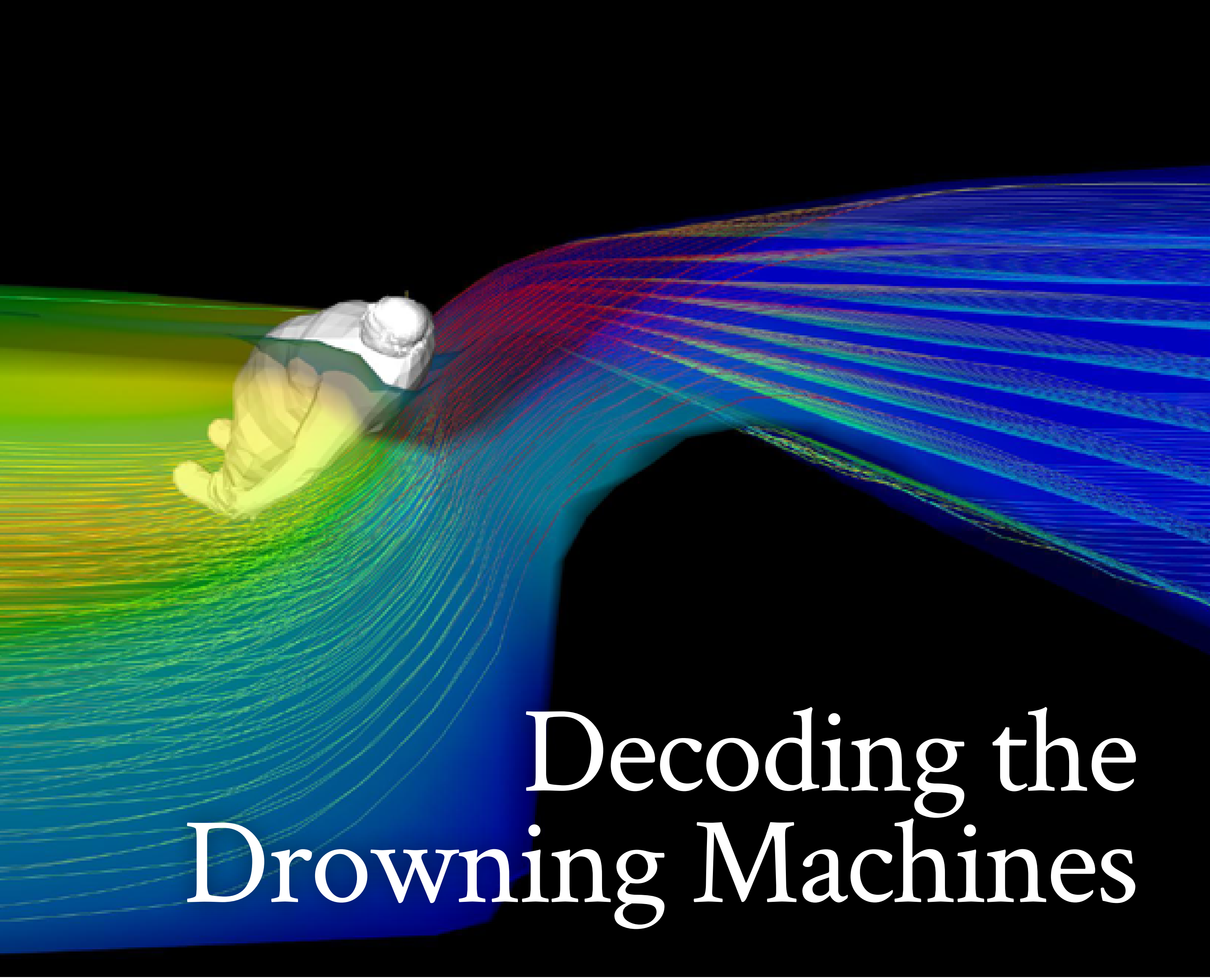

# Decoding the Drowning Machines

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## *Using CFD Modeling to Predict and Design Solutions to Remediate the Dangerous Hydraulic Roller at Low Head Dams*

*Abstract:*
Hundreds of deaths have occurred at low head dams throughout the United States because of improper understanding of the hazardous hydraulic condition at these dams. A transient recirculating current (submerged hydraulic jump) can develop immediately downstream that can trap and drown victims. More than 50 deaths have occurred at low head dams in the US within the past two years alone. Some dams, like the Dock Street Dam in Harrisburg, Pennsylvania, have claimed more than 30 lives. With an increasing number of fatalities occurring at these dams, the need for dam owners and engineers to identify and mitigate hydraulic hazards at low head dams is urgent.

Public safety at low head dams starts with a proper awareness and understanding of the hydraulic hazards at the site. Once identified and defined, these hazards can be addressed with a variety of strategies ranging from creating exclusion zones using warning signs and buoys, to eliminating the hazard with structural modifications.  Until recently the only way to evaluate the complex three-dimensional flow conditions at a low head dam was with a physical model study. Conventional numerical hydraulic analyses using one-dimensional and two-dimensional models are unable to simulate the three-dimensional complex transient flow conditions that occur at these dams. Structural modification to eliminate the hazards was therefore often based on rules of thumb or best judgment.

Recent advances in three-dimensional Computational Fluid Dynamics (CFD) now provide a powerful and economical approach to simulate complex hydraulic conditions that occur at low head dams. A feature of CFD modeling is the ability to simulate floating objects, including human prototypes trapped in recirculating currents, and to provide visual output that can display complex hydraulic data in a manner that is easily understood by first responders, government officials, and the public.

This paper demonstrates how CFD modeling can be used to evaluate the complex hazardous hydraulic environment at low head dams. A CFD modeling case study at a low head dam that has claimed 30 lives is presented to illustrate the hydraulic hazard. CFD modeling used as a tool to confirm the effectiveness of structural modifications to remediate hydraulic hazards is also discussed.

## *Background:*

Most low head dams are run-of-the-river structures that span the entire width of a stream or river. Though there is no official definition for low head dams, they are typically less than 15 feet high and have a near vertical drop at the downstream face. Thousands of low head dams were built during the 1800s and early 1900s to raise the water level to power mills, harvest ice, facilitate navigation, provide municipal and industrial water supply, protect utility crossings, and enhance recreation.

As flow passes over these dams, the plunging nappe over the dam crest entrains air. The rising air bubbles create a current on the surface that gives the appearance of a "boil" immediately downstream of the dam (see Figure 1). The aerated water in this zone significantly decreases the buoyancy of floating objects. For certain flow conditions the plunging nappe causes a vertical vortex to develop, creating a recirculating current (return flow) on the surface that is directed upstream towards the dam. This return flow transports floating objects upstream towards the dam only to be subjected again to the forces of the plunging nappe. The combination of: (1) the plunging nappe force, (2) reduced buoyancy due to aeration, and (3) the recirculating current immediately

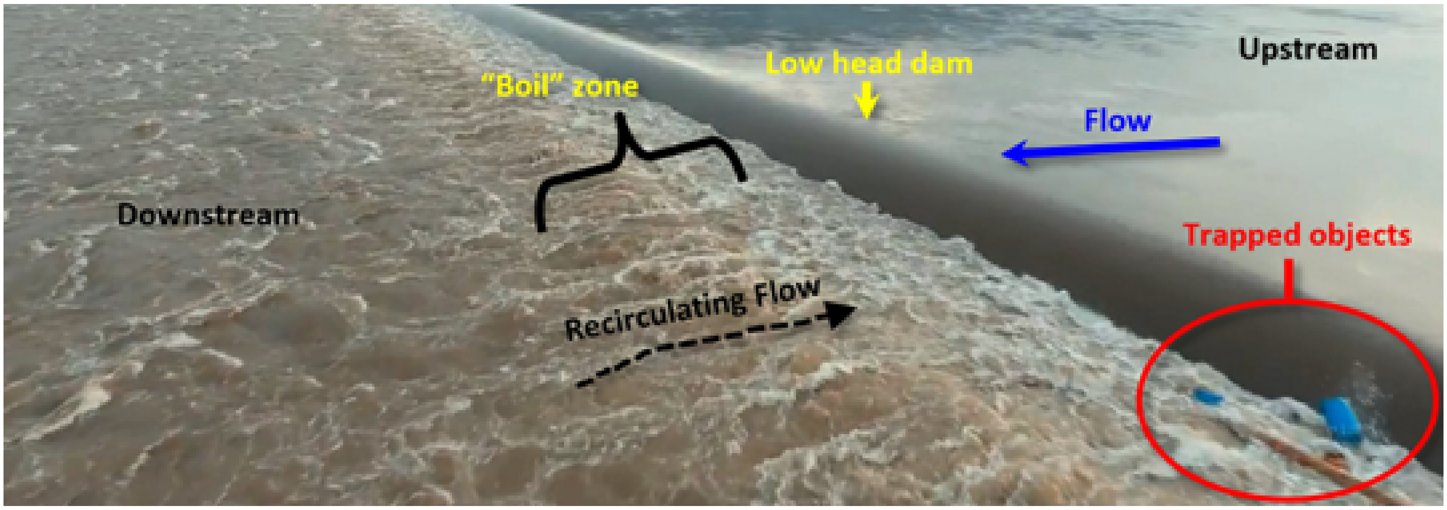


**Figure 1. Photograph of a typical low head dam**

downstream of the dam renders this zone an inescapable trap for victims. When trapped in this zone, unwary swimmers, kayakers, canoers, anglers, rafters, tubing enthusiasts, stalled boaters and jet skiers, and even trained water-rescue personnel often find it impossible to overcome the hydraulic forces and drown. Victims are often deceived by the calm appearance of the water surface both upstream and downstream of these dams. Due to the hazardous nature of these dams, they are often called "drowning machines," "killer dams," or "death traps" (Borland-Coogan, 1980; Schweiger, 2011).

## *Nature and scope of the problem:*

As of August 2019, more than 700 documented drownings have occurred at low head dams in the US. This number is based on records collected by the authors, the late Dr. Bruce Tschantz, Professor Emeritus from the University of Tennessee, and former Brigham Young University students Ed Kern and John Guymon, under the direction of Dr. Rollin Hotchkiss. Since this number is based on news reports and other publicly available information, the actual total number of fatalities at low head dams is likely much higher. Figure 2 presents the cumulative count of reported low head dam drownings from 1900 to 2019.

A disturbing trend observed in Figure 2 is the fatality rate at low head dams increasing at an accelerated rate. The current decade has seen this record jump to an unprecedented average of more than 20 lives per year with a peak of approximately 50 drownings in 2018. Of significant concern are the growing populations near these

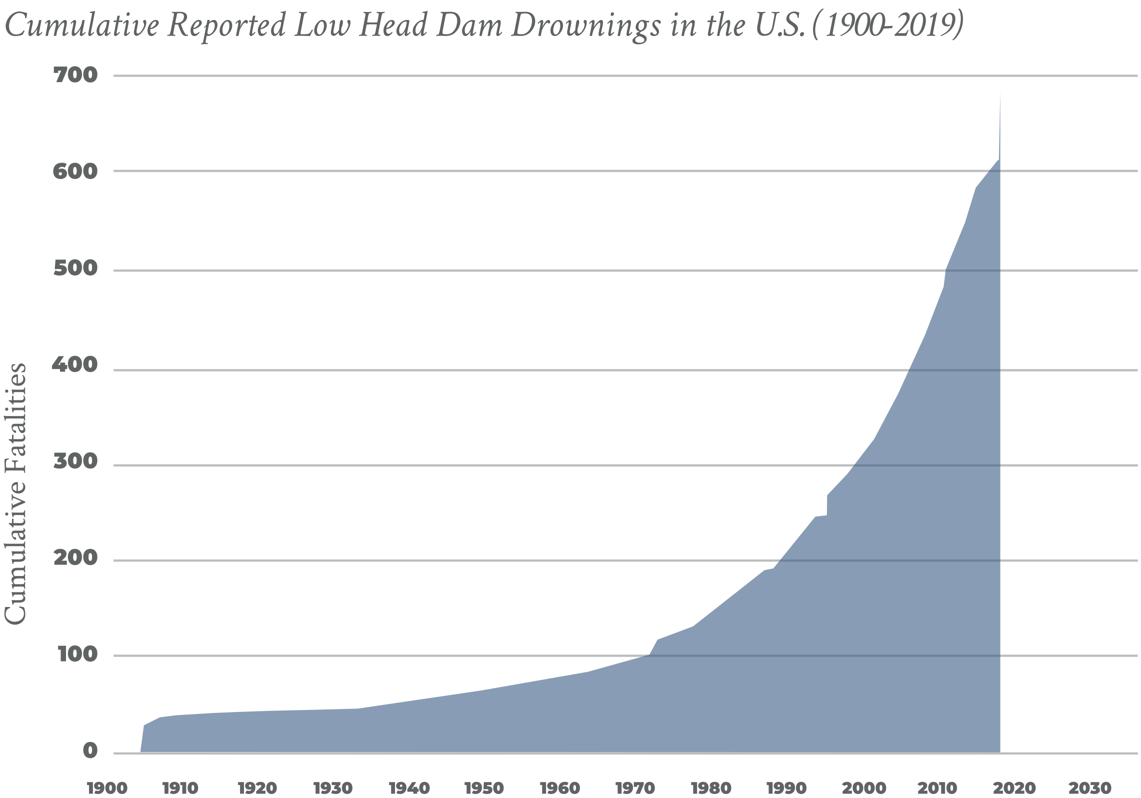


**Figure 2. Partial database of documented drownings at low head dams in the US between 1900 and 2019**

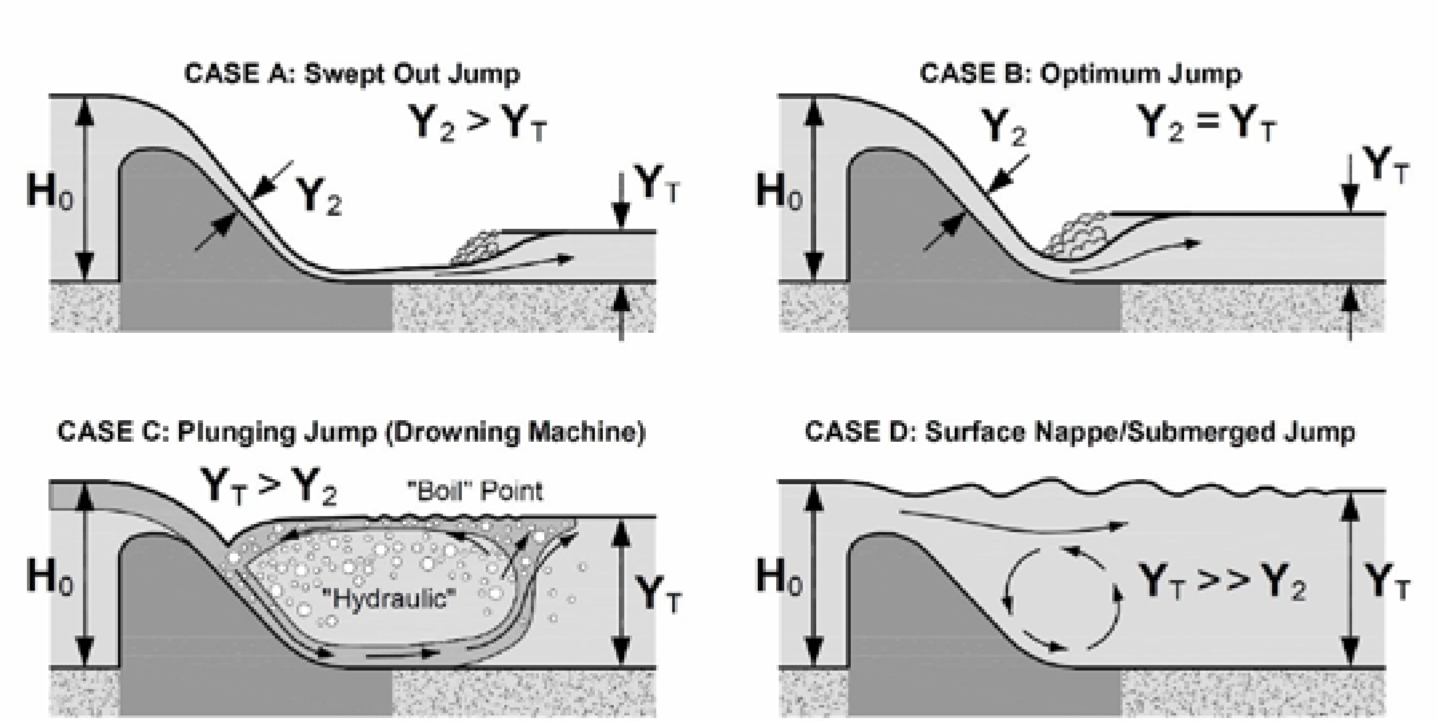


**Figure 3. Schematic showing different states of weir flow as a function of tailwater depth ($Y_T$) (Tschantz and Wright, 2010)**

structures and the increasing water recreation where there was once little public exposure. Water-based recreation activities in the United States are projected to increase 20 to 30% by 2030 (Federal Outdoor Recreation Trends, 2016). Using the data currently available, fatalities near low head dams should be expected to rise proportionally as well. From a dam safety perspective, over the past 40 years, the number of fatalities at low head dams has been more than 15 times the fatalities from dam failures.

## *Low Head Dam Hydraulics*

The flow over low head dams may be characterized similar to the flow over an ogee weir. Four distinct states of a hydraulic jump that are a function of the relative sequent depth or the hydraulic jump depth ($Y_2$) to local tailwater depth ($Y_T$) can occur immediately downstream of low head dams, as shown in Figure 3. The sequent depth depends on the discharge over the weir; whereas, the tailwater depth depends on the downstream channel characteristics. The swept-out jump (Case A) occurs during low flow conditions when the tailwater depth is smaller than the sequent depth ($Y_T<Y_2$). When this occurs, the hydraulic jump is pushed downstream to a point where the sequent and local tailwater depths match. Since this type of hydraulic jump occurs at low flows, it generally has shallow depths and non-hazardous currents below the dam.

The optimum or ideal jump (Case B) occurs when the hydraulic jump forms immediately downstream of a weir at the point of the overflow nappe impact and the local tailwater depth in the channel just matches the sequent depth ($Y_T=Y_2$). This transient condition is relatively rare and occurs during moderate flows and results in high energy dissipation and high air entrainment but only localized weak circulating currents that are normally not hazardous.

The plunging jump or partially-submerged jump (Case C) occurs when the tailwater is relatively high ($Y_T>Y_2$). During this condition the smooth-looking nappe plunges into a deceptively quiescent tailwater surface and creates a strong underwater rotating current that begins at the front of the plunging nappe. The underwater vortex formed by the partially submerged hydraulic jump is often called a "hydraulic." This is the most hazardous condition, and it is often called a "drowning machine" because the vertically rotating vortex can easily trap victims by forcing them downward at the overflow and keeping them circulating, first by downstream-directed underwater current and then by the relentless reversed surface countercurrent, until the victim becomes exhausted and drowns. As the plunging nappe entrains air the circulating water becomes less dense and buoyancy is reduced, thus making it difficult for one to remain afloat, even when wearing a life jacket.

The fully-submerged or wiped-out jump (Case D) takes place at flood conditions for a combination of very high flows and high tailwater ($Y_T>>Y_2$). During this scenario, the weir and overflow nappe become fully submerged and the jump is wiped out, resulting in only undulating surface conditions. This condition is not hazardous because the dam and overflow nappe are completely submerged and the hydraulic jump, together with entrapping countercurrents, is eliminated.

**Figure 4. Photograph of  Dock Street Dam**

Additional important conclusions made from model tests conducted by researchers on low head dam hydraulics are:

a) During the occurrence of a plunging or partially-submerged jump (Case C) the velocity of the counter currents is highest for mild submergence of the jump, and for all hydraulic conditions, its magnitude is approximately one-third of the supercritical inflow velocity of the corresponding unsubmerged jump. The countercurrent velocity decreases with increasing submergence or tailwater depth until it suddenly drops to zero. When this happens, the submerged nappe that moves along the channel bottom suddenly "flips" to the free surface and, simultaneously, the vortex vanishes. The phenomenon of nappe "flip" and its counterpart, nappe "flop" induced by a decrease of the tailwater depth, occur when the ratio of upstream depth ($H_o$) to tailwater depth ($Y_T$) is approximately 1:15. (Leutheusser and Fan, 2001)

b) The longitudinal extent of the counter current (hydraulic) zone, measured downstream from where the plunging nappe meets the tailwater, is between three and four weir or dam heights. The downstream end of the hydraulic zone is typically observed as a transverse band area across the channel, causing the appearance of a boil, where the rotating current rises to the surface, marking a splitting point between upstream and downstream currents. (Leutheusser and Birk, 1991)

c) The dynamic impact force of the falling nappe is estimated to be "in the neighborhood" of 1.5 times the weight of a mature person. (Leutheusser, 1988)

d) Computed surface countercurrents ($V_s$) of up to six feet per second are easily achieved under certain overflow and tailwater conditions.  Such velocities are difficult to overcome for victims who fall into the countercurrent zone, and they challenge even the most highly trained swimmers to escape the pull toward the overflowing nappe. (Tschantz and Wright, 2011)

As described above, since the plunging jump (Case C) takes place only during certain flow conditions, based on the upstream and downstream water depths and the shape of the dam crest, it is important to note that the hazardous conditions with recirculating currents are transitional in nature. Due to the transitional nature of the danger present at these dams, often unsuspecting victims, who may have experienced non-threatening conditions during lower or higher flow conditions, fall prey as victims, completely unaware of the newly prevailing deadly flow conditions.

## *Using CFD Modeling to Determine Hydraulics at Low Head Dams*

Currently available and widely used one- and two-dimensional numerical flow modeling tools (e.g., HEC-RAS, XP2D, Flo2D, etc.) do not have the ability to simulate hydraulic conditions where there is change in momentum in the vertical dimension. Since flow dynamics at low head dams involve significant force and momentum transfer along the vertical axis, a three-dimensional model is required to accurately characterize the changing hydraulics and simulate the complex flow conditions.

Computational Fluid Dynamic (CFD) modeling refers to three-dimensional flow modeling where numerical methods and solution algorithms are used to solve flow problems. Typical hydraulic parameters that are solved using CFD modeling include flow depths, velocities, turbulences, and fluid pressures. CFD modeling has applications to a wide range of dam safety problems including analysis of spillway flow, nappe impingement, pressure/shear distribution, tractive force, energy dissipation in stilling basins, and currents at intakes. CFD modeling can be used to assess and evaluate hydraulic conditions at low head dams including air entrainment, flow turbulence, and three-dimensional momentum transfer.

The rest of this paper presents a case study of a low head dam where CFD modeling was used to replicate the hazardous transient hydraulic roller and evaluate modifications to eliminate the roller.

*Case Study 1 – Dock Street Dam*

The Dock Street Dam is a run-of-the-river low head dam located on the Susquehanna River in Harrisburg, Pennsylvania. The dam is a hollow, reinforced concrete slab-and-buttress structure approximately six feet high and 3,460 feet long that creates a three-mile-long, 1,500-acre lake. The Dock Street Dam was built in 1913 and is classified as a low hazard structure.

The original purpose of the dam was to eliminate mosquito breeding pools in the river during low flow periods, control odors by submerging the sewer outfall pipe outlets along the riverbanks, and create a lake for recreation. Today the dam creates important flatwater recreation for the City of Harrisburg and surrounding communities and is a destination for fishermen.

The Dock Street Dam has also been the site of numerous drownings. Christine Vendel, a local news reporter investigated the fatalities and the circumstances surrounding the incidents at the Dock Street Dam. She uncovered 30 documented drownings and 25 rescues between 1935 and 2019 (Vendel, 2018).

CFD modeling was used to see if it could simulate the dangerous hydraulic conditions at the Dock Street Dam. A recent well-documented incident when the dangerous hydraulics existed was selected to be modeled. On May 26, 2016, at approximately 11:30 a.m., a 69-year-old fisherman was trapped at the recirculating current downstream of Dock Street Dam but was rescued after a near-fatal experience. The CFD model was developed using FLOW-3D software, consisting of a 400-foot reach of the Susquehanna River including the Dock Street Dam. The dam's geometric details, including the shape of the weir, were obtained from design drawings, and water surface elevations during the incident both upstream and downstream of the dam were obtained from USGS gaging stations. The air entrainment and turbulence simulation features of the model were used. The model simulated a 30-minute period of constant river flow. A feature of FLOW-3D is the ability to simulate a human body within the flow. The CFD model is capable of estimating the forces acting on the person, including buoyancy.

Figure 5 presents a snapshot in time from a CFD model simulation showing the flow velocity upstream and downstream of the dam. The human prototype simulated is shown in orange. The CFD model successfully predicted the nappe flow, the hydraulic roller, the return currents, and the entrapment of the human prototype. As seen in Figure 6, the human prototype was subjected to the

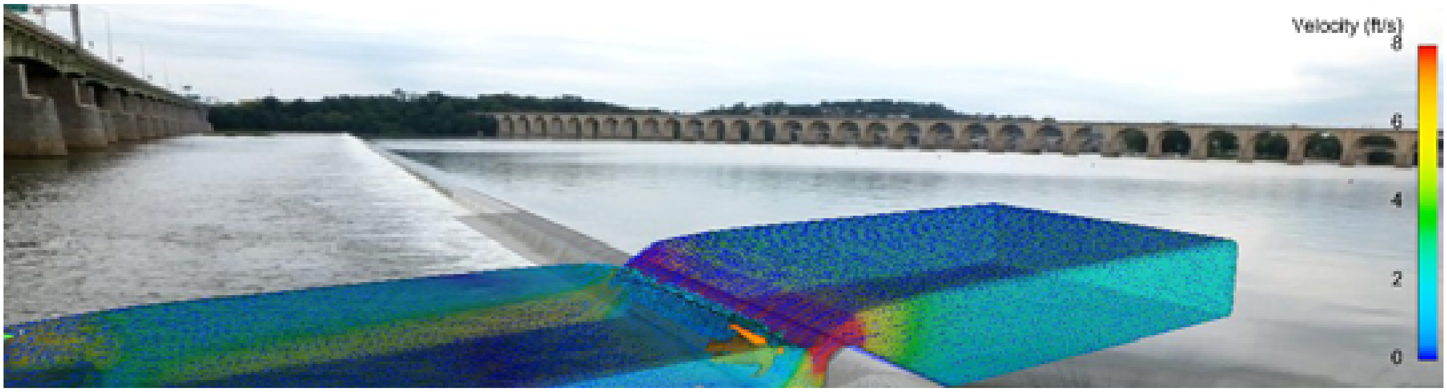


**Figure 5. Still images from the CFD model showing the human prototype and flow velocity where the fisherman was trapped**

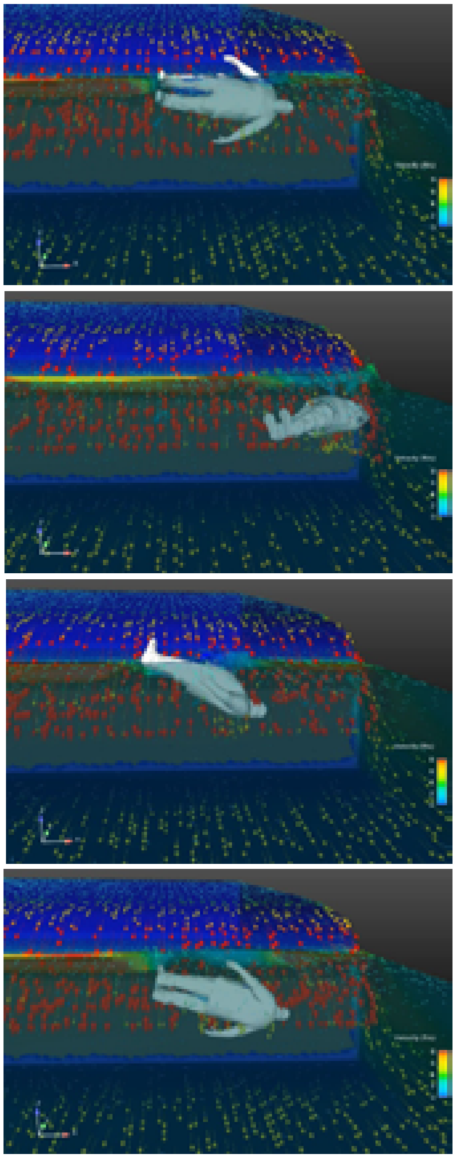

**Figure 6. Still images from the CFD model animations (looking upstream) showing a human prototype (in white) trapped at the downstream face of the dam by the powerful recirculating currents**

dangerous re-circulating currents downstream of the dam. The forces tossed and twirled the human prototype trapped at that location, making the human prototype unable to escape the powerful currents. The results from the CFD simulation, when correlated with the observed experiences of other victims at low head dams, provided confirmation of the CFD model's effectiveness in replicating the dangerous hydraulic forces experienced by the victim.

The same CFD model that was used to successfully simulate the near-fatal incident described above was used to simulate higher and lower flow conditions in order to determine the range of flows that create the hazardous hydraulic roller capable of trapping victims. For the reach of the Susquehanna River where the Dock Street Dam is located, daily flow records are available from 1890 to the present. Using this flow data, a flow exceedance relationship was plotted (see Figure 7). On the flow exceedance plot, the range of flows where the CFD model predicted the hazardous submerged hydraulic jump is demarked within the dashed rectangular window. The flows recorded on the dates when past incidents at the dam occurred are plotted as red triangles. Approximate flows over the crest of the dam that resulted in Case A-, Case C-, and Case D-type hydraulic jumps are also shown. Review of the river flow data, the CFD-predicted range of dangerous flows, and the plots of flows from actual incidents at the dam that resulted in the fatal or near-fatal experience, confirm that CFD modeling can be used to accurately define the range of the hazardous transient flows at low head dams.

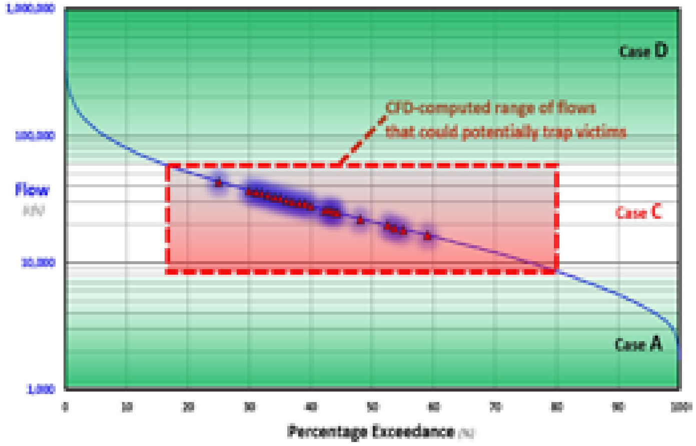


**Figure 7. Flow exceedance plot at the Dock Street Dam. Plotted red triangles represent flows during actual incidents involving victims trapped by the hydraulic roller.**

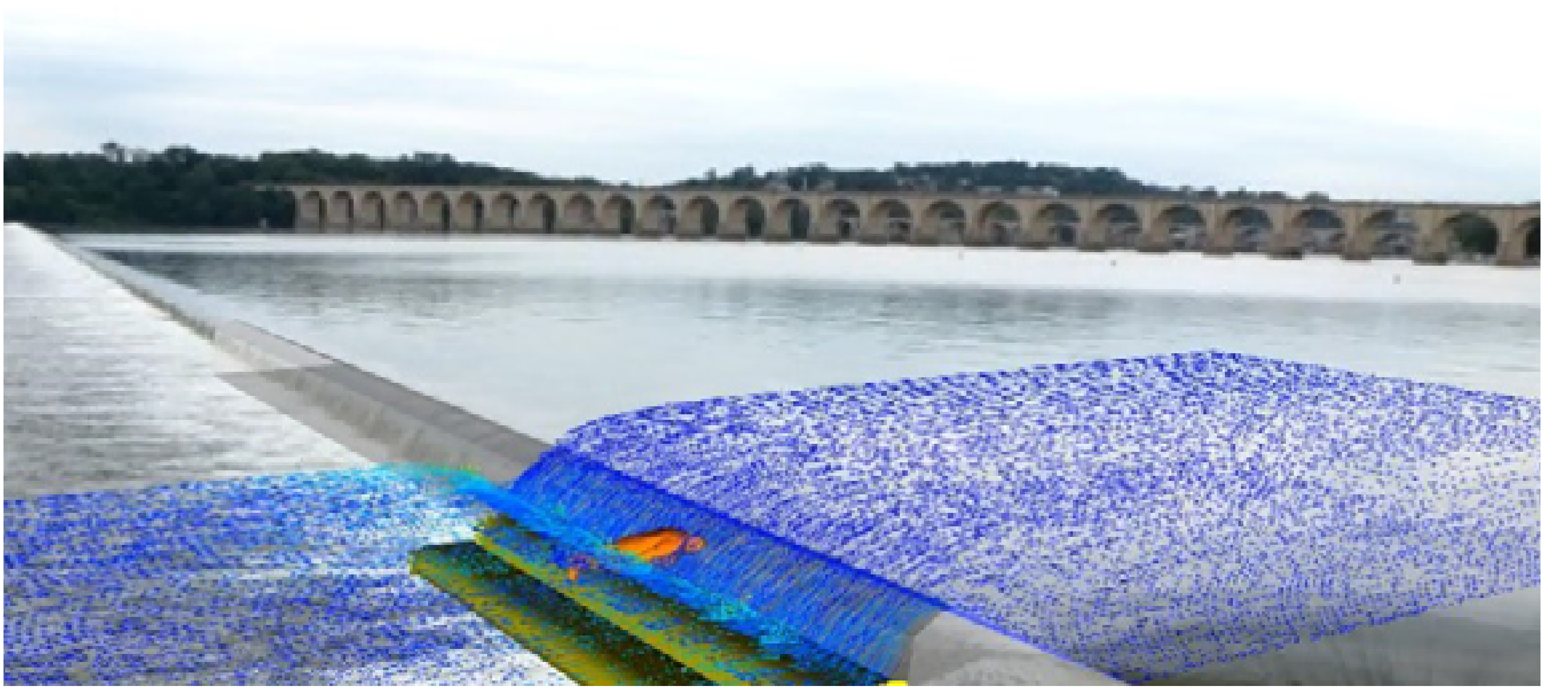

**Figure 8a. Still image from the CFD model simulation demonstrating the effectiveness of a flattened downstream dam face using a stepped configuration. This image shows the instant when the human prototype reached the location of the re-circulating hydraulic roller.**

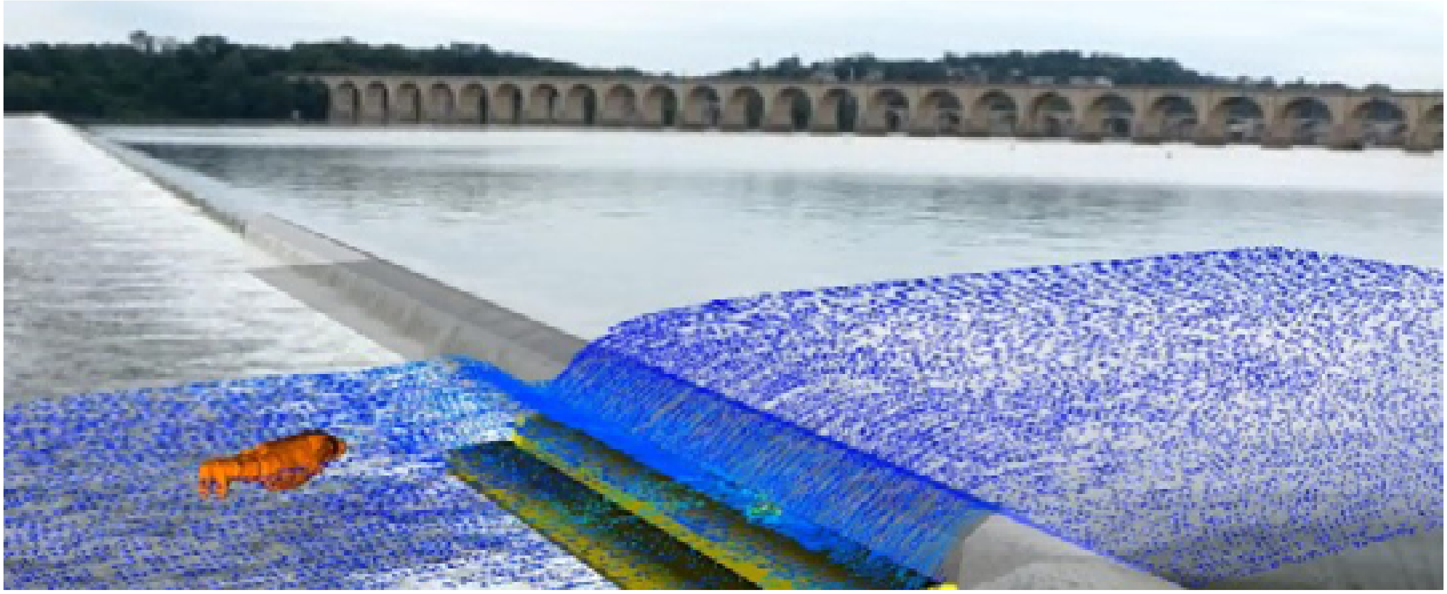

**Figure 8b. Still image from the CFD model simulation demonstrating the effectiveness of a flattened downstream dam face using a stepped configuration. This image shows the human prototype washed downstream.**

The CFD model was also used to simulate a structural retrofit for the Dock Street Dam that would eliminate the deadly hydraulic roller at this dam for all flow conditions. Typical recommended structural retrofits to eliminate the "hydraulic" at low head dams generally include modification of the downstream face of the dam by flattening the downstream face with steps or boulder fill. Various configurations of steps were modeled using a trial and error.

A two-step configuration at the downstream slope ultimately eliminated the hydraulic hazard. This configuration was assessed for a range of flows to confirm its effectiveness for all flow conditions.

Figure 8 presents still images from the CFD model simulations demonstrating the effectiveness of the two-step configuration.

## Conclusion

Low head dams pose a deadly hazard to both the unsuspecting public and first responders. CFD modeling can be used to determine if swimmers, boaters, kayakers, canoers, or rescue personnel are susceptible to becoming trapped downstream of a low head dam. Once the problem of recirculating currents is identified and the range of hazardous flow conditions is estimated, CFD modelling can be used to design permanent modifications to eliminate the hydraulic hazard.

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