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Dams Are Coming Down, but Not Always by Choice: The Geography of Texas Dams, Dam Failures, and Dam Removals

Erin D. Dascher^{*a}, Kimberly Meitzen^b

Abstract: This study examines spatial and temporal trends in Texas dams, dam failures, and dam removals. Dams were examined from a statewide perspective and within 10 major river basins that collectively account for over 80% of all dams in the state. The state-scale and basin-scale analyses revealed similar patterns of dam occurrence, but there was greater variation in the patterns observed in both the purpose of dams and the timing for when most of the storage was created in each basin. Climate factors, mainly precipitation, influenced dam location. Population was not directly measured in this study but was an obvious influence on the spatial distribution of dams and their functions. While new dams are being built in Texas to secure future water supplies, documented dam incidents/failures have occurred in 15 of the 23 major river basins in Texas, with 328 total instances occurring since 1900. As the number of newly constructed dams and dam failures continue to grow across the state, so should the number of planned dam removals. Between 1983 and 2016, 50 dams were removed across the state. The purpose for the majority of removals was to eliminate liability concerns associated with aging dams. Future dam removals will likely continue to occur based on the number of older, smaller dams with potential liability concerns. As Texas' dam infrastructure continues to age, dam removal is a practical management option for mitigating potential dam-related hazards and improving the connectivity and ecological function of river systems.

Keywords: dams, Texas, dam removal, dam failure

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Terms used in paper

Acronym/Initialism	Descriptive Name
ac-ft	acre-feet
ASCE	American Society of Civil Engineers
CGIAR-CSI	CGIAR Consortium for Spatial Information
DRIP	Dam Removal Information Portal
FEMA	Federal Emergency Management Association
FRRN	functionally reconnected river network
ft	feet
in	inches
km	kilometers
km ²	square kilometers
LCRA	Lower Colorado River Authority
mi	miles
mi ²	square miles
mm	millimeters
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NPDP	National Performance of Dams Program
PET	global potential evapotranspiration
PRISM	Parameter-elevation Regressions on Independent Slopes Model Climate Group of Oregon State University
SWIFT	State Water Implementation Fund of Texas
TCEQ	Texas Commission on Environmental Quality
TWDB	Texas Water Development Board
USACE	United States Army Core of Engineers
USGS	United States Geologic Society
WCID	Water and Control Improvement Districts

INTRODUCTION

In 2011, Texas experienced the worst single-year drought in recorded history (Folger et al. 2013). During October of 2011, 88% of the state experienced exceptional drought, and much of the state continued to experience extreme to exceptional drought conditions through January 2012 (Folger et al. 2013). The winter of 2012 brought relief through increased precipitation to the eastern portion of Texas, but much of the state remained in drought conditions ranging from moderate to exceptional (Folger et al. 2013; USDM 2000–).

In response to the 2011 drought and other major water-resource related concerns in Texas, the 2013 Texas Legislature passed Proposition 6, which provided funding for water projects outlined in the state water plan (Henry 2013). Proposition 6 was a constitutional amendment that transferred two billion

dollars from Texas's rainy day fund to create the State Water Implementation Fund of Texas (SWIFT; Henry 2013). The 2012 Texas state water plan included recommendations for 26 new major reservoir sites to be built by 2060, a major reservoir being one that generates 5000 acre-feet (ac-ft) or more of water storage (TWDB 2012). By late 2017, four major dam projects received the necessary permits and funding to begin construction, including the Lake Ralph Hall Reservoir planned for the upper Trinity River Basin, the Turkey Peak Reservoir in the upper Brazos River Basin, the Lower Basin Reservoir in the lower Colorado River Basin, and the Lower Bois d'Arc Reservoir in the Red River Basin (TWDB 2017; Kellar 2017).

While dams are being built to secure Texas' future water supply, there is increasing concern about the future quality of riverine and aquatic habitats due to fragmentation from barriers such as dams (Graf 1999; Chin et al. 2008; Erős et al.

2015). Across the United States, dams are being removed at an increasingly rapid pace to the benefit of hazard mitigation and river restoration (Grabowski et al. 2018). Yet in Texas, dam removal receives substantial negative connotation and can be highly controversial, as documented by the rhetoric surrounding examples such as Cape's Dam in San Marcos, Texas (Rollins 2015; Thorne 2016a, 2016b; Brusuelas 2018; Green 2019). A 2011 news article by Eva Hershaw was even titled "Dams Are Coming Down, But Not in Texas" (Hershaw 2011). Despite this seemingly negative connotation, little in the way of actual data has been presented showing dam removal trends in Texas.

The Texas Commission on Environmental Quality (TCEQ) is responsible for the monitoring and regulation of public and private dams that meet their criteria (DamFailuresPIR92671900–). A 2008 audit of the TCEQ's Dam Safety Program concluded that the program was not able to accomplish its mandate to ensure the safe construction, maintenance, repair, and removal of dams (Keel 2008). The report found that the high number of dams in Texas compared to the available program resources was a major reason for the program's ineffectiveness (Keel 2008). Additionally, the report stated that a goal of the Dam Safety Program should be to estimate the rehabilitation cost of the "structurally deficient and hydraulically inadequate dams" throughout the state (Keel 2008, pii). According to data reported in the Texas Observer, 314 dams have failed in Texas since 1910, the majority of which impounded less than 1000 ac-ft and failed between the years 2000 and 2019 (Sadavivam 2019). With limited funding available for dam repairs and maintenance, and as dams continue to age, issues related to structural inefficiency and hydraulic inadequacy are likely to increase the risk of dam incidents and failures throughout the state. Instead of increasing the number and frequency of dam inspections, Texas passed House Bill No. 677 in 2013, which exempts thousands of state documented dams from safety regulations based on the following five criteria: they are privately owned, impound a maximum capacity less than 500 ac-ft, retain a hazard criteria of low or significant (measured by potential loss of life downstream of the reservoir), occur in a county with a population less than 350,000, and are not located within the corporate limits of a municipality (H.B. 677 2013). Dam owners must still comply with maintenance and operation requirements; however, with limited resources available through the Dam Safety Program, uncertainty exists regarding dam owner compliance.

The purpose of this study is to explore the spatial and temporal trends in the available data on extant dams, dam failures, and dam removals. To an extent, this study builds on previous research containing data on Texas dams presented by Chin et al. (2008) by incorporating new data and an additional scale of analysis. This analysis addresses the following four questions: (1) What are the spatial patterns of dam occurrence in Texas and how do these patterns change over time and relate to cli-

mate? (2) How do these patterns vary among the 10 major river basins in the state? (3) What are the spatial and temporal trends of dam removals in Texas? and (4) What are the spatial and temporal trends of dam failures? In addition to answering these questions, the authors aim to provide some insight into how patterns of dam occurrence, failure, and removal are potentially related. Dam distributions, failures, and removals involve many physiographic, social, political, and historical factors. The intent of this paper is not to provide a comprehensive overview of all these interacting factors. The focus is to provide a broadscale overview of state- and basin-scale distributions and bring much needed attention to discussions involving the hazards and management of aging dam infrastructure and the opportunity for using dam removal to benefit river ecology.

A brief history of dams

From a global perspective, the earliest dams were constructed 5,000 years ago (Petts and Gurnell 2005). They were small impoundments, built as earthen structures to store water for use during drier periods (ICOLD 2007). As civilizations grew, dam use began to diversify to include water supply, irrigation, flood control, navigation, water quality purposes, sediment control, energy generation, and recreation (ICOLD 2007). The Romans built a large and complex system of dams for water supply, many of which are still in use today (ICOLD 2007). During the 16th century, Spain began to build large dams for irrigation, and in the 1800s dams began to be built for navigation and hydropower (ICOLD 2007). The construction of mega dams was begun by European engineers in the 19th century (ICOLD 2007), but by the 20th century the United States led the world in dam construction (Clark 2009).

Large dams became symbols of technological and social advancement (Petts and Gurnell 2005; Duchiem 2009). This was especially true of hydropower projects that were viewed as important for both the prosperity of the nation and national defense (Reinhardt 2011). While the Hoover Dam ushered in the modern era of dam building in the United States (Reisner 1986; Petts and Gurnell 2005), the number of large dams constructed did not drastically increase until after WWII (Petts and Gurnell 2005).

In the United States, the Bureau of Reclamation alone constructed 40 hydropower dams between 1945 and 1955 (Reinhardt 2011), and during the 1960s, the number of dams continued to increase at a rate of nearly two dams a day worldwide (Petts and Gurnell 2005). According to the National Inventory of Dams (NID), a total of 20,145 documented dams were completed in the United States between 1960 and 1969 (NID 2013–), and the 1960s has become known as the "dam-building" decade (Graf 2005). This rapid pace of dam construction would not slow until the 1980s (WCD 2000; Petts and Gurnell 2005).

As dams increased in number and size across the landscape, so did the understanding of their impacts on river systems. Studies on downstream effects of dams began in the 1920s, yet as early as 1784 efforts were made to prevent dam construction, due to the already apparent impact on migratory fishes along East Coast rivers in the United States (Graf 2005). Despite the growing scientific understanding of environmental impacts created by dams, the dam-building era would continue until the 1970s, when American attitudes toward the environment shifted. By this time, ideal sites to build new large dams had already become scarce (Reisner 1986), and today every major river in the United States is, in part, controlled and impacted by dams and reservoirs (Graf 2006).

Nationwide data on dam failures differs relative to how a dam failure is defined, and it is important to note that discrepancies exist in how different organizations obtain, classify, and report dam failures. The National Performance of Dams Program (NPDP) compiles one of the most comprehensive national-scale databases, reporting a total of 1,645 dam failures in the United States (1848–2017), from sources including the U.S. Committee on Large Dams, Federal Emergency Management Association (FEMA), United States Army Corps of Engineers (USACE), Association of State Dam Safety Officials, voluntary contributions by state dam safety programs, and supplemental searches (McCann 2018). However, the NPDP database still differs from that reported in other publications. The NPDP (McCann 2018) report lists 53 dam failures for Texas, defined as events that resulted in the uncontrolled reservoir release.

A database on Texas dam failures reported by Sadasivam (2019) in the Texas Observer included 314 dam incidents ranging from catastrophic failures to minor overtopping documented by the TCEQ. However, the TCEQ only defined 119 of those incidents as official failures, which they define by overtopping or breaching and draining of the reservoir. The conservative 53 failures reported by the NPDP rank Texas in the top 10 U.S. states with the most dam failures; if all 119 state-defined failures were reported, Texas would rank second after Georgia (McCann 2018). The American Society of Civil Engineers (ASCE) Texas Section reports only eight failures, one partial failure, and 108 other incidents in their 2017 Infrastructure Report Card, based on data obtained from multiple sources (ASCE 2017). The lack of consistency among sources indicates a need for the standardization of terms regarding dam failures and how they are categorized and discussed.

As of 2019, over 1,722 dams have been removed in the United States primarily for reducing hazard risks and improving ecologic functions (ARRDRD 1912–2019), and this number is expected to increase as many dams in the United States reach the end of their usefulness (Doyle et al. 2003a). The increasing number of dam removals is emblematic of the paradoxical shift in the United States from trying to control and manipulate rivers to attempting to restore them. The rate of dam removals

has been climbing rapidly (Grant and Lewis 2015). In 2017 alone, 86 dam removals occurred (Thomas-Blate 2018), which was nearly four times the number of new dams completed in the same year (NID 2013–). Some states, such as Wisconsin and Pennsylvania, have removed well over 100 dams (Bellmore et al. 2017).

While the majority of dam removals involved smaller, older damaged structures requiring expensive repairs (Stanley and Doyle 2003; Bellmore et al. 2017), the number of larger dam removals to restore fish habitat are increasing. In 2011, the largest dam removal in U.S. history took place with the removal of Condit Dam from the White Snake River in Washington (Gillman 2016). This was followed by the removal of two even larger dams on the Elwha River: the 210-foot-tall Glines Canyon Dam and the 108-foot-tall Elwha Dam, both also in Washington (Gillman 2016; Souers Kober 2016). Four large dam removals are planned on the Klamath River (Gosnell and Kelly 2010; Gillman 2016), which will result in 482 kilometers (km; 299.5 miles [mi]) of reconnected river habitat (Souers Kober 2016).

Of all the dam removals in the United States, over half of them have occurred during the last 10 years (Grant and Lewis 2015). During this time, scientists have transitioned from calling for empirical and predictive environmental studies (Bednarek 2001; Poff and Hart 2002) to generalizing the geomorphic and ecological impacts of dam removals (Bednarek 2001; Doyle et al. 2003; Doyle et al. 2003a; Stanley and Doyle 2003; Grant and Lewis 2015).

DATA AND METHODS

Data

The analyses in this study used a variety of data sources. The state-scale analyses included available data for documented dams that meet state and/or federal regulations and subsets of national precipitation and global potential evapotranspiration (PET) datasets to analyze the temporal and spatial patterns of dams in Texas. Two dam datasets exist for the state of Texas; one is managed by NID and includes 7,338 registered dams (NID 2013–) and the other is managed by the TCEQ and includes 7,280 documented dams that meet state regulations as of 2014 (Dams.gdb 1800–). Due to federal limitations on NID data use, this research used the state-level TCEQ dataset. Through a memorandum of user agreement from this research, the TCEQ provided a geodatabase with the location and attributes of dams. Dam attributes used for these analyses included year complete, purpose, and maximum storage capacity.

Of the documented dams, 7,161 included a year of completion (98.4%), and 6,567 had at least one purpose identified (90.3%). For dams with multiple purposes listed, only the first purpose listed was considered. The TCEQ reportedly does not

list dam purpose by any order, but the NID still reports the first purpose listed as the primary or most important purpose. All dams had a maximum storage value (defined as the maximum impoundment capacity at the top of the dam). There were 37 (0.005%) dams that reported a maximum storage value of 0 ac-ft, indicating a lack of data.

A table of ownership information, including the organization type of the owner, was provided as a separate file. There were over 10,000 entries in the ownership table, the result of multiple owners for individual dams. Entries in the ownership file that matched a corresponding ID in the dam shapefile were joined to the attribute table of the dam shapefile. Dams that did not have an owner listed or that did not have a matching owner ID were less than 0.01% ($n = 69$). An additional six dams did not have a listed owner organization type or affiliation.

Precipitation data was obtained from a national 4-km (2.5-mi) resolution raster file of the 30-year annual average (1981–2010) precipitation produced by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group of Oregon State University ([30-Year Normals 2012](#)). Potential evapotranspiration (PET) data was acquired from the Consortium for Spatial Information (CGIAR-CSI) Global Aridity and Global-PET Database ([CGIAR-CSI 2007–2019](#)). The Global-PET Database is a global 1-km (.6-mi) resolution raster of the 50-year annual average (1950–2000; [Zomer et al. 2007, 2008](#)). The precipitation and PET datasets are freely available online and were used to account for climatic trends across Texas. The United States Census Bureau ([TIGER 2015–2016](#)) provided shapefiles of Texas, and the Texas Water Development Board ([Major River Basins 2014](#)) provided shapefiles of the 23 major Texas river basins.

Data on dam incidents and dam failures were provided from the TCEQ Dam Safety Program through an open records request ([DamFailuresPIR9267 1900](#)). There was a total of 209 dam incidents, which resulted in damage to the dam but not a draining of the reservoir, and 119 dam failures, which included either overtopping or breaching and resulted in the draining of the reservoir. The data included the Texas dam ID, geographic coordinates, the date of the reported damage, the mode of failure, the dam name, type, height, and normal storage. Of the original 328 records of damaged dams, 18 had no associated geographic coordinates, resulting in a reduced dataset of 310 dams.

Data to analyze the patterns of dam removal in Texas were obtained from the TCEQ's Dam Safety Program ([Dam Removals 1983](#)). This dataset included information for 49 dam removals and provided attributes and locations for the removed dams, including the year and reason for removal. An additional dam removal was added to the original dataset of 49 removals by the authors: the Ottine Dam removal. The Ottine Dam, located in the Guadalupe River Basin, was damaged in

2008 by a storm and scheduled for removal in 2012 ([Montagne and Jobs 2016](#)). This dam was 104 years old when it was removed in 2016 ([Montagne and Jobs 2016](#)).

Analyses of temporal and spatial patterns in Texas dams

Analyses used ArcGIS to organize and analyze the available data on documented dams and climate. Twelve of the 7,280 dams in the TCEQ geodatabase had inaccurate or problematic geographic coordinates. Of these 12, six were relocated to the correct location using aerial imagery validation, and six were deleted as their true coordinates could not be determined. This resulted in a final dataset of 7,274 dams. This statewide dataset was subdivided by river basin, generating 23 additional sub-datasets, for a total of 24 dam datasets. Analysis of the Global-PET and national precipitation datasets determined the average, minimum, and maximum precipitation and PET values for each river basin using spatial analysis. The drainage area (square miles [mi^2]) for the land surface of each river basin was also calculated in ArcGIS.

The statistics package, IBM SPSS Statistics 22, was used to analyze the dam and climate data. The authors calculated the total reservoir storage and percentage of total storage for all 24 datasets. To further investigate spatial patterns of dam occurrence in Texas, the variables of size, time period (year of completion), purpose, and ownership from the dam attributes of maximum storage, year complete, purpose, and organization type (of owner) were assigned to each dam in the statewide dataset. This was also done for 10 major river basins: the Trinity, Brazos, Colorado, Red, Nueces, Sabine, Rio Grande, Neches, Guadalupe, and San Antonio river basins (Figure 1). These 10 basins contain nearly 90% of all the dams and 85% of the storage and drain over 80% of the land area in Texas.

There were 17 separate organization types in the TCEQ database for ownership, including null values. The authors aggregated these original organization types into six classifications: federal, state, and other governments, private entities, other, and not listed (Appendix 1). The authors recognize that categorizing the 7,274 dams into six categories minimizes the diversity of entities involved with dam ownership and management. While the federal, state, and private categories are fairly intuitive, the "other government" category includes the full array of cities, counties, county level Water and Control Improvement Districts (WCID), the Texas Soil and Water Conservation Districts, and river authorities, among others. The Guadalupe-Blanco River Authority, Sabine River Authority of Texas, and the Coastal Water Authority were listed as state governments by the TCEQ, but all other river authorities were included in other governments. The head of the TCEQ's Dam and Safety Program confirmed that other governments is the preferred organization type for river authorities (2020 email

Table 1. Size classifications based on [Graf 2005](#).

Size classification	Max. reservoir storage (cubic meters)	Max. reservoir storage (acre-feet)
Small	< 100,000	< 100
Medium	100,000–10,000,000	100–10,000
Large	10,000,000–1,000,000,000	10,000–1,000,000
Very large	>1,000,000,000	>1,000,000

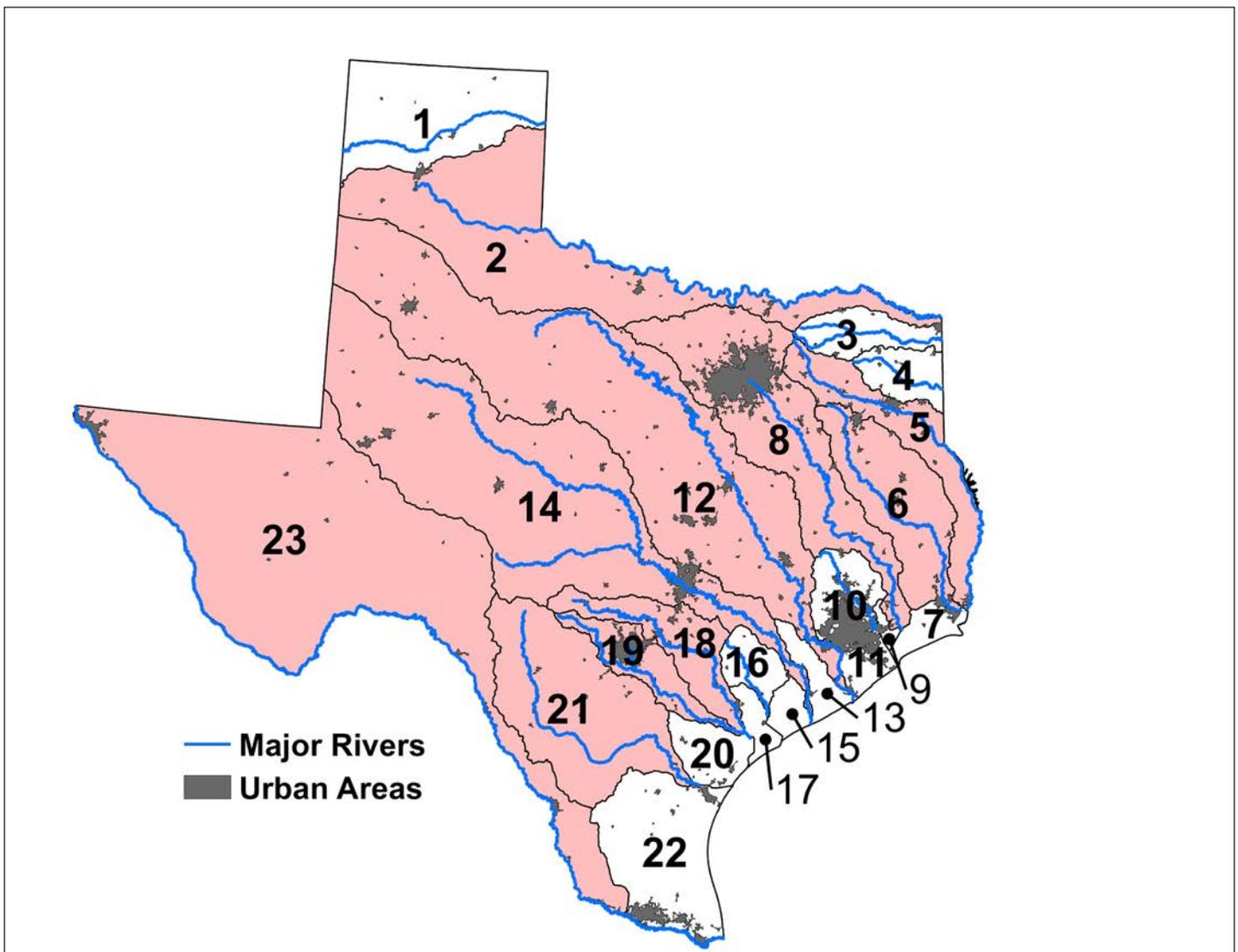


Figure 1. Map of Texas and 23 major river basins with major rivers and urban areas. River basins highlighted in rose represent the river basins analyzed in this study. Numbers correspond to river basin names: 1) Canadian, 2) Red, 3) Sulphur, 4) Cypress, 5) Sabine, 6) Neches, 7) Neches-Trinity, 8) Trinity, 9) Trinity-San Jacinto, 10) San Jacinto, 11) San Jacinto-Brazos, 12) Brazos, 13) Brazos-Colorado, 14) Colorado, 15) Colorado-Lavaca, 16) Lavaca, 17) Lavaca-Guadalupe, 18) Guadalupe, 19) San Antonio, 20) San Antonio-Nueces, 21) Nueces, 22) Nueces-Rio Grande, 23) Rio Grande.

to Kimberly Meitzen from Warren D. Samuelson, TCEQ; unreferenced), so these three organizations were reclassified and included in the “other government” category. The “other” category includes diverse entities such as ranches, water treatment facilities, utility facilities, homeowner associations, and churches, among others. Dams with multiple owners listed were included in the “other” category if the owners represented disparate owner categories. The first listed purpose for each dam was identified as the purpose; this same ordering logic is used by the federal government for the NID data set, and both NID and the TCEQ contained the same purpose order for each dam. The TCEQ specifically indicates that this order is not relevant to a dam’s purpose, revealing an inconsistency in federal and state data reporting.

There were multiple size classifications available for dams; the TCEQ used a size classification based on dam height and reservoir storage. For the purposes of this analysis, the authors used the size classification developed in 2002 by the Heinz Center and later modified by Graf (2005; Table 1). This classification system was used due to its ease of calculation and because reservoir size is more directly related to potential impacts to downstream hydrology than other measures of dam size (Graf et al. 2002). The authors sorted dams by size and used descriptive statistics to analyze the variables of time period, purpose, and ownership for each size class.

The temporal analysis followed similar logic. The authors sorted dams by five time periods and used descriptive statistics to analyze each time period by size, purpose, and ownership. The first time period included dams completed between 1800 and 1899. A large number of dams were completed in 1800 ($n = 282$), and few were completed between 1800 and 1899 ($n = 10$), instigating suspicion of these completion dates. It is likely that many older dams potentially built in the 1800s had 1800 listed as the year of completion, when the exact year of completion was unknown. While 1800 is likely a placeholder rather than an accurate year of completion, it is similarly unlikely that only 10 documented dams were built in Texas between 1800 and 1899. Despite some uncertainty regarding the age of these dams, for this analysis the authors have included dams with the year 1800 listed as the year of completion in the 1800–1899 time period. It should be noted that the TCEQ reports dams with a completion year of 1800 as having an unknown year of completion, and the NID lists only 15 dams completed before 1900 (NID 2013–).

The second time period represented an early age in dam building between 1900 and 1939 ($n = 518$). The third time period, 1940–1959 ($n = 1382$), designated the time when dam building began to progressively develop. The 1960–1979 time period ($n = 4154$) captures the peak of dam construction in Texas, and 1980–2014 ($n = 814$) represents the most recent time period.

Analysis of dam failures

The authors classified the damaged dam dataset by damage category, divided first by incident or failure and then sub-classified by type/mode. Dam incidents are events that resulted in some damage to the dam but not an event that resulted in the draining of the reservoir and are therefore not recognized as official dam failures by the TCEQ. Dam failures resulted in overtopping or breaching and draining of the reservoir. There were originally 85 unique values for mode of failure; these were grouped into six failure mode classifications: other or not provided, spillway or gate damage, slide/erosion, breach or collapse, overtopping, and piping. Additional information for the 310 damaged dams was obtained by linking the dataset to the Texas dam dataset via the Texas dam IDs. This resulted in additional information on the age and size of 261 of the damaged dams. Presumably, the 49 damaged dams without matching records were only included or added to the TCEQ’s dam database after 2015 or represented structures smaller than those regulated by the TCEQ. Descriptive statistics were used to categorize records of damaged dams by year, basin, mode of failure, dam age, and dam size.

Analysis of dam removals in Texas

The dam removal dataset was analyzed in a GIS framework in combination with the National Hydrography Dataset (NHD). The most current version of the NHD, the NHD High Resolution, is mapped at a 1:24,000 scale or better, representing the nation’s drainage networks and related features (NHD 1999–). It is part of The National Map maintained by the United States Geological Society (USGS) and is the most current and detailed hydrography dataset for the United States (NHD 1999–). The NHD and aerial imagery were used for the following four tasks: (1) to confirm the location of each dam removal; (2) to determine if it was located on the river network; (3) to validate if the dam was still absent or had been rebuilt; and (4) to measure the length of resulting functionally reconnected river network (FRRN). The river network was considered functionally reconnected if the NHD flowlines were connected and there was no documented dam located on the river network. The extent of FRRN was measured as the length of the upstream NHD flowlines from each removal by either summing the length of the flowlines in the attribute table and/or using the measure tool in ArcGIS. Descriptive statistics were used to summarize the dam removal dataset by river basin, height, owner, year built, year removed, reason for removal, and the calculated FRRN length.

Table 2. Climatic and geographic variables for major Texas river basin.

	General	Precipitation (inches)			Potential ET (inches)			Area (square miles)		Dams		Total Reservoir Storage	
	Location	Mean	Min	Max	Mean	Min	Max	N	%	N	%	Million acre-feet	%
Texas	---	28.7	8.1	61.5	58.9	44.3	73.9	268,580	100.0	7,274	100.0	104.3	100.0
Cypress	Eastern	48.2	44.5	51.6	55.6	54.1	56.6	2,941	1.1	161	2.2	2.6	2.5
Neches	Eastern	51.4	42.0	60.1	57.4	53.5	59.0	9,984	3.7	308	4.2	8.6	8.2
Sabine	Eastern	49.6	41.0	61.4	56.4	53.3	58.5	7,603	2.8	335	4.6	8.8	8.4
San Jacinto	Eastern	49.6	44.1	56.1	56.6	51.8	58.5	3,954	1.5	162	2.2	1.5	1.5
Sulphur	Eastern	47.3	43.3	51.0	54.7	53.2	56.2	3,591	1.3	162	2.2	7.5	7.1
Trinity	Eastern	41.4	30.1	60.2	56.7	52.6	59.4	17,987	6.7	1,787	24.6	17.0	16.3
Canadian	Northern	19.5	15.0	24.5	54.1	51.3	57.4	12,837	4.8	153	2.1	2.8	2.6
Red	Northern	26.9	18.2	52.0	56.0	51.7	60.2	24,335	9.1	619	8.5	12.5	12.0
Brazos	NW - SE	29.9	17.4	54.3	57.7	51.9	60.8	43,034	16.0	1,391	19.1	14.80	14.2
Colorado	NW - SE	24.3	13.4	47.9	59.7	51.1	62.9	39,605	14.7	775	10.7	12.2	11.7
Guadalupe	South-central	34.4	28.1	40.4	59.5	54.8	61.6	5,977	2.2	215	3.0	1.60	1.5
San Antonio	South-central	32.0	27.9	38.8	60.1	54.4	62.6	4,196	1.6	160	2.2	0.70	0.7
Nueces	Southwest	25.2	19.5	33.7	63.3	56.9	67.4	16,749	6.2	456	6.3	1.80	1.7
Rio Grande	W - S	15.3	8.1	27.1	63.1	44.3	74.0	49,590	18.5	329	4.5	10.9	10.4
Brazos-Colorado	Coastal	47.0	41.4	52.3	56.2	51.1	59.6	1,871	0.7	26	0.4	0.04	0.04
Colorado-Lavaca	Coastal	44.5	40.6	47.6	54.4	49.1	58.2	1,270	0.5	11	0.2	0.30	0.25
Lavaca	Coastal	41.5	36.9	46.3	58.3	53.3	60.0	2,318	0.9	24	0.3	0.30	0.32
Lavaca-Guadalupe	Coastal	41.2	37.3	44.0	54.5	48.7	59.3	1,289	0.5	8	0.1	0.01	0.01
Neches-Trinity	Coastal	57.9	49.0	60.9	52.9	46.0	56.3	1,692	0.6	15	0.2	0.01	0.01
Nueces-Rio Grande	Coastal	25.1	20.1	35.3	61.2	49.6	65.6	11,455	4.3	101	1.4	0.03	0.32
San Antonio-Nueces	Coastal	34.0	28.7	39.1	57.7	49.6	62.0	3,033	1.1	10	0.1	0.004	0.005
San Jacinto-Brazos	Coastal	52.6	45.6	57.8	52.5	45.2	57.6	1,741	0.6	51	0.7	0.02	0.142
Trinity-San Jacinto	Coastal	55.9	54.0	56.8	54.1	52.0	56.7	390	0.1	14	0.2	0.05	0.05

RESULTS

Climatic and geographic trends

As expected with general climate gradients across Texas, PET generally increased from east to west, with the highest PET values located in parts of the southwest (Table 2). Inversely, precipitation declined from east to west, with an average yearly precipitation range of 8.1 to 61.5 inches (in; 205.7 to 1562.1 millimeters [mm]; Table 2). There was a 42.6-in (1082-mm) range of average yearly precipitation variables by basin, with the Rio Grande Basin's 15.3 in (388.62 mm) being the dri-

est and the Neches-Trinity River Basin's 57.5 in (1460.7 mm) basin being the wettest (Table 2).

In general, river basins receiving less than 30 in (762 mm) of average annual rainfall had larger percentages of dams and storage, with the exception of the Trinity River Basin. The Trinity River Basin contained the largest percentage of dams and storage and an average of 41.4 in (1051.6 mm) annual rainfall (Figure 2; Table 2). Larger river basins contained a larger proportion of dams, except for the Trinity River Basin and the Rio Grande Basin (Table 2). The Trinity River Basin contained nearly a fourth of all dams but only the fifth largest drainage area (46,586 square kilometers [km²; 17,987 mi²], 6.7%), while the Rio Grande Basin with the largest drainage area

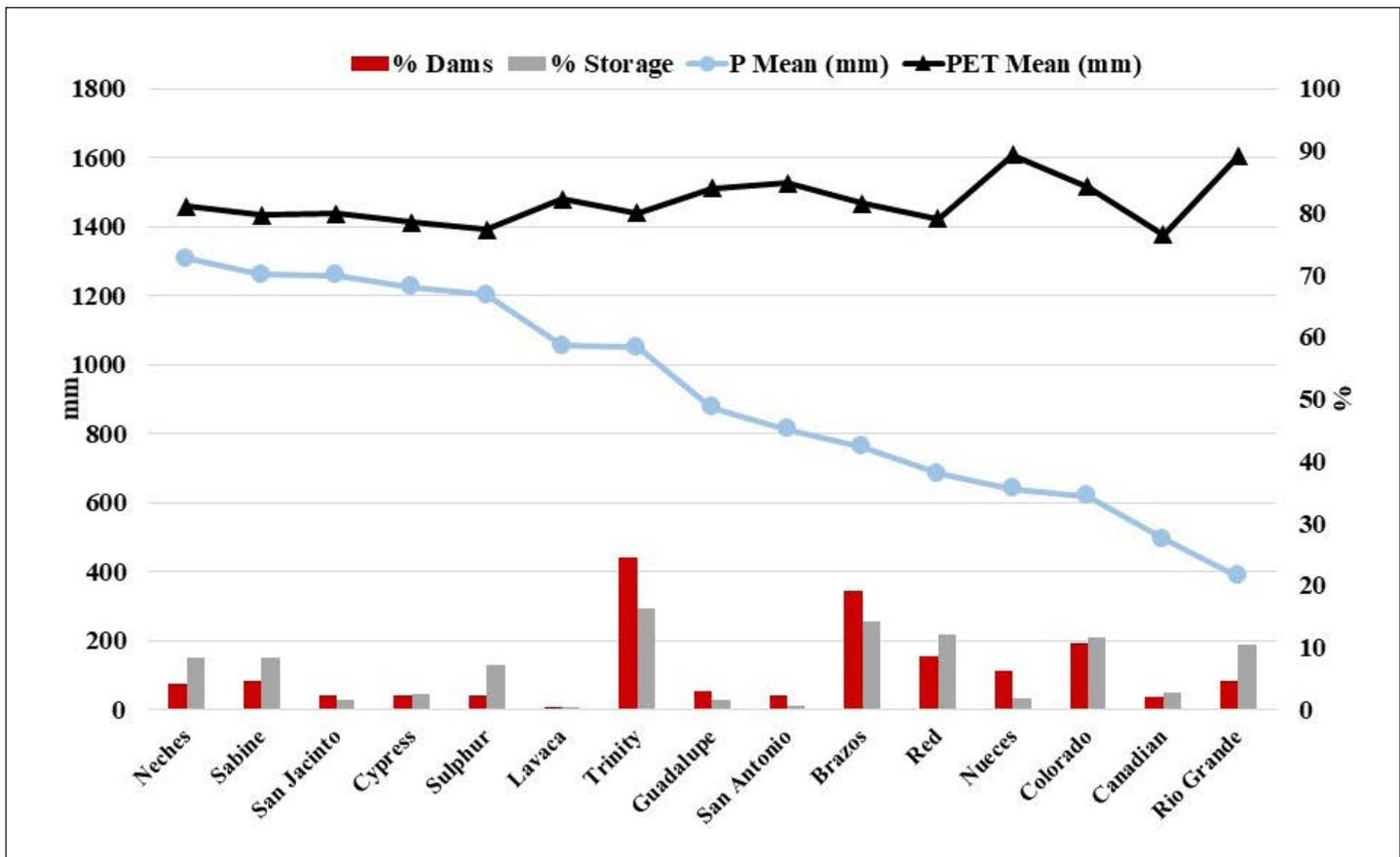


Figure 2. Climate and geographic distribution of dams. Percent of all Texas dams (red bars) and total reservoir storage (grey bars), with mean precipitation (blue line with circles) and potential evaporation (black line with triangles) in major river basins. Note that basins containing less than 1% of the total number of dams and/or reservoir storage in Texas are omitted from this graph. [mm, millimeters]

(128,437.5 km² [49,590 mi²], 18.5%) contained less than 5% of the total number of dams (Table 2). Coastal basins, being among the smallest major river basins, each contained less than 1% of the total number of dams in Texas (Table 2).

Analysis of 10 selected major river basins

The 10 largest river basins revealed a few notable patterns. The combined Trinity (n = 1787, 24.6%), Brazos (n = 1391, 19.1%), Colorado (n = 776, 10.7%), Red (n = 619, 8.5%), and Nueces (n = 456, 6.3%) river basins contained 69.2% of Texas dams (Table 2). The Rio Grande Basin had the largest drainage area in Texas and 4.5% of dams (n = 329). The Guadalupe (n = 215, 3%), San Antonio (n = 160, 2.2%), Sabine (n = 335, 4.6%), and Neches (n = 308, 4.2%) river basins represented an additional 14% of the total number of dams. Together these 10 river basins accounted for 87.7% of dams and 81.5% of the drainage area in Texas.

Dam size

Medium dams were the most abundant at the state scale (n = 5586, 76.8%). Similarly, medium dams comprised more than 70% of the total number of dams at the basin scale (Appendix 2). Small dams comprised the second largest proportion (n = 1452, 20%) at the state scale and represented 14.9% to 26% of the dams in each river basin, except for the Trinity River Basin, where small dams constituted only 1.8% of dams (Appendix 2). Large (n = 207, 2.8%) and very large (n = 29, 0.4%) dams represented the smallest proportion of dams (Appendix 2).

While the amount of large and very large dams was low compared to medium and small dams, together they accounted for nearly 95% of the total reservoir storage in Texas and over 90% of the reservoir storage in each river basin (Appendix 2). The exception was the San Antonio River Basin; in this basin, large dams constituted over 70% of the storage, with no very large dams (Appendix 2). Very large dams alone accounted for 50% or more of the storage in each basin and nearly 70% of the storage in Texas (Appendix 2).

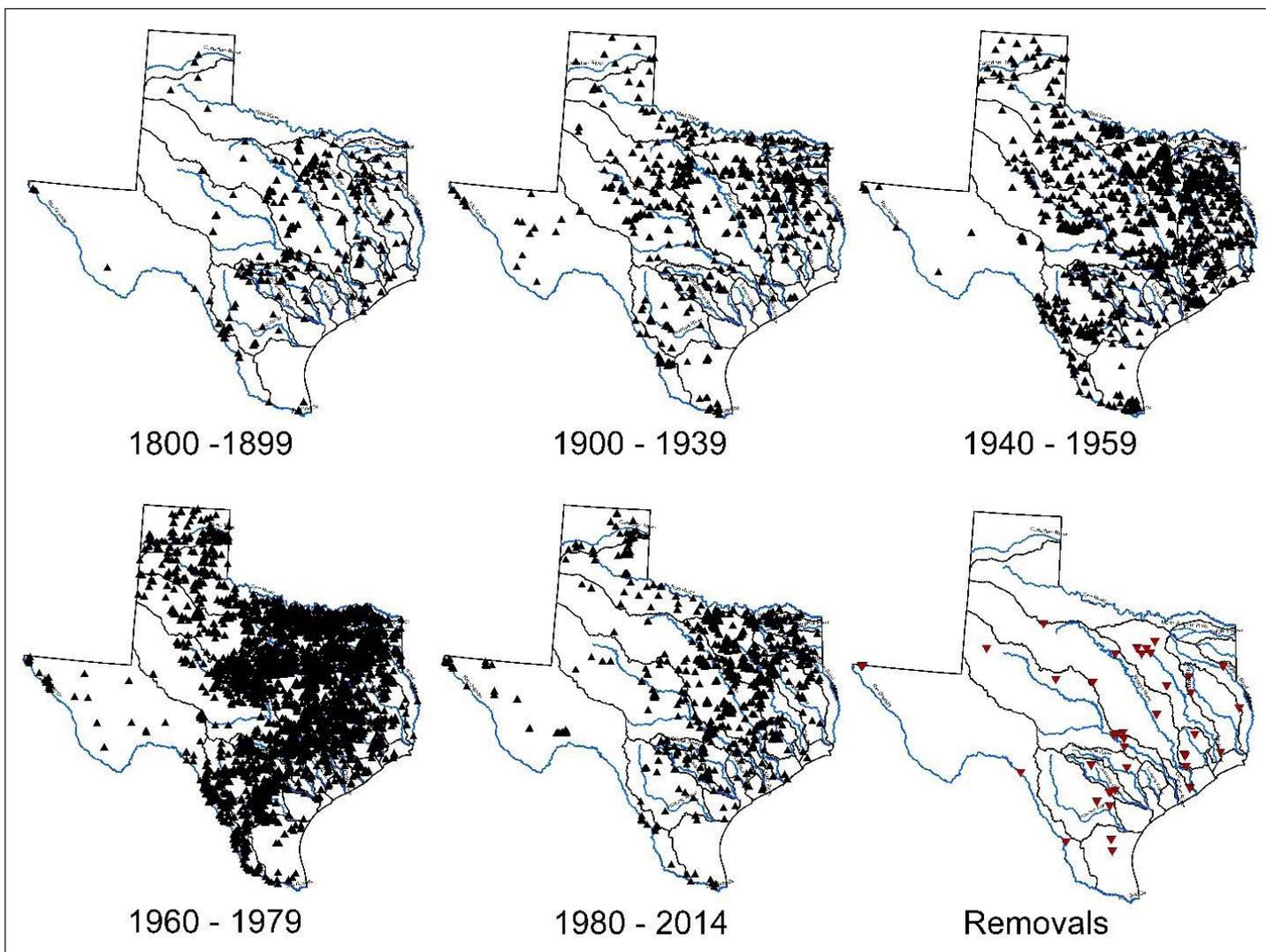


Figure 3. Location of dams completed during each time period and all dam removals (1983-2016) in Texas. Major rivers shown in blue.

Time periods and reservoir storage

A general trend existed relative to the number of dams completed during each time period; dam construction increased during the first four time periods and then declined in the 1980–2014 time period (Figure 3). In the 1800s, the most commonly built dams were small and medium; only three large and no very large dams were built during this same time (Appendix 3). The majority of dams built for all other time periods were medium dams (Appendix 3). The number of large and very large dams constructed increased throughout 1900–1979. The largest number of dams were built between 1940 and 1979, and most of the large and very large dams were also completed during this time. Specifically, 1940–1959 saw the construction of 59 large and nine very large dams. An additional 72 large dams and 12 very large dams were constructed from 1960 to 1979 (Appendix 3).

Most reservoir storage capacity by volume was created between 1940 and 1979, with the largest percentage created during 1960–1979, and this same pattern applied to the Trinity, Brazos, Sabine, Rio Grande, Neches, and Guadalupe river basins (Figure 4). However, in the Colorado and Red river basins the majority of reservoir storage was created in the 1940s (Figure 4). The Nueces River Basin gained over 60% of its reservoir storage during the 1980s, while in the San Antonio River Basin nearly half of the reservoir storage was built in the early 1900s (Figure 4).

The Trinity River Basin experienced the construction of one very large and 10 large dams from 1940 to 1959, and between 1960 and 1979, two very large and eight large dams were completed. An additional six large and two very large dams were completed in the Trinity River Basin between 1980 and 2014. The Brazos River Basin gained 11 large dams and three very large dams between 1940 and 1959, and an additional 19 large

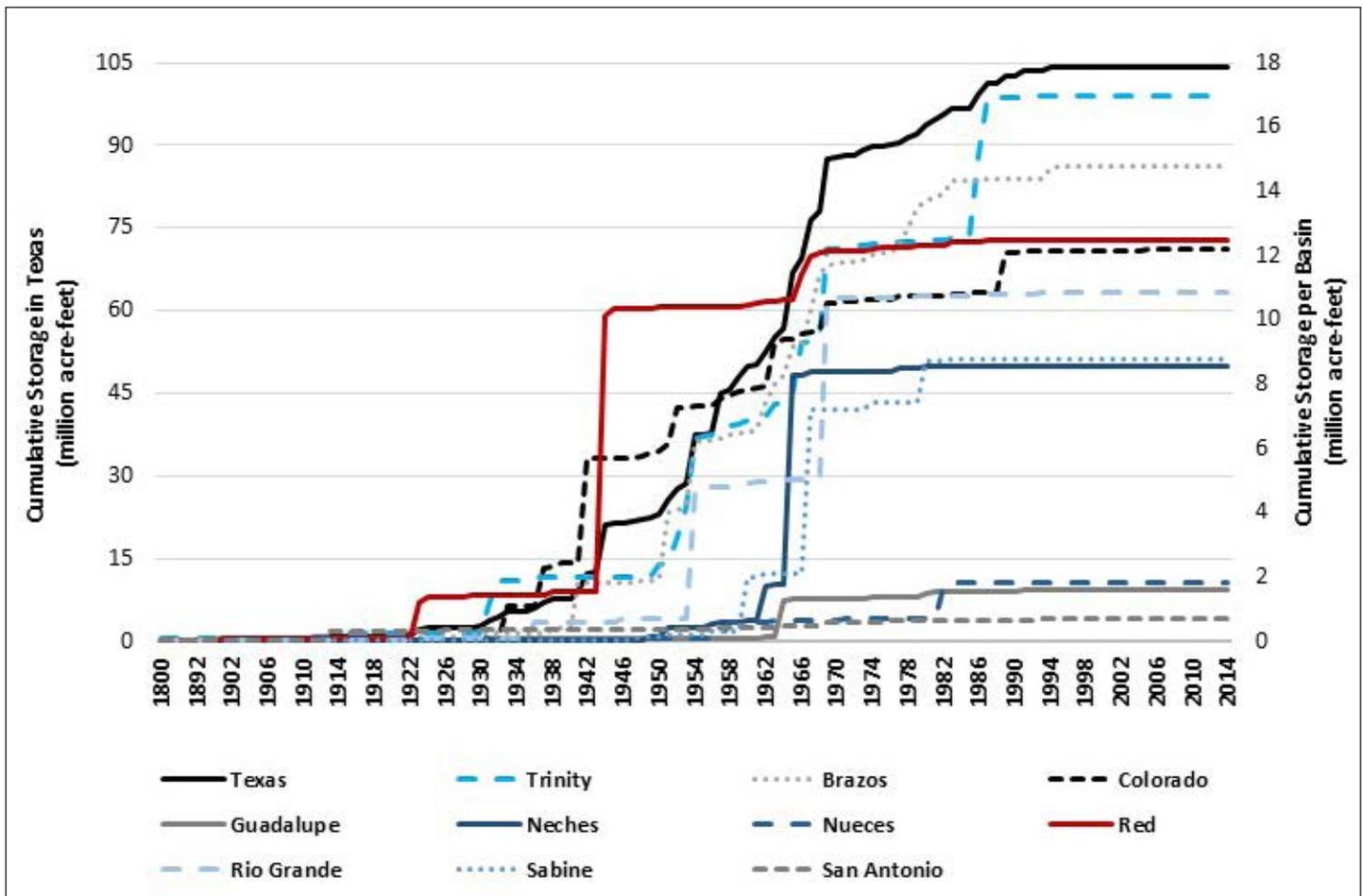


Figure 4. Total maximum cumulative reservoir storage in Texas and 10 major river basins.

and two very large dams were constructed between 1960 and 1979.

In the Sabine River Basin, two of the three very large dams were built between the years of 1960 to 1979. These two dams were the Iron Bridge Dam, completed in 1960 with a maximum storage of over 1 million ac-ft, and the Toledo Bend Dam, built in 1967 with a maximum storage of over 5 million ac-ft. Together these two dams constituted 77.3% (6,757,523 ac-ft) of the total reservoir storage in the river basin (8,776,518 ac-ft).

The Rio Grande Basin had a total reservoir storage of nearly 11 million ac-ft and only two very large dams. The international Falcon Dam, with a maximum storage of over 4 million ac-ft, was completed in 1954, and the international Amistad Dam, with a maximum storage of over 5.5 million ac-ft, was completed in 1969. The only two very large dams in the Neches River Basin were both completed during the 1960–1979 time period and together had a maximum storage capacity of over 7.5 million ac-ft. The Guadalupe River Basin had one very large dam, Canyon Dam, completed in 1964 with a maximum

reservoir storage of over 1 million ac-ft. Canyon Dam was over eight times larger than the second largest dam in the river basin and accounts for 71.7% of the total reservoir storage.

Most of the large dams in the Colorado River Basin were built between 1940 and 1959, with one very large dam built during this period. The Denison Dam was completed on the Red River in 1944, with a maximum storage capacity of 8,600,000 ac-ft, and was the largest dam in this basin by over 7.5 million ac-ft.

The only very large dam in the Nueces River Basin was completed in 1982. With a storage capacity of over 1 million ac-ft, the Choke Canyon Dam had twice the maximum storage capacity of the second largest dam in the river basin. The San Antonio River Basin had no very large dams but did have five large dams. Two were built between 1900 and 1939, with a combined maximum storage of 349,220 ac-ft, that accounted for nearly half of the total reservoir storage in the river basin. The other three had a combined maximum storage of 148,787 ac-ft and were constructed during the 1960–1979 time period.

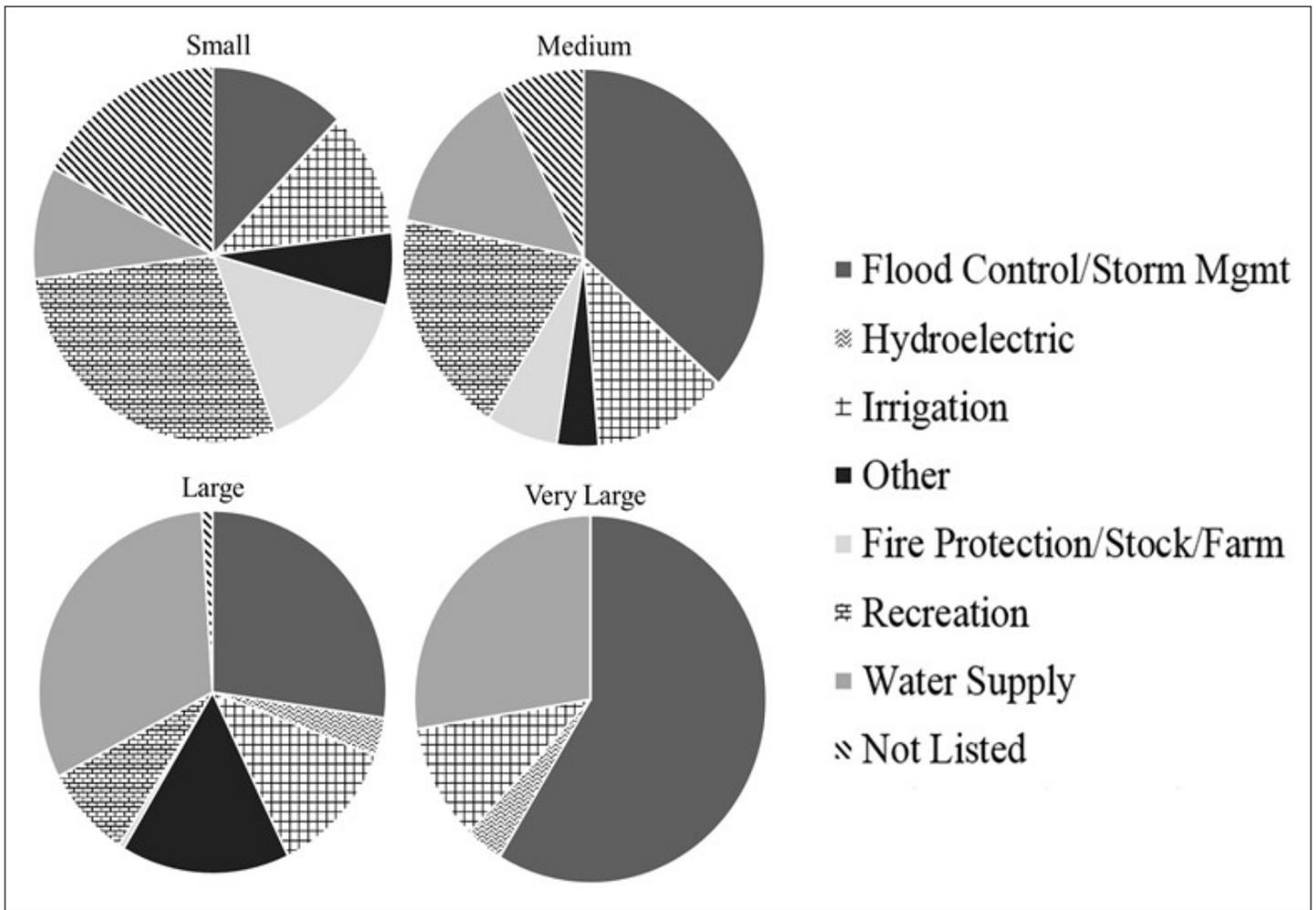


Figure 5. Purpose for all dams (1800-2014) in Texas based by dam size.

Owners

The largest percentage of dam owners in Texas were private entities (n = 4263, 58.6%), and the second largest percentage were other governments (n = 2359, 32.4%). This was also true for each river basin, except for the Trinity and Colorado river basins, where other governments owned the majority of dams, 54.3% (n = 970) and 56.4% (n = 438) respectively. Private entities owned 78.9 % (n = 1146) of small dams and 55% (n = 3072) of medium dams in the state, over 60% of total small dams in each river basin, and 30% to over 90% of the total medium dams in the majority of the river basins. Other governments owned the majority of large dams in all river basins. The federal government owned over 50% of the very large dams in Texas, and this was fairly consistent across most river basins. In the Colorado and Sabine river basins, other governments owned most of the very large dams. Data is shown in Appendix 4.

Purpose

The most common first listed purpose for all dams in Texas was flood control and stormwater management (31.5%), followed by recreation (20.7%) and water supply (13.8%; Figure 5). Only a small percentage of dams in Texas listed no purpose (9.7%) or “other” as the purpose (3.4%; Figure 5). The variety of purposes declined as dam size increased, and the sharpest decline occurred from large to very large dams.

For small dams, the most common purpose was recreation (27.8%), followed by fire protection, stock and farm pond (14.6%; Figure 5). Most medium dams had flood control and stormwater management (36.6%) as a purpose, followed by recreation (19.4%) and water supply (14.2%; Figure 5). Very large dams listed flood control and stormwater management (n = 17, 58.6%), water supply (n = 8, 27.6%), irrigation (n = 3, 10.3%), and hydroelectric power generation (n = 1, 3.5%) as their purpose (Figure 5). Over 19% of small dams and 7.6% of

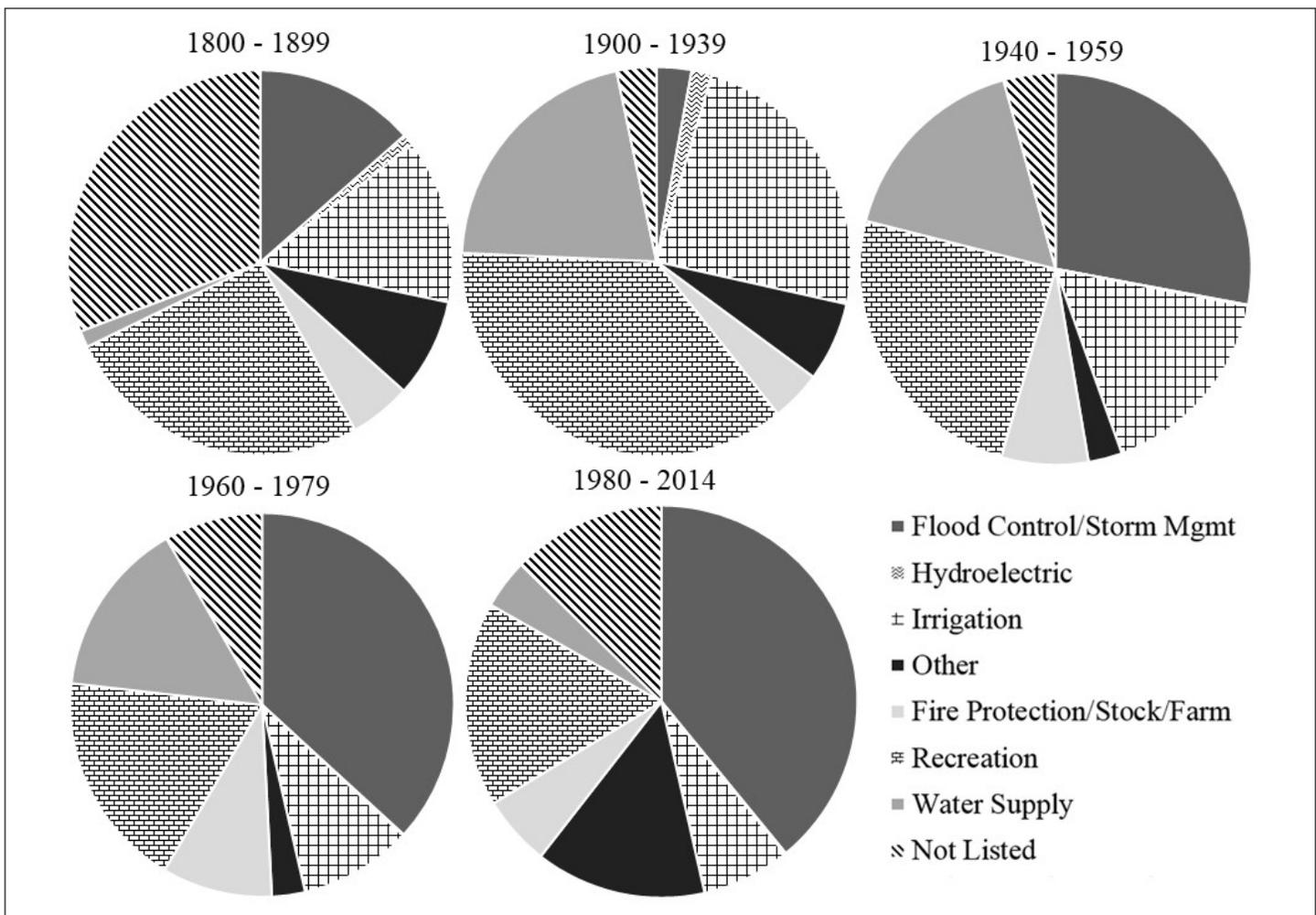


Figure 6. Purpose of dams by time period.

medium dams had no recorded purpose (Figure 5), while only two large dams had no purpose listed and all very large dams had a recorded purpose (Figure 5).

Over 30% of dams completed between 1800 and 1899 had no purpose listed. The most common recorded purpose for dams built between 1800 and 1899 was recreation (26%), followed by flood control and stormwater management (13.4%) and irrigation (14%; Figure 6). Recreation was the most prevalent purpose for dams completed during the 1900–1939 time period (36.5%), while irrigation (23.9%) and water supply (21%) were the next most common (Figure 6). Flood control and stormwater management (28%) and recreation (24.5%) were the most common purposes for dams built from 1940 to 1959 (Figure 6). Dams completed during 1960–1979 had flood control and stormwater management (36.8%), recreation (18.3%), and water supply (14.9%) listed as the top purposes (Figure 6). Similarly, dams constructed from 1980 to 2014

had the purpose of flood control and stormwater management reported most frequently (39.1%), followed by recreation (16.8%) and irrigation (7.2%; Figure 6). Only 3.3% of dams built during 1900–1939 did not include a purpose. Of the dams built during the most recent time period, 1980–2014, 12.8% listed no purpose (Figure 6).

The Brazos, Red, and Guadalupe river basins generally followed state trends for purpose (Figure 7). A noticeably larger proportion of the dams in the Trinity, Colorado, and San Antonio river basins reported flood control as their purpose, 56.9%, 45.9%, and 34.4% respectively (Figure 7). In the Sabine (42.7%) and Neches (50.6%) river basins recreation was the purpose for the majority of dams, while the majority of dams in the Nueces River Basin listed water supply (45.6%) as the purpose (Figure 7). In the Rio Grande and Nueces river basins, there were a larger number of dams without a purpose listed (25.8%, 19.7% respectively; Figure 7).

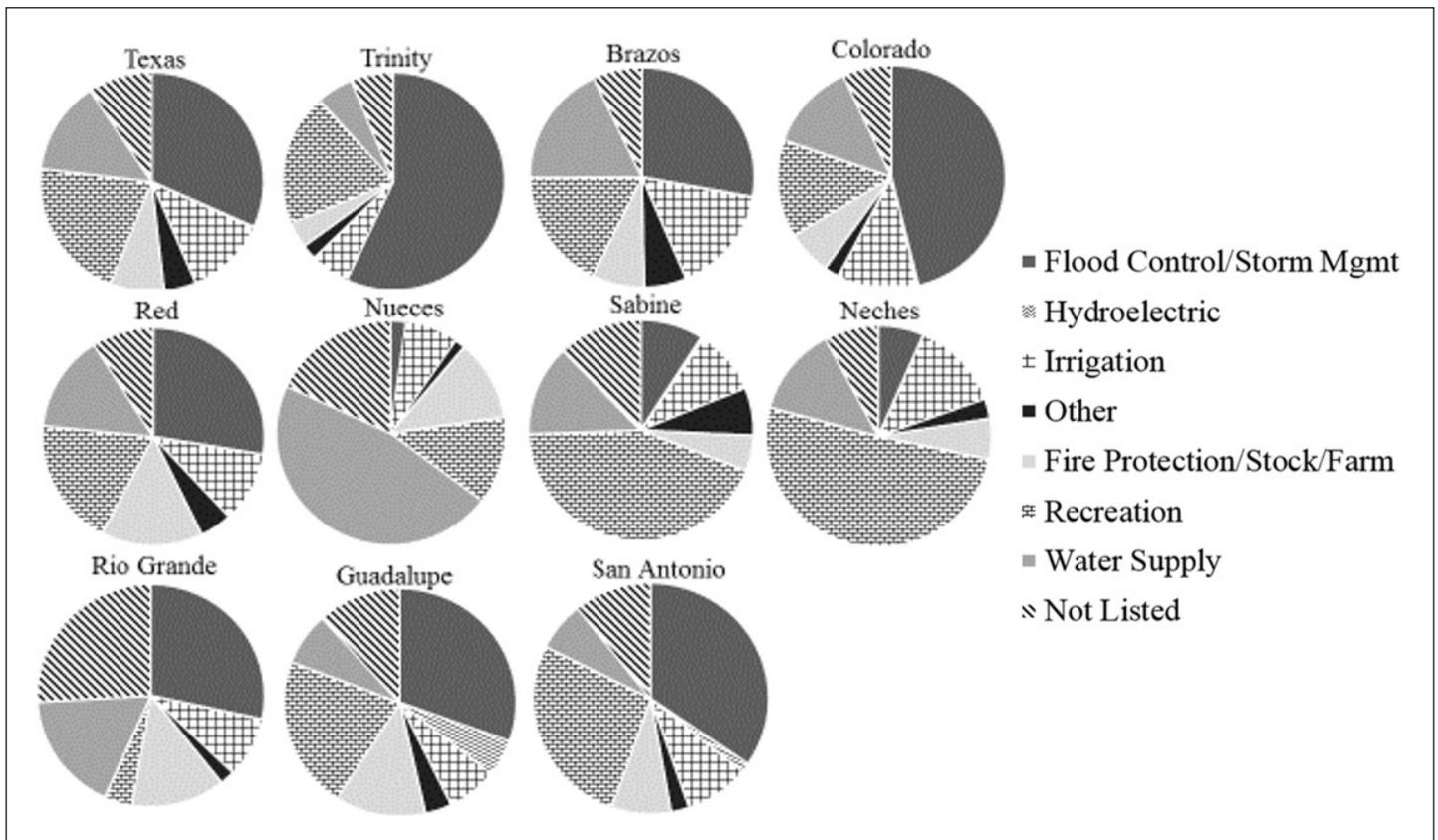


Figure 7. Purpose of dams (1800-2014) in 10 major river basins.

Dam failures in Texas

Dam failures, defined as overtopping or breaching events that resulted in the draining of the reservoir, occurred in 14 of the 23 major river basins, while dam incidents, involving all modes of damage with the exception of a drained reservoir, occurred in 15. Nearly 10% (29 dams) of the original 328 dams reported as damaged were listed more than once. Nine dams were listed as having failed twice, and one dam was recorded as having failed on three separate occasions. Two dams had four separate incidents reported, one had three reports of incidents, and an additional 10 dams had two separate incidents recorded. There were five dams listed as having failed, and then at a later date had one or more separate incidents occur. One dam had an incident reported and then failed at a later date.

The majority of dam damage reports were incidents rather than failures, with the vast majority of incidents occurring in the Trinity River Basin (Figure 8). Only five reports of dam incidents and two reports of dam failures involved dams built during the 1800s, while 16 incidents and 36 failures involved dams with unknown dates of completion. Over 75% (n = 151) of dam incidents involved medium dams and 59% (n = 119) involved dams built between 1960 and 1979 (Figure 9). Sim-

ilarly, 50% (n = 54) of dam failures involved medium dams, but only 22% (n = 24) involved dams built between 1960 and 1979 (Figure 9). Thirty-three percent (n = 36) of reported dam failures involved dams with unknown dates of completion, and 21% (n = 23) were dams built between 1900 and 1939 (Figure 9).

The first recorded dam failure occurred in 1900, while the first incident was not recorded until 1926 (Figure 10). Between 1900 and 1986 there were 41 reported dam failures and an additional 19 incidents (Figure 10). The next 20 years, 1987 to 2006, would see a doubling of dam failures (n = 43) and incidents (n = 21; Figure 10). There were nine additional failures and 39 incidents from 2007 to 2014 (Figure 10). In 2015 alone there were seven dam failures and 93 separate incidents recorded (Figure 10), with over 58% of the reported damaged dams occurring in the Trinity River Basin (Figure 11). The vast majority of the reports of dam damage in the Trinity River Basin occurred on two separate dates, May 30th, 2015 (n = 24) and December 25th, 2015 (n = 37). Nine more dam failures and 32 incidents were recorded between 2016 and 2019 (Figure 10, 11).

The majority of reported incidents involved spillway damage (n = 114, 57%), while the majority of reported failures involved

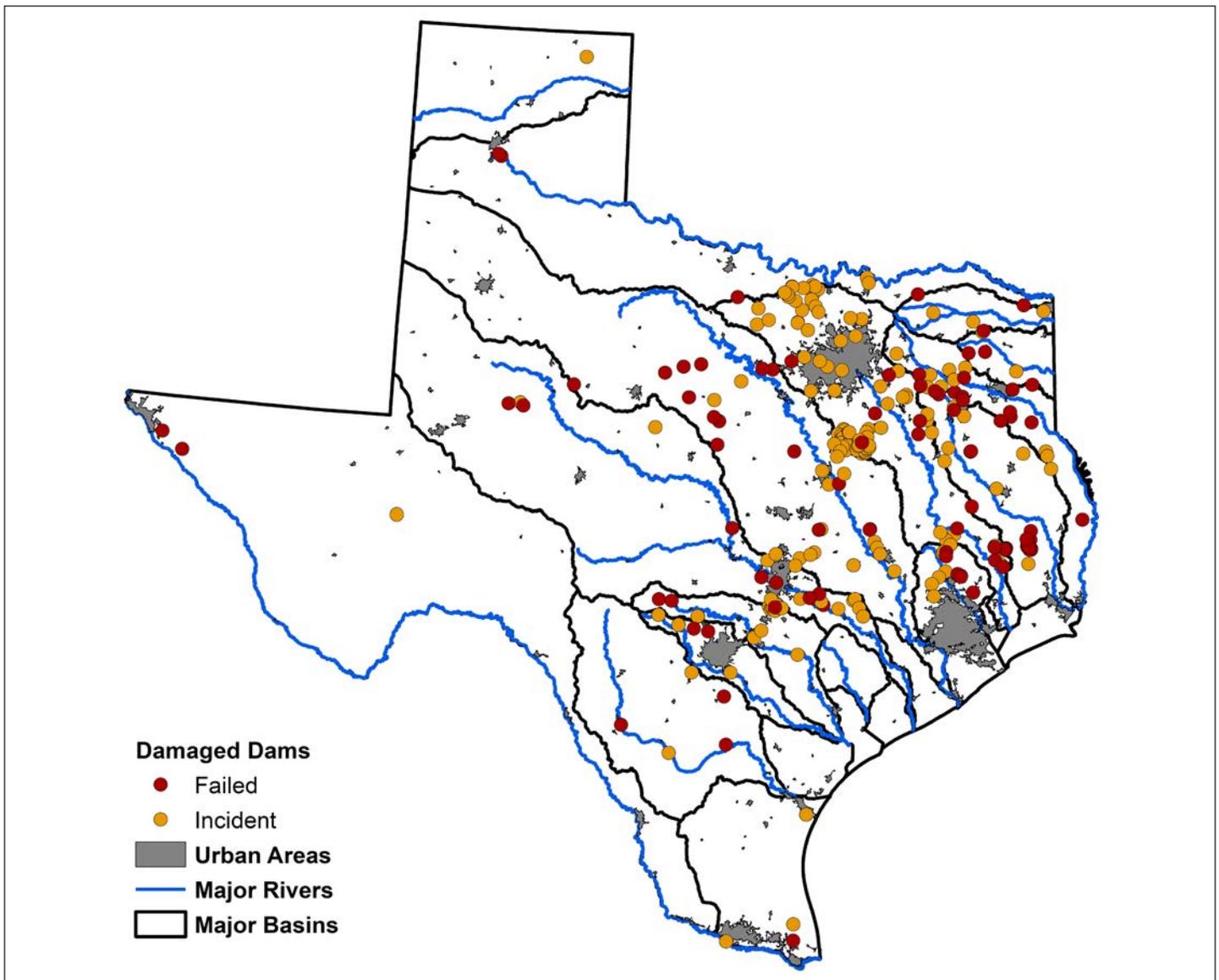


Figure 8. Reported dam incidents and failures (1900-2019).

overtopping ($n = 67$, 62%; Figure 12). Across the major river basins, spillway or gate damage and overtopping constituted the largest percentage of reported damage, followed by piping (Figure 13). The Association of Dam Safety Officials (2018) describes piping as the internal erosion of the soil or embankment of the dam's foundation caused by seepage that often begins at the downstream end of the dam and erodes towards the reservoir. Spillway or gate damage accounted for 20% or more of the reported incidents and failures in all river basins except the Nueces-Rio Grande Basin, which had no occurrences of spillway or gate damage reported, and the Neches River Basin, where spillway or gate damage accounted for only 13% of damaged dams. The Neches River Basin was the only basin to have more recorded failures than incidents (Figure 14) and

had the second highest percentage of overtoppings reported (Figure 13). The San Antonio River Basin had the highest percentage of overtopping events listed (Figure 13), but this is the result of three of five damaged dam reports, as opposed to 26 reports of overtopping out of 46 total reports of damaged dams in the Neches River Basin (Figure 13). Similarly overtopping accounted for 20% or more of the reports of damage, except for the Red and Canadian river basins (Figure 13). Slide/erosion accounted for less than 26% of reported occurrences of dam damage across all basins (Figure 13). Reports of damaged dams categorized as other or not provided accounted for less than 25% of reports in all basins, except for the Nueces-Rio Grande Basin, where 50% ($n = 3$) of damaged dam reports were classified as other or not provided (Figure 13).

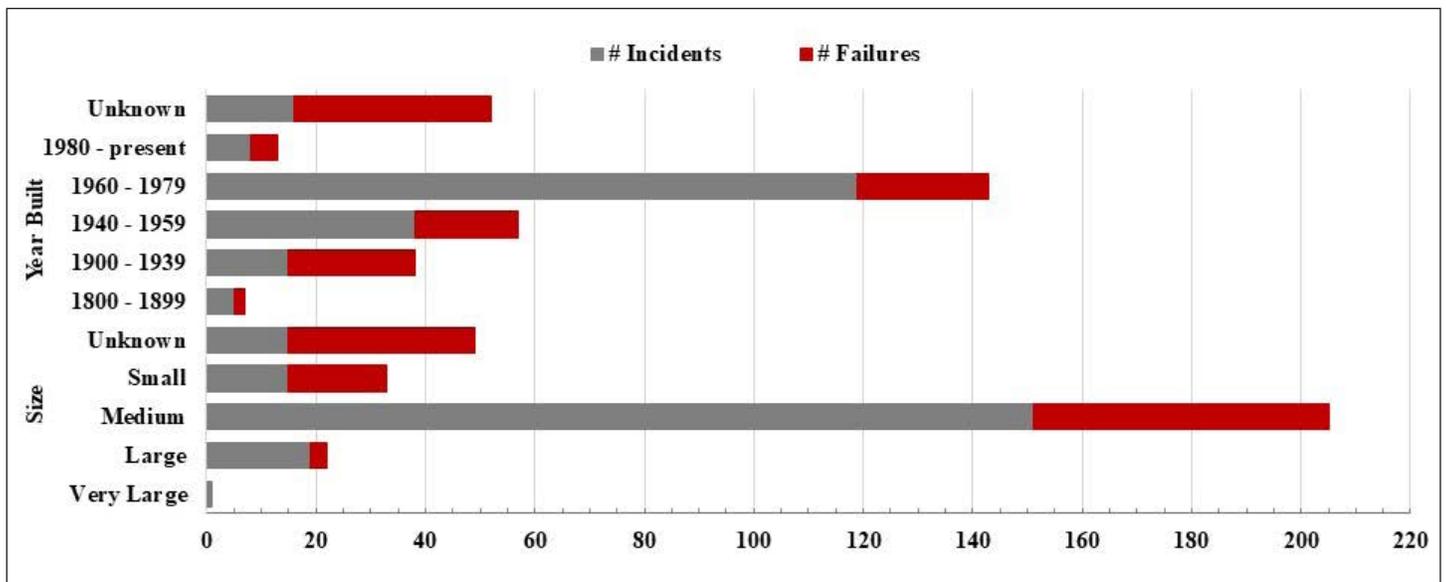


Figure 9. Year built and size for dams with reported incidents or failures (1900-2019).

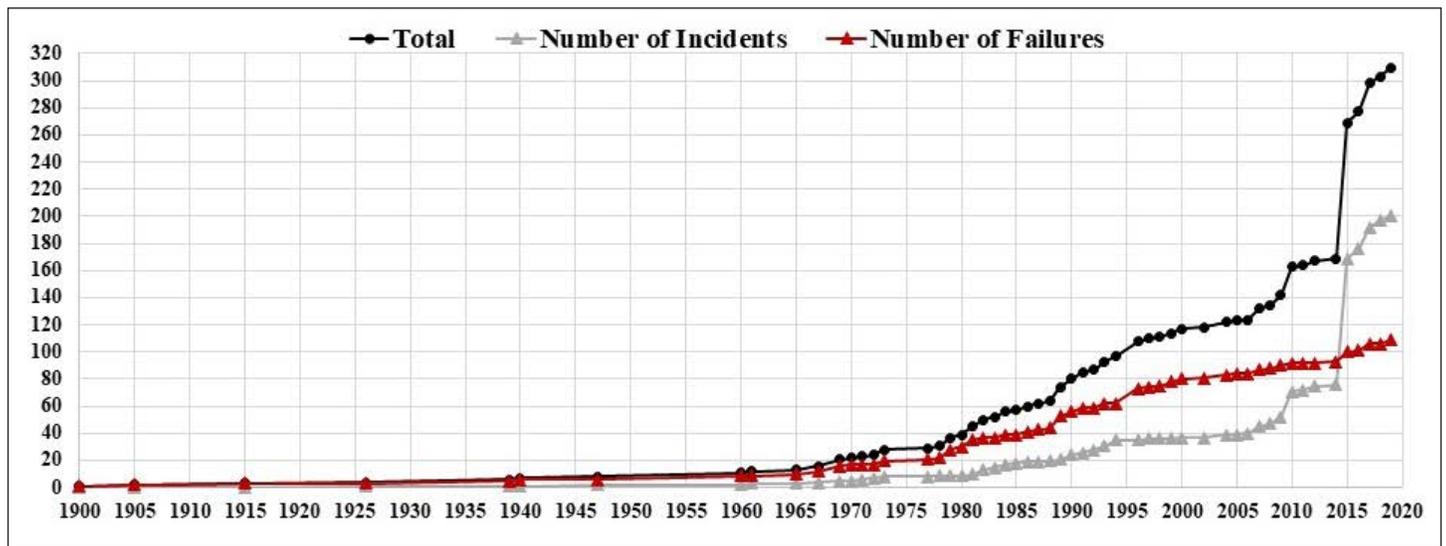


Figure 10. Cumulative number of dam incidents and failure by year reported.

Dam removals in Texas

There have been 50 dam removals in Texas between 1983 and 2016, resulting in a total of 1816.1 km (1128.5 mi) of FRRN. There was a noticeable spike in dam removals between 1994 and 1996 (Figure 15). Four tailing ponds were removed in 1995, and another four oxidation dams were removed in 1996. These four tailing pond dams did not occur on the NHD-defined river network and thus resulted in 0 km (0 mi) of FRRN. Dam removals in 2006 and 2015 sharply increased the cumulative length of FRRN (Figure 15).

Dams have been removed in 13 of the 23 major river basins in Texas, and many appear to be clustered around urban centers

within these basins (Figure 16). Three removals have occurred within coastal basins, and the largest number of removals have occurred in the Colorado (n = 9), Rio Grande (n = 7), and Trinity (n = 7) river basins (Figure 17). Dams with an unknown or unrecorded year of completion accounted for 26% of the removals (n = 13). Of the dams removed, most were at least 37 years old, built between 1960 and 1979 (n = 17, 34%). (Figure 18). Over 80% of removed dams had a height of less than 30 feet (Figure 18), and nearly all were privately owned (n = 40, Figure 18). The main purpose for dam removals (n = 20) was the removal of a liability and state agency involvement (Figure 18). Removal of liability and state agency involvement was the

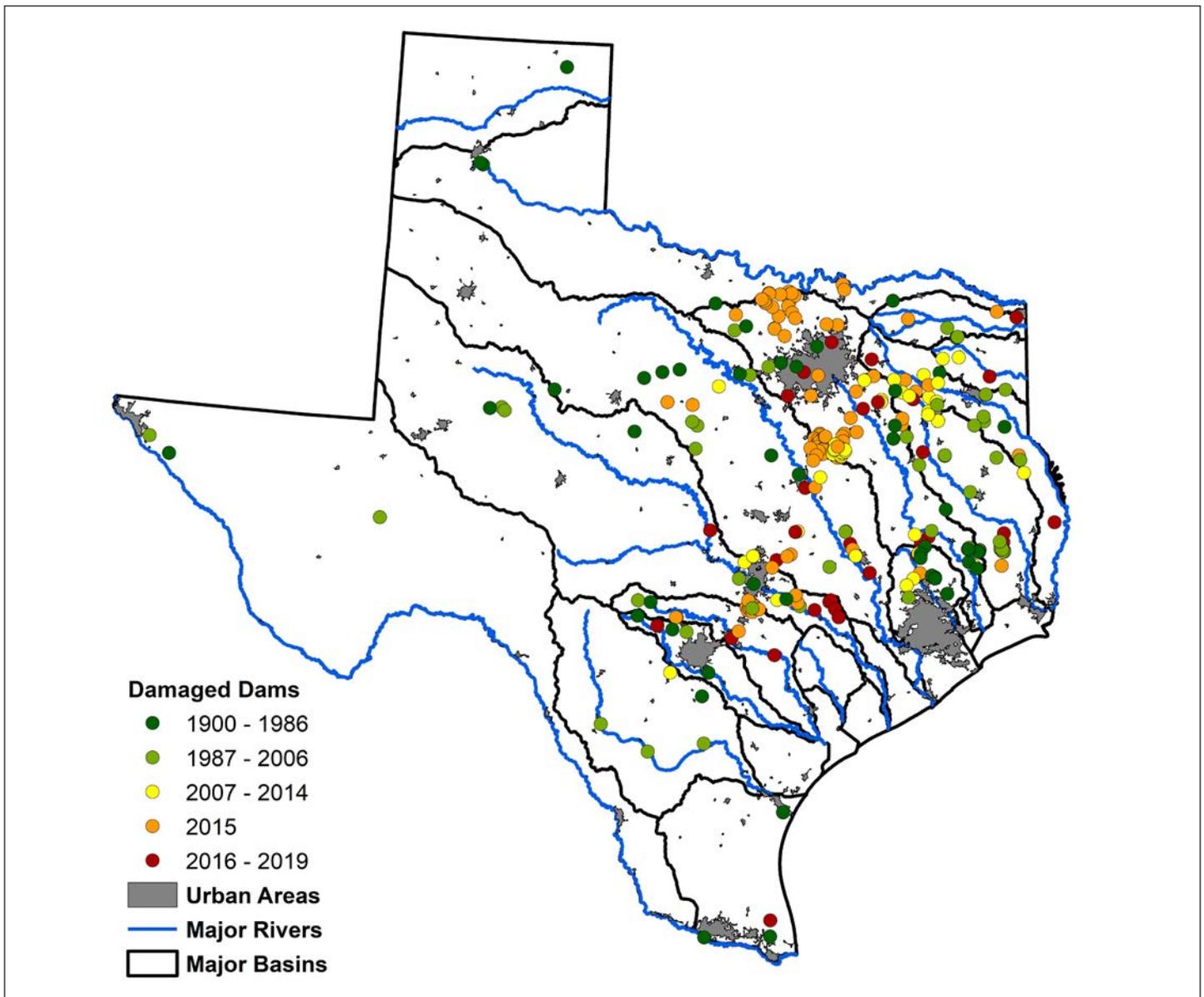


Figure 11. Dam incidents and failures by year reported.

listed reason for the three dam removals that resulted in over 100 km (62 mi) of FRRN (Figure 19).

The Bolch Pond Dam, formerly located in the upper portion of the Colorado River Basin, had an unknown age, was 16 feet (ft) tall, and resulted in 115.5 km (71.8 mi) of FRRN when it was removed in 2009. The Patricio Lake Dam, located in the Nueces-Rio Grande Basin on the Santa Gertrudis Creek, was 19 ft tall and built in 1939. Its removal in 2007 resulted in the second largest FRRN length, 305.3 km (189.7 mi). The removal of the Ottine Dam, which was 15 ft tall when it was built in 1911, occurred on the San Marcos River in the Guadalupe River Basin in 2016. This removal resulted in 1283 km (797.2 mi) of FRRN, 70.6% of the total FRRN.

The removal of the Patricio Lake, Ottine, and the Bolch Pond dams were responsible for 93.8% of the total FRRN. The average FRRN length was 36.3 km (22.6 mi), but the median was 0.2 km (0.12 mi), revealing the strongly skewed distribution driven by the Ottine Dam removal. Nine dams were rebuilt, and 15 dam removals did not occur on the river network, so 24 dam removals resulted in 0 km (0 mi) of FRRN (Figure 19). Of the dam removals that resulted in FRRN, the majority resulted in less than 10 km (6.2 mi; $n = 20$), and nine of these dams resulted in less than 1 km (0.62 mi) of FRRN (Figure 19). Additionally, the total amount of FRRN was likely overestimated as only documented dams were considered as river barriers in the study.

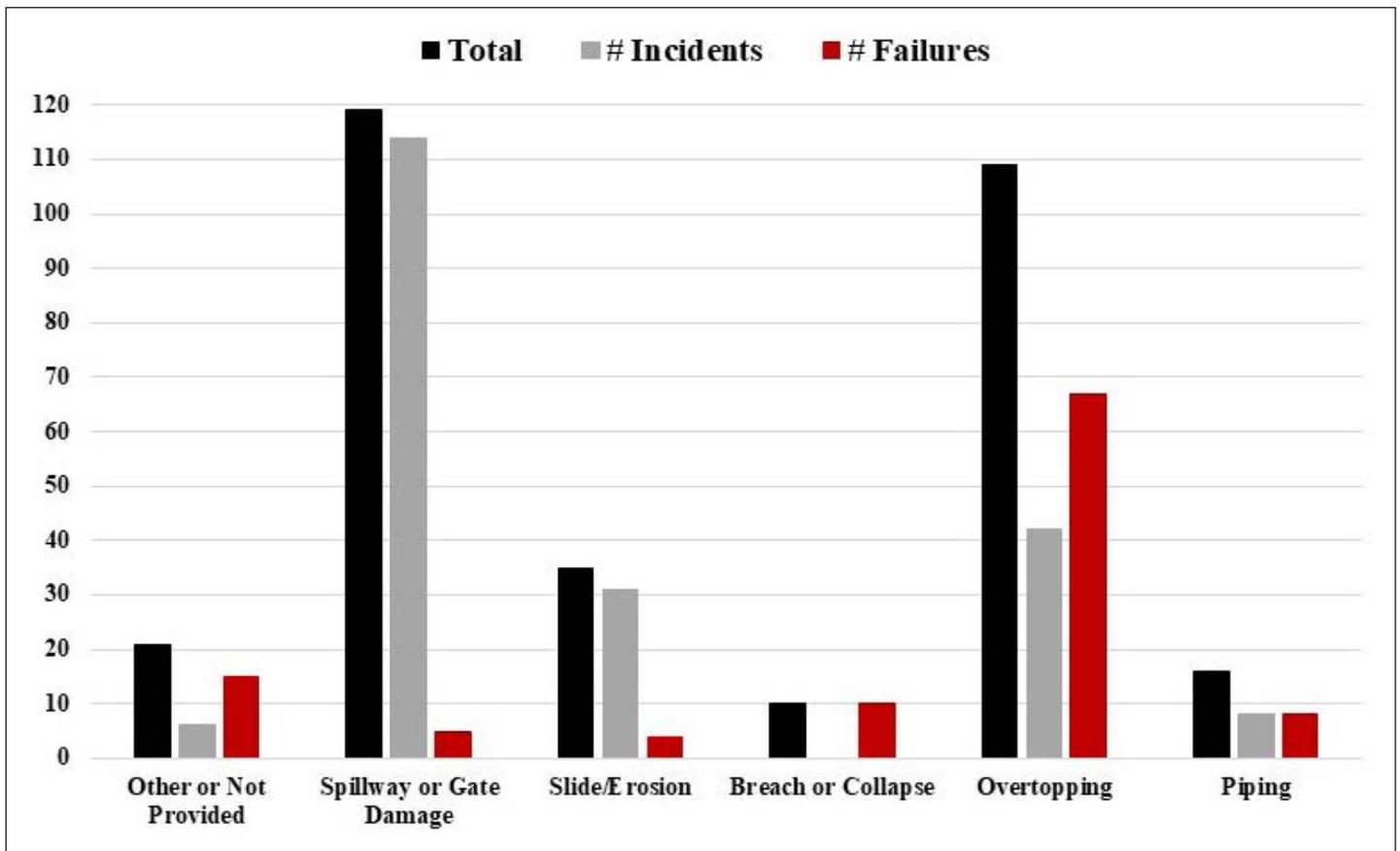


Figure 12. Dam incidents and failures (1900-2019) by mode of failure.

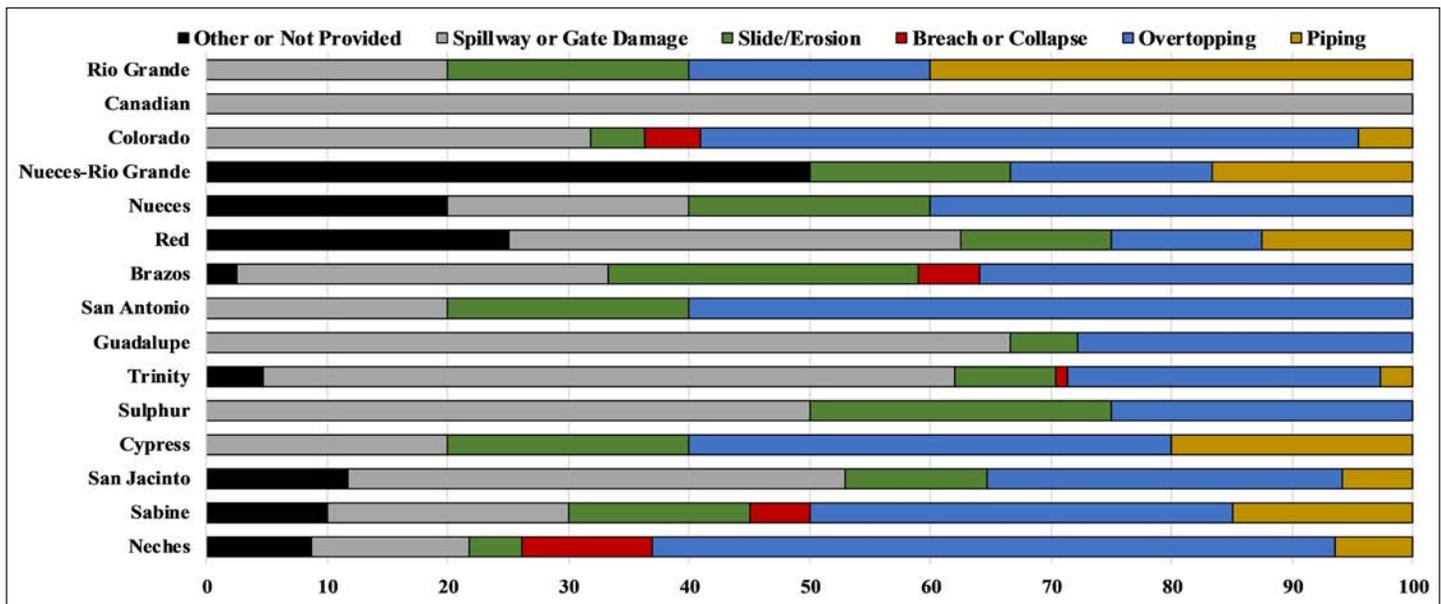


Figure 13. Mode of failure for dam incidents and failures (1900-2019) by major river basin.

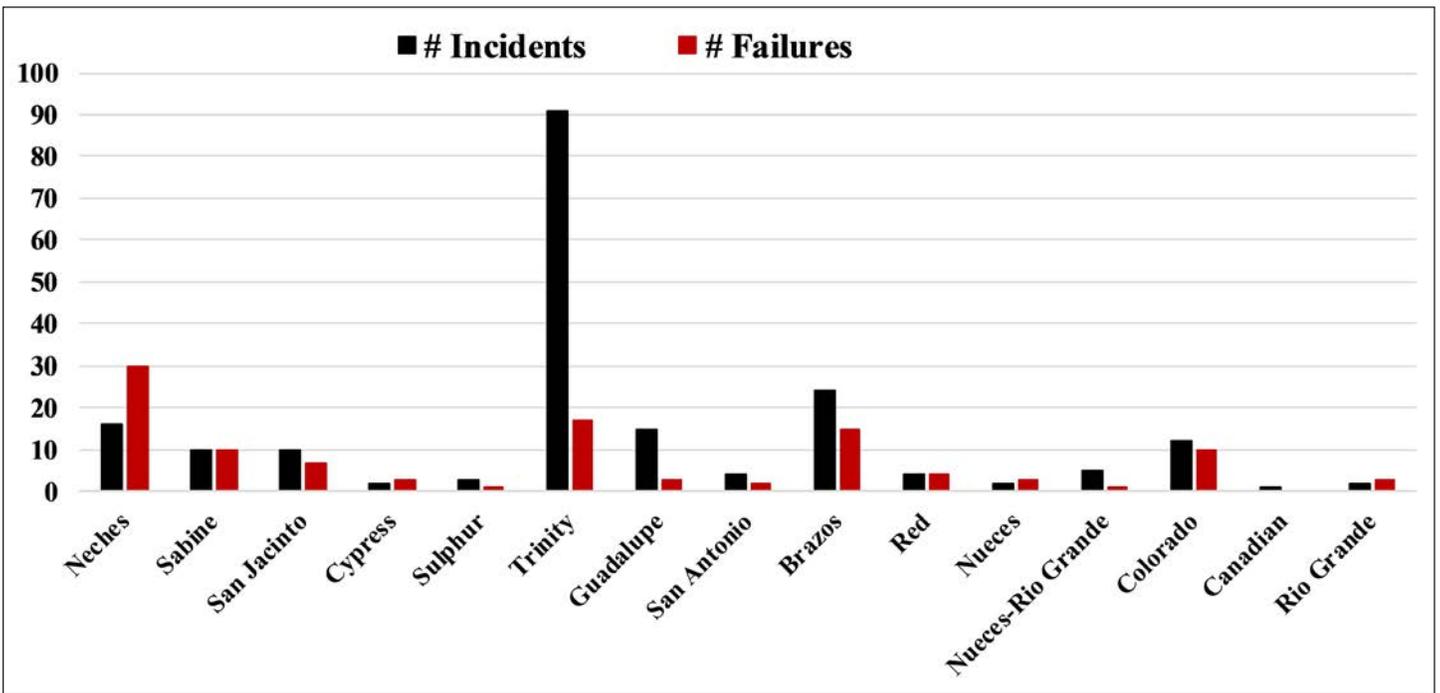


Figure 14. Number of dam incidents and failures (1900-2019) by major river basin.

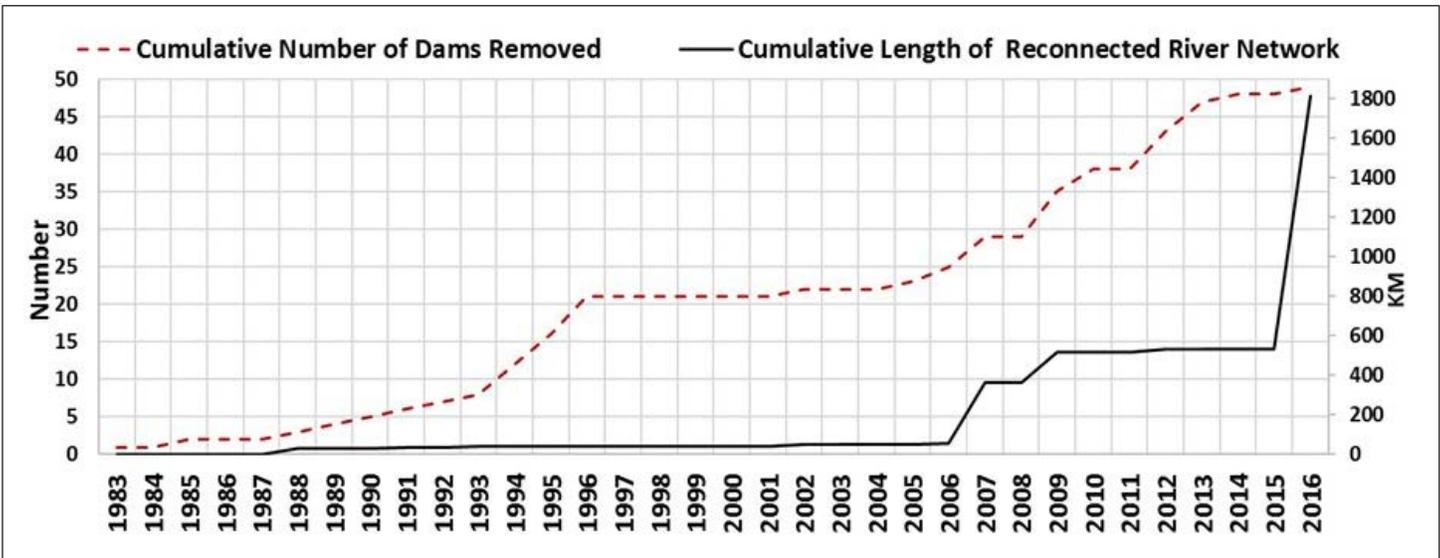


Figure 15. Cumulative number of dam removals in Texas and resulting functionally reconnected stream network (FRRN). [km, kilometer]

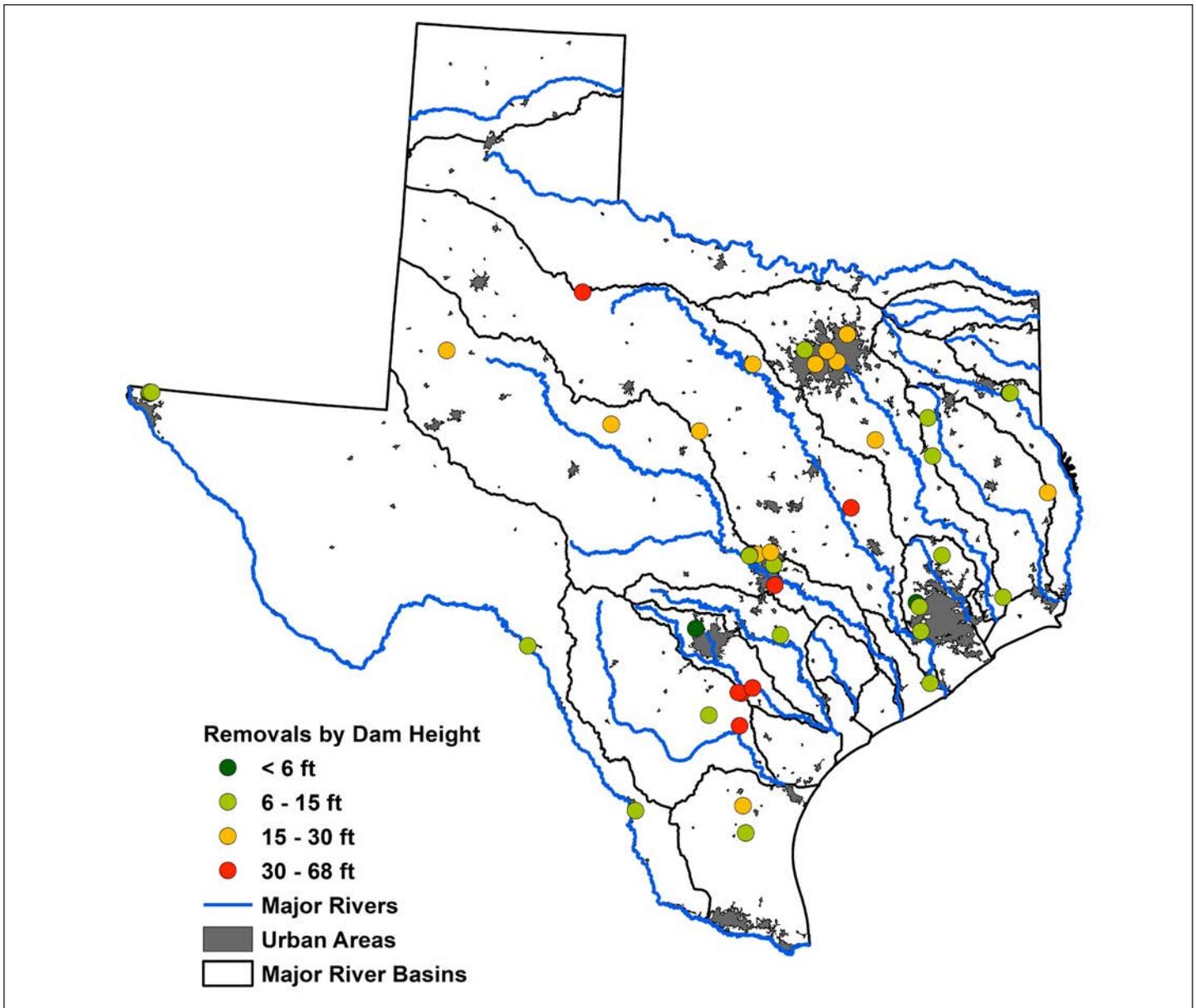


Figure 16. Dam removals (1983-2016) by location and height. [ft, feet]

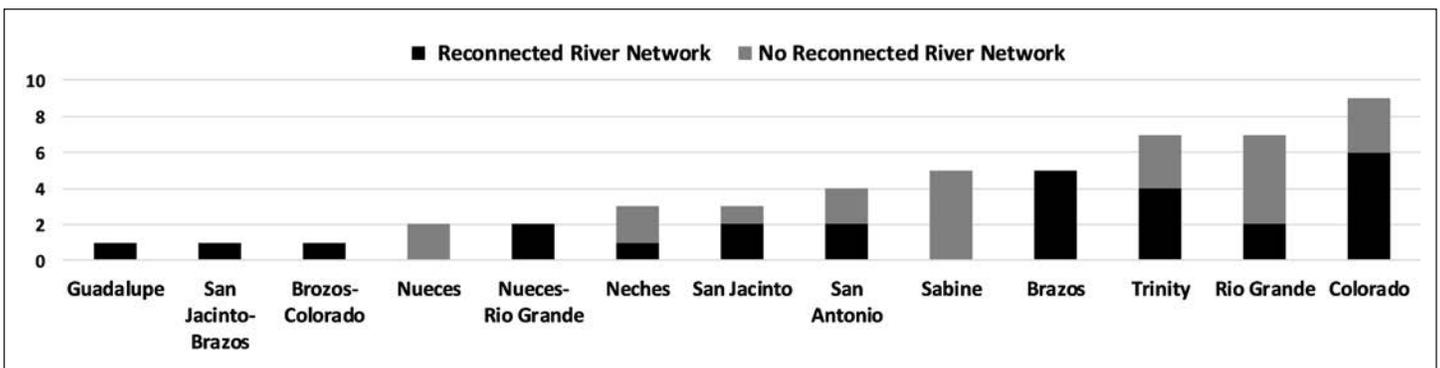


Figure 17. Number of dam removals (1983-2016) by major river basin.

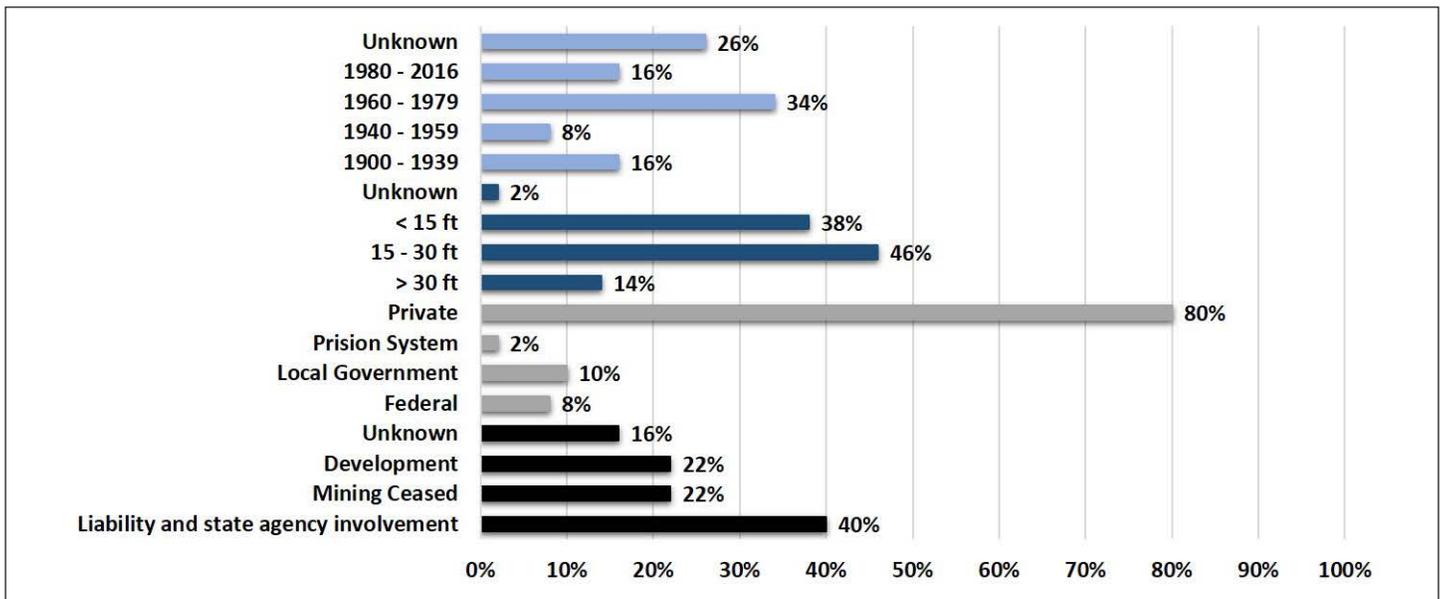


Figure 18. Percent of dam removals (1983-2016) by time period of completion (relative age), height, owner, and reason for removal. [ft, feet]

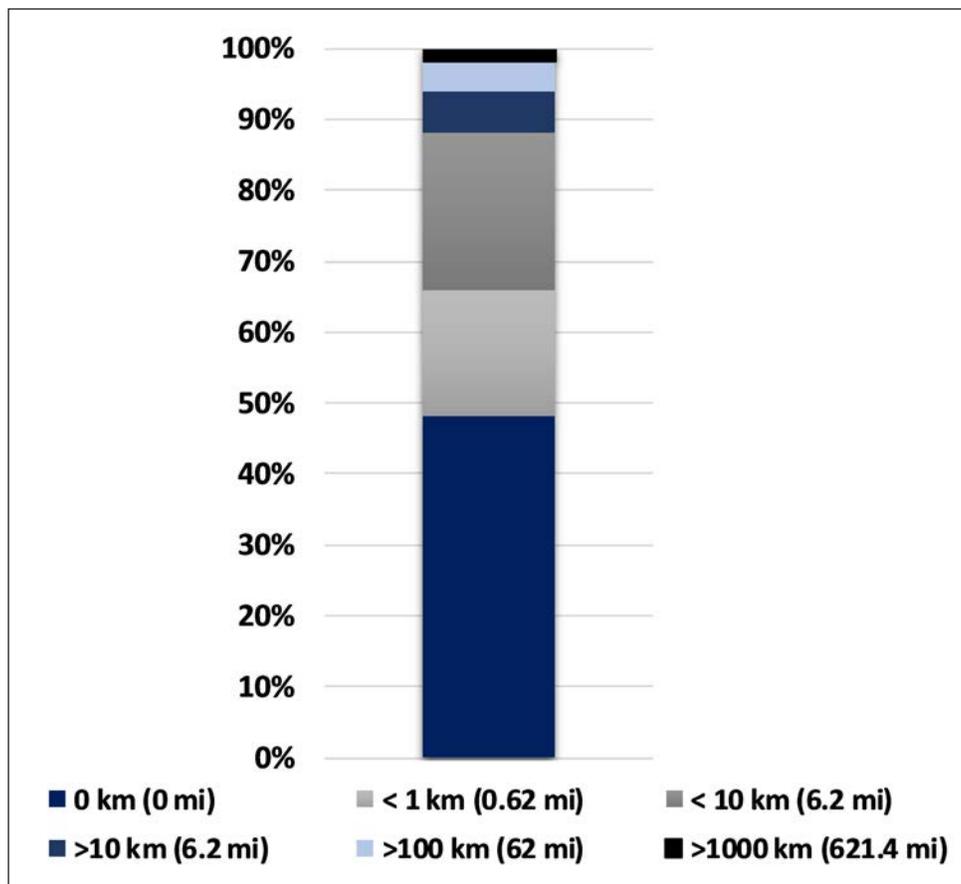


Figure 19. Number of dam removals (1983-2016) by resulting length of FRRN. [mi, miles; km, kilometers]

DISCUSSION

Compared to the 2005 NID data presented in Chin et al. (2008), the number of dams in Texas increased for all sizes except large dams. Chin et al. counts 212 large dams (Chin et al. 2008), while this analysis counts only 207. This decline in large dams was accounted for by differences in state and federal data recording. The NID included dikes and levees and used average reservoir storage to classify size. Since 2005 the total amount of reservoir storage increased for all dam sizes (Appendix 1), and small and medium dams continued to dominate by sheer numbers.

Climatic and geographic trends

As documented in previous studies, dam distribution is related to the climate gradient and location of urban centers in Texas (Chin et al. 2008; Graf 1999). Precipitation decreases and PET increases from east to west, and most of the dams in Texas occur in the wetter eastern portion of the state. Further, basins that receive 30 in (762 mm) or less of average annual precipitation have a larger percentage of dams, indicating the importance of irrigation demand to dam storage. Additionally, the Nueces River Basin has the highest PET, receives less than 30 in (762 mm) of water a year on average, and is the only river basin where the majority of dams are used for water supply. This may indicate the added importance of securing elusive water supplies in this west Texas river basin.

The Rio Grande Basin contains nearly 20% of Texas' land mass but less than 5% of its dams, and the majority of these dams occur in south Texas where irrigation is critical to the agriculture land use of the lower Rio Grande Valley region. The low number of dams compared to drainage area in this river basin is due to climate and international politics. The western part of the Rio Grande receives extremely low precipitation and is even characterized as the "Forgotten Reach" between El Paso and Presidio, because there are no major tributaries or surface flow draining into the mainstem (Sansom 2008). The waters of the Rio Grande are governed by international treaties mandated by the International Boundary Water and Commission (IBWC) and dam construction and management require complex international cooperation between the United States and Mexico. The IBWC manages the large and very large mainstem dams (e.g. American Dam, Amistad Dam, Falcon Dam, and Anzalduas Dam) for water supply, diversion to Mexico, flood control, and other uses, whereas many of the other small and medium dams are owned by other government organizations.

In contrast to the Rio Grande Basin, the Trinity River Basin has less than 7% of Texas' drainage area but has nearly a fourth of all Texas dams. Additionally, other governments own higher percentages of dams in the Trinity River Basin, and a much larger percentage of the dams are for flood control. These trends

are probably best explained by the eastern location of the Trinity River Basin, where there are relatively higher amounts of precipitation, and the presence of the Dallas-Fort Worth area with a population over 7 million people in the upper portion of the river basin (U.S. Census 2018).

The Colorado River Basin has the third highest numbers of dams with 776 total dams. As with the Trinity River Basin, other governments own higher percentages of dams, and a much larger percentage of dams are primarily for flood control, likely accounted for by the large urban areas and downstream agricultural communities located in the river basin. Nearly 350 dams were built in the Colorado Basin between 1960–1970, and 69 of those were constructed within the Austin city limits. The city of Austin's current population is nearly 1 million (U.S. Census 2019). Although this basin receives less than 30 in (762 mm) of precipitation a year, it occurs in one of the most flash flood prone areas in the United States according to the National Weather Service (NWS 2000). The increased chances for both floods and droughts, and the location of a large urban area within its boundaries demonstrates how both climate and population have led to increased numbers of dams in this river basin, especially with regard to the numerous small to medium-sized structures built for stormwater management and flood control.

An exception to the urban population trend within the Colorado Basin includes the six Highland Lakes dams and four other downstream dams owned by the Lower Colorado River Authority (LCRA) built between 1935 and 1951. Situated in the Hill Country characterized by high-relief bedrock incised limestone canyons, these dams were specifically constructed to capture large volumes of runoff, providing flood control, irrigation (to downstream coastal community rice farmers), municipal water supply, hydroelectric power, and recreation (Williams 2016). The safety provided by flood control, the increased reservoir storage for water supply, and the electricity revenue generated by the LCRA dams likely supported the increased population growth throughout the basin that led to the increased dam construction for stormwater and urban flood control in the later time periods. This increased population within the basin has ultimately led to intermittent conflict between the LCRA and the water-intensive rice farming industry over municipal water allocations. During a recent drought, the LCRA reduced water delivery to the coastal irrigation communities for 3 straight years, 2012–2014, to meet the municipal demand fueled by the growing Hill Country population. These conflicts highlight the changing social and political dynamics influencing dam purpose and management.

Texas has more dams than any other state (NID 2013–), and in a previous study, the Texas-Gulf water resource region had one of the highest ratios of storage capacity to drainage area (Graf 1999), further demonstrating the fragmented state of the Texas' rivers. The main hydrologic effect of medium and small

dams on river landscapes has been fragmentation ([Chin et al. 2008](#)), and 97% of the dams in Texas were small and medium. River fragmentation has led to declining fish and mussel populations ([Richter et al. 1997](#); [Wofford et al. 2005](#)) and altered migration routes ([Jager et al. 2001](#)).

The amount of storage established in the United States rapidly increased during 1950s through the 1970s, with only minor increases after 1980 ([Graf 1999](#)). Texas has a pronounced history of flooding and drought ([TWDB 2017](#)), and its river basins have been documented as having some of the highest runoff to storage ratios ([Graf 1999](#)). In Texas, very large dams accounted for the smallest number of dams, and unlike other size categories their temporal pattern of construction was not uniform across the different basins. A variety of factors likely influence this spatial variation including physiographic settings suitable for very large dams coupled with the amount of precipitation runoff available to store. The temporal variation in dam construction is partially due to the federal and state legislative politics linked to dam purpose, available capital, and the engineering required to build them. Rubinstein ([2015](#)) provides a detailed, though not comprehensive, timeline from 1900 — the contemporary period highlighting significant drought and flood events, federal and state legislative acts, and the historical evolution of Texas water management organizations and plans that have collectively contributed to the temporal variability of dam construction statewide. The time period when the bulk of storage is created in a basin is directly linked to when these very large reservoirs are built. This is particularly well demonstrated in the Red, Nueces, and Rio Grande river basins (Figure 4).

Recreation was the main listed purpose for dams built before 1900, most of which were small or medium dams. The shift in the purpose to flood control for dams built in the 1940s and 1950s is in part linked to federal funding through the New Deal programs and the Flood Control Act of 1936, which provided funding for river surveys and dam construction that occurred during the proceeding decade. Irrigation increased from slightly over 10% in the 1800s to nearly a fourth of all purposes for dams built during the mid-20th century. After this time period irrigation declined as a purpose, potentially exhibiting the increased agriculture in Texas during the 1800s and early 1900s, followed by the impact of the drought of record in the 1950s on the industry.

The 1960s and 1970s have often been referred to as the dam-building era in the United States, and the greatest national increase in dams occurred from the late 1950s to the late 1970s ([Graf 1999](#)). Similarly, in Texas, the majority of dams dated back to this time period. After 1980, the pace of dam construction slowed in the United States ([Graf 1999](#)), including in Texas. In addition, the small number of dams constructed post-1979 with water supply recorded as the purpose potentially reflects the increased scarcity of locations to build large water supply dams after this time period, as was also observed

nationwide ([Reisner 1986](#)). The vast abundance of Texas' dams provides numerous benefits to society and the economy, and as a result more reservoirs are still desired across the state, as evidenced by the 26 new major reservoirs designated by the TWDB to secure the state's future water supply and help mitigate drought impacts ([TWDB 2017](#)). These new dams will increase the fragmentation of Texas river systems and make it even harder to maintain a balance between the competing interest for human-related water uses and maintaining the ecological integrity of rivers, bays, and estuaries.

Dam failures in Texas

Both the number and rate of dam incidents and failures are increasing across Texas. Patterns of dam incidents appear related to patterns of dam occurrence. The majority of dams in Texas are medium dams built between 1960 and 1979, so it makes sense that the majority of incidents involve dams with these attributes. Similarly, nearly a quarter of all dams in Texas reside within the Trinity River Basin, and this is where the majority of dam incidents have occurred.

The majority of dams in Texas are small to medium privately owned dams that are either beyond or nearing the end of their usable lifespan ([Buchele 2013a](#)). Despite their small size, these dams can still pose a serious risk. After Hurricane Harvey made landfall in August of 2017, 20 dams across East Texas either failed or were damaged ([Sadasivam 2019](#)). Of these 20 dams, all were classified as small dams by the TCEQ, and 11 were exempt from state regulations due to their small size ([Sadasivam 2019](#)). Overtopping was the most common mode of failure, and this highlights the impacts of large precipitation events on the dam infrastructure in Texas. This trend is particularly concerning given the increased rainfall magnitude, frequency, and recurrence intervals predicted by the new NOAA Atlas 14 Volume 11 Precipitation-Frequency Atlas of the United States for Texas ([Perica et al. 2018](#)). In 2015, over half of all dam incidents/failures were the result of increased amounts of precipitation and flooding within the Trinity River Basin.

There was a flash flood warning issued for Johnson and Tarrant counties near Dallas-Fort Worth on May 30th, 2015 ([The Associated Press 2015](#)). In the proceeding weeks the Dallas area had already experienced over 16 in of rainfall, enough to break a 1982 record. This precipitation came on the heels of a severe drought throughout the state. Torrential downpours lead to flooding and loss of life and are the most likely cause of the 24 dam incidents/failures that were reported on the Trinity River Basin on May 30th, 2015. Similarly, December 2015 was the 13th wettest December on record for Texas ([NOAA 2016](#)), and on December 25th, 37 dam incidents/failures were reported in the Trinity River Basin. On the same day a large storm complex dubbed Winter Storm Goliath by the Weather Channel formed and began to move through parts of the Unit-

ed States, including Texas ([MacFarlane 2015](#), [Warren 2015](#)). There had been heavy snow and flooding from a storm the weekend before in the Dallas area ([Warren 2015](#)), and several tornadoes touched down during Winter Storm Goliath in the same area ([MacFarlane 2015](#)).

While heavy rains can lead to dam failure, as seen with the clusters of dam incidents and failures in 2015 and more recently during Hurricane Harvey, prolonged drought followed by severe flooding also contributes to the deteriorating condition of dams. Over 95% of dams in Texas are earthen dams ([NID 2013](#)), meaning they are particularly susceptible to cracking during dry conditions ([Marks 2013](#)). Once damaged, a dam is more likely to fail or experience problems during a rain event, as the water can potentially increase the size of existing cracks and places more pressure on the damaged dam by increasing the amount of water it must retain ([Marks 2013](#)). This unique cycle of extended dry periods punctuated by torrential rains and/or flash floods is particularly relevant to the Flash Flood Alley that runs along Interstate-35 with the Balcones Fault Zone to the west and the Blackland Prairie to the east. This corridor collectively encompasses multiple major urban areas, including Dallas, Austin, and San Antonio, where these drying/wetting cycles of natural land surfaces and earthen dams may exacerbate the issue of Texas' aging dam infrastructure.

The likelihood of a dam incident or failure is related to dam age. A larger percentage of dams built between 1900 through 1939 have had an incident or have failed compared to dams built during more recent time periods. Older antiquated engineering styles are often more difficult to maintain and pose greater failure risks, as has been the case with a series of six dams on the Lower Guadalupe River, all of which are greater than 90 years old and have exceeded their useful life capacity. Two of the six dams experienced spill gate failures and partial lake draining, Lake Wood in 2016 and Lake Dunlap in 2019, with the remaining four dams expected to follow a similar fate ([Black & Veatch 2019](#)). Though neither the Lake Wood or Lake Dunlap dam incidents met the TCEQ classification of a dam failure, they were portrayed as such in the media, and their very publicized damage sparked a highly controversial debate on what entity is responsible for the hazard liability, maintenance, and repair of aging dam infrastructure and who ultimately benefits from the dams. The six dams, owned and managed by the Guadalupe-Blanco River Authority (GBRA), are primarily recreational and serve as pass-by structures for downstream water supply. They do not provide flood control and are admittedly generating hydroelectric power at an "unsustainable deficit" ([GBRA n.d.](#)).

Following the incident with Lake Dunlap and the subsequent publication of the Black & Veatch ([2019](#)) engineering report, GBRA made the decision to dewater all six reservoirs to reduce the risk of a future failure. This action was halted by a temporary injunction issued in favor of the lakefront prop-

erty owners, motivated by aesthetics and property values, who did not want the lakes drained. This same group of plaintiffs initiated litigation with the GBRA challenging the organization's expenditures with the goal to require them to burden the majority costs of repairing or replacing the six dams. Although public access to the lakes is limited, the lakeside property tax base benefits the county school districts and is at risk of reduction if the lakes are drained or the dams are removed. As of June 2020, stakeholders formed three new WCIDs, the Lake Dunlap WCID, Lake McQueeney WCID, and Lake Placid WCID, to provide a financing and planning process for replacing the dams. The Lower Guadalupe Valley Lakes case study highlights the social, institutional, and economic challenges of managing dam infrastructure for very different stakeholders and purposes.

A study of flood fatalities across the United States reported 309 fatalities associated with nine structural failures, constituting 12% of the flood fatalities in the United States between 1959 and 2005 ([Ashley and Ashley 2008](#)). A 2015 review of flood fatalities in Texas found that no deaths were due to structural failures between 1959 and 2008 ([Sharif et al. 2015](#)). However, a 2018 study reported that four dam failures in Texas had resulted in at least one fatality ([McCann 2018](#)). The 2013 Texas law that exempts a large number of dams from safety regulations could prevent awareness of hazard risks in many rural areas experiencing rapid population growth and development. As dams continue to fail across the state and the population continues to grow, there is a serious and increasing potential for loss of life.

In addition to loss of life, dam failure can lead to possible toxic pollutant releases downstream as exhibited by recent dam failures in Michigan. On March 20th, 2020, the Edenville and Sanford dams on the Tittabawassee River in Midland County, Michigan failed due to rapidly rising water. The failure resulted in the evacuation of 10,000 people, massive flooding ([Holden 2020a](#)), and fears that a containment system for contaminated soil at a Dow Chemical superfund site might breach and distribute toxic soil through the community ([Holden 2020b](#)). The Edenville Dam was a hydropower dam with a high hazard potential rating ([Holden 2020a](#)) built in 1924 and owned by Boyce Hydro ([CBS/AP 2020](#)). The Federal Energy Regulatory Commission revoked the dam's license in 2018 due to issues of noncompliance, particularly related to the dam's spillway capacity, and cited a long history of noncompliance ([CBS/AP 2020](#)). After its federal license was revoked, the Edenville Dam was regulated by the state and received a rating of unsatisfactory in 2018 ([CBS/AP 2020](#); [Holden 2020a](#)). The Edenville Dam failure serves as a canary in the coal mine example of the hazards posed to downstream communities from aging dams in disrepair and noncompliance and should serve as a warning for future disasters.

Dam failure is not the only risk that outdated dams pose to human life and well-being. There have been 555 fatalities at 276 low-head dams throughout the United States since the 1950s (Kern et al. 2015), 19 of which occurred in Texas between 1995 and 2016 (Kern et al. 2015). Low-head dams generally result in fatalities when someone goes over top of the dam and becomes trapped in the submerged jump the dams create (Wright et al. 1995; Elverum and Smalley 2012; Kern et al. 2015). River users are often unaware of the hazard these dams present (Tschantz and Wright 2011), and older structures may often go unregulated (Kern 2014). Removal of low-head dams that pose a threat to human life can help make Texas' waterways safer for recreationists and other river users.

There are 29 dams that have had two or more instances of either an incident or failure reported to the TCEQ. This may be evidence that after a reported incident/failure some dams may not be fully or adequately repaired, leading to future instances of damage. In 2013, StateImpact Texas ran a three-part series investigating the conditions of Texas' dam infrastructure (Buchele 2013a, 2013b, 2013c). The series highlighted the number of dams in bad condition and the lack of available funds (Buchele 2013a), how a large number of dams go undocumented or unregulated due to state legislation (Buchele 2013b), and the lack of transparency regarding dam hazard classifications (Buchele 2013c). Between 2012 and 2017, 217 dams received higher hazard classifications, and eight dam failures, one partial dam failure, and 108 additional incidents including damaged spillways, slides, and pipe failures occurred across the state (ASCE 2017). The cost to rehabilitate Texas' dam infrastructure has also risen to over an estimated \$800 million in 2017 (ASCE 2017), yet this amount is likely an underestimate given the low numbers of dam failures included in their report. The GBRA has already spent \$25 million to date on maintenance repairs to the six aging dams in the lower Guadalupe Valley lakes system, with the full cost of repairs currently unknown. A recent partnership between GBRA and Preserve Lake Dunlap Association have agreed to share the costs for at least one of the dam-reservoir complexes (GBRA n.d.).

An even larger high-risk dam, such as the Lewisville Dam (Trinity Basin, upstream of Dallas metropolitan area) with its variety of problems, including seepage, sand boils, and embankment instability, warrants costly repairs due to its importance for water supply and flood control (Getschow 2015). In response to catastrophic failure warnings in 2015, the Fort Worth District USACE created the Lewisville Dam Safety Modification project with a full cost of \$150 million to be funded by multiple stakeholders (Scruggs 2019). As of 2019, only \$39.1 million has been allocated to the initial phases of hard and soft engineering related to dam repairs and flood mitigation projects (Scruggs 2019). The Lewisville Dam serves multiple purposes, in contrast to the example of Lake Dunlap dam on the Guadalupe River, which is managed primarily for

recreation, and the two dams have very different stakeholder groups. However, they share a similar discourse regarding uncertainty around what organization should be accountable for their repair, maintenance, and liability in the event of a failure. It can be expected for these contentious proceedings to increase in frequency as more large dams face imminent failure risks.

The discrepancies in defining dam failures and incidents highlights the need to standardized terms or at the very least to clearly demarcate how such distinctions are made at different institutional levels. A preliminary inquiry by the authors into how such terms were defined by reporting agencies other than the TCEQ yielded no new insights beyond the definitions already provided on websites or within existing publications. These definitions were not sufficient to determine which cases of failure versus incidents were being counted compared to those listed by the TCEQ.

The TWDB is the regulatory authority charged with administering the Texas state water plan planning process and preparing and adopting it every 5 years (TWDB 2017). In 2019 the governor and state legislature expanded the TWDB's role in flood planning and financing (TWDB 2019). The TWDB will now be responsible for the state and regional flood planning process; the first state flood plan is due to be completed by September 2024 (TWDB 2019). To support this new endeavor, the legislature transferred \$793 million from the rainy day fund to the TWDB for the creation of a new flood funding program (TWDB 2019). Before 2019, there was no unified flood plan for Texas, and existing flood programs consisted of grant programs for flood protection and mitigation and federal insurance programs (TWDB 2019). Considering the relationship between dam incidents/failures and flooding in Texas, it would seem prudent that future flood plans include evaluations of and recommendations for managing Texas' dam infrastructure, particularly in terms of aging and damaged dams. While only a small number of dams built in the 1800s have failed, a third of all failed dams have unknown years of completion. It is possible that many these dams also represent older structures at a greater risk of failure, and their removal could be a priority for hazard mitigation.

Dam removals in Texas

In the Trinity and Colorado river basins, dam removals appear to be grouped around major cities, such as Austin and the Dallas-Fort Worth Area (Figure 11), and dam removals after 2002 (Figure 15) were motivated by liability and development issues, according to the records received from the TCEQ (Dam Removals 1983–). While the authors do not have the specific details for each dam removal with this reasoning, they may reflect increasing population growth in these areas associated with increased land values. Removing dams for develop-

ment purposes may signify land use change in these areas, such as agricultural to urban land use. Additionally, as urbanization continues in these areas, older, damaged dams may become increasingly dangerous with increased population downstream, and this increased liability may be a catalyst to dam removal in these areas.

Other clusters of dam removals, such as those in the Sabine River and Rio Grande basins, were the result of ceased industrial operations where multiple dams were removed together. Dam removals that resulted in 0 km (0 mi) of FRRN were mostly industrial use ponds. These industrial use ponds were connected to the river network through artificial canals, and when the ponds were no longer needed, both the ponds and canals were removed.

Dam removals in Texas generally follow national dam removal trends, with the majority of removals involving smaller, older structures ([Graf et al. 2002](#); [Stanley and Doyle 2003](#); [Bellmore et al. 2017](#)). Most of the dams in Texas are smaller, privately owned structures built before 1980. These patterns indicate a potentially considerable number of outdated structures that likely require expensive upkeep or repairs. Such dams are prime candidates for removal ([Graf et al. 2002](#); [Stanley and Doyle 2003](#)). Additionally, removing these structures involves working with private individuals as opposed to coordinating with multiple stakeholders.

It has been suggested that a deterrent to private owners removing dams in Texas is the lengthy permitting process ([Hershaw 2011](#)). Potentially, a dam owner is responsible for obtaining multiple permits before removal can begin ([TCEQ 2006](#)), but according to the manager of the Dam Safety Program, the permitting process is in reality fairly simple ([Hershaw 2011](#)). While the Dam Safety Program recommends multiple permits, there are no penalties for removing a private dam without them ([TCEQ 2006](#); [Hershaw 2011](#)). Additionally, if a dam owner wants permission to remove a dam, all they have to do is provide the Dam Safety Program with the dam's engineering plans ([Hershaw 2011](#)). However, some owners may not have these plans, and the appearance of a cumbersome permitting process may still prevent private dam owners from proceeding with removal. The permitting process should be streamlined where possible and provide additional resources and outreach about the removal process to the public to eliminate the permitting process' perceived barrier to dam removal in Texas.

While larger dams such as those at Lake Lewisville and Lake Dunlap have multiple interest groups lobbying for their repairs, many smaller aging and damaged dams exist that no longer serve their original purposes yet pose risks to downstream communities and continue to fragment rivers. For these derelict dams, removal may provide a more cost-efficient solution.

Online decision support tools such as the Southeast Aquatic Barrier Prioritization Tool managed by the Southeast Aquatic Resource Partnership (SARP) provide a user-friendly platform to view dam inventories for a select set of basins and prioritize dam removals using a set of metrics related to increasing the amount of functionally connected river networks ([SARP 2019](#)). SARP's dam removal prioritization tool currently includes all 215 documented dams in the Guadalupe Basin and an additional inventory consisting of numerous smaller dams in the upper portion of the basin that do not meet criteria for federal or state documentation.

In addition to removing damaged and potentially hazardous dams from Texas waterways, dam removal provides a way to restore riverine habitat for Texas' aquatic species. In particular, freshwater mussels have been receiving increased attention in Texas due to concerns over their conservation status ([Randklev et al. 2010](#); [Winemiller et al. 2010](#); [Burlakova et al. 2011a, 2011b](#); [Karatayev et al. 2012](#); [Randklev et al. 2013a, 2013b](#); [Karatayev et al. 2018](#); [Dascher et al. 2018](#)). There are approximately 50 known species of mussels that inhabit Texas ([Howells et al. 1996](#)). In addition, three new species of freshwater mussels were recently described, including the Guadalupe Fatmucket ([Inoue et al. 2019](#)) and the Guadalupe Orb ([Burlakova et al. 2018](#)), both endemic to the Guadalupe River Basin, and the Brazos Heelsplitter ([Smith et al. 2019](#)) in the Brazos River Basin. Currently 15 mussel species are listed as state-threatened in Texas. Of these, five are currently candidates for federal listing and one, the Texas Hornshell, was recently listed as federally endangered ([FWS 2018](#)). Due to the importance of fish hosts in the life cycle of freshwater mussels, the positive response of fish to dam removal may result in an increase of native mussels ([Gottgens 2009](#)). Dam removal is a potential tool for restoring freshwater mussel habitat and conserving these imperiled species, but to date no dam has been removed solely or primarily for ecological concerns in Texas.

The Ottine Dam was over 100 years old, damaged, and no longer performing its intended purpose ([Montagne and Jobs 2016](#)). The removal of this dam reconnected over 1000 km (621.4 mi) of river and is a powerful example of the ability of dam removals to restore river connectivity. However, most of the dam removals in Texas resulted in less than 1 km (0.62 mi) of FRRN. Three dam removals accounted for nearly 90% of the total FRRN: the Ottine Dam removed from the Guadalupe Basin in 2016, the Bolch Pond Dam removed from the Colorado Basin in 2009, and the Patricio Lake Dam removed from the Nueces-Rio Grande Basin in 2007. All three dams were removed with state agency involvement to eliminate liability issues. These results highlight the isolated and opportunistic nature of most dam removals ([Bellmore et al. 2017](#);

[Magilligan et al. 2016](#)) and further support the need for more strategic planning and management of dam removals ([Magilligan et al. 2016](#)).

Previous studies have called for more reliable record keeping and communication between organizations regarding dam removals ([Graf et al. 2002](#); [Bellmore et al. 2017](#)). American Rivers (2016) only lists seven dam removals for Texas, as opposed to the 49 recorded by the TCEQ, not including the Ottine Dam. These additional removals potentially make Texas sixth in the nation for number of dams removed, but other states likely also have undocumented dam removals and thus underrepresented totals. Because permits are required to remove a dam, there is already a mechanism in place for obtaining data on dam removal. This data, however, unless voluntarily reported to American Rivers, is not collected or maintained in a national database.

A congressionally authorized national inventory of dam removals that assigns formal responsibility to a single agency, similar to the National Inventory of Dams maintained by the USACE, has previously been recommended ([Graf et al. 2002](#)). Such a national inventory would provide a way to reliably maintain and organize data about dam removals and would standardize record keeping and data reporting.

The USGS maintains the USGS Dam Removal Science Database ([USGS 2018-](#)). The USGS Dam Removal Science Database is a collection of empirical monitoring data from 214 publications for 181 dam removals worldwide ([USGS 2018-](#)). This data has been combined with the American Rivers Dam Removal Database, which is updated on a regular basis, to create an online database tool, the USGS Dam Removal Information Portal (DRIP; [Bellmore et al. 2017](#); [Duda et al. 2016](#); [DRIP 2016-](#); [ARDRD 2019](#)). Thus, the USGS would be a reasonable choice to maintain a national inventory of dam removals.

CONCLUSIONS

Currently, dam removals in Texas appear to occur as isolated incidents. Broad-scale prioritization models would allow for dam removals to be planned more strategically in terms of providing safety, ecological, and economic benefits and in terms of securing funding for these projects. There is an emerging body of research on dam removal prioritization ([McKay et al. 2017](#)), particularly at the regional and watershed scale ([Kuby et al. 2005](#); [Mader and Maier 2008](#); [Martin and Apse 2011](#); [Martin and Apse 2013](#); [Benner et al. 2014](#); [Hoenke et al. 2014](#); [Martin 2018](#)). Texas has an opportunity to develop regional or river basin-scale prioritization models based on maintaining

important water resource infrastructure while removing hazardous dams and restoring stream habitat. Such models should be developed so that their results are easily interpretable and can act as decision support tools to help inform the complex decision making behind dam removal ([McKay et al. 2017](#)).

Developing such models requires a need for standardized and expanded datasets of dams and other instream barriers ([McKay et al. 2017](#)). State and federal datasets should be better coordinated so there is less discrepancy between the reported data. Additionally, there are a vast number of undocumented smaller dams in Texas ([Chin et al. 2008](#)), and efforts should be made to catalogue these dams to address both issues of liability and ecological restoration.

The utilitarian services provided by dams yield substantial benefits to society, most notably in Texas through flood control and water supply. Texas supports an immense dam infrastructure with plans to expand the number of major reservoirs, as evidenced by the continued recommendation of new dams in the Texas state water plan and the progression of at least a few of these projects. Although the analyses presented here focused only on dams that meet state regulatory criteria, a critical management question needs to be addressed regarding the persistence of the thousands of smaller undocumented dams that are no longer serving their original purpose and become hazardous as they age. The authors recommend a statewide inventory of the location, size, purpose, and condition of these undocumented structures. Many of these undocumented dams, along with many of the documented dams, may be good candidates for removal to help mitigate the hazard liability and ecological impacts of the abundant state-documented dams and future dam projects. Dam removal is a viable option for addressing human safety concerns and restoring rivers and should be given equal consideration when making decisions to repair dams and construct new dams.

NOTES

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APPENDIXES

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3. Table A3. Number of dams per time period sorted by size classification.
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Table A1. Texas dam owner crosswalk. For instances where there are two or more owner organizations for a single dam, if the owner organizations are dissimilar these were included in the "Other" aggregation group.

Original owner organization	Aggregation group
City government	Other government
Corporation	Private
County government	Other government
Federal government	Federal government
Individual owner type	Private
Local government	Other government
Organization	Private
Other	Other
Other government	Other government
Partnership	Other
Sole proprietorship	Other
State government	State government
Trust	Other
Multiple owners - dissimilar	Other
<<null>>	Not listed

Table A2. Number of dams and total reservoirs storage sorted by size classification

	Number of dams	% Dams	Total reservoir storage (million acre-feet)	% Total storage
*Texas (2005)	7053		94.20	
Small	1368	19.4	0.090	0.1
Medium	5446	77.2	5.60	5.9
Large	212	3.0	29.6	31.4
Very large	27	0.4	58.9	62.5
Texas (2014)	7274		104.30	
Small	1452	20	0.111	0.1
Medium	5586	76.8	6.92	5.4
Large	207	2.8	32.3	25.1
Very large	29	0.4	89.3	69.4
Trinity	1787		17.00	
Small	323	1.8	0.02	0.1
Medium	1426	79.8	1.62	7.7
Large	33	1.8	7.90	37.7
Very large	5	0.3	114	54.5
Brazos	1391		14.80	
Small	267	19.2	0.02	0.1
Medium	1072	77.1	1.1	7.4
Large	47	3.4	6.30	42.6
Very large	5	0.4	7.40	50.0
Colorado	776		12.20	
Small	144	18.6	0.008	0.1
Medium	600	77.3	0.9	7.4
Large	27	3.5	3.60	29.5
Very large	5	0.6	7.70	63.1
Red	619		12.50	
Small	147	23.7	0.01	0.1
Medium	449	72.5	0.40	3.2
Large	21	3.4	2.40	19.2
Very large	2	0.3	9.7	77.6
Nueces	456		1.80	
Small	87	19.1	0.01	0.3
Medium	364	79.8	0.20	11.1
Large	4	0.9	0.60	33.3
Very large	1	0.2	1.10	61.1

	Number of dams	% Dams	Total reservoir storage (million acre-feet)	% Total storage
Sabine	335		8.80	
Small	82	24.5	0.005	0.1
Medium	241	71.9	0.20	2.3
Large	9	2.7	0.60	6.8
Very large	3	0.9	8.00	90.9
Rio Grande	329		10.90	
Small	49	14.9	0.003	0.03
Medium	266	80.9	0.40	3.67
Large	12	3.6	0.70	6.42
Very large	2	0.6	9.70	88.99
Neches	308		8.60	
Small	67	21.7	0.004	0.05
Medium	229	74.4	0.20	2.3
Large	10	3.3	0.90	10.5
Very large	2	0.6	7.60	88.4
Guadalupe	215		1.60	
Small	56	26	0.003	0.2
Medium	152	70.7	0.20	12.5
Large	6	2.8	0.20	12.5
Very large	1	0.5	1.100	68.8
San Antonio	160		0.70	
Small	30	18.8	0.002	0.3
Medium	125	78.1	0.20	28.6
Large	5	3.1	0.50	71.4
Very large	0	0	0	0.0

*Note: Values for Texas (2005) are from Chin et al. 2008.

The total reservoir storages was converted from cubic meters reported in Chin et al. 2008, Tabel 3, p.245.

Table A3. Number of dams per time period sorted by size classification.

	1800–1899		1900–1939		1940–1959		1960–1979		1980–2014	
	N	%	N	%	N	%	N	%	N	%
Texas										
Small	146	50.0	63	12.2	180	13.0	774	18.6	219	26.9
Medium	143	49.9	415	80.1	1134	82.1	3296	79.3	556	68.4
Large	3	0.1	37	7.1	59	4.3	72	1.7	34	4.2
Very large	0	0.0	3	0.6	9	0.7	12	0.3	5	0.6
Total	292	100.0	518	100.0	1382	100.0	4154	100.0	814	100.1
Trinity										
Small	35	60.3	9	13.0	25	6.8	177	16.4	63	33.9
Medium	22	37.9	52	75.4	332	90.2	893	82.7	115	61.8
Large	1	1.7	8	11.6	10	2.7	8	0.7	6	3.2
Very large	0	0.0	0	0.0	1	0.3	2	0.2	2	1.1
Total	58	100.0	69	100.0	368	100.0	1080	100.0	186	100.0
Brazos										
Small	24	47.1	8	8.2	28	13.1	168	20.2	31	16.9
Medium	27	52.9	81	82.7	172	80.4	644	77.3	145	79.2
Large	0	0.0	9	9.2	11	5.1	19	2.3	7	3.8
Very large	0	0.0	0	0.0	3	1.4	2	0.2	0	0.0
Total	51	100.0	98	100.0	214	100.0	833	100.0	183	100.0
Colorado										
Small	16	57.1	11	18.0	13	9.2	71	15.3	19	29.2
Medium	12	42.9	45	73.8	116	82.3	383	82.7	40	61.5
Large	0	0.0	3	4.9	11	7.8	8	1.7	5	7.7
Very large	0	0.0	2	3.3	1	0.7	1	0.2	1	1.5
Total	28	100.0	61	100.0	141	100.0	463	100.0	65	100.0
Red										
Small	4	66.7	6	11.5	17	21.8	100	24.8	19	24.7
Medium	2	33.3	38	73.1	57	73.1	293	72.7	57	74.0
Large	0	0.0	7	13.5	3	3.8	10	2.5	1	1.3
Very large	0	0.0	1	1.9	1	1.3	0	0.0	0	0.0
Total	6	100.0	52	100.0	78	100.0	403	100.0	77	100.0
Nueces										
Small	4	23.5	2	9.5	19	21.4	51	16.7	1	8.3
Medium	13	76.5	19	90.5	67	75.3	255	83.3	9	75.0
Large	0	0.0	0	0.0	3	3.3	0	0.0	1	8.3
Very large	0	0.0	0	0.0	0	0.0	0	0.0	1	8.3
Total	17	100.0	21	100.0	89	100.0	306	100.0	12	100.0

	1800–1899		1900–1939		1940–1959		1960–1979		1980–2014	
	N	%	N	%	N	%	N	%	N	%
Sabine										
Small	8	50.0	5	11.1	29	29.3	18	15.0	13	36.1
Medium	8	50.0	40	88.9	67	67.7	95	79.2	21	58.3
Large	0	0.0	0	0.0	3	3.0	5	4.2	1	2.8
Very large	0	0.0	0	0.0	0	0.0	2	1.7	1	2.8
Total	16	100.0	45	100.0	99	100.0	120	100.0	36	100.0
Rio Grande										
Small	14	46.7	3	7.9	4	7.5	22	13.2	5	12.5
Medium	16	53.3	33	86.8	44	83.0	141	84.4	32	80.0
Large	0	0.0	2	5.3	4	7.5	3	1.8	3	7.5
Very large	0	0.0	0	0.0	1	1.9	1	0.6	0	0.0
Total	30	100.0	38	100.0	53	100.0	167	100.0	40	100.0
Neches										
Small	12	60.0	6	14.0	12	13.3	24	7.8	12	35.3
Medium	8	40.0	37	86.0	74	82.2	84	27.5	21	61.8
Large	0	0.0	0	0.0	4	4.4	5	1.6	1	2.9
Very large	0	0.0	0	0.0	0	0.0	2	0.7	0	0.0
Total	20	100.0	43	100.0	90	100.0	306	100.0	34	100.0
Guadalupe										
Small	12	57.0	3	23.1	6	28.6	23	17.7	7	29.2
Medium	9	43.0	7	53.8	15	71.4	106	81.5	14	58.3
Large	0	0.0	3	23.1	0	0.0	0	0.0	3	12.5
Very large	0	0.0	0	0.0	0	0.0	1	0.8	0	0.0
Total	21	100.0	13	100.0	21	100.0	130	100.0	24	100.0
San Antonio										
Small	9	81.8	2	25.0	4	10.8	11	13.9	3	13.6
Medium	2	18.2	4	50.0	33	89.2	65	82.3	19	86.4
Large	0	0.0	2	25.0	0	0.0	3	3.8	0	0.0
Very large	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Total	11	100.0	8	100.0	37	100.0	79	100.0	22	100.0

*Note: Dams with out year complete were omitted.

Table A4. Number of dams in each size classification sorted by ownership.

	Small		Medium		Large		Very large		Total	
	N	%	N	%	N	%	N	%	N	%
Texas										
Federal	22	1.5	49	0.9	26	12.3	16	55.2	113	1.6
State	9	0.6	49	0.9	9	4.3	2	6.9	65	0.9
Other government	185	12.7	2039	36.5	125	59.2	10	34.5	2359	32.4
Private	1146	78.9	3072	55.0	44	20.9	1	3.4	4263	58.6
Other	45	3.1	347	6.2	7	3.3	0	0.0	399	5.5
Not listed	45	3.1	30	0.5	0	0.0	0	0.0	75	1.0
Trinity										
Federal	1	0.3	2	0.1	7	21.2	2	40.0	12	0.7
State	1	0.3	25	1.8	3	9.1	2	40.0	31	1.7
Other government	82	25.4	872	61.2	15	45.5	1	20.0	970	54.3
Private	221	68.4	420	29.5	7	21.2	0	0.0	648	36.3
Other	12	3.7	99	6.9	1	3.0	0	0.0	112	6.3
Not listed	6	1.9	8	0.6	0	0.0	0	0.0	14	0.8
Brazos										
Federal	16	6.0	25	2.3	5	10.6	4	80.0	50	3.6
State	2	0.7	7	0.7	1	2.1	0	0.0	10	0.7
Other government	24	9.0	329	30.7	28	59.6	1	20.0	382	27.5
Private	212	79.4	636	59.3	10	21.3	0	0.0	858	61.7
Other	6	2.2	72	6.7	3	6.4	0	0.0	81	5.8
Not listed	7	2.6	3	0.3	0	0.0	0	0.0	10	0.7
Colorado										
Federal	3	2.1	2	0.3	2	7.4	1	20.0	8	1.0
State	0	0.0	3	0.5	0	0.0	0	0.0	3	0.4
Other government	28	19.4	384	64.0	23	85.2	3	60.0	438	56.4
Private	101	70.1	201	33.5	2	7.4	1	20.0	305	39.3
Other	8	5.6	10	1.7	0	0.0	0	0.0	18	2.3
Not listed	4	2.8	0	0.0	0	0.0	0	0.0	4	0.5
Red										
Federal	1	0.7	5	1.1	4	19.0	1	50.0	11	1.8
State	2	1.4	5	1.1	0	0.0	0	0.0	7	1.1
Other government	4	2.7	126	28.1	12	57.1	1	50.0	143	23.1
Private	127	86.4	250	55.7	4	19.0	0	0.0	381	61.6
Other	12	8.2	62	13.8	1	4.8	0	0.0	75	12.1
Not listed	1	0.7	1	0.2	0	0.0	0	0.0	2	0.3

	Small		Medium		Large		Very large		Total	
	N	%	N	%	N	%	N	%	N	%
Nueces										
Federal	0	0.0	1	0.3	0	0.0	1	100.0	2	0.4
State	2	2.6	0	0.0	0	0.0	0	0.0	2	0.4
Other government	2	2.6	15	4.1	3	100.0	0	0.0	20	4.4
Private	73	93.6	343	94.2	1	0.0	0	0.0	417	91.4
Other	1	1.3	4	1.1	0	0.0	0	0.0	5	1.1
Not listed	9	11.5	1	0.3	0	0.0	0	0.0	10	2.2
Sabine										
Federal	0	0.0	1	0.4	0	0.0	0	0.0	1	0.3
State	0	0.0	1	0.4	0	0.0	0	0.0	1	0.3
Other government	3	3.7	17	7.1	5	55.6	3	100.0	28	8.4
Private	73	89.0	188	78.0	4	44.4	0	0.0	265	79.1
Other	1	1.2	30	12.4	0	0.0	0	0.0	31	9.3
Not listed	5	6.1	4	1.7	0	0.0	0	0.0	9	2.7
Rio Grande										
Federal	1	2.0	2	0.8	2	16.7	2	100.0	7	2.1
State	0	0.0	3	1.1	0	0.0	0	0.0	3	0.9
Other government	12	24.5	74	27.8	7	58.3	0	0.0	93	28.3
Private	36	73.5	180	67.7	2	16.7	0	0.0	218	66.3
Other	0	0.0	7	2.6	1	8.3	0	0.0	8	2.4
Not listed	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Neches										
Federal	0	0.0	2	0.9	1	10.0	1	50.0	4	1.0
State	0	0.0	3	1.3	0	0.0	0	0.0	3	1.0
Other government	3	4.5	32	14.0	9	90.0	1	50.0	45	14.7
Private	60	89.6	190	83.0	0	0.0	0	0.0	250	81.4
Other	1	1.5	2	0.9	0	0.0	0	0.0	3	1.0
Not listed	3	4.5	0	0.0	0	0.0	0	0.0	3	1.0
Guadalupe										
Federal	0	0.0	0	0.0	0	0.0	1	100.0	1	0.5
State	2	3.6	1	2.6	0	0.0	0	0.0	3	1.4
Other government	11	19.6	44	27.0	6	100.0	0	0.0	61	28.4
Private	39	69.6	81	53.3	0	0.0	0	0.0	120	55.8
Other	1	1.8	26	17.1	0	0.0	0	0.0	27	12.6
Not listed	3	5.4	0	0.0	0	0.0	0	0.0	3	1.4

	Small		Medium		Large		Very large		Total	
	N	%	N	%	N	%	N	%	N	%
San Antonio										
Federal	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
State	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Other government	2	6.7	45	36.0	5	100.0	0	0.0	52	32.5
Private	25	83.3	59	47.2	0	0.0	0	0.0	84	52.5
Other	0	0.0	21	16.8	0	0.0	0	0.0	21	13.1
Not listed	3	10.0	0	0.0	0	0.0	0	0.0	3	1.9