Methodology to Determine the Presence of Submerged Hydraulic Jumps at Low-Head Dams

Science and Technology Program
Research and Development Office
Final Report No. ST-2021-21020-01

U.S. Department of the Interior September 2021

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
September 2021	Research	October 2020-September 2021

4. TITLE AND SUBTITLE	
Methodology to Determine the Presence of Submergence Hydraulic Jumps at Low-Head Dams	5a. CONTRACT NUMBER X1020
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 21020 (S&T)

6. AUTHOR(S)
Connie D. Svoboda, P.E.
Tony Wahl, P.E.

5d. PROJECT NUMBER	ST-2021-21020-01
5e. TASK NUMBER	
5f. WORK UNIT NUMBER	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Bureau of Reclamation, Technical Service Center Hydraulic Investigations and Laboratory Services, 86-68560 P.O. Box 25007, Denver, CO 80225-0007	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	Reclamation 11. SPONSOR/MONITOR'S REPORT NUMBER(S) Final Report ST-2021-21020-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The purpose of this research project was to develop a methodology to determine the presence of dangerous submerged hydraulic jumps at low-head hydraulic structures. Even when low-head dams are operating as intended, strong currents, hydraulic forces, and other hazardous conditions may exist in localized areas downstream from the dam and may trap persons who pass over the dam or approach the dangerous zone. After reviewing related literature, a spreadsheet was created to examine the hydraulic conditions downstream of a given structure over a wide range of flows. The calculations show the range over which a submerged hydraulic jump occurs and whether the surface velocity is directed upstream or downstream based on the tailwater depth at which the surface velocity "flips" direction. The calculations also show estimated surface velocities which can be compared to human swimming capability. Results of this research can be used by federal, state, and private dam owners to properly identify structures of concern and institute appropriate short-term and long-term mitigation strategies. Proper classification of low-head hydraulic structures will assist nationwide efforts to improve public safety.

15. SUBJECT TERMS
Submerged hydraulic jump, low-head, low-head dams, public safety, recreation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Connie D. Svoboda
a. REPORT U	b. ABSTRACT U	THIS PAGE U			19b. TELEPHONE NUMBER *(Include area code)* 303-445-2152

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. Dr. Rollin Hotchkiss of Brigham Young University heads an industry task force studying these issues and was very helpful to this project. The cover photograph shows Bureau of Reclamation's Superior Courtland Diversion Dam in Nebraska.

Methodology to Determine the Presence of Submerged Hydraulic Jumps at Low-Head Dams

Final Report No. ST-2021-21020-01

prepared by

Technical Service Center
Connie D. Svoboda, P.E., Hydraulic Engineer
Tony Wahl, P.E., Hydraulic Engineer

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2021-21020-01

Methodology to Determine to Presence of Submerged Hydraulic Jumps at Low-Head Dams

CONNIE SVOBODA Digitally signed by CONNIE SVOBODA
Date: 2021.10.12 15:42:41 -06'00'

Prepared by: Connie D. Svoboda, P.E.
Hydraulic Engineer, Bureau of Reclamation, Technical Service Center

TONY WAHL Digitally signed by TONY WAHL
Date: 2021.10.12 17:07:17 -06'00'

Prepared by: Tony Wahl, P.E.
Hydraulic Engineer, Bureau of Reclamation, Technical Service Center

JOSEPH KUBITSCHEK Digitally signed by JOSEPH KUBITSCHEK
Date: 2021.10.13 14:07:05 -06'00'

Peer Review by: Joseph Kubitschek, Ph.D., P.E.
Hydraulic Engineer, Bureau of Reclamation, Technical Service Center

Contents

Page

Executive Summary

The purpose of this research project was to develop a methodology to determine the presence of dangerous submerged hydraulic jumps at low-head hydraulic structures. Even when low-head dams are operating as intended, strong currents, hydraulic forces, and other hazardous conditions may exist in localized areas downstream from the dam and may trap persons who pass over the dam or approach the dangerous zone.

After reviewing related literature, a spreadsheet was created to examine the hydraulic conditions downstream of a given structure over a wide range of flows. The calculations show the range over which a submerged hydraulic jump occurs and whether the surface velocity is directed upstream or downstream based on the tailwater depth at which the surface velocity "flips" direction. The calculations also show estimated surface velocities which can be compared to human swimming capability. Results from the spreadsheet compared well to a case study presented in Israel-Devadason and Schweiger (2019) for Dock Street Dam in Harrisburg, Pennsylvania.

Results of this research can be used by federal, state, and private dam owners to identify structures of concern based on when recreationists are likely to be present at the site and institute appropriate short-term and long-term mitigation strategies. Proper classification of low-head hydraulic structures will assist nationwide efforts to improve public safety.

1. Introduction

Oversight of low-head hydraulic structures may not occur under formal dam safety programs because dam failure will not cause life loss. Low-head hydraulic structures are typically not captured in the National Inventory of Dams database because they do not impound water and are not classified as high or significant hazard. However, even when these structures are operating as intended, strong currents, hydraulic forces, and other hazardous conditions may exist that can trap persons in a localized area downstream of the structure. Tschantz (2014) shows that the number of 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 time period. There were 9 reported fatalities due to dam failure from 2000-2014 versus 199 drownings related to low-head dams.

Potentially dangerous low-head structures typically have the following physical characteristics:

- Less than 15 ft high
- Continuous overflow across the full width of the structure
- Not designed for long-term water storage
- Not equipped with appurtenant hydraulic equipment such as gates, pipes, penstocks, and powerplants
- Located on natural river systems where recreationists such as kayakers, anglers, boaters, and swimmers are common

In addition to the physical characteristics of the structure, certain downstream hydraulic conditions must form over part of the operational regime to create a hazardous condition. A hydraulic jump occurs when there is a rapid change from a low stage/high velocity condition (supercritical flow) to a high stage/low velocity condition (subcritical flow), resulting in an abrupt rise in the water surface elevation and reverse circulation of flow near the surface (countercurrent velocities). This flow condition typically occurs downstream of the low-head dam.

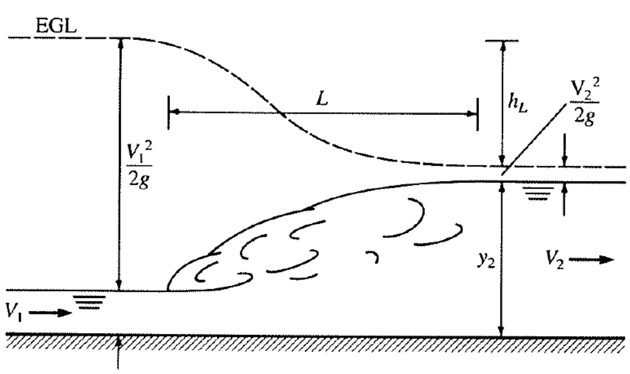

Figure 1. Schematic of hydraulic jump where the initial depth (y_1) and velocity (V_1) are upstream from the hydraulic jump and the sequent (or conjugate) depth (y_2) and velocity (V_2) are downstream from the hydraulic jump (Roberson, et al. 1995).

Flow over a vertical drop structure such as a low-head dam can produce four possible flow conditions based on the sequent (or conjugate) downstream depth required to cause a hydraulic jump and actual tailwater depth. The sequent depth depends on the discharge over the weir and the tailwater depth depends on the downstream channel characteristics. A hydraulic jump will form when the actual tailwater depth is equal to or greater than the sequent depth. The exact flow characteristics (e.g., strength of recirculating flow) vary with the ratio of actual tailwater depth to sequent depth. Because of changing hydrologic conditions (i.e., river flow rates) at the same structure, recreationists may experience dangerous hydraulic conditions in a location that was safe during previous visits.

The calculated sequent depth is maximum at the toe of the dam and decreases as the flow decelerates downstream from the dam. If the tailwater depth is less than the sequent depth at the toe of the dam, the result is a "swept-out hydraulic jump". In this case, the hydraulic jump is formed further downstream at a point where the sequent depth reduces to a value matching the actual tailwater depth (Figure 2 - Case A, Tschantz and Wright 2011). With an "optimal hydraulic jump", a fully developed hydraulic jump is formed directly downstream of the structure (Figure 2 - Case B). A "submerged hydraulic jump" is formed when the tailwater depth exceeds the sequent depth needed to form an optimal jump at the toe of the dam (Figure 2 - Case C). Submerged hydraulic jumps produce strong rotational currents toward the dam face, but the calm appearance of submerged hydraulic jumps makes low-head dams deceptively dangerous for recreationalists. As the submergence or tailwater depth increases, the countercurrent velocity decreases (Leutheusser and Fan 2001). In this "drowned-out hydraulic jump" condition, the tailwater depth far exceeds the sequent depth of the hydraulic jump such that the hydraulic jump is completely drowned out and only an undulating water surface exists (Figure 2 - Case D).

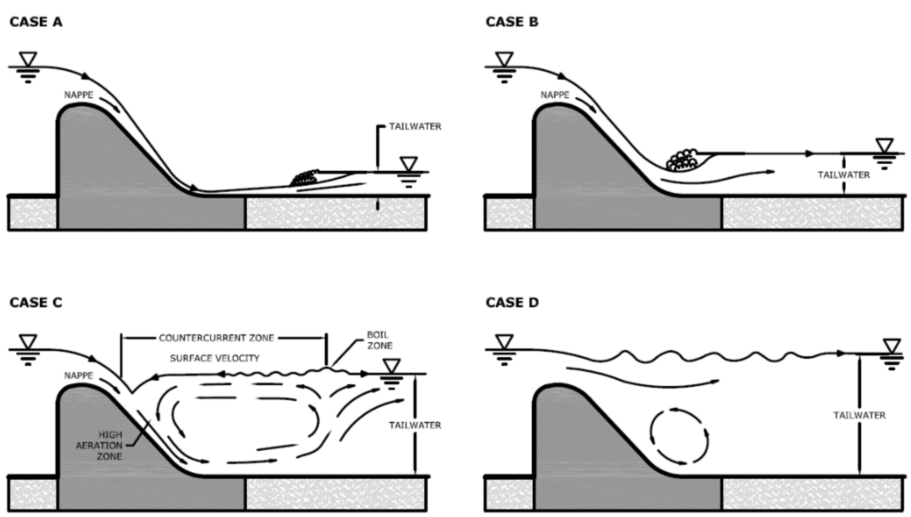

Figure 2. Four possible flow conditions over a low-head hydraulic structure: Case A – Swept-out Hydraulic Jump, Case B – Optimal Hydraulic Jump, Case C – Submerged Hydraulic Jump, Case D – Drowned-out Hydraulic Jump (modified from Tschantz and Wright 2011). Case C is the most dangerous condition.

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 working groups or committees reviewing public safety at dams with a focus on low-head hydraulic structures which generate hydraulic conditions that increase the risk of drowning. In January 2020, USSD, ASDSO, and American Society of Civil Engineers' Environmental and Water Resources Institute (EWRI) began a combined effort focused on creating a national inventory of low-head dams led by Dr. Rollin Hotchkiss (Brigham Young University).

The purpose of this research project was to develop a methodology to determine the presence of submerged hydraulic jumps at low-head hydraulic structures. This will help dam owners to properly identify structures of concern and institute appropriate short-term and long-term mitigation strategies. Researchers reviewed related literature and developed a computational process for estimating when dangerous hydraulic conditions may exist at low-head dams.

2. Previous Work

There are numerous journal articles, reports, professional society publications, theses, and news articles on the topic of public safety at low-head dams. Selected references can be found in a Reclamation report on public safety issues related to low-head hydraulic structures (Svoboda, et al. 2017). This report documented the characteristics and 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 and Fan (2001) provide information on quantifying the hydraulic processes involved with submerged hydraulic jumps downstream of low-head hydraulic structures. They provide a series of empirical equations based on experiments conducted in a physical hydraulic model with a horizontal, glass-walled flume and a 15-m long by 375-mm wide by 450-mm deep test section. Data were collected on velocity magnitude and direction downstream of a sharp-crested weir with a ventilated nappe for various combinations of weir height, head on the weir, and tailwater depth. Countercurrent velocities were found to decreases with increasing tailwater depth until the velocity suddenly drops to zero. For a critical degree of submergence (Rao and Rajaratnam 1963), nappe "flip" occurs causing the recirculating eddy or roller to disappear, and velocities are oriented solely in the downstream direction. Nappe "flop" occurs when tailwater decreases and the upstream counter-rotation begins. Leutheusser and Fan (1995) found that nappe "flip" occurs when the ratio of upstream depth to tailwater depth is about 1.10 and nappe "flop" occurs at a ratio of about 1.19, with varying values due to hysteresis caused by changing nappe ventilation conditions. Human swimming speed can be compared to surface velocities to better understand when victims are not able to escape the countercurrent velocities.

Israel-Devadason and 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. The authors provide a case study at Dock Street Dam in Harrisburg, Pennsylvania, a 6-ft-high run-of-the-river dam which has caused 30 drownings and 25 documented rescues between 1935 and 2019, although it is classified as a low-hazard dam (Vendel 2018). Using the CFD model, the physical motions of a victim could be simulated in the hydraulic roller downstream of the dam for a 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 area of hydraulic concern (Figure 2 - Case C).

3. Methods

3.1 Input Data and Process

A spreadsheet was created to examine the hydraulic conditions downstream of a variety of low-head dam structures over a wide range of flows. The calculations show the range over which a submerged hydraulic jump occurs and whether the surface velocity is directed upstream (Figure 2 - Case C) or downstream (Figure 2 - Case D) based on the tailwater depth at which the surface velocity "flips" direction. The calculations also show estimated surface velocities which can be compared to human swimming capability.

The following project data is needed to estimate submerged hydraulic jump conditions over the operational range. These data are entered into the spreadsheet in the orange data cells (Figure 3).

- Flow range
- Weir length
- Structural height of the dam above the downstream invert
- Bed slope
- Manning's n (channel roughness factor)
- Channel width

The spreadsheet generally follows the process presented in Leuthausser and Fan (2001) using equations derived from their experimental data. The spreadsheet requires turning on "iterative calculation" in Microsoft Excel, since several cells use circular-reference formulas. The spreadsheet steps through the process described in Table 1.

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

Step	Description	Equations
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	Eqn. 3 and 4 (Leuthausser and Fan 2001); weir flow equation
3	Estimate flow parameters at the base of the dam (y_1, v_1, F_1)	Eqn. 7, 8, 9 (Leuthausser and Fan 2001)
4	Calculate sequent depth (y_2)	Eqn. 1 (Leuthausser and Fan 2001)
5	Estimate tailwater depth (or input measured values from field, y_t)	Manning's equation
6	Determine degree of submergence	Rao and Rajaratnam (1963)
7	Calculate countercurrent surface velocity and compare to average human swimming capability	Eqn. 13, 15 (Leuthausser and Fan 2001)
8	Determine tailwater depth at which velocity direction "flips"	Pg. 515 (Leuthausser and Fan 2001)

3.2 Limitations

Calculations based on experimental equations from Leutheusser and Fan (2001) were derived from experiments using a simple sharp-crested weir, but should be generally applicable to broad-crested or ogee-shaped weirs which are more common on low-head dams. With a sharp-crested weir, "flip" and "flop" tailwater values are significantly different due to alternating ventilation of the nappe and suction below the nappe when non-ventilated. A broad-crested weir would likely exhibit smaller differences between the "flip" and "flop" tailwater levels, since ventilated nappe conditions are less likely for these weir types. However, general trends in the "flip" or "flop" elevations would probably be similar for all weir types.

The base calculations in the spreadsheet assume normal depth downstream of the low-head hydraulic structure; however, downstream check structures or river constrictions could affect this value. 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. Tailwater information can be input directly if it is known for a range of discharges. Base calculations also assume a wide channel whose width does not change with discharge, but these calculations could be modified in the spreadsheet if necessary.

One modification to the procedure identified in Leutheusser and Fan (2001) was made. They developed an equation to predict the reverse-flow velocity that depended upon a parameter α, and they determined values of α for three specific flow conditions to obtain a good fit of their equation to the experimental data. To apply their method to other flow conditions, a relation was developed between α and the Froude number values (Fr_1) at the toe of the dam in their experiments ($\alpha = 39/Fr_1^{0.5}$). This allows their equation for reverse-flow velocity to be applied to other values of Fr_1. With follow-up physical or CFD experiments, more data points could be collected to refine the α-Fr_1 relationship.

4. Results

An example of the spreadsheet layout is presented in Figure 3. After the spreadsheet is used to calculate data, a graph is created to visually summarize the flow range of concern (Figure 4). 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 (Figure 2 - Case A or B). When tailwater depth (Y_t, solid blue line) is greater than the conjugate depth of the jump (Y_2, solid gray line), the hydraulic jump is either submerged (Figure 2 - Case C) or drowned-out (Figure 2 - Case D). Using the spreadsheet, the "flip" point can be calculated where upstream-oriented surface velocities suddenly become downstream-oriented. On the graph, the "flip" point occurs where the dashed gray line crosses the solid blue line (about 61,000 cfs). At flows greater than the associated "flip" discharge, the submerged jump is drowned-out and the hydraulic condition is safer (Figure 2 - Case D). At flows less than the associated "flip" discharge, the submerged jump may be potentially dangerous (Figure 2 - Case C).

The solid red line describes 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 4.5 mph (2 m/s or 6.6 ft/s) for an Olympic athlete. Average human swimming velocity is closer to 2 mph (0.89 m/s or 2.9 ft/s). In the case shown in Figure 3, there is a small window of about 58,000 to 61,000 cfs where a human 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 for part of the Case C range.

Weir Length, L	3460 ft		Bed Slope, S_o	0.0001
Structural Height of Dam Above Tailwater Invert, P	6 ft		Manning's n	0.028
			Channel Width, b	3460 ft

Flow Information	**Hydraulic Calculations**						**Ideal Jump**							**Tailwater Conditions (Normal Depth)**	**Submerged Hydraulic 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	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	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/sqrt(2gH)	V_1	(Eqn. 9) F_1	(Eqn. 1) Y_2/H	Y_2	Y_t	$S = (Y_t - Y_2)/Y_2$	ΔE_{DM}	α	V_s/V_1	V_s	(pg. 515) Y_{flip}
cfs	ft	ft	-	-	-	-	-	ft	-	ft/s	-	-	ft	ft		ft			ft/s	ft
5000	0.58	6.58	0.09	0.62	3.31	1.04	0.18	0.10	2.35	14.3	7.92	1.88	1.08	1.82	0.68	4.74	14.04	0.29	4.10	5.98
10000	0.91	6.91	0.13	0.62	3.33	0.66	0.20	0.18	2.11	16.2	6.73	1.78	1.62	2.76	0.71	4.13	15.21	0.26	4.18	6.28
15000	1.19	7.19	0.17	0.63	3.35	0.50	0.21	0.25	1.97	17.2	6.05	1.71	2.03	3.53	0.74	3.64	16.04	0.24	4.16	6.53
20000	1.43	7.43	0.19	0.63	3.36	0.42	0.22	0.32	1.87	18.0	5.58	1.66	2.38	4.19	0.76	3.21	16.69	0.23	4.09	6.76
25000	1.66	7.66	0.22	0.63	3.38	0.36	0.23	0.39	1.79	18.5	5.23	1.62	2.70	4.79	0.78	2.83	17.23	0.22	4.00	6.96
30000	1.87	7.87	0.24	0.63	3.39	0.32	0.24	0.46	1.73	19.0	4.96	1.59	2.98	5.34	0.79	2.48	17.70	0.20	3.88	7.15
35000	2.07	8.07	0.26	0.64	3.41	0.29	0.25	0.52	1.68	19.4	4.74	1.57	3.24	5.86	0.81	2.16	18.11	0.19	3.75	7.33
40000	2.25	8.25	0.27	0.64	3.42	0.27	0.26	0.59	1.64	19.7	4.55	1.55	3.48	6.35	0.82	1.85	18.48	0.18	3.61	7.50
45000	2.43	8.43	0.29	0.64	3.43	0.25	0.27	0.65	1.60	20.0	4.39	1.53	3.71	6.82	0.84	1.56	18.81	0.17	3.44	7.67
50000	2.60	8.60	0.30	0.64	3.44	0.23	0.27	0.71	1.57	20.3	4.25	1.51	3.93	7.26	0.85	1.28	19.12	0.16	3.25	7.82
55000	2.77	8.77	0.32	0.65	3.45	0.22	0.28	0.77	1.54	20.6	4.12	1.49	4.14	7.69	0.86	1.01	19.40	0.15	3.03	7.97
60000	2.93	8.93	0.33	0.65	3.46	0.20	0.29	0.83	1.51	20.8	4.01	1.48	4.34	8.10	0.87	0.75	19.66	0.13	2.77	8.12
65000	3.08	9.08	0.34	0.65	3.47	0.19	0.29	0.89	1.49	21.0	3.91	1.47	4.52	8.50	0.88	0.51	19.91	0.12	2.44	8.26

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

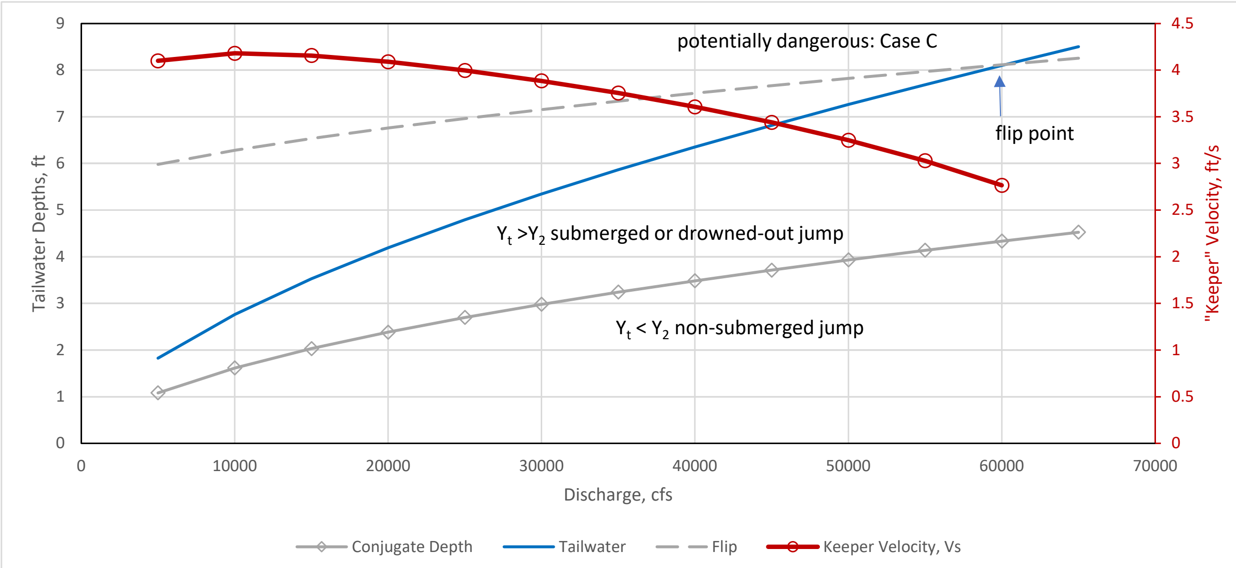

Figure 4. Graphical depiction of flow rates where potentially dangerous submerged hydraulic jumps occur, the associated surface velocities, and the "flip" point transitioning to a safe condition as a drowned-out jump. The heavy line (red) shows surface velocities that act to "keep" a person in the recirculating zone.

As a case study, the spreadsheet was applied to the Dock Street Dam case discussed in Israel-Devadason and Schweiger (2019) with estimated values of downstream slope and roughness since these were not documented in detail. An online article written by Benjamin Israel-Devadason for Association of Dam Safety Officials (https://damfailures.org/case-study/dock-street-dam-pennsylvania/) shows incident data for Dock Street Dam. An analysis of these data and the related CFD modeling in Israel-Devadason and Schweiger (2019, Figure 7) shows that the dangerous range of flow conditions is from about 8,000 to 60,000 cfs. The spreadsheet created for this project predicts a similar danger range (Figure 4).

5. Discussion

The submerged hydraulic jump spreadsheet analysis shows that the danger zone for many dams is typically very broad. Low-head dams almost always create dangerous hydraulic conditions for a significant range of 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 estimate the range over which a submerged hydraulic jump may occur.

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 heavily grouted riprap downstream of the dam face can reduce roller strength and break up dangerous downstream hydraulics (Schweiger 2011). Israel-Devadason and Schweiger

(2019) showed in their CFD model that installation of a two-step configuration on the downstream dam face could eliminate the hydraulic hazard at Dock Street Dam. Other remediation techniques such as baffled chute spillways (Leutheusser and 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 based on when recreationists are likely to be present at the site. Proper classification of low-head hydraulic structures will assist nationwide efforts to improve public safety.

References

Israel-Devadason, Benjamin and Paul G. Schweiger. 2019. "Decoding the Drowning Machines: Using CFD Modeling to Predict and Design Solutions to Remediate the Dangerous Hydraulic Roller at Low Head Dams". The Journal of Dam Safety. Winter 2019. p. 20-31.

Kern, Edward W. 2014. "Public Safety at Low-Head Dams: Fatality Database and Physical Model of Staggered Deflector Retrofit Alternative". Brigham Young University. All Graduate Theses and Dissertations. Paper 3984.

Klumpp, Cassie C., Clifford A. Pugh, Jerry R. Fitzwater. 1989. "Union Avenue Dam Boatchute Study". Bureau of Reclamation, Hydraulics Laboratory Report R-89-12.

Leutheusser, H. & Fan, J. 2001. "Backward flow velocities of submerged hydraulic jumps". The American Society of Civil Engineers. Journal of Hydraulic Engineering, Volume 127, Issue 6.

Leutheusser, H. J., and Fan, J. J. 1995. "Transcritical weir flow." Zeitschrift fuer angewandte Mathematik und Mechanik (ZAMM), 75(SI), S343–S344.

Leuthesser, Hans J. and Warren M. Birk. 1991. "Drownproofing of Low Overflow Structures". American Society of Civil Engineers. Journal of Hydraulic Engineering, 117(2): 205-213.

Olsen, Riley J., Michael C. Johnson, and Steven L. Barfuss. 2014. "Low-Head Dam Reverse Roller Remediation Options". American Society of Civil Engineers, Journal of Hydraulic Engineering, 140(4).

Rao, N. S., and Rajaratnam, N. (1963). "The submerged hydraulic jump." J. Hydr. Div., ASCE, 89(1), 139–162.

Roberson, John A., John J. Cassidy, and M. Hanif Chaudry. 1995. *Hydraulic Engineering*. John Wiley & Sons, Inc.

Schweiger, Paul G. 2011. "Saving Lives While Improving Fish Passage at 'Killer Dams'". Association of State Dam Safety Officials. Journal of Dam Safety, Volume 9, Issue 2.

Tschantz, Bruce A. 2014. "What We Know (and Don't Know) About Low-head Dams". Association of State Dam Safety Officials. The Journal of Dam Safety, Volume 12, Issue 4.

Tschantz, Bruce A. and Kenneth R. Wright. 2011. "Hidden Dangers and Public Safety at Low-Head Dams". Association of State Dam Safety Officials. The Journal of Dam Safety, Volume 9, Issue 1.

Vendel, C. (2018). Harrisburg's "Drowning Machine" dam has killed at least 29 people. Their Stories. PennLive.com (https://www.pennlive.com/news/erry-2018/06/72b6e927394991/victims_of_the_dock_street_dam.html).