Defining Dangerous Flow Ranges of Low-Head Dams

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ABSTRACT

Low-head dams can produce dangerous conditions for recreational river users when a nearly inescapable reverse-flow condition (a “roller”) develops below the dam due to a submerged hydraulic jump. A national task force is using aerial imagery to identify potentially dangerous structures, but a more definite determination requires field data and analysis of hydraulic conditions for a range of flow rates. To aid this effort, a straightforward analysis procedure has been implemented in a spreadsheet application. The upstream head and ideal (non-submerged) hydraulic jump conditions are computed for the range of likely flow rates. Downstream river channel conditions are then used to identify the flow rates for which dangerous degrees of submergence will occur, based on experimental work by Hans Leutheusser and colleagues beginning in the early 1990s. The reverse-flow velocity in the roller and the limiting tailwater conditions for a plunging jet and reverse flow are estimated. The spreadsheet is valuable for analysis of specific sites, and general application provides insight into common characteristics of dangerous dams.

INTRODUCTION

Low-head dams are commonly not listed in the National Inventory of Dams database because they do not impound significant volumes of water and have a low probability for causing life loss or serious property, environmental, or infrastructure damage in the event of dam failure. Only the consequences of dam failure determine whether a dam is classified as high or significant hazard. However, low-head dams can also cause loss of life during non-failure situations and normal operations when recreational river users pass over the dams or approach the downstream area that contains dangerous currents, strong hydraulic forces, and the potential for entrapment by recirculating flows. Tschantz (2014) shows that the number of nationwide dam failure fatalities has decreased from 1960 to 2014 while the number of low-head dam fatalities associated with recreational use has increased over the same period. Potentially dangerous low-head dams typically have the following physical characteristics:

- less than 4.6 m (15 ft) high,
- continuous overflow across the full width of the structure,
- not designed for long-term water storage,
- usually not equipped with appurtenant hydraulic structures such as gates, pipes, penstocks, and powerplants, and
- located on natural river systems where recreationists such as kayakers, anglers, boaters, and swimmers are common.

The great danger posed by these structures is due to the recirculating flows that occur over a surprisingly wide operational range, the continuity of the recirculating flow condition from bank to bank (with no locations for mid-channel refuge and often no easy avenue of escape even at the edges of the structure) and the deceptively calm appearance of the flow at some of the most dangerous conditions. Even with the aid of emergency responders, escape from the recirculating zone can be almost impossible because the flow spins, disorients, and exhausts the captured person. Additionally, the aerated water churning below the dam is less dense, making personal flotation devices less effective. In many of the most tragic events, well-meaning rescuers have become additional victims (Elverum & Smalley 2012).

Flow in an open channel (e.g., river or canal) can exist in three states. The flow may be deep and slow (subcritical), shallow and rapid (supercritical), or at the transition between the two (critical). Low-head dams create the supercritical flow condition characterized by low depths and high velocities (Figure 1). Downstream, a hydraulic jump must occur to return the flow to a subcritical condition of larger depth and slower velocity. The jump is marked by an abrupt rise in the water surface elevation and reverse circulation of flow on the surface (countercurrent velocities). Momentum of the flow is conserved, but energy is lost in this process as the downstream waters try to fill the empty space above the surface of the upstream flow, tumbling over the jet of water flowing down the face of the dam.

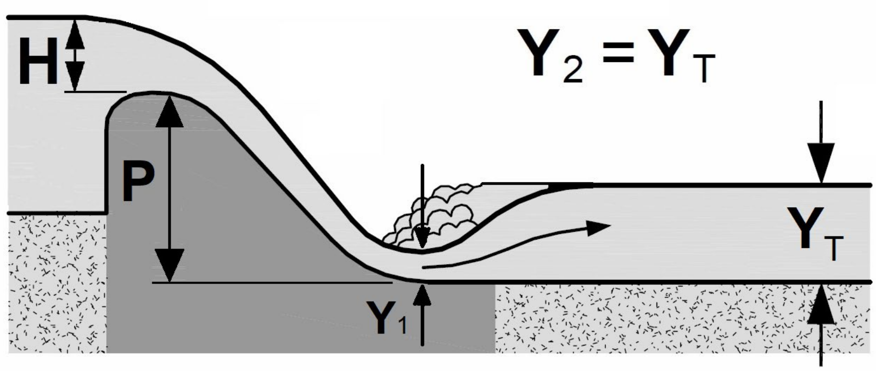

Figure 1. Schematic of hydraulic jump showing the initial depth (Y_1) entering the jump and the conjugate depth (Y_2) downstream from the jump (adapted from Tschantz & Wright 2011).

The hydraulic jump below a low-head dam can take four possible forms depending on the downstream depth relative to the ideal depth required to position the jump exactly at the toe of the dam (conjugate depth). The conjugate depth can be calculated mathematically knowing the discharge per unit width over the weir, while the actual tailwater depth is established by downstream channel characteristics (e.g., channel slope and roughness, constrictions such as bridges, gates, culverts, etc.). A hydraulic jump will form whenever the actual tailwater depth is equal to or greater than the calculated conjugate depth. The exact flow characteristics (strength of recirculating flow, etc.) vary with the ratio of actual tailwater depth above conjugate depth, or the degree of submergence. Moderately submerged jumps are the most dangerous, with the strongest reverse-flow currents. Because of changing hydrologic conditions at the same structure, recreationists may experience dangerous hydraulic conditions in a location that was safe during previous visits.

If the tailwater depth at the toe of the dam is less than the conjugate depth, the result is a "swept-out hydraulic jump" in which supercritical flow persists for some distance and the hydraulic jump forms further downstream at a point where the flow has slowed due to friction and the conjugate depth has dropped to a value matching the actual tailwater depth (Figure 2, Case A). These hydraulic jumps appear to be powerful and dangerous due to the energy of the flow, so recreationists see them readily and usually avoid them. An "optimal hydraulic jump" forms immediately downstream from the structure (Figure 2, Case B) when the tailwater depth at the base of the dam equals the conjugate depth of the overflow. A "submerged hydraulic jump" (Figure 2, Case C) is formed when the tailwater is deeper than the conjugate depth. Submerged hydraulic jumps have a strong downstream-directed jet near the bottom of the channel and a strong upstream-directed current at the water surface. Despite the strong rotational current toward the dam face, these jumps have a calmer appearance on the surface than Case A jumps; this makes low-head dams deceptively dangerous for recreationists. As the submergence or tailwater depth increases, the countercurrent velocity decreases (Leutheusser & Fan 2001). When the tailwater depth far exceeds the conjugate depth, the hydraulic jump is completely drowned out and only an undulating water surface exists (Figure 2, Case D). The downstream-directed jet near the bed also detaches from the bed at high submergence, creating a downstream-directed current at the water surface. This is described as the "flip" condition (Rao & Rajaratnam 1963).

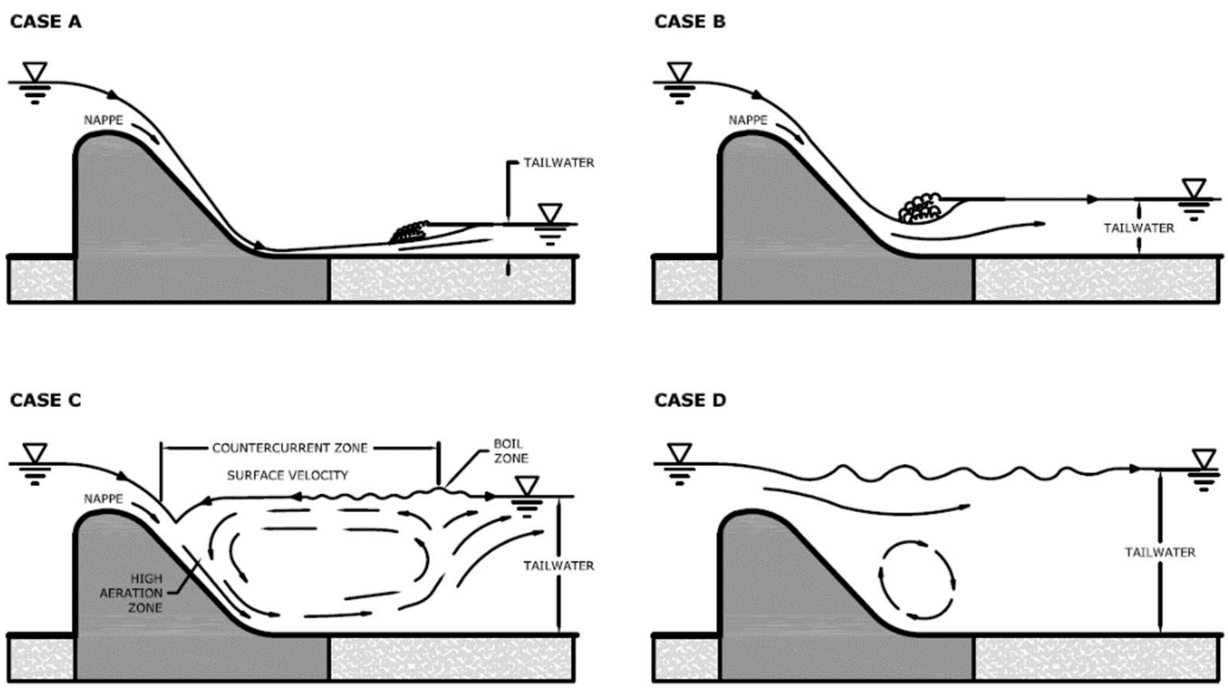

Figure 2. Four possible flow conditions over a low-head dam: Case A – Swept-out Hydraulic Jump, Case B – Optimal Hydraulic Jump, Case C – Submerged Hydraulic Jump, Case D – Drowned-out Hydraulic Jump (modified from Tschantz & Wright 2011).

Recently, professional engineering organizations have increased their focus on public safety at low-head dams. The National Dam Safety Review Board, United States Society on Dams (USSD), and Association of State Dam Safety Officials (ASDSO) all have work groups or committees reviewing public safety at dams with a focus on low-head dams. In January 2020, USSD, ASDSO, and American Society of Civil Engineers' Environmental and Water Resources

Institute (EWRI) began combining their efforts to create a national inventory of low-head dams. This task force is led by Dr. Rollin Hotchkiss (Brigham Young University). Initially, this group is using aerial imagery to identify potentially dangerous structures, but a more definite determination requires field data and analysis of hydraulic conditions for a range of flow rates. To aid this effort, this paper presents a spreadsheet application that quantifies the danger presented by submerged hydraulic jumps at low-head dams. The spreadsheet can help to properly identify structures of concern and institute appropriate short-term and long-term mitigation strategies.

PREVIOUS WORK

Numerous journal papers, reports, professional society publications, theses, and news articles address the topic of public safety at low-head dams. Select references were compiled during a scoping study of public safety issues related to low-head hydraulic structures (Svoboda et al. 2017). This report documented the hydraulic characteristics of submerged hydraulic jumps and the hazards associated with submerged hydraulic jumps, common characteristics of potentially dangerous hydraulic structures, types of low-head hydraulic structures that may cause public safety concerns, and structural modifications or other design techniques that can be used to mitigate risk for existing structures and new construction.

Leutheusser & Fan (2001) provide quantitative information on submerged hydraulic jumps downstream from low-head dams, based on experiments conducted in a physical hydraulic model of flow over a sharp-crested weir with a ventilated nappe. Although many low-head dams use ogee-shaped weirs, the flow conditions on the downstream side of the sharp-crested weir model are still representative of the typical low-head dam situation. In the experiments, near-surface velocity magnitude and direction were measured in the submerged hydraulic jump for a range of weir heights, headwater levels, and tailwater depths. Human swimming speed can be compared to surface velocities to better understand when victims are not able to escape the countercurrent velocities. Countercurrent velocity rises quickly to a maximum as a jump becomes submerged, then decreases with increasing tailwater depth until the velocity suddenly drops to almost zero. At this critical degree of submergence nappe "flip" occurs (Rao & Rajaratnam 1963), causing the recirculating vortex to disappear, and surface velocities are then directed downstream. As tailwater elevation is reduced from this condition, nappe "flop" occurs when the counter-rotation begins again. Leutheusser & Fan (1995) found that nappe flip occurs when the ratio of upstream total head (H+P) to tailwater depth (T) is about 1.10 and nappe flop occurs at a ratio of 1.19, with the difference due to hysteresis caused by changing nappe ventilation conditions. For ogee-crest structures, nappe ventilation is unlikely, so the flip and flop points will probably be closer together. Experiments like those performed by Leutheusser & Fan (2001) have not been carried out for ogee-crest dams.

Israel-Devadason & Schweiger (2019) used computational fluid dynamics (CFD) modeling to simulate complex hydraulic conditions at low-head dams, predict the presence of submerged hydraulic jumps, and assess potential structural remediation options. They considered the case study of Dock Street Dam in Harrisburg, Pennsylvania, a 1.8-m (6-ft) high run-of-the-river dam which caused 30 drownings and 25 documented rescues from 1935 to 2019, although it is classified as a low-hazard dam (Vendel, 2018). Using the CFD model, the physical motions of a victim were simulated in the hydraulic roller downstream from the dam for one documented near-fatal incident. A flow exceedance plot was used to identify the range of flow conditions over which a submerged hydraulic jump occurs at Dock Street Dam. Reported incidents at the dam plot within the Case C condition described earlier.

METHODS

A spreadsheet was created to examine the hydraulic conditions downstream from a given structure for a range of flows. The calculations show the range over which a submerged hydraulic jump occurs and whether the surface velocity is directed upstream (Case C) or downstream (Case D) based on the tailwater depth at which the surface velocity flips direction. In the Case C range, the calculations also show estimated surface velocities for comparison to human swimming capability.

Dam dimensions and project data are entered in the orange cells (Fig. 3).

- Flow rate range
- Weir length across the channel
- Structural height of the dam above the downstream channel invert (P; see Fig. 1)
- Downstream channel bed slope
- Manning's *n* (roughness factor for the downstream channel)
- Channel width downstream from the dam (may be different from weir length)

The spreadsheet calculations follow the process presented in Leutheusser & Fan (2001), using equations they developed from the experimental data. Iterative calculations must be enabled in Excel since some of the equations cannot be solved algebraically and use circular-reference formulas. The calculation process is outlined in Table 1.

Table 1. Process for identifying submerged hydraulic jumps at low-head dams.

Step	Description	Equation and Page References from Leutheusser & Fan (2001)
1	Input structure data (flow range, weir length, structural height above downstream invert, bed slope, Manning's *n* parameter, channel width)	
2	Estimate head on the dam	Eq. 3 and 4; weir flow equation
3	Estimate flow parameters at the base of the dam (depth, velocity, Froude number)	Eq. 7, 8, 9
4	Calculate conjugate depth (Y_2)	Eq. 1
5	Estimate tailwater depth (or input measured values from field, Y_T)	Manning's equation
6	Determine degree of submergence	Eq. 10
7	Calculate countercurrent surface velocity and compare to average human swimming capability	Eq. 13, 15
8	Determine tailwater elevation at which the overflowing jet flips up and surface velocities are directed downstream	$(H+P)/Y_T \approx 1.10$, pg. 515

The calculations in the spreadsheet assume normal depth downstream from the low-head hydraulic structure; however, downstream check structures or other river constrictions could affect the tailwater. The assumption of normal depth is most accurate when the downstream channel is uniform in shape, size, roughness, and slope for a long distance downstream. The calculations assume a wide channel whose width does not change with discharge, but this could be modified in the spreadsheet, or other methods for defining the tailwater conditions could be used if desired.

One modification was made to the procedure outlined by Leutheusser & Fan (2001). Their equation to predict the reverse-flow velocity depended upon a parameter α that they determined for only three specific flow conditions. We used their experimental data to relate α to the value of the flow Froude number entering the hydraulic jump, $\alpha = 39/(Fr_1)^{0.5}$, where $Fr_1 = V_1/(gY_1)^{0.5}$ and g and V_1 are the acceleration due to gravity and the velocity entering the jump. This allows prediction of the reverse-flow velocity for other values of Fr_1. With additional physical or CFD modeling, more data points could be collected to refine the α vs. Fr_1 relationship.

RESULTS

An example spreadsheet is shown in Figure 3 for a 1.83-m (6-ft) high dam. The results are used to create a graph that visually indicates the dangerous flow range (Figure 4).

Weir Length, L	1054.61 m
Structural Height of Dam Above Tailwater Invert, P	1.8288 m

Flow Information	Hydraulic Calculations						Ideal Jump						
Discharge	Overtopping Head	Total Head	Overtopping Fraction				Toe Depth Ratio	Toe Depth	Toe Velocity Ratio	Toe Velocity	Froude Number	Conjugate Depth Ratio	Conjugate Depth
Q	H	H+P	H/(H+P)	(Eqn. 4) C_{weir}	(Eqn. 3) C_d	(pg. 514) C_{loss}	(Eqn. 7) Y_1/H	Y_1	(Eqn. 8) $V_1/\mathrm{sqrt}(2gH)$	V_1	(Eqn. 9) F_1	(Eqn. 1) Y_2/H	Y_2
m^3/s	m	m	-	-	-	-	-	m	-	m/s	-	-	m
150	0.18	2.01	0.09	0.62	1.83	1.00	0.18	0.03	2.33	4.4	7.82	1.87	0.34
300	0.29	2.12	0.14	0.62	1.84	0.63	0.20	0.06	2.09	5.0	6.64	1.77	0.51
450	0.38	2.20	0.17	0.63	1.85	0.49	0.21	0.08	1.95	5.3	5.96	1.70	0.64
600	0.45	2.28	0.20	0.63	1.86	0.40	0.23	0.10	1.85	5.5	5.49	1.65	0.75
750	0.53	2.35	0.22	0.63	1.87	0.35	0.24	0.12	1.77	5.7	5.15	1.62	0.85
900	0.59	2.42	0.24	0.64	1.88	0.31	0.25	0.15	1.71	5.8	4.87	1.58	0.94
1050	0.65	2.48	0.26	0.64	1.88	0.28	0.26	0.17	1.66	6.0	4.65	1.56	1.02
1200	0.71	2.54	0.28	0.64	1.89	0.26	0.26	0.19	1.62	6.1	4.47	1.54	1.10
1350	0.77	2.60	0.30	0.64	1.90	0.24	0.27	0.21	1.58	6.2	4.31	1.52	1.17
1500	0.82	2.65	0.31	0.64	1.90	0.22	0.28	0.23	1.55	6.2	4.17	1.50	1.24
1650	0.88	2.70	0.32	0.65	1.91	0.21	0.28	0.25	1.52	6.3	4.05	1.49	1.30
1800	0.93	2.75	0.34	0.65	1.92	0.20	0.29	0.27	1.50	6.4	3.94	1.47	1.36
1950	0.97	2.80	0.35	0.65	1.92	0.19	0.29	0.29	1.47	6.4	3.84	1.46	1.42

Bed Slope, S_o	0.0001
Manning's n	0.028
Channel Width, l	1054.608 m

Flow Information	Tailwater Conditions (Normal Depth)	Submerged Hydraulic Jump							
Discharge	Actual Tailwater Depth	(Eqn. 10) Jump Submergence	(Eqn. 13) Head Loss in Keeper	Fig. 3 (Eq. 15) Curve Fitting Parameter	(Eqn. 15) Surface Recirculation Ratio	"Keeper" Velocity	Flip Tailwater		
Q	Y_t	$S = (Y_t\text{-}Y_2)/Y_2$	ΔE_{DM}	α	V_s/V_1	V_s	(pg. 515) Y_{flip}	Human unstable?	Flipped?
m^3/s	m		m			m/s	m		
150	0.58	0.69	1.43	14.12	0.28	1.25	1.83	FALSE	FALSE
300	0.87	0.71	1.24	15.32	0.26	1.27	1.92	TRUE	FALSE
450	1.11	0.74	1.08	16.16	0.24	1.26	2.00	TRUE	FALSE
600	1.32	0.76	0.95	16.83	0.22	1.24	2.08	TRUE	FALSE
750	1.51	0.78	0.83	17.38	0.21	1.21	2.14	TRUE	FALSE
900	1.69	0.80	0.72	17.85	0.20	1.17	2.20	TRUE	FALSE
1050	1.85	0.81	0.62	18.27	0.19	1.13	2.26	TRUE	FALSE
1200	2.00	0.83	0.52	18.64	0.18	1.08	2.31	TRUE	FALSE
1350	2.15	0.84	0.43	18.98	0.17	1.02	2.36	TRUE	FALSE
1500	2.29	0.85	0.34	19.29	0.15	0.95	2.41	TRUE	FALSE
1650	2.43	0.87	0.26	19.57	0.14	0.87	2.46	TRUE	FALSE
1800	2.56	0.88	0.18	19.84	0.12	#N/A	2.50	#N/A	TRUE
1950	2.68	0.89	0.10	20.09	0.10	#N/A	2.55	#N/A	TRUE

Figure 3. Example of spreadsheet used to calculate submerged hydraulic jump information.

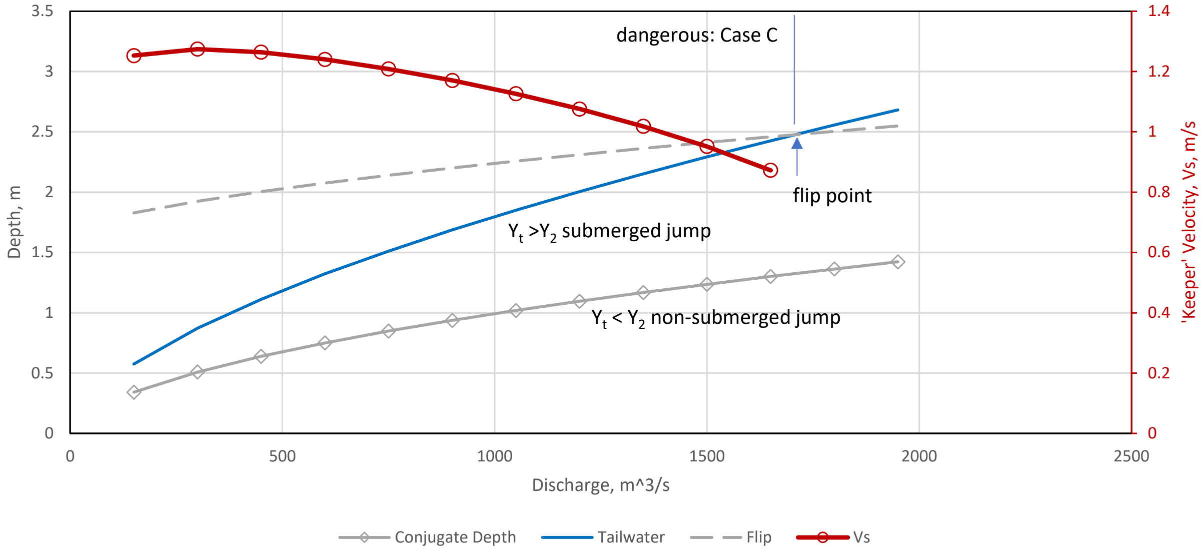

Figure 4. Flow rates where dangerous submerged hydraulic jumps occur and associated surface velocities.

When tailwater depth (Y_t, solid blue line) is less than the conjugate depth of the jump (Y_2, solid gray line), the jump is not submerged (Case A or B). When tailwater depth is greater than the conjugate depth of the jump, the hydraulic jump is either submerged (Case C) or drowned-out (Case D). Using the spreadsheet, the flip point can be calculated where upstream-oriented surface velocities become downstream-oriented. On the graph, the flip point occurs where the dashed gray line crosses the solid blue line (about 1,700 m^3/s or 60,000 ft^3/s in this example). At flows less than the flip discharge, the submerged jump may be potentially dangerous (Case C).

The solid red line indicates the calculated surface velocity at a given discharge. The surface velocity can be compared to human swimming capability to determine if victims may be able to swim against the current even if the hydraulic jump falls in the potentially dangerous flow range. Maximum human swimming velocity is reported at about 2 m/s (6.6 ft/s or 4.5 mph) for an Olympic athlete. Average human swimming velocity is closer to 0.9 m/s (2.9 ft/s; 2 mph). In the case shown in Figure 3, there is a small window of about 1640 to 1730 m^3/s (58,000 to 61,000 ft^3/s) where a person may be able to swim out of the submerged hydraulic prior to the flip point. For dams with smaller drop heights the magnitude of surface velocities will be reduced, so it may be more feasible for a person to swim out at the upper end of the Case C range. A potential secondary criterion for evaluating the danger presented by the flow conditions is the product of the flow depth and surface velocity, $Y_T V_s$, or product number. Abt et al. (1989) found that the critical product number for standing human stability varied with the height and mass of the person and was in the range of 1 to 1.6 m^2/s (11 to 17 ft^2/s) for typical adults. Values below 0.9 m^2/s (10 ft^2/s) may enable most adults to stand and walk out of the submerged hydraulic jump zone.

As a case study, the spreadsheet was applied to the Dock Street Dam case discussed in Israel-Devadason & Schweiger (2019) with estimated values of downstream slope and roughness since these were not documented in detail. An online article by Israel-Devadason (https://damfailures.org/case-study/dock-street-dam-pennsylvania/) provides detailed incident data for Dock Street Dam. The CFD modeling by Israel-Devadason & Schweiger (2019) shows that the dangerous range of flow conditions is from about 225 to 1,700 m^3/s (8,000 to 60,000 ft^3/s).

The spreadsheet created for this project predicts a similar danger range. Twenty-eight of the thirty known drowning fatalities at this dam have occurred in this discharge range, and two at slightly lower flows.

DISCUSSION

The submerged hydraulic jump spreadsheet shows that the danger zone for many dams is very broad. Low-head dams almost always create dangerous hydraulic conditions for a significant range of their flow conditions, unless the tailwater is always unusually low or high for some reason. Because of this broad range, it is unlikely that every parameter in the spreadsheet needs to be fully accurate to identify dangerous dams.

After hydraulic assessment is completed to determine when submerged hydraulic jumps occur at specific low-head dams, appropriate short-term and long-term mitigation strategies can be identified. The most common remediation technique is reshaping the downstream face of the dam. Installation of a stepped spillway or large concrete steps on the downstream face of the dam or placement of large boulders or heavy grouted riprap downstream from the dam face can break up dangerous downstream hydraulics (Schweiger 2011). Features that create discontinuity of the flow conditions can be helpful by allowing mid-channel refuge. Israel-Devadason & Schweiger (2019) showed in their CFD model that installation of a series of two steps on the downstream dam face could eliminate the hydraulic hazard at Dock Street Dam. Other remediation techniques such as baffled chute spillways (Leutheusser & Birk 1991), upstream-facing ramps and protruding platforms (Olsen et al 2014), staggered flow deflectors (Kern 2014), boat chutes (Klumpp et al. 1989), moveable crest dams (Schweiger 2011), and nature-like rock ramps may be suitable retrofits.

Results of this research can be used by federal, state, and private dam owners to better understand which low-head dams in their inventory present the most concern and at which flow rates. This will allow for consideration of the conditions associated with the times when recreationists are likely to be present at the site. Better classification of low-head hydraulic structures will assist nationwide efforts to improve public safety.

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