What We Know (and Don't Know) About Low-head Dams

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INTRODUCTION

Low-head, or run-of-the-river, types of dams - usually spanning the entire river or stream - can present a safety hazard to the public because of their capability to produce dangerous recirculating currents, large hydraulic forces, and other hazardous conditions sufficient to trap and drown victims immediately downstream from the overflowing water. Thousands of these dams, mostly of concrete or masonry construction and ranging up to about fifteen feet in height, have been built across U.S. rivers and streams to raise the water level for purposes of improving municipal and industrial water supplies, producing hydropower, and diverting irrigation water. Tens of thousands were built in the 1800s to power gristmills and small industries. U.S. manufacturing census data of 1840 reveals more than 65,000 water-powered mill dams in 872 counties in the eastern United States (Walter & Merritts, 2008). The highest densities were in the Piedmont and the Ridge- and-Valley physiographic provinces of Maryland, Pennsylvania, New York, and central New England as shown in Figure 1. A typical low-head mill dam is shown in Figure 2.

Hundreds more have been constructed across the U.S. since the mid-1800s for irrigation, mining, milling, water supply, and manufacturing. Low-head structures were also built in the East for diverting water to early navigation canals. While many of these dams still exist and are in use across the country, most have been washed out or removed. Several remaining structures have fallen into disrepair, forgotten and abandoned - in some cases without a known or distinct owner - posing dangerous conditions to the public. Structures such as bridge or culvert apron drop-offs, grade control structures (GCS), pipe crossings, dam spillways, and gauging station weirs can produce dangerous submerged hydraulic jump conditions typical of low-head dams as illustrated in Figure 3. A submerged hydraulic jump occurs when the tailwater depth in the downstream channel exceeds the jump's subcritical sequent depth[1] forcing a strong rotating current to form immediately downstream from the plunging overflow nappe. The frontal vortex is a degenerate jump and is commonly called a "hydraulic."

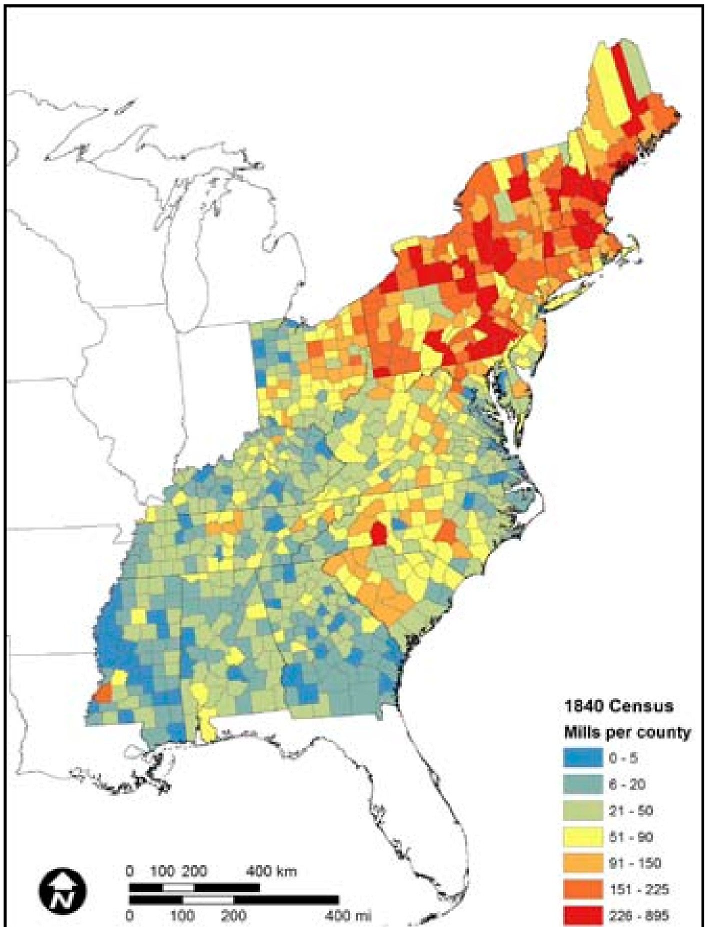

FIGURE 1. DISTRIBUTION OF MILL DAMS IN THE EASTERN U.S., FROM 1840 MANUFACTURING CENSUS. (COURTESY WALTER AND MERRITTS)

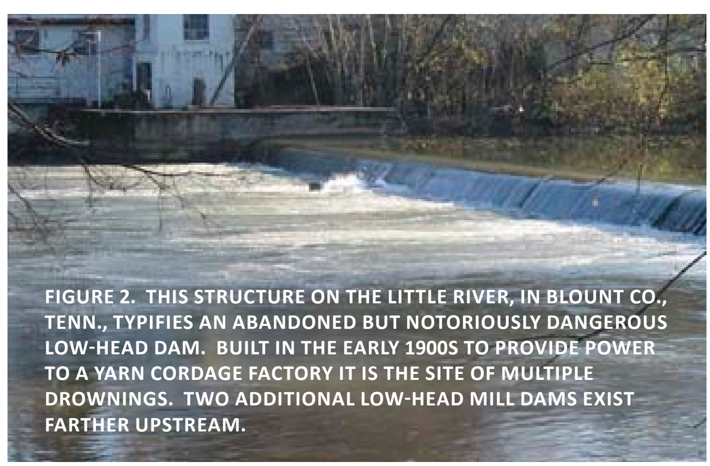

FIGURE 2. THIS STRUCTURE ON THE LITTLE RIVER, IN BLOUNT CO., TENN., TYPIFIES AN ABANDONED BUT NOTORIOUSLY DANGEROUS LOW-HEAD DAM. BUILT IN THE EARLY 1900S TO PROVIDE POWER TO A YARN CORDAGE FACTORY IT IS THE SITE OF MULTIPLE DROWNINGS. TWO ADDITIONAL LOW-HEAD MILL DAMS EXIST FARTHER UPSTREAM.

[1] The sequent depth is water depth after a hydraulic jump and is determined from the well-known Bélanger's momentum equilibrium equation that relates this depth to the incoming initial depth and Froude Number.

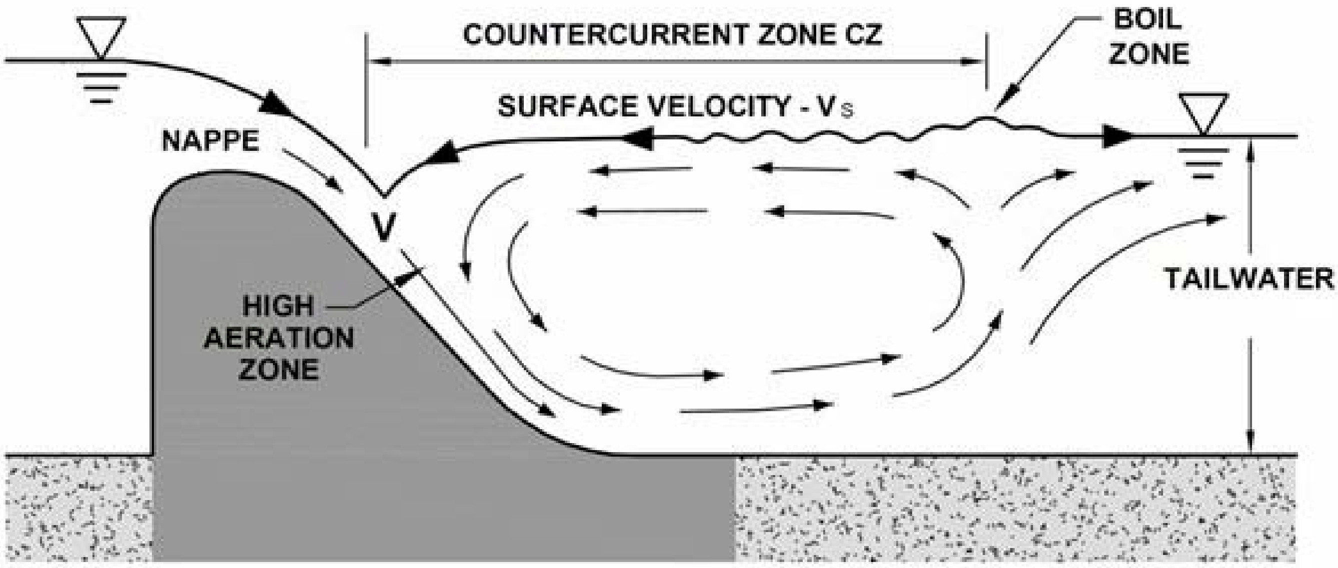

FIGURE 3. SCHEMATIC ELEMENTS OF A SUBMERGED HYDRAULIC JUMP DOWNSTREAM FROM A LOW-HEAD DAM OR SIMILAR SILL SHOWING THE BOIL, REVERSED OR COUNTERCURRENT VELOCITY, CENTRAL RECIRCULATING HYDRAULIC, AND HIGH AERATION ZONES.

Kayakers, canoers, rafters, boaters, anglers and swimmers are often unaware of the dangerous forces and fast recirculating currents that these dams can produce, especially if there are no warning signs, floating barriers or portages. Experienced swimmers have difficulty overcoming the velocities around these structures. Stranded motor boaters, canoers, rafters, and kayak paddlers are often unable to prevent themselves from being pulled over the dam crest by the rapid drawdown current. Once they are trapped in the turbulent foam below low-head dams, life vests become less effective because of greatly reduced buoyancy. In fact, incidents have been documented where the life vests have been ripped off victims in the churning hydraulic below the dam. Overflowing water is capable of pounding trapped victims with relentless forces exceeding hundreds of pounds (Tschantz and Wright, 2011). Heavy and dangerous debris trapped in the recirculating current, together with disorientation and the possibility of hypothermia, add to an already dangerous hydraulic condition. Dozens of rescuers have drowned attempting to rescue victims trapped in the flow reversal or countercurrent zone between the dam and the downstream "boil zone"[2] where the surface velocity reverses. Some dams, including structures on the Little River in Tennessee, the Red River between Minnesota and North Dakota, the Fox River in Illinois, and the Des Moines River in Iowa, have produced multiple drownings.

RECENT STATE SURVEY OF LOW-HEAD DAMS

In early 2014, a short state survey of four questions on low-head, or run-of-the-river, types of dams was sent out to all state dam safety managers through the Association of State Dam Safety Officials (ASDSO, 2014). The purpose of the survey was to estimate the extent of low-head dams in the U.S., while gaging the level of state regulation or policy aimed at requiring dam owners to warn the

TABLE 1. STATE LOW-HEAD DAM SURVEY QUESTIONS.

1. **Are you aware of any low-head dams in your state?** (Includes weir-like masonry or concrete structures, ranging up to 15-ft high – also other hydraulic structures such as bridge or culvert apron drop-offs, spillways, or flow gauging station control weirs capable of producing similar dangerous submerged hydraulic jump conditions).
2. **Does your state maintain an inventory of low-head dams?** If so, list agency and contact.
3. **Does your state have regulations or policy that requires or advises owners to reduce risk to public waterway users? (includes warning signs, marking exclusion zones, installing barrier booms, fencing, etc. –list regulation or policy.)**
4. **Estimate range of number of low-head dams in your state and level of confidence of your estimate (i.e., 10%, 25%, 50%, 75%, etc.). Give actual number if state inventory number is available.**

a.	0 -None known	[_____%]
b.	1 – 50	[_____%]
c.	50-100	[_____%]
d.	100-200	[_____%]
e.	200-300	[_____%]
f.	300-400	[_____%]
g.	400-500	[_____%]
h.	>500	[_____%]
i.	______	(Actual inventory number)

[2] The boil is a turbulent upheaval of water occurring at a distance of about 3 to 4 dam heights downstream from the overflowing water at the low-head dam and marking an uneven line across the river where the surface current reversal/split occurs. For certain flows and tailwater conditions, persons and objects such as boats trapped in this reversal zone are pulled toward the dam by a surface current stronger than most people can escape.

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public of the inherent dangers at these small structures. In May 2014, survey results from 42 states were tabulated and distributed to the states for review and comments. Access to detailed state responses to the four questions is available through the members' section of the ASDSO website, www.damsafety.org. The survey questions are listed in Table 1.

1. State Awareness – Are you aware of any low-head dams in your state? While 49 states maintain inventories and have dam safety regulations for structural and hydraulic integrity and for protecting the public from potential failure, all but a handful of states do not maintain inventories of low-head because the dams are so small. Historically speaking, state dam safety programs were established primarily for regulating and improving the structural integrity *of* dams, raising awareness of dam safety issues, and protecting the public from dam failure, rather than for focusing on or regulating public safety *around* or *at* smaller, non-jurisdictional low-head dams. Consequently, attention to public safety at low-head dams usually falls between the cracks at the state level between dam safety and other water-related divisions responsible for boating or water safety, game and fish, or ecological resources.

2. State Inventory – Does your state maintain an inventory of low-head dams? It came as no surprise that only a handful of responding states had any jurisdictional responsibility for maintaining an inventory or regulating and promoting public safety at these types of small structures. Of 42 responding states, most (37) indicated that they were aware of low-head dams in their states; one was aware of none; and four lacked sufficient information to answer the question.

3. State Regulations or Policy – Does your state have regulations or policy that requires owners to reduce risk to public waterway users? Only three states (IL, PA, & VA) indicated having statutory authority for regulating public safety at low-head dams. Illinois and Pennsylvania require owners of new and existing dams located in public waters to warn the public of the hazards posed by these dams. Both states require the establishment of enforceable "exclusion zones" upstream and downstream from low-head dams marked with specified buoys and signs. However, Pennsylvania permits owners of dams less than 200 ft. in length to maintain general warning signs on their dams – one pair facing upstream and one pair facing downstream. Illinois indicated that the development of rules to regulate this activity "has not been as successful." Virginia has established a type of permissive legislation that sets standards for encouraging the owner of a low-head dam to mark areas above and below the dam and on the banks immediately adjacent to the dam with signs and buoys of a design and content, in accordance with regulations, to warn the swimming, fishing and boating public of the hazards posed by the dam. Any owner of a low-head dam who marks a low-head dam shall be deemed to have met the duty of care for warning the public of the hazards posed by the dam. Any owner of a low-head dam who fails to mark a low-head dam shall be presumed not to have met the duty of care for warning the public of the hazards posed by the dam. Virginia's Game and Inland Fisheries adopted a Uniform State Waterway Marking System that mirrors the federal uniform waterway marking system.

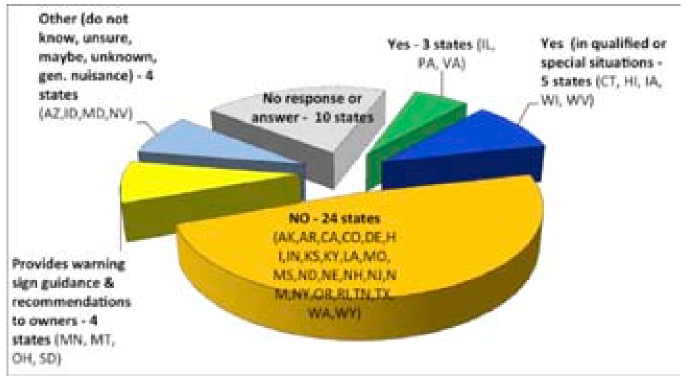

FIGURE 4. STATE RESPONSE TO SURVEY Q#3: DOES YOUR STATE HAVE REGULATIONS OR POLICY THAT REQUIRES OR ADVISES OWNERS TO REDUCE RISK TO PUBLIC WATERWAY USERS (INCLUDES SIGNS, EXCLUSION ZONES, BARRIERS, ETC.)?

Five states (CT, HI, IA, WI, & WV) provide for limited degrees and types of warnings for different situations – state-owned dams only; general natural hazards that may or may not cover low-head dams; local or state waterway trails programs; and for case-by-case situations based upon an engineer's inspection recommendation. For example, Iowa works with dam owners and provides detailed standards for sign types, sizes, placement and installation standards for warning water users at low-head dams on state-designated water trails. Wisconsin requires "Dangerous Currents" signs, devices and portages at all dams that are known to create hazardous boating safety conditions in their vicinity. Connecticut's Attorney General has issued an opinion that state-owned hazardous dams are required to be marked with warning signs, exclusion zones, barrier booms, fencing, etc., for three public hazard categories vetted by the Department of Energy and Environmental Protection. In West Virginia, the inspecting dam engineer has discretion to recommend warning signs, booms, etc., as a matter of public safety. Four states (MN, MT, OH, & SD) have extensive awareness and educational programs with pamphlets and informational websites and/or provide warning sign guidance and templates devoted to low-head dams and their owners. Four states (AZ, ID, MD, & NV) didn't know or were unsure of any regulations or policy. Idaho suggested that this hazard may be covered under its "Public Nuisances" ordinance or statute. The remaining ten states did not answer or respond to this question.

4. Number of Low-Head Dams – Estimate a range of number of low-head dams in your sate and level of confidence of your estimate. Nine states that maintain some type of inventories reported a total of 916 low-head dams. States reporting the highest inventories include Pennsylvania (253), Iowa (246), and New Hampshire (244). However, twenty-seven states that do not maintain inventories of low-head dams but provided requested approximations in the form of a range with varying degrees of stated confidence, resulted in an estimated a range of 1814 to 3660 total additional low-head dams. Six states indicated that while low-head dams existed in their states, they lacked adequate information to submit an estimate. This means that there may be 2730 to 4576 low-head dams in 42 reporting states. Table 1 at the end of this article summarizes the state responses to the question of estimated number of low-head dams and their respective levels of confidence in making an estimate.

U.S. FATALITIES AND INJURIES AT LOW-HEAD DAMS: FACTORS AND DEMOGRAPHICS

Water users should avoid these dams at all times, both upstream and downstream, as safe passage on one day does not guarantee a safe condition on another; small changes in flow can affect the degree of hazard produced by a submerged hydraulic jump. The combination of reversed currents, large hydraulic forces, low buoyancy, moving submerged debris, potential hypothermia, and victim disorientation combine to create what has been described as a perfect "drowning machine." Hundreds of deaths have occurred at these structures across the U.S. since the 1960s, with drownings and injuries increasing annually as more people participate in water sports.

Research data collected by the author over the last ten years shows that, during the period 1960- July 2014[3], 308 fatalities and 84 injuries in 253 incidents occurred at low-head dams, with fatalities occurring in 234 of the incidents. The Figure 5 map shows the general distribution of fatalities by state. As of July 2014, 39 states have had at least one low-head dam death. Over one-third of the documented fatalities have occurred in Iowa, Minnesota, and Pennsylvania.

The research data shows that 2/3, or 199 of the 308 fatalities, have occurred over the last 15 years (Figure 6). These data do not include approximately 12 deaths since 1964 at Drayton Dam on the Red River between Minnesota and North Dakota and an estimated 14 deaths at Williams Z-dam on the James River in Virginia prior to 1983. Of 112 fatalities where information about life vests, or personal flotation devices (PFDs), was available, 49 (44%) had worn PFDs and 63 (56%) had not. The close split is not surprising given the low buoyancy environment and other factors that may render PFDs less effective or even cause them to be ripped off in the turbulence.

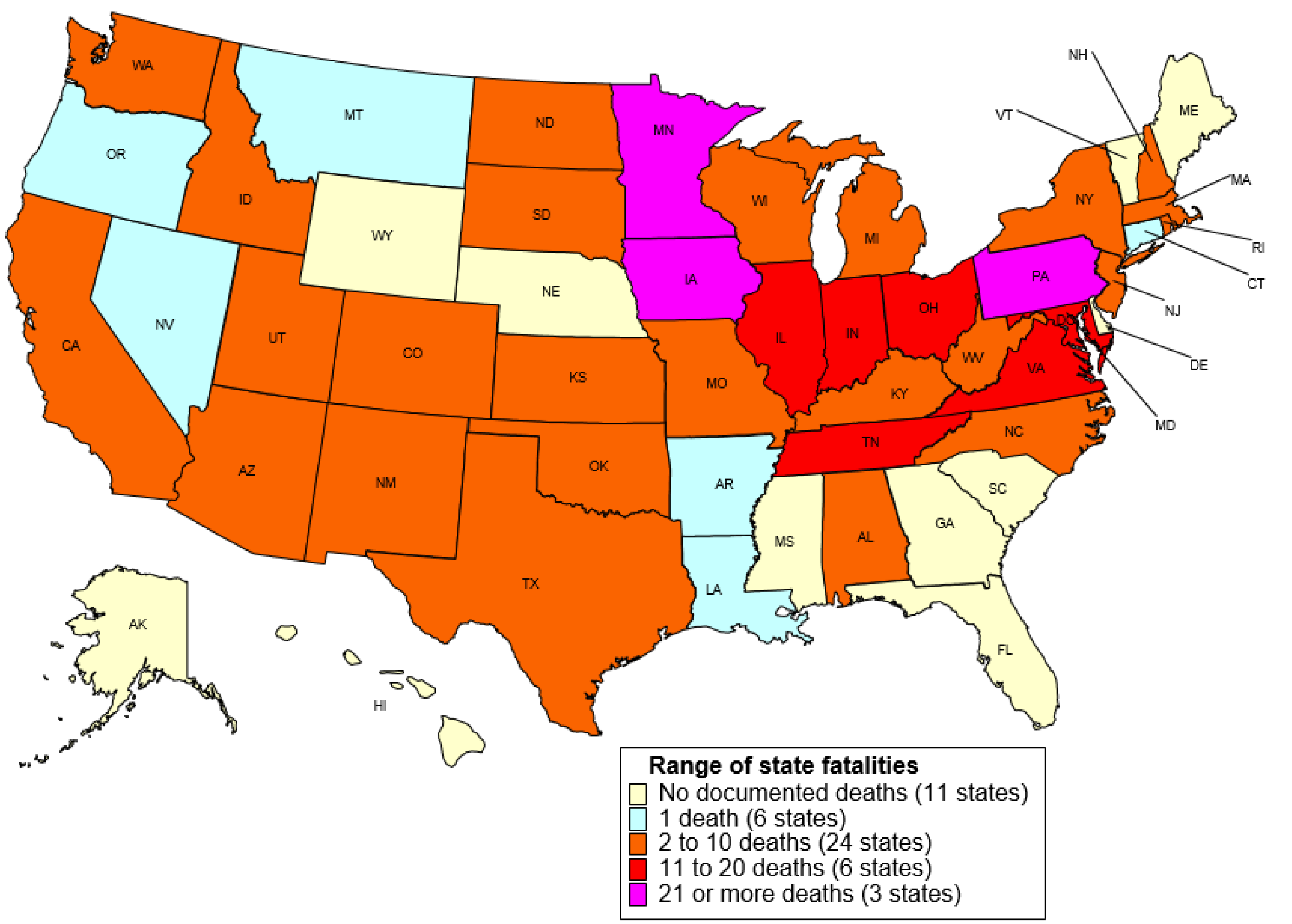

FIGURE 5. DISTRIBUTION OF 308 DOCUMENTED LOW-HEAD DAM FATALITIES IN THE U.S. FROM 1960 THROUGH JULY 2014.

[3] The number of incidents and fatalities continues to increase in 2014. Dr. Rollin Hotchkiss, Brigham Young University Professor of Civil & Environmental Engineering and his graduate students have, as of this writing, described and mapped 435 fatalities at 229 different low-head dam sites in 38 states at their interactive Submerged Hydraulic Jump website: http://krcproject.groups.et.byu.net/browse.php

The same research also shows that going over low-head dams is always a risky adventure. Figure 7 shows that of 153 incidents in which 335 people were known to go over a low-head dam, 68 percent either drowned (53%) or were injured (15%). Some boaters were unaware of the dam before it was too late or lost power and were pulled over by the current, while many kayakers, canoers, and rafters deliberately paddled over the dam, challenging the danger by underestimating the tremendous power of moving water while overestimating their ability to overcome these forces and currents. Wearing a life vest while going over a dam improved the survival rate by a margin of 57% to 43%.

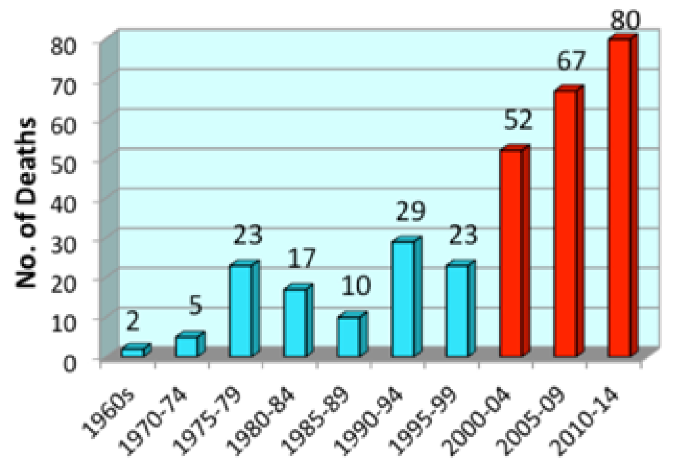

FIGURE 6. DISTRIBUTION OF LOW-HEAD FATALITIES ACROSS THE U.S THROUGH JULY 2014

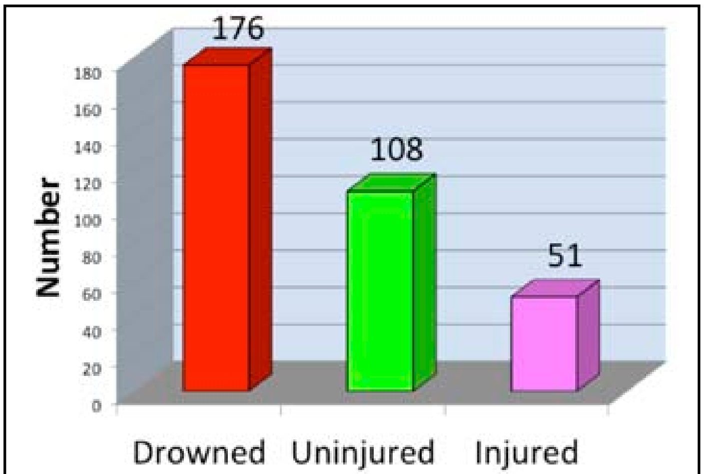

FIGURE 7. CONSEQUENCES OF 335 PEOPLE KNOWN TO GO OVER A LOW-HEAD DAM IN 153 SEPARATE INCIDENTS

The demographics of drowning incidents show that for a total of 253 victims whose ages and gender are known, 87 percent were male and 13 percent were female. The median age for all drowning victims is 27 years. Figure 8 shows a detailed distribution of fatalities by age and gender.

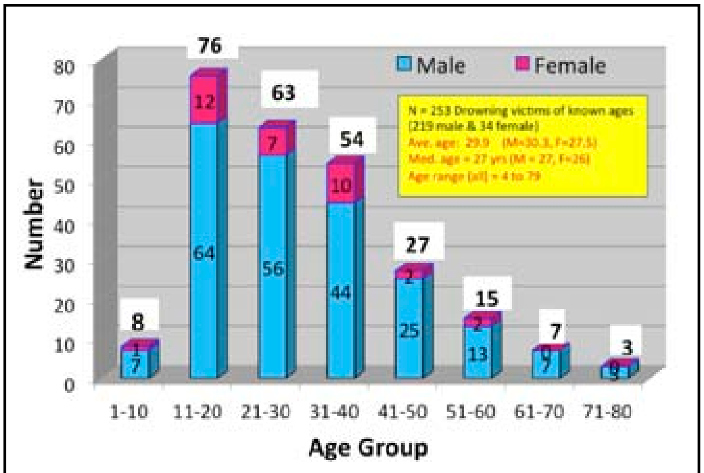

FIGURE 8. KNOWN AGE AND GENDER DISTRIBUTION OF 244 DROWNING VICTIMS

Out of 253 documented incidents involving fatalities and/or injuries, this same research data shows that only 57 incident locations were known to have water hazard warning signage at the time of accident[4]. Analysis of the data shows that over half (163/308 or 53 percent) of the fatalities occurred over three-day weekends during April through August.

SUMMARY

The combination of increased public use of waterways for fishing, swimming, boating, and paddle sports; lack of public understanding or appreciation of forces, currents, and changing hazards around low-head dams; paucity of upstream and downstream warning signs or hazard markers; and somewhat limited efforts by state dam and boating safety programs, has left public safety at and around low-head dams in most parts of the country untethered to any regulatory standards. Owners of low-head dams who accept the responsibility to warn and educate the public about the hazards created around these structures, should be aware of established state and federal[5] warning system standards and guidelines.

In its effort to increase public safety at its run-of-river dams, Illinois has reviewed and documented existing public safety measures at 25 dams where dam removal, structural modifications, and signage guidelines and plans were evaluated for eliminating or lessening public safety hazards posed by these dams. (2007). The Illinois public safety program, Pennsylvania's (1998) and Virginia's (2008) legislative and regulatory approaches, and the Iowa Water Trails signage program (2010) bear consideration by other states as templates for increasing public safety and reducing fatalities at low-head dams in the U.S. The Canadian Dam Association (CDA) has developed comprehensive (2011) for assessing risk and hazards associated with dams, including low-head dams; warning systems, including signage standards; and safety booms and boat barrier systems.

[4]Fourteen incident locations were known not to have any warning signs or markers. The signage situation at the remaining incident sites where injuries or fatalities occurred was not documented, especially for most earlier (i.e., 1960-1980) incidents where information details were scarce.

[5]Refer to listed FERC, USACE and USBR references

ASDSO initiatives and successful state and federal dam safety programs have had a major impact on dam safety and lives saved since the outbreak of dam failures during the notorious decade of the 1970s. Disasters during that period included dam failures at Buffalo Creek (WV), Teton (ID), Canyon Lake (SD), Laurel Run (PA) and Kelly Barnes (GA), when at least 258 lives were lost and damage was measured in the billions. In the 3 1/2 decades since 1980, the number of dams has grown by almost 50 percent, the average age of U.S. dams has doubled to 53, and creeping urbanization below dams has increased the number of high hazard dams, but "only" 40 people have died from dam failures. That is good news indeed. The bad news, however, is that over the same period, almost seven times more drowning deaths (278) have occurred at low-head dams. Figure 9 shows a decade-by-decade comparison of fatalities from dam failures to low-head dam incidents over the period 1960 to present.

ASDSO has the professional resources and the organizational structure and precedence for a coordinated effort, as the CDA has undertaken, to assess the problem, review successful state and federal approaches, and develop guidelines and tools for helping owners and states improve public safety at and around low-head dams. Public safety is of paramount importance at and around all dams.

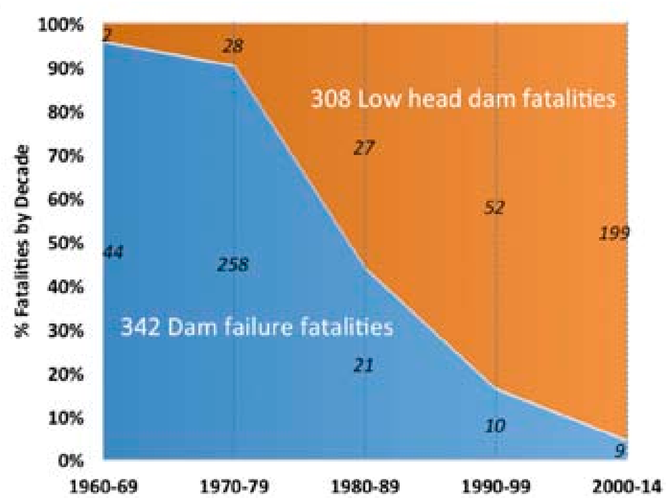

FIGURE 9. DECADE BY DECADE FATALITIES: DAM FAILURES VS. LOW-HEAD DAMS 1960-2014

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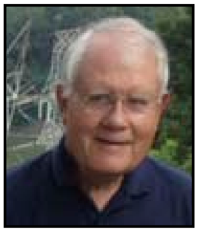
Table 1. State responses for Q#4 estimated number or range of low-head dams. (*No state survey response)

State	Confid. Level (%)	Est. LH dams (low end of range)	Est. LH dams (high end of range)	Actual Inventory reported
AK	5	1	50	
*AL				
AR	75	1	50	
AZ		Do not know		
CA		None known - no inventory		
CO	25	200	300	
CT	75	1	50	
DE	100			30
FL	100			3
*GA				
HI	25	1	10	
IA	100			246
ID		dozens	hundreds	
IL	90	200	300	
IN	20	100	200	
KS	75	50	100	
KY	100			16
LA		Numbers not available		
*MA				
MD	50	100	200	
ME	50	0	0	
*MI				
MN	100			50
MO	80	50	100	
MS	50	1	50	
MT	10	500	500	
*NC				
ND	100			64
NE	50	1	50	
NH	100			244
NJ	75	100	200	
NM	50	1	50	
NV	30	100	200	
NY	10	200	300	
OH	75	100	200	
*OK				
OR	50	1	100	
PA	100			253
RI		Not answered		
*SC				
SD	80	1	50	
TN	90	1	50	
TX	25	100	200	
UT		Several but no inventory		
VA	50	1	50	
*VT				
WA	10	1	50	
WI	100	1	50	
WV	100			10
WY	90	1	50	
TOTALS	**(AVERAGE) 50.6%**	**1814**	**3510**	**916**



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