Submitted in Partial Satisfaction of the Requirements for the Degree of
Master of Science in Environmental Engineering

INTRODUCING A CALIFORNIA LOW-HEAD DAM INVENTORY METHODOLOGY

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December 18, 2020

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ABSTRACT

Low-head dams, a.k.a. "drowning machines", are ubiquitous throughout the U.S. and have killed hundreds of people in the past few decades, with the numbers increasing each year. Although their size and upstream conditions do not make these structures look intimidating, dangerous recirculating hydraulics can form at the downstream face that will drown any unsuspecting person who passes over the dam. Due to their small height and lack of water storage, low-head dams and the safety concerns that they present have slipped through the cracks in dam safety management. For this reason, low-head dams are poorly documented. This trend is especially true in California, where even a rough estimate of the number of low-head dams has not yet been possible. This study presents a new inventory method that utilizes category designation and unique attribute tagging to assign hazard potential to low-head dam structures in California. The primary purpose of this study is to introduce the idea of hazard potential ratings for use in low-head dam inventories, and to provide a sample that exemplifies a first step that California can take in mitigating this significant public safety concern. The resulting open-access interactive map can be used to prioritize the most hazardous low-head dams and inform subsequent mitigation options for 226 located structures in 2 specific study sites within California. The map and database are located at http://riverlab.berkeley.edu/index.php/low-head-dams/

INTRODUCTION

WHAT ARE LOW-HEAD DAMS?

Low-head dams (LHD) are small, run of river dams usually spanning the entire width of a river or stream. They are usually of concrete or masonry construction and range up to approximately 15 feet in height. These structures are ubiquitous across the U.S., most being built in the 1800s and early 1900s. Many were built to raise the water level to provide water supply for industrial, municipal, and agricultural needs, with tens of thousands being built in the 1800s to power mills and small industries. Many were built as grade control structures (GCS) or drop structures designed to flatten the slope of steep riverbed profiles in order to prevent erosion and to dissipate the energy of high flows. Some were constructed as small hydroelectric dams, some to create flat lakes for recreation, and some were built simply to create jobs, being sold as recreation or aesthetic improvements or "beauty dams". Today, many of these low-head dams across the country are no longer serving their intended purpose and many are outdated and falling apart (Wright 2006).

DROWNING MACHINES

Low-head dams are nicknamed drowning machines. Over the past few decades, hundreds of people have drowned in low-head dams in the U.S. because they can produce dangerous recirculating hydraulics that can easily trap and drown unsuspecting victims. The recirculating hydraulic is created by a submerged hydraulic jump (SHJ) that forms just downstream of the low-head dam, and it is impossible to escape at certain flow conditions (Tschantz and Wright 2011). A submerged hydraulic jump occurs when the face of a low-head dam is vertical or near vertical, and the flows are such that the backwater sits above the location where the supercritical flow transitions to subcritical flow, causing the surface water to recirculate back toward the face of the dam (Devadason 2019). To the average river user, low-head dams do not look intimidating in comparison to large dams and large whitewater, especially at lower flows, thus they are often underestimated. To make matters worse, from an upstream river user's perspective, low-head dams are virtually invisible, with only a subtle horizon line to be seen. "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. Hydraulic engineers are aware of the forces created by moving water and have a professional responsibility to design safe structures to control and contain these forces." (Tschantz 2014:40).

Prior research to document fatalities at submerged hydraulic jumps in the U.S. includes a comprehensive, online, publicly accessible inventory of documented submerged hydraulic jump fatalities by Kent et. al. (2015), which has since been expanded to include data on 555 fatalities at 276 sites across the country, mostly in the east and mid-west. However, it is clearly noted by the authors that it is not a complete inventory, with many missing and many completely undocumented fatalities over the past 100 years can be assumed as no state or organization has ever kept a database of low-head dam deaths (Kent et. al. 2015). For example, I have knowledge of multiple low-head dam deaths that have occurred in my home state of Colorado that are missing from the inventory. I have since reported these on the website and they will be added to the inventory.

Dam safety has been at the forefront of public safety concern in and around rivers for almost five decades. The concern was initiated by multiple notable dam failure disasters in the 1960s and 1970s. It was decided by the Army Corps of Engineers that the first priority in mitigating dam failure safety is upkeeping a complete and descriptive national inventory of dams. Today the national inventory of dams includes more than 90,000 dams nationwide (USACE 2019) and assigns a hazard potential grade to each dam based on structural condition, size, storage, and downstream potential damage and loss of life. The inventory only includes dams that are at least 25 feet in height or have more than 50 acre-feet of storage, thus most low-head dams are left out. The subsequent state and federal initiatives and programs have had a major impact on dam failure safety, with the number of dam failure fatalities decreasing since 1960 despite the increase in number of dams, average dam age, and urbanization below dams. 40 people died due to U.S. dam failures from 1960 to 2014, while there were 7 times as many documented low-head dam drownings over the same time period, with the death rate growing each year likely due to increased participation in river sports (Tschantz 2014). Currently, low-head dams do not lie within the jurisdiction of state dam safety managers or the bureau of reclamation, so federal or state coordinated efforts to assess the low-head dam public safety problem are few and far between.

KNOWLEDGE GAP: INVENTORY

As with the issue of dam failure public safety concern in the 1970s, the first priority in addressing low-head dam drowning machines in the U.S. is to create complete and descriptive inventories, either federal or state coordinated. A rough estimate of the number of low-head dams in existence in the United States is 2 million (Fencl et al. 2015), yet the true number is completely unknown. In 2014, Bruce Tschantz conducted a study in which he administered a survey to 42 state dam safety managers all across the country. The purpose of the survey was to estimate the extent of low-head dams in the U.S. while gaging the level of state awareness and regulation of low-head dams. The vast majority of the state dam safety managers in Tschantz's survey responded that they do not maintain any low-head dam inventory, and some stated that they lacked adequate information to even make a broad estimate of the number of low-head dams in their state (Tschantz 2014).

LOW-HEAD DAMS IN CALIFORNIA

In the survey of state dam safety managers reported by Tschantz in 2014, when asked to estimate the number or range of low-head dams in the state of California, the California state dam safety manager reported “none known – no inventory” (Tschantz 2014). There are 1576 dams in California that meet the criteria for the national inventory of dams, yet there is no specific LHD inventory. There are 19 recorded LHD deaths at 9 different sites in California according to BYU’s inventory of submerged hydraulic jump fatalities, although the actual death toll is likely much greater (Kern et al. 2015). California is unique and a LHD inventory method should be designed as such. There are many large dams and small creeks, and the hydrology has been heavily manipulated by society. California is a diverse large state with extensive irrigation in rural areas, many heavily populated urban areas with vast flood control measures, and significant river recreation in some parts of the state. For low-head dams, this means that every type can be found on California’s waterways from irrigation check dams to flood control drop structures to channel-wide diversion dams to minor rock rubble structures, each with a unique setting that can further influence the hazard potential.

PROJECT OBJECTIVES

The objective of this study was to create a California specific method for a descriptive and useful low-head dam inventory in which each dam found is given a category and additional descriptors used to determine hazard potential for each dam and also to inform subsequent safety mitigation. I then tested my method by implementing it in varied locations across the state as well as a sample inventory for a specific county, resulting in an interactive map tool. This inventory project is intended to be instruction for and a sample of what should be done for the entire state, and to be an example for inventories in other states across the U.S.

METHODS

STUDY AREA

To test my methodology, I defined my study area to be a cross-section of California’s diverse landscape, land use, and river use. I first located the rivers with a fatal LHD with at least one documented SHJ fatality in the BYU inventory (Kern et. al. 2015). I defined these rivers and their tributaries as Study Area 1. These locations are shown in Figure 1, and are located across the state in areas with very different environments and levels of human activity. Next, I defined Study Area 2 as the major streams and their tributaries in Sacramento County in order to provide a complete inventory sample within a well-defined political boundary.

EXISTING DATA

I began by accessing public databases that may include potential low-head dam structures. These included the fatal dams listed in BYU's inventory from which I defined Study Area 1, California water rights data downloaded from eWRIMS from which I extracted points of diversion, the USACE's national inventory of dams from which I eliminated any dam over 15' in height, and potential fish passage barriers documented by CalTrout from which I deleted all structures that were not tagged 'dam'. I imported the .kml files from these databases to Google Earth Pro. Of these, the most useful database was the potential fish passage barrier locations which are shown in Figure 7.

LOCATION MAPPING

I located LHD structures in rivers and streams using Google Earth Pro, from which I derived latitude and longitude for each LHD location. I started with locations of dams less than 15' in the NID, potential fish passage barriers, and water rights diversion points in my two study areas, I manually scrolled over major rivers and streams with the satellite imagery layer turned on. Where heavy vegetation or image quality made detailed river visibility challenging, I used the imagery date toggle option in Google Earth to change the imagery date. It was also useful to change the imagery date to a date that showed optimal river flow conditions for LHD identification (Figure 6). Often times, the location of a potential structure shown in one of my existing databases needed correction, and more often than not these structures were not instream low-head dams. After locating structures using the existing databases, I manually scrolled over all major streams and their tributaries in my study areas, changing the aerial imagery date when necessary. Most structures that I identified in this study were not in any of the databases, especially in urban areas. After locating and pinning the identified LHDs in Google Earth Pro, I exported the .kml file from Google Earth and imported it to Google My Maps.

CATEGORIZATION

Categorization of different types of low-head dams helps present valuable information in addition to simply a dam's location that can be useful in both hazard potential rating and determination of mitigation options. I assigned every located LHD in my study area to one of the categories listed in Table

1 below. These categories are based on the structures' evident current intended purpose or function, as I inferred from the aerial imagery and context.

Table 1: California low-head dam categories.

Category	**Description**
Diversion	LHD diverts water for some use – irrigation, water supply, hydro, etc. See Figure 3.
Grade Control	LHD designed to ease the grade of a channel for erosion or energy dissipation (drop structures included). See Figure 4.
Irrigation Canal	LHD is located in an irrigation canal = check dam. See Figure 5.
Crossing	LHD is a road crossing
Lake Outflow	LHD controls a lake level
Recreation	LHD's primary purpose is to provide some form of recreation
Removed	LHD has been removed
Unused	LHD no longer serves its intended purpose, or never was useful
Unknown / Further Investigation Needed	LHD's intended purpose is not determinable from aerial imagery

ATTRIBUTES

In addition to the categories listed above, I added attributes to each located low-head dam structure. The attributes are listed in Table 2 below. I developed the attribute list to include key but obtainable information that gives prompt insight into the hazard potential of the structure and can inform safety mitigation. In this study, if an attribute was not discernable from aerial imagery, the entry was left blank. To complete a future complete inventory project, it will be important to collect information on all attributes for the more hazardous dams and any attribute entered based on aerial imagery observation should be supported by field investigations or document review before any mitigation effort is made. These attributes are accessible in the interactive map and associated database.

Table 2: Low-head dam attribute table.

Attribute	**Description**	**Tag Options**
Location	Latitude and Longitude	
River Name	Name of the river/creek	
Dam Name	If available	
Deaths	# of recorded deaths	
Height	Approximate height of the LHD	
Construction	General construction category based on aerial imagery, documentation, or site visit	Vertical Concrete / sloped concrete / Rock Rubble / gates / wood / breached

Hydraulic Condition	Submerged Hydraulic Jump?	SHJ / SHJ likely
Instream Human Activity	Based on the dam's location and environment, is it likely that people will be in the channel (accidental or purposeful) just upstream of the structure?	Likely / somewhat likely / unlikely / very unlikely
Flood Control Channel	In flood control channel?	True
Safety Mitigation	Any measures in place?	signs / portage / fence / buoy line / blockage / energy dissipation / breached / downstream features
Condition	Current structural condition	New / like new / failing / will fail
Photo(s)	Attach photo	

HAZARD POTENTIAL

As the National Inventory of Dams was designed for dam failure safety, the USACE assigns a hazard potential grade to each dam based on structural condition, size, storage, and downstream potential damage and loss of life. In this study, I designed a similar hazard potential scale, but I designed it specifically for low head dams and the public safety hazard potential that they have in place. The hazard potential ratings are listing in the Table 3 below. In this study, I assigned a hazard potential to each LHD structure using the attributes listed above in Table 2.

Table 3: Low-head dam hazard potential ratings.

Hazard Potential	**Definition**
Extreme Hazard	▪ Drownings have occurred here
High Hazard	▪ Failure to avoid during some range of flows will likely result in loss of human life. ▪ Instream human activity is likely at this location, intentional or accidental ▪ Upstream avoidance is difficult ▪ No mitigation in place
Significant Hazard	▪ Failure to avoid during some range of flows will likely result in serious injury or possible loss of life. ▪ Upstream avoidance is possible ▪ Safety mitigation in place OR ▪ Instream human activity is unlikely at this location.
Low Hazard	▪ Failure to avoid does not likely result in loss of human life. Structure is navigable. OR ▪ Instream activity is very unlikely

QUALITY CONTROL PROCEDURES

As this study was undertaken completely remotely, and with little prior knowledge or data describing the mapped structures, many attribute entries were left blank. The information entered in this study comes from aerial imagery observation alone and is by no means conclusive. It should be supported by field investigations or document review, starting with the highest hazard potential dams. However, many attributes including construction, hydraulic condition, instream human activity, flood control channel, and mitigation were often discernable from aerial photography alone using the aerial date toggle feature in Google Earth. For example, dangerous currents and boils characteristic of submerged hydraulic jumps are only visible at higher flows in the river, which might appear in only one of a sequence of images. Figure 6 shows an example of a dangerous LHD with a SHJ that is visible in one aerial photograph and not another. The date toggle function was also useful when dense vegetation makes river visibility difficult for some seasons.

In order to test my hazard potential assignment methodology, I located the rivers or streams in which 10 different documented LHD fatalities occurred using BYU's inventory, but did not locate the specific dam site itself. Manually scrolling along the waterways in Google Earth, I located all LHD structures in the river. I assigned each structure a category and as many attributes as possible and used them to assign a hazard potential. After completing these mini-inventories of these rivers, I located the fatal structures using BYU's interactive map to test and calibrate my hazard potential assignment strategy.

RESULTS

The results of my study include an interactive map of low-head dams in California that tested the methodology described above. Images of the inventory maps for the study sites can be seen in Figures 1 and 2, and the results are summarized in Tables 4-7 below. The resulting California low-head dam interactive map and database can be viewed at the following web URL: http://riverlab.berkeley.edu/index.php/low-head-dams/

Table 4: Number of low-head dams in Study Area 1 sorted by hazard potential rating.

Hazard Potential	Extreme	High	Significant	Low	Further Investigation Needed	Total
# LHDs	7	22	49	69	20	**167**

Table 5: Number of low-head dams in Study Area 1 sorted by category.

Category	Diversion	Grade Control	Irrigation Canal	Crossing	Outfall	Recreation	Removed	Unused	Unknown	Total
# LHDs	21	85	28	6	2	2	1	2	20	**167**

Table 6: Number of low-head dams in Study Area 2 (Sacramento County) sorted by hazard potential.

Hazard Potential	Extreme	High	Significant	Low	Further Investigation Needed	Total
# LHDs	1	5	9	41	3	**59**

Table 7: Number of low-head dams in Study Area 2 (Sacramento County) sorted by category.

Category	Diversion	Grade Control	Irrigation Canal	Crossing	Outfall	Recreation	Removed	Unused	Unknown	Total
# LHDs	7	23	11	9	0	0	0	1	8	**59**

DISCUSSION

A complete inventory of low-head dams in the state of California, the 3rd largest state by area and 1st largest state by population, is beyond the scope of this study. The intent of this study was to design a methodology that can be effectively used in the future to complete a low-head dam inventory for the entire state and to introduce hazard potential ratings.

METHODOLOGY

My method outlined above is based on factors that are directly related to public safety, and can be used to inform mitigation prioritization and strategies. The basis of my method is the accumulated experience from low-head dam inventories in other U.S. states, prior research by others on the specific characteristics of LHDs that make them hazardous, and my own knowledge as an experienced river user and river engineer.

Some states (non-coincidentally some of the states with the most LHD fatalities) have seen some LHD inventory successes. BYU's LHD fatality inventory reports 15 SHJ drownings in Colorado at 11 different locations (Kern et. al. 2015), yet the true death count is significantly more. In 2020, the Colorado

Department of Natural Resources and CO state dam safety managers completed a LHD inventory including location information for engineered structure in main stem rivers and their major tributaries (Zimmer, 2019). The structures were divided into three categories: diversion structures, grade control structures, and recreational structures. In Iowa, the state with the largest number of LHD fatality sites and arguably the country's leader in LHD mitigation, the Iowa Division of Natural Resources completed a LHD inventory in 2010. In order to aid policy decision making and make the inventory more useful and comprehensive, the dams were separated into 9 categories based on the dams' construction and function, with 'low-head dam' being by far the largest category (IDNR 2010). Indiana, North Dakota, Alabama, Minnesota, and Pennsylvania also have completed similar low-head dam inventories.

In review of these inventories, I noticed that while the dams are categorized, there is no ranking of hazard or priority. Although all low-head dams should be located and mapped, some structures are of more concern than others (Svoboda et al. 2017). For example, within the Colorado inventory's 'diversion dam' and 'grade control structure' categories, there are many with extremely dangerous submerged hydraulic jumps, but plenty of dams that are easily navigable by river users, yet no way to distinguish between them in the inventory. Even two low-head dams with the same hazardous submerged hydraulic jump condition can have different hazard potential based on the river upstream and the likelihood that a person might be in it.

It is evident that the number of low-head dams in each state in the U.S. makes mitigating safety concerns at all of them a vastly difficult and overwhelming project requiring tremendous coordination, funding, and time commitment. As has been implemented in the National Inventory of Dams for dam failure safety reasons, a hazard potential ranking system is needed to prioritize LHD structures that are most dangerous to the public. BYU's national inventory of SHJ fatalities certainly highlights many of the most dangerous dams across the country, however, we can assume that there are significantly more LHDs that are just as dangerous but do not have any confirmed kills. Not only is a hazard scale important for mitigation prioritization, but it is also a very useful tool for public education. As LHD inventories should be made publicly available and interactive, steering river users away from the most dangerous dams while not scaring them away from every man-made feature in the river is an important distinction to make.

The attributes listed in Table 2 are useful in determining the hazard potential of a LHD or choosing from mitigation options, or both. Prior research by others helped highlight the most important LHD attributes to include in the inventory. BYU's interactive fatality database shows a broad range of structure types that have caused fatalities (Kern et al. 2015). Most dangerous low-head dams are generally characterized by continuous overflow from bank-to-bank, no hydraulic structures such as gates, pipes, or penstocks, formation of a submerged hydraulic jump at some range of flows, and are located on natural river systems where recreationalists are found (Svoboda et al. 2017). However, especially in California, many deaths have occurred in high density urban areas with drop structure grade control LHDs with SHJs, and many of the victims entered the channel accidentally or for an objective other than recreation. The environment around the dam, and particularly upstream of the dam, is important in order to evaluate the likelihood that a person may be in the stream channel upstream of the structure, whether it be for recreation or other purposes.

Some of the fatal structures in California are located in flood control channels (FCCs). A flood control channel makes the likelihood of accidentally entering a low-head dam much higher, as the channels are nearly impossible to escape during most flow conditions (LBFD 2015) and most in California incorporate multiple drop structures or end in a drop structure. This is the case for the low-head dam structure in Walnut Creek in Concord in which there are 8 recorded fatalities, 3 of which occurred after a child entered the channel to retrieve a ball. LA county confirms that on average approximately 6 people drown in flood control channel incidents every year, and it is likely that the actual drownings occur in the drop structures rather than travelling down the channel. Fortunately, most flood control channels are fenced off and it is illegal to enter. However, in high density urban areas like Concord and Los Angeles, many people, most commonly children, still enter the channels. Due to the densely populated environment in which flood control drop structures are usually located, many of these LHDs are assigned the attribute 'instream human activity likely' and are given a high hazard potential. There are also many dangerous check dam structures in irrigation canals in California, which are also illegal to enter. However, in contrast to flood control channels, irrigation canals are almost always located in rural areas where accidental or purposeful instream activity is very unlikely, thus check dams in irrigation canals can usually be categorized as having low hazard potential.

RESULTS

Study area 1, all rivers in CA with a fatal LHD and their tributaries, was used to test the inventory method. Figure 1 shows the extent of Study Area 1, which extends across most of the state and incorporates a lot of varied terrain and human activity. Before exact location of the fatal structures was determined, I assigned each dam in these rivers a hazard potential. All but one of California's documented fatal LHDs had been assigned high hazard potential, which provides some support for my method. The distribution of the located LHD structures in Study Area 1 is shown in Tables 4-5, and demonstrates a broad range of assigned categories. The most common category is grade control structures, and about 20% of these are high hazard LHDs. The most common hazard potential rating in Study Area 1 is low hazard potential. Not shown in the tables are the assigned attributes that were used along with the categories to assign hazard potential to each structure. Approximately half of the structures in Study Area 1 are located where instream human activity is likely or somewhat likely. The vast majority are of vertical concrete or sloped concrete construction. About half of the structures have a SHJ or likely SHJ, and most of the other half need further investigation. ~30% are located in flood control channels, which is not surprising given that the highest densities of LHDs in Study Area 1 are in urban areas (Figure 1). Only 5% of the LHDs in Study Area 1 have some kind of safety mitigation that is visible from aerial imagery.

Study Area 2 is Sacramento County. The results of my sample inventory for Sacramento County are shown in Table 6-7 and Figure 2. 40% of the located LHDs in Sacramento County are grade control structures, and the vast majority of the structures have low hazard potential. The documented fatality in Sacramento County occurred in a diversion structure. ~30% of the structures have a SHJ or likely SHJ. ~40% were determined to be in locations where instream human activity is likely or somewhat likely. These results can be extrapolated to the rest of California. As Sacramento County is 994 square miles and California is 163,696 square miles, a rough estimate of the number of low-head dams in California is nearly 10,000 structures. Approximately 25% of these LHDs (2,500 LHDs) would have higher than low hazard potential.

NEXT STEPS

This study outlines and tests a first step in low-head dam mitigation in California. The most important next step is to mitigate the dangers presented by the extreme hazard low-head dams in California (where fatalities have occurred). Next, the hazard potential methodology defined in this study needs to be further tested and refined, and detailed instructions and trainings to make attribute and hazard potential assignments less subjective (similar to dam failure hazard potential) should be created. This effort would include site visits to confirm assigned categories and attributes and to add more attribute information as well as verify the hazard potential for each structure. For this effort, dams with the highest remotely assigned hazard potential would take precedence. As other states have done, California should initiate a full state inventory effort after an effective methodology has been tested and agreed upon. Following a successful inventory and hazard potential assignment effort, a LHD safety mitigation strategy focusing on the highest hazard potential LHDs should be implemented.

MITIGATION OPTIONS

Although site visits are required before any physical safety mitigation measures are put into place, some attributes in this inventory methodology including location, category, height, construction, instream human activity, and condition can help with initial, informal evaluation of possible mitigation strategies.

One of the most effective and broad-reaching low-head dam safety mitigation strategies can be public outreach and education. Providing information on the websites and pages of influential well-known river related programs has been done and can be effective. There are a number of national, state, and local organizations and departments that work to educate the public about the hazards of low-head dams including American Society of Dam Safety Officials (ASDSO), department of Natural Resources for multiple states, American Whitewater, Canadian Dam Association, Indiana Silver Jackets, and others. A recent coordinated effort between Brigham Young University and Wright Water Engineers based out of Colorado recently sent out letters and instructional packets to every hydraulic engineering college professor in the country to implore them to include a brief lecture on SHJs at LHDs in their curriculum. This education effort is especially important because future hydraulic engineers will be the principal solution finders to this issue they will inherit.

The Illinois public safety program, Pennsylvania's and Virginia's legislative and regulatory approaches, and the Iowa Water Trails signage program are examples of what some states have done. The Canadian Dam Association (CDA) has developed comprehensive guidelines for assessing hazards associated with low-head dams. Public awareness, signage, fencing, buoys, lighting, and portage opportunities can minimize risk, but dangers from hydraulic forces remain (Svoboda et al. 2017). However, these methods are proven to be an effective first step before a dam can be physically modified (IDNR 2020).

"Dangerous downstream currents are unnecessary for a successful low-head dam or grade control structure (Wright 2006)." This means that a LHD can be designed or modified to still accomplish its intended purpose without being a death trap. Many possible options have been recommended in literature for physical remediation of the submerged hydraulic jump common at low-head dams. Placement of large boulders or grout bags immediately downstream of the dam face to dissipate energy (Schweiger 2011), installation of a stepped spillway or large concrete steps on the downstream face of the dam (Klumpp et al. 1989), installation of boat chutes (Klumpp et al. 1989), raising the height of the dam to eliminate the hydraulics (Leutheusser and Birk 1991), installing upstream facing ramps spaced along the channel width and horizontal platforms protruding from the downstream dam face (Olsen et al. 2014), channel-wide horizontal flow deflectors and staggered flow deflectors on the downstream face (Kern 2014), replacing the LHD with a moveable crest dam (Schweiger 2011), adding nature-like rock ramp fishways, rock rapids, boulder weirs just downstream of the dam (Aadland 2010), installing a timber crib weir with rock-fill and heavy steel grating over the fill (Hauser 1991), installing a labyrinth weir (Hauser et al. 1992), or boat chutes or a whitewater park (Klumpp et al. 1989) have all been suggested and supported over the years. Complete dam removal is also an attractive option for LHDs, as it can also accomplish significant environmental benefits as well. Dam removal is feasible for LHDs that are no longer serve their intended purpose, but cannot be done if the dam is still providing a necessary function unless that functional need can be met through an alternative method (Conyngham et al. 2005). Lastly, a low-head dam has the potential to be transformed from a drowning machine into a recreational amenity (Figures 8-9). Whitewater features designed for instream recreation can be constructed downstream of a LHD, and sometimes even serve the same function as the original dam (IDNR 2010).

CONCLUSION

There are likely more low-head dams in the U.S. than the total number of dams reported in the National Inventory of Dams (90,000). Their locations are mostly unknown and undocumented, and their dangers have been severely underestimated. As their dangers certainly are not all equal, prioritization informed by hazard potential can decrease the size of the immediate mitigation task at hand. American Society of Dam Safety Officials (ASDSO) and state dam managers have the professional resources and the organizational structure to implement coordinated efforts. As some other states have done, California could start with an inventory of all low-head dams in the state. Unlike Iowa, a state that has pioneered LHD mitigation efforts, the vast and diverse landscape of California will require a specialized effort. The state's size makes hazard potential assignment to inform prioritization even more important as mitigation of every LHD in the state is currently an insurmountable task. California's diversity of low-head dam use, design, and hazard needs to be accounted for in a comprehensive inventory that can inform both decision-makers and the public.

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FIGURES

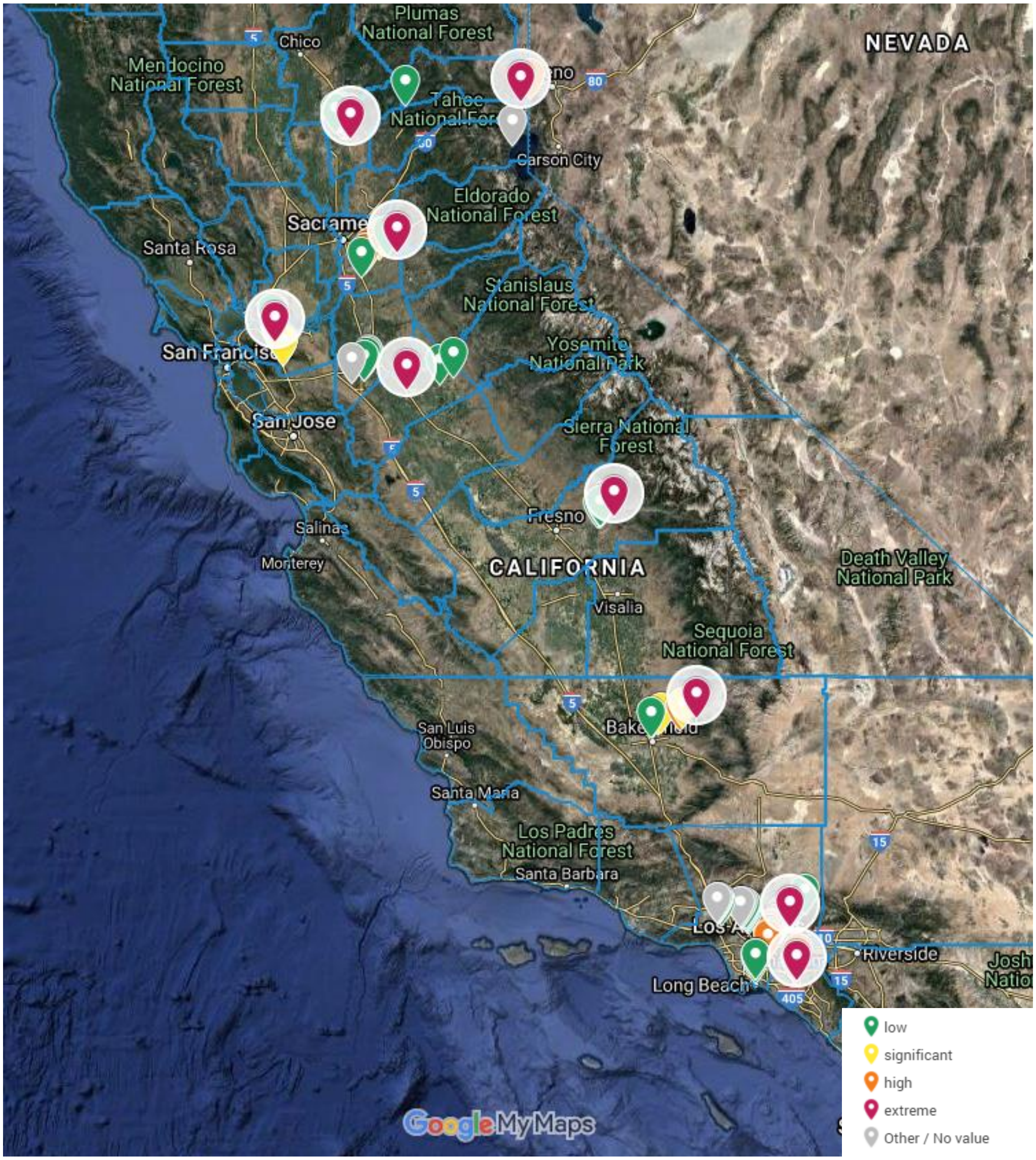

Figure 1: Study Site 1 LHD inventory map showing hazard potential of the 167 located structures.

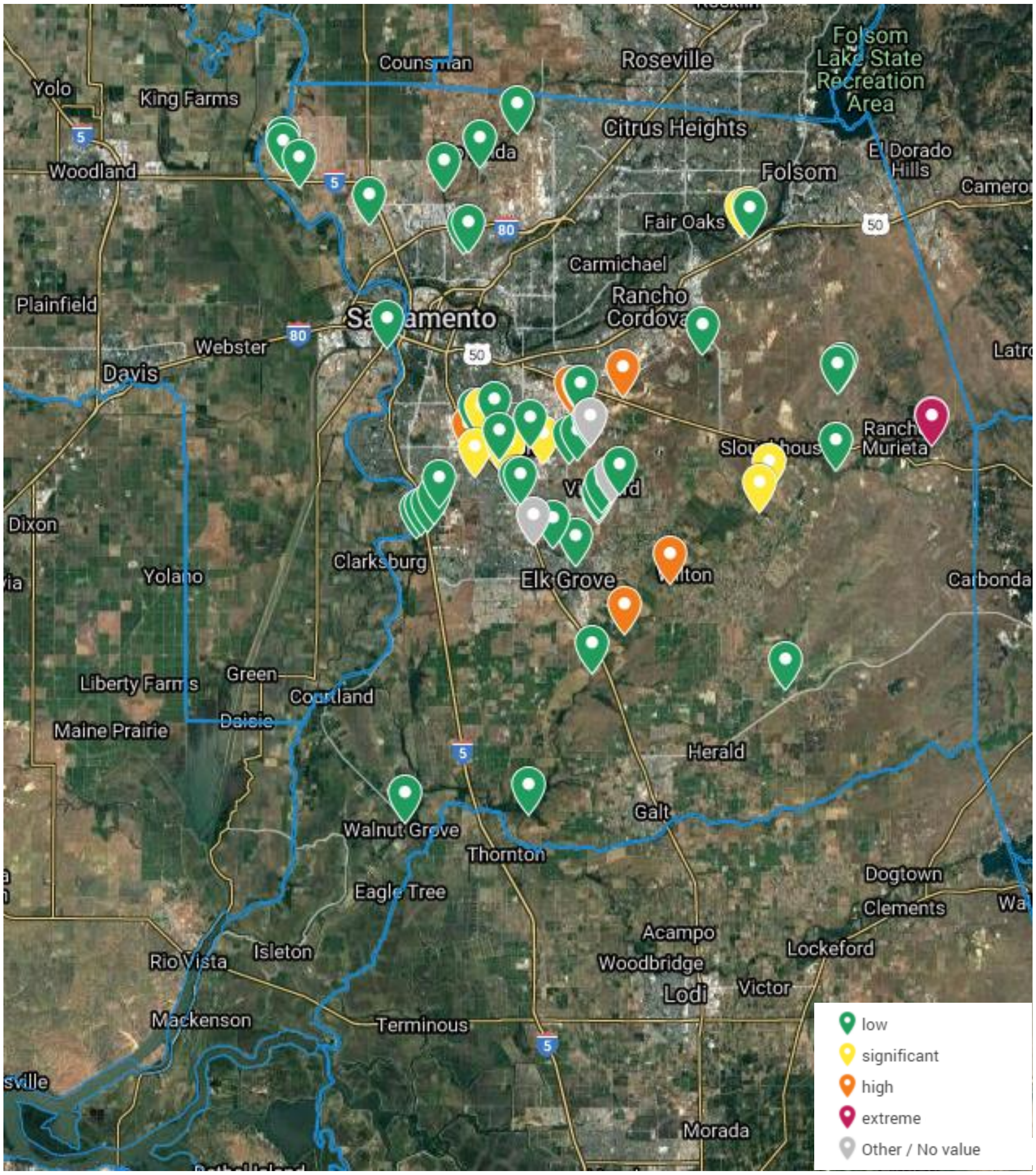

Figure 2: Study Site 2 (Sacramento County) LHD inventory map showing hazard potential of the 59 located structures.

Figure 3: Two examples of diversion low-head dams in CA. Left: Diversion for irrigation. Right: Diversion for small hydroelectric.

Figure 4: Two examples of grade control structure low-head dams in CA.

Figure 5: Two examples of low-head dams in irrigation channels.

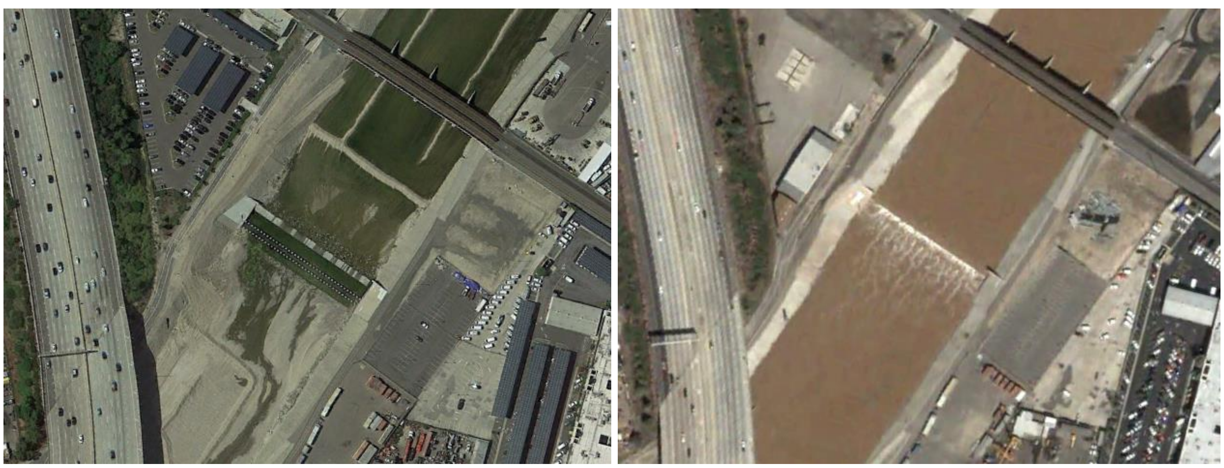

Figure 6: Google Earth aerial imagery from two different dates of the same low-head dam in Los Angeles.

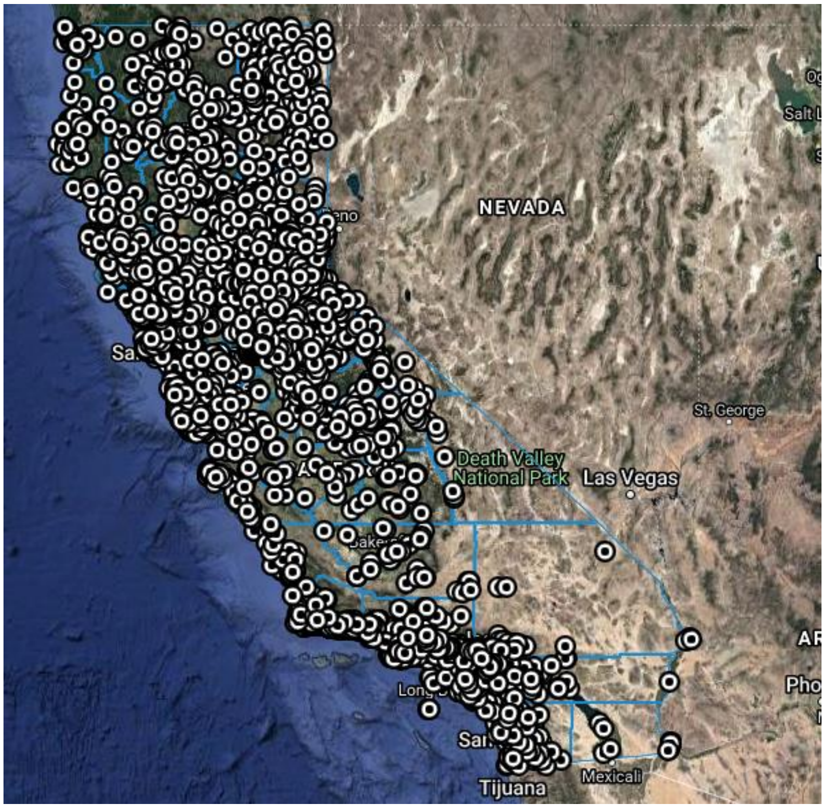

Figure 7: Potential fish passage barrier data imported into Google My Maps

Figure 8: A dam that drowned multiple victims (left) turned into the Charles City Whitewater Park (right).

Figure 9: A low-head dam that drowned 11 people in Calgary, Alberta (left) transformed to a recreational amenity (right).