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Have Large Dams Altered Extreme Precipitation Patterns?

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Dams and their impounded waters are among the most common civil infrastructures, with a long heritage of modern design and operations experience. In particular, large dams, defined by the International Commission on Large Dams (ICOLD) as having a height greater than 15 meters from the foundation and holding a reservoir volume of more than 3 million cubic meters, have the potential to vastly transform local climate, landscapes, regional economics, and urbanization patterns.

In the United States alone, about 75,000 dams are capable of storing a volume of water equaling almost 1 year's mean runoff of the nation [*Graf*, 1999]. The World Commission on Dams (WCD) reports that at least 45,000 large dams have been built worldwide since the 1930s. These sheer numbers raise the question of the extent to which large dams and their impounded waters alter patterns that would have been pervasive had the dams not been built.

Of interest is more than just land cover change: Through case studies and theoretical investigations, scientists are exploring the impact large dams have on extreme weather patterns. This issue is of particular importance for aging dams around the world—for example, in the continental United States the majority of dams will be more than 50 years old by 2020 (see Figure 1)—leading scientists to wonder whether these structures can withstand the extreme precipitation events they may generate.

Mechanisms for Altering Extreme Precipitation

The notion that large reservoirs could be built to alter natural precipitation patterns surrounding dams is nothing new [*Eltahir and Bras,* 1996]. More than 70 years ago, *Jensen* [1935] suggested such an idea to "engineer" rainfall, spurring much debate [e.g., *Holzman,* 1937; *Horton,* 1943; *McDonald,* 1962]. An often overlooked aspect of dams is that they trigger regional systematic changes in large-scale land use and land cover (LULC) due to the multiple purposes they serve. Dams provide the means for irrigation, and downstream regions may become more urbanized due to reduced risk of flooding and increased availability of hydropower.

But what could be the physical basis for large dams to alter precipitation patterns? Among the many catalysts for precipitation, one common ingredient is the propensity for the vertical profile of temperature and humidity to contain local atmospheric instabilities. The degree of such instabilities is usually characterized by convective available potential energy (CAPE). The significant changes in LULC that large dams invariably trigger, combined with the greater availability of atmospheric moisture through evaporation from open-water bodies and irrigated land, can result in a similar change in land surface fluxes of heat and moisture. Thus, under certain circumstances, dams and reservoirs can be considered as "enhancers" of CAPE, which in turn may induce more precipitation.

In fact, research over the past 2 decades revealed that systematic changes in LULC can indeed alter regional hydroclimatology [*Feddema et al.,* 2005; *Pielke et al.,* 2007; *Ray et al.,* 2009]. For example, data and modeling studies support the notion that atmospheric moisture added by irrigation can increase rainfall, provided that mesoscale conditions are met [*Lohar and Pal,* 1995]. Research also suggests that dam-driven land cover change can trigger changes in extreme precipitation patterns. *Avissar and Liu* [1996] showed that LULC patchiness can enhance heavy rainfall. Through LULC sensitivity studies [*Pielke et al.,* 1997; *Pielke and Zeng,* 1989; *Pielke et al.,* 2007], irrigated land near multipurpose reservoirs is seen to enhance thunderstorm development more than natural land cover conditions do (e.g., before the dam was built). Additionally, *Kishtawal et al.* [2009] recently

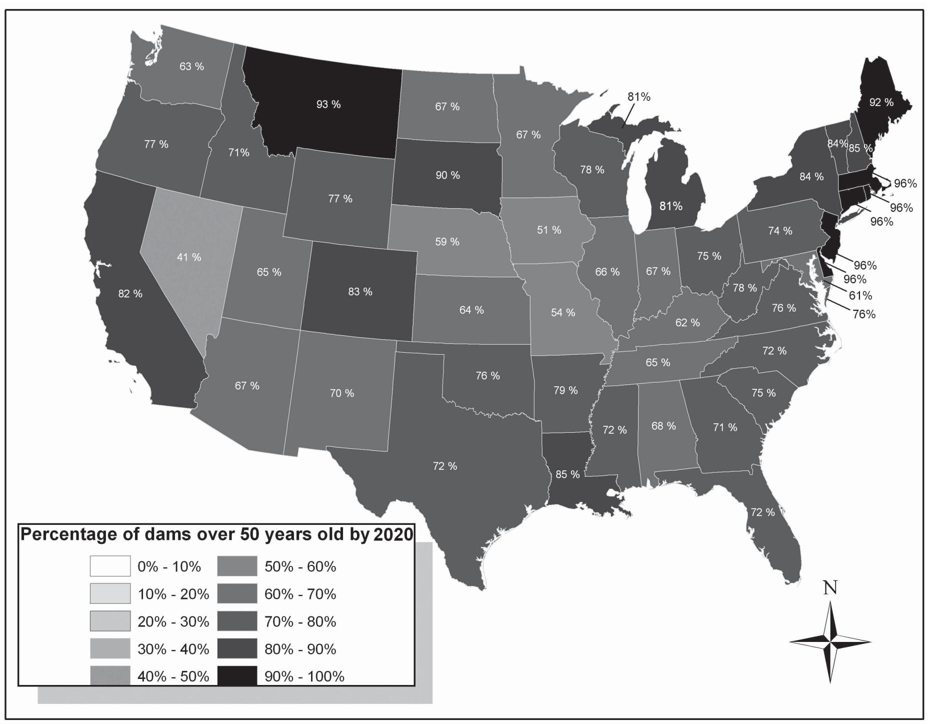

Fig. 1. Distribution of dams in the continental United States that will be older than 50 years by 2020 (darker shades represent higher percentages). These dams may be inducing regional weather extremes they were not built to handle. Source: National Inventory of Dams, U.S. Army Corps of Engineers.

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showed that increased urbanization downstream of large flood control dams can also trigger heavy rainfall patterns.

If extreme precipitation patterns change, then the assumption of stationarity in flood frequency relationships, which is fundamental to the design of flood-safe dams in engineering practice, is violated. Though this is only one of the many sources of nonstationarity observed in hydrologic variables, it is therefore possible that a large dam may be found years later to actually have been designed for a flood with a much lower recurrence interval (or higher frequency) than originally expected because the frequency of extreme precipitation events has increased due to the reservoir's presence. Such a possibility raises concerns about dam safety, particularly if the loss of storage (i.e., reservoir fill-up due to sedimentation) is also assessed through time—an increase in extreme precipitation rates and a decrease of reservoir volume through sedimentation imply that more floodwater than expected would need to be routed through the dam's spillways.

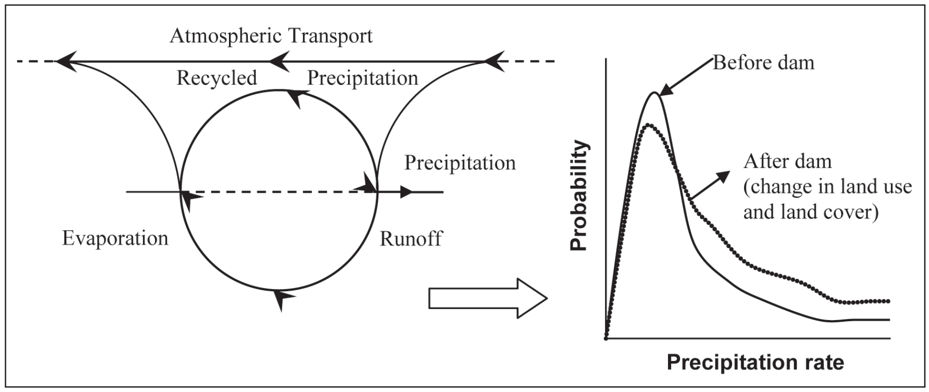

Fig. 2. (a) Schematic conceptualization of man-made alteration of extreme precipitation by a reservoir [from Eltahir and Bras, *1996]. The dashed line through the circle represents the land-atmosphere interface. (b) Graph representing the alteration in extreme precipitation frequency due to dams.*

Understanding How Large Dams Affect Extreme Precipitation Patterns

To understand and predict the impact of a planned (or existing) dam on extreme precipitation, scientists first need to understand how the water cycle interacts with land cover and use in the vicinity of a large dam. More important, scientists must know the physical processes by which large-scale surface evaporation can trigger changes in precipitation recycling (Figure 2). *Eltahir and Bras* [1996, p. 367] define precipitation recycling as a study about "what happens to water vapor molecules after they evaporate from the surface, and where [they] will…precipitate." Precipitation recycling depends on the probability of precipitation being harvested from local evaporation, a factor that increases with the size of the region or the basin. Although considerable studies on large river basins show that precipitation recycling can range from 10% to 50% [*Brubaker et al.,* 1993], none have been directed at understanding the human modification of extreme precipitation and flood frequency by artificial reservoirs.

Before a dam is built, local precipitation may originate from local evaporation and/or advection of atmospheric water vapor, depending on a site's location and the surrounding regional climate. *Eltahir* [1989] analyzed data on swamps in southern Sudan to demonstrate that a wet year usually favored increased precipitation the following year through increased evaporation from the expanded open-water surfaces. Conversely, *Pielke et al.* [1999] have shown that the draining of swamps can result in decreased precipitation through a negative feedback mechanism.

But once large dams are in place, dynamics change. Recent research [i.e., *Hossain et al.,* 2009; *Hossain,* 2009] shows that extreme precipitation (99th percentile) has increased considerably more than increases seen in median precipitation (50th percentile) during the past century. This alteration may be more pronounced in arid and semiarid regions after the dam is built. The 99th percentile of precipitation experienced on average a 4% increase per year after dams were built. In particular, large dams in the regions of southern Africa, India, western United States, and Central Asia appeared to induce a greater increase in extreme precipitation than in other regions.

Hence, after dams impound large reservoirs, it is physically plausible that the increased evaporation from the open-water surface of a reservoir and irrigated land will alter both average and extreme precipitation patterns through a feedback mechanism. Thus, understanding current changes in precipitation flux, frequency, and volume in terms of flood frequency relationships is important, particularly because these changing terms are key to understanding hazards and risks of planned and aging dams.

A word of caution: Atmospheric model–based studies of precipitation recycling remain somewhat controversial [*Ruiz-Barradas and Nigam,* 2005]. Further, other factors may be involved, such as global climate change, effects of aerosols and urbanization, etc. However, not enough is known about these other factors or the extent to which they influence the patterns observed in the vicinity of dams. Thus, more research is needed on all fronts, including dam-induced extreme precipitation.

Planning for the Future

In the continental United States alone, more than 85% of large dams will be more than 50 years old by 2020 (Figure 1). How can society be certain that a 100-year precipitation event for a large dam will not be undermined statistically as a less than 100-year event during the life span of the dam? To what extent can a large reservoir be planned with minimal impact on the regional/local flood frequency relationship? How much land cover change in the vicinity is sustainable to ensure that the dam will remain flood-safe? These are some of the questions that the water resources community must address to ensure sustainable design and management of flood-safe dams and reservoirs for the 21st century.

Hazards and risks associated with such dam-induced precipitation are compounded by the fact that conventional dam and reservoir design over the past century has been "one-way," with no acknowledgment of the possible feedback mechanisms affecting the regional water cycle. Indeed, dam design protocol in civil engineering continues to assume unchanging statistical parameters of extreme precipitation events during the life span of the dam.

More research is necessary to gain insights on contributing physical mechanisms for altering extreme precipitation. To better ensure infrastructural safety and efficient resource management, society would be prudent to embrace an interactive hydrologic and atmospheric science approach to safe dam design and operations for the 21st century.

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G E O P H Y S I C I S T S

Robert Osborne Reid (1921–2009)

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Robert Osborne Reid, Distinguished Professor of Oceanography Emeritus at Texas A&M University (TAMU), passed away on 23 January 2009 at age 87. He was a founding member of the TAMU Department of Oceanography in 1951 and remained an active researcher until his death. Teaching and advising students was his passion. During his career, he chaired or cochaired the doctoral advisory committees of some 70 students in the fields of oceanography, meteorology, civil engineering, and physics. Of the 38 M.S. students he advised, 11 are included in the 70 who completed their Ph.D.s with Professor Reid.

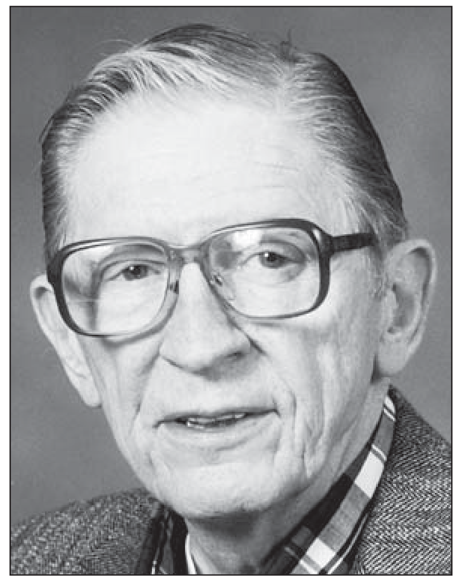
Reid began his academic career as an engineering student at the University of Southern California (USC). That career was interrupted in 1943 when he joined the U.S. Army Air Corps. His military career began with 1 year of training in meteorology at University of California, Los Angeles to become a weather officer. Other notable future oceanographers also received weather training then, including John Cochrane, Donald Pritchard, and Maurice Rattray.

After completing training, Reid was shipped in 1944 to England to await the invasion of France. He was landed on Omaha Beach on 9 June 1944, three days after D-Day, to set up a weather post. The mission was to observe and forecast tides, wave heights and periods, and fog, as well as improve estimates of bathymetry along the beaches, with the objective of rendering safer the offloading of men and materials along the beaches, because ports were not usable at that time. This effort continued, including in ports as well as on beaches, well into the war in Europe. After Paris was cleared, the command of his weather detachment moved into the city. In March 1945, following the Battle of the Bulge, Reid was shipped to Hawaii, where he trained on the north shore of Oahu, observing and predicting beach conditions. He was then sent to Guam in preparation for the planned invasion of Kyushu, Japan.

At the end of the war Reid returned to USC where he completed in 1946 his B.E. degree in mechanical engineering. He then enrolled at the Scripps Institution of Oceanography where he earned his M.S. in oceanography in 1948 while working as a meteorologist at the U.S. Navy Electronics Laboratory in San Diego. On graduating, he accepted a position as a research scientist in the newly formed Marine Life Research Program at Scripps. He left in 1951 to take a faculty position at Texas A&M University, where he was a member of the departments of Oceanography and Meteorology, Civil Engineering, and later Oceanography. Reid served as head of the Department of Oceanography from 1981 until 1987. He formally retired in 2001 but continued to mentor students and perform research.

Reid married Marjorie Ferry in February 1947 at St. James-by-the-Sea in La Jolla, Calif. His groomsmen were fellow oceanographers Warren Thompson, Nick Lundgren, Harald Sverdrup, and Don Pritchard. Bob and Marjorie had six children—three boys and three girls.

Reid was the consummate teacher and advisor. He was a recipient of the Minnie Piper Foundation Award and two TAMU Faculty Distinguished Achievement Awards for Teaching. Perhaps the most vivid thread running through Reid's career at Texas A&M was his unswerving commitment to the highest academic and ethical standards. Beyond teaching, his reputation as a distinguished researcher was recognized nationally and internationally, especially for his works on wave forces, tsunamis, storm surges, and edge waves. His many honors and awards included membership in the National Academy of Engineering and the Coastal Engineering Research Board; the Medal of the University of Liege, Belgium; a Faculty Distinguished Achievement Award for Research from the TAMU Association of Former Students, and an honorary doctor of science from Old Dominion University. He was a Fellow of AGU and the American Meteorological Society, which also awarded him the Special Award and honorary membership.



Robert Osborne Reid

Bob Reid never sought the spotlight; he relied on a much admired ability to initiate research and orchestrate its completion through teamwork with his students and colleagues. Many people have said they worked "*with* Bob" rather than *under* him or *for* him. His selfless dedication to improving oceanographic education and research has become legendary. He will be sorely missed.

His friends and former students have established the Robert O. Reid Oceanographic Fellowship fund (Account 04-57877) with the Texas A&M Foundation, 401 George Bush Drive, College Station, TX 77840-2811.

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