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.

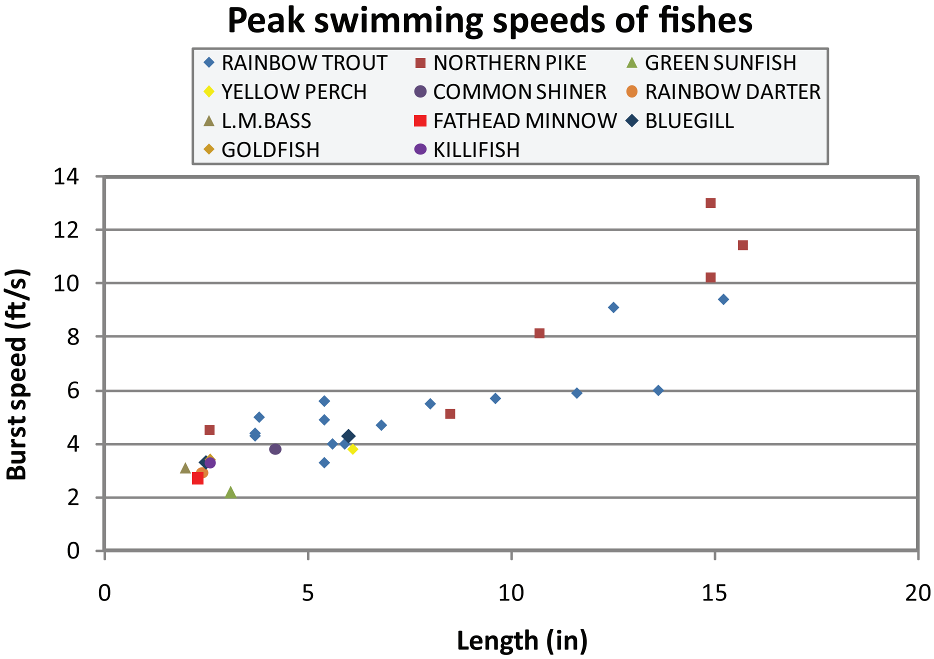


Figure 50. Burst swimming speeds of rainbow trout and some warm and cool water fishes (data from Domenici and Blake 1997).

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 proportionally 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.

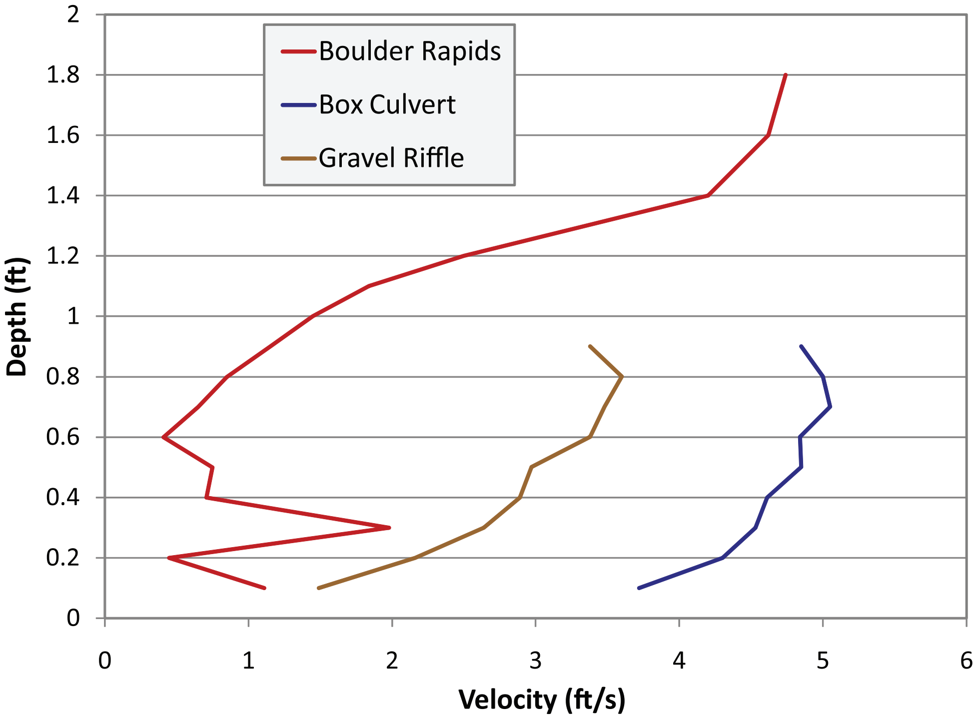


Figure 52. Velocity profiles over three different substrate types in the Otter Tail River. The rock rapids profile was from a constructed fishway.

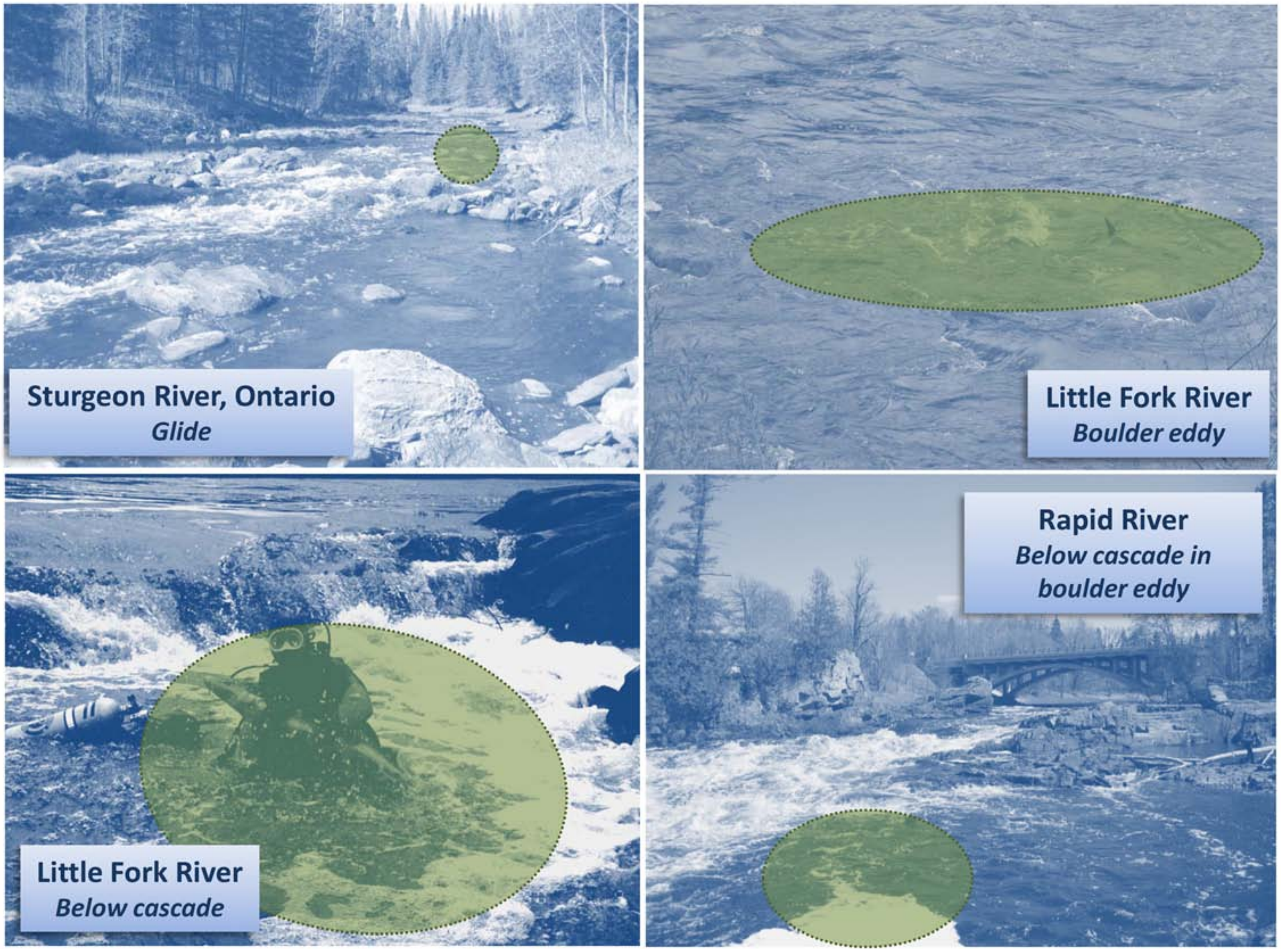


Figure 53. Lake sturgeon spawning areas in tributaries of the Rainy River.

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.*

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).

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

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/m^2 = 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

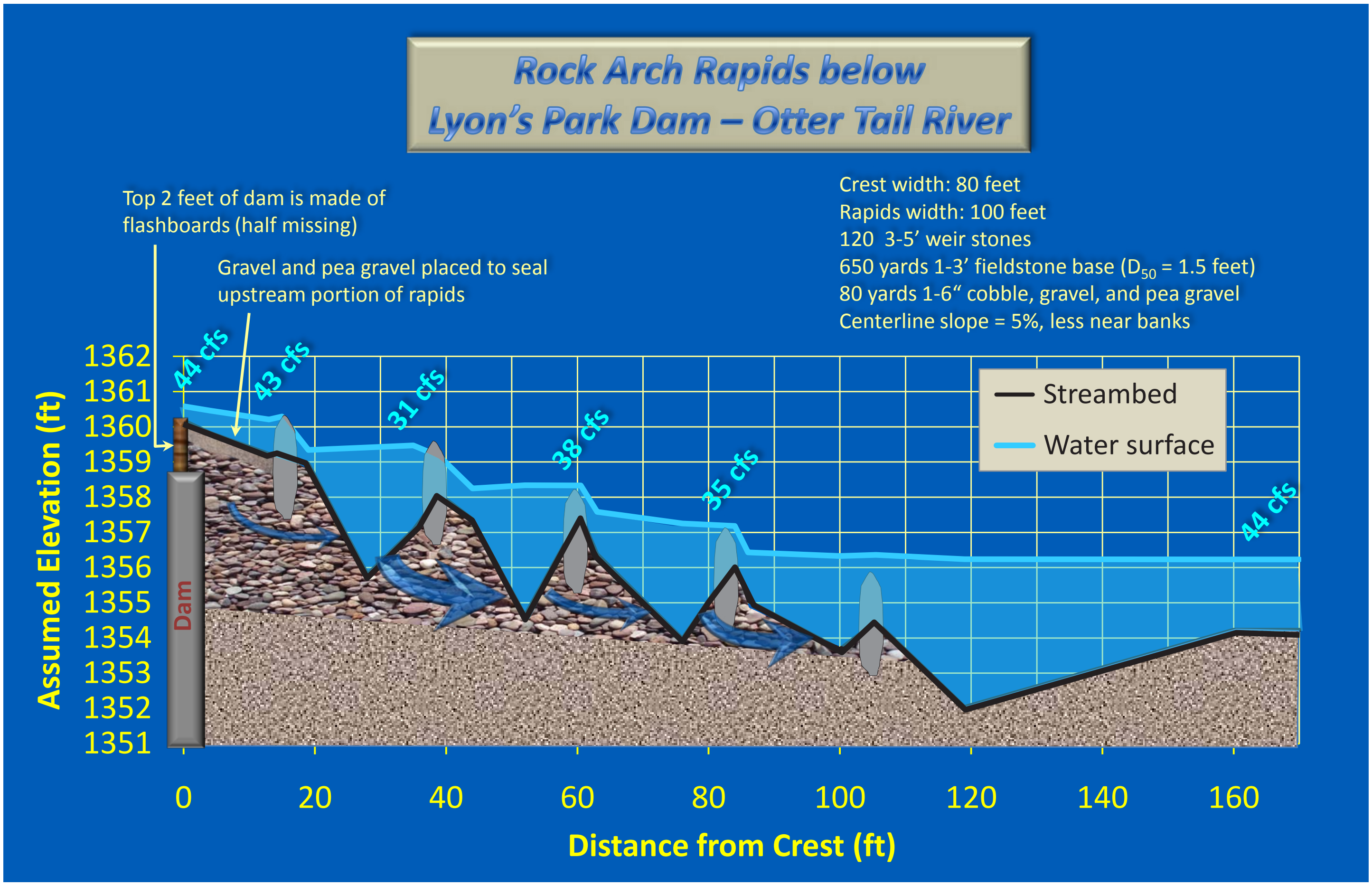


Figure 56. Centerline profile and surface discharge measurements in Lyon's Park Dam Rock Arch Rapids. Discharge measurementst were taken at 4, 13, 35, 60, 85, and 170 feet downstream of crest.

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.

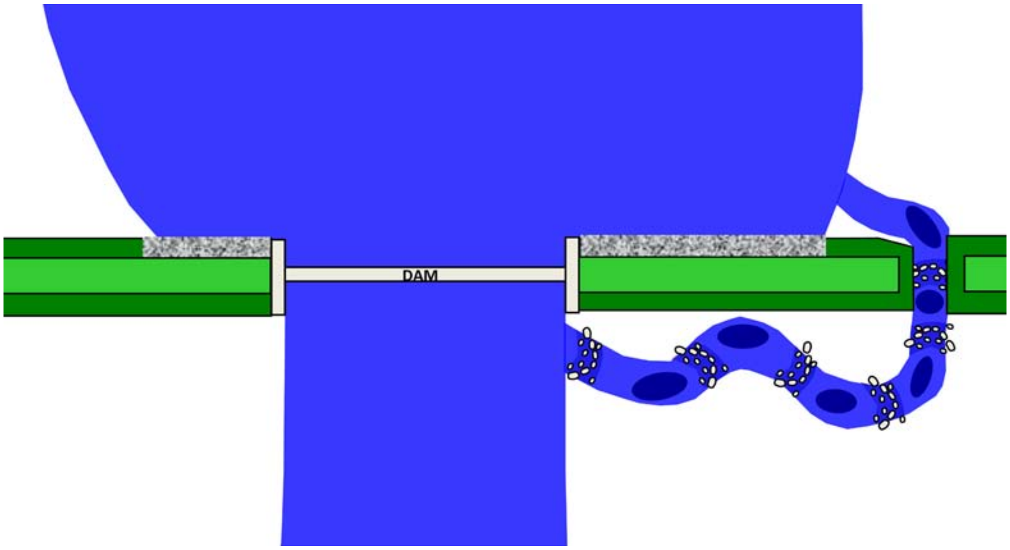


Figure 57. A generalized by-pass fishway.

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.

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.

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.

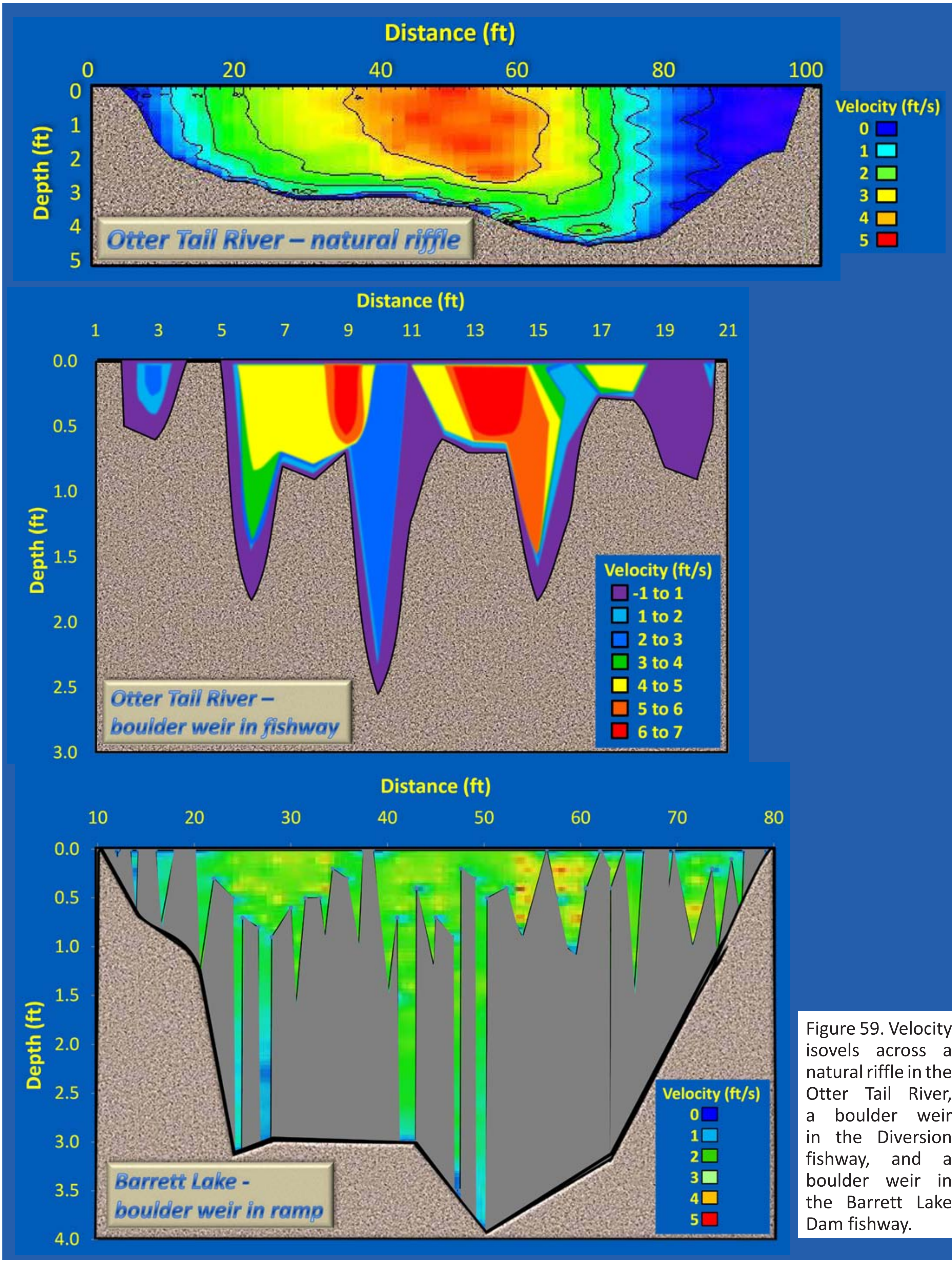


Figure 59. Velocity isovels across a natural riffle in the Otter Tail River, a boulder weir in the Diversion fishway, and a boulder weir in the Barrett Lake Dam fishway.

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.

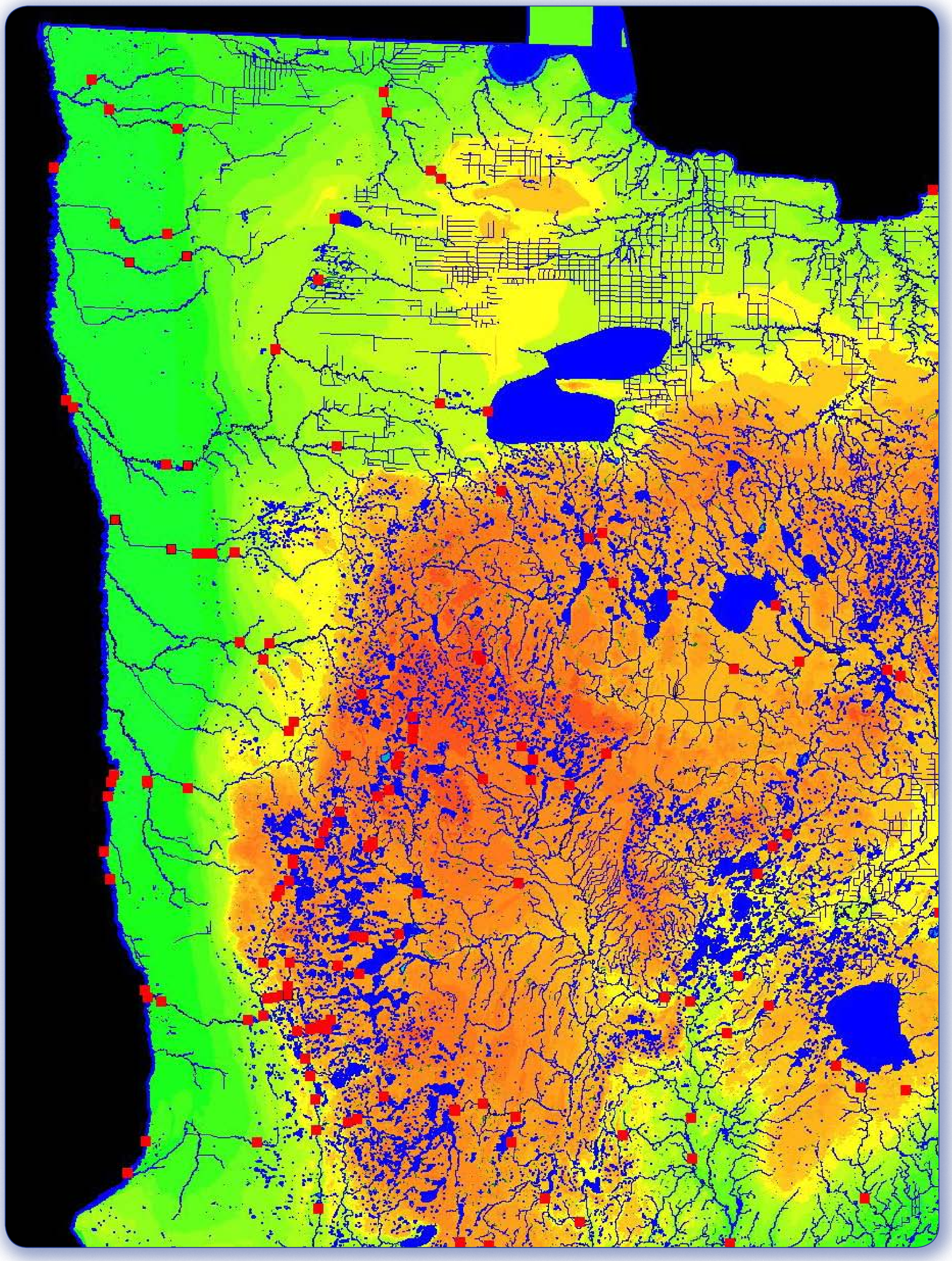


Figure 60. Map of Northwestern Minnesota showing the Red River of the North Basin and the location of barrier dams as they existed in 1993.

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).

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

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

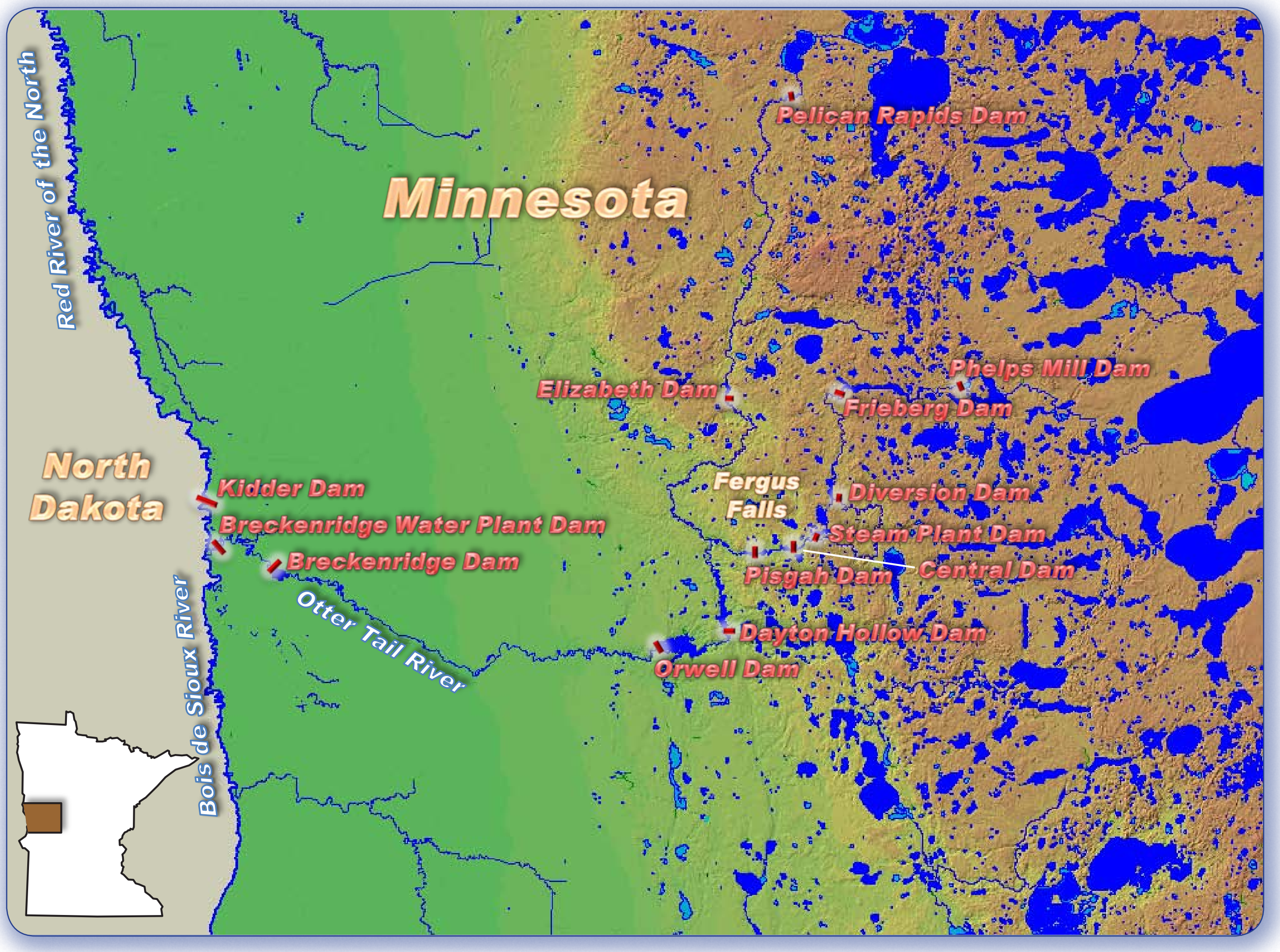


Figure 61. Topographic relief map showing the Otter Tail River and some of the barrier dams.

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.

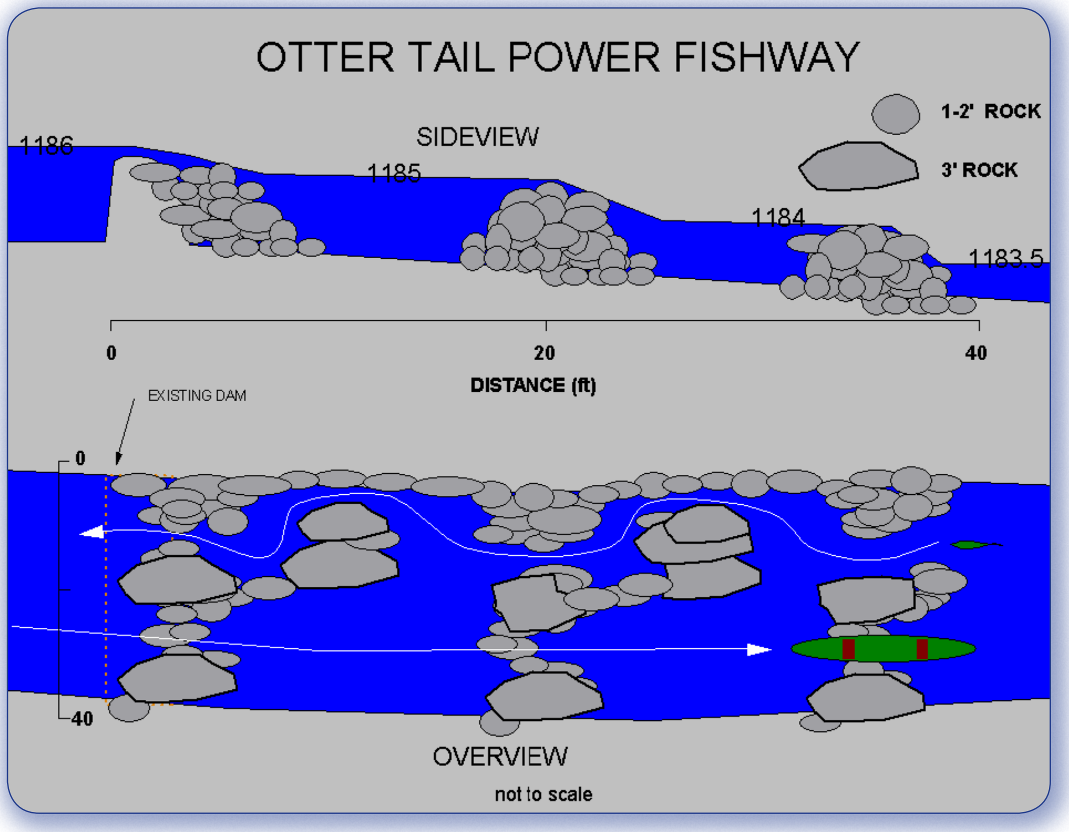


Figure 63. The Steam Plant Dam on the Otter Tail River. The dam was made of concrete and burlap bags filled with fly ash.

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.

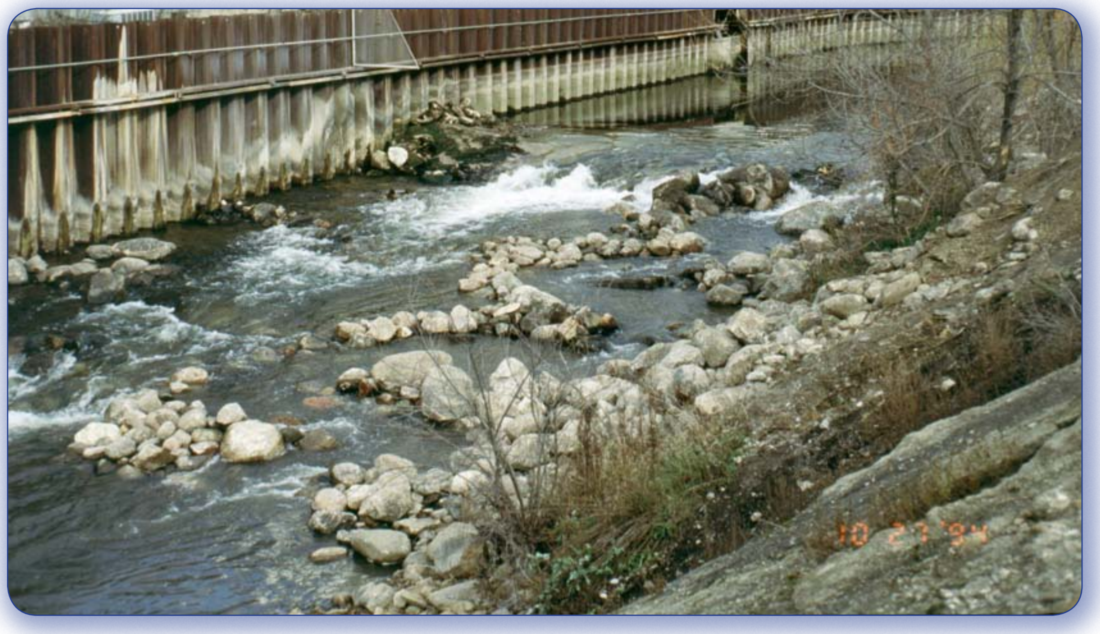


Figure 65. Steam Plant Rapids during low flows on the Otter Tail River in 1994.

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.

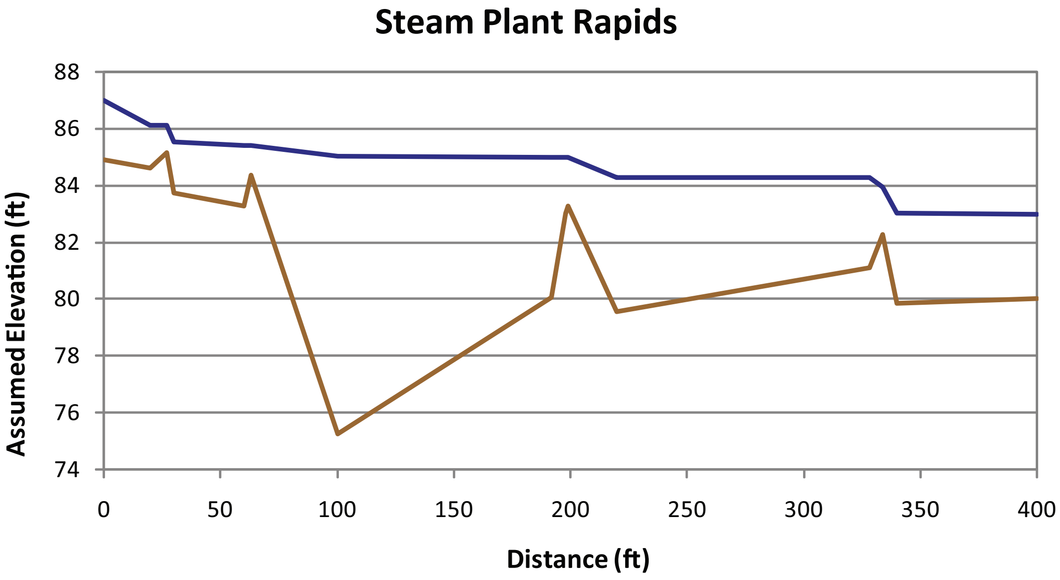


Figure 69. Center-line profile of the Steam Plant Rapids after improvements. Water surface elevations are shown in blue, the bed is shown in brown.

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).

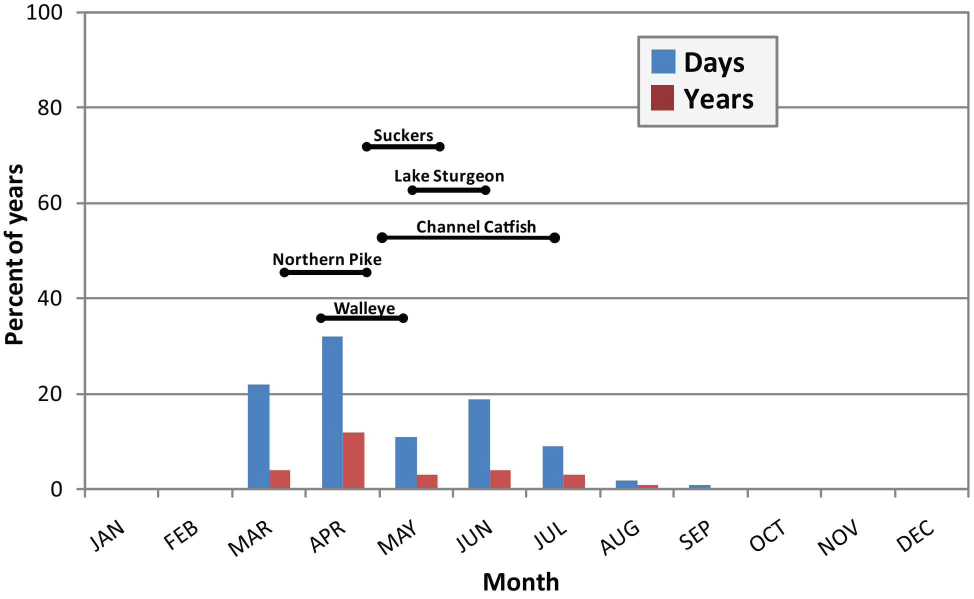


Figure 71. Percent of days and years that Midtown Dam was passable. Based on U.S.G.S gage 05054000 records from 1901 to 1997 and the assumption that the dam was passable at flows greater than 3000 cfs. Approximate migration periods are shown by lines for northern pike *Esox lucius*, walleye *Lucioperca 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.

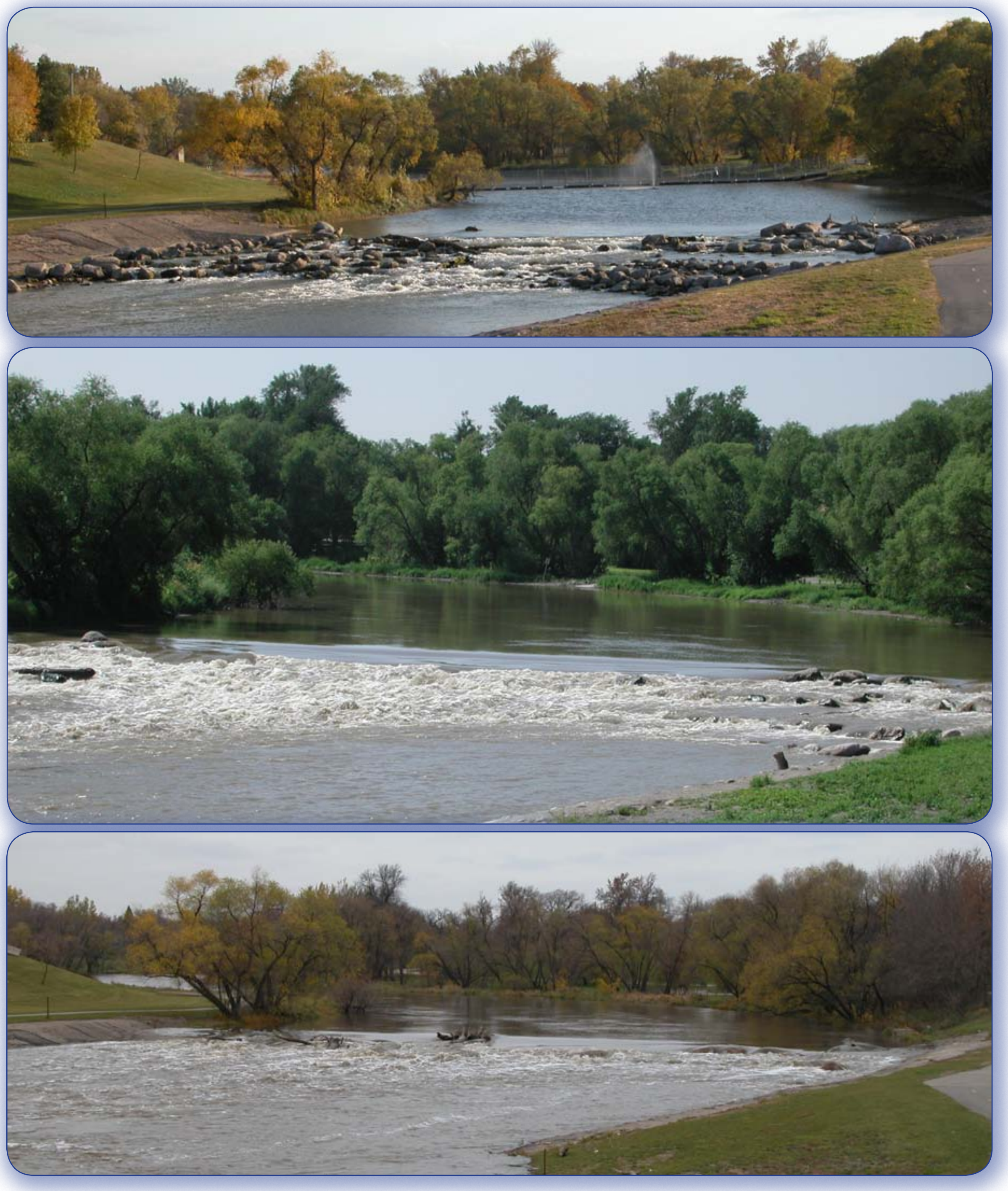


Figure 75. Midtown Rapids at flows of 405 cfs (upper photo), 1,640 cfs (middle photo), and 2,560 cfs (bottom photo).

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

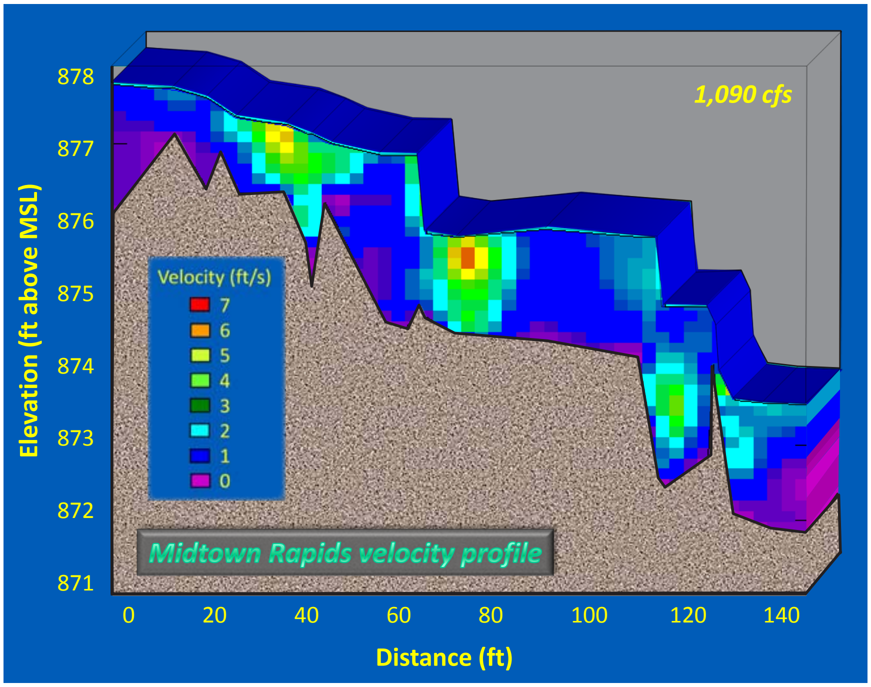


Figure 76. Longitudinal velocity distribution taken on August 3, 1999 at a flow of 1,090 cfs. This does not necessarily represent the best route for a migrating fish but is intended to show the velocity gradients one would encounter.

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).

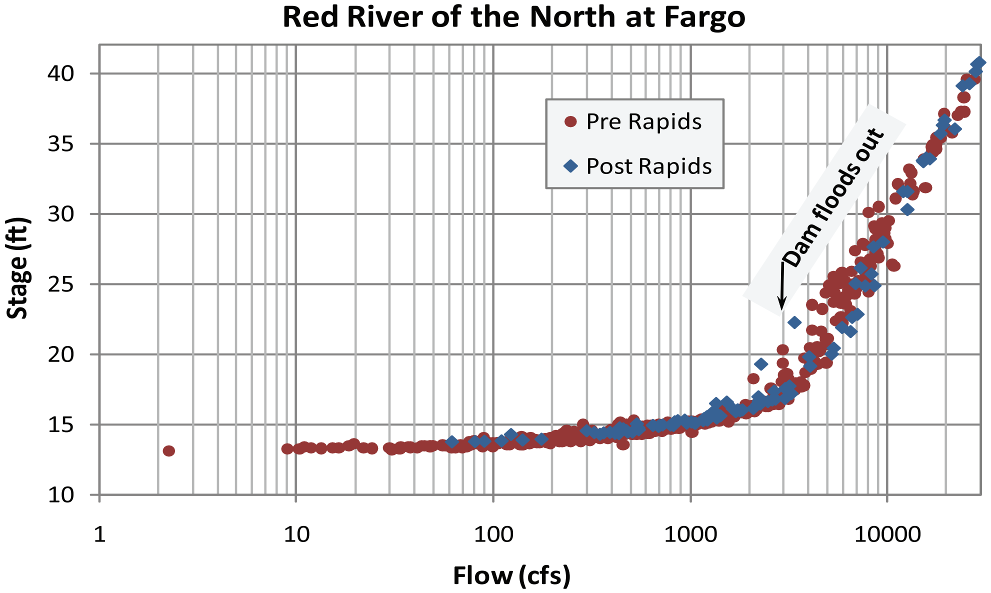


Figure 77. Stage and discharge measurements made by the U.S. Geological Survey at the gage (05054000) upstream of Midtown Dam before and after it was converted to rapids.

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 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.

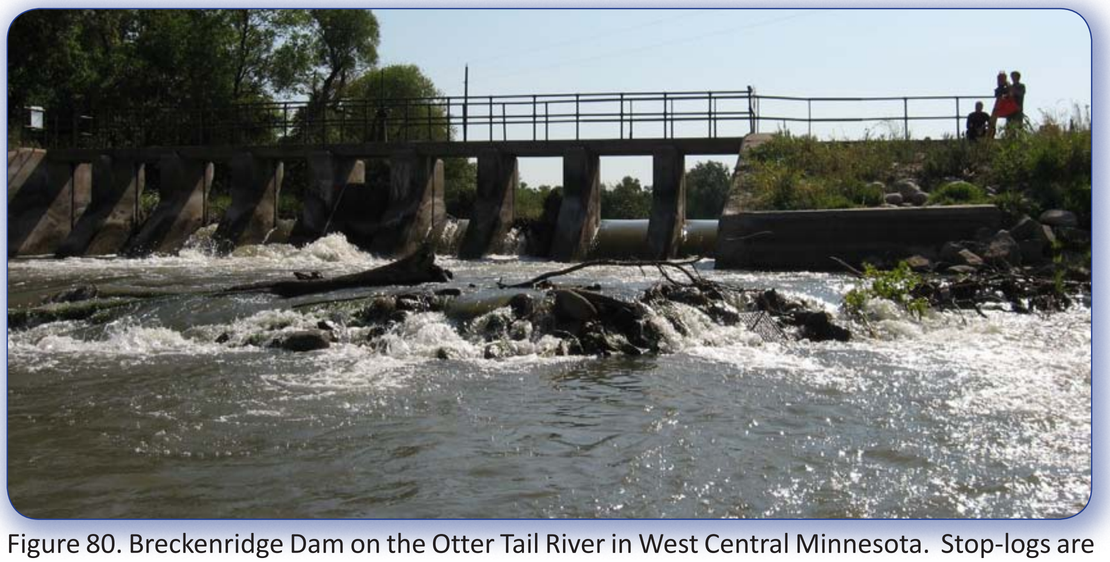


Figure 80. Breckenridge Dam on the Otter Tail River in West Central Minnesota. Stop-logs are not installed in this photo.

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

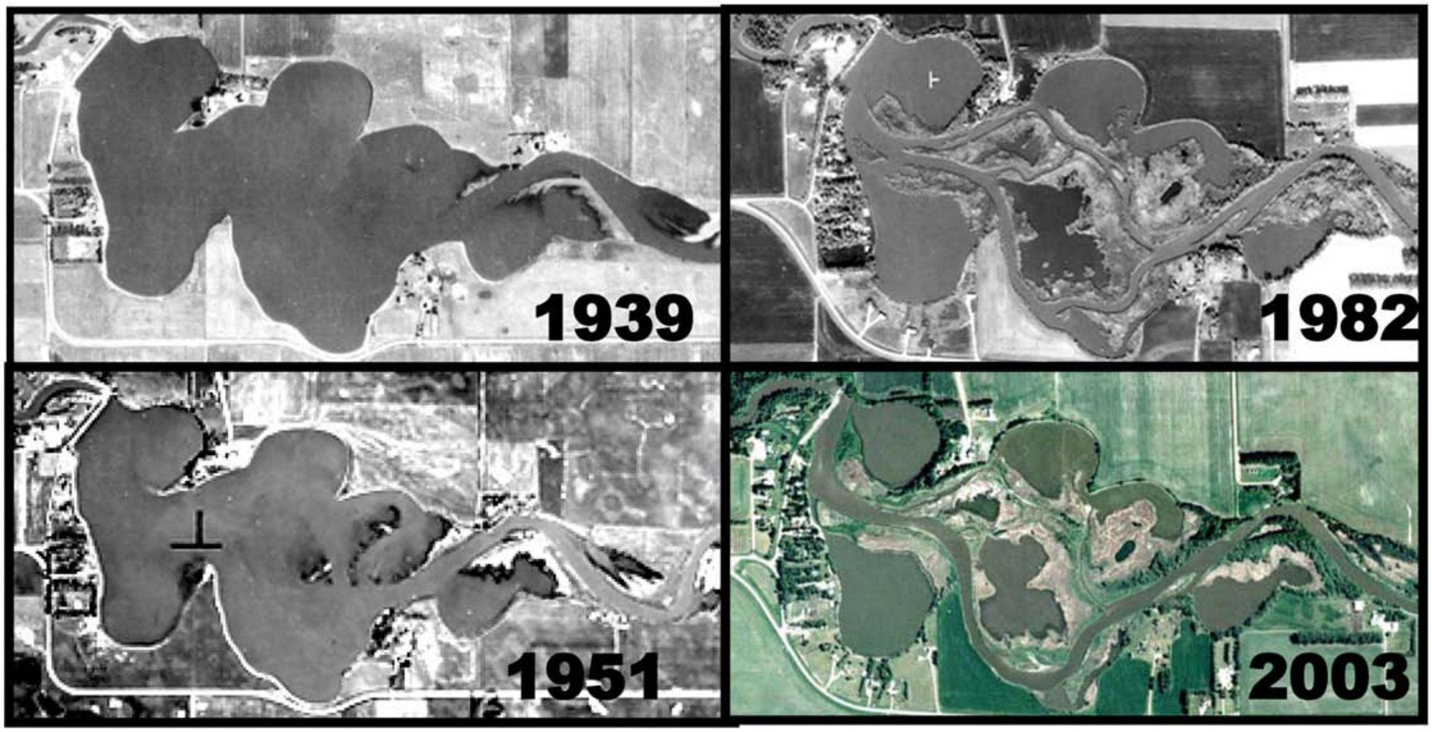


Figure 81. Breckenridge Reservoir in 1939, 1951, 1982, and 2003 showing sedimentation.

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

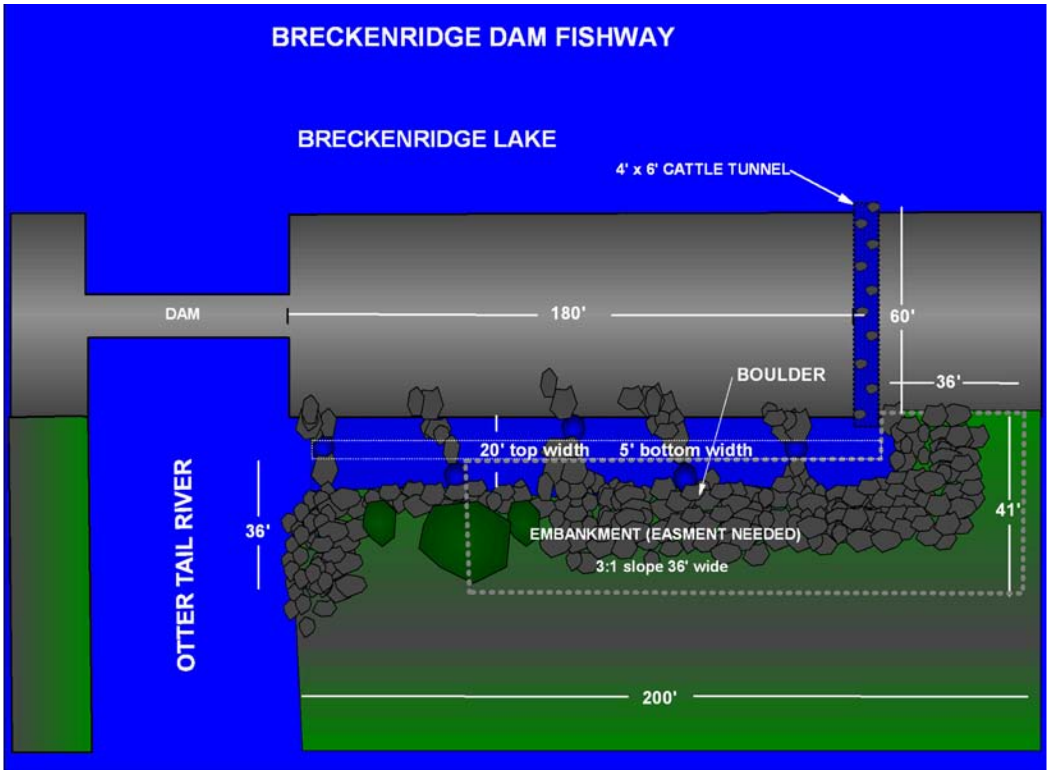


Figure 82. Plan-view conceptual design of the Breckenridge Fishway on the Otter Tail River.

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.

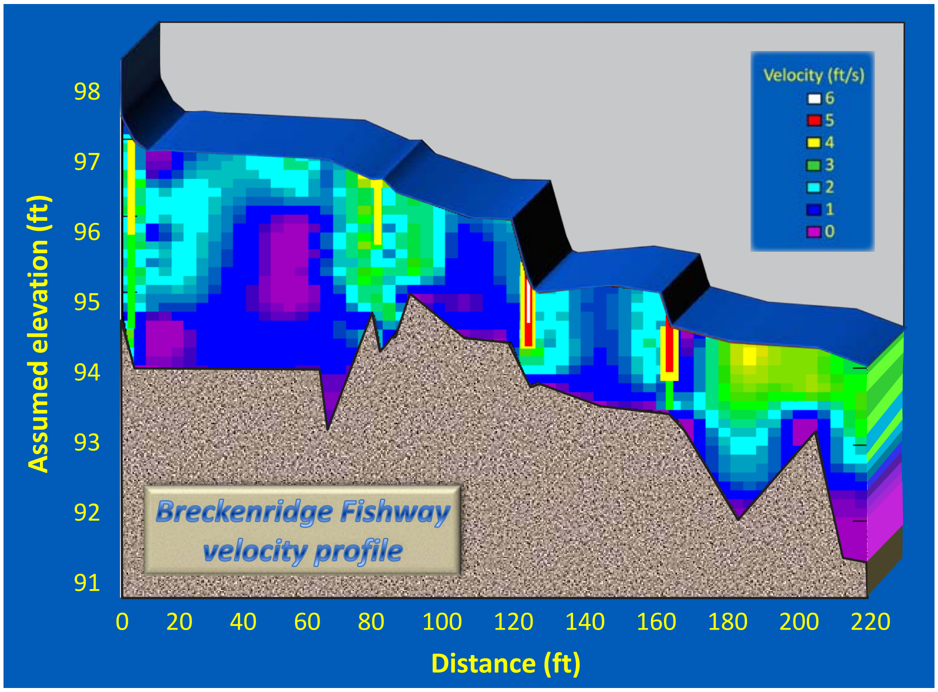


Figure 87. Breckenridge Fishway velocity distributions. Profile path went through the gap between boulders in the weirs.

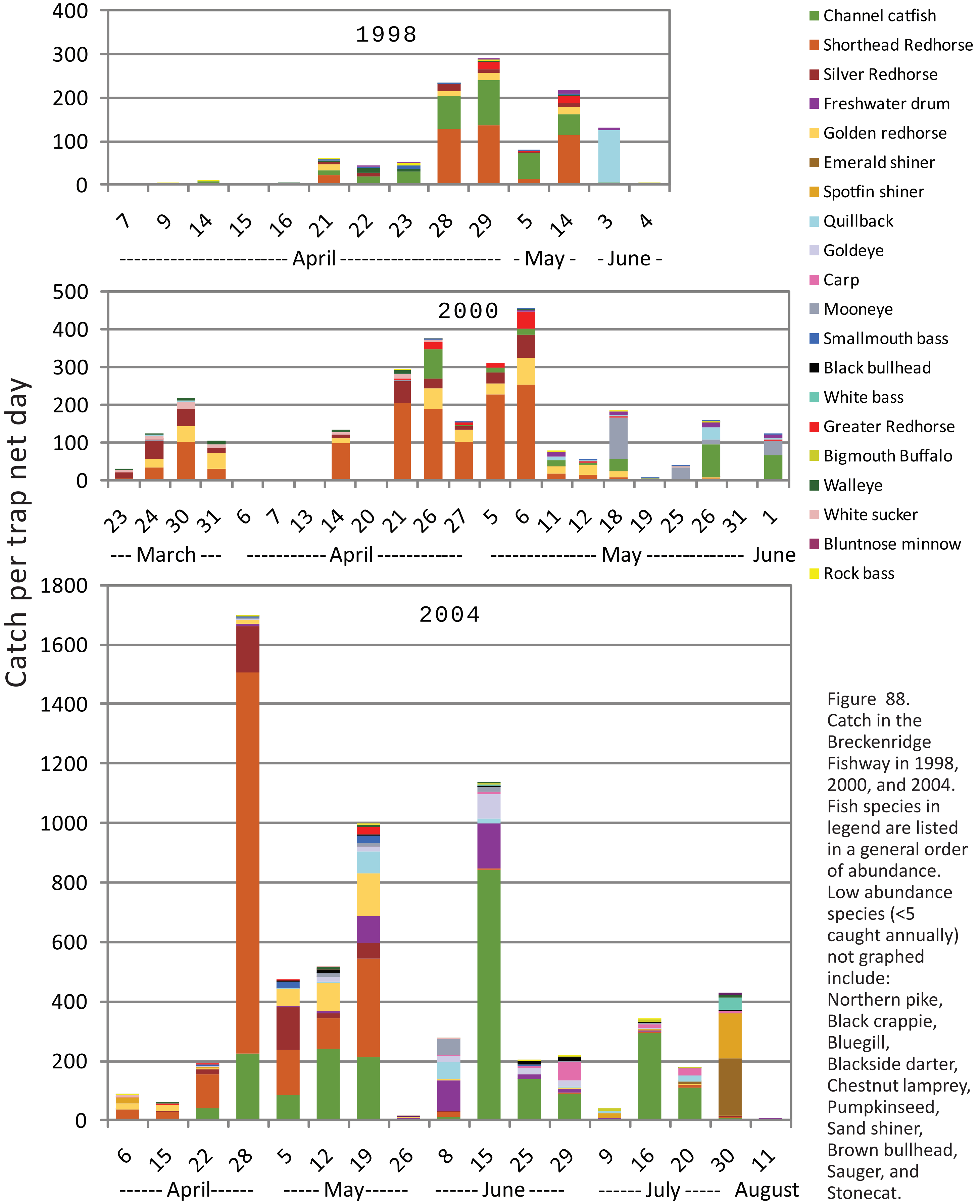


Figure 88. Catch in the Breckenridge Fishway in 1998, 2000, and 2004. Fish species in legend are listed in a general order of abundance. Low abundance species (<5 caught annually) not graphed include: Northern pike, Black crappie, Bluegill, Blackside darter, Chestnut lamprey, Pumpkinseed, Sand shiner,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

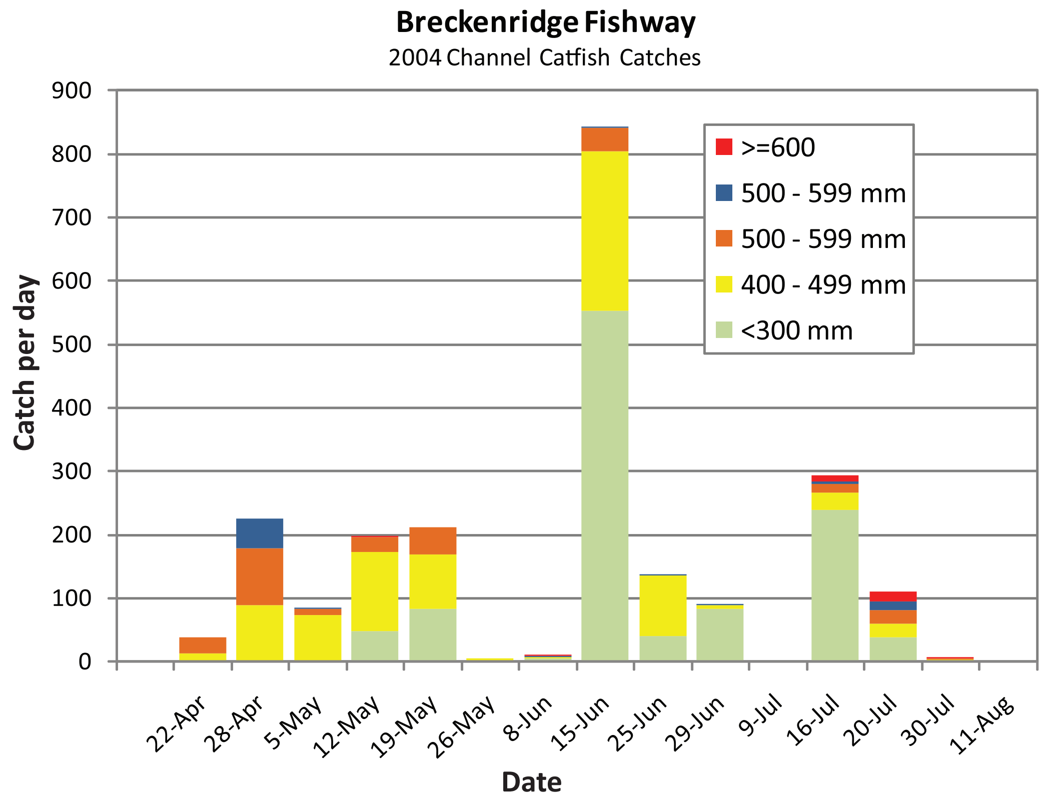
not limiting. While greater numbers of small bodied and young of the year fishes passed in 2004, this was likely because the fishway was monitored into August rather than early June as in 1998 and 2000. Many of the small-bodied fishes spawn in the summer. Third, there may have been a return of fishes 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



Breckenridge Fishway

2004 Channel Catfish Catches

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

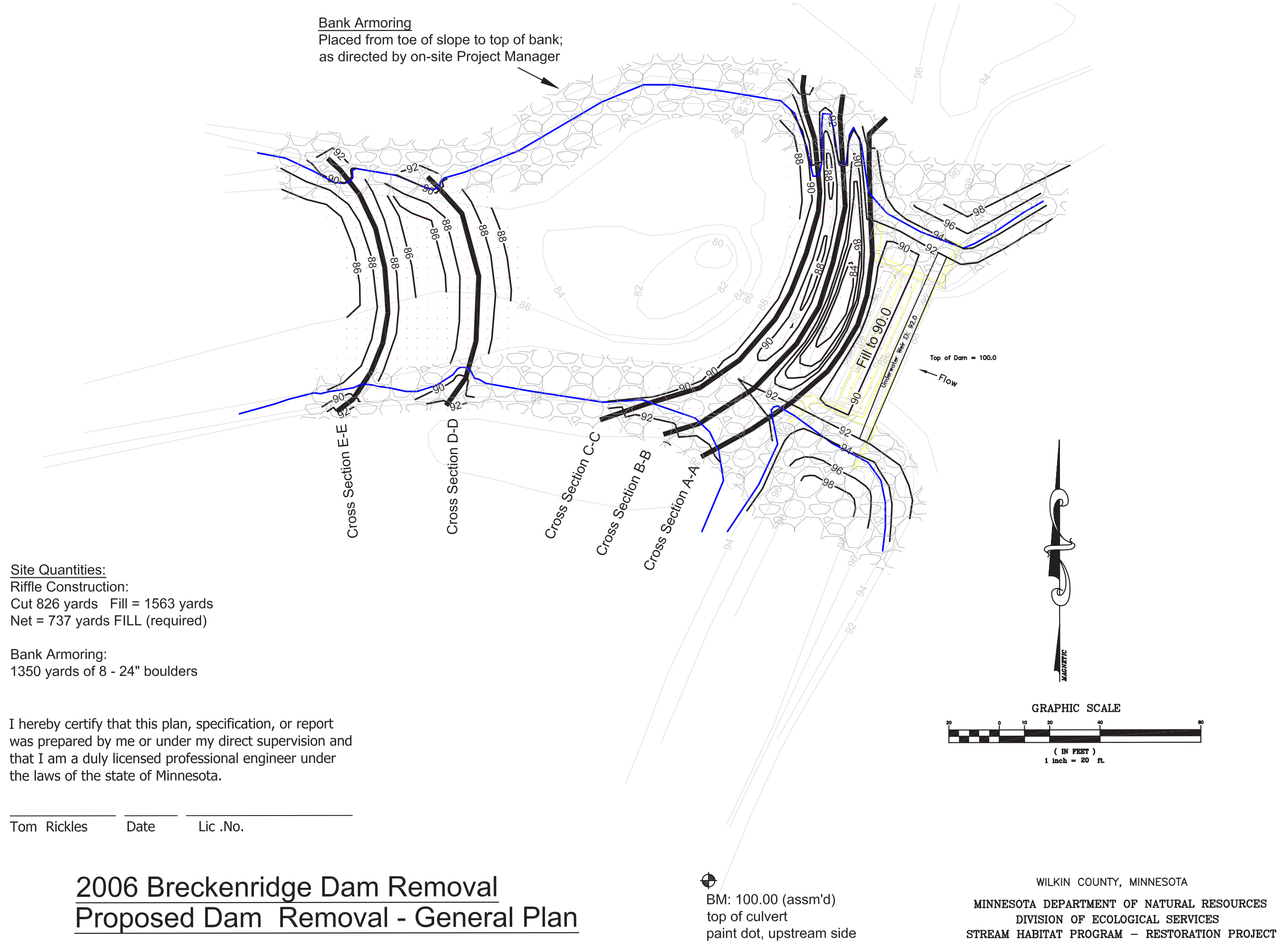


Figure 90. Plan-view for Breckenridge Dam removal. Bold lines indicate weir alignment.

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.

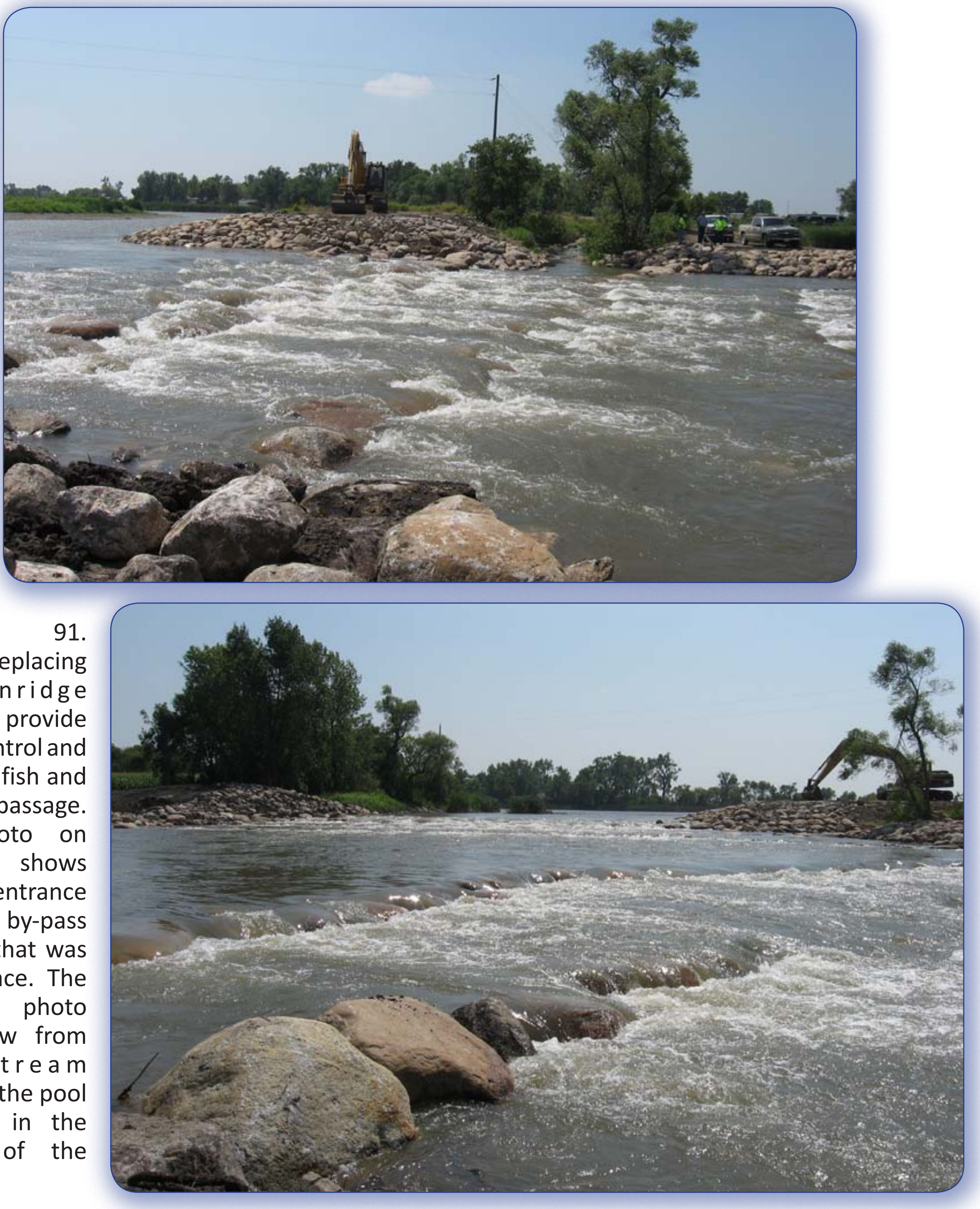


Figure 91. Rapids replacing Breckenridge Dam to provide grade control and facilitate fish and canoe passage. The photo on the top shows the entrance of the by-pass fishway that was left in place. The bottom photo is a view from downstream showing the pool retained in the middle of the rapids.

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.

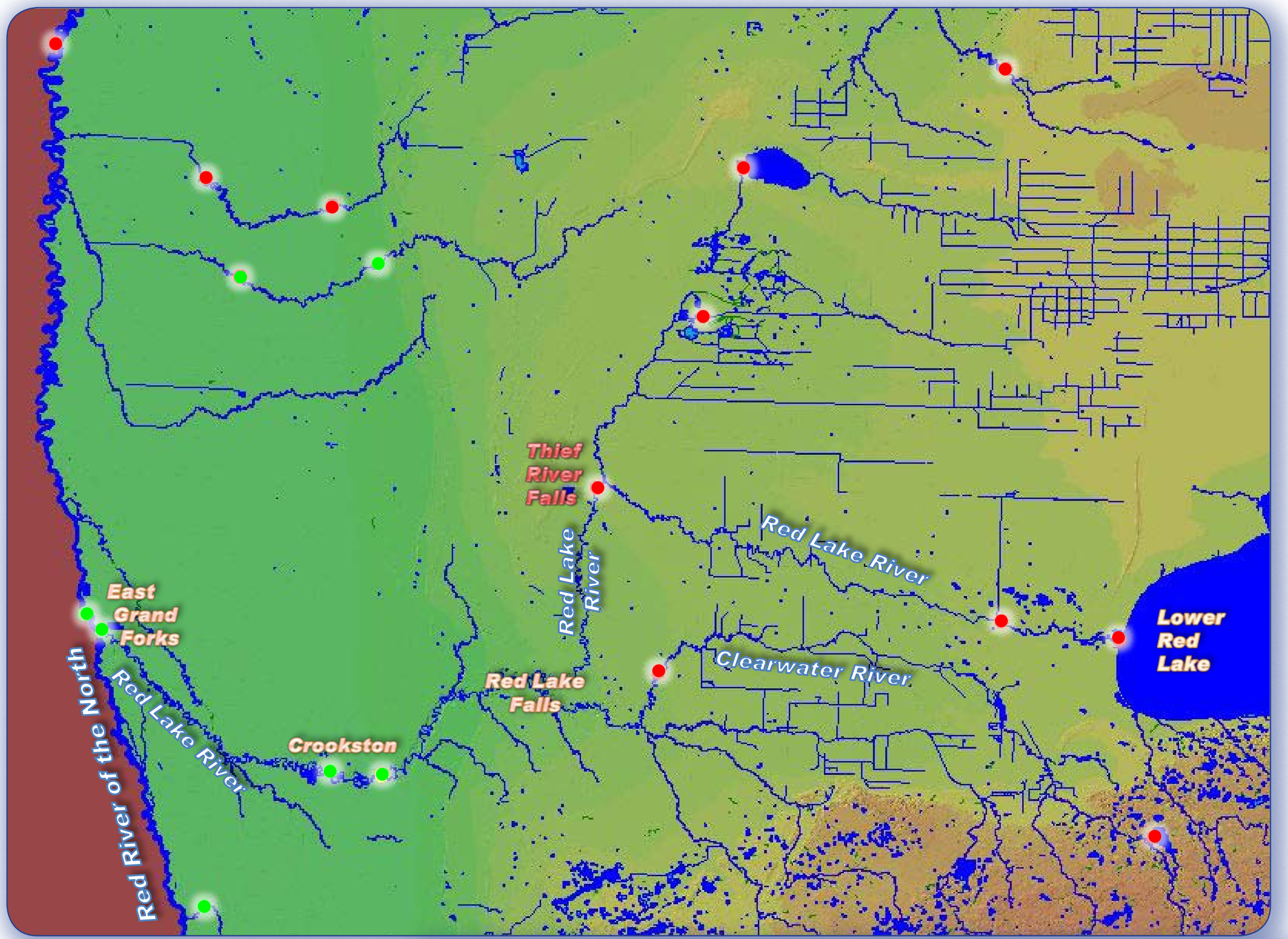


Figure 93. Red Lake River showing impassable dams (red dots), and dams removed or converted to rapids for fish passage (green dots). The green dot in Crookston is the Crookston Dam.

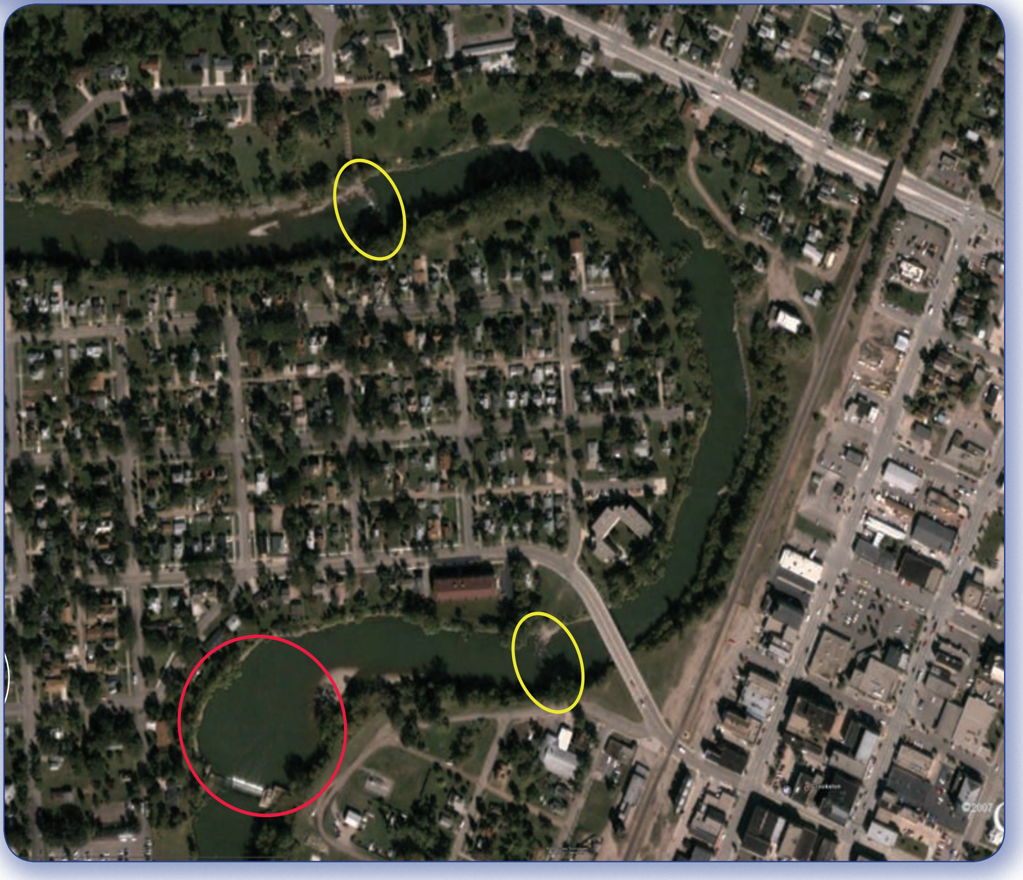


Figure 94. Aerial photo of the Crookston Dam showing downstream tailwater erosion (red circle) and riffles (yellow ovals) built to protect against further bed degradation and to raise minimum tail-water elevation.

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.

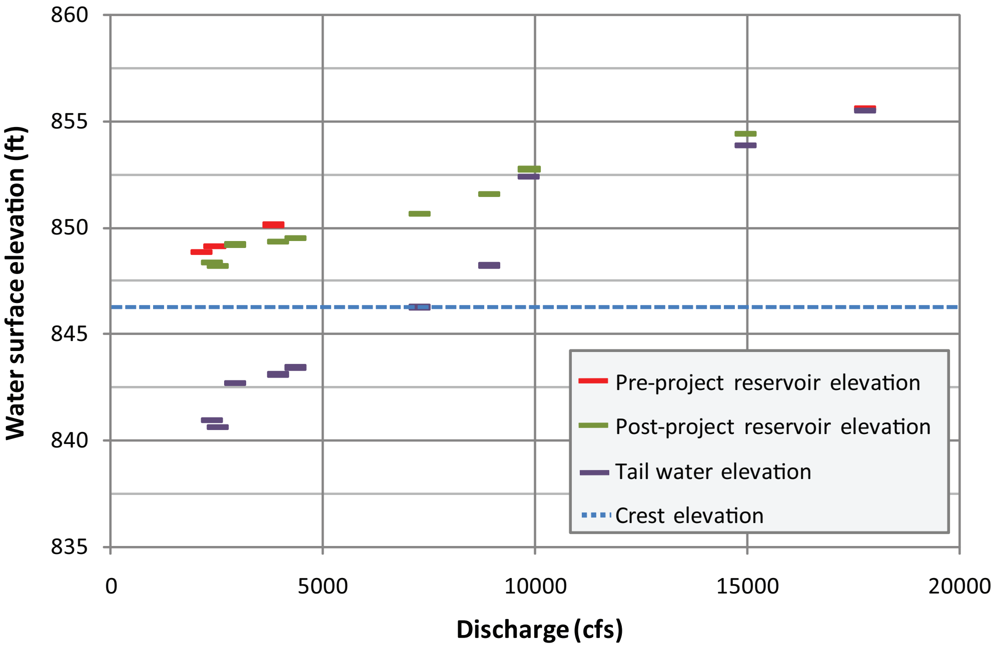


Figure 96. Surveyed headwater and tailwater elevations for the Crookston Dam showing submergence at approximately 18,000 cfs.

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

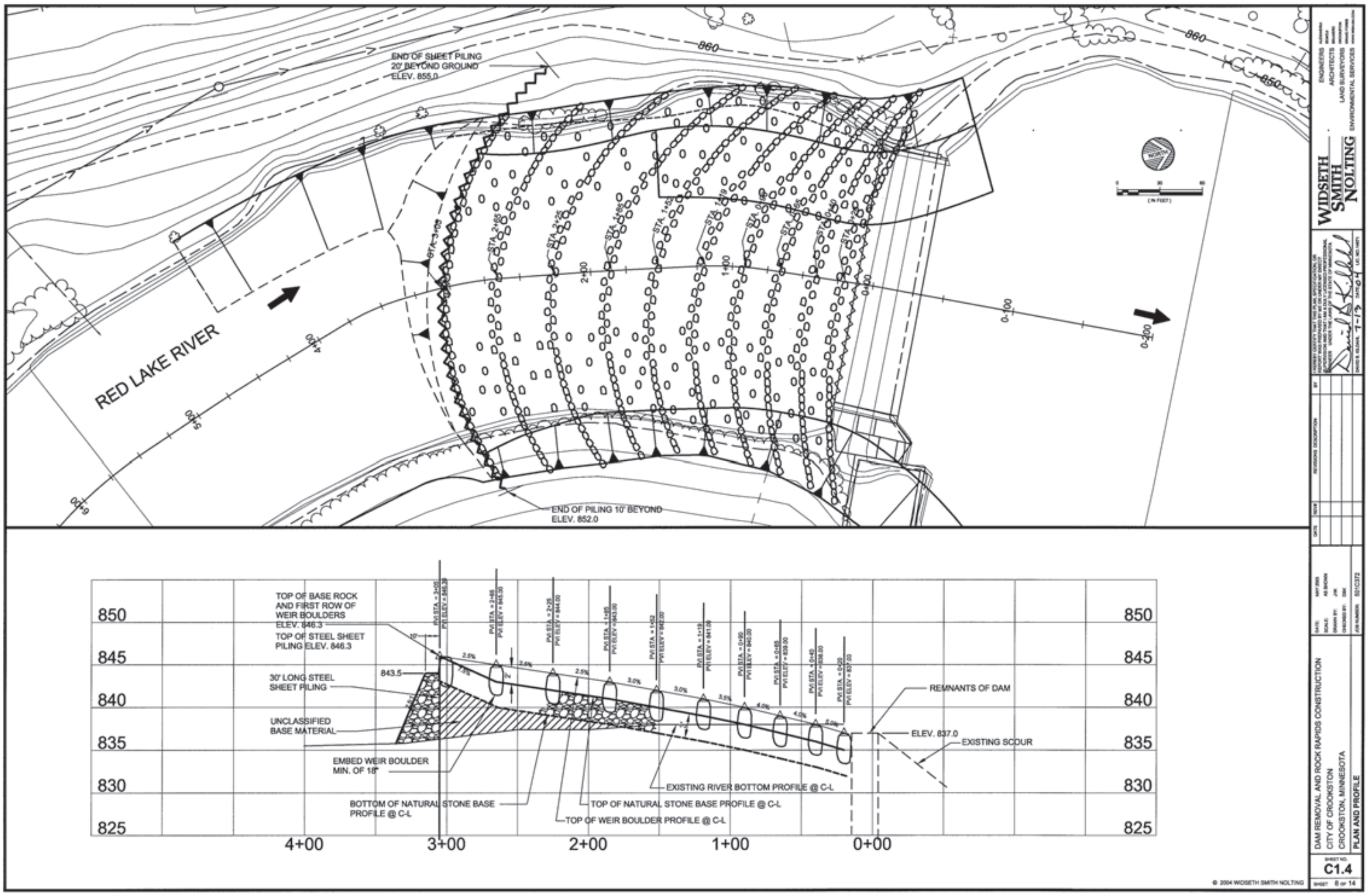


Figure 97. Planview and profile of the Crookston Rapids. David Kildahl, P.E. Widseth Smith Nolting, Project Engineer.

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.*

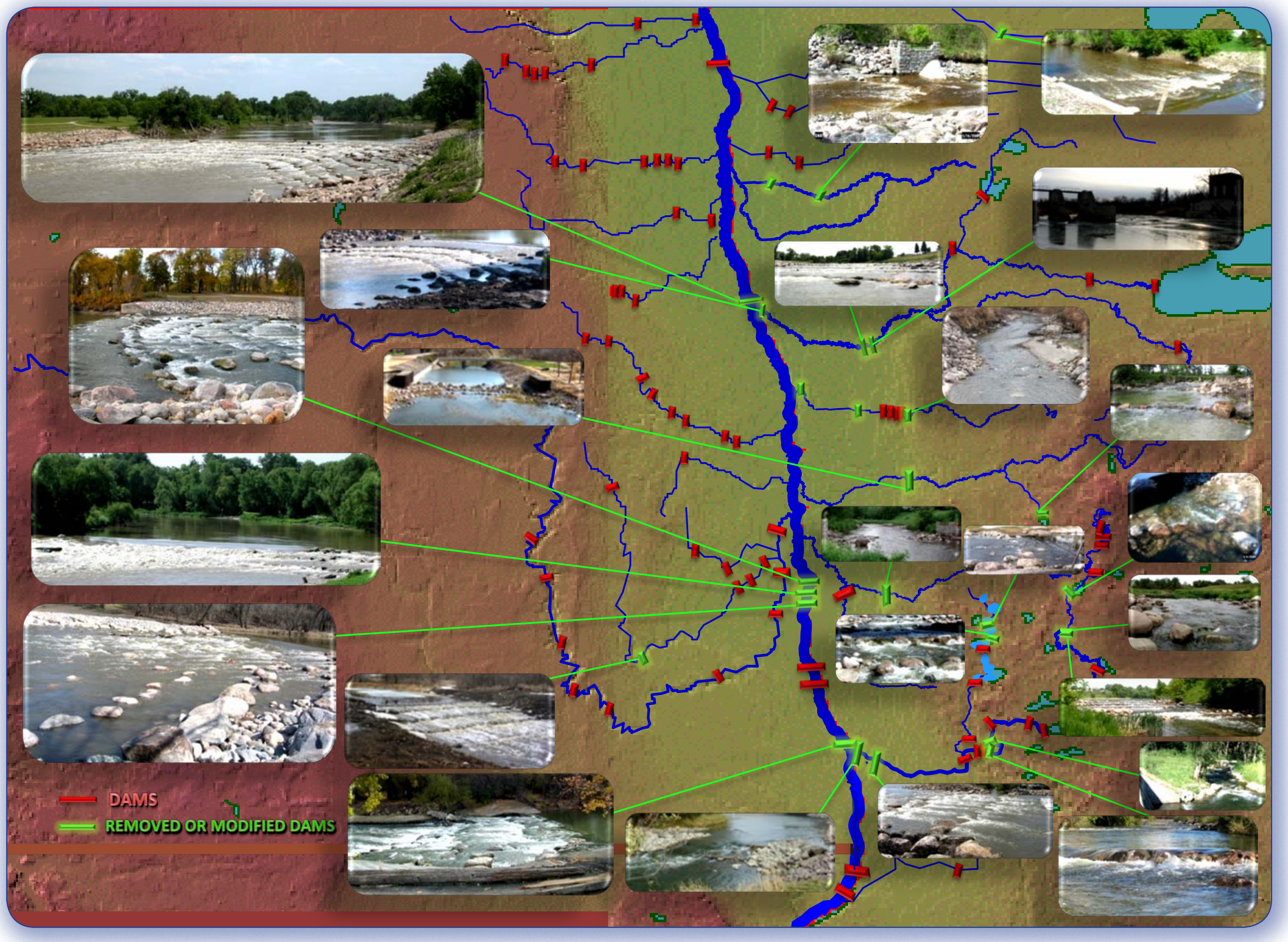


Figure 104. Map of the Red River of the North Basin showing dam removal and fish passage projects. The red lines represent existing barriers while the green lines represent dams that have been removed or modified for fish passage.

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.

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.

> *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.*

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.

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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.

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.