# MULTI-SCALE RISK AND IMPACT ASSESSMENT

# OF POTENTIAL DAM FAILURE IN THE UNITED STATES

by

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## ABSTRACT

Aging water infrastructure in the United States (U.S.) is a growing concern. According to the 2018 National Inventory of Dams (NID) database, there are more than 90,000 dams registered in the U.S, and their average age is 57 years. The compounding impact of climate change with aging dams has increased the potential for and exposure risk of dam failure-driven floods. At the national level, dam failure with an absence of a state dam safety program and Emergency Action Plans (EAPs) trigger local-economic collapse causing malfunction of flood control, economic paralysis, and fatalities with property losses. Since the 1950s, which is known as the Dam nation period, dams have been providing sustainable water resources for the entire continental United States (CONUS). Dams are considered a vital infrastructure providing water and water ways to communities and industries, therefore, a dam safety program is required along with increasing economics.

At the state level, dams play a significant role as well (e.g., agriculture, navigation, and recreation) to increase the quality of life. Therefore, a scheduled inspection of dams inevitably leans on dam management agencies and private owners for protecting benefits from the existing dams. However, due to the various regional characteristics and legislations by the states, such as topography, privacy, and security issues, systematic administrating of dams is poorly conducted. Dams in the Black Belt areas of Alabama, home to some of the most socioeconomic vulnerable communities in Alabama, indicate an extremely low level of regular dam inspection based on the NID.

At the site level, hyper-resolution inundation floodplain mapping for dam breach is crucial to improve EAPs and to minimize adverse impacts of the dam failure. However, hyper-resolution 2D modeling for hydrodynamics and costly bathymetric surveys limit understanding of the impact of antecedent flow conditions on flood mapping at the site level.

This dissertation proposes a multiple-scale risk and impact assessment of potential dam failure in the United States with a focus on the state of Alabama, the only state in the CONUS with no formal dam safety legislation, in order to better understand 1) how the risk and preparedness of potential dam failure in the United States vary at a range of spatial scales (site-level to national-level), 2) how the economic benefits of the existing dams vary across the U.S. states in terms of the marginal cost of water use, and 3) what are the values of cutting-edge technologies are beneficial in better describing the flood inundated areas due to potential dam failure.

This dissertation consists of five main chapters. In Chapter 1, the objectives and goals of this dissertation are addressed. In Chapter 2, the spatiotemporal patterns of the growth of dams and their potential hazard and economic benefit are assessed, using more than 70,000 NID-registered dams in the CONUS. In Chapter 3, the state-level risk of dam failure is assessed using more than 2,000 dams in the state of Alabama. The vulnerability of communities to dam failure is high in populated counties with high incomes while less populated counties with lower incomes show a low vulnerability to dam failure due to the relatively small storage capacities of the existing dams. In Chapter 4, the sensitivity test of inundation flood mapping to initial river depth with antecedent flow condition is also conducted using the experimental simulations of the two-dimensional hydrodynamic model with a Remotely Operated Vehicle (ROV).

Applying the NID database which is updated with EAP data for the entire dams in the U.S, the results of the dissertation provide quantified data on potential economic values and hazards of dams. Therefore, the results of the dissertation are useful to not only estimate the total cost of recovery but also assess potential losses of the water cost due to dam failures. In addition, providing calculated cost of flood damage restoration would be a valuable index for flood insurances and increasing public awareness as a beginning step of dam safety. Furthermore, using an underwater drone has been successfully applied to acquire precise Digital Elevation Model (DEM) data and flood maps. If fully autonomous underwater drones are available later, the drones would play a key role in floodplain research areas as well as not only river streams, but also river basins are accessible to measure the bathymetric survey. The findings of this study can be useful data for reconsideration of the dam safety programs and EAPs, and it further emphasizes the need for careful design of EAPs accounting for antecedent flow conditions and accurate river channel depths for places that are required to establish safety programs.

# DEDICATION

I dedicate my dissertation to

my advisors, Dr. Steven Jones, Dr. Jonghun Kam, Dr. Jaehong Park, and

my beloved wife, Miseon.

LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| E | Evaporation |
| $g$ | Acceleration of gravity |
| h | Water level |
| H | Depth of water |
| P | Precipitation |
| $q$ | Flux per unit width |
| Q | Runoff |
| $S_f$ | Friction slope |
| t | Time |
| $x$ | X-direction |
| $y$ | Y-direction |
| $\Delta S$ | Change in Water Storage |
| $\Delta t$ | Change in Time |

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# CHAPTER 1. INTRODUCTION

A dam creates an artificial water impoundment such as reservoirs or ponds and then alters its surrounding flow regime depending on its storage capacity (Vorosmarty & Sahagian, 2000; Ward, 1976). Based on this unique ability, the major purpose of a dam is not only to provide sustainable water resources throughout the year but also to increase community resilience to natural hazards such as floods and droughts (Hurst, 1951). Therefore, dams are an essential component of the water infrastructure of the United States (U.S.). This fact is best evidenced by noting that more than 90,000 dams have been built in the U.S. since the 1950s which is called the Dam nation (Graf, 1999) period. Both residents and commercial industries have benefited greatly from these dams through recreation, navigation, irrigation, and flood control. Additionally, the freshwater reservoirs created by dams are also an important society benefit with significant economic value.

The potential economic benefits of water from the dams in the U.S. can be assessed in terms of the marginal costs of water storage for various types of uses (Turvey, 1976). Hence, the freshwater that is stored in the dams can be considered a vital water resource. In order to secure and preserve economic benefits from existing dams, a comprehensive dam safety program should consist of structural inspection and rehabilitation (proactive), emergency action in the event of a disaster situation (reactive), and recovery (post-reactive) plans. According to a 2017 American Society of Civil Engineering (ASCE) report that details the annual infrastructure report card at national and state levels raised concerns over the impact of aging water infrastructure on public safety and resilience (ASCE, 2017). In addition, ASCE estimated that it will require nearly $45 billion U.S. dollars to repair aging, yet critical, high-hazard potential dams. Spatiotemporal patterns of the hydrologic impact, cumulative hazard potential, and economic values of multiple dams at large-scale basins, such as the twelve National Weather Service River Forecast Centers (RFC) regions, however, have never been assessed systematically. This integrative assessment combining the potential hazard and economic impact could help address a need to reinforce current dam safety programs at the national and regional levels. Explicitly, large-scale assessment of dam-related hazard risks and economic benefits would help to develop a region-specific dam safety program that could account for spatial variation in terms of preparation and recovery programs.

The risks, benefits, and ecological impacts of existing dams have been studied at the site level, in particular, to better understand the impact of the construction or removal of a new dam or existing dam, respectively (He et al., 2020; Lin et al., 2021). However, human alteration of the river due to dams and reservoirs is ubiquitous and various (Wohl, 2020) - consequently, cumulative impact assessment of multiple dams is still challenging. For instance, over 90,000 dams have been built across the U.S. to meet the water demand for various purposes and to mitigate the adverse effect of extreme hydrometeorological events since the dam nation period. The U.S Army Corps of Engineers (USACE) has been collecting dam databases under the National Dam Inspection Act (Public Law 92-367), and as a result of the inventory, it published the National Inventory of Dams (NID) database in 1975 (USACE, 2018). Nevertheless, understanding spatiotemporal variations of potential contributions in the artificial water storage to the regional water budget still remains limitations. In addition, understanding the accumulative hazard risks and potential benefits of the existing dams is not well studied particularly for watersheds with multiple dams.

Cumulative hazard potential and potential economic assessment of dam failure enable the identification and prioritization of vulnerable RFC regions to dam failure by combining the risk of the hazard potential and potential economic losses at regional scales. This information would also help to increase public awareness of perceived risk and garner support for the upgrade of the current dam safety program justifying the hydraulic mission (Hussein et al., 2020) and reconciling the sociopolitical conflicts of water security across the U.S (Swyngedouw, 2015).

In this dissertation, Alabama (AL), which is located in the Southeast RFC region, is identified as the only state that has no formal dam safety legislation among the states. This absence of dam safety regulation raises a serious concern about not only public safety risks related to dam failure but also potential sources of economic and ecological risks. Since AL does not have a dam safety program, consequently the state cannot receive crucial benefits from federal assistance such as the National Dam Safety Program (NDSP). Due to the scarcity of resources for increasing safety levels, only AL was graded with a question mark rather than a defined grade from the ASCE 2017 report, specifically in the section of the infrastructure and dam safety. The 2018 NID database indicates that 2,273 dams have been built in AL since 1914, and only 16 percent, 226 dams which are categorized as the high hazard potential dams in AL, has an Emergency Action Plan (EAP). A major barrier to the development of a dam safety program in the AL is the general lack of knowledge about the potential risk and daily benefits of the entire dams stemming from the absence of management authority. This lack of knowledge results in the perception of a low-level risk to the potential for dam-related hazards. In order to establish formal dam safety legislation and a state-level dam safety program, the Alabama Department of Economic and Community Affairs (ADECA) has been using a Federal Emergency Management Agency (FEMA) grant to create a statewide inventory using aerial photography, mapping tools, and satellite imagery as the first step of establishing the formal dam safety legislation and on which to build dam safety program (ASCE, 2015).

The development of a dam safety program for AL is necessary to conduct a comprehensive impact assessment on the current value and hazard potential of existing dams to elevate public awareness, interest, and support for a dam safety program. Public awareness could lead to elevated risk perception on the part of the public and, then eventually, the public support for establishing water legislation and participating in the National Dam Safety Program (NDSP). To fill the gap between the public perceived risk and potential risk of aging dam failure at the state level in AL, an understanding of the economic benefits of dams must be developed in order to quantify the cost of further inaction. Therefore, AL could demonstrate the significance of a dam safety initiative, inform the community of dam-related risks, and build momentum for a statewide dam safety program to prevent catastrophic losses of life and property. As seen from the above, there are 2,273 existing dams in AL. Currently, lack of administrative capacity, political governance, public participation, and social learning not only exacerbate the adverse effects of potential dam failures, but they also decrease the resilience of the communities to the possibility of dam-related catastrophes (Lebel et al., 2005; Pahl-Wostl et al., 2007; Tortajada, 2010).

In the absence of the risk and impact assessment, it might be assumed that the largest dam-related risk would be a dam failure. In terms of failure events, flooding is an unescapable disaster. Therefore, high-accuracy flood inundation maps are necessary. Accurate flood inundation mapping can help communities adjust the received risk of dam failure and improve public awareness by visualizing potential impacts on the communities. Accurate and high-resolution flood inundation maps for a dam could provide crucial information to quantify socioeconomic impacts on adjacent communities and develop efficient and effective evacuation plans. However, since previous flood inundation maps were generally created by the Light Detection and Ranging (LiDAR)-based Digital Elevation Models (DEMs), there are serious limitations in data precisions, especially, over open-water surfaces such as rivers and streams (Toscano et al., 2015). This is because LiDAR cannot penetrate the water surface and consequently often registered river channels much shallower than they are. This way of measuring causes significant uncertainties such as flood time, depth, and extent of flood inundation mapping. It is possible, however, to reduce uncertainties directly with bathymetry survey tools such as underwater drones.

Uncertainties in flood inundation mapping are affected by multiple factors including the lack of site-based bathymetric data, antecedent flow conditions, and hydrodynamic models. For increasing accuracy and decreasing uncertainties in flood inundation mapping, Remotely Operated Vehicle (ROV), a type of underwater drone, is used to measure rivers. Therefore, to understand how uncertainties are propagated in flood inundation mapping, this study conducts a sensitivity analysis of ROV-based flood inundation mapping to site-based bathymetry measurements and antecedent river conditions.

Dams are important to the economy and our way of life. As well as providing supplying sustainable water resources, dams provide valued recreational spaces and reduce the risk of floods and droughts. However, malfunction and failure of dams result in catastrophic losses in our society. The findings of this dissertation will advance the knowledge of actual benefits and related hazard potential and alert our society to a need to upgrade the current dam maintenance and rehabilitation programs for a safer built-in environment.

Through a multi-scale and multi-disciplinary approach with cutting-edge technologies, this dissertation will provide a direction to create new value in the fields of water resources engineering and safety engineering.

# CHAPTER 2. RISK AND IMPACT ASSESSMENT OF DAMS IN THE CONTIGUOUS UNITED STATES USING THE 2018 NATIONAL INVENTORY OF DAMS DATABASE

## 2.1. Motivation

A dam creates an artificial water impoundment and alters the flow regime. The main goal of a dam is to provide sustainable water resources throughout the year and to increase community resilience to natural hazards such as floods and droughts (Hurst, 1951). The artificial water impoundment alters the surrounding flow regime, particularly downstream from the dam, by increasing low flows and decreasing high flows (Ward, 1976) while the hydrologic impact of a dam varies depending on the size and purpose (Vorosmarty & Sahagian, 2000). Land-use and land-cover changes such as dams and irrigation have influenced the local climate by changing the atmospheric conditions such as humidity and surface temperature via land–atmospheric coupling (Degu et al., 2011).

The potential economic benefits of water from the existing dams can be assessed in terms of the marginal costs of water for different uses (Turvey, 1976). In the contiguous United States (CONUS), freshwater values are diverse depending on the uses (Frederick et al., 1996b) and the regions (Graf, 1999). In 2017, the American Society of Civil Engineering issued the infrastructure report card at the national and state levels. The report raises a concern about the impact of aging water infrastructure on public safety and resilience (ASCE, 2017). In the report, they estimate it will require nearly $45 billion U.S. dollars to repair aging, yet critical, high-hazard potential dams. Spatiotemporal patterns of the hydrologic impact, cumulative hazard potential, and economic values of multiple dams at large-scale basins, such as the 12 National Weather Service River Forecast Centers (RFC) regions, have never been assessed synthetically.

To secure and maintain the economic benefits from existing dams, a comprehensive dam safety program should consist of structural inspections and rehabilitation (proactive), emergency action (reactive), and recovery (post-active) plans. When assessing the potential hazard of dam failure, the economic benefits from the multiple uses of water stored in the reservoir should be counted as economic losses in the event of dam failure. An integrative assessment of potential hazard assessment and the economic impact of dam failure can help address a need to improve the current dam safety program at the national and regional levels for policymakers and water resources managers. Also, the large-scale assessment of dam-related hazard risk and economic benefits helps develop region-specific dam safety programs, which can account for spatial variation of the level of the preparation and recovery programs for dam failure.

Conventionally, the risk of dam failure has been estimated based heavily on stochastic models that are in turn based on the stationarity theory (Baecher et al., 1980; Lee & You, 2013). However, structural inspection and maintenance programs are also necessary to move toward greater resilience to unprecedented extreme weather and climate events. Changing climate makes the stationarity of water-engineered systems redundant (Milly et al., 2008) and thus requires the development of an integrated approach to dam design, operations, and water management. Dams are a key component of the coupled human-natural systems for hydroclimatic extreme event adaptation and mitigation (Hossain et al., 2012), which can compound the climate change impacts through the interactions of natural and human systems. In a changing climate, the hydrologic impact of dams and related risks and benefits should be assessed since the maintenance and upgrade of aging hydraulic missions can be influential in reducing hazard potential at not only the national but the international level as well (Conker & Hussein, 2019, 2020).

The risk, benefits, and ecological impacts of the existing dams have been studied at the site level, in particular, to better understand the impact of the construction/removal of a new dam (He et al., 2020; Lin et al., 2021). However, human alteration of rivers due to dams and reservoirs are ubiquitous and various (Wohl, 2020) and thus the accumulative impact assessment of multiple dams is still challenging. For example, dams have been built across the U.S. states to meet the water demand for various purposes and mitigate the adverse effect of extreme hydrometeorological events. Currently, the U.S. has over 90,000 dams with an average age of 57 years old and has been often called a Dam nation (Graf, 1999). A previous study (Fergus et al., 2021) found that lakes with no potential for human hydro-alteration, such as dams and land use, have been decreased since 2007. To better understand the accumulative impact of multiple dams at the regional scale and their spatial variation, detailed information of these 90,000 dams in the U.S. are necessary.

In 1975, the U.S. Army Corps of Engineers (USACE) inventoried dams in the United States under the National Dam Inspection Act (Public Law 92–367). The USACE first published the National Inventory of Dams (NID) database in 1975 (USACE, 2015). In response to the Federal Dam Safety Act of 2006 (Public Law 109–460), the Federal Emergency Management Agency (FEMA) requires a biennial report to Congress on the status of the existing dams and progress achieved in dam safety during the previous two years. Using the NID database that was limitedly assessed, the potential large-scale hydrologic and environmental effects on the flow regime (Graf, 1999).

Recently, the NID has reauthorized as part of the Water Resources Reform and Development Act of 2014 (Public Law 113–121) and the Water Resources Development Act of 2018 (Public Law 115–270). The 2018 NID database was populated using the 116th Congressional District information. Two major changes to the 2018 NID database are that (1) the 2018 NID database is downloadable from the website (https://nid.sec.usace.army.mil) (accessed on 25 August 2020) and (2) the information about the hazard potential due to the failure or malfunction of dams is publicly available (USACE, 2018).

The understanding of spatiotemporal variations of the potential contribution of artificial surface water storage to the regional surface water budget remains limited. Understanding the accumulative hazard risk and potential benefits of the existing dams also remains limited, particularly, in the multiple dam setting. This study strives to evaluate the hydrologic impact on the regional surface water budget and hazard assessment of dam failure over time in terms of the upstream catchment area of the corresponding dam per the number of the total dams and total storage per area, respectively. The cumulative hazard potential and potential economic assessment of dam failure enable identification of RFC regions that are more or less vulnerable to dam failure, by combining the risk of the hazard potential and potential economic losses of dam failure at the regional scale. This information can help increase the public's perceived risk and garner support for the upgrade of the current dam safety program by justifying the hydraulic mission (Hussein et al., 2020) and reconciling the sociopolitical conflicts of water security across the U.S. states

(Swyngedouw, 2015). Eventually, the findings of this study will advance the limited understanding of "Anthropocene risk" (Keys et al., 2019).

## 2.2. Data and Methods

### 2.2.1. National Inventory of Dams Database

The NID database includes the existing dams in the United States that meet at least one of the following four categories: (1) dams are classified as high hazard potential, (2) dams are classified as significant hazard potential, (3) dams exceed 2 m (6 feet) in height with equal or exceed 61,700 m3 (50 acre-feet) of storage, and (4) dams that are equal or exceed 8 m (25 feet) in height with exceeding 18,500 m3 (15 acre-feet) of storage. All dams registered in the NID database are categorized into five types of downstream hazard potential due to failure or malfunction of the dam or facilities: high (potential human life loss), significant (potential economic loss and environmental damage, but not human life loss), low (low economic and/or environmental loss limited to the owner's property), undetermined, and missing. This potential hazard assessment does not account for the likelihood of failure occurrence of the corresponding dam. In other words, it only reflects the consequences of a dam failure, but not the condition of a dam failure (FEMA, 2013). The 2018 NID database includes the 91,191 dams over the CONUS. This study found that 15,690 NID-registered dams (17%) have no information for geographic location (latitude and longitude), year of completion, or maximum storage capacity. In this study, 75,501 dams over the CONUS were applied while a previous study (Graf, 1999) used 74,921 dams to study the artificial water storage growth due to dam constructions. In this study, the hazard potential assessment contains the error range of 3.5% of the total maximum storage of the total 75,501 dams because 7763 (5778) dams have no information for hazard potential over the CONUS (the West Gulf RFC region), which was not reported previously (Graf, 1999). Despite the relatively small contribution, there are likely numerous dams in the United States that are smaller than the categories used in the NID database (height and storage capacity), indicating that this report represents the conservative assessment for hazard potential due to dam failure or malfunction.

### 2.2.2. Evaluations of Potential Hydrologic Impact

To evaluate the potential hydrologic impact of the NID-registered dams on the land surface water budget, the cumulative maximum reservoir storage created by the dams within each RFC area was calculated (Table 2-1).

Table 2-1. Summary for the National Inventory of Dams (NID) registered dams across the 12 River Forecast Centers (RFC) regions.

| ID | RFC Region | Number of Dams | Area | | Cumulative Storage (a) | | Annual Precipitation (b) | | (a)/(b) |
|---|---|---|---|---|---|---|---|---|---|
| | | | [$10^6$ acres] | [$10^3$ km$^2$] | [$10^6$ acres-ft] | [km$^3$] | [$10^6$ acres-ft] | [km$^3$] | |
| 1 | Northeast | 4647 | 67 | 271.35 | 46.8 | 57.73 | 276.3 | 340.82 | 0.17 |
| 2 | Mid-Atlantic | 2735 | 53 | 214.65 | 15.7 | 19.37 | 207.7 | 256.20 | 0.08 |
| 3 | Southeast | 10,565 | 159 | 643.95 | 232.6 | 286.91 | 683.1 | 842.60 | 0.34 |
| 4 | Ohio | 4066 | 112 | 453.6 | 46.7 | 57.60 | 441.7 | 544.84 | 0.11 |
| 5 | North Central | 7796 | 217 | 878.85 | 338.4 | 417.42 | 629.3 | 776.24 | 0.54 |
| 6 | Lower Mississippi | 5124 | 131 | 530.55 | 95.4 | 117.68 | 586 | 722.83 | 0.16 |
| 7 | Missouri | 20,345 | 333 | 1348.65 | 207.6 | 256.07 | 634.6 | 782.78 | 0.33 |
| 8 | Arkansas | 8214 | 135 | 546.75 | 92.5 | 114.10 | 343.2 | 423.34 | 0.27 |
| 9 | West Gulf | 6198 | 257 | 1040.85 | 66.8 | 82.40 | 626.4 | 772.66 | 0.11 |
| 10 | Northwest | 2139 | 201 | 814.05 | 84 | 103.61 | 549 | 677.19 | 0.15 |
| 11 | Colorado | 1972 | 196 | 793.8 | 103.4 | 127.54 | 208.8 | 257.55 | 0.50 |
| 12 | California | 1700 | 160 | 648 | 43.2 | 53.29 | 279.4 | 344.64 | 0.15 |
| Total (Contiguous United States) | | 75,501 | 2021 | 8185.05 | 1373.1 | 1693.71885 | 5465.5 | 6741.69 | 0.25 |

Over the long-term average (at least 10 years), the terrestrial storage tendency is often negligible, so the long-term average land surface water balance is supposed to be closed. The cumulative maximum storage capacity of dams and reservoirs can significantly increase the terrestrial water storage tendency term in the water balance equation ($\Delta S/\Delta t$ in Equation (2.1)), which requires some modification of other components such as precipitation (P), evaporation (E), and runoff (Q) for the water surface storage closure.

$$\Delta S/\Delta t = P - E - Q \quad (2.1)$$

The ratio of the cumulative maximum storage capacity of dams and reservoirs to the long-term annual precipitation is a good indicator to measure the potential hydrologic impact of the dams on the regional land surface water balance. The long-term average (2002-2012) of total annual precipitation for each RFC area (Prat & Nelson, 2015) is also reported in Table 2-1. The area per dam is a useful index to assess the hazard potential and preparedness of the existing dams because the location of the dams determines how many residents and properties would be adversely affected due to the adjacent dam failure. In this report, the area per dam is computed to measure the density of the NID-registered dams within the RFC area. The total storage per the upstream catchment area from the corresponding dam is also computed to quantify the relative size of the cumulative storage capacity of dams within an RFC region. These metrics are normalized by the corresponding RFC regional area so the potential hydrologic impact and hazard potential assessment of the dams and reservoirs can be directly compared across the 12 RFC regions.

### 2.2.3. Detection of the Dams within the River Forecast Centers (RFC) Region

The original NID database includes detailed information about dams and reservoirs. In this study, a key challenge was to identify which of the 75,501 dams are located inside the boundaries of the 12 RFC areas. The shapefiles of the 12 RFC River basins and the geographical information (longitude and latitude) of 75,501 NID-registered dams were used to identify which dams are inside the RFC area boundaries; it took 906,012 iterations (12 RFC basins × 75,501 dams). The NCAR Common Language (NCL) function "gc_inout.ncl" was used to perform these iterations (NCAR, 2020).

### 2.2.4. Economic Benefits in Each RFC region

To assess the potential economic value of water stored in the existing dams within each RFC region, this study followed the methodologies used in a previous study (Frederick et al., 1996a). They estimated the monetary value of freshwater, per acre-feet. of volume, based on the purpose they served. This method was also used in a previous study (Graf, 1999) for the national-scale economic assessment. This study updated the economic and hazard assessment using the 2018 NID database, including 91,191 dams over the CONUS. This study also calculates the marginal cost of freshwater to the cumulative economic benefits of existing dams in each RFC region, using the accumulated storage capacity and purpose of dams and 12 RFC geographical information such as the total number of the dams in a region. The result for the value of freshwater by purpose was then adjusted for inflation using the Bureau of Labor's Consumer Price Index (CPI) calculator. For the large-scale assessment, this study simplified the economic impact assessment as a function of storage volume; however, it can depend strongly on their operations and authorized purposes along with the geographic and economic text of their own designed purpose. Furthermore, the implication that the cost of a dam failure is equal to the loss of these (average) benefits is also limited, failing to account for the damage and potential loss of life from the dam failure itself. However, more information about dam structures and operation policy and the size of the exposed community to dam breach-related potential hazards are required to assess the detailed assessment of dam-related risk and impact. Some information for dams is not still publicly accessible due to the security issue and private ownership. In this study, the focus is the large-scale assessment for risk and impact assessment of the existing dams in the U.S. A further study of a site-specific assessment with detailed information about dam operation and water demand is critical at the local scale, which is, however, beyond this study.

## 2.3. Results and Discussions

The 2018 NID database shows a slight increase in the total number of dams within the 12 RFC regions compared with the previous report (Graf, 1999) (Table 2-1). The numbers of dams within the 12 RFC areas range from 1700 dams within the California RFC area (2% of the total dams) to 20,345 dams for the Missouri RFC region (27%). The cumulative maximum storage capacities of the dams within the 12 RFC regions range from 19,400 million cubic meters (15.7

million acre-feet; Mid-Atlantic) to 418 billion cubic meters (338.4 million acre-feet; North Central). In the North Central RFC area, there are the Soo Locks, a set of parallel locks, which has a reported maximum storage of over 334 billion cubic meters (270 million acre-feet). In recent years, the locks serve 10,000 vessels per year including small passenger vessels and workboats to large ships (USACE, 2018). Over the 12 RFC regions, the ratios of the cumulative storage capacity to the long-term averaged precipitation range from 8% (Mid-Atlantic) to 50% (Colorado), which indicates that the significant human disturbance, particularly due to dam construction. Figure 2-1 shows the percentages of the total dams by the four levels of hazard potential (High, Significant, Low, Undetermined, and Missing) in terms of both the area per dam and the cumulative storage per RFC region. From the area per dam indices, the percentage of dams with high hazard potential ranges from 3% (West Gulf) to 46% (California). However, 93% of the total dams (5,776 out of the 6,197 dams) have an undetermined level of hazard potential in the West Gulf RFC area. 93% of the total dams over the West Gulf RFC area are equivalent to 39% of the regional cumulative storage. The Missouri and Arkansas RFC areas have the second and third lowest percentages of dams with high hazard potential (8% and 9%, respectively). It is worth noting that most of the RFC regions except for the West Gulf and Northeast RFC areas show that 75% of the cumulative storage or more is under high hazard potential. The Missouri RFC basin shows a noticeable change such that the second-lowest percentage (8%) of the dams with high hazard potential becomes the highest percentage (97%) of the cumulative storage per dam. This result indicates that the dams with high hazard potential in the Missouri RFC area are large dams.

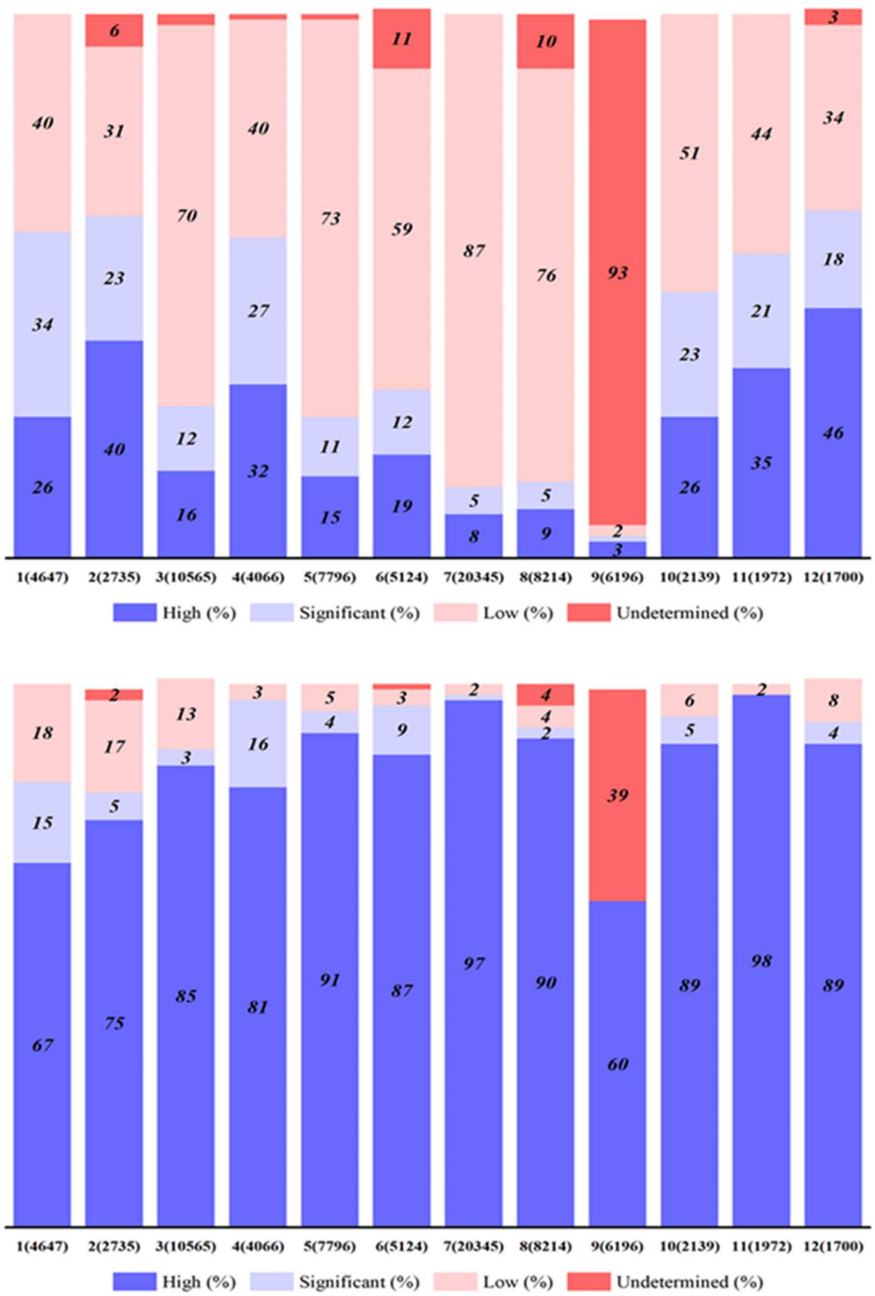


Figure 2-1. Percentages of the area per dam (top) and the cumulative storage per area (bottom) over the 12 RFC regions for the potential hazards: high, significant, low, and undetermined.

Over the CONUS, 30% of the dams (23,386 out of 75,501) are supposed to have an Emergency Action Plan (EAP) (Table 2-2); 67% of these dams have an EAP program while the rest of the dams have no EAP. The percentage of the EAP-required dams but with no EAP ranges from 10% (Colorado; well prepared) to 61% (Southeast; poorly prepared) across the RFC regions.

Table 2-2. Dams with and without hazard potential and Emergency Action Plan (EAP) over the 12 River Forecast Centers (RFC) regions.

| ID | RFC Region | Number of Dams | Hazard Potential | | | | | Emergency Action Plan (EAP) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Required | | | Not Required |
| | | | High | Significant | Low | Undetermined | Missing | Yes (a) | No (b) | (b)/((a)+(b)) | |
| 1 | Northeast | 4647 | 1191 | 1571 | 1868 | 17 | 0 | 1893 | 363 | 0.16 | 2391 |
| 2 | Mid-Atlantic | 2735 | 1107 | 618 | 835 | 175 | 0 | 1687 | 258 | 0.13 | 793 |
| 3 | Southeast | 10,565 | 1694 | 1235 | 7420 | 216 | 0 | 1750 | 2840 | 0.62 | 5975 |
| 4 | Ohio | 4066 | 1314 | 1095 | 1632 | 25 | 0 | 1646 | 773 | 0.32 | 1647 |
| 5 | North Central | 7796 | 1182 | 870 | 5693 | 51 | 0 | 1531 | 1282 | 0.46 | 4983 |
| 6 | Lower Mississippi | 5124 | 950 | 590 | 3026 | 240 | 318 | 837 | 283 | 0.25 | 4004 |
| 7 | Missouri | 20,345 | 1551 | 1027 | 17,711 | 56 | 0 | 1337 | 344 | 0.20 | 18,664 |
| 8 | Arkansas | 8214 | 708 | 420 | 6260 | 69 | 757 | 851 | 115 | 0.12 | 7248 |
| 9 | West Gulf | 6198 | 215 | 52 | 153 | 0 | 5778 | 1480 | 425 | 0.22 | 4293 |
| 10 | Northwest | 2139 | 561 | 486 | 1085 | 7 | 0 | 716 | 479 | 0.40 | 944 |
| 11 | Colorado | 1972 | 685 | 410 | 873 | 3 | 1 | 982 | 105 | 0.10 | 885 |
| 12 | California | 1700 | 776 | 302 | 572 | 50 | 0 | 715 | 697 | 0.49 | 288 |
| | Total (CONUS) | 75,501 | 11,934 | 8676 | 47,128 | 909 | 6854 | 15,425 | 7964 | 0.34 | 52,115 |

It is worth noting that the Southeast RFC area includes the state of Alabama which has 2273 dams but does not have a state-level dam safety program, raising concern for public safety related to dam breaches in the Southeast RFC area, particularly in Alabama. Over the CONUS, 18% and 26% of the dams that have no EAP have a high and significant hazard, respectively, while 82% of the dams that have an EAP have high or significant hazard potential (Figure 2-2).

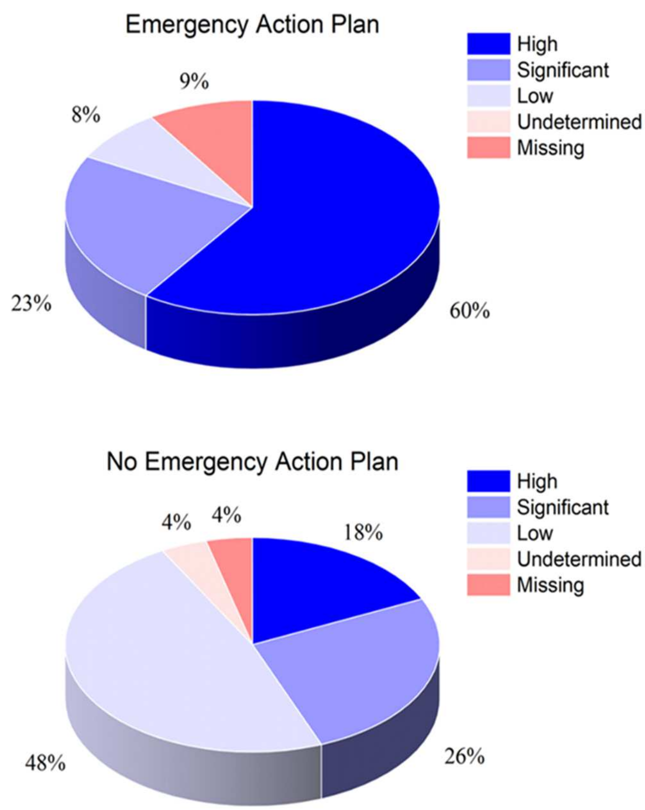


Figure 2-2. Percentages of dams with (top) and without (bottom) Emergency Action Plans (EAP) at the high, significant, and low hazard potential over the CONUS.

The ranks for the NID-registered dams that have an EAP and are designated high or significant hazard potential are shown in Figure 2-3. The ranks are based on the indices of the upstream area per dam and the cumulative storage per area. It is only the Mid-Atlantic RFC area that shows that 90% of the EAP-required dams have an EAP, in terms of both the upstream catchment area per dam and cumulative storage per area, indicating that this region is well prepared for dam failure. Over the North Central and Southeast RFC areas, less than 90% of the EAP-required dams have an EAP, based on the cumulative storage per area. The Southeast RFC area has the most cumulative storage per dam that has either high or significant hazard potential, regardless of the absence of an EAP (Figure 2-3).

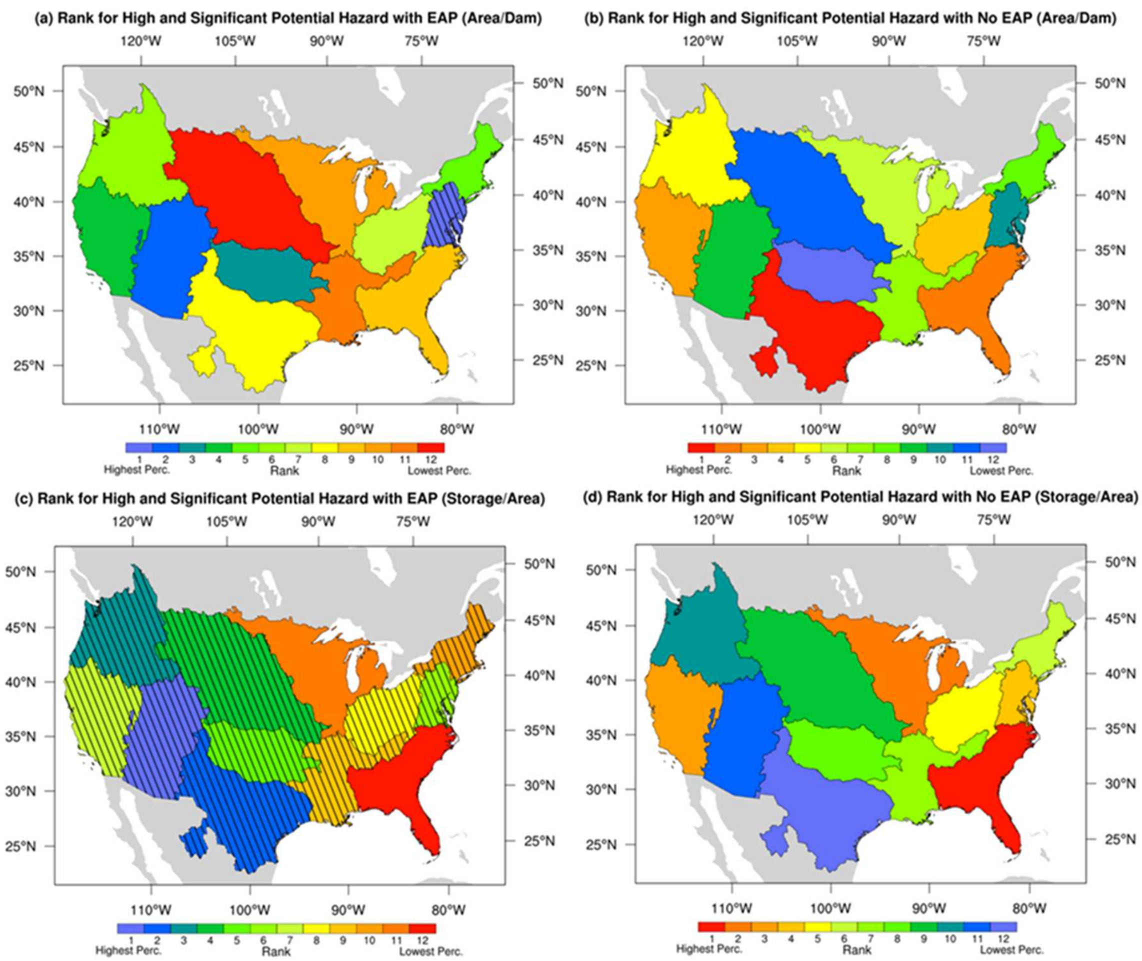


Figure 2-3. Ranks for high and significant hazard potential with and without EAPs in terms of the area per dam (a and b) and cumulative storage per area (c and d).

Hatched areas depict the RFC areas that have 90% or more of the area per dam or cumulative storage per area that are classified into high or significant hazard potential and have an EAP.

Classified hazard potentials in the 2018 NID database account only for the consequences of a dam failure, not the current condition of a dam failure. The conventional methods of the likelihood estimation of dam failure have been based on stationarity theory, which means that a record-breaking event is unlikely to happen year after year post-completion of dam construction (Munger et al., 2009). However, structures are aging and are significantly damaged during the occurrence of extreme events such as floods, droughts, and heatwaves. As a dam gets older, the maintenance of the structure is crucial for public safety and community resilience. This study computed the annual time series of cumulative storage per the upstream catchment area over the 12 RFC regions to understand the temporal patterns of dam construction over the 12 RFC areas and identify which regions are at the risk in terms of the age of dams (Figures 2-4 and 2-5).

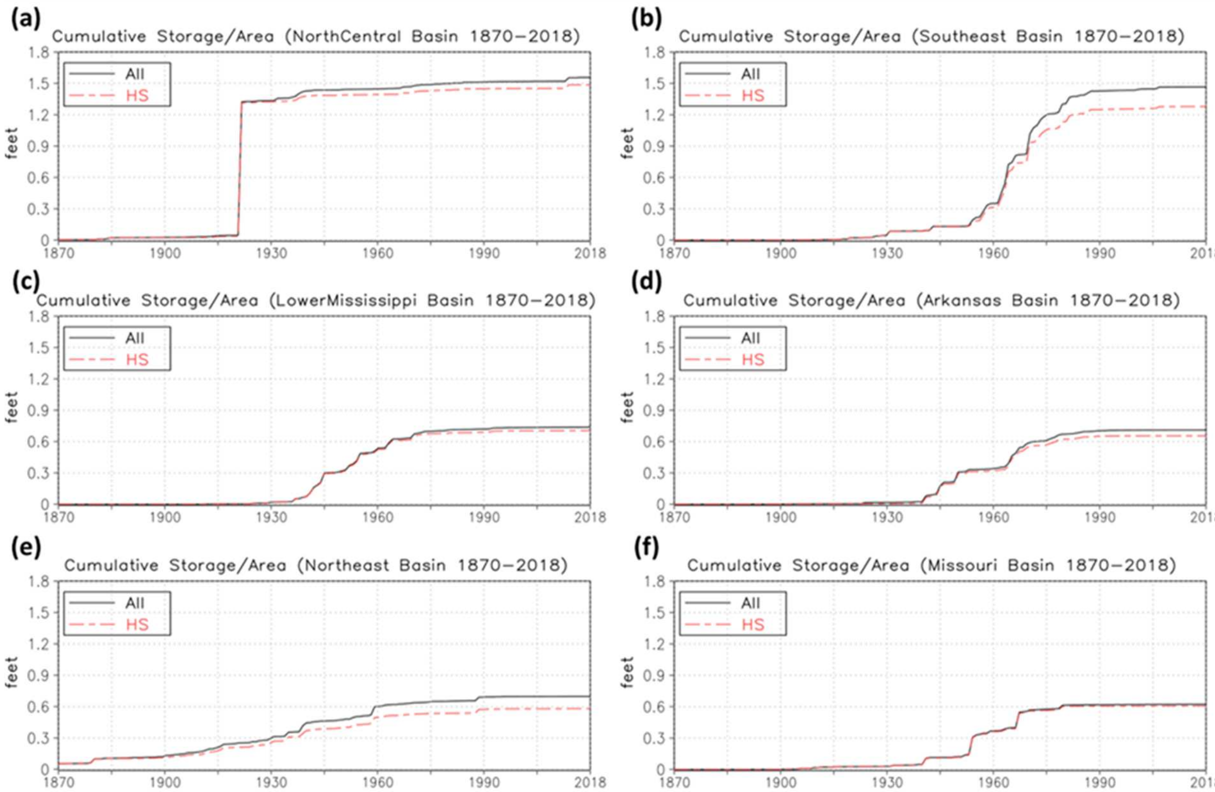


Figure 2-4. Annual time series of the cumulative storage per area (1870-2018) of the dams with all the types of hazard potential (All; black solid lines) and only high and significant hazard potential (HS; red dashed lines) over the North Central (a), Southeast (b), Lower Mississippi (c), Arkansas (d), Northeast (e), and Missouri (f) RFC areas.

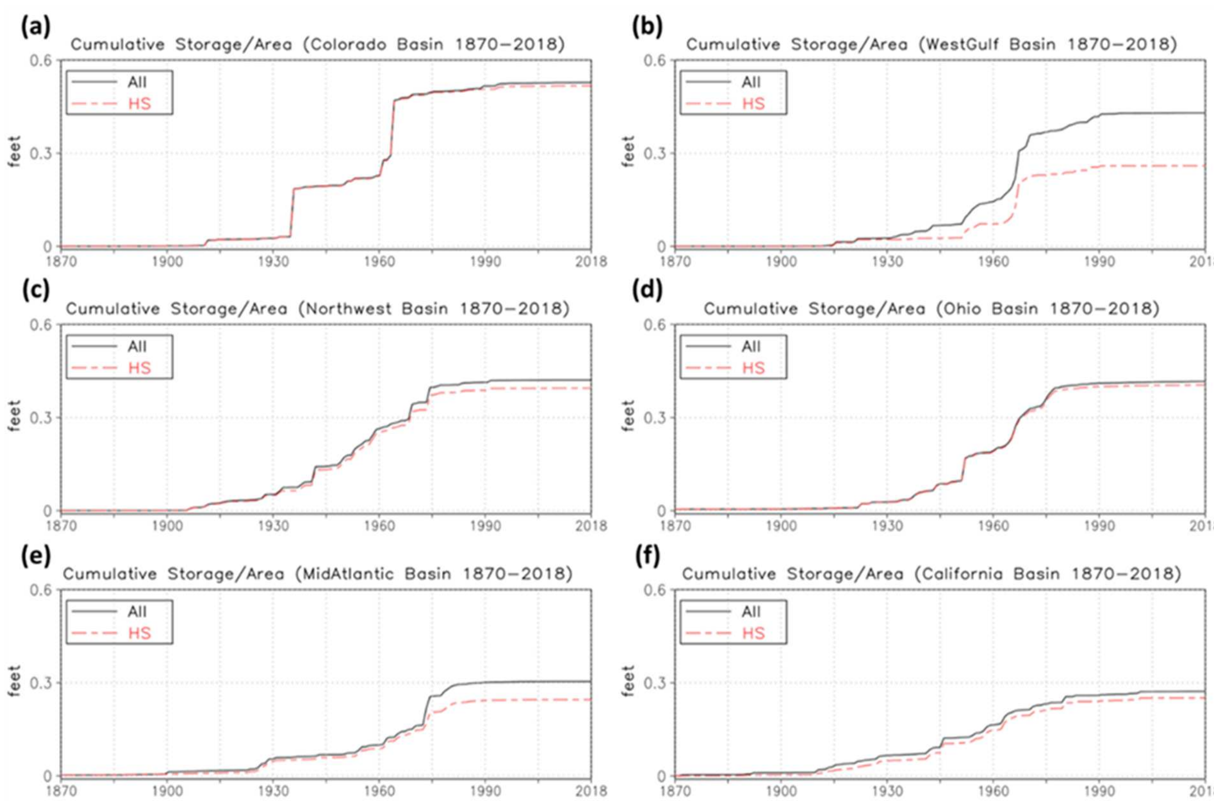


Figure 2-5. Same as Figure 2-4 except for Colorado (a), West Gulf (b), Northwest (c), Ohio (d), Mid-Atlantic (e), and California (f) RFC areas.
The scale of the y-axis is one-third of the scale of the y-axis in Figure 2-4.

The total maximum reservoir storage capacity in the CONUS increased rapidly in the 1950s and 1960s, and additional dams have not been built since 2000 except in the North Central and Southeast RFC areas. The eastern U.S., including Northeastern, Mid-Atlantic, and Southeast RFC regions, shows a rapid increase in the cumulative storage per the upstream catchment area during a relatively short period (1950-1970), while the dams in the northern part of the CONUS such as the North Central, Northeast, Northwest, and California regions were constructed consistently from the 1880s through the 1980s. The eastern U.S. regions are more likely to have a higher chance of structural failure or dam malfunction and are where more dam failure occurrences have been reported since 1991 (Association of State Dam Safety Officials, 2013). These gradual and rapid increases in the dam construction patterns are consistent with the growth trends of the dams with high and significant hazard potential. The findings of this study are in line with the findings of a previous study (Graf, 1999).

Table 2-3 shows the cumulative economic benefits from the existing dams across the 12 RFC regions. Over the CONUS, the average of the potential economic benefits per dam is 0.8 million dollars. The RFC regions with the top four highest economic benefits (greater than one million dollars) include Colorado (1st highest), Northwest (2nd), West Gulf (3rd), and California (4th) while the RFC regions with the bottom four lowest economic benefits (less than half-million dollars) include Southeast (9th), Mid-Atlantic (10th), Missouri (11th), and Northeast (12th). The RFC regions with high benefits from existing dams are more vulnerable to climate change-driven droughts (Cook et al., 2015; Milly & Dunne, 2020; Rogers et al., 2011; Swain et al., 2014), which suggests the economic value of freshwater is expected to increase in the future while the RFC regions with low benefits are water-ample due to diverse precipitation generating mechanisms (e.g., tropical cyclones, convective systems, frontal systems, etc.). The results imply that the value of the existing dams becomes more critical for water resource management over drought-prone regions.

Table 2-3. Freshwater costs of accumulated storage capacity in the 12 River Forecast Centers (RFC) regions.

| ID | RFC Region | Number of Dams | Cumulative Storage | | Cost Average | | Potential Benefit | |
|---|---|---|---|---|---|---|---|---|
| | | [-] | [$10^6$ acres-ft] | [$km^3$] | $/Acre-ft | $/Million Liters | [Million US Dollars] | [Thousands US Dollars/dam] |
| 1 | Northeast | 4647 | 46.8 | 57.7278 | 20.9 | 16.94 | 978.12 | 210.48 |
| 2 | Mid-Atlantic | 2735 | 15.7 | 19.36595 | 40.8 | 33.08 | 640.56 | 234.21 |
| 3 | Southeast | 10,565 | 232.6 | 286.9121 | 19.6 | 15.89 | 4558.96 | 431.52 |
| 4 | Ohio | 4066 | 46.7 | 57.60445 | 37.8 | 30.65 | 1765.26 | 434.15 |
| 5 | North Central | 7796 | 338.4 | 417.4164 | 29.2 | 23.67 | 9881.28 | 1267.48 |
| 6 | Lower Mississippi | 5124 | 95.4 | 117.6759 | 34.4 | 27.89 | 3281.76 | 640.47 |
| 7 | Missouri | 20,345 | 207.6 | 256.0746 | 21.2 | 17.19 | 4401.12 | 216.32 |
| 8 | Arkansas | 8214 | 92.5 | 114.0988 | 50.5 | 40.94 | 4671.25 | 568.69 |
| 9 | West Gulf | 6198 | 66.8 | 82.3978 | 139.7 | 113.26 | 9331.96 | 1505.64 |
| 10 | Northwest | 2139 | 84 | 103.614 | 89.7 | 72.72 | 7534.80 | 3522.58 |
| 11 | Colorado | 1972 | 103.4 | 127.5439 | 122.4 | 99.23 | 12,656.16 | 6417.93 |
| 12 | California | 1700 | 43.2 | 53.2872 | 81.1 | 65.75 | 3503.52 | 2060.89 |
| Total/Average (CONUS) | | 75,501 | 1373.1 | 1693.719 | 57.28 | 46.43 | 63,204.75 | 837.14 |

## 2.4. Conclusions

This study succeeded to harness the 2018 NID database to assess the spatiotemporal patterns of the potential hydrologic impact of the existing dams in the U.S. This study found that the cumulative maximum storage capacities of the 12 RFC river basins ranged between 8% in the Mid-Atlantic and 50% in Colorado of the long-term averages of annual precipitation, which is no longer negligible in the regional land surface water balance. According to the assessment of dam failure-related hazard potential in this study, the Mid-Atlantic and Colorado RFC regions are well prepared for potential hazards (90% of the EAP-required dams with EAPs) while the Southeast RFC region is at the highest risk for potential hazards among the 12 RFC river basins, due to poor preparation in terms of the EAPs. Since the 1950s, cumulative storage capacity in the Southeast and Missouri regions has rapidly increased along with the number of dams with high or significant hazard potential, which raises a concern about community resilience to dam failure. In addition, recent extreme weather such as hurricanes and atmospheric river-driven floods over the U.S. have caused several dam crises, such as the Oroville Dam crisis in February 2017 and Hurricane Harvey in August 2017 (Vano et al., 2019). Dam failure/crisis will exacerbate the adverse effects of an unprecedented extreme event and cause a longer recovery time for the community. The findings of this study suggest a need to develop and improve a regional-specific dam safety program across the 12 RFC regions.

This chapter also found that the existing dams have been a vital resource of the nation's river systems, not only for water supply but also for other uses such as navigation and flood control. Due to the aging of dams and reservoirs, however, the development of a comprehensive dam safety program is crucial for preserving the benefits to our daily lives from existing dams. For the preparedness of potential dam failures, most of the 12 RFC regions are at a high level of hazard risk due to potential failure or malfunction of the existing dams. The results of the economic assessment of the existing dams found that the national average potential economic benefit per dam is 0.8 million dollars with a wide range between \$0.2 and \$6 million. The top four RFC regions with the highest economic benefits experience a higher risk of drought in the future, causing a higher level of vulnerability to water scarcity/crisis.

The dam safety program should consist of dam inspection and rehabilitation programs (proactive), emergency action plans (reactive), and recovery plans (post-active). For the first step of the improvement of the dam safety program in the U.S., the Emergency Action Plan program for all the NID-registered dams at high hazard potential is mandatory, and then secondary efforts should be transitioned toward proactive and post-active approaches to increase public safety and community resilience to dam-related hazard potential. The comprehensive dam safety program can secure the economic benefits from the existing dams and make our environment safer and more sustainable.

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# CHAPTER 3. ECONOMIC ASSESSMENT OF DAMS IN ALABAMA USING THE 2018 NATIONAL INVENTORY OF DAMS DATABASE

## 3.1. Motivation

Dams create a manmade water impoundment and alter the flow regime of a river in various ways, depending on the storage capacity and purpose. Due to their well-known benefits and costs, dams are a key aspect of water infrastructure and one of the most influential components in the built environment. In the Global Reservoir and Dam Database, the United States (U.S.) leads in terms of the number of registered large dams, with 672 (Chen et al., 2016). At the national scale, the United States Army Corps of Engineers (USACE) has developed and maintained the National Inventory of Dams (NID) database (USACE, 2015). In January 2018, they released the updated NID database and made it publicly accessible. According to the 2018 NID database, the U.S. has over 90,000 dams. Over the last 40 years, the U.S. has taken steps to shore up dam safety, a responsibility resulting from the widespread use of dams.

Over the Contiguous U.S. (CONUS), three tragic dam failures in the 1970s catalyzed federal action on dam safety. First, in 1972, the failure at Buffalo Creek in West Virginia killed 125 people, injured 1,100 more, and made 3,000 homeless, sparking rigorous debates on dam safety issues (Seals et al., 1972). The resulting Dam Inspection Act of 1972 authorized the USACE to inspect non-federal dams (Public Law 92-367). Next, the famous Teton Dam failure of 1976 killed 11 people, destroyed 8,000 homes and farm buildings, and caused $1 billion in damages in Idaho (Bolton Seed & Duncan, 1987). The third failure was the Kelly Barnes dam in Georgia in

1977; 39 people were killed, and as a result, inspections of high hazard potential dams, authorized by the 1972 act, began (Federal Investigative Board, 1977). In 1979, an executive order created the Federal Emergency Management Agency (FEMA) and tasked it with overseeing dam safety for the nation (FEMA, 2013).

The National Dam Safety Program (NDSP) was established to protect Americans from dam failure or malfunction under the Water Resources Development Act of 1996 (Public Law 104-303) and functions as a vital source of information in preventing dam crises and reducing the adverse impacts on lives and property. The NDSP provides safety training programs, research development to improve dam safety information further, and grant assistance to support states in their effort to increase inspections (FEMA, 2013). Also, the NDSP assists state governments to develop plans for emergency action and purchase necessary equipment.

Alabama has 2,273 dams, but it is the only state of the U.S. continent that has no formal dam safety legislation. Consequently, the state cannot receive many of the potential benefits from the federal assistance for dam safety, such as NDSP, and thus has no recourse for improving the status of dams in Alabama. The absence of federal assistance raises a serious concern about public safety risks related to dam failure or malfunction, as well as a potential source of economic and ecological risk. Using the NID database, the American Society of Civil Engineers (ASCE) reported on the state of dams in the U.S. and gave several suggestions. These recommendations include a thorough inventory, a publicly available map of all of the dams, and the development of emergency action plans (EAPs). Ultimately, ASCE asserts that establishing a dam safety program is necessary to achieve the goals of comprehensive management (ASCE, 2015). In the ASCE report for dam safety, Alabama was graded with a question mark, rather than a defined grade, until such a time when there is sufficient information even to compose a grade.

The 2018 NID database shows that 226 dams under high hazard potential dams only 16% located in Alabama have an EAP. The national average of high hazard potential dams is 74% (USACE, 2018). A comparison between Alabama and a neighboring state, Mississippi (MS), shows that Alabama is lagging behind. Over 6,000 dams in MS. are registered in the 2018 NID database. MS. has 381 dams with high hazard potential, but 71% of those dams have an EAP (USACE, 2018). The Mississippi Department of Environmental Quality has comprehensive rules to govern dam safety, including permitting applicability and limitations, application content and procedure, permit requirements, design and maintenance requirements, inspections, risk analysis, EAPs, and compliance and enforcement.

A major barrier to the development of a dam safety program in the State of Alabama is the general lack of knowledge about the potential risk, and it results in the perception of a low level of risk of the dam-related hazard potential. To develop a state dam safety program, the Alabama Department of Economic and Community Affairs (ADECA) has been using a FEMA grant to create a state-wide inventory using aerial photography, computer mapping tools, and satellite imagery. However, ADECA is working despite the scarcity of resources, and the process has been slow-moving (ASCE, 2015). The results of the study are not yet publicly available.

The development of a dam safety program for Alabama is necessary to conduct a comprehensive impact assessment on the current value and hazard potential of the existing dams. This impact assessment would elevate public awareness of the importance of a dam safety program and ideally elicit greater public interest and support. Eventually, this public awareness can lead to elevate perceived risk on part of the public, public support for water legislation, and also the participation of the NDSP. While the hazard potential assessment has been reported on the 2018 NID database, an economic assessment of the dams in Alabama has never been conducted, which perpetuates a lack of knowledge about the unseen benefits from existing dams.

To fill the gap between the public perceived risk and potential risk of aging dam failure in the state of Alabama, this study aims to describe the economic benefits of dams better to quantify the cost of further inaction. Using the NID database the objectives of this study are to 1) report the accumulated maximum storage capacities of all dams in the state, 2) categorize the dams into four primary purposes: recreation, fish and wildlife habitat, navigation, or irrigation, and 3) evaluate the economic benefit of the existing dams. The findings of this study will demonstrate the importance of a dam safety initiative, inform the community of dam-related risks, and build momentum for a state-wide dam safety program: to prevent catastrophic loss of life and property.

In the next section, Data and Methods, the NID database, and the methods for the economic assessment of the marginal cost of water use are introduced. The cumulative maximum storage capacities of the total dams and the dams with the four purposes (recreation, navigation, irrigation, and domestic use) and their potential economic benefits are reported in the following section, Results. The economy of Alabama is briefly introduced in the Results section to help readers understand the relative size of the economic value of the existing dams in A.L. to the state economy. In the Discussion, the cost of recovery in the event of a failure of the Lake Tuscaloosa Dam is estimated and compared with the economy of Alabama. In the section Conclusion, our findings from the economic assessment of the dams in AL are summarized and some suggestions for building more resilience to potential dam crises for Alabamian communities are discussed.

## 3.2. Data and Methods

A comprehensive dam safety policy faces a challenge due to incomplete information about the existing dams in Alabama. Alabama's lack of legislation to maintain, inspect, and inventory the dams means the only source of publicly available information on the dams comes from the NID database. Following (Public Law No: 113-121) the Water Resources Development Act of 2018 (H. R. 8), USACE produces a biennial report to Congress on the status of America's dams.

The NID includes dams that meet at least one of the following four criteria: 1) high hazard potential classification (loss of human life is likely in the event of failure); 2) significant hazard potential classification (no loss of life but other concerns such as economic loss, environmental damage, disruption to lifeline services); 3) greater than or equal to 25 feet high and greater than 15 acre-feet of storage; 4) greater than or equal to 50 acre-feet of storage and greater than 6 feet high (USACE, 2015). The NID provides detailed information about the physical characteristics of each dam including the length, width, and maximum storage capacity, as well as the hazard potential based on the geographic location.

Information for 2,273 dams in Alabama was obtained from the NID website. The USACE made the NID data downloadable from the webpage beginning in January 2019. The annual accumulated water storage capacities were compiled for over 200 years, from 1800 through 2016, to assess the amount of water dammed in the state over time. Then the cumulative storage overtime was subdivided by primary purpose to depict both how that stored water is functioning and which types of dam functions provide the most economic benefit to Alabamians based on the marginal cost of water use. It is worth noting that there is an additional volume of 13,767 acre-feet not represented due to a missing year of complete information and 75 dams with no reported storage in the 2018 NID database.

To assess the economic value of the existing dams in Alabama, this study follows the methodologies of (Frederick et al., 1996). Their study sought to place a monetary value, per acre-foot of volume, on freshwater sources based on the purpose they served. This method was also used in the (Graf, 1999) census of dams for the national-scale economic assessment of the entire NID database, including 75,187 dams while the 2018 NID database has 91,468. In this study, the economic values of the dams in Alabama are accessed following the estimates of the marginal cost of water use from (Frederick et al., 1996) and the methods of (Graf, 1999). However, this study conducts the sensitivity test of the marginal cost of water use to the economic benefits from the dams in Alabama using different marginal costs of water use for other regions that were provided by (Frederick et al., 1996).

The results for the value of freshwater by purpose were then applied to the relevant dams and adjusted for inflation using the Bureau of Labor's Consumer Price Index (CPI) calculator (https://www.bls.gov/news.release/cpi.toc.htm for January 2019). It is worth noting that water often serves multiple purposes, but for the sake of this paper, only the primary purposes were considered, which leads to a conservative assessment. This paper examines the economic values using the marginal cost of water use based on the main region encompassing the state (the South

Atlantic Gulf region), as well as values nationally and for the following three regions of interest. The Mid-Atlantic and Ohio regions were selected for their relatively high value of freshwater used in irrigation and navigation, respectively. The Texas-Gulf region was included for its lower values. This sensitivity analysis of the marginal cost of water use will provide the upper and lower boundaries of the economic values of Alabama's dams.

Lastly, a case study of the Lake Tuscaloosa Dam was examined to estimate the recovery cost due to potential reconstruction costs after a dam breach or failure. The final construction cost was over $7 million in 1970 (Our Great Lake, 2008). A comparison was made to reconstruction costs on a dam that experienced a partial degree of failure, the Lake Oroville Dam spillways in February 2017 (Vano et al., 2019).

## 3.3. Results and Discussions

### 3.3.1. Accumulated Storage Capacity of the Dams in Alabama (AL)

The annual total cumulative storage of dams is calculated to visualize the quantity of water stored by the dams and reservoirs (Figure 3-1). The annual cumulative storage of dams is computed by the completion year of dam construction. The water storage in acre-feet is accumulated from 1800 to 2011 since there has been no dam construction since 2011. Based on the NID database, the total storage in the state hovers around 14 million acre-feet, equivalent to over 4.5 trillion gallons of water. This volume can fill the entire state with ½-foot of water (Area of Alabama: 52,419 squared miles (33.6 million acres)). The average storage of the 2,273 dams in Alabama is 6,159 acre-feet. From 1961 to 1965, the dams built during this time added an appreciable amount of the total cumulative storage by 5.3 million acre-feet (4.7 million acre-feet in 1960 and 10 million acre-feet in 1965). In 1926, 1939, and 1983, there were other significant increases in the maximum cumulative storage. The most massive jumps in storage occurred more than 40 years ago, indicating that much of the water (about 4 of the 4.5 trillion gallons) is behind infrastructure that is nearing or past its design life. Older dams require further attention due to a heightened risk of failure, meaning that the number of vital inspections and necessary EAPs will increase substantially in the coming years.

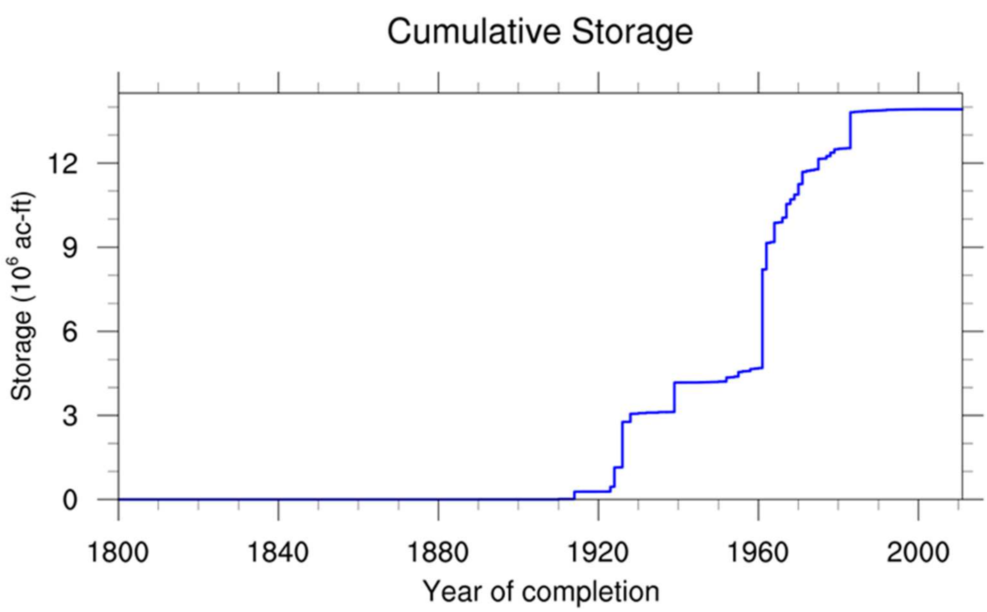


Figure 3-1. Cumulative storage of the total dams from 1800 to 2011.

### 3.3.2. Cumulative Storage: Recreation, Navigation, Fish and Wildlife Pond, and Irrigation

In the state of Alabama, there are only twelve dams for the primary purpose of navigation, but it accounts for about half of the total accumulative storage (about 1.5 million acre-feet). The average size of their storage is 0.13 million acre-feet. They represent a significant portion of the stored water in the state. Navigation also presents an excellent model for high-value dams; each of them has an EAP in place. Dollar values for navigational use are also included in the economic assessment. Figure 3-2 below shows the cumulative storage over time for navigation. These 11 major navigational dams have emergency action plans in place due to their economic significance and the risk to the downstream population and environment.

Recreation and Fish & Wildlife Habitat represent the first (1,034) and second (755) largest proportions of dams in the state by number. These two primary uses are also of interest because they are evaluated in (Frederick et al., 1996). The total cumulative storage for Recreation and Fish and Wildlife Pond, respectively, in Figures 3-2 (b) and (c). Recreational dams contribute to the spike in storage shown in the 1960s, and dams to create habitats for fish and wildlife contribute to the jump in the 1980s (see Figure 3-1). Outdoor recreation is a vital part of the cultural fabric of Alabama, and so these dams are very important for the wellbeing of residents in the state, as evidenced by the number of such dams in addition to the revenue they generate.

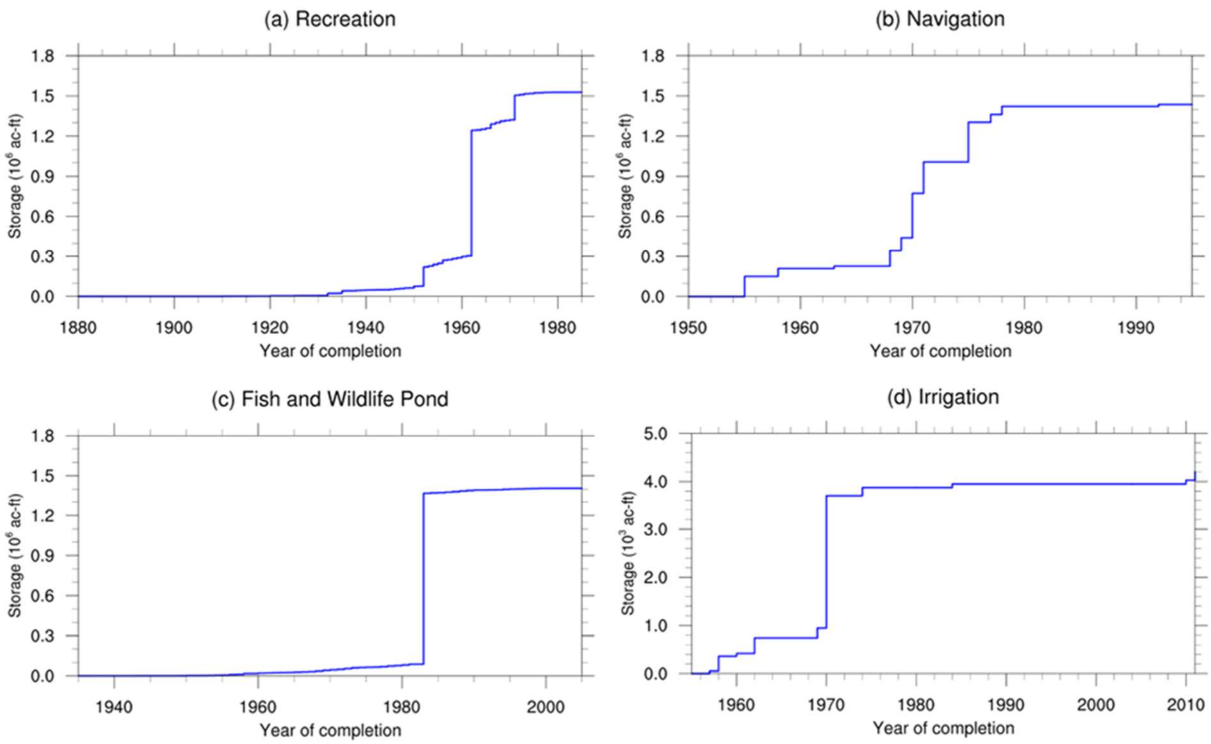


Figure 3-2. Cumulative storage of the dams for Recreation, Navigation, Fish and Wildlife Pond, and Irrigation.

The last applicable value in the economic assessment is for the purpose of irrigation. Though irrigation is not a widespread purpose for dams (20), it is considered primarily because of the growth potential. Irrigation is an increasingly popular agricultural process to provide sustainable water resources and is an effective option for water use diversification in the existing dams and reservoirs over Alabama. The accumulation of storage for irrigation is shown in Figure 3-2 (d). Irrigation is under-utilized in the state because of the absence of state water law, and that is reflected in the potential benefit in the future. However, there has been much discussion surrounding irrigation practices in Alabama, intending to improve agricultural productivity. It is worth noting that if there were to be an increase in the use of reservoirs for irrigation, the economic benefit would increase, as evidenced by the greater worth of irrigation in places with higher utilization.

### 3.3.3. The Economy of Alabama

According to Federal Reserve Economic Data (FRED) for 2019 (Fred Economic Data, 2019), the estimated population of AL is close to five million, which ranks 24th among the U.S. states. The growth rate of the population is at 0.26 percent a year, making it the 36th fastest-growing state. Along with the increasing pattern of population, population density has also been increased. There are 94.4 people per square mile (36 per square kilometer) over a total surface area of 52,420 square miles, which ranks Alabama 27th in population density in the United States. For the Gross Domestic Product (GDP) for Alabama, $181 billion represents 1.11 percent of the total US GDP, which is ranked in the 27th place among the U.S. states in 2016 (Fred Economic Data, 2019). Another useful economic indicator could be GDP per capita (GDP per person). GDP per capita is a significant index of economic status to compare the average living standard and level of the economy. Based on the reported population and GDP, the GDP per capita is $36,200 ($181 billion divided by 5 million residents), which is ranked 44 out of the 50 States.

The primary industries of Alabama have been diversified and growing recently. According to the Economic Development Partnership of Alabama (2010–2017), high growth industries are included: administrative and waste services (20.7%), accommodation and food services (19.1%), arts, entertainment, and recreation (16.3%), transportation and warehousing (15.7%) and manufacturing (10.6%). Alabama has key industries, which shore up the parts of the economy rapidly, such as aerospace, automotive, and chemical. Alabama is ranked 8th in the concentrated aviation industry with 160 more companies among the U.S states, and the automotive industry is ranked first place in terms of exporting in Alabama, including $10.7 billion in 2016. Furthermore, Alabama plays a leading role in the U.S. chemical industry. According to Alabama Power Company, the chemical industry that ranks 2nd in the field of export in Alabama produced $2.3 billion in 2016 Alabama showed a 2.2 percent increase in the industry growth rate in 2018, which is a higher rate than the national rate, 1.8 percent.

### 3.3.4. Economic Assessment of Dams in Alabama

(Frederick et al., 1996) presented value estimates for four withdrawal and four instream uses of water. The value of water varies from region to region, which illustrates differences in the amount of economic benefit a dam can serve. Table 3-1 shows the economic values for dam storage for the nation, the regions that encompass Alabama, and three regions of interest.

Table 3-1. The economic value of dam storage (USD 2019 / Acre-feet).

| Region | Recreation Fish and Wildlife | Navigation | Irrigation |
|---|---|---|---|
| National | $78.24 | $237.98 | $122.25 |
| Mid-Atlantic | $9.78 | - | $322.74 |
| Ohio | $4.89 | $787.29 | - |
| Texas-Gulf | $13.04 | - | $132.03 |
| South-Atlantic Gulf | $4.89 | $60.31 | $32.60 |

Table 3-2 shows the total economic value of dams and reservoirs in Alabama based on the cumulative storage capacity for each purpose of the existing dams and applies the cumulative storage to the values for the other regions. This economic assessment with different regional costs enhances our understanding of how the value of water varies over space. Both the value of water as a whole and the value of water by use are subject to variation, as illustrated below. The potential economic values of the water stored by the dams from recreation, navigation, and irrigation ranges from \$0.58 billion (\$23.4 millions (recreation) + \$556.8 millions (navigation) + \$0.9 million (irrigation)) to \$11 billion (\$3.7 billions (recreation) + \$1.8 billions (navigation) + \$2.3 million (irrigation)). The ranges of the potential values are equivalent to 0.3% to 6% of the GDP of Alabama, \$181 billion, reported in the previous section.

Table 3-2. The total economic value of dams and reservoirs in Alabama.

| Region | Recreation Fish and Wildlife | Navigation | Irrigation |
|---|---|---|---|
| National | \$3,748,662,230 | \$556,794,524 | \$898,896 |
| Mid-Atlantic | \$46,858,279 | - | \$2,373,085 |
| Ohio | \$23,429,139 | \$1,841,998,322 | - |
| Texas-Gulf | \$62,477,705 | - | \$970,807 |
| South-Atlantic Gulf | \$23,429,139 | \$141,105,462 | \$239,706 |

There are almost 70 more dams that provide domestic water as a secondary purpose, and they serve as a model to maximize dam benefits through water use diversification. (Frederick et al., 1996) also reviewed the benefit of water for domestic supply use. Here, this study estimates the potential economic value of water for domestic use. The marginal cost of water for domestic use for the South Atlantic Gulf is a region that had been reported in (Frederick et al., 1996). In 1996, the marginal value of water for domestic supply was $37/acre-feet, and after adjusting for inflation, $60.31 in 2019. Over the state of Alabama, there are 36 dams primarily for water supply storing 43,250 acre-feet. These dams provide an economic benefit of around two million dollars. With recent population and economic growth, domestic supply becomes a higher use of water, and thus dams in the state will provide critical water resources to meet water demand for domestic use.

### 3.3.5. Impacts of Potential Dam Failure on Vulnerable Counties in Alabama

Alabama is one of the states that belong to the Southeast RFC region which is the highest risk region where dam-related potential hazard and the region includes the parts of the black belts that refer to low rank of quality of life in terms of poverty and education. The 18 counties of Alabama (red-colored counties) are not only involved in the black belt area but also categorized as poor and vulnerable counties (Figure 3-3).

To compare the dam failure impacts between the vulnerable and invulnerable counties, this study applied the median household income rate (2019) and 2018 NID database to identify the ranks of the county in Alabama.

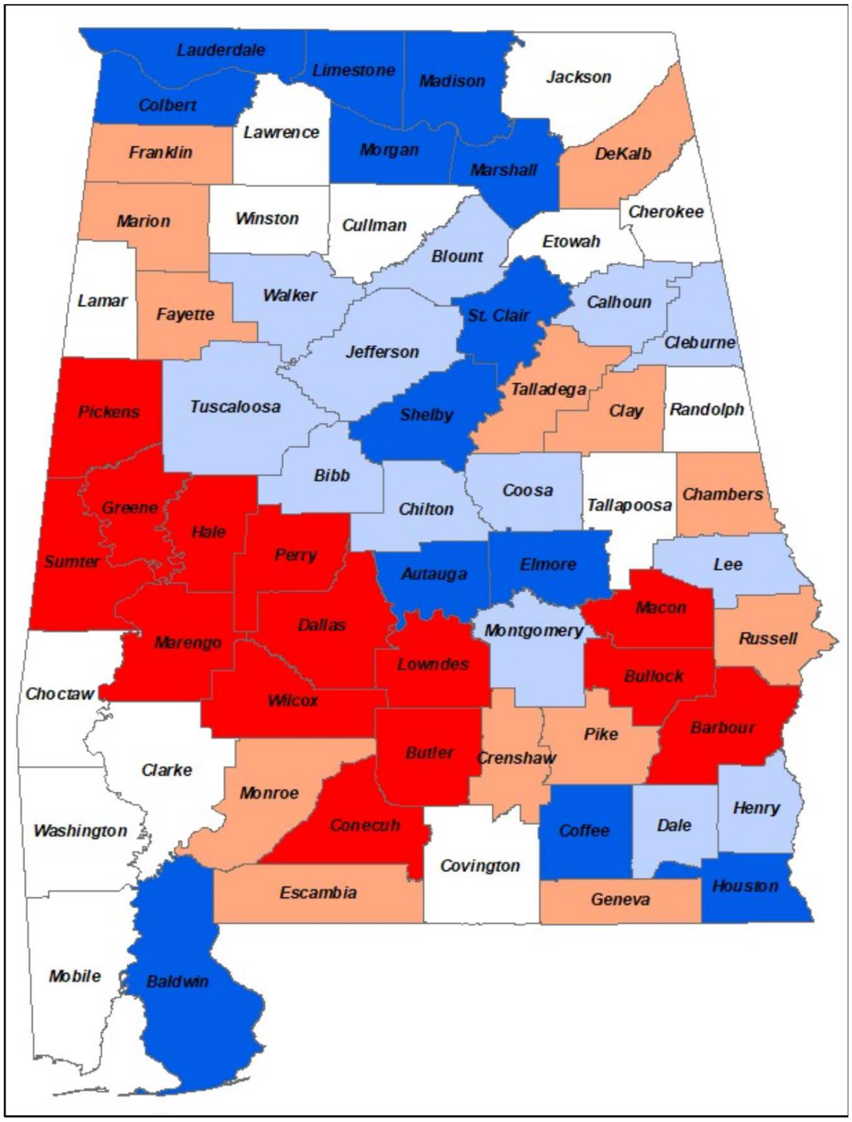


Figure 3-3. A map of vulnerability for the counties in the state of Alabama.

The selected counties are matched with the black belts, and figure 3-3 shows that the counties imply that the lowest quality in not only economics but also the potential hazard of dams. In order to evaluate potential economics and hazards, the assumptions that (1) there would be severe impacts on potential economic losses and (2) flood damage for potential hazards due to dam failures in vulnerable counties are considered while the opposite assumptions are applied to wealthy counties. For the two types of the county, such as vulnerable and wealthy, twenty dams are selected based on the absence of EAP and hazard levels (high and significant) for each of them.

Results of the twenty dams in vulnerable counties show lots of pond-type dams, that are small-scale dams, due to the fact that low economic level and poor preparation for dam-related disasters. Therefore, the potential impacts of dam failure-driven floods are comparatively lower in reality. In the vulnerable counties (red-colored counties in Figure 3-3), 304 out of 868 (35%) dams are required to have EAP for dam safety, and only six dams (1.9%) have EAP while the rest of dams (63%) in the black belt region are not required to have EAP for safety. From the dams that are required EAP in the areas, high and significant hazards dams account for 7.8 and 92.2 percentages, respectively.

In order to evaluate potential economic losses, property damages by dam failure-driven flood inundation are calculated as an example for improving public awareness, using the HEC-RAS model and real estate data from Zillow. Through the flood maps from the HEC-RAS, the costs of the property damages applied to inundated locations using the federal guidelines of water damage restoration cost (FEMA, 2015, 2021). Figure 3-4 shows that flood inundation maps of the Lawrence dam in Dallas County in AL which is categorized as a significant hazard. Two flooded houses (here, A and B) indicate that 2,130 and 1,622 sq. feet home size, 2.5 and 2.0 rooms, and $191,500 and $136,600 values, respectively. Along with those aspects, flood levels show 0.1 meters and 0.5 meters for the entire story of the houses, therefore, the estimated potential cost of the water damage restoration for houses is around $120,000 ($38,552 and $82,271 for A and B, respectively). The fatality due to dam failures is not expected since the dams are comparatively small. These findings are consistent with the rest of the 19 vulnerable counties, fortunately indicating a low exposed hazard potential of the local communities to dam failure.

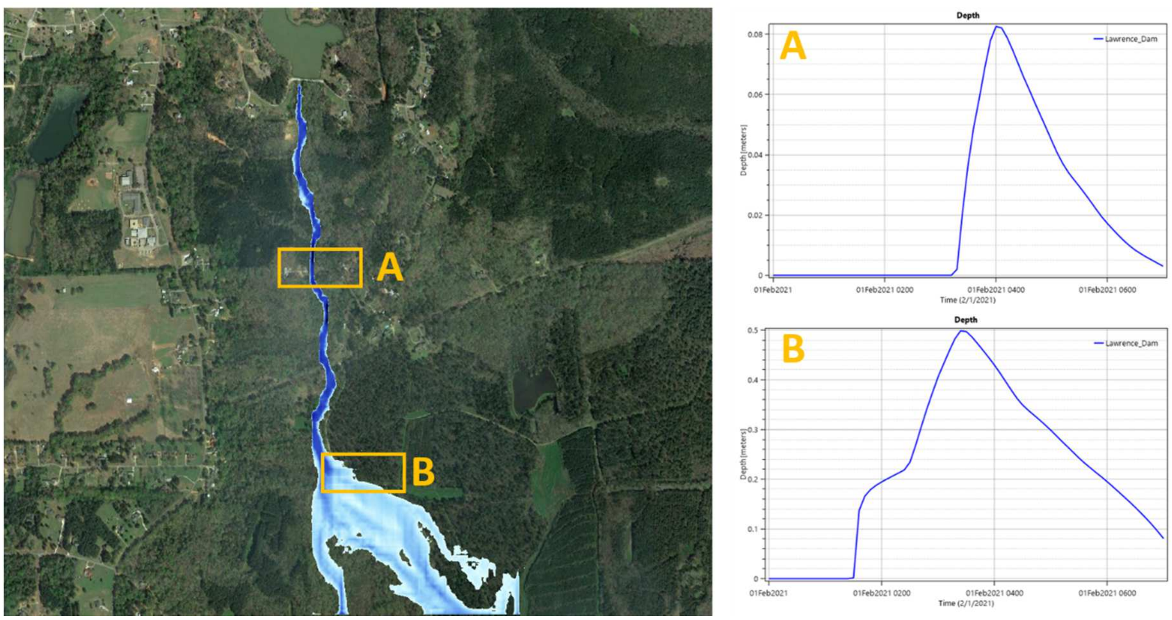

Figure 3-4. A flood map of Lawrence dam in Dallas County. A and B imply inundated locations with depth (unit: meter).

As a comparison study, the top 20 existing dams have been constructed in wealthy counties (herein, defined by Median household income, 2019). The total number of the dams in wealthy counties in this study is considered as 847 existing dams. According to the 2018 NID database, 23% of the dams are not required EAP, however, 74% of the dams (high, significant, and low potential hazards) are still required having EAPs (3% missing data) among the dams in wealthy counties. Among the 74 percentages of the EAP required dams, high and significant potential hazards account for 19.2 and 23.3 percentages, respectively. Even though the wealthy counties are assumed as well-prepared for hazard and safer than vulnerable counties based on economic standards, our results from a comparison between the percentages of vulnerable and wealthy counties show the rate of no EAPs dams is much higher in reality mainly due to more dams that EAPs require.

In order to evaluate potential economic losses, the dams that do not have EAPs, a high potential hazard, and also a large-scale storage capacity are chosen from the wealthy counties in Alabama. Figure 3-5 indicates that a flood map of the Choccolocco dam failure in Cleburne County in AL as an example case, and its volume is over 218 million cubic meters. This dam has no EAP program. An inundated house (A in Figure 3-5) is a single-family house, and the home size is 4,600 sq. feet which are equal to $394,200. In addition, a house at location B in Figure 3-5 is a single-family home with a size of 7,056 sq. feet that implies $348,860 on the search date, September 3, 2021. This house would be inundated over the two meters of flood level for the entire house. Since the flood levels in the houses at both locations are over two meters, therefore, cost of the water damage restoration would be over $789,160. However, in this case, if a house is inundated above two meters, it could not be possible to consider restoration.

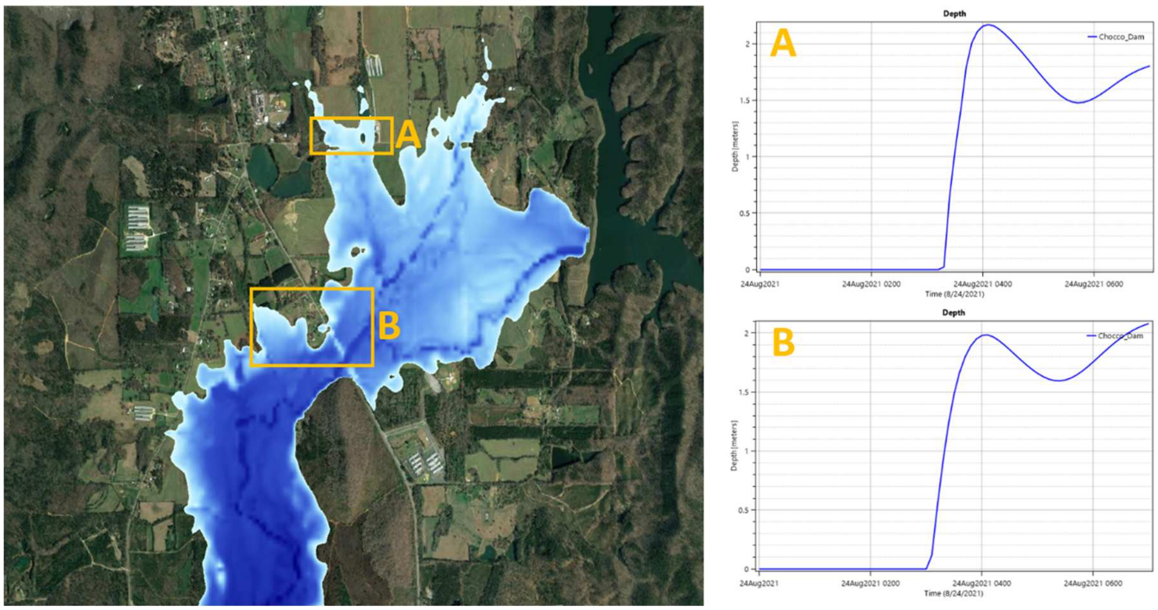


Figure 3-5. A flood map of Choccolocco dam in Cleburne County. A and B imply inundated locations with depth (unit: meter).

After the assessment of potential economic and potential hazards for the two types of counties in AL, the results indicate that due to the dam failure, flood impact, especially, property damage could not be ignored, and the entire cost of property damage restoration per each flooded house could be included as an index of property losses at the stage of the recovery plan to compute potential economic loss more precisely. The results of this comparative study between vulnerable and wealthy counties could be a helpful method to increase public awareness for flood impact due to dam failure disasters. For wealthy counties, although there is enough budget that makes the counties are considered wealthy, still the dams in the wealthy counties are required EAPs for public safety. These results are also available to conduct establishing an evacuation plan for the public in disaster situations.

### 3.4. Conclusions

This study succeeds to quantify the potential financial risk the state takes on as a potential consequence of its current lack of dam safety legislation. The data analysis shows multiple aspects of the economics of dams in Alabama. By focusing on both the value functioning dams provide, and the subsequent cost of the loss of that benefit in the event of a failure, and the cost to reconstruct the infrastructure, this paper seeks to show the full picture. A helpful example of water use diversification is the use of dammed water for domestic supply purposes. Though it is a withdrawal use, not instream, it is a higher use of water and is valuable at $37/acre-foot of storage in the South Atlantic Gulf region. This is another source of potential value for the state, and also a source of benefit that must be protected as it is intertwined with public health and welfare.

This study is the first economic assessment of the value of dams in the state of Alabama and was done to raise awareness of the financial scope of the problem. There are 2,273 dams across the state that have been characterized at some level of potential economic benefits, leaving Alabama vulnerable to large economic losses compounded by the steep recovery costs and the loss of economic benefits. The combined economic benefit of dams for recreation, fish & wildlife, navigation, irrigation, and domestic water supply ranges between $0.6 billion and 11 billion. These estimates do not include the value from the secondary and other purposes of dams or the value from other uses not covered.

This assessment advances the conversation on dam safety in the state by illuminating an area of risk that has not been previously studied. By quantifying the value of dam and reservoir resources, and discussing the cost of failure, this paper seeks to change perceptions by showing that inaction is costlier and more burdensome than regulation, and thereby promoting action on dam safety. A further economic assessment of dams in Alabama must include considerations of the cost of rebuilding in the wake of a failure event. Dams serve an essential purpose, and in many cases would have to be reconstructed. Take the Lake Tuscaloosa Dam, for example, the reservoir supplies drinking water to the city of Tuscaloosa and much of the county, which is a service that would need to be restored. There is also the emergency response and disruption to service cost that must be considered. Lake Tuscaloosa Dam supplies a single-access road crucial for local traffic to reach the town. A breach in the dam would disrupt accessibility for many citizens. Even one failure in Alabama would produce an expensive bill for the state, even in cases that will take more time to recover from a dam failure. With federal financial aid, the development of a comprehensive dam safety program in Alabama is our best course of action to mitigate this risk and build a safer environment.

This study aimed to overcome the obstacle from the limited knowledge about economic benefits and perceived risk from the existing dams in AL and succeeded to quantify their benefits and risk at the state level. The most recent attempt to introduce dam safety legislation occurred in 2014, but the state legislature opted not to take action on the bill that would establish a program under ADECA - Office of Water Resources. The state representative who sponsored the bill stated that the problem was, “People in Alabama do not want more regulations” (Sharp, 2014). In a 2018 follow-up, the discussion surrounding dam safety regulations had not changed. Insufficient political will, fear of big government in terms of higher taxes, increased regulation, and the widespread lack of knowledge of the scope of the problem were the setbacks identified by the engaged stakeholders (Sheets, 2018). The findings of this study urge local politicians and non-governmental organizations to engage the initiative of the dam safety program toward a safer environment for the next generation.

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# CHAPTER 4. UTILITY OF REMOTELY OPERATED UNDERWATER VEHICLE IN FLOOD INUNDATION MAPPING FOR DAM FAILURE A CASE STUDY OF LAKE TUSCALOOSA DAM

## 4.1. Motivation

The U.S. has 90,000+ dams that have been built and their average age is over 57 years old (USACE, 2015, 2018). These aging water infrastructures are a major concern of the United States because of the potential failure of their functionality, loss of associated economic benefits, and the recovery of an affected community. The U.S. National Dam Safety Program (NDSP) of the Federal Emergency Management Agency (FEMA) provides financial and human resources to state-level governments. Despite the effort of FEMA, the level of safety and preparedness programs for these aging water infrastructures vary across the U.S. states. A recent study (Song et al., 2021) found that the 2018 National Inventory of Dams database shows various levels of the vulnerability of the exposed community to dam breaches across the U.S. states. Lack of administrative capacity and public participation, missing of political governance, and dearth of social learning can exacerbate casualties and economic losses from dam breach-driven floods (Lebel et al., 2005; Pahl-Wostl et al., 2007; Tortajada, 2010). For example, Alabama (AL) is the only state among the 49 contiguous U.S. states that does not have the state dam safety program while it has 2,000+ dams and reservoirs. Because of not participating in the national dam safety program, AL missed the limited support of federal financial and human resources from the FEMA National Dam Safety Program. The lack of federal financial aids supports results in the missing of risk and impact assessments for the existing dams. Accurate flood inundation mapping from a "hypothetic" dam failure can help communities with a high vulnerability, like AL counties, to dam failure adjust the hidden risk of the exposed hazard potential due to dam failure through visualization of the potential impacts on their communities.

Accurate high-resolution flood inundation maps for a dam breach (e.g., 30-meter resolution or higher) provide key information to quantify socioeconomic impacts on adjacent communities and improve evacuation and recovery plans. The quality of topography information is vital to estimate probable flood extent and flood wave travel time. High-resolution two-dimensional (2-D) hydrodynamic modeling has been used with the high-resolution Light Detection and Ranging (LiDAR)-based Digital Elevation Models (DEMs). Although high-resolution DEM and Triangular Irregular Networks (TIN) data from the LiDAR data provide high accuracy over terrestrial areas, the LiDAR-based DEM still includes errors over an open-water surface (Toscano et al., 2015). The LiDAR-based DEM data provides the large-scale coverage of the land surface. However, river channels are much shallower than in reality when the DEM data is directly used for flood inundation mapping. It can cause significant uncertainties in flood inundation mapping. It can be reduced directly if a costly-efficient bathymetry survey tool is available.

Previously, bathymetric data has been limitedly available particularly along coastal regions because of the inefficient cost. Recently, remotely operated underwater vehicles (ROVs) have been introduced as a cost-efficient bathymetry survey tool. ROVs have been applying to various fields, such as marine science, wreck inspection, landslide, underwater archaeology, and maritime security (Casalbore et al., 2011; Ridao et al., 2010). Previous studies used ROVs to develop dam inspection and maintenance programs that can conduct regular dam inspections without draining water in the reservoir (Hirai & Ishii, 2019; Sakagami et al., 2019), but few previous studies have examined the utility of ROVs in flood inundation mapping.

Uncertainties in flood inundation mapping are affected by the availability of bathymetry survey data, the accuracy of antecedent flow conditions, and the model physics in hydrodynamic modeling. To better understand the uncertainties in flood inundation mapping, this study conducts the sensitivity of flood inundation mapping to site-based bathymetry measurements and different initial stream conditions. Therefore, this study aims to quantify the relative importance of bathymetry survey data on flood inundation mapping to initial streamflow conditions. By answering these questions, this study will offer a new role of ROVs in the dam safety program not only for the states with a high risk of potential failure of the aging water infrastructures.

## 4.2. Data and Methods

### 4.2.1. Study Region

The state of Alabama has been a beneficiary of the existing dams, such as navigation, irrigation, and flood control. The reservoirs of the existing dams have also provided water environments for the recreational activities of Alabamians. An exemplary dam is the Lake Tuscaloosa Dam in the city of Tuscaloosa, AL near the University of Alabama main campus. In 1970, Lake Tuscaloosa Dam was built in Northport of Tuscaloosa County with the construction cost of over 14 million United States Dollars (over 93 million USD in 2020), including the purchase of about 20.2 km2 (5,000 acres) of land. Its maximum storage capacity is 180,000 acre-feet. The tailwater area of the dam is the North River and drains water into the Black Warrior River basin (Figure 4-1).


Figure 4-1. Inundated locations of the study area in the city of Tuscaloosa, Alabama during February 14-19, 2019. Pictures at A, B, C, and D letters are displayed with the corresponding letter. The red box in Tuscaloosa County (bottom-left) depicts the study area.

Since the completion of the dam construction, Lake Tuscaloosa Dam has been a landmark of the city of Tuscaloosa, creating socioeconomic benefits from industrial use and recreation for the Tuscaloosa industries and residents and navigation through the Tombigbee-Alabama River system. Despite a range of advantages, Lake Tuscaloosa Dam does not have a dam safety program, which means that it does not have a scheduled inspection of the main body and spillway since the construction completion (ASCE, 2015; Sheets, 2018; USACE, 2015, 2018). Missing the safety program for Lake Tuscaloosa Dam can worsen adverse effects on the communities along the Black Warrior River and the North River when its functionality is failed.

The city of Tuscaloosa is vulnerable to flood due to the proximity of the downtown and local economic activities to the Black Warrior River (Figure 4-1). In Tuscaloosa County, especially the Black Warrior River between downtown areas and Northport, several severe flood events have been reported since 1874 (Roger A. Pielke et al., 2002). During February 16-24, 2019, intense rainfall events caused flood inundation over the areas where the relatively lower elevations along the Black Warrior River (A, B, C, and D in Figure 4-1). In February of 2019, the city of Tuscaloosa was the highest record among the cities in the state of Alabama (National Weather Service, 2019). A better understanding of the potential hazard risk associated with Lake Tuscaloosa Dam failure is warranted for safe built-in environments.

### 4.2.2. Remotely Operated Vehicle (ROV)

In this study, an ROV, Deep Trekker DTG Smart 3 (Figure 4-2) has been applied to conduct a bathymetric survey. The ROV is connected to the remote controller with a 175-meter tether. It has a built-in High-Definition (1080p) video camera with a 270° total range view, and the user can see the underwater environment from the screen of the remote controller. It can also record a video or picture through digital video glasses (Figure 4-2C). On the screen, the information about heading direction, depth from the water surface, and the stream temperature at the water depth of the ROV are displayed. All the information is stored on a memory card in the digital video glasses as a type of video/picture file.

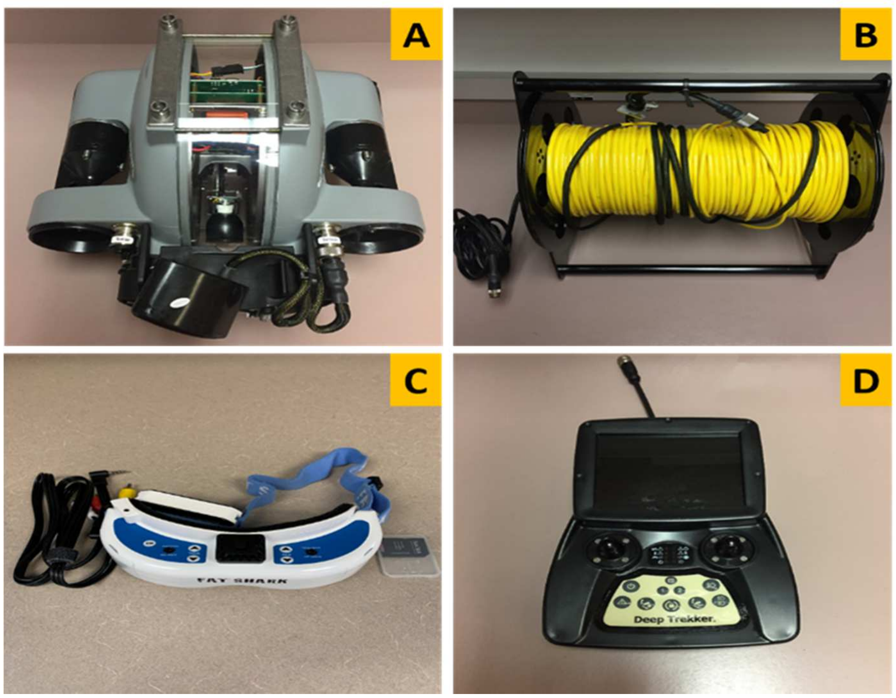

Figure 4-2. pictures of Remotely Operated Vehicle (A) and 150-meter tether wire.
C and D show goggles and a remote controller, respectively.

For the bathymetry survey, this study launched the ROV multiple times to measure the water depths along the cross-section of the Black Warrior River. It measured the water depths at the 5-meter intervals along the cross-section of the Black Warrior River from the park at the Manderson Landing (a public boat landing park) near the main campus of the University of Alabama Tuscaloosa. Before and after the heavy rain events (February 16-24, 2019) to use them as the reference water depth for dry and wet initial flow conditions. According to the FEMA guidelines for dam safety, the antecedent/initial flow conditions should be identified on flood maps (Federal Emergency Management Agency (FEMA), 2015). Along with guidelines from FEMA, this study applies three initial flow conditions, including normal, dry (e.g., before heavy rainfall event), and wet (two days after heavy rainfall event) initial conditions. Between the dry (wet) period, the river depth along the cross-section of the Black Warrior River increased by 2 meters from 7.8 to 10.9 (9.6-12.5) meters. The average of the surveyed water depths is 11 meters. To compute the elevation of the river bottom, the LiDAR-based elevation at a grid box along the river (e.g., 38.244 meters) was subtracted by 11 meters (e.g., 27.244 meters).

#### 4.2.3. Dam-Break Discharge Calculation: Hypothetic Discharge

The outbreak discharge estimation is sensitive to the geometric characteristics of the failure (e.g., the location and size) (Balloffet & Scheffler, 1982; Scott, 1977). However, having the information related to dam properties, such as inner materials, breaking patterns, and geological data is limited for security and safety issues. Therefore, this study used the weighted outbreak flow rate by the observed streamflow hydrograph during the Teton Dam breach (Figure 4-3). Teton Dam was failed in 1976 by releasing over 230,000 acre-feet of water and thus causing 11 deaths and 400 million dollars in property damage. Since the floodwater was moved and kept 70 miles downstream from the dam, the towns and parts of Idaho were inundated (Bolton Seed & Duncan, 1987). Teton Dam is an earth dam and has a storage capacity (about 290 thousand acre-feet) that is comparable to the maximum storage capacity of Lake Tuscaloosa Dam (about 180 thousand acre-feet). This study estimated the 8-hour outbreak discharge for Lake Tuscaloosa Dam by weighting the ratio of the maximum storage capacity of Lake Tuscaloosa Dam to that of Teton Dam (0.62=1.8/2.9).

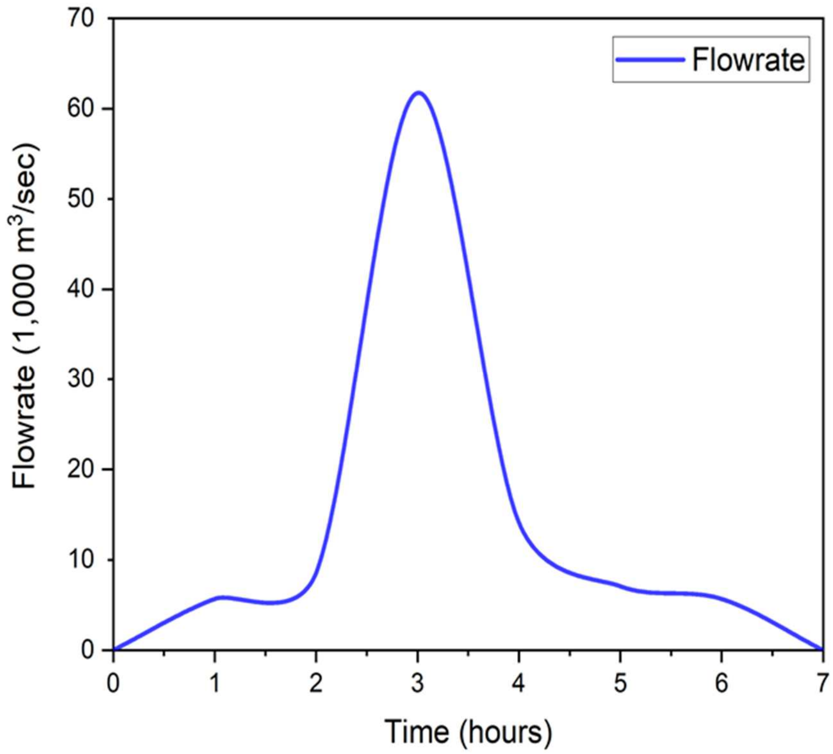


Figure 4-3. Hourly hydrograph during hypothetic dam-break discharge water for Lake Tuscaloosa Dam failure.

### 4.2.4. Parallelization of Diffusion Hydrodynamic Model Computing

Kinematic and diffusion hydrodynamic modeling is an approximation of the full dynamic modeling (the complete Saint-Venant equations). The former assumes that inertia and pressure terms are negligible as compared with the friction and gravity terms while the latter assumes that the inertia terms in the equation of motion are negligible as compared with the pressure, friction, and gravity terms (Ponce et al., 1978). Because of different assumptions, diffusion hydrodynamic modeling can account for the backwater effect while kinematic routing modeling is not able to account for this backwater effect (Hromadka et al., 1989).

Here this study selected Diffusion Hydrodynamic Model (DHM) that was developed by the United States Geological Survey (USGS) in 1987 (Theodore V. Hromadka II & Chung-cheng Yen, 1987). Previously, 2D hydrodynamic diffusion models require a long time to complete simulations (Lamb et al., 2009). High-resolution flood inundation mapping from diffusion hydrodynamic modeling requires efficient computational coding over a large area. For the efficient computation of the 30-meter resolution flood mapping, this study parallelized the USGS DHM code and coupled it with the two-dimensional overland and one-dimensional open-channel flow.

This study conducted the sensitivity test of the computational time to different numbers of processors (Figure 4-4). This study found that the computational times of the pDHM runs were reduced overall by 80% through parallelized coding. It is worth noting that the pDHM model runs with the deep-water channel depth show slight a short computational time compared with the pDHM model runs with the shallow water channel depth. The results found that the performance is non-linear along with the increased number of processors. For example, the computational time of the pDHM run with 4 processors decreased by over 50% of that of the pDHM with 2 processors and the computational time decreased by 20% from the pDHM runs with 16 processors to that with 32 processors.

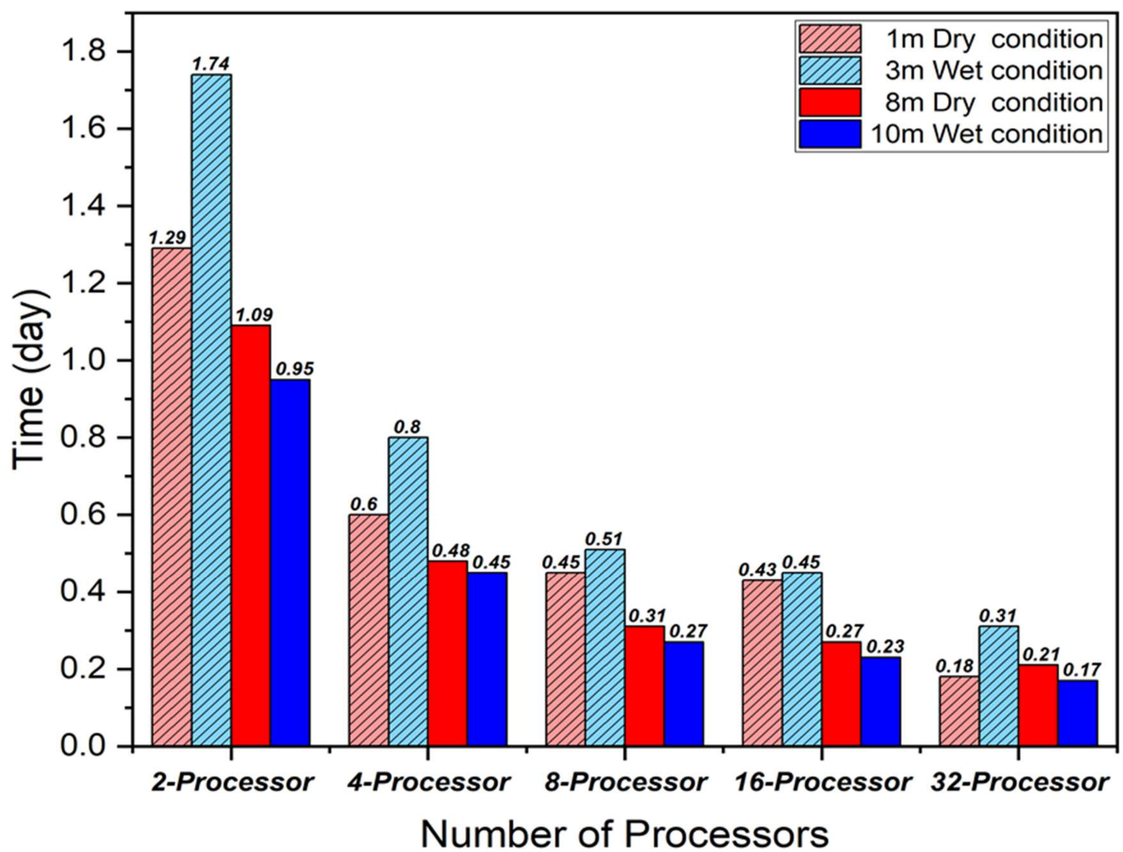


Figure 4-4. Sensitivity test of the computational time to the number of processors used in the pDHM simulations (unit: day).

### 4.2.5. The pDHM Experiment Simulations

This study conducted a sensitivity test of the pDHM to river channel depth and initial flow conditions (Figure 4-5). This study used the 30-meter DEM data for the pDHM simulation over the study region that includes 22,500 grid cells over the downstream regions from Lake Tuscaloosa Dam. This study used 0.05 for Manning's roughness coefficient, which is a typical number for light brush and weeds (Arcement & Schneider, 1989). It is worth noting that the selection of Manning's roughness coefficient plays a minor role in dam breach-driven flood mapping due to extreme flow rates after dam breach (Gallegos et al., 2009). This study focused on a dam failure-driven river flood inundation mapping and therefore a precipitation event is not considered in the pDHM simulation.

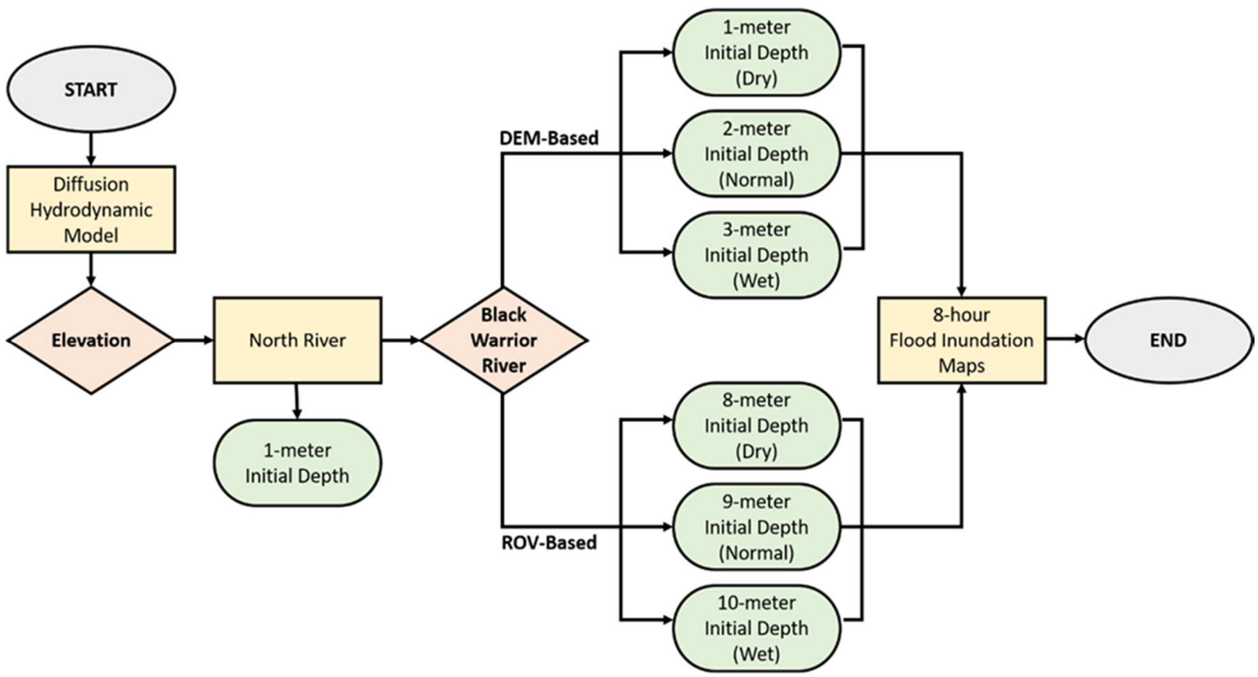


Figure 4-5. Flowchart of the sensitivity test of the pDHM simulations to the initial flow condition and the river depth.

In the pDHM simulations, the ROV-based river channel depth of the normal flow condition was set at nine meters from the ROV's bathymetry survey while the DEM-based river channel depths were set at two meters from the elevation differences between the two rivers and adjacent areas. The sensitivity test consists of the six pDHM runs with a combination of DEM- and ROV-based river channel depths and three initial flow conditions (e.g., dry, normal, and wet flow conditions).

## 4.3. Results and Discussions

### 4.3.1. Sensitivity of Flood Inundation Mapping to Flow Conditions

Figure 4-6 shows flood inundation maps from pDHM simulations with 1-meter and 3-meter initial depth conditions at 1-hour, 3-hour, and 5-hour after the "hypothetic" failure of Lake Tuscaloosa Dam. After the peak flow is released at the dam-breaking hour (3 hours after the first-timestep of the pDHM simulation), the inundated areas along the North River and downstream of the Black Warrior River are developed. The flood inundation maps at 5-hour after the dam failure (E and F in Figure 4-6) show that the flood inundated areas are rapidly extended to the Rice Mines Road for the case of the wet initial flow condition (that is, the initial water depth is 3 meter) while the dry initial condition (the 1-meter water depth) shows no significant flood inundation. At the 8-hour time step of the simulation, the maximum of flood-inundated areas is 2.8 km2 (692 acres; 3,117 grid cells), 3.0 km2 (740 acres; 3,373 grid cells), and 3.2 km2 (790 acres; 3,549 grid cells). The maximum water depths over the inundated area are 4.18, 4.19, and 4.27 meters for 1-meter, 2-meter, and 3-meter initial flow conditions, respectively.

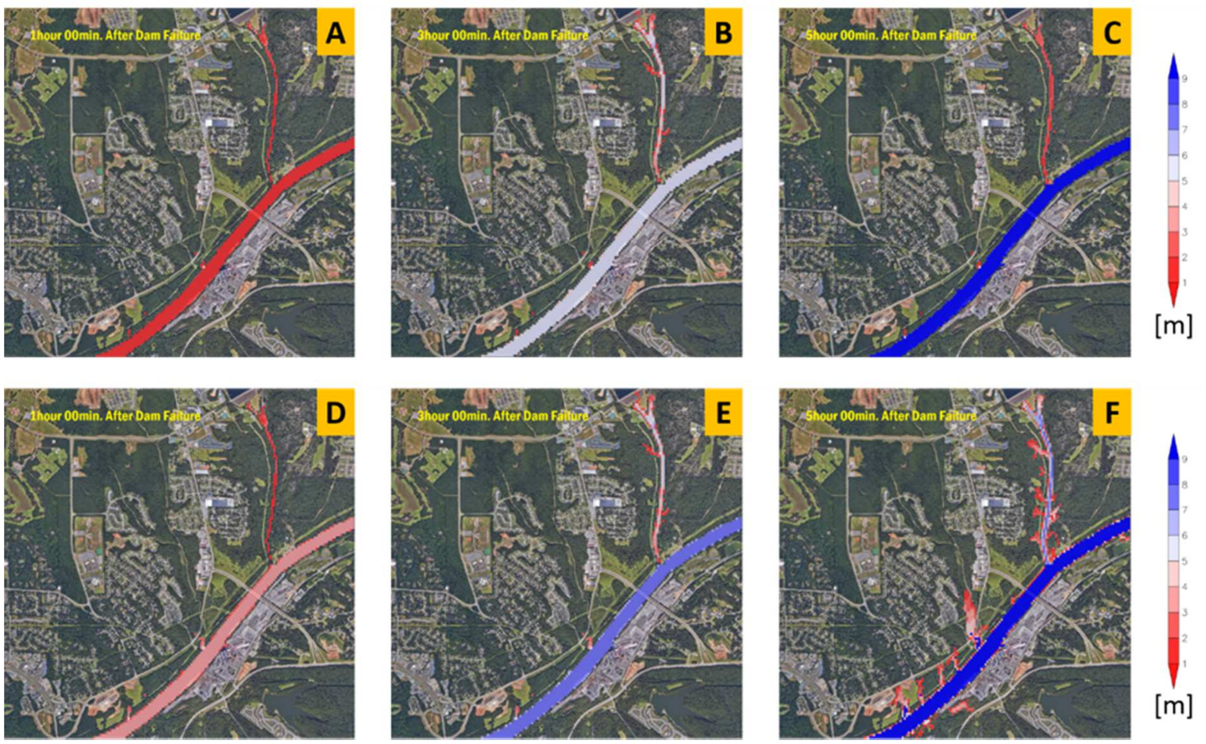

Figure 4-6. Flood inundation maps at one (A and D), three (B and E), and five (C and F) hours after Lake Tuscaloosa Dam break with 1-meter (top) and 3-meter (bottom) initial conditions. The color bar depicts the water depths of the inundated area in the unit of meters.

The ROV-based pDHM runs show different spatial patterns of flood inundated areas from the flood inundation maps from the DEM-based pDHM runs (Figure 4-7). From the ROV-based pDHM simulation, the water depths along Black Warrior River significantly increased one hour after the dam break. Three hours after dam failure, the inundated extent and the depths of the North River show a rapid increase of the water depth from one meter to seven meters, and the water depth is above nine meters along Black Warrior River. Three hours after the dam breach, the flood inundation occurs at the confluence area of Black Warrior and North Rivers. The maximum water depth and flood inundated area are not significantly affected by the initial flow condition. The maximum water depths are 7.41, 7.32, and 7.21 meters for the 8-, 9-, and 10-meter initial conditions, respectively. The inundated areas are 3.0, 3.1, and 3.22 km2 for 8-, 9-, and 10-meter initial conditions, respectively.

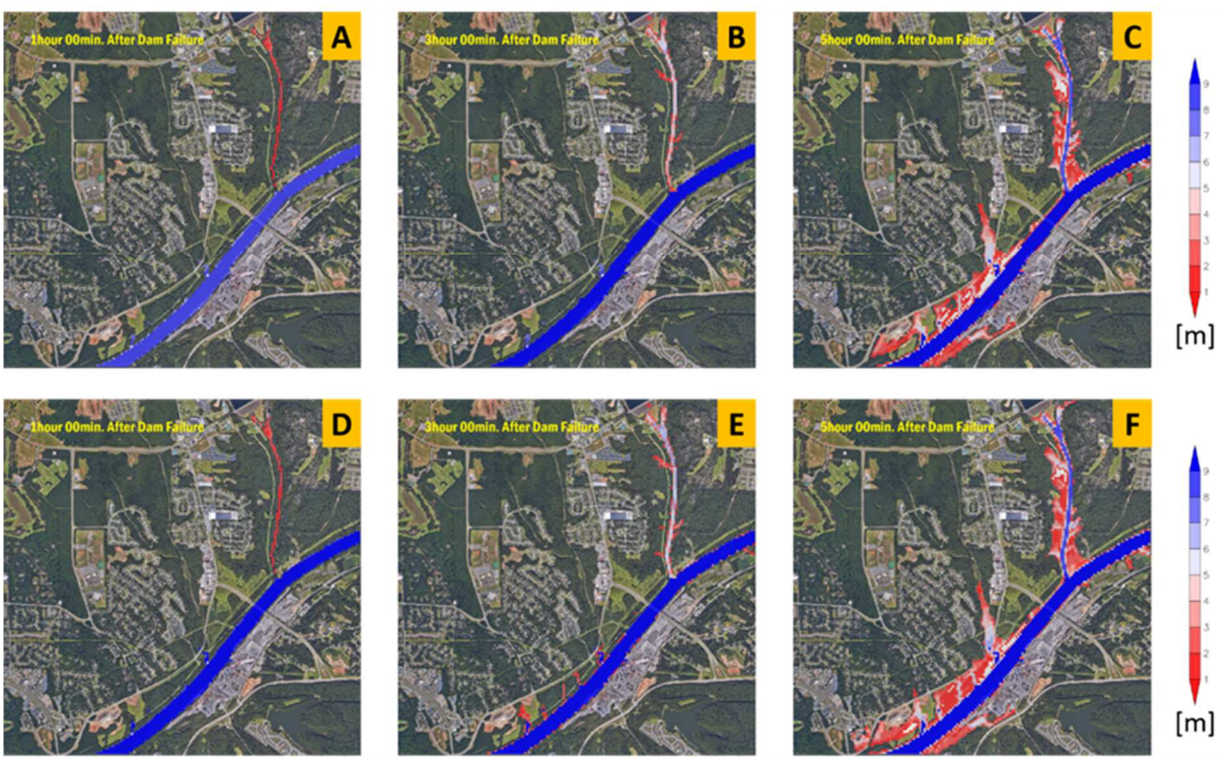


Figure 4-7. Same as Figure 4-6, except for the 8-meter and 10-meter initial conditions (top and bottom, respectively).

Table 4-1 shows the flood depths at the four locations eight hours after the dam breach. The flood inundation maps from the DEM-based pDHM with the normal flow condition show that the flood depths around the Rice Mine Road range from 4.9 to 6.3 meters. The ROV-based pDHM runs show significantly increased water depth (12-16 meters) over the residential and commercial areas to Black Warrior River (C in Figure 4-1). The result indicates that the DEM-based pDHM runs underestimate the flood inundation depths compared to the ROV-based pDHM runs, regardless of the initial river conditions.

Table 4-1. The depths in different locations at the eight hours after the dam breach.

| Locations | Without-ROV, DEM | | | With-ROV, Bathymetry | | |
|---|---|---|---|---|---|---|
| | 1-meter | 2-meter | 3-meter | 8-meter | 9-meter | 10-meter |
| Upstream (A) | 3.181 | 3.493 | 0.492 | 0.794 | 0.981 | 1.147 |
| Rice Mine (B) | 4.885 | 5.196 | 6.319 | 5.214 | 5.4 | 5.566 |
| Downstream (C) | 1.981 | 2.296 | 6.096 | 18.184 | 18.349 | 18.519 |
| Nucor Steel (D) | 0.291 | 0.602 | 0.983 | 0.708 | 0.894 | 1.059 |

The DEM- and ROV-based pDHM runs show different dynamic patterns of the maximum depth over the study region (Figure 4-8). In general, both DEM- and ROV-based pDHM runs showed that the maximum depth within the study region was significantly increased three hours after the dam failure. The DEM-based pDHM runs with three initial flow conditions showed a similar growth pattern until three hours after the dam failure, but the time to reach the maximum depth of the entire simulation was shorter in the wet initial flow condition (3-meter initial water depth) run (4.5 hours after the dam failure) than the time in the dry and normal initial flow condition (5.5 or 6.5 hours, respectively). The ROV-based pDHM runs with three initial flow conditions showed a similar growth pattern over time, resulting in the same time to reach the maximum depth of the entire simulation five hours after the dam failure.

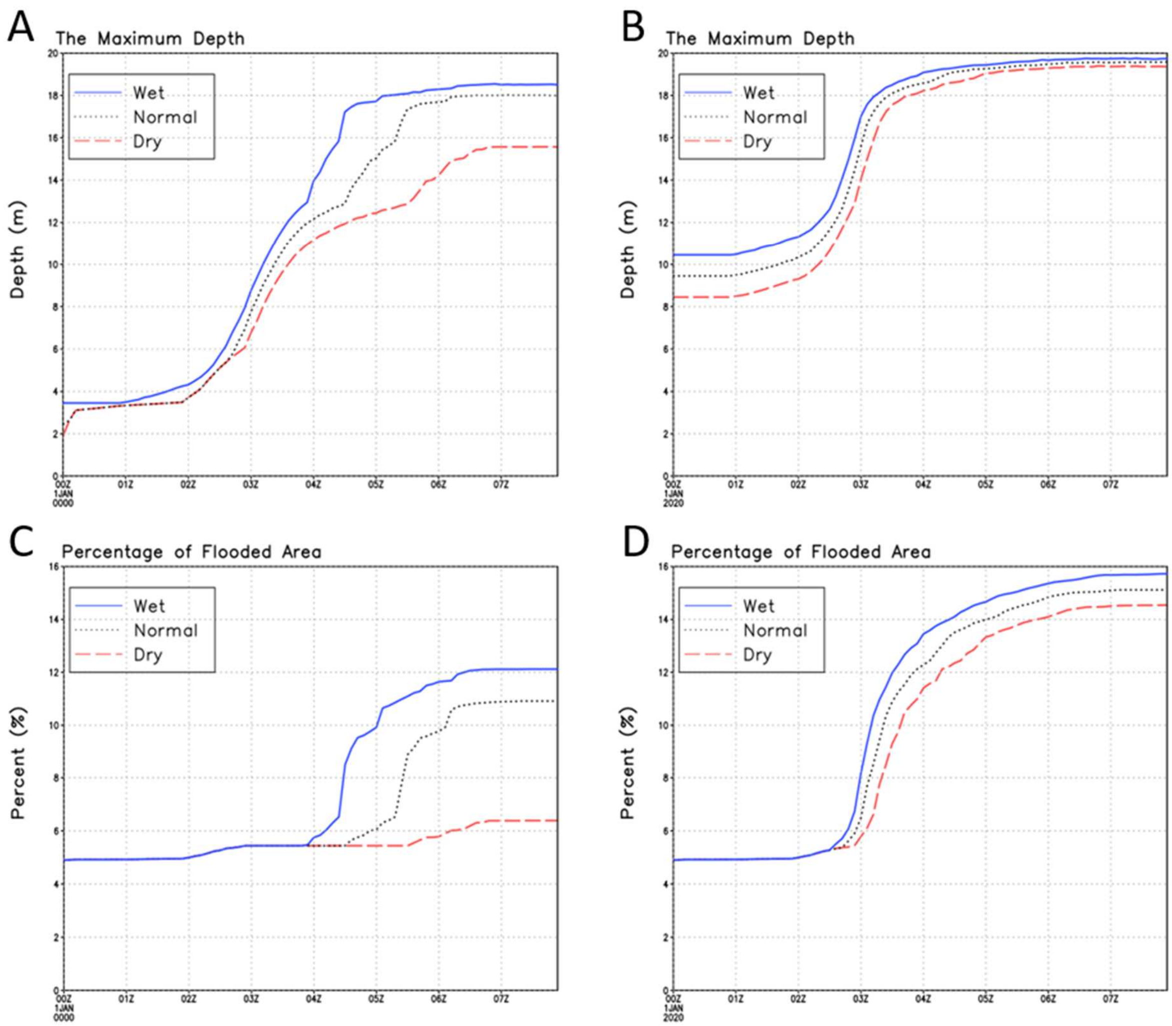


Figure 4-8. Maximum flood depth (A and B) over the study area and the percentage of the flooded area (C and D) for DEM-based (A and C) and ROV-based (B and D) pDHM simulations.

From the beginning of the dam failure to the peak period, the DEM-based pDHM runs show no change of the areal fraction of inundation (Figure 4-8). However, the time to reach the maximum inundated areas of the entire simulation is various four hours after the dam break. The maximum inundated areas from the DEM-based runs are 6%, 10.4%, and 12% of the study area for 1-, 2-, and 3-meter condition runs, respectively. The ROV-based runs show that around 2.5 hours after the dam failure, all the cases show a rapid increasing pattern regardless of antecedent flow conditions. The results indicate that the hydrodynamic modeling with a shallow river channel would have a delayed hydrologic response (herein, 30-minute delay) than the modeling with a deep river channel, which is important information to develop an effective and efficient evacuation plan during the emergence of a dam failure.

Figures 4-9 and 4-10 show the simulated water depths from the DEM- and ROV-based pDHM, respectively, with different initial flow conditions (dry, normal, and wet) over the eight-hour simulations after the dam breach at the four different locations (Figure 4-1 A-D). DEM-based pDHM runs with the normal and wet initial flow conditions showed that the water depths were increased up to three to four meters four hours after the dam breach. The DEM-based pDHM runs with the dry initial flow condition showed a rapidly increasing pattern of water depths at Locations B and C where their elevations are relatively lower than the surrounding. These relatively low elevations at Locations B and C might result in flood inundation even given the dry initial flow condition. However, the ROV-based pDHM runs showed that the increasing patterns of water depths are similar, regardless of the initial flow conditions (Figure 4-10).

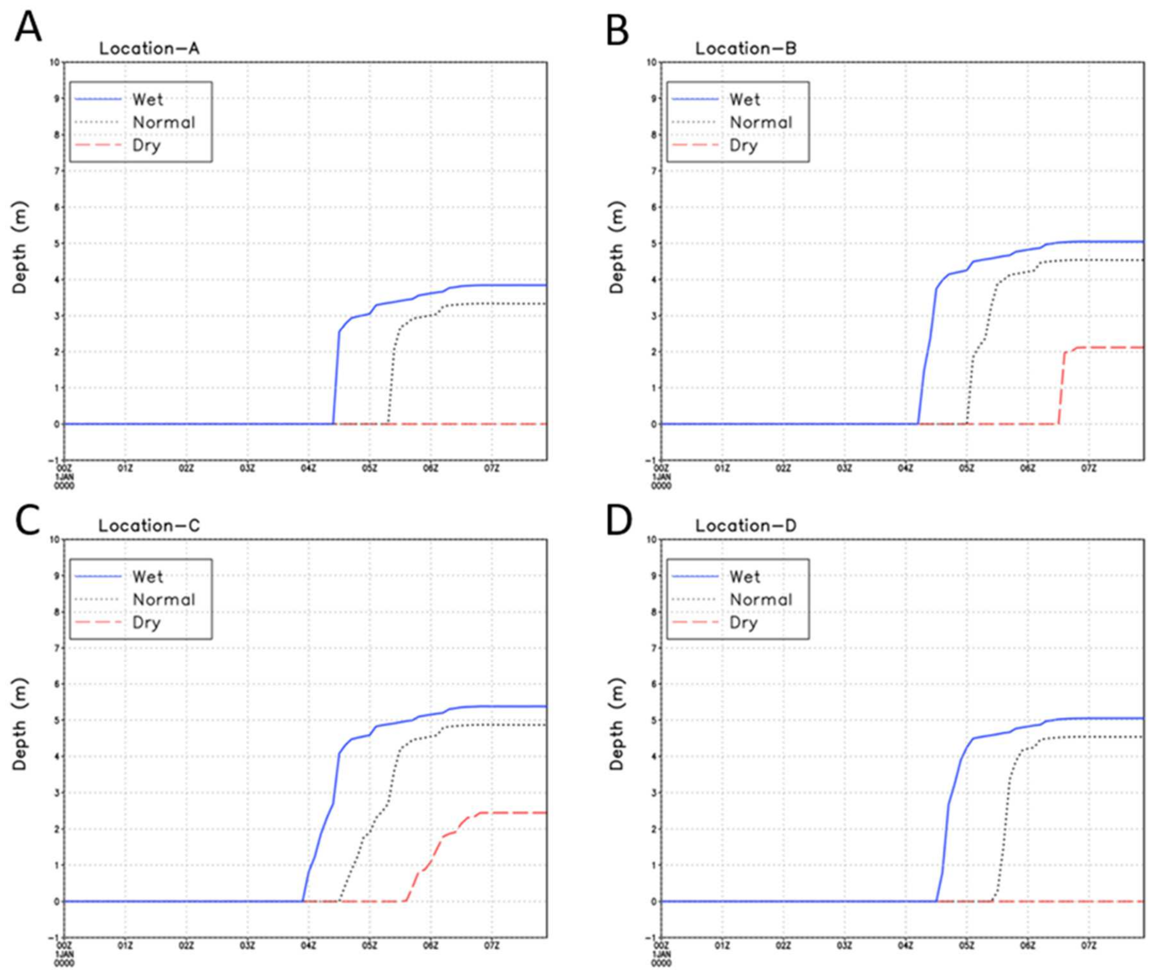


Figure 4-9. A comparison of the flood depth at the four locations (A, B, C, and D in Figure 4-1) from the DEM-based pDHM simulations with the wet (blue solid lines), normal (gray dotted lines), and dry (red dash lines) initial flow condition.

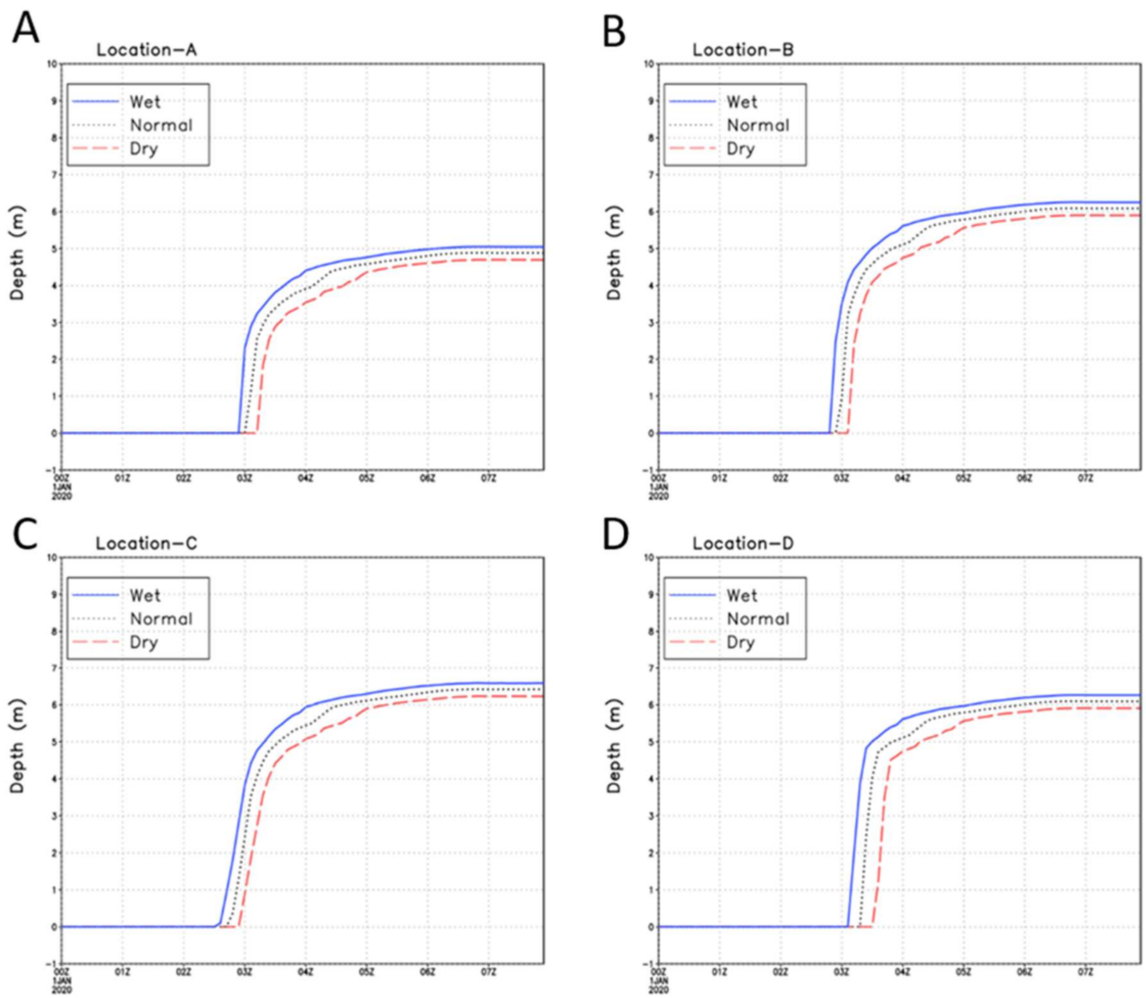

Figure 4-10. Same as Figure 4-9, except for the ROV-based pDHM simulations.

Figure 4-11 shows the map for flood inundation frequencies from the DEM-based and ROV-based pDHM simulations with the wet initial flow condition to visualize the maximum frequencies of flood inundation among the DEM-based and ROV-based pDHM simulations. This study computed the frequency of flood inundation at each grid by the ratio of the number of the time steps when a grid cell is inundated to the number of the total time step (480 = 8 hours * 60 minutes/hour / 6 minutes). The DEM-based pDHM runs showed that the downstream areas from

Lake Tuscaloosa Dam, where the major industrial (e.g., Nucor Steel Tuscaloosa, Inc.) and residential areas are located, had a higher chance of flood inundation during the dam failure while the ROV-based pDHM simulations with the wet initial flow condition show high frequencies of flood inundation over the industrial areas and near the junction of the two rivers.

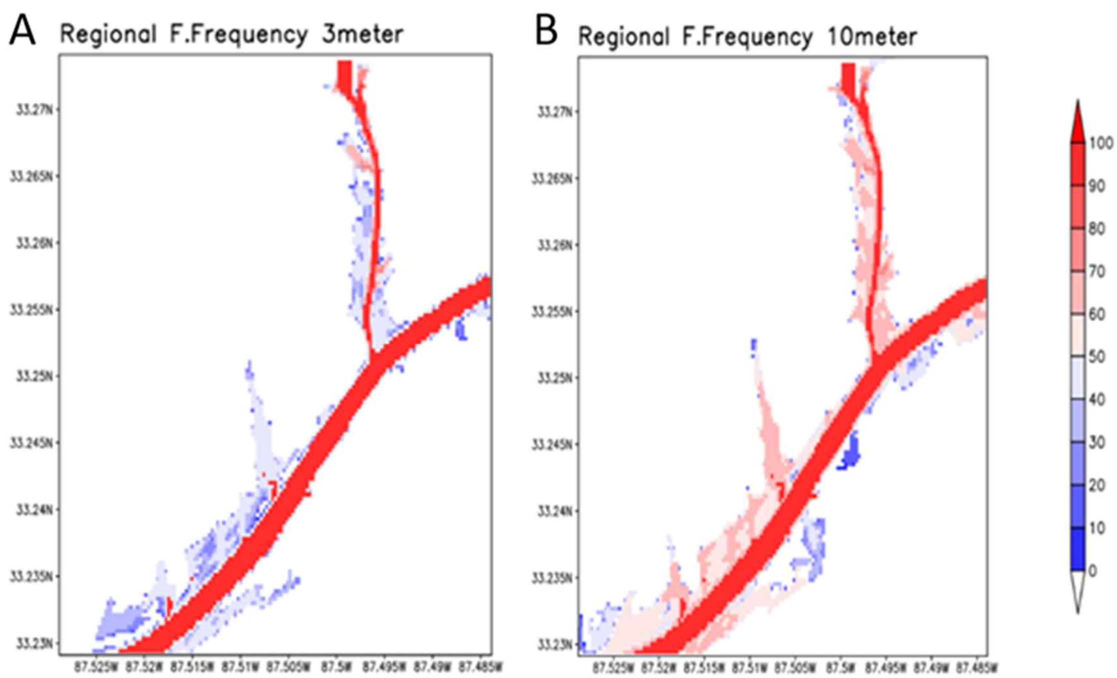


Figure 4-11. Frequencies of flood inundation during the total simulation time steps from the DEM-based (A) and ROV-based (B) pDHM simulations with 3-meter initial depth.

The DEM-based pDHM runs with the 1-meter initial flow condition had a lower chance to be inundated by 30% than the chances from the pDHM runs with 2-meter and 3-meter initial flow conditions, indicating a significant effect of the initial flow condition on the risk of flood inundation (Figure 4-12).

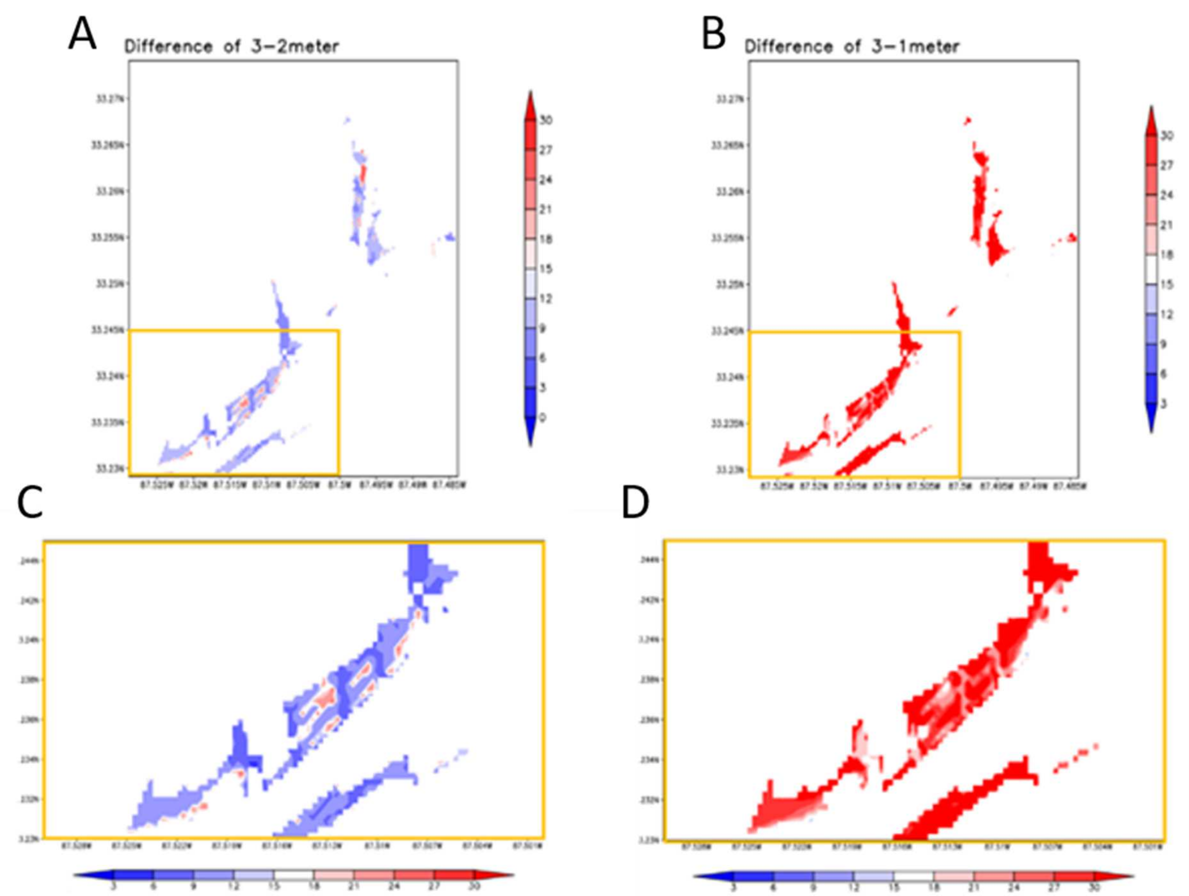


Figure 4-12. Differences in the frequencies of flood inundation between the DEM-based pDHM simulation with 3-meter initial flow condition and the DEM-based simulation with 2-meter (A) and 1-meter (B) initial flow conditions.
In C and D, the area within a yellow box in A and B, respectively, are zoomed.

However, the ROV-based pDHM simulations show a small difference in the flood inundation frequencies over the study region between the dry and wet initial flow conditions. Overall, the ROV-based runs show a higher frequency of flood inundation than the DEM-based pDHM runs. This result indicates that the simulated flood extent along deep river channels is less sensitive to the initial flow condition while deep river channels cause flood inundation longer over the adjacent areas.

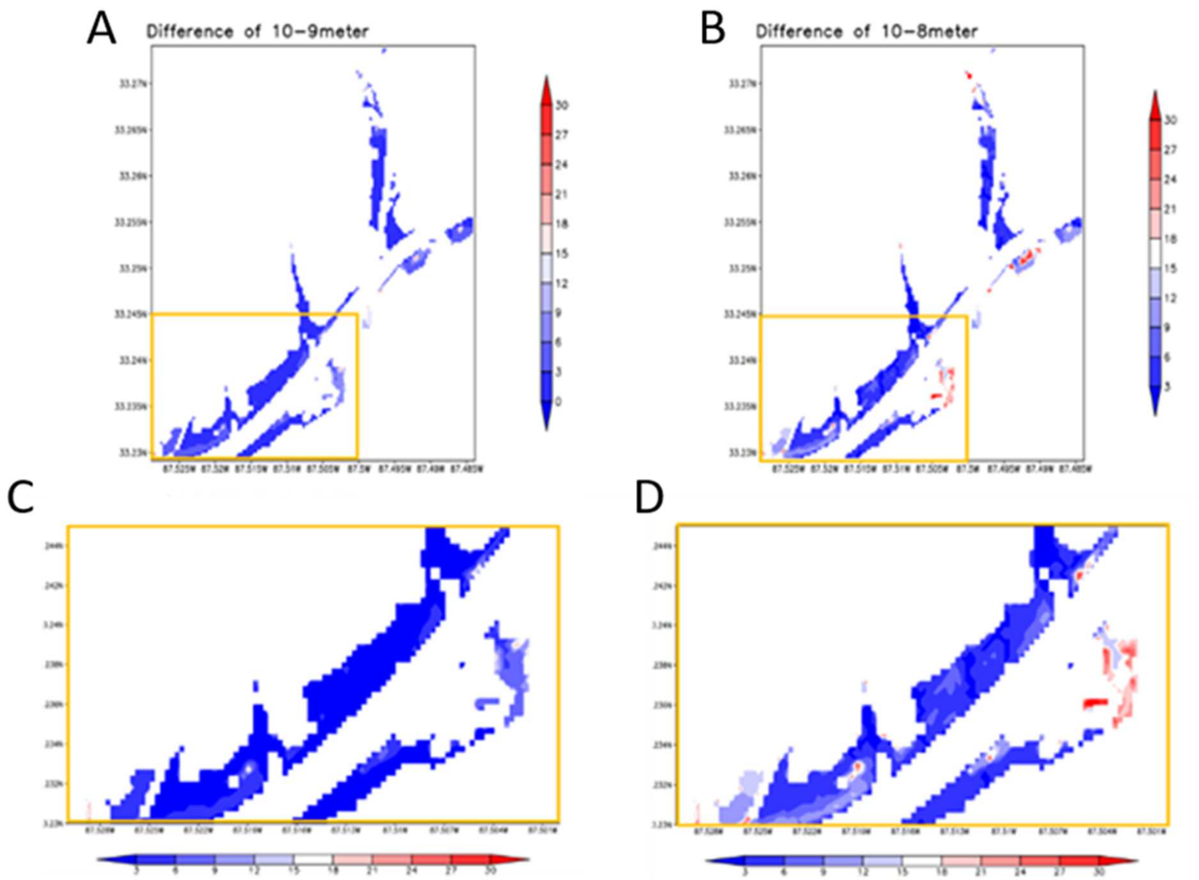


Figure 4-13. Differences in the frequencies of flood inundation between the ROV-based pDHM simulation with 10-meter initial flow condition and the ROV-based simulation with 9-meter (A) and 8-meter (B) initial flow conditions.
In C and D, the area within a yellow box in A and B, respectively, are zoomed.

## 4.4. Conclusions

High-resolution hydrodynamic model simulations with large spatial coverage require not only heavy computing power (hardware) but also sizeable computational time (software, particularly coding). This study applied a parallel technique to hydrodynamic modeling, and it results in efficiently reducing the model simulation times of the eight-hour flood inundation maps at a high spatial resolution. By using 32 cores, the computational time of pDHM runs was reduced by 80 percent of the computational time of the pDHM run with two cores. Furthermore, this study applied bathymetric data from the on-site ROV surveys in the study area. Combining the ROV-based bathymetry survey data with the pDHM improved flood inundation maps during the dam failure, and also this study found the DEM-based pDHM runs underestimated the maximum water depth, the area of flood inundation, and the frequency of flood inundation compared to the ROV-based pDHM runs. It is because of a misrepresentation of the realistic shape of river channels in the DEM-based pDHM runs, resulting in shallow river channels. The findings of this study inform that ROV is a useful tool in creating accurate flood inundation mapping for a dam breach. To develop the dam safety program in the state of Alabama, more large-scale bathymetric survey data are required.

This study succeeded to utilize an underwater drone to acquire more realistic bathymetry data and apply these bathymetric data to parallelized computing for creating hyper-resolution flood inundation mapping for dam breaches. Through the sensitivity test of the pDHM runs, this study assessed the impact of the river channel depth and initial flow condition on flood inundation mapping. This study found that different river channel depths and initial flow conditions can cause a variation of dam-break flood inundation mapping. The findings of this study suggest a need for more active effort to adapt the cutting-edge technologies, such as autonomous underwater vehicles and ROVs, in flood inundation mapping, which can be utilized for public education and outreach programs to create public support for the dam safety program through careful risk communication with actionable and reliable information about the hidden risk and benefits from the aging water infrastructures.

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# CHAPTER 5. CONCLUSIONS

This dissertation conducted a multi-scale risk and impact assessment of dam failure in the United States. The Southeast RFC region (the highest risk region for dam failure), the state of Alabama (the only state that does not have a dam safety program in the U.S., and is situated in the Southeast RFC region), and the parts of the Black Belt where some of the most socioeconomically vulnerable populations in Alabama live were the representative multiple scales used to investigate potential economic and hazard impacts from aging dams. Through the top-down approach, this study harnessed the 2018 NID database in order to assess the spatiotemporal pattern of the potential hydrologic impact of the existing dams in the U.S.

The study assessed the cumulative maximum storage capacities of the twelve RFC basins and dam failure-related hazard potential in the CONUS. Among the basins, the Mid-Atlantic and Colorado basins show 8% and 50% of cumulative maximum storage capacities, respectively, and represent well-prepared regions for hazard potential, especially 90% of the EAP-required dams have EAP while the Southeast basin is at the highest risk due to the poor preparation of EAPs. The results from the economic assessment of the existing dams found that the national average potential economic benefit per dam is 0.8 million U.S. dollars with a wide range from 0.2 and 6 million. Colorado, Northwest, and West Gulf basins show high potential economic benefits; however, Northeast, Missouri, and Mid-Atlantic indicate low potential benefits.

This coupled approach of risk and impact assessment provides a consideration that most of the 12 RFC regions were placed at a high level of hazard risk due to potential failure or malfunction of the dams. The average age of existing dams is 57 years old, and still, in the CONUS, 45% of dams have no existing EAP for high and significant hazards. Therefore, dam safety programs should be reinforced and established in each region not only to increase public safety and community resilience to dam-related hazard potential, but also to secure potential economic benefits, make the environment safer, and be more sustainable.

In terms of dam failure-driven flood inundation mapping, the approach for acquiring DEM is limited by bathymetry resulting in potential flood impacts being underestimated. However, computationally efficient 2D hydrodynamic modeling with remotely operated vehicle-based (ROV-based) bathymetric surveys shows the utility of ROV-based bathymetric surveys to overcome DEM-based flood inundation maps and to create actionable information for dam failure-driven flood maps for public outreach programs. A comparison between LiDAR and ROV floodplains, ROV-based flood plains indicate that after a dam failure, flood depth, extent, and velocity are significantly increased as compared to the LiDAR-based cases. The findings of this study could be valuable resources for the development of the state dam safety program in the state of Alabama hopefully in the near future, and also fully autonomous underwater drones could be a key tool to measuring precise bathymetric data for large areas such as river stream and basins. Hence, this study could offer insight into how to design the Alabama dam safety programs with cutting-edge techniques combined with big data.

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## APPENDICES

### Appendix A

The governing equations of the Diffusion Hydrodynamic Model (DHM). These equations are fully described in Hromadka II and Yen (1987).

The two-dimensional shallow water equation consists of one equation of continuity (1) and two equations of motion in x and y directions, (2) and (3).

$$\frac{\partial \mathrm{h}}{\partial \mathrm{t}} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \tag{1}$$

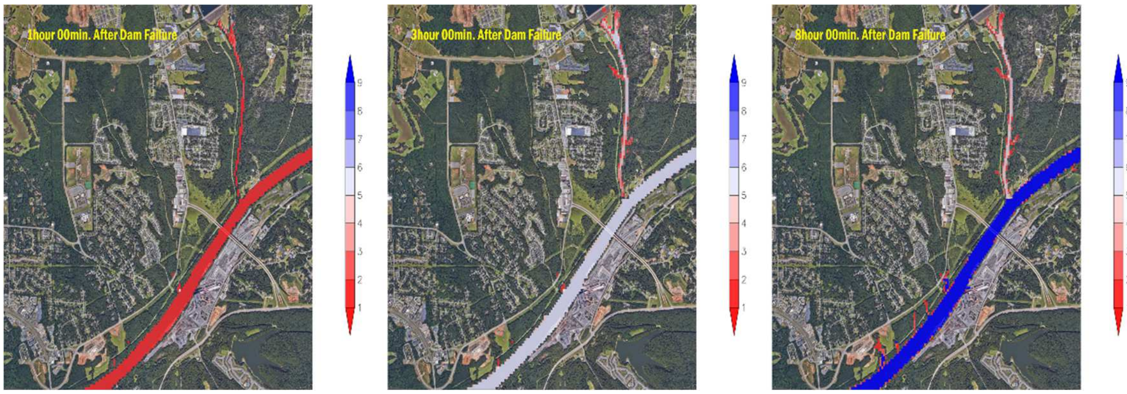
$$\frac{\partial q_x}{\partial \mathrm{t}} + \frac{\partial}{\partial x}\left(\frac{{q_x}^2}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{H}\right) + gH\left(S_{fx} + \frac{\partial \mathrm{h}}{\partial x}\right) = 0 \tag{2}$$

$$\frac{\partial q_y}{\partial \mathrm{t}} + \frac{\partial}{\partial y}\left(\frac{{q_y}^2}{H}\right) + \frac{\partial}{\partial x}\left(\frac{q_x q_y}{H}\right) + gH\left(S_{fy} + \frac{\partial \mathrm{h}}{\partial y}\right) = 0 \tag{3}$$

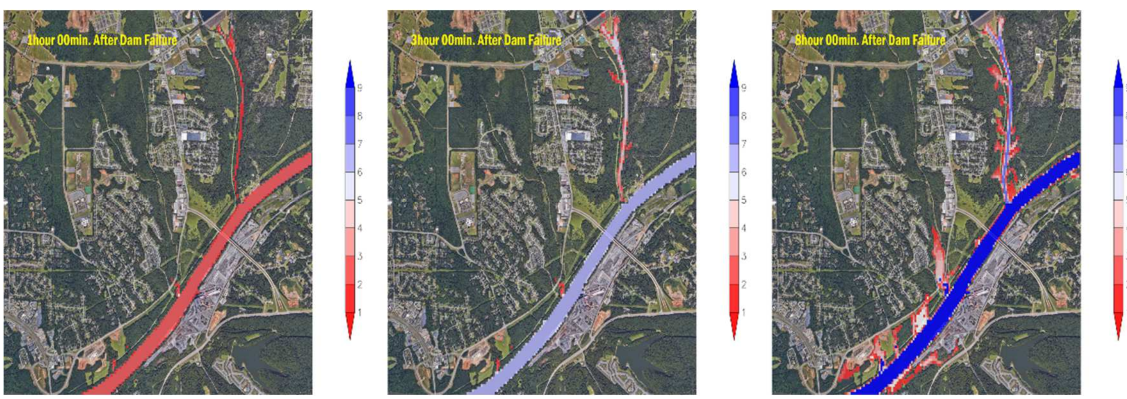
The diffusion wave equation is

$$\frac{\partial \mathrm{h}}{\partial \mathrm{t}} = \frac{\partial}{\partial x} F_x \frac{\partial \mathrm{h}}{\partial x} + \frac{\partial}{\partial y} F_y \frac{\partial \mathrm{h}}{\partial y} \tag{4}$$

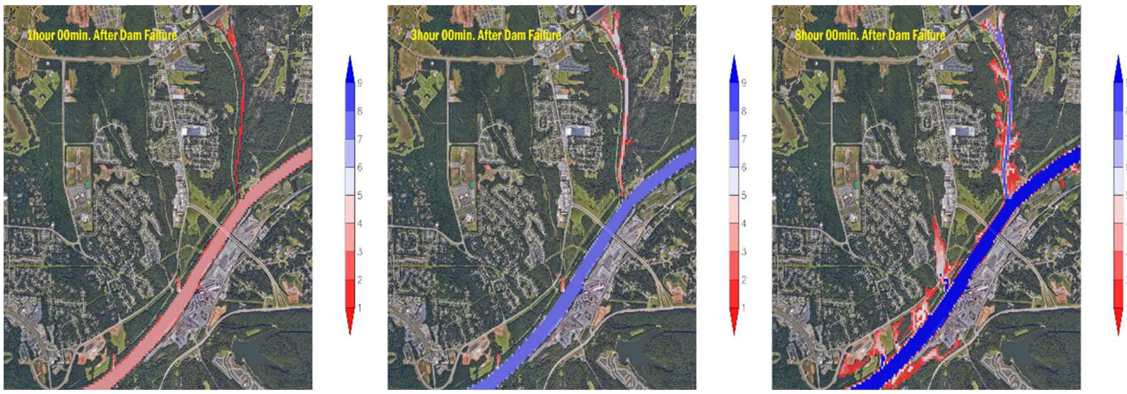
Appendix B



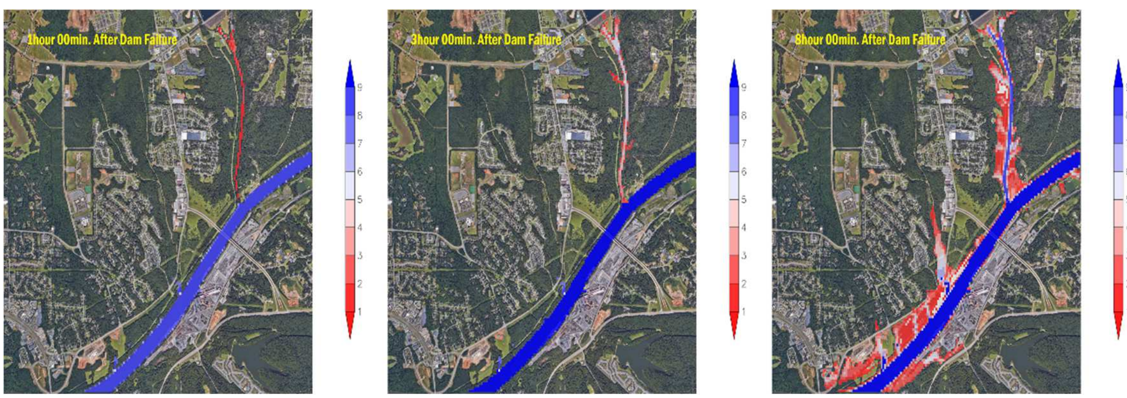

Flood inundation maps at one, three, and eight hours after Lake Tuscaloosa Dam failure with 1-meter dry condition without-ROV (unit: meter).



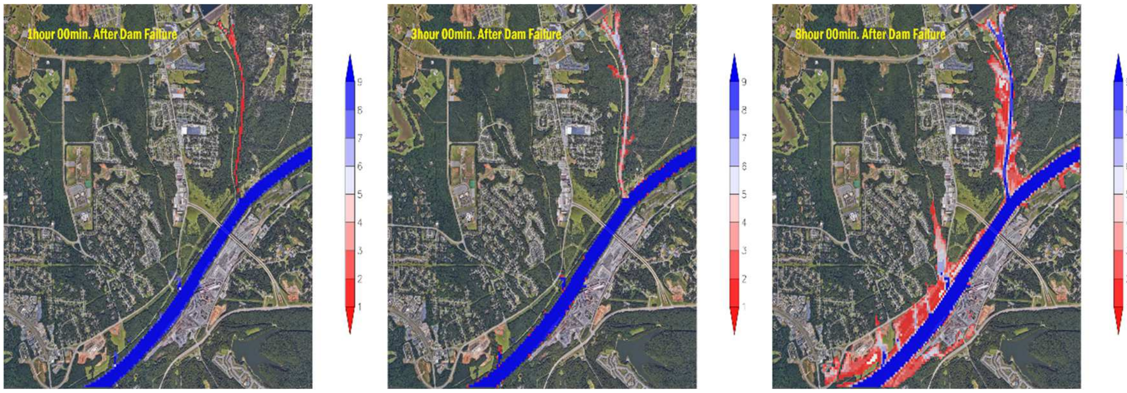

Flood inundation maps at one, three, and eight hours after Lake Tuscaloosa Dam failure with 2-meter normal condition without-ROV (unit: meter).



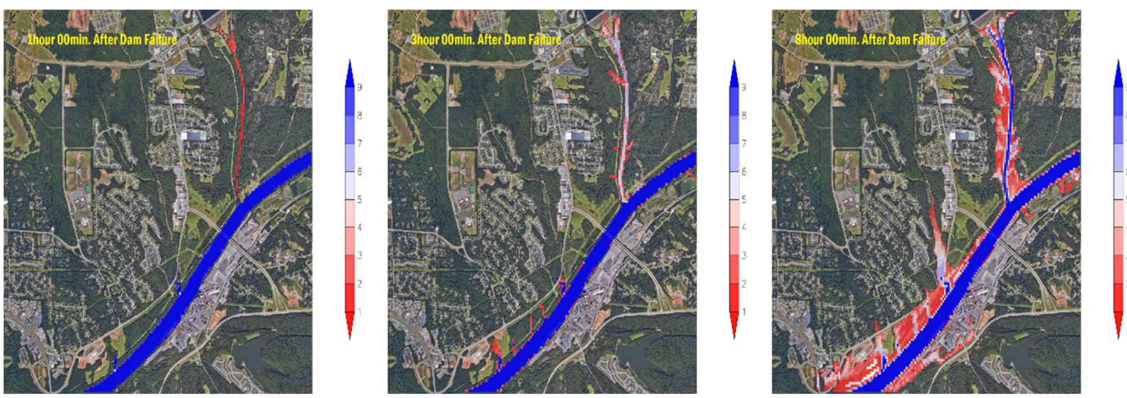

Flood inundation maps at one, three, and eight hours after Lake Tuscaloosa Dam failure with 3-meter wet condition without-ROV (unit: meter).




Flood inundation maps at one, three, and eight hours after Lake Tuscaloosa Dam failure with 8-meter dry condition using ROV (unit: meter).




Flood inundation maps at one, three, and eight hours after Lake Tuscaloosa Dam failure with 9-meter normal condition using ROV (unit: meter).




Flood inundation maps at one, three, and eight hours after Lake Tuscaloosa Dam failure with 10-meter wet condition using ROV (unit: meter).