

The Future Role of Dams in the United States of America

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Key Points

- Climate change projections suggest more hydrologic extremes. Are more dams subsequently needed?
- Most dams in the United States are now older than their economic design life and represent a need for infrastructure investment and recognition of associated risks.
- A national water assessment that critically examines dam removal and modified storage provision options in the context of hydroclimatic risk exposure is needed.

Abstract

Storage and controlled distribution of water have been key elements of a human strategy to overcome the space and time variability of water, which have been marked by catastrophic droughts and floods throughout the course of civilization. In the United States the peak of dam building occurred in the mid-20th century with knowledge limited to the scientific understanding and hydrologic records of the time. Ecological impacts were considered differently than current legislative and regulatory controls would potentially dictate. Additionally, future costs such as maintenance or removal beyond the economic design life were not fully considered. The converging risks associated with aging water storage infrastructure and uncertainty in climate in addition to the continuing need for water storage, flood protection, and hydropower result in a pressing need to address the state of dam infrastructure across the nation. Decisions regarding the future of dams in the United States may, in turn, influence regional water futures through groundwater outcomes, economic productivity, migration, and urban growth. We advocate for a comprehensive national water assessment and a formal analysis of the role dams play in our water future. We emphasize the

urgent need for environmentally and economically sound strategies to integrate surface and groundwater storage infrastructure in local, regional, and national water planning considerations. A research agenda is proposed to assess dam failure impacts and the design, operation, and need for dams considering both paleo and future climate, utilization of groundwater resources, and the changing societal values towards the environment.

1. Introduction

Dams have been an integral component of economic and societal development across the United States. However, the construction and operation of dams have been controversial - several major dams have been seen as public infrastructure failures in terms of social equality, taxpayer investment, and environmental impacts [World Commission on Dams, 2000; George et al., 2016]. Evolving environmental philosophies [Sewell, 1987], perceived fiscal waste [Office of Inspector General, 2013; Gelman, 2014; Snyder, 2016], and the mismatch between planned and actual dam use [Economist Group, 2010] are cited as reasons for diminished public willingness to relicense or authorize and construct new dams. However, a changing climate combined with projected increases in population and shifting water demands promises increased water risks and raises a debate as to whether we need dams more than ever, where and why, and how dams may need to be designed and operated differently to meet social and environmental goals for rivers.

It is likely that the economic and societal landscape of the United States would be unrecognizable without the ~85,000 dams that together store almost one year's mean annual natural runoff, the equivalent of around 5000 m³ of storage per person [Graf, 1999]. These dams also produce hydropower and enabling the production of high value irrigated produce [Bureau of Reclamation, 2016]. Around 20% of dams listed in the national inventory of dams are primarily used for flood control [US Army Corps of Engineers, 2015], reducing the risks of loss of life and property to millions with potential flood exposure. Estimates indicate that over \$5 billion of flood damage has been circumvented to date by flood control dams and levees in both the Central Valley, California, and the Tennessee Valley respectively [Stene, 2015; Tennessee Valley Authority, 2016], while investments in US Army Corps of Engineers (USACE) flood control structures have an estimated six-fold return in terms of flood loss prevention [Comiskey, 2010].

Legislation such as the National Environmental Policy Act (1970) requires all federally funded projects to address negative environmental impacts as part of the design. Subsequently, revised dam operation strategies have enabled the alleviation of some environmental impacts (e.g. sediment flushes [Hsieh, 1999; Yin et al., 2014], optimizing release patterns [McKinney et al., 2001; Richter and Thomas, 2007; Kolesar and Serio,

2011]). In some cases, the environmental impacts of dams are not clear cut [Hard et al., 1996; Soumis et al., 2004] and some dams have been considered as a tool to improve environmental streamflows [McCartney, 2005]. The sedimentation of existing reservoirs continue to be problematic impacting water quality and riverine systems around dams [Webb et al., 2013; George et al., 2016]. In time, unaddressed sedimentation will render many dams obsolete by reducing storage and flood control capacity [Morris and Fan, 1998] unless potentially costly maintenance practices are implemented. In deliberating the future need for dams, one needs to also consider the environmental and social impacts resulting from alternatives to dam services such as hydropower (e.g. coal mining and coal generators, nuclear power and nuclear waste, oil and gas) or water supply (groundwater sustainability and quality, desalination, water recycling) in planning for the future of water, electricity and food infrastructure. It is currently unclear how such a comparative benefit-impact-cost analysis would result in general particularly when considering the newly released Principles Requirements and Guidelines [Council on Environmental Quality, 2014]. These guidelines aim to “allow communities more flexibility to pursue local priorities; take a more comprehensive approach to water projects that maximizes economic, environmental, and recreational benefits; promote more transparent and informed decision-making across the Federal government....”.

In contrast to widely explored environmental and economic aspects of dams, hydroclimatic variability, climate change, and associated impacts on dam operation and risk have not been adequately evaluated for most dams, particularly non-Federally-owned dams that make up 97% of United States' dams. This is despite projected increased in the imbalance between water demand and supply in many regions of the United States [e.g. Zarriello, 2002; Vicuna et al., 2007; Goralczyk, 2015]. An improved understanding of hydroclimatic variability and extremes using long, continuous instrumental records, paleoclimate records [e.g. Cook and Jacoby, 1977; McCord, 1990; Therrell and Bialecki, 2015], projected changes in hydroclimate conditions, land use, and subsequent water quality is needed to improve water management. Understanding the potential role of dams in exacerbating or mitigating hydroclimatic variability and change is critical [Annandale, 2013] yet has also not been thoroughly explored.

Many dams in the United States are nearing or have exceeded their design economic and physical life spans and the question now is what to do about the increasing costs and risks associated with aging dams? How will we maintain, restore, redirect, replace or eliminate the need for the vital services that dams provide? In addition, what will our plan be for the role of dams in the United States in meeting the multiple needs (e.g. water supply, irrigation, hydroelectricity, flood control) of a growing population [Colby and Ortman, 2015] and the associated evolving demands for land, food, water, and energy? Given our understanding of

107 dam impacts on the environment in addition to some environmental groups advocating for a
108 return to unaltered streamflows, is it appropriate to remove all the dams? In contrast, should
109 more investments in dam restoration and upgrades be made considering the economic benefits
110 of existing dams, water supply and flood control into the future, and the cost of dam removal?
111 The peak of dam construction in the United States occurred when economic design life
112 assessments focused on short-term benefits and costs, while discounting or ignoring
113 altogether the long-term fiscal aspects of dam maintenance and decommissioning [George et
114 al., 2016]. Consequently, many dams are today perceived to be poor investments. This raises
115 questions as to whether existing and future tax-payer-funded investments in dams should be
116 avoided or can alternative decision mechanisms, funding structures, or ownership
117 frameworks, including public-private partnerships, be found and implemented?
118 This commentary discusses several critical questions addressing how dams have shaped our
119 society and economic development and the need for a research agenda to identify safety
120 concerns and examine the future role of dams in the United States. In this context, we
121 consider the following issues:

- 122 • potential dam failure risks and cascading impacts on critical infrastructure (e.g. other
123 dams, energy, transportation, water treatment), and how extreme rainfall and regional
124 flooding could act as a failure trigger. Quantifying these risks would provide a basis for
125 prioritizing dam inspections, warning systems, restoration, recovery, and removal plans;
- 126 • the large disparity between state and Federal dam regulations and resultant differences in
127 safety, maintenance, and ensuing decisions and discourse regarding water management;
- 128 • where dam removal, renewal, or new dam construction may be needed;
- 129 • how a national water infrastructure investment, planning, cost recovery, and governance
130 program can be informed using paleoclimate and future climate scenarios;
- 131 • How local, regional, and national planning and guidelines for water resources could
132 incorporate ecological, water allocation, risk management, cost allocation, and economic
133 development goals of society.

134 The physical danger associated with inadequately monitored aging dams coupled with
135 indications of future changes in the frequency and severity of droughts and floods in the
136 United States means that there is a certain urgency with which such questions need to be
137 addressed. Water assessment and planning processes are needed for addressing water
138 requirements, accounting for regional and watershed differences in water supply and demand,
139 and the role of dams in such a landscape [Annandale, 2013]. These decisions will shape the
140 degree of economic viability and ecosystem equity that may be achieved into the future.

141 2. Dams: development, aging dams, and an uncertain future

142 2.1. Dams and economic development

143 Dams were constructed as early as 3000 BC to regulate the spatial and temporal variability of
144 water and marked the major episodes of human civilizations in Asia and Europe. Globally,
145 greater seasonal and interannual variability is significantly correlated with lower per capita
146 GDP [Brown and Lall, 2006] and higher water storage capacity emerges as a pathway to
147 resilience and economic growth.

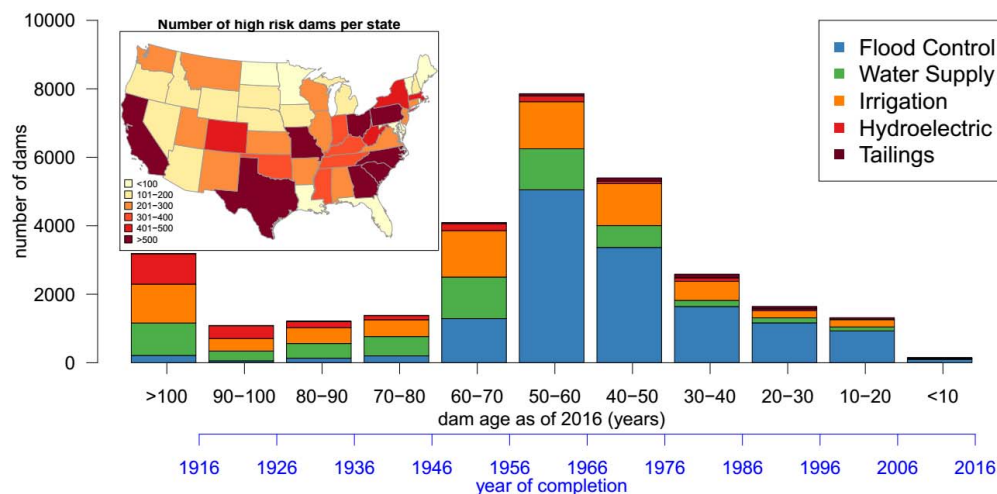
148 In the United States dams provided a gateway and supporting mechanism to industrialization,
149 urbanization, and agricultural expansion. During the industrial revolution, the construction of
150 small dams (< 15 m in height) in the Northeast provided on-site hydropower, water storage,
151 and ensured reliable navigation. There are now over 6500 small dams (< 15 m high) in the
152 East, accounting for around 90% of all dams in the region [US Army Corps of Engineers,
153 2015]. In the Midwest, South, and Southeast, the widespread construction of levee systems by
154 the USACE's implementation of the 1936 Flood Control Act encouraged urban and
155 agricultural development on the fertile floodplains along the Mississippi River and in the
156 Floridian wetlands.

157 The passage of the Reclamation Act by Congress in 1902 led to the creation of the Bureau of
158 Reclamation and the construction of major dams for irrigation and hydroelectric production in
159 the West, such as the Hoover Dam and Glen Canyon Dam, each over 200 m tall. This Act
160 was perhaps the most transformative legislation in the history of the western United States
161 enabling urban, energy, and irrigated agricultural development. Although only 17% of United
162 States farmland is irrigated, irrigated produce accounts for approximately half of total
163 agricultural revenue [U.S. Department of Agriculture, 2015]. Subsequently, over the last half
164 of the 20th century demands for irrigation water sourced from reservoirs tripled [Biemans et
165 al., 2011]. In regions where surface water resources are not available, groundwater is
166 typically used to supply the deficit [Ho et al., 2016b].

167 2.2. Monitoring aging dams and addressing risks across the US

168 Across the US, many dams are nearing or have already exceeded the nominal 50-year
169 economic design life planned for government permitted dams (Figure 1). While the physical
170 life span of dams is typically greater than 50 years, the physical diminishment of constructed
171 dams and their components results in increased budgets needed for maintenance and repair.
172 The subsequent *state of dams* in the United States is dire: the American Society of Civil
173 Engineers [2013] recently awarded dam infrastructure in the United States a grade of “D”,
174 indicating poor maintenance of dams. State-directed and managed dam safety programs are

175 responsible for inspections of around 97% of dams in the United States and are often
 176 inadequately funded. Each state's dam safety inspector is, on average, responsible for over
 177 200 dams [American Society of Civil Engineers, 2013]. As a result the probability of at-risk
 178 dams going undetected is increasing. Furthermore, inspection requirements, and emergency
 179 dam failure plan requirements differ from state to state. For example, in Alabama regulations
 180 for dam safety in design, construction, and ongoing inspections do not exist (a house bill for
 181 dam safety was introduced in 2014 but is yet to progress further). In Texas, a 2005 ruling by
 182 the Texas Attorney General resulted in limitations to accessing dam hazard information citing
 183 homeland security concerns [Buchele, 2013] and the ability of citizens to remain informed of
 184 proximal dam risks. In some other states, the qualifications for dam safety inspectors are not
 185 specified [Association of State Dam Safety Officials, 2000] and many of these dams are only
 186 physically inspected on a 10 year schedule.



187
 188 *Figure 1. Age of dams in the United States (that meet the criteria of 1. Possible or likely loss of human life in the*
 189 *event of dam failure; 2. Dam height ≥ 7.6 m and reservoir storage $\geq 18.5 \times 10^3$ m³; or 3. Dam height ≥ 1.8 m and*
 190 *reservoir storage $\geq 61.7 \times 10^3$ m³) with primary uses of flood control, water supply, irrigation, hydroelectric or*
 191 *tailings dams [US Army Corps of Engineers, 2015] and (inset) Number of high risk dams per state (where failure*
 192 *or mis-operation would result in the probable loss of human life [Federal Emergency Management Agency,*
 193 *2004]). Data from Stanford University [2016].*

194 The inability to adequately fund safety inspections and address dam vulnerabilities result in
 195 real societal risks in terms of public safety and potential economic losses. During the April
 196 2016 floods, Houston residents were evacuated over flooded roadways out of the potential
 197 flood zone of two dams, both of which have exceeded their economic design life spans by
 198 around 20 years [Borrello, 2016]. Alabama, the state with no dam safety laws, is not immune
 199 to dam failures either: six families were evacuated after heavy rains in 1990 caused the face
 200 of a dam to slump [Association of State Dam Safety Officials, 2016]. In 2015, a single storm
 201 event in South Carolina triggered the failure of over 30 dams. Such an event may be a

precursor of future flood destruction under both a changing climate and aging dam infrastructure.

Federal and some state agencies are beginning to consider a climate-informed risk model for dam safety by considering the occurrence of different types of extreme rainfall events (e.g. high intensity storms versus prolonged low intensity storms) [Raff et al., 2009], similar to recent guidance for flood risk management [Meadow et al., 2016]. Modeling the potential for dam failures or a series of cascading dam failures at a watershed or regional scale is needed across the nation to better inform risks to critical infrastructure that is operationally or physically linked to a dam break (e.g. power plants, highways, water treatment facilities) [Rodrigues et al., 2002; Perkins et al., 2011]. The catastrophe associated with such a scenario and potentially long-term recovery period warrant these investigations to enable adequate planning, preparation, and citizen outreach and education.

Encouragingly, some recent efforts towards funding non-federal dam safety works have been made through direction in the Water Resources Development Act of 2016 that would allow non-federal dam owners to apply for grants to address high hazard dam issues. In addition, the USACE proposed the introduction of a nation-wide permit in June 2016 to streamline the removal of superfluous low-head dams in order to restore riverine systems and enhance public safety [Department of the Army - Corps of Engineers, 2016].

A method of prioritizing at-risk dams and determining appropriate funding structures is needed to ensure that dam safety improvements or dam failure emergency response plans are addressed and implemented. Metrics for the level of hazard associated with a dam exist and have been embraced by organizations and agencies at both federal and state levels (e.g. Federal Emergency Management Agency (FEMA), Bureau of Reclamation, U.S. Army Corps of Engineers and Association of State Dam Safety Officials). These metrics use risk-based frameworks including consideration for probable loss of human life, environmental damage, and societal and economic disruption, but differ in the consideration of dam integrity, age, and potential failure causes and mechanisms. Although federal agencies conduct quantitative risk-based analyses to determine *hazard potential ratings*, ratings for non-Federally owned or operated dams may be qualitative and judgment based. The lack of rigor is reflected in the more frequent occurrence of dam failures amongst privately owned dams [Costa, 1985]. Approximately 15% of the 85,225 dams listed in the National Performance of Dams Program are identified as a high hazard (see Figure 1b). This suggests that either the risk metric is perceived as too general for prioritizing funding allocations or there is a serious issue with the increasing potential for dam failures across the country.

2.3. Dam adequacy in the United States considering instrumental, paleo, and projected climate

The peak period of dam design and construction in the United States occurred when there was a limited history and understanding of instrumental hydrologic and climatic data. For example, the Colorado River Compact of 1922, which stipulates water transfers from the upper to lower Colorado today largely regulated through water releases from Glen Canyon Dam, was predominantly based on less than 20 years of instrumental streamflow data. The limited hydrologic record was collected during the wettest decade in the 20th century and excluded data from an anomalously dry period prior to 1905 [Hundley Jr, 1986; Advisory Committee on Water Information Open Water Data Initiative (OWDI), 2014].

A major national question exists as to whether existing dams are able to meet their design objectives over a full range of probable hydrologic variability given that paleoclimate records show the occurrence of catastrophic droughts and floods larger than any event considered in the design scope of existing dams [Cook et al., 2014; Greenbaum et al., 2014; Kwon and Lall, 2016]. Furthermore, no dam design guidelines, including those that use stochastic models, consider the quasi-periodic, inter-annual to multidecadal variations in streamflow, which have been identified in paleoclimate records in the United States [e.g. Cook and Jacoby, 1983; Gray et al., 2003; Woodhouse et al., 2006a]. A recent evolution of stochastic models that consider such features is starting to inform operational aspects [Kwon et al., 2006; Kwon et al., 2007; Nowak et al., 2011; Erkyihun et al., 2016].

Despite the use of watershed dams, including Glen Canyon Dam, which allow for management and equitable distribution of water between upper and lower Colorado basin states (in addition to hydropower, flood control and recreational services), there have been ongoing calls to remove Glen Canyon Dam [Joint Hearing on the Sierra Club's Proposal to Drain Lake Powell or Reduce its Water Storage Capability, 1998; Lustgarten, 2016]. Ongoing efforts, stimulated by persistent drought, have allowed research and study of approaches to managing Colorado River water supplies and demands using studies of observed, paleoclimate, and climate-informed projected water supplies and demands [e.g. Bureau of Reclamation, 2012]. To illustrate our point, we evaluate the performance of the Colorado River Compact's distribution of water between the upper and lower basins to complement existing Bureau of Reclamation [2012] studies. We consider the presence and the absence of Glen Canyon Dam and Lake Powell using a paleoclimate perspective.

The 1490-1997 tree-ring based reconstruction of the Colorado River streamflows at Lee's Ferry is used. Lee's Ferry streamflow delineates streamflow between the upper and lower basins and was developed by Woodhouse et al. [2006a]. From this data we developed 100

271 stochastic simulations using wavelet auto regressive models [Kwon et al., 2007] that are
272 designed to preserve the multi-timescale variability of streamflow. The Colorado River
273 Compact stipulates a minimum delivery of 75 million acre feet of water over a 10 year period
274 from the upper to lower basin. An average of 7.5 million acre feet per year was used to
275 develop a time series of shortages for each of the stochastic simulations with (using a water
276 balance model) and without Lake Powell. With Lake Powell, reservoir mass balances are
277 computed annually, and spills occur if the reservoir capacity is exceeded in a given year. This
278 time series is composed of 0 values in years when the streamflow meets the target release and
279 a negative value for years in which the target demand is not met.

280 An analysis of the frequency spectrum of shortages reveals recurrence intervals greater than
281 20 years (similar to findings in Bureau of Reclamation [2012]). The most severe hydrologic
282 shortages have a recurrence interval of 60-80 years irrespective of whether or not the dam is
283 in place (see Figure 2). Notable water shortages with periodicities of approximately 8, 20 and
284 40 years occur without Glen Canyon Dam (see Figure 2 left graph), with amplitudes of about
285 50%, 75%, and 75% of the spectral peak respectively with a peak period of 60-80 years.

286 Including the dam, which has a storage volume of around twice the mean annual streamflow
287 of the Upper Colorado River [Woodhouse et al., 2006a; Dettinger et al., 2015; Goteti, 2015],
288 dramatically reduces the relative amplitude of the 8 and 20 year peaks to be 15% and 50%
289 respectively (Figure 2 right graph). The peak periodicity for severe shortages remains at 60-
290 80 years even with storage in Lake Powell. Consequently, where streamflows display multi-
291 year, quasi-periodic variability, as displayed in the Colorado River paleoclimate streamflow
292 record, a dam with storage capacity of up to two years of mean annual streamflow could
293 mitigate shortages associated with decadal and perhaps bidecadal variability. However, such a
294 dam may have little functional impact in mitigating severe lower frequency shortages such as
295 those characterized in the Colorado River.

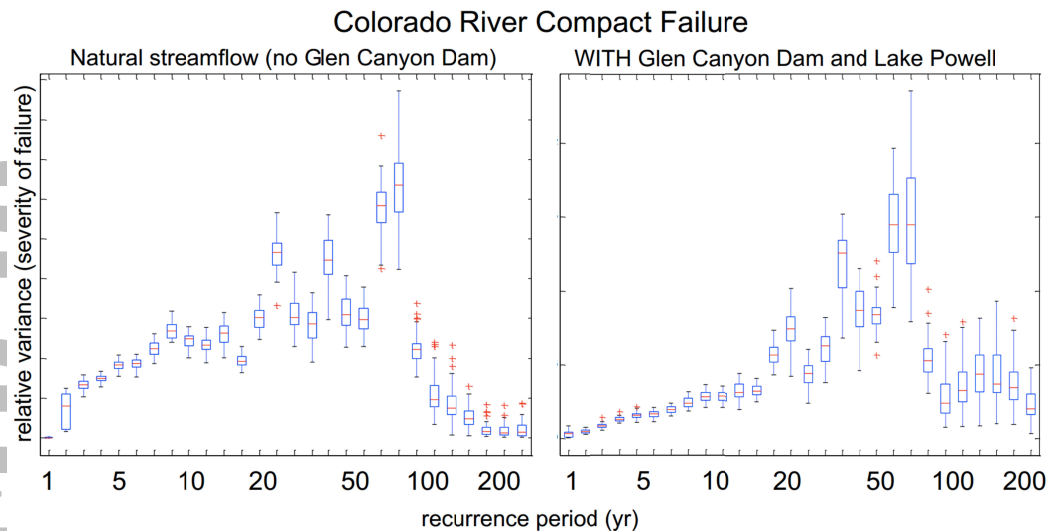


Figure 2. A wavelet analysis of failure to comply with the Colorado River Compact of delivering at least 75 million acre-feet of water over a 10 year period. The figures contrast variance of failure vs. frequency under free-flowing conditions (left) and consider the operation of Glen Canyon Dam to provide water as needed. The wavelet analysis was performed on simulated time series of failure occurrences determined using simulations of paleoclimate streamflow at Lee's Ferry by Woodhouse et al. [2006a] generated using a wavelet autoregression model [Kwon et al., 2009] by Francisco Assis Souza Filho.

The primary utility of a dam such as Glen Canyon is the ability to meet administratively defined water allocation requirements. An even longer reconstruction of Lee's Ferry streamflow from 762 AD to 2005 (not included in the analysis here) highlights an even drier period in the 12th and 13th centuries [Meko et al., 2007]. This drought is theorized to be a contributing factor to the disappearance of the Ancestral Pueblo civilization that previously populated the Four Corners region [Cordell et al., 2007; Kohler et al., 2008]. Consequently, even if the dam were not removed, one needs to think of financial, social and ecological risk management strategies to mitigate the impacts of catastrophic adverse effects associated with extreme hydrologic events.

In addition to the consideration of past hydroclimatic variability informed by both instrumental and paleoclimate records, projections of future water availability across the United States show that changes in water supply should be expected. For example, Christensen et al. [2004] found that water shortages at Glen Canyon Dam increased from 8% to 25% - 41% of the time under projected climate impacts. Projections also show shifts in the timing of peak streamflow earlier in the year away from the growing seasons in the West, a reduction of water stored in the snowpack, and a change in the phase (frozen/liquid) and intermittence of precipitation [Barnett et al., 2005]. This is in addition to increases in evapotranspiration [Walter et al., 2004] and increased extreme precipitation intensities in the North [Wuebbles and Hayhoe, 2004], increased variability in the Southeast (i.e. more extremes both wet and dry) [Li et al., 2012], and increased winter precipitation and higher frequency droughts in the Northeast [Hayhoe et al., 2008]. Flood risks will be further

exacerbated through land use changes that increase runoff peaking and volume [Kousky and Kunreuther, 2009; Ceylan and Devineni, 2014] leading to higher sedimentation rates [Kondolf, 1997]. Projected increases in temperature would also enhance eutrophication resulting in anoxic conditions in reservoirs [Paerl et al., 2011].

As understanding and detection of hydroclimatic variability and change improves with longer observations and subsequent analysis, we have come to the realization that many dams, particularly older dams designed with limited climate data, omitted extreme climate scenarios that are not or are no longer considered to be remote events. The recent record low reservoir water levels at both Lake Mead and Lake Powell, behind the Hoover and Glen Canyon dams respectively, exemplify the risks associated with prolonged droughts with return periods of more than 20 years (see right graph of Figure 2) and the inability to meet legal flow requirements. Both paleoclimate and future climate scenarios suggest that administrative and legal structures should be reformed to reflect and adapt to existing and future hydrological conditions.

2.4. Dam capabilities in the United States considering social expectations

2.4.1 Balancing basin scale water demands using dams

The Delaware River Commission comprised of the Federal Government and the states of New York, New Jersey, Delaware, and Pennsylvania provides a forum for discussion, debate and decision-making to facilitate appropriate watershed level management efforts and follows a complex history [Albert, 2010; Ravindranath et al., 2016]. To address the challenges of managing the streamflow releases and water requirements from different sectors, Kolesar and Serio [2011] documented a citizen and Non-Government Organization driven process. Kolesar, a business school professor and, as a private citizen, an avid fisherman developed an optimization model for the timing and volume of releases from the Delaware reservoirs that maximize fisheries benefits while meeting water demands with no increase in drought exposure. Working with a number of fishing and ecological interests, he was instrumental in the Delaware River Basin Commission adopting a flexible streamflow management program using his modeling as a tool for making operational changes in water releases. The success of this assessment and implementation signals a significant change in the way ecological and water supply goals can be achieved using dams. Although the Delaware River Basin reservoirs are operated largely for seasonal storage the need to have a management strategy for the financial, social, and ecological impacts remains given the risk of exposure to severe [Namias, 1966] and sustained [Devineni et al., 2013] drought in the region.

The Delaware River Commission is one of only three River basin Commissions in the United States that are currently functioning to address basin-scale water management. A number of

359 states, such as Michigan, Massachusetts, Connecticut, and Colorado, have implemented river
360 basin programs [Kendy et al., 2012], while a joint project by the USACE and The Nature
361 Conservancy aims to implement dam reoperation schemes for USACE dams within eight
362 river systems across the USA to balance human water use and ecosystem services. The
363 existence of watershed and river basin groups, state programs, and collaborations have
364 enabled the management of basin-scale streamflows balanced for multiple user interests,
365 suggesting that holistic approaches to water management in the United States are possible, but
366 still wanting across much of the country.

367 2.4.2 Developing the floodplain - the perception of safety behind dams

368 Although floodplains are, by definition, at risk of flooding, these areas also offer amenity
369 values (e.g. views, recreation opportunities) and can be desirable locations to live. The fact
370 that homeowners do not bear the full cost of building and locating in floodplains has led to
371 substantial exposure of flood-prone areas in the United States and current trends indicate
372 continuing development in these areas [Pinter, 2005]. In addition, many individuals, who are
373 least financially capable of rebuilding, live in the most dangerous flood zones and are denied
374 adequate emergency assistance when floods eventuate [Barry, 1998; Gladwell, 2015]. These
375 locations continue to be liabilities to the National Flood Insurance Program, due to large
376 insurance claims and high prevalence of repetitive loss properties [Kousky and Michel-
377 Kerjan, 2015]. Efforts to raise flood insurance rates in the aftermath of Hurricane Katrina in
378 2005, and other recent flooding events such as Hurricane Sandy in 2012, were intended to
379 send a price signal that reflected the true cost of locating in a flood plain. These efforts have
380 seen Congressional resistance and have had little success so far.

381 In addition to subsidies for flood insurance, the provision and maintenance of flood control
382 infrastructure continues to encourage development in the flood plain. The Natomas
383 subdivision in Sacramento, CA, is a case in point. Record flooding in 1988 and 1997
384 [National Research Council et al., 1999] led to a reassessment of flood control infrastructure
385 originally intended to protect Sacramento from flood events with a 1 in 100 year average
386 recurrence interval (ARI). The subsequent revision found that the existing flood control
387 capacity was as low as a 1 in 85 year ARI [Governor's Flood Emergency Action Team, 1997]
388 or 1 in 77 when climate-informed analysis was considered [National Research Council et al.,
389 1999] resulting in a halt to further development in 2008. However, the 2014 Water Resources
390 Reform and Development Act authorized the USACE to fortify levees encircling the Natomas
391 basin “much to the excitement of developers, realtors and Sacramento City Hall – all of
392 whom are ready to cash in” [Maiman, 2014]. The occurrence of a flood event similar to the
393 1862 flood with an estimated 1 in 500-1000 year ARI [Porter et al., 2011] would still likely
394 overwhelm the upgraded flood control infrastructure. Putting Natomas in the context of such

395 a scenario is downright scary, and speaks to the human tendency to discount low probability,
396 high impact events [Kousky and Kunreuther, 2009].

397 2.5. The environmental and social costs of dams

398 The present day public perception of dams in the United States is vastly different from that in
399 the early 20th century. We are now conscious of the environmental impacts caused by dams.
400 These include fragmentation of water ways [Graf, 2001], obstructing movements of keystone
401 fish species or rearing habitats and resulting impacts that propagate through the watershed
402 [Bednarek, 2001], trapping sediment and altering river beds and banks [Kondolf, 1997;
403 Wisser et al., 2013], replacing riverine habitats with thermally stratified reservoirs [Poff et al.,
404 1997; Elçi, 2008], greenhouse gas emissions [St. Louis et al., 2000], modifying water quality,
405 and altering seasonal streamflow variability [Nilsson and Berggren, 2000] to name a few.
406 There are now multiple environmental coalitions and advocacy groups emphasizing river
407 restoration ecology and recommending direct intervention.

408 Historically, the social and economic benefits of dams were perceived to be high and took
409 precedence over environmental degradation, the protection of downstream water supplies
410 [Lawson, 1994; Pitt, 2001], and indigenous communities, which have often been displaced
411 without adequate compensation [Babbitt, 2002; Cernea, 2008]. The trade-offs between dam
412 construction and maintaining ecosystem health and services, food growth, and the provision
413 of clean water [Foley et al., 2005; Young, 2013] are now better understood. Federal agencies
414 and watershed commissions now address some concerns through the Secretary's Indian Water
415 Rights Office to facilitate settlements of Native American water rights claims [Department of
416 the Interior, 2009] and addressing climate change and environmental streamflow
417 requirements through more flexible water release policies.

418 In summary, a discussion as to whether or not to renew or remove dams in the face of age
419 related structural decline and an unfavorable climate immediately takes on larger social
420 dimensions. These decisions consist of a set of tradeoffs between the often-conflicting
421 objectives of developing capacity to manage climate variability, environmental and social
422 justice, and economic activity and development. The social aspect of dams requires an
423 examination of the variety of interventions, ranging from structural to financial to non-
424 structural, and the notion of acceptable risk for society and for individuals. There have been
425 strong calls to remove dams to restore riverine systems, such as calls to remove Glen Canyon
426 and the Snake River dams but the question remains: Are we prepared to live without some of
427 these dams?

3. Are we prepared to do away with some dams?

The national rhetoric surrounding dams has moved from one of “monumental dams” to one of “healing” rivers (the latter made by Californian Governor Jerry Brown [Showstack, 2016]), calls to “protect the arteries of our planet” [Bosshard, 2015], and more extreme calls to “tear down” the dams [Beard, 2015]. The converging issues of growing populations [Colby and Ortman, 2015], evolving demands for food, energy, and water, aging dams, and reduced water storage capacity through decommissioning and sedimentation highlights the pressing need for a national water assessment and a subsequent national water plan. Past national assessments of water are somewhat limited in scope and have in general focused on environmental impacts at the expense of considering economic impacts [e.g. Caldwell et al., 2012] or omitted the consideration of water storage influences [e.g. Hurd et al., 1999]. The consideration of economic impacts and water storage in these national assessments of water would have likely resulted in quite different conclusions. While such results have sometimes been used to highlight regional dependencies on stored or imported water [Devineni et al., 2015], the consideration of stored water such as reservoirs, groundwater, or lakes, can change conclusions regarding water scarcity and economic risk [Padowski and Jawitz, 2012]. Although national assessments of water storage risks have been made [Gleick, 1990; Lane et al., 1999; Vogel et al., 1999], consideration of water demands, environmental impacts, water storage potential, and infrastructure risks are still needed to inform a holistic national water assessment and a subsequent national water plan. These are needed to identify dam service requirements, solutions for water storage [Annandale, 2013], potential for water reallocation [Qureshi et al., 2009; Kirby et al., 2014; Marston and Cai, 2016], and conservation in order to determine the role of dams in the United States into the future.

Debates over dams are typically based around ideology with limited scientific analysis, incomplete knowledge of the arguments for or against dam removal, or adequate policies to guide and govern dam removal [Doyle et al., 2003; The Heinz Center, 2003; Jørgensen and Renöfält, 2013]. While ideology will always influence decisions, systematic evaluations of the value of a dammed versus a free flowing catchment are fundamental to providing the debate with scientifically sound reasoning. Evaluations of dam removal have typically emphasized environmental streamflow restoration [e.g. Grantham and Viers, 2014], structural age, and related failure risks [International Rivers, 2007; Struck, 2014] but also need to consider the likely socioeconomic and ecological responses within the context of climate risk. A thorough economic assessment should consider subsidies, regional benefits, passive-use benefits, and the ability of a regional economy to adjust to changes in water storage through changes in sectorial production [Whitelaw and Macmullan, 2002].

463 The decommissioning and removal of non-Federal dams for financial, environmental, and
464 safety reasons is not uncommon [Walton, 2015]. A small number of large Federally owned or
465 regulated dams, such as the Elwha Dam in the state of Washington, have recently been
466 removed and plans exist for the proposed removal of four dams on the Klamath River in
467 Oregon and California, and another four on the Lower Snake River. While the removal of
468 small dams that no longer serve their purpose makes economic and common sense, the same
469 conclusion cannot be applied automatically to larger dams in the West. In addition to the
470 higher costs of removal, large dams in the West typically serve numerous functions (e.g.
471 hydropower, water supply, irrigation, navigation, flood control) and alternatives for these
472 services would need to be found.

473 4. Deciding the future of dams and research for a way forward

474 As we noted earlier, dams have supported human civilizations since the very beginning, and
475 now, at a time when climate challenges, global population, and demands on United States'
476 resources are all increasing, we appear to be on the verge of having a national discussion
477 regarding the need to dismantle dams [Shuman, 1995]. A decision matrix is introduced in
478 Table 1 to help structure and direct thinking as to some of the factors that need to be
479 systematically analyzed as we consider dam removal or rehabilitation. In all such decisions
480 today, we need to consider expected impacts, costs, benefits, and adaptations over multiple
481 decades. Over such a long period, our exposure to climate risk will change in significant and
482 unpredictable ways. Furthermore, consideration needs to be given to potential changes in
483 demand for water and flood protection. These include changes in demographics, preferences,
484 and the mechanics, demands, and efficiencies of agriculture, energy production, and industry.
485 Sustainability, resilience, hydromorphology, social hydrology and system complexity have
486 been popular concepts and have expanded thinking in the recent literature [Sivapalan et al.,
487 2012; Lall, 2014; Montanari, 2014; Gober and Wheeler, 2015; Vogel et al., 2015]. These
488 concepts will help inform the future of dams on the United States landscape.

489 *Table 1. Options for balancing water supplies and demands.*

Impacts and adaptations	Options for aging/inadequate dams				
	Expand /retrofit ¹	Preserve / restore ²	replace	Replace with smaller dams	Remove
Costs					
Deconstruction			\$\$\$*	\$\$\$	\$\$\$
Construction	\$\$	\$\$	\$\$\$\$	\$\$\$	
Loss of services			Temporary loss of services	Temporary loss of services	Permanent loss of hydroelectricity / flood control / storage capacity and controlled releases (e.g. for water supply and irrigation)
				Loss of reservoir storage for controlled low flows	Loss of reservoir storage for controlled low flows
Change in environmental impacts/management	Changes in storage and/or release capacity			Spatially distributed environmental costs (e.g. increased surface areas and habitat for disease carriers)	Temporary impacts associated with release of water, sediment and restoration of riverine environment and reservoir footprint
Benefits					
Change in environmental impacts/management				Spatially distributed environmental benefits (e.g. reduced barriers for fish migration)	Eventual restoration of riverine habitat
Reduced risk of catastrophic failure	✓✓*	✓	✓	✓	✓✓✓
Potential adaptations			Temporary conservation or increase in service imports	Temporary conservation or increase in service imports	Develop alternative energy (e.g. gas, distributed storage) or accept reduction in electricity supply
				Change in reservoir and catchment management – develop multi-site reservoir management	Develop alternative flood protection (levees, rezone developments, relocate populations) or accept increase risk of property damage and loss of life
					Develop alternative water resources (groundwater, aquifer storage, desalination, reuse, rainwater harvesting) or adopt water conservation or accept drought risk and resultant loss of production (e.g. manufacturing, irrigation) or abandon the region

490 * \$ and ✓ symbols are intended to portray a relative cost or benefit amongst alternatives

491 1. Add to existing capacity through additional dam wall height or additional spillway capacity

492 2. Restore aged dam to original design strength and capacity

493 4.1. Research agenda – dams and climate in the 21st century:

494 Suggestions regarding the future of dams in the United States have been proposed by various
 495 institutes [e.g. Aspen Institute, 2002; The Heinz Center, 2003]. However, a search on Google
 496 Scholar reinforces the extreme paucity of critical research on water infrastructure planning
 497 and development in the United States, especially on the need for dams or an assessment of
 498 their potential risk of failure, in the context of climate change adaptation, hydroclimatic risk
 499 mitigation, aging infrastructure, and modification of river basin water flows and water
 500 quality. These deficiencies in research point to the need for a holistic water assessment. From
 501 this assessment a strategic approach to rivers, dams and water use across the country could be
 502 assembled that considers local and regional jurisdictions, priorities, and perspectives.

503 As a conclusion to this paper, we sketch some areas that could form the core of a basic and
504 applied research program focusing on two key components of dam failure risks and water
505 storage solutions in the United States.

506 *Dam Failure Risk Assessment:*

507 1. *Hydroclimatic considerations:* Many existing dams were designed using relatively
508 short instrumental records. The use of longer accurate instrumental records,
509 paleoclimate records, and future climate modeling is needed. Projections of regional
510 climate aspects relevant to river and dam management and risk assessments will
511 require adequately constrained projections of climate change that reflect observations
512 of both long-term variability (i.e. paleoclimate records) and recent hydrological
513 change. Research is needed for developing suitable methods of assessing dam risks
514 with respect to climate in conjunction with dynamic risks associated with
515 sedimentation and subsequent changes in flood control capacity.

516 An understanding of inter-annual to decadal scale hydrological variability is needed
517 to inform multi-annual predictions of regions that may be transitioning to a riskier
518 regime (either prolonged drought or increased flood risk). The degree to which
519 protracted dry and wet spells influence pore pressures, water table levels, and
520 subsequently impact on the structural safety of dams requires investigation.
521 Research on shorter timescales is also needed – both individual and sequential severe
522 storms are a significant risk to interconnected reservoir systems. An approach to
523 modeling extreme hydrologic events that utilizes the complete range of available data
524 from radar rainfall fields as well as hydrometeorological models could be developed.
525 Quantifying how the risk associated with such storms changes over space and time in
526 response to changing climatic conditions can improve risk characterization,
527 conjunctive reservoir management and flood insurance pricing.

528 2. *Failure impact dynamics:* Given that an extreme regional rainfall event could be a
529 trigger for dam failure, research is needed to develop assessments of potential
530 impacts from flooding that may result with and without dam failure. These include
531 quantifying the potential of cascading failures of multiple dams and subsequent
532 impacts on critical infrastructure elements including power plants, bridges and
533 highways, and water and wastewater treatment plants. Such an approach could inform
534 the probability of property and life losses, health impacts, and interruptions to
535 business and services. An understanding of these impacts would enable elements
536 critical to the physical and socio-economic recovery of the region to be informed.

537 3. *Risk-based portfolio management:* A strategy for prioritizing dam safety
538 requirements in the United States needs to be developed given the large portfolio of

dams with mixed ownership and responsibilities (Federal dams with risk-informed portfolio management strategies vs variable state plans for state, public, local or private dams) and the general public exposure to dam failure risk. This prioritizing strategy should be developed to inform the financing and cost allocation of dam monitoring, downstream warning programs (field sensors, remote sensing), emergency management and response planning, risk reduction activities, insurance or other financial interventions, and, if appropriate, the potential for dam removal. This strategy would need to be informed by accurate hydroclimatic factors and assessments of failure impact dynamics articulated in the previous two points.

Strategies for managing climate induced flood and drought risk in the 21st century:

1. *A water storage portfolio for the nation:* Dams with reservoirs holding multi-year or seasonal storage in addition to groundwater from shallow or deep aquifers are critical reserves of water in the United States and their use varies regionally. Changes in deep groundwater systems, driven by withdrawals, rapidly responds to wet and dry periods on inter-annual to decadal timescales [Russo and Lall, 2016], while agricultural and municipal water demands appear to drive groundwater use in many systems [Ho et al., 2016b]. Addressing persistent and recurrent climate anomalies would certainly be easier if both surface and groundwater storage options were considered. Conjunctive surface and groundwater use, including consideration of reservoir development, has been studied in academia for at least 40 years [Burt, 1964; Yu and Haines, 1974; Lall, 1995; Pulido-Velazquez et al., 2016]. However, in almost all of the United States, there is no regulatory structure or physical infrastructure in place to easily optimize conjunctive surface and groundwater management [National Research Council, 1997]. The implantation of regulatory structures that do exist are relatively new [e.g. California Department of Water Resources, 2015]. Rapid groundwater resource development combined with ill-suited groundwater policies has meant that conjunctive use management is often implemented retrospectively [Schlager, 2006]. Metering of surface and ground water use is critical to understanding how water storages are used and are needed to permit the market based trading of these resources. In order to understand and optimize water use from both surface and groundwater storages information is also required on who could potentially use these resources, the current condition of aquifers and surface storage infrastructure, and the associated economics of cost allocation and regulation of water use across these users. This would inform a strategy to assess which dams can be removed and where new dams or other mechanisms to deal with imbalances in water supply and demand may be needed from a regional and a national perspective. In addition, suitable

policies would need to be developed in parallel to facilitate such a transition to ensure that ecological objectives are met and that the potential for extreme volatility in spot market prices under climate exigencies are regulated.

2. *Exploring climate scenarios*: An appropriate set of climate scenarios is required (e.g. ranging from single large runoff events to seasonal and multi-year streamflow anomalies) to explore portfolios of surface and groundwater storage relative considering water use requirements (e.g., urban, industrial, energy and minerals production, food) under flood and drought scenarios. The climate scenarios should include information from both paleoclimate reconstructions and climate change projections. A national-scale reconstruction of drought over the past 2000 years could be utilized [Cook et al., 1994; Cook et al., 2010] in addition to a recently developed 500 year-long national reconstruction of paleoclimate streamflow [Ho et al., 2016a]. There is an indication that extreme rainfall could also be reconstructed using similar proxies [Steinschneider et al., 2016]. While there is much research on producing future climate change scenarios, in this specific case, research that considers both the spatial correlation of climate projections over river basins and the inter-annual to decadal variations in the context of hydrologic extremes is needed. No such national or even regional analysis of conjunctive water management considering this range of climate scenarios exists to date.

3. *Institutional coordination and operation of dams*: The ability to balance the competing demands of water use sectors was exemplified by Kolesar and Serio [2011] for the case of the Delaware River Basin Commission through the modification of water releases. The management of multiple dams within the same river system requires integrated management of both storage and release patterns often involving different countries, agencies, and private entities (e.g. Colorado, Rio Grande, Columbia and Snake River Basins) with different operation objectives and varying design capacities. Developing suitable institutional and legal reforms to help manage these basin-scale activities are critical to developing solutions that respect physical hydrology. Dynamic frameworks updated under different climates for storage assessment, capacity expansions, and inter-basin water transfers and rights need to be co-designed with real-world stakeholders in a mutual learning mode.

4. *Role of conservation and smart management*: The amount of required water storage reflects the cumulative imbalance between supply and demand. It is therefore critical to examine water use to identify opportunities for improvement. As a result, the reliability and marginal cost of reducing demand can be compared with the marginal cost of improved storage and hence supply during critical periods. There needs to be continued research in water conservation, the economics of water use, valuation of

ecosystem services, and the value of flood risk mitigation using non-structural measures. Such economic assessments at regional and national scales are currently limited by systematic data collection and analyses at these larger scales. Research is needed on improving these aspects to help provide insights into a water risk mitigation strategy that considers both structural and non-structural measures. Innovative smart water management that balances multi-time-scale forecasts of reservoir inflows with flood reduction goals and demand for different water uses, including ecosystem uses, requires coordination as well as management of the associated residual risks. In addition to the development of technical innovations, social and financial factors associated with such innovations need to be understood.

5. *Role of financial instruments and markets:* Given the need for significant financial outlays for removing, restoring or replacing dams, research is needed to understand the potential role of public and private partnerships for financing and operating large water infrastructure. Appropriate regulatory, cost recovery, and cost allocation mechanisms need to be considered and integrated in a financially sound manner. As one considers such a trajectory, emerging questions include how the role of public and private marketing mechanisms and financial instruments could be used to address the residual risks of dam failure. These mechanisms and instruments could include option contracts, forward contracts, insurance of operation rules and contracts [e.g. Brown and Carriquiry, 2007; Khalil et al., 2007; Sankarasubramanian et al., 2009; Zeff and Characklis, 2013], reduction in subsidies for federal flood insurance to improve awareness of true flood risks, and catastrophe bonds amongst others. Research is needed to understand the utility of such mechanisms, who could participate in them, and how they would affect water management and risks for specific societal groups and the nation as a whole.

6. *Legal, social and institutional factors:* Existing water laws are not unchangeable and these laws and management regimes should be evaluated and, where appropriate, modified to reflect current and future conditions. The governmental and institutional constraints on the development of water policy and the role of the states and local communities in facilitating effective water governance [Kirchhoff and Dilling, 2016] need to be studied. There is a need to thoroughly explore water management strategies and reforms that have or have not been successful in other countries and couple these with economic policies [Young, 2014] to appropriately evaluate and reform water management, including the use of dams, in the United States. Decisions regarding the future of dams and water management, potential implementation of forecast-based management and financial risk management systems, and changes in the role of the private sector and water costs are imminent and will be disruptive and

649 controversial. Understanding the social dynamics and the mechanisms that may lead
650 to conflict resolution and cooperation across different affected actors is needed as part
651 of the process that determines the socio-political acceptability, and hence the
652 viability, of any plans related to dams and water management.

653 We suggest that the water resource community can take this on as a very practical challenge
654 that is universal in its scope. Using the United States as a case study, the water resource
655 community may foster directed research efforts on understanding and guiding our future. It is
656 time to move beyond statements as to the putative impacts of climate change and the need for
657 adaptation strategies to address a timely set of questions. This can lead to a research agenda
658 that is central to the academic and professional water community, and clearly has a bearing on
659 the water-energy-food nexus as well as aging water supply infrastructure into the future.

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Figure 1.

Accepted Article

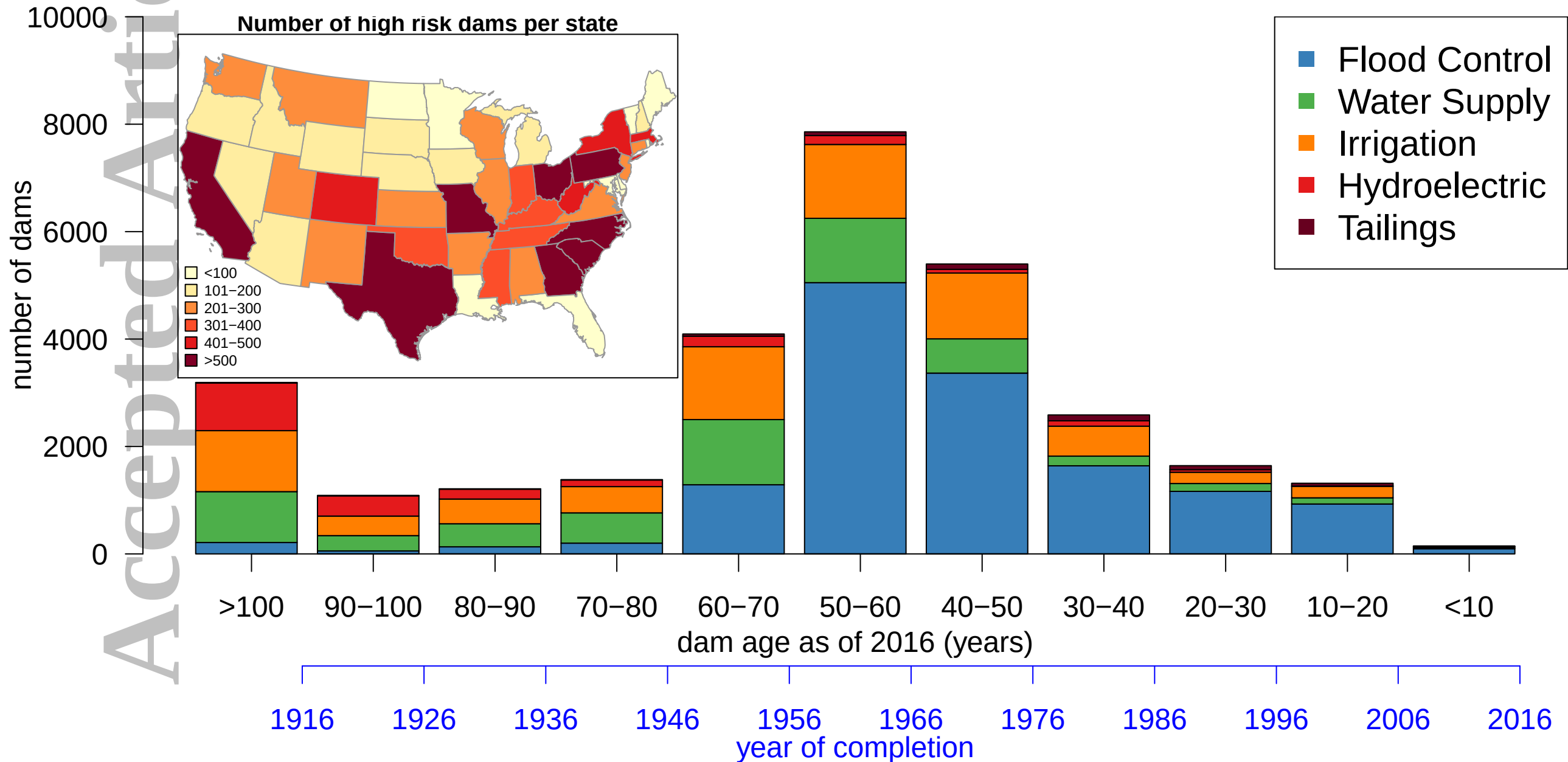
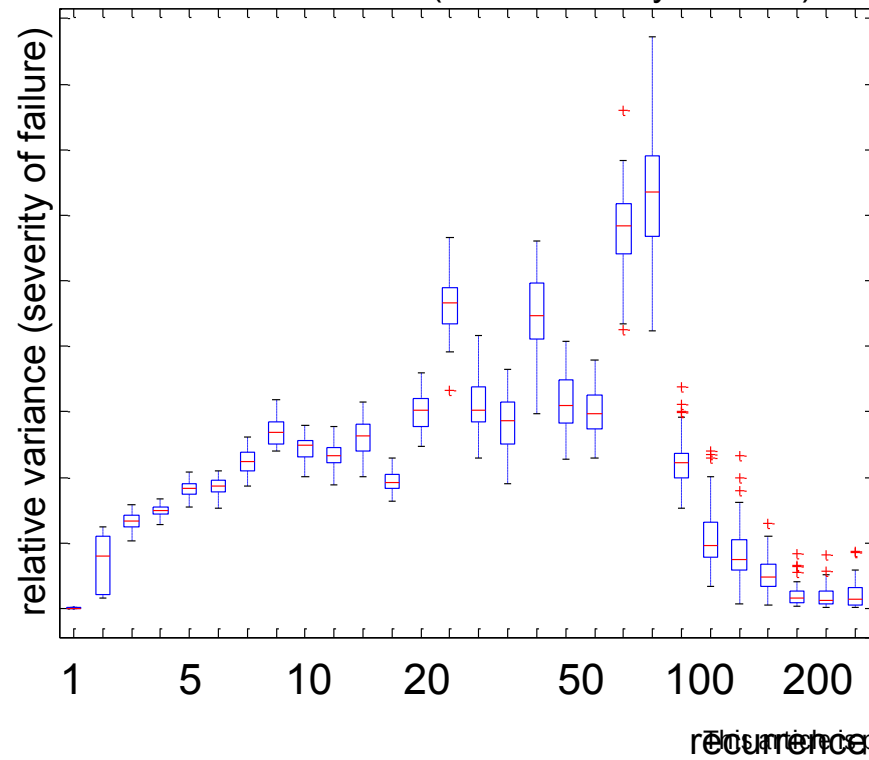


Figure 2.

Accepted Article

Colorado River Compact Failure

Natural streamflow (no Glen Canyon Dam)



WITH Glen Canyon Dam and Lake Powell

