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Dam safety effects due to human alteration of extreme precipitation

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[1] Very little is known about the vulnerability of dams and reservoirs to man-made alteration of extreme precipitation and floods as we step into the 21st century. This is because conventional dam and reservoir design over the last century has been "one-way" with no acknowledgment of the possible feedback mechanisms affecting the regional water cycle. Although the notion that an impoundment could be built to increase rainfall was suggested more than 60 years ago, dam design protocol in civil engineering continues to assume as "static" the statistical parameters of a low exceedance probability precipitation event during the lifespan of the dam. It is time for us to change our perceptions and embrace a hydrometeorological approach to dam design and operations.

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1. Introduction

[2] One of the most common public infrastructures with the longest heritage of modern design and operations experience are perhaps dams and their impounded water reservoirs. Reservoirs today may serve more than one application, such as hydropower generation, fisheries, navigation, recreation, water supply (for public consumption and irrigation) and flood control. In the United States alone, there are about 75,000 registered dams capable of storing a volume of water almost equaling 1 year's mean runoff of the nation [*Graf*, 1999]. Around the world, the *World Commission on Dams* [2000] reports that there have been at least 45,000 dams built since the 1930s. It is estimated that half of the world's rivers have at least one dam somewhere along the reach.

[3] While it may be argued that most large reservoirs that needed to be planned are already in operation, there is a critical need to reassess the whole concept of reservoir operations and dam design from the paradigm of safety during this century. Numerical experiments involving climate model output, water budgets, and socioeconomic population data, clearly indicate that water stress is projected to worsen by 2025 in the United States [*Sun et al.*, 2008] and around the globe [*Vörösmarty et al.*, 2000, 2003, 2005]. This rising water demand due to population growth will require the continuation of existing reservoirs and the construction of new dams at water-stressed locations [*Gleick*, 2002].

[4] Also, dams and their impounded reservoirs are types of infrastructures that trigger a systematic change in large-scale land use and land cover (LULC) due to the multiple purposes they serve. With the advent of a dam, more land may be brought under irrigation and the downstream regions may become more urbanized due to a reduced risk of flooding. Research over the last two decades has demonstrated that a change in LULC can alter the regional hydroclimatology [e.g., *National Research Council*, 2005; *Kabat et al.*, 2004; *Cotton and Pielke*, 2007; *Pielke and Avissar*, 1990, *Pielke*, 2005; *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 the mesoscale conditions are appropriate [*Lohar and Pal*, 1995; *Barnston and Schickedanz*, 1984; *Stidd*, 1975].

[5] If a dam-driven land cover change (LCC) can trigger changes in precipitation patterns, then it will mostly likely also change the patterns of extreme precipitation [*Avissar and Liu*, 1996; *Pielke and Zeng*, 1989]. If extreme precipitation patterns change, then the assumption of stationarity in flood frequency relationships that is fundamental to the current design practice for flood-safe dams is violated [see also *Milly et al.*, 2008]. It is therefore possible that a large dam may be found years later to actually have been designed for a flood with a much shorter recurrence interval (or higher frequency) than the original design flood. Such a possibility raises concerns on dam safety if the loss of storage (i.e., reservoir fill-up due to sedimentation [*Trimble and Bube*, 1990]) is assessed in conjunction with an unaccounted increase in flood volume from extreme precipitation events that would need to be routed through the reservoir.

[6] Have large dams and their impounded reservoirs really played a significant role in altering the extreme precipitation patterns the last century? The notion that a large reservoir could be built to alter the natural precipitation patterns in the vicinity is not new [*Eltahir and Bras*, 1996]. More than 60 years ago, *Jensen* [1935] suggested such an idea to "engineer" rainfall, which has also been debated by *Holzman* [1937] and *Horton* [1943]. However, due to lack of awareness or regulations, the potential impact of these large civil infrastructures on climate was not studied during the dam-building stage of the early 20th century. Now that there are a sufficient number of dams around the world with

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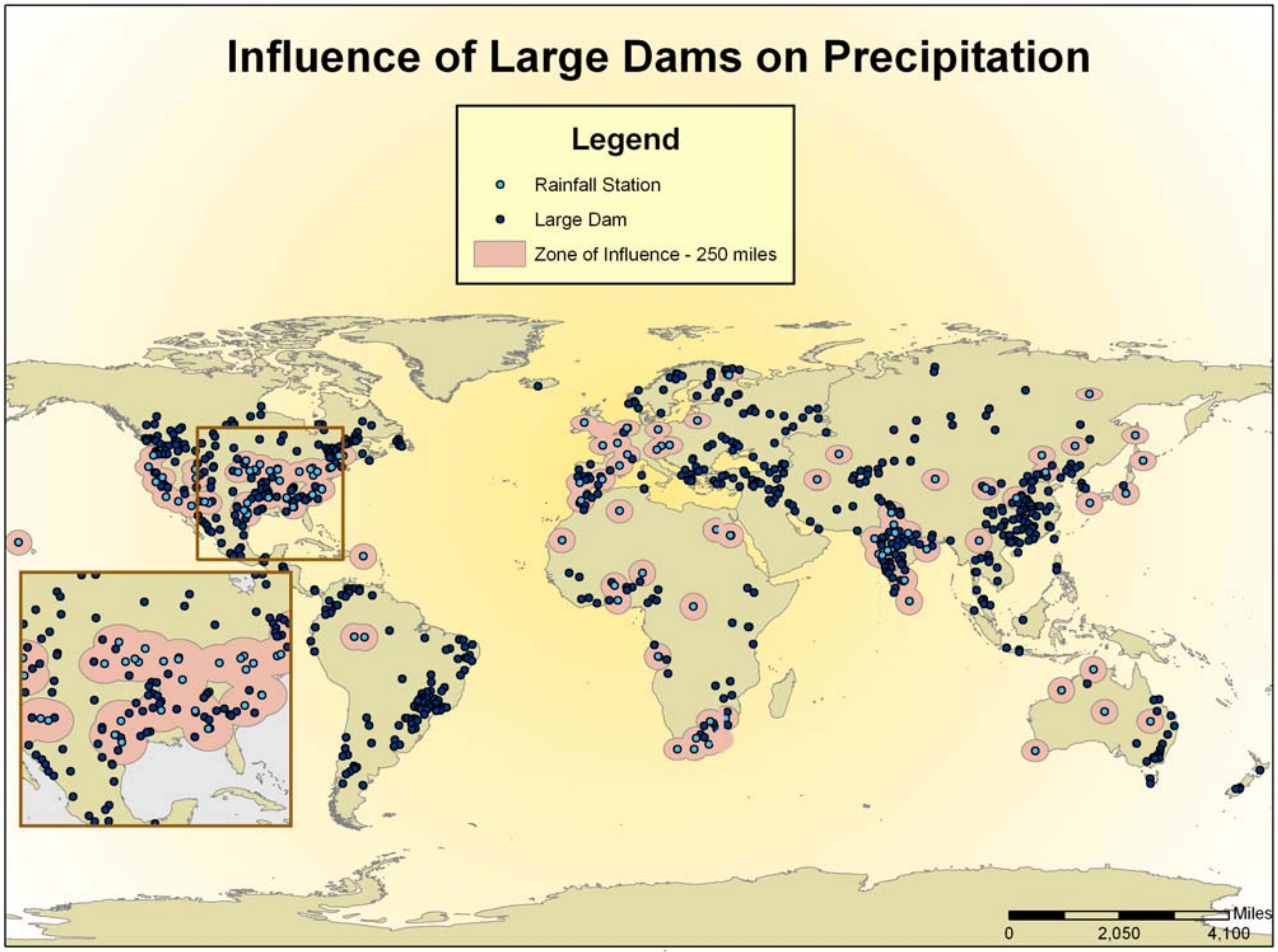

Figure 1. The 633 ICOLD large dams overlaid with 92 precipitation stations. The pink circles indicate a 250 mile (402.336 km) radius of influence around each precipitation station.

a fairly long record of precipitation monitoring, we can comment on the effect that dams may have had on altering precipitation and the consequential implications on dam safety.

2. Influence of Large Dams on Extreme Precipitation Alteration

[7] According to the International Commission on Large Dams (ICOLD) and UNESCO, a large dam is defined as having a height higher than 15 m from the foundation, or holding a reservoir volume of more than 3×10^6 m^3. For our analysis of the impact of dams on extreme precipitation, we first acquired the geographic information system (GIS) for a global databank of 633 large impoundments. This GIS database was available from a series of world dam registers published by the Global Water Systems Project Digital Water Atlas (Dams and capacity of artificial reservoirs (V1.0), Map 41, 2008, available at http://atlas.gwsp.org). This data set was then overlaid with the Global Historical Climate Network (GHCN)–Daily data set. The GHCN-Daily currently serves as the official archive for daily meteorological data from the global climate observing system (GCOS) Surface Network (GSN) of the National Climatic Data Center (NCDC). This data set is particularly appropriate for analyzing activities related to the frequency and magnitude of extremes as it contains meteorological observations at more than 40,000 stations that are distributed across all continents. We identified a set of 92 precipitation stations from the GHCN data set that were distributed around the world and had a sufficiently long and uninterrupted record (>60 years) of daily precipitation observations. Approximately half the stations were in the close vicinity of a large ICOLD dam while the rest were considered too far away to be influenced by the reservoir (i.e., no dams within the 250 mile (402.336 km) radius around a station).

[8] Figure 1 shows the location of the 633 large dams overlaid with the 92 precipitation stations. Our earliest record of precipitation dated back to the early 1900s while the most recent record used in the analysis was from 2008. We analyzed the time series of the 50th and 99th percentile of precipitation for each station and year. Hereafter, these percentiles will be called P50 (median) and P99 (extreme precipitation with 1% probability of exceedance), respectively. The percentiles were computed for a given year using a moving window of the previous 15 years of record at the daily time step. This yielded a fairly stable estimate of the quantiles of precipitation which was not sensitive to the effect of the El–Nino Southern Oscillation (ENSO) on precipitation.

[9] In order to generalize our analysis of the time series of percentiles, we computed the average annual change (%) for

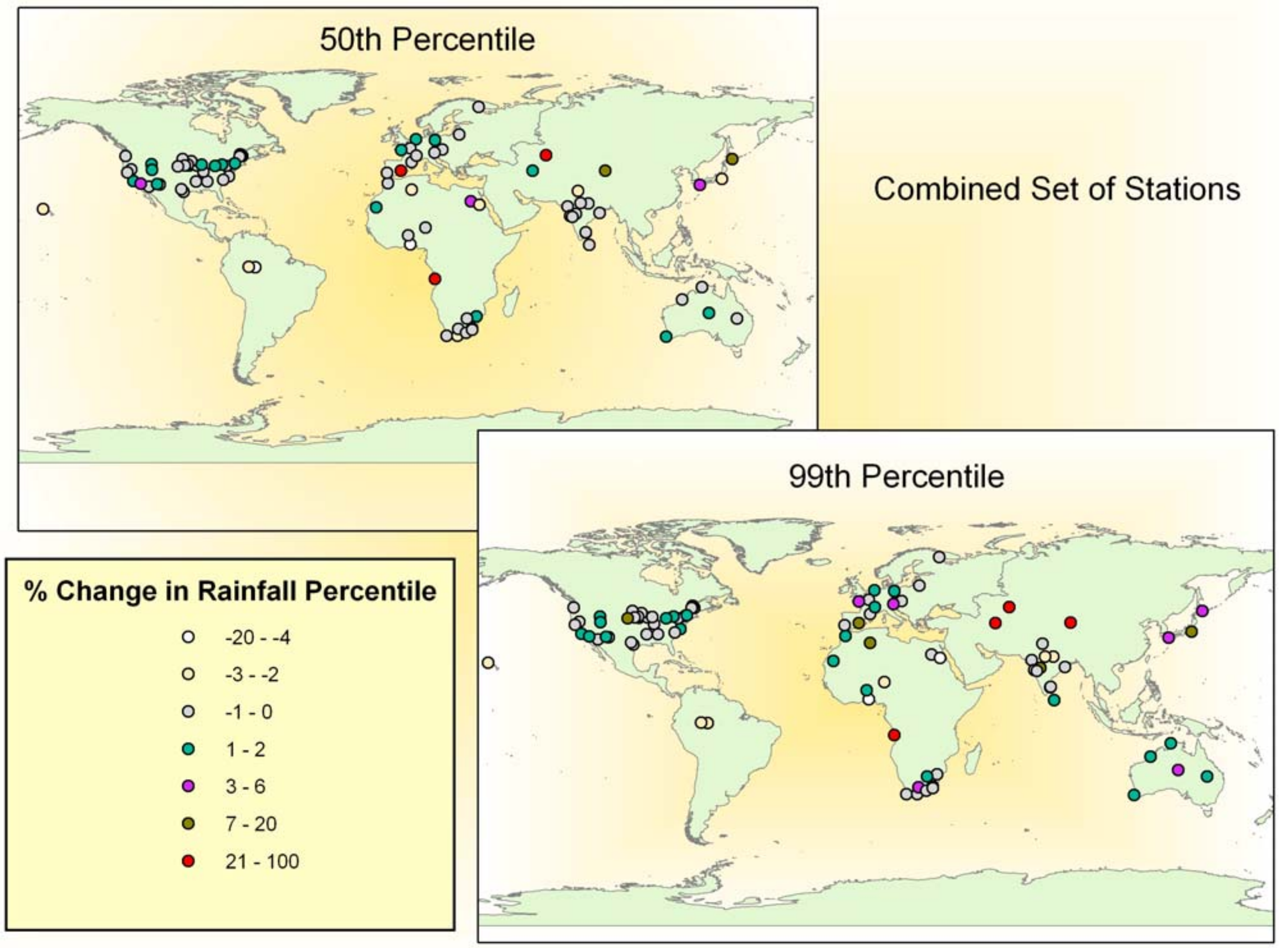

Figure 2. Change in precipitation percentile (averaged over the entire record) for the combined set of stations (those with at least one dam within a 250 mile radius and those without) (from *Hossain* [2009], with permission from ASCE).

a specific percentile over a specific time period (i.e., predam period, postdam period or entire record). First, the percentage change in a percentile value was computed for each year. A positive change for a given year indicated that the magnitude of the percentile had increased relative to the previous year. Next, the average annual percentage change was computed for a specific period. Figure 2 shows the average annual percentage change in percentile value for the entire record. This figure seems to confirm that the extreme precipitation (P99) has been impacted more than the median precipitation (P50) over the last century at several locations. An average annual increase in P99 is observed in the regions of southern Africa, India and central Asia.

[10] When only stations with at least one dam within a 250 mile radius are analyzed (Figure 3) as a function of predam (before the commissioning of the dam) and postdam (after the commissioning of the dam), some interesting trends are observed. For southern Africa and southern Europe, dams appeared to have increased extreme precipitation (P99 events) by as much as 20% during the last century. Stations in southern India are found to have experienced a modest increase in the P99 value (Figure 3). In the U.S., the P50 (mean) and P99 values are found similarly sensitive to the effect of dams. However, the midwestern and western USA regions are found to have been affected less by the presence of dams. These regions experienced an average annual increase in the magnitude for the P99 rainfall event in the ranges of just 1–5% during the last century. Finally, in Figure 4, the time series of percentiles are shown for three select stations that experienced an increase in magnitude of P99 for a distinct period after the construction of dams within a 250 mile radius. The name and year of commissioning of the dams are shown in the right column in parentheses.

3. Issues of Dam Safety Against Human Alteration to Extreme Precipitation

[11] The past century has witnessed tremendous progress on dam safety against hazards of earthquakes [e.g., *Marcuson et al.*, 1996], piping/seepage [e.g., *Casagrande*, 1961; *Sherard*, 1987], and structural instability [e.g., *Terzaghi and LaCroix*, 1964; *Vick and Bromwell*, 1989]. Similarly, much is now known about the management of postdam effects on aquatic ecology [e.g., *Ligon et al.*, 1995; *Richter et al.*, 2002], riparian vegetation [e.g., *Merritt and Cooper*, 2000], and geomorphology [e.g., *Graf*, 2006]. Yet, very little is known about the vulnerability of dams and reservoirs to man-made modifications of extreme precipitation and flood frequency risks. Our global study of precipitation records shows that,

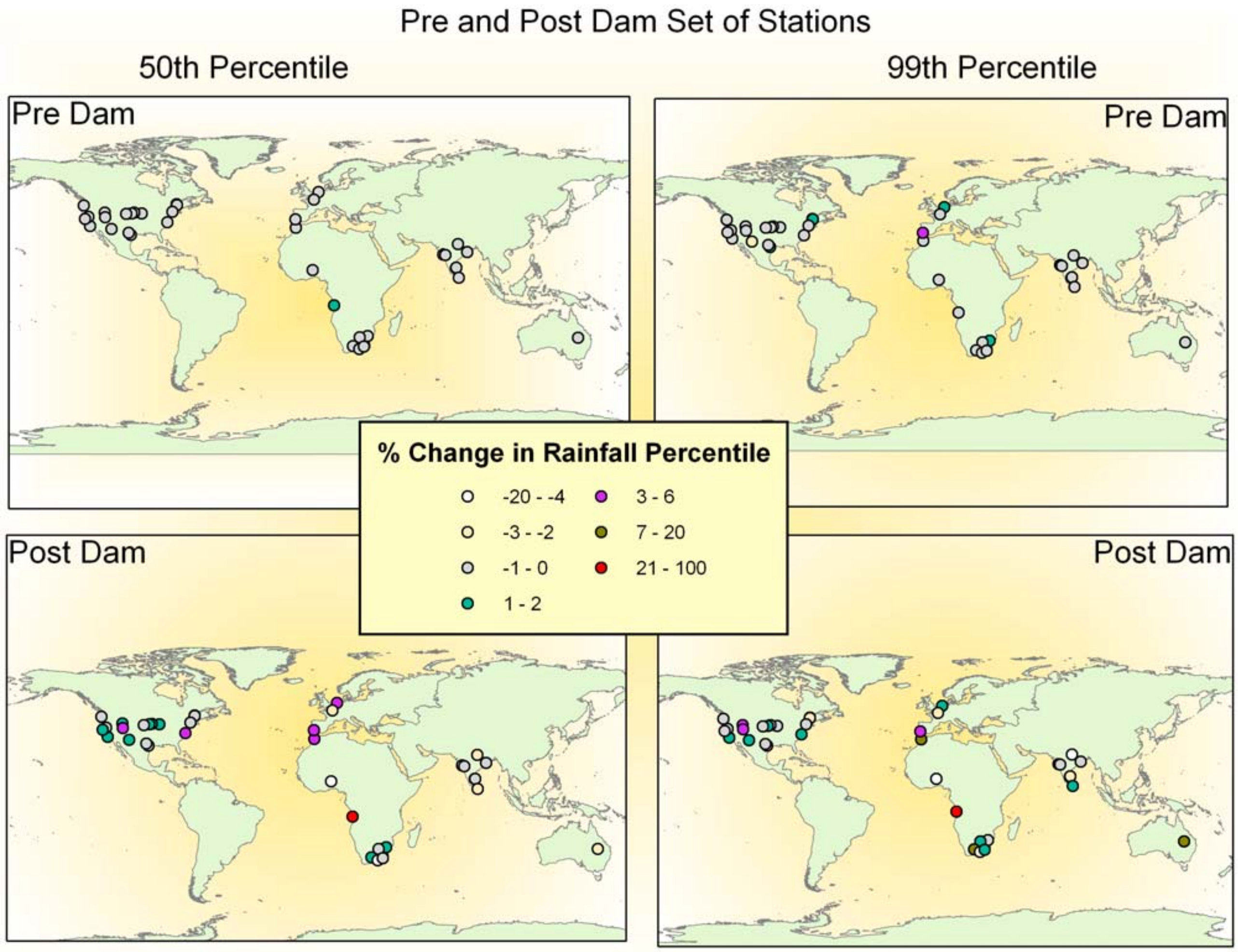

Figure 3. Same as Figure 2 but only for stations that had at least one dam built within a 250 mile radius during the last century (from *Hossain* [2009], with permission from ASCE).

while there are distinct trends around the neighborhood of dams, we probably do not know as much about the physical mechanisms associated with an artificial reservoir that trigger such observed alteration in precipitation patterns.

[12] Our limited knowledge of dam safety against human alteration of extreme precipitation is because conventional dam and reservoir planning over the last century has been "one-way," without acknowledging the possible feedback mechanisms on precipitation recycling due to local evaporation [*Eltahir and Bras*, 1996, 1994]. Some of the questions that the we believe the civil engineering profession must address for a more flood-safe design and management of dams and reservoirs for the 21st century are as follows.

[13] 1. How can we be certain that the design magnitude of a 100 year precipitation event for a large dam will not be invalidated during the life span of the dam?

[14] 2. To what extent can a large reservoir be planned (in terms of volume and surface area of impoundment) to take into account the change in the regional-local flood frequency relationship?

[15] 3. How much land cover change in the vicinity is sustainable to ensure that the dam will remain flood-safe?

[16] 4. The implication of human-altered extreme precipitation statistics on the safety of a large reservoir can be appreciated with a real-world disaster story of the Folsam Dam in California described next.

[17] When the Folsam Dam was built in 1955 to impound the American River and provide flood control for Sacramento City in California, the hydraulic and structural design features were assumed adequate to withstand a flood with a recurrence interval of 250 years. Repeated flooding and overtopping beginning from the late 1950s until the mid 1980s have now led to a revision of the recurrence interval of the design flood from 250 years to 70 years [*Hornberger et al.*, 1998; *National Research Council* (*NRC*), 1999]. Today, approximately 440,000 people and 110,000 structures are at risk downstream of Folsom Dam, and the Sacramento metropolitan area is considered among the greatest flood risk regions in the nation by the U.S. Army Corps of Engineers–USACE [*NRC*, 1999]. As a remedial measure, a proposal has recently been put forward by the USACE to raise the dam height by 7 feet (2.1336 m) at a cost of 1 billion dollars and make the dam safe against 200 year flood events (source: USACE).

[18] For now, it cannot be established categorically that the increase in magnitude of a low-frequency flood for the American River at Folsam was triggered by the reservoir impoundment. The overestimation of design recurrence interval is "officially" attributed to the use of a relatively

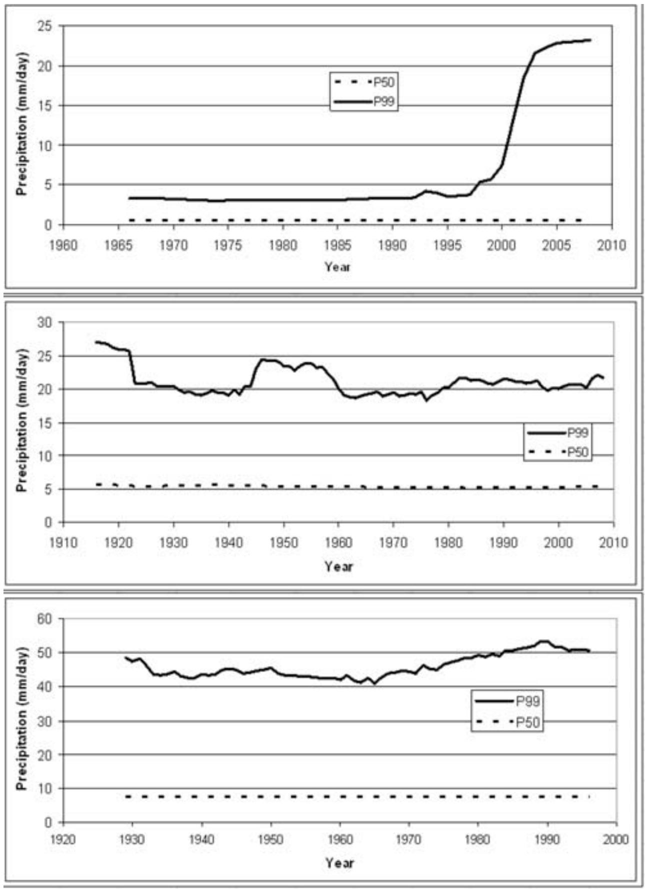

Figure 4. Time series of 99th percentile of precipitation for three regions that experienced alteration in precipitation pattern in the vicinity of large dams. (top) Spain (GHCN station SP000008280) with dam locations at Alarcon (1955), Cijara (1956), and Negratin (1984). (middle) Western United States (GHCN station USC00425402) with dam locations at Glen Canyon (1966), Soldier Creek (1973), and Flaming Gorge (1964). (bottom) Botswana (GHCN station SF0001810730) with dam location at Sterkfontain (1980). The years indicate the construction year for each dam.

drier period (1900–1950) of rainfall to establish flood frequency relationships for a considerably wetter half of the century [*NRC*, 1999]. However, the repeated flooding from 1950 onward that was preceded by a period of less frequent flooding may also be a *Hurst* [1951] phenomenon [*Koutsoyiannis*, 2003]. *Hurst* [1951, p.?] wrote: "Although in random events groups of high or low values do occur, their tendency to occur in natural events is greater. This is the main difference between natural and random events." Another issue might be the inadequacy of current mainstream methodologies to statistically model hydrological extremes, particularly for rainfall [*Koutsoyiannis*, 2004a, 2004b, 2006]. The growth of irrigated landscape around the dam may also have contributed to greater precipitation [*Pielke and Zeng*, 1989]. Nevertheless, the story of the Folsam Dam clearly indicates the risks posed by the incorrectly accepted assumption of stationarity in flood frequency analysis that is fundamental to water resources infrastructure design.

[19] Flood frequency analysis is traditionally computed under the assumption that annual maximum floods conform to a stationary, independent, identically distributed random process. The assumption that floods are independent and identically distributed in time, therefore, contradicts the accepted notion that climate naturally varies at all scales, and that climate additionally may be responding to the footprint introduced by human activity [*Rial et al.*, 2004]. *Milly et al.* [2008] and *Pielke* [2009] have recently questioned the assumption of stationarity in water management with bold statements such as "stationarity is dead" or "collateral damage from death of stationarity," respectively. Herein, the notion of stationarity should not be confused with the notion of a process having a "static" or "flat" temporal average. A process that exhibits a "nonflat" or "nonstatic" average in time may also be considered stationary (e.g., a Hurst-Kolmogrov process described above). For example, if one examines Figure 4 (middle and bottom), it can be argued that the lack of a flat moving average in the P99 after the commissioning of the dams is as likely as the absence of a deterministic component in the P99 trend line and, this P99 line could probably be recreated using the Hurst-Kolmogrov process.

[20] We therefore need to recognize that stationarity is a feature of man-made models which we have traditionally used to describe the natural processes, but which requires a more balanced and rigorous verification given the scientific tools available today [see, e.g., *Villarini et al.*, 2009]. Historically, "stationarity" has been a property that is invoked more out of necessity for modeling convenience, based on available information, and in making the design process in civil engineering more tractable. In the old days of dam building, there were no atmospheric models available to simulate possible changes to extreme precipitation during the life span of the structure and predict the changes in the flood frequency relationships. But now, since there has been significant progress on weather and hydrometeorological modeling, we need to reassess dam safety from the perspective of the possible human alteration of extreme precipitation patterns.

4. Conclusion

[21] Today, we know little about the impact of dams and reservoirs on the alteration in precipitation patterns as we step into the 21st century. Dam design protocol in civil engineering continues to assume as "static" the statistical parameters of a low exceedance probability precipitation event during the life span of the dam. Our study seems to indicate that the impact of large dams on extreme precipitation is clearly a function of surrounding mesoscale and land use conditions [e.g., see *Pielke et al.*, 2007; *Douglas et al.*, 2009], and that more research is necessary to gain insights on the physical mechanisms of extreme precipitation alteration by dams. The changes in land use, for example from added irrigation, add a significant amount of water vapor into the atmosphere in the growing season, thereby fueling showers and thunderstorms [e.g., see *Pielke and Zeng*, 1989; *Pielke et al.*, 1997; *Pielke*, 2001]. Such landscape changes can even alter large-scale precipitation patterns such as the Asian monsoon [e.g., see *Takata et al.*, 2008].

[22] Although the focus of our paper is primarily on how dams may alter extreme precipitation patterns and consequentially the flood frequency relationship, we should also recognize that there are other direct ways that the discharge into a reservoir may increase in frequency and magnitude (such as urbanization and other changes in land cover). Whatever the possible causes might be, it is timely for the civil engineering profession to change perceptions and embrace an interactive hydrology-atmospheric science approach to safe dam design and operations for the 21st century.

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