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

Minnesota Department of Natural Resources

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Reconnecting Rivers:

Natural Channel Design in Dam Removals and Fish Passage

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Acknowledgements

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

Disclaimer

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

Preface

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

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Introduction

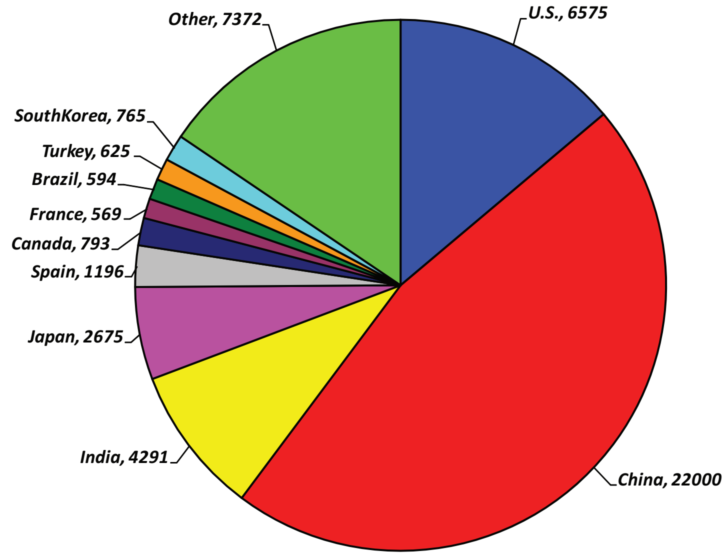

Figure 1. Number of large dams (≥15 m high) by country. Source: World Commission on Dams

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

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

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

Dam Problems

Structural Integrity and Dam Failure; Diminishing Functions, Growing Liabilities

From a strict economic view, dam and reservoir deterioration, failure risks, and costs of dealing with obsolete dams is a crisis that countries with large numbers of dams will need to face.

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

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

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

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

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

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

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

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

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

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

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

Reservoir Sedimentation

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

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

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

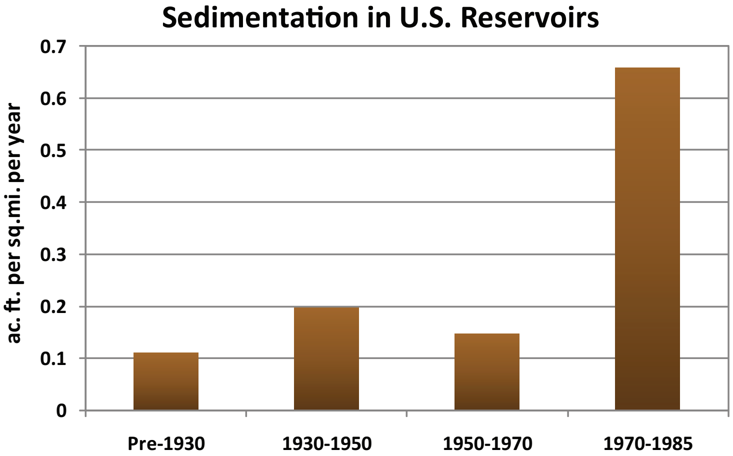

Figure 5. Sedimentation rates in acre-feet per square mile of drainage area per year. The lower rate in the 1950 to 1970 time period is due to addition of the large drainage reservoirs that have a lower sedimentation rate per drainage area. Data from Bernard and Iivari (2000).

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

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

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

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

Channel Degradation

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

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

Channel incision, primarily due to channelization, has caused over $1.1 billion in damages to roads, bridges, and cropland in Western Iowa.

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

River Delta Effects

Another problem associated with sediment interception by dams is the effect on river deltas. Despite five- to ten- fold increases in sediment loads in the Ohio River from deforestation and row-crop agriculture, there has been a 70% reduction in sediment supply to the lower Mississippi due to dam construction on the Missouri and Mississippi Rivers. The reduction in sediment supply associated with the construction of Fort Randall Dam (1952), Garrison Dam (1953), and Gavin's Point Dam (1955) could be observed almost immediately at the mouth of the Mississippi River (Williams and Wolman, 1984; Meade, 1995; Julien and Vensel, 2005). The City of New Orleans and the Mississippi River Delta are sinking at a rate of 5 to 25 mm/y due to sediment compaction and tectonic subsidence (Dixon 2008). Lack of sediment to rebuild the delta, loss of coastal wetlands increasing vulnerability to hurricanes, and construction of levees that redirect sediment off the continental shelf have resulted in loss of land area of coastal Louisiana of 102 km^2 (66 mi^2) per year (Kesel, 1989). The sediment annually intercepted by the large Missouri River dams alone would be enough to cover 139 mi^2 with a foot of sediment per year.

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Hydraulic Undertows – The Drowning Machine

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

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

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

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

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

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

Most of these fatalities occur below low-head dams with a low hazard rating.

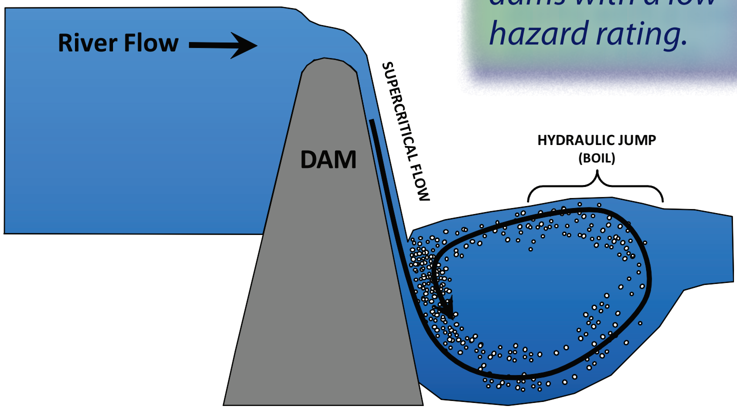

Figure 8. Formation of the hydraulic roller below low-head dams.

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

Socioeconomic and Cultural Effects

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

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

Inundation of Critical Habitat

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

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

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

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

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

Flow Regulation

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

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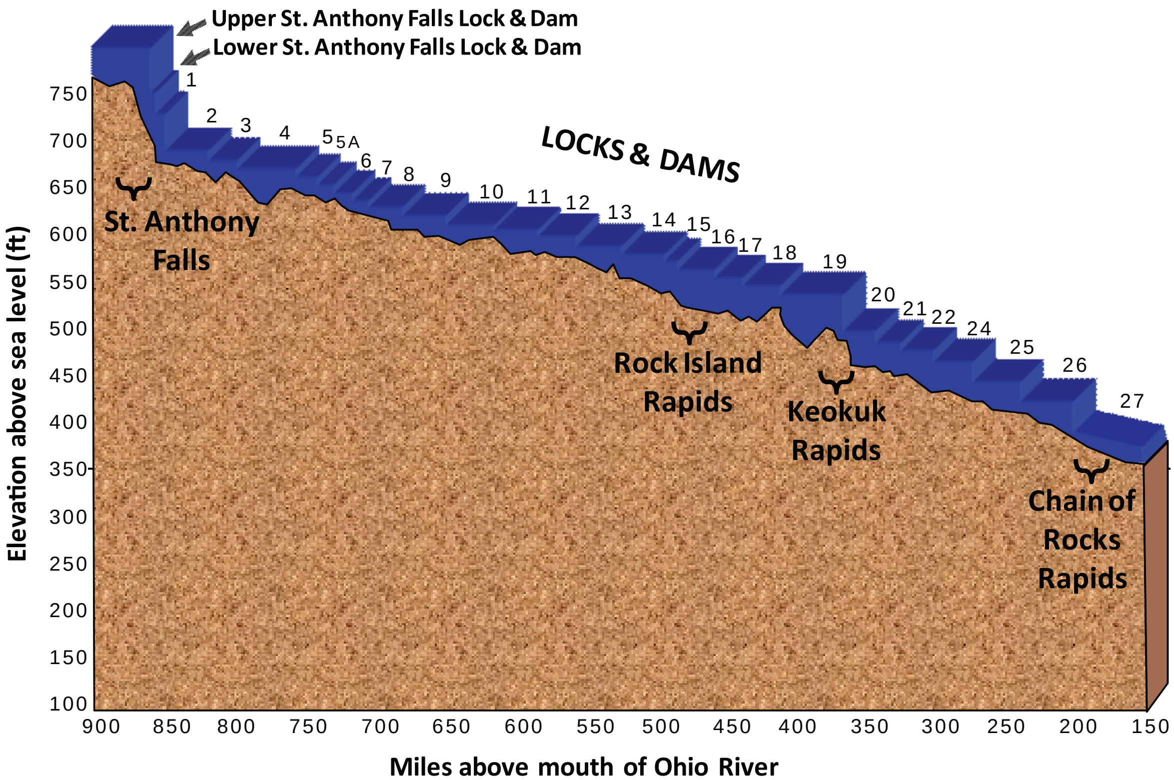

Figure 10. Profile of the Upper Mississippi River showing the dams and historic rapids.

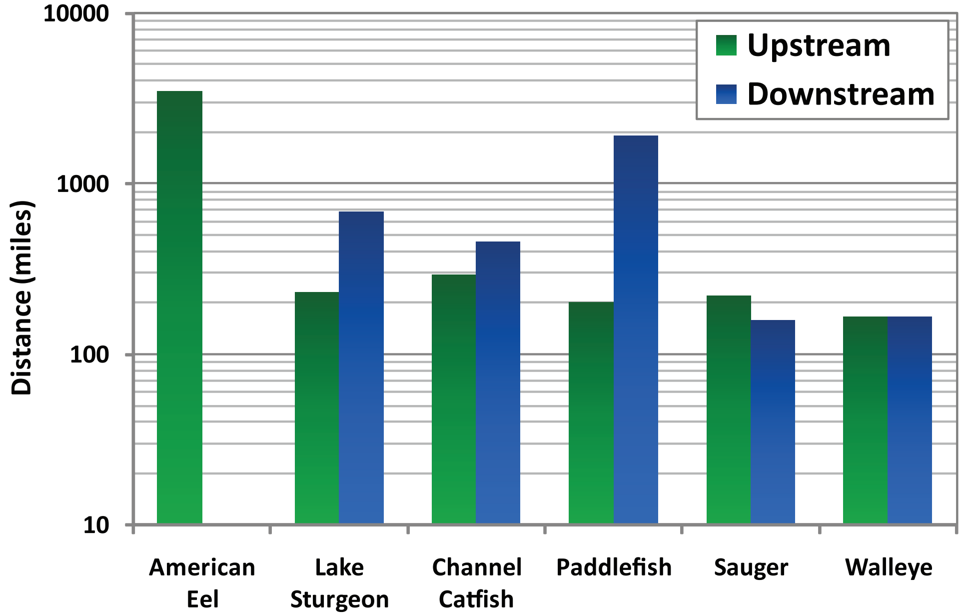

Figure 11. Observed migration distances of Minnesota fishes. References: Stancill et al. 2002, Mosindy and Rusak 1991, Bellgraph 2006, Ron Bruch, Wisconsin DNR, personal communications, Mike Larson, Minnesota DNR, personal communications, Jaeger 2004.

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

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

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

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

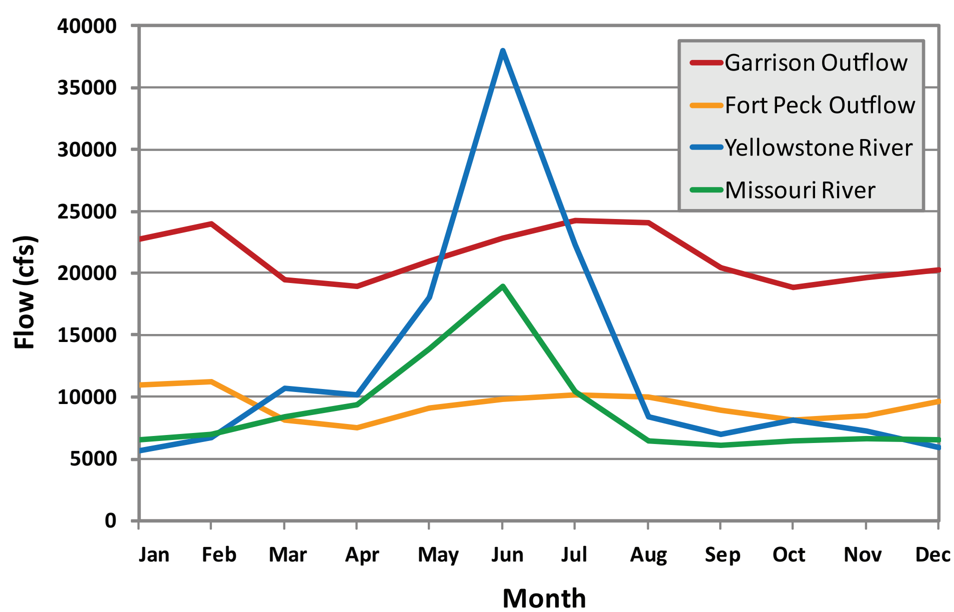

Figure 12. Average monthly outflows of Garrison and Fort Peck dams (1967-2008) and mean monthly unregulated flows of the Missouri River at Landusky, Montana (USGS gage number 06115200, 1934-2007) and the Yellowstone River at Sidney, Montana (USGS gage number 06329500, 1911-2007). Source: U.S. Army Corps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

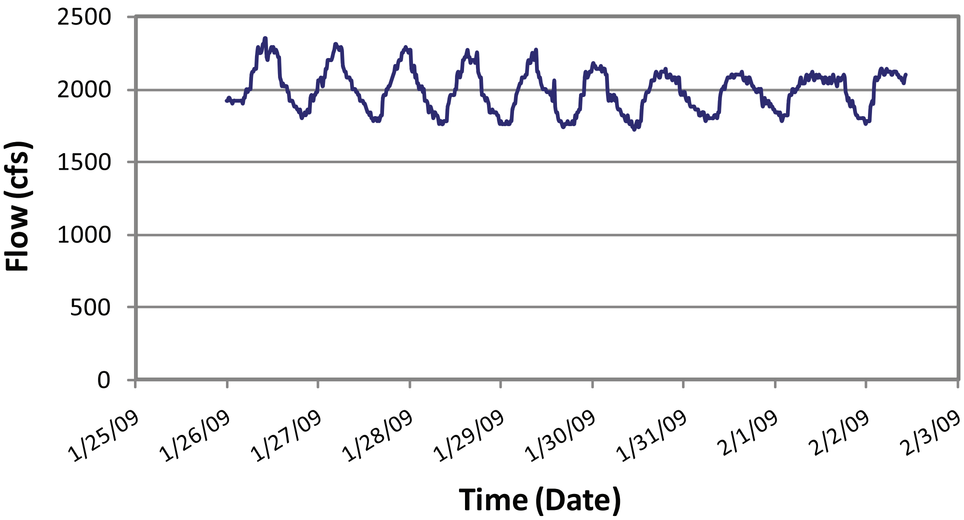

Figure 13. Daily flows fluctuations caused by a hydropower dam at Taylor's Falls, Minnesota on the St. Croix River. Flow fluctuations at this site were much greater prior to implementation of protected flows.

Water Quality Effects

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

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

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

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

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

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

Invasive Alien Species

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

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

In many cases, introduced non-native species have been more successful in part, because native river fishes are not well suited to the altered environment and therefore cannot successfully compete.

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

Propagation of Parasites

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

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

Gas Supersaturation

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

Hydropower Effects

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

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

Blockage of Fish Migrations

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

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

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

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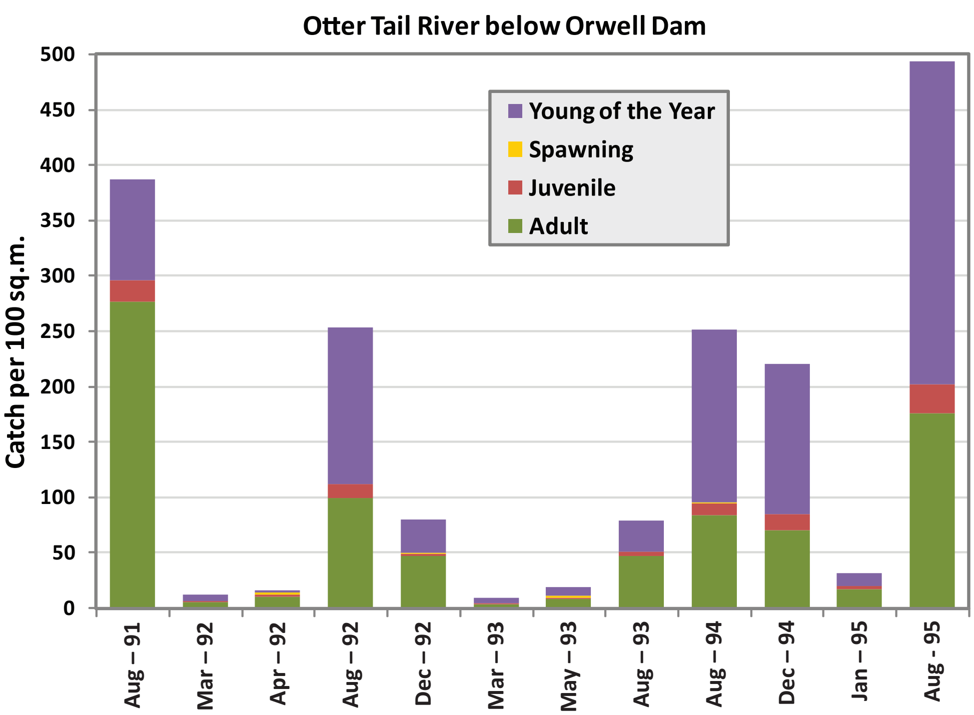

Figure 15. Seasonal changes in density (catch per 100 m^2 with prepositioned area samplers) of fish by life stage in the Otter Tail River, 1991-1995. Most of the species present spawn in spring (early April to June).

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

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

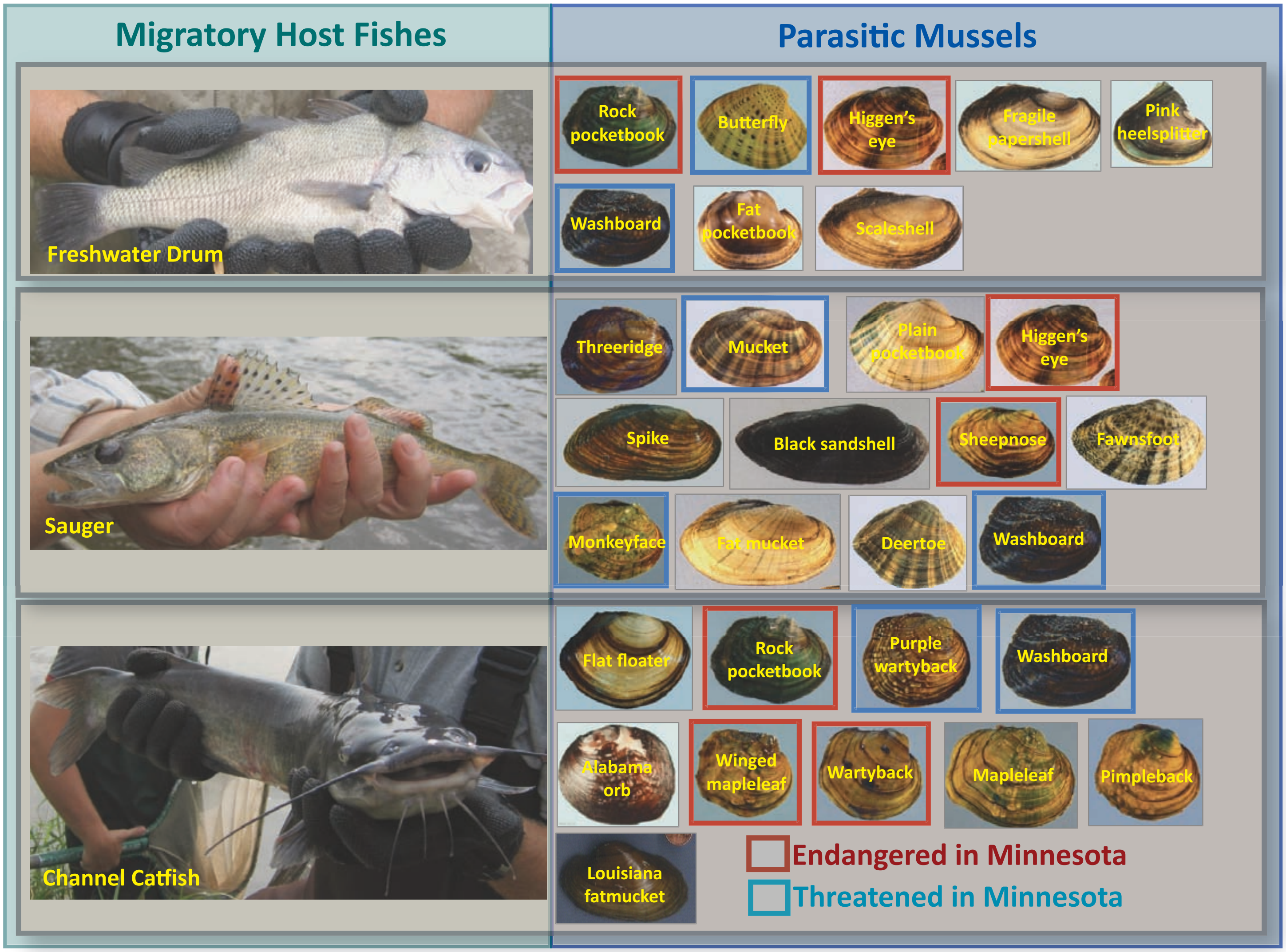

Figure 16. Mussel species that use freshwater drum *Aplodinotus gruniens*, sauger *Sander canadense*, and channel catfish *Ictalurus punctatus* (from Mollusk Division of the Museum of Biological Diversity at the Ohio State University data base).

River Restoration Philosophy and Definition

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

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

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

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

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

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

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

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

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

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

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

Natural Channel Design in River Restoration

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

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

Three different applications of natural channel design are discussed here:

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

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

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