AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2016WR019905

The future role of dams in the United States of America

Michelle Ho[1], Upmanu Lall[1,2], Maura Allaire[1,3], Naresh Devineni[1,4], Hyun Han Kwon[1,5], Indrani Pal[1,2], David Raff[6], and David Wegner[7]

[1]Columbia Water Center, Columbia University, New York, New York, USA, [2]Department of Earth and Environmental Engineering, Columbia University, New York, New York, USA, [3]The Nature Conservancy, Albany, New York, USA, [4]Department of Civil Engineering, Center for Water Resources and Environmental Research, NOAA Cooperative Remote Sensing Science and Technology Center, City University of New York (City College), New York, New York, USA, [5]Department of Civil Engineering, Chonbuk National University, Jeonju, Jeollabuk-do, South Korea, [6]Department of the Interior, Bureau of Reclamation, [7]Jacobs Engineering, Tucson, Arizona, USA

Key Points:

- Climate change projections suggest more hydrologic extremes. Are more dams subsequently needed?
- Most US dams now exceed their economic design life and represent a need for infrastructure investment and recognition of associated risks
- A national water assessment is needed to examine dam removal and modified storage provision options considering hydroclimatic risk exposure

Correspondence to:
M. Ho,
mh3538@columbia.edu

Citation:
Ho, M., U. Lall, M. Allaire, N. Devineni, H. H. Kwon, I. Pal, D. Raff, and D. Wegner (2017), The future role of dams in the United States of America, *Water Resour. Res.*, *53*, 982–998, doi:10.1002/2016WR019905.

Received 6 OCT 2016
Accepted 19 JAN 2017
Accepted article online 24 JAN 2017
Published online 15 FEB 2017

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 toward the environment.

Plain Language Summary Water storage and control have been key elements of a human strategy to overcome differences between water availability and water needs. The future promises changes to when and where water will be available and many regions in the USA will likely see an increase in the imbalance between existing water storage and evolving demands for water. This indicates the need for more storage or new dams to meet human and ecological needs. The current trend for removal of old, hazardous or unpopular dams now and into the future may impact regional groundwater outcomes, food and energy production, migration, and urban growth. We advocate for a formal analysis of the role dams play in the future of the USA's water landscape. We also stress the need for national water planning considerations to develop environmentally and economically sound strategies to integrate the management of surface and groundwater storage infrastructure in the USA.

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 m^3 of storage per person [*Graf*, 1999]. These dams also produce hydropower and enable 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 [*U.S. 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 U.S. Army Corps of Engineers (USACE) flood control structures have an estimated sixfold 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 continues to be problematic with impacts on 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 increases 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 dam impacts on the environment in addition to some environmental groups advocating for a return to unaltered streamflows, is it appropriate to remove all the dams? In contrast, should more investments in dam restoration and upgrades be made considering the economic benefits of existing dams, water supply, and flood control into the future, and the cost of dam removal? The peak of dam construction in the United States occurred when economic design life assessments focused on short-term benefits and costs, while discounting or ignoring altogether the long-term fiscal aspects of dam maintenance and decommissioning [*George et al.*, 2016]. Consequently, many dams are today perceived to be poor investments. This raises questions as to whether existing and future tax-payer-funded investments in dams should be avoided or if alternative decision mechanisms, funding structures, or ownership frameworks, including public-private partnerships, can be found and implemented?

This commentary discusses several critical questions addressing how dams have shaped our society and economic development and the need for a research agenda to identify safety concerns and examine the future role of dams in the United States. In this context, we consider the following issues:

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

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

2. Dams: Development, Aging Dams, and An Uncertain Future

2.1. Dams and Economic Development

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

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

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

2.2. Monitoring Aging Dams and Addressing Risks Across the United States

Across the United States, many dams are nearing or have already exceeded the nominal 50 year economic design life planned for government permitted dams (Figure 1). While the physical life span of dams is

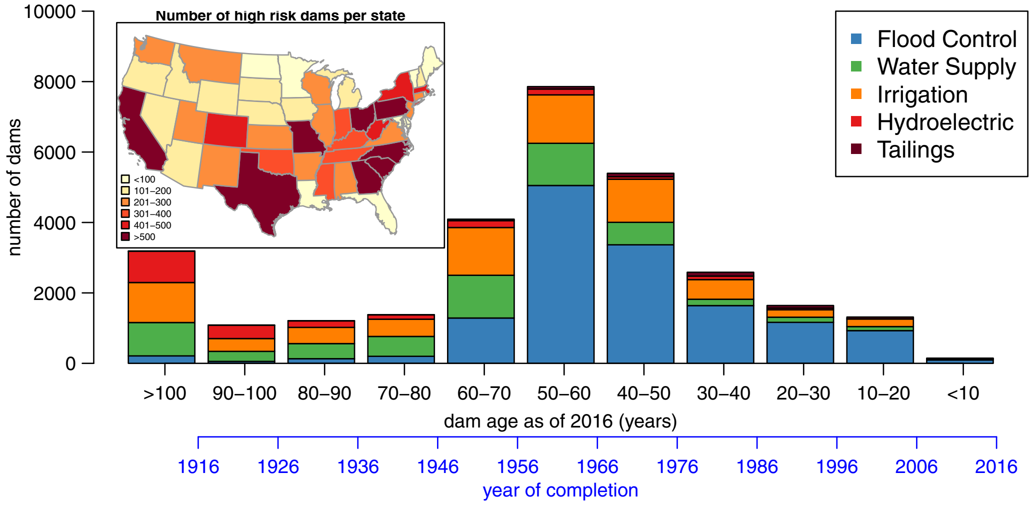

Figure 1. Age of dams in the United States (that meet the criteria of 1. Possible or likely loss of human life in the event of dam failure; 2. Dam height $\geq$ 7.6 m and reservoir storage $\geq 18.5 \times 10^3$ m^3; or 3. Dam height $\geq$ 1.8 m and reservoir storage $\geq 61.7 \times 10^3$ m^3) with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

typically greater than 50 years, the physical diminishment of constructed dams and their components results in increased budgets needed for maintenance and repair. The subsequent *state of dams* in the United States is dire: the *American Society of Civil Engineers* [2013] recently awarded dam infrastructure in the United States a grade of "D," indicating poor maintenance of dams. State-directed and managed dam safety programs are responsible for inspections of around 97% of dams in the United States and are often inadequately funded. Each state's dam safety inspector is, on average, responsible for over 200 dams [*American Society of Civil Engineers*, 2013]. As a result the probability of at-risk dams going undetected is increasing. Furthermore, inspection requirements and emergency dam failure plan requirements differ from state to state. For example, in Alabama regulations for dam safety in design, construction, and ongoing inspections do not exist (a house bill for dam safety was introduced in 2014 but is yet to progress further). In Texas, a 2005 ruling by the Texas Attorney General resulted in limitations to accessing dam hazard information citing homeland security concerns [*Buchele*, 2013] and the ability of citizens to remain informed of proximal dam risks. In some other states, the qualifications for dam safety inspectors are not specified [*Association of State Dam Safety Officials*, 2000] and many of these dams are only physically inspected on a 10 year schedule.

The inability to adequately fund safety inspections and address dam vulnerabilities result in real societal risks in terms of public safety and potential economic losses. During the April 2016 floods, Houston residents were evacuated over flooded roadways out of the potential flood zone of two dams, both of which have exceeded their economic design life spans by around 20 years [*Borrello*, 2016]. Alabama, the state with no dam safety laws, is not immune to dam failures either: six families were evacuated after heavy rains in 1990 caused the face of a dam to slump [*Association of State Dam Safety Officials*, 2016]. In 2015, a single storm 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 toward funding nonfederal dam safety works have been made through direction in the Water Resources Development Act of 2016 that would allow nonfederal 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*, 1986; *Advisory Committee on Water Information Open Water Data Initiative*, 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, interannual 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 large 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 informed by observed, paleoclimate, and climate-informed projections of 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 stochastic simulations using wavelet auto regressive models [*Kwon et al*., 2007] that are designed to preserve the multitime-scale variability of streamflow. The Colorado River Compact stipulates a minimum delivery of 75 million acre feet of water over a 10 year period from the upper to lower basin. An average of 7.5 million acre feet per year was used to develop

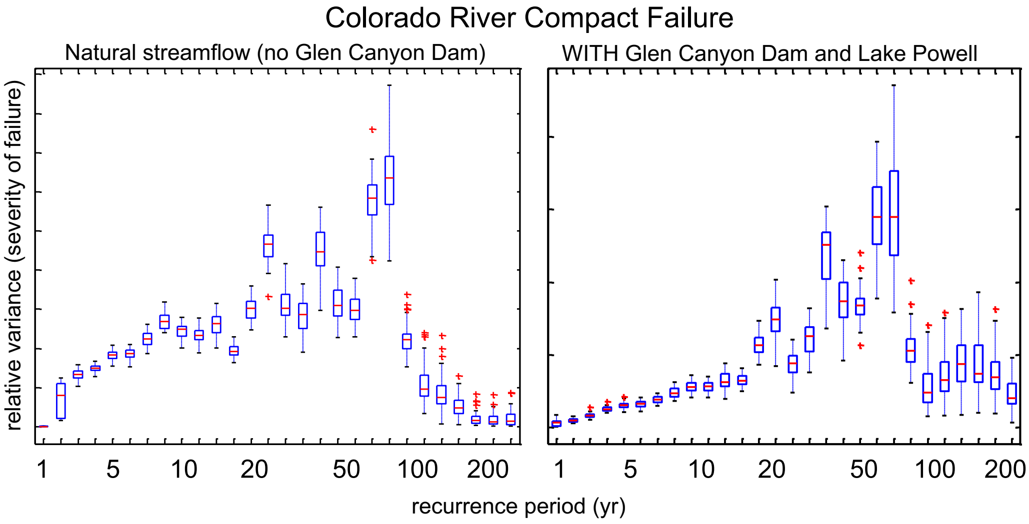

Figure 2. A wavelet analysis of failure to comply with the Colorado River Compact of delivering at least 75 million acre-feet of water over a 10 year period. The figures contrast variance of failure versus frequency under free-flowing conditions (left) and consider the operation of Glen Canyon Dam to 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.

a time series of shortages for each of the stochastic simulations with (using a water balance model) and without Lake Powell. With Lake Powell, reservoir mass balances are computed annually, and spills occur if the reservoir capacity is exceeded in a given year. This time series is composed of 0 values in years when the streamflow meets the target release and a negative value for years in which the target demand is not met.

An analysis of the frequency spectrum of shortages reveals recurrence intervals greater than 20 years (similar to findings in *Bureau of Reclamation* [2012]). The most severe hydrologic shortages have a recurrence interval of 60–80 years irrespective of whether or not the dam is in place (see Figure 2). Notable water shortages with periodicities of approximately 8, 20, and 40 years occur without Glen Canyon Dam (see Figure 2, left graph), with amplitudes of about 50%, 75%, and 75% of the spectral peak respectively with a peak period of 60–80 years. Including the dam, which has a storage volume of around twice the mean annual streamflow of the Upper Colorado River [*Woodhouse et al.*, 2006a; *Dettinger et al.*, 2015; *Goteti*, 2015], dramatically reduces the relative amplitude of the 8 and 20 year peaks to be 15% and 50%, respectively (Figure 2, right graph). The peak periodicity for severe shortages remains at 60–80 years even with storage in Lake Powell. Consequently, where streamflows display multiyear, quasi-periodic variability, as displayed in the Colorado River paleoclimate streamflow record, a dam with storage capacity of up to 2 years of mean annual streamflow could mitigate shortages associated with decadal and perhaps bidecadal variability. However, such a dam may have little functional impact in mitigating severe lower-frequency shortages such as those characterized in the Colorado River.

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

2.4.2. Developing the Floodplain: The Perception of Safety Behind Dams

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

In addition to subsidies for flood insurance, the provision and maintenance of flood control infrastructure continues to encourage development in the flood plain. The Natomas subdivision in Sacramento, CA, is a case in point. Record flooding in 1988 and 1997 [*National Research Council et al*., 1999] led to a reassessment of flood control infrastructure originally intended to protect Sacramento from flood events with a 1 in 100 year average recurrence interval (ARI). The subsequent revision found that the existing flood control capacity was as low as a 1 in 85 year ARI [*Governor's Flood Emergency Action Team*, 1997] or 1 in 77 when climate-informed analysis was considered [*National Research Council et al*., 1999] resulting in a halt to further development in 2008. However, the 2014 Water Resources Reform and Development Act authorized the USACE to fortify levees encircling the Natomas basin "much to the excitement of developers, realtors and Sacramento City Hall—all of whom are ready to cash in" [*Maiman*, 2014]. The occurrence of a flood event similar to the 1862 flood with an estimated 1 in 500–1000 year ARI [*Porter et al*., 2011] would still likely overwhelm the upgraded flood control infrastructure. Putting Natomas in the context of such a scenario is downright scary, and speaks to the human tendency to discount low probability, high impact events [*Kousky and Kunreuther*, 2009].

2.5. The Environmental and Social Costs of Dams

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

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

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

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

4. Deciding the Future of Dams and Research for A Way Forward

As we noted earlier, dams have supported human civilizations since the very beginning, and now, at a time when climate challenges, global population, and demands on United States' resources are all increasing, we appear to be on the verge of having a national discussion regarding the need to dismantle dams [*Shuman*, 1995]. A decision matrix is introduced in Table 1 to help structure and direct thinking as to some of the factors that need to be systematically analyzed as we consider dam removal or rehabilitation. In all such decisions today, we need to consider expected impacts, costs, benefits, and adaptations over multiple decades. Over such a long period, our exposure to climate risk will change in significant and unpredictable ways. Furthermore, consideration needs to be given to potential changes in demand for water and flood protection. These include changes in demographics, preferences, and the mechanics, demands, and efficiencies of agriculture, energy production, and industry.

Sustainability, resilience, hydromorphology, social hydrology and system complexity have been popular concepts and have expanded thinking in the recent literature [*Sivapalan et al*., 2012; *Lall*, 2014; *Montanari*, 2014; *Gober and Wheater*, 2015; *Vogel et al*., 2015]. These concepts will help inform the future of dams on the United States landscape.

Table 1. Options for Balancing Water Supplies and Demands

	Options for Aging/Inadequate Dams				
Impacts and Adaptations	Expand/ Retrofit[a]	Preserve/ Restore[b]	Replace	Replace With Smaller Dams	Remove
Costs					
Deconstruction			$$$[c]	$$$	$$$
Construction	$$	$$	$$$$	$$$	
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 multisite 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

[a] Add to existing capacity through additional dam wall height or additional spillway capacity.
[b] Restore aged dam to original design strength and capacity.
[c] $ and ✓ symbols are intended to portray a relative cost or benefit amongst alternatives.

4.1. Research Agenda: Dams and Climate in the 21st Century

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

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

4.1.1. Dam Failure Risk Assessment

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

   An understanding of interannual to decadal-scale hydrological variability is needed to inform multiannual predictions of regions that may be transitioning to a riskier regime (either prolonged drought or increased flood risk). The degree to which protracted dry and wet spells influence pore pressures, water table levels, and subsequently impact on the structural safety of dams requires investigation.

   Research on shorter timescales is also needed—both individual and sequential severe storms are a significant risk to interconnected reservoir systems. An approach to modeling extreme hydrologic events that utilizes the complete range of available data from radar rainfall fields as well as hydrometeorological models could be developed. Quantifying how the risk associated with such storms changes over space and time in response to changing climatic conditions can improve risk characterization, conjunctive reservoir management, and flood insurance pricing.
2. *Failure impact dynamics*: Given that an extreme regional rainfall event could be a trigger for dam failure, research is needed to develop assessments of potential impacts from flooding that may result with and without dam failure. These include quantifying the potential of cascading failures of multiple dams and subsequent impacts on critical infrastructure elements including power plants, bridges and highways, and water and wastewater treatment plants. Such an approach could inform the probability of property and life losses, health impacts, and interruptions to business and services. An understanding of these impacts would enable elements critical to the physical and socioeconomic recovery of the region to be informed.
3. *Risk-based portfolio management*: A strategy for prioritizing dam safety 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 versus 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.

4.1.2. 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 multiyear 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 interannual to decadal timescales [*Russo and Lall*, 2017], 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 Haimes*, 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 implementation 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 multiyear streamflow anomalies) to explore portfolios of surface and groundwater storage relative considering water use requirements (e.g., urban, industrial, energy, minerals production, and 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, 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 interannual 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 interbasin water transfers and rights need to be codesigned 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 nonstructural 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 nonstructural measures. Innovative smart water management that balances multitime-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, and 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 controversial. Understanding the social dynamics and the mechanisms that may lead to conflict resolution and cooperation across different affected actors is needed as part of the process that determines the sociopolitical acceptability, and hence the viability, of any plans related to dams and water management.

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

Acknowledgments
We thank Connie Woodhouse from the School of Geography and Development, University of Arizona, for providing the Colorado streamflow reconstruction and providing feedback on the manuscript. We thank Francisco Assis Souza Filho for generating Figure 3 and Luc Bonnafous from the Columbia Water Center, Columbia University, for help with data collection. We would like to thank the three anonymous reviewers for providing us with suggestions, insightful comments, and additional facts that improved the manuscript. M. Ho, U. Lall, I. Pal, and N. Devineni are funded by NSF award 1360446. M. Allaire is funded by a Nature Net Postdoctoral Fellowship, through the Nature Conservancy. H. H. Kwon is supported by a grant [MPSS-NH-2015-78] through the Disaster and Safety Management Institute funded by the Ministry of Public Safety and Security of the Korean government. Dams data may be obtained from *U.S. Army Corps of Engineers* [2015] and *Stanford University* [2016]. Paleoclimate reconstructions may be obtained from *Woodhouse et al.* [2006b].

References

Advisory Committee on Water Information Open Water Data Initiative (2014), *Drought in the Colorado River Basin*, Washington, D. C. [Available at <https://www.doi.gov/water/owdi.cr.drought/en/>, accessed 28 Sep. 2016.]

Albert, R. C. (2010), *Damming the Delaware: The Rise and Fall of Tocks Island Dam*, Penn State Press, University Park, Pa.

American Society of Civil Engineers (2013), *2013 Report Card for America's Infrastructure: Dams*, Reston, Va. [Available at <http://www.infrastructurereportcard.org/a/ - p/dams/overview>, accessed 13 June 2016.]

Annandale, G. (2013), *Quenching the Thirst: Sustainable Water Supply and Climate Change*, 250 pp., CreateSpace Independent Publ. Platform, Charleston, SC.

Aspen Institute (2002), *Dam Removal A New Option For a New Century: Aspen Institute*, The Aspen Inst., Queenstown, Md.

Association of State Dam Safety Officials (2000), *Summary of State Laws and Regulations on Dam Safety*, 168 pp., Lexington, KY.

Association of State Dam Safety Officials (2016), Dam Failures, Dam Incidents (Near Failures), 18 pp., Lexington, KY.

Babbitt, B. (2002), What goes up, may come down: Learning from our experiences with dam construction in the past can guide and improve dam removal in the future, *BioScience*, *52*(8), 656–658, doi: 10.1641/0006-3568(2002)052[0656:WGUMCD]2.0.CO;2.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005): Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, *438*(7066), 303–309, doi:10.1038/nature04141.

Barry, J. M. (1998), *Rising Tide: The great Mississippi Flood of 1927 and How It Changed America*, 528 pp., Simon and Schuster, New York, N. Y.

Beard, D. P. (2015), *Deadbeat Dams: Why We Should Abolish the US Bureau of Reclamation and Tear Down Glen Canyon Dam*, Johnson Books, Boulder, Colo.

Bednarek, A. T. (2001), Undamming rivers: A review of the ecological impacts of dam removal, *Environ. Manage.*, *27*(6), 803–814, doi: 10.1007/s002670010189.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R. W. A. Hutjes, J. Heinke, W. von Bloh, and D. Gerten (2011), Impact of reservoirs on river discharge and irrigation water supply during the 20th century, *Water Resour. Res.*, *47*, W03509, doi:10.1029/2009WR008929.

Borrello, S. (2016), 'Extremely High Risk' Dams a Concern Amid Historic Houston Floods, *ABC NEWS*, 20 April.

Bosshard, P. (2015), 12 Dams that Changed the World, *The Guardian*, 12 Jan. 2015.

Brown, C., and U. Lall (2006), Water and economic development: The role of variability and a framework for resilience, *Nat. Resour. Forum*, *30*(4), 306–317, doi:10.1111/j.1477-8947.2006.00118.x.

Brown, C., and M. Carriquiry (2007), Managing hydroclimatological risk to water supply with option contracts and reservoir index insurance, *Water Resour. Res.*, *43*, W11423, doi:10.1029/2007WR006093.

Buchele, M. (2013), Want to Learn About a Nearby Dam? In Texas, Some Questions Are Off Limits, *KUT News*, 3 Aug 2016.

Bureau of Reclamation (2012), Colorado River Basin Water Supply and Demand Study, 85 pp., Boulder City, NV.

Bureau of Reclamation (2016), *About Us: Fact Sheet*, Washington, D. C. [Available at <http://www.usbr.gov/main/about/fact.html>, accessed 23 Aug. 2016.]

Burt, O. R. (1964), The economics of conjunctive use of ground and surface water, *Hilgardia*, *36*(2), 31–111, doi:10.3733/hilg.v36n02p031.

Caldwell, P. V., G. Sun, S. G. McNulty, E. C. Cohen, and J. A. Moore Myers (2012), Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US, *Hydrol. Earth Syst. Sci.*, *16*(8), 2839–2857, doi:10.5194/hess-16-2839-2012.

California Department of Water Resources (2015), *Groundwater Information Center: Key Legislation*, Sacramento, Calif. [Available at <http://www.water.ca.gov/groundwater/groundwater_management/legislation.cfm>, accessed 13 Jan. 2016.]

Cernea, M. M. (2008), Compensation and benefit sharing: Why resettlement policies and practices must be reformed, *Water Sci. Eng.*, *1*(1), 89–120, doi:10.1016/S1674-2370(15)30021-1.

Ceylan, G., and N. Devineni (2014), Drought risk assessment for greater New York area: A paleo view, Abstract #H23N-1080 presented at 2014 Fall Meeting, AGU, Washington, San Francisco, Calif.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer (2004), The effects of climate change on the hydrology and water resources of the Colorado River basin, *Clim. Change*, *62*(1), 337–363, doi:10.1023/B:CLIM.0000013684.13621.1f.

Colby, S. L., and J. M. Ortman (2015), *Projections of the Size and Composition of the U.S. Population: 2014 to 2060, Population Estimates and Projections*, 13 pp., US Census Bureau, Washington, D. C.

Comiskey, J. J. (2010), Overview of flood damages prevented by US Army Corps of Engineers flood control reduction programs and activities, *J. Contemp. Water Res. Educ.*, *130*(1), 13–19.

Cook, B. I., J. E. Smerdon, R. Seager, and E. R. Cook (2014), Pan-continental droughts in North America over the Last Millennium, *J. Clim.*, *27*(1), 383–397, doi:10.1175/JCLI-D-13-00100.1.

Cook, E. R., and G. C. Jacoby (1977), Tree-ring-drought relationships in the Hudson Valley, New York, *Science*, *198*(4315), 399–401, doi:10.1126/science.198.4315.399.

Cook, E. R., and G. C. Jacoby (1983), Potomac river streamflow since 1730 as reconstructed by tree rings, *J. Clim. Appl. Meteorol.*, *22*(10), 1659–1672, doi:10.1175/1520-0450(1983)022 < 1659:PRSSAR>2.0.CO;2.

Cook, E. R., K. R. Briffa, and P. D. Jones (1994), Spatial regression methods in dendroclimatology: A review and comparison of two techniques, *Int. J. Climatol.*, *14*(4), 379–402, doi:10.1002/joc.3370140404.

Cook, E. R., R. Seager, R. R. Heim, R. S. Vose, C. Herweijer, and C. Woodhouse (2010), Megadroughts in North America: Placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context, *J. Quat. Sci.*, *25*(1), 48–61, doi:10.1002/jqs.1303.

Cordell, L. S., C. R. Van West, J. S. Dean, and D. A. Muenchrath (2007), Mesa Verde settlement history and relocation, *KIVA J. Southwest. Anthropol. Hist.*, *72*(4), 379–405, doi:10.1179/kiv.2007.72.4.001.

Costa, J. E. (1985), Floods from Dam Failures, *U.S. Geol. Surv. Open File Rep.*, *85-560*, pp. 54.

Council on Environmental Quality (2014), *Updated Principles, Requirements and Guidelines for Water and Land Related Resources Implementation Studies*, Washington, D. C. [Available at <https://www.whitehouse.gov/administration/eop/ceq/initiatives/PandG>, accessed 13 Jan. 2016.]

Department of the Army-Corps of Engineers (2016), *Federal Register: Proposal To Reissue and Modify Nationwide Permits; Proposed Rule Department of Defense*, 81 ed., 56 pp., Washington, D. C.

Department of the Interior (2009), *109 DM 1 Secretarial Officers*, 2nd ed., Washington, D. C.

Dettinger, M., B. Udall, and A. Georgakakos (2015), Western water and climate change, *Ecol. Appl.*, *25*(8), 2069–2093, doi:10.1890/15-0938.1.

Devineni, N., U. Lall, N. Pederson, and E. Cook (2013), A tree-ring-based reconstruction of Delaware river basin streamflow using hierarchical Bayesian regression, *J. Clim.*, *26*(12), 4357–4374, doi:10.1175/jcli-d-11-00675.1.

Devineni, N., U. Lall, E. Etienne, D. Shi, and C. Xi (2015), America's water risk: Current demand and climate variability, *Geophys. Res. Lett.*, *42*, 2285–2293, doi:10.1002/2015GL063487.

Doyle, M. W., E. H. Stanley, J. M. Harbor, and G. S. Grant (2003), Dam removal in the United States: Emerging needs for science and policy, *Eos Trans. AGU*, *84*(4), 29–33, doi:10.1029/2003EO040001.

Economist Group (2010), The Ups and Downs of Dams, *The Economist*.

Elçi, Ş. (2008), Effects of thermal stratification and mixing on reservoir water quality, *Limnology*, *9*(2), 135–142, doi:10.1007/s10201-008-0240-x.

Erkyihun, S. T., B. Rajagopalan, E. Zagona, U. Lall, and K. Nowak (2016), Wavelet-based time series bootstrap model for multidecadal streamflow simulation using climate indicators, *Water Resour. Res.*, *52*, 4061–4077, doi:10.1002/2016WR018696.

Federal Emergency Management Agency (2004), *Federal Guidelines for Dam Safety: Hazard Potential Classification System for Dams*, 8 pp., Frederick, Md.

Foley, J. A., et al. (2005), Global consequences of land use, *Science*, *309*(5734), 570–574, doi:10.1126/science.1111772.

Gelman, A. (2014), Mega-dams are a mega-waste of Moneh and resources, *The Washington Post*, 25 March 2014.

George, M. W., R. H. Hotchkiss and R. Huffaker (2016), Reservoir Sustainability and Sediment Management, *J. Water Resour. Plann. Manage.*, *8*, 1–8, doi:10.1061/(ASCE)WR.1943-5452.0000720.

Gladwell, M. (2015), Starting Over, *The New Yorker*, Conde Nast, pp. 32–37, New York, N. Y.

Gleick, P. H. (1990), Vulnerability of water systems, in *Climate Change and U.S. Water Resources*, edited by P. E. Waggoner, pp. 223–240, Wiley-Interscience, New York.

Gober, P., and H. S. Wheater (2015), Debates: Perspectives on socio-hydrology: Modeling flood risk as a public policy problem, *Water Resour. Res.*, *51*, 4782–4788, doi:10.1002/2015WR016945.

Goralczyk, M. (2015), *Quantifying how Drought and Increases in Water Demand may Impact Municipal Water Supplies for Durham, North Carolina*, 32 pp., Sch. of the Environ., Duke Univ., Durham, N. C.

Goteti, G. (2015), *Dams in the United States from the National Inventory of Dams (NID)*, U.S. Army Corps of Eng., East Lansing, Mich. [Available at <https://cran.r-project.org/web/packages/dams/index.html>.]

Governor's Flood Emergency Action Team (1997), *Final Report*, 173 pp., Sacramento, Calif.

Graf, W. L. (1999), Dam nation: A geographic census of American dams and their large-scale hydrologic impacts, *Water Resour. Res.*, *35*(4), 1305–1311, doi:10.1029/1999WR900016.

Graf, W. L. (2001), Damage control: Restoring the physical integrity of America's rivers, *Ann. Assoc. Am. Geogr.*, *91*(1), 1–27, doi:10.1111/0004-5608.00231.

Grantham, T. E., and J. H. V. Viers (2014), 100 years of California's water rights system: Patterns, trends and uncertainty, *Environ. Res. Lett.*, *9*(8), 084012, doi:10.1088/1748-9326/9/8/084012.

Gray, S. T., J. L. Betancourt, C. L. Fastie, and S. T. Jackson (2003), Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains, *Geophys. Res. Lett.*, *30*(6), 1316, doi:10.1029/2002GL016154.

Greenbaum, N., T. M. Harden, V. R. Baker, J. Weisheit, M. L. Cline, N. Porat, R. Halevi, and J. Dohrenwend (2014), A 2000 year natural record of magnitudes and frequencies for the largest Upper Colorado River floods near Moab, Utah, *Water Resour. Res.*, *50*, 5249–5269, doi:10.1002/2013WR014835.

Hard, J. J., R. G. Kope, W. S. Grant, F. W. Waknitz, L. T. Parker, and R. S. Waples (1996), *Status Review of Pink Salmon from Washington, Oregon, and California*, 131 pp., Seattle, Wash.

Hayhoe, K., C. Wake, B. Anderson, X.-Z. Liang, E. Maurer, J. Zhu, J. Bradbury, A. DeGaetano, A. M. Stoner, and D. Wuebbles (2008), Regional climate change projections for the Northeast USA, *Mitig. Adapt. Strat. Glob. Change*, *13*(5), 425–436, doi:10.1007/s11027-007-9133-2.

Ho, M., U. Lall, and E. R. Cook (2016a), *Missouri River Basin 533 Year Annual Streamflow Reconstructions*, NOAA, Boulder, Colo. [Available at <https://www.ncdc.noaa.gov/paleo/study/19520>.]

Ho, M., V. Parthasarathy, E. Etienne, T. A. Russo, N. Devineni and U. Lall (2016b), America's water: Agricultural water demands and the response of groundwater, *Geophys. Res. Lett.*, *43*, 7546–7555, doi:10.1002/2016GL069797.

Hsieh, W. S. (1999), Flushing sediment through reservoirs, *J. Hydraul. Res.*, *37*(6), 743–757, doi:10.1080/00221689909498509.

Hundley, N., Jr. (1986), *The West Against Itself: The Colorado River—an Institutional History. New Courses for the Colorado River: Major Issues for the Next Century*, 9–49 pp., Univ. of N. M. Press, Albuquerque.

Hurd, B., N. Leary, R. Jones, and J. Smith (1999), Relative regional vulnerability of water resources to climate change, *J. Am. Water Resour. Assoc.*, *35*(6), 1399–1409, doi:10.1111/j.1752-1688.1999.tb04224.x.

International Rivers (2007), *Dam Performance and Safety*, Berkeley, Calif. [Available at <https://www.internationalrivers.org/dam-performance-and-safety>, accessed 4 Aug. 2016.]

Joint Hearing on the Sierra Club's Proposal to Drain Lake Powell or Reduce its Water Storage Capability (1998), *Subcommittee on Water and Power of the Committee on Resources, House of Representatives*, 147, Washington, D. C.

Jørgensen, D., and B. M. Renöfält (2013), Damned if you do, dammed if you don't: Debates on dam removal in the Swedish media, *Ecol. Soc.*, *18*(1), 1–9, doi:10.5751/ES-05364-180118.

Kendy, E., C. Apse, and K. Blann (2012), *A Practical Guide to Environmental Flows for Policy and Planning*, pp. 72, Nat. Conservancy, Arlington, Va.

Khalil, A. F., H.-H. Kwon, U. Lall, M. J. Miranda and J. Skees (2007), El Niño-Southern Oscillation-based index insurance for floods: Statistical risk analyses and application to Peru, *Water Resour. Res.*, *43*, W10416, doi:10.1029/2006WR005281.

Kirby, M., R. Bark, J. Connor, M. E. Qureshi, and S. Keyworth (2014), Sustainable irrigation: How did irrigated agriculture in Australia's Murray–Darling Basin adapt in the Millennium Drought?, *Agric. Water Manage.*, *145*, 154–162, doi:10.1016/j.agwat.2014.02.013.

Kirchhoff, C. J., and L. Dilling (2016), The role of U.S. states in facilitating effective water governance under stress and change, *Water Resources Research*, *52*, 2951–2964, doi:10.1002/2015WR018431.

Kohler, T. A., M. D. Varien, A. M. Wright, and K. A. Kuckelman (2008), Mesa verde migrations, *Am. Sci.*, *96*(2), 146–153, doi:10.1511/2008.70.3641.

Kolesar, P., and J. Serio (2011), Breaking the deadlock: Improving water-release policies on the Delaware river through operations research, *Interfaces*, *41*(1), 18–34, doi:doi:10.1287/inte.1100.0536.

Kondolf, M. G. (1997), PROFILE: Hungry water: Effects of dams and gravel mining on river channels, *Environ. Manage.*, *21*(4), 533–551, doi:10.1007/s002679900048.

Kousky, C., and H. Kunreuther (2009), *Improving Flood Insurance and Flood Risk Management: Insights from St. Louis, Missouri*, 34 pp., Resources for the Future, Washington, D. C.

Kousky, C., and E. Michel-Kerjan (2015), Examining Flood Insurance Claims in the United States: Six key findings, *J. Risk Insur.*, 1–32, doi:10.1111/jori.12106.

Kwon, H.-H., and U. Lall (2016), A copula-based nonstationary frequency analysis for the 2012–2015 drought in California, *Water Resour. Res.*, *52*, 5662–5675, doi:10.1002/2016WR018959.

Kwon, H.-H., U. Lall, Y.-I. Moon, A. F. Khalil, and H. Ahn (2006), Episodic interannual climate oscillations and their influence on seasonal rainfall in the Everglades National Park, *Water Resour. Res.*, *42*, W11404, doi:10.1029/2006WR005017.

Kwon, H.-H., U. Lall, and A. F. Khalil (2007), Stochastic simulation model for nonstationary time series using an autoregressive wavelet decomposition: Applications to rainfall and temperature, *Water Resour. Res.*, *43*, W05407, doi:10.1029/2006WR005258.

Kwon, H.-H., U. Lall, and J. Obeysekera (2009), Simulation of daily rainfall scenarios with interannual and multidecadal climate cycles for South Florida, *Stochastic Environ. Res. Risk Assess.*, *23*(7), 879–896, doi:10.1007/s00477-008-0270-2.

Lall, U. (1995), Yield model for screening surface- and ground-water development, *J. Water Resour. Plann. Manage.*, *121*(1), 9–22, doi:10.1061/(ASCE)0733-9496(1995)121:1(9).

Lall, U. (2014), Debates—The future of hydrological sciences: A (common) path forward? One water. One world. Many climes. Many souls, *Water Resour. Res.*, *50*, 5335–5341, doi:10.1002/2014WR015402.

Lane, M. E., P. H. Kirshen, and R. M. Vogel (1999), Indicators of impacts of global climate change on U.S. water resources, *J. Water Resour. Plann. Manage.*, *125*(4), 194–204, doi:10.1061/(ASCE)0733-9496(1999)125:4(194).

Lawson, M. (1994), *Dammed Indians: The Pick-Sloan Plan and the Missouri River Sioux, 1944-1980*, illustrated reprint ed., Univ. of Okla. Press, Norman.

Li, L., W. Li, and Y. Kushnir (2012), Variation of the North Atlantic subtropical high western ridge and its implication to Southeastern US summer precipitation, *Clim. Dyn.*, *39*(6), 1401–1412, doi:10.1007/s00382-011-1214-y.

Lustgarten, A. (2016), Unplugging the Colorado River: Could the end be near for one of the West's biggest dams, *The New York Times*.

Maiman, B. (2014), Building again in Natomas is too risky, *The Sacramento Bee*.

Marston, L., and X. Cai (2016), An overview of water reallocation and the barriers to its implementation, *WIREs. Water*, *3*(5), 658–677, doi:10.1002/wat2.1159.

McCartney, K. (2005), *Frequently Asked Questions about the Potential Black Rock Project and the Yakima River Basin Water Storage Feasibility Study*, Yakima, Wash. [Available at <http://www.usbr.gov/pn/programs/storage_study/pdf/faq_091605.pdf>, accessed 27 Sep. 2016.]

McCord, V. A. S. (1990), Augmenting flood frequency estimates using flood-scarred trees, Dep. of Geosci., The Univ. of Ariz., Tucson, Ariz.

McKinney, T., D. W. Speas, R. S. Rogers, and W. R. Persons (2001), Rainbow Trout in a Regulated River below Glen Canyon Dam, Arizona, following Increased Minimum Flows and Reduced Discharge Variability, *N. Am. J. Fish. Manage.*, *21*(1), 216–222, doi:10.1577/1548-8675(2001)021 < 0216:RTIARR>2.0.CO;2.

Meadow, A. M., Z. Guido, M. A. Crimmins, and J. McLeod (2016), From principles to action: Applying the National Research Council's principles for effective decision support to the Federal Emergency Management Agency's watch office, *Clim. Serv.*, *1*, 12–23, doi:10.1016/j.cliser.2016.02.002.

Meko, D. M., C. A. Woodhouse, C. A. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and M. W. Salzer (2007), Medieval drought in the upper Colorado River Basin, *Geophys. Res. Lett.*, *34*, L10705, doi:10.1029/2007GL029988.

Montanari, A. (2014), Debates—The future of hydrological sciences: A (common) path forward? introduction, *Water Resour. Res.*, *50*, 5334–5334, doi:10.1002/2014WR015714.

Morris, G. L., and J. Fan (1998), *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use*, McGraw-Hill, New York, N. Y.

Namias, J. (1966), Nature and possible causes of the Northeastern United States drought during 1962–65, *Mon. Weather Rev.*, *94*(9), 543–554, doi:10.1175/1520-0493(1966)094 < 0543:NAPCOT>2.3.CO;2.

National Research Council (1997), *Valuing Ground Water: Economic Concepts and Approaches*. The Natl. Acad. Press, Washington, D. C.

National Research Council, Committee on American River Flood Frequencies, Commission on Geosciences Environment and Resources and Division on Earth and Life Studies (1999), *Improving American River Flood Frequency Analyses*, Natl. Acad. Press, Washington, D. C.

Nilsson, C., and K. Berggren (2000), Alterations of Riparian Ecosystems Caused by River Regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of rivers remains one of the most important questions of our time, *BioScience*, *50*(9), 783–792, doi: 10.1641/0006-3568(2000)050[0783:AORECB]2.0.CO;2.

Nowak, K. C., B. Rajagopalan, and E. Zagona (2011), Wavelet Auto-Regressive Method (WARM) for multi-site streamflow simulation of data with non-stationary spectra, *J. Hydrol.*, *410*(1–2), 1–12, doi:10.1016/j.jhydrol.2011.08.051.

Office of Inspector General (2013), *Central Valley Project, California: Repayment Status and Payoff*, 16 pp., Washington, D. C.

Padowski, J. C., and J. W. Jawitz (2012), Water availability and vulnerability of 225 large cities in the United States, *Water Resour. Res.*, *48*, W12529, doi:10.1029/2012WR012335.

Paerl, H. W., N. S. Hall, and E. S. Calandrino (2011), Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change, *Sci. Total Environ.*, *409*(10), 1739–1745, doi:10.1016/j.scitotenv.2011.02.001.

Perkins, R. H., M. Bensi, J. Philip, and S. Sancakatar (2011), *Screening Analysis Report for the Proposed Generic Issue on Flooding of Nuclear Power Plant Sites Following Upstream Dam Failures*, pp. 42, Off. of Nucl. Regul. Res., Div. of Risk Analysis, Washington D. C.

Pinter, N. (2005), One step forward, two steps back on U.S. floodplains, *Science*, *308*(5719), 207–208, doi:10.1126/science.1108411.

Pitt, J. (2001), Can we restore the Colorado River delta?, *J. Arid Environ.*, *49*(1), 211–220, doi:10.1006/jare.2001.0843.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg (1997), The Natural Flow Regime, *BioScience*, *47*(11), 769–784, doi:10.2307/1313099.

Porter, K., et al. (2011), Overview of the ARkStorm scenario, *U.S. Geol. Surv. Open File Rep., 2010-1312*, pp. 183.

Pulido-Velazquez, M., G. F. Marques, J. J. Harou, and J. R. Lund (2016), Hydroeconomic models as decision support tools for conjunctive management of surface and groundwater, in *Integrated Groundwater Management: Concepts, Approaches and Challenges*, edited by A. J. Jakeman, et al., pp. 693–710, Springer, Cham, Switzerland.

Qureshi, M. E., T. Shi, S. E. Qureshi and W. Proctor (2009), Removing barriers to facilitate efficient water markets in the Murray-Darling Basin of Australia, *Agric. Water Manage.*, *96*(11), 1641–1651, doi:10.1016/j.agwat.2009.06.019.

Raff, D. A., T. Pruitt, and L. D. Brekke (2009), A framework for assessing flood frequency based on climate projection information, *Hydrol. Earth Syst. Sci.*, *13*(11), 2119–2136, doi:10.5194/hess-13-2119-2009.

Ravindranath, A., N. Devineni, and P. Kolesar (2016), An environmental perspective on the water management policies of the Upper Delaware River Basin, *Water Policy*, *18*(6), 1399–1419, doi:10.2166/wp.2016.166.

Richter, B. D., and G. A. Thomas (2007), Restoring environmental flows by modifying dam operations, *Ecol. Soc.*, *12*(1), 1–26.

Rodrigues, A. S., M. A. Santos, A. D. Santos, and F. Rocha (2002), Dam-break flood emergency management system, *Water Resour. Manage.*, *16*(6), 489–503, doi:10.1023/A:1022225108547.

Russo, T. A., and U. Lall (2017), Depletion and response of deep groundwater to climate-induced pumping variability, *Nat. Geosci.*, *10*(2), 105–108, doi:10.1038/ngeo2883.

Sankarasubramanian, A., U. Lall, F. A. Souza Filho, and A. Sharma (2009), Improved water allocation utilizing probabilistic climate forecasts: Short-term water contracts in a risk management framework, *Water Resour. Res.*, *45*, W11409, doi:10.1029/2009WR007821.

Schlager, E. (2006), Challenges of governing groundwater in U.S. western states, *Hydrogeol. J.*, *14*(3), 350–360, doi:10.1007/s10040-005-0012-1.

Sewell, W. (1987), The politics of hydro-megaprojects: Damming with Faint Praise in Australia, New Zealand, and British Columbia, *Nat. Resour. J.*, *27*, 497–532.

Showstack, R. (2016), Controversial pacts aim for dam removals on western U.S. river, *Eos*, *97*, doi:10.1029/2016EO049983.

Shuman, J. R. (1995), Environmental considerations for assessing dam removal alternatives for river restoration, *Regul. Rivers*, *11*(3-4), 249–261, doi:10.1002/rrr.3450110302.

Sivapalan, M., H. H. G. Savenije, and G. Blöschl (2012), Socio-hydrology: A new science of people and water, *Hydrol. Processes*, *26*(8), 1270–1276, doi:10.1002/hyp.8426.

Snyder, S. (2016), Alaska can't afford to waste another dime on Susitna dam, *Alaska Dispatch News*, 17 May 2016.

Soumis, N., É. Duchemin, R. Canuel, and M. Lucotte (2004), Greenhouse gas emissions from reservoirs of the western United States, *Global Biogeochem. Cycles*, *18*, GB3022, doi:10.1029/2003GB002197.

St. Louis, V. L., C. A. Kelly, É. Duchemin, J. W. M. Rudd, and D. M. Rosenberg (2000), Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: A Global Estimate: Reservoirs are sources of greenhouse gases to the atmosphere, and their surface areas have increased to the point where they should be included in global inventories of anthropogenic emissions of greenhouse gases, *BioScience*, *50*(9), 766–775, doi: 10.1641/0006-3568(2000)050[0766:RSASOG]2.0.CO;2.

Stanford University (2016), *National Performance of Dams Program*, Stanford, Calif. [Available at <http://npdp.stanford.edu/>, accessed 25 July 2016.]

Steinschneider, S., M. Ho, E. R. Cook, and U. Lall (2016), Can PDSI inform extreme precipitation?: An exploration with a 500 year long paleoclimate reconstruction over the U.S, *Water Resour. Res.*, *52*, 3866–3880, doi:10.1002/2016WR018712.

Stene, E. A. (2015), *The Central Valley Project*. [Available at <https://www.usbr.gov/history/cvpintro.html>, accessed 20 Dec. 2016.]

Struck, D. (2014), Setting rivers free: As dams are torn down, nature is quickly recovering. *The Christian Science Monitor*.

Tennessee Valley Authority (2016), *Flood Damage Reduction*. [Available at <https://www.tva.gov/Environment/Flood-Management>, accessed 20 Dec 2016.]

The Heinz Center (2003), *Dam Removal Research: Status and Prospects*, The H. John Heinz III Cent. for Sci., Econ. and the Environ., Washington, D. C.

Therrell, M. D., and M. B. Bialecki (2015), A multi-century tree-ring record of spring flooding on the Mississippi River, *J. Hydrol.*, *529*(2), 490–498, doi:10.1016/j.jhydrol.2014.11.005.

U.S. Department of Agriculture (2015), *Irrigation and Water Use*, Washington D. C. [Available at <http://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/background.aspx>, accessed 5 Aug. 2016.]

U.S. Army Corps of Engineers (2015), *National Inventory of Dams*, Washington D. C. [Available at <http://nid.usace.army.mil/cm_apex/f?p=838:1:0::NO::APP_ORGANIZATION_TYPE,P12_ORGANIZATION:15>, accessed 10 June 2016.]

Vicuna, S., E. P. Maurer, B. Joyce, J. A. Dracup, and D. Purkey (2007), The Sensitivity of California Water Resources to Climate Change Scenarios1, *J. Am. Water Resour. Assoc.*, *43*(2), 482–498, doi:10.1111/j.1752-1688.2007.00038.x.

Vogel, R. M., M. Lane, R. S. Ravindiran, and P. H. Kirshen (1999), Storage reservoir behavior in the United States, *J. Water Resour. Plann. Manage.*, *125*(5), doi:10.1061/(ASCE)0733-9496(1999)125:5(245).

Vogel, R. M., U. Lall, X. Cai, B. Rajagopalan, P. Weiskel, R. P. Hooper, and N. C. Matalas (2015), Hydrology: The interdisciplinary science of water, *Water Resour. Res.*, *51*, 4409–4430, doi:10.1002/2015WR017049.

Walter, M. T., D. S. Wilks, J.-Y. Parlange, and R. L. Schneider (2004), Increasing evapotranspiration from the conterminous United States, *J. Hydrometeorol.*, *5*(3), 405–408, doi:10.1175/1525-7541(2004)005 < 0405:IEFTCU>2.0.CO;2.

Walton, B. (2015), *Pace of U.S. Dam Removals Accelerates*, Circle of Blue, Calif. [Available at <http://www.circleofblue.org/2015/world/pace-u-s-dam-removals-accelerates/>, accessed 12 Aug. 2016.]

Water Resources Development Act (2016), 114th Congress ed., S.2848, Washington, D. C.

Webb, R. H., D. L. Wegner, E. D. Andrews, R. A. Valdez, and D. T. Patten (2013), Downstream effects of glen Canyon Dam on the Colorado River in Grand Canyon: A review, in *The Controlled Flood in Grand Canyon*, edited by R. H. Webb, pp. 1–21, AGU, Washington, D. C.

Whitelaw, E., and E. Macmullan (2002), A framework for estimating the costs and benefits of dam removal, *BioScience*, *52*(8), 724–730, doi:10.1641/0006-3568(2002)052[0724:AFFETC]2.0.CO;2.

Wisser, D., S. Frolking, S. Hagen, and M. F. P. Bierkens (2013), Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs, *Water Resour. Res.*, *49*, 5732–5739, doi:10.1002/wrcr.20452.

Woodhouse, C. A., S. T. Gray, and D. M. Meko (2006a), Updated streamflow reconstructions for the Upper Colorado River Basin, *Water Resour. Res.*, *42*, W05415, doi:10.1029/2005WR004455.

Woodhouse, C. A., J. Lukas, B. Brice, K. Hirschboeck, H. Hartmann, M. Kostuk, E. Lay, D. Martinex, B. McMahan, and A. Shah (2006b), *Data Access by Basin*, The University of Arizona, Tucson, Ariz. [Available at <http://treeflow.info/content/tree-rings-and-streamflow>, accessed 1 June 2016.]

World Commission on Dams (2000), *Dams and Development: A New Framework for Decision-making: the Report of the World Commission on Dams*, Earthscan, London.

Wuebbles, D. J., and K. Hayhoe (2004), Climate Change Projections for the United States Midwest, *Mitig. Adapt. Strat. Glob. Change*, *9*(4), 335–363, doi:10.1023/B:MITI.0000038843.73424.de.

Yin, X.-A., Z.-F. Yang, G. E. Petts, and G. M. Kondolf (2014), A reservoir operating method for riverine ecosystem protection, reservoir sedimentation control and water supply, *J. Hydrol.*, *512*, 379–387, doi:10.1016/j.jhydrol.2014.02.037.

Young, M. D. (2013), Investing in water services infrastructure policies and management, in *Investing in Water for a Green Economy*, edited by M. D. Young and C. Esau, pp. 3–42, Routledge, New York.

Young, M. D. (2014), Designing water abstraction regimes for an ever-changing and ever-varying future, *Agric. Water Manage.*, *145*, 32–38, doi:10.1016/j.agwat.2013.12.002.

Yu, W., and Y. Y. Haimes (1974), Multilevel optimization for conjunctive use of groundwater and surface water, *Water Resour. Res.*, *10*(4), 625–636, doi:10.1029/WR010i004p00625.

Zarriello, P. J. (2002), Simulation of reservoir storage and firm yields of three surface-water supplies, Ipswich River Basin, Massachusetts, *Water Resour. Invest. Rep., 2002-4278*, pp. 50.

Zeff, H. B., and G. W. Characklis (2013), Managing water utility financial risks through third-party index insurance contracts, *Water Resour. Res.*, *49*, 4939–4951, doi:10.1002/wrcr.20364.