Assessing the Resilience of Dams to Unexpected Events and Emerging Threats

by

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ABSTRACT

Crises at Teton Dam in 1976, Roosevelt Dam in 1980, Tempe Town Lake Dam in 2010, Oroville Dam in 2017, and the Edenville and Sanford Dams in 2020 prove the substantial and continuing threats to communities posed by major dams. Sociotechnical systems of dams encompass both social or governance characteristics as well as the technical or architectural characteristics. To reduce or overcome chances of failure, experts traditionally focus on making the architectural characteristics of dams safe from potential modes of failure. However, governance characteristics such as laws, building codes, and emergency actions plans also affect the ability of systems of dams that include downstream communities to sustainably adapt to crises. Increasingly, emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires worsen known modes of failure such as overtopping.

Considering these emerging threats, my research assesses whether the architectural and governance characteristics of the aging population of systems of dams in the United States can sustainably adapt to challenges posed by emerging threats. First, by analyzing architectural characteristics of dams, my research provides a useful definition of infrastructures of dams. Next, to assess the governance characteristics of dams, I review institutional documents to heuristically outline seven sociotechnical imaginaries and assess whether an eighth based on resilience is appearing. Further, by analyzing interview transcripts and professional conference presentations, and by conducting case studies, my research reveals ways that experts and stakeholders assess the safety and resilience of systems of dams.

The combined findings of these studies suggest that experts and stakeholders are not sufficiently informed about or focused upon important aspects of the resilience of dams. Therefore, they may not be able to sustainably adapt to crises caused or worsened by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires. I offer explanations of why this is so and formulate recommendations.

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INTRODUCTION

On June 5, 1976, Cecil Andrus, the governor of Idaho, boarded a plane in Boise after receiving notice that Teton Dam in the southeastern part of the state had failed catastrophically. After flying over the failed dam, the pilot flew downstream over the flood that resulted from the breached dam. Andrus saw a family in the path of the flood enjoying a peaceful Saturday morning, unaware that a deluge was bearing down on them. The pilot tried to signal members of the family that they were in danger, but they did not understand the intended warning and innocently waved back. Although Andrus along with the entire Idaho Congressional delegation supported construction of Teton Dam, he watched helplessly as the torrent swept the family away (Shaw & Nelson, 1977, p. 32).

By releasing eighty billion gallons of water, the collapse of Teton Dam confirmed the enormous potential power of water stored behind major dams. The resulting flood scoured topsoil from land that farmers would have irrigated with water impounded in the reservoir to grow Idaho’s most famous product: potatoes. More important, the eleven people who lost their lives in the disaster showed that in addition to property and economic damage failed dams imperil human lives and devastate communities (Balloffet & Scheffler, 1982).

After the Teton Dam disaster in 1976, President Jimmy Carter in 1977 appointed Andrus to be Secretary of the Interior, the bureaucratic home of the United States Bureau of Reclamation (USBR), which designed and built Teton Dam. In his new role, Andrus sent Congress a draft of a bill that became the Reclamation Safety of Dams Act (1978) (Reisner, 1986). The title of the Act confirms that it addresses the *safety* of dams owned or operated by the United States Bureau of *Reclamation*. The Act, which has been amended several times to increase appropriations, helps the USBR to improve the *safety* of the dams that it owns or operates (Reclamation Safety of Dams Act, 1978). Congressional testimony and documents produced during hearings about the failure of Teton Dam reveal that the USBR had become overconfident in its ability to design, construct, and operate dams that were safe (*Dam Safety*, 1977; *Oversight: Teton Dam Disaster*, 1977).

The USBR traces its roots to the Reclamation Act (1902). Until Teton Dam failed 75 years later, the USBR developed a reputation for engineering excellence epitomized by iconic structures such as Hoover Dam. Projects built by the USBR "reclaimed" arid lands in the western United States and supplied benefits to communities such as irrigation and municipal water, hydropower, flood control, and recreational amenities.

About four years after the failure of Teton Dam in 1976, storms drenched watersheds that feed the Salt and Verde Rivers in central Arizona with up to 16 inches of rain in February 1980 (Chin et al., 1991, p. 1). Since forecasters predicted that more storms were on the way, the USBR as owner and the Salt River Project as operator of six storage dams on the Salt and Verde Rivers were concerned that Roosevelt Dam and Stewart Mountain Dam might fail and flood the Phoenix metropolitan area. Fortunately, the predicted storms did not materialize, and disaster was averted (Chin et al., 1991).

After the narrow escape, engineers at the USBR reassessed the design of Roosevelt Dam and tripled the inflow design flood, a standard used to calculate the amount of water that a reservoir can absorb or pass water downstream through outlet works or spillways after weather events like heavy rains. To expand capacity of the reservoir to handle the increased inflow design flood, the USBR redesigned and reconstructed the old Roosevelt Dam by overlaying it with a thick mantle of concrete, which raised the height of the crest of the dam by 77 feet. The USBR completed reconstruction of the dam in 1996, or sixteen years after the crisis in 1980, at a cost of $430 million. Funds appropriated under the Reclamation Safety of Dams Act (1978) paid for most of the cost (Ester, 2006).

Three years after the USBR completed reconstructing Roosevelt Dam in 1996, the City of Tempe opened Tempe Town Lake in 1999. The dam that impounded the reservoir consisted of inflated rubber bladders that operators could deflate to allow floods to flow downstream. The design allowed operators to reinflate the bladders to capture water as the flood receded to refill the reservoir. However, rubber in the bladders deteriorated over time as the west facing dam baked in the intense solar radiation that assaults Tempe. As a result, one of the bladders sprang a leak and deflated suddenly at 9:45 p.m. on July 20, 2010, releasing about 3,000 acre-feet of water down the dry bed of the Salt River. Fortunately, no one was injured, and property damage was minimal. After the flood, the City of Tempe replaced the failed bladder on a temporary basis and refilled the reservoir. In 2016, the City of Tempe constructed a new dam downstream of the old dam at a cost of $47 million. Mimicking the functionality of the rubber bladders of the original dam, the new dam consists of six steel gated structures that operators can mechanically lower to release floods and raise to refill the reservoir as the flood waters abate (City of Tempe, n.d., *Town Lake Dam*).

In February 2017, news videos of cascading water eroding spillways at Oroville Dam in California illustrated tradeoffs posed by aging infrastructure projects such as dams as they approach the end of their design lives. Since the State of California completed the Oroville Dam in 1968, the crisis in 2017 took place two years before its 50-year design life expired (Ho et al, 2017). As the tallest dam in the United States at 771 feet, Oroville Dam impounds 3.5 million acre-feet of water, which would devastate downstream communities including Sacramento if released in an uncontrolled flood (Metropolitan Water District of Southern California, 2017; France et al., 2018).

About three years after the crisis at Oroville Dam in 2017, six to eight inches of rain drenched mid-Michigan in May 2020. At 5:35 p.m. on May 19, 2020, Edenville Dam failed and released an uncontrolled flood down the Tittabawassee River. About two hours later, floodwaters overtopped Sanford Dam, six miles below Edenville Dam, causing it to fail. The flood continued flowing downstream and inundated large parts of Midland. Since 11,000 residents were evacuated before Edenville Dam failed, no injuries or fatalities resulted; however, 2,500 buildings were damaged. Costs to clean up the debris, rebuild, and pay claims are expected to exceed $250 million (Mauney & Risher, 2021).

During the boom in the construction of tens of thousands of dams in the 20th century, representatives of the USBR, the United State Army Corps of Engineers, and state dam safety agencies as well as legislators, regulators, and experts focused on the safety of the physical structures of dams and reservoirs. However, stakeholders in downstream communities that rely on dams to supply social and economic benefits often ignore or are unaware of safety issues (Burby, 2006; Di Baldassarre et al., 2013; Reisner, 1986). Therefore, few stakeholders are concerned about the resilience of downstream communities due to fragmented contractual, liability, and governance organizations. To avoid the fate of Cecil Andrus who favored constructing Teton Dam but watched helplessly as a flood released by the catastrophic failure of the dam swept away a family of four, experts and stakeholders need to reassess the safety of major dams and ask if they should take steps to improve the social and technical characteristics of the sociotechnical systems of dams so that they can sustainably adapt after emerging threats like climate change, earthquakes, terrorism, cyberattacks, or wildfires strike.

Rationale

Crises at Teton Dam in 1976, Roosevelt Dam in 1980, Tempe Town Lake Dam in 2010, Oroville Dam in 2017, and the Edenville and Sanford Dams in 2020 illustrate the substantial and continuing threats to the safety of major dams posed by long-recognized potential modes of failure such as overtopping caused by weather events. To address recognized modes of failure related to weather, engineers review climate trends and historical records of past weather events at upstream watersheds. After adding margins for safety, engineers use the resulting calculations to design the physical characteristics of dams such as their strength and height with the goal of safely absorbing excess water in the reservoirs or passing the water downstream through outlet works under normal conditions or through spillways during high water events or emergencies (Federal Emergency Management Agency [FEMA], 2013).

However, designs of dams constructed many years ago do not account for emerging threats such as climate change, which may increase amounts of precipitation produced by storms beyond design limits of dams. Therefore, both the social as well as the technical characteristics of sociotechnical systems of dams, associated structures such as canals and levees, and downstream communities must be resilient if earlier efforts to make dams safe(r) are inadequate to meet emerging threats and the structures fail or release excessive amount of water over prolonged periods of time.

According to the National Inventory of Dams maintained by the United States Army Corps of Engineers, the average age of the more than 90,000 major dams in the United States is over 60 years (United States Army Corps of Engineers [USACE], 2022). As dams age beyond their design lives, which is typically 50 years, chances of impairment or failure inexorably increases (Ho et al., 2017). Unfortunately, the political will needed to preserve or enhance the safety of dams often is not mobilized until crises strike (Burby, 2006; Di Baldassarre et al., 2013). However, emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires potentially worsen traditional challenges to the safety of dams. For instance, the historic rains that followed an historic drought and triggered the crisis at Oroville Dam may be a harbinger of future crises caused or worsened by climate change. Therefore, the urgency needed to improve the capacity of systems of dams to sustainably adapt to unexpected and sudden events like climate change ratchets up as time marches on (Levin et al., 2021; France et al., 2018).

In contrast to the dramatic crisis at Oroville Dam in 2017, which was caused by an excess of water, the system of dams on the Salt and Verde Rivers in Arizona has been challenged in another way by climate change because the southwestern United States has been plagued by a long-running megadrought (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). As it stands now, Roosevelt Dam is the only dam on the Salt River with capacity reserved to absorb excess runoff produced by heavy storms (Ester, 2006). However, the dam has not been tested by excessive waters since it was reconstructed in 1996 due to the megadrought. Therefore, experts and stakeholders do not know if the improvements made to the physical or technical aspects of the dam will be sufficient to allow experts and stakeholders to make tradeoffs needed to sustainably adapt to excess water that may be produced by the emerging threat of climate change.

Furthermore, responding to the crisis at Roosevelt Dam in 1980 and the failure of the Tempe Town Lake Dam in 2010 required prolonged periods of time (sixteen years for Roosevelt Dam and six years for Tempe Town Lake Dam) and substantial sums ($430 million for Roosevelt Dam and $40 million for Tempe Town Lake Dam) to reconstruct or replace the dams. The substantial costs and long construction schedules interfere with efforts to modify the path dependent technical or architectural characteristics of major dams (Puffert, 2009). Nevertheless, risks of impairment or failure increase steadily as dams continue to age and approach or exceed their design lives, which is typically 50 years (Ho et al., 2017). The crisis at Oroville Dam in 2017 showed that precipitation caused or worsened by climate change may exceed historical patterns that inform standards such as the inflow design flood that experts use to size the physical aspects of dams. Therefore, the designs of dams and reservoirs constructed in the past may not be sufficient to resist challenges posed emerging threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires. For example, when the megadrought in the southwestern United States abates, heavy rains may again test the dams on Salt and Verde Rivers with the amounts equal to or more than the heavy precipitation that often plagued that system of dams in 20th Century. Emerging threats like climate change increasingly challenge deterministic standards, methods, and knowledge such as the inflow design flood that designers and regulators continue to use to define or evaluate the safety of major dams and associated structures such as canals and levees. Although more probabilistic methods such as "risk-informed decision making" are becoming more prominent (Federal Energy Regulatory Commission [FERC}, 2016; Regan, 2010; Scott, 2011), they may not be sufficient to allow downstream communities to cope with uncertainties posed by emerging threats like climate change. However, that is beyond the scope of my research.

The rationale for this dissertation is based on the need to investigate whether experts and stakeholders of systems of dams should also enhance resilience as well as safety to prepare for potential crises arising from emerging threats like climate change. Insights provided by this investigation may help experts and stakeholders to recognize and reassess tradeoffs and synergies needed to rebalance the social and technical aspects of the sociotechnical systems of dams that to allow society to adapt to changing circumstances. Therefore, in addition to addressing the *safety* of the physical structures, experts and stakeholders need to proactively monitor, model, and remember ways to improve the *resilience* of both the social *and* the technical aspects of the sociotechnical systems of dams so that they can sustainably adapt to emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires (Woods, 2015). If Roosevelt Dam were to fail catastrophically due to one of these emerging threats, the resulting flood waters would inundate sizable portions of the Phoenix metropolitan area including the campus of Arizona State University (Maricopa County, 2015; Maricopa County, 2021).

Defined Terms

The following defines terms used in this dissertation.

Systems of Dams

Systems of dams are the units of analysis in the research conducted for this dissertation (Yin, 2018, pp. 101-103, 288). Systems encompass interrelated elements that interact based on rules to form unified wholes. Dams are barriers that modulate or restrict flows of water. They are essential, but not the only, elements in “systems of dams,” which refers collectively in this dissertation to the governance or social characteristics of adjacent and downstream communities as well as to the architectural, physical, or technical characteristics of major dams, reservoirs, associated structures such as canals, levees, and hydroelectric plants. Systems of dams supply resources such as water and hydropower as well as services such as flood control and recreational amenities but have the potential to impose casualties including loss of life and economic damages if they fail partially or catastrophically. Recognizing the relevance and importance of both the governance or social and architectural or technical characteristics, my research investigates whether, to what extent, and in what ways the governance (social) and architectural (technical or physical) characteristics of sociotechnical systems of major dams in the United States are operationalized to promote or hinder resilience to sudden and unexpected events caused or worsened by climate change, earthquakes, terrorism, cyberattacks, or wildfires. To encapsulate and address the architectural characteristics of dams, the term “infrastructure of dams” is defined in Chapter 2, which, according to my usage, is different from systems of dams.

Stakeholders

The term “stakeholders” as used in this dissertation refers to members of organizations that govern or rely on systems of dams including, but not limited to, owners, legislators, contractors, regulators, experts, and residents of downstream communities who are affected by the potential failure of major dams. Emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires may exceed the abilities of stakeholders to increase the safety of the technical or physical components of dams and associated structures that may potentially devastate downstream communities. To prepare for adverse events caused by emerging threats such as climate change, intermediaries such as public interest organizations need to mediate conversations among experts and stakeholders. Such conversations would explore initiatives aimed at changing the architectural and governance characteristics of systems of dams in ways that would improve the ability of downstream communities to understand synergies or make the tradeoffs needed sustainably adapt to threats to systems of dams posed by emerging threats such as climate change.

Experts

The term “expert” refers to designers, regulators, consultants, and academics who are knowledgeable about and take part in conversations with stakeholders about the safety or resilience of systems of dams. Although resilience is a popular research topic within academia, experts who design or regulate major dams often do not define or use the term in ways that are consistent with the findings of academic researchers such as Woods (2015) who assessed and conceptualized four concepts of resilience discussed in this dissertation.

The different expectations of experts who are knowledgeable about systems of dams show that consensus has not been achieved about the definition of resilience. Instead, due to their places within hierarchical and fragmented systems of dams, experts traditionally focus on making the architectural, physical, or technical aspects of systems of dams and associated structures such as canals and levees *safe(r)* by assessing whether they are vulnerable to recognized modes of failure such as overtopping. As a result, they take steps to mitigate or eliminate associated threats by “armoring” the physical structures of major dams by making them higher, bigger, stronger, or more impervious. For instance, the USBR raised the height and increased the strength of Roosevelt Dam when it reconstructed the dam after the crisis in 1980. Furthermore, in papers and presentations given to or made at conferences dam safety officials justifiably focus on improving the stability or safety of the physical structures of dams and associated structures because that is what owners contract with them to perform. These are vital and necessary functions that must continue. Although experts may participate in conservations with other stakeholders about the safety or resilience of systems of dams, relevant contracts tie the legal obligations of experts to the interests of their clients, not to residents of downstream communities. However, beyond statistically modeling potential loss of life, experts do not assess or address the longer-term effects of failure of dams on downstream communities because the scope of the contractual and legal obligations do not extend to those issues.

As emerging threats like climate change, earthquakes, terrorism, cyberattacks, or wildfires increasingly impact systems of dams, the fragmented nature of institutions such as laws, standards, rules, and regulations as well as organizations such as agencies, bureaucracies, and consulting firms may inhibit or reduce the ability of downstream communities to recover over the long-term from sudden and unexpected failures caused or worsened by climate change, earthquakes, terrorism, cyberattacks, or wildfires. Since scholars (like me) are not subject to adversarial legal, contractual, economic, budgetary, or political obligations, they may expand the scope of the conversations beyond safety of the physical structures of dams by promoting efforts among all stakeholders that aim at increasing the resilience of communities potentially affected by failures of dams.

Overarching Concepts

To gain insights on how to improve or supplement standards or methods that inform the safe and resilient design, operation, and regulation of the social and technical characteristics of the sociotechnical systems of dams to surprising events caused or worsened by emerging threats, the literature reviewed below addresses overarching concepts of resilience, knowledge infrastructure, multiscalar framework, emerging threats, and operationalization.

Resilience

My research distinguishes the resilience of systems of dams from their safety. The glossary of terms for the guidelines on dam safety by the Department of Homeland Security and the FEMA defines “dam safety” as:

> the art and science of ensuring the integrity and viability of dams such that they do not present unacceptable risks to the public, property, and the environment. It requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that a dam is a structure whose safe function is not explicitly determined by its original design and construction. It also includes all actions taken to identify or predict deficiencies and consequences related to failure, and to document, publicize, and reduce, eliminate, or remediate

> to the extent reasonably possible, any unacceptable risks." (Interagency Committee on Dam Safety, 2004, p. 7)

The glossary affirms that the purposes of a dam safety program are:

> to protect life, property, and the environment by ensuring that all dams are designed, constructed, operated, and maintained as safely and as effectively as is reasonably possible. Accomplishing these purposes requires commitments to continually inspect, evaluate, and document the design, construction, operation, maintenance, rehabilitation, and emergency preparedness of each dam and the associated public. It also requires the archiving of documents on the inspections and histories of dams and the training of personnel who inspect, evaluate, operate, and maintain them. Programs must instill an awareness of dams and the hazards that they may present in [stet] the owners, the users, the public, and the local and national decision-makers. On both local and national scales, program purposes also include periodic reporting on the degree of program implementation. Key to accomplishing these purposes is to attract, train, and retain a staff proficient in the art and science of dam design. (Interagency Committee on Dam Safety, 2004, p. 7)

Safety ("freedom from the occurrence or risk of injury, danger, or loss. the quality of averting or not causing injury, danger, or loss"[1]) is a concept predicated on stasis, which connotes efforts to protect physical architectures or infrastructures such as dams from expected modes of failure. Consistent with this point of view, the glossary of terms

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[1] Dictionary.com, https://www.dictionary.com/browse/safety

for the guidelines on dam safety defines stability as “the condition of a structure or a mass of material when it is able to support the applied stress for a long time without suffering any significant deformation or movement that is not reversed by the release of the stress” (Interagency Committee on Dam Safety, 2004, p. 22). In contrast, resilience (“an ability to recover from or adjust easily to misfortune or change”[2]) is a concept that is more dynamic than safety; it arises when unexpected events expose the insufficiency of efforts to make infrastructures safe.

Consistent with the static connotation of safety and the dynamic connotation of resilience, Ahern (2011), Park et al. (2013), and Kim et al. (2017) refer to safety and resilience with the terms *fail-safe* and *safe-to-fail*, respectively. Fail-safe supports stasis, stability, and safety; safe-to-fail signifies recovery, dynamism, and resilience.

As a property of ecological systems, Holling (1973) finds that resilience “determines the persistence of relationships within a system” and measures “the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist” (p. 17). Consistent with the way experts evaluate the safety of dams, Holling (1973) describes stability as found in ecological systems by supporting a predictable world that collects the excess production of nature without significant variation. As with systems of dams, resilience in ecological systems supports persistence and “domains of attraction” in which stability prevails. Holling (1973) finds that random events can interact with deterministic forces that define domains of attraction in stable systems in ways that lessen resilience.

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[2] Merriam-Webster.com, https://www.merriam-webster.com/dictionary/resilience

According to Hollnagel (2014), resilience originally referred to properties of materials. For instance, the “modulus of resilience” measures the ability of wood to absorb surprising and harsh loads without collapsing (p. 221). Building on the metaphor of absorbing sudden and severe loads, Hollnagel (2014) describes four meanings of resilience that address properties of materials, ecological systems, psychological systems, and dynamic and intentional systems, the last of which is the focus of resilience engineering (p. 222). Hollnagel (2014) applies lessons of resilience engineering to dynamic and intentional “built systems” such as systems of dams, which include “sentience” provided by experts, operators, and regulators. He finds that “safety specialists started to use resilience engineering to describe an alternative approach dealing with safety issues, accidents as well as risks.” He defines resilience as “the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions” (Hollnagel, 2014, p. 222).

Since the architectural characteristics of systems of dams cannot adjust “prior to, during, or following changes or disturbances” caused or worsened by emerging threats, it is conceptually useful to address expected and unexpected conditions separately when evaluating systems of dams. According to this conception, *safety* aims at defending against *expected* threats to architectural characteristics of dams. In contrast, *resilience* aims to recover from *unexpected* threats. While experts and stakeholders have traditionally strived to make dams as safe as possible against expected events, resilience is triggered when steps taken to improve the safety of systems of dams turn out to be inadequate when challenged by unexpected events that may be caused or worsened by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires.

Woods (2015) reviewed the literature and derived four concepts of resilience:

1. As *rebound* from trauma and return to equilibrium
2. As a synonym for *robustness*
3. As the opposite of brittleness, i.e., as *graceful extensibility* when surprise challenges boundaries
4. As network architectures that can *sustain the ability to adapt* to future surprises as conditions evolve. [emphases added] (p. 5).

Woods (2015) claims that the first two concepts – rebound and robustness – suggest that systems can return to conditions that prevailed before the occurrence of traumatic events. However, he finds that changes wrought by events will irrevocably alter affected systems, thereby making return to preexisting states impossible. The third concept – graceful extensibility – applies to systems of dams. However, the enormous geophysical forces restrained by major dams lead experts to design and construct enormous dams with extremely path dependent technical characteristics that cannot change or adapt after crises strike (Puffert, 2009). Therefore, the physical structures, dams are brittle when challenged and cannot gracefully extend architectural characteristics after crises arise. My research focuses on the last concept by investigating the ability of systems of dams to sustainably adapt to future surprises as conditions evolve.

Woods (2015) poses three questions about sustained adaptability, the first of which asks, “what governance or architectural characteristics explain the difference between systems that produce sustained adaptability and those that fail to sustain adaptability?" (p. 8). To address that question, my research investigates efforts to promote sustained adaptability of systems of dams including governance characteristics such as laws, regulations, and guidelines and architectural characteristics such as increasing the storage capacity of reservoirs to absorb excess water produced due to climate change. The current knowledge infrastructure does not address the dynamic nature of resilience because it focuses on ensuring stability of the architectural, physical, or technical aspects of dams by concentrating on safety instead of promoting resilient approaches that are sustainably adaptable because they address both architectural and governance characteristics.

Sustained adaptability as conceptualized by Woods (2015) keeps options open, views contexts from broader perspectives, and promotes diversity. Resilience, according to Holling (1973), acknowledges irreducible ignorance by not assuming "that future events are expected, but that they will be unexpected" (p. 21). Assessing threats to the resilience of systems of dams to potential crises by using the concept of sustained adaptability searches for insights that will help communities recover more quickly and efficiently from disasters. Sustained adaptability allows stakeholders to assess the unique tradeoffs implicated by the unique architectural and governance characteristics of each sociotechnical system of dams. For instance, the threat of an extensive, uncontrolled flood if the architectural characteristics of the spillways at Oroville Dam failed forced authorities to assess available tradeoffs. They chose to sustainably adapt governance characteristics by ordering the evacuation of residents below the dam. As it turned out, the architectural characteristics of the spillways at dam withstood the crisis. However, after the crisis abated, the legislature of California appropriated over $1 billion to settle claims and to repair the architectural characteristics of the damaged spillways (Gaynor, 2019, p. iv; Vartabedian, 2018).

To investigate the status of efforts to meet these challenges, my research builds on a report called *Dam and Levee Safety and Community Resilience: A Vision for Future Practice* (National Resource Council, 2012). The report endorses the need to improve the resilience of communities because most dams and levees are not resilient to surprising threats. Relevant challenges include climate change (increasing volatility and volume of precipitation), earthquakes (growing evidence that experts and stakeholders underestimated seismic threats to dams in the past), terrorism (heightened concerns that bad actors may blow up dams or crash planes into them) or cyberattacks (documented evidence that criminals may hack into or disable computer software or hardware that control the operation of dams or components, especially spillways). National Resource Council (2012) emphasizes and describes approaches based on community resilience.

Norris et al. (2008) extend the concept of resilience to communities by finding that the issues addressed are consistent with properties of psychological systems as described by Hollnagel (2014). The resilience of a community links networks “of adaptive capacities,” which Norris et al. (2008) define as “resources with dynamics attributes” that adapt “after a disturbance or adversity” (p. 127). Norris et al. (2008) describe four types of adaptive capacities that address the economy, society, communication, and competence. To enhance adaptive capacities, they advocate reducing inequalities, engaging residents in mitigation efforts, linking organizations, improving social supports, and planning “for not having a plan” (p. 127).

After reviewing the literature, Meerow et al. (2016) subject the 25 definitions of urban resilience that they identified to a bibliometric analysis to reveal “six conceptual tensions fundamental to urban resilience: (1) definition of ‘urban’; (2) understanding of system equilibrium; (3) positive vs. neutral (or negative) conceptualizations of resilience; (4) mechanisms for system change; (5) adaptation versus general adaptability; and (6) timescale of action” (p. 38). Based on these conceptual tensions, Meerow et al. (2016) define urban resilience as “the ability of an urban system – and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales – to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity” (p. 45). Norris et al. (2008) and Meerow et al. (2016) supply helpful insights into resilience of individuals and communities.

Although it is essential that experts such as designers and regulators who are knowledgeable about *safety* of systems of dams take part in conservations about improving *resilience*, the conversations also require participants who represent all relevant stakeholders especially those who are knowledgeable about or can speak for downstream communities. Responding to emotional, social, or physical needs of stakeholders after crises involving systems of dams usually extends over prolonged periods of time and across large geographical areas. To preserve the ability to assess and make the types of tradeoffs needed sustain adaptability over the long term and across large territories potentially affected by floods and debris released if major dams fail due to emerging threats like climate change requires that experts and stakeholders assess entire systems of dams, especially downstream communities, and make changes before disasters strike, not after when confusion reigns.

Experts who address the safety of the architecture or physical structures of systems of dams are often not in a position contractually, professionally, or socially to make changes needed to promote sustained adaptability since they are embedded within fragmented institutional, governance, legal, insurance, and liability regimes, which have grown up around the federalist system of government in the United States. Fragmentation, therefore, inhibits the willingness or ability of experts to participate in conversations aimed at improving resilience because responsibility for failures may be assessed against individuals and organizations and civil and criminal damages or sanctions may be imposed against them.

Knowledge Infrastructure

To assess the sustained adaptability of systems of dams, experts and stakeholders need to address relevant physical, temporal, and social factors. Ostrom (2011) usefully distinguishes among frameworks, theories, and models. Frameworks are “the most general forms of theoretical analysis.” By describing elements, relationships, and variables, frameworks “organize diagnostic and prescriptive inquiry” and “provide a metatheoretical language” needed to ask relevant questions and assess theoretical responses. Elements, relationships, and variables interact in many ways within the contexts of specific systems (Ostrom, 2011, p. 8). For instance, the multiscalar framework defined by Edwards (2003), and explored in more depth below, describes and quantifies the interconnected elements of force, time, and social organizations applicable to infrastructure projects like systems of dams by illustrating relationships and variables among them that are relevant to the safety and resilience conceived of as sustained adaptability of systems of dams.

Theories, according to Ostrom (2011), select relevant elements from an applicable framework to describe unique contexts such as individual systems of dams by making "assumptions about the shape and strength of these elements." This allows analysts "to diagnose a specific phenomenon, explain its processes, and predict outcomes." Multiple theories are usually consistent with each framework. Theories assessing safety such as modes of failure and resilience conceptualized as sustained adaptability describe or define the shape and strength of the elements selected from the multiscalar framework of Edwards (2003) and apply them to systems of dams. For instance, the enormous quantities of water impounded by major dams dominate downstream structures and communities and, therefore, affect the choice and application of theories useful in diagnosing phenomena such as modes of failure caused or worsened by climate change, earthquakes, terrorism, cyberattacks, or wildfires, explain responsive processes, and predict outcomes.

Models, according to Ostrom (2011), make "precise assumptions" about discrete subsets of variables and parameters to predict how they will interact according to selected theories. Many types of models including "logic, mathematics, game-theory models, agent-based models, experimentation and simulation, and other means" are available to assess variables and parameters that are consistent with relevant theories (Ostrom, 2011, p. 8). For purposes of research on the safety and resilience of systems of dams, experts traditionally use static models such the inflow design flood and dynamic threedimensional simulations of excess water produced after the impairment or interruption of services provided by dams, canals, or levees within specific watersheds.

Researchers have formulated several frameworks to evaluate infrastructure. For instance, Star & Ruhleder (1996) lay out widely cited “steps toward an ecology of infrastructure” that include embeddedness, transparency, reach or scope, learned as part of membership, links with conventions of practice, embodiment of standards, built on an installed base, and becoming visible upon breakdown (p. 113). They pose a counterintuitive question: “When is an infrastructure?” This alludes to their finding that “infrastructure is something that emerges for people in practice, connected to activities and structures” (p. 112). Therefore, systems of dams develop into infrastructure as experts and stakeholders interact with the social or governance characteristics as well as the technical structures or architectural characteristics within the context of each system.

As regards the safety of infrastructure projects, Perrow (1984) suggests analyzing disasters according to their design, equipment, procedure, operators, supplies and materials, and environment, which he reduces to the mnemonic acronym: DEPOSE (p. 8). When infrastructure projects fail, Perrow (1984) recommends that investigators scrutinize the failure against the elements of the DEPOSE acronym. For instance, forensic teams investigated the elements of the failures at Oroville Dam in 2017 (France et al., 2018) and Edenville Dam in 2020 (France et al., 2021a).

De Graaf et al. (2009) proffer a four-element “vulnerability framework,” which includes threshold capacity, coping capacity, recovery capacity, and adaptive capacity (p. 407). Gersonius et al. (2010) extends these four elements of vulnerability in ways that bridge the conceptual dichotomy between the safety and resilience of systems of dams.

Threshold capacity seeks to prevent adverse events by improving architectural characteristics through “building higher and stronger embankments and implementing additional flood storage.” Coping capacity lessens adverse effects after events that surpass relevant thresholds by putting in place measures to control the architectural characteristics of dams and improving the governance characteristics by creating emergency and evacuation plans. Recovery capacity promotes efforts to recuperate efficiently and effectively from adverse effects that exceed relevant thresholds through governance characteristics such as insurance, disaster funding, reconstruction plans, and, most important, communicating with experts and stakeholders more effectively. Adaptive capacity improves the ability of stakeholders to adjust to future changes by enhancing the flexibility and reversibility of infrastructure by creating slack in financial governance characteristics and spatial architectural facilities (p. 16).

The National Academy of Sciences (2012) advocates planning for, absorbing, recovering from, and adapting to actual and possible disruptive events to improve resilience (p. 1). Consistent with this approach, Park et al. (2013) find that resilience grows out of a “recursive process” that cycles through sensing, anticipation, learning, and adaptation (p. 361). To measure resilience, Eisenberg et al. (2014) cites four “resilience metrics” used by the Department of Defense, which are relevant to systems of dams. The physical metric includes engineering capabilities and “data collection equipment and measurable real-life system components.” The information metric assesses the use, transfer, analysis, and storage of data about physical domains. The cognitive metric evaluates processes used by humans to translate, share, and act on knowledge “to make, communicate, and implement decisions throughout the system.” The social metric weighs interactions that affect decisions including governance, religion, culture, and language (Eisenberg et al., 2014).

Edwards (2016) defines knowledge as a "useful understanding of patterns and causal relationships, expressed in a shared vocabulary (including math and statistics), and backed by data (evidence)." He applies the concept of infrastructure to knowledge by defining "knowledge infrastructures" as "robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds." Weather forecasting, which is vital to the safety and resilience of systems of dams, censuses, and the Centers for Disease Control, as revealed during the COVID-19 pandemic, are examples of knowledge infrastructures that perform three essential functions: "They *monitor* features of interest, *model* complex systems to find and test causal relationships, and record data in *memory* systems to track change over time" [emphasis in original] (p. 3).

Although all the frameworks reviewed above supply useful insights, the framework described by Edwards (2016) encapsulates knowledge that is relevant to the architectural and governance characteristics of sustained adaptability of systems of dams (Woods, 2015) because they *monitor* relevant features such as the water levels in reservoirs over time, *model* causal relationship such as inflow design floods or maximum credible earthquakes, and store in *memory* data that tracks the evolution of changes to systems of dams. The following databases are knowledge infrastructures that may be extended or enhanced to *monitor* fields relevant to the sustained adaptability of systems of dams to emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires, *model* associated challenges and responses, and record status or outcomes over time in *memory* in databases (Edwards, 2016): Salt River Watershed Connection (Salt River Project, 2022), National Inventory of Dams (USACE, 2022), the Association of State Dam Safety Officials (ASDSO) Dam Incident Database (ASDSO, 2022), the Arizona Water Blueprint (Kyl Center for Water Policy, 2022), or Resilience Analysis and Planning Tool (FEMA, 2022). To describe and assess emerging threats that increasingly challenge systems of dams, it helps to apply the multiscalar framework defined by Edwards (2003) to knowledge infrastructures defined by Edwards (2016) because it attends to the *scale* of architectural characteristics of force and time that are relevant to enormous major dams and categorizes social organizations responsible for governance characteristics heuristically.

Multiscalar Framework

Owners and experts design and construct major dams that are extremely path dependent because the enormous geophysical forces that the structures must withstand require huge quantities of materials that take a long time to put in place. Therefore, it is extremely difficult if not impossible to change the architectural or physical characteristics of major dams and associated structures such as canals and levees after crises strike (Puffert, 2009). The inability to change the path dependent nature of major dams as crises appear is illustrated by the futile efforts of construction workers to push dirt into the widening breach in the embankment of Teton Dam and jumping off the bulldozer just before it was swallowed by the expanding hole. If changes to architectural characteristics of an existing system of dams are needed, experts and stakeholders must undertake long and expensive processes years before crises erupt. However, changes to governance characteristics such as building codes and emergency action plans can be put in place before crises strike to help communities make tradeoffs needed to sustainably adapt during crises so that they recover more quickly after disaster strikes.

In describing the multiscalar framework, Edwards (2003) starts by finding that some large technological systems like dams have become so integrated into society that residents do not notice them. In fact, Edwards (2003) finds that the term infrastructure is applied to large sociotechnical systems such as dams that are not noticed because they shape – and are shaped by – the environment, society, and modernity in which they are embedded (p. 4-6). Therefore, Edwards (2003) defines infrastructures as "spaces of flow" without which society cannot function (p. 3). Collier et al. (2016) point out that John Dewey in *The Public and Its Problems* (Dewey, 1927) found that voluntary acts of will do not connect people. Instead, consistent with the metaphor of "spaces of flow," members of the public are joined by "vast currents" of interconnection and circulation, which are not political institutions but material artifacts that may be conceived as infrastructures: "Green and red lines, marking out political boundaries, are on the maps and affect legislation and jurisdiction of courts, but railways, mails and telegraph-wires disregard them." Infrastructures "influence more profoundly those living within the legal local units than do boundary lines" by establishing "the most significant constituents of the public and the residence of power" (Dewey, 1927, p. 107). Consistent with the metaphors of "spaces of flow" and "vast currents," systems of dams regulate flows of a substance fundamental to life: water. For example, systems of dams on the Colorado, Salt, and Verde Rivers modulate flows of water that connect millions of residents in a "vast current" or "spaces of flow" that allows them to thrive during an unprecedented megadrought (Williams et al., 2020; Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022).

Instead of separating nature, science, and technology, Edwards (2003) claims that societies “imbricate” infrastructure within nature. Although imbricate technically means “(of scales, sepals, plates, etc.) having adjacent edges overlapping,”[3] Edwards (2003) invokes the metaphor of overlapping edges to describe complementary interrelationships between nature and infrastructure. For instance, although the scales of force and time differ significantly, beavers pioneered natural methods of imbricating dams into natural streams. Infrastructures like systems of dams scale up natural processes by imbricating physical dams within rivers to impound water in reservoirs and modulate flows through outlet works or spillways in ways that are like natural lakes. As Edwards (2003) points out: “A less-noticed point is that many modern energy-based infrastructures also rely, at least in part, on natural forces.” Imbrication as illustrated by “hydroelectric dams and air travel’s use of the high-altitude jet stream are only two of many possible examples” (p. 7).

Natural variability constrains infrastructures. Edwards (2003) points that the Dutch learned that natural variability limits the effectiveness of carefully constructed infrastructure projects made up of dikes and pumps because challenges posed by natural events may exceed design limits (p. 7). Similar challenges may affect systems of dams as threats like climate change continue to emerge. In fact, failures of infrastructure often cause more casualties and property damage than weather events themselves. As Edwards (2003) put it: “Flooding can result as much from shattered dams and levees, or silt

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[3] Oxford English Dictionary, https://www.lexico.com/definition/imbricate

buildup actually caused by flood-control systems, as from heavy rainfall" (p. 7-8). When heavy rains threatened Roosevelt Dam in 1980, Governor Bruce Babbitt considered evacuating residents to protect against the possibility that the architectural characteristics of Roosevelt Dam or Stewart Mountain Dam might fail and release millions of acre-feet of water (Seper, 1980). The resulting flood would have carried debris and sediment that would have severely damaged downstream communities and overwhelmed both the architectural and governance characteristics of communities in the Phoenix metropolitan area, which would have been needed to make the tradeoffs to sustainably adapt to the disaster.

Edwards (2003) points out that Edward Tenner described cascading failures that magnify interdependencies among connected types of infrastructure projects as the "revenge effects" of technology. In fact, societies depend so heavily on infrastructures that Edwards (2003) finds that the concept of "natural disaster" actually refers to the "<u>relationship</u> between natural events and infrastructures" [emphasis in original] (p. 8). For instance, if a natural event like heavy rains had caused Roosevelt Dam to fail in 1980, the flood would have cascaded down the Salt River, overtopped or destroyed three other storage dams that impound substantial volumes of water, and inundated the Phoenix metropolitan area. In addition to interrupting modulated flows of irrigation and domestic water, the "natural disaster" would have caused "revenge effects" by, for instance, disabling interdependent infrastructures such as ground and air transportation.

Edwards (2003) finds that "risk society" as described by Beck (1992) represents "an emerging <u>post</u>-modernist settlement" that renders "the natural and the sociotechnical commensurate via the omnipresent category of risk" [emphasis in original] (p. 10). Beck

(2008) goes on to state that “a central contradiction of risk society results from the fact that the world is confronted with large-scale threats whose origin lies in the triumphs of modern society.” Despite “institutionalized state promise of security,” risks associated with “large-scale threats” such as major dams cannot “be adequately confirmed nor attributed, nor compensated, nor (preventively) managed in accordance with prevailing legal, scientific and political principles” (p. 30). Therefore, scientific and engineering practices such as the risk-informed decision making (FERC, 2016; Regan, 2010; Scott, 2011) may worsen threats posed by “natural disasters” because risks are possibilities “marked by a high degree of unreality,” which prevents experts and stakeholders from understanding them before consequences manifest (Beck, 2008, p. 30).

We often invoke a linguistic construction by saying that a “dam failed,” which may be misleading because the sentence focuses on the architectural or physical characteristics of a major dam. However, saying that a dam failed does not address governance or social characteristics of systems of dams writ large. Edwards (2003) investigates these misguided constructions and finds that societies code failures of infrastructure under the category of “hardware” even though, for instance, dams are not simply huge physical artifacts that impound water (p. 5). Instead, societies co-produce sociotechnical systems and imaginaries in which dams are embedded by including both the “hardware” of the architectural or physical characteristics of the artifacts of dams as well as the “software” of the governance or social characteristics.

Co-production is a fundamental insight of science and technology studies and intellectual leaders of the field such as Sheila Jasanoff, Bruno Latour, and Langdon Winner explore its nuances. Consistent with the multiscalar approach advocated by

Edwards (2003), Jasanoff (2004) finds that “co-production is shorthand for the proposition that the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it.” Therefore, “knowledge and its material embodiments” such as the architectural characteristics of dams “are at once products of social work and constitutive of forms of social life.” As a result, “society cannot function without knowledge any more than knowledge can exist without appropriate social supports.” Standards such as the inflow design flood are “scientific knowledge, not a transcendent mirror of reality.” Governance characteristics of systems of dams both embed and are embedded “in social practices, identities, norms, conventions, discourses, instruments and institutions – in short, in all the building blocks of what we term the social.” Jasanoff (2004) finds that “the same can be said even more forcefully of” technologies like major dams (p. 2-3).

All systems of dams co-produce costs and benefits that affect the relevant knowledge infrastructure. For instance, by imposing enormous costs and not delivering promised benefits, but instead tremendous damages, the failure of Teton Dam in 1976 co-produced substantial changes to knowledge infrastructure relevant to the architectural and governance characteristics of the *safety* of systems of dams. The disaster prompted congressional and bureaucratic investigations, which led to the passage of the Reclamation Safety of Dams Act (1978) and allowed the USBR to rehabilitate several dams in its portfolio based on the revised knowledge infrastructure. Furthermore, the Act primed the pump for the National Dam Safety Program that was set up under later legislation (Water Resources Development Act, 1996), which inaugurated the sociotechnical imaginary that emphasizes the safety of dams. However, the disaster at

Teton Dam and the passage of the Act did not necessarily improve the resilience conceptualized as sustained adaptability of other systems of dams by clarifying or improving the tradeoffs available when disasters strike.

The multiscalar framework described by Edwards (2003) assesses infrastructures on three scales: force, time, and social organization. Force and time define the architectural characteristics of major dams; social organizations describe the governance characteristics. The dimension of force is bounded by muscle and geophysical power; energy systems and systems of dams, for instance, lie between those two poles. The dimension of time runs from the duration of human lives of less than a century, to historical time extending over several centuries, and to the vast continuum of geophysical time; systems of dams restrain perpetual geophysical forces with structures that last less than a century.

Since social organizations are not quantifiable along linear dimensions like force and time, Edwards (2003) heuristically addresses them at the micro (individual), meso (institutional), and macro (functional) scales. The microscale focuses on how infrastructures affect individuals such as residents who consume water stored in reservoirs. Mesoscale refers to organizations that own or operate (e.g., USBR), regulate (e.g., FERC), or research (e.g., ASDSO) large infrastructure projects such as systems of dams. Macroscale refers to functional aspects supplied by infrastructure projects such as water, flood control, hydropower, or recreational amenities provided by dams (p. 6-13).

The multiscalar framework highlights interactions between scales in a process that Edwards (2003) calls “mutual orientation” (p. 22-24). Instead of emphasizing discrete transitions between landscapes, regimes, and niches as defined by Geels (2002), Edwards

(2003) finds that scales mutually orient or influence – and are mutually oriented or influenced by – other scales in an ongoing interactive process. For purposes of my research, characterizing co-production (Jasanoff, 2004) as mutual orientation (Edwards, 2003) is useful in analyzing the operation of systems of dams. Mutual orientation describes interactions of systems of dams among the architectural characteristics of force and time as well as governance characteristics at the micro, meso, and macro scales of social organization (p. 22-24). Applying the multiscalar framework provides "metatheoretical language" (Ostrom, 2011, p. 8) that helps experts and stakeholders monitor, model, and remember tradeoffs needed to sustainably adapt to emerging threats systems of dams (Woods, 2015). Table 1 applies the multiscalar framework to systems of dams:

Table 1

Application of Multiscalar Framework to Systems of Dams

Scale	*Units*	*Description*
Force	Muscle to geophysical	Path dependent structures designed and put in place by muscle power augmented with machines to resist geophysical forces
Time	Human, historical, & geophysical	Temporal limits defined by designing dams to last 50 years to resist perpetual geophysical time
Social Organizations		
Microscale	Individuals	Residents benefit from services supplied by dams, but suffer costs if interrupted
Mesoscale	Organizations	Organizations such as the private corporations or governments own and operate dams, regulators apply laws and standards, and professional organizations investigate and train
Macroscale	Functional	Dams supply services such as water, flood control, hydropower, navigation, and recreational amenities

Applying the multiscalar framework to analyze the failure of Teton Dam in Table 2 illustrates its usefulness in assessing the knowledge infrastructure of systems of dams.

Table 2

Application of Multiscalar Framework to Teton Dam

Scale	*Units*	*Examples*
Force	Muscle to geophysical	Internal erosion (piping) caused embankment to fail and release geophysical force of the water stored in reservoir
Time	Human, historical, & geophysical	Dam did not survive initial filling or fulfill its design life of 50 years or until reservoir silted up
Social Organizations		
Microscale	Individual	• Family swept away in Teton Dam disaster • Andrus becomes secretary of the interior
Mesoscale	Organizations & Institutions	• Laws: Reclamation Safety of Dams Act passed • Owner: USBR reforms procedures
Macroscale	Functional	• Services: Water to grow potatoes and recreational amenities not delivered

Although the dam is no longer available to inspect, researchers believe that a hole or "pipe" developed that allowed material in the dam to erode in a process called piping, which over time eventually caused the embankment to cave in and release the geophysical forces of the water stored in the reservoir. Photographs show that the dam failed at 11:57 a.m. on Saturday, June 5, 1976, a time that precisely demarcates the temporal boundary between controlled inundation of water in the reservoir and its conversion into a chaotic flood that released geophysical forces that scoured topsoil from the land that the reservoir was intended to irrigate and destroyed downstream communities. Members of the family swept away by the flood are examples of individuals at the micro scale. The fate of the family viscerally shows the impact that failures of major dams can inflict on individuals. The disaster mutually reoriented later actions taken by Cecil Andrus because he was a politician who supported the project before becoming governor but saw firsthand the failure of the architectural and governance characteristics of Teton Dam. According to the multiscalar framework, the USBR, a bureau embedded within the Department of the Interior, is a social organization at meso scale. After the disaster, Andrus as the secretary of the Department of the Interior offered legislation in the form of the Reclamation Safety of Dams Act (1978), which changed governance characteristics and enabled the USBR to improve the safety of the architectural characteristics of other dams constructed by the USBR, but not their sustained adaptability. The failure of Teton Dam prevented the USBR from delivering macro-level functions such as water for irrigation or municipal purposes, hydropower, flood control, or reactional opportunities services to relevant communities and instead caused enormous damages and eleven deaths.

Traditionally, experts design or inspect the architectural characteristics of dams based on deterministic projections like the inflow design flood, which are based on historical weather patterns to which safety factors are added. Under normal conditions, multiscalar systems of dams do not require mutual orientation among the scales to work safely. However, events that exceed normal patterns that are caused or worsened by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires may stress systems of dams beyond design parameters. If so, the ensuing crises may require experts and stakeholders to assess and make tradeoffs mediated by the mutual orientation of the force, time, and social organizations that allows systems of dams to sustain adaptability to emerging threats such as climate change (Edwards, 2003).

Multiscalar evaluations of threats to the design, construction, operation, maintenance, rehabilitation, or decommissioning of systems of dams extend beyond traditional deterministic standards such as the inflow design flood or maximum credible earthquake by addressing governance characteristics as well as architectural characteristics. Multiscalar assessments facilitate more nuanced and holistic understandings of the strengths, weaknesses, opportunities, and threats posed to architectural and governance characteristics systems of dams by revealing insights into relevant tradeoffs among individual (micro), institutional (meso), and functional (macro) scales needed to sustain adaptability, which are not as visible from the perspective of one scale. Investigating the ability to make tradeoffs involving systems of dams requires understanding whether potential tradeoffs are fundamental and whether they differ among human, social, and physical systems according to differing scales (Woods, 2015, p. 6). For instance, some of the multipurpose storage dams on the Salt River such as Roosevelt Dam can produce hydropower by releasing water through generators; however, releasing water from reservoirs to turn generators reduces the amount of water stored for future use by communities in the Phoenix metropolitan area during the hot and dry summer months. To address this conundrum, officials at the Salt River Project continually assess the knowledge infrastructure by monitoring, modeling, and storing in memory data about the ability to make tradeoffs so that the organization may mutually reorient tradeoffs between multiscalar dimensions of force, time, and social organizations as described by Edwards (2003). For instance, the Salt River Project constantly assesses the architectural characteristics related to the level of water in the reservoirs as well as the effects on the governance characteristics of downstream communities if water is released to make room for inflows generated by unusually large weather events that may be worsened by emerging threats like climate change (Phillips et al., 2009). This is an example of the way that the multiscalar framework allows experts and stakeholders to mutually orient (or reorient) scales needed to make tradeoffs that respond to both expected and unexpected threats to systems of dams in more comprehensive and dynamic ways that are needed to sustainably adapt to crises posed by emerging threats like climate change.

The monumental height and mass of some major dams makes them seem permanent on geophysical force and time scales. However, engineers design them to last about 50 years (Ho et al., 2017) because owners do not have unlimited budgets to construct structures that can withstand every challenge including emerging threats. For instance, the crisis at Oroville Dam in 2017 occurred about 50 years after the state of California completed construction of the dam. Furthermore, the Edenville Dam failed in 2020, or about 100 years after it was completed in 1925. Complicating matters further, the mode of failure of Edenville Dam – static liquefaction – was not recognized when the dam was designed because the relevant science – soils mechanics – had not been invented (France et al., 2021b).

As the end of the design life of major dams approaches, stakeholders of systems of dams should monitor the structures and rehabilitate, replace, or remove them according to *safety* protocols that prevail at the time. However, I argue that the stakeholders should also improve the governance and architectural characteristics of systems of dams to improve their sustained adaptability or *resilience* if efforts to design, build, operate, or maintain dams *safely* are exceeded due to emerging threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires. For instance, by implementing reforms to the governance characteristics of systems of dams that Congress and regulators put in place after Teton Dam failed, the USBR rehabilitated the architectural characteristics of several structures including Roosevelt Dam, which increased their capacity to absorb or withstand expected threats to their safety. However, these efforts did not change governance characteristics of downstream communities such as land use patterns to improve their ability to sustainably adapt to failures caused or exacerbated by emerging threats such as climate change. It will be interesting to see if and how the architectural and governance characteristics of the system of dams on the Tittabawassee River are mutually reoriented after the failures of the Edenville and Sanford Dams (France et al., 2021a).

Emerging Threats

Experts designed structures like Teton Dam, Roosevelt Dam, and Oroville Dam based on deterministic standards like the inflow design flood, which "is used to design and/or modify specific dams and appurtenant works; particularly for sizing the spillway and outlet works, and for evaluating maximum storage, height of dam, and freeboard requirements" (FEMA, 2013, p. 30). Although the probability that a major dam will fail is extremely low, consequences to life and property of downstream communities are immense if they do. Therefore, regulators mitigate threats to the safety of dams by adjusting the architectural characteristics of the dams. For instance, if a regulator finds that an embankment dam is unsafe due to increased risk of overtopping due to an inadequate spillway, the regulator may require the owner to reduce the amount of water stored in the reservoir. Risk-informed decision making informs assessments of the safety of systems of dams by supplementing deterministic standards such as inflow design floods with more probabilistic methods based on risk (FERC, 2016; Regan, 2010; Scott, 2011).

The USBR, the USACE, the FEMA, and the FERC increasingly prescribe the use RIDM to address modes of failure (FERC, 2016; Regan, 2010; Scott, 2011). However, evaluating long-recognized modes of failure associated with dams such as overtopping or internal erosion of materials within the body of dams is complicated by increasing concerns that current standards such as the inflow design flood may not account for emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires. Traditionally, inflow design floods are based on hydrometeorological reports prepared by the National Weather Service (NWS). However, since the NWS has not updated hydrometeorological reports due to lack of funding, some regulators are pursuing other methods. For instance, representatives of the Colorado Division of Water Resources developed “new extreme rainfall, runoff, and hydrologic-risk assessment tools that are regionally-specific, based on best available science, and are appropriate for state dam safety regulation” (Perry & McCormick, 2020, p. 1). In addition, the Infrastructure Investment and Jobs Act (2021) authorized $492 million to update nationwide probable maximum precipitation estimates.

Although current safety programs at the national and state levels have improved the governance characteristics of the safety of dams, deterministic standards such as the inflow design flood may not account for probabilistic risks associated with climate change, earthquakes, terrorism, cyberattacks, or wildfires since the size or scope of the emerging threats may exceed historical and stationary patterns upon which deterministic standards like the inflow design flood are based. As a result, emerging threats make balancing tradeoffs needed to promote sustained adaptability of systems of dams by, for instance, adjusting amounts of water stored in a reservoir more complex and dynamic. Emerging threats increase the possibility of sudden unexpected crises and underscore the need for conversations among experts and stakeholders to address whether, to what extent, and in what ways they should adjust knowledge infrastructure of systems of dams to improve sustained adaptability. Systems of dams may not be sufficiently *resilient* to extreme and surprising events associated with emerging threats despite competent efforts to make them *safe(r)*.

Recognizing the physical, financial, social, and cognitive limits to how *safe* experts and stakeholders can make the architectural characteristics of dams, experts were asked in interviews about governance characteristics such as regulatory mechanisms used to evaluate the safety and resilience of systems of dams now and the changes that have been made to them in the past. Some of the experts described ways to mitigate threats to the safety of systems of dams, but none specified regulatory mechanisms that addressed sustained adaptability. Even if analyses of dams performed under RIDM protect structures and downstream communities from expected risks, stakeholders should assess and take steps to improve the architectural and governance characteristics of systems of dams that would be needed to sustainably adapt if dams and associated structures do not survive unexpected threats associated with extreme and surprising events.

Climate Change. In a statutorily required letter dated May 3, 2019, the Acting Administrator of FEMA summarized crises that affected systems of dams between 2015 and 2017:

> In October 2015, the eastern United States weathered severe storms and historic flooding in the Carolinas, resulting in 19 deaths. The flooding led to dozens of dam failures which strengthened the floodwaters exponentially. In 2016, Hurricane Matthew resulted in a record 17 dam failures in North Carolina alone. In February 2017, the main spillway at the Lake Oroville Dam in California failed, forcing the evacuation of 180,000 people in the surrounding communities. In late 2017, the Atlantic Ocean produced a succession of storms including Hurricanes Harvey, Irma and Maria, and flooded areas across the United States. Hurricane Harvey filled the reservoirs of the Addicks and Barker Dams in Texas to record levels, prompting emergency actions to relieve pressure on the dams and prevent overtopping. In Florida, strong winds and rain from Hurricane Irma raised concern for potential over wash at the Herbert Hoover Dike, prompting evacuations. In Puerto Rico, the Guajataca Dam overtopped, prompting evacuations there as well and significant concern over potential dam failure. (Gaynor, 2019, p. iv)

Climate change may have caused or worsened many of these events. Although the current megadrought in the southwestern United States is the worst one since the 14th Century, prolonged droughts normally last around 30 years (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). When megadroughts end, extreme weather events worsened by climate change may drench watersheds above populated areas such as that Phoenix metropolitan area and cause the Salt River to flood as it did repeatedly in the 20th Century. Excess water could overtop levees engineered to handle quantities of water calculated under deterministic methods like the inflow design flood and damage infrastructure and buildings constructed along the banks of the Salt River. Extreme and surprising storms have not tested many vulnerable areas such as the perimeter of Tempe Town Lake, which the City of Tempe initially filled with water in 1999, or four years since the current megadrought started (City of Tempe, n.d., *Town Lake Dam*; Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). Therefore, improving sustained adaptability of both the governance and architectural characteristics systems of dams on the Salt and Verde Rivers as well as on rivers below other major dams across the United States may save lives and reduce property damage by allowing communities to function more quickly after crises abate and recovery begins.

Earthquakes. In addition to climate change, the designs of many dams do not account for knowledge gained about the size or frequency of seismic disturbances including earthquakes. Vajont Dam in Italy is the quintessential example of geophysical forces that can overwhelm dams. During the night of October 9, 1963, a landslide displaced water impounded in the reservoir behind the 860-feet high Vajont Dam, creating an impulse wave estimated to be 820 feet high. The wave overtopped the dam at a height of 300 to 450 feet, destroyed downstream communities, and killed about 1,900 victims (Bosa & Petti, 2013; Petley, D., 2008). Although Vajont Dam was being filled for the first time, Humbert et al. (2019) confirm that “the age of many dams calls into question the methods used to determine the design earthquake loads and construction methodologies used” (p. 1).

In 2019, the San Francisco Public Utilities Commission constructed a replacement dam downstream from the Calaveras Dam because the original dam was near a seismic zone. Regulators reduced the amount of water that the old dam could impound due to fears that if it failed a 30-foot flood would inundate Fremont. However, inadequate geological conditions and at least two landslides plagued the site of the replacement dam. The amount of excavation needed to cope with the seismic redesign ballooned by millions of cubic yards and construction took much longer than expected. As a result, costs skyrocketed from $420 million to $810 million (Blair, 2017).

Terrorism and cyberattacks. Terrorism is “politically motivated violence against noncombatants that seeks a broad psychological effect.” In the aftermath of 9/11, it is not difficult to imagine terrorists bombing dams or flying airplanes into spillways, causing the release enormous quantities of water over extended periods of time. In 2021, the United States did not suffer any mass terrorist attacks despite substantial political polarization (Byman, 2021a). Despite fears that terrorists would be inspired by the attacks on 9/11, no attacks of a similar scale have been launched in the United States over the last two decades (Byman, 2021b). However, the Department of Homeland Security issued a report in 2012 that described 25 attacks on dams around the world from 2001 to 2011 including one in the United States. On July 4, 2010, two Molotov cocktails were detonated at the Black Rock Dam in Connecticut, but no suspects were apprehended (National Protection and Programs Directorate’s Office of Infrastructure Protection, p. 34). About half of the attacks were perpetrated in Afghanistan, Burma, and Iraq. Types of attacks ranged from explosive devices (15), standoff weapons (5), assault teams (5), and incendiary devices (pp. 9-11). The report noted that many dams are hard to defend because they are “normally large structures that are often located in remote areas.” Nevertheless, the report finds that “dams are designed and built according to well-documented engineering principles and regulated standards” that allows them to "withstand a variety of unusual and extreme conditions, which makes them inherently robust structures" (pp. 6-7). The question is whether bad actors will find innovative ways to circumvent the safety measures designed and built into dams.

The incorporation of sophisticated technology into systems of dams may provide virtual modes of attack in addition to those launched from land, water, or air. In 2016, an indictment in the United States District Court of the Southern District of New York charged an Iranian with accessing a server housing the supervisory control and data acquisition system (SCADA) of the Bowman Dam in Rye, New York. Although the owners had disconnected sluice gate on the dam for maintenance purposes before the intrusion, SCADAs normally control such devices. If the hack had been successful, terrorists could have opened the sluice gate and released a flood that would have inundated downstream communities (United States District Court of the Southern District of New York, 2016; Thompson, 2016).

Wildfires. I did not understand until recently that wildfires pose another emerging threat to the architectural and governance characteristics of systems of dams. However, Bauer et al. (2021), who are employed by the Colorado Department of Natural Resources - Dam Safety, confirm the increasing nature of the threat by describing the unprecedented series of wildfires that burned watersheds in Colorado in 2020. Within a period of one year, the Pine Gulch, East Troublesome, and Cameron Peak wildfires successively became the largest wildfires in the history of the state. The three wildfires scorched basins with 25 dams, 13 of which were classified as high hazard. Wildfires alter vegetation patterns, soil properties, and runoff dynamics. The risk of overtopping increases significantly after fires due flashy runoff caused by denuded basins, changed soil properties, and extreme sediment loading in reservoirs. To assess the impact of wildfires on dams, researchers need to understand the context of each structure as well as the conditions of the basins involved. Completing inspections requires coordinating with diverse entities such as the Forest Service, health departments, and watershed protection groups. Burn Area Emergency Response mapping can help analysts understand how burn severity and estimated runoff amounts caused by wildfires will affect dams. GIS maps help to calculate how much of the drainage basins burned and the severity of the burn. Restoration activities can help dam owners protect their dams. Bauer et al. (2021) recommend "coordinating with the National Weather Service to understand the threshold warnings for rainfall in these burn areas." After wildfires, emergency action plans should be updated to address actions to be taken when thresholds are exceeded. Although the dams were resilient after fires, the impacts will linger for years. Unfortunately, threats to dams posed by wildfires will continue to grow (Bauer et al., 2021).

The dangers posed to systems of dams by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires are plausible and foreseeable. Interviews revealed that experts understand that these threats are emerging and potentially dangerous; however, they did not identify or describe efforts to address them in ways that enhance sustained adaptability.

Operationalization

My research focuses on whether, to what extent, and in what ways the knowledge infrastructure of systems of dams is *operationalized* to create and support governance and architectural characteristics associated with sustained adaptability (Woods, 2015). Hollnagel (2014) assesses whether the built environment can sustain operations under changing conditions while keeping the ability to act "quickly and effectively, and even in some cases to respond pre-emptively" (p. 222). Interviews with experts explored whether, to what extent, and in what ways architectural or governance characteristics related to systems of dams have changed to account for extreme and surprising events caused or worsened by emerging threats like climate change.

Operationalizing sustained adaptability requires thinking beyond current methods that try to optimize systems based on the expectation of returning to equilibria that may have existed only in theory, not practice. Society invests substantial resources in organizations such as FEMA, state dam safety offices, and professional organizations such as ASDSO, United States Society on Dams, and International Commission on Large Dams to improve the safety of systems of dams. In addition, experts investigate the causes of potential modes of failure that may disrupt the stability of the architectural characteristics of systems of dams to allow stakeholders to operationalize remedies.

However, Woods (2015) finds that experts and stakeholders of systems of dams need to be *prepared to be unprepared* when responding to dynamic conditions that appear spontaneously during the confusion that ensues after unexpected events such as storms caused or worsened by climate change. Events like these may exceed carefully designed safety measures that experts have incorporated into the physical structures of dams or linked components such as canals or levees. Woods (2015) points out that experts and stakeholders can *predict unpredictability* during and after unexpected events, which should prompt them to update or upgrade the architectural or governance characteristics of systems of dams in ways that allow them to adapt – or to be adaptable – at earlier stages to dynamic changes that occur over lifecycles.

Based on experiences with other types of systems that Woods (2015) has reviewed, experts and stakeholders concerned with the safety or resilience of systems of dams should expect that surprises will recur over lifecycles of systems of dams; that conditions and contexts of use will change as boundaries are adjusted to take advantage of benefits provided to stakeholders; that adaptive shortfalls will arise and require responsible participants to intervene to bridge gaps in performance; that factors affecting graceful extensibility will transform repeatedly; and that systems of dams will respond to opportunities or threats by modifying themselves or their relationships to other systems (p. 8).

Experts investigate and isolate basic architectural principles that are preserved during dynamic challenges to systems of dams and stakeholders to enhance the flexibility of governance characteristics to determine whether, to what extent, and in what ways knowledge infrastructures of systems of dams are operationalized to meet emerging challenges. Lessons adduced by Woods (2015) advance the sustained adaptability of systems of dams by allowing experts and stakeholders to uncover fundamental constraints and associated tradeoffs; to understand that systems of dams are based on social and technical tradeoffs that interact in unpredictable ways at multiple scales; and to allow basic architectural principles to adjust multi-dimensional tradeoffs that allow movement toward new sustainably adaptable positions.

Woods (2015) finds that adaptive capacities are subject to resilient mechanisms that control or manage fundamental trade-offs. Sustained adaptability balances tradeoffs among multiple scales within parameters that constrain how adaptive systems work. Judging whether systems of dams are sustainably adaptive is based how well they balance tradeoffs (p. 8). Tradeoffs include considering whether, how, and to what extent to increase slack, diversify options, or decouple components of systems of dams to increase adaptive capacities before crises strike (Pinheiro et al., 2017).

Research Question

The dangers illustrated by the crises involving systems of dams described above threaten not only the *technical* characteristics of the infrastructure of dams and associated works such as canals, levees, or hydropower plants, but imperil *both the technical as well as the social characteristics* of the downstream communities that are components of these large *sociotechnical* systems. My research questions whether concepts like safety and risk, which experts and stakeholders currently use to evaluate the *technical* aspects of dams and associated structures, are adequate to identify, assess, prepare for, and adapt to emerging threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires to the *social* aspects of downstream communities. For purposes of my research, the *social and technical aspects* of the large sociotechnical systems are synonymous respectively with the *governance and architectural characteristics* of resilience conceptualized as sustained adaptability of systems of dams (Woods, 2015).

In more formal terms, my research investigates whether, to what extent, and in what ways the resilience of dams, associated structures such as canals and levees, and downstream communities is operationalized (Hollnagel, 2014) within the knowledge infrastructures (Edwards, 2016) that inform and support the *governance (social)* or *architectural (technical)* characteristics of sustained adaptability (Woods, 2015) to emerging threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires.

Subsidiary Questions

The investigation explored five subsidiary questions related to the architectural or governance characteristics of the safety and resilience of systems of dams. First, how safe or resilient are systems of dams currently? The research addressed systems associated with major dams in the United States. Since the major dams are huge, path dependent technical structures such as Roosevelt Dam that are physically brittle when challenged beyond design thresholds, the research focused on current capabilities of sociotechnical systems of dams to respond over the long term to the social and technical challenges implicated after crises. A mixed methods approach investigated the governance and architectural characteristics of sustained adaptability of systems of dams.

Second, what are the definitions of and relationships between safety and resilience? During interviews experts were asked to define safety as well as the architectural and governance characteristics of resilience, or sustained adaptability, of systems of dams. Sociotechnical imaginaries related to the governance of systems of dams were heuristically periodized by analyzing the history of systems of dams and legislative responses that followed. For instance, the failure of Teton Dam in 1976 prompted Congress to pass the Reclamation Safety of Dams Act (1978), which inaugurated a sociotechnical imaginary that focuses on safety. Although legislatures enact or amend relevant laws, experts continue to evaluate the safety of the technical or architectural characteristics of dams and associated structures according to deterministic standards such as the inflow design flood, which is consistent with the safety imaginary. However, the research finds that experts increasingly use more probabilistic methods such as risk-informed decision making to evaluate the safety of the architectural characteristics of dams, which is also consistent with the safety imaginary. The question is whether risk-informed decision making will lead to the emergence of a resilience imaginary, which would promote sustained adaptability of social, or governance, characteristics as well as the technical or architectural characteristics of systems of dams during and after crises (FERC, 2016; Regan, 2010; Scott, 2011).

Third, how relevant are the concepts of safety and resilience to systems of dams that are vulnerable to emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires? The investigation asks whether social factors such as constrained budgets or technical factors such as path dependence or limits imposed by geophysical forces associated with the massive structures that make up major dams make it increasingly difficult, time consuming, and expensive to enhance the architectural or physical size or strength of dams and associated structures to withstand unexpected challenges posed by emerging threats such as climate change. Therefore, increasing social capacities needed to improve sustained adaptability during or immediately after crises confronts many cultural, legal, institutional, and economic limits that constrain the emergence of a resilience imaginary.

Fourth, how has society improved the resilience of systems of dams? Woods (2015) finds that sustained adaptability requires experts and stakeholders to make tradeoffs to cope dynamically with the unpredictability that ensues after crises develop. During interviews, some experts described regulatory mechanisms such as laws, standards, and guidelines such as the Reclamation Safety of Dams Act (1978) that aim at improving the *safety* of architectural characteristics of dams. However, most of the experts interviewed were unable to name regulatory mechanisms that have improved the *resilience* of systems of dams. Although my research found many regulatory mechanisms such as laws, policies, guidelines, and regulations that affect the *safety* of systems of dams, I did not find any laws or regulatory mechanisms aimed specifically at increasing the *resilience* of systems of dams.

Fifth, what are the barriers to making systems of dams safer or more resilient? During interviews experts said that the major obstacle to making dams safer or more resilient, which they defined in ways that were consistent with safety or some other concept, was the governance characteristic of cost. However, they did not name governance barriers that impede efforts to make systems of dams more resilient. A review of relevant documents confirmed their testimony because I was unable to find regulatory mechanisms in the form of laws, policies, guidelines, or regulations that promote the resilience conceptualized as sustained adaptability (Woods, 2015).

Hypotheses

The federalist system in the United States combines a central federal government with 50 state governments in a single political system that is supposed to carefully assess all options. Gribbin (2019) points out that a multitude of public entities own infrastructure projects in the United States. For instance, 51,000 communities own water systems. Philosopher Immanuel Kant extolled the virtues of federalism because “the problem of setting up a state can be solved even by a nation of devils” if opposing factions are pitted against each other in a system that promotes checks and balances. Kant believed that federalist systems reduce the possibility of war (Kant, 2013). In Federal No. 51, John Madison hoped that “the practicable sphere may be carried … by a judicious modification and mixture of the *federal principle*” that would reduce the chances of anarchy in which the stronger faction unites “as in a state of nature” in which weaker individuals are “not secured against the violence of the stronger” (Madison, 1788). However, despite the positive views of Kant and Madison, the federalist system in the United States encourages inefficiency, which complicates and delays efforts to fund, operate, maintain, and regulate infrastructure projects such as systems of dams in an integrated manner over time.

The federalist system also allows local governments develop floodplains downstream from dams while failing to plan for disasters or limit growth in areas that are prone to flooding. Scholars describe such oversights as the “safe development paradox” (Burby, 2006) or the “levee effect” under which “flood control structures might even increase flood risk as protection from frequent flooding reduces perceptions of risk” (Di Baldassarre et al., 2013, p. 3295). These counterproductive effects lead communities to develop floodplains that are “vulnerable to high-consequence and low-probability events” (p. 3295-3296), which inhibits the ability of systems of dams sustainably adapt after crises strike.

Legal and liability regimes that underlie markets for the design, construction, operation, and maintenance of systems of dams mirror the fragmentated federalist system of government. The fragmented federalist system and adversarial liability regimes reduces the willingness or ability of experts and stakeholders to take part in candid conversations aimed at improving the sustained adaptability of systems of dams. Experts may in fact fear that participating in efforts to improve resilience may come back to haunt them in later litigation or insurance claims.

Emphasis on Safety

As a result of these factors, the working hypothesis at the start of my research was that knowledgeable experts, stakeholders, and organizations would be more focused on making the architectural characteristics of dams and associated components such as canals and levees *safe(r)*. Consequently, they would be less willing to participate in efforts aimed at making entire systems of dams including the downstream communities more *resilient*.

Fragmentation

In addition, I hypothesized that the willingness of experts and stakeholders to discuss and assess sustained adaptability of systems of dams would be limited by boundaries or constraints imposed by fragmented jurisdictions, laws, and liability regimes such litigation and insurance as well as by enduring sociotechnical imaginaries that limit ways that experts and stakeholders assess and respond to issues about systems of dams.

Incommensurability

Furthermore, I hypothesized that contending experts and stakeholders would support inconsistent or incommensurate perspectives on the safety or resilience of systems of dams that would inhibit their ability to interact reflexively with other stakeholders or experts on efforts to improve sustained adaptability.

Use-Inspired Research

However, despite these concerns, I assumed based on the use-inspired research described by Stokes (2011) that experts who are knowledgeable about systems of dams would distinguish between safety and resilience and apply them in ways that are consistent with how those concepts are used by academics and social scientists.

Mixed Methods Research

My research investigated whether, to what extent, and in what ways the resilience of dams, associated structures such as canals and levees, and downstream communities is operationalized (Hollnagel, 2014) to inform and support the governance or architectural characteristics of sustained adaptability (Woods, 2015). The knowledge infrastructure associated with sustained adaptability monitors, models, and remembers information (Edwards, 2016) that is relevant to the multiscalar framework (Edwards, 2003) of systems of dams. My research concentrates on initiatives or innovations that are or can be operationalized (Hollnagel, 2014). My research used multiple methods to investigate the architectural and governance characteristics of systems of dams to assess their sustained adaptability.

To enhance the validity of the research, I reviewed, coded, and analyzed multiple sources of relevant data including documents and interviews (Yin, 2018, p. 43-44). Chains of the evidence about documents and interviews were tracked and archived. By using a mixed-methods approach, the investigation supported the main findings with multiple sources of evidence, which enhanced construct validity, external validity, and reliability.

Document Reviews

First, I researched, accessed, reviewed, catalogued, and analyzed relevant laws, policies, guidelines, and standards and saved notes, documents, and recordings and transcripts of interviews (Yin, 2018, p. 96-99).

Participant Observation: Conferences

Second, I took part in conferences that addressed the safety of dams. In September 2019, I attended a conference sponsored by the ASDSO in Orlando, Florida. About 1,000 officials and consultants attended, many of whom are knowledgeable about systems of dams. The proceedings of the conference were over 800 pages. Most of the articles addressed issues related to the safety of dams. Searches of the proceedings only found eight hits for the words "resilience" or "resiliency." However, most of the content associated with each hit addressed safety, not resilience as described above (ASDSO, 2019). Despite its prominence in academia, dam safety officials or consultants do not think of or address resilience in ways that are consistent with those used in academia (Ahern, 2011, Park et al., 2013, and Kim et al., 2017).

In September 2020, the ASDSO conducted the conference online due to the pandemic. I downloaded, stored, reviewed, and analyzed PowerPoint slides and papers for the 106 presentations that were the produced on the conference website. Consistent with the proceedings of the 2019 conference, most of the presentations and slides dealt with safety, not resilience.

I submitted abstracts for presentations to both ASDSO conferences in 2019 and 2020. The title of my abstract in 2019 was "Assessing the Governance, Safety, and Resilience of Dams and Downstream Communities." The abstract stated:

> Designers of dams are tasked with engineering safe structures that meet the laws, regulations, and standards in effect when the designs were prepared. However, dams are increasingly challenged by threats associated with terrorism, earthquakes, and climate change that raise concerns that they may not be

sufficiently resilient if surprising events cause failures despite efforts to promote their safety. As a graduate student at Arizona State University, I researched whether contemporaneous laws applicable to the design and construction of Teton Dam and related to our national dam safety program are adequate to ensure the safety of dams. The investigation addressed whether the laws in place at the time of the failure of Teton Dam were consistent with one of the four current concepts of resilience identified by Woods (2015) – sustained adaptability. The research demonstrated that imprecise usage of the concepts of "safety" and "resilience" causes confusion. The resilience of dams and downstream communities is best measured when surprising events exceed regulatory standards for dam safety.

Today's governance regime aims at making dams and downstream communities safe, or "fail-safe." However, the safety of dams differs from their resilience. Dams fail when the design parameters or standards related to safety are exceeded by unexpected, or surprise, events like increasingly frequent or severe storms caused by climate change. Currently, many dams and downstream communities do not have the adaptive capacity needed to cope with surprise events. Under these circumstances, decision makers should assess and implement measures to increase the resilience of dams and downstream communities by making them "safe-to-fail" if the unthinkable happens. After assessing the four concepts of resilience offered by Woods (2015), a case study of Roosevelt Dam, which was threatened by unusually heavy rains in 1980, provides an empirical basis to differentiate between the safety and resilience of dams and downstream communities.

The title of the abstract submitted to the 2020 ASDSO conference was, "Are Roosevelt Dam and Tempe Town Lake Resilient to Emerging Threats?" It stated:

> In February 1980, storms drenched the watershed east of the Phoenix, Arizona with up to 16 inches of rain. High waters flooded down the Salt and Verde Rivers and snarled traffic at metropolitan river crossings. Ominously, forecasters predicted more storms. Officials feared that Roosevelt Dam and Stewart Mountain Dam might fail. The governor prepared to evacuate thousands of threatened residents. Fortunately, the predicted storms did not arrive, and disaster was averted.
>
> The crisis prompted the Bureau of Reclamation to reconstruct Roosevelt Dam in 1996 for $430 million and expand its capacity to 3.5 million acre-feet. About half of the expanded capacity is reserved for safety factors: flood control (560,000 acre-feet) and safety of dams (1,200,000 acre-feet). Roosevelt Lake is the only reservoir behind the six storage dams on the Salt and Verde Rivers with capacity to store excess water.
>
> In 1999, the City of Tempe created Tempe Town Lake by constructing a dam on the Salt River, about 60 miles below Roosevelt Dam. The reservoir impounds only about 3,000 acre-feet of water but has promoted residential and commercial development around its banks. Since the region has been plagued by a megadrought since 1995, Tempe Town Lake has not had to pass extreme precipitation in the amounts and duration that plagued the region during the last century. Based on reviews of tree-ring and historical data, researchers found that

> megadroughts normally last on the order of 30 years, which implies that the current one may end sometime around 2025.
>
> To illustrate the interplay between reservoirs with large flood storage capacity and smaller downstream impoundments that are vital to the economic and social development of vibrant communities, my research as a graduate student at Arizona State University focuses on dams on the Salt and Verde Rivers including Roosevelt Dam and Tempe Town Lake. Since the megadrought may end soon and risks associated with climate change, earthquakes, terrorism, cyberattacks, and wildfires are increasing, stakeholders should collaboratively explore ways to increase resilience of dams, reservoirs, associated structures such as levees and canals, and downstream communities. The research reviewed and assessed governance characteristics such as building codes and emergency actions plans that could be modified to better address threats to these important sociotechnical systems. The presentation will address potential ways to improve governance characteristics such as laws, regulations, and guidelines to improve the adaptive capacities of communities to emerging threats to systems of dams.

The organizers of both ASDSO conferences in 2019 and 2020 rejected my abstracts. Since the mission of the organization is to improve the safety of dams, the organizers understandably selected presentations by engineers who are knowledgeable and are employed in positions that address safety. Very few social scientists attended or took part on teams selected to give presentations at the ASDSO conferences in 2019 or 2020.

In February 2021, I took part in the online National Dam Safety Program Technical Seminar (NDSPTS) sponsored by Emergency Management Institute at FEMA. Consistent with the ASDSO conferences, presenters at the NDSPTS mostly concentrated on safety, not resilience. I downloaded and stored but did not analyze the slides.

In October 2021, I downloaded, stored, reviewed, and analyzed PowerPoint slides and papers for the presentations that were the produced on the website for the 2021 ASDSO conference and reviewed relevant videos of the presentations. Consistent with the proceedings of the 2019 and 2020 conferences, the presentations and slides dealt with safety, not resilience. Video presentations about the failure of the Edenville and Sanford Dams in Michigan were especially valuable for my research because they addressed the architectural and governance characteristics of systems of dams. The case study below about the Tittabawassee River system of dams addresses insights generated by reviewing the relevant presentations and papers.

Although other organizations such as the United States Society on Dams and the American Water Resources Association address the safety of systems of dams, my research focused on the ASDSO because its mission "is to improve the condition and *safety* of dams through education, support for state dam *safety* programs, and fostering a unified dam *safety* community" [emphasis added] (ASDSO, 2021). In contrast, the USSD asserts that it is "the preeminent society in the U.S. for professionals involved with all aspects of dams, including engineering, construction and rehabilitation, operation and maintenance, and safety of dams. The society also addresses related contemporary issues such as environmental effects, dam decommissioning and public awareness" (United States Society on Dams, 2021).

Although USSD addresses “all aspects of dams,” the mission of members of ASDSO focuses of the safety of dams. Also, FEMA plays a leading role in addressing the safety of dams. Therefore, the seminar sponsored by FEMA in February 2021 was helpful in assessing the safety of systems of dams. Although the seminar did not address the sustained adaptability of systems of dams, FEMA is beginning to offer resources such as the Resilience Analysis and Planning Tool, which may help experts and stakeholders improve the resilience of systems of dams, especially of downstream communities (FEMA, 2022).

Case Studies

Third, I conducted case studies of the systems of dams on the Salt and Verde Rivers in Arizona and the Tittabawassee River in Michigan. The case study on the Salt and Verde Rivers includes three smaller storage dams that are below the venerable Roosevelt Dam (Horse Mesa, Mormon Flat, and Stewart Mountain) and Tempe Town Lake Dam. The dams are vulnerable to sudden, extreme, and unexpected events caused or worsened by climate change, earthquakes, terrorism, cyberattacks, or wildfires. This system of dams emphasizes the networked nature of dams because they include more than one dam interacting with others. Although the Verde River flows into the Salt River, the case study does not directly address Horseshoe Dam and Bartlett Dam, which are on the Verde River.

Although the heavy rains associated with the failure of Edenville and Sanford Dams on the Tittabawassee River have not been attributed to climate change, the second case study supplies insights into the architectural and governance characteristics that affect the sustained adaptability of systems of dams. In this case, the governance characteristics of the downstream communities sustainably adapted to make tradeoffs needed to compensate for the shortcomings of the governance of the safety of the Edenville Dam, which illustrated the fragmentated regulatory regime based on the federalist system of government in the United States. Although no died in the flood caused by the collapse of the Edenville Dam, damage to the physical assets of the downstream communities was devastating.

The case studies are holistic because they focus on the theory of sustained adaptability at the project level (Yin, 2018, p. 52). The system of dams on the Feather River in California, which was the site of the crisis at the Oroville Dam in February 2017 supplements the investigations into the Salt and Verde Rivers and Tittabawassee River systems of dams.

Interviews

Fourth, I interviewed experts who are knowledgeable about safety or resilience systems of dams. The goals of the interviews were to understand how experts define and distinguish safety from resilience; whether it is critical to pursue resilience in addition to safety as related to systems of dams; how prepared communities are for emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires; and how communities have improved resilience of systems of dams. The semi-structured interviews were conducted and recorded through Zoom, which transcribed them. Using the inductive principles of grounded theory, I coded themes or patterns related to safety and resilience to test my hypotheses, explore contemporary and emerging imaginaries, and inform my findings and recommendations (Corbin & Strauss, 2008; Yin, 2018, p. 118-121).

Infrastructure of Dams

Fifth, I researched and defined the infrastructure of dams, which primarily addresses the architectural characteristics of systems of dams.

Sociotechnical Imaginaries

Sixth, I investigated and defined sociotechnical imaginaries related to systems of dams that informs and supports my assessment of the architectural and governance characteristics of systems of systems of dams.

Participant Observation: Salt River System of Dams

Seventh, since I live in Tempe, I logged my observations of the system of dams on the Salt River during the summer and fall of 2020. The observations helped me understand the scope of the challenges that face the design, construction, operation, maintenance, and regulation of the safety and resilience of systems of dams. Relevant findings from the log are addressed below.

General Characteristics of Mixed Methods Research

Focusing on governance and architectural characteristics of sustained adaptability of systems of dams enhanced the external validity and generalizability of my findings (Woods, 2015). By concentrating on the operationalization (Hollnagel, 2014) of the sustained adaptability, my findings are relevant to other systems of dams and to other forms of infrastructure (Yin, 2018, p. 45-46).

By creating a protocol and documenting in a database the procedures used, the documents reviewed, and maintaining appropriate chains of evidence, the reliability of the case studies was enhanced. The database is available for review and audit (Yin, 2018, p. 46-47).

A protocol entitled, “Investigation into the Design, Construction, and Rehabilitation of Dams,” was submitted to the Institutional Review Board (IRB) of Arizona State University. On April 10, 2018, the IRB found that “the proposed activity is not research involving human subjects as defined by DHHS and FDA regulations.” (Yin, 2018, p. 88-89). In June 2020, I confirmed with the IRB that my research did not involve human subjects as defined by the relevant regulations.

Interpretation and analysis of the data gathered as part of the mixed methods approach is subject to plausible hypotheses that may rival the ones that I assessed during my research. Rival hypotheses include the multiple actors and agencies that exercise cross-cutting authority over water projects that include systems of dams and that one or more of those actors or agencies may address resilience in ways that I have not found. My research concentrated on the federal governance of systems of dams; however, many jurisdictions and regulatory agencies at the state and local levels influence systems of dams. For instance, the Department of Water Resources inspects dams in Arizona and the Maricopa County Flood Control District supervises levees. Although I am familiar with their roles in general, I did not investigate these types of organizations comprehensively. Their relevance and impact on the sustained adaptability of systems of dams may be significant.

My father worked as civil engineer for the USBR for many years and my brother continues to work for an engineering consulting firm that designs water projects and dams. Therefore, a potential for researcher bias exists. However, my experience working on claims and lawsuits for a large general contractor for about 20 years sensitizes me to need to consider multiple perspectives. Nevertheless, I sought feedback from experts and others with divergent points of view to combat my biases (Yin, 2018, p. 245-246).

Organization of Dissertation

Chapter 2 addresses the physical or technical aspects of dams by describing the architectural or technical characteristics of infrastructure of dams. Chapter 3 addresses the governance or social characteristics of systems of dam by periodizing relevant federal laws tied to sociotechnical imaginaries that continue to influence attitudes or decisions related to systems of dams. Chapter 4 analyzes data gathered from mixed methods including conference proceedings and semi-structured interviews used to investigate the sustained adaptability of systems of dams in the United States. For comparison purposes, Chapters 5 presents a case study of the system of dams on the Salt and Verde Rivers in Arizona. Chapter 6 presents a case study of the system of dams on the Tittabawassee River in Michigan. Chapter 7 summarizes my conclusions and recommendations about the sustained adaptability of systems of dams.

CHAPTER 2

AN ANALYSIS OF THE ARCHITECTURAL CHARACTERISTICS OF INFRASTRUCTURES OF DAMS

To assess sustained adaptability, the following two chapters describe and define relevant architectural and governance characteristics associated with major dams separately (Woods, 2015). This chapter focuses on the architectural, technical, or physical characteristics of the "infrastructure of dams," a term defined and analyzed in terms of six elements. In a complementary undertaking, Chapter 3 explores the governance or social characteristics by describing and assessing several sociotechnical imaginaries related to systems of systems of dams. Taken together, the two chapters supply background useful in assessing interview transcripts, conference presentations and papers, and governance documents in Chapter 4 as well as the case studies in Chapters 5 and 6.

The word "infrastructure" is used in the defined term "infrastructure of dams" because the Department of Homeland Security designates dams as one of the 16 infrastructures in the National Infrastructure Protection Plan (2019). This chapter explains my definition of "infrastructure of dams" as "path dependent, multiscalar, hierarchical, physical parts of dams and appurtenant structures that are integrated to maintain flows of water for human purposes." Each of the following six elements, which are explored in more detail below, supply insights that are helpful in assessing both the safety and the resilience of the systems of dams: path dependence, multiscalar, hierarchy, integrated parts, maintenance, and flows of water for human purposes.

The National Research Council (2012) suggests that stakeholders pay closer attention to the physical aspects of dams because "information on dam and levee location, physical properties (e.g., size and type), design requirements, ownership, maintenance responsibility, and regulatory framework is critical for understanding the hazards and risks" (p. 51). Although the National Inventory of Dams lists over 90,000 major dams in the United States (USACE, 2022), it does not include millions of less significant dams such as those on parks or golf courses because they do not threaten life or property (Walls, 2020). Although a small number of major dams are monumental physical structures that impound enormous quantities of water, most major dams are smaller structures that nevertheless pose significant threats to life or property if they fail (USACE, 2022).

Research that investigates environmental or social justice issues related to the impact of infrastructure projects is beyond the scope of the dissertation. Although major dams and associated structures such as canals and levees disrupt the natural environment in fundamental ways and impact disadvantaged neighborhoods disproportionately, this chapter concentrates on physical aspects of existing major dams built in the United States during the boom in dam construction in the 20th century that diminished in the 1960s (Reisner, 1986). Since then, construction of major dams in the United States slowed considerably because dams have been built at many of the best sites and because environmental concerns complicate the process of constructing new dams or reconstructing old ones.

The design life of dams is typically between 50 and 100 years (Ho et al., 2017). However, according to the National Inventory of Dams, the average age of major dams in the United States is over 60 years (USACE, 2022). Therefore, the safety and resilience of dams initially built over 50 years ago are becoming of more concern. Dams and associated structures such as canals, levees, and hydropower plants deteriorate as they age and standards used to design and construct them has changed or become obsolete as challenges posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires increasingly emerge. To meet current standards or to address emerging threats, substantial investments by public and private owners must be made over many years, if not decades, to rehabilitate, reconstruct, or decommission the huge structures that make up large dams (ASDSO, 2019a).

Traditionally, owners and designers strengthened, armored, or raised the height of the dams to address deficient architectural characteristics based on deterministic standards such as the inflow design flood or maximum credible earthquake. However, since the mean age of dams and levees is over 50 years and thousands of dams are classified as "high hazard," Vahedifard et al. (2017) find that "their design did not account for changes in the statistics of extremes over time" even though "past hydrologic events, emerging patterns, and projected climatic conditions all point to a future with more extreme events." Vahedifard et al. (2017) find that the crisis at Oroville Dam in California in February 2017 in which heavy rains followed severe drought was "a portent of the risks that our aging dams and levees face from compounding events in a changing climate" (p. 1139-1140). Risks associated with other emerging threats such as earthquakes, terrorism, or cyberattacks are also becoming better understood.

These increased risks suggest that experts and stakeholders need to increase the *resilience* of the architectural or physical aspects of dams and appurtenant structures such as canals or levees to cope with surprising threats that may exceed traditional and deterministic standards by making them *safe-to-fail* (Ahern, 2011; Kim et al., 2017, Park et al., 2013). However, the current knowledge infrastructure focuses on making dams *fail-safe* by meeting deterministic standards such as the inflow design flood. Risk-informed decision making supplements deterministic standards by assessing the probability of identified potential modes of failure such as overtopping (FERC, 2016; Regan, 2010; Scott, 2011). However, the current knowledge infrastructure does not necessarily make infrastructures of dams s*afe-to-fail* if challenged by unexpected or surprising modes of failure caused or worsened by emerging threats like climate change. Before explaining the components of the definition of the infrastructure of dams and exploring more detail inform the assessment of safety and resilience of systems of dams, the evolution of the word infrastructure is explored.

Infrastructure in General

To understand my definition of the infrastructure of dams within a more general context, it is helps to understand that the increasingly extended application of the word infrastructure by scholars and commentators today belies its humble origins. Carse (2016) traces the origin of the term infrastructure to civil engineering in France in the 19th Century. The term originally described the physical but often invisible or overlooked components of large physical or technical structures such as ties that lie below and support the rails of railroads. Infrastructure in this sense was literally “under” (*infra-*) more visible and better understood structures such as the rails of railroads.

Infrastructure now refers “new projects of spatial integration, particularly …supranational military coordination and international development” (Carse, 2016, p.

27). Increasingly, scholars and commentators construct metaphors around the term infrastructure that extend beyond its original physical connotations to describe intellectual or social aspects of systems that support modern life. For instance, the metaphor of infrastructure is now applied online technologies such as social media. After Mark Zuckerberg proposed changing the business model of Facebook, *The New Yorker* claimed: "Under this new model, the value and defining use of Facebook would be the online infrastructure that it has assembled …" (Heller, 2019). Earlier, poet John Ashbery further extended metaphorical use of infrastructure to describe underlying aspects of human relationships: "I'll be on your side, searching / for what we both know is there: our crumbling infrastructure" (Ashbery, 2017). Dewey (1927) argued people do not assemble according to collective will but are linked by "vast currents," which Collier et al. (2016) view as a reference to "infrastructural publics": "Green and red lines, marking out political boundaries, are on the maps and affect legislation and jurisdiction of courts, but railways, mails and telegraph-wires disregard them. The consequences of the latter influence more profoundly those living within the legal local units than do the boundary lines" (Dewey, 1927, p. 107).

For purposes of my research, Edwards (2016) applied the metaphor of infrastructure to knowledge in his conception of "knowledge infrastructure." Although the rigor and focus of the word infrastructure has diminished with its metaphorical extension to fields such as social media or human relationships, engineers and politicians continue to use the term unmetaphorically to refer to the design, construction, operations, and maintenance of physical projects like highways or dams. During the Trump Administration, pundits joked that every week was infrastructure week in Washington, D.C. because the president and his Administration did not introduce or facilitate passage of legislation. However, in 2021, the Biden Administration managed to pass the Infrastructure Investment and Jobs Act (2021).

Background

To assess the relationship between the safety and resilience of individual systems of dams, an aggregated baseline of past failures and the costs needed to upgrade existing dams supplies context and insights. Between 1850 and 2012, about 1,500 dams of all types or sizes, or about ten per year, failed in United States. However, beginning with the failures of the Buffalo Creek Dam in 1972 and Teton Dam in 1976, the failure rate increased. This may be due to the increasing numbers of dams that exceed the typical design life of 50 years for (Ho et al., 2017), have spillways not designed to meet standards that are in effect today (National Research Council, 2012, p. 21), or not designed to meet challenges associated with emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires (Vahedifard et al., 2017).

The USACE supports the National Inventory of Dams, a searchable online database that lists and describes over 90,000 major dams in the United States. The inventory reveals that the average age of major dams in the United States is over 60 years (USACE, 2022). Ho et al. (2017) find that owners need to repair, rebuild, or decommission dams based on their age and that efforts by regulators at the national, state, and local levels are insufficient to ensure safety of aging dams. Unless aging dams are maintained, rehabilitated, or decommissioned before their design lives expire, it is more likely that they will fail or that regulators will restrict the amount of water that may be impounded behind structures that predictably deteriorate as they age.

Major dams are owned by a wide variety of public and private owners with varying abilities to detect deficiencies as they manifest or to effect repairs due to limited financial means. A variety of materials including earth and concrete have been used in constructing dam and the quality and methods of construction vary. In addition, engineers design dams to meet unique physical conditions found at each site and to fulfill the varying purposes for the impounded water including agricultural and municipal uses, flood control, and recreation (ASDSO, 2019).

Page (2006) confirms that it is extremely difficult and expensive to change water delivery systems after construction because they are strongly path dependent. As evidence of the path dependent nature of dams, it took 16 years and $430 million to reconstruct Roosevelt Dam after heavy rains challenged its integrity in 1980 (Ester, 2006). Furthermore, the State of California repaired the spillways of Oroville Dam after a crisis in 2017 more quickly than Roosevelt Dam was reconstructed but costs exceeded $1 billion (Vartabedian, 2018; France et al., 2018).

Since 1850, about 4,000 fatalities have resulted from dam failures in the United States. The collapse of the South Fork Dam in Johnstown, Pennsylvania in 1889, which claimed 2,209 victims, caused over half of all fatalities caused by dam failures since the founding of the United States (National Research Council, 2012, p. 22). Although no one has established the exact total, Reisner (1986) found that over 400 died when the Saint Francis Dam collapsed in southern California on March 12, 1928, a few hours after William Mulholland, the legendary head of the Los Angeles Department of Water and Power, inspected the dam and dismissed concerns about leaks (p. 96-100).

In 2003, the ASDSO issued a report entitled *The Cost of Rehabilitating Our Nation's Dams: A Methodology, Estimate and Proposed Funding Mechanisms*. Leveraging data from the National Inventory of Dams (USACE, 2022), ASDSO developed a method to estimate aggregated cost to rehabilitate non-federal dams and non-federal high hazard dams. Since then, ASDSO has updated the estimates periodically as shown in Table 3. In 2019, the estimated cost to rehabilitate non-federal dams and non-federal high hazard dams was about $66 billion and $20.5 billion, respectively (ASDSO, 2019a):

Table 3

Costs to Rehabilitate Non-Federal Dams and Non-Federal High Hazard Dams

Year	*Funding needs, non-federal dams*	*Funding needs, non-federal high hazard dams*
2003	$34 billion	$10.1 billion
2009	$51.46 billion	$16 billion (($8.7 billion public; $7.3 billion private)
2012	$53.69 billion	$18.2 billion ($11.2 billion public, $7 billion private)
2016	$60.7 billion	$18.71 billion
2019	$65.89 billion	$20.42 billion

(ASDSO, 2019a)

In the 2019 update, the ASDSO estimated that $4.20 billion was needed to rehabilitate dams owned by the federal government with $2.93 billion of that amount needed to repair high hazard dams (ASDSO, 2019a). The amount needed to rehabilitate high hazard dams on an aggregated basis does not seem unreasonable; however, on a distributed basis, many private owners do not have the skills to monitor deteriorating dams or the financial capacity to repair and make them safe. As regards resilience, social capacities to conduct conversations about improving the resilience of downstream communities to the possible failure of systems of dams is limited by fragmented jurisdictional, legal, and liability regimes.

Although 4,000 victims have died as the result of failures of dams over the history of the United States, the number is small when compared to other large infrastructure systems that inflict thousands of injuries and fatalities every year. Under these circumstances, the public may have inconsistent or incommensurate attitudes toward systems of dams, and experts and stakeholders may be reluctant to take on the challenge of improving the architectural or governance characteristics of sustained adaptability of systems of dams.

Infrastructure of Dams: Definition

For purposes of the dissertation, I avoid metaphorical extensions of the word by concentrating on the physical aspects of one type of infrastructure: dams. Before inquiring into the governance of dams in the next chapter, I explore implications posed by the architectural characteristics of dams. Consistent with limiting the word infrastructure to its original physical sense, an introductory textbook for civil and environmental engineers defines “infrastructure” as “the system of **public works** of a country, state, region, or **municipality**” [emphasis in original] (Penn & Parker, 2012, p. 1). Except for nuclear power plants, no infrastructure projects harness the scale of geophysical forces that equal or exceed those associated with impounding millions of acre-feet of water behind huge major dams constructed out of massive quantities of earth or concrete. If sudden and unexpected events worsened by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires release those forces instantaneously, irreversibly, and catastrophically they can devastate downstream communities and test sustained adaptability of residents and organizations over the long term (Woods, 2015).

Carse (2016) points out that the definition of infrastructure in Oxford English Dictionary states that it is “a collective term for the subordinate parts of an undertaking; substructure, foundation.” The definition then segues to a more specific meaning as “the permanent installations forming a basis for military operations, as airfields, naval bases, training establishments, etc.” Similarly, according to Carse (2016), infrastructure is a collective term that “denotes a plurality of integrated parts” while supporting a “higher-order project” (p. 27), which is relevant to my definition of the infrastructure of dams. For purposes of my research, I define the term “infrastructure of dams” as the **path dependent, multiscalar, hierarchical, physical parts of dams and appurtenant structures that are integrated to maintain flows of water for human purposes**. Although this definition of the infrastructure of dams draws selectively on the definitions of infrastructure described above, the elements are limited to the architectural characteristics of dams and associated structures such as canals and levees. Before exploring them in more depth below, the following paragraphs briefly describe the six elements of the defined term of the infrastructure of dams.

1. *Path dependence*: The first element combines permanence with dependence in a term commonly used to study complex adaptive systems: path dependence (Puffert, 2009). To supply benefits like agricultural and municipal water, flood control, hydropower, or recreational amenities, infrastructures of dams follow predictable paths during development, design, and construction. The historical paths of the massive physical structures that constitute the architectural

characteristics of infrastructure of major dams are not adaptable in the short-term in response to surprises.

2. *Multiscalar*: The second element addresses infrastructures of dams as systems that supply resources such as water or services such as hydropower on several scales. Differing scales may interact in ways that prevent optimization. For instance, if the primary purpose of a dam is to conserve water for dry summer months, then operators assess levels of water in reservoirs by scales that show the size of the stock in the spring to assess whether enough water has been stored to meet demands that increase during the summer; however, this goal may conflict with other scales used to calculate flows of water needed to produce hydropower or supply recreational benefits. Increasing one scale may reduce the capacity of a reservoir to store excess water produced by surprising events like unexpected storms worsened by climate change. If excessive water flows at unanticipated times, operators may lower reservoirs during an emergency by opening spillways, which may reduce other services such as the production of hydropower or cause damage to downstream lands or properties (Phillips, et al., 2009).
3. *Hierarchy*: The third element refers to hierarchical networks in which several dams are embedded. In some systems of dams, the volume of water impounded by certain reservoirs may physically dominate dams and reservoirs downstream in the hierarchy. For instance, Roosevelt Dam is the only dam on the Salt and Verde Rivers with capacity reserved to store excess water produced by storms. By reserving a significant capacity to cope with possible excess water, the quantity of water impounded by Roosevelt Dam dwarfs the amount of water stored behind

the four major dams below it on the Salt River (USACE, 2022). Therefore, catastrophic failure of Roosevelt Dam would devastate the dams below it because they do not reserve space to absorb excess water. Coordinating hierarchical networks of infrastructures of dams requires careful monitoring, modeling, and memory of the knowledge infrastructure (Edwards, 2016; Phillips, et al., 2009).

4. *Integrated Parts*: The fourth element recognizes the integration of physical structures other than dams. For example, infrastructures of dams often incorporate canals, levees, hydropower generators, and recreational facilities that help to supply resources or services to communities. Within networks that include more than one dam, operators must coordinate all relevant structures. For instance, the Salt River Project manages its dams under a program that it calls the Project Reservoir Operations Plan (PROP), which coordinates operation of the reservoirs along with water produced by the Central Arizona Project and pumped from groundwater wells (Phillips et al., 2009).
5. *Maintenance*: The fifth element addresses the maintenance of the infrastructure of dams. Consistent with the second law of thermodynamics, dams degrade physically over time. During their service lives, dams pass through predictable lifecycle phases including design, construction, operation, maintenance, rehabilitation, and, finally, decommissioning or abandonment. In addition, standards by which experts design or assess infrastructures of dams change over time as knowledge increases, which should prompt owners to rehabilitate or decommission the structures as needed. Traditionally, designers looked to physically maintain infrastructures of dams by making them safe according to

deterministic standards based on stationary historical records. For instance, after heavy storms threatened dams on the Salt River in 1980, the USBR reassessed the capacity Roosevelt Dam, which was completed in 1911, and decided that it was not large enough. Therefore, the USBR tripled the inflow design flood when it redesigned the dam (Ester, 2006).

6. *Flows*: The sixth element refers to flows of water from infrastructures of dams. Stakeholders originally built dams to modulate or control flows of rivers to either to supply water for use by farmers or residents or to prevent or reduce damage caused by floods. For instance, the Phoenix metropolitan area would not exist in its present configuration without the modulation of flows of water provided by dams on the Colorado, Salt, and Verde Rivers. Over time, stakeholders converted farmland into communities that use the water stored in reservoirs for municipal purposes instead of irrigating crops. Although other methods of delivering water could support a smaller population in the Phoenix metropolitan area, it is difficult to imagine alternatives to dams that could support millions of residents.

Each of the six elements of the definition of the infrastructure of dams supplies insights into the safety, the traditional goal of the engineering of the architectural or physical characteristics of infrastructures of dams. Resilience is an emerging approach devoted to improving responses to hazards and risks that exceed existing standards and methods of safety. Improving the safety and resilience of the infrastructure of dams requires assessing relevant knowledge infrastructures, which Edwards (2016) defines as "robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds" (p. 3). In pairing infrastructure with knowledge, Edwards (2016) succumbs to the metaphorical extension of the word infrastructure that I bemoaned earlier. While conceding the inconsistency, I focus on one part of the relevant knowledge infrastructure as defined by Edwards (2016): *artifacts* in the form of physical dams, appurtenant structures, and downstream communities that the definition of the infrastructure of dams encompasses. The *people* and *institutions* described by Edwards (2016) constitute *social* aspects of the *socio*technical systems that co-produce infrastructures of dams, which the next chapter on governance characteristics of systems of dams addresses. Society inserts or, invoking the term used by Edwards (2003), *imbricates* the physical artifacts of dams into natural processes to modulate the physical flows of water. Focusing on physical artifacts that are at the heart of infrastructure of dams reveals and highlights criteria that influence or limit the pursuit of safety or resilience.

Knowledge infrastructures change over time. The traditional knowledge infrastructure related to the infrastructure of dams emphasizes safety by employing “fail-safe” measures like increasing control, armor, or strength of the physical elements of the infrastructure of dams to account for predicted changes in the size and periodicity of extreme weather events based on historical data (Ahern, 2011; Kim et al., 2017; Markolf et al., 2018; Park et al., 2013). Experts use fail-safe approaches standards like return periods (the “100-year flood”) or inflow design floods based on historical data to promote *safety, stability, and mitigation*. These standards inform the design and construction of physical artifacts associated with the infrastructure of dams but are not subject to revision during crises because the physical structures of the infrastructure of dams are path dependent and, therefore, not modifiable in the short term (Puffert, 2009; Busch, 2011).

Design and construction according to these standards meet expected challenges associated with stationary weather patterns but may not respond effectively or efficiently to surprising events that surpass those expectations.

In contrast, a “safe-to-fail” knowledge infrastructure concedes that predictions of the size and periodicity of surprising events like non-stationary extreme weather or terrorist attacks based on predefined standards are impossible because some events are unexpected and therefore not addressable by the standards. Plagued by the uncertainty of climate change, terrorism, or cyberattacks, safe-to-fail knowledge infrastructures look to increase *resilience, capacity, and adaptation* of both the architectural and governance characteristics of infrastructures of dams during and after crises. Effective responses displayed by the infrastructure of dams during and after crises are more critical than responses developed during the original design phase (Ahern, 2011; Kim et al., 2017; Markolf et al., 2018; Park et al, 2013). Operators do not have time to change the architectural characteristics of infrastructures of dams during or after surprising events such as terrorist attacks, which may impair or destroy major dams. In such cases, the resulting floods are overwhelming and unstoppable. Therefore, increasing the *resilience, capacity, and adaptation* of infrastructures of dams requires stakeholders to take steps *before* surprising events happen.

Experts knowledgeable about infrastructures of dams increasingly recognize the shortcomings of approaches based on fail-sale standards in the design of the infrastructures of dams. An emerging method called “risk-informed decision making” encourages stakeholders to expand the types and range of risks assessed to help make infrastructures of dams less dependent on deterministic standards devised to promote safe or fail-sale approaches (FERC, 2016; Regan, 2010: Scott, 2011). The question is whether risk-informed decision making sufficiently promotes safe-to-fail responses needed during crises and increase sustained adaptability. However, that is beyond the scope of my research.

Resilience

Real and perceived risks associated with climate change, earthquakes, terrorism, cyberattacks, or wildfires increasingly threaten infrastructure of all types. Perception of increased risk may be based more on psychological responses to science, data, or sensitivity than on actual risks established through a close reading of current scientific evidence and findings (Kahneman, 2011). Although scholars analyze many aspects of infrastructure including social, ecological, and technical systems (Markolf et al., 2018), this chapter concentrates on actual risks to physical aspects of the infrastructure of dams.

Since a megadrought has plagued the southwestern United States for over twenty years (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022), the question of whether the infrastructures of dams on the Salt and Verde Rivers are safe-to-fail may become more urgent when the megadrought ends. For instance, severe storms worsened by climate change have not tested the infrastructures of dams on the Salt and Verde Rivers since the USBR reconstructed Roosevelt Dam in 1996. Reconstruction raised the height of Roosevelt Dam by 77 feet with much of increased capacity reserved to absorb excess water; however, the USBR redesigned Roosevelt Dam according to deterministic standards like the inflow design flood aimed at making infrastructure of dams fail-safe, not safe-to-fail (Ester, 2006).

Woods (2015) reviews the literature and finds four different concepts of resilience; however, my research emphasizes the fourth concept: sustained adaptability. Since the physical, or architectural characteristics, of infrastructure of dams cannot sustainably adapt in the short-term to surprises that exceed standards based on historical records that guided the design and construction of dams, then governance characteristics must adapt in sustained ways as the consequences of crises unfold over prolonged periods of time. For instance, if a major dam like Roosevelt Dam fails, communities may need to find other sources of water and electricity provided by hydropower for years until owners reconstruct the dams and associated structures like canals or until stakeholders make alternative arrangements. Communities should consider improving the architectural and governance characteristics of infrastructures of dam *before* crises strike to facilitate synergies and tradeoffs needed to sustainably adapt by increasing safe-to-fail measures if current efforts to make them fail-safe do not hold. For instance, the Salt River Project now stores water in underground aquifers to supplement water stored in reservoirs (Salt River Project, 2022).

Consistent with a safe-to-fail approach, Hollnagle (2014) addresses the built environment and supplies the following definition of resilience, which is consistent with the concept of sustained adaptability described by Woods (2015): “the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both *expected and unexpected* conditions” (emphasis added) (p. 224). Traditional fail-safe approaches cover *expected* conditions; evolving safe-to-fail approaches address *unexpected* conditions that are sustainably adaptable. Improving the sustained adaptability of the infrastructure of dams requires shifting the prevailing knowledge infrastructure. Ahern (2011) found that fail-safe approaches emphasize stability and mitigation. In contrast, safe-to-fail approaches enhance adaptive capacity by allowing complex physical systems like infrastructures of dams to recover from disasters more quickly. Safe-to-fail approaches are consistent with Allenby & Fink (2005) who find that "enhanced resiliency is a rational strategy when the probability and specifics of a particular challenge are difficult to define" (p. 1034), which is the case with infrastructures of dams threatened by emerging threats like climate change.

Operationalization

William James, the philosopher who systemized the philosophy of pragmatism, stated: "The truth of an idea is not a stagnant property inherent in it. Truth *happens* to an idea. It *becomes* true, is *made* true by events. Its verity is in fact an event, a process: the process namely of its verifying itself, its veri-*fication*. Its validity is the process of its valid-*ation* (emphases in original)" (James, 2000, p. 88). In keeping with James (2000), this chapter focuses on how the safety (fail-safe) and resilience (safe-to-fail) of infrastructures of dams are verified and validated when they are operationalized by events and processes in the real world (Hollnagel, 2014).

Language is a linear construct that makes it difficult to explore and articulate possible safe-to-fail events that are contingent on multiple non-linear threats associated with the components of the definition of infrastructure of dams. The operation of the physical aspects of infrastructures of dams must work under both expected (fail-safe) and unexpected (safe-to-fail) conditions that occur in the real world. However, infrastructures of dams are not traditionally operationalized to handle unexpected surprises such as extreme weather events, earthquakes, or terrorist attacks that exceed standards like the inflow design flow, which are based on historical records. Monumental structures constructed of concrete, steel, and earth that make up the infrastructure of major dams cannot be changed in the short-term during disasters or emergencies. Therefore, operationalizing the sustained adaptability of the physical infrastructure of dams requires addressing tradeoffs among the six elements of infrastructures of dams.

Ideally, all six elements of the infrastructure of dams would be operationalized interactively and simultaneously in nonlinear ways subject to unpredictable feedbacks if surprises happen. However, the federalist system of government with multiple overlapping jurisdictions interferes with the ability of stakeholders to change the architectural or physical characteristics of infrastructures of dams in ways that promote sustained adaptability before surprising crises happen. For instance, agencies at the state and local level that influence the design, construction, and maintenance of the physical aspects of infrastructure of dams on the Salt and Verde Rivers include agencies below the federal level. These include the Arizona Department of Water Resources, which assesses the safety of Tempe Town Lake, and Flood Control District of Maricopa County, which addresses flood control and maintaining levees (City of Tempe, 2014). Efforts by state and local governments to promote safety or resilience of the infrastructure of dams is therefore uneven (National Research Council, 2012). Operationalization of the safety (fail-safe) and resilience (safe-to-fail) includes knowing what to do (responding), what to look for (monitoring), what has happened (learning), and what to expect (anticipating) (Hollnagel, 2014, p. 224-225; Edwards, 2016).

Architectural Characteristics of Infrastructures

The following addresses the six elements of the infrastructure of dams in more depth.

Infrastructure of Dams: Path Dependence

The National Inventory of Dams (NID), managed by the USACE, lists information on major dams in the United States. Based on legislative mandate, major dams meet one of the following criteria:

1. High hazard potential classification - loss of human life is likely if the dam fails,
2. Significant hazard potential classification - no probable loss of human life but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns,
3. Equal or exceed 25 feet in height and exceed 15 acre-feet in storage,
4. Equal or exceed 50 acre-feet storage and exceed 6 feet in height (USACE, 2022).

Until recently, the NID tracked 69 fields. All but three of the fields were accessible to users; however, the three fields – Condition Assessment, Condition Assessment Detail, and Condition Assessment Date – included specific and detailed information on the current condition of the dams but were only available by password to governmental users that the USACE approved. In Conclusion No. 4, the National Research Council (2012) complained about governmental restrictions on the access to "information critical to public risk awareness, mitigation, preparedness, response, recovery, and community capacity for adaptation" such as "dam and levee safety processes and products (such as inspections, Emergency Action Plans [EAPs], and inundation maps) are intended to support decision making and enhanced community resilience but are not readily available to all community members and stakeholders who make those decisions" (p. 5). According to National Research Council (2012), it is more difficult for stakeholders to improve the resilience, or sustained adaptability, of downstream communities to emergences related to infrastructures of dams without these types of information.

However, the USACE has revamped the NID since the National Research Council (2012) issued its complaint. On January 25, 2021, the USACE announced that it published Engineer Circular 1110-2-6075, "Inundation Maps and Emergency Action Plans and Incident Management for Dams and Levee Systems," in October 2020. The Circular "allows for the use and public dissemination of inundation maps in emergency action plans (EAP) and the National Inventory of Dams (NID)" and "provides the dam safety community access to critical information about residual flood risks from USACE dams and levees." The USACE advised that inundation maps will be available on the NID webpage in late 2021 (USACE, 2021, January 25).

At the ASDSO conferences in 2020 and 2021, representatives of the USACE confirmed that it has adopted an open access approach that encourages public dissemination of information including inundation maps (Ragon & Carey, 2020; Ragon et al., 2021). The revised NID is now a dynamic geographic information systems database with over 70 fields that authorized users may update in real time so that the data is more up to date. For instance, on May 1, 2021, the NID listed 91,457 dams with an average age of 57 years. However, on February 17, 2022, after the update the NID included 92,071 total dams with an average age of 61 years, which represents an increase of 614 dams and increase in average age of four years (USACE, 2022).

Many of the fields contain information relevant to an assessment of the physical aspects of the infrastructure of dams that are relevant to the six elements of the definition of the infrastructure of dams. For instance, the inventory lists age and the types of repairs made to Roosevelt Dam, which are relevant to the path dependence of that major dam. Users may download the data in the NID to assess path dependence and other characteristics (USACE, 2022).

Although many major dams are monumental structures that appear to be permanent, chances of failure increase as the structures age. Ho et al. (2017) confirm that due to insufficient efforts by owners or regulators at the national, state, and local levels many dams need repairs, reconstruction, or decommissioning. Puffert (2009) traces the origin of the term path dependence to an observation by Thorstein Veblen in 1915 that "technical interrelatedness" may "inhibit adaptation to changing conditions" (p. 247). Puffert (2009) uses standardization of railroad gauge, or width between rails, to illustrate the path dependence inherent in many large infrastructure projects. Unequal railroad gauges prevent wheels of railroad cars built to the width of one gauge from working on tracks with a different gauge. The incompatibility illustrates the technical interrelatedness to which Veblen referred. In the 1980s, Paul David and Brian Arthur rechristened "technical interrelatedness" as path dependence and used the concept:

> to explain how a process of economic change might 'remember' its history. In a path dependent process, multiple outcomes are possible, and the specific course of events determines which one of the possible outcomes is actually realized. Positive feedbacks in the process magnify the impact of idiosyncratic choices or other nonsystematic events, taking the process along

> one branching path rather than another. Fundamental or systematic factors still play a role, but the specific history of the process is crucial to determining the outcome. History matters. (Puffert, 2009, p. 7)

The concept of path dependence applies in many contexts. The “idiosyncratic choices” that take “the process along one branching path rather than another” resonates with the infrastructure of major dams that modulate flows of water to enables the development of downstream communities. The history of choices made in the design and construction major dams are embedded in path dependent physical structures that cannot be changed rapidly after surprising events that may be worsened by emerging threats like climate change.

Page (2006) counters increasingly ambiguous or illogical uses of the concept of path dependence by defining processes that display varying degrees of historical dependence. He stresses the significance of positive and negative externalities as well as increasing returns that promote dependence. Water delivery systems like infrastructures of dams are strongly path dependent because “for any two distinct histories, the outcome differs” (p. 102). For instance, after private interests were unable to fund and complete systems to deliver water to the arid farmlands around the lower Salt River, the USBR stepped in and completed Roosevelt Dam in 1911. As the first dam constructed under the Reclamation Act (1902), Roosevelt Dam inaugurated a distinctive path dependent history that still guides outcomes for infrastructure of dams in the Phoenix metropolitan area (Reisner, 1986).

Hommels (2005) found that cities have a type of permanence or obduracy not easily changed within short periods. Cities can be modified in time periods that approximate the typical span of human lives by "changing the taken-for-grantedness of its reality, and making its obduracy flexible" (p. 324). The physical aspects of the infrastructure of dams are also obdurate. Beyond built-in engineered components of dams that modulate flows of water such as outlet works and spillways, infrastructure of dams resist modification in the short term. Although owners and operators can reconstruct dams or expand the capacity of spillways or canals measured by seasons, years, or election cycles, the ability of the infrastructure of dams to sustain adaptability during the extremes of crises is severely limited or nonexistent. Although the USBR planned to raise the height of Roosevelt Dam before the crisis in 1980, it took 16 years after the crisis to complete the reconstruction of Roosevelt Dam in 1996 and, thereby, alter the course of its path dependence (Ester, 2006).

The obdurate and path dependent nature of dams encourages the construction or improvement of appurtenant physical artifacts like canals or levees that improve the overall sustained adaptability of systems to the remote possibility that the dams might fail during surprising events. Obduracy and path dependence also make it important to create and disseminate emergency action plans (EAP) to improve sustained adaptability of the governance characteristics associated with architectural characteristics of infrastructures of dams. However, modifying the architectural characteristics of major dams is expensive, time-consuming, and must be completed before crises erupt. EAPs promote the safety (fail-safe), not the sustained adaptability (safe-to-fail), of the infrastructure of dams. Stakeholders may integrate emergency action plans with those of downstream communities, which may improve safety but not sustained adaptability of the entire infrastructure of dams (National Research Council, 2012).

David Collingridge describes the "dilemma of control" that plagues many technologies by finding that "the social consequences of a technology cannot be predicted early in the life of the technology" because when "undesirable consequences are discovered" it has become "so much part of the whole economic and social fabric that its control is extremely difficult." Collingridge sums up by confirming the uncomfortable truth: "When change is easy, the need for it cannot be foreseen; when the need for change is apparent, change has become expensive, difficult, and time consuming (Collingridge, 1980, Preface). The dilemma of control applies to the infrastructures of dams because changing design is straightforward when dams are designed on paper or computer screens but become increasingly difficult if not impossible after construction has been put in place.

Other forces also influence the path dependence of architectural characteristics of infrastructures of dams. Market forces like water prices, policies that restrict or encourage agricultural or municipal uses, demographic factors such as population or housing density, environmental issues like pollution, legal and regulatory schemes such as the national dam safety program, and psychological and sociological factors such as status seeking behavior all influence the path dependence of the infrastructure of dams over the long term. The regulatory system is also path dependent, which further constrains flexibility needed to make the infrastructure of dams both safer (fail-safe) or more sustainably adaptable (safe-to-fail).

Stakeholders may reduce the path dependence of the infrastructure of dams by constructing other types of facilities that can store water. For instance, the Salt River Project now stores water in aquifers at the Granite Reef Underground Storage Project and the New River-Agua Fria River Underground Storage Project. By storing the water underground, it does not evaporate as quickly as it would from reservoirs. According to the Salt River Project, water stored in aquifers will supplement amounts stored in reservoirs behind infrastructures of dams (Salt River Project, 2022).

Since the temporal order of development constrains future options, systems that are strongly path dependent are locked-in by increasing returns as well as by positive and negative externalities. To garner the benefits including storage capacity, flood protection, hydropower production, and recreational amenities, infrastructures of dams regulate tremendous forces associated with huge quantities of impounded water. Infrastructures of dams are based on path dependent physical structures that cannot be modified easily, especially in the fleeting time frames associated with surprising events like terrorist or cyberattacks.

Infrastructure of Dams: Multiscalar

Major dams are often imposing physical structures that impound enormous quantities of water, often in coordination within a network of other dams. If Roosevelt Dam were to fail catastrophically with the reservoir at full capacity, the resulting flood would overtop and destroy dams downstream on the Salt River (Horse Mesa, Mormon Flat, Stewart Mountain Dams, and Tempe Town Lake). As an indication of the geophysical forces at issue with major dams, Tempe Town Lake impounds about 3,000 acre-feet of water. In contrast, the total capacity of Theodore Roosevelt Lake, the reservoir impounded by Roosevelt Dam, is 3.5 million acre-feet, which is more than 1,000 times larger than Tempe Town Lake. If Roosevelt Dam failed when completely full, the flood would inundate an area from the Highway 101 on the north to near South

Mountain on the south in the Phoenix metropolitan area (Maricopa County, 2021). Although likelihood of Roosevelt Dam failing catastrophically is exceedingly small, it is important to consider ways to increase sustained adaptability (safe-to-fail) of the infrastructure of dams if the worst happens.

Reservoirs slowly but inexorably fill with silt as the flows of incoming water erode and transport particles of earth into reservoirs where they are deposited. Over time silt reduces the physical capacity of reservoirs to store water or generate hydropower. As silt accumulates, reservoirs eventually become unviable, absent costly dredging and removal of the silt. Some environmentalists advocate removing dams to return rivers to free-flowing states. However, decommissioning dams is not as simple as breaching them and letting the water flow naturally. Silts that accumulate behind dams often contain heavy metals that are toxic to fish and other wildlife. Before returning a reservoir to a free-flowing river, owners and regulator must stabilize the silt and managed it over the long term (McCann and Paxson, 2016; Walls, 2020). However, decommissioning dams eliminates the need to consider the safety (fail-safe) or the resilience (safe-to-fail) of the associated infrastructure of dams.

Infrastructure of Dams: Hierarchy

After completion of the Roosevelt Dam in 1911, the USBR built three other dams on the Salt River below Roosevelt Dam (Horse Mesa, Mormon Flat, and Stewart Mountain) and two dams on Verde River (Horseshoe and Bartlett Dams). Theodore Roosevelt Lake, the reservoir created by Roosevelt Dam, can impound about 70 percent of the conservation of capacity of the entire reservoir system operated by the Salt River Project. Roosevelt Dam reserves over half of its capacity of 3.5 million acre-feet, or about 1,775,000 acre-feet, to store excess water generated by expected and unexpected events such as storms or snowpack runoff. However, Roosevelt Dam is the only dam on the Salt and Verde Rivers with capacity reserved to store excess water. For these reasons, Roosevelt Dam dominates the physical hierarchy of the network of infrastructure of dams operated by the Salt River Project.

About twenty years before Tempe Town Lake opened in 1999, officials at the USBR and the Salt River Project feared in February 1980 that Roosevelt Dam might fail. A series of storms drenched the watershed east of Phoenix, which forced the Salt River Project to open the spillways at Roosevelt Dam and the other dams below it on the Salt River to full capacity to pass excess water (Chin et al., 1991). Disaster was avoided when more predicted storms did not arrive.

Subsequently, the USBR upgraded the obduracy of the infrastructure of Roosevelt Dam by raising it 77 feet at a cost of $430 million. Since reconstruction of Roosevelt Dam in 1996, the southwestern United States has been suffering through a megadrought that began in 1995 (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). Tempe Town Lake opened in 1999, or three years after the reconstruction of Roosevelt Dam was completed. Since then, stakeholders have constructed significant development around the perimeter of Tempe Town Lake and levees around the reservoirs have been raised or strengthened to improve their safety (fail-safe); however, the levees have not been tested by surprising amounts of precipitation that may be worsened by emerging threats associated with climate change, earthquakes, terrorism, cyberattacks, or wildfires. All these factors interact in unpredictable ways within the hierarchy of challenges facing the network of infrastructure of dams on the Salt and Verde Rivers and affect their resilience (safe-to-fail).

Infrastructure of Dams: Integrated Parts

Consistent with the earlier discussion of the expansive use of the word infrastructure, Slota & Bowker (2017) find that science and technology studies (STS) has become *infrastructural* to other fields like organizational studies, media studies, and computer-supported cooperative work. However, infrastructure for Slota & Bowker (2017) is not “a single thing,” but relationships among “a bundle of heterogeneous things (standards, technological objects, administrative procedures)” that includes organizations and technologies (p. 531). This characterization of infrastructure by STS scholars is consistent with the definition of the infrastructure of dams, which integrate relationships of among many physical parts.

Infrastructures of dams integrate appurtenant physical artifacts on or near the dams such as outlet works and spillways as well as those that help deliver the resources or service made possible by dam such as canals, levees, and power lines. Canals feed water from reservoirs to downstream communities that use it. Levees channelize rivers so that they may better handle flows of the water that would be released if dams fail. Power lines deliver hydropower to industry and residents. However, canals, levees, and other parts of the infrastructure of dams are not infrastructural in and of themselves. Consistent with the findings of Slota & Bowker (2017), parts only become infrastructure after they are integrated into infrastructures of dams and the relationships among them are operationalized (Hollnagle, 2014). For instance, the Granite Reef Dam on the Salt River diverts water into two canals that serve the northern and southern parts of Salt River

Project service area at which point the canals become integrated into the relevant infrastructure of dams. Levees are integrated into the infrastructure when storms produce enough excess water to affect them. However, stakeholders traditionally construct canals and levees according to fail-safe standards that may not be sufficient to sustainably adapt to meet emerging challenges such as climate change, earthquakes, terrorism, cyberattacks, or wildfires.

Infrastructure of Dams: Maintenance

As the physical parts of the infrastructure of dams inevitably deteriorate over time, they should not be simply maintained according to standards that prevailed when they were originally designed and constructed but should be upgraded to meet current standards. However, it is also important to improve the sustained adaptability of the physical aspects downstream communities to cope with the possible physical failure of the infrastructure of dams caused or worsened by events that exceed standards based on historical data. Enhancing the sustained adaptability of the infrastructure of dams requires going beyond anticipating and preparing for known risks and modes of failure that lie within historical stationary norms (fail-safe). Improving sustained adaptability of infrastructures of dams requires capacity to absorb unanticipated risks such as unprecedented amounts of precipitation that fall within short periods or devastation resulting from terrorist attacks on the physical infrastructure of the dams themselves (safe-to-fail).

To appreciate the distinction between fail-safe and safe-to-fail approaches to the maintenance of the infrastructure of dams, it helps to compare paired concepts related to equilibrium and non-equilibrium paradigms in Table 4. Considering each pair sensitizes users to changing mindsets needed to understand the difference between fail-safe (equilibrium) and safe-to-fail (non-equilibrium) approaches (Novotny et al., 2010).

Table 4

Paired Concepts Related to Equilibrium and Non-Equilibrium Paradigms

Equilibrium	*Non-Equilibrium*
Modern	Postmodern
Linear	Networked
Rational	Chaotic
Closed, One Way	Open, Circular
Predictable	Uncertain
Hierarchy	Panarchy
Deterministic	Stochastic
Reductionist	Holistic
Tactical	Strategic
Disciplinary	Transdisciplinary
Terra firma	Terra fluxus

(Novotny et al., 2010, p. 142)

In the context of the resilient approach advocated by Ahern (2011), an equilibrium paradigm is consistent with a sustainability, or fail-safe, approach. The non-equilibrium paradigm aligns more closely with a sustained adaptability, or safe-to-fail, approach. Extending analyses and design responses created under an equilibrium to a non-equilibrium paradigm is difficult because the latter does not lead to reductionist fail-safe solutions embodied in physical structures. Therefore, designers often default to an equilibrium approach because it allows them to reduce potential responses to the physical artifacts. Nevertheless, looking at problems from a broader, more complex, non-equilibrium way leads to more sustainably adaptable or safe-to-fail analyses and decisions. When Roosevelt Dam was reconstructed, the design was based on the inflow design flood, which calculated the maximum capacity of the reservoir based on historical records with a safety factor added. However, if the real or perceived risks have increased due to emerging threats like climate change or if the threats are becoming more recognized, then downstream communities should consider preparing for the possibility that the infrastructure of dams may fail despite the best efforts of designers to make them fail-safe.

Novotny et al. (2010) describe strategies to improve the resilience of infrastructure including practicing multifunctionality, practicing redundancy and modularization, promoting (bio)diversity and heterogeneity, building, and restoring networks and connectivity, and building adaptive capacity. Table 5 lists strategies aimed at increasing urban resilience capacity related to dams and water control features along with attributes, characteristics, and examples. Jack Ahern, the author of Ahern (2011) included the strategies in a chapter in Novotny et al. (2010) that he prepared about the difference between fail-safe and safe-to-fail approaches.

Table 5

Strategies for Building Urban Resilience Capacity

Strategies	*Attributes/Characteristics*	*Examples*
Practice multifunctionality	Spatially efficient Economically efficient Builds a constituency of social / political support	Stormland wetlands
Practice redundancy and modularization	Risk-spreading Backup functionality Metasystems Decentralized, adaptable Can "contain" disturbance Flexible and adaptable Spatial segregated	Watersheds and "neighbor-sheds" Gray water recycling systems
Promote (bio)diversity and heterogeneity	Differential response to disturbance, stress, and opportunity Bio-library of memory / knowledge Complementarity of resource requirements	Urban bioreserves Conventional, ecosystem-based, and hybrid functional types
Build and restore networks and connectivity	Metasystems Circularity and redundancy Risk spreading Design for functions and flows	Ecological networks
Build adaptive capacity	Actions as opportunities for experimentation and innovation "Learn-by-doing" and "Safe-to-fail" design experiments	

(Novotny et al., 2010, p. 146)

The Multi-Jurisdictional Hazard Mitigation Plan (MJHMP) prepared by 28 jurisdictions in Maricopa County in 2015 (Maricopa County, 2015), which participants updated as part of a legislatively mandated five-year cycle (Maricopa County, 2021), describes efforts to mitigate and adapt to hazards that may threaten included communities due to a variety of hazards including dam failure. The MJHMP addresses dams and spillways in a spatially and economically efficient way. Consistent with mitigation and adaptation strategies, the Indian Bend Wash Greenbelt in Scottsdale, Arizona emphasizes environmental and social benefits of green infrastructure, which employs landscaped areas in potential flood zones that can absorb or pass excess water without failing at the boundaries. In contrast, grey infrastructure, which relies on grey concrete structures typical of many current infrastructures of dams, fends off challenges by making the parts stronger or higher but are brittle as physical boundaries are approached and may fail suddenly and catastrophically when boundaries are exceeded. Emerging threats such as climate change, earthquakes, terrorism, cyberattacks, and wildfires may increase chances that the capacity of physical boundaries will be exceeded. As described below, the Indian Bend Wash Greenbelt uses several strategies advocated by Novotny et al. (2010) to promote sustained adaptability by allowing parks and recreational areas to return to functioning as a wash to absorb occasional floods and reduce damage. Stakeholders concerned with infrastructures of dams may adopt similar strategies to mitigate or sustainably adapt to emerging threats like climate change.

In the 1950s and 1960s the USACE proposed constructing a massive concrete aqueduct through Indian Bend Wash but officials and citizens in Scottsdale convinced the USACE to alter its plans. As a result, stakeholders redesigned the wash as the Indian Bend Wash Greenbelt, which rapidly converts parks, playfields, and golf courses to a free-flowing wash during floods caused by heavy storms (Indian Bend Wash Greenbelt, n.d.). Allowing the greenbelt to return to its original function as a wash during floods reduces physical damage by promoting multifunctionality in a way that is more efficient spatially and economically as defined by Novotny et al. (2010).

On a physical basis, the Indian Bend Wash Greenbelt also meets other strategies advocated by Novotny et al. (2010). The Greenbelt is redundant and modular because it spreads the potential risk of physical loss across many properties and reduces chances of eastern and western parts of Scottsdale from becoming disconnected during floods as happened during the past floods that inundated larger geographical areas. The Greenbelt enhances backup functionality by returning parks and playgrounds to the original function of a wash. The project is decentralized, flexible, and adaptable because it retains flood waters that exceed the amounts expected based on existing standards. The Greenbelt spatially segregates the risk of damage to buildings by directing excess water into the wash and promotes biodiversity and heterogeneity in its differentiated response to disturbance, stress, and opportunity by operationalizing parks and playgrounds as a wash during floods. In addition, the Greenbelt complements resource requirements by building upon the ability of grassed landscapes to change physical functions when required to by changing weather conditions. The Greenbelt builds adaptative capacity by showing how residents can influence operations of large bureaucracies like the USACE to allow experimentation, innovation, and learning by doing, which promotes sustained adaptability (Woods, 2015) as well as the type of safe-to-fail experiments advocated by Novotny et al. (2010).

Inspired by the Indian Bend Wash Greenbelt during storms, the cities of Tempe and Phoenix may want to extend the strategies advocated by Novotny et al. (2010) to areas around and downstream of Tempe Town Lake. The analysis of Chin et al. (1991), which assessed floods caused by storms in February 1980 when officials feared that Roosevelt Dam might fail, may supply insights into how to extend greenbelt ideas to the areas around and below Tempe Town Lake. Although risks associated with climate change, earthquakes, terrorism, cyberattacks, or wildfires have increased since the late 1990s, major extreme weather events have not assaulted Roosevelt Dam or the Salt River since the megadrought started in 1995 (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022).

Roberge (2002) points out that stakeholders have altered the geomorphology of the Salt River in the Phoenix metropolitan area by “channelizing” the natural streambed with levees and other features that increase the efficient flow of water but also make them more intense. Levees designed and constructed to traditional standards address safety during expected events such as normal storms that are within historical expectations. However, they may not resist unexpected events like extreme weather events that exceed calculations made using deterministic standards when, for instance, the megadrought ends or terrorists destroy or impair a dam. Under these circumstances, unanticipated forces not assessed during the design phase may release torrents of water that cascade downstream on the Salt River for extended periods, which may “scour” sand and gravel around piers that support highway bridges and cause them to fail. Dangerous events of this sort have not occurred since the current mega-drought began in 1995, which may increase vulnerability of structures such as bridges downstream of dams when the megadrought ends (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). The resulting floods may exceed the fail-safe design of the channel when surprise strikes and tests the safe-to-fail capacity of the channelized stream and downstream communities that cannot sustainably adapt as the crisis unfolds. According to Roberge (2002), the Salt River was “braided” with sand banks and vegetation before channelization, which inhibited or absorbed flows and damages caused by excess water. By applying the strategies advocated by Novotny et al. (2010), the complexity of the channel increases, the force of deluges is resisted, damage caused to the physical structures on Salt and Verde Rivers is minimized, and sustained adaptability and safe-to-fail responses of the infrastructure of dams are improved.

Infrastructure of Dams: Flows

In simplified and abstract ways, stocks and flows define systems of many types. A stock represents a quantity of something real or imagined as measured at a specific point in time. A flow represents the rate at which a stock increases or decreases (Mirchi et al., 2012). For instance, stocks and flows may represent the amount or stock of electrons stored in a battery that are available to flow to the bulb in a flashlight when the switch is turned on, the capacity of transportation systems to handle the flow of vehicles during rush hours, or the amount of memory used by computers to store information as users open and modify documents. More relevant for infrastructure of dams, the stock of reservoirs increases as rains fall on watersheds above the structures or decreases as water flows out to irrigate crops or fill glasses of water. In short, infrastructures of dams are technical systems that modulate flows of water between stocks.

Infrastructures of dams include the dams themselves and stocks of water in reservoirs and associated structures such as canals and levees, which modulate flows of water from reservoirs. Downstream communities rely on stocks impounded in reservoirs to supply water for irrigation and municipal uses, hydropower, flood control and recreational amenities that support agriculture, industry, and domestic consumption. For instance, the difference between safe (fail-safe) or sustainably adaptable flows (safe-to-fail) depends on the rate and quantity of flows between infrastructures of dams.

If events stay within design standards, then infrastructures of dams handle the flows of water in a safe way (fail-safe); if, not, infrastructures of dams reveal whether they can sustain adaptability (safe-to-fail) to rapidly changes circumstances. After the USBR completed Roosevelt Dam in 1911, flows in the Salt River would occasionally exceed the design standards of the infrastructure of dams. For instance, after a series of storms in February 1980 showed the inadequacy of stock of the reservoir, the USBR raised the height of Roosevelt Dam and increased the capacity of the reservoir to reduce the possibility of excess water flowing down the Salt River under predicted storms based on standards using historical data (Chin et al., 1991; SRP Photo Archive. n.d.). The question is whether those efforts will be adequate ensure safety (fail-safe) during surprising events worsened by emerging threats such as climate change. If the architectural characteristics of current structures are insufficient, then the operators may need to improve the sustained adaptability (safe-to-fail) of the architectural characteristics of infrastructure of dams.

Although he believes in anthropogenic climate change, Pielke (2018) finds that construction of buildings and infrastructure in vulnerable areas increased damages and costs after extreme hurricanes. An analogous situation may be unfolding around the perimeter of Tempe Town Lake where owners have constructed many large residential and commercial buildings since the megadrought started in 1995 (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). When the megadrought ends, the resulting storms may test the sustained adaptability of the physical structures around Tempe Town

Lake in ways that have not occurred since the City of Tempe opened the facility in 1999. Emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires mean that infrastructures of dams have entered a new era in which fail-safe approaches based on standards like inflow design floods need to be supplemented by efforts to make the entire infrastructure of dams sustainably adaptable, or safe-to-fail. Pielke (2018) quotes Gilbert White, the famed geographer and disaster expert from the University of Colorado, who said: “Floods are ‘acts of God,’ but flood losses are largely acts of man” (p. 6). The following assessment criteria and metrics may help smooth transitions from systems of dams based on fail-safe approaches to ones based on safe-to-fail approaches.

Assessment Criteria and Metrics

Since conditions of each infrastructure of dams are unique, assessing them is context specific. Dams are not identical widgets produced on assembly lines that researchers test according to fail-safe standards based on statistical techniques. Instead, each dam is designed, constructed, operated, and maintained in ways that cannot be applied to other dams. Therefore, creating a comprehensive, quantitative, and generalizable scorecard to compare the safety or resilience of infrastructures of dams is a fraught endeavor. By identifying and defining six elements that underlie the physical aspects of the infrastructures of dams, this chapter has developed conceptual dimensions that can be used to develop and compare qualitative case studies (Yin, 2018) that use premortems to assess safety (fail-safe) and resilience (safe-to-fail) of infrastructures of dams (Kahneman, 2011, p. 264).

If researchers conduct, compare, and contrast more case studies of infrastructures of dams, then the elements of my definition of infrastructure of dams may change, which will influence methodologies used to perform future research including the types or content of interview or survey questions to be posed to knowledgeable people and the structure of qualitative or ethnographic observations or investigations. After completing case studies, researchers may be able to pick out patterns that will support creating maps or methods that may help experts or stakeholders discern interactions and balance the physical and social elements of the infrastructure of dams and to assess them individually or as nodes in networks. Below criteria for the safety and resilience are assessed for each of the six elements of the definition of infrastructure of dams:

1. *Path dependence*: To assess whether an infrastructure of dams is sustainably adaptable to surprise events and is safe-to-fail, researchers should investigate its path dependence. One important criterion of path dependence is the age of the infrastructure of dams. For instance, record rainfall that fell after a record drought threatened the spillways at Oroville Dam in California in February 2017, or about 50 years after the dam was completed in 1968 (France et al., 2018). Fifty years is the typical design life of dams (Ho et al., 2017) and, therefore, age is a useful to judge the path dependence of the infrastructure of dams.
2. *Multiscalar*: To assess whether an infrastructure of dams is sustainably adaptable to surprise events and is safe-to-fail, researchers should assess the scales and metrics of its components (Edwards, 2003). If during a premortem, participants discover that different scales apply, then the assessment should map them. Owners request and experts design major dams intended to respond to multiple

purposes on various scales that may conflict or harmonize in unpredictable ways. For instance, generating hydropower and conserving water within the network of the infrastructures of dams operated by the Salt River Project are in tension. Therefore, operators must assess conflicting objectives on a continuous basis by adjust the amount of water flowing through generators with to the volume of water stored in reservoirs (Phillips, et al., 2009; Ellison, 1999).

3. *Hierarchy*: To assess whether an infrastructure of dams is sustainably adaptable to surprise events and is safe-to-fail, researchers during a premortem should map how relevant hierarchies operate and assess whether emergency action plans increase the sustained adaptability of vulnerable communities to the possibility of that dams may fail partially or catastrophically. In 2014, the City of Tempe completed an emergency action plan that included disaster scenarios related to dams on the Salt River prepared by the USBR. The most disastrous scenario calculated that a flow rate of 2,600,000 cubic feet per second would start inundating the ASU campus seven hours after Roosevelt Dam failed "at normal conservation pool, causing overtopping and failure of Horse Mesa, Mormon Flat, and Stewart Mountain dams" below it (City of Tempe, 2014). The failure of the hierarchy that includes Roosevelt Dam and three other dams on the Salt River would overwhelm large areas of the Phoenix metropolitan area by flooding Tempe, Tempe Town Lake, and the ASU campus. However, the emergency action plan prepared by the City of Tempe focuses on safety (fail-safe), not sustained adaptability (safe-to-fail), approaches.

4. *Integrated Parts*: To assess whether an infrastructure of dams is sustainably adaptable to surprise events and is safe-to-fail, researchers should assess the operation of integrated parts during a crisis during the premortem. One of the integrated parts of infrastructure of dams are levees. Although this research focuses on dams in the United States, it is relevant to note that in 1938 the Nationalist government in China breached levees on the Yellow River to impede the Japanese invasion. Dutch (2009) called the resulting flood, during which the Chinese government estimates that over 800,000 people died, “the largest act of environmental warfare in history.” If terrorists bombed Roosevelt Dam, the failure would devastate integrated parts of the associated infrastructure of dams such as levees around and below Tempe Town Lake. Therefore, researchers should map integrated parts to be able to assess of the sustained adaptability of infrastructure of dams.
5. *Maintenance*: To assess whether an infrastructure of dams is sustainably adaptable to surprise events and is safe-to-fail, researchers need to understand how, in what ways, and to what extent standards such as the inflow design flood have been used in the design, operation, maintenance, and regulation of infrastructures of dam and assess during premortems their usefulness in facilitating safe-to-fail approaches. After a series of storms endangered Roosevelt Dam in 1980, the USBR proposed constructing a flood control dam at confluence of Salt and Verde Rivers, which the Department of the Interior rejected (Espeland, 1998). Instead, the USBR tripled the inflow design flood to 3,000,000 acre-feet over 16-day period with peak of 654,000 acre-feet on the third day (Ester, 2006).

Although an enormous increase over the earlier inflow design flood, it may not make the infrastructure of dams more sustainably adaptable to events that worsened by emerging threats such as climate change or terrorist attacks.

6. *Flows*: To assess whether an infrastructure of dams is sustainably adaptable to surprise events and is safe-to-fail, researchers should assess the operation of relevant stocks and flows during a crisis as part of premortems. During a safe-to-fail assessment, it is important to map the stocks and flows in the area of the infrastructure of dams under study and to assess if and how they are sustainably adaptable during a surprise event.

Scholars define many templates to analyze infrastructures or large-scale technologies. In his celebrated analysis of "normal accidents" involving high risk technologies, Perrow (1984) finds that dams are linear, not complex, systems that are nevertheless tightly coupled. Before the advent of emerging threats like climate change, Perrow (1984) finds that accidents involving dams are foreseeable and avoidable. Therefore, he recommends tolerating and improving them, not abandoning or restricting them. To evaluate high risk technologies, Perrow defines an acronym, DEPOSE, to address the following six elements: design, equipment, procedure, operators, supplies and materials, and environment.

Star & Ruhleder (1996) defined an "ecology" of infrastructure with the following characteristics: embeddedness, transparency, reach or scope, learned as part of membership, links with conventions of practice, embodiment of standards, built on an installed base, and becomes visible upon breakdown.

Gersonius et al. (2010) list the following system capacities defined by another scholar to define the architecture of dams: threshold/resistance capacity; coping capacity; recovery capacity; and adaptive capacity. The National Academy of Sciences (2012) argues for the following elements: plan for, absorb, recover from, and adapt to actual and possible disruptive events. Park et al. (2013) find four socio-technical processes: sensing, anticipating, adapting, and learning. Hollnagel (2014) claims that if performance of systems is to be resilient, then they must respond, monitor, learn, and anticipate. Grabowski (2017) argues for a framework based on dams as systems with interrelated political, financial, environmental, social, and technological dimensions.

In an article addressing resilience metrics, Eisenberg et al. (2014) lists the following domains listed by the Network Centric Organization (Alberts & Hayes, 2003):

- Physical: the engineering capabilities of infrastructure or devices, efficiencies, and network structures. This includes all data collection equipment and measurable real-life system components;
- Information: the usage of what we measure and know about the physical domain, including data use, transfer, analysis, and storage;
- Cognitive: human processes, i.e., translating, sharing, and acting upon knowledge to make, communicate, and implement decisions throughout the system; and
- Social: interactions and entities that influence how decisions are made, including government regulations, religions, cultures, and languages. (Eisenberg et al., 2014)

Table 6 describes metrics that researchers may use to assess functioning of the physical infrastructures of dams to threats or disturbances caused by surprises. Table 6 is adapted from three produced by Eisenberg et al. (2014). The vertical columns are criteria defined by the National Academy of Sciences (2012): prepare, absorb, recover, and adapt. The horizontal rows are the elements of my definition of the infrastructures of dams. The metrics focus on networks of infrastructures of dams in anticipation of comparing the safety (fail-safe) or resilience (safe-to-fail) of two or more infrastructures of dams.

Table 6

Elements of Infrastructure of Dams Evaluated Against Functions

	Prepare	Absorb	Recover	Adapt
Path Dependence	Percent of dams or structures that are over 50 years old or that have not failed or lost function	Length of time needed to reconstruct or rehabilitate dams or structures to maintain functions	Assess time between disturbances and restoration of functions of dam or structures	Compare time needed to modify functions of dams or associated structures to conditions before disturbance
Multiple scales	Assess, describe, and map scales needed dams or structures to function	Ability of dams or structures to detect disturbances to scales and the amount of time to absorb impacts	Assess time to restore interactions between scales when hazards threaten or disturb dams or structures	Assess ability of dams or structures to adapt to disturbing trends among scales
Hierarchy	Assess and describe the interactions between levels of hierarchy among dams or structures when threatened or disturbed	Assess the ability of dams or structures to change operations among levels of hierarchy when threatened or disturbed	Assess ability of dams or structures to recover from threats or disturbances to hierarchy	Assess adaptations made to dams or structures after threats or disturbances to hierarchy

Integrated parts	Assess, describe, and map integration between the parts of dams or structures	Assess and describe the ability of dams or structures to absorb threats or disturbances to integration of parts	Assess ability of dams or structures to recover from threats or disturbances to integration of parts	Assess adaptations made to dams or structures after threats or disturbances to integration of parts
Maintenance	Assess and describe the maintenance schedules and repair work on dams or structures	Assess and describe maintenance of dams during threats or disturbances	Assess ability of dams to recover maintenance function after threats or disturbances	Assess adaptations or modifications to maintenance after threats or disturbances
Flow	Assess, describe, and map threats and disturbance to flows delivered by dams or structures	Assess and describe alternations to flows of dams or structures after threats or disturbances	Assess ability of dams or structures to recover flows after threats or disturbances	Assess adaptations or modifications to flows after threats or disturbances

(National Academy of Sciences, 2012; Eisenberg et al., 2014)

As the elements for each infrastructure of dams are assessed during premortems, it is likely that one or more other elements may be affected in ways that may become clear. For instance, increasing storage capacity of a dam may make it more path dependent. As experts and stakeholders conduct more premortems, patterns may appear that may facilitate the development of maps that will help decision makers assess and compare the infrastructures of dams by region, watershed, type of dam or appurtenant structures, or other useful categories. Since dams rarely fail in the United States, statistically validated data points are not available to assess the sustained adaptability of the infrastructure of dams. Therefore, stakeholders may use premortems to conduct assessments for infrastructures of dams. If the risks associated with climate change, earthquakes, terrorist attacks, cyberattacks, or wildfires are increasing, stakeholders must conduct premortems before surprising events strike.

Conclusion

To assess operationalization (Hollnagel, 2014) of resilience with reference to the knowledge infrastructure (Edwards, 2016) that informs the architectural characteristics of sustained adaptability of resilience as conceptualized by Woods (2015), this chapter described the increased use of the word infrastructure since the 1960s; defined the infrastructure of dams consisting of six elements; explored the current knowledge infrastructure of the infrastructure of dams that emphasizes traditional fail-safe approaches to *safety, stability, and mitigation* and argued for increasing attention to safe-to-fail operations that promote *resilience, capacity, and adaptation*; illustrated the sustained adaptability of the infrastructure of dams as a relevant concept of resilience; explored the operationalization of efforts to make the network of infrastructure of dams more sustainably adaptable; and assessed various attempts frame the architecture of infrastructures. The chapter also argued that surprising events associated with emerging threats such as climate change, earthquakes, terrorism, cyberattacks, and wildfires may challenge infrastructures of dams.

CHAPTER 3

GOVERNANCE CHARACTERISTICS OF MAJOR DAMS

Two chapters address the social and technical aspects of dams separately. Chapter 2 focuses on the technical aspects by describing and assessing the architectural or physical characteristics of the "infrastructure of dams," a term defined and analyzed in terms of six elements. In a complementary undertaking, this chapter explores the social aspects by describing and assessing the governance or social characteristics of systems of dams. Taken together, the two chapters supply a flexible but robust conceptual framework needed to study the architectural and governance characteristics of systems of dams that will be explored further in my analysis of interview transcripts, conference presentations and papers, and governance documents in Chapter 4 and the case studies in Chapters 5 and 6. This chapter analyzes the governance, or social, characteristics of systems of dams primarily through pivotal federal laws that demarcate the appearance of sociotechnical imaginaries that continue to influence attitudes of experts and stakeholders relevant to systems of dams.

To reiterate, my research investigates whether, to what extent, and in what ways the resilience of dams, associated structures such as canals and levees, and downstream communities is operationalized (Hollnagel, 2014) within knowledge infrastructures (Edwards, 2016) that inform and support the *governance (social)* or *architectural (technical)* characteristics of sustained adaptability (Woods, 2015) to address emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires. For the purposes of my research, resilience is conceptualized as sustained adaptability, which Woods (2015) describes "as network architectures that can sustain the ability to adapt to future surprises as conditions evolve" (p. 5). Woods (2015) further explores the concept of sustained adaptability by posing three questions, one of which is: "What governance or architectural characteristics explain the difference between networks that produce sustained adaptability and those that fail to sustain adaptability?" (p. 8). According to Woods (2015), governance characteristics consistent with sustained adaptability balance tradeoffs that constrain networks. Therefore, this chapter analyzes how governance characteristics such as relevant laws and policies mediate tradeoffs needed to sustain the adaptability of dams, associated structures, and downstream communities.

By applying the concept of networks to dams, researchers can view them as nodes that modulate flows of water from natural sources for human uses. Unprecedented or surprising conditions such as weather events caused or worsened by climate change may disrupt the safe modulation of flows of resources such as water and services such as recreational amenities by testing the sustained adaptability of entire systems of dams. The term network emphasizes the interconnected and interrelated nature of dams, associated structures, and downstream communities. Therefore, this chapter explores the networking of complex sociotechnical systems of dams.

According to my theoretical framework, safety includes measures taken to reduce or eliminate expected or known modes of failure such as overtopping of dams that owners, designers, and regulators design and construct into the architectural characteristics of dams and associated structures. As described below, laws related to the safety of dams appeared periodically at the federal level to address issues that have risen to the top of the "garbage can" (Kingdon, 2010). The first key federal law that specifically addressed dams was the Reclamation Act (1902), which promoted development of arid lands in the western United States through the construction of water projects; however, the Act does not mention safety. Seventy years later, Congress passed the National Dam Inspection Act (1972) to address safety after a series of failed dams including of Buffalo Creek Dam in West Virginia, which caused 125 deaths. However, the USACE did not complete inventories and inspections required under the Act before Teton Dam failed catastrophically in 1976. After this disaster, the USACE pursued requirements mandated in the National Inspection of Dams Act more aggressively, After the failure of Kelly Barnes Dam in 1977 in Georgia, the home state of President Carter, added fuel to efforts ignited by the Teton Dam disaster, Congress passed the Reclamation Safety of Dams Act (1978). Later, Congress put National Dam Safety Program in place by enacting the Water Resources Development Act (1996).

Since the laws do not explicitly define the safety of major dams, policy makers do so. At the federal level, improved knowledge about safety is incorporated into policy documents such as standards, guidelines, and regulation issued by relevant bureaucracies such as the USBR, the USACE, and FEMA (Interagency Committee on Dam Safety, 2004). At the local level, emergency action plans and policy measures like building codes address safety of downstream communities.

This chapter argues that current laws and policies about the safety of systems of dams may not sufficiently promote governance characteristics consistent with the sustained adaptability that would be needed to deal with surprising or unexpected events including those caused or exacerbated by climate change, earthquakes, terrorism, cyberattacks, or wildfires. If unexpected events exceed safety measures designed and constructed into architectural characteristics of dams and associated structures when they were built or rehabilitated, then the governance characteristics associated with the sustained adaptability of downstream communities must respond. For instance, after the crises at the Oroville Dam in 2017 and the Edenville Dam in 2020, residents living in downstream communities evacuated according to the governance characteristics of each system of dams. If architectural characteristics of systems of dams are impaired or overwhelmed, resources and services provided by systems of dams may be diminished, disrupted, or interrupted for extended periods of time until the owners replace or repair the dams or alternatives are put in place. For instance, failures of major dams may reduce or interrupt hydropower, make recreational activities like boating and fishing on reservoirs unavailable or dangerous, or inundate downstream communities.

To assess the governance of major dams, it is important to understand the overall profile of major dams in the United States. Background information helps experts and stakeholders assess responses aimed at bridging the fragmentated federalist governance regimes needed to improve the sustained adaptability of systems of dams. Safety of major dams improved significantly after the failure of Teton Dam in 1976, which prompted passage of the Reclamation Safety of Dams Act (1978).

The USACE operates an online National Inventory of Dams (NID) that includes information on over 90,000 major dams in the United States. Major dams meet one of the following criteria:

1. High hazard potential classification - loss of human life is likely if the dam fails.
2. Significant hazard potential classification - no probable loss of human life but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.

3. Equal or exceed 25 feet in height and exceed 15 acre-feet in storage.
4. Equal or exceed 50 acre-feet storage and exceed 6 feet in height (USACE, 2022)

Beginning in 2020, the USACE upgraded the NID to improve its usefulness by allowing registered users to dynamically update data through a geographic information database that allows users to access to inundation maps (Ragon & Carey, 2020; Ragon et al., 2021). The NID includes data and information that can help experts and stakeholders assess the safety and resilience of major dams (USACE, 2022). Owners such as the USBR or the USACE, regulators such as FERC, and various agencies at the state level regularly inspect dams.

The National Inventory of Dams reveals many helpful facts about major dams in the United States. For instance, depending on the site and needs of the owner, dams may serve several purposes at the same time. Many stakeholders may be surprised to learn that as of February 19, 2022, the most popular purpose of dams in the NID – at 30 percent – is recreational activities. Other purposes of the 92,071 major dams listed on that date include flood control (17 percent); fire protection (11 percent); irrigation (8 percent); water supply (5 percent); and fish and wildlife (4 percent). Only about 2 percent of dams generate hydropower. Eight percent of dams are listed as “underdetermined” or “other,” which may mean that they address multiple purposes (USACE, 2022; Lane, 2008, p. 2). The diversity of purposes of dams may cause conflicts and contribute to the complexity of the governance characteristics of laws or policies across all types of dams.

Although earthen embankments make up about 80 percent of dams, dams vary in size and location, which complicates governance characteristics of dams because standards, guidelines, and regulations must address vastly different contexts. The design life of dams is typically between 50 and 100 years (Ho et al., 2017). Therefore, with an average age of over 60 years, owners will increasingly need to rehabilitate or decommission deficient major dams to prevent regulators from reducing storage capacities to compensate for threats associated with deterioration (USACE, 2022). Reducing storage of water in reservoirs to absorb excess waters also decreases the amount of water available for irrigation and municipal uses and constrains hydroelectricity production. This illustrates the conflicting tradeoffs that plague the operation of multipurpose dams.

Private owners own 63 percent of major dams with local governments owning about 20 percent, states about 7 percent, and public utilities about 4 percent. To the surprise of many stakeholders, the federal government owns less than 4 percent of major dams, but they include iconic structures like Hoover Dam and Grand Coulee Dam. States and local jurisdictions such as municipalities own about 25 percent of major dams (USACE, 2022). These percentages track with the fragmentation inherent in the federalist system of government in the United States, which combines a central, or federal, government with state and local governments in a complex political system, which complicates efforts to fund, operate, maintain, regulate, and decommission dams in an integrated and coherent manner.

In 2019, the ASDSO estimated that it would cost $4.78 billion to rehabilitate 3,828 federal dams and $65.89 billion rehabilitate 87,640 non-federal dams (ASDSO, 2019a). However, budgets of owners under current governance characteristics are not sufficient to rehabilitate or decommission deficient dams (Walls, 2020). My research finds that fragmentation in ownership of dams and disjointed and adversarial liability regimes reduce or inhibit the willingness of stakeholders to take part in conversations aimed at improving the governance characteristics needed to promote the sustained adaptability of systems of dams. In addition, variation in the sophistication, expertise, and financial resources of the owners of dams complicates inspection, operation, maintenance, and reconstruction of deficient dams.

The wide variety of purposes, owners, types of construction, and age of major dams complicates efforts to improve governance of safety and resilience. However, each system of dams is unique, which means that laws, policies, guidelines, and standards must be flexible to allow differentiated responses to meet the needs of the unique circumstance associated with each system.

However, scientific research about climate change, earthquakes, terrorism, cyberattacks, or wildfires is advancing faster than changes to relevant laws or policies (Vahedifard et al., 2017). Although the USACE recently upgraded the NID to improve the *safety* of major dams and downstream communities by providing access to inundation maps (Ragon & Carey, 2020; Ragon et al., 2021), it may want to consider additional modifications or extensions of the NID aimed at including data that would improve sustained adaptability of entire systems of dams. One possibility is to combine data from the NID with data in the Resilience Analysis and Planning Tool (RAPT), a free online geographical information system model operated by FEMA that allows “emergency managers and other community leaders to examine the interplay of census data, infrastructure locations, and hazards, including real-time weather forecasts, historic disasters and estimated annualized frequency of hazard risk.” (USACE, 2022; FEMA, 2022; Edwards, 2016; Woods, 2015).

Sociotechnical Imaginaries

I argue below that several sociotechnical imaginaries related to the governance characteristics of dams in the United States have formed since the middle of the 19th Century and continue to influence attitudes of experts and stakeholders toward systems of dams. According to my heuristic analysis, the most recent imaginary appeared after the failure of Teton Dam in 1976; it encouraged stakeholders to improve safety of the physical structures of major dams and is the imaginary most relevant to my inquiry. However, my research finds that stakeholders do not assess the *resilience* of both the architectural or governance characteristics of systems of dams to meet challenges posed by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires. If my assessment is accurate, then decision makers should consider assessing and modifying both architectural and governance characteristics of major systems of dams according to the multiple scales on which systems of dams operate to increase sustained adaptability.

During his description of his multiscale analysis of infrastructure, Edwards (2003) points out that Langdon Winner asserted in *The Whale and the Reactor* (Winner, 2010) that infrastructures act like laws in that they impose limits (p. 6). Laws related to the construction of dams in the 20th Century reflect the appearance of distinct and durable normative consensuses toward the governance and architectural characteristics of dams that culminated with concerns about their *safety*, which justifiably continues to dominate the perspective of professional groups such as the ASDSO despite efforts by others to promote other preexisting consensuses such as reclamation. Nevertheless, I found that a normative consensus has not developed about the *resilience* of systems of dams that embraces the downstream communities that they serve.

In addition to describing a “garbage can” model in which three independent streams of problems, policies, and politics interact in unpredictable ways, Kingdon (2010) finds that the content of ideas is integral to the consideration and enactment of laws and policies. Ideas are not simply rationalizations or smokescreens. Participants evaluate the content of ideas, debate them, marshal evidence, solve puzzles, and address dilemmas or tradeoffs. Kingdon (2010) quotes John Maynard Keynes to support his contention that working through content as opposed to lobbying or organizing political power is more typical of the policy making process: “I am sure that the power of vested interests is vastly exaggerated compared with the gradual encroachment of ideas” (p. 125).

Sociologists refer to the consensuses discussed above as imaginaries, which has been extended by science and technology studies scholars to sociotechnical imaginaries. Taylor (2002) found that imaginaries embody rules, values, institutions, and symbols that are common to groups and allows them to imagine themselves and their environment. Sarewitz (1996) and Appadurai (2004) agree that imaginaries are not illusions or fantasies. Appadurai (2001) maintains that imagination does not connote escape, pastime, or simply contemplation, but is a disciplined social practice in which work and negotiations are conducted among agents. Appadurai (2004) highlights the need to understand imaginaries that apply to multiple cultures depending on their ability to aspire. For instance, poverty limits the capacity of communities to aspire to or imagine better futures because of weaker links, poorly defined pathways, and worries about immediate needs.

The concept of sociotechnical imaginaries incorporates and extends the concept of imaginaries by recognizing the capacity of science and technology to shape them at various levels. In the context of science and technology studies, Sheila Jasanoff defines sociotechnical imaginaries as “collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology” (Jasanoff, 2015, p. 4). Applying her earlier work on co-production to sociotechnical imaginaries, Jasanoff finds that scientific processes mold social outcomes, which in turn shape scientific practice. In science and technology studies, co-production is not limited to cognitive processes but seeks to understand how social relations and order shape the production of knowledge (Jasanoff, 2004). Therefore, truth claims are linked to values and objectives of people who create them and to how they can be empowered or disempowered by changes in the status quo. Although systems of dams are heterogeneous and must be assessed individually within each context by experts and stakeholders, laws and policies embody ideas related to overarching governance and architectural characteristics.

Jasanoff and Kim (2009) contrast sociotechnical imaginaries when comparing contests over knowledge, power, and politics in the development of nuclear energy policies in the United States and South Korea. Jasanoff and Kim (2009) use sociotechnical imaginaries to illustrate cultural aspects that coproduce desires for futures based on preparing or modifying policies and institutions. They find that institutions such as norms, practices, identities, and discourses help cultures interpret forms of knowledge in society (Jasanoff, 2004).

Consistent with the analysis of Jasanoff (2004), Jasanoff, (2009), and Jasanoff (2015), my research describes a set of durable sociotechnical imaginaries that encapsulate ideas that continue to influence the governance characteristics of systems of dams. Therefore, the resulting sociotechnical imaginaries are useful in understanding challenges that successively rise to the top of the metaphorical garbage can of Kingdon (2010). My research speculates that as experts and stakeholders learn more about emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires, they will increasingly see the benefits of improving the resilience conceptualized as sustained adaptability of systems of dams, which may become the next sociotechnical imaginary. The following describes the appearance of seven durable sociotechnical imaginaries and the possible emergence of an eighth based on resilience.

Deductive Imaginary: William Gilpin

In the 19th century, governance of irrigation and municipal water projects in the western United States was based on narratives that now seem delusional. In an entertaining article with an intriguing title, *Geopolitics with Dew on It*, DeVoto (1944) describes assertions concocted by William Gilpin in his magnus opus, *Mission of the North American People, geographical, social, and political* (Gilpin, 1874). As an explorer, politician, and man of letters and science who President Lincoln appointed as the first governor of the territory of Colorado in 1861, Gilpin asserted that there “was no limit to its productiveness” of the lands between the Rockies and Sierra Mountains because “crops would be raised by scientific irrigation, independent of the variation in rainfall" (DeVoto, 1944, p. 320). Summarizing Gilpin's approach, DeVoto (1944) concedes in a long quotation worthy of careful consideration that Gilpin's:

> science was early nineteenth century, which is to say that much of it was a priori, deduced, generalized, falsely systematized, and therefore wrong. Much of his extrapolation, though based on persuasive data and worked out with rigorous logic, was sheer fantasy. Nevertheless, his system contains also remarkable intuitions and anticipations, and his vision of the future in America, perfumed though it is with the optimism of a simpler age, may be worth scrutiny today. In it one sees America learning to think continentally, at a moment when the nation could exult over achievements unlike anything else in history. It is an America still ignorant of frustration, still confident, still sure that the future will be majestic. Also it is an America vividly aware of energies which, though we have grown progressively to disregard them, have not yet spent their force. (p. 314-315)

Although Gilpin's science did not address safety or resilience, his optimism was consistent with the robust attitude of settlers who homesteaded the western United States. They focused on economic opportunities while ignoring or overcoming physical, social, environmental, or safety risks in a rush to develop wide open but arid lands. However, the unrealistic narratives spun by Gilpin and others led to enormous environmental damage and increased risks of all types to settlers (Reisner, 1986).

In one of his fantastical findings, Gilpin described the Isothermal Zodiac, a 30-degree band that he said circles the globe and supplies the type of climate and geography that is beneficial to civilization. According to Gilpin's conception, the Axis of Intensity, which was an "isothermal line representing a mean average temperature of 52 degrees Fahrenheit," lies within the boundaries of Isothermal Zodiac and connects "the primary cities of history" (DeVoto, 1944, p. 315). In another fantasy, Gilpin deduces that mountains on either side of the North American continent create a concave bowl known as the Basin of the Mississippi, which Gilpin calculates could support a population of 1,300,000,000. However, the Plateau of North America situated between the Rockies and the Sierra Nevada surpasses the promise of the Basin of the Mississippi because it could support an unlimited population. According to Gilpin (1874), there was "no limit to its productiveness" because "crops would be raised by scientific irrigation, independent of the variation in rainfall" (p. 320). Motivated in part by the deductive sociotechnical imaginary of the type described by Gilpin (1874) and many others, hardy souls homesteaded arid lands in the western United States with the expectation that irrigation was the means of salvation.

Inductive Imaginary: John Wesley Powell

In contrast to the fantasies spun by Gilpin, Stegner (1992) in *Beyond the Hundredth Meridian: John Wesley Powell and the Second Opening of the West* chronicles the career of John Wesley Powell who led a pioneering and perilous expedition down the Grand Canyon in 1869. Based on information gathered during the expedition, Powell et al. (1879) produced a well-researched report entitled, *Report on the lands of the arid region of the United States: With a more detailed account of the lands of Utah. With Maps,* that Powell hoped would inform and guide the rational governance of development in the western United States. In contrast to the "a priori, deduced, generalized, falsely systematized" science of Gilpin (DeVoto, 1944, p. 314), Powell produced a fact based, inductive, specific, and realistically systemized report on the conditions of the landscape in the west (Powell et al., 1879).

Consistent with the title of Stegner (1992) – *Beyond the Hundredth Meridian* – the 100th meridian is a longitudinal meridian that bisects the United States from North Dakota to Texas into two parts. To the east of the 100th meridian, lands receive more than 20 inches of precipitation per year, an amount sufficient to raise crops without irrigation. In contrast, lands to the west of the 100th meridian receive less than 20 inches of precipitation per year and, therefore, require irrigation to grow crops despite the popular myth in the 19th century that rains followed the plough (Powell et al., 1879).

In contrast with the *deductive* sociotechnical imaginary described by Gilpin (1874), Powell et al. (1879) *inductively* found that stakeholders could only develop western lands through irrigation. However, contrary to Gilpin (1874), he recognized that there were limits to the productiveness of these arid lands. For instance, Powell et al. (1879) focused its investigation on Utah and found that only 2.8 percent of its 80,000 square miles were irrigable.

After completing an expedition down the Grand Canyon in 1869, Powell was the director of the United States Geological Survey from 1881 to 1894. He wanted to survey the entire country with methods developed during the expedition and documented in the report; however, politics, bureaucracy, and the lure of other interests interfered with his ambitions. Nevertheless, law and policy makers did not heed his careful and comprehensive approach to the governance of development. Instead, they promoted rapid and piecemeal development that circumvented natural limits by engineering responses that that focused on the construction of dams and associated structures. As part of the process, the federal government gave railroad companies enormous amounts of land to encourage development of the western frontier. Encouraged by advertisements blandished by the railroad companies and false narratives promoted by Gilpin and others, farmers jumped at the opportunity to settle arid regions (Stegner, 1992). A prophet with no honor in his country, stakeholders ignored the admonitions of the inductive sociotechnical imaginary of Powell et al. (1879) in favor of rushing to “reclaim” the western United States.

Reclamation Imaginary

In *Cadillac Desert: The American West and its Disappearing Water*, Reisner (1986) critiques governance characteristics of water projects from environmental and economic points of view during the boom in the construction of dams in the 20th century. Earlier, in the 19th Century, the federal government encouraged settlement of the western part of the United States by enacting statutes like the Homestead Laws, which promised prospective settlers 160 acres if they settled on the land for five years and improved it. However, the homesteading program did not acknowledge the limited ability of the arid lands to support agriculture. Although a 160-acre farm may support a family on land eastern part of United States where annual rainfall exceeds 20 inches, it was often inadequate in the west where corps required irrigation projects that small farms could not justify economically (Stegner, 1992; Powell et al., 1879).

As farmers struggled to raise crops, investors formed corporations that tried to build irrigation projects with private funds. However, most projects failed including one promoted by an entity that eventually took part in forming the Salt River Project in Phoenix, Arizona. After failures mounted, the federal government passed the

Reclamation Act (1902) under the leadership of President Theodore Roosevelt and the providentially named Frederick Newlands, a congressperson from Nevada. The Act aimed to reclaim arid land by funding construction of water projects through "receipts from the sale and disposal of public lands in certain States and Territories to the construction of irrigation works for the reclamation of arid lands" (Reclamation Act, 1902, p. 388). According to my heuristic analysis, the Act demarcates the start of the reclamation sociotechnical imaginary, which emphasizes the economic benefits of constructing water projects in the western United States. USBR completed the first one in Arizona in 1911 by constructing Roosevelt Dam (Reisner, 1986; Reclamation Act, 1902).

When Arizona was granted statehood in 1912, the state seal featured Roosevelt Dam. The gesture confirms the vital role that water projects played in the rise of Arizona (The Arizona Experience, n.d.). For most of the 20th century, the reclamation sociotechnical imaginary advocated impounding water in reservoirs, which served the interests of agriculture and development by overriding concerns about safety.

Like the Homestead Acts, the Reclamation Act (1902) limited its application to "tracts of not less than forty nor more than one hundred and sixty acres" (p. 389). The inductive sociotechnical imaginary of Powell et al. (1879) understood that lands east of the 100th meridian received annual precipitation over 20 inches and that 160 acres was sufficient to support a family (Powell et al., 1879). However, the 160-acre limitation contributed to the failure of many homesteaders west of the 100th meridian and fueled efforts to avoid the limits by putting together farms or ranches large enough to survive (Reisner, 1986). In contrast with the reclamation imaginary that prevailed in the western

United States, which suffers from aridity, an excess of water in the form of floods hampered the productivity of lands east of the 100th meridian.

Flood Control Imaginary

In contrast to Arizona and the western United States where water is scarce and dams impound water for agricultural and municipal uses under the reclamation sociotechnical imaginary, Congress enacted a series of flood control acts consistent with a flood control sociotechnical imaginary after devastating floods inundated substantial portions of midwestern and southern states in 1920s and 1930s. For instance, the Great Mississippi Flood of 1927 inundated 27,000 square miles in southern and midwestern states with up to 30 feet of water. Damages totaled $1 billion, or about a third of the total federal budget. Adjusted for inflation, the damages suffered due to the 1927 Great Mississippi Flood are equal to about $1 trillion in 2007 dollars (Barry, 2007). In comparison, property damage caused by Katrina, the costliest Atlantic hurricane in history, totaled about $108 billion in 2005 dollars, or about a tenth of the costs associated with the Great Mississippi Flood. Beyond physical devastation, the Great Mississippi Flood of 1927 caused enormous social and political dislocations. Instead of returning to the agricultural economy of the south, hundreds of thousands of victims took part in the Great Migration to northern and midwestern industrial cities, which altered the social fabric of the country (Barry, 2007).

As Secretary of Commerce, Herbert Hoover earned plaudits for his leadership in responding to the flood and parleyed the renown that he gained into a successful run for the presidency in 1928. Consistent with an emerging sociotechnical imaginary that envisioned controlling flood waters, the Great Mississippi Flood prompted Congress to pass the Flood Control Act of 1928, which directed the USACE to control the Mississippi River and its tributaries (Flood Control Act, 1928). The Act was one of the largest public works projects in the history of the United Stated and contributed to the boom in the construction of dams and levees in the 20th Century (Barry, 2007).

Floods in succeeding years led to the passage of additional laws including the Flood Control Act of 1936, which defined floods as threats to the national interest and assigned responsibility for controlling them to the USACE, which was housed within the War Department (later the Department of Defense). However, other agencies in the federal government are also responsible for addressing issues associated with floods. The Natural Resources Conservation Service, formerly known as the Soil Conservation Service, within the Department of Agriculture is responsible for controlling watersheds, retarding waterflow, and preventing soil erosion. The USBR, a part of the Department of the Interior, is responsible for reclamation projects in the western United States (Flood Control Act, 1936). Competition and turf battles among the agencies contributed the boom in construction of water projects during the 20th Century. In fact, the boom became so expensive and out of control that Congress mandated the use of cost-benefit analysis to assess demands by citizens and their eager representatives for even more questionable water projects (Reisner, 1986; Porter, 1996), which is the basis for the next sociotechnical imaginary.

Cadillac Desert Imaginary

Fueled by passage of flood control acts in the 1920s and 1930s, the public, farmers, and irrigation districts lobbied Congress to authorize and appropriate funds needed by the USBR, the USACE, the Tennessee Valley Authority, and other federal agencies to build dams. In *Cadillac Desert: The American West and its Disappearing Water*, Reisner (1986) documents the fierce competition between agencies to build dams under what I characterize as a “Cadillac desert” sociotechnical imaginary. The National Inventory of Dams shows that construction of major dams peaked in the 1960s when owners constructed about 20 percent of 92,000 major dams. Further, in the three decades between 1950 and 1979, owners built about 50 percent of the major dams in the United States (USACE, 2022).

By the 1960s, owners such as the USBR built dams at most of the good sites. Iconic dams such as Hoover Dam and Grand Coulee Dam were constructed at exceptional sites. Due to increasing concerns about environmental and safety issues, the influence of the Cadillac Desert sociotechnical imaginary lessened over time but continues to influence attitudes toward proposed dams in some contexts.

As a capstone to the Cadillac Desert imaginary, Congress passed, and President Lyndon Johnson signed the Colorado River Basin Project Act in 1968. The Act approved construction of the Central Arizona Project (CAP), which pumps water through a 336-mile canal system from the Colorado River to Phoenix and Tucson (Reisner, 1986). In 1973, the USBR started constructing CAP at Lake Havasu and completed the project 20 years later in Tucson at a cost of $4 billion. CAP starts by pumping water from the Colorado River uphill 800 vertical feet over a horizontal distance of seven miles through the Buckskin Mountain Tunnel with six 66,000 horsepower pumps. Over the entire system, CAP lifts water over 2,900 feet in elevation by using up to 2.8 million megawatt hours per year, an amount that could power 250,000 homes. The project loses about one percent of the water pumped, or 16,000 acre-feet per year, to evaporation (Central

Arizona Project, n.d.). These types of concerns about the damages caused by major dams became more prominent in the 1960s, which led to development of an environmental imaginary.

Environmental Imaginary

Concerns about the environment increasingly prompted concerned citizens and legislators to demand changes to the architectural and governance characteristics of water projects. According to my heuristic analysis, National Environmental Policy Act (1969) institutionalized the environmental sociotechnical imaginary in 1970 by requiring owners of large infrastructure projects like dams to file environmental impact statements. During the same year that NEPA was enacted, the USBR filed an inadequate environmental impact statement in 1970 for the proposed Teton Dam, which Congress approved and funded in the 1960s. However, the entire Congressional delegation from Idaho including its two senators, Frank Church and John McClure, supported construction of Teton Dam (Shaw & Nelson, 1977, p. 32). Concerns about the governance of environmental issues related to dams continue today, but no one mounted serious criticism of the governance characteristics of dams – even on marginal sites like the one at Teton Dam – in the 1960s and 1970s.

Safety Imaginary

The Reclamation Act (1902) did not address governance characteristics of safety of systems of dams. Instead, the reclamation imaginary inaugurated by the Act focused on the economic aspirations of settlers, politicians, and businesses. Although designers and owners understood that potential modes of failure such as overtopping could damage the architectural or physical characteristics of dams and flood downstream communities, the Congress did not address the safety of dams in law until it passed the National Dam Inspection Act (1972) after failures of dams on the Buffalo Creek in West Virginia and in Rapid City in South Dakota (*Teton Dam Disaster*, 1976, p. 7-8). By passing the Act, Congress, according to my heuristic analysis, initiated a sociotechnical imaginary based on the safety of dams 70 years after it enacted the Reclamation Act (1902).

The following edited excerpt from the transcript of a hearing before the House Committee on Governmental Operations after the failure of Teton Dam shows that the safety sociotechnical imaginary is characterized by *engineering competence* and continues to compete with other imaginaries:

> When Teton Dam failed on June 5, it was the first failure of a dam built by the major Federal water resource development agencies. **Two tragic dam failures in 1972** – Buffalo Creek, West Virginia and Rapid City, South Dakota – had **made dam safety an issue** and **induced enactment of a Federal dam safety inspection program**. These were non-Federal projects, however, one built by a private coal mining operation and the other by a local government with W.P.A. funding. And while the Buffalo Creek disaster was the result of a poorly engineered structure, the Rapid City flood was also a truly freakish weather phenomenon. At any rate, there was **little concern that this could happen to a dam built by one of the Federal resource development agencies**. The Bureau, the Corps of Engineers and the T.V.A. have frequently been criticized on *environmental* **[environmental imaginary]** and *economic* **[Cadillac Desert imaginary]** grounds but *engineering competence* **[safety**

> **imaginary]** in the **design of their structures had never been questioned** [author added emphases and insertions in square brackets] (*Teton Dam Disaster*, 1976, p. 7-8).

The Act required the USACE to inventory all dams in the United States and to complete and send a report to Congress on inspections conducted by July 1, 1976. As it turned out, this was about a month after Teton Dam failed on June 5, 1976. The Act directed the USACE to institute a national program to inspect and regulate the safety of all dams by assigning responsibilities among federal, state, and local governments and between public and private owners (National Dam Inspection Act, 1972; *Teton Dam Disaster*, 1976, p. 29-30). The Act led to the initial creation of the National Inventory of Dams (USACE, 2022). However, the Act exempted the USBR, the Tennessee Valley Authority, and the International Boundary Commission from its provisions, which signals the respect that Congress had for the engineering competence of those organizations.

When Teton Dam collapsed four years after the passage of the Act in 1972, the mandated inventory was duplicative, incomplete, and filled with mistakes. Regulators had not completed any inspections. The USACE blamed the inadequate report on the failure of Congress to authorize and appropriate funds for the inventory or inspections. From a bureaucratic or institutional point of view, the USACE was reluctant to inventory dams owned or operated by other owners out of fear of assuming liability (*Teton Dam Disaster*, 1976). However, the mediocre performance of the USACE demonstrated that the governance of the safety of dams was not a high priority before the collapse of Teton Dam in 1976. The USACE confirmed this finding by refraining from crossing governance boundaries to complete the National Inventory of Dams even if it served the interests of the public by reducing the possibility of failed dams.

However, concerns about the safety of dams ratcheted up dramatically after Teton Dam failed in 1976. Senator Frank Church of Idaho who supported construction of Teton Dam in his state confirmed the prevailing lackadaisical attitude toward the governance of safety of dams during hearings that addressed the failure of Teton Dam:

> …it seems to me that as we go back over the history of Teton, when the dam was first authorized there was overwhelming support for it. When the money was first secured for its construction, there was overwhelming support. In no case at any point, from the beginning to the end, had any of us any reason to believe that the dam would be unsafe. When the dam moved toward construction contracts and actual construction, then a new awareness had developed about possible adverse effects of dams. A new kind of thinking had emerged that didn't really exist at the time that the dam was first authorized (*Oversight: Teton Dam Disaster*, 1977, p. 264).

In Table 7, Rayner & Cantor (1987) offer a matrix that summarizes typical orientations of constituencies in policy debates about principles related to consent, trust, and liability. The typology supplies insights into the ways that participants in law and policy debates about the governance of systems of dams think.

Table 7

Preferred Principles of Consent, Trust, and Liability by Type of Constituency

Principles	Atomized individual	Competitive / Market	Bureaucratic / Hierarchical	Egalitarian
Consent	None sought or given	Implicit / revealed preference	Hypothetical	Explicit / expressed preference
Trust	Nonhuman forces (nature, luck, spirits)	Successful individuals (e.g., Red Adair)	Long-established formal organizations (AMA, USCG)	Participatory information institutions (town meetings, affinity groups)
Liability	No principles	Loss-spreading	Redistributive	Strict liability
Justification	No consistent justification	Consequentialist	Contractualism	Rights-based
Goal	Survival	Market success	System maintenance	New social order

(Rayner and Cantor, 1987)

Following the failure of Teton Dam, representatives at the USBR acted in accordance with the “Bureaucratic / Hierarchical” type as described in Table 7 by believing that consent to water projects was hypothetical, not revealed or expressed; trust was embedded in formal organizations, not in individuals or participatory institutions; liability was redistributive, not spread across society or strictly enforced; justification was premised on contracts, not consequences or rights; and that agencies like the USBR strived to maintain water projects, but did not subscribe to market values or advocate the imposition of a new social order. Businesspeople tend to meet the criteria under the “Competitive/Market” column by believing that preferences are implicit and revealed through the markets, not hypothetical or expressed through explicit preferences. The “Egalitarian” column characterizes environmentalists who insist on express and explicit preferences, which if transgressed lead to new social orders.

Negotiating compromises within a sociotechnical imaginary characterized by inconsistent principles of consent, trust, and liability requires deep understanding of the organizations and institutions involved. Alert and active experts and stakeholders who subscribe to the safety imaginary may be able to negotiate tradeoffs needed to prompt the appearance of a resilience imaginary that enhances sustained adaptability of systems of dams. However, before addressing the possible appearance of a resilience imaginary, I address implications of the failure of Teton and the subsequent enactment of the Reclamation Safety of Dams Act (1978) because they demonstrate the ways that governance characteristics of systems of dams and associated sociotechnical imaginaries change.

Teton Dam. At 11:57 a.m. on Saturday, June 5, 1976, the right abutment of the Teton Dam in eastern Idaho failed catastrophically, releasing a deluge of 80 billion gallons water. Because workers discovered leaks on the face of the dam earlier that morning, officials had time to warn downstream communities, which allowed many residents to evacuate. Nevertheless, eleven people and thousands of cattle died as the flood washed away topsoil from thousands of acres of land that water from the reservoir was expected to irrigate.

After the failure of Teton Dam, Congress enacted the Reclamation Safety of Dams Act (1978), which allowed the USBR to rehabilitate many dams in its portfolio. Subsequently, Congress put in place the National Dam Safety Program by enacting laws such as the Water Resources Development Act (1996) that are consistent with a safety sociotechnical imaginary. Congressional investigations after the disaster revealed that

Teton Dam was poorly conceived, inadequately designed, and deficiently constructed by the USBR as described below:

- *Site Selection*. The boom in the construction of dams peaked in the 1960s, partially because owners had constructed dams at most of the good sites. After rejecting multiple sites on the Teton River several times, the USBR finally acceded to pleas by a local irrigation district and a united Idaho Congressional delegation by agreeing to build the dam after floods in 1962 followed a drought in 1961. Congress approved the project in 1964 but did not fund it until the administration of President Nixon several years later. The purpose of Teton Dam was to supply irrigation water to grow the low-value crop that Idaho is famous for: potatoes (Reisner, 1986, p. 383-410).
- *Incompetent Soils*. Despite warnings from representatives of the United States Geological Service that the site was plagued by seismic activity and "ultravolcanic" soils with voids large enough for people to walk through, the USBR continued to construct the dam (Reisner, 1986, p. 383-410).
- *Excessive Grout*. Designers at the USBR estimated that contractors would need to stabilize the poor "ultravolcanic" soils beneath the foundation of the dam by pumping 260,000 cubic feet of grout into the cracks. Instead, the contractors pumped over 600,000 cubic feet of grout, or about 2.5 times more than the USBR estimated (Balloffet & Scheffler, 1982).
- *Rate of Filling*. The USBR began filling the reservoir behind the dam in October 1975 at the standard rate of one foot per day; however, in a misguided attempt to

capture runoff from melting snow the USBR was filling the reservoir at twice the standard rate before the disaster (Balloffet & Scheffler, 1982).

- *Costs*. The Teton Dam disaster cost taxpayers between $300 and $400 million to settle claims and may have caused total economic losses of more than $1.5 billion (Balloffet & Scheffler, 1982).

A video featuring retired employees of the USBR confirms that the failure of Teton Dam in 1976 prompted the USBR to revise the ways that the organization designed and constructed dams. After the failure, the USBR instituted independent boards to review dams, required designers to take part at the construction site and to formally document design decisions, installed instruments at major dams including in the foundations, and monitored dams during and after construction (Bureau of Reclamation, n.d.).

Relevant policies, standards, and guidelines address the safety of dams and associated structures through traditional deterministic approaches like the inflow design flood, a method used to assess the maximum probable flood that a dam and reservoir can store or pass through outlets or spillways (FEMA, 2013; Achterberg et al., 1998; USBR, 2011). Although Busch (2011) finds that standards issued by powerful bureaucracies traditionally evaluate and define risks in ways that privilege those in power, in *Understanding Risk: Informing Decisions in a Democratic Society* the National Research Council (1996) expanded the understanding and assessment of risk. According to the report, experts and agencies are increasingly pursuing efforts to expand the scope of assessments to more broadly account for risks that threaten systems of dams. For instance, FERC (2016), Regan (2010), and Scott (2011) describe a probabilistic approach called “risk-informed decision making,” which the USBR, USACE, and other regulators now promote. Increasingly, designers and regulators recognize that risks assessed with deterministic methods may not be broad enough to cope with emerging threats like climate change, earthquakes, terrorism, cyberattacks, or wildfires. However, my research does not assess whether, to what extent, and in what ways risk-informed decision making improves sustained adaptability as well as the safety of systems of dams as part of the possible appearance of a resilience sociotechnical imaginary.

The ultimate cause of the failure of Teton Dam was not just the failure of the architectural or physical characteristics but, more importantly, the failure of the governance characteristics epitomized by the institutional hubris of the USBR. During its storied history, the USBR built iconic structures such as Hoover Dam, which buoyed the spirits of a beleaguered country during the Great Depression. Until the Teton Dam disaster in 1976, no dam constructed by the USBR had failed since the agency completed its first project – Roosevelt Dam – in 1911. However, the long string of successes inflated an organizational hubris that maintained that designers at the USBR could engineer solutions to any problem. The public and its elected officials further inflated the dominant hubris by asking the USBR to construct dams at poor or marginal sites (Reisner, 1986). By encouraging renewed efforts to meet the requirements of the National Dam Inspection Act (1972) and by prompting enactment of the Reclamation Safety of Dams Act (1978), the failure of Teton Dam was an inflection point that deflated the organizational hubris of USBR by heralding the sociotechnical imaginary based on the safety of dams.

Reclamation Safety of Dams Act (1978). The failure of Teton Dam did not implicate emerging threats such a climate change, earthquakes, terrorism, cyberattacks, or wildfires. Instead, the dam collapsed when the right abutment failed as the USBR was filling the reservoir for the first time. However, later investigations into the disaster and passage of the Reclamation Safety of Dams Act (1978) supplies a baseline against which to assess the governance characteristics of systems of dams. Although risks and uncertainties associated with threats like climate change, earthquakes, terrorism, cyberattacks, and wildfires have emerged or increased since the failure of Teton Dam, the legislative and implementation history of the Reclamation Safety of Dams Act (1978) supplies insights that may help experts and stakeholders to make changes to the governance characteristics of systems of dams that will be needed under a resilience sociotechnical imaginary.

The dramatic failure of Teton Dam in 1976 rekindled interest in the governance of safety of dams that had drifted since the passage of the National Dam Inspection Act (1972). Cecil Andrus, the Secretary of the Department of the Interior, the institutional home of the USBR, sent identical letters dated February 14, 1978, to the House of Representatives (*Authorizing the Secretary of the Interior*, 1978, pp. 6-8) and the Senate (*S. 2820: Reclamation Safety of Dams Act*, 1978, pp. 4-22). The letters traced efforts by the USBR to address the safety of dams and transmitted a draft of the law that became the Reclamation Safety of Dams Act (1978). The letters said that in 1948 the USBR instituted the “Review of Maintenance Program,” which inspected dams on a regular basis. Specialists from Engineering and Research Center in Denver took part in the reviews of dams every six years. Reviewers prepared reports on the condition of each dam and noted corrective actions taken or recommended (*S. 2820: Reclamation Safety of Dams Act*, 1978, pp. 4-5).

As “the engineering profession” develops “new criteria and technology for the design of dams,” the USBR reevaluates older dams. The USBR formed the “Examination of Existing Structures” (EES) program in 1965 to assess whether older dams could “withstand safely the currently estimated maximum probable floods and to prescribe corrective action” (*S. 2820: Reclamation Safety of Dams Act,* 1978, p. 5). A maximum probable flood was defined as “the largest flood that theoretically could occur at a given site during our present geological and climatic era.” Although not defined, the return period was more than 100 years (, p. 6).

The EES program found that 88 dams owned or operated by USBR needed to be studied “to determine their ability to withstand safely the currently estimated inflow design flood.” When the USBR performed the studies, it found that 27 dams needed structural modifications. The USBR had completed modifications of 10 of the 27 dams and repairs on four dams were underway at the time. However, Congress needed to authorize and appropriate funds needed to upgrade the remaining 13 dams (*Authorizing the Secretary of the Interior,* 1978, p. 3) so that they could withstand “the inflow design flood and/or the maximum credible earthquake” (*S. 2820: Reclamation Safety of Dams Act*, 1978, p. 5). Two of the remaining 13 dams were on the Salt River: Stewart Mountain Dam and Roosevelt Dam.

The report on the Stewart Mountain Dam suggested reconstructing the spillway at a cost of $6.8 million (based on costs in January 1977) despite not expecting the dam to fail during a “maximum probable flood” (*S. 2820: Reclamation Safety of Dams Act,* 1978, p. 18). Pending completion of repairs, the report proposed reducing maximum discharges from the spillway to 105,000 cubic feet per second, or about two thirds of capacity. The report updated an earlier 1970 assessment that estimated the cost of repairing the spillway at $3.2 million (in 1970 dollars) (*Dam Safety*, 1977, p. 580).

The report on Roosevelt Dam asserted that the dam would fail if it were overtopped by 2.5 feet during a maximum probable flood. The report proposed raising the dam by four feet and rehabilitating the spillways at a cost of $1.2 million (based on costs in January 1977) (*S. 2820: Reclamation Safety of Dams Act*, 1978, p. 17). The report updated an earlier 1970 report that estimated that raising the height and changing the spillways would cost $595,000 (in 1970 dollars) (*Dam Safety*, 1977, p. 578).

The Reclamation Safety of Dams Act (1978) authorized "the Secretary of the Interior to construct, restore, operate, and maintain new or modified features at existing Federal reclamation dams for safety of dams purposes" (Reclamation Safety of Dams Act, 1978). The Reclamation Safety of Dams Act (1978) is limited to dams constructed by the USBR and the initial $100 million authorization was directed specifically toward "dam safety." However, the Reclamation Safety of Dams Act (1978) does not define safety, which leaves the task to regulators and agencies. Congress forbid the USBR from "providing additional conservation storage capacity or developing benefits over and above those provided by the original dams and reservoirs" (Reclamation Safety of Dams Act, 1978) because legislators were justifiably concerned that interest groups would lobby the USBR to instead redirect authorizations to increase the capacity of reservoirs. Reisner (1986) shows that reclamation projects constructed by the USBR often supplied subsidized water that eased development of fragile lands.

For fiscal year 2018, the total budget of the USBR was $1.1 billion. After the shock of the failure of Teton Dam and the passage of the Reclamation Safety of Dams

Act (1978), the USBR claimed that dam safety was one of its “highest priorities.” Under the 2018 budget, the USBR requested $88.1 million for dam safety, which included “$66.5 million to correct identified safety issues … $20.3 million for safety evaluations of existing dams and $1.3 million to oversee the Safety of Dams program” (USBR, 2018, p. BH-34).

After the original $100 million authorization in 1979, Congress amended the Act five times to increase authorizations to correct safety problems at USBR dams. In 2015, Congress increased the authorization by $1.1 billion. Authorizations under the total $2,517,000,000 (Reclamation Safety of Dams Act, 1978 as amended).

By report dated April 25, 1986, the Comptroller General summarized the two methods used by the USBR to address the safety of dams under Reclamation Safety of Dams Act (1978). The Safety Evaluation of Existing Dams (SEED) program “identifies safety deficiencies that could cause” dams to fail (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 4). The USBR’s “operation and maintenance appropriations” fund the SEED program, not the Reclamation Safety of Dams Act (1978, p. 4).

After the USBR identifies deficiencies of dams under the SEED program, the bureau places deficient dams in the Safety of Dams (SOD) program “where corrective action alternatives are assessed and modification work is completed” (p. 4). The USBR charges costs incurred under the SOD program against appropriations under the (Reclamation Safety of Dams Act, 1978, p. 4). The Dam Safety page on the USBR website confirms that the USBR continues to use both the SEED and SOD programs (Dam Safety, n.d.).

According to a Comptroller Report, instead of using “the term ‘unsafe’” (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 6), the USBR classifies dams on a scale from satisfactory to unsatisfactory. The most common safety problems are “hydrologic” signifying that “the dam would not be able to pass the probable maximum flood;” “seismic” meaning that the “dam would not be able to withstand the maximum credible earthquake;” or as “seepage related,” which means that water is leaking through the dam. The Comptroller Report found that the potential problems would only cause failure “in the remote event of such a flood or earthquake” (p. 6).

A Senate Report dated July 31, 2014, lists information about the implementation of the Reclamation Safety of Dams Act (1978) (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014). The Report includes testimony of Robert Quist, Senior Advisor to the USBR. According to Quist, the USBR implemented “80 risk reduction corrective actions” costing about $1.43 billion since Congress created the Safety of Dams program with the passage of the Reclamation Safety of Dams Act (1978). Quist asserted the USBR implemented corrective actions “at the lowest feasible cost.” Relationships formed by the USBR “with the end users of the water and power from these projects” helped in completing the repairs. To make the rehabilitation of dams in the future easier, the USBR changed policies and directives in the Reclamation Manual to promote better communication with “water and power contractors” and to develop “alternatives, selection of a preferred alternative, and implementation of the actions required to reduce risk” (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 6). These are important indications that the governance characteristics of safety at the USBR have improved, which is relevant to improving sustained adaptability and promoting the appearance of a resilience sociotechnical imaginary.

The USBR oversees the safety of 476 dams (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 3-4). The USBR constructed about 50 percent of the dams it is responsible for between 1900 and 1950. Therefore, “90 percent of the dams were built before current state-of-the-art design and construction practices” were instituted (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 3-4). As they age, infrastructure projects designed and constructed under old standards are vulnerable to predictable and increasing risks. According to Quist, the USBR was “proud” of its safety work, but “ongoing monitoring, facility reviews, analysis, investigations, and emergency management are critical components of the dam safety program” (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 5). Standards used by the USBR have changed over time to address improvements in the science of the safety of dams, a significant factor in changing governance.

At the time of his testimony, Quist estimated that about $200 million remained under the authorization ceiling but that the amount was not sufficient to rehabilitate “six projects planned for the next 10 to 20 years with total estimated costs of about $1 billion.” The Congressional Budget Office (CBO) estimated that the USBR would need about $90 million per year for work planned over the next few years. The Reclamation Safety of Dams Act (1978) requires that “local partners share 15% of the associated costs” when the USBR modifies a dam (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 2). Although the interest rate is modest and the payback period is long, users pay for water projects constructed by the USBR through fees. Therefore, unlike most infrastructure projects, users repay the costs of USBR dams, which may be a source of funds that the USBR can use to improve the governance characteristic of sustained adaptability. Brad Allenby, a President's Professor of civil, environmental, and sustainable engineering in the Ira A. Fulton Schools of Engineering at Arizona State University, stated recently, "Funding infrastructure is a significant problem in part because we've let deficiencies accumulate over time. We spend only when we have to fix something." He went on by stating: "Of course, that is a very expensive way to manage infrastructure. It means that we're always tackling significant problems, whether it's roads that become impassable because of potholes or fragmentation of the power grid, the consequences of which Texas suffered very recently … We continually 'fix' our infrastructure systems, but we don't invest to bring them up to necessary standards. That needs to change" (Werner, 2021).

Quist testified that the classification of 370 USBR dams is "High" or "Significant Hazard," which means that failure "would cause loss of life or significant damages." Quist listed 12 dams that the USBR anticipated changing over the succeeding years. Six other dams, according to Quist, require modifications totaling $1 billion (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 6).

Quist confirmed that emergencies require immediate action and cited two safety problems that the USBR had resolved. In 2006, the USBR "discovered voids beneath the outlet works conduit and embankment material was being removed through cracks in the outlet work conduit" at the Deer Flat Dam in Idaho. Collaborating with local representatives, the USBR implemented "an interim solution to reduce risk to the downstream public without significantly curtailing service to water users." Without the

Reclamation Safety of Dams Act (1978), the USBR could not have finished the investigation and repairs before snows melted in the watershed above the dam. Since the USBR completed the repair expeditiously the reservoir captured run-off useful for beneficial purposes in 2007 (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 6). In another crisis, the USBR found sinkholes and cracking in the embankment of the Red Willow Dam in Nebraska. After drawing down the reservoir to protect downstream communities, the USBR expedited repairs of the embankment and restored the water supply quickly (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 7).

Quist called attention to a report from a team from ASDSO in 1996 that approved the safety program of the USBR. The ASDSO found that "highly competent staff using state-of-the-art technical standards and expertise" supervised the USBR safety program. Experts from outside of the USBR annually review its safety program to assess adequacy to protect the public (*Report: Reclamation Safety of Dams Act of 1978 Amendments*, 2014, p. 5-6). Emergency repairs to Deer Flat Dam and Red Willow Dam show that the USBR responds more quickly and effectively since the failure of Teton Dam. Implementation of Reclamation Safety of Dams Act (1978) helped reform the governance characteristics of safety at the USBR and contributed to the safety imaginary that continues to influence attitudes of relevant experts and stakeholders.

Resilience Imaginary?

Experts continue to evaluate the safety of dams with deterministic standards such as the inflow design flood that are based on historical data. To cope with the shortcomings of deterministic methods, organizations like the USBR and the USACE increasingly use or prescribe the use of more probabilistic methods such as "risk-informed decision making" to identify and compensate for a broader range of risks (FERC, 2016; Regan, 2010; Scott, 2011). While the question of whether methods such as risk-informed decision making will help experts and stakeholders meet challenges associated with the kinds of events and emerging challenges investigated in this dissertation is beyond the scope of my research.

Theoretically, the safety and resilience of systems of dams are distinguishable. On one hand, the safety of dams focuses on making dams "fail-safe" to expected threats. Resilience, on the other hand, enhances the ability of systems of dams to be "safe-to-fail" by adapting in sustainable ways to unexpected events (Ahern, 2011, Kim et al. 2017). A sociotechnical imaginary based on sustained adaptability would mean that stakeholders affected by systems of dams would consider and prepare for the possibility that dams and associated structures might unexpectedly fail partially or completely and to conduct conversations across institutional or jurisdictional boundaries to increase sustained adaptability by enhancing relevant architectural or governance characteristics. Since dams and associated structures are strongly path dependent, it is not possible to change their architectural characteristics during emergencies. Therefore, improving the resilience of systems of dams requires all relevant stakeholders to take part in uncomfortable conversations *before* crises develop. However, the following illustrates the messy and controversial tradeoffs that may result if experts and stakeholders consider and implement a sociotechnical imaginary based on the resilience of systems of dams.

In 2011, the USACE followed a plan put in place before a crisis struck by breaching levees to allow flood waters to inundate farmland in the New Madrid

Floodway in southeast Missouri below the confluence of the Ohio and Mississippi Rivers. Although farmers argued against breaching the levees, the tradeoff invoked by the USACE reduced or prevented damages to other assets in the interconnected system that were more valuable than the damage suffered by the farmers. Unlike safety measures based on quantitative calculations of risk, the tradeoffs needed to sustain adaptability are more ambiguous and qualitative in nature. Consistent with the possibility that an imaginary of resilience may be appearing, Park et al. (2013) point out that analyzing resilience is "differentiable from, but complementary to, risk analysis, with important implications for the adaptive management of complex, coupled engineering systems" (p. 356). Efforts to make dams safe are based on calculations of risk aimed at preventing crises. In contrast, a resilience sociotechnical imaginary would allow experts and stakeholders to assess tradeoffs that stakeholders would need to make if efforts to make dams safe fail and floods inundate downstream communities. Emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires may require stakeholders to assess tradeoffs aimed at facilitating long term recovery after disasters strike. Conversations about the tradeoffs extend beyond the limited number of participants who traditionally define, implement, and assess the safety of dams by including a broader range of stakeholders including representatives of downstream communities.

Discussion

By heuristically analyzing changes in the governance characteristics of systems of dams prompted by the speculations or findings of investigators such as Gilpin and Powell or events that led to the passage of federal laws, I identified seven sociotechnical imaginaries summarized in the following Table 8:

Table 8

Summary of Sociotechnical Imaginaries

Description	*Starting Date*	*Law / Publication*	*Examples*
Deductive	1874	Gilpin: *Mission of the North American People*	Homestead Acts
Inductive	1879	Powell: *Arid Lands Report*	Limited development
Reclamation	1902	Reclamation Act	Construction of Roosevelt Dam
Flood control	1928	Flood Control Act	Great Mississippi Flood of 1927
Cadillac Desert	1950	Start of boom in construction of dams	Almost 50 percent of major dams constructed between 1950 and 1979
Environment	1970	National Environmental Policy Act	Inadequate environmental impact statement for Teton Dam
Safety	1972	National Dam Inspection Act	Failure of Teton Dam in 1976
Resilience?	2020s or later?	None to date	Threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires

The relevant problems, policies, and politics rose to the top of the “garbage can” of intellectuals such as Gilpin or Powell or stakeholders such as farmers, homesteaders, businesspeople, or environmentalists advocated novel deductive, inductive, economic, or environmental approaches or because events such as flooding became more salient (Kingdon, 2010). These durable imaginaries continue to influence attitudes of stakeholders and experts regarding the architectural or governance characteristics of systems of dams. The question is whether emerging threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires will lead to an imaginary that addresses the resilience of systems of dams conceptualized as sustained adaptability.

The governance characteristics of systems of dams as embodied in federal laws were not initially concerned about safety as epitomized by the reclamation sociotechnical imaginary inaugurated by the passage of the Reclamation Act (1902). Seventy years later, Congress inaugurated the sociotechnical imaginary based on safety by passing the National Dam Inspection Act (1972). After the failure of Teton Dam in 1976, Congress reinforced the safety imaginary by passing the aptly named Reclamation Safety of Dams Act (1978), in which the word “safety” is consistent with my evaluation and the word “reclamation” refers to the United States Bureau of *Reclamation*, not to reclamation in general or the reclamation sociotechnical imaginary. Later laws expanded the scope of the safety imaginary by creating, sustaining, and funding the National Dam Safety Program, which covers dams owned by all entities, not just the USBR.

While concentrating on economic development under the reclamation or Cadillac Desert imaginaries, downstream communities have become more susceptible to disorders described by scholars. For instance, Burton et al. (1968) defines the *technological approach*, which advocates building improved or additional infrastructure projects to alleviate future crises, and the *social or behavioral approach*, which encourages long term planning that often merely helps victims after a crisis but does not address root causes. Burby (2006) describes two paradoxes. The *safe development paradox* decreases the number of disasters caused by normal events, but at the same time decreases sustained adaptability to surprising events. The *local government paradox* finds that local leaders do not acknowledge the vulnerability of their constituents. Di Baldassarre et al.

(2013) describes the *levee effect*, which reduces the willingness of communities to change current laws and policies because they have put in place interventions like levees. After prolonged periods of time pass without problems, officials and the public tend to forget earlier crises.

Consistent with these shortcomings, my case study of the dams on Salt River revealed that the City of Tempe has not amended building codes or emergency action plans to improve the sustained adaptability that may be needed if floods caused by or exacerbated by emerging threats overwhelm Tempe Town Lake. Tempe Beach Park is an economic and social amenity that enhances the livability of arid Tempe by accommodating more visitors than any other destination in Arizona except for the Grand Canyon (Pineda, 2019). As discussed above, fragmentation in the federalist system of government in the United States and the associated adversarial liability regime inhibits free exchange of ideas across social, political, and geographical boundaries aimed at improving sustained adaptability of systems of dams (Gribbin, 2019).

The City of Tempe should evaluate whether to improve sustained adaptability of system of dams centered around Tempe Town Lake before the megadrought that has plagued Arizona for over 20 years ends (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). In addition to finding that the current megadrought is the most severe one since the 13th century (p. 19), Murphy & Ellis (2019) also found that "previous megadroughts have been followed by pluvial periods [increased rainfall], indicating there are risks of wet extremes on the watersheds in coming decades" (p. 20). According to Murphy & Ellis (2019), megadroughts normally last about 30 years. Therefore, if the current megadrought may end within the next few years, it is possible that unusually wet weather will follow and thereby test the capacity of communities like those around Tempe Town Lake to sustainably adapt (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022).

Since the City of Tempe completed Tempe Town Lake in 1999, it has not experienced the types of floods that plagued the area in the in 1970s and 1980s. In the interim, businesses, residences, and public parks have been constructed in the floodplain around the reservoir. Unless a new normal is now in place, it seems reasonable to expect that the current megadrought will end at some point and that the sustained adaptability of the network that connects dams operated by the Salt River Project on the Salt and Verde Rivers and by the City of Tempe on Tempe Town Lake will be challenged. If so, the urgency of improving resilience will ratchet up suddenly after surprising events overwhelm measures taken to make the dams on the Salt River including Tempe Town Lake safe(r) and challenge the ability of the systems to sustainably adapt (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022).

Conclusion

This chapter shows that current laws and policies related to the governance of safety of systems of dams do not address the governance of sustained adaptability needed to recover from surprising events caused or worsened by climate change, earthquakes, or attacks. These findings suggest that policy and lawmakers should assess whether, to what extent, and in what ways the governance of the resilience of systems of dams to surprising events should be changed through new or supplemental policies or legislation aimed at creating a resilience sociotechnical imaginary.

Headlines describing unprecedented and devastating weather events such as hurricanes Katrina, Sandy, Harvey, and Maria signal the enormous risks associated with climate change. Increasingly, we can expect that surprising events will test the sustained adaptability of all types of infrastructure projects including systems of dams. When surprising events arise, it will be impossible to immediately change the governance of the sustained adaptability by changing laws or policies. As emerging threats like climate change, earthquakes, terrorism, cyberattacks, or wildfires interact with aging infrastructure and sclerotic legal and regulatory regimes that change only in response to crises, the sustained adaptability of affected communities may be exceeded. The approach used to decide whether to build Orme Dam, which is described below, provides insights into the difficulty of negotiating responses among groups with incommensurate values. However, governance of resilience may become a priority on the public policy agendas after disasters devastate communities and encourage representatives to reach across boundaries. Under any disaster scenario, proactively assessing and planning for resilience will allow communities to recover more quickly in the wake of disasters.

Edwards (2016) found that knowledge infrastructures have three functions, all of which resonate with the governance of the resilience of systems of dams, associated structures, and downstream communities: “They *monitor* features of interest, *model* complex systems to find and test causal relationships, and record data in *memory* systems to track change over time” [emphasis in original] (p. 3). If policy and law makers decide to improve the sustained adaptability of systems of dams, the National Inventory of Dams (NID) supplies a venue that experts and stakeholders could build upon to enhance sustained adaptability. The NID, which traces its origins to the National Dam Inspection

Act (1972), constitutes a knowledge infrastructure for safety that could be expanded to monitor, model, and remember laws and policies aimed at improving resilience (USACE, 2022; Edwards, 2016), including strategies suggested by Novotny et al. (2010) above. The knowledge infrastructure could *monitor* features or functions of dams and associated structures for compliance with the governance of resilience, *model* associated complex systems to find and test causal relationships of threats to resilience and proposed responses, and record data in *memory* that tracks changes over time needed to store and assess resilience plans.

In 2000, Congress passed the Disaster Mitigation Act (2000), which is consistent with the safety imaginary because it encourages local organizations to communicate with each other while creating hazard mitigation plans such as the Maricopa County Multi-Jurisdictional Hazard Mitigation Plan (Maricopa County, 2021). At this point, Congress has not passed or amended laws in ways that promote conversation and cooperation across boundaries and among actors responsible for making tradeoffs needed to improve the sustained adaptability of systems of dams and thereby inaugurate a resilience imaginary (Woods, 2015).

This chapter described the fragmented governance profile of major dams in the United States by heuristically exploring the formation of durable sociotechnical imaginaries demarcated by the publications of reports that range from the fantastical musings of William Gilpin to the enactment of federal laws prompted by issues that continue to influence the governance of systems of dams. The next chapter analyzes expert discourses about the architectural and governance characteristics of the safety and resilience conceptualized as sustained adaptability of systems of dams.

CHAPTER 4

EXPERT DISCOURSES: ANALYSIS OF INTERVIEW TRANSCRIPTS AND CONFERENCE PRESENTATIONS

Iconic major dams such as Hoover Dam seem indestructible as they squat monumentally above communities such as Las Vegas to which they supply services such as municipal and industrial water, hydropower, flood control, and recreational amenities. However, to supply those services major dams must reliably withstand enormous geophysical forces by relying on architectural characteristics of physical structures designed to last about 50 years (Ho et al., 2017). Contrary to naïve beliefs of the uninitiated, dams are not indestructible. Instead, like any infrastructure project they age and deteriorate over time. Experts and knowledgeable stakeholders understand and fear the tremendous damage unleashed when major dams fail. Therefore, they invest considerable expertise, time, and resources to improve the *safety* of the architectural characteristics of dams.

Efforts to improve the safety of dams are typically based on deterministic standards such as the inflow design flood, probable maximum flood, or the maximum credible earthquake supplemented by probabilistic approaches such as risk-informed decision making. It is important to note that this chapter does not explore whether such efforts to improve the safety of the architectural characteristics of dams are sufficient to sustainably adapt to emerging threats. Rather, it investigates how, to what extent, and in what ways experts assess the architectural and governance characteristics of systems of dams.

According to the National Research Council (2012), Stephen Verigin, the former chief of the Division of Safety of Dams at the California Department of Water Resources and the former president of the ASDSO, summarized efforts needed to improve the resilience of systems of dams. Mr. Verigin believes that “a major paradigm shift would be necessary to move the nation’s dam and levee safety programs toward a culture of resilience.” According to him, “such a shift would include new authorizing legislation, changes in management, a reorientation from deterministic to risk-based approaches, and engagement and support from a much larger community, including local government, planning agencies, elected officials, and the public.” Verigin promoted “statutory definitions and broadening of dam safety programs that would include well-documented risk-based design criteria, disciplined land-use and zoning activities, flood control requirements set in law, and integrated flood control systems that include highly protected areas, planned floodways, and flood easements” (p. 30-31).

The steps advocated by Mr. Verigin would improve the current culture but are consistent with the sociotechnical imaginary that focuses on safety as described in Chapter 3 rather than contributing to the emergence of an imaginary focused on resilience. In a safety culture, experts concentrate on finding, assessing, and mitigating *expected* modes of failure that may undermine or destroy the architectural characteristics of the *physical* structures of dams. However, as we saw in Chapter 2, the architectural characteristics of dams are extremely path dependent and, therefore, are brittle at the physical boundaries because they cannot sustainably adapt when challenged by *unexpected* events caused or worsened by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires. Therefore, emerging threats may increasingly impair or overwhelm the architectural characteristics of aging systems of dams by testing existing synergies and requiring experts and stakeholders to make tradeoffs under emergency conditions (Woods, 2015).

To explore how tradeoffs between safety and resilience are operationalized in systems of dams, I interviewed experts and analyzed relevant documents that experts produced at conferences. More specifically, I sought to understand from the interviews how safety and resilience were conceptualized and operationalized in the professional experience and writing of experts and knowledgeable stakeholders who work on systems of dams.

Exploratory Conversations

To prepare for this empirical research, I conducted a pilot case study as part of a class at Arizona State University. As part of the pilot case study, I conducted exploratory conversations with about 20 experts by phone or after events at or around the Tempe campus of Arizona State University about issues related to the safety and resilience of systems of dams. They supplied insights that informed my semi-structured interviews and document reviews described below.

Semi-Structured Interviews

To gain a better understanding of how, to what extent, and in what ways experts assess the architectural and governance characteristics of systems of dams, I interviewed eleven experts. Since major dams are huge structures with path dependent architectural characteristics that require substantial expertise, resources, and time to modify, questions asked during semi-structured interviews focused on the knowledge of experts about governance characteristics and regulatory mechanisms related to the safety and resilience of systems of dams.

The selection of interviewees, which was informed by the exploratory conversations, was intended to include experts from a broad range of professions or disciplines who were knowledgeable about the architectural and governance characteristics of dams or about safety or resilience. Consequently, I interviewed engineers, consultants, advisors, and contractors as well as an historian, a book author, and a lawyer. The semi-structured interviews were conducted, recorded, and transcribed by Zoom. An interview protocol was developed to probe for relevant information regarding the research question and based on insights gained from the exploratory conversations. The protocol included 13 questions that revolved around the safety and resilience of dams. For instance, questions asked interviewees about their conceptual understanding of these terms and their knowledge of regulatory mechanisms, vulnerabilities, barriers, and recommendations pertaining to the operationalization of the terms.

Summaries of Semi-Structured Interviews

To analyze transcripts of the interviews, I used the grounded theory approach described by Corbin & Strauss (2008) and Yin (2018). This approach yielded an additional characteristic of safety and resilience, which I term “Ability.” This third term is introduced because it was not uniformly associated with either architectural or governance characteristics. Table 9 summarizes ways that experts assess safety and resilience of the architectural and governance characteristics of systems of dams.

Table 9

Characteristics of Safety and Resilience Attributed by Experts Interviewed

	Expert	Safety Characteristic(s)	Resilience Characteristic(s)
1	Water policy advisor	Architectural, Ability	Ability
2	Construction contractor	Architectural	Governance
3	Water project consultant	Architectural	Ability
4	Natural hazards professor	Architectural	Ability
5	USBR/TVA engineer	Architectural	Architectural
6	Dam historian	Architectural, Governance	Architectural, Governance
7	Consultant/ASDSO	Governance	Governance
8	Operations supervisor	Architectural	Ability
9	Lawyer	Governance	Governance
10	Hydrologist	Governance	Ability
11	Book Author	Architectural, Governance	Governance

Findings from Semi-Structured Interviews

Overall, I found that the interviewees have inconsistent knowledge as to whether, to what extent, and in what ways the resilience of dams, associated structures such as canals and levees, and downstream communities is operationalized within knowledge infrastructures that inform and support the *governance (social)* or *architectural (technical)* characteristics of sustained adaptability to emerging threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires. I elaborate upon the nature and potential sources of this inconsistency below by summarizing the interview findings in relation to five subsidiary questions derived from the overarching research question.

How safe and resilient are dams currently? As stated, experts do not interpret the concepts of safety or resilience among themselves in consistent and common ways. Furthermore, experts do not apply the concepts of safety and resilience to the same issues or differentiate between safety and resilience in the same ways. Thus, there is no clear answer to this initial subsidiary question.

How are safety and resilience related to one another? As stated, experts conceptualize these terms inconsistently as a group and, in a couple of cases, as individuals. Thus, among the eleven experts interviewed, it is possible to identify at least six different conceptual understandings of safety in relation to resilience (see Table 9). Some experts conflate the concepts of resilience and safety. For instance, three of the experts identify or closely relate the two terms. One expert suggested that safety encompasses resilience. Some of the experts applied the concept of resilience to the physical structures of dams. Other experts said that resilience follows from safety, i.e., if a dam is safe, then it is resilient. Interestingly, some of the experts described resilience as an ability to supply water or to adapt to variable precipitation while one expert described safety as an ability (see Table 9).

How relevant are the concepts of safety and resilience to emerging threats? A few of the experts were concerned about climate change; however, most were not concerned about earthquakes, terrorism or cyberattacks. None mentioned wildfires.

How can society improve the resilience of systems of dams? One of the experts was concerned about downstream communities, but none offered recommendations.

What are the barriers to making systems of dams more resilient? Few of the experts were able to identify clear barriers. Two opined that cost was an impediment to making dams safer or more resilient, whereas one identified using the term resilience as a buzzword as the greatest problem.

To my surprise, I discovered when conducting the interviews that my understanding of resilience was not consistent with the ways that knowledgeable experts define and evaluate the term. Before the interviews, I studied the academic literature about resilience and infrastructure. As a result, I understood resilience in broad terms as referring to the ability of communities to respond to and recover from disasters. In retrospect, the inconsistent results of the semi-structured interviews should not have surprised me since there is no reason to expect that experts must have consistent understandings of terms like safety and resilience or that they would not conflate the terms. They trained in diverse disciplines and work for a variety of organizations that pursue different and on occasion contradictory missions.

In the next section, I use the same subsidiary research questions to assess expert discourses drawn from a much wider pool of experts and over a multi-year period.

Expert Conference Presentation Analysis

To gain a more robust sense of how experts understand resilience as well as to better understand the governance characteristics of major dams, I analyzed papers and presentations given by experts at professional conferences. More specifically, I reviewed abstracts of papers or slides produced by presenters at ASDSO conferences in 2019, 2020, and 2021 as well as at a seminar sponsored by FEMA in 2021. Papers and slides from the ASDSO 2020 and 2021 conferences were identified, retained, and analyzed.

Analysis consisted of using a set of codes developed inductively (see Table 10). In this way, I coded all 216 presentations from the 2020 and 2021 ASDSO conferences and recorded the results in a large spreadsheet (available for inspection by request). Because it was difficult or impossible to search the documents individually, I did not code the papers or slides given by presenters at the 2019 ASDSO or 2021 FEMA conferences. I did however perform an electronic search of the 2019 ASDSO proceedings, which was over 800 pages.

Using the codes summarized in Table 10, I coded 216 presentations from the 2020 and 2021 ASDSO conferences based on a grounded theory approach described by Corbin & Strauss (2008) and Yin (2018) as a representative sample that addressed current concerns of the dam engineering community about the architectural and governance characteristics of systems of dams that are relevant to sustained adaptability.

Table 10

Description of Codes Used to Analyze Interviews and Papers

Codes	Description
Session	Conference identification number
Title	Title of the paper and presentation
Presenter	Names of the presenters and organizations
Abstract	Abstract of the presentations and papers
Organization Type	Type of organization: e.g., academic, consultant, or owner
Safety / Resilience Ratio	Number of times “safe” or “safety” appear in each paper versus the number of times that “resilience” or “resiliency” appear

Non-technical Papers or Sources	Number of non-technical papers or sources cited in each paper
Sustainable Adaptation: Architectural or Governance Characteristics	Describes whether the presentation or paper addresses architectural or governance characteristics (Woods, 2015)
Type of structure	Describes the type of physical structure, e.g., dam or spillway
Intervention	Briefly describes of the intervention assessed, e.g., investigate failure of dam
Methods	Briefly describes the method assessed, e.g., inflow design flood
Knowledge Infrastructure: Monitor, Model, or Remember	Describes whether the presentation or paper primarily monitored, modeled, or remembered the knowledge infrastructure (Edwards, 2016)
Multiscalar Level	Describes whether the presentation or paper describes force, time, or social organization (Edwards, 2003)
Rules-in-Use: Constitutional, Collective Choice, or Operational	Describes whether the paper or presentation was based on constitutional, collection choice or operational rule-in-use (Ostrom, 2011)

How safe and resilient are dams currently?	Subsidiary question: Whether the paper or presentation addresses safety or resilience (Yes or No)
How are safety and resilience related to one another?	Subsidiary question: Whether the paper or presentation describes the relationship between safety and resilience (Yes or No)
How relevant are the concepts of safety and resilience to emerging threats?	Subsidiary question: Whether the paper or presentation is relevant to emerging threats, e.g., climate change (Yes or No)
How can society improve the resilience of systems of dams?	Subsidiary question: Whether the paper or presentation improves the resilience of dams (Yes or No)
What are the barriers to making systems of dams more resilient?	Subsidiary question: Whether the paper or presentation describes barrier to resilience (Yes or No)

In addition to reading and coding the abstracts for the 216 presentations made at the 2020 and 2021 ASDSO conferences, I reviewed or read additional slides and papers deemed relevant. Furthermore, I watched some presentations online in real time. Finally, I watched videos of presentations if I deemed them relevant to my inquiry into the architectural or governance characteristics of major dams. For instance, the presentations about the failures of the Edenville and Sanford Dams in Michigan were particularly informative.

While coding the presentations, I made entries for the codes in a spreadsheet and highlighted presentations that I deemed were relevant to my inquiry. I then selected a sub-group of these relevant presentations for in-depth descriptive analysis. Before addressing these selected presentations from the 2020 and 2021 ASDSO conferences, I selectively describe the overall results of the coding (Corbin & Strauss, 2008; Yin, 2018).

Search and Coding Results

As mentioned, I performed an electronic search of the 2019 ASDSO proceedings. This search revealed that "safe" and "safety" appeared 1,240 times in the 821 pages, but that "resilience" or "resiliency" only appeared eight times (ASDSO, 2019b).

Applying the *Organization Type* category revealed the following range of organizations represented by the presenters: Academic (13), Consultant (105), Contractor (5), Designer (11), Non-Governmental Organization (1), Owner (31), Professional (4), and Regulator (46). The Consultant organization type has the largest number of presentations. Thus, about half of the 216 presentations were by consultants who highlighted their expertise or products in addressing problems associated with the safety of dams. Regulators such as USACE and FEMA made about 20 percent of the presentations in which they promoted improved practices in the dam engineering community. Owners of dams made about 15 percent of the presentations during which they shared lessons learned about owning or operating dams.

The *Safety / Resilience Ratio* code produced the most revealing insight. This code records the number of times that the words "safe" or "safety" versus "resilience" or "resiliency" appear in the 115 papers given during both conferences. Since the presentations were made at dam *safety* conferences sponsored by the Association of State

Dam *Safety* Officials, it is not surprising that the words “safe” or “safety” appeared much more often than “resilience” or “resiliency.” In fact, in one paper, “safe” or “safety” appeared 115 times (including in the footers) and “resilience” appeared only once. In contrast, and much to my surprise, only one paper mentioned “resilience” or “resiliency” as many as three times. The rest of the papers mentioned “resilience” or “resiliency” fewer than three times, which suggests that when the two conferences were conducted resilience was not a major topic of interest in the dam engineering community.

Non-Technical Papers or Resources counts the number of sociology or humanities papers cited in each paper to support relevant arguments. Few papers cited non-technical papers. One paper cited seven non-technical papers (this paper was not selected for in-depth analysis because it did not address safety or resilience) and another paper (Walls, 2020) cited four non-technical papers. In the latter case, the author was an economist, not an engineer like most of the presenters at the ASDSO conferences. In short, the vast majority of the 115 papers submitted at the two conferences did not cite any non-technical papers, which suggests that research performed by sociology and humanities scholars has not penetrated the dam engineering community or that engineers do not value the scholarship of academics. Instead, the papers at the two conferences relied primarily on empirical data collected during projects, technical papers given at earlier conferences, or publications or guidelines from relevant agencies such as the USACE or FEMA.

The *Sustainable Adaptation: Architectural or Governance Characteristics* code categorizes presentations according to whether they primarily addressed architectural or governance characteristics of systems of dams as defined by Woods (2015). Of the 216 presentations that were coded, 152 addressed architectural characteristics; 20 addressed governance characteristics; and 44 addressed both. For reasons explored throughout this dissertation, it is not surprising that presentations at conferences at which most of the participants are engineers who were concerned about the safety of dams emphasized architectural more than governance characteristics.

Type of structure categorizes the physical structures addressed in each presentation. Not surprisingly, the most common types are dam (for a single dam) and dams (for dams in general), which, in total, described over 130 of the 216 presentations. Since they are often the primary components of dams that allow operators to release excess water, about 40 presentations dealt with spillways.

The *Knowledge Infrastructure: Monitor, Model, or Remember* code describes which level of the knowledge infrastructure described by Edwards (2016) applies to each presentation. The subtotals for the 216 presentations were: monitor (79), model (95), remember (37), and all (5).

Multiscalar Level describes the scale of each presentation according to the multiscalar framework defined by Edwards (2003): force, time, and social organization. A majority, or 133, of the presentations addressed *force*, which is not surprising given the enormous size of the structures needed to deal with the geophysical forces at issue in the design, construction, and operation of major dams. Seventy-seven of the presentations addressed *social organizations* at the *mesoscale*, which includes organizations like ASDSO and FEMA. No presentations addressed *microscale* or *macroscale* organizations. Only six presentations addressed the *time* scale, which is surprising because many aging dams now exceed the typical design life of 50 years. The time scale may become more salient as dams constructed during the last century continue to age.

The *Rules-in-Use: Constitutional, Collective Choice, or Operational* code describes the rules used in the presentations as defined by Ostrom (2011) as part of her institutional analysis and development framework. Unsurprisingly, since the presenters were mostly engineers who worked on the operations of dam, 176 of the presentations discussed *Operational* issues while only 37 dealt with *Collective Choice* among organizations such as USACE, FEMA, or state dam safety offices. Three addressed *Constitutional* issues such as changes made to California dam safety laws after the crisis at Oroville Dam in 2017 (Tapia, 2020).

The last five codes stand for the five subsidiary questions that explore the overarching research question (see Table 11). To my surprise, except for the first question, none of the presentations explicitly addressed resilience or resiliency, which was the topic of the other four subsidiary questions. The third question (*How relevant are the concepts of safety and resilience to emerging threats?*), revealed the lowest count. Of the 28 presentations coded as "Yes," the emerging threats that were mentioned are broken down as follows: climate change (21), earthquake (9), terrorism (1), wildfires (1), and seepage (1). Overall, the small number of ASDSO presentations found to address the subsidiary questions, while initially surprising, is consistent with the results from the expert interviews.

Table 11

ASDSO Presentations Addressing Subsidiary Questions

Subsidiary Question (abbreviated)	Addressed by Paper (Yes)	Unaddressed by Paper (No)
Safety and resilience of dams	215	1
Relation of safety and resilience to one another	36	180
Relevance of safety and resilience to emerging threats	28	155
How to improve resilience	42	174
Barriers to improving resilience	41	174

Sociotechnical Imaginaries Invoked in Conference Presentations

During my exploratory research into the history dams, I noticed that publications by William Gilpin and John Wesley Powell and the passage of federal laws heuristically demarcated several historically contingent sociotechnical imaginaries that were discussed in my prospectus and Chapter 3. After coding the presentations at the ASDSO conferences, I revisited my analysis in Chapter 3 and confirmed that the sociotechnical imaginaries are durable, co-exist, and continue to influence attitudes of relevant groups about systems of dams.

In short, although the selected presentations overwhelmingly refer to the safety imaginary (Table 12 illustrates the wide variety of topics that are contained by the safety imaginary), a small fraction indicate that a resilience imaginary may be appearing (Table 13 presents the three presentations that touch upon the resilience imaginary).

Table 12

Variety of Topics in ASDSO Presentations Invoking Safety Imaginary

Year	Title	Topic
2020	Recent advancements in California's dam safety program	Legal reform
2020	A methodology to evaluate probable maximum precipitation (PMP) under changing climate conditions	Probable maximum precipitation
2020	Making the case for developing realistic inflow design floods in Colorado's Rocky Mountains	Inflow design flood
2020	Aligning dam removal and dam safety: Comparing policies and institutions across states	Removal of dams
2020	Is our emergency action plan time sensitive?	Emergency action plans
2020	Dam rehabilitation and the perpetuation of human factors across time and space	Human factors
2020	10th anniversary of the failure of Tempe Town Lake Dam	Material selection

2020	The need for keeping pace with the science for earthquake dam safety	Earthquakes
2020	No pain, no gain! Building collective muscle memory through sector-wide exercises	Exercises
2020	Public dissemination of USACE inundation maps	Inundation maps
2020	Comprehensive needs assessment for Oroville dam and appurtenant facilities	Comprehensive needs assessment
2020	Soapbox - Updating the Model Dam Safety Program	Model program
2021	Edenville dam failure – Overview of the event and emergency response	Emergency response
2021	Getting Creative to Reduce the Risk of Hazard Creep	Hazard creep
2021	Edenville Dam Failure – Overview of the Event and Emergency Response	Forensic investigation
2021	The many ways spillways can contribute to dam failures and incidents	Spillways
2021	Selecting the appropriate risk analysis method for dam projects	Risk analysis
2021	The worst fire season in Colorado history: Its impact on dams	Wildfires

2021	Quantification of uncertainty related to PMP parameters	Uncertainty
2021	Edenville and Sanford dam failures: A case study on warning and evacuation	Warning and evacuation
2021	Stochastic weather generation for hydrologic analysis for critical design infrastructure	Hydrologic analysis
2021	Public dissemination of USACE inundation maps and risk information	Sharing risk information
2021	Dam disaster in World War II - Destruction of the Dnieper Hydroelectric Station in 1941	Terrorism
2021	Dam safety engineers need business understanding with new ODSP audit requirements	Organizational design
2021	Alignment of the National Levee Safety Program and National Dam Safety Program by USACE & FEMA	Aligning NDSP and NLSP

Table 13

ASDSO Presentations That Invoke a Resilience Imaginary

Year	Title	Topic
2020	A California dam safety Collaborative Technical Assistance case study: Using GIS to integrate community profile analysis, critical	Collaborative Technical Assistance

	infrastructure information, and inundation mapping to support consequence analysis and dam-related planning activities	
2020	Structure Integrity Hierarchy: A tool for incident planning and response	Tradeoffs
2021	Coordinated and effective planning for dam-related emergencies - The dam owner's perspective	Collaborative Technical Assistance

Findings from Analysis of Conference Presentations

The topics listed in the third columns of Tables 12 and 13 provide rudimentary insight into whether, to what extent, and in what ways experts who presented at the 2020 and 2021 ASDSO conferences are knowledgeable about the resilience of dams and the ways in which resilience is operationalized within the knowledge infrastructures that inform and support the *governance (social)* or *architectural (technical)* characteristics of sustained adaptability to emerging threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires.

In short, contrary to my initial expectations but consistent with the interview findings, experts who made presentations at the ASDSO conferences do <u>not</u> have consistent knowledge as to whether, to what extent, or in what ways that resilience (conceptualized as sustained adaptability) is applied to systems of dams. Moreover, the knowledge that they have does not in general differentiate safety from resilience nor does it include a robust understanding of resilience or the need for measures to increase resilience.

Below, I summarize my findings about the conference presentations by grouping them under the five subsidiary questions.

How safe and resilient are dams currently? As summarized in Tables 12 and 13 above, experts who participated in professional conferences sponsored by ASDSO in 2020 and 2021 were concerned with a variety of issues related to the sociotechnical imaginary based on safety. For instance, the issues addressed include reform of laws related to dam safety in California after the crisis at Oroville Dam in 2017 (Tapia, 2020); assessing probable maximum precipitation estimates and improving inflow design flood standards (Kappel & Hultstrand, 2020); removing aging or unneeded dams (Walls, 2020); testing the time sensitivity of emergency action plans (Tam & Jain, 2020); discovering and assessing "human factors" (Walter et al., 2020); investigating the safety of materials (Kabala et al., 2020); keeping pace with the science of earthquakes (Wong et al., 2020); conducting exercises to improve responses to emergencies (Matheu et al., 2020); distributing inundation maps (Ragon & Carey, 2020; Ragon et al., 2021); conducting comprehensive needs assessments (Wilson et al, 2020; Wilson & White, 2021); revising the model dam safety programs to incorporate experience gained from responding to incidents (Mills et al., 2020); investigating dam failures (Perri & DeVaun (2021); taking steps to reduce or prevent hazard creep (Peterson & Miriovsky, 2021); understanding ways that spillways can contribute to failed dams (Baker et al., 2021); selecting method to perform risk analyses (Heitland et al., 2021); understanding the increasing risk of wildfires (Bauer, 2021); understanding the uncertainty associated with probable maximum precipitation estimates (Kappel & Hultstrand, 2021a); understanding the importance of warning and evacuation (Mauney & Risher, 2021); understanding hydrologic analysis (Kappel & Hultstrand, 2021b); sharing more risk information (Ragon et al., 2021); compensating for the risk of terrorism (Miyamoto & Richards, 2021); appreciating the importance of organizational design (Ciomei & Sanford, 2021); and aligning the National Dam Safety Program with the National Levee Safety program (Conforti et al., (2021).

Although the experts researched and made presentations about many different safety issues and recommended ways to address those issues, it was not possible to derive a general assessment of the safety (or resilience) of dams based on this data except to say that most of the presentations related to the architectural characteristics of systems of dams.

How are safety and resilience related to one another? Unlike the expert interviews, presentations at the ASDSO conferences did not relate safety and resilience to one another. This suggests that the interview questions, and by extension the academic literature upon which they were based, do not signify that this is an ongoing concern within the professional discourse of dam experts and knowledgeable stakeholders.

How relevant are the concepts of safety and resilience to emerging threats? As described above, only a few of the 28 papers that were analyzed in depth showed that experts displayed knowledge about threats posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires. Furthermore, of these, most of them discussed the threats in terms of safety as opposed to resilience.

How can society improve the resilience of systems of dams? As with the interviews, the presenters did not address resilience conceptualized as sustained adaptability of systems of dams; in other words, they made few if any recommendations for improving resilience.

What are the barriers to making systems of dams more resilient? Similarly, as the presenters did not address resilience conceptualized as sustained adaptability of systems of dams, they also did not identify specific barriers to resilience.

Three of the selected presentations do, however, offer evidence that a sociotechnical imaginary based on resilience conceptualized as sustained adaptability may be emerging (see Table 13). One of the presentations advocates preparing a Structure Integrity Hierarchy that inventories components of dams to improve incident response. The authors contend that the tool is useful making the tradeoffs required after emergencies erupt (Morley et al, 2020). Identifying and assessing tradeoffs during emergencies is essential to sustainably adapting during the stressful times that inevitably follow disasters, which is central to the approach advocated by Woods (2015).

Two presentations, both of which were led by the same FEMA representative, discussed Collaborative Technical Assistance (CTA), which may constitute a tentative step toward the emergence of a sociotechnical imaginary based on resilience, which addresses the architectural characteristics and governance characteristics needed to sustain adaptability of systems of dams. Under the CTA program, FEMA collaborates with communities to plan for emergencies associated with dams (Wilson et. al., 2020; Wilson & White, 2021). In one presentation, FEMA states that the best practice is that "disaster operations are federally supported, state managed, and locally executed"

(Wilson & White, 2021). The CTA program may be used by experts and shareholders to assess and extend the arc of sustained adaptability over the prolonged periods of time that will be needed to recover from disasters that may take years to fully resolve.

Summary of Findings from Expert Discourses Analysis

My analysis of interview transcripts and presentations at the ASDSO conferences suggests that none of the experts across a wide variety of disciplines and organizations or from the dam engineering community are knowledgeable about both the architectural characteristics and the governance characteristics of resilience conceptualized as sustained adaptability. Furthermore, my analysis of interviews with experts revealed that their knowledge about the resilience of dams was inconsistent.

My analysis of presentations at the ASDSO conferences demonstrate that experts in the dam engineering community do not address topics pertaining to the resilience of dams, much less the entire systems of dams including downstream communities, to threats posed by emerging threats such as climate change. Instead, they primarily address topics pertaining to the safety of the architectural characteristics of the dams and the governance characteristics related to the immediate loss of life after failures. Furthermore, academic research into resilience has not gained a foothold within the dam engineering community. These findings suggest that neither the architectural characteristics nor the governance characteristics of systems of dams can sustainably adapt to unexpected events.

The next two chapters examine case studies of the Salt and Verde Rivers system of dams in Arizona and the Tittabawassee River in Michigan.

CHAPTER 5

CASE STUDY: SALT AND VERDE RIVERS SYSTEMS OF DAMS

This case study investigates the system of six major storage dams on the Salt and Verde Rivers, which are owned by the USBR and operated by the Salt River Project, and Tempe Town Lake, which is owned and operated by the City of Tempe. The case study assesses the operationalization (Hollnagel, 2014) of sustained adaptability by the USBR, SRP, Maricopa County, and the City of Tempe (Woods, 2015). The unit of analysis of case study is the system of dams on Salt and Verde Rivers because it is questionable if, to what extent, and in what ways the system would sustainably adapt to challenges posed by emerging threats like climate change, earthquakes, terrorism, cyberattacks, or wildfires.

By operating six storage dams on the Salt and Verde Rivers and associated infrastructure such as canals and power lines, SRP supplies water, hydropower, flood protection, and recreational amenities to municipal and agricultural users in the SRP service area, which includes much of the Phoenix metropolitan area. Two of the storage dams are on the Verde River: Horseshoe Dam and Bartlett Dam. The four others are on the Salt River: Roosevelt Dam, Horse Mesa Dam, Mormon Flat Dam, and Stewart Mountain Dam. Granite Reef Dam does not store water; instead, it diverts water from the Salt River into canals that distribute water throughout the service area. The City of Tempe owns and operates Tempe Town Lake, which is also within the SRP service area.

Participant Observation: Salt River System of Dams

During my investigation, I toured Roosevelt Dam and other storage dams and reservoirs on the Salt and Verde River systems of dams on May 16, 2020, and

November 21, 2020. Roosevelt Dam and the Theodore Roosevelt Lake Bridge are depicted in the following Figures 1 and 2, which I took on May 16, 2020.

Figure 1

Photograph of Roosevelt Dam dated May 16, 2020

Figure 2

Photograph of Theodore Roosevelt Lake Bridge dated May 16, 2020

After the advent of the COVID-19 pandemic in March 2020, I started riding my bike on the Rio Salado Trail, which extends along the Salt River from 19th Avenue in Phoenix to Alma School Road in Mesa. In addition, I occasionally rode along Indian Bend Wash from Tempe Town Lake to the India Bend Wash Center in Scottsdale and along many of the canals operated by the Salt River Projects such as the Cross Cut, Arizona, and Consolidated Canals. I also often hiked up Hayden Butte and biked or walked around Tempe Town Lake many times.

I took and logged about 200 photos from March 24, 2020, to January 17, 2021. Often, I toured the area downstream from Tempe Town Lake Dam, which includes Phoenix Sky Harbor Airport and the City of Phoenix. Occasionally, I accessed the Water Connection website maintained by the Salt River Project to track changes to inflow and outflow amounts for Salt and Verde Rivers system of dams and logged the overall results. For instance, on March 24, 2020, I took the following photo of Tempe Town Lake Dam and noted that the Water Connection website said that the total inflow to the system was 6,592 cubic feet per second compared to the total outflow amount of 4,092 cubic feet per second. Since the reading was for a day in March, snow was melting in the watershed and demand for water in the Phoenix area was low. Therefore, inflow exceeded outflow of the systems of dams, which caused water to spill over Tempe Town Lake Dam as shown in the Figure 3 below.

Figure 3

Photograph of Tempe Town Lake Dam dated March 24, 2020

In contrast, on June 27, 2020, the inflow was 131 and the outflow was 1,600 cubic feet per second. Since these readings were taken in the hot dry summer month of June when inflow from the watershed was low and demand from downstream communities was high, the outflow exceeded the inflow. Therefore, water was not flowing over Tempe Town Lake Dam as confirmed by dry conditions shown in Figure 4 below.

Figure 4

Photograph of Tempe Town Lake Dam dated June 27, 2020

During my hikes and bike trips, I noted many essential infrastructure projects that line the banks of the Salt River above and below Tempe Town Lake. For instance, highway interchanges the east of Tempe Town Lake at State Routes 101 and 202 stand on massive columns founded in the bed of the Salt River. Consistent with the emergency caused in 1980 by heavy rains that threatened the survival of Roosevelt Dam and Stewart Mountain Dam, which was discussed above in Chapter 4, a flood caused by a failure of one of one of the dams on the Salt or Verde Rivers might damage or disable the interchanges, which have not endured similar crises since the onset of megadrought. A disaster of this kind would disrupt traffic flows for a prolonged period and require time-consuming and expensive repairs.

To the west of Tempe Town Lake long bridges span the Salt River at Priest Drive, State Route 143, and Interstate 10. As Roberge (2002) points out flood waters may “scour” sand and gravel at the base of the piers that support highway bridges and compromise their strength. Furthermore, engineered levees on the banks of the Salt River that protect Phoenix Sky Harbor Airport west of Priest Drive bridge might be damaged by prolonged exposure to floods caused or worsened by emerging threats such as climate change that exceed their design capacity of 150,000 cubic feet per second (Ester, 2006).

The types of events that can affect operation of dams varies widely. On the morning of Wednesday, July 29, 2020, I rode my bicycle to the east under the Union Pacific Salt River bridge on the Rio Salado Trail at Tempe Beach Park at about 5:30 AM. As I returned from Alma School Road in the Mesa area after 6:00 AM, I noticed that the sky was dark, which seemed unusual because the sun was rising. As I pulled into Tempe Beach Park, a woman told me that a train had derailed on the bridge across Tempe Town Lake and was on fire. After a police officer ordered us to leave, I rode to the other side of the Tempe Beach Park on city streets where I watched fire fighters dousing the fire with water as depicted on Figures 5 and 6.

Figure 5

Photograph of Fire Caused by Derailment of Train dated July 29, 2020

Figure 6

Photograph of Fire Caused by Derailment of Train dated July 29, 2020

Tempe Fire and Medical Chief Greg Ruiz said about ten railroad cars loaded with lumber and hazardous materials derailed on the bridge at about 6:00 AM on July 29, 2020. The freight train was made up of 102 cars. Fire engulfed the bridge after the accident, which partially collapsed at the point of the accident (Curtis, 2021). One of the railway cars carried lumber that spilled into the reservoir. If the lumber had floated down to the dam, it may become bound up in the steel gates. Over the next several months, I watched as Union Pacific reconstructed the bridge.

Concerns about the ability of architectural characteristics of Salt and Verde River system of dams to sustainably adapt in a timely and cost effective manner were illustrated by fears that Roosevelt Dam or Stewart Mountain Dam might fail during heavy rains in February 1980; by the later redesign and reconstruction of Roosevelt Dam in 1996, which took 16 years and $430 million to complete (Ester, 2006); and by the failure of the Tempe Town Lake Dam in 2010 and its replacement in 2016, which took six years and $47 million to complete (City of Tempe, n.d., *Town Lake Dam*).

History of Modification of Roosevelt Dam

In 1978, the USBR prepared a report finding that the maximum probable flood would overtop Roosevelt Dam by 2.5 feet, which would cause the dam to fail. The 1978 report proposed reducing the threat by raising the height of the dam by four feet and reconfiguring the spillways at an estimated cost of $1.2 million (*S. 2820: Reclamation Safety of Dams Act*, 1978, p. 17). The 1978 report was based on earlier one dated 1970 that estimated that raising the height of the dam by four feet and changing the spillways would cost about half as much, or $595,000 (*Dam Safety*, 1977, p. 578). The estimated cost of $595,000 for the modifications was simply “whited out” on the 1970 report and a new amount of $1.2 million was typed in on the 1978 report.

Cecil Andrus, the Interior Secretary under President Carter, submitted the 1978 report with the proposed Reclamation Safety of Dams Act in February 1978. Comparing the two reports dated 1970 and 1978 indicates that the USBR understood that the architectural characteristics of Roosevelt Dam were inadequate before Teton Dam failed in 1976. However, the 1978 report on its face indicates that the USBR only reassessed the costs, not the adequacy, of raising the height of the dam by four feet after the failure of Teton Dam in 1976.

Two years later, the *Arizona Republic* featured the following headline on February 16, 1980: “500-year flood feared possible” (Harris & Kowalec, 1980). Heavy rains had soaked the watershed above Roosevelt Dam and the ensuing flood closed all but three bridges in the Phoenix metropolitan area (Chin et al, 1991). Bruce Babbitt, Arizona’s governor at the time, recommended that the public should “be prepared for the ‘unthinkable’” because he was considering evacuating up to 200,000 residents who lived within one mile of the Salt River if the crises did not abate soon (Seper, 1980). Fortunately, residents in Phoenix metropolitan area avoided evacuation and the associated damage because “the second storm was late and weaker while the third storm quickly passed over the state with only scattered showers” (SRP Photo Archive, n.d.).

After the crisis in 1980, the USBR reevaluated the design of Roosevelt Dam and decided to raise its height by 77 feet. As with many remodeling projects, raising the height of Roosevelt Dam triggered a cascade of problems. For instance, the USBR had to strengthen the foundation and abutments to bear the weight of redesigning spillways and encasing the old dam in concrete up to 50 feet thick. In addition, the mortar between the stone blocks that made up the original dam was deteriorating. Therefore, the dam was increasingly “unsafe” as it aged and outlived its design life until it was reconstructed in 1996. Furthermore, raising the dam required constructing the Theodore Roosevelt Lake Bridge to carry traffic that formerly traveled across the crest of the dam (Ester, 2006).

Three factors accounted for the raised height and increased costs. First, six cities in the Phoenix metropolitan area paid for a 15-foot increment to increase the amount of water stored for their use. Second, the USBR increased the “inflow design flood” to 3,000,000 acre-feet over 16-day period with peak of 654,000 acre-feet on the third day. This increase meant that maximum amount of water that Roosevelt Dam could pass tripled from 214,000 to 680,000 cubic feet per second. This raised the height of the dam by 43 feet (Factbook, p. 19; Ester, 2006). Third, the USBR decided not to construct Orme Dam at the confluence of the Salt and Verde Rivers. This decision eliminated the flood control that the Orme Dam would have been provided but required raising the height of Roosevelt Dam by 19 feet (Ester, 2006).

The precise numbers associated with the increments of raising the height of Roosevelt Dam by 77 feet after it had been in service for about 80 years disguise the imprecise and uncertain science of the architectural characteristics of dams that interacts with the governance characteristics of systems of dams. Although experts and stakeholders may improve governance characteristics in ways that are salient, credible, and legitimate, achieving those qualities at certain points in time does not mean that improved methods to assess architectural characteristics will not change as science evolves and risks change in ways that are not consistent or predictable (Cash et al., 2003).

Examples of problems that may appear over time are evidenced by the reports for Roosevelt Dam and Stewart Mountain Dams that were submitted to Congress in 1978 with the initial draft of the Reclamation Safety of Dams Act. The amounts and dates were simply “whited out” on the 1970 reports and new amounts were typed in on the 1978 reports. These documents show that USBR was aware of safety issues on both dams more than ten years before the crisis in February 1980. In fact, the report on Roosevelt Dam stated that it would fail if overtopped. However, the USBR only reassessed costs in 1978, not the adequacy of the proposed repairs proposed in 1970. However, as described above, the repairs were much more extensive and expensive. The cost to raise the height of Roosevelt Dam by four feet *doubled* from an estimated $595,000 in 1970 to $1.2 million in February 1978. However, the costs increased *exponentially* after the USBR reconstructed Roosevelt Dam in 1996 by raising its height 77 feet over a period of 16 years at a cost of $430 million.

Despite the reconstruction of Roosevelt Dam, climate change may worsen rainstorms that fall on the watershed above the Salt and Verde Rivers when the current megadrought ends (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022). As described in Chapter 2, the astonishing increase in the cost and scope of reconstructing Roosevelt Dam shows that changing the *architectural* characteristics of path dependent major dams is time consuming, expensive, and, therefore, not sustainably adaptable in the short term. However, improving *governance* characteristics across the fragmented jurisdictional boundaries within which systems of dams operate may cost significantly less than changing the *architectural* characteristics. Changing governance characteristics to enhance tradeoffs takes more time and patience to coordinate conversations among fragmented experts and stakeholders (Woods, 2015).

Implementation of the Reclamation Safety of Dams Act (1978) demonstrates that passing new laws and issuing new or revised policies and procedures under the National Dam Safety Program can improve safety of the architectural characteristics of individual dams by providing direction and funds that influence the operations of large bureaucratic cultures like the USBR. As a result, the safety of individual dams has improved, but changing governance characteristics of entire systems of dams including downstream communities to improve sustained adaptability may be less expensive but more complicated because conversations and negotiations must extend beyond single bureaucracies to include multiple parties that operate in adversarial legal and liability regimes with incommensurate values. Next, I describe the proposal by the USBR to build Orme Dam, a potential seventh storage dam on the system of dams on the Salt and Verde Rivers. The process used to decide whether to build Orme Dam supplies useful insights into understanding differing points of view and ways to facilitate or mediate conversations about the governance of the safety or resilience of systems of dams.

Orme Dam

The USBR proposed building Orme Dam at the confluence of the Salt and Verde Rivers as part of the Central Arizona Project. Although the dam would have supplied increased the conservation capacity for irrigation or municipal uses, the main purpose of the dam was to control floods. After crises in 1978, 1979, and 1980, interest in flood control on Salt River increased dramatically and decision makers decided to act. The following editorial from the *Arizona Republic* dramatically illustrates the increasing frustration of residents in the Phoenix metropolitan area:

> Are you fed up with sitting in traffic, creeping to work, because floods have taken out all but two of the major bridges crossing the Salt River? Are you fed up with reading stories about a new study and more hearings into whether the construction of Orme Dam would interrupt the nesting habits of bald eagles … of this community playing second-fiddle to high-and-dry special pleaders who shed tears over nesting eagles, but can't find compassion for the thousands of families who endure hardship, fear, and ruin as flood waters rampage through the valley? I'm mad … I am mad as hell that high-and-dry Washington bureaucrats have been dilly-dallying for at least ten years over approval of Orme Dam …. Now, dammit, give us our dam!" (Reisner, 1986, p. 297).

The aggrieved sense of entitlement expressed by the editor-in-chief of the largest newspaper in Arizona summarizes the attitude that prevailed during an era that favored constructing dams. Politicians and business leaders in Arizona often decry wasteful government spending, but dams were exempt from those diatribes. For several decades, Carl Hayden led the efforts of Arizona's Congressional delegation in its campaigns for water projects. In 1912, the newly enfranchised voters elected Hayden to the House of Representatives after Arizona became a state. In 1927, the voters promoted him to the Senate. After negotiating passage of a bill to create the Central Arizona Project, Hayden retired in 1969 as chair of the Senate Appropriations Committee after serving Arizona in Congress for six decades (Espeland, 1998, p. 98). During his long tenure, Hayden cajoled

Congress to pass many laws that led to the construction of dams. However, after Hayden left the scene in 1969, the outcome of negotiations about Orme Dam show that support for constructing dams was eroding and that the boom in construction of dams between 1950 and 1969 that added almost half of the 90,000 major dams in the United States was waning (Reisner, 1986; USACE, 2022).

After describing a “garbage can” model in which three independent streams of problems, policies, and politics interact in unpredictable way, Kingdon (2010) asserts that political scientists usually focus on concepts like power and strategy, which sophisticated brokers like Hayden deftly wield. However, assessing public policy based on stark concepts like power may miss nuance. Instead, Kingdon (2010) finds that content of ideas is integral to making decisions, not rationalizations or smokescreens. Those who argue about the content of ideas get trapped in dilemmas, marshal evidence, and untangle puzzles. Kingdon (2010) quotes John Maynard Keynes to support his finding that working through content as opposed to lobbying or organizing political power is more typical and more availing: “I am sure that the power of vested interests is vastly exaggerated compared with the gradual encroachment of ideas" (p. 125).

Consistent with this contention of Kingdon (2010), Espeland (1998) offers an illuminating description of a policy process in which incommensurate values of USBR collided with those of the Yavapai Indian Tribe over the proposal to construct Orme Dam. In this process, ideas about constructing dams were thoroughly evaluated after attempts to apply political power proved inadequate to decide whether to construct Orme Dam. Governance characteristics of sustained adaptability of systems of dams will also invoke incommensurate values held by groups with conflicting loyalties and ideologies.

Therefore, the process used to decide whether to build Orme Dam is relevant to conversations about increasing the sustained adaptability of systems of dams.

The narrative opens with officials of the USBR offering $400 million to the 400 members of the Yavapai Tribe to approve inundating the Fort McDowell Indian Reservation, which constructing Orme Dam would have entailed. By rejecting the offer, the Tribe stunned representatives of the USBR (Espeland, 1998, p. ix). In her description of three classes of protagonists who battled over Orme Dam, Espeland (1998) supplies insights that may be relevant to the mediating conversations needed to change the architectural and governance characteristics of systems of dams.

Senior engineers at the USBR, which Espeland (1998) labels as the Old Guard, are the first class. They identified with the ethos of the Progressive era that advocated building dams to control nature by “reclaiming” arid land with “conserved” water that would be “wasted” if allowed to flow into the ocean. The Old Guard believed that the rejection of Orme Dam was a “betrayal” of older values in favor of an “inferior compromise project” that, in fact, brought similar conservation capacity and flood control (Espeland, 1998, p. 14-16).

The second class, which Espeland (1998) designates as the New Guard, were social scientists, biologists, planners, and younger engineers who were hired by the USBR to improve the environmental impact statements (EIS) required with the passage of NEPA in 1969. After the USBR submitted an inadequate EIS for Orme Dam in 1976, the USBR allowed the New Guard to conduct a five-year, $15 million study called the Central Arizona Water Control Study (CAWCS). The investigation evaluated several alternatives to enhance water supply and flood control in Arizona (Espeland, 1998, p. 4).

The third class was the Yavapai Community, which consisted of about 400 members of the Yavapai Tribe who lived on the 25-square mile Fort McDowell Reservation. President Theodore Roosevelt created the reservation in 1903, a year after he signed the Reclamation Act (1902). The Tribe was not willing to sacrifice its reservation because the federal government had relocated the tribe several times and abused members of the Tribe for 150 years. The USBR insulted members of the Tribe by assuming that they would sell land that they valued in ways that were incommensurate with the value of money (Espeland, 1998, p. 1-2).

Although Espeland (1998) sympathizes with the Yavapai Community, she fairly describes the motivations and actions of the three groups. Rational choice theory frames her assessment and is based on three assumptions. First, participants assess tradeoffs through the mechanism of utility that integrates values and cost-benefit analysis. Second, participants evaluate outcomes based on the consequences of different actions. Third, although expectations of participants change when more they learn more, the rational choice theory applies the same metric (p. 23).

Commensuration, which represents diverse properties with “different units with a single, common standard or unit,” is at the heart of the analysis by Espeland (1998, p. 24). Commensuration defines “a relation between two attributes or dimensions where value is revealed in comparison, in the trade-offs that are made among different components of choice” (p.24). However, commensuration “does not permit the expression of incommensurate values, things which people believe have some intrinsic, incomparable worth” (p. 24). The Yavapai Community believed that the intrinsic incommensurate value of their reservation could not be exchanged for money.

Espeland (1998) found that embedded in commensuration is the fundamental idea that “disparate or idiosyncratic ideas can be expressed in standardized forms and that doing so does not fundamentally change their meaning” (p. 26-27). The approach “denies that meaning is intimately linked to form” (p. 27) and that separating meaning “from cultural form and context … transforms value” (p. 27). The Tribe believed that the attempt by the USBR to separate meaning from the form and context of its reservation was impossible because the transformed value was unacceptable to them.

In April 1977, President Jimmy Carter included Orme Dam on a “hit list,” which demanded that Congress eliminate 19 water projects. In addition to fulfilling his campaign promise to balance the federal budget by the end of his first term, Carter also wanted to placate environmentalists who supported his victory in November 1976 election, a few months after the failure of Teton Dam. The National Environmental Policy Act (1969) provided significant power to environmentalists to fight water projects. However, despite the drama of the “hit list” and increasing concerns about the environmental impact of dams, Congress refused to eliminate any of the water projects. Even though Carter eventually capitulated, the hit list shows that the formerly rock-solid support for constructing dams was eroding and that the governance characteristics applicable to systems of dams was changing (Reisner, 1986, p. 306-331).

Marginalized groups object to cost-benefit analysis because it reduces incommensurable values to quantities to ease trade-offs (Porter, 1996). Dominant actors like the USBR traditionally leverage agreements by imposing commensuration on less powerful groups. In the case of Orme Dam, the Tribe stunned the USBR when it refused to accept a type of rationality that it found abhorrent. In the end, James Watt, the controversial Secretary of the Interior at the time, rejected Orme Dam in 1981 when he selected “Plan 6,” one of eight plans presented to him by CAWCS after significant public participation. Plan 6 anticipated building several new or replacement dams as well as raising the height of Roosevelt Dam (Espeland, 1998, p. 14). In the end, none of the new or replacement dams were constructed. Instead, the USBR raised the height of Roosevelt Dam by 77 feet to compensate for the loss of flood protection that would have been provided by Orme Dam and to increase capacity needed to absorb the increased “inflow design flood” that the USBR calculated for after the crisis in 1980.

Since a single person made the decision without the direct participation of all relevant groups, the ability to apply the methods used by CAWCS to other situations is limited. However, the process used to assess and devise the alternatives including Plan 6 provides insights that may be useful in assessing tradeoffs needed to improve the sustained adaptability of systems of dams.

The major dams on the Salt and Verde Rivers that have been addressed so far in this chapter are owned by the federal government. The failure of the architectural characteristics any of these major dams would flood downstream communities such as Mesa, Tempe, and Phoenix. As a result, the governance characteristics of sustained adaptability of those communities would be challenged. In the following section, I describe my investigation into the governance characteristics of Tempe Town Lake, which is on the Salt River but is owned by the City of Tempe, not the federal government.

Tempe Town Lake

Throughout the 20th century, the Salt River flooded several times (City of Tempe, n.d., *A Guide to Tempe Town Lake*; City of Tempe, n.d., *Historic Guideline*). After fears that Roosevelt Dam might fail in 1980, the USBR tripled the size of the inflow design flood and decided to raise the height of the dam by 77 feet by installing a concrete overlay on top of the old dam to make room to absorb excess water. When the USBR completed reconstructing Roosevelt Dam in 1996, the total capacity of the reservoir increased by 40 percent from 1,348,324 acre-feet to 3,432,408 acre-feet. About 50 percent, or 1,779,365 acre-feet, of the total capacity of the reservoir is reserved to absorb excess runoff. Of the reserved amount of 1,779,365 acre-feet, 556,196 acre-feet is for "Flood Control," or the amount of flood control that Orme Dam would have provided if it had been constructed, and 1,223,169 acre-feet is for the "Safety of Dams," or the amount needed to absorb the increased inflow design flood. Roosevelt Dam is the only dam on the Salt River with capacity reserved to absorb excess water (Ester, 2006). The SRP, which operates the storage dams on the Salt and Verde Rivers, conserves water in the other storage reservoirs on the Salt and Verde Rivers for use during dry summer months and to produce hydropower (Phillips, et al., 2009).

Tempe Town Lake is about 50 miles west of Roosevelt Dam on the Salt River. After securing water from the Central Arizona Project to fill the reservoir, the City of Tempe created Tempe Town Lake in 1999, or three years after the USBR reconstructed Roosevelt Dam, by constructing a dam across the dry riverbed of the Salt River. The original dam at Tempe Town Lake consisted of four inflated rubber bladders. However, the dam failed in 2010 after one of the west-facing bladders deflated because it deteriorated after years of exposure to the intense Arizona sun (Fisher, 2016). No injuries and insignificant damage resulted from the failure because the flood flowed down the dry bed of the Salt River.

On a temporary basis, the City of Tempe replaced the failed bladder and refilled the reservoir until it could construct another dam downstream from the original dam. In 2016, the City of Tempe completed construction of a steel-gated dam at a cost of $47 million. The gated design of the new dam allows operators to quickly lower the one or more gates to convert the reservoir back into a free-flowing river to pass excess water down the dry bed of the Salt River west of the dam to reduce or prevent flooding the City of Tempe. As the excess water starts subsiding, operators can refill the reservoir by raising the gates. Without this capability, the City of Tempe would have to buy water to refill the reservoir (City of Tempe, n.d., *Town Lake Dam*).

The gated structure of the new dam marginally increases the safety (fail-safe) and sustained adaptability (safe-to-fail) of the Tempe Town Lake system of dams to challenges posed by modest floods over the brief periods. However, with a capacity of 3,000 acre-feet, Tempe Town Lake would be overwhelmed if the full capacity of Roosevelt Dam, which can impound up to 3.5 million acre-feet of water, were suddenly released. A disaster of that magnitude would destroy Tempe Town Lake and large areas of the Phoenix metropolitan area.

Local governments often encourage economic development of floodplains downstream from dams instead of planning for disasters. Scholars have identified factors that reduce the chance that communities will act proactively to reduce the risk. After describing the paradox of “man’s apparently growing susceptibility to injury from natural hazards during a period of enlarged capacity to manipulate nature," Burton et al. (1968) identify the two policy approaches stakeholders often pursue to address damages from floods (p. 1). The *technological approach* advocates building more dams and levees to reduce hazards or influence causes. The *social or behavioral approach* promotes planning and careful use of flood plains in theory, but in practice the approach is often limited to providing relief to the victims of floods. After a disaster recedes from collective memory and damages have been repaired, more dams and levees are often constructed, and the cycle is renewed.

Consistent with the technological and social approaches described by Burton et al. (1968), which resonate with the architectural and governance characteristics of systems of dams, Burby (2006) demonstrates that Hurricane Katrina was a socially constructed catastrophe, not a natural disaster. Burby (2006) describes two paradoxes of governance characteristics found in disaster policy. The *safe development paradox* finds that by improving the safety of hazardous areas, society reduces risks associated with "normal" threats, which decreases the number and scope of disasters that fit within patterns based on historical records but increases the likelihood of catastrophic losses caused by future events that exceed historical patterns that inform standards. The *local government paradox* finds that local leaders do not pay enough attention to reducing vulnerability of their constituents even though they are the victims who suffer when disasters exceed historical patterns (p. 171).

Di Baldassarre et al. (2013) describe the "levee effect," a paradoxical condition under which "flood control structures might even increase flood risk as protection from frequent flooding reduces perceptions of risk" (p. 3295). Enabled by the levee effect, governments allow builders to construct businesses and residences in floodplains, which "are then vulnerable to high-consequence and low-probability events" (p. 3295-3296).

As part of a pilot case study conducted in 2019 that addressed the governance characteristics at Tempe Town Lake, I investigated hazard mitigation plans prepared by 28 jurisdictions in Maricopa County along with emergency action plans and building codes issued by the City of Tempe. Before addressing the building codes and emergency action plans, the next section addresses the mitigation plans.

Maricopa County Multi-Jurisdictional Hazard Mitigation Plan

In 2021, 28 jurisdictions in Maricopa County prepared a Multi-Jurisdictional Hazard Mitigation Plan (MHMP) (Maricopa County, 2021) pursuant to the Disaster Mitigation Act (2000), which authorized programs "for predisaster mitigation, to streamline the administration of disaster relief, to control the Federal costs of disaster assistance, and for other purposes" (Disaster Mitigation Act, 2000). Since the Disaster Mitigation Act focuses on "predisaster mitigation," the MHMP consequently addresses the governance characteristics of safety, not resilience conceptualized as sustained adaptability.

FEMA approved the first MHMP in 2010. An updated version was approved in 2015. In 2021, the MHMP plan was updated for the third time (Maricopa County, 2021, p. ES 1). The MHMP assesses the following hazards: Dam Inundation, Drought, Extreme Heat, Fissure, Flood, Levee Failure, Severe Wind, Subsidence, and Wildfire (Maricopa County, 2021, p. 178). Dam Inundation and Levee Failure are most relevant to my research. Those two hazards may be affected by the emerging threat of climate change, which the MHMP addresses: "FEMA and others have begun to take a harder look at the impacts of climate change on natural hazards and the mitigation planning process. In March 2015, FEMA released new state mitigation planning guidance that will require all state hazard mitigation plans to address climate change beginning with all updates submitted after March 2016" (Maricopa County, 2021, p. 180). Due to climate change, the MHMP projects that "snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems" (Maricopa County, 2021, p. 181).

The MHMP assesses vulnerability based on the Calculated Priority Risk Index (CPRI). The CPRI includes the following factors with levels, descriptions, and index values defined in the MHMP (weighting factors are noted in parentheses): probability (45%), magnitude/severity (30%), warning time (15%), and duration (10%) (Maricopa County, 2021, p. 182). According to the MHMP, the State of Arizona has adopted eight categories of critical facilities and infrastructure including water supply systems (Maricopa County, 2021, p. 184). MHMP states that "two primary scenarios" address the downstream risk of inundation in Maricopa County that may be caused by dams: emergency spillway discharges and dam failure (Maricopa County, 2021, p. 188).

Since the crisis at Oroville Dam in 2017 involved spillways (France et al., 2018), it is interesting to note that the MHMP differentiates between the risks posed by emergency spillway discharges and dam failure for three reasons. First, professionally designed and maintained dams are less likely to fail. Therefore, downstream assets "are more likely to be impacted by an emergency spillway discharge than by a dam failure." Second, since emergency spillways are located at fixed positions, the inundation limits are easier to predict than those associated with the failure of dams, which may happen at any point of the structure. Third, the dynamics of floods flowing down emergency spillways are different from those caused by the uncontrolled release of water through a breach in a dam, which “is usually catastrophically destructive.” In contrast, discharges from an emergency spillway increase and decrease gradually as the reservoir drains. (Maricopa County, 2021, p. 188)

Although damages caused the failure of spillways or dam can be huge, the probability of failure is low, which is consistent with experience in Maricopa County. In fact, the MHMP only cites two examples, both of which happened before the period covered by the report. In 1993, a large precipitation event caused SRP to release discharges of up to 124,000 cubic feet per second from its dams. The flows caused 200 families to evacuate, damaged areas along the Salt and Gila Rivers costing $38 million. In September 1997, a tropical storm drenched the western part of the county, which caused a peak discharge of 2,610 cubic feet per second from the spillway at Narrows Dam (Maricopa County, 2021, pp. 188-189).

The MHMP uses assessments provided by the Arizona Department of Water Resources and the National Inventory of Dams to calculate the risk of dams in Arizona failing. According to the MHMP, the average CPRI emergency spillway flow and dam failure was 2.01. In comparison, the CPRI was 2.25 for Phoenix and 2.55 for Tempe (p. 192). With reference to emergency spillway discharges and dam failure, the MHMP concludes:

> In summary, 1,197, 21 [stet] and 3,800 critical and non-critical MJPT identified assets with a cumulative reported replacement cost of $2.84 billion, $23.3 million and $820.6 million are exposed to emergency

> spillway high hazard and dam failure high and medium hazard inundations, respectively, for the planning area. An additional $72.7 billion, $88.4 million and $38.9 billion of census block residential structures are exposed to emergency spillway high hazard and dam failure high and medium hazard inundations, respectively, for the planning areas. (Maricopa County, 2021, p. 193)

MHMP advises:

> Regarding human vulnerability, a total population of 553,274 people, or 13.37% of the total census planning area population, is potentially exposed to an emergency spillway inundation event. Similarly, total populations of 854 and 331,796 people, or 0.02% and 8.0% of the total census planning area population, are potentially exposed to a high or medium hazard dam failure inundation event. The potential for deaths and injuries are directly related to the warning time and type of event. Given the magnitude of such events, it is realistic to anticipate at least one death and several injuries. There is also a high probability of population displacement for most of the inhabitants within the inundation limits downstream of the dam(s). (Maricopa County, 2021, p. 193)

The Disaster Mitigation Act (2000) successfully encouraged 28 jurisdictions in Maricopa County to proactively engage with improving the governance of the *safety* of dams and spillways, among other risks, and to create the MHMP. However, the MHMP does not address the governance characteristics applicable to the *resilience* of systems of dams. The next two sections address the building codes and emergency action plans issued by the City of Tempe.

Building Codes

After reviewing relevant documents about building codes and emergency action plans, I conducted exploratory conversations with knowledgeable experts encountered at events sponsored by Arizona State University that were relevant to the pilot case study. Consistent with the findings of Burton et al. (1968), Burby (2006), and Di Baldassarre et al. (2013), the pilot case study found that the City of Tempe has not changed building codes or emergency action plans to increase the sustained adaptability of the architectural or governance characteristics of Tempe Town Lake. In the future, building codes and emergency action plans should be modified to help experts and stakeholders improve the sustained adaptability of systems of dams.

The City of Tempe, like many cities, adopted the International Building Codes (IBC) but prescribes exclusions and additions approved by ordinances. A retired Assistant Fire Chief and Fire Marshall for the City of Tempe confirmed that Fire Marshalls suggest changes to the boilerplate language of the relevant IBC (personal communication, March 18, 2019). None the amendments to the 2018 IBC imposed by the City of Tempe through April 4, 2019, address or improve the sustained adaptability of Tempe Town Lake or of the buildings constructed around its perimeter (City of Tempe, 2018).

A representative of the Community Development/Building Safety Department at the City of Tempe who coordinates updates to building codes said that no buildings around Tempe Town Lake are in a 100-year floodplain because levees are built to withstand 500-year floods. As a result, the code does not require building owners to address the possibility of floods because, by definition, no buildings in Tempe are in a 100-year floodplain. The representative advised that no efforts are afoot to make Tempe Town Lake more resilient to climate change, earthquakes, terrorism, or cyberattacks (personal communication, April 4, 2019).

Emergency Action Plans

The City of Tempe issued an Emergency Operations Plan in 2014. It does not operationalize the sustained adaptability of Tempe Town Lake specifically although it includes responses to emergencies involving Tempe Town Lake. According to a deputy chief of the Fire Department, the City of Tempe has updated the 2014 plan. However, he said that the new plan does not address the resilience of Tempe Town Lake specifically (City of Tempe, 2014) (personal communication, April 3, 2019). An emergency services planner for the Maricopa County Department of Emergency Management who synthesizes emergency action plans from several jurisdictions confirmed that "no recovery plan is in place" for Tempe Town Lake (personal communication, April 5, 2019).

A consultant who works with private and university clients told me that resilience planning is becoming more popular because policy makers increasingly do not believe that government leaders will takes steps to mitigate threats posed by climate change. Therefore, they are looking to increase resilience so that their communities can recover from more volatile and larger weather events. However, local governments are financially unable to address resilience. He does not believe that the City of Tempe has addressed resilience through governance programs like building codes or emergency action plans (personal communication, March 7, 2019).

Although it does not address resilience explicitly, the 2014 Emergency Operations Plan does address flooding and risks associated with the possible failure of SRP dams by summarizing eight disaster scenarios prepared in 1997 by the USBR. The least catastrophic scenario assesses the possible failure of Stewart Mountain Dam, which would release a maximum flow rate of 150,000 cubic feet per second that would reach Tempe in five hours (City of Tempe, 2014). The other seven scenarios analyze flows that range from 300,000 to 2,600,000 cubic feet per second after failures of the dams. However, according to the City of Tempe, Tempe Town Lake can handle flows of up to 250,000 cubic feet per second (City of Tempe, n.d., *A Guide to Tempe Town Lake*).

The most destructive scenario assumes that Roosevelt Dam fails "at normal conservation pool, causing overtopping and failure of Horse Mesa, Mormon Flat, and Stewart Mountain dams." A maximum flow rate of 2,600,000 cubic feet per second would reach the campus of Arizona State University about seven hours after failure. A flood of this magnitude would overwhelm Tempe Town Lake (the capacity of Roosevelt Dam is 3.5 million acre-feet, or over 1,000 times more than the 3,000 acre-feet that Tempe Town Lake impounds), devastate Tempe and the ASU campus, and substantial portions of the Phoenix metropolitan area. Even if Roosevelt Dam did not fail catastrophically, representatives of SRP contend that the Salt River in Phoenix is engineered to withstand 180,000 cubic feet per second and, therefore, could withstand indefinitely the maximum output of 150,000 cubic feet per second from the spillways at Roosevelt Dam.

The operations manager for the City of Tempe said that to his knowledge the City was not concerned about the resilience of Tempe Town Lake to the possible failure of dams operated by the SRP. If Roosevelt Dam or any other SRP dam were to fail, he said that the City would close Tempe Beach Park, lower the gates on the Tempe Town Lake dam, and expect SRP to respond to the crisis (personal communication, March 27, 2019). A senior representative of SRP said that SRP was not concerned about the resilience of Roosevelt Dam because the USBR rebuilt the dam in 1996 so that it can absorb a 200-year flood along with the inflow design flood. However, he conceded that potential threats to the integrity of the dam include earthquakes and terrorism (personal communication, March 25, 2019). These diametrically opposed positions illustrate that the City of Tempe and SRP carefully patrol the jurisdictional and physical boundaries between organizations and are reluctant to cross them to discuss ways to improve the governance characteristics of the Salt and Verde Rivers system of dams. The positions of the two jurisdictions seems like the boundary work used by scientists to distinguish science from non-science (Gieryn, 1983), but may also reflect concerns about the adversarial legal liability regime.

Several officials asserted that it is difficult to start conversations about improving the governance of resilience in today's constrained and polarized environment. For instance, the head of the Maricopa County Department of Emergency Management asserted during a meeting at ASU that most citizens have not cached the recommended three-day supply of water and non-perishable food in anticipation of an emergency. Therefore, those who work in emergency management prioritize safety and are reluctant to extend conversations to address resilience.

The paucity of efforts to enhance the resilience of Tempe Town Lake also reflect factors such as the levee effect that was identified by Di Baldassarre et al. (2013). A false sense of security may prevail among officials and residents because levees and other measures to direct the flows of excess water have been engineered along the Salt River, which inhibits efforts to improve governance of resilience. Also, the southwest region the United States has suffered from a megadrought since 1995, which means that the system has not been tested by the types of storms and floods afflicted the area many times in the 20th Century (Murphy & Ellis, 2019; Williams et al., 2020; Williams et al., 2022).

Other institutional barriers also hamper efforts aimed by improving resilience of systems of dams. For instance, owners refuse to produce emergency action plans for dams to the public. Consistent with this attitude, the USBR refuses to provide emergency action plans due for the dams on the Salt and Verde Rivers due to concerns about security. Although the Multi-Jurisdictional Hazard Mitigation Plan for Maricopa County discussed is available online, the Emergency Operations Plan is reserved for official use only (Maricopa County, 2021).

Building codes and emergency action plans are examples of governance characteristics that help define whether communities can make tradeoffs needed to sustainably adapt to the possible sudden and unexpected failure of one of the dams on the Salt River due to climate change, earthquakes, terrorism, cyberattacks, or wildfires. However, the case study finds that the building code and the emergency action plan of the City of Tempe do not address the sustained adaptability of Tempe Town Lake.

Conclusion

Although the dams on the Salt and Verde Rivers were challenged by heavy precipitation many times in the past, the megadrought has led to problems associated with aridity. In contrast, the next chapter explores the failure of two dams on the Tittabawassee River in Michigan in 2020 precipitated by an excess of water. Ironically, the challenges faced by both systems of dams may have caused or exacerbated by the emerging threat of climate change, which can lead to an excess of precipitation or its opposite.

CHAPTER 6

CASE STUDY: TITTABAWASSEE RIVER SYSTEM OF DAMS

The case study in Chapter 5 addressed major dams on the Salt and Verde Rivers, which are among the four percent owned by the federal government. However, since private interests own 65 percent of major dams (USACE, 2022), the following case study of events leading up to and following the failure of Edenville Dam on May 19, 2020, which was owned by a private entity and provides a wider lens through which to assess the complex and context sensitive nature of the architectural and governance characteristics of most major dams. The case study demonstrates that preserving the ability to make tradeoffs needed to ensure safety or sustain adaptability is often undermined by problems that play out over prolonged periods of time. The following explores events leading up to the breach of Edenville Dam, the resulting disaster, which overwhelmed Sanford Dam and flooded downstream communities such as Midland, the subsequent forensic investigations, and legislative reforms.

Introduction

After Wolverine Power Corporation defaulted on a loan over $1 million in 2003, Synex Energy Resources, an engineering and consulting firm based in Vancouver, foreclosed on the Secord, Smallwood, Edenville, and Sanford Dams on the Tittabawassee River in Michigan. In September 2003, Synex Energy Resources sold Wolverine Power Corporation to Synex Michigan, LLC. On June 23, 2004, the FERC license on the Edenville Dam was transferred to Synex Michigan, LLC (Kukulka, 2020).

On March 17, 2006, Boyce Hydro Power LLC (Boyce) bought Synex Michigan LLC. On July 12, 2007, Boyce applied its name to Synex. Lee Mueller, an architect who lives in Las Vegas, controlled Boyce Hydro Power. Mueller is the grandson of William Dickson Boyce, the founder of the Boy Scouts of America. As trustee of the William D. Boyce Trusts, Mueller controls many other entities connected with the estate of his grandfather (Kukulka, 2020).

After a contentious series of disputes spanning a decade, FERC revoked the license of Boyce to generate hydroelectric power at the Edenville Dam by order dated September 10, 2018. The order stated that the revocation was due to the failure of Boyce to “increase the project’s spillway capacity to safely pass flood flows.” The order also found that Boyce failed to abide by terms of the license, the regulations of FERC, and a compliance order dated June 2017 (FERC, 2018, p. 1).

After revocation of the FERC license, the Michigan Department of Environment, Great Lakes, and Energy (EGLE) assumed responsibility for regulating Edenville Dam (Michigan Department of Environment, Great Lakes, and Energy, 2021, p. 1).

The Four Lakes Task Force was formed by the Wixom Lake Association, the Sanford Lake Association and the Sanford Lake Preservation Association after the FERC revoked the license of Boyce. The purpose of the FLTF was to maintain and operate the four dams and reservoirs on the Tittabawassee River (Kukulka, 2020).

In April 2019, the FLTF as the “delegated authority” of Midland and Gladwin counties, tentatively agreed to buy the four dams and reservoirs from Boyce for $9.1 million with title to transfer in 2022. After finalizing the transfer, the FLTF planned to resume generating hydroelectricity at the Edenville Dam and to use the proceeds to defray some of the cost associated with the special assessment district set up to finance the purchase (Nims, 2019).

Boyce sued EGLE, the Michigan Department of Natural Resources, and relevant officials. According to a press release from Boyce, the suit claimed that the agencies improperly regulated Edenville Dam and that Boyce reduced the water level of Wixom Lake by about seven feet below normal in October 2018 as a “pre-emptive measure” aimed ensuring “the safety of the dam and the operators under hazardous winter conditions” (Kukulka, 2020).

Boyce began reducing the level of water in the reservoir on November 12, 2019, due to concerns about the safety of its operators and downstream communities despite not receiving a permit to do so. Although the Michigan Department of Natural Resources denied the permit on November 25, 2019, Boyce continued to lower the level of the lake as it appealed the decision (Kukulka, 2020).

On December 1, 2019, FERC issued a permit allowing FLTF to investigate expanding hydropower production at Edenville Dam by installing an additional powerhouse (FERC issues preliminary permit, 2019).

A few weeks before the failure of Edenville Dam on May 19, 2020, Dana Nessel, the attorney general of Michigan, sued Boyce, Mueller, and several other defendants on April 30, 2020. The suit claimed that by drawing down the reservoir impounded by the Edenville Dam in 2018 and 2019, Boyce killed freshwater mussels, a protected endangered species (Kukulka, 2020).

Due to pressure applied by EGLE, Michigan Department of Natural Resources, and residents around Wixom Lake who objected to the unsightly mud flats, Boyce started raising the level of the reservoir in April 2020. In early May 2020, the reservoir reached its normal level. In a news release, Boyce claimed the EGLE approved the permit to raise that level of the reservoir despite knowing that Edenville Dam could pass only 50 percent of the probable maximum flood. Previously, FERC demanded that Boyce reconstruct the spillways so that they could pass 100 percent of the probable maximum flood (Kukulka, 2020).

Disaster

After several days of heavy rain, a bystander captured on video the failure of Edenville Dam on May 19, 2020. The video, which was posted to YouTube and has been viewed more than three million times, shows that a section of the eastern embankment breached at 5:35 p.m. (MLive, 2020). The resulting flood overtopped Sanford Dam, about ten miles downstream from Edenville Dam, causing it to fail at about 7:45 p.m. After the failure of the two dams, the Tittabawassee River crested at over 35 feet on May 20, 2021, severely damaging the village of Sanford and flooding eastern Midland and lower lying parts of the downtown area (France et al., 2021a). The flood threated the operations of Dow Chemical, which is headquartered in Midland, but the plant “does not appear to have had a material impact on contamination in the overall river system because of the upstream dam failures” (Michigan Department of Environment, Great Lakes, and Energy, 2020, p. 6).

In a press release issued after the disaster, Boyce claimed it spent “hundreds of thousands” of dollars to design and construct projects aimed at complying with demands by FERC to update the spillways so that they could pass the “probable maximum flood.” According to Boyce, the estimated cost to modify the spillways according to plans approved by FERC in 2012 was over $8 million, an amount that Boyce said that it could not afford (Kukulka, 2020).

In another press release, Boyce confirmed that its only source of funds to repair the spillways came from the sale of electricity, which FERC cut off by the revoking its license in 2018. According to Boyce, even it could sell electricity, the amounts received would not have been sufficient to reconstruct the spillways. Boyce claimed that it told state and local agencies about its financial plight in the years leading up to the disaster (Kukulka, 2020).

Despite the complications caused by the COVID-19 pandemic, Jenifer Boyer, the leader of Midland County Emergency Management, coordinated the evacuation of 11,000 residents before the flood inundated their residences. As a result, no serious injuries or deaths resulted from the disaster (France, et al., 2021b; Mauney & Risher, 2021).

At a press conference on May 27, 2020, in Midland, Governor Gretchen Whitmer declared a state of emergency. She announced that EGLE would investigate the failures of the two dams. The Attorney General of Michigan and other plaintiffs filed lawsuits against Boyce and EGLE to assess responsibility for the damages. In addition, several class action lawsuits were brought by those who were damaged by the disaster (Kukulka, 2020).

Before the Edenville Dam failed on May 19, 2020, in January 2020, the FLTF agreed to buy the four dams and reservoirs from the Boyce entities for $9.4 million with closing scheduled for January 2022. However, after the disaster, the FLTF announced on May 26, 2020, that the sale would not be closed because the agreement was conditioned on delivering the dams in the same condition as they were at the time that the agreement was negotiated (Kukulka, 2020).

After the disaster, EGLE posted a FAQ document to its website that says: “FERC regulations require dam spillways be able to manage 100 percent of a probable maximum flood. The state only requires it meet half that” (Michigan Department of Environment, Great Lakes, and Energy, 2020, p. 3). In same document, EGLE says that it “did not have the decade’s worth of records held by FERC” during its first inspection of Edenville Dam in 2018. However, in the next bullet point says that “by late January 2020,” or two years after FERC had revoke the license of Boyce, that “EGLE staff, based on a review of data and records held by FERC, had reached a *preliminary conclusion* that the dam likely did not meet the state spillway flow requirement” (emphasis added) (p. 3). In other words, it took over two years after it assumed responsibility for regulating Edenville Dam for EGLE to reach a “preliminary conclusion” about the spillways. Therefore, FERC and EGLE disagreed on the metric to use in evaluating the spillways at Edenville Dam and did not cooperate on enforcing the inconsistent regulations.

Forensic Investigation

John France, the leader of the forensic team investigating the disaster and a prominent member of ASDSO, led a presentation at the 2021 ASDSO conference in September 2021 that discussed the conclusions of an interim report issued before the conference (France et al., 2021a) along with the regulatory status of the dams before the disaster, and the emergency response before and after the disaster (France et al., 2021b). The interim report summarized the investigation into physical mechanisms of the failures of the Edenville and Sanford Dams. The report advised that the forensic team planned to issue another report on “human factors” that contributed to the failure of the Edenville and Sanford Dams (France et al., 2021a).

Several years before leading the investigation into the failures of the Edenville and Sanford Dams in 2020, France led the forensic investigation into the crisis at the Oroville Dam in 2017 (France et al., 2018). In Appendix J of that report, Irfan A. Alvi addressed "human factors," which the forensic team found facilitated the crisis at Oroville Dam (Alvi, 2018). In an earlier paper, Alvi (2013) asserts:

> because physical processes are assumed to deterministically follow physical laws (leaving aside quantum mechanics), with no possibility of physical 'mistakes', we can assert that failure of dams – in the sense of not fulfilling human intentions – is ultimately *always* due to human factors, in other words humans falling short in various ways. These human factors necessarily involve individuals, but they also involve groups of various kinds and scales, including private firms, government agencies, design teams, professional societies, communities, international consortia, etc. (p. 1).

At the time of this dissertation, the forensic team has not released the full report, which will include their analysis of the human factors that led to the failure of Edenville Dam. At this point, we know that although FERC revoked the license of Boyce to produce hydropower at Edenville Dam in 2018 because the spillways were inadequate, and that Boyce did not rehabilitate the dam before it failed on May 19, 2020. However, as it turned out, the dam did not fail due to inadequate spillways. Instead, the forensic team found in its interim report that the earthen embankment of the dam failed due to "static liquefaction," a recognized mode of failure that experts understood to affect tailings dams more than earthen embankments dams that store water such as Edenville Dam (France et al., 2021a).

Since a bystander captured the failure of Edenville Dam on a video as it happened, the forensic team had an unusual contemporaneous window on the failure as it unfolded, which helped forensic team investigate the mode of failure. The video may be viewed at: https://youtu.be/Hc3u_CHVHJ8 (MLive, 2020). The interim report from the forensic team points out that the video shows that the bottom of the embankment of Edenville Dam failed before water overtopped the crest of the dam. Furthermore, the report states: “An American Society of Civil Engineers investigation team completed pixel tracing analysis on the failure video and concluded that the failure mass reached a velocity of about 5 meters per second” or about 11 miles per hour (France et al., 2021a, p. 29). The fact that soils in the embankment accelerated instantaneously to 11 miles per hour confirms the enormous geophysical forces that may be released if major dams are breached suddenly and unexpectedly.

During the presentation at the ASDSO conference, France pointed out that Edenville Dam was constructed in 1924, which predates the founding of the science of soil mechanics by Terzaghi (1925). Engineers trained in soils mechanics can better understand how soils perform in earthen dams, which constitute over 80 percent of all major dams (USACE, 2022), and can take steps to design architectural characteristics that will lessen threats such as static liquefaction. In the case of Edenville Dam, designers and constructors of the original dam may not have understood that unconsolidated sands incorporated into the embankment of Edenville Dam might lead to failure caused by static liquefaction one hundred years later.

France speculated that static liquefaction may have contributed to failures of other dams, but the mode of failure may have been incorrectly attributed to overtopping or some other cause. Therefore, according to France, the dam engineering community needs to review and amend relevant standards and guidelines to reduce the chances of failure caused by overtopping or static liquefaction (France et al., 2021a).

Legislative Reforms

On December 10, 2020, representatives from Michigan introduced the National Dam and Hydropower Safety Improvements Act (2000) in the United States House of Representatives. The law would require the FERC to "issue a license for a dam and other project works only if the project meets the relevant safety requirements and the licensee can operate and manage the project works in a manner that ensures dam and public safety. A licensee with an already-issued license must also meet these safety requirements" (National Dam and Hydropower Safety Improvements Act, 2020). However, less than three percent of major dams produce hydropower and are, therefore, regulated by FERC. In 2021, the legislature in Michigan considered legislation that would set up a $500 million fund to repair dams in Michigan and to respond to emergencies (Leblanc, 2021).

Conclusion

Events leading to the failure of Edenville Dam including the contentious interactions between the private owner and regulators at the federal and state levels illustrate the complex tradeoffs involving major dams and makes it important that experts and stakeholders consider how to proceed if efforts to make dams safe(r) are overwhelmed by unusual interactions among architectural characteristics and governance characteristics of systems of dams. Sustaining adaptability under these convoluted conditions may allow experts and stakeholders to respond more quickly and efficiently if disaster strikes. The next chapter discusses my findings and recommendations.

CHAPTER 7

CONCLUSION

My introduction to the conceptualization of resilience as defined by Woods (2015) came early in my graduate studies and was reinforced in subsequent classes. In fact, Dr. Woods, a professor at Ohio State University, appeared by online video in one of my classes. In a separate video presentation, another respected scholar suggested that little academic research had been performed on the architectural or governance characteristics that support the sustained adaptability of infrastructure projects. Since I had worked for almost two decades in the legal department of a large general contractor, I was intrigued by the idea of applying the experience I had gained from resolving legal disputes involving large construction projects to the academic research into the governance characteristics of infrastructure projects. Therefore, many of the research projects and papers submitted in my classes addressed architectural and governance characteristics of dams including reviews of the legislative history and implementation of the Reclamation Safety of Dams Act (1978) and a pilot case study of the dams on the Salt and Verde Rivers.

However, my exploratory research revealed that experts, knowledgeable stakeholders, and relevant organizations such as the ASDSO were primarily concerned about safety of the architectural characteristics of dams. Therefore, my exploratory research expanded to address safety as well as resilience. In particular, the hypotheses and subsidiary questions sought to explore issues related to both safety and resilience.

To investigate the research question, hypotheses, and subsidiary questions, Chapter 1 reviewed the literature on resilience, knowledge infrastructure, multiscalar frameworks, emerging threats, and operationalization. I contextualized the research by distinguishing between the governance and architectural characteristics of the *sociotechnical* systems of dams, which define the two aspects needed to assess the resilience conceptualized as sustained adaptability of systems of dams as well as their safety.

To bound the architectural characteristics of dams, Chapter 2 defined the term "infrastructure of dams" by exploring six relevant elements, the most important of which in the context of my research is path dependence: the history of events embedded in the massive physical artifacts of structures like the Edenville Dam cannot be modified or reversed immediately after crises strike.

Chapter 3 outlined my heuristic assessment of the governance characteristics of dams by linking them to the appearance of seven sociotechnical imaginaries demarcated by reports by explorers such as William Gilpin and John Wesley Powell or federal laws such as Reclamation Safety of Dams Act (1978) and speculated on the possible appearance of an eighth based on resilience. When first applying the heuristic analysis, I naively assumed that succeeding imaginaries replaced the preceding ones. However, after formulating my research question as described in Chapter 1, I discovered that some Idahoans continue to lobby for the reconstruction of Teton Dam. Therefore, I realized that powerful imaginaries such as those related to reclamation and safety can coexist and endure. Consequently, I revisited my analysis of sociotechnical imaginaries in Chapter 3 to account for their endurance.

In Chapter 4, I assessed expert discourses by assessing semi-structured interviews and presentations at professional conferences. I was surprised by the extent to which expert discourse focused on the safety of dams instead of addressing resilience in ways that were consistent with findings of academic scholars such Woods (2015).

The Salt and Verde Rivers case study in Chapter 5 confirmed the path dependent nature of the architectural characteristics of major dams by investigating the reconstruction of Roosevelt Dam, which took 16 years and $430 million after a crisis erupted along the Salt River in 1980. In addition, the case study showed that one downstream community had not changed building codes or emergency action plans as a precaution against threats posed to upstream dams by emerging threats such as climate change. The Tittabawassee River case study in Chapter 6 further complicates the uncertainty that surrounds attempts to make systems of dams safe or resilient from events worsened by emerging threats like climate change. In the case of Edenville Dam, the mode of failure was not inadequate spillways as anticipated by regulators at both the federal and state levels. Instead, an underappreciated mode of failure – static liquefaction – may have been unknowingly built into the dam when it was constructed about 100 years ago because the dam was designed before the advent of science of soils mechanics. The poorly understood potential mode of failure lurked in the background until conditions coalesced in a way that allowed it to unfold with catastrophic consequences. It is sobering to realize that the failure of Edenville Dam would have occurred regardless of whether the spillways had been reconstructed based on the recommendations of the regulators at both the federal and state levels.

In 2008, I submitted a paper entitled, “Lessons in Humility: An Analysis of the Cement Sustainability Initiative,” in Advanced Earth Systems Engineering and Management, a class taught by Dr. Braden Allenby. Since I worked for a general contractor at the time, the paper researched the process of manufacturing cement, a vital ingredient in the product that is essential to construction of some major dams: concrete. Hoover Dam, for instance, contains millions of cubic yards of concrete. However, the process of manufacturing cement emits about five percent of the carbon dioxide produced by human activities and, therefore, contributes to climate change, an emerging challenge to the safety and resilience of systems of dams (Rubenstein, 2012).

Although the Cement Sustainability Initiative aimed at reducing the amount of carbon produced by manufacturing cement, my paper found that these efforts furnished many lessons in humility due to the complex nature of the interactions of social and technical factors. The result of that study resonates with the complex interactions of architectural and governance characteristics of systems of dams that my research has addressed in this dissertation. Inherent complexity interferes with the ability of experts and stakeholders concerned about systems of dams to ensure their safety. Therefore, experts and stakeholders should find it useful to supplement their vitally important and necessary efforts to improve the safety of the architectural characteristics of the aging population of major dams by enhancing governance characteristics needed to sustainably adapt during crises that may be increasingly caused or worsened by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires.

In the following, I describe my findings regarding the hypotheses, subsidiary questions, and case studies as well as offering additional findings that flowed from my research. I then offer recommendations that experts and stakeholders who are knowledgeable about and concerned about the safety or resilience of systems of major dams may want to consider.

Hypotheses Findings

As regards the hypotheses posed at the beginning of my research, I found as follows:

Emphasis on Safety

The hypothesis that knowledgeable experts, stakeholders, and organizations would be more focused on making the architectural characteristics of dams and associated components such as canals and levees *safe(r)* and, consequently, that they would be less willing to participate in efforts aimed at making entire systems of dams including the downstream communities more *resilient* was supported by my research. While the content of this finding was not surprising, I was extremely surprised by the extent to which this finding applied. For instance, experts consistently referred much more often to “safe” or “safety” than to “resilience” or “resiliency” in the 115 papers submitted at the two ASDSO conferences.

Fragmentation

The hypothesis that the willingness of experts and stakeholders to discuss and assess sustained adaptability of systems of dams would be limited by boundaries or constraints imposed by fragmented jurisdictions, laws, and liability regimes such litigation and insurance as well as by enduring sociotechnical imaginaries that unconsciously describe ways that experts or stakeholders assess and respond to issues about systems of dams was not proven one way or the other by my research. Of course, experts cannot be expected to articulate concerns about resilience in the explicit terms of sustained adaptability or to refer sociotechnical imaginaries explicitly because such concepts and imaginaries are abstract artifacts of scholarly inquiry. However, the discourse analyses clearly identified the enduring presence of the safety imaginary and relative absence of an emerging resilience imaginary. Thus, the continued domination of the safety imaginary among the dam engineering community reflects a general unwillingness or inability to discuss issues related to the resilience of dams.

Furthermore. the dissertation provides evidence that suggests that fragmentation fostered by the federalist system of government in the United States lessens or interferes with the willingness of experts and stakeholders to explore issues beyond safety. For instance, as described in the case study in Chapter 6 that addressed the failure of Edenville Dam, FERC, at the federal level, demanded that Boyce modify the spillways so that they could pass the 100 percent of the probable maximum flood. However, EGLE, at the state level, only required the spillways to pass 50 percent of the probable maximum flood (Kukulka, 2020; Michigan Department of Environment, Great Lakes, and Energy, 2020, p. 3). In addition, FERC, a federal agency, and EGLE, a state agency, did not cooperate in enforcing concerns about the adequacy of the spillways at Edenville Dam (Michigan Department of Environment, Great Lakes, and Energy, 2020, p. 3).

Fragmentation is also evident in “hazard creep,” which is an evocative metaphor that describes how communities downstream from dams may be owned or regulated by other levels of government that may allow or promote development in floodplains after the dams are constructed. Therefore, as discussed at one of the ASDSO presentations, hazards that were not evident when the dams were constructed creep up over time on unsuspecting dam owners (Peterson & Miriovsky, 2021). As described in several places in the dissertation, hazard creep may be facilitated by the “levee effect” addressed by Di Baldassarre et al. (2013) or the “safe development paradox” described by Burby (2006).

Incommensurability

The hypothesis that contending experts and stakeholders would support inconsistent or incommensurate perspectives on the safety or resilience of systems of dams that would inhibit their ability to interact reflexively with other stakeholders or experts on efforts to improve sustained adaptability was supported by my research. Although experts may not explicitly invoke resilience in their discourses about systems of dams, they nonetheless exhibit a variety of perspectives about the characteristics of the resilience or safety of dams, such as documented in Table 9 Characteristics of Safety and Resilience Attributed by Experts Interviewed in Chapter 4. For instance, eight of the eleven experts associated architectural characteristics with the safety of dams but perspectives for resilience were more ambiguous and the compromise characteristic of Ability was exhibited by five of the eleven interviews. Nevertheless, the dam engineering community as represented by presenters at the ASDSO conferences relentlessly and justifiably investigates issues related to safety including identifying and resolving potential modes of failure such as static liquefaction, which as described in Chapter 6, the forensic investigators found was the proximate cause of the failure of the Edenville Dam.

As observed at several points in the dissertation, risk-informed decision making expands the scope of the inquiries into the safety of dams because it encourages experts to supplement deterministic standards such as the inflow design flood with probability assessments of the consequences of potential modes of failure. (As previously mentioned, my research does not address whether risk-informed decision making will be sufficient to deal with emerging threats such as climate that may increasingly plague systems of dams.)

Use-Inspired Research

My assumption that experts who are knowledgeable about systems of dams would distinguish between safety and resilience in ways that were oriented toward use-inspired research as described by Stokes (2011) and apply safety or resilience in ways that are consistent with the ways that those concepts are used by academics and social scientists was not supported by my research. I was surprised that research performed by academics and sociologists has not penetrated the discourse related to systems of dams. Based on subtle body language and averted gazes of a few interlocuters, my sense is that engineers who are aware of academic or sociology research about safety or resilience do not believe that it is useful, that they are not knowledgeable about or aware of its findings, or that they consider academic research to be ideologically driven and, therefore, incompatible with their needs or the needs of their employers or clients.

Subsidiary Questions Findings

To explore the implications of the research question, my investigation explored five subsidiary questions related to the governance and architectural characteristics of dam safety and resilience.

How safe or resilient are systems of dams currently?

Major dams are path dependent physical structures designed to be safe within thresholds calculated by applying deterministic standards such as the inflow design flood. Since the architectural characteristics of dams are physically brittle when challenged by events that exceed design thresholds, my research focused on assessing the current capabilities of systems of dams to respond in safe or resilient ways to governance or social challenges posed by crises. As described above (under the “Fragmentation” finding), fragmented governance characteristics such as legal, policy, and liability regimes appear to lessen or interfere with the willingness of experts and stakeholders to explore issues beyond safety. This allows experts to devote most of their attention to improving the architectural characteristics of the physical structures of dams by, for instance, identifying static liquefaction as the proximate cause of the failure of Edenville Dam instead of addressing both the architectural and governance characteristics.

Efforts to make the physical structures of dams, canals, and levees safer is vital work that must continue. However, when experts address resilience, their responses are more consistent with efforts to make physical dams safe(r) or to achieve other goals not related to safety or resilience. Their responses do not aim at improving the sustained adaptability of entire systems of dams including governance characteristics related to downstream communities. Therefore, current efforts may not be sufficient to enable experts and stakeholders concerned about systems of dams to assess and make the tradeoffs needed to sustainably adapt when confronted by emerging challenges posed by climate change, earthquakes, terrorism, cyberattacks, or wildfires.

During interviews, experts did not advocate making changes related to the governance characteristics of systems of dams that would allow for the emergence of a culture of resilience that would supplement the current culture characterized by the dominant sociotechnical imaginary centered on safety. A culture of resilience would facilitate tradeoffs needed to sustainably adapt over extended durations when unexpected crises caused or worsened by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires exceed efforts to make path dependent physical structures of dams safe. No documents reviewed or experts interviewed for my research distinguish clearly between safety and resilience or promote a culture of resilience. Moving toward a culture of resilience requires that experts and stakeholders communicate across physical and jurisdictional boundaries to develop abilities to negotiate tradeoffs among architectural and governance characteristics of systems of dams to promote sustained adaptability as defined by Woods (2015).

What are the definitions of and relationships between safety and resilience?

During interviews, experts were asked to define safety as well as the resilience of systems of dams. Based on the enormous geophysical forces at issue, experts justifiably emphasize the safety of the architectural characteristics of dams and associated structures, which traditionally are addressed with deterministic standards such as the inflow design flood. Document reviews confirm that influential organizations such as USBR, USACE, and FEMA increasingly promote the use of more probabilistic approaches such as risk-informed decision making to evaluate the architectural characteristics of physical dams (FERC, 2016; Regan, 2010; Scott, 2011). However, experts and stakeholders do not clearly distinguish between the concepts of safety and resilience as applied to systems of dams in ways that are consistent with the efforts of academic researchers such as Woods (2015). For instance, reviews of presentations made at ASDSO conferences in 2020 and 2021 reveal very few references to relevant peer-reviewed academic articles.

How relevant are the concepts of safety and resilience to systems of dams that are vulnerable to emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires?

This subsidiary question addresses whether concepts of safety and resilience as commonly used by experts and stakeholders are relevant concepts when it comes to meeting challenges posed by emerging threats such as climate change. In Chapter 2, my definition of the “infrastructure of dams” found that the path dependent nature of the of the architectural characteristics of systems of dams inhibits efforts to make them safe(r) or more resilient against emerging threats. For instance, the reconstruction of Roosevelt Dam as described in Chapter 5 was based on the deterministic standard of the inflow design flood, which resulted in the construction of a dam with path dependent architectural characteristics that may fail when tested by surprising emerging threats such as weather events that exceed tripled inflow design flood. Efforts to improve the stability of the architectural characteristics of dams reduces flexibility needed to sustain adaptability in the short term after emergencies strike simply because path dependence prevents modifying the architectural characteristics of dams in the short term. It took 16 years and $430 million dollars to modify Roosevelt Dam after a crisis (Ester, 2006). Thus, knowledgeable experts and stakeholders who work on systems of dams should be aware that despite the prevalence of academic jargon and abstract ideas, academic conceptions of safety and resilience are in fact relevant to their efforts to improve the safety and resilience of dams.

More probabilistic methods such as risk-informed decision making may improve the ability experts and stakeholders to find and assess expected threats to the ability of systems of dams to sustainably adapt during crises involving emerging threats, but they may not help in dealing with unexpected threats because they unpredictably emerge after crises strike.

How has society improved the resilience of systems of dams?

During interviews, some experts said that regulatory mechanisms such as laws like the Reclamation Safety of Dams Act (1978) or risk-informed decision making have improved the safety of architectural characteristics of dams. Woods (2015) finds that sustained adaptability requires making tradeoffs that allow systems to cope dynamically with the unpredictability that inevitably arises after crises strike. Although document reviews found regulatory mechanisms such as laws, policies, guidelines, and regulations that promote the safety of systems of dams, no laws or regulatory mechanisms were found that aim specifically at increasing the sustained adaptability of systems of dams.

What are the barriers to making systems of dams safer or more resilient?

As this research has shown, there are currently few if any governance mechanisms for resilience conceptualized as sustained adaptability at the federal level, and extremely limited understanding of the concept and importance of resilience among experts and stakeholders. Several explanations for these findings emerged during the research. As describe above, these include: (1) the lack of communication and productive exchange across academic and practitioner communities, (2) the additional costs that efforts aimed at resilience would entail, (3) the fragmentary nature of the governance characteristics of dams, (4) the diverse ownership of dams, and (5) the aging population of major dams.

For instance, during interviews, a few experts stated that the major obstacle to making dams safer or more resilient (as they defined the term) was cost as reflected by insufficient budgets. However, I did not discover any governance characteristics or regulatory mechanisms in the form of laws, policies, guidelines, or regulations that explicitly promoted the sustained adaptability of the architectural or governance characteristics systems of dams (Woods, 2015). My sense after completing the research for this dissertation is that experts and stakeholders realize that enduring efforts to "reclaim" arid lands or make dams safe may be insufficient or inadequate to meet the challenges posed by emerging threats such as climate change to systems of dams. For example, experts and stakeholders can eliminate the danger of a failing dam by removing it, which in the case of many older reservoirs that are no longer productive because they have silted up, makes sense. However, if dams continue to offer benefits at scales not easily obtained by other methods, then they may need to reach across jurisdictional and other boundaries to conduct conversations to promote sustained adaptability after crises strike.

Case Studies Findings

The case studies of the systems of dams on the Salt and Verde Rivers in Arizona and the Tittabawassee River in Michigan demonstrate the wide range of different and even contrasting problems that can result from too little or too much precipitation. The system of dams on Salt and Verde Rivers are mired in a megadrought that encourages operators of dams to conserve as much water as possible. In contrast, the system of dams on the Tittabawassee Rivers suffered from excess water in May 2020, which was the proximate if not the only cause of the failure of Edenville Dam. This finding demonstrates the importance of adapting each system of dams according to its unique contexts. This is further elaborated upon in the additional findings described below.

The motivation of Boyce to rehabilitate the Edenville Dam before it failed on May 19, 2020, may have been reduced because Boyce was not receiving income from the sale of hydropower due to the license revocation by FERC. In addition, at the time of the failure, EGLE had demanded that Boyce raise the level of the reservoir to save freshwater mussels. Therefore, the regulators ordered the owner of a dam with inadequate spillways to increase the amount of water impounded in the reservoir to save freshwater mussels. However, the dam did not fail due to an expected and well-understood mode of failure such as overtopping caused by an inadequate spillway. Instead, it collapsed due to an unexpected mode of failure that engineers considered to be rare in embankment dams like Edenville: static liquefaction.

Not surprisingly, lawyers and experts hired by stakeholders such as homeowners are litigating disputes within a fragmented federalist legal system, which is a painful and expensive way for society to create and disseminate knowledge needed to improve safety or sustained adaptability of systems of dams. Nevertheless, it is important to recognize that although damages will exceed $250 million, 11,000 people were evacuated before the failure of Edenville Dam and that no one died due to the tireless work of people like Jenifer Boyer at the Midland County Emergency Management.

Additional Findings

Aging Population of Major Dams

The National Inventory of Dams dynamically lists over 90,000 major dams in the United States. About half of major dams were constructed between 1950 and 1970 and the average age of major dams is over 60 years (USACE, 2022). These stark facts underscore the most salient finding of my research, which I repeatedly invoked throughout the dissertation. Since the typical design life of dams is 50 years and the average age of dams is over 60 years, most major dams have aged out of their design lives (Ho et al, 2017). Unless they are rehabilitated or removed, major dams will continue to deteriorate and possibly fail. Therefore, it is reasonable to expect that the rate of impairment or failure of major dams will tend to increase in the future unless aging dams are rehabilitated or removed. In addition, emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires increase the urgency to improve both the safety and resilience of systems of dams.

Shifting and Competing Sociotechnical Imaginaries

The research reveals limited evidence that suggests that the current dominant sociotechnical imaginary based on safety is beginning to be augmented by one based on resilience. In support of this interpretation, my research finds that experts increasingly supplement traditional deterministic standards such as the inflow design flood and the maximum credible earthquake with risk-informed decision making, which improves the ability of experts and stakeholders to weigh the consequences of known potential modes of failure probabilistically. Risk-informed decision making may improve the ability of experts and stakeholders to assess and improve both the architectural and governance characteristics of systems of dams so that they may be able to make the tradeoffs needed to sustainably adapt during crises, but that is beyond the scope of my inquiry. Although analyses of emergencies at dams informs future inspections and assessments at other dams as well as at associated structures such as canals and levees and downstream communities, as stated in the findings and the recommendations below, each major dam is unique, and experts and stakeholders must evaluate each one on its own terms.

Variability of High Hazard Dams

In an award-winning article dated November 11, 2019, the Associated Press identified 1,688 high-hazard dams in 44 states and Puerto Rico that were "rated in poor or unsatisfactory condition as of" 2018. The authors of the article downloaded data from the National Inventory of Dams and obtained data from states by filing requests under open records laws (Lieb et al., 2019). Emerging threats like climate change, earthquakes, terrorism, cyberattacks, or wildfires increase the urgency to improve sustained adaptability of systems of dams.

Although many dams have common types of architectural and governance characteristics, each system of dams faces distinctive, complex, and interacting strengths, weakness, opportunities, and threats. Under these conditions, it is foreseeable that dams will increasingly develop deficiencies that will not be addressed before crises erupt.

Diversity of Ownership

In addition to the unique nature of each dam and dam site, the National Inventory of Dams reveals that major dams are owned by diverse types of owners, which mirrors the fragmented governance structure in the United States and complicates efforts to improve the safety or sustained adaptability of systems of dams. The federal government owns less than 4 percent of major dams including iconic structures like Hoover Dam. Public utilities own about 3,800, or 4 percent. States own about 6,700, or 7 percent. Local governments own about 18,000, or 20 percent. Private owners own about 57,000 dams, or 65 percent (USACE, 2022). Diverse ownership complicates effort to address safety or resilience.

Lack of Knowledge and Funding of Private Owners

As illustrated by the failure of the Edenville and Sanford Dams in Michigan in 2020 described in Chapter 6, many private owners are not knowledgeable about the intricacies of operating, maintaining, reconstructing, or decommissioning dams or have insufficient financial resources to update and improve the architectural characteristics of dams. Legislatures at every level of government need to understand and address these shortcomings.

Current State of Legal Reforms and Funding

Crises at Teton Dam in 1976, Oroville Dam in 2017 and Edenville Dam in 2020 prompted legislators and regulators to introduce new or modify existing laws or regulations aimed at improving the architectural or governance characteristics of systems of dams. For instance, after Teton Dam failed in 1976, the Congress passed the Reclamation Safety of Dams Act (1978), which, among other rehabilitation projects, partially funded reconstruction of the 70-year-old Roosevelt Dam at the cost of $430 million after it was threatened by heavy rains in 1980 (Ester, 2006). After the spillways at Oroville Dam were damaged by excess water in 2017, the California state legislature passed legislation that, among other things, allowed wider sharing of inundation maps (Tapia, 2020). After Edenville Dam collapsed in 2020, representatives from Michigan introduced the National Dam and Hydropower Safety Improvements Act (2020) in the House of Representatives that proposed modifying the ways that FERC issued licenses to owners of dams. Increasingly, legislators and policy makers recognize that many private dam owners do not have the knowledge or financial resources to maintain, rehabilitate, or remove deficient dams (Walls, 2020). For instance, in 2021, the state legislature in

Michigan considered legislation that would set up a $500 million fund to repair dams in Michigan and to respond to emergencies (Leblanc, 2021).

The most significant indication that the federal government has recognized the deteriorating condition of dams was the passage of the Infrastructure Investment and Jobs Act (2021), which President Biden signed on November 15, 2021. The Act authorized:

- $585 million for grants to states to rehabilitate high hazard dams under section 8A of the National Dam Safety Program Act (1996), with $75 million to remove dams;
- $148 million for grants to states under section 8(e) of the National Dam Safety Program Act (1996);
- $67 million for dam safety activities and assistance to states under sections 7 through 12 of the National Dam Safety Program Act (2020) managed by FEMA Operations and Support;
- $118 million for grants under Natural Resources Conservation Service Small Watershed Rehab Program;
- $64 million under the Water Infrastructure Finance and Innovation Act (2014) including $64 million for the Corps Water Infrastructure Financing Program, a new program managed by USACE that provides low-interest loans to repair dams;
- $492 million to the National Oceanic and Atmospheric Administration to update nationwide probable maximum precipitation estimates;
- $800 million for dam removal projects; and

- $800 million for dam safety, environmental and electric grid upgrades for hydropower dams. (ASDSO, 2021b)

These expenditures are primarily directed toward improving the safety of the architectural characteristics of dams pursuant to the prevailing safety sociotechnical imaginary. However, some of the amounts such as the $67 million for dam safety activities and assistance to states could be used to advance sustained adaptability.

Recommendations

I offer the following recommendations.

Formulate Definitions and Standards

To sustainably adapt to emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires within the distinct contexts of systems of dams, it will help participants if they understand that they may have inconsistent or conflicting conceptions of safety and resilience. Groups intent on improving the safety and sustained adaptability of systems of dams should seek to negotiate consensus definitions of safety and resilience as a preliminary step.

Expand Human Factors

As mentioned in the Edenville Dam case study, Irfan Alvi prepared an appendix, which was appended to the forensic report about the crisis at Oroville Dam in 2017, that described the human factors that contributed to the crisis (Alvi, 2018). In a presentation at the 2020 ASDSO conference Walter et al. (2020) discussed problems associated with human factors that arise years after dams are constructed, which were caused by mistakes made by engineers due to fallible human factors that were built into the structures. Alvi (2013) finds that

> because physical processes are assumed to deterministically follow physical laws (leaving aside quantum mechanics), with no possibility of physical ‘mistakes’, we can assert that failure of dams – in the sense of not fulfilling human intentions – is ultimately *always* due to human factors, in other words humans falling short in various ways. These human factors necessarily involve individuals, but they also involve groups of various kinds and scales, including private firms, government agencies, design teams, professional societies, communities, international consortia, etc. (emphasis in original) (p. 1)

Alvi (2013) maintains that “high-reliability organizations” can “reduce rates of substantial failures by being preoccupied with avoiding failure.” He describes a set of traits that help form a “paranoid mindset,” which he maintains helps to overcome errors caused by human factors (p. 3). While rightly applauding efforts to reduce errors before they are constructed into the architectural characteristics of dams, experts and stakeholders concerned with the operation of systems of dams should also expand the scope of human factors research to include other governance characteristics such as, for instance, the “levee effect” addressed by Di Baldassarre et al. (2013) or the “safe development paradox” described by Burby (2006). These efforts would help expand the tradeoffs needed to sustainably adapt to emerging threats to systems of dams.

Prioritize Governance Characteristics

Since the architectural characteristics of dams and associated structures such as canals and levees cannot be modified in the short term to withstand potential modes of failure including those caused or worsened by climate change, earthquakes, terrorism, cyberattacks, or wildfires, experts, stakeholders must improve governance characteristics of entire systems of dams *before* disaster strikes. The financial and temporal costs associated with such efforts are insignificant compared to the costs and time needed to modify the architectural characteristics of path dependent architectural characteristics of the physical structures of dams. However, improving governance characteristics of systems of dams to increase sustained adaptability requires investing social as well as economic capital (see next recommendation).

In general, stakeholders can increase the sustained adaptability of systems of dams by acknowledging the brittleness of architectural characteristics of the physical structures while preserving the ability of the governance characteristics systems to make tradeoffs after surprises are unleashed by creating or changing regulatory mechanisms such as emergency action plans or building codes before crises strike.

Facilitate Expert-Stakeholder Interactions

Conversations among experts and stakeholders conducted before crises have the potential to increase awareness and to promote practices and measures that may help reduce casualties and property damage and quicken recovery efforts during and after unexpected events that befall aging systems of dams that have exceeded their design lives.

Such conversations should be informed by research that bridges the academic-practitioner divide. For instance, the findings of this dissertation have the potential to inform conversations (1) about ways to improve the sustained adaptability of increasingly aging systems of dams and (2) that define and explore relationships between safety and multiple conceptions of resilience. It can do this (3) by demonstrating the relevance of sustained adaptability to systems of dams that are vulnerable to emerging threats such as climate change, earthquakes, terrorism, cyberattacks, or wildfires; and (4) by guiding experts and stakeholders to improve the sustained adaptability of systems of dams.

If the laws, policies, standards, and guidelines employed to design, construct, operate, and maintain systems of dams are not sufficient to meet the challenges to the architectural characteristics of systems of dams caused or worsened by unexpected and surprising events, then the dissertation findings may also inform conversations among experts and stakeholders (5) aimed at bridging jurisdictional, legal, or liability boundaries that define the limits of the governance characteristics of systems of dams.

Develop an Evaluation Tool

I recommend that experts and stakeholders integrate data from the National Inventory of Dams maintained by the USACE (USACE, 2022) and the Resilience Analysis and Planning Tool (RAPT) maintained by FEMA (FEMA, 2022) to expand the knowledge infrastructure regarding systems of dams. Combining data from the two databases would help experts and stakeholders explore and assess tradeoffs needed to sustain adaptability of systems of dams.

As described above, the National Inventory of Dams is a knowledge infrastructure that monitors, models, and records the architectural characteristics of systems of dams (USACE, 2022). FEMA and Argonne National Laboratory created RAPT to help emergency managers and community leaders at all levels “to examine the interplay of census data, infrastructure locations, and hazards, including real-time weather forecasts, historic disasters and estimated annualized frequency of hazard risk.” Data accessible through RAPT prioritizes “community resilience” at the county level, which focuses on generalized risk relevant to all hazards available before disasters strike. The data in

RAPT is quantitative, non-proprietary, and publicly available. As listed in Table 14, RAPT categorizes data into “11 *population*-focused indicators and 9 *community*-focused indicators for all 3,220 counties (and county equivalents) in the United States” (emphasis added) (FEMA, 2022).

Table 14

Resilience Analysis and Planning Tool (RAPT) Indicators

	Population-Focused Indicators (11)
1	Educational Attainment: Lack of High School Diploma in Adults over Age 25
2	Unemployment Rate: Percent of the Labor Force That Is Unemployed
3	Disability: Percent of the Population with a Disability
4	English Language Proficiency: Percent of Households with Limited English Proficiency
5	Home Ownership: Percent of Owner-Occupied Housing Units
6	Mobility: Percent of Households without a Vehicle
7	Age: Population Age 65 and Older
8	Household Income: Median Household Income
9	Income Inequality: Gini Index
10	Health Insurance: Percent without Health Insurance (Public or Private)
11	Single-Parent Households: Percent of Single-Parent Households as a Function of All Families
	Community-Focused Indicators (9)
12	Connection to Civic and Social Organizations: Civic and Social Organizations per 10,000 Population
13	Hospital Capacity: Hospitals per 10,000 Population
14	Medical Professional Capacity: Health Diagnosing and Treating Practitioners per 1,000 Population
15	Affiliation with a Religion: Percent of Religious Adherents
16	Presence of Mobile Homes: Percentage of Mobile Homes as a Function of Total Housing Units
17	Public School Capacity: Schools per 5,000 Population
18	Population Change: Percent Population Change
19	Hotel/Motel Capacity: Hotels and Motels per 5,000 Population
20	Rental Property Capacity: Percent Vacant Rentals

The indicators include maps, data sources, binning methods, numbers of counties within each bin, national averages, and findings. Most of the data is accessed from the American Community Survey sponsored by the U.S. Census

Bureau. The data is updated annually each December with the five-year estimates. Using multiyear estimates increases statistical reliability because single-year estimates are suspect "for small geographic areas and small population subgroups" (FEMA, 2022).

Conduct Premortems

Experts and stakeholders can prospectively test the resilience of systems of dams by subjecting them to "premortems" (Kahneman, 2011). "Premortems" ask stakeholders to forecast things that can go wrong during crises while avoiding the dangers of the planning fallacy in which participants optimistically but unrealistically expect that newly created recovery plans will unfold seamlessly even though earlier plans encountered difficulties (Kahneman, 2011, p. 264-265). Although they cannot predict the emergent problems that arise during and after emergencies, premortems help stakeholders anticipate and assess known and expected risks under fail-safe approaches directed toward increasing safety. Although stakeholders can adjust the amount of water flowing through spillways during floods, the path dependent nature of the architectural characteristics of dams makes it difficult, if not impossible, to make fundamental changes to the physical elements of dams or associated structures such as canals or levees during crises because those types of changes require enormous time and resources. Therefore, to sustainably adapt experts and stakeholders concerned about systems of dams must prepare for crises by adjusting governance characteristics *before* crises strike.

Premortems allow stakeholders to assess and improve governance characteristics of systems of dams, which may allow stakeholders to rebalance or mutually orient tradeoffs among scales that may needed when unexpected, but inevitable, contingencies arise during crises. If a crisis is severe enough, the architectural characteristics of dams or associated structures may fail catastrophically, but if relevant capacities are in place before crises strike governance characteristics can sustain adaptability that will allow the system of dams to survive or to fail gracefully, a state that Ahern (2011), Kim et al. (2017); and Park et al. (2013) refer as safe-to-fail. For instance, experts and stakeholders responding to a crisis may create or modify a multiscalar analysis regarding the implications of ordering populations at risk to evacuate.

Proceed Without Waiting for National Reforms

Due to the age and uniqueness of major dams and the urgency of the emerging threats they face, local communities would be well advised to undertake appropriate and context-specific assessments rather than wait for large-scale policy or institutional reforms. Therefore, downstream communities should assess their ability to sustainably adapt if dams fail partially or catastrophically even if the dams have been found to meet relevant safety standards.

Future Research

Consistent with the conception of sustained adaptability conceptualized by Woods (2015), future research that builds on the findings of this dissertation should investigate (1) if and how systems of dams sustain adaptability of architectural and governance characteristics in general and across scales; (2) how systems of dams have developed capacities of sustained adaptability to deal with surprises while delivering important services to communities; (3) what architectural and governance mechanisms permit systems of dams avoid brittleness at boundaries of normal function; and (4) what architectures allow systems of dams to adapt sustainably over the long term and many cycles (Woods, 2015, p. 8). Two possible avenues to address these questions are described below.

Standards

Standards such as the inflow design flood and guidelines such as risk-informed decision making address the architectural and governance characteristics of dams, associated structures such as canals or levees, and downstream communities (systems of dams). Usually, applicable standards and methods are defined by federal agencies that regulate or own dams or associated structures such as USBR, USACE, FERC, or the Natural Resources Conservation Service or professional organizations such as the ASDSO, the United States Society on Dams, or the International Commission on Large Dams. After standards or methods are defined, they are distributed to stakeholders and experts concerned about dams or associated structures. If parties agree to do so, relevant standards and guidelines are incorporated into contracts for the design, construction, or operation of dams and associated structures. Although standards and methods play central roles in addressing the safety or other concerns related to systems of dams, to my knowledge no standard or method for assessing resilience of systems of dams has been defined. In light of the threats posed by climate change, earthquakes, terrorism, cyberattacks, and wildfires to the design, construction, and operation of dams or associated structures, experts at relevant governmental or professional organizations should investigate the scope and likelihood of the hazards and as needed define new, or extend existing, useful standards or guidelines. However, prescribing deterministic standards or guidelines that can help stakeholders and experts make tradeoffs needed to sustain adaptability as crises unfold over the long term will be very difficult because crises are probabilistic, non-linear, and emergent. Sustained adaptability emerges as events caused or worsened by emergent threats contingently play out across the unique architectural and governance characteristics of each system of dams. Thus, procedural standards that can be adapted to numerous contextual situations will likely be of the most use to the broadest number of stakeholders. Furthermore, guidelines aimed at improving the sustained adaptability of systems of dams may be useful to stakeholders and experts if they investigate past crises, identify possible hazards such as static liquefaction (which became a more prominent hazard after the failure of the Edenville Dam in 2020), and alert relevant stakeholders and experts who are knowledge about each system of dams so that they can amend architectural or governance characteristics that facilitate tradeoffs *before* crises strike.

Boundary Organizations

The emerging threats posed to major dams should also lead to the creation or modification of organizations that can span boundaries between science and politics by supplying opportunities or incentives to create boundary objects such as standards, guidelines, or best practices, or, better yet, standardized packages such as model contracts. These efforts would augment efforts to make dams safer by improving the ability of stakeholder organizations assisted by experts to make tradeoffs among architectural or governance characteristics needed to sustainably adapt to crises caused or worsened by emerging threats like climate change. These new or modified boundary organizations would operate at “the two relatively different social worlds of politics and science” and “have distinct lines of accountability to each” (Guston, 2001, p. 401). Due to the perceived partisan orientation of higher education today, and the lack of regular concourse and communication between academic and expert professional communities (as is suggested by this research), it is unlikely that these boundary organizations could be usefully housed within university centers or organizations. However, it is possible that universities could join with external professional or charitable organizations to create boundary organizations that could facilitate efforts to improve the ability of systems of dams to sustainably adapt over the long term as crises unfold.

Conclusion

Alongside the need to improve understandings of and mechanisms for resilience as expressed in this dissertation, it is important to understand that dams offer significant benefits to surrounding communities including water for irrigation and municipal uses, flood control, hydropower, navigation, and recreational amenities at scales cannot be easily replaced by other types of infrastructure. However, the purpose that motivated my research was to assess the extent to which experts and stakeholders are sustainably adapting the architectural and governance characteristics of systems of major dam to meet to the challenges posed by emerging threats such as climate change, earthquakes, terrorism, cyberattacks, and wildfires.

Therefore, since we are confronted with an aging population of deteriorating dams, experts and stakeholders at all levels especially those responsible for downstream communities need to understand that focusing solely on making dams safe(r) may not meet challenges posed by emerging threats such as climate change. In addition to taking steps to improve the safety of dams, experts and stakeholders may want to supplement their efforts by exploring ways to improve the sustained adaptability of systems of dams after crises strike. The findings of my research suggest that the dam engineering community justifiably concentrates on improving the safety of the architectural characteristics of major dams. However, the lack of attention to matters pertaining to the resilience of dams is both palpable and potentially concerning. That said, the evidence suggests that the emerging threats like climate change are shifting conversations toward the need to improve the resilience of entire systems of dams, including downstream communities, if the architectural characteristics fail despite the best efforts of the dam engineering community. More needs to be done to ensure the resilience of both dams and their downstream communities. As the recommendations suggest, much of this work should begin now.

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