Don’t Go With the Flow!
Identifying and Mitigating Hydraulic Hazards at Dams

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ABSTRACT

Between 2015 and 2016 there were more than 100 documented drownings at dams in the United States, and many more near misses or serious incidents that almost led to tragedy. The increasing number of incidents from hydraulic hazards at dams is a disturbing trend. According to Dr. Bruce Tschantz, professor emeritus at the University of Tennessee and long-time researcher involved in monitoring incidents at dams, there have been more than nine times as many fatalities from hydraulic hazards at dams than there have been from dam failures over the past 35 years. Examination of these incidents shows that the vast majority were the result of transient hydraulic conditions that were not identified or addressed by the dam owner. In other words, the hazardous hydraulic condition did not normally occur at the dam, but occurred unexpectedly as a result of sudden operational or hydrologic circumstances.

The purpose of this paper is to provide descriptions of the seven primary hydraulic hazards at dams that have resulted in loss of life along with actual incident examples. A brief discussion of effective strategies to mitigate each hydraulic hazard is also provided. When performing a hydraulic assessment at a dam site, considerations should be given to simulating flows which represent a reasonable worst-case scenario where the public or maintenance staff have interaction at the site. The intent is to define the extent of hazardous water areas created specifically by the operation of the facility in the immediate vicinity of the dam, in the reservoir, and in downstream reaches of the river. The information included in this paper is intended to help dam owners, regulators and designers become aware of the potential hydraulic hazards at dams and develop successful mitigation and risk reduction strategies to address each hazard.

I. INTRODUCTION

Research presented by Dr. Bruce Tschantz, shows that between 1980 and 2016, there have been in excess of nine times more fatalities at dams than from dam failures: 347 reported drownings at dams versus 40 deaths from dam failures (Tschantz, 2017). These figures only include accidents obtained by Dr. Tschantz from documented news articles and local officials primarily at low-head dams, the focus of his research. The actual number of accidents are unknown and are likely much higher, but collective statistical data is lacking. Dr. Tschantz's research shows a disturbing trend that the number of documented accidents at low-head dams in the U.S. is accelerating. The state of Iowa alone reports an estimated 97 drowning deaths at dams, of which 18 occurred since 1998 [Beeman, 2012]. 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. Of significant concern are the growing populations near these structures and the increasing online postings of extreme sports activities by youth in and around restricted industrial sites at water control structures. These statistics demonstrate the need for the dam industry to focus attention on identifying and correcting the hydraulic roller hazard created by dams.

The seven primary hydraulic hazards at dams that have resulted in loss of life were identified and are presented in this paper. Examples of actual incidents relating to each hydraulic hazard as well as a brief discussion of effective strategies to mitigate each hydraulic hazard are also provided.

II. HYDRAULIC ROLLER

Description: Under most flow conditions 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 when the hydraulic roller forms, the dams can become significant hazards, which cause many drownings of persons unaware of the danger, often even despite posted warnings. This is an issue that is often overlooked or ignored during the design process of run-of-the-river dams, spillways and outlet works. Typically, a hydraulic jump is formed downstream of a dam to dissipate the excess energy and return the flow to subcritical conditions. This jump can take one of three different forms: a swept-out condition, an optimum condition (overflowing nappe impinges just upstream of the hydraulic jump), or a submerged condition, as described by Leutheusser and Fan (2001). When the jump formed is in the submerged state because of the presence of tailwater, a strong reverse roller can form at the downstream face of the dam. This roller has caused the deaths of many unsuspecting recreational water users and first responders, and is the leading cause of fatalities at dams. Because of this, these types of dams have often been nicknamed "drowning machines".

When flow conditions are such that the hydraulic jump at a run-of-the-river dam, spillway, or outlet works is swept downstream or at its optimum state of energy dissipation, the vast majority of the flow is directed downstream at high velocities. These high velocities usually allow debris to be flushed through the jump without the risk of being trapped by a roller. Similarly, when the tailwater is high enough that the nappe flips to the surface, as explained by Leutheusser and Fan (2001), the surface velocity is directed entirely downstream. This allows debris to continue downstream without risk of entrapment. In contrast, when the tailwater conditions are such that the hydraulic jump takes the submerged form (excluding tailwater depths so excessive that the nappe has flipped), a strong reverse roller is created at the downstream face of the dam. This is usually a transient condition that only occurs intermittently during higher flow conditions and is often counterintuitive in nature.

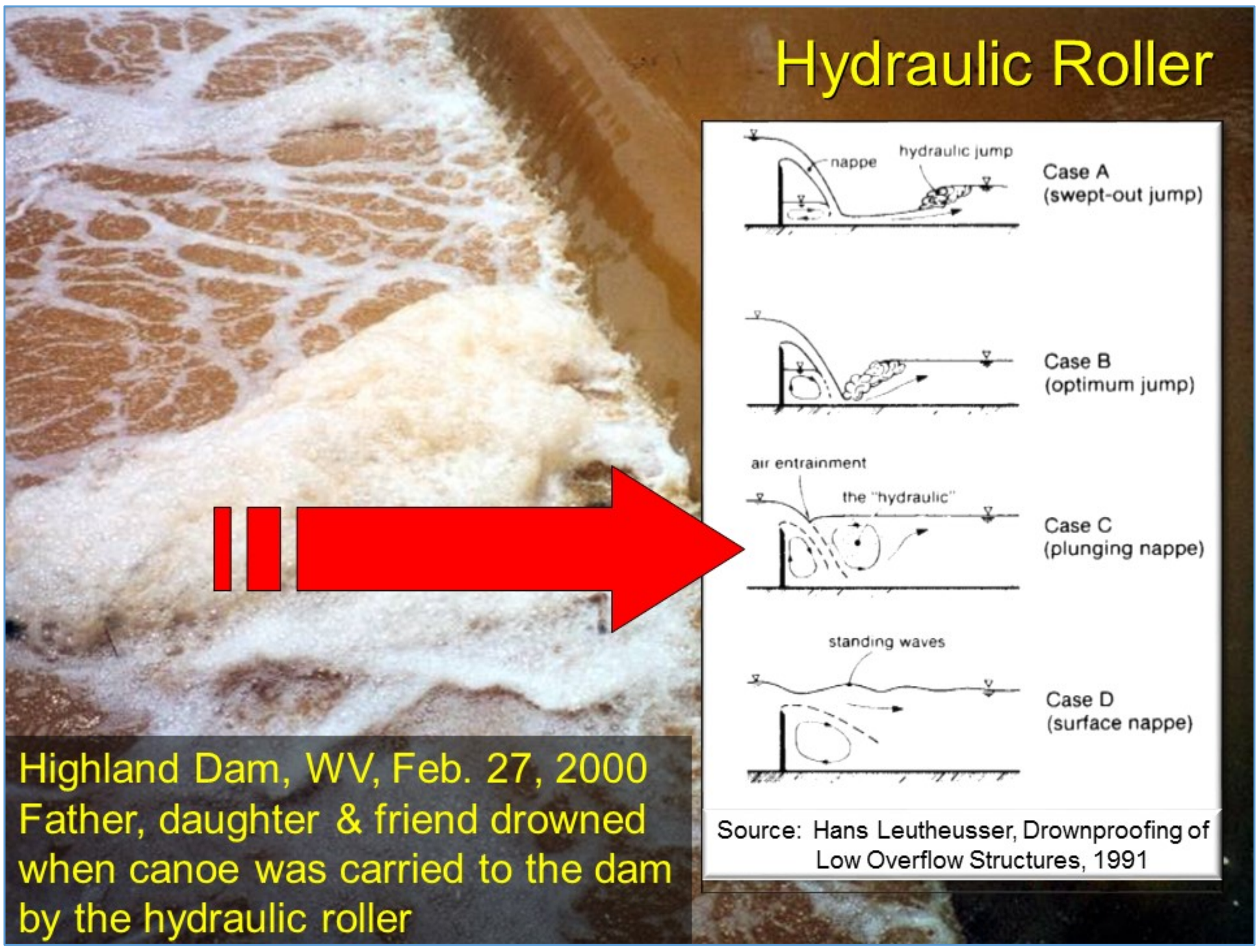

Figure 1. Illustration showing hazardous transient flow condition commonly found at low-head dams referred to as a "submerged hydraulic roller" (Case C) that can trap and drown victims.

The roller from a submerged hydraulic jump can feature an upstream directed surface velocity that is strong enough to trap debris or people near the face of the dam for prolonged periods of time. The length of the standing vortex or "hydraulic roller" can be about three to four dam heights in length and have an upstream surface velocity comparable in magnitude to the maximum human swimming velocity of about seven 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.

In most cases the hydraulic drop over the structure may only be 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 other floating debris 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 the strongest swimmers.

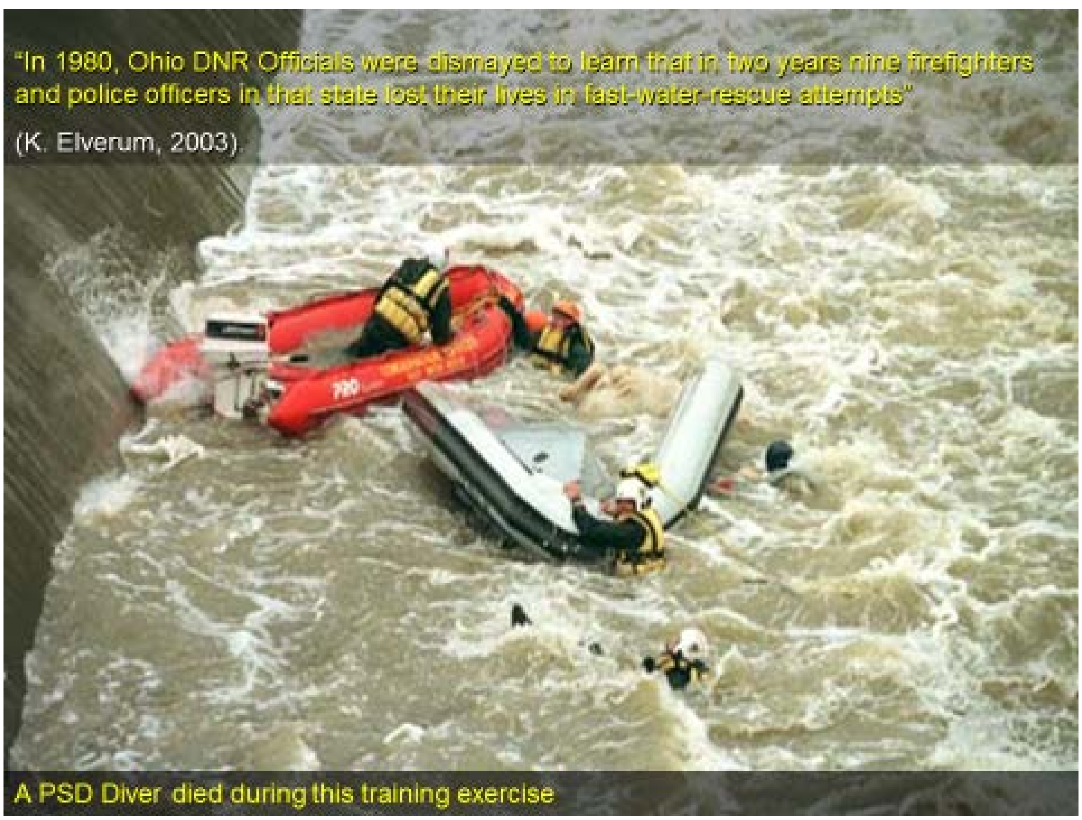

Figure 2. Photo taken during training exercise for fast water rescue responders at a low-head dam in Illinois. A PSD diver died during the exercise. Source: "Over, Under, Gone" video.

Incident 1: Island Farm Weir, Bridgewater, New Jersey (1995-1998). Construction of the Island Farm Weir (water supply intake dam) on the Raritan River in New Jersey was completed in October 1995. Six months later, on April 12, 1996, a recreational canoeist paddled over the dam crest while attempting to rescue his comrade who had capsized. In his attempt to rescue his friend, the man was drowned in the recirculating flow of the reverse roller. Several months later a jet skier went up to the base of the dam where he was also trapped and drowned in the reverse roller. Later, a local television station was at the Island Farm Weir to do a piece on water hazards. During the filming, a canoeist unexpectedly appeared upstream and paddled over the dam crest. He capsized his canoe and drowned in a spectacular recording on the evening TV broadcast [Wright et al., 2003]. During a three-year period, a total of four separate drownings occurred at the dam. The dam was retrofitted to eliminate the reverse roller in 1999. The retrofit consisted of flattening the downstream face of the dam by constructing a series of steps to dissipate energy and to eliminate the opportunity for a reverse roller to form below the dam. No incidents have been reported at the dam since it was retrofitted.

Incident 2: Low-Head Dam on Big Wills Creek, Etowa County, Alabama (April 25, 2015). A 25-year-old man was out kayaking with family members in Big Wills Creek when he was trapped and drowned by the submerged hydraulic roller at a low head dam that was once used to pump water into the nearby Gulf States steel mill. The Etowah County Rescue Squad began a search for the body at the dam, and employed two rescue boats. As one of the boats approached the dam it was carried to the face of the dam by the recirculating current and capsized. A second rescue boat soon followed and capsized leaving nine Rescue Squad workers caught in the hazardous hydraulic roller. There were no safety lines attached to the boats. Rescue personnel were not wearing helmets and lacked safety lines. Members of the Gadsden Fire Department and the Etowah County Sheriff's Office assisted in rescue efforts. Four of the nine first responders were taken to medical centers with injuries. One of the rescue workers succumbed to her injuries later in the evening. The body of the missing kayaker was found the next day approximately 300 yards below the dam. The captain of the Etowah County Rescue Squad was subsequently indicted in the death of the squad member who drowned, charged with one count of criminally negligent homicide, and booked into the county jail with bond set at $2,500.

Risk Reduction Strategies: The transient submerged hydraulic jump and hazardous reverse roller that can trap victims is relatively well understood and can be replicated using advanced computational fluid dynamics (CFD) software like Flow-3D or verified using physical modeling [Olsen et. al., 2013]. Reshaping the downstream face of dams has been one of the most common modification alternatives to prevent the formation of a submerged hydraulic jump and eliminate the hazard. Methods used to reshape the downstream face of dams have included (1) placement of large diameter boulders, (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. The result is a very rough incline with a slope of 4:1 or flatter.

Other effective risk reduction methods include removing the dam if it is no longer needed, posting warning signs and buoys, creating exclusion zones, patrolling, and public education. For a more comprehensive discussion of available risk reduction measures refer to "*Saving Lives While Improving Fish Passage At Killer Dams*" [Schweiger, 2011].

Figure 3. Photograph showing rescue of the nine rescue squad members during a body recovery effort at a low head dam in Etowah County, Alabama. One of the squad members died from injuries sustained during the recovery effort.

III. SWIFT CURRENT OVER SPILLWAYS

Description: Overflow spillways are particularly dangerous as they may be difficult to recognize and may not be visible from above the dam due to their low profile and lack of superstructure. Dams without piers and other structure indicators can make the submerged dam difficult to identify by upstream boaters until it is too late. A condition often referred to as an "infinity pool" can occur, where the edge of the spillway is not visible from upstream. If the crest of the spillway is left unmarked and unprotected, boaters in the reservoir can be drawn over the spillway. Jet skiers and power boats have driven off the crest of spillways unaware of the sudden drop with tragic consequences. More often, motor boaters experience engine problems and lose control of their boats and are carried by the current over the spillway. Narrow or channelized reservoirs upstream of overflow spillways will naturally produce higher approach velocities to the spillway during a flood condition than will a wide reservoir.

Incident 3: Lake Linganore Dam, New Market, Maryland, (June 29, 2015). Nine people were on board a pontoon boat when the vessel went over the spillway of Lake Linganore Dam. The crew included a grandfather (age 62) with his 16-year old granddaughter and her friends who were all under 18 years of age. Numerous emergency medical crews, fire personnel and deputies responded to the scene which was in a remote area that included much foliage and hilly terrain. Three of the eight rescued were stranded in the spillway, clinging to rocks as a Maryland State Police helicopter hoisted them up to the aircraft one by one. Others were pulled out of the water by first responders and neighbors. The grandfather was first seen alive wedged between two large rocks about 100 yards downstream of the spillway. Though he survived the fall over the spillway, the rapidly-rising and turbulent waters likely caused his death before he could be rescued.

Lake Linganore only allows boats with electric motors like that of the pontoons. Given the turbulence and runoff caused by storms, the motor was likely not powerful enough to steer the boat out of harm's way once it was swept toward the spillway. The boat was owned by a friend and presumably borrowed by the grandfather for the day.

Figure 4. Photograph showing rescue of three teenagers swept over the spillway at Lake Linganore.

Incident 4: Goose Creek Dam, Loudoun County, Virginia (April 11, 2017). A family of five was rescued from their boat teetering on the crest of the spillway of Goose Creek Reservoir Dam. According to reports, the Loudoun County Emergency Communications Center received a call at approximately 5:30 p.m. from an individual stating he and his family were stranded in a boat on top of the Goose Creek Reservoir Spillway. The man said the motor on the small fishing boat had failed leaving them to drift and ultimately stop atop of the 20-foot high concrete ogee spillway. A portion of the boat was hanging over the edge of the dam. Fire and Rescue units were dispatched with rescue boats. When the first unit arrived they found a small boat teetering precariously on the edge of the dam. The boat was occupied with two adults and three small children.

The swift moving current made the boat unstable, and all the occupants were seated in the bow of the boat to keep it from falling over the dam. With the exception of one adult, all were wearing life vests. Initial attempts to reach them using an aerial ladder were unsuccessful because the stranded boat was too far from shore. First responders were eventually able to successfully deploy an additional lifejacket to the stranded vessel using a throw rope from the end of the aerial device. Crews were also deployed downstream with rescue equipment in the event that the vessel fell over the dam. Upon arrival of the water rescue team, a boat and crew quickly launched and made their way out to the stranded family. Rescuers connected a tow rope to the fishing boat and pulled the family safely to shore.

Figure 5. Photograph showing family of five being rescued from spillway crest of Goose Creek Dam. Photo courtesy of Loudoun County Fire and Rescue.

Risk Reduction Strategies: Installation of a boom or buoy line upstream of the spillway can be used to limit boat access in the approach of a spillway. Installation of warning buoys and signs can be used to alert boaters to the hazard and create an exclusion zone. In determining the extents of an exclusion zone, two- or three-dimensional hydraulic computer modeling can be used to estimate surface velocities that would be experienced in a range a potential operating conditions. In the event that an incident does occur, it is also prudent to ensure that both the upstream and downstream spillway approaches can be easily accessed by first responders.

IV. STRAINERS

Description: Excessive seepage or leakage paths through a dam can create a danger to swimmers or divers during low flow conditions. A swimmer or diver can become trapped against the upstream face of the dam, trashracks or other features, by the suction created as the result of a substantial seepage or leakage. Swimmers and divers can also become trapped in strainers created by fallen trees and other debris that tend to accumulate at a dam. Water passes through the debris, but solid objects like boats or people can become trapped.

Incident 5: Borough of Lykens Dam, Lykens, Pennsylvania (1972). Once flows had returned to normal following a flood event on Rattling Creek, a young man and his friends went swimming in the pool upstream of Lykens Dam, a favorite swimming location for local youth. On this day, unknown to the swimmers, a submerged leak had developed in the upstream face of the dam. The young man dove into the pool near the upstream face of the dam and did not resurface. Rescuers found him pinned against the upstream face of the dam as a result of the suction created by a leak. The young man was resuscitated but sustained brain damage.

Incident 6: Low Head Dam on House Creek, Temple Lake Park, Killeen, Texas (April 12, 2017). Lori Pohanka-Kalama was a volunteer diver for the Morgan's Point Police Department. According to a news release from Fort Hood, Pohanka-Kalama was rescued after being sucked into a hole where she became trapped at a low head dam on House Creek. Upon being rescued, she was rushed to Carl R. Darnall Army Medical Center before being transferred to Baylor Scott & White Hospital in Temple. She passed away from her injuries. One of the rescuers said, "*It was a freak accident… There was some deficit at the bottom of the dam where water was flowing through. The vacuum of the water is what pulled her into a hol*e."

Risk Reduction Strategies: Performing regular dam inspections to identify potential seepage or debris problems and subsequently correcting those problems can reduce the risk of entrapment due to strainers. If a significant amount of seepage has been observed at the dam, divers should be apprised of this fact and the associated risk prior to inspection or other underwater work. In order to protect the public, an exclusion zone can be created around a dam in areas where seepage could occur or strainers could otherwise develop. Providing training and appropriate equipment to first responders and underwater inspectors and contractors can also reduce the risk of an incident occurring.

V. SUDDEN DOWNSTREAM RELEASES AND STRANDING

Description: Sudden releases from dams can create a fast moving and deadly flood wave that can overwhelm and kill unsuspecting victims recreating or working downstream. The rapidly changing water levels and flows can result in downstream users being stranded on opposite shores from where they entered, or on islands within the river system.

Incident 7: Brookfield Power Hydroelectric Dam on the Oswego River, Oswego, New York (September 28, 2010). Two men were fishing in the river downstream of the hydropower dam on the Oswego River when rapidly rising water carried them away. One of the men died that day in Oswego Hospital. The other died a week later. A lawsuit, filed in federal court in the Northern District of New York against Brookfield Renewable Energy, was settled for $1.8 million. The lawsuit stated that the men died as "a result of drowning after a massive quantity of water was negligently, carelessly and/or intentionally released, without proper advance warning, into the Oswego River by the owners and/or operators of the power plant facility."

Witnesses said that warning sirens went off too early, then did not sound at all when the water rose later that day, sweeping the two men away. Brookfield Renewable Energy subsequently installed warning lights, new 911 and rescue stations, and ladders near the hydroelectric plant to improve safety as a result of the deaths and the lawsuit, according to news reports.

Figure 6. Photograph showing fishermen downstream of hydropower dam on the Oswego River near Oswego, New York.

Incident 8: Barrett Chute Hydroelectric Dam on the Madawaska River, Ottawa, Canada (June 23, 2002). In June 2002, a rarely used gate at the Barrett Chute Hydroelectric Dam on the Madawaska River was opened to drain off excess water, engulfing a group of sunbathers in a surge of water that swept them over a 30-foot-high cliff and onto rocks below. Weather was determined to be a key factor in the chain of events because it had drawn people to the popular spot known as High Falls, just downstream from the Barrett Chute dam. Warm pools of water can be found there within the scoured bedrock river channel. At the time of the sudden release from the dam, about 20 people were sunbathing on the rocks below or swimming nearby. A 32-year old mother and her 10-year old son were swept away by the flow and subsequently died of drowning. Several other people received minor injuries.

Two Ontario Power employees were tried for criminal negligence causing death. Initially, the company and the two employees were each charged with two counts of criminal negligence causing death. All charges were subsequently dismissed.

Incident 9: Center Hill Dam, Lancaster, Tennessee (August 16, 2012). Quick-thinking, experience and teamwork of individuals at the U.S. Army Corps of Engineers' Center Hill Dam aided in the rescue of two people after their boat capsized while fishing in turbulent tail waters during sluice gate releases. Fortunately, both were wearing personal flotation devices and nearby fisherman appropriately responded to the crisis. An experienced Corps employee at the facility spotted the daring rescue attempt in progress.

"I was returning to the power plant and saw a woman trapped on a small ledge across the river and a man in a small Jon boat trying to rescue her," said Bob Tower, a retired Corps employee from the Cordell Hull Power Plant who now works as a rehired annuitant on the Center Hill Seepage project. *"I called the power plant shift operator and asked him to turn his camera on the area and to close the sluice gate so the woman could be rescued,"* Tower added. Corps Construction Office employees who also observed the situation placed a 911 call and then notified Center Hill natural resource manager's office of the situation.

After observing the rescue of the woman and while reporting it to the shift operator, Tower said he saw something blue floating in the water (later found to be part of the destroyed boat) and then spotted what appeared to be a man in the water below spillway gate five. At this point, Tower asked the shift operator to shut off all the water.

The man in the Jon boat delivered the woman to the boat ramp and then went back up the river and rescued the man in the water before all the water was shut off, according to Tower. Center Hill Rangers recovered the boat which had been broken in half from being tossed around in the sluice gate release.

"Warning signs are posted above and below all Corps and TVA dams but the extreme danger of operating a small boat near a dam during water releases cannot be over-emphasized," said Kevin Salvilla, Natural Resource Manager at the Lake. *"These two individuals were very fortunate."* (*Source: Nashville District Public Affairs*)

Risk Reduction Strategies: One approach to reducing risk due to sudden releases from a dam is to develop procedures for clearing or warning downstream users of imminent releases. This could include the installation of audible alarms, sirens and flashing lights for early warning notification of those both upstream and downstream of a dam before gates are operated or having some other method of communication with recreational facilities located in the downstream area of influence. Having some means of active visual monitoring of the impacted areas before operating the gates to ensure the public is clear of the impacted zone could also facilitate this approach. This can be done via monitored CCTV or operational maintenance staff on site. Established procedures could also include a period of time in which access to downstream river reaches is denied prior to large releases. Furthermore, hydraulic modeling software can be used to gain an increased understanding of the magnitude and extent of impacts of a range of potential releases.

An additional risk reduction strategy would be to establish operating rules and procedures so that changes to the downstream flow conditions are not sudden but gradual. This could be achieved by specifying minimum gate opening times or other such operating limitations. Coordination should be maintained with other facilities that regulate or release flow to the downstream area to ensure that independent, simultaneous releases that may seem harmless and routine do not combine to create hazardous conditions downstream. Rescue stations, ladders and other forms of egress can also be provided.

VI. FLOW INTO CONDUIT OPENINGS

Description: The inlets to conduits can be extremely dangerous to swimmers, divers and boaters. From the surface, such areas may provide little visible evidence of the dangerous undercurrents and suction. Once sucked into or against the conduit opening, it is virtually impossible to overcome the hydraulic pressure, and the victim can become trapped and drown or be fatally injured from passing through the conduit.

Incident 10: Diver Larry Coach, Small NRCS Dam in Garrison, Texas, (Date Unknown). Based on a video of the body recovery of the incident, a local man with scuba diving skills was engaged to remove debris from a clogged opening located at the base of a small intake structure in the reservoir. The depth of flow at the opening of the intake was less than 6 feet. The diver was overcome by the suction force at the entrance of the opening and became trapped inside the opening and drowned. Rescuers were unable to pull the body of the diver from the opening until they installed a pneumatic plug into the downstream conduit to equalize the pressure.

Incident 11: Lake Wanahoo Dam, Lincoln, Nebraska (June 12, 2012). An 11-year-old boy pestered his mother about going to his favorite spot, just south of the Lake Wanahoo Dam spillway on Sand Creek, to go fishing. His mother had other plans for Bayden and his siblings. He became upset and decided to go anyway by himself. Bayden's body was recovered in the spillway of the dam. One of the boy's legs apparently got caught in a 12-inch concrete drain pipe. He was pulled down into the water and drowned. An employee of the Nebraska Game and Parks Commission spotted the body, and the spillway was shut down to retrieve him. It appeared that the boy climbed up into the outlet works, a place that is normally not accessible. The lawsuit involving the drowning of the 11-year-old boy was settled for $300,000.

Figure 7. Photograph showing inlet pipe at Lake Wanahoo Dam where boy became trapped and drowned. Photographs courtesy of Tim Gokie.

Risk Reduction Strategies: The primary means of reducing risk is the installation of warning buoys and signs along with a boom or buoy line upstream of conduit entrances to create an exclusion zone. In determining the extents of an exclusion zone for a conduit opening, advanced CFD or physical modeling can be used to identify hazardous conditions and estimate surface velocities that would be experienced in a range a potential operating conditions. Furthermore, training should be provided to divers, first responders and others who work around submerged conduits.

As described in Incident 10, a diver endeavored to remove debris from the inlet of a relatively shallow conduit entrance (less than six feet of water) and became trapped and drowned. When attempting to remove debris from a conduit, the safest approach is to first equalize the pressure on both sides of the conduit entrance. This can be accomplished by inserting and inflating a pneumatic plug in the downstream conduit and allow the water levels to equalize. This stops any discharge through the conduit and thereby eliminates the hydraulic hazard. It also makes removal of debris from the opening much easier since the suction force is no longer present.

VII. ENTRAPMENT FROM BUOY LINES AND OTHER FLOW CONTROL STRUCTURES

Description: Similar to strainers, water surface flow velocities under or through buoy lines and other flow control structure such as debris booms, and fish screens can trap, submerge, or capsize boaters, kayakers, canoers, and persons tubing or using other watercraft under certain flow conditions. Although these features are often installed as public safety features, if they are incorrectly configured, they create a hazard. For example, a buoy line installed upstream of a dam in a straight line from bank to bank normal to the flow can bulge at the center and create an entrapment that forces floating objects (including boaters) against the buoy line. If the surface current is fast enough, it can capsize the trapped object under the line and push it downstream.

Incident 12: Lac St. Jean Dam No. 7, Quebec, Canada (2008). Lac St. Jean is a large reservoir approximately 15 miles wide and 31 miles long. The reservoir and its environs are used by the public for recreational activities including camping, fishing, kayaking, canoeing, hiking, and cycling. A safety boom or buoy line was installed approximately 500 feet upstream of Lac St. Jean's Dam No. 7 to discourage public access and protect boaters from being swept through the spillway gates. Under certain flow conditions at the dam, the buoy line was subject to swift currents and became completely submerged. In 2008, a 16-year-old girl in a canoe capsized against the submerged boom line as a result of this condition. The girl was subsequently swept through the spillway gates and drowned.

Figure 8. Photograph showing buoy line upstream of dam on Lac St. Jean, Quebec, where a canoeist became capsized and subsequently drowned.

Risk Reduction Strategies: Buoy lines and other features that have the potential to entrap boaters and other watercraft on the water surface can be designed so that the potential for entrapment is minimized. For relatively short spans, this can be accomplished by installing the buoy line or other feature at an angle to the flow. This configuration would help direct boaters to one side of the riverbank rather than creating an entrapment bulge. The termination of the buoy line or other feature at the riverbank can include a facility to enable boaters to safely exit. For wider bodies of water upstream of a dam, the buoy line can be installed in a "V-shape" with the invert of the "V" located near the center facing the upstream direction. This configuration would then to force floating objects to either riverbank.

VIII. FLOW UNDER LOCK GATES AND GATE OPENINGS

Description: Similar to flow entering conduits, headgate structures near entrances to locks, spillways and intake structures create hazards as water flows under or through the gate openings. An undercurrent, undertow, or sudden and unexpected discharge can occur when the gates are raised, especially if done under remote or automatic control. This hydraulic hazard is most commonly found at locks, gated spillways, and intake structures.

Incident 13: Melvin Price Lock and Dam, Alton, Illinois (June 19, 2016). A man was knocked off his jet ski near the upstream face of Melvin Price Lock and Dam on the Mississippi River when he hit a floating log. Even though he was wearing a life jacket, the man and his jet ski were subsequently sucked down through the gate opening about 17 feet below the water surface before resurfacing on the opposite side of the dam. He was rescued nearly one half of a mile downstream. Although he was physically exhausted from the ordeal, he suffered only minor injuries as a result of the incident.

Incident 14: Tom Miller Dam, West Austin, Texas (March 7, 2005). A couple miraculously survived an incident in which their boat was sucked under the gate at Tom Miller Dam. When Dirk Hoekstra turned off his boat's motor while waiting near the dock to load it onto a trailer, the boat was pulled back toward the open spillway gate by a strong current. Mr. Hoekstra tried unsuccessfully to restart the motor and grab onto the warning buoys as the boat was pulled closer to the gate, but the strong current slammed the boat into the gate where it remained precariously wedged in rapid flow between the gate and the spillway crest.

In the midst of all of this, Mr. Hoekstra was swept out of the boat, through the spillway gate, and down the 60-foot plunge to the water below. Although his clothes were ripped off by the force of the water, he was able to maintain consciousness through the turbulent fall. He resurfaced about one quarter of a mile downstream and was able to swim to shore where he sought help from the tenants of a nearby apartment. He suffered only minor injuries from the fall.

Meanwhile, Monica Barnes remained trapped on the boat at the spillway crest. She was able to grab a rope that was dropped to her by security staff from the dam above. She dangled perilously over the rushing current before swinging into a rescue boat. In order to reach the woman, the rescue boat dangerously backed toward the spillway and actually collided with the spillway gate before motoring upstream away from the dam with Ms. Barnes in tow. Shortly thereafter, the couple's boat was sucked through the spillway and completely destroyed.

Risk Reduction Strategies: One way to reduce the risk of this hydraulic hazard is the installation of warning buoys and signs along with a boom or buoy line upstream to create an exclusion zone. In determining the extents of an exclusion zone, two- or three-dimensional hydraulic computer modeling can be used to estimate surface velocities that would be experienced in a range a potential operating conditions.

An additional approach to reducing risk due to flow under lock gates and gate openings is to develop procedures for clearing or warning upstream users of imminent releases. This could include the installation of audible alarms and sirens and flashing lights for early warning notification of nearby boaters before gates are operated. Having some means of active visual monitoring or patrolling of the impacted areas before operating the gates to ensure the public is clear of the impacted zone could also facilitate this approach. This can be done via monitored CCTV or operational maintenance staff on site.

IX. SUMMARY

This paper is intended to bring awareness of the hydraulic hazards that can occur at dams. Seven hydraulic public safety hazards are presented of which the submerged hydraulic jump is the most deadly. Fortunately effective solutions are available to resolve all of these hazards.

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Paul Schweiger is a Vice President and Manager of Gannett Fleming's Dams and Hydraulics Section in Camp Hill, Pennsylvania. Paul received his bachelor's and master's degrees in Civil Engineering from the University of New Brunswick, Canada. He has over 30 years of experience working on dams, flood control projects, and water supply systems. His technical specialties include conducting dam assessments, designing new dams, and dam rehabilitation. He is an approved FERC facilitator for performing potential failure modes analysis exercises for dams, and serves as an expert hydrology and hydraulics engineer on Independent External Peer Review panels for several United States Army Corps of Engineers dam and flood control projects. Paul is also the Chairman of the ASDSO Committee on Public Safety Around Dams.

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Steve has been performing physical model studies at the Utah Water Research Laboratory (UWRL) in Logan, Utah since 1985. The UWRL at Utah State University is well known for its modeling expertise as well as its ability to construct and test large-size physical models. Since 1985, Steve has been either a principal investigator or team member on more than 100 physical model studies and has been instrumental in helping countless engineers from consulting firms, government agencies and municipalities to appreciate the monetary and hydraulic efficiency-based value of the physical modeling process. Currently as a professional engineer and research professor at USU, he performs physical model studies, while mentoring undergraduate and graduate students in physical modeling and flow measurement techniques, providing for them a one-of-a-kind, hands-on experience in hydraulic structure design and laboratory experience. Steve currently serves as the Spillways Subcommittee chair within the USSD Hydraulics of Dams committee.

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