SAVING LIVES WHILE IMPROVING FISH PASSAGE AT "KILLER DAMS"

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ABSTRACT

During the 19th and 20th centuries, many low head dams were constructed on rivers for water supply, ice harvesting, recreation, navigation, power generation (mills), and flow measurement. Little consideration was given to fish passage and public safety when most of these structures were designed and constructed. With significant development occurring in the vicinity of these structures, growing interest in river recreation, and the recent movement to restore river and stream environments to a more natural condition, many of these dams are now subject to intense pressures for their removal. When it is necessary to keep the structure in service, the dam owner is often faced with the difficult problems of addressing public safety concerns and providing effective fish passage.

This paper presents the author's experience rehabilitating low head dams to improve public safety and provide effective fish passage. Lessons learned from experience with litigation related to drownings at low head dams are discussed with an emphasis on design concepts for modifying low head dams to eliminate the hazardous submerged hydraulic jump. A state-of-the-art design for fish passage for low head dams, recently developed by Dr. Luther Aadland of the Minnesota Department of Natural Resources, is also presented. Dr. Aadland's design not only provides fish passage for all species of fish, but also effectively eliminates the hazardous hydraulic roller.

BACKGROUND

The terms "killer dams", "drowning machines", "death traps" and "dams of death" have often been used to describe low head (usually less than 15 feet high), run-of-the-river dams. Despite these negative connotations, many streams and rivers have low head dams that continue to provide useful functions including water supply, recreation, irrigation, navigation, power generation, and flow measurement. Under most flow conditions these dams pose little or no threat and have become favorite destinations for increasing numbers of fisherman, boaters, waders and other visitors. However, under certain flow conditions low head dams can become significant hazards when a hydraulic roller forms, which contributes to many drownings of persons unaware of the danger, often even despite posted warnings.

Research presented by Dr. Bruce Tschantz, professor emeritus of the University of Tennessee, shows that between 2000 and 2010, alone, there have been 115 documented drownings at low head dams in 26 states [Tschantz, 2011]. The victims included expert swimmers, rescue workers and other professionals equipped with state-of-the-art life saving and rescue gear who were aware of the hazards but still succumbed to the lethal hydraulic forces. In some instances particular low head dams have been the site of multiple drownings, yet many of these dams continue to operate without modification to mitigate the hazards. South Island Dam on the Kankakee River in Illinois, Midtown Dam on the Red River in North Dakota, Glen Palmer Dam on the Fox River in Illinois, and Dock Street Dam on the Susquehanna River in Pennsylvania have each claimed more than 15 lives.

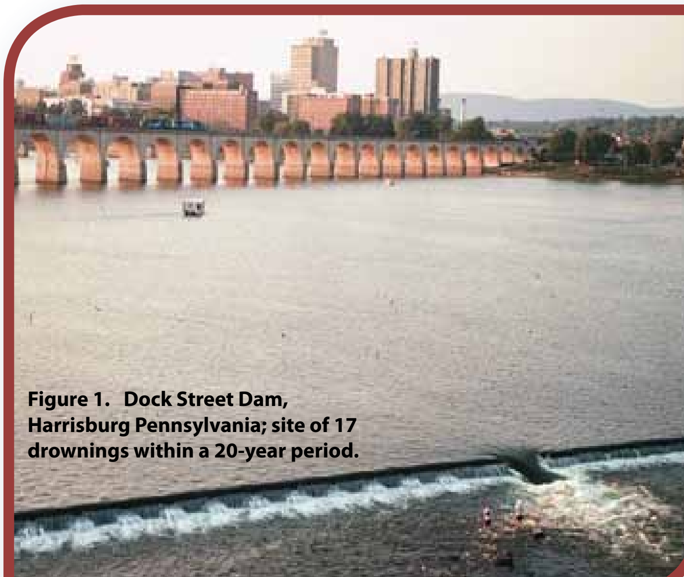

Figure 1. Dock Street Dam, Harrisburg Pennsylvania; site of 17 drownings within a 20-year period.

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A troubling statistic uncovered by Dr. Tschantz's research is that during the past 30 years there have been more than four times as many fatalities from drowning at low head dams than there have been deaths resulting from dam failures (160 reported drownings at low head dams versus 40 deaths from dam failures). Of significant concern are the growing populations near these structures and the increasing water recreation where there was once little public exposure. Dr. Tschantz's research has also shown the disturbing trend that the number of documented drownings at low head dams in the U.S. is increasing each year. These statistics demonstrate the need for the dam safety community to focus much attention on identifying and correcting the hazards created by these dams.

At the same time, fish passage at low head dams has become a growing concern. During the 19th and 20th centuries many low head dams were constructed on rivers and streams, blocking the upstream migration routes of anadromous fishes to the spawning areas. Significant efforts have been undertaken to construct fish passage facilities at many of these dams to re-establish the migratory fish populations and to allow other native fish species greater access throughout their river system. Biological requirements such as fish behavior, motivation, preferences, migration timing, swimming ability, and fish population size drive the design and construction criteria for installing fishways. Anadromous fish species such as the American shad and river herring and other fish species do not share the same leaping ability or swimming characteristics as salmonids and are much more dependent upon carefully designed fish passage facilities to pass man-made barriers. Recent experiences in designing, constructing, and operating fishways to pass American shad and other species demonstrate the need to accommodate their special preferences, motivation and swimming ability.

The need to modify low head dams to improve public safety and fish passage is pressing. Fortunately, recent technical advancements have been made to solve both issues, often conjunctively with a single modification.

PUBLIC SAFETY HAZARDS AT LOW HEAD DAMS

Several hazardous conditions can exist at low head dams. A brief description of common potential hazards is provided on the following pages.

Submerged Hydraulic Jump at the Downstream Face of the Dam. One of the most significant risks to public safety at low head dams is the hydraulic roller phenomenon that occurs at the downstream face of the dam under certain flow conditions based on flow rate and tailwater depth (see Figure 3). This rotational flow phenomenon is created by a submerged hydraulic jump. The length of the standing vortex or "hydraulic roller" can be about three to four dam heights in length and feature an upstream surface velocity comparable in magnitude to the maximum human swimming velocity of about 7 feet per second [Leutheusser, 1991]. The rolling water takes any object, including a person, to the bottom of the stream, releases it to the surface, draws it back to the face of the dam, and then pushes it back to the bottom. This cycle is a function of streamflow and can continue for an extended period of time. Air bubbles mixing in the water can decrease buoyancy by as much as one third [Wright et. al., 2003]. The victim may therefore have a difficult time staying afloat, even with a life jacket. These factors combined with the recirculating current create a nearly inescapable drowning machine.

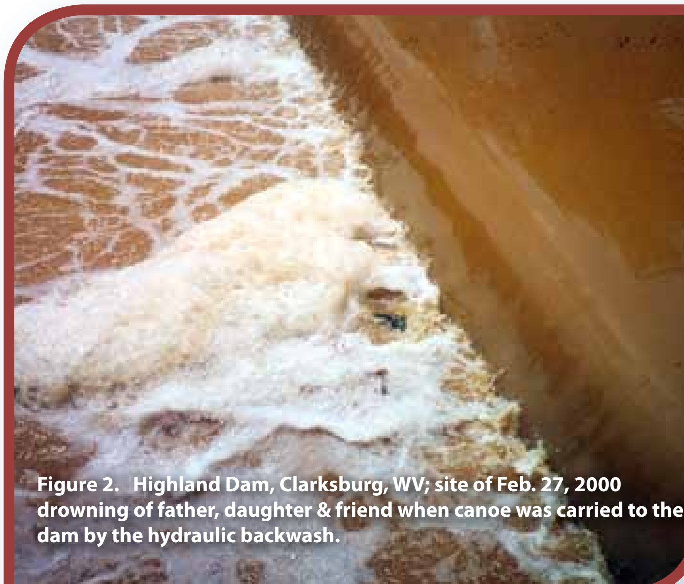

Figure 2. Highland Dam, Clarksburg, WV; site of Feb. 27, 2000 drowning of father, daughter & friend when canoe was carried to the dam by the hydraulic backwash.

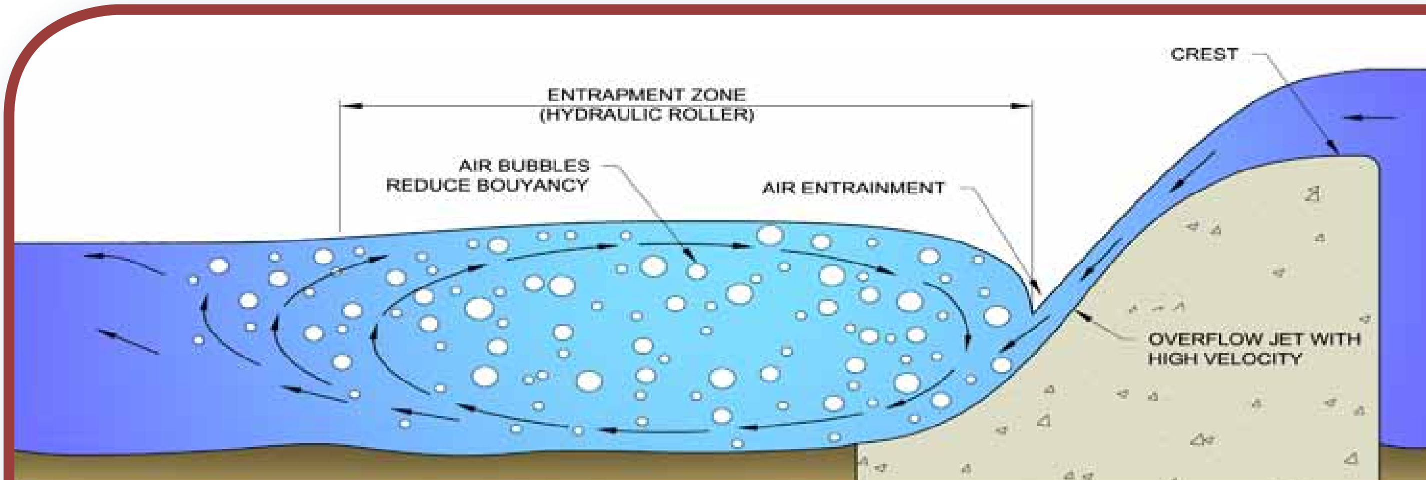

Figure 3. Schematic showing typical features of a hydraulic roller.

In most cases the hydraulic drop over the structure may be only a few feet with a smooth streamline over the crest and relatively placid appearing water below the structure, except for bubbles rising to the surface. When the conditions appear tranquil, they can be most dangerous [Wright et. al., 1995]. A reverse flow velocity in this scenario may be so modest as to go unnoticed by recreational boaters, fisherman, or swimmers. Under these conditions, one might see tree limbs or tires bobbing at the base of the dam. The upstream velocity from the boil area to the face of the dam, even if only a few feet per second, can create a trap that is often fatal to even strong swimmers.

Strainers and Excessive Seepage Paths Through Dam. Excessive seepage paths through the dam can create a danger to swimmers during low flow conditions. A swimmer can become trapped against the upstream face of the dam by the suction created by a substantial seepage path. Swimmers can also become trapped in strainers such as fallen trees and other obstacles that tend to accumulate at a dam. Water passes through the debris but solid objects like boats or people potentially become trapped.

Figure 4. Voids under dam foundations can create "strainer" and trap swimmers.

Strong, Unpredictable Currents Above and Below the Dam. These currents tend to draw unsuspecting boaters or swimmers into the hydraulic roller, strainers or other hazards at the dam.

Slippery Surfaces on Dam Structures, Shorelines and Steep Riverbanks. Slippery surfaces on dam structures, the river shoreline and steep riverbanks can cause site visitors to slip and fall into the river. This condition can also hamper rescue/recovery efforts.

Open Spillways Which May Not Be Visible from Above the Dam. Dams without piers and other structure indicators can make the submerged dam difficult to identify by upstream boaters until it is too late.

Submerged Hazards. Submerged hazards, like strainers, can trap and/or capsize boats and injure swimmers.

Steep River Banks with No Exit. Steep river banks upstream of the dam with no exit facility are a hazard for boaters who cannot navigate upstream because of mechanical trouble, fast river currents, high winds and other problems. Under such circumstances boaters have no means of exiting the river upstream of the dam and can be forced to go over the dam.

Unrestricted Public Access. Features such as fences, handrails and other barriers can be effective means to discourage access to unsafe areas of the dam. Lack of such barriers can be a safety hazard, especially for children.

LEGAL RESPONSIBILITY AND LIABILITY OF DAM OWNERS

General Liability and Responsibility of Dam Owners. The Commonwealth of Pennsylvania, Department of Environmental Protection Bureau of Waterways Engineering (PADEP), has prepared several fact sheets for dam owners, including a fact sheet titled "Liability and Responsibility of Dam Owners", to help dam owners reduce their exposure to liability [PADEP, 2006]. According to this publication, dam ownership carries significant legal responsibilities. Under state and federal laws, dam owners are responsible for maintaining their dams – and dam sites – in a safe condition. Potential liability problems for dam owners include personal injury and liability.

Are Warning Signs Enough? In general, dam owners are charged with doing what is necessary to avoid injury to people and property. This usually applies to circumstances and situations that can be anticipated with reasonable certainty. A dam owner is responsible for making and keeping the premises safe. The general rule is that a dam owner must avoid conditions which could injure any person, even one who trespasses. If the dam owner knows that an unsafe condition exists, he is responsible to correct it and/or post warnings (see Figures 5 and 6). This includes protecting children from the dangers of a dam site. Since signs may not adequately warn children, security fencing may be necessary. Many dams are not only lacking warning signs but are simply overlooked or neglected.

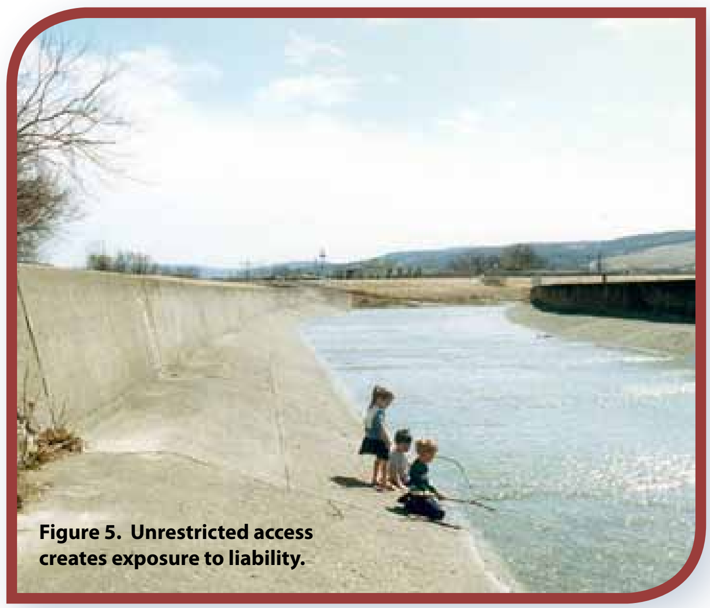

Figure 5. Unrestricted access creates exposure to liability.

"Negligence is the most commonly used cause of action both in general tort litigation and in dam failure cases. Negligence is defined in terms of the failure to exercise the standard of care of a reasonable person under similar circumstances. This standard in turn is based upon the reasonable foreseeability of the risk. The legal duty of reasonable care becomes the calculus of three components: (1) the risk of an accident occurring, (2) the magnitude of the harm should the risk materialize, and (3) the availability of alternatives" (Binder, 1996). If litigation ensues due to an accident at a dam site, both plaintiffs and defendants would introduce expert testimony on the standard of care to be exercised under the circumstances. The appropriate standard would then be determined, often by a jury.

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Figure 6. Sample warning signs used at low head dams.

Regulatory Requirements. Although many states have aggressive public education programs to inform and warn the public of the hazards at low head dams, along with well-trained and equipped emergency response and rescue personnel, most states have not established design or public safety requirements specifically tailored to address the unique hazards found at low head dams. Those states that have enacted laws and safety requirements for low head dams have done so recently.

In 1998, following several drownings at low head dams, the Commonwealth of Pennsylvania enacted a Dam Safety Bill requiring owners of certain low head dams to warn the swimming, fishing, and boating public of the hazards at such dams by installing warning signs and buoys, and to establish an exclusion zone in the area around the dam. For low head dams 200 feet or more in length, the exclusion zone ordinarily extends 200 feet upstream from the face of the dam and 100 feet downstream from the toe. The size of the exclusion zone upstream and downstream of smaller dams is 100 feet upstream from the face of the dam and 50 feet downstream from the toe; however, the state of Pennsylvania reserves the right to adjust the size of the exclusion zone based on conditions at the dam.

Guidelines for the design of warning signs and buoys were developed and published by the Pennsylvania Fish and Boat Commission (PFBC) to support this effort. A copy of these guidelines along with sign and buoy design examples are available at http://fishandboat.com/damnot2.htm.

TRADITIONAL MODIFICATIONS TO IMPROVE PUBLIC SAFETY

For a detailed discussion of modifications related to installing signs, buoys, fences, portages, and rescue facilities, the reader is directed to a previous paper [Schweiger & Morrison, 2006]. Structural modifications to eliminate the power of the hydraulic roller downstream of the dam crest are discussed in the paragraphs that follow.

Dam Removal. Removal of a dam is an obvious solution for enhancing public safety since all of the hazards associated with the dam are eliminated. Dam removal also effectively restores fish passage. Removal of a dam involves consideration of the health of the river, the fish and wildlife it contains, the impact on people who live nearby, the impact on recreational activities, sediment accumulation, public safety and sources of financing. Solving all of these issues often means that compromises will have to be made. Removal of a dam should be considered as a permanent action and not as an interim solution with the expectation that a new dam can or will be constructed at the same site at a later date. The current regulatory climate for constructing a new dam is not favorable, and permit-related studies alone can be very costly. Even if a dam previously existed at the proposed site, there is no guarantee that a permit can be obtained to construct a new dam.

Reshaping the Downstream Face of the Dam. Reshaping the downstream face of dams has been one of the most commonly used modification alternatives in recent years. Methods used to reshape the downstream face of dams have included (1) placement of large diameter boulders, each with a mass between 2,000 and 8,000 pounds (see Figure 7), (2) placement of grout bags against the downstream face, and (3) construction of concrete steps along the entire downstream face or at sufficient spacing to break up the downstream hydraulics (see Figure 8). The result is a very rough incline with a slope of 4:1 or flatter.

Reshaping the downstream face of low head dams with large-diameter boulders appears to be the most popular method. Where large boulders are not available, grout bags are used. These two methods can be placed in the wet during low flow periods and eliminate the need for dewatering. Constructing downstream steps by placing conventional concrete or roller-compacted concrete requires dewatering.

Figure 7. Infilling downstream face of Twolick Dam on the West Fork River at Clarksburg, West Virginia with large boulders to eliminate the hazardous submerged hydraulic jump.

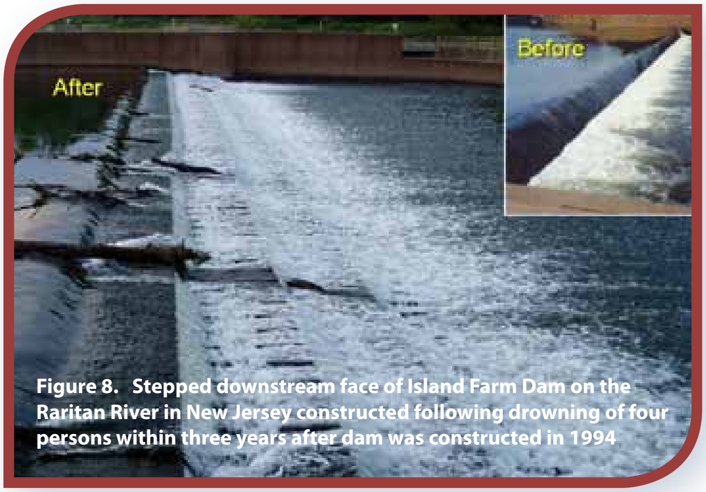

Figure 8. Stepped downstream face of Island Farm Dam on the Raritan River in New Jersey constructed following drowning of four persons within three years after dam was constructed in 1994

Canoe chutes combine elements of downstream face and crest reshaping alternatives. A boat chute transforms the dam from being a boating hazard to a recreational asset by directing canoers and kayakers approaching the dam to a man-made white-water channel. These channels feature a series of artificial rapids and still pools that boaters could use to progress from upstream of the dam to the downstream channel without encountering a hydraulic roller. A downside to a canoe chute is that it may become an open invitation or destination for canoers and kayakers, and the added interest and visitation to the dam site can increase the dam owner's exposure to liability. Constructing a canoe chute may also convey a measure of safety to boaters, skilled and unskilled alike, that may not exist.

Replace Dam with New Movable Crest Structure. By definition, moveable crest dams have the ability to vary the crest elevation of the dam from a fully down position, to replicate natural river flow conditions, to a partial or fully up position to raise upstream water levels (see Figure 9). Moveable crest dams can also be operated to change or vary the hydraulic conditions downstream of the dam and theoretically reduce or eliminate the dangerous hydraulic roller. The author is not aware of any studies or physical model tests that have been performed to evaluate optimum modes of operation to reduce or eliminate the hydraulic roller.

Figure 9. Bridgestone Inflatable Dam on Susquehanna River at Sunbury, Pennsylvania, with no drowning incidents since it was constructed in 1969, despite intense recreation activity.

Three types of dams with moveable crests have been widely used for controlling water levels and creating temporary low head impoundments. Each of these dam types can be used to replace existing low head dams and include: (1) hydraulically operated steel gates, (2) an inflatable rubber dam, and (3) a bascule gate dam with an inflatable rubber bladder (Obermeyer Hydro, Inc. Gate System). All three of these controlled-crest type dams have been used successfully in river environments.

Moveable-crest dams have the added capability of automated programmable operation based on (1) headwater and tailwater conditions; or (2) time of day, week, or season; or they can be manually operated. During flood conditions the dam can be in the fully down position so as not to induce an upstream backwater effect. The dam can also be operated in a cascade mode to maintain the upstream reservoir level at a constant elevation despite increasing or decreasing river flows. The dam can also be operated in a partially deflated mode to allow fish passage over the dam while realizing the benefits of a partial pool.

ROCK RAMP FISHWAY – THE PERFECT SOLUTION?

Traditional approaches to improving fish passage at low head dams such as Alaskan Steeppass, Denil, Vertical-Slot and Pool and Weir type fishways have required the use of reinforced concrete and steel structures that are designed to satisfy very specific, narrow objectives. For example, many of these fishways satisfactorily pass the target species but effectively exclude other desirable species and lack any useful aquatic habitat. Dr. Luther Aadland of the Minnesota DNR Ecological Resources Division, a nationally recognized expert in natural channel design and fish passage using nature-like fishways, recently published a book that includes design guidelines and examples for constructing nature-like fishways [Aadland, 2010]. This reference divides nature-like fishways into two subcategories: (1) by-pass channels, and (2) rock ramps. Bypass channels are designed to circumvent or "bypass" some of the river around the dam, while rock ramp fishways modify the riverbed grade directly downstream of the dam crest by constructing a wedge to create a passable slope over a dam.

The rock ramp fishway is an effective alternative to structures designed only to eliminate the hazardous hydraulic roller or to pass a particular species of fish (see Figures 10, 11, and 12). Rock ramp fishways emulate natural rapids, and, thus, not only completely

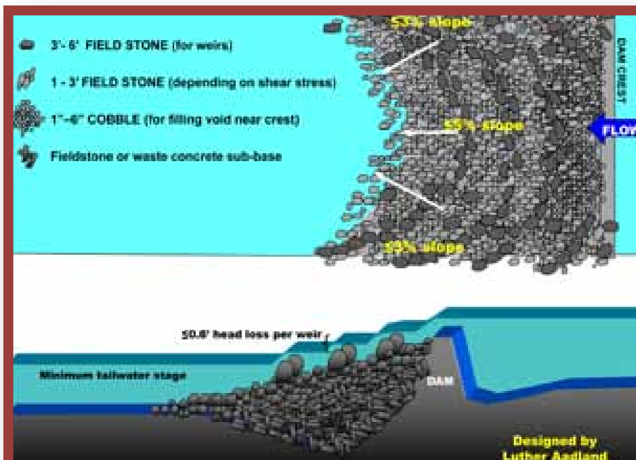

Figure 10. Generalized conceptual design of the Rock Arch Rapids developed by Dr. Luther Aadland.

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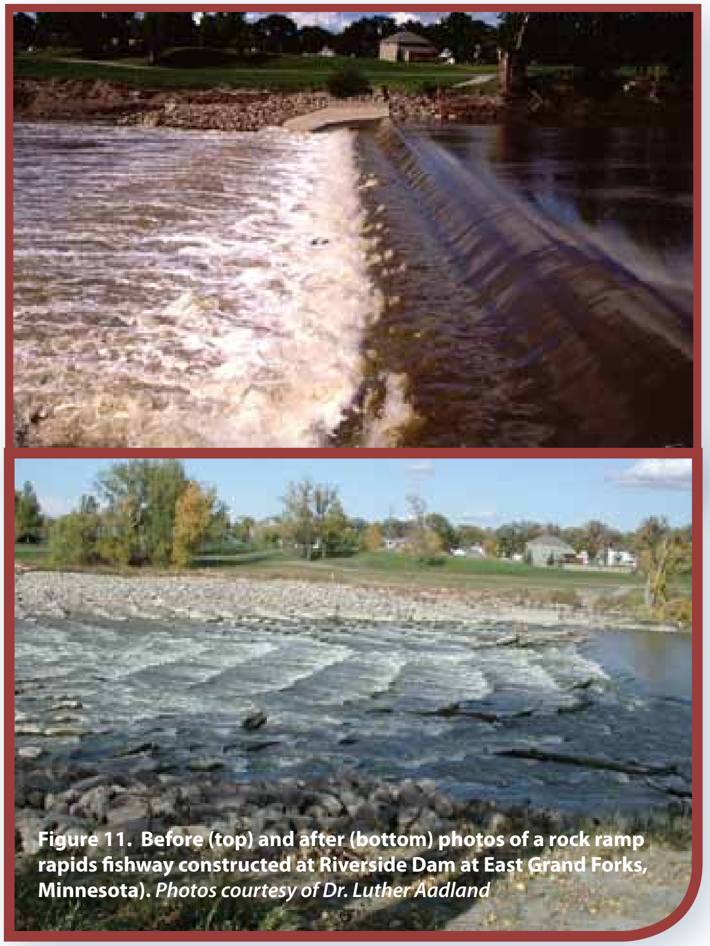

Figure 11. Before (top) and after (bottom) photos of a rock ramp rapids fishway constructed at Riverside Dam at East Grand Forks, Minnesota). *Photos courtesy of Dr. Luther Aadland*

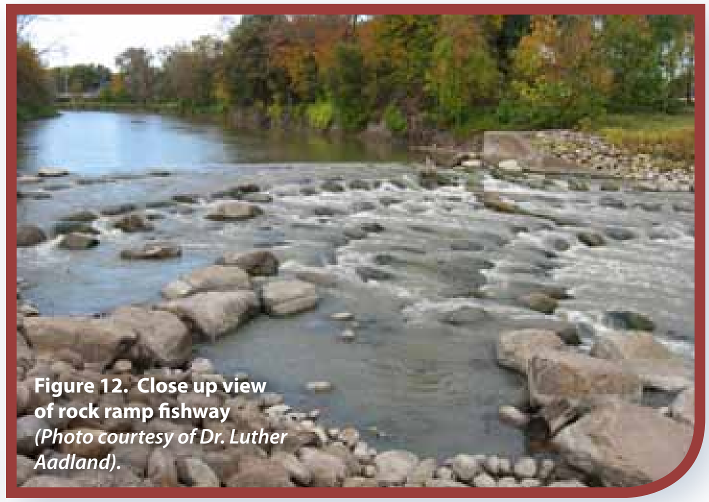

Figure 12. Close up view of rock ramp fishway *(Photo courtesy of Dr. Luther Aadland).*

eliminate the hydraulic roller and pass a wider range of fish species, but also provide habitat similar to that lost due to dam construction. The rock ramp fishway 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.

The new rock ramp nature-like fishway approach is based on the philosophy of observing and applying features found in the natural riverine system and designing the fishway to mimic a natural system. The design strives to pass a diversity of fish species at varying life stages in the most efficient manner possible and to provide suitable aquatic habitat for the many organisms that live in a natural river system.

Emulating natural channel geomorphology and materials has several distinct advantages over traditional man-made structures.

1. Fish react to complex current and bathymetry cues, and channels similar to natural channels are less likely to cause fish disorientation.
2. Natural channel design allows fishways to provide internal habitat as well as passage. This is important because some species may use the fishway for spawning habitat. A greater number of alternative spawning areas are also likely to provide greater reproductive success and resilience.
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 may be rare due to reservoir inundation. Rapids are a habitat that may have been largely eliminated by the construction of the dam. The conversion of a low head dam to a rock-ramp or rapids can restore this lost habitat.
5. Aesthetics of the dam site can be improved.

Modifying a dam with a rock ramp fishway is best suited for 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 are submerged during bankfull events usually experience maximum flow shear stresses at flows below the point of inundation. High dams that do not submerge have maximum shear stresses during record flood events, requiring larger stones or reduced slope.

Most rock ramp fishways have been constructed with natural fieldstone, which is more rounded than quarry stone but somewhat angular, and thus stable, in large gradations. Quarry stone can present problems due to sharp edges. Most applications of the Rock Arch Rapids have been built in flowing water and have not used filter fabric as it would be difficult to place in flowing water and it has not proven to be necessary or desirable.

Subsurface flows have not been a concern because of several factors that tend to limit their flows over time including: (1) placement of gravel and pea gravel on the surface of the completed rapids to reduce leakage, (2) sediments supplied by the river to fill interstitial spaces in the rock base, and organic matter including leaves, wood, and aquatic plants that are drawn into voids where subsurface flows enter the rock base. Subsequent fine sediments collect on these organics and further plug subsurface flow.

The maximum base slope is 20H:1V, and, in sites with high shear stress, the slope should be reduced. A flatter slope is preferable. The boulder weirs built on the rock ramp base create a step-pool configuration. The boulder weirs are constructed using stones that are substantially larger than the base stones and add stability to the rapids. For most projects, stones 3.5 to 6.5 feet in diameter with weights ranging from about 3,600 to 23,000 pounds have been used to construct the weirs. 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 the weirs for spawning habitat has generally remained in place.

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The weirs are built with a hemi-circular or U-shaped configuration with the center of the U pointing upstream (see Figure 13). The individual weirs slope downward from the banks to the center opposite the slope of the base. This creates flow convergence, as the energy slope and velocity vectors are perpendicular to the weir tangent. 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 full semi-circle and still maintain the proper invert slope along the weir. 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.

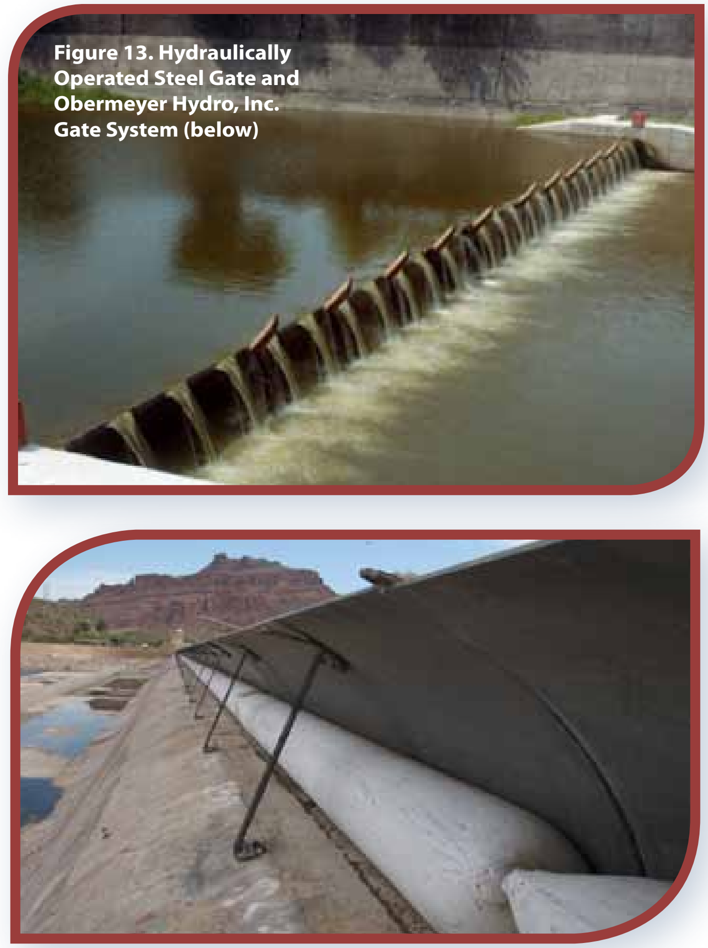
Figure 13. Hydraulically Operated Steel Gate and Obermeyer Hydro, Inc. Gate System (below)

A sufficient number of weirs are 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.

Dr. Aadland's experience with several rock ramp fishways shows that they are capable of passing all species of fish, effectively eliminate the hazardous hydraulic roller, and are relatively maintenance free. The early success of rock ramp designs demonstrates the potential for this new technology to become the solution of choice for modifying low head dams. Interested readers can download a copy of Dr. Aadland's new book titled *Reconnecting Rivers: Natural Channel Design in Dam Removal and Fish Passage* at the following website: http://www.dnr.state.mn.us/eco/streamhab/reconnecting_rivers.html.

SUMMARY

Several public safety hazards can occur at low head dams; the submerged hydraulic jump is the most deadly. Providing fish passage at low head dams is also an important issue. Fortunately effective solutions are available to resolve both of these deficiencies. Of all of the solutions available, the innovative rock-ramp design approach to converting low-head dams to rapids, similar to those that occur in nature, appears to most effectively correct both deficiencies while also creating additional habitat and improving aesthetics.

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