

Analyzing cyber-physical threats to Pennsylvania dams through a lens of vulnerability

Lauren Dennis
Department of Civil and Environmental
Engineering
Penn State University
University Park, PA USA
lud93@psu.edu

Sarah Rajtmajer
College of Information Sciences and
Technology
Rock Ethics Institute
Penn State University
University Park, PA USA
smr48@psu.edu

Caitlin Grady
Department of Civil and Environmental
Engineering
Rock Ethics Institute
Penn State University
University Park, PA USA
cgrady@psu.edu

Abstract—Protecting critical infrastructure, such as water supply systems and dams, remains a top priority across multiple administrations in the United States. We study the ethical and environmental justice implications of potential disruptions to 29 dams across the State of Pennsylvania that serve as a water supply. Using census data, we investigate the communities surrounding these dams to look for relationships between community demographics and dam characteristics that may contribute to risk. We highlight the role of dam age, dam ownership, dam capacity, and dam downstream hazard potential in this analysis. Our results reveal associations between dam ownership, age, and capacity with the race of the population served, as well as an association between dam ownership and household income band. We conclude with a discussion on the increasing complexity of cyber-physical critical infrastructure and the need for future research which explicitly takes the populations served by this infrastructure into account.

Keywords— critical infrastructure, cyber attack, failure, dams, water supply, vulnerability, ethics

I. INTRODUCTION

Critical infrastructure (CI) systems organize much of modern life, and as technology and cyber capabilities have advanced and systems have become more complex, our infrastructure has become increasingly connected and interdependent. Protection of CI has been a priority for multiple administrations in the United States [1], [2]. Despite this focus, CI faces continued threat underlain by emerging cyber-physical vulnerabilities. Both risks and impacts of CI disruption vary widely. In this paper, we showcase and discuss variation across the risk landscape for a subset of dams in Pennsylvania. The following introduction highlights several important motivations for this work: 1) cyber-physical critical infrastructure interdependencies are increasing; 2) dams represent an important interdependent CI system; 3) cyber-attacks can cause physical damage; and 4) attacks or disruptions to CI may not have equitable impacts on communities in which they reside. In this work, we examine vulnerable populations whose water supply could be impacted by a cyber attack on dams in Pennsylvania.

Cyber-physical CI resides within an emerging threat landscape, meaningfully distinct from past counterparts. Integration of new technologies and increased automation within industrial control systems (ICSs) has increased

opportunities for both error and attack [2]. This concern is magnified by inconsistent adoption of technology across systems and sectors, and lack of regulation in this space [3]. In addition, artificial intelligence (AI) has borne a new generation of cyber weapons which will revolutionize targeting, deployment, and concealment of cyber threats [4]. Modern cyber attacks will be increasingly hard to attribute, which will undermine traditional approaches to deterrence and retaliation [5]. Perhaps most worryingly, the impact of failures and attacks on connected cyber-physical infrastructure will often be far-reaching and difficult to predict. These disruptions in systems critical to densely populated megacities of the future may be catastrophic [3], [6].

Dams represent one sector of critical infrastructure systems that is particularly interdependent with several other sectors [7]. In the United States, hydropower dams generate about 7% of the total electricity and nearly 40% of renewable energy electricity [8]. Water storage dams are also critical for firefighting emergency service response. The transportation sector uses dams and locks throughout our inland waterway system to move over 600 million tons of commodities each year, representing an economic value of over \$180 billion [9]. Dams are also fundamental in water provisioning for both the Food and Agriculture CI sector and the Water and Wastewater CI sector. With this multi-sector interconnectedness, dams have been a target of both traditional terrorism and cyber-related risks.

A global analysis of water-related terrorism found 675 incidences of water-related terrorism across 71 different countries between 1970 and 2016, of which over half of all attacks targeted a water related infrastructure like dams, levees and pipes [10]. In 2013 and 2014 the Islamic State of Iraq and the Levant (ISIL) captured the Tabqa and Mosul dams in Iraq and Syria and utilized them as strategic refuge and potential weapons [11], [12]. At the time, military campaigns to reclaim control of the dams had to take extreme care with airstrikes and primarily focused on a ground campaign because airstrikes risked damage of infrastructure that would leave thousands flooded and without power [11], [12]. In 2013, Iranian actors successfully hacked into the command and control system of a small dam outside of New York City through a cellular modem [13], heightening concerns about cyber threats to critical water infrastructure. More recently, a group of actors infiltrated several government websites in Ethiopia to showcase support

for Egypt in its dispute with Ethiopia over the building of the Grand Ethiopian Renaissance Dam on the Nile River, raising tensions over the transboundary river [14]. Although this did not represent a cyber-physical disruption (i.e. the actors did not infiltrate the dam systems themselves but rather government websites), it does showcase the role that water related infrastructure continues to play within geopolitics.

Dams responsible for the water supply of a community can be particularly vulnerable to cyber attacks. Since these dams supply water to a local community, there is a need for the local water organization and community to interact with the system, resulting in an industrial control system that may be more open to attacks [15]. Gaining access to the industrial control system could allow attackers to either close or open gates, affecting the supply of water available in a rapid onset event [15]. Slow onset events are also a risk to dam and water supply systems. For example, if sub-components of the control system which alert controllers to abnormalities regarding water level or even water quality are subtly manipulated over a period of time, great damage could be done to the local water supply without much notice, as was the case for the Maroochy water breach in Queensland Australia [16]. In theory, large scale cyber attacks on dams could cause catastrophic damages in the billions of dollars to business owners, residents, and insurers across the community [17].

Disruptions to CI have multiple ethical implications that impact communities connected to various CI sectors. Further research and exploration is needed in this area, as evaluations of CI security and disruption sometimes exclude the very users of this CI. In a 2015 report entitled “Roadmap to Secure Control Systems in the Dams Sector,” the DHS identified key stakeholders as asset owners and operators, government agencies, industry organizations, commercial entities, R&D organizations, and universities and colleges [15], notably excluding communities served by this CI. We are interested in studying the ethical implications of the connection between community users of CI and CI disruption. Particularly, we are interested in furthering understanding around the unequal distribution of impacts across communities.

Social vulnerability assessments have highlighted a number of differences across community populations with regard to the impacts of infrastructure access, disaster recovery, and environmental hazards [18], [19]. Often focusing on basic need provisioning after disasters, several authors have utilized socioeconomic measures to present metrics and frameworks showing how the consequences of one disaster or disruption would have different impacts across different communities [18], [20]–[22]. These works describe how different subpopulations have unique infrastructure needs, so the same disruption may not be experienced equally by the impacted community. As such, socially vulnerable populations are often disproportionately affected. Case studies of specific critical infrastructure sector disruptions have also highlighted different allocations in response and recovery after disruption. For example, two cases investigating power outages found that communities with higher proportions of disadvantaged groups experienced longer time to recovery [23], [24], yet those differences may be related to other compounding factors such as the co-location (or lack thereof) of other priority critical assets such as hospitals [23]. After

hurricane Harvey, social groups with low socioeconomic status, racial minority groups, and/or children younger than 10 years old were found to have significantly higher hardship due to critical infrastructure service disruptions across the transportation, power, communication, and water sectors [25]. While similar social vulnerability studies have been a part of the natural hazards research for several decades, tying these themes of equity and equality to critical infrastructure security research has received much less focus. Theoretically, several scholars have highlighted ethical issues that arise in critical infrastructure security [19], [26], [27], yet there is still an important need to further threat assessment and simulation-based research to build better understanding around the ethical implications of critical infrastructure risk.

As highlighted throughout this introduction, cyber-physical critical infrastructure interdependencies are increasing and cyber-attacks have the potential to cause physical damage to CI and communities nearby. Dams represent important interdependent CI systems that are tied to several other CI sectors and have faced threats of terrorism and cyber-attacks in recent decades. Finally, the impacts of CI disruption may not have equitable impacts across communities, thus, research is necessary to contribute to the gap in CI risk research pursued alongside social vulnerability framing. Our study sought to address this gap by investigating a case study of theoretical dam risks in Pennsylvania. Utilizing the National Inventory of Dams dataset, we chose a subset of large-scale dams with water-service provisioning functions. Leveraging these data, we compared the water service areas to census tract level demographic information to identify potentially vulnerable groups. After presenting our results, we utilize this case to discuss multiple additional implications for cyber-physical CI risks relating to socio-technical futures.

II. METHODS

A. Dam Selection

Dams were selected for analysis from the National Inventory of Dams (NID) dataset provided by the US Army Corps of Engineers [28]. All dams are located in Pennsylvania and have a NID height greater than 100 feet or a length greater than 1500 feet. Dams were selected for analysis by size, since dams with a larger geographical footprint tend to have more sophisticated industrial control systems [15] that could be accessed by a malicious actor. For the focus of this study, we examined dams whose listed purposes included serving as a water supply. Dam characteristics used to examine various factors that may present a risk to users of the dam include the dam downstream hazard potential, the dam age, dam capacity, and dam ownership. The dam downstream hazard potential indicates “the potential hazard to the downstream area resulting from failure or mis-operation of the dam or facilities” and is categorized by the Interagency Committee on Dam Safety as high, significant, low, or undetermined [28]. Failure of high risk dams may cause loss of human life, whereas failure of dams with significant risk may cause only economic loss or environmental damage and low risk dams would mainly cause damage to the owner’s property [28]. The age of a dam has been a leading indicator for dam failure in the United States, because the integrity and operational effectiveness of a dam may deteriorate over time [29]. We

measured risk due to dam age by calculating the dam age and adjusting the dam's age based upon any documented modifications to the dam. A dam's age was reduced for each documented modification by multiplying the age of the modification by 0.25 and subtracting that from the dam's age. A dam's capacity may determine the extent of damage in the case of an impaired water supply or flood. The dam capacity was represented by the NID Storage, which is the maximum of the normal storage or the maximum storage and is "accepted as the general storage of the dam" [28]. Dam ownership was identified in the NID dataset as federal, state, local government, public utility, or private. We included this variable because we hypothesized that variations in dam ownership could result in variations in risk to the dam based upon an owner's capacity to address risk to the dam. A company's size may also impact a company's vulnerability to a cyber attack [30]–[32]. Information about the company size for each dam owner was compiled based upon information gathered from internet searches of each company. The final set of dams utilized in subsequent analyses consisted of 29 individual facilities primarily located in the central and eastern portions of the State of Pennsylvania.

B. Water Supply Area Determination

We utilized a dataset from the PA Department of Environmental Protection outlining Public Water Supplier's (PWS) Service Areas [33] to link dams that are designated for use as a water supply in the NID dataset to their assumed area of service (Fig. 1). We linked these service areas when the ownership name between the dam and the water supplier service area was the same, or when the dam designated as a water supply was within 5 km of a service area which received water from a surface water source. When more than one dam was associated with a water supply area, one dam was randomly selected for the purposes of examining the relationship between dam characteristics and demographic information associated with the population within the water supply area.

C. Census Data

We analyzed population vulnerability to environmental hazards with tract level data from the American Community Survey 5-year dataset from 2015-2018 [34]. In particular, we were interested in variables that may contribute to human

vulnerability to environmental hazards. Cutter et al. (2003) used county-level socioeconomic and demographic census data to create an index of social vulnerability to environmental hazards [20], and we chose a subset of these variables that we believe particularly apply to social vulnerabilities to a cyber attack on a dam: race, age, poverty and income, and housing ownership status. A number of scholars within the environmental justice literature have established links between environmental hazards and communities of color [20], [35], [36]. As such, we chose to include the variable of race, specifically white and communities of color (minority) at a census tract level, because minority communities may face barriers in access to information about potentially unsafe water supplies, or recovery activities to address an impaired supply. The age of community members contributes to social vulnerability to environmental hazards as both young and elderly populations may have a limited capacity to remove themselves from harm or participate in activities to create personal resilience [20]. We identified socially vulnerable ages as the population less than 5 years of age or greater than 65 years of age. These ages may be particularly vulnerable as they may not have access to alternative water supplies or may not be able to otherwise inform or protect themselves adequately. Cutter et al. (2003) describe socioeconomic status as related to the "ability to absorb losses and enhance resilience to hazard impacts" [20]. In the case that the water supply of a dam is impacted in some way, whether it be through the loss of the supply or an impairment of the supply, socioeconomic status may determine whether the person is able to obtain access to an alternate water supply. Renters may be more vulnerable to environmental hazards as they often do not have access to aid provided during recovery, and they are also in a vulnerable position if their housing becomes uninhabitable or unaffordable due to the hazard [20]. These five variables from tract-level American Community Survey census data were analyzed when a portion of a water supply area overlapped with more than 60% of a census tract.

D. Analysis of Potential Risk Factors in a Cyber Attack on a Dam Providing a Water Supply

We analyzed demographic and socioeconomic information of populations living within the assumed water supply area of a dam by examining variations in these demographics based upon various dam characteristics that may present a risk to users of the dam. These included the dam downstream hazard potential, the dam age, dam capacity, and dam ownership. A chi-squared test with Bonferroni corrections was performed to compare differences in demographic and socioeconomic characteristics for populations living within dam water supply areas with various dam characteristics that may contribute to risk. The effect size of the chi-squared test was calculated using Cramer's V to further discern significant results. Using guidance from Rea and Parker (1992), we determine an effect size to be weak or negligible for values between 0-0.2, moderate between 0.2-0.4, and strong between 0.4-1 [37]. Further spatial analysis was performed by examining patterns presented by census tract level data.

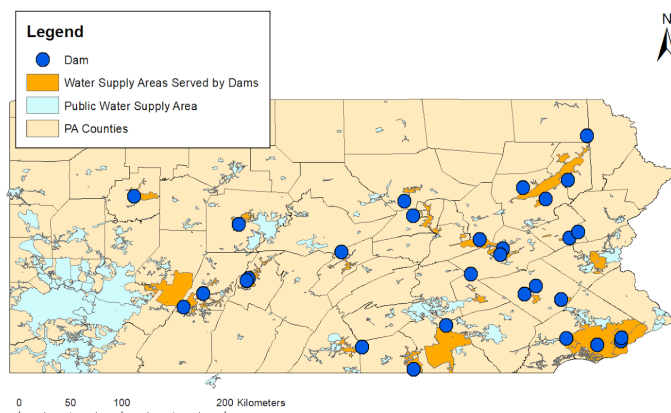


Fig. 1. Dams selected for analysis from the Army Corps of Engineers NID dataset and water supply areas from the Pennsylvania Department of Environmental Protection.

III. RESULTS

We find statistically significant variation ($p=0$) between dam characteristic categories and demographic/socioeconomic census data for the population living within dam water supply areas for all dam characteristics and census variables based upon a chi-squared test. Dam characteristics of ownership, age, and capacity showed the greatest variation between sub-categories within the dam characteristic when examining the race of the population served by the dam. Bonferroni corrections were applied to the results of the chi-squared tests, but the results remained significant as all p-values remained zero. Despite this significance, it is important to note that large sample sizes often lead to chi squared results that are biased or difficult to interpret [38]. To further discern differences in the relationships between dam characteristic categories, we examine the Cramer's V effect size (Table 1). The test shows a moderate effect for differences in dam ownership, age, and capacity when comparing the race of the population served, a moderate effect for the association between dam ownership and a household income of under \$75,000, and otherwise weak or negligible effects (Table 1).

TABLE I. CRAMER'S V EFFECT SIZE FROM CHI-SQUARED TESTS OF DAM CHARACTERISTICS AND DEMOGRAPHIC CENSUS VARIABLES

Dam Characteristics	Census Variables				
	Race	Poverty Level	Income Below 75k	Vulnerable Age	Housing
Dam Ownership	0.301*	0.173	0.202*	0.028	0.127
Dam Company Size	0.190	0.036	0.010	0.012	0.032
Dam Age	0.279*	0.129	0.143	0.024	0.119
Dam Capacity	0.233*	0.161	0.193	0.024	0.148
Dam Hazard	0.110	0.031	0.011	0.005	0.028

* Denotes a moderate effect size

A. Dam Ownership

Our dataset includes 4 federally owned dams, 15 locally owned dams, 3 privately owned dams, and 7 dams owned by a private utility. Governmentally owned dams serve the largest population: locally owned dams serve a population of 1,938,225, and federally owned dams serve a population of 235,295. Privately owned dams serve a population of 43,447,

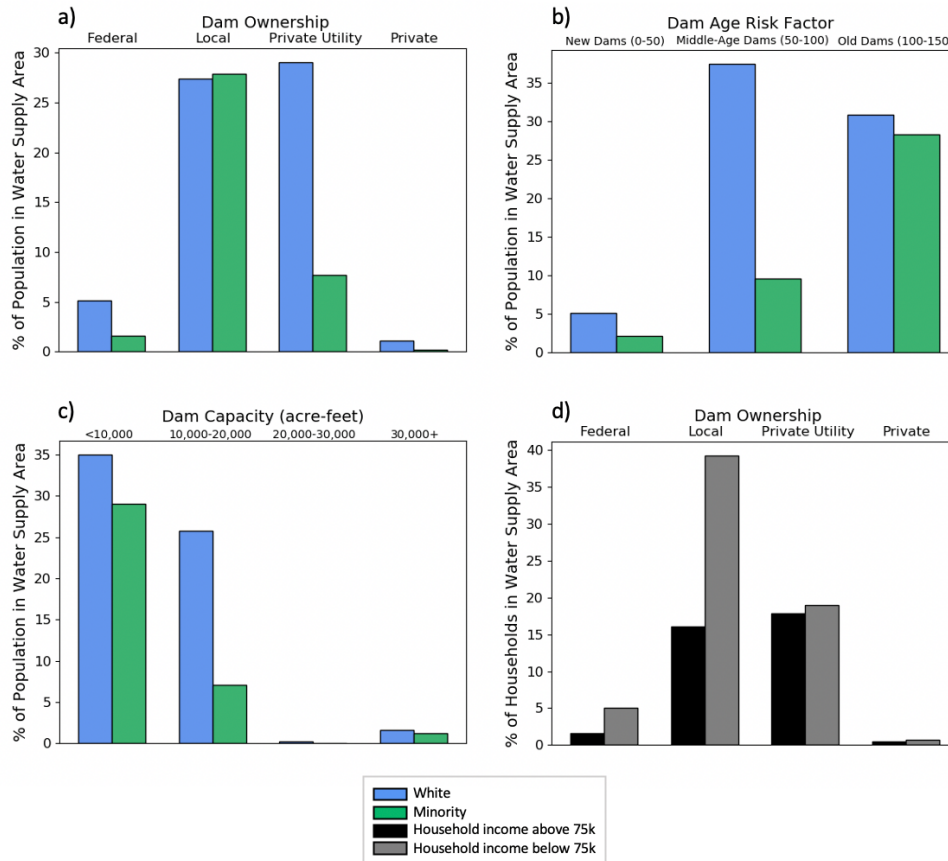


Fig. 2. Population by race or socioeconomic characteristic separated by dam characteristic. Panel a) shows race and panel d) shows household income based upon dam ownership categories. Panel b) shows race by dam age risk factor, and panel c) shows race by dam capacity. All percentages represent the number of people within a particular category divided by the population within dam water supply areas.

and dams owned by a private utility serve 1,287,491. We find differences between the proportion of the population within our variable chosen to represent race (white and minority) living in water supply areas of dams with various ownership (Fig. 2a). In the supply area of dams owned by local governments, defined as a government that has “taxing authority or is supported by taxes” [28], the percentage of the population identified as minority is 0.33 percent greater than the percentage of the population identified as white (Fig. 2a). This stands in contrast to the ratio of white to minority citizens in all other dam ownership categories, where white residents comprise the majority in all cases (Fig. 2a). Nearly 22% of white people in water supply areas of dams are served by dams owned by private utilities, whereas only around 8% of the minority population is served by dams owned by private utilities. The effect size of the association between dam ownership and race is found to be moderate at 0.3 (Table 1).

In areas served by locally owned dams, there are more than twice as many households whose annual household income is below \$75,000 than those whose household income is above \$75,000. For areas served by private utilities, nearly the same number of households make below and above \$75,000 (Fig. 2d). The association between dam ownership and household

income has a Cramer’s V effect size of 0.2, which indicates a weak to moderate effect.

B. Dam Age

Within the downscaled dataset of dams matched with water supply areas, 26 dams have a documented age from the National Inventory of Dams. There are 4 new dams (less than 50 years old), 14 middle-aged dams (between 50-100 years old), and 8 old dams (between 100-150 years old). Old dams serve a population of 1,289,300 people, whereas middle-aged dams serve 1,339,376 people and new dams serve 132,436 people. The proportion of the minority population to the white population in water supply areas of old dams (0.9) is much larger than that of middle-aged dams (0.3) and new dams (0.4) (Fig. 2b). The Cramer’s V effect size of the association between dam age and race is 0.28, showing a moderate association (Table 1).

C. Dam Capacity

The majority of the population (2,244,070) live in a water supply area of a dam that has a capacity of less than 10,000 acre-feet. Dams with a capacity of 10,000-20,000 acre-feet provide a water supply for 1,152,588 people, dams with a

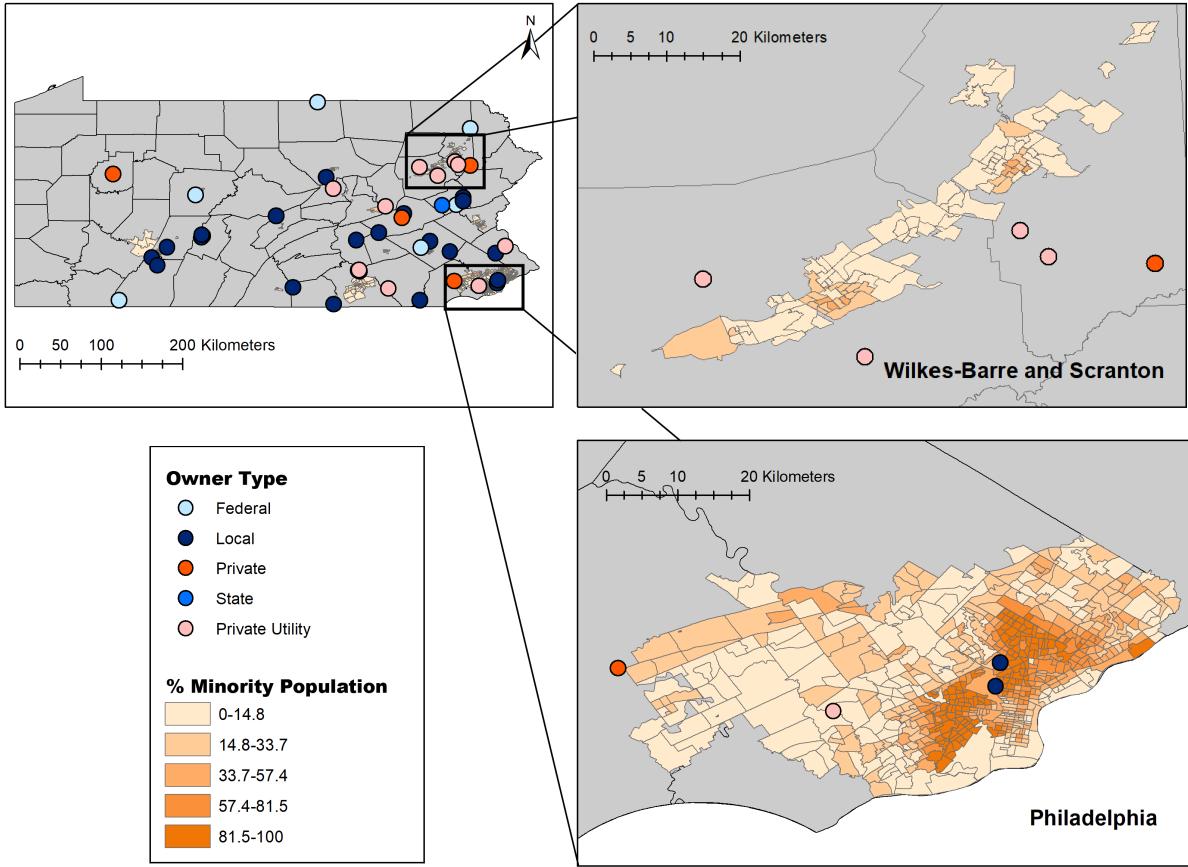


Fig. 3. Census tracts within dam water supply areas displaying the percentage of the population within the census tract comprising a racial minority. Dam ownership is indicated by color, and the percentage of minority residents is indicated by the orange color bar.

capacity of 20,000-30,000 acre-feet serve 9,035 people, and dams whose capacity is greater than 30,000 acre-feet serve 98,765 people. The ratio of the minority population to the white population is largest in supply areas of dams with the smallest capacity (0.8) and second largest in supply areas of dams with the largest capacity (0.7) (Fig. 2c).

D. Spatial Variation

When examining the particular locations of dams with various ownership, further insight can be gained by relating the patterns observed in Fig. 2 to spatial differences. For example, Fig. 2 showed that a larger percentage of the population identified as a racial minority is served by local government owned dams. In Fig. 3, we can observe a higher percentage of racial minorities located in census tracts in Philadelphia, which is served by dams owned by local government. In the Wilkes-Barre and Scranton area, census tracts have a lower percentage of the population identified as a racial minority, and this area is served by private dams.

The spatial distribution of various community demographics may be related to processes associated with community development and differences in urban/rural environments that have the potential to help explain dam ownership types. Since the exploration of this relationship is outside the scope of this study, we instead emphasize the importance of examining potential spatial patterns of vulnerable populations in addressing risk and building resilience.

IV. DISCUSSION

This work has showcased an exploratory study on theoretical dam risk and community vulnerability in Pennsylvania water supply areas. We have argued that considerations surrounding community characteristics are important to assess when discussing cyber-physical critical infrastructure security. Literature across several areas of scholarship articulate the necessity for such considerations. Based on an examination of our results, we reflect on particular ways in which dam characteristics may affect vulnerable populations. While our results serve as a case study to explore critical infrastructure risk, throughout this discussion section we will articulate several limitations within this approach as well as important areas for future pursuit. Although a chi-squared test showed significant associations between the selected community demographics and all selected dam characteristics, our large sample sizes likely distorted these differences, thus our chi-squared results are of limited practical use. To overcome this limitation, we also investigated the effect of these associations with the Cramer's V test of effect size. Our results indicated that a moderate effect size was present for differences in dam characteristic categories for dam ownership, age, and capacity when comparing the race of the population served, and a moderate effect was present for the association between dam ownership and a household income of \$75,000. While we do not know the cause of these associations, we find value in discussing possible influences surrounding these questions that could drive future research in this area.

Dam ownership: If specific policy is not put into place for the security of ICSs, the security protocols put in place will be left

up to the owners of individual dams. They are, of course, incentivized to protect their assets, but the decision of how to invest in new technologies and whether and to what extent to abide by voluntary guidelines (e.g., those put forward by NIST [39]) will ultimately be an economic one, at the level of the company. Thus companies will no doubt have varied capabilities in securing their ICSs in the face of cyber-physical disruption. Smaller companies may have smaller capabilities and less advanced ICSs, but their more simplistic systems may have fewer access points vulnerable to attack. The advantages and disadvantages in ICS sophistication warrant further analysis, especially regarding when these systems may be advantageous in protecting vulnerable populations or simply creating more risk. Future disruption or vulnerability analyses within cyber-physical systems could study ownership within the context of finer resolution details on ICS systems, risk, and security, to provide meaningful results on how ownership may influence risks across different communities.

Infrastructure Age: The average age of physical infrastructure in the US is increasing and costs to improve it are high and rising [40]. For dams, age is a leading indicator of the potential for failure [29]. In 2009, FEMA identified 2,047 "high hazard" dams [41]. While we observed that dams selected for analysis in this study were usually inspected within the past 2-7 years, these dams are not inspected at a rate that would be consistent with identifying vulnerabilities within a cyber-physical system. Our results show that a larger proportion of communities of color compared to white communities live in water supply areas of old dams than that of middle-aged and newer dams. This adds to the urgency is addressing risk due to dam age, as potentially vulnerable communities might disproportionately suffer. One way to address this risk may be increasing inspections, as the current rate of inspections does not likely adequately address cyber-physical risk.

Flooding, information, and risk research: When studying dams, particularly in a water-abundant state like Pennsylvania, flooding mitigation and flooding concerns are important issues. We did not undertake formal flood risk exercises through this research. We did however investigate flood risks from these dams by searching for documentation on inundation maps for Emergency Action Plans within the state. The development of Emergency Action Plans is required for all dams in the state of Pennsylvania [42]. As such, we found many resources that pointed to the development of these plans, yet most of these plans are not easily accessible to the general public. When they are, the inundation maps are coarse and difficult to discern. One reason for this lack of publicly available information is most likely because this information presents a security risk if malicious actors are seeking to identify high value targets. While important, we raise a counter question: how do we ensure vulnerable populations are properly protected without actual knowledge of risks to these communities? Transparent discussions on how to incorporate vulnerability and equity analyses in risk hazard planning may help alleviate concerns about a lack of data availability in the future, though this would need to be undertaken by multiple stakeholders with ownership interests.

V. CONCLUSIONS

Disruptions to CI have multiple ethical implications that influence communities connected to various CI sectors. We highlight the need for further research and exploration in this area, as evaluations of CI security and disruption sometimes exclude the very users of this CI. The Department of Homeland Security has highlighted dams as an important CI sector and identified key stakeholders as asset owners and operators, government agencies, industry organizations, commercial entities, R&D organizations, and universities and colleges road [15], notably excluding communities served by this CI. This research sought to address this gap by showcasing a case study of theoretical dam risks in Pennsylvania comparing a subset of water supply dams to census tract level demographic information to identify potentially vulnerable groups.

In this study we analyzed spatially variable characteristics of water supply dams and demographic information in the state of Pennsylvania. After performing chi-squared tests and studying effect size using Cramer's V, we found a moderate effect for differences in dam characteristic categories for dam ownership, age, and capacity when comparing the race of the population served, a moderate effect for the association between dam ownership and a household income of under \$75,000, and otherwise weak or negligible effects with other selected variables. By analyzing the spatial distribution of vulnerable populations, planners may prioritize security and resilience efforts in areas in which residents are particularly vulnerable to impacts. We also highlight the need for research on where advancement in industrial control systems could protect vulnerable communities and address risk. For example, where can enhanced security within these systems serve as the best protection, and when should we accept risk and work to ensure resilience within water supplies themselves? Understanding the role that technology and policy play in risk and resilience in cyber-physical systems in relation to the communities these systems serve will help us better protect lives.

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