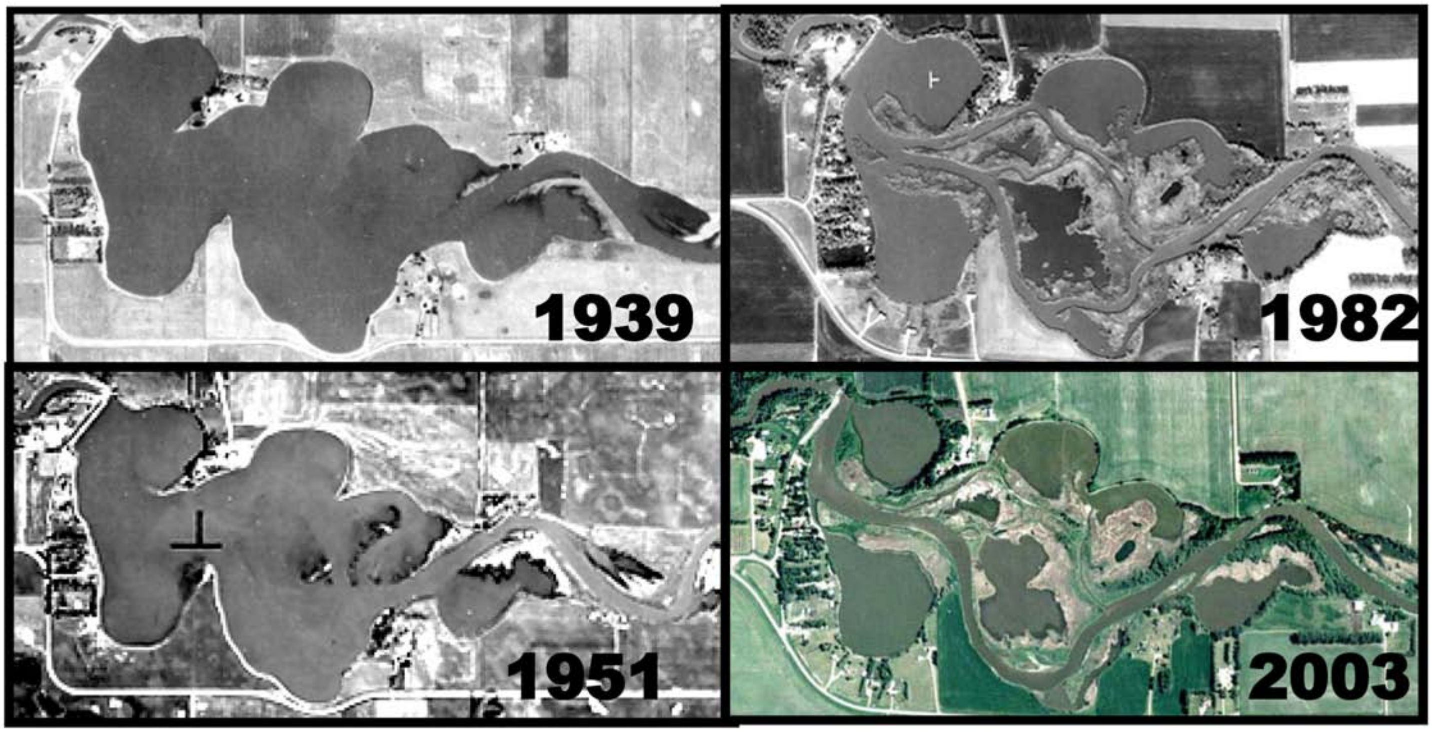

Figure 81. Breckenridge Reservoir in 1939, 1951, 1982, and 2003 showing sedimentation.

effective in passing a diversity of fish body types and sizes. The stop-log operation of the dam prevented conversion of the dam to rapids as we had done at the Steam Plant Dam already discussed. A "nature-like" by-pass fishway had been constructed on the Little Saskatchewan River at a dam in Rapid City, Manitoba in 1992 (Gaboury et al. 1994). This provided a concept that fit well with the similar Breckenridge Dam. The fishway channel would be constructed along the downstream toe of the dam embankment and where a culvert would be installed (Figure 82). The entrance was located in the immediate tailwater of the dam.

The channel was designed with a 2.5% slope or four feet of fall in 160 feet. Total length of the fishway including the culvert was 220 feet. Actual water surface slope varied due to the addition or removal of stop-logs. Stop-logs were normally installed after the spring flood and

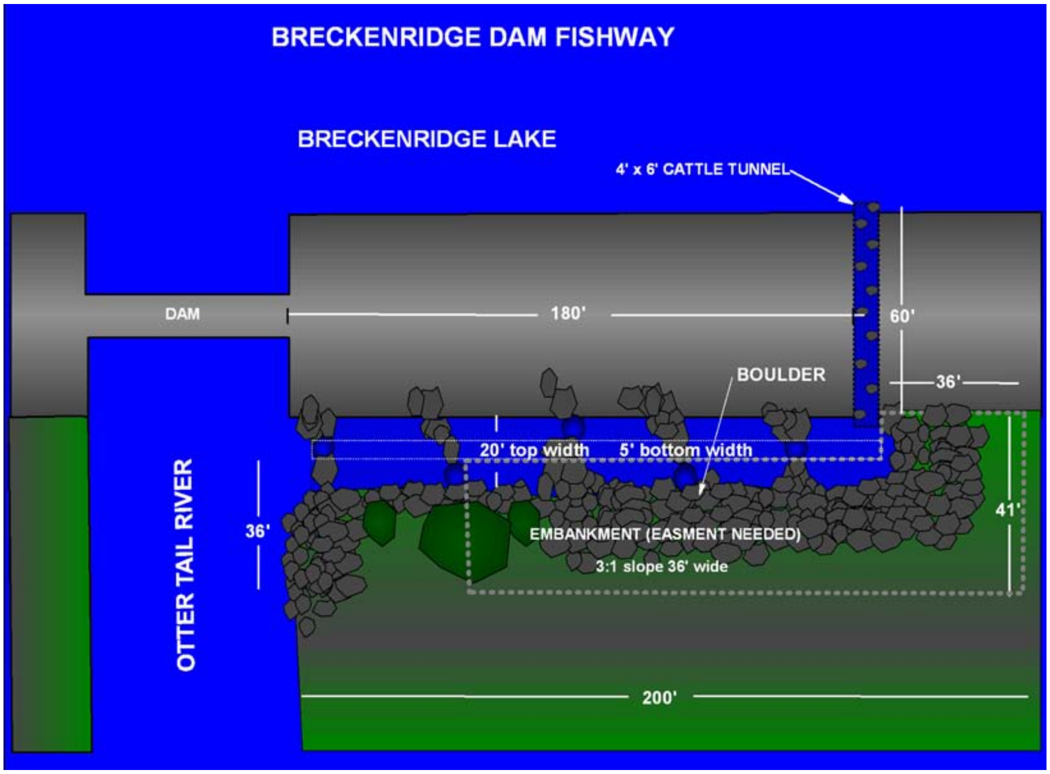

Figure 82. Plan-view conceptual design of the Breckenridge Fishway on the Otter Tail River.

increased reservoir elevations by as much as three feet and observed head-loss ranged from three to six feet. The spring flood also raised reservoir levels due to the limited capacity of the stop-log bays and frequent log jams that collected in them. Due to this variation in reservoir levels the project was designed to function over the range of conditions with the channel and materials sized for maximum flows. Five boulder weirs in the channel created a step-pool configuration and each weir was designed for about 0.8 feet of head-loss. The dam embankment and a constructed clay embankment with 3:1 side-slopes were designed to contain the channel. The channel was lined with fieldstone and willows were planted along the channel margins.

The confined easement and working area, the use of the dam embankment to contain the channel, and the need to put the fishway entrance in the immediate tailwater limited the ability to add sinuosity to the channel. Varying the channel thalweg through the boulder weirs created some sinuosity. Natural channels of this slope (2.5%) often occur in steep valleys where sinuosity is also relatively low (Rosgen 1996).

The culvert and the first boulder riffle controlled flows into the fishway. Manning's equation was used to estimate inflow. Boulders were placed in the culvert to increase roughness and create resting places for migrating fish. A four by six foot cattle crossing culvert was to be removed from a nearby road so was available for the project. The high profile and narrow width made the culvert well suited to the fishway and the variable reservoir levels. A large boulder was placed at the entrance to limit inflow and was braced to keep it in position. The fishway was designed for flows of 30 cfs during high reservoir levels with lower but passable flows during low reservoir levels.

A control structure was not included in the design for two reasons. First, the site was in a rural area that was prone to vandalism. The dam itself had been subject to individuals tampering with the control structures. Second, as with all projects presented here, an underlying philosophy has been to design projects that are self-sustaining and do not require operation or maintenance.

Construction

The project was constructed by the Wilkin County Highway Department using an excavator and a bulldozer. The embankment and fishway channel were built first (Figure 83). Care was taken to avoid unnecessary damage to vegetation and two large black willow *Salix nigra* trees were left in place adjacent to the channel. Several clumps of sandbar willow *Salix exigua* and redosier dogwood *Cornus sericea* within the footprint of the fishway were transplanted to the channel margin. The channel bottom was lined with

Figure 83. Construction of the Breckenridge Fishway channel showing placement of the boulder weirs.

fieldstone and the boulder weirs were constructed. All disturbed areas and the fishway channel banks were seeded and covered with excelsior fabric.

Once the channel was completed, culvert sections were excavated into the dam embankment and placed successively from the downstream end. Two to three-foot boulders were placed inside the culvert as each section was laid (Figure 84). The embankment had a wooden sheetpile core that was cut to fit tightly around the culvert section. A clay cofferdam was built to allow placement of the final culvert section. The entire culvert was wrapped with geotextile fabric to prevent leakage. Clay was packed around the culvert and both ends were armored with fieldstone. The cofferdam was removed and flow was allowed to enter the fishway.

Initial discharge measurements indicated slightly higher flows entering the fishway than were designed. This was likely due to irregular boulders used in construction that made the roughness coefficient difficult to predict. Some adjustment had been anticipated due to this uncertainty. A large four-foot boulder was placed at the entrance to further limit inflow and was braced to keep it in position. This reduced flow to the designed range. The project was completed in September 1996.

Figure 84. Placement of the culvert for the Breckenridge Fishway.

The spring of 1997 brought the largest flood of record to the Red River Valley due to record snowfall preceding it. The limited capacity of the spillway and its tendency to plug with ice and trees caused major flows to pass over the embankment (Figure 85) and eroded its entire length to the wooden sheet-piling core. Even portions of the concrete spillway were broken and the flood bent the orifice gate and made several stop-log bays inoperable. Since the fishway had been built during the preceding September there was not adequate time for vegetation to become established. Despite this fact, the fishway was relatively unscathed except for some erosion of the new embankment containing the channel and where the culvert passed through the failed dam embankment.

A federal disaster declaration provided funds to repair the dam embankment. The orifice screw and stop-log bays were not repaired so the reservoir levels varied with river flows, but also rose when debris collected in the stop-log bays. Repairs to the fishway were minor, primarily to scour of the embankment. A concrete seep collar was added to the culvert. Repairs to the dam embankment were substantial including replacement of fill and armoring both side-slopes. The spillway was not repaired. The dam washed out again in 2001, 2006, and 2007. No repairs to the fishway were required following the 2001, 2006 or 2007 floods as it was well vegetated when these events occurred.

Monitoring

The fishway has performed as designed and has been passable over a wide range of river flows and reservoir elevations (Figure 86). Flow in the fishway is a function of reservoir levels while high river flows raise tailwater elevations and inundate the downstream portion of the fishway. Since the dam has limited spillway

Figure 85. The 1997 flood and damage to the Breckenridge Dam.

capacity, reservoir levels rise with river flows causing the seasonal hydrology of the fishway to parallel that of the river.

Measured velocity profiles through the fishway are similar to those observed in the full channel rapids with high point velocities through the boulder weirs and moderate to low velocities in the pools and along the channel bed (Figure 87). As with velocity distributions in the Midtown Rapids, velocities exceeded six feet per second at points high in the water column through the boulder weirs. However, velocities near the streambed were generally less than two feet per second, even through the weirs.

Unlike the large, full river width rapids, fish passage through the Breckenridge Fishway has been relatively easy to monitor. A trap-net was set on the reservoir end of the fishway in 1998, 2000, and 2004 to collect migrating fish (Figure 88). A mesh size of ¼” was used to capture small bodied species. The nets were set one or two days per week. A three by five foot trap-net was used in 1998 and 2000 and a four by six foottrap-net was used in 2004.

Fish catches in the sampled years of 1998, 2000, and 2004 progressively increased. There are several possible explanations for this increase. First, the larger four by six foot net was used for the 2004 monitoring. The smaller three by five foot net likely approached capacity on some days and may have prevented fish from entering the net. However, this would not explain the greater consistency of moderate catches (below capacity of the smaller net) observed in the 2004 catch or the increases observed in 2000 over 1998. Second, two additional weirs were added in 2001 to reduce head-loss over each weir. This may have reduced peak velocities at some points and increased the number of slower swimming fish that passed. However, I observed a school of black bullhead fry swim through the fishway shortly after it was completed in 1996 suggesting that velocities were

Figure 86. Breckenridge Fishway during a range of river flows and reservoir levels.

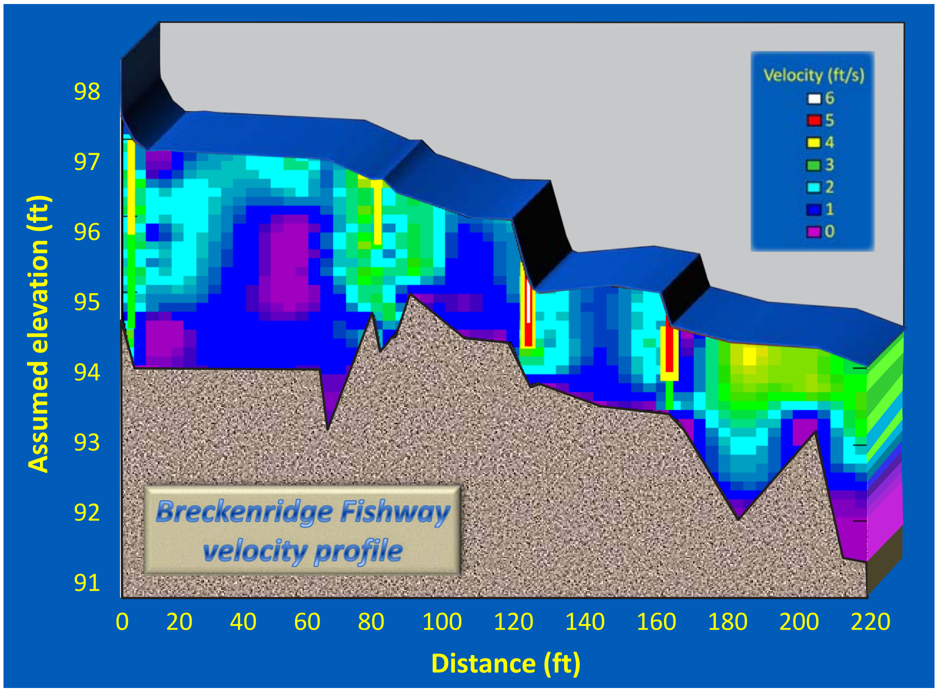

Figure 87. Breckenridge Fishway velocity distributions. Profile path went through the gap between boulders in the weirs.

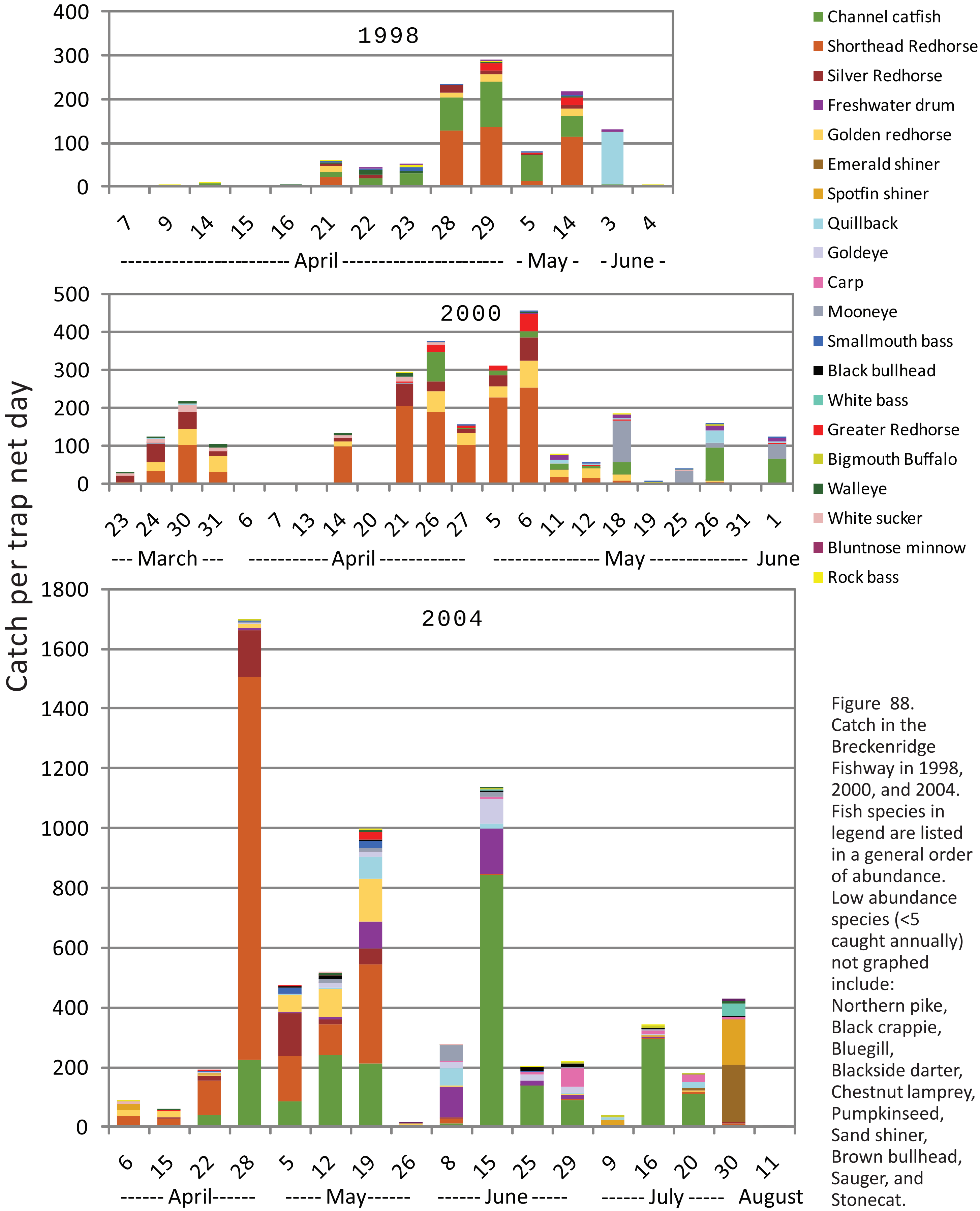

Figure 88. Catch in the Breckenridge Fishway in 1998, 2000, and 2004. Fish species in legend are listed in a general order of abundance. Low abundance species (<5 caught annually) not graphed include: Northern pike, Black crappie, Bluegill, Blackside darter, Chestnut lamprey, Pumpkinseed, Sand shiner, Brown bullhead, Sauger, and Stonecat.

not limiting. While greater numbers of small bodied and young of the year fishes passed in 2004, this was likely because the fishway was monitored into August rather than early June as in 1998 and 2000. Many of the small-bodied fishes spawn in the summer. Third, there may have been a return of fishes that had been spawned in habitat upstream of the dam that returned to this spawning area by the fishway. Since the first passage would have occurred in 1997, fish spawned in this year would not have been mature in 1998 for most species. An increasing number of cohorts would be present with time, and by 2004 most species spawned in 1997 would be sexually mature. Fourth, several mainstem barrier dams were converted to passable rapids between 1998 and 2004. Dams converted to rapids downstream of the Breckenridge Dam include: Midtown Dam in 1999, Kidder Dam and the Breckenridge Water Plant Dam in 2000, Riverside Dam in 2001, Fargo North in 2002, and Fargo South Dam in 2003. Finally, variations in catch may be due to variations in flow, weather and other environmental factors affecting migrating fish numbers as well as the efficiency of our gear.

Several findings in our assessments challenge traditional assumptions regarding fish migration.

» First, virtually the entire species assemblage of this river was represented in our catches. This contradicts the idea that stream fish communities are comprised of migratory and non-migratory species and suggests that all species are migratory to varying extents at this latitude. Species, thought to be non-migratory (probably because they had not been studied) were observed in large numbers passing the fishway.

» Second, migrating fishes included all life stages, not just mature fish on a spawning migration. Large numbers of juvenile and even young of the year fish passed through the fishway.

» Third, timing of migrations varied with size and life stage. For instance, channel catfish began passing the fishway in April, but the largest individuals (600 mm and larger) didn't peak until late July (Figure 89). These large fish were likely spawners while earlier migrants included large numbers of juveniles. The Red River of the North is noted for a trophy catfish fishery and the late migration of large individuals has significant implications. Low-head dams on the Red River submerge and are passable during floods greater than bankfull discharge or about half of the 110 years of record. Two thirds of these floods occur in March and April following snow melt meaning that early migrants could pass

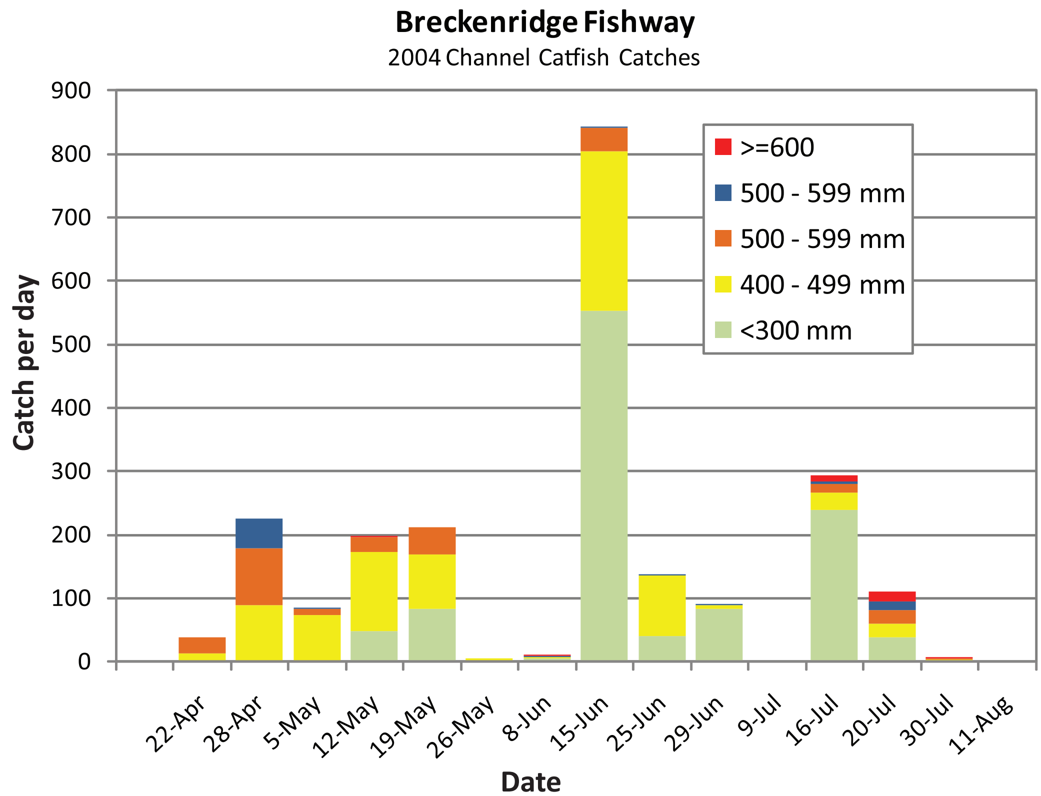

Figure 89. Trap-net catches of channel catfish at the reservoir end of the Breckenridge Fishway by length group in 2004.

while later migrants such as large catfish would not be able to pass in most years (see Figure 71).

» Fourth, the season over which fish passage was important included virtually the entire period over which the fishway was monitored. It is a common perception that fish passage is only important during spawning migration of one or few game species. These data suggest that migration of successive taxa of pre-spawn fishes and migration of juvenile and young-of-the-year fishes may comprise much of the spring and summer migration. The fishway was not monitored in the fall and winter so it is unknown whether significant migrations occur in those months.

Breckenridge Dam was finally removed in September of 2007 as a result of the frequent washouts and the exacerbation of flooding it caused to homes along the reservoir. Since the reservoir was filled with sediment, the dam was removed to the bottom of the stop-log bays and rapids were built to provide fish and canoe passage (Figure 90). The rapids will provide grade control to prevent incision and allow the existing reservoir sediments to function as floodplain. The dam removal should prevent debris accumulation and provide significantly more cross-sectional area for flood flows. This was demonstrated during a record flood flow in 2009 where no significant damages to the embankment were caused, unlike previous flood events. The by-pass fishway was retained as an alternate fish-pass.

The rapids were built using a variation of the Rock Arch Rapids design with an overall slope of about 1.5%. Each successive weir had less than 0.8 foot of

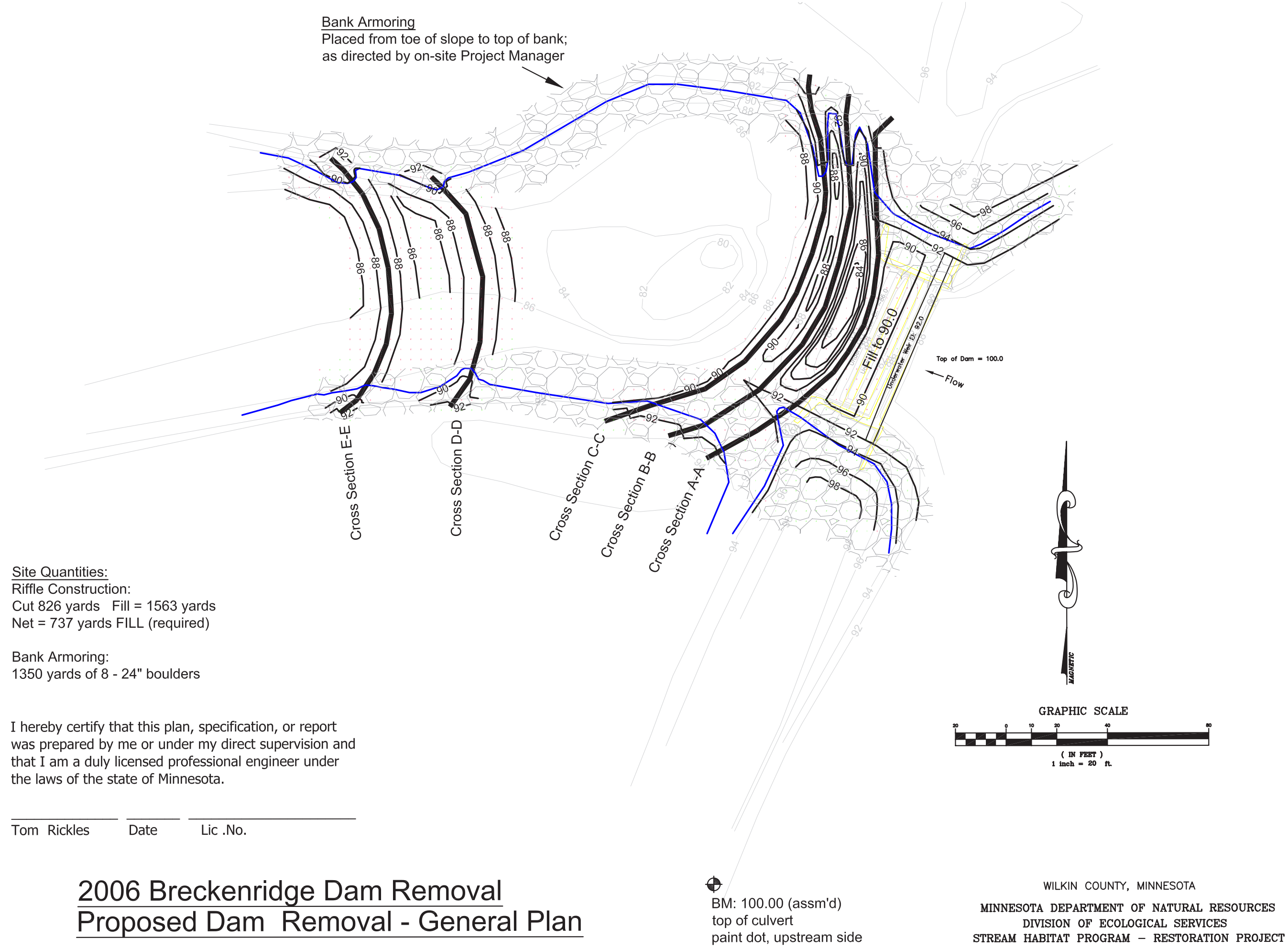

Figure 90. Plan-view for Breckenridge Dam removal. Bold lines indicate weir alignment.

head loss. A deep pool, popular with local fishermen was preserved in the middle of the rapids by building the last two weirs in a riffle downstream of the pool (Figure 91). This also reduced the amount of base material needed.

The sequence of events ultimately resulting in the removal of Breckenridge Dam was a lesson in perseverance. We had initial concerns that construction of the fishway would lessen interest in removing it. This did not prove true as the fishway brought attention to the importance of fish passage and the value of a free-flowing river. People frequently stopped to see the assortment of fish species that we caught in the net as we monitored passage. Attitudes of the residents changed regarding the reservoir as it continued to fill with sediment and cause flood damages and people started asking about when I thought the dam would be removed. Removal of the dam has been well received and the rapids have already become popular with visitors. The site has been linked to a trail system and a bridge has been built where the dam had been.

Figure 91. Rapids replacing Breckenridge Dam to provide grade control and facilitate fish and canoe passage. The photo on the top shows the entrance of the by-pass fishway that was left in place. The bottom photo is a view from downstream showing the pool retained in the middle of the rapids.

Crookston Rapids

The Crookston Dam was originally built in 1883, apparently as a milldam. The dam was a rock filled timber crib structure that was later capped with concrete (Figure 92). It was converted to hydropower in 1905 and retired in 1970. The powerhouse had two turbines rated at 176 and 200 KW. The 176 KW turbine was retired in the late 1950s with the 200 KW turbine retired in 1970 (Terry Graumann, Otter Tail Power, personal communications). A number of similar sized hydropower dams in Minnesota have been retired due to low power production and high dam maintenance costs.

Dam Description

- **Year built:** 1883, rebuilt in 1942
- **Owner:** City of Crookston
- **Hydraulic height:** approximately 12 feet
- **Structural height:** 15 feet
- **Maximum head-loss:** approximately 9 feet (reduced by downstream riffle construction)
- **Crest elevation:** 846.3
- **Crest width:** 192 feet
- **River flow:** 1,201 cfs average
  record flow of 28,400 cfs
- **Appendix:** Project Brief #7

Location: The Crookston Dam was located on the Red Lake River in Crookston, Minnesota (Figure 93). The river slope increases upstream of Crookston and at Red Lake Falls the river is dominated by boulder-strewn rapids.

A number of environmental problems were attributable to the dam. The dam blocked fish migrations, eliminated several species from upstream of the structure and may have been a major factor in the extirpation of lake sturgeon from the Red River of the North basin by blocking access to historic spawning rapids near Red Lake Falls. The dam also was a significant drowning hazard and caused the deaths of nine to as many as 26 people. City of Crookston staff were concerned about this safety issue as well as environmental problems associated with the structure. The dam caused severe bank erosion in the tail-water and the river was over twice normal bankfull width downstream of the dam (Figure 94). River bank and bed erosion is common in reaches downstream of dams (ACOE 1994). The Army Corps of Engineers did not support removal due to the contention that hydrostatic pressure created by the reservoir may lessen the landslide risk upstream of the dam. The city has had several landslides over the years due to floodplain development and addition of fill on clay riverbanks. The floodplain is entirely separated from the river by flood control dikes built on the riverbanks. This confinement of flood flows further increases the potential for riverbed degradation and bank erosion. A high flow meander cutoff built by the Corps of Engineers in 2002 further increased velocities through the city.

Figure 92. Photo of Crookston Dam showing the footings of the former powerhouse in the foreground.

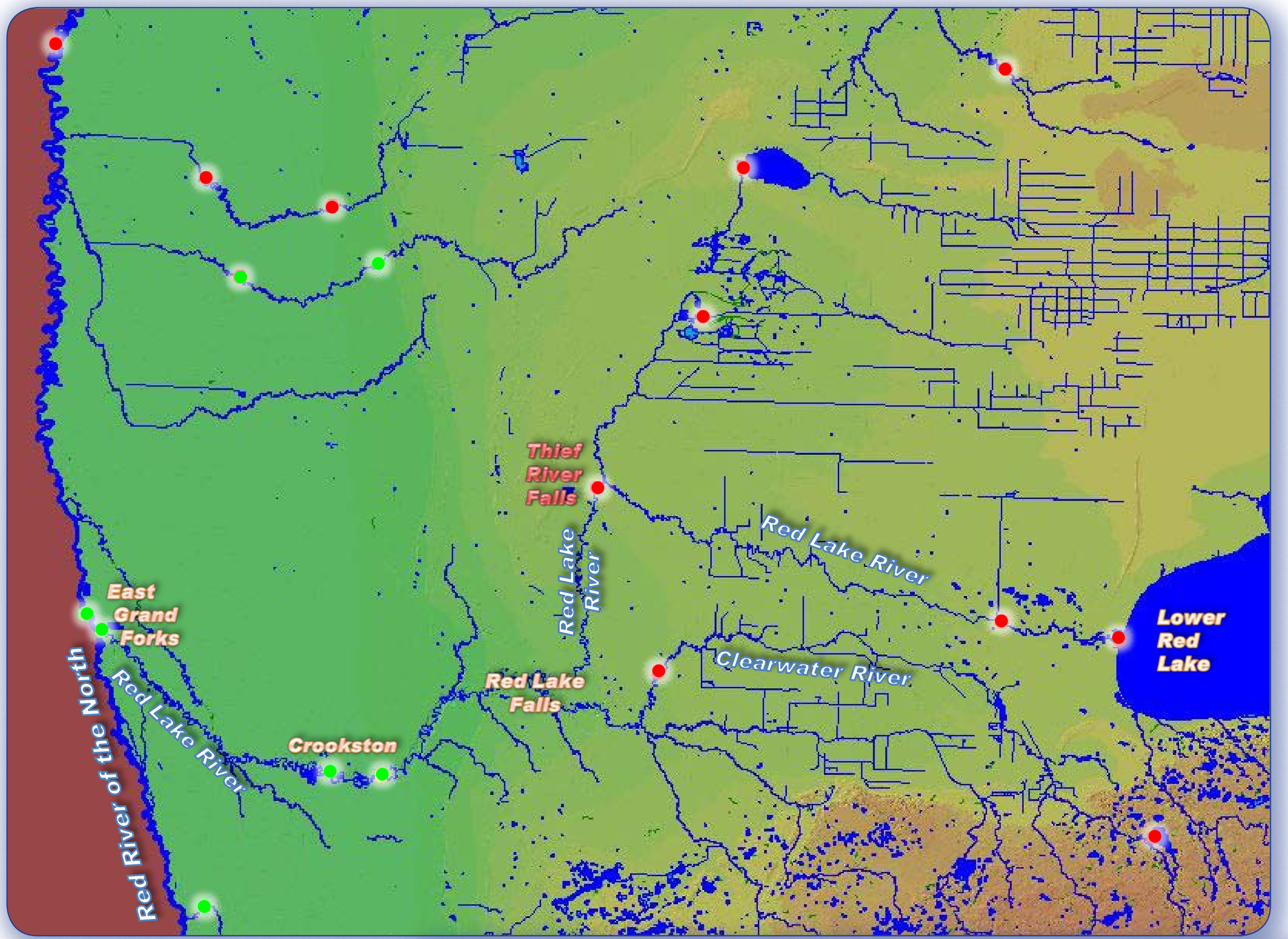

Figure 93. Red Lake River showing impassable dams (red dots), and dams removed or converted to rapids for fish passage (green dots). The green dot in Crookston is the Crookston Dam.

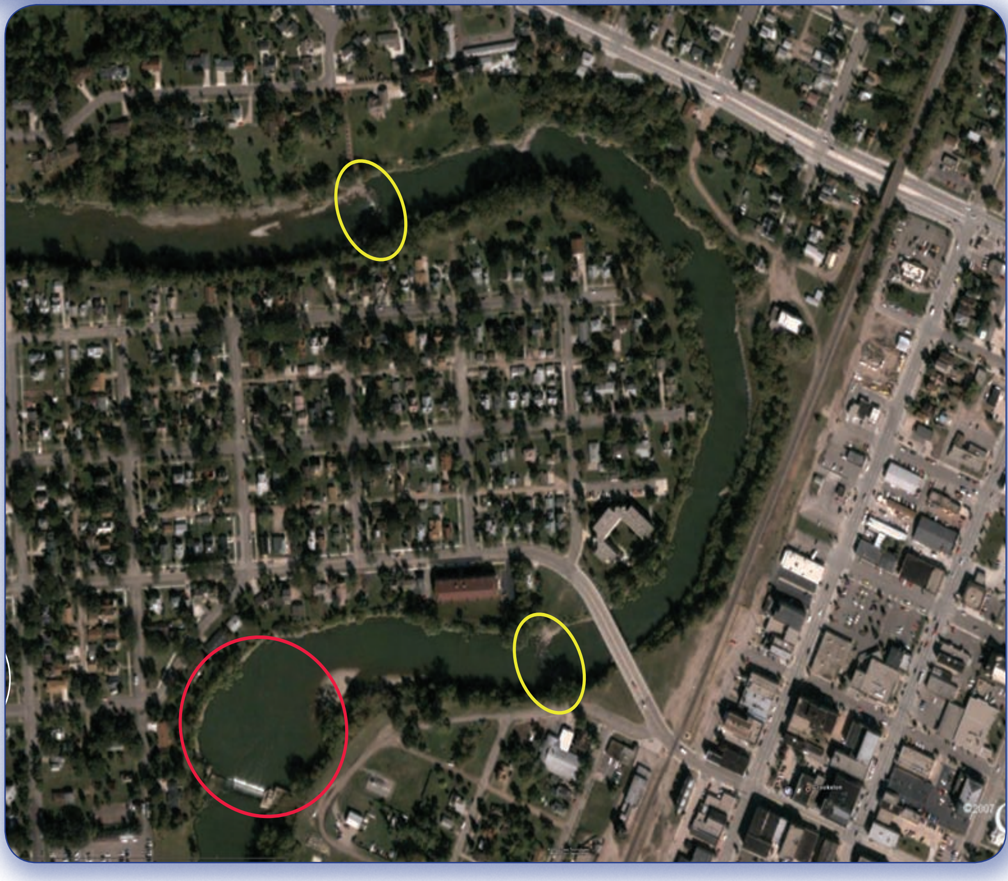

Figure 94. Aerial photo of the Crookston Dam showing downstream tailwater erosion (red circle) and riffles (yellow ovals) built to protect against further bed degradation and to raise minimum tail-water elevation.

Project Goals

1. Eliminate hydraulic undertows and reduce drowning hazard.
2. Restore fish passage for all species during all seasons and flows.
3. Provide passage for kayakers and whitewater canoeists.
4. Stabilize the site and reduce tail-water erosion.
5. Provide spawning habitat for lake sturgeon and other species.
6. Improved aesthetics for the adjacent City Park.
7. Maintain or improve angling opportunities at the site.

Project Design

Project Engineer: David Kildahl, P.E., Widseth Smith Nolting.

The Crookston Dam presented several design challenges. 1) The existing crest elevation had to be maintained to address bank stability concerns. 2) The dam was located in a river bend. 3) The tail-water had a very wide and deep scour hole. 4) The dam did not submerge until flows reached a 10-year flood level or about 17,700 cfs. 5) The left bank upstream of the dam had a progressing slump near the city's hospital.

A related project proceeded work on the dam to address a downstream riverbank collapse and storm sewer failure. City staff wanted to use environmentally sound techniques to address the problem. A bankfull bench (floodplain) was built to restore the site. Root wads, boulder vanes, and coconut matting with native plantings were used to protect the bank. Two fieldstone riffles were built in the reach to protect against further bed degradation and to raise the minimum tail-water stage at the dam (Figure 95).

The dam's location at the river bend and the large

Figure 95. Bank failure (upper left) and restoration using rootwads, boulder vanes, native plantings (upper right), and boulder riffles (bottom) downstream of Crookston Dam.

scour area made construction of rock arch rapids in the tail-water problematic. A rapids built downstream of the crest would have moved high velocity flows even closer to the outside bend and the large scour area would have required very large volumes of material to fill. It also would have filled a popular fishing area.

Removal of the existing dam and replacing it with rapids that reached the same crest elevation 300 feet upstream of the dam had several advantages. First, rock volumes and cost were substantially less since the river channel was narrower and shallower than the scour hole. Second, energy would be dissipated upstream of the erosion prone river bend and favor deposition in the near bank areas of the scour hole. Third, mass of the rapids would help to ballast and stabilize the slump upstream of the dam.

Stage: discharge relationships for the tailwater were available from the U.S.G.S. gage located 1,400 feet downstream of the dam. A headwater rating-curve was developed from surveyed water surface elevations (Figure 96). Analysis of gage data indicated a significant calibration error and an incorrect dam crest elevation in the Army Corps of Engineer's hydraulic model. While these errors were subsequently corrected and the model was used to assess permit concerns, empirical data was used as an assurance of accuracy. Based on observations of earlier similar projects, it was assumed that the rapids would have a similar headwater rating-curve if the floodway cross-section remained the same.

The rapids longitudinal profile was given a graduated slope to keep shear stress and stone size at an acceptable level. Since the crest of the rapids submerged at the highest flow it was given the most gradual slope (2.5%) with slopes increasing to 5% downstream where submergence occurred at a lower flow (Figure 97). This also provides fish passage benefits to fish that migrate during higher spring flows and as a result encounter lower velocities associated with the more gradual slopes.

Stone sizing was based on the two procedures outlined earlier (relationships of shear stress to stone size mobilized and methods in the Army Corp of Engineers Report 1110-2-1601). This approach yielded a D_{50} of 2.4 feet and a D_{30} of 1.9 feet as minimum gradations.

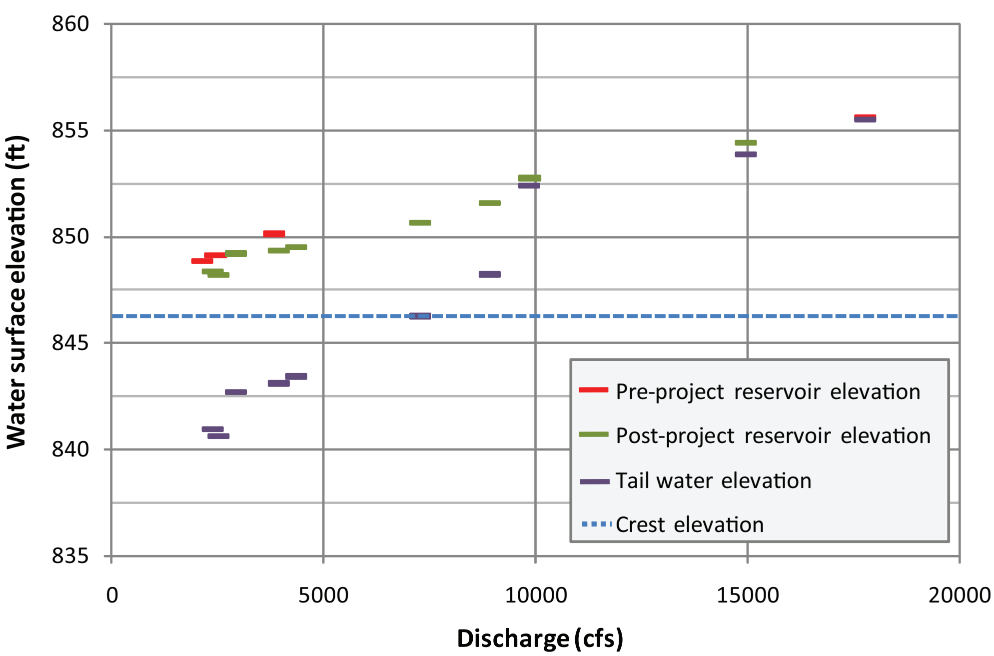

Figure 96. Surveyed headwater and tailwater elevations for the Crookston Dam showing submergence at approximately 18,000 cfs.

Concerns associated with leakage during severe drought conditions led to the addition of a steel sheet-piling crest within the fieldstone rapids.

Project Construction

Initial phases of construction (December, 2004) involved bank armoring and installation of the sheet-piling crest. After the new crest was completed, the old dam was demolished (Figure 98).

Permit provisions required installation of inclinometers to monitor the slump upstream of

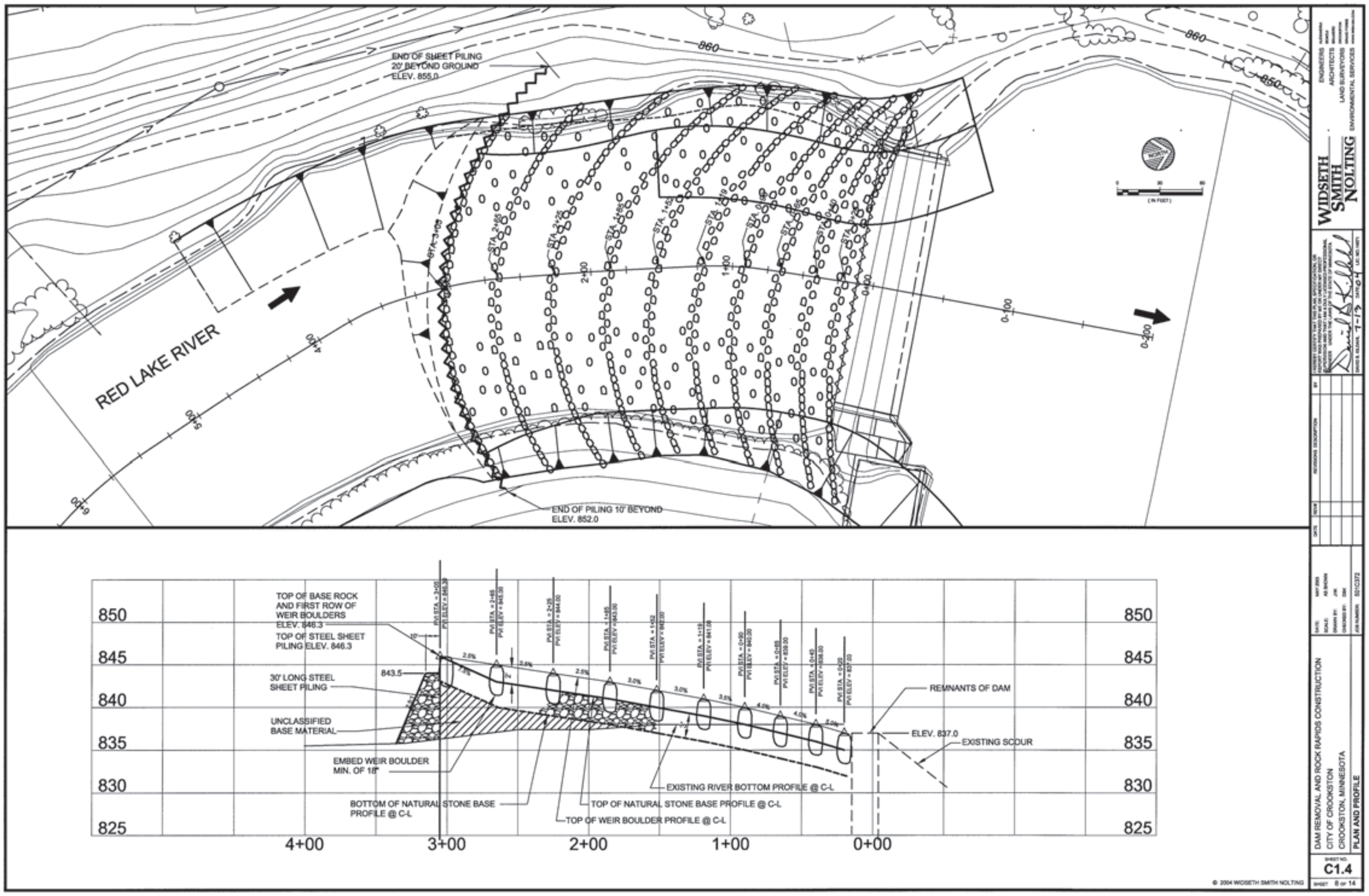

Figure 97. Planview and profile of the Crookston Rapids. David Kildahl, P.E. Widseth Smith Nolting, Project Engineer.

Figure 98. Construction of the rapids crest in the background and the old dam crest in the foreground.

the dam during construction. This stemmed from concerns that loss of hydrostatic pressure between the existing dam and the new dam crest 300 feet upstream could exacerbate the slump. The slump had moved an estimated 15 feet in two years prior to construction according to the dam safety engineer. Inclinometers showed movement of about 1.5 inches during the five months of construction. The dam base was only partly constructed and was much steeper than design grade when a spring flood submerged the structure (Figure 99). No apparent damage to the rapids occurred as a result of this event. Work resumed in May 2005.

The contractor used clean waste concrete as a sub-base covered with three feet of fieldstone base. This worked well as it was angular and inexpensive for the large volume needed. Since it was entirely buried with fieldstone, no waste concrete was exposed. A bulldozer was used to establish the base grade (Figure 100).

Figure 99. A flood in the spring of 2005 that submerged the partly constructed rapids. The photo was taken on April 1, 2005 at a flow of 9,850 cfs; a peak of 10,100 cfs was reached on April 2.

Figure 100. Grading of the fieldstone base with a bulldozer in May, 2005.

Once the base grade was established, the boulder weirs were placed. This was done with large track excavators (Figure 101). The weir stones were up to 6.5 feet in diameter and weighed up to 11.3 tons (22,600 pounds) each. Center boulders were placed first to provide a target for the operator for weir alignment and top elevation.

Construction of the rapids was completed in August 2005 (Figure 102). The disturbed areas including the realigned dike were seeded with native vegetation and covered with coconut fiber matting.

Evaluation

Comparing pre- and post- stream surveys upstream of the dam assessed fish passage effectiveness. Section of Fisheries staff conducted these fish surveys. Prior to the project, no sauger *Sander canadensis* had been recorded upstream of the dam, and surveys in 1996 and 2001 yielded only one channel catfish *Ictalurus punctatus* each (Huberty 1996, Huberty 2001). The post-project 2005 survey yielded 222 channel catfish (Huberty 2005). Sauger catches were reported by anglers 75 river miles upstream to the Thief River Falls Dam.

Figure 101. Placement of boulder weirs in the Crookston Rapids.

Figure 102. Photo showing completed Crookston Rapids.

Direct observations of passage through the rapids were limited due to the size of the rapids and turbidity of the water. A school of small sand shiners *Notropis stramineus* were observed passing the upstream-most weir during construction. At this point, the weir had approximately two feet of head (compared to less than one foot after completion) and the shiners were passing through voids under the large boulders where boundary velocities near the bed were apparently passable for the small fish. In the summer of 2007, very large schools of unidentified shiners were observed passing the rapids. Larger fish were later observed in the rapids but could not be identified. In May 2009, Freshwater drum *Aplodinotus grunniens* were observed passing and spawning in the rapids. Later in July Carmine *Notropis percobromus* and spottail shiners *Notropis hudsonius* were captured on video as they passed through the rapids.

Sheet piling placed in the crest at the first weir, as required in permitting to address seepage concerns, created a potential passage problem during low flows observed in the fall of 2006. The sheet piling caused elevated head loss since it did not pass flow between gaps in the boulders as subsequent downstream weirs did. Since river flows during construction were relatively high, voids in the base stone were not visible. In addition, large ice rafts in the spring of 2006 moved some of the weir boulders reducing their pooling effect. The problem was likely due, in part, to inadequate bedding of the boulders with base stone. In December 2007, base material was placed to the appropriate elevation, and weir boulders were replaced and embedded to correct the problem. This rock ramp is especially subject to ice movement since it does not inundate during bank-full floods and the channel is confined and separated from its floodplain by flood control dikes.

Unfortunately, the trees and vegetation lining the banks near the rapids were removed and replaced with riprap during a dike realignment project in the fall of 2007. While the riprap is intended to increase bank stability, removal of vegetation increases soil saturation and decreases cohesiveness provided by the roots, which weakens soils and increasing the risk of slumping (Simon and Collison 2002).

As predicted, the rapids design has alleviated the tailwater erosion problems downstream of the original dam site by dissipating energy within the rapids and converging flow vectors. Sediment deposition has created floodplain along the previously eroded right bank while maintaining mid-channel pool depth (Figure 103). A large cottonwood behind this bar was at the water's edge but is now surrounded by a depositional bar at the same elevation as that determined to be bankfull elevation prior to the project's construction. Connected floodplain is rare in this reach of the Red Lake River due to flood control levees on the riverbanks and channel incision.

The sturgeon spawning habitat at Red Lake falls that Alexander Henry noted in 1800 is once again connected to the Red River of the North by this and the two other Red Lake River projects. This was a critical project in advancing efforts to re-establish lake sturgeon in the Red River of the North Basin.

Figure 103. Floodplain deposition along the previously eroded right bank below Crookston Rapids.

Reconnecting the Red

The projects previously discussed are all part of a larger effort to reconnect the Red River of the North and its tributaries. While I have worked on the design of dam removals and fish passage across Minnesota and the country, nowhere have we come so far in reconnecting critical habitats than in this watershed. Numerous agencies, local units of government, non-government resource groups, and individuals contributed to this effort. While the initial efforts were driven by safety issues and use of the rapids to eliminate hydraulic undertows as much as restoration of the river, the broader goal gained momentum with each successive project. Efforts are under way in both the U.S. and Canada to reestablish lake sturgeon populations in the Red River of the North Basin. The success of these efforts depends heavily on the reconnection of habitats on which they depend. The impressive size and unique characteristics of this species made them an ideal political representative of the fish community. Reconnection of the system has already resulted in the return of many species to previously fragmented river reaches.

To date, 33 barriers to fish migration have been eliminated in the Red River of the North Watershed including 12 removals or partial removals, 17 conversions to rapids, two by-pass fishways, and five culvert projects. Critical spawning habitat on the Roseau, Middle, Red Lake, Wild Rice, Buffalo and Otter Tail rivers has been reconnected to the Red (Figure 104). This list includes projects in North Dakota (Maple River) and Manitoba (Roseau River). Four mainstem barriers (3 in the U.S.) remain on the Red River. The St. Andrews Dam in Manitoba has open gates during flood flows and has a conventional baffle fish ladder. However, the fishway is not passable for lake sturgeon and the dam is likely a barrier for later migrating fishes (Aadland et al. 2005). The three remaining mainstem dams in the U.S. are passable during flood flows above bankfull but are barriers at non-flood flows. They are currently in design phase and should be converted to rapids within the next few years.

To date, 33 barriers to fish migration have been eliminated in the Red River of the North Watershed including

- *12 removals or partial removals,*
- *17 conversions to rapids,*
- *2 by-pass fishways, and*
- *5 culvert projects.*

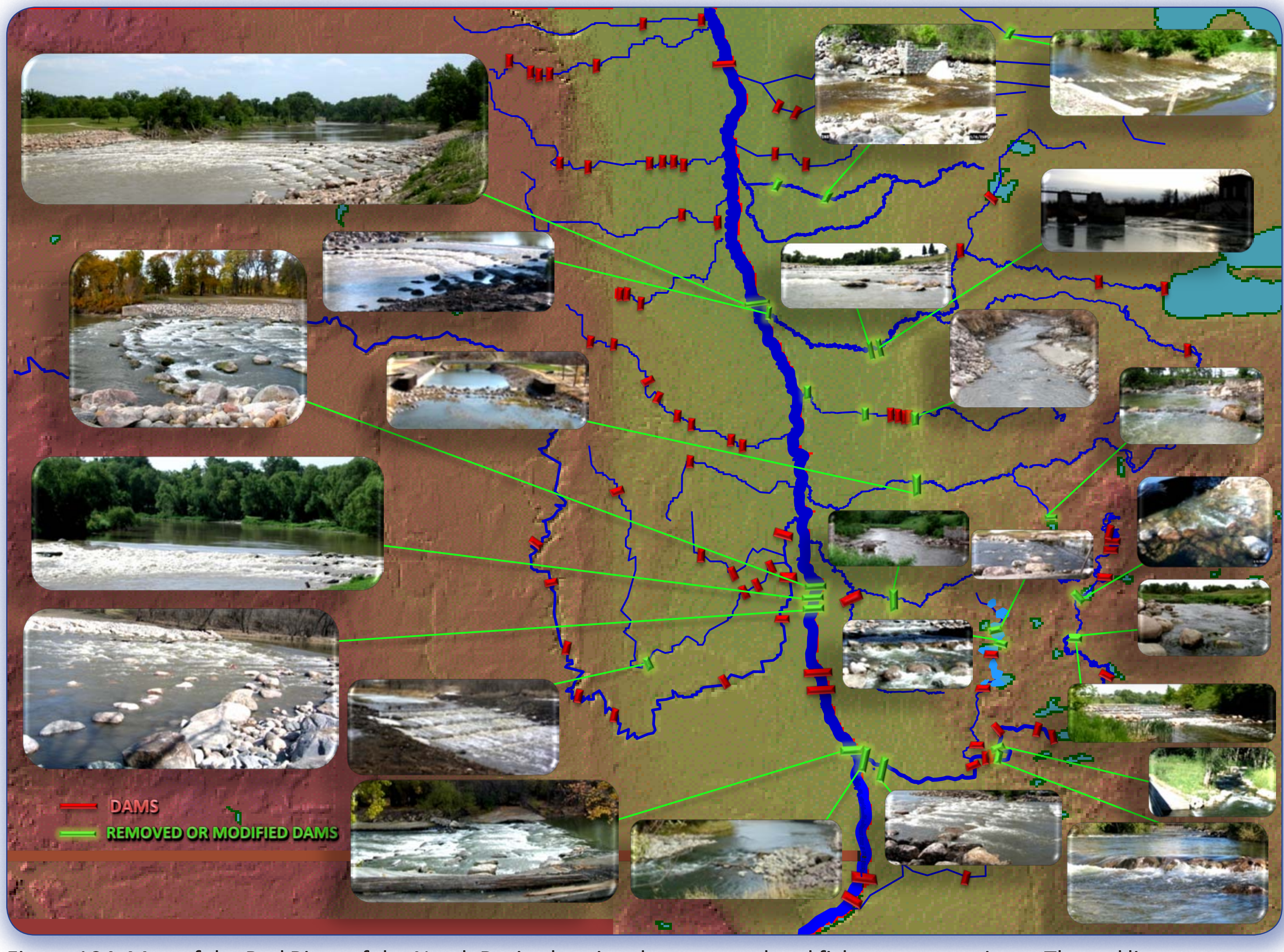

Figure 104. Map of the Red River of the North Basin showing dam removal and fish passage projects. The red lines represent existing barriers while the green lines represent dams that have been removed or modified for fish passage.

Discussion

River restoration is, by definition, a reversal of our past approaches. Instead of applying constraints, it seeks to relax them. Rather than requiring maintenance and manipulation, restored systems are implicitly self-sustaining.

Historical Context of Restoration Work

The process of river restoration presents substantial technical, political, social, and institutional challenges that are a direct result of past philosophy and practices. Most of the last century and a half of river management has involved ever increasing constraints and exerted control over rivers. Engineering practices focused on specific objectives such as flood control, floodplain encroachment, water supply, power production and land drainage, with the construction of dams, levees, and channel straightening. Most of the currently accepted design standards and approaches are based on these objectives and practices. The resulting environmental damages of past river alterations have stemmed from a narrow focus and a lack of recognition of related consequences.

River restoration is, by definition, a reversal of our past approaches. Instead of applying constraints, it seeks to relax them. Rather than requiring maintenance and manipulation, restored systems are implicitly self-sustaining. It requires that we broaden our understanding not only in terms of the local effects of a project but that we acknowledge effects that may occur over broad spatial and temporal scales. Dams can eliminate fish populations and communities hundreds even thousands of miles away in formerly connected rivers and oceans. Reservoirs that provide storage and recreation after construction can be completely lost to sedimentation within decades. Conversely, reconnection of a river system can restore fish communities far from the site. Channel restoration can reestablish the processes that create habitat and adjust to watershed and climatic changes for centuries into the future. Shifting to a new paradigm that allows for natural river functions requires society to adopt compatible strategies and live with these natural processes rather than fighting them.

Shifting to a new paradigm that allows for natural river functions requires society to adopt compatible strategies and live with these natural processes rather than fighting them.

A fundamental flaw of traditional river management and engineering has been to assume that rivers are static and that their functions and processes are adequately addressed by one-dimensional hydraulic models. Sediment transport has been largely ignored while biological processes have been ignored almost completely. This approach has resulted in unstable aggraded or degraded channels and rivers that are impaired in terms of water quality and biological diversity. Meandering channels with living banks and riparian zones have been replaced by straight armored channels. Incredibly, this practice of destabilizing and sterilizing rivers has been termed "channel improvement". Clearly, the criteria for which this practice was considered an improvement were not based in an understanding of fluvial, biological and ecological processes.

Ironically, the engineering community charged by society to construct dams, levees, and ditches is now being asked to remove dams and restore rivers. River restoration projects often require the signature of a licensed engineer who assumes the daunting responsibility and liability for the design. The paradox is that engineering colleges rarely provide training in the fluvial geomorphology of natural channels or river ecology nor are these concepts covered in engineering manuals. Design standards established for dams, concrete and steel do not transfer to ecologically functional river systems. Traditional engineering goals have centered on locking channels in place, preventing scour, maximizing conveyance, separation of channels from floodplains, and other objectives that are in direct opposition to restoration goals. Simplification and homogenization of river channels have been due, in part, to the limitations of hydraulic models used in design since uniform, straight channels are easier to model. The complexity of fluvial and biological processes, variable habitat requirements of hundreds of species of fish, invertebrates, amphibians, reptiles, mammals, and plants, force the practitioner is to acknowledge the limitations of our models and the need to accept some level of uncertainty.

Since the signing engineer assumes liability for restoration design, new definitions of project success or failure are critical. The contention that any channel movement constitutes "failure" does not apply to restoration since restoring channel and floodplain forming processes requires that the channel is allowed to move. A "restoration" project in an alluvial channel that cannot move fails to restore channel forming process and is, in that respect, a failure as a channel restoration. This issue is further complicated by the fact that natural channel banks are often stabilized by deep rooted vegetation that can take several years to become established. As a result, restored channels may be more vulnerable to bank erosion until this vegetation becomes established adding more uncertainty.

A fundamental assumption of this approach is that the more precisely these natural systems are emulated, the more likely the project will restore critical fluvial and ecological functions and processes. Ultimately, it is these processes that construct and maintain habitat rather than constructed features.

An Alternative Approach

Natural Channel Design (NCD), as the name implies, uses natural channels as physical models and templates for restoration. These reference channels are chosen both for their channel stability and equilibrium with sediment transport and fluvial processes, and for their diverse habitat that supports biodiversity and ecological processes. A fundamental assumption of this approach is that the more precisely these natural systems are emulated, the more likely the project will restore critical fluvial and ecological functions and processes. Ultimately, it is these processes that construct and maintain habitat rather than constructed features. Since rivers and watersheds are dynamic, restoration normally does not yield an identical channel to that which existed at some point in the past. It should, however, result in a stream that is in dynamic equilibrium with current water and sediment supplied by the catchment, and provides diverse habitat and complex ecological functions. The emulation of natural river morphology increases the probability that complex, poorly understood processes, functions, and habitats are addressed.

Controversy

The relatively recent emergence of river restoration science and the fact that it challenges the efficacy of traditional river engineering has predictably resulted in controversy. A series of criticisms of the Natural Channel Design approach have been voiced by Simon et al. 2007. A theme of these criticisms is that NCD is a "form-based" approach that ignores process and therefore cannot predict channel stability.

These criticisms have been individually addressed by Rosgen (2008) primarily as misrepresentations of the approach. Shear stress, bedload quantification, channel competence and other process calculations are, in fact, fundamental elements of NCD as are empirical measurements of channel migration and stability. Rosgen states, "Form and function are not mutually exclusive; they are critically linked and must be used interchangeably". While this is true of physical processes, it is equally true of biological processes that are directly linked to riffle, run, pool, glide and floodplain habitat, sediment distribution, and other morphological characteristics of natural channels.

While dam removal allows restoration of fluvial processes, nutrient and water quality effects, habitat, and other corrections of impairments associated with reservoirs, nature-like fish passage concedes persistence of the dam and usually falls short of restoring full river functions. As such, structural elements of the dam are retained as are regulatory issues pertaining to structural integrity. This forces at least portions of the fishway to be locked in place to meet the same structural and permit requirements of the dam. It does not, however, lessen the need to emulate the form and function of natural channels to the degree possible. The habitat elements present in nature-like fishways help to offset some of the losses due to inundation and reconnection through passage of the entire aquatic community is critical to the health of the river.

The long-term health of our river systems depends on a fundamental change in the way that we manage them. Our past approach and philosophy has been costly in terms of maintenance and in terms of damages to channel stability, water quality, fisheries, and ecosystems. Aging dams and sediment filled reservoirs will ultimately force decisions as lost functions, failures and other problems increase. Maintaining status quo will be economically costly and result in continued degradation of our rivers. Conversely, restoration of natural river processes will assure sustainable benefits for future generations. The collective efforts of the engineers, hydrologists, biologists and ecologists involved in designing, permitting, funding, and constructing the projects discussed here show that this new paradigm is possible.

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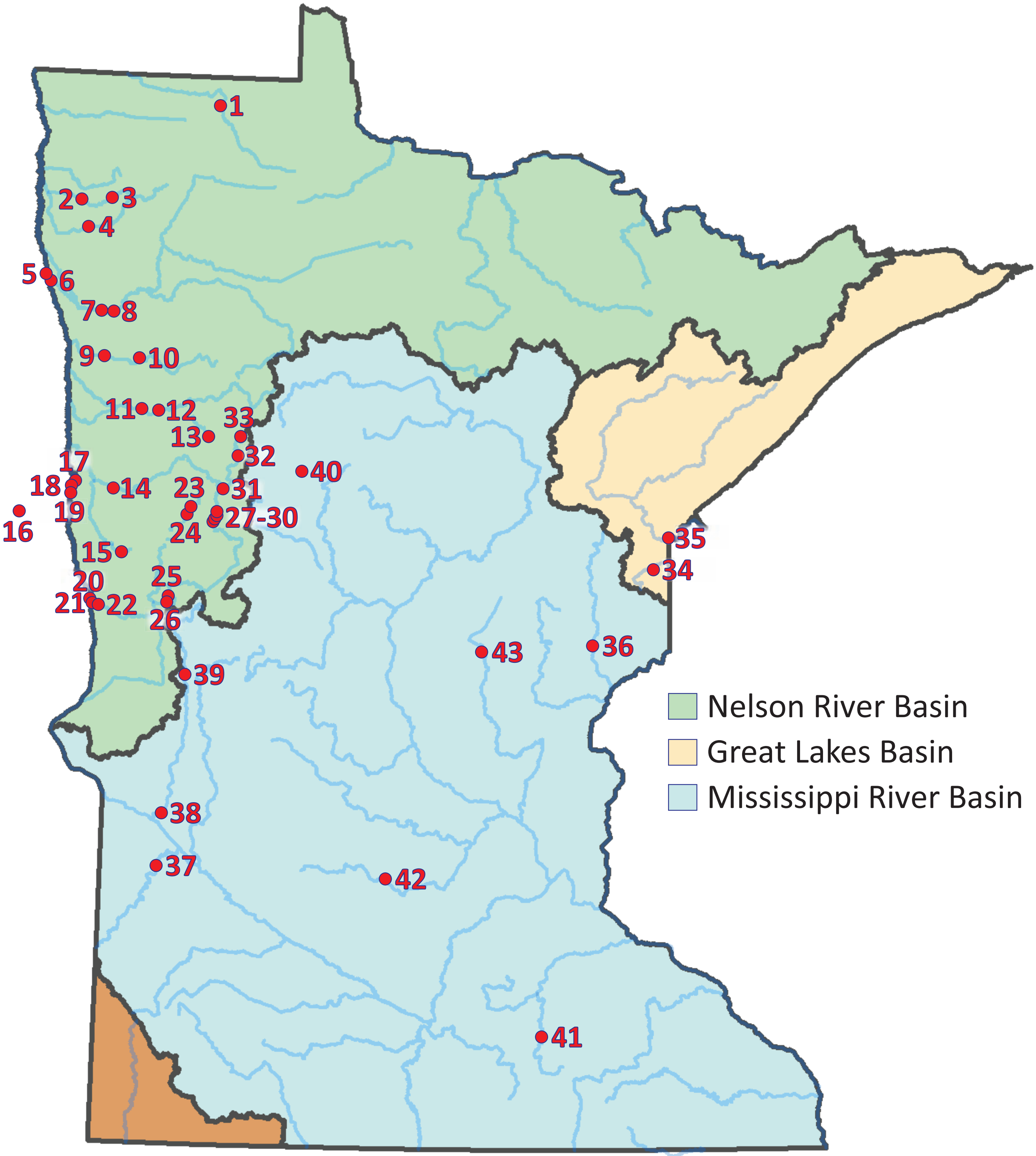
Notes:

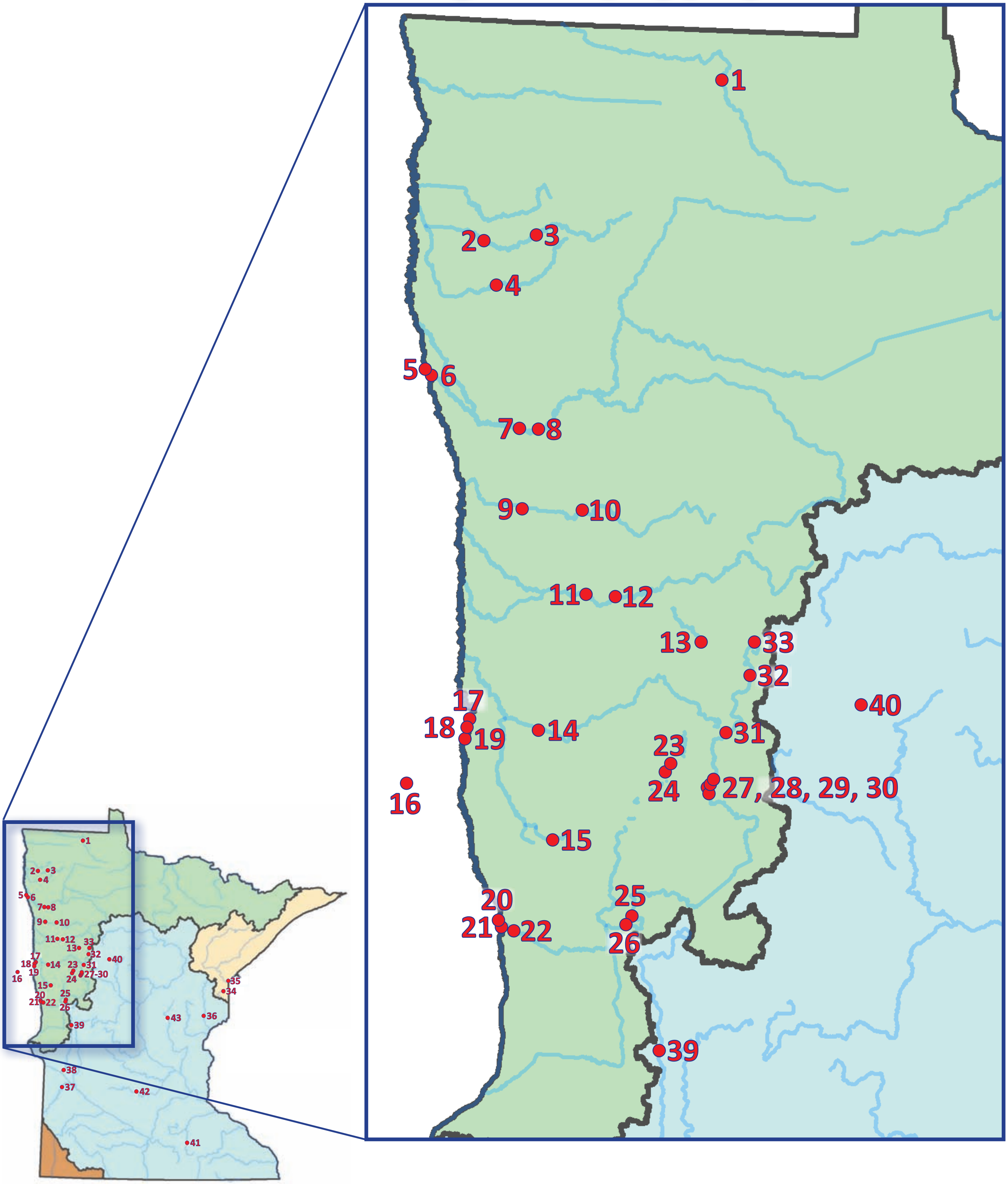
» Projects are listed in increasing distance from the mouth of the river basin.

» **Dam height** is defined as **maximum head loss**, which is the elevation difference between the crest of the dam and the first downstream riffle (hydraulic control), unless noted otherwise.

Statewide map of projects



Northwest region map of projects



#1

ROSEAU DAM

Roseau River

Nelson River Basin

Dam Facts

Mean flow: 143 cfs at Malung gage (430 m^2 DA)
Record flow: 16,000 cfs

Drainage area: 474 mi^2

Dam height: 5 feet

Crest width: 80 feet

Crest elevation: 1,031.8 MSL

Year built: 1930s

Original dam function: water supply

Drowning deaths: 1 known

Location: Roseau, MN
48° 51' 05.24° N
95° 45' 41.90° W

River network:

- ■ Roseau River: 136.8 miles upstream of confluence with...
- ➥ Red River of the North in Canada: 140.37 upstream of Lake Winnipeg,
- ≈ A total of 920.54 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ river restoration
- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide spawning habitat for sturgeon, walleye, and other species
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project designers:
Charlie Anderson (Project Engineer), JOR
Dennis Topp, Mike Larson, & Luther Aadland, MN DNR

Builder/Contractor: Wright Construction

Materials: 1,022 tons fieldstone
700 tons waste concrete

Cost: $40,000

Year completed: 2001

Connectivity

Upstream river miles connected:
41 miles to next barrier (small partial barriers 12.8 and 14.7 miles upstream)

Upstream barriers:
Hayes Lake at river mile 177.9
Flood storage impounment at river mile 200.38
Headwaters (Lost Lake) at river mile 205.89

Downstream barriers:
None to confluence with the Red River of the North

Before

Side view of dam from left bank during low flow

The largest lake sturgeon ever recorded (405 pounds) taken from this river in October 1903 in Dominion City, Manitoba (river mile 16.8). Bankfull river width is about 90 feet at this location.

During

Construction of rapids base

Construction of weirs

After

Downstream view of completed rapids

#2

ARGYLE DAM

Middle (Snake) River

Nelson River Basin

Dam Facts

Mean flow: 52.4 cfs at Argyle gage
Record flow: 5,020 cfs

Drainage area: 255 mi^2

Dam height: 7.9 feet

Crest width: 48 feet
with a 16 x 1 foot center notch

Crest elevation: 839 MSL

Year built: 1934

Original dam function: mill

Drowning deaths: unknown

Location:
48° 20' 16.35° N
96° 48' 43.00° W

River network:

■ Middle River: 17.3 miles upstream of confluence with...
➥ Snake River: 10.6 miles upstream of condfluence with...
➥ Red River of the North: 230.2 miles upstream of Lake Winnipeg,
≈ A total of 901.47 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam removal & river restoration

Project goals:

☆ river restoration
☆ provide fish passage and habitat
☆ improve safety by eliminating hydraulic roller
☆ eliminate dam maintenance
☆ maintain fishing pool below dam

Design concept:
Dam was removed and a single arching boulder weir was built for maintenance of downstream scour pool and grade control.

Project designers:
Jeffrey Erickson (Project Engineer)
Dennis Topp and Luther Aadland, MN DNR

Builder/Contractor: Spruce Valley Construction

Materials: 280 yards class III riprap
120 yards class IV fieldstone
50 3-5' boulders

Cost: $50,000

Year completed: 2007

Connectivity

Upstream barriers:
None - open to the headwaters since the removal of Old Mill (next brief)

Downstream barriers:
None to confluence with the Red River of the North

Before

Upstream view of dam from left bank

After

Downstream view of site after dam removal

During

Stockpiled boulders

Construction of boulder weir

#3

OLD MILL DAM

Middle (Snake) River

Nelson River Basin

Dam Facts

Mean flow: 52.4 cfs at Argyle gage
Record flow: 5,020 cfs

Drainage area: 225 mi^2

Dam height: 8.5 feet

Crest width: 48 feet

Year built: Original dam built in 1886, replaced in 1938

Original dam function: mill

Drowning deaths: unknown

Location:
48° 21' 44.54° N
96° 34' 22.03° W

River network:
- ■ Middle River: 44.09 miles upstream of confluence with...
- ➥ Snake River: 10.6 miles upstream of confluence with...
- ➥ Red River of the North: 230.2 miles upstream of Lake Winnipeg,
- ≈ A total of 928.26 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam removal & river restoration

Project goals:
- ☆ river restoration
- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ eliminate failure potential

Project description:
Dam abutments were historically significant and were left in place. Three boulder weirs were built for grade control and habitat.

Project designers:
Memos P. Katsoulis (Project Engineer)
Dennis Topp and Luther Aadland, MN DNR

Builder/Contractor: Spruce Valley Construction

Materials: 30 yards riprap
240 yards of 3' boulders

Cost: $51,000

Year completed: 2001

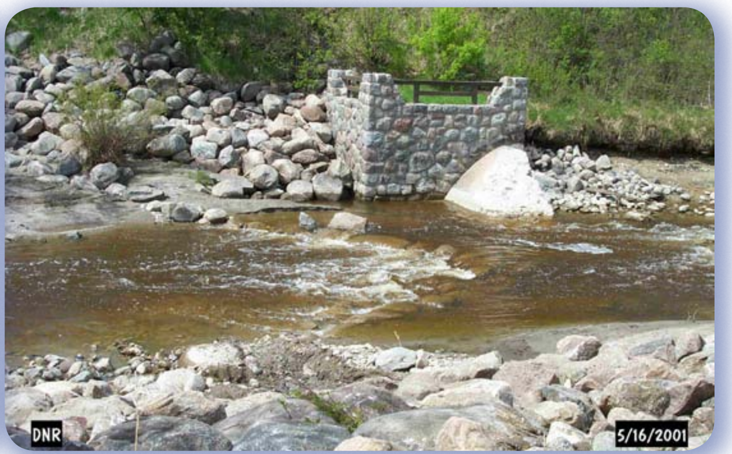
Connectivity

Upstream barriers:
None to the headwaters

Downstream barriers:
None - open to the Red River of the North since the removal of Argyle Dam (previous brief)

Before	After

Upstream view of dam during high flow



Upstream view of removed dam and constructed boulder weir

Weir for grade control and habitat

#4 SNAKE RIVER PL566 PROJECT MITIGATION

Snake River

Nelson River Basin

Dam Facts

Mean flow: Approximately 12 cfs

Drainage area: 59.6 mi^2

Dam height: 5.5 feet

Crest width: 50 feet

Crest elevation: 963.5 MSL

Diversion function: floodwater retention

Year built: 2005

Location:
48° 15' 0.782° N
96° 31' 48.38° W

River network:

- ■ Snake River: 79.4 miles upstream of confluence with...
- ➥ Red River of the North: 230.2 miles upstream of Lake Winnipeg,
- ≈ A total of 952.97 miles upstream of Hudson Bay.

Restoration Design

Project type: Installation of rock ramp upstream of intake

Project goals:
- ☆ river restoration through grade control

Design concept:
Rock Arch Rapids with a maximum head loss of 5.5 feet

Slope: 2.5%

Project description:
Snake River PL566 is an off-channel stroage project that diverts flows at 75 cfs (bankfull is 249 cfs) for flood storage. The steeper energy slope of the intake weir caused a headcut of the Snake River degrading the channel bed 3.1 feet at a cross-section 661 feet upstream of the intake. The rapids were designed for grade control and to provide fish passage. An additional riffle was built upstream of the headcut.

Project designers:
Dave Jones (Project Engineer) and Sonia Jacobson, NRCS
Dennis Topp, Nicholas Schlesser, and Luther Aadland, MN DNR

Builder/Contractor: Steven Olson

Materials: 284 tons riffle boulders
1,806 tons type A riprap
356 tons bedding material

Cost: $92,100 for rock

Year completed: 2008

Before

After

Flood storage intake

Upstream incised channel


Rapids looking upstream


Rapids side view

#5

RIVERSIDE DAM

Red River

Nelson River Basin

Dam Facts

Mean flow: 3,029 cfs at Grand Forks gage
Record flow: 137,000 cfs

Drainage area: 30,100 mi^2

Dam height: 13 feet

Crest width: 320 feet
rapids 400 ft

Crest elevation: 793.3 MSL

Year built: Original dam built in 1922, replaced in 1989

Original dam function: water supply

Location: Grand Forks, ND, East Grand Forks, MN
47° 56' 31.19° N
97° 2' 53.59° W

River network:

- ■ Red River of the North: 296.1 miles upstream of Lake Winnipeg,
- ≈ A total of 939.5 miles upstream of Hudson Bay.

Drowning deaths: 1 known at current site, several below previous dam

Additional dam problems:
Severe downstream bank erosion threatened the dam and stability of flood dikes.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ erosion control
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide fish passage and habitat
- ☆ provide spawning habitat for lake sturgeon and othe species
- ☆ provide whitewater boating opportunity

Design concept:
Rock Arch Rapids. Weirs were truncated to reduce slope compensation. This is the world's largest full width rock ramp fishway in terms of tonnage and height.

Slope: 5% (3% near banks)

Project designers:
Mike Lesher (Project Engineer), U. S. Army Corps of Engineers
Luther Aadland, MN DNR

Contractor: Park Construction

Materials: 80,000 tons fieldstone
1,200 5-7' boulders

Cost: $4.7 million

Year completed: 2001

Connectivity

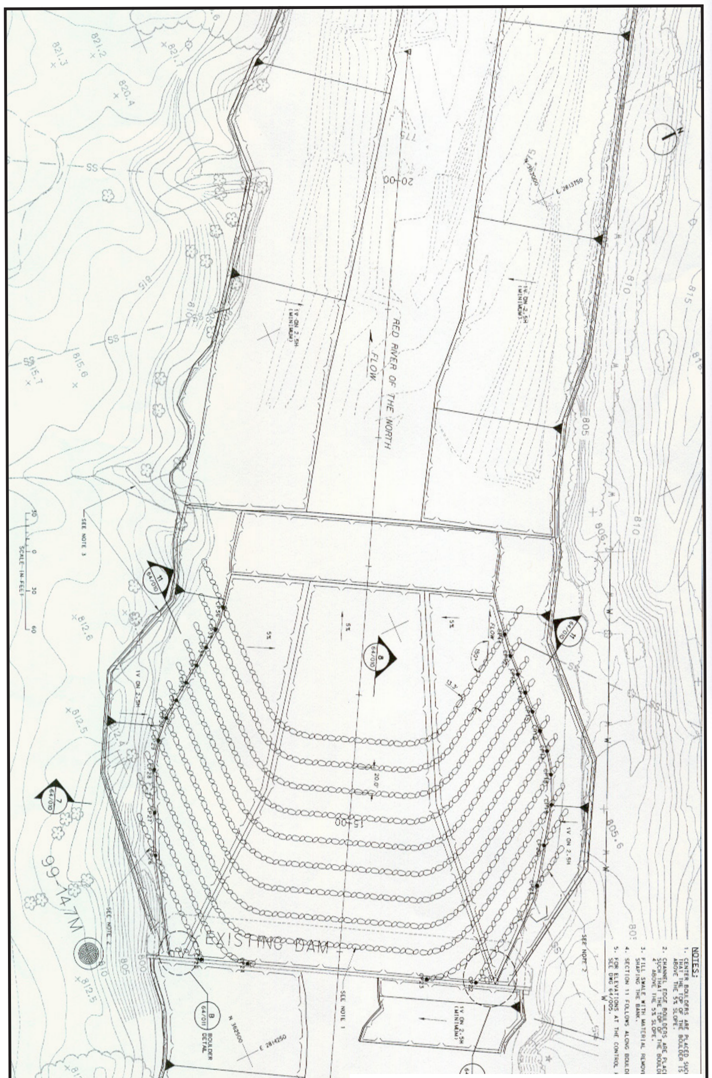
Upstream main-stem barriers:
Hickson Dam (river mile 482.9) and Christine Dam (river mile 496.5) are passable during floods but are barriers during most of the year.
Orwell Dam (Otter Tail River) at river mile 587.4 is a complete barrier.

Downstream barriers:
Drayton Dam (river mile 203.4) and St. Andrews Dam at Lockport, Manitoba (river mile 27.1) are passable during floods but are barriers during most of the year.

Assessment:
Northern pike and channel catfish have been observed passing the rapids.

Before

Downstream view of dam from left bank



Design planview (U.S. ACOE)

After

Rapids side view from left bank

Rapids looking upstream

Upstream view of boulder weirs

#6

POINT DAM

Red Lake River

Nelson River Basin

Dam Facts

Mean flow: 1,210 cfs at Crookston gage
Record flow: 28,400 cfs

Drainage area: 5,760 mi^2

Dam height: 2.4 feet due to downstream Riverside Dam

Crest width: 121.3 feet

Crest elevation: 795.7 MSL

Year built: 1937

Original dam function: water supply

Location: East Grand Forks, MN
47° 55' 22.83° N
97° 01' 06.07° W

River network:

■ Red Lake River: 0.15 miles upstream of confluence with...
➥ Red River of the North: 296.1 miles upstream of Lake Winnipeg,
≈ A total of 939.6 miles upstream of Hudson Bay.

Drowning deaths: none known

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide lake sturgeon spawning habitat
- ☆ provide whitewater boating opportunity

Design concept:
Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project description:
Clean waste concrete was used as a sub-base and covered with fieldstone.

Project designers:
Greg Boppre (Project Engineer), Floan-Sanders
Luther Aadland, MN DNR

Contractor: Spruce Valley

Materials: 16,653 tons fieldstone and waste concrete

Cost: $170,000

Year completed: 2003

Connectivity

Upstream barriers:
Thief River Falls Dam (river mile 125) is a complete barrier. Weir at river mile 180.9 and Red Lake Dam at river mile 193 are complete barriers for most species.

The removal of Crookston Dam in 2005 and Crookston Dam #2 in 2006 provided passage to historic sturgeon spawning habitat at Red Lake Falls (next two briefs).

Red River catfish caught below rapids. Photo courtesy of Brad Dokken, Outdoors Editor Grand Forks Herald.

Before

Upstream view of dam from right bank during high flow

After


View of completed rapids from right bank

During


Placing waste concrete sub-base


Building boulder weirs

#7 CROOKSTON DAM

Red Lake River — Nelson River Basin

Dam Facts

Mean flow: 1,210 cfs at Crookston gage
Record flow: 28,400 cfs

Drainage area: 5,270 mi^2

Dam height: 12 feet (reduced to 9 feet with downstream riffles)

Crest width: 192 feet

Crest elevation: 846.3 MSL

Year built: 1883 (original structure)

Original dam function: Mill converted to hydropower in 1905 with two turbines (176 and 200 KW). The hydropower facility was retired in 1970.

Location: Crookston MN
47° 46' 28.43° N
96° 31' 38.18° W

River network:
- ■ Red Lake River: 53.6 miles upstream of confluence with...
- ➥ Red River of the North: 296.1 miles upstream of Lake Winnipeg,
- ≈ A total of 993.1 miles upstream of Hudson Bay.

Drowning deaths: 9 to as many as 27

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide fish passage and habitat
- ☆ provide lake sturgeon spawning habitat
- ☆ river bank stabilization
- ☆ provide whitewater boating opportunity

Design concept:
Rock Arch Rapids

Slope: graduated from 2.5% near crest to 5% at downstream end

Project designers:
Dave Kildahl (Project Engineer), Widseth Smith Nolting Inc.
Luther Aadland, MN DNR

Builders/Contractor: Davidson (rapids)
Spruce Valley (downstream riffles)

Materials: 48,527 tons including:
18,515 tons fieldstone
1,098 tons 5-7' boulders
7,909 tons filter material
5,238 tons waste concrete

Cost: $1.4 million

Year completed: 2005

Connectivity

Upstream barriers:
Thief River Falls Dam (river mile 125) is a complete barrier. Weir at river mile 180.9 and Red Lake Dam at river mile 193 are complete barriers for most species.

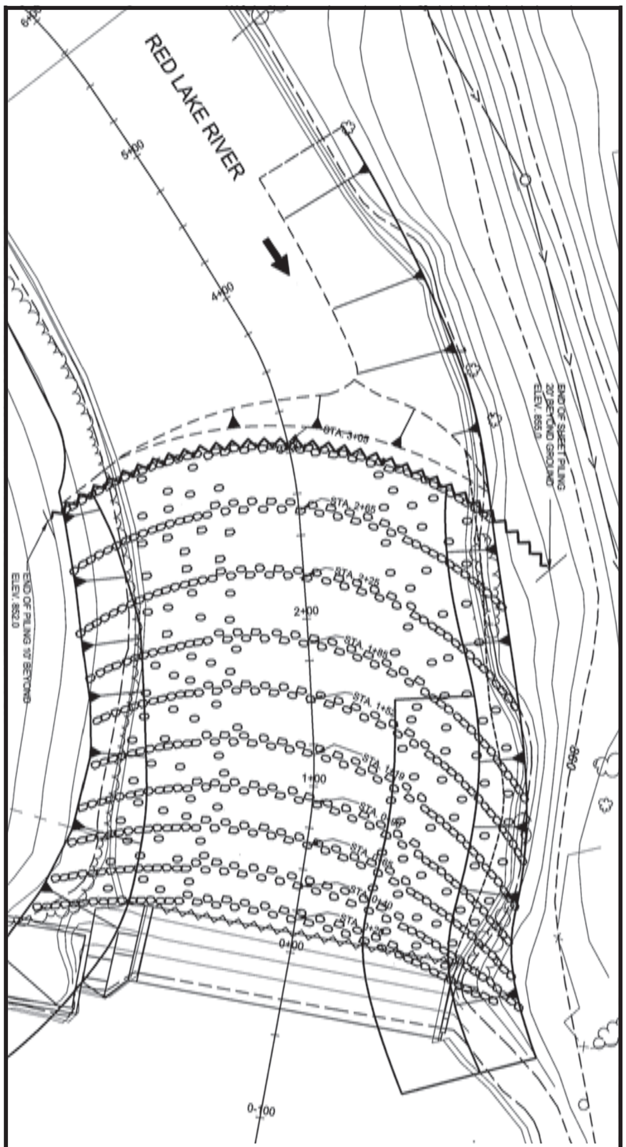
Downstream barriers:
None to Red River of the North confluence.

Observed passage:
Sand shiners were observed passing during construction. Fisheries stream surveys documented the return of channel catfish and sauger upstream following project completion.

** This project is discussed in detail in Chapter 2.*

Before

View of dam from right bank



Design planview (Widseth Smith Nolting Inc.)

After

Upstream view of completed rapids

One of two downstream riffles constructed for grade control and to raise tailwater elevation below rapids

#8

CROOKSTON DAM #2

Red Lake River

Nelson River Basin

Dam Facts

Mean flow: 1,210 cfs at Crookston gage
Record flow: 28,400 cfs

Drainage area: 5,255 mi^2

Maximum head loss: 4 feet (Original dam height was about 20 ft. Dam failed in 1950 but sheet-piling weir was retained.)

Crest width: 147 feet

Crest elevation: approximately 860 MSL

Year built: 1916 (original structure)

Original dam function: hydropower (two turbines of 500 and 1000 KW) retired in 1949.

Location: Crookston MN
47° 46' 21.45° N
96° 31' 38.18° W

River network:

- ■ Red Lake River: 62.8 miles upstream of confluence with...
- ➥ Red River of the North: 298 miles upstream of Lake Winnipeg,
- ≈ A total of 1,004.17 miles upstream of Hudson Bay.

Drowning deaths: unknown

Restoration Design

Project type: Dam removal

Project goals:

- ☆ river restoration
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide fish passage

Project description:
A 200' x 15' x 3' fieldstone causeway was constructed upstream of the sheet-piling crest for access. This was retained as a riffle grade control. Underwater divers were used for cutting sheet piling. An excavator was then able to peel and remove the cut piling.

Project designers:
Luther Aadland & Chad Konickson, MN DNR

Builders/Contractor: Spruce Valley

Materials: 300 yards 0.5-2' fieldstone

Cost: $27,000

Year completed: 2006

Connectivity

Upstream barriers:
Thief River Falls Dam (river mile 125) is a complete barrier. Weir at river mile 180.9 and Red Lake Dam at river mile 193 are complete barriers for most species.

Downstream barriers:
None to Red River of the North confluence.

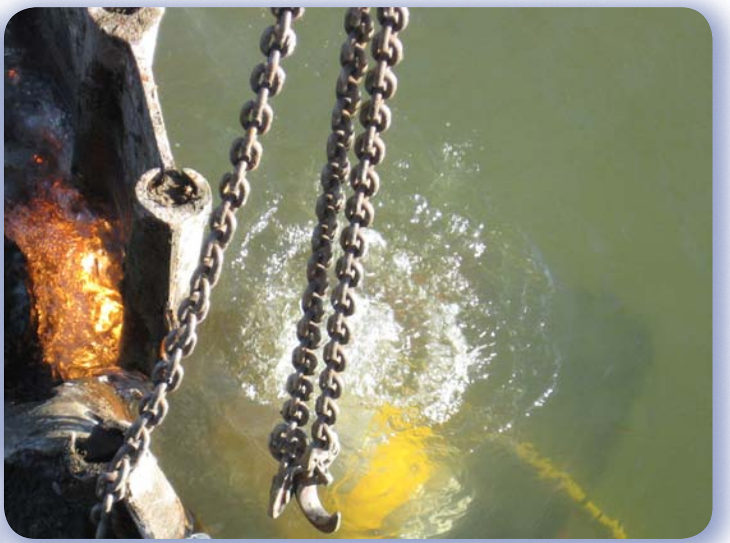
Before

Aerial upstream view of dam

Sideview of dam showing sheet piling crest

Upstream view of dam

During



Divers cutting sheet piling

After

After spillway removal

#9

SANDHILL CROSSING

Sandhill River

Nelson River Basin

Dam Facts

Mean flow: 86.6 cfs at Climax gage
Record flow: 4,560 cfs

Drainage area: 314 mi^2

Location:
47° 32' 6.901° N
96° 34' 47.38° W

River network:
- ■ Sandhill River: 23.16 miles upstream of confluence with...
- ➥ Red River of the North: 346.4 miles upstream of Lake Winnipeg,
- ≈ A total of 1,012.9 miles upstream of Hudson Bay.

Restoration Design

Project type: Replacement of barrier crossing with passable culverts

Project purpose:
- ☆ provide fish passage - low water crossing had undersized culverts that created high velocity barriers.

Project description:
Replacement culverts matched bankfull width and were set below streambed. Crossing maintained passable velocities over full range of flow conditions.

Project designers:
Eric Jones (Project Engineer), Houston Engineering

Builders/Contractor: Davidson Corporation

Materials: three 10' x 4' x 36' box culverts

Cost: $122,702

Year completed: 2006

Connectivity

Upstream barriers:
Check dams at river miles 28.65, 29.61, 30.4, and 31.52 are complete barriers. Funding is currently being pursued to convert these to Rock Arch Rapids.

Downstream barriers:
None to Red River of the North confluence

Before

Upstream view of high velocity culverts

After

Upstream view of new culverts

#10 WEST MILL DAM SITE

Sandhill River — Nelson River Basin

Dam Facts

Mean flow: 86.6 cfs at Climax gage
Record flow: 4,560 cfs

Drainage area: 232 mi^2

Maximum head loss: 6.3 feet elevation difference between upstream and downstream culvert inverts over 56 feet lenght

Crest elevation: 1,043.8 MSL

Original dam function: mill

Drowning deaths: unknown

Location:
47° 30' 41.649° N
96° 21' 57.29° W

River network:

- ■ Sandhill River: 36.42 miles upstream of confluence with...
- ➥ Red River of the North: 346.4 miles upstream of Lake Winnipeg,
- ≈ A total of 1,026.2 miles upstream of Hudson Bay.

Restoration Design

Project type: Barrier removal and river restoration

Project goals:

- ☆ river restoration
- ☆ provide fish passage and habitat

Project description:
The original culverts replaced a milldam and were placed at a steep slope (10%) presumably for grade control. This created a barrier to fish passage. The project involved replacing the sloped culverts with culverts set at the downstream riverbed and constructing 7 fieldstone riffles for grade control.

Slope: 0.45% (5% for each of the 7 individual riffles)

Project designers:
Eric Jones (Project Engineer), Houston Engineering
Luther Aadland, MN DNR

Builders/Contractor: Davidson Corporation

Materials: 3,210 yards class V fieldstone

Cost: $272,237

Year completed: 2006

Connectivity

Downstream barriers:
Check dams at river miles 28.7, 29.6, 30.4, and 31.5 are complete barriers.

Before	After


Upstream view of perched culverts


Upstream view of reset culverts


1939 aerial photo of the West Mill Dam Reservoir


2008 aerial photo of former reservoir


Riffle grade control

#11

HEIBERG DAM

Wild Rice River — **Nelson River Basin**

Dam Facts

Mean flow: 207 cfs at Twin Valley gage
Record flow: 20,300 cfs

Drainage area: 930 mi^2

Dam height: 8 feet

Crest width: 155 feet

Crest elevation: 1,000 MSL

Year built: 1875 (original structure)

Original dam function: flour milldam which was later retrofitted for hydropower that functioned until the 1950s. The dam failed in 1965 and was rebuilt for ice control in 1975.

Location:
47° 16' 58.372° N
96° 16' 37.08° W

River network:
- ■ Wild Rice River: 57.6 miles upstream of confluence with...
- ➥ Red River of the North: 380.4 miles upstream of Lake Winnipeg,
- ≈ A total of 1,081.37 miles upstream of Hudson Bay.

Drowning deaths: none known

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:
- ☆ restoration of cutoff reach and inundated habitat
- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ retention of ice control function

Project description:
Dam failed in 2002 flood by cutting through embankment into a tributary channel and cut off 1.5 miles of river initiating a headcut that nearly undermined the MN 32 bridge. Project involved plugging gully to restore flows to the cut-off meander and largely removing the dam. Design had to maintain ice break function – shark-fin structures compensated for head-loss reduction. Crest was lowered 6 feet in center 72 feet and 4 feet on sides to match river bankfull width. Maximum head-loss was reduced to 2 feet.

Project designers:
Jerry Bents (Project Engineer), Houston Engineering
Luther Aadland, MN DNR (fishway rapids)

Builders/Contractor: Landwehr Construction

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to boulder weirs)

Materials: 1,670 yards 12"-30" fieldstone
600 yards 36"-60" boulders

Year completed: 2006

Funding: Federal Emergency Management Agency, U.S. Fish and Wildlife Service, White Earth Band of Ojibwa, MN DNR

Connectivity

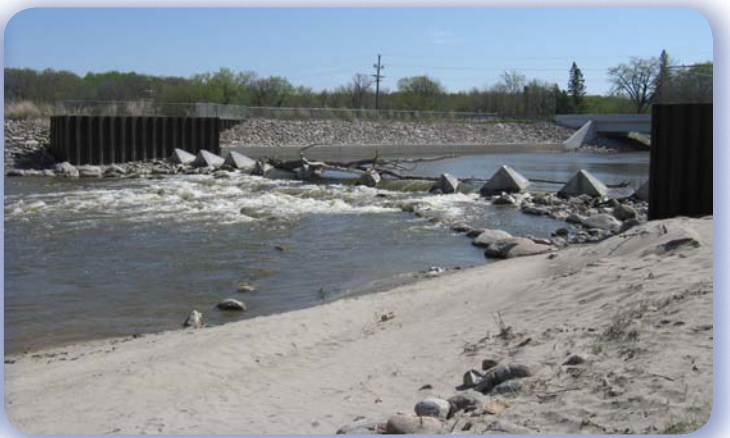
Barriers: Open downstream to Red River of the North and upstream to headwaters.

Assessment: 2003 Fisheries and Ecological Resources surveys found channel catfish, smallmouth bass, sauger, walleye, freshwater drum, shorthead redhorse, pumpkinseed sunfish, goldeye, spotfin shiner, and pearl dace, had returned to upstream reaches as far as 75 miles upstream a year after the dam failure where they were absent in surveys prior to the dam failure.

Before

After

Upstream view of dam from left bank



Upstream view of completed rapids

Dam failing in 2002 flood

Aerial upstream view of rapids

Channel cut off by dam failure

#12 MARSH CREEK CULVERT

Marsh Creek

Nelson River Basin

Dam Facts

Location: Crossing at Norman County Rd 29
47° 16' 53.48° N
96° 9' 6.046° W

Year built: 2003

River network:
- ■ Marsh Creek: 1.3 miles upstream of confluence with...
- ➥ Wild Rice River: 70.91 miles upstream of confluence with...
- ➥ Red River of the North: 380.4 miles upstream of Lake Winnipeg,
- ≈ A total of 1,096 miles upstream of Hudson Bay.

Restoration Design

Project type: Culvert passage

Project purpose:
- ☆ provide fish passage

Project description:
A riffle was constructed to raise tailwater on a perched culvert. A group of poorly designed culverts created a barrier.

Project designers:
Dave Friedl, MN DNR

Materials: 150 yards of 18-24" fieldstone

Cost: $5,828.16

Year completed: 2005

Connectivity

Assessment:
The project reduced velocities and raised tailwater in the lowest culvert providing fish passage. The site likely remains a barrier at high flows and will likely continue to have erosion problems due to the odd array of culverts.

Before

Perched culvert array

Lowest perched culvert as a barrier to fish passage

After

View of culverts showing tailwater pooling into lower culvert following riffle construction

Dowstream view of constructed riffle

During

Construction of riffle

#13 WHITE EARTH LAKE DAM

White Earth River — Nelson River Basin

Dam Facts

Mean flow: Approximately 24 cfs

Drainage area: 108 mi^2

Dam height: 3 feet

Crest width: 20 feet

Crest elevation: 1,451 MSL

Year built: 1937

Original dam function: lake level control

Drowning deaths: unknown

Location:
47° 8' 58.373° N
95° 45' 50.47° W

River network:
- ■ White Earth River: 49.3 miles upstream of confluence with...
- ➥ Wild Rice River: 99.67 miles upstream of confluence with...
- ➥ Red River of the North: 380.4 miles upstream of Lake Winnipeg,
- ≈ A total of 1,172.74 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project purpose:
- ☆ provide fish passage
- ☆ provide spawning habitat for lake sturgeon and other species

Design concept:
Rock Arch Rapids

Slope: 5% center, 3% near banks due to boulder weirs

Project designers:
Luther Aadland, MN DNR

Builders/Contractor: Gordon Construction of Mahnomen, Inc.

Materials: 200 yards of fieldstone

Cost: $50,000

Year completed: 2003

Funding: Fish and Wildlife Service, White Earth Band of Ojibwa

Connectivity

Assessment:
Bluegills were observed passing the rapids. Lake sturgeon have been reintroduced to White Earth Lake but are not yet mature.

Before

Upstream view of dam

After

Upstream view of completed rapids (2003)

Upstream view of completed rapids (spring 2009)

#14 BUFFALO STATE PARK DAM

Buffalo River — Nelson River Basin

Dam Facts

Mean flow: 85.6 cfs at Hawley gage
Record flow: 2,360 cfs

Drainage area: 359 mi^2

Dam height: 3.5 feet

Crest width: 80 feet

Crest elevation: 978 MSL

Year built: 1937 (a milldam near this site was mentioned in an 1893 U.S. Fisheries survey by Albert Wolman)

Original dam function: diversion into swimming pond

Location: Buffalo State Park
46° 51' 50.39° N
96° 27' 59.04° W

River network:
- ■ Buffalo River: 59.7 miles upstream of confluence with...
- ➥ Red River of the North: 417.1 miles upstream of Lake Winnipeg,
- ≈ A total of 1,120.2 miles upstream of Hudson Bay.

Drowning deaths: 2

Restoration Design

Project type: Dam removal and river restoration

Project goals:
- ☆ river restoration
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide fish passage and habitat

Project description:
Two rock riffles were used for grade control, bank protection and habitat, and two boulder vanes were built to replace rock filled gabions and provide bank protection. Historically significant abutments were retained.

Slope: 0.5%

Project designers:
Dave Sobania (Project Engineer), MN DNR
Tom McDonald (Project Engineer), Barr Engineering
Luther Aadland, MN DNR

Contractor: Moorhead Construction Company Inc.

Materials: approximately 60 4'+ boulders
400 yards fieldstone

Cost: $60,000

Year completed: 2002

Funding: MN DNR

Connectivity

Barriers:
Open downstream to Red River of the North and upstream to headwaters

Before

Upstream view of dam from right bank

After

Upstream view of removed dam and completed rapids

During

Placing boulders

Upstream constructed riffles

#15

LAWNDALE CULVERT

Lawndale Creek

Nelson River Basin

Dam Facts

Location:
46° 32’ 22.86° N
96° 23’ 10.24° W

Mean flow: 2 cfs

Drainage area: 9.4 mi^2

Head-loss: 2 feet

Bankfull channel width: 8-10 feet

River network:
- ■ Lawndale Creek: 6.2 miles upstream of confluence with...
- ➥ Deerhorn Creek: 4.6 miles upstream of confluence with...
- ➥ South Branch Buffalo: 49.3 miles upstream of confluence with...
- ➥ Red River of the North: 417.1 miles upstream of Lake Winnipeg,
- ≈ A total of 1,120.6 miles upstream of Hudson Bay.

Restoration Design

Project type: Culvert passage

Project purpose:
- ☆ provide fish passage

Design concept: Arch riffles

Project description:
Five constructed riffles were used to raise stage through a perched culvert for passage of brook trout and other species.

Project designers:
Howard Fullhart and Luther Aadland, MN DNR

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: approximately 50 yards fieldstone

Cost: $5,257.14

Year completed: 2008

Connectivity

Barriers:
Open downstream to South Branch Buffalo River and upstream to headwaters

After

Downstream view of culvert after riffle construction. Prior to the project the culvert had over two feet of fall.

Downstream view of riffle

Constructed riffle

Constructed riffle

#16 ENDERLIN DAM

Maple River — Nelson River Basin

Dam Facts

Location: Enderlin, ND
46° 37' 39.58° N
97° 36' 02.16° W

Mean flow: 58.6 cfs

Drainage area: 843 mi^2

Dam height: 4 feet

River network:
- ■ Maple River: 102.1 miles upstream of confluence with...
- ➥ Sheyenne Creek: 21.1 miles upstream of confluence with...
- ➥ Red River of the North: 427.5 miles upstream of Lake Winnipeg,
- ≈ A total of 1,194.07 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project purpose:
- ☆ provide fish passage and habitat
- ☆ provide whitewater boating opportunity

Slope: 5%

Project designers:
Jonathan Kelsch, ND State Water Commission

Year completed: 2006

Connectivity

Barriers:
Numerous dams upstream and downstream fragment the Maple and Sheyenne Rivers

Before

Sheet piling crest of rock ramp

After

Upstream view of completed ramp

During

Constructed rock ramp base

Upstream view of rock ramp

#17

FARGO NORTH DAM

Red River of the North

Nelson River Basin

Dam Facts

Mean flow: 694 cfs at Fargo gage
Record flow: 28,000 cfs

Drainage area: 6,802 mi^2

Dam height: ~ 5 feet

Crest width: 108 feet

Crest elevation: 870.38 MSL

Year built: 1933

Original dam function: water supply

Location: Fargo, ND
46° 53' 26.75° N
96° 46' 12.81° W

River network:

- ■ Red River of the North: 448.9 miles upstream of Lake Winnipeg,
- ≈ A total of 1,092.3 miles upstream of Hudson Bay.

Drowning deaths: 3 known

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide lake sturgeon spawning habitat
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project designers:
Doug Crum, Richard Sunberg, Jeff Stanek, and Jim Murphy (Project Engineers), U.S. Army Corps of Engineers
Luther Aadland, MN DNR

Builders/Contractor: United Construction and Supply

Materials: 2500 yards (3500 tons) fieldstone

Year completed: 2002

Cost: $117,871.50

Funding: U.S. Army Corps of Engineers Section 206 funds, City of Fargo, City of Moorhead, Fargo Park District, MN DNR, North Dakota Game and Fish, Buffalo-Red Watershed District, Southeast Cass Water Resource District, ND State Water Commission

Connectivity

Upstream barriers:
Hickson Dam at river mile 482.5 and Christine Dam at river mile 496.5

Downstream barriers:
Drayton Dam at river mile 206.7

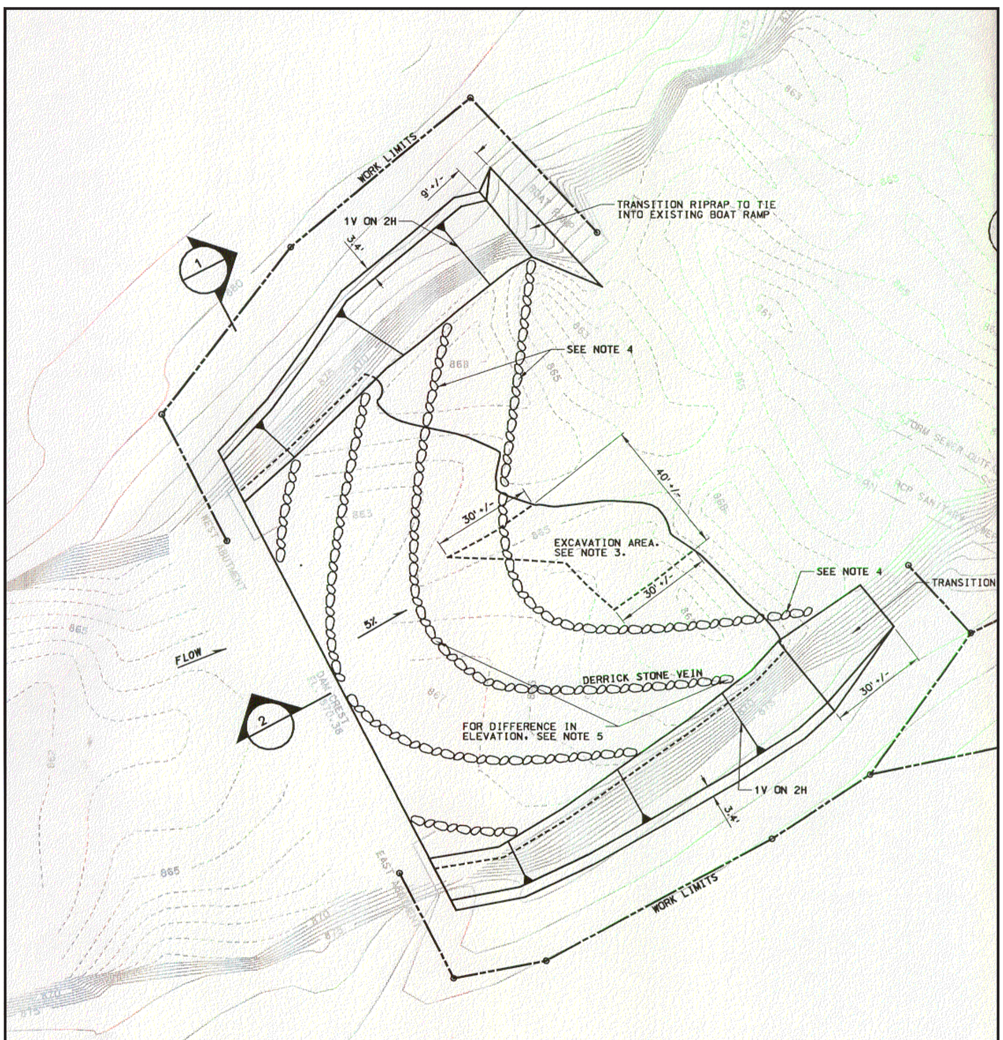
Assessment:
Unidentified fish have been observed passing the rapids, freshwater drum were observed spawning in the upstream (glide) part of the rapids.

Before

Upstream view of dam

After

Upstream view of completed rapids



Design planview (U.S. ACOE)

#18 MIDTOWN DAM

Red River of the North — Nelson River Basin

Dam Facts

Mean flow: 694 cfs at Fargo gage
Record flow: 28,000 cfs

Drainage area: 6,800 mi^2

Dam height: 5.3 feet

Crest width: 120 feet at 875.7 sloping to 190 feet at 877

Crest elevation: 875.7 MSL

Year built: 1929 (rebuilt in 1961)

Original dam function: water supply

Location: Fargo, ND; Moorhead, MN
46° 52' 16.09° N
96° 46' 55.55° W

River network:

■ Red River of the North: 452.2 miles upstream of Lake Winnipeg,

≈ A total of 1,095.6 miles upstream of Hudson Bay.

Drowning deaths: 19 known, as many as 25 total

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ improve safety by eliminating hydraulic roller
- ☆ provide fish passage and habitat
- ☆ provide lake sturgeon spawning habitat
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids (this was the first project to use this design)

Slope: 5% (3% near banks due to weirs)

Project designers:
Roger Less (Project Engineer), U.S. Army Corps of Engineers,
Mark Bitner and Vern Tomanack (Project Engineers), City of Fargo
Luther Aadland, MN DNR

Builders/Contractor: Industrial Builders

Materials: 4,345 yds fieldstone

Year completed: 1998-1999

Cost: $235,000

Funding: City of Fargo, City of Moorhead, Fargo Park District, MN DNR, North Dakota Game and Fish, Buffalo-Red Watershed District, Southeast Cass Water Resource District, ND State Water Commission

Connectivity

Upstream barriers:
Hickson Dam at river mile 482.5 and Christine Dam at river mile 496.5

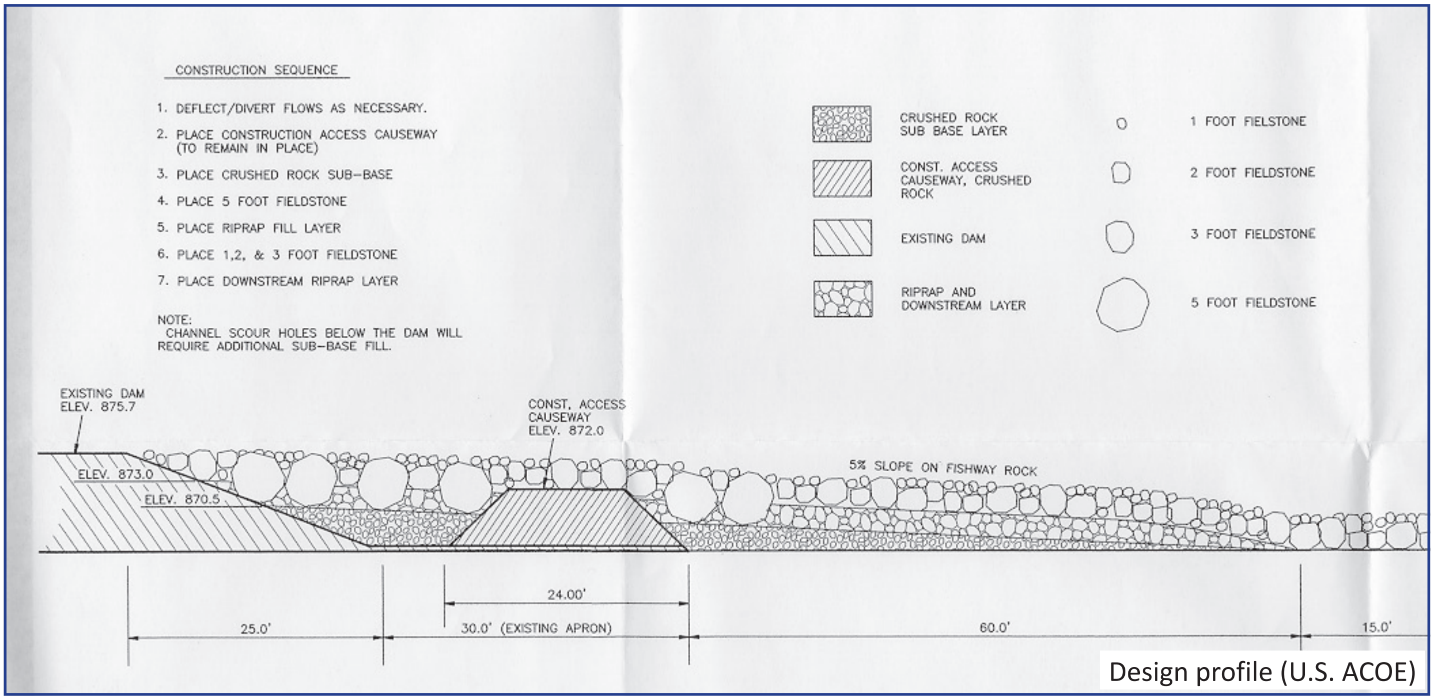
Downstream barriers:
Drayton Dam at river mile 206.7

** This project is discussed in detail in Chapter 2.*

Before | **After**

View of dam from left bank during low flow

Upstream view of completed rapids



Design profile (U.S. ACOE)

#19 FARGO SOUTH DAM

Red River of the North — Nelson River Basin

Dam Facts

Mean flow: 694 cfs at Fargo gage
Record flow: 28,000 cfs

Drainage area: 6,789 mi^2

Watershed area: 6,800 mi^2

Dam height: 4 feet due to downstream Midtown Dam

Crest width: 150 feet

Crest elevation: 879.7 MSL

Year built: 1933

Original dam function: water supply

Location: Fargo, ND; Moorhead, MN
46° 49' 54.13° N
96° 47' 29.18° W

River network:
- ■ Red River of the North: 458.1 miles upstream of Lake Winnipeg,
- ≈ A total of 1,101.5 miles upstream of Hudson Bay.

Drowning deaths: 3 known

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide fish passage and habitat
- ☆ provide lake sturgeon spawning habitat
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project designers:
Aaron Busing, Jeff Stanek, and Brian Johnson (Project Engineers), U.S. Army Corps of Engineers
Luther Aadland, MN DNR

Builders/Contractor: Rising Sun

Materials: 23,650 tons fieldstone

Year completed: 2003

Cost: $916,260

Funding: U.S. Army Corps of Engineers Section 206 funds, City of Fargo, City of Moorhead, Fargo Park District, MN DNR, North Dakota Game and Fish, Buffalo-Red Watershed District, Southeast Cass Water Resource District, ND State Water Commission, U.S. Fish and Wildlife Service

Connectivity

Upstream barriers:
Hickson Dam at river mile 482.5 and Christine Dam at river mile 496.5

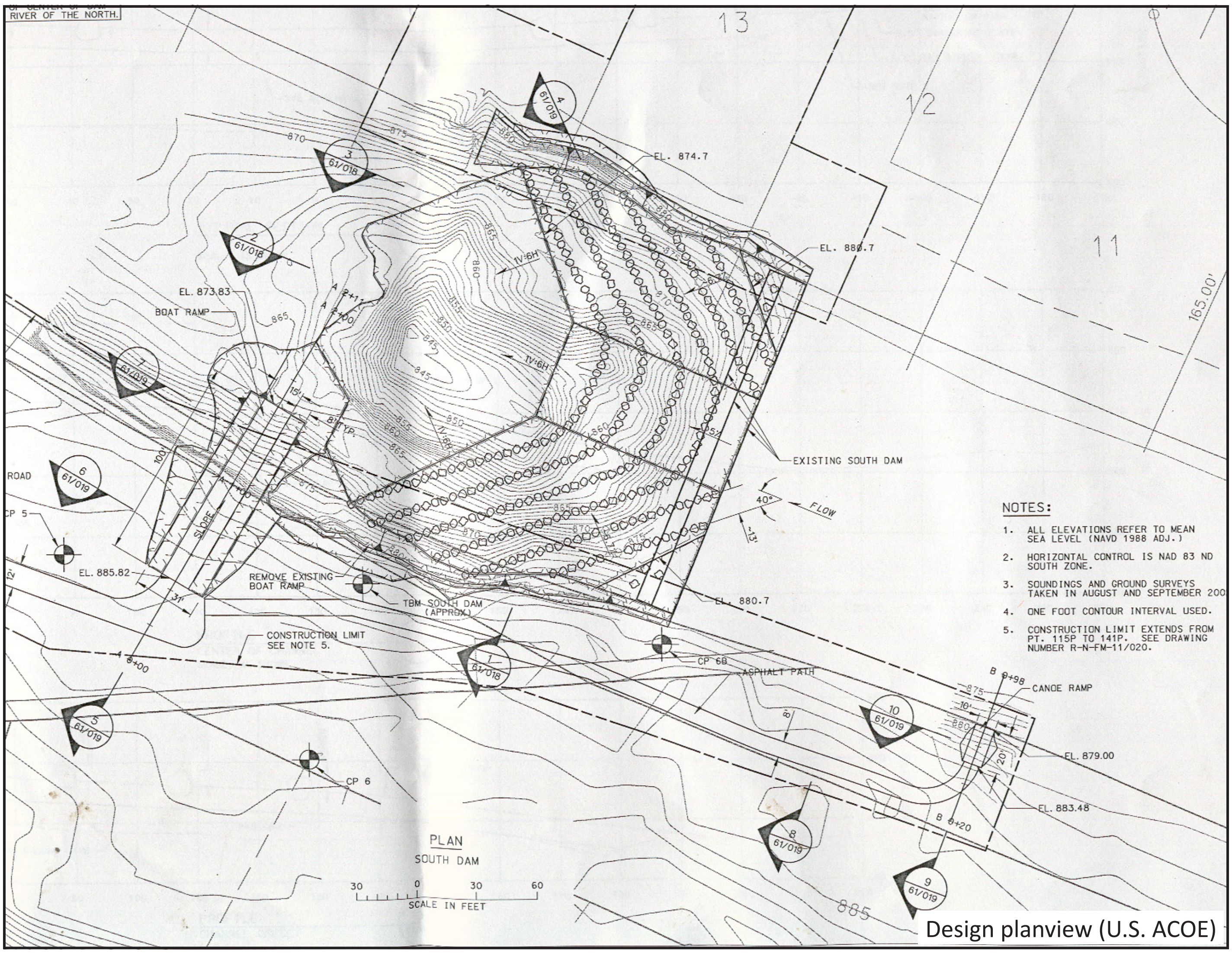
Downstream barriers:
Drayton Dam at river mile 206.7

Before

View of dam from left bank

After

View of completed rapids from left bank



Design planview (U.S. ACOE)

#20 KIDDER DAM

Red River of the North — *Nelson River Basin*

Dam Facts

Mean flow: 670 cfs

Drainage area: 4,012 mi^2

Dam height: ~ 5 feet

Crest width: 80 feet

Crest elevation: 945 MSL

Year built: 1927

Original dam function: water supply for coal plant

Location: Wahpeton, ND; Breckenridge, MN
46° 16' 05.25° N
96° 35' 19.58° W

River network:

- ■ Red River of the North: 546.5 miles upstream of Lake Winnipeg,
- ≈ A total of 1,189.9 miles upstream of Hudson Bay.

Drowning deaths: none known

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide lake sturgeon spawning habitat
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project description: Two rock vanes were buildt to protect banks and infrastructure.

Project designers:
Luther Aadland, MN DNR

Builders/Contractor: Sheryl's Construction

Materials: 2,700 yards fieldstone

Year completed: 2000

Cost: $95,000

Funding: MN DNR – Fisheries, North Dakota Game and Fish, North Dakota Water Commission

Connectivity

Upstream barriers:
Orwell Dam on the Otter Tail River
Mud Lake Dam on the Bois de Sioux River

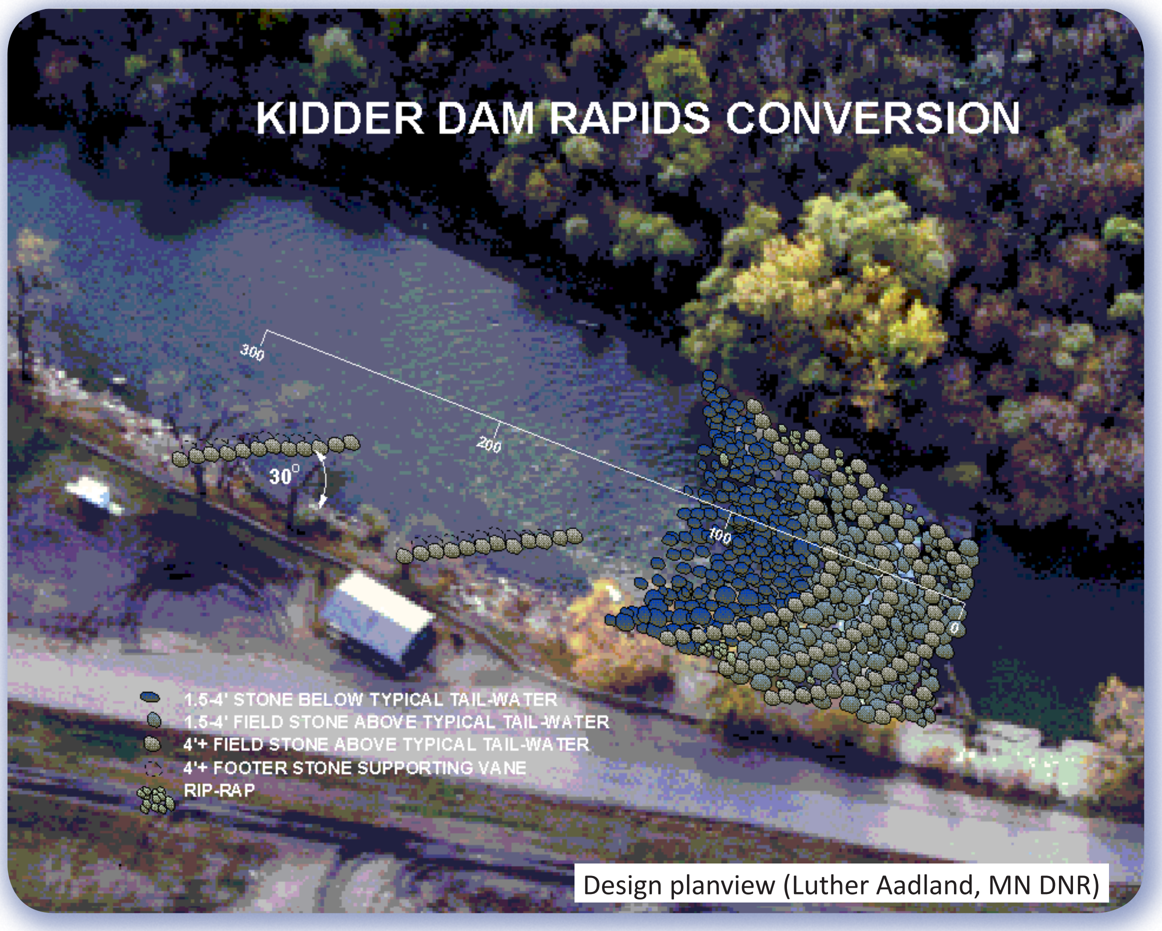
Downstream barriers:
Hickson Dam at river mile 482.5
Christine Dam at river mile 496.5
Drayton Dam at river mile 206.7

Before

View of dam from left bank

After

View of completed rapids from left bank



Design planview (Luther Aadland, MN DNR)

#21 BRECKENRIDGE WATER PLANT DAM

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow: Approximately 434 cfs

Drainage area: 1,984 mi^2

Dam height: 2 feet

Crest width: 80 feet

Original dam function: water supply

Drowning deaths: unknown

Location: Breckenridge, MN
46° 16' 5.362 N
96° 35' 20.17° W

River network:

- ■ Otter Tail River: 2 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,194.07miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide lake sturgeon spawning habitat
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project designers:
Luther Aadland, MN DNR
Tor Hanson (Project Engineer), Barr Engineering

Builders/Contractor: Industrial Builders

Materials: 504 tons fieldstone

Year completed: 2000

Cost: $50,000

Connectivity

Upstream barriers:
Orwell Dam on the Otter Tail River

Downstream barriers:
Christine Dam on the Red River of the North at river mile 496.5

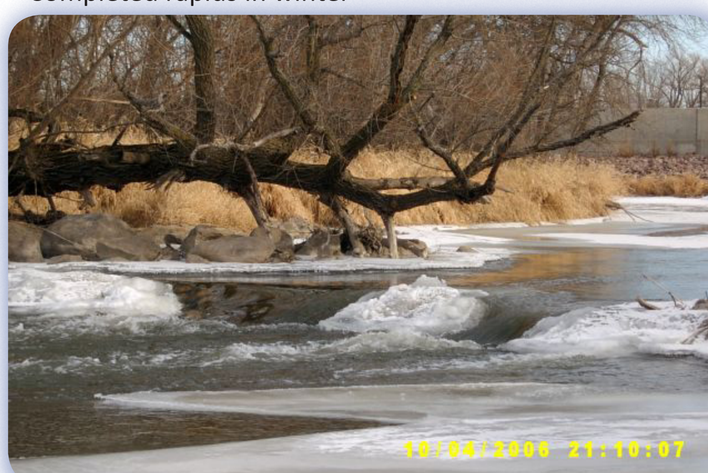
Before

Sideview of dam during high flow

After

Completed rapids

Completed rapids in winter



Closeup view of rapids in winter

#22a BRECKENRIDGE LAKE DAM

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow: Approximately 434 cfs

Drainage area: 1,976 mi^2

Dam height: 8 feet with stop logs, 4 feet without

Crest width: 48 feet combined bay width and 3' x 3'gated orifice

Crest elevation: approximately 963 MSL

Year built: 1935

Original dam function: water supply

Drowning deaths: 1 known

Location:
46° 15' 26.88° N
96° 32' 10.04° W

River network:
- ■ Otter Tail River: 7.7 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,199.8 miles upstream of Hudson Bay.

Restoration Design

Project type: Bypass fishway

Project goals:
- ☆ provide fish passage and habitat

Design concept: Bypass fishway

Slope: 2%

Project designers:
Tom Rickles (Project Engineer), Wilkin County
Luther Aadland, MN DNR

Builders/Contractor: Wilkin County Highway Department

Materials: 350 tons fieldstone
600 yards clay
4' x 6' used cattle crossing culvert

Year completed: 1996

Cost: $20,000

Connectivity

Upstream barriers:
Orwell Dam is 31 river miles upstream on the Otter Tail River

Downstream barriers:
Christine Dam on the Red River of the North at river mile 496.5

Assessment:
A trap-net set at the reservoir end of the fishway has confirmed passage of 34 species of fish. These ranged in size from shiners as small as a couple of inches to a 48.5 inch muskellunge. Species passed included: walleye, sauger, blackside darter, northern pike, muskellunge, goldeye, mooneye, silver lamprey, chestnut lamprey, channel catfish, black bullhead, brown bullhead, stonecat, shorthead redhorse, golden redhorse, greater redhorse, silver redhorse, white sucker, quillback, bigmouth buffalo, bluntnose minnow, emerald shiner, spottail shiner, sand shiner, spotfin shiner, common shiner, common carp, bluegill, pumpkinseed sunfish, black crappie, smallmouth bass, white bass, and freshwater drum.

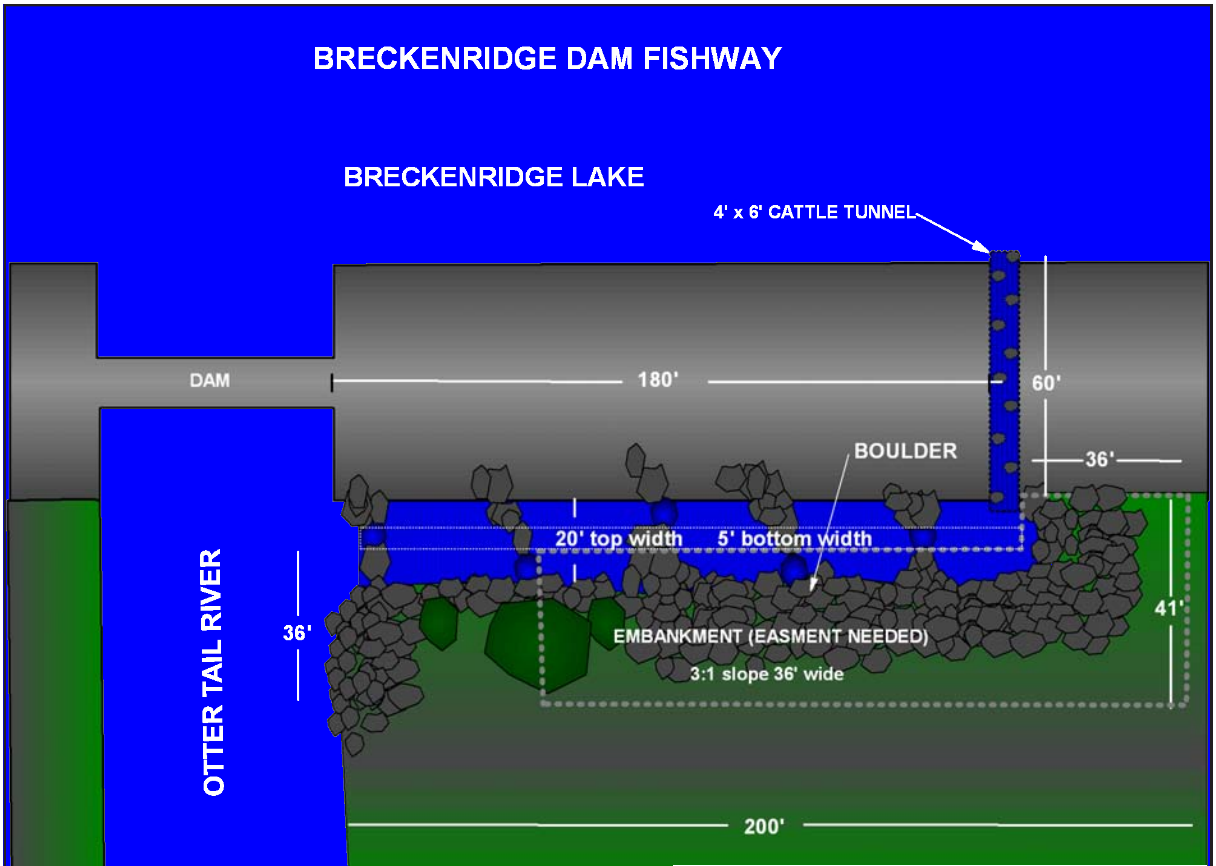
* This project is discussed in detail in Chapter 2.

Before

Upstream view of dam

After

Upstream view of completed fishway



Design planview (Luther Aadland, MN DNR)

#22b BRECKENRIDGE LAKE DAM

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow: Approximately 434 cfs

Drainage area: 1,976 mi^2

Dam height: 8 feet with stop logs, 4 feet without

Crest width: 48 feet combined bay width and 3x3 foot gated orifice

Crest elevation: approximately 963 MSL

Year built: 1935

Original dam function: water supply

Drowning deaths: 1 known

Location:
46° 15' 26.88° N
96° 32' 10.04° W

River network:
- ■ Otter Tail River: 7.7 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,199.8 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:
- ☆ river restoration
- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 2%

Project designers:
Tom Rickles (Project Engineer), Wilkin County
Luther Aadland and Kevin Zytkovicz, MN DNR

Builders/Contractor: Wilkin County Highway Department

Materials: 1,500 yards fieldstone

Year completed: 2007

Cost: $100,000

Project description:
The dam embankment failed in floods of 1989, 1997, 2001, 2006, and 2007. Stop-log bays and gate were inoperable after the 1997 flood. The reservoir was filled with sand but the river had re-meandered within these sediments. The dam was removed to the bottom of the stop-log bays. Rock Arch Rapids were built to provide grade control, fish passage and habitat. A 10' deep pool, popular with anglers, was retained within the rapids. Bypass fishway was retained.

Connectivity

Upstream barriers:
Orwell Dam is 31 river miles upstream on the Otter Tail River

Downstream barriers:
Christine Dam on the Red River of the North at river mile 496.5

* This project is discussed in detail in Chapter 2.

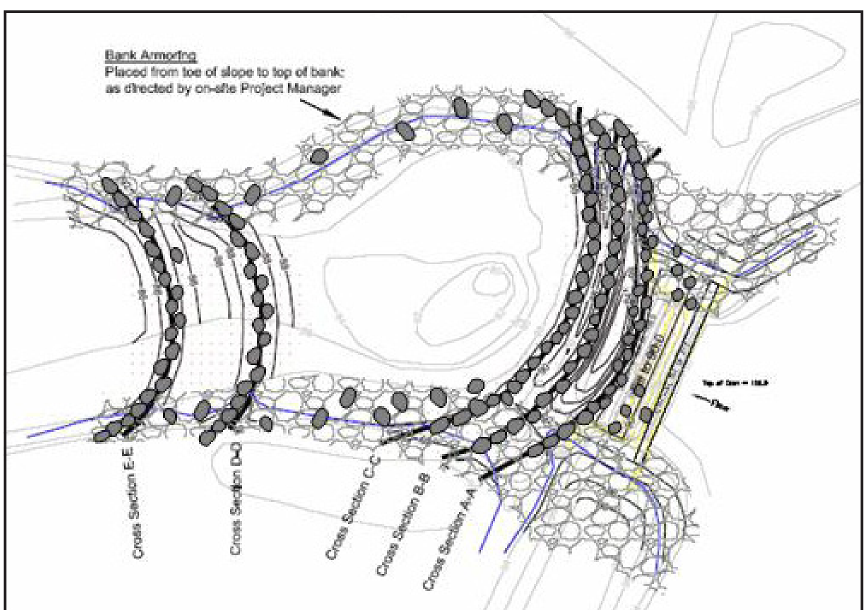
Before	After

Side view of dam during high flow

Aerial view of completed rapids

Removing dam

Constructed rapids



Design planview (Wilkin County)

#23

SHOREHAM DAM

Pelican River

Nelson River Basin

Dam Facts

Mean flow: Approximately 20 cfs

Drainage area: 90.5 mi^2

Dam height: 1 foot

Crest width: 40 feet

Crest elevation: ~ 1,329 MSL

Original dam function: lake level control

Drowning deaths: unknown

Location: Shoreham, MN
46° 45' 21.131° N
95° 54' 0.534° W

River network:

- ■ Pelican River: 59.7 miles upstream of confluence with...
- ➥ Otter Tail River: 47.1 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,298.87 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5%

Project designers:
Dave Friedl, MN DNR

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: 322 tons fieldstone

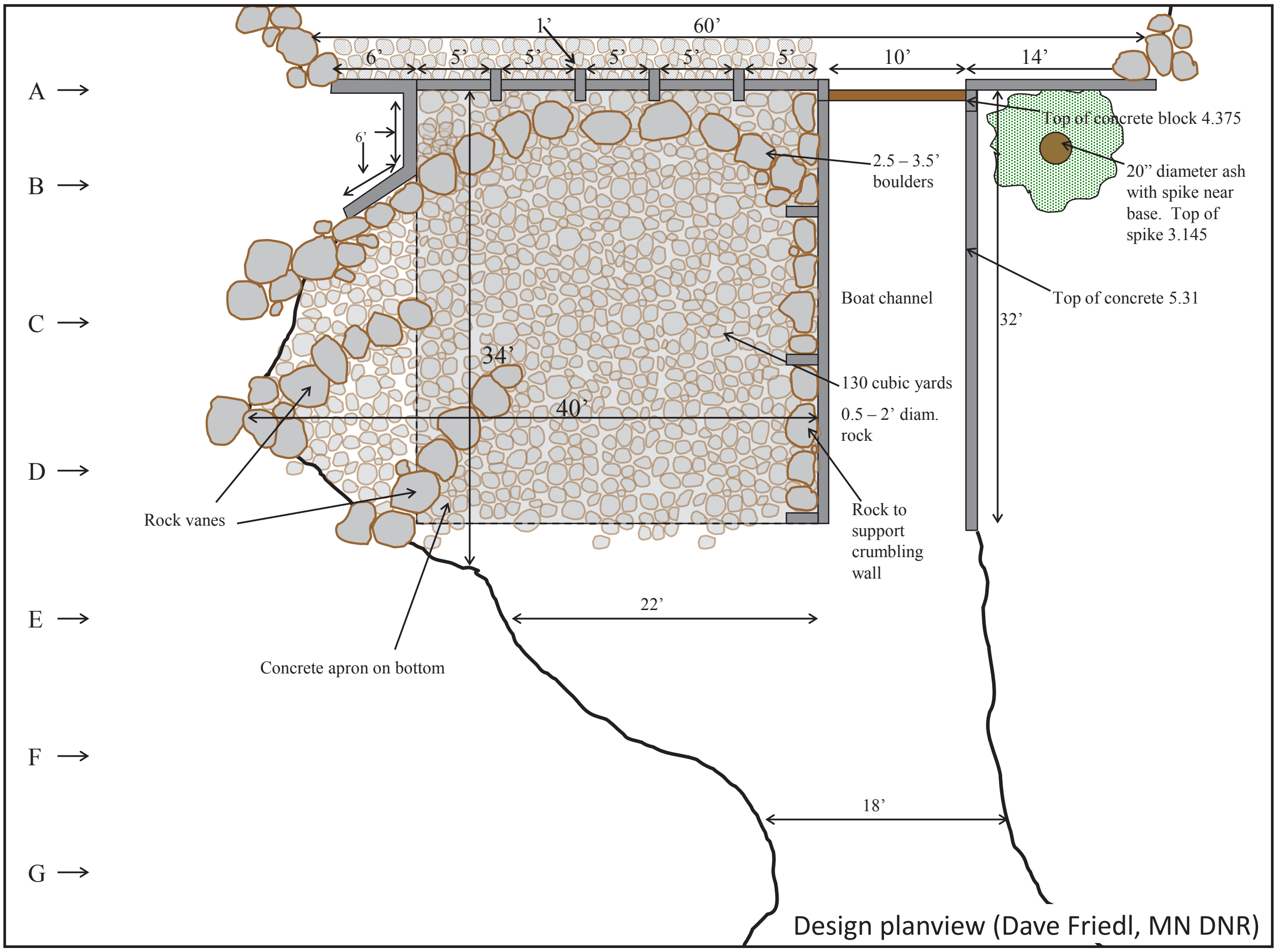
Year completed: 2004

Cost: $12,358.39

After

Side view of boulder weir

Upstream view of completed ramp



Design planview (Dave Friedl, MN DNR)

#24

DUNTON LOCKS

Pelican River

Nelson River Basin

Dam Facts

Mean flow: Approximately 19 cfs

Drainage area: 84.5 mi^2

Dam height: 5 feet

Crest width: 40 feet

Crest elevation: 1,334 MSL

Year built: 1889

Original dam function: lake level control and boat lockage

Drowning deaths: unknown

Location:
46° 46' 49.92° N
95° 38' 15.59° W

River network:
- ■ Pelican River: 61.7 miles upstream of confluence with...
- ➥ Otter Tail River: 47.1 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,300.87 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:
- ☆ provide fish passage and habitat

Design concept: Rock Arch Rapids

Slope: 6% (only 80 feet of land separates Muskrat Lake and Lake Sallie limiting use of a more gradual slope)

Project designers:
Matt Zimmerman and John Filardo (Project Engineers), MN DNR
Dave Friedl and Luther Aadland, MN DNR

Builders/Contractor: Gary Korby Construction

Materials: 22 yards aggregate base
310 yards class III riprap
50 2-3' boulders

Year completed: 2001

Connectivity

Assessment:
Walleye, white sucker, bluegill, muskellunge, northern pike, spottail shiners, yellow perch, log perch, and lake sturgeon have been observed passing the rapids. White sucker have been observed spawning in the rapids. The steep slope of these rapids is marginal and the project could be improved with an additional boulder weir.

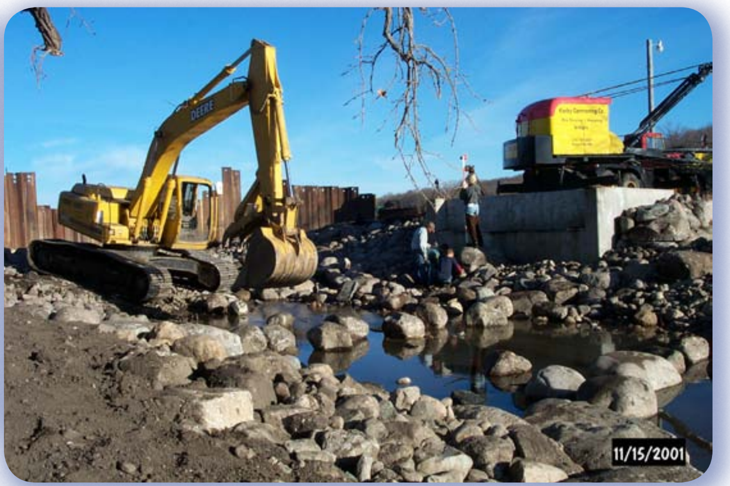
Before

Sideview of Dunton Locks

Upstream view of right spillway

Upstream view of left spillway

During



Construction of weirs

After

Completed rapids

Closer view of rapids showing boulder weir

#25a OTTER TAIL POWER STEAM PLANT DAM

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow:
Approximately 280 cfs during natural flows, up to 250 cfs are diverted for hydropower
Seasonal protected flows are:
30 cfs from September through March,
110 cfs in April and May, and
60 cfs from June through Labor Day
for the 12 river miles upstream of this point.

Drainage area: 1,281 mi^2

Dam height: 7 feet

Crest width: 50 feet

Crest elevation: 1,189 MSL, lowered to 1,187 MSL

Year built: 1972

Location: Fergus Falls, MN
46° 45' 21.131° N
96° 02' 38.81° W

River network:
- ■ Otter Tail River: 53.7 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,245.8 miles upstream of Hudson Bay.

Original dam function: water supply

Drowning deaths: none known

Restoration Design

Project type: Partial removal and rock ramp

Project goals:
- ☆ provide fish passage and habitat
- ☆ river restoration
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide whitewater boating opportunity

Slope: 10% (designed to be 6%)

Project description:
Partial removal and conversion to a rapids. Due to the lack of adequate equipment to break the hardened concrete, the dam was not lowered to design elevation causing a steeper slope.

Project designers:
Luther Aadland, MN DNR

Builders/Contractor: Delzer Construction

Materials: 174 tons of fieldstone

Year completed: 1994

Cost: $2,580

Connectivity

Upstream barriers:
Diversion Dam is 12 river miles upstream

Downstream barriers:
Central Dam is 1.9 river miles downstream

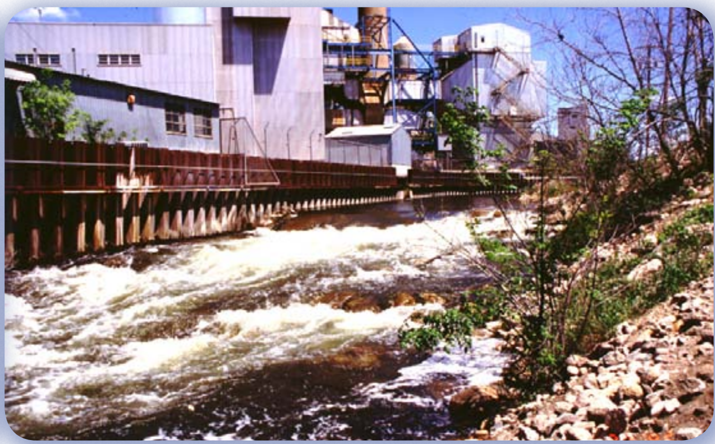
Assessment:
While fish passage was observed, the steep slope likely limited its effectiveness. Kayakers used the rapids but canoeists were prone to taking in water. The fishway was improved in 2005 (next brief).

* *This project is discussed in detail in Chapter 2.*

Before

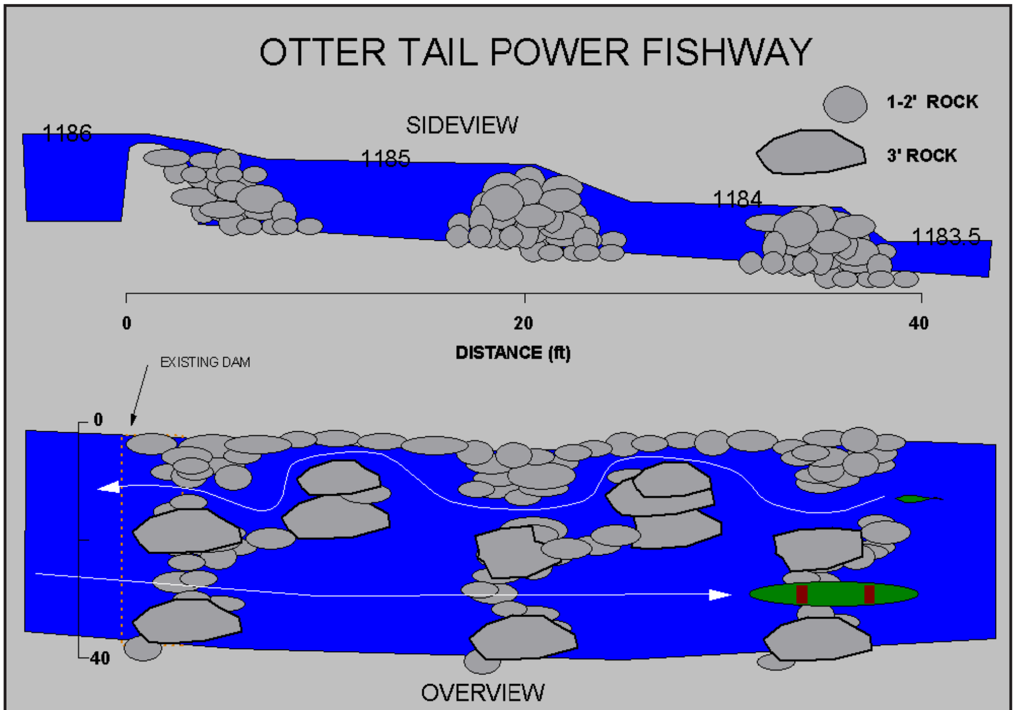
Upstream view of dam

After



Upstream view of completed ramp during high flow

Upstream view of completed ramp and fishway during low flow



Design profile and planview (Luther Aadland, MN DNR)

#25b OTTER TAIL POWER STEAM PLANT DAM

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow:
Approximately 280 cfs during natural flows, up to 250 cfs are diverted for hydropower
Seasonal protected flows are:
30 cfs from September through March,
110 cfs in April and May, and
60 cfs from June through Labor Day
for the 12 river miles upstream of this point.

Drainage area: 1,281 mi^2

Dam height: 7 feet

Crest width: 50 feet

Crest elevation: 1,189 MSL, lowered to 1,187 MSL

Year built: 1972

Location: Fergus Falls, MN
46° 45' 21.131° N
96° 02' 38.81° W

River network:
- ■ Otter Tail River: 53.7 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,245.8 miles upstream of Hudson Bay.

Original dam function: water supply

Drowning deaths: none known

Restoration Design

Project type: Partial removal and rock ramp - modification

Project goals:
- ☆ provide fish passage and habitat
- ☆ river restoration
- ☆ provide whitewater boating opportunity

Slope: 1.2%

Project designers:
Luther Aadland, MN DNR

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: 1,260 tons fieldstone
100 three-foot plus boulders

Year completed: 2005 (initial project was 1994)

Cost: approximately $30,000

Project description:
Dam was lowered and converted to a rapids in 1994 but was not lowered to design elevation causing a steeper slope. In 2005, two riffles were built at 200 and 330 feet downstream of the dam crest to raise tail-water and reduce head-loss through the rapids at the dam. Two boulder weirs were also added at 20 and 40 feet downstream of the dam crest to equalize head-loss through each weir.

Connectivity

Upstream barriers:
Diversion Dam is 12 river miles upstream

Downstream barriers:
Central Dam is 1.9 river miles downstream

Assessment:
The lower slope appeared to improve passage considerably and juvenile smallmouth bass were observed swimming through the rapids.

* This project is discussed in detail in Chapter 2.

Before

Upstream view of ramp before modications were made

After

Upstream view of completed lower riffle

Kayakers in the rapids

Design planview (Luther Aadland, MN DNR)

#26

DIVERSION DAM

Otter Tail River

Nelson River Basin

Dam Facts

Mean flow:
Approximately 280 cfs during natural flows, up to 250 cfs are diverted for hydropower
Seasonal protected flows are
30 cfs from September through March,
110 cfs in April and May, and
60 cfs from June through Labor Day
for the 12 river miles upstream of this point.

Drainage area: 1,241 mi^2

Dam height: 8 feet

Crest elevation: 1,252 MSL

Year built: 1913

Original dam function: water diversion for hydropower

Location: Fergus Falls, MN
46° 19' 01.46° N
96° 01' 27.03° W

River network:
- ■ Otter Tail River: 64.7 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,256.8 miles upstream of Hudson Bay.

Drowning deaths: none known

Restoration Design

Project type: Bypass nature-like step-pool channel

Project goals:
- ☆ provide fish passage and habitat
- ☆ river restoration

Slope: 4%

Project designers:
Luther Aadland, MN DNR
Geoff Griffin, GGG Inc.

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: 714 yards clay
66 yards top soil
710 tons fieldstone

Year completed: 2002

Cost: $42,000

Connectivity

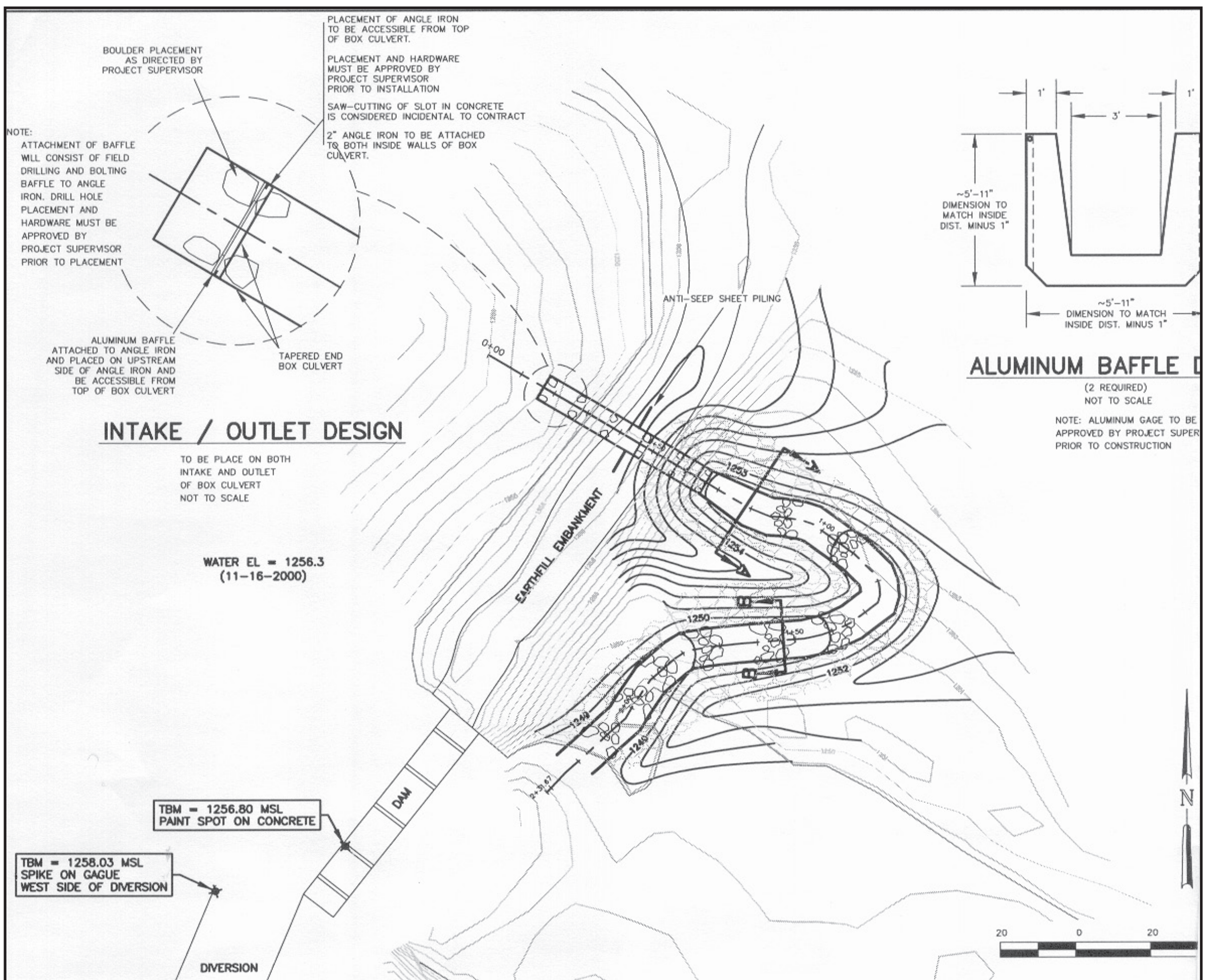
Assessment:
A trap-net set in the reservoir end of the fishway documented passage of 30 fish species including: smallmouth bass, walleye, rainbow darter, Iowa darter, blackside darter, northern pike, northern hog sucker, white sucker, shorthead redhorse, silver redhorse, golden redhorse, greater redhorse, black bullhead, yellow bullhead, bowfin, hornyhead chub, common shiner, sand shiner, bluntnose minnow, fathead minnow, spottail shiner, spotfin shiner, creek chub, central stoneroller, common carp, longnose dace, bluegill, pumpkinseed sunfish, rock bass, and yellow perch. A mudpuppy and snapping turtle were also observed passing the fishway.

Before

Side view of dam

After

View of bottom portion of completed fishway



Design planview (GGG Inc.)

#27 U.S. HIGHWAY 10 BOX CULVERT

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow: Approximately 74 cfs

Drainage area: 337 mi^2

Invert elevation: 1,351.3 MSL

Location: Fergus Falls, MN
46° 43' 14.57° N
95° 41' 55.19° W

River network:

- ■ Otter Tail River: 139.6 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,331.7 miles upstream of Hudson Bay.

Restoration Design

Project type: Culvert modification

Project goals:

- ☆ provide fish passage

Project description:
A 12' x 12' x 260' box culvert under U.S. highway 10 created a velocity barrier for migrating fish. The bankfull width of the channel is 50 to 60 feet. A boulder weir at downstream end of the culvert and a fieldstone riffle were constructed to increase flow depth and decrease velocities.

Project designers:
Dave Friedl and Luther Aadland, MN DNR

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: 713 tons fieldstone including 125 3-6' boulders

Year completed: 2007

Cost: $29,508.68

Connectivity

Assessment:
Walleye and white sucker were observed passing the culvert. Passage is still limited during larger floods due to narrow dimensions of the culvert.

Before

After


Box culvert


Boulder weir at downstream end of culvert


Constructed riffle

#28

LYON'S PARK DAM

Otter Tail River

Nelson River Basin

Dam Facts

Mean flow: Approximately 74 cfs

Drainage area: 336 mi^2

Dam height: 5 feet

Crest width: 80 feet

Crest elevation: ≈ 1,360 MSL

Original dam function: water level

Drowning deaths: none known

Location: near Frazee, MN
46° 43' 16.88° N
95° 42' 29.31° W

River network:
- ■ Otter Tail River: 139.9 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,332 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:
- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide spawning habitat for lake sturgeon and other species
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project designers:
Dave Friedl and Luther Aadland, MN DNR

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: 1,260 tons fieldstone

Year completed: 2003

Cost: $38,005

Connectivity

Assessment:
Walleye and white sucker have been observed passing and spawning in the rapids.

Walleye passing weir

Before


Upstream view of dam during low flow

After


Upstream view of completed ramp


Closer view of rapids showing boulder weirs

#29 FRAZEE MILLDAM

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow: Approximately 65 cfs

Drainage area: 296.6 mi^2

Dam height: ~ 9 feet

Crest width: 20 feet

Crest elevation: 1,368.5 MSL

Year built: 1881

Original dam function: milldam

Drowning deaths: none known

Location: Frazee, MN
46° 43' 30.79° N
95° 41' 50.30° W

River network:

- ■ Otter Tail River: 141.1 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,333.2 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam removal and river restoration

Project goals:

- ☆ river restoration
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide fish passage and habitat

Design concept: Natural Channel Design

Project description:
The reservoir had accumulated up to 7 feet of sediment (predominantly silt and peat) resulting in an incising channel after removal of the dam. Channel restoration included installation of 9 rock riffles for grade control, root wads, boulder vanes, and willow stakes for bank protection, and excavation of 1,200 feet of channel to stabilize the sediments and stream. The restored channel's dimension and pattern were based on nearby reference reaches.

Project designers:
Luther Aadland, MN DNR (river restoration)
Marty Rye (Project Engineer), Short Elliot Hendrickson Inc. (dam removal),
Eugene Redka and Shane Rustin (Project Engineers), MN DNR (restoration)

Builders/Contractor: Gothman Excavating Inc. (dam removal), Chuck Minge Backhoe Services Inc. (river restoration)

Materials: 2,000 yards fieldstone (riffles)
50 root wads

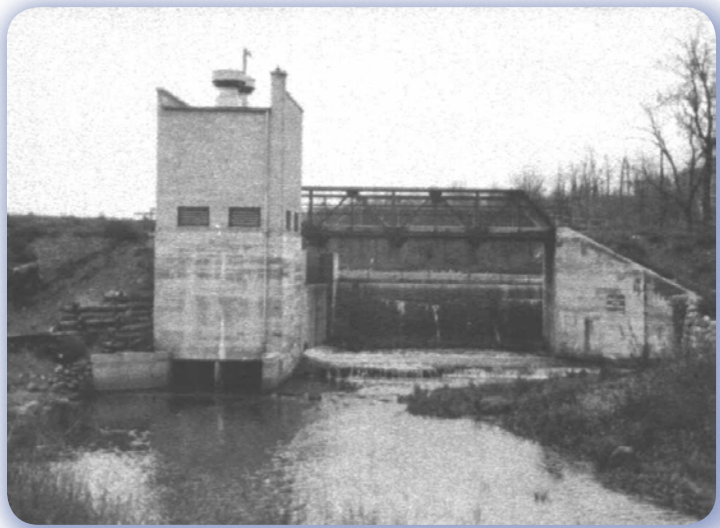
Year completed: dam removal in 1999
restoration in 2001

Cost: $107,725.50 Removal
$59,952.00 Engineering for removal
$395.84 Miscellaneous costs

Connectivity

Assessment:
The restored channel has been stable since completion. Gravel bedload moved into the reach and covered much of the streambed that was previously silt.

Before



Frazee Dam

Frazee Reservoir in 1991

During

Driving root wad into bank

After

Otter Tail River after dam removal

Otter Tail River after restoration

Otter Tail River after restoration showing riffle

#30

FRAZEE BOX CULVERT

Otter Tail River

Nelson River Basin

Dam Facts

Location: Frazee, MN
46° 43’ 49.12° N
95° 41’ 40.85° W

Mean flow: Approximately 65 cfs

Drainage area: 296.5 mi²

Head loss: 2.5 feet

Invert elevation: 1,364.5 MSL

River network:

- ■ Otter Tail River: 141.6 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,333.7 miles upstream of Hudson Bay.

Restoration Design

Project type: Culvert passage

Project goals:

- ☆ provide fish passage and habitat
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 5% (3% near banks due to weirs)

Project description:
The culvert became perched when the dam discussed above was removed and the channel headcut through the accumulated sediment.

Project designers:
Marty Rye (Project Engineer), Short Elliot Hendrickson Inc.
Luther Aadland, MN DNR

Builders/Contractor: Gothman Excavating Inc.

Materials: 350 tons fieldstone

Year completed: 1999

Cost: part of removal cost listed in previous brief

Connectivity

Assessment:
White suckers were observed passing the rapids immediately following construction. Head-loss through the rapids was reduced when the river downstream was restored and grade control riffles were constructed.

Northern pike concentrated below the impassable culverts

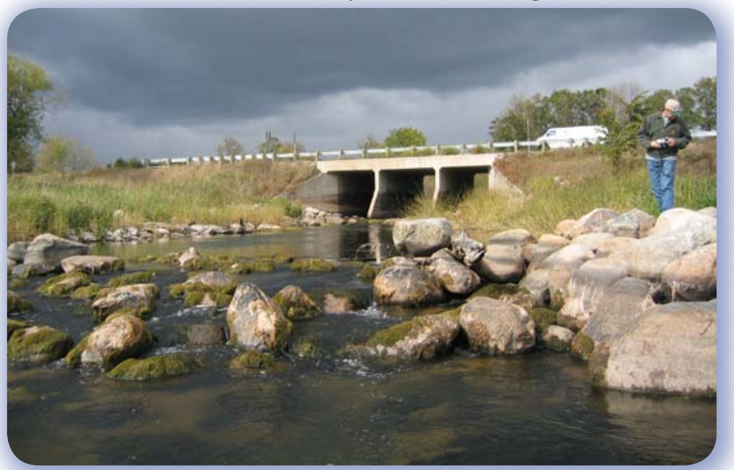
Before

Upstream view of perched culverts

After

Upstream view of the modified culverts

Downstream view of the rapids from road grade



Upstream view of a riffle downstream of the culverts following river restoration in the former reservoir

#31

HEIGHT OF LAND LAKE DAM

Otter Tail River

Nelson River Basin

Dam Facts

Mean flow: Approximately 65 cfs

Dam height: 2 feet

Crest width: 30 feet

Crest elevation: ≈ 1,453 MSL

Year built: 1938

Original dam function: lake level control

Drowning deaths: none known

Location:
46° 52' 50.48° N
95° 38' 15.79° W

River network:

- ■ Otter Tail River: 159.6 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,351.7 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Project description:
Dam was a partial barrier due to supercritical flows over concrete crest. Project involved the use of a boulder weir to create sub-critical velocities.

Project designers:
Dave Friedl and Luther Aadland, MN DNR

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: 75.6 tons fieldstone including 20 2.5 to 3' boulders

Year completed: 2003

Cost: $3,800

Connectivity

Upstream barriers:
Round Lake Dam is 11 river miles upstream

Downstream barriers:
Hubbel Pond WMA Dam is 3.2 river miles downstream

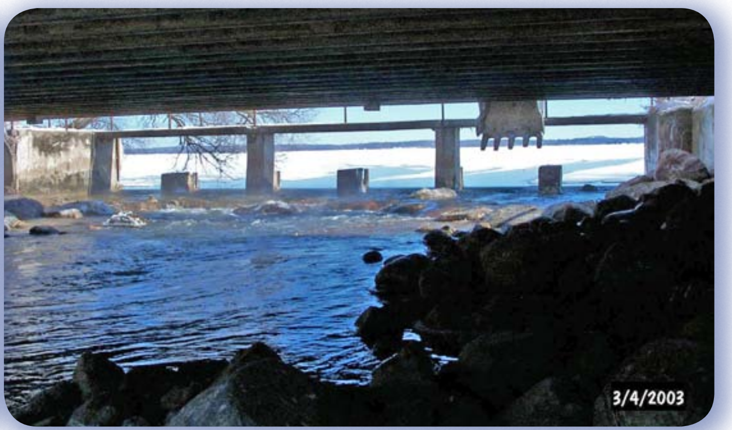
Before

Dam viewed from the road grade

Dam viewed from under road grade

After

Constructed riffle viewed from embankment



Riffle viewed from under road grade

During

Riffle construction

#32 MANY POINT LAKE DAM

Otter Tail River — Nelson River Basin

Dam Facts

Mean flow: Approximately 14 cfs

Drainage area: 64.3 mi^2

Dam height: 2 feet

Crest width: 30 feet

Crest elevation: 1,496.3 MSL

Year built: 1937

Original dam function: lake level control

Drowning deaths: unknown

Location: White Earth Indian Reservation
47° 3' 18.52° N
95° 32' 35.91° W

River network:

- ■ Otter Tail River: 185.21 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,377.3 miles upstream of Hudson Bay.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide lake sturgeon spawning habitat
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 4%

Project description:
Dam was a barrier to fish migration. The White Earth Band of Ojibwa is reintroducing lake sturgeon in several of the lakes of the upper chain.

Project designers:
Luther Aadland, MN DNR
Dave Friedl and Neil Haugerud, MN DNR (oversaw construction)

Builders/Contractor: Racer Construction, Inc.

Materials: 100 yards clay
150 yards 6-15" fieldstone
150 yards 15-24" fieldstone
50 2-3' boulders
20 yards 0.25-2" gravel
20 yards topsoil
12' x 100' coconut blanket

Year completed: 2008

Cost: $58,750

Connectivity

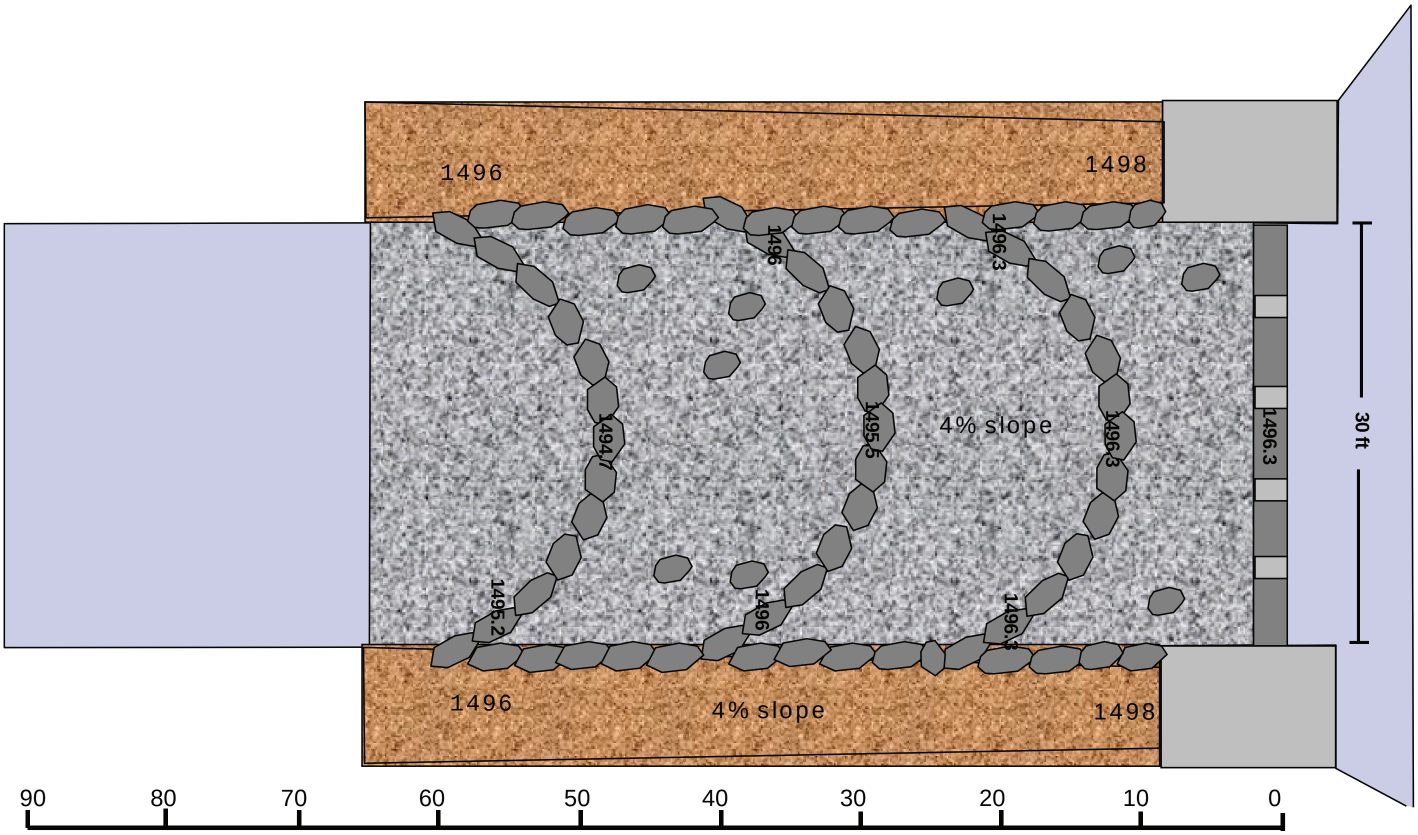
Downstream barriers:
An outlet dam 2 miles downstream at Round Lake will be modified in 2010.

Before

Upstream view of dam

After

Upstream view of completed rapids



Design planview (Luther Aadland, MN DNR)

#33 SOLID BOTTOM CREEK CULVERT

Solid Bottom Creek — *Nelson River Basin*

Dam Facts

Location: Becker County Road 113 crossing
47° 9' 8.838° N
95° 31' 50.51° W

Mean flow: Approximately 3.5 cfs

Drainage area: 15.9 mi^2

Head loss: 1.03 feet

Culvert elevation: 1,540 MSL

River network:

- ■ Solid Bottom Creek: 0.6 miles upstream of confluence with..
- ➥ Otter Tail River headwaters: 194.4 miles upstream of confluence with...
- ➥ Bois de Sioux at Red River of the North headwaters: 548.7 miles upstream of Lake Winnipeg,
- ≈ A total of 1,387.1 miles upstream of Hudson Bay.

Restoration Design

Project type: Culvert passage

Project goals:

☆ provide fish passage

Project description:

A riffle was built to raise tailwater below a perched culvert. The riffle raised the stream bed 2.1 feet and the tailwater 1.8 feet to reduce velocities and provide fish passage through the culvert.

Project designers:
Dave Friedl, MN DNR

Builders/Contractor: MN DNR Fisheries Construction Crew

Materials: 90 yards fieldstone

Year completed: 2005

Cost: $3,500

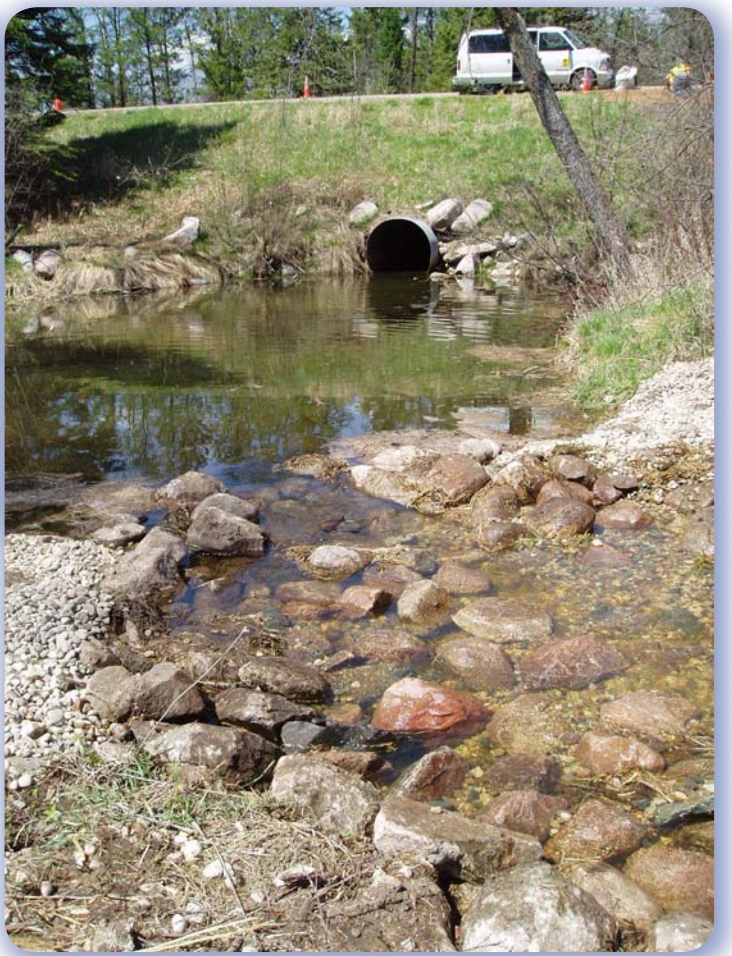
Connectivity

River miles connected:
Reconnected 1.25 miles of coldwater stream.

Before

Upstream view of perched culvert

After



View of culvert showing tailwater pooling following riffle construction

#34 HIGHWAY 23 BOX CULVERT

South Fork Nemadji River — *Great Lakes Basin*

Dam Facts

Mean flow: Approximately 18 cfs

Drainage area: 19.4 mi^2

Head loss: 4 feet

Width: 20 feet (two 10' x 10' box culverts)

Invert elevation: 819 MSL

Location: near Holyoke, MN
46° 29' 37.18° N
92° 24' 35.38° W

River network:

- ■ South Fork Nemadji River: 12.6 miles upstream of confluence with..
- ➥ North Fork Nemadji to form the Nemadji River: 20 miles upstream of Lake Superior,
- ≈ A total of 32.6 miles upstream of Lake Superior.

Restoration Design

Project type: Culvert passage

Project goals:

- ☆ provide fish passage (especially for steelhead)
- ☆ provide spawning habitat
- ☆ erosion control

Design concept: Rock Arch Rapids

Slope: 5%

Width: 40 feet

Project description:
Six boulder weirs were installed to create a step pool channel and provide fish passage. Boulder weirs were used to address downstream bank erosion.

Project designers:
Jon Bergstrand (Project Engineer), MN DOT
Luther Aadland, MN DNR

Materials: 1,770 tons quarried granite (includes riprap placed on highway embankment and two J-hook vanes downstream of rapids.

Year completed: 2003

Cost: $55,000

Before

Upstream view of perched culverts

After

View of completed rapids

#35 FOND DU LAC DAM

St. Louis River — Great Lakes Basin

Dam Facts

Mean flow: 2,491 cfs

Drainage area: 3,594 mi^2

Dam height: 85 feet

Crest width: 600 feet

Year built: 1924

Original dam function: hydropower - owned by Allete Inc. (Minnesota Power) generates 10 MW power.

Drowning deaths: unknown

Location:
46° 39' 57.08° N
92° 17' 49.70° W

River network:
- St. Louis River: 21.3 miles upstream of Lake Superior.

Restoration Design

Project type: Tailwater river restoration

Project goals:
- ☆ restore flows to the width of the river channel
- ☆ provide spawning habitat for lake sturgeon, walleye, and other species

Reach slope: 1%

Cost: $136,006

Project designers:
Kevin Zytkovicz and Luther Aadland, MN DNR

Builders/Contractor: RJS Construction and the MN DNR Fisheries Construction Crew

Materials: 203 tons 4-10" boulders
176 tons 12-36" boulders
456 36-60" boulders

Year completed: 2009

Project description:
The site had been altered by construction of a berm that confined flows to the channel center causing high velocity and bed scour. The berm was removed and three arch-shaped rapids were built to redistribute flows and provide spawning habitat. The arching rapids used a series of honeycomb shaped boulder cells that buttress the weirs and provide semi-protected spawning areas for lake sturgeon. The rapids provide glides, cascades, and eddies that are consistent with natural spawning areas identified in Minnesota rivers that have wild sturgeon populations. Sturgeon were extirpated from the Western Lake Superior Basin by the early 1900s by over-harvest, and fragmentation due to Fond du Lac and other dams that blocked access to natural rapids upstream. Lake sturgeon fry and fingerlings have been stocked since 1983 by the Minnesota and Wisconsin Departments of Natural Resources.

Connectivity

Downstream barriers:
none

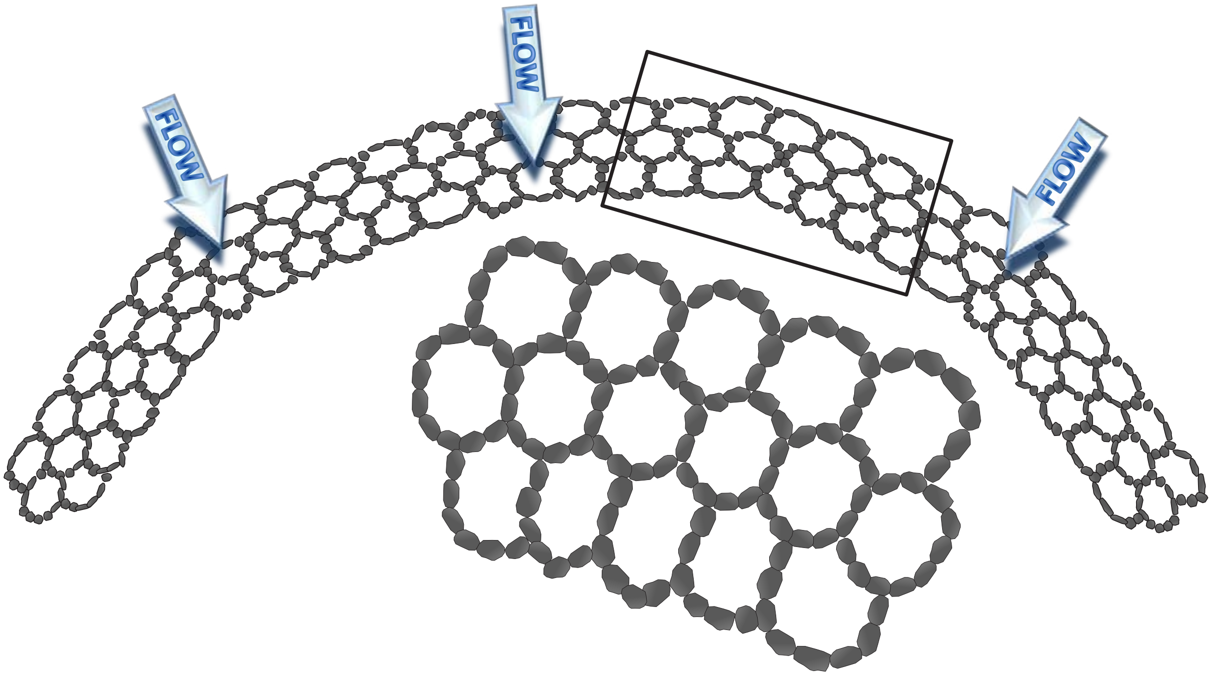
Assessment:
Lake sturgeon were observed in the rapids immediately after its construction. Surveys will be conducted in spring 2010.


View from dam crest at 200 cfs before construction


View of completed rapids from dam crest at 200 cfs


View of completed boulder cells at 1,600 cfs


View of completed rapids from dam crest at 1,600 cfs



Honeycomb shaped boulder cells planview (Luther Aadland, MN DNR)

#36

SANDSTONE DAM

Kettle River

Mississippi River Basin

Dam Facts

Mean flow: 693 cfs

Drainage area: 868 mi^2

Dam height: 16.1 feet

Crest elevation: 956.6 MSL

Year built: 1908

Original dam function: hydropower - retired in 1963

Drowning deaths: 1 known

Location:
46° 6' 27.97° N
92° 51' 47.47° W

River network:

■ Kettle River 22.4 miles upstream of confluence with...

➥ St. Croix River: 106 miles upstream of confluence with...

➥ Mississippi River: 811.5 miles upstream of confluence with the Ohio River

≈ A total of 1898.7 miles upstream of the Gulf of Mexico.

Restoration Design

Project type: Dam removal

Project goals:

- ☆ river restoration
- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ improve safety by eliminating dam failure potential

Project description: The dam was removed, no river restoration was done.

Project designers:
Tim Petersen (Project Engineer) and Joseph Beck, MN DNR (design)
Jerry Fabian (Project Engineer) and Dave Nelson, MN DNR (dam removal)

Builders/Contractor: Mills Concrete Restoration, Inc.

Year completed: 1995

Cost: $208,000

Connectivity

Downstream barriers:
None to confluence with St. Croix River
Taylor's Falls Dam on St. Croix River

Assessment:
Tagged lake sturgeon have moved upstream through the former dam site and submerged falls. Significant sedimentation occurred in the downstream channel causing reductions in mussel density. A large pool that had filled with sediment following removal is getting progressively deeper. Upstream benefits to mussels due to the restored passage have not been assessed.

** This project is discussed in detail in Chapter 1.*

Before

Upstream view of dam from left bank

After

View of Big Spring Falls which had been inundated by the reservoir for 87 years

#37

DAWSON DAM

West Branch Lac qui Parle River — *Mississippi River Basin*

Dam Facts

Location: Dawson, MN
44° 55' 47.15° N
96° 03' 1.754° W

Mean flow: Approximately 78 cfs

Drainage area: 472 mi^2

Dam height: 8 feet

Crest width: 55 feet

Crest elevation: 1132.9 MSL

Year built: 1913

Original dam function: water supply

River network:

- ■ West Branch Lac qui Parle River 1.5 miles upstream of confluence with...
- ➥ Lac qui Parle River 29.4 miles upstream of confluence with...
- ➥ Minnesota River: 285.8 miles upstream of confluence with...
- ➥ Mississippi River: 844 miles upstream of confluence with the Ohio River
- ≈ A total of 2,119.5 miles upstream of the Gulf of Mexico.

Drowning deaths: none known

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller

Design concept: Rock Arch Rapids

Slope: 4%

Width: 120 feet

Year completed: 2009

Cost: $650,000

Project designers:
Shane Rustin (Project Engineer), Chris Domeier, and Luther Aadland, MN DNR

Builders/Contractor: Park Construction

Materials: 2,920 tons granular filter
6,020 tons fieldstone
550 4'+ boulders
1,820 tons quarry stone (for banks)
1,810 tons 3-6" filler stone
1,010 tons 0.5-3" filler stone

Project description:

The community wanted to retain the pool level and downstream fishing hole. The rapids was built to the same elevation as the dam and entirely of loose rock and aggregate with no sheet piling or artificial leakage barrier. The river is subject to low flows so voids in the rock base were filled with 6" and smaller aggregate to minimize leakage. Discharge measurements taken during construction were 132.2 cfs at the crest of the rapids and 135.0 cfs at a river cross-section 433 feet downstream indicating minimal leakage since measurement error was ±2.7 cfs. It is anticipated that the rapids will be further sealed by organic matter and sediment carried by the river.

Connectivity

Upstream barriers:

None within the 50 river miles to headwaters

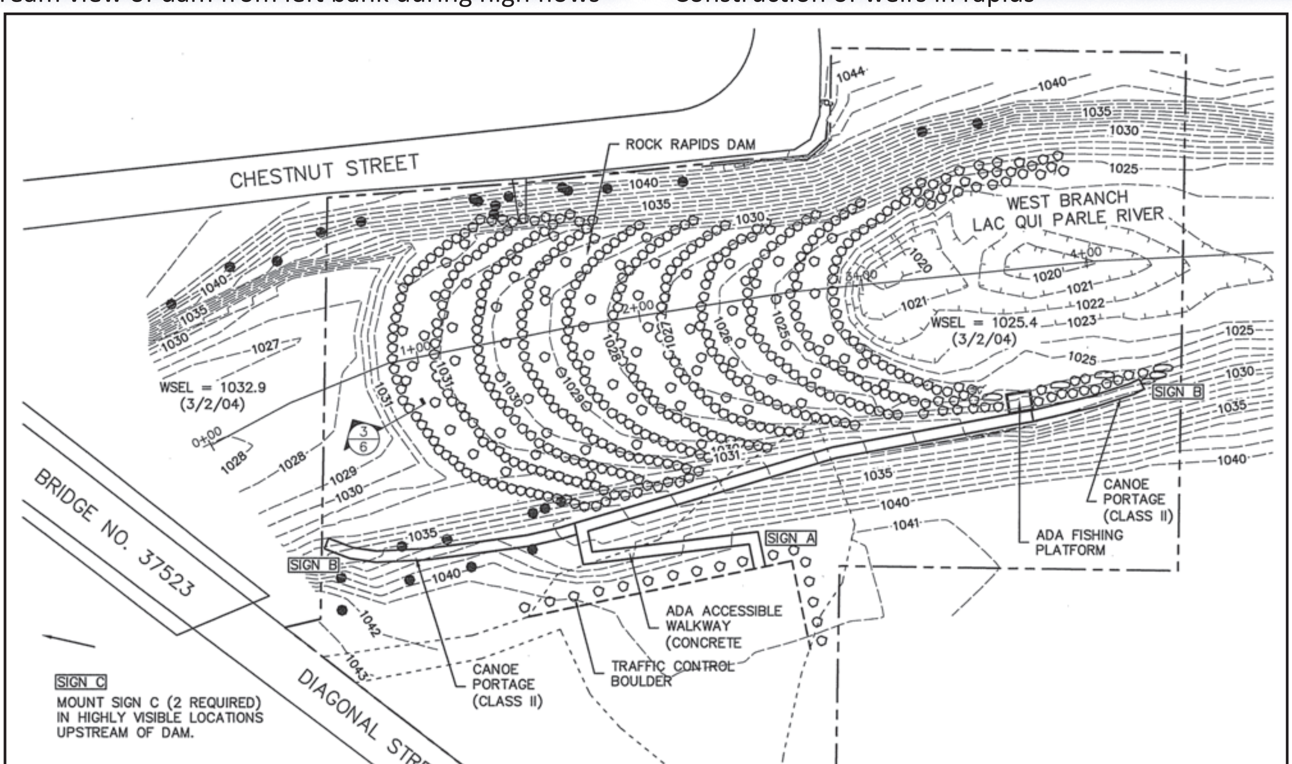
Downstream barriers:

Lac qui Parle Lake dam is 31 miles downstream on the Minnesota River. Further downstream is Granite Falls and Minnesota Falls below which the Minnesota River is free flowing to its confluence with the Mississippi River.

Assessment:

Post-project fisheries surveys will be conducted in 2010. Pre-project surveys indicated that channel catfish and several other species present downstream of the dam were absent upstream of the dam.

Before	**During**
 Upstream view of dam from right bank during low winter flows	 Upstream view of dam showing notch to lower pool during construction
 Upstream view of dam from left bank during high flows	 Construction of weirs in rapids



Design planview (Shane Rustin, MN DNR)

#38

APPLETON MILLDAM

Pomme de Terre River

Mississippi River Basin

Dam Facts

Mean flow: 136 cfs
Record flow: 8,890 cfs in 1997

Drainage area: 905 mi^2

Dam height: 12.8 feet (may have historically been as much as 16 feet with flashboards)

Crest width: 130 feet

Crest elevation: 994 MSL

Year built: 1872

Original dam function: mill

Drowning deaths: unknown

Location: Appleton, MN
45° 12' 14.51° N
96° 1' 9.007° W

River network:

- ■ Pomme de Terre River 9.2 miles upstream of confluence with...
- ↪ Minnesota River: 302 miles upstream of confluence with...
- ↪ Mississippi River: 844 miles upstream of confluence with the Ohio River
- ≈ A total of 2,114 miles upstream of the Gulf of Mexico.

Restoration Design

Project type: Dam removal and river restoration

Project goals:

- ☆ provide fish passage and habitat
- ☆ river restoration
- ☆ improve safety by eliminating hydraulic roller

Project description:
The dam partly failed in 1997 and was removed and replaced with a Rock Arch Rapids. 2,500 feet of channel was excavated to re-meander the river in the old reservoir. Nine rock riffles were installed for grade control in addition to root wads, boulder vanes, and willow stakes for bank protection. Channel dimensions and pattern was based on upstream and downstream reference channels.

Project designers:
Luther Aadland, MN DNR (restoration)
Eugene Redka, and Shane Rustin (Project Engineers for restoration), MN DNR,
Marty Rye (Project Engineer for dam removal), Short Elliot Hendrickson Inc.

Builders/Contractor: D&C Dozing for dam breech; Landwehr Construction for dam removal; and Sheryl's Construction for river restoration

Excavation: 24,410 yards

Year completed: Dam was breached on July 9, 1998, removed and replaced with rapids on March 6, 1999, river restoration was completed in February, 2001

Cost: $117,000 for dam removal,
$250,000 for river restoration

Connectivity

Upstream river miles connected:
45.1 (including subsequent removal of a dam at river mile 15)

Assessment:
The restored channel has become a quality walleye fishery. A number of species including walleye, yellow perch, channel catfish, stonecat, freshwater drum, golden redhorse, silver redhorse, blackside darter, and white bass were sampled in the restored channel that were not collected in reservoir surveys or upstream river reaches prior to dam removal.

** This project is discussed in detail in Chapter 1.*

Before

After


Reservoir in 1997


River after dam removal, 1999


Upstream view of failed dam showing eroded left embankment and breach near right bank


River after restoration, 2003


Dam site after restoration, 2007

#39 BARRETT LAKE DAM

Pomme de Terre River — *Mississippi River Basin*

Dam Facts

Mean flow: Approximately 50 cfs

Drainage area: 332 mi^2

Dam height: 4 feet

Crest width: Original dam: 56 feet
New dam: 110 feet graduated crest

Crest elevation: 1,146 MSL

Year built: 1937 (previous dam; original dam unknown)

Original dam function: mill

Drowning deaths: unknown

Location: Barrett, MN
45° 54' 43.14° N
95° 52' 57.85° W

River network:

- ■ Pomme de Terre River 88.71 miles upstream of confluence with...
- ➥ Minnesota River: 302 miles upstream of confluence with...
- ➥ Mississippi River: 844 miles upstream of confluence with the Ohio River,
- ≈ A total of 2,193.5 miles upstream of the Gulf of Mexico.

Restoration Design

Project type: Dam replacement/modification

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller

Design concept: modified Rock Arch Rapids

Slope: 5%

Project designers:
Pete Sarberg (Project Engineer), Widseth Smith Nolting Inc.
Luther Aadland, MN DNR

Builders/Contractor: Riley Brothers

Materials: 125 yards fieldstone base,
100 3' to 5' boulders

Year completed: 2006

Cost: $9,000 for rapids
($240,264 for dam replacement)

Funding: City of Barrett (population 388) and boulder donations by area farmers

Connectivity

Evaluation:
Northern pike, walleye, bluntnose minnow, smallmouth bass, Iowa darter and common carp were observed passing the rapids. Iowa darters were observed spawning in the boulder weirs. Overall slope and head-loss per weir is excessive and passage may be limited for some species. Passing northern pike and smallmouth bass were observed jumping the weirs.

Before

Dam viewed from under road grade

After

Completed rapids

Pelicans fishing below lower weir during shiner migration

#40 POTATO LAKE DAM

Potato River — Mississippi River Basin

Dam Facts

Mean flow: Approximately 83 cfs

Drainage area: 179 mi^2

Dam height: 4 feet

Crest width: original dam: 55 feet,
new dam: 120 feet graduated crest

Crest elevation: 1,439 MSL

Year built: 1939 (original dam)

Original dam function: lake level control

Drowning deaths: unknown

Location: Potato Lake, MN
46° 58′ 41.59° N
95° 2′ 47.78° W

River network:

- ■ Potato River 3.23 miles upstream of confluence with...
- ➥ Fishhook River: 8.1 miles upstream of confluence with...
- ➥ Shell River: 12.13 miles upstream of confluence with...
- ➥ Crow Wing River: 86 miles upstream of confluence with...
- ➥ Mississippi River: 993 miles upstream of confluence with the Ohio River,
- ≈ A total of 2,061.3 miles upstream of the Gulf of Mexico.

Restoration Design

Project type: Dam replacement/modification

Project goals:

- ☆ provide fish passage and spawning habitat
- ☆ improve safety by eliminating hydraulic roller

Design concept: modified Rock Arch Rapids

Slope: 5%

Project designers:
Pete Sarberg (Project Engineer), Widseth Smith Nolting Inc.
Luther Aadland, MN DNR

Builders/Contractor: Robert R. Schroeder

Materials: 320 yards Class III riprap
89 yards Class I riprap
36 4′ boulders

Year completed: 2004

Cost: $27,380

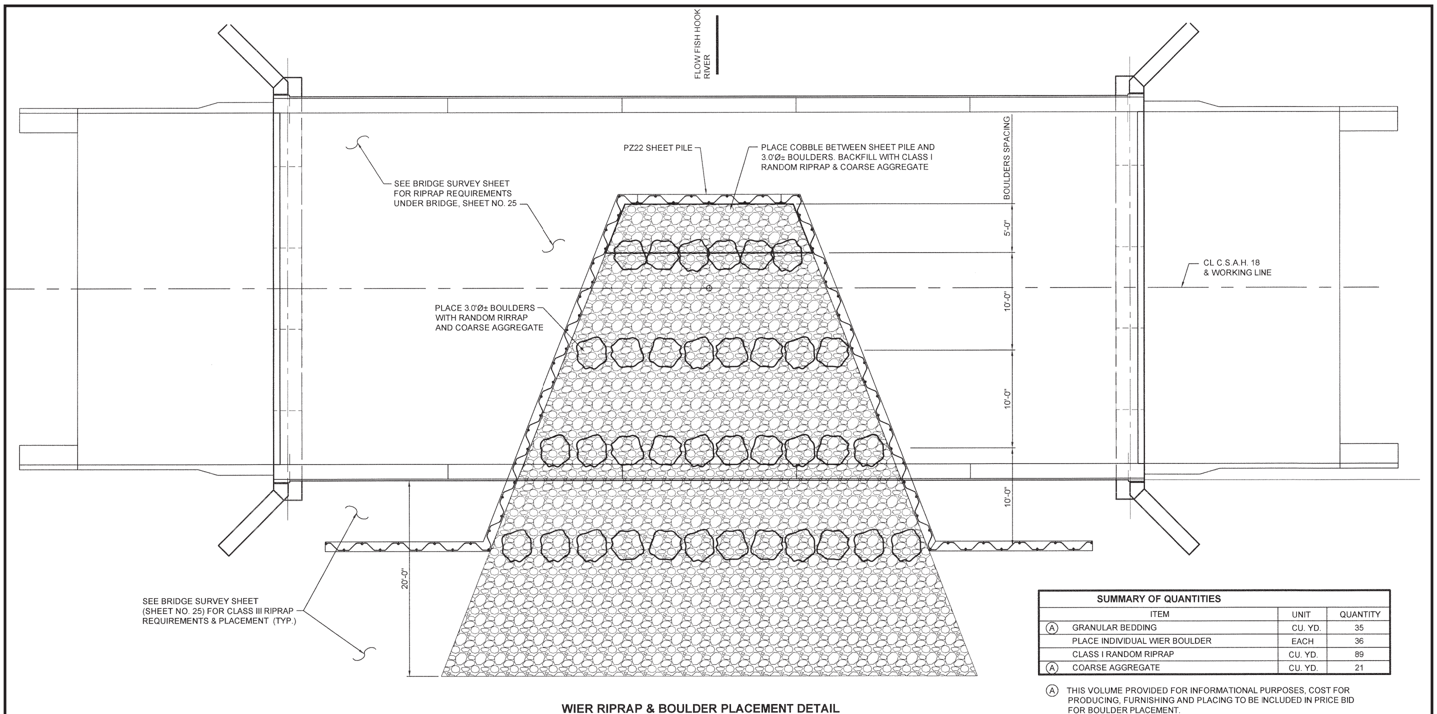
Connectivity

River miles reconnected:
16.23 miles to tributary headwaters including lakes

Before | **After**

View of dam from upstream lake

Completed rapids



Design planview (Widseth Smith Nolting Inc.)

#41

MOREHOUSE DAM

Straight River

Mississippi River Basin

Dam Facts

Mean flow: Approximately 149 cfs

Drainage area: 218 mi^2

Dam height: 5.1 feet (at low flows during construction)

Crest width: 93 feet

Crest elevation: 1,124.9 MSL

Year built: 1930, original structure was built about 1859

Original dam function: grist mill

Drowning deaths: unknown

Location: Owatonna, MN
44° 5' 1.050° N
93° 13' 57.02° W

River network:

- ■ Straight River 27.3 miles upstream of confluence with...
- ➥ Cannon River: 58.2 miles upstream of confluence with...
- ➥ Mississippi River: 795.5 miles upstream of confluence with the Ohio River,
- ≈ A total of 1,839.8 miles upstream of the Gulf of Mexico.

Restoration Design

Project type: Full river width bypass

Project goals:

- ☆ provide fish and turtle passage and habitat

Design concept: Rock Arch Rapids bypass channel. The project also has a wet path adjacent to the rapids for turtle passage.

Slope: 3%

Channel width: 60 feet

Project designers:
Tor Hanson (Project Engineer), Barr Engineering
Luther Aadland, MN DNR

Builders/Contractor: Park Construction

Materials: 2,350 tons rock filter
3,775 tons natural stone base
980 tons riprap
300 boulders

Year completed: 2006

Cost: $1,150,000 (primarily for dam repairs)

Connectivity

Mainstem river miles reconnected:
30.5 to headwaters

Assessment:
The fishway has excessive head-loss per weir (1-foot). This was partially corrected by building boulder pockets downstream of weir gaps to distribute head-loss but the project would've benefitted from two additional weirs.

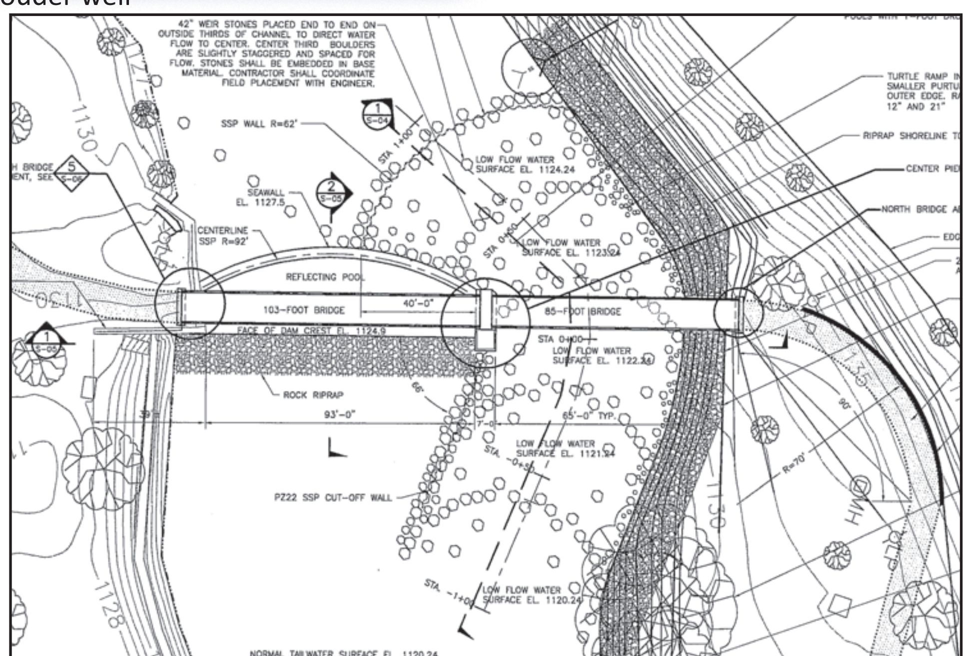
Before	**After**


Upstream view of dam from right bank


Upstream view of fishway and dam at low flow


Construction of bouder weir


Partial weir to reduce headloss



Design planview (Barr Engineering)

#42

HUTCHINSON DAM

South Fork Crow River — *Mississippi River Basin*

Dam Facts

Mean flow: Approximately 141 cfs

Drainage area: 446 mi^2

Dam height: 7.5 feet (two constructed riffles downstream maintain minimum tailwater)

Crest width: 90 feet (old crest)
240 feet (new crest)

Crest elevation: 1,038.8 MSL, gaps between boulders at 1,037.8 MSL

Year built: 1857(original dam)

Original dam function: mill

Drowning deaths: unknown

Location: Hutchinson, MN
44° 53' 43.87° N
94° 22' 12.79° W

River network:

- ■ South Fork Crow River 66.8 miles upstream of confluence with...
- ➥ Crow River mainstem: 25 miles upstream of confluence with...
- ➥ Mississippi River: 879 miles upstream of confluence with the Ohio River,
- ≈ A total of 1,929.6 miles upstream of the Gulf of Mexico.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller
- ☆ provide whitewater boating opportunity

Design concept: Rock Arch Rapids

Slope: 3%

Project description:
A gated dam was replaced with fixed-crest rapids with a sheet-pile core. The first boulder weir had a top elevation a foot above the sheet piling. The crest was widened to compensate for the lack of gates and to maintain 100-year flood elevations.

Project designers:
Jon Ausdemore, and Tom McDonald (Project Engineers), Barr Engineering,
Kent Exner (Project Engineer), City of Hutchinson
Rob Collett and Luther Aadland, MN DNR

Builders/Contractor: Park Construction

Materials: 8,230 tons base fieldstone
2,515 tons filter rock
1,400 tons granular filter
150 tons 1-6" cobble
150 tons 3/8-3/4" chinking gravel
330 4' boulders
6 flat fishing boulders and other materials

Year completed: 2008

Cost: $1,043,198.65

Connectivity

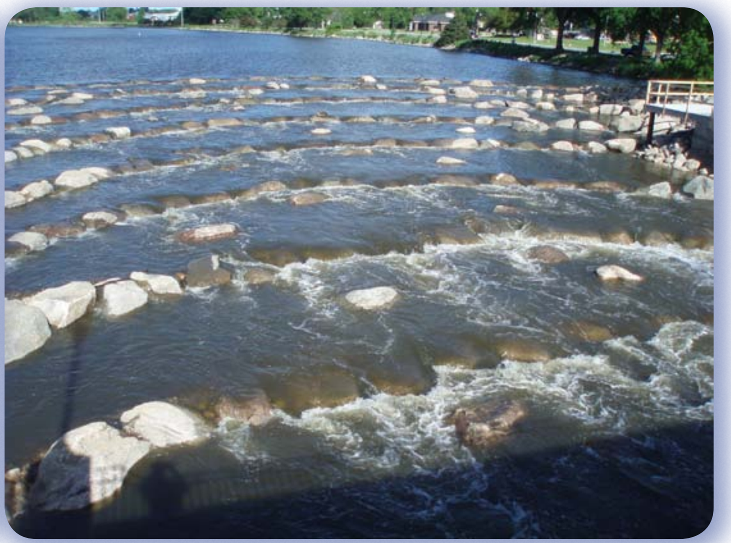
Mainstem river miles reconnected:
124 miles to headwaters (the South Fork Crow is free-flowing to the Mississippi). A dam with about 2-feet of head in Watertown is a partial barrier at river mile 14 on the South Fork Crow River.

Assessment:
The very wide flat crest (about four times natural bankfull width) created fish passage problems, as depth of flow over the crest was shallow. My recommendations of an elliptical or graduated crest were overridden by lake level concerns. This problem was partially compensated with narrow gaps through the weirs that provided greater depth for passage. Walleye, bigmouth buffalo, channel catfish, black bullhead, and common carp were observed passing the rapids.

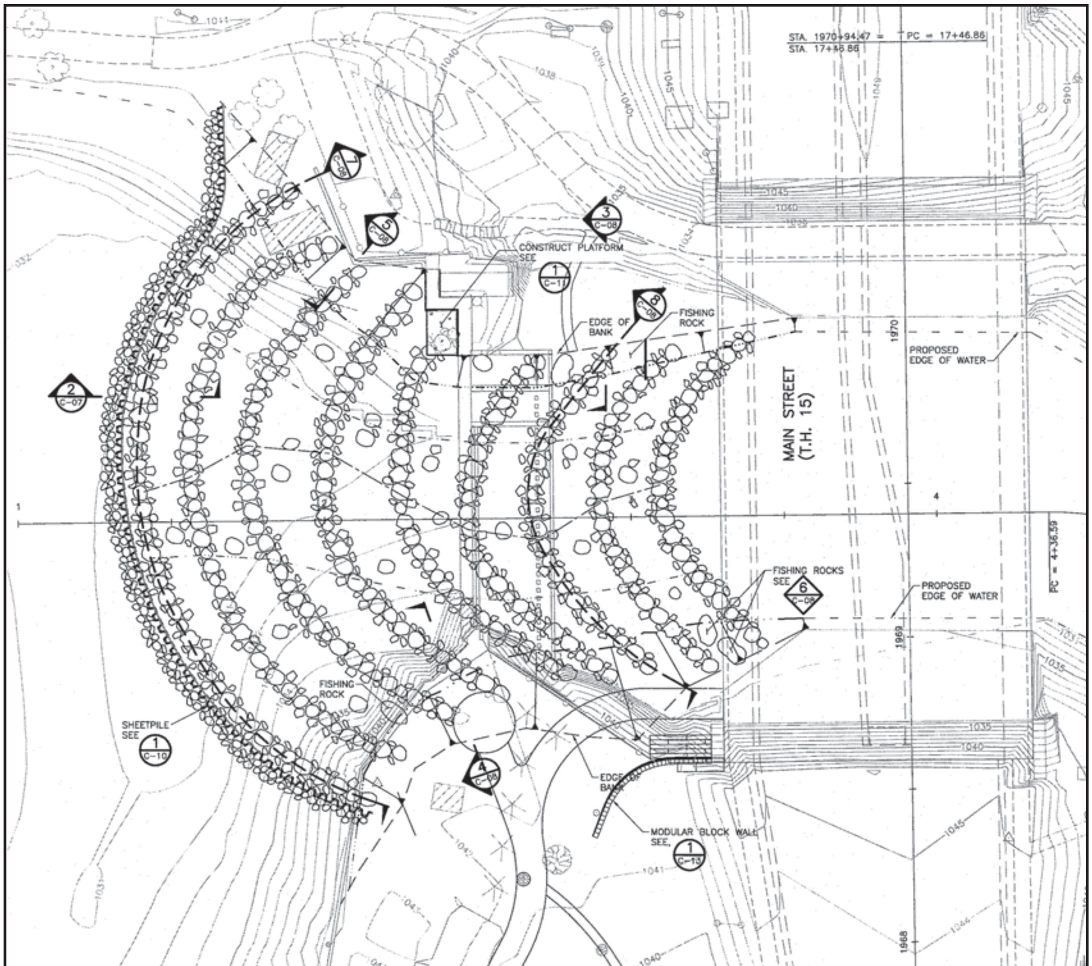
Before

Upstream view of dam from right bank

After



Upstream view of completed ramp



Design planview (Barr Engineering)

#43

ONAMIA DAM

South Fork Crow River

Mississippi River Basin

Dam Facts

Mean flow: Approximately 210 cfs

Drainage area: 444 mi^2

Dam height: 6 feet

Crest width: 48 feet

Crest elevation: 1,245.35 MSL

Year built: 1938

Original dam function: lake level control

Drowning deaths: none known

Location:
46° 4' 9.002° N
93° 40' 48.2° W

River network:

- ■ Onamia River: 137.1miles upstream of confluence with...
- ➥ Mississippi River: 871.4 miles upstream of confluence with the Ohio River,
- ≈ A total of 1,967.3 miles upstream of the Gulf of Mexico.

Restoration Design

Project type: Dam replaced with rock ramp

Project goals:

- ☆ provide fish passage and habitat
- ☆ improve safety by eliminating hydraulic roller

Project designers:
Jon Hendrickson, MN DNR

Materials: 490 yards fieldstone
166 2-4' boulders

Year completed: 2007

Cost: $53,556.46

During	After

Removal of dam

Completed rapids viewed from right bank

Construction of rapids