Empirical Relationship between Large Dams and the Alteration in Extreme Precipitation

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Abstract: This study looks at the empirical relationship between the presence of large dams and the potential alteration in extreme precipitation patterns in their vicinity. The global analysis indicates that extreme precipitation has altered considerably more than mean precipitation during the last century. We found this alteration to be more pronounced during the postdam period where the 99th percentile of precipitation experienced an average of 4% increase per year in magnitude. While the density of dams within a given radius did not correlate tangibly with the change in the percentile value, the frequency of rain (average number of rainy days per year) was found to have twice as much correlation during the postdam period than during the predam period. In general, dams in the regions of Southern Africa, India, Western U.S., and Central Asia were found to have increased extreme precipitation more than other regions. It also appeared that large dams alter extreme precipitation patterns more in the arid/semiarid regions more than other places. The study confirms that the impact of large dams on extreme precipitation is clearly a function of surrounding mesoscale and land-use conditions and that more research is necessary to gain insights on the physical mechanisms of precipitation alteration by dams. What is needed hereafter to understand how a reservoir triggers changes in precipitation patterns and affects dam safety is a coupled land-atmosphere modeling approach. Due to the interactions of the atmospheric processes with surface water, understanding and predicting the effect that human-modified flood-frequency behavior has on sustainable dam design and reservoir operations cannot be achieved by stand-alone hydrologic-hydraulic models as has been historically pursued by the engineering profession.

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Introduction

Research over the past two decades has comprehensively proven that a systematic change in land use and land cover (LULC) can alter the state of regional hydroclimatology [for a comprehensive summary, refer to Pielke (2005), Feddema et al. (2005), Pielke et al. (2007), and 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; Eddy et al. 1975). Similarly, Pielke et al. (1999) showed that the draining of swamps can decrease future precipitation through a negative feedback mechanism. Recent study by Takata et al. (2009) has shown that a large-scale increase in irrigated land can even shift rainfall patterns in the Asian Monsoon. Overall, predicting the change in water availability at the climate scale seems to hinge on our ability to accurately monitor and assimilate land cover change (LCC) in any climate modeling study (Ray et al. 2009).

Dams and their impounded reservoirs are one such type of infrastructure that triggers a systematic change in LULC patterns due to the multiple purposes, such as power generation, irrigation, and recreation that 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 reduced risk of flooding. In the United States alone, there are about 75,000 dams capable of storing a volume of water almost equaling one year's mean runoff of the nation (Graf 1999). Around the world, the World Commission on Dams reports that there have been at least 45,000 large dams built since the 1930s. It is estimated that half of the world's rivers have at least one dam somewhere along the reach [World Commission on Dams (WCD) 2000]. Other than the impoundment acting as a large source for direct evaporation, the associated LCC, both upstream and downstream of a dam, is a potential catalyst for alteration in the regional hydroclimatology. Land irrigated by reservoir water acts as a further source for evaporation and can potentially alter the frequency of convective storms in the region (Pielke and Zeng 1989).

The past century has witnessed tremendous progress on dam safety against the 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). We also have a reasonably good understanding of the postdam effects on aquatic ecology (e.g., Ligon et al. 1995; Richter et al. 1996), riparian vegetation (e.g., Merritt and Cooper 2000), and geomorphology (e.g., Graf 2006). Yet, very little is known about the impact of dams and reservoirs on extreme precipitation patterns. If a dam-driven LCC can trigger changes in precipitation patterns, then it will mostly likely also change the patterns of extreme precipitation. If extreme precipitation patterns change, then the assumption of stationarity in flood-frequency

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relationships that is fundamental to the design of flood-safe dams is violated (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 lower 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) is assessed in conjunction with an unaccounted increase in magnitude of the design flood volume that would need to be routed through the reservoir.

Although the notion that an impoundment could be built to increase rainfall was suggested more than 70 year ago by Jensen (1935), dam design continues to assume as stationary the statistical parameters of extreme precipitation events during the life span of a dam. How can we be certain that the design magnitude of 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 (in terms of volume and surface area of impoundment) with minimal impact on the regional/local flood-frequency relationship? How much LCC in the vicinity is sustainable to ensure that the dam is flood safe? These are some of the questions that the civil engineering profession must address for a more sustainable climate-friendly design and management of flood-safe dams and reservoirs for the 21st century.

Now that there are a sufficient number of large dams around the world with a fairly long record of precipitation, we need to identify, as a first cut, the trends that the existing record of data manifest on the impact of dams to extreme precipitation alteration. This study therefore looks at the empirical relationship between the presence of dams and the potential alteration in extreme precipitation patterns in their vicinity using a global data set of 633 large dams and 7,000 precipitation stations. We are motivated by the need to raise awareness of the potential for climate modifications by man-made water reservoirs and to initiate a fundamental change in the perception of how reservoirs and dams should be operated and designed for the 21st century. In the United States alone, more than 85% of large dams will be over 50 years old by 2020, thus becoming prone to higher flood risks not just from loss of storage but also from a potential increase in magnitude of extreme precipitation. Across the globe, more water resource projects will continue to be planned due to increasing water demand from population growth and projected changes in climate. Hence, the potential impact of dams on extreme precipitation and the conjugal relationship on dam safety cannot be ignored.

Global Datasets on Large Dams and Precipitation

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 according to the International Commission on Large Dams (ICOLD). We used a geographic information system (GIS) database on 633 large impoundments from a series of world dam registers published by ICOLD. This GIS database was digitized by the Global Water Systems Project at the Univ. of New Hampshire and was available at http://atlas.gwsp.org/. For precipitation data, we used 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 surface network of the National Climatic Data Center. This data set is useful for analyzing activities related to the frequency and magnitude of extremes as it contains observations at more than 40,000 stations that are distributed across the globe. We identified a set of 92 precipitation stations from the GHCN data set that were distributed around the world and had a sufficiently long record (>60 years) of daily precipitation observations. Approximately half the stations were in the close vicinity of a large ICOLD dam (i.e., within a maximum radius of 500 mi) while the rest were considered not to be in the vicinity. The 500-mi radius is considered inclusive of all types of convective events at the local (~10 mi), mesosale (10–100 mi), and synoptic scale (100–500 mi).

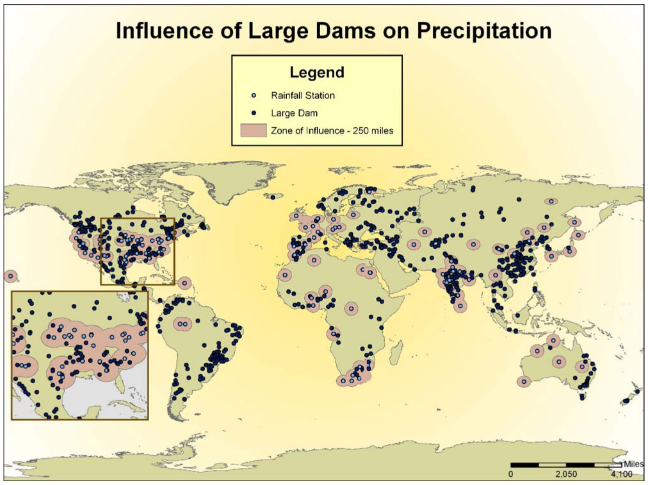

Fig. 1. 633 ICOLD large dams overlaid with 92 precipitation stations. The pink circles indicate a 250-mi radius of influence around each precipitation station.

Fig. 1 shows the location of the 633 large dams overlaid with the 92 precipitation stations. GHCN station precipitation data were verified against an independent measurement, such as the NEXRAD Stage IV data radar rainfall in the U.S. or the Climate Research Unit data set published by the Univ. of East Anglia. The GHCN data set was found to match closely with the temporal trends with occasionally modest bias at a few stations (see Fig. 2 for an example of verification of data at a U.S. GHCN station in a semiarid area).

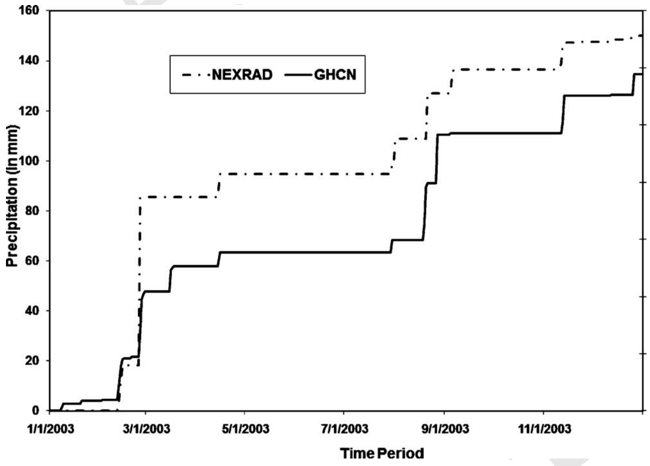

Fig. 2. Comparison of GHCN station rainfall data with NEXRAD Stage IV (radar) rainfall data from the U.S. National Weather Service. GHCN Station ID USC00040983. Location: Borrego Desert Park, Calif.

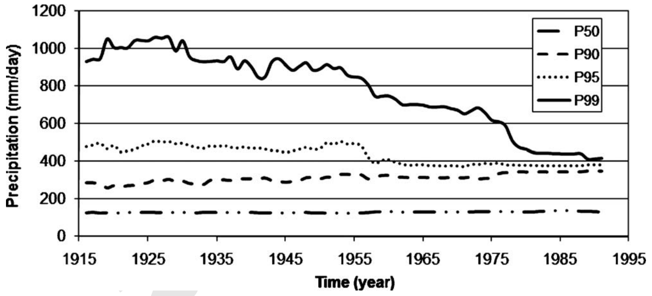

Fig. 3. Historical time series of P50, P90, P95, and P99 for a GHCN station in Central India. Station Id IN011340100; Location: Satna, Madhya Pradesh.

Empirical Relationships

General Trends

We analyzed the time series of four percentiles of precipitation—50th, 90th, 95th, and 99th for each station and year. Hereafter, these percentiles will be called P50, P90, P95 and P99, 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 percentiles of precipitation.

In order to generalize our analysis of the time series of percentiles, we computed the average annual change (percentage) for a given percentile over a specific time period (i.e., predam period, postdam period, or entire record). As an example, Fig. 3 shows the historical time series of the percentiles for a GHCN station in Central India. The annual 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 for each GHCN station. Fig. 4 shows the percentage change in percentile value for the combined set of precipitation stations (those in the vicinity of a dam and vice versa). An increase (positive change) in P99 is observed in the regions of Southern Africa, India, Western U.S., and Central Asia (Fig. 4). Table 1 shows the mean and standard deviation in the average annual percentage change in percentiles for all the 92 GHCN stations studied across the entire record (see second and third rows of Table 1). The rows below the third row of the table show the same statistics for the set of stations not within 500 mi of a dam (no dam) and vice versa (predam and postdam). Two specific trends are clear from this table: (1) across the globe, extreme precipitation patterns have been much more sensitive to change in time than the mean precipitation during the last century and (2) this temporal sensitivity of extreme precipitation has been most pronounced for stations that are in the vicinity of a large dam during the postdam period. On an average, the 99th percentile precipitation has increased by more than 4% a year after the construction of a large dam.

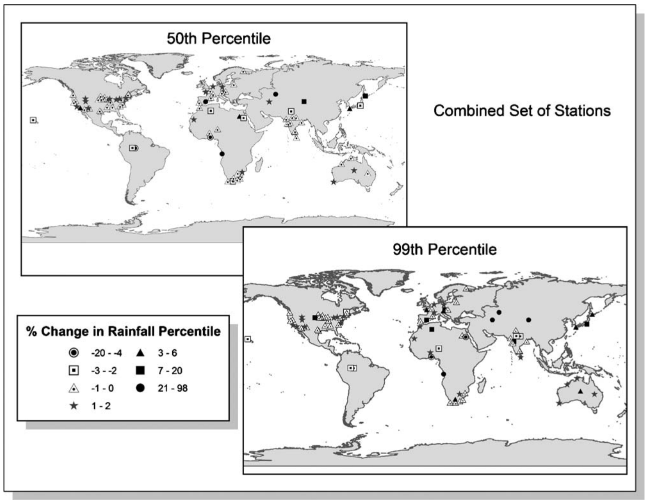

Fig. 4. Change in precipitation percentile for P50 and P99 (averaged over the entire GHCN record) for the combined set of stations (those with at least a dam within a 500-mi radius and vice versa)

Table 1. Global Summary of the Mean and Standard Deviation of the Average Annual Percentage Change in Percentile for All the 92 GHCN Stations Studied; "No Dam" Refers to the Set of GHCN Stations beyond 500 mi of a Large Dam

		P50 (%)	P90 (%)	P95 (%)	P99 (%)
All stations	Mean	0.153	0.199	0.234	0.326
	Standard deviation	1.11	1.216	1.645	1.774
No dam	Mean	0.124	0.087	0.095	0.188
	Standard deviation	0.511	0.249	0.296	0.647
Predam	Mean	0.000	−0.023	−0.011	0.0049
	Standard deviation	0.0148	0.111	0.093	0.0896
Postdam	Mean	0.252	0.286	0.426	0.488
	Standard deviation	1.855	2.014	2.749	2.841

Specific Trends

When only stations with at least one dam within a 250-mi radius are analyzed as a function of predam and postdam scenarios, specific and localized trends are observed. For Southern Africa and Southern Europe, dams appeared to have increased extreme precipitation (P99) significantly by as much as 20% during the last century. Stations in Southern India are found to have experience modest increase in the P99 value (Fig. 5). In the U.S., the P50 (mean) and P99 values are found similarly sensitive to the effect of dams. However, the mid-Western and Western regions are found to be affected more by the presence of dams. These regions experienced an average annual increase in the magnitude for the P99 rainfall event in the ranges of 1–5% during the last century.

Because accurate identification of the open surface area of a reservoir was difficult to pinpoint from the ICOLD digital database, we looked into the relationship between the density of dams within a given radius (100, 250, and 500 mi) and the average annual percentage change in percentile. Table 2 shows that there exists weak and rather inconclusive correlation between the number of dams within the vicinity and the alteration in extreme precipitation. Nevertheless, we show this table to highlight the considerably more insightful powers of using the annual frequency of rain as an indicator for understanding the impact of dams (discussed next and shown in Table 3).

If a dam alters precipitation, then it is plausible to expect a corresponding change in the frequency of rain. For example, if more precipitation is recycled via local evaporation from a reser-

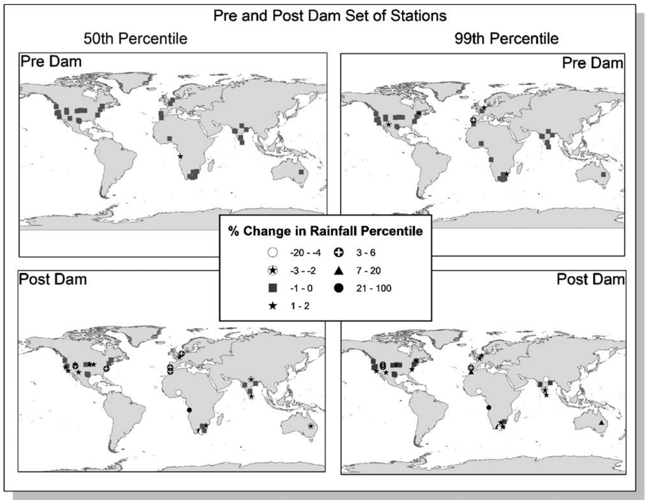

Fig. 5. Same as Fig. 4 but only for stations with at least one dam in a 500-mi radius

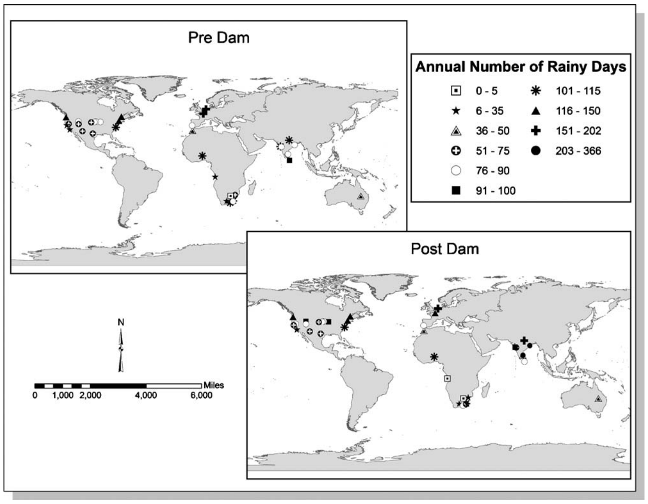

Fig. 6. Effect of dams on the frequency of rain for stations having at least one dam in a 500-mi radius

voir and the irrigated land, then one may expect a higher frequency of convective showers after the construction of the dam (Pielke and Zeng 1989). Table 3 shows that the number of dams within a 500-mi radius is twice as correlated to the frequency of rain as those GHCN stations with no dams within the same vicinity. It also indicates that the "zone" of influence of a large dam may need to be assumed at least 500 mi if its impact on precipitation is to be properly identified. Fig. 6 provides a global summary of the effect of dams on the annual frequency of rain. The regions of Central and Southern India appeared to have experienced the most increase in rain frequency after the construction of dams. However, this could also be due to changing Monsoonal patterns in rainfall.

Earlier in Fig. 5, we noted that the extreme precipitation in Southern Europe was affected considerably by the presence of dams. For a closer look at the temporal analysis of alteration, we selected the GHCN station SP000008280 in Southern Spain. Fig. 7 shows the time series for percentiles (uppermost panel) and rain frequency (middle and lowermost panels). The lowermost panel uses a rainfall threshold of 10.0 mm/day as a way to filter out the light/stratiform rain and retain mostly convective rainfall events. If precipitation is being recycled from local evaporation, then most of this recycled rainfall should manifest as convective events. When the time series is analyzed with respect to the dates of construction of the three large dams in the vicinity of the sta-

Table 2. Correlation between Number of Dams within a Specific Radius and the Average Annual Percentage Change in a Precipitation Percentile

	100 mi		250 mi		500 mi	
	Predam	Postdam	Predam	Postdam	Predam	Postdam
P50	−0.141	−0.041	0.011	−0.050	−0.101	−0.189
P90	0.073	−0.042	0.116	−0.086	0.252	−0.229
P95	0.040	−0.041	0.185	−0.099	0.096	−0.226
P99	0.008	−0.045	0.174	−0.090	−0.033	−0.227

Table 3. Correlation between Number of Dams within a Specific Radius and the Average Number of Rainy Days per Year

100 mi		250 mi		500 mi	
Predam	Postdam	Predam	Postdam	Predam	Postdam
0.001	−0.002	−0.012	0.053	0.119	0.221

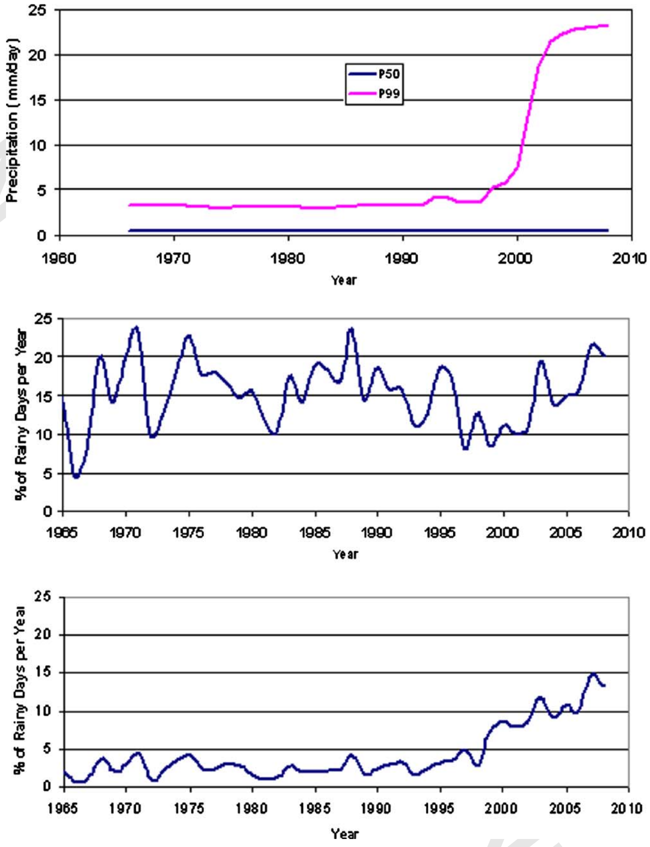

Fig. 7. Time series of percentiles (uppermost panel) and frequency of rain (middle and lower panels) for GHCN station SP000008280 located in Albacete of Southern Spain. The lower panel shows the time series for frequency of rain exceeding 10 mm/day. Three large dams are within a 500-mi radius of SP000008280: Alarcon (built in 1955), Cijara (built in 1956), and Negratin (built in 1984).

tion, it appears that the P99 and the frequency of "convective" rainfall have increased considerably over the last two decades in Southern Spain.

Conclusion

Because our dam and precipitation data sets were globally comprehensive and spanning an extensive record (60+ years), we can reasonably claim that extreme precipitation patterns have altered considerably more than mean precipitation during the past century. The alteration in precipitation patterns has been more pronounced during the postdam period where the 99th percentile of precipitation experienced an average of 4% increase per year in magnitude. While the density of dams within a given radius did not correlate tangibly with the change in the percentile value, the frequency of rain (average number of rainy days per year) was found to have twice as much correlation during the postdam period than during the predam period. In general, dams in the regions of Southern Africa, India, Western U.S., and Central Asia were found to have increased extreme precipitation more than other regions. It also appeared that large dams alter extreme precipitation patterns more in the arid/semiarid regions more than other places.

Our study is not without limitations. As future extension, a more appropriate follow up study would be to consider the statistical significance of the analysis to filter out instances where the postdam impact on precipitation may be more of a chance phenomenon than anthropogenic. Also, the impact of area under irrigation and reservoir size should be studied in conjunction with precipitation patterns. While our study confirms 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) and Douglas et al. (2009)], more research is necessary to gain insights on the physical mechanisms of precipitation alteration by dams. What is needed hereafter to understand how a reservoir triggers changes in precipitation patterns and affects dam safety is a coupled land-atmosphere modeling approach. Due to the interactions of the atmospheric processes with surface water, understanding and predicting the effect that human-modified flood-frequency behavior has on sustainable dam design and reservoir operations cannot be achieved by stand-alone hydrologic-hydraulic models as has been historically pursued by the engineering profession.

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