Spatial distribution of the largest rainfall-runoff floods from basins between 2.6 and 26,000 km^2 in the United States and Puerto Rico

Jim E. O'Connor and John E. Costa

U.S. Geological Survey, Portland, Oregon, USA

Received 8 April 2003; revised 4 October 2003; accepted 28 November 2003; published 31 January 2004.

[1] We assess the spatial distribution of the largest rainfall-generated streamflows from a database of 35,663 flow records composed of the largest 10% of annual peak flows from each of 14,815 U.S. Geological Survey stream gaging stations in the United States and Puerto Rico. High unit discharges (peak discharge per unit contributing area) from basins with areas of 2.6 to 26,000 km^2 (1–10,000 mi^2) are widespread, but streams in Hawaii, Puerto Rico, and Texas together account for more than 50% of the highest unit discharges. The Appalachians and western flanks of Pacific coastal mountain systems are also regions of high unit discharges, as are several areas in the southern Midwest. By contrast, few exceptional discharges have been recorded in the interior West, northern Midwest, and Atlantic Coastal Plain. Most areas of high unit discharges result from the combination of (1) regional atmospheric conditions that produce large precipitation volumes and (2) steep topography, which enhances precipitation by convective and orographic processes and allows flow to be quickly concentrated into stream channels. Within the conterminous United States, the greatest concentration of exceptional unit discharges is at the Balcones Escarpment of central Texas, where maximum U.S. rainfall amounts apparently coincide with appropriate basin physiography to produce many of the largest measured U.S. floods. Flood-related fatalities broadly correspond to the spatial distribution of high unit discharges, with Texas having nearly twice the average annual flood-related fatalities of any other state. *INDEX TERMS:* 1821 Hydrology: Floods; 1860 Hydrology: Runoff and streamflow; 9350 Information Related to Geographic Region: North America; *KEYWORDS:* floods, stream gaging stations

Citation: O'Connor, J. E., and J. E. Costa (2004), Spatial distribution of the largest rainfall-runoff floods from basins between 2.6 and 26,000 km^2 in the United States and Puerto Rico, *Water Resour. Res.*, *40*, W01107, doi:10.1029/2003WR002247.

1. Introduction

[2] Riverine floods are the most lethal and costly natural hazard in the United States, causing an average of 140 fatalities and $5 billion damage each year [*Schildgen*, 1999]. Despite great advances in flood science and implementation of Federal hazard-reduction policies, damage from flooding continues to escalate [*Pielke and Downton*, 2000]. While flooding is a pervasive hazard, few national-scale analyses have been conducted on the magnitude and spatial distribution of floods, and none has fully drawn on the extensive collection of flow records collected and maintained by the U.S. Geological Survey (USGS). This study of flow records from nearly 15,000 USGS stream gaging stations throughout the United States and Puerto Rico active over the last 100+ years shows that the spatial distribution of large flows is neither uniform nor random, but relates to specific topographical and climatological settings.

2. USGS Peak Flow Records

[3] To characterize the spatial distribution of large U.S. floods, we have analyzed the *Peak Flow Files* derived from records of USGS stream gaging stations and maintained as part of the USGS National Water Information System [*Lepkin and DeLapp*, 1979] (data are available at http://waterdata.usgs.gov/usa/nwis/nwis). The peak flow file for each station contains values for the largest instantaneous discharge (peak flow) for each water year (1 October to 30 September) of station operation, along with notes regarding factors affecting the flow and the quality of the flow record. For records compiled through water year 1997 (ending 30 September 1997), annual peak flows are reported for 23,216 current and former stations, together comprising more than 0.5 million annual peak discharge values.

2.1. Largest Meteorological Floods From Basins Between 2.6 and 26,000 km^2

[4] From the peak flow files of stream gaging stations with drainage areas between 2.6 and 26,000 km^2 (1 to 10,000 mi^2) and with 5 or more years of record, we extracted the top 10% of annual peak discharges. The resulting database consisted of 43,645 annual peak flows from 18,735 stations. Each station has 1 to 15 annual peak discharges per station, depending on length of record. From these data, we rejected nearly 8000 (about 19%) of the annual peak flows that were coded in the peak flow files as estimated, influenced by dam failures, or affected by regulation, diversion, urbanization, mining, agricultural changes,

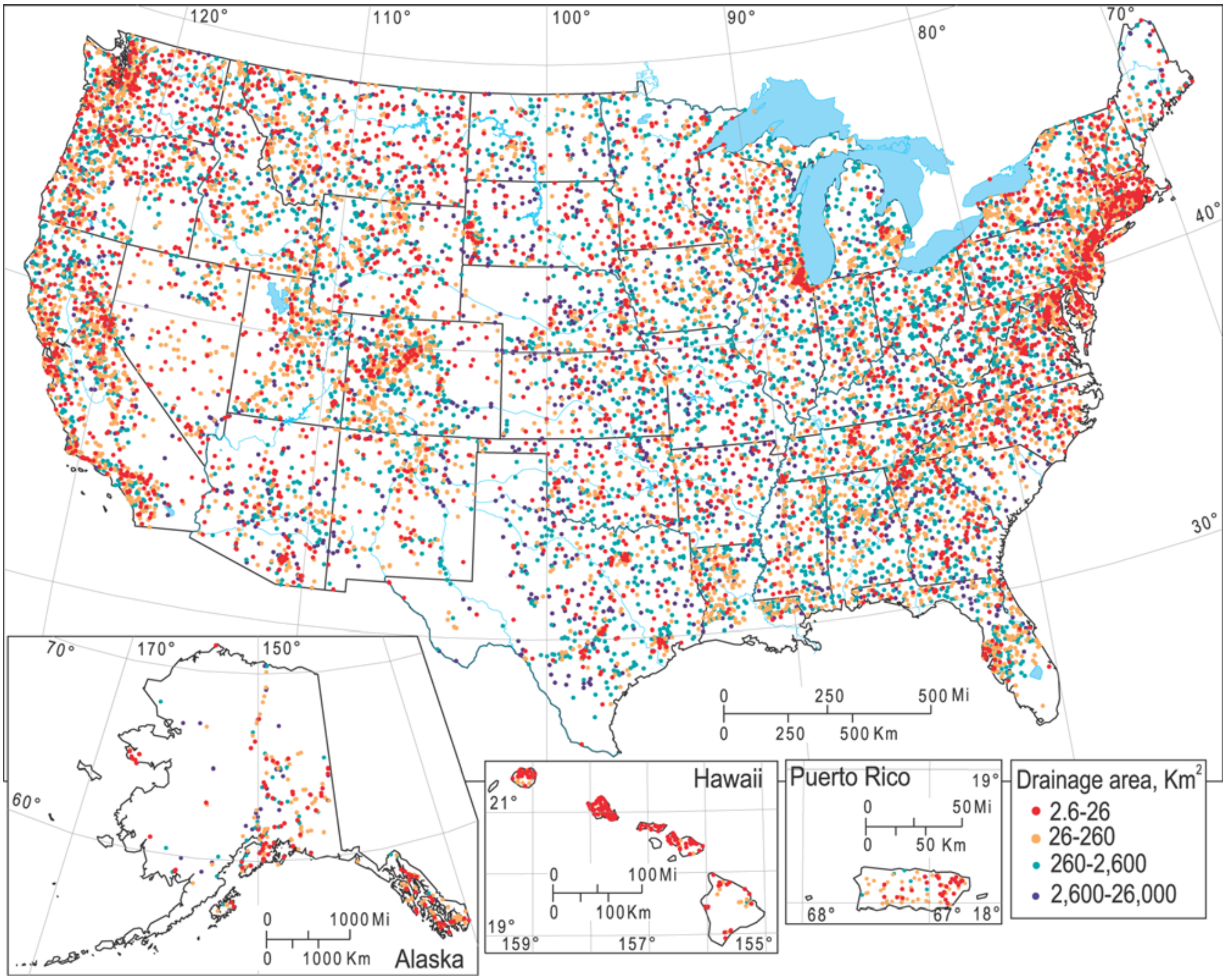

Figure 1. Locations of 14,815 former and active USGS stream gaging stations with peak discharge records used in this analysis, color coded by drainage area size.

or channelization. The resulting database consists of 35,663 annual peak flows from 14,815 stream gaging stations in the United States and Puerto Rico (Figure 1).

[5] By focusing on basins between 2.6 and 26,000 km^2, and excluding records coded as being affected by anthropogenic factors such as regulation or diversion, we have probably reduced the influence of these factors on the remaining annual peak flows. Inspection of retained records, however, indicates that many of the analyzed annual peak discharges were indeed affected by regulation, diversion, and urbanization to some degree. In sum, inconsistent coding practices with time and among the various offices reporting these data make it difficult to completely isolate annual peak flows affected by such factors solely on the basis of information in the peak flow files.

[6] Other aspects of the data in its present form also hinder unbiased quantitative assessment of the spatial distribution of large flows. While USGS stream gaging stations measure flow from basins in every state and Puerto Rico, coverage is not uniform, with station density partly corresponding to population density, evident by the large number of stations along the eastern seaboard and other urban areas (Figure 1). Additionally, many drainage basins included in the analysis have multiple stations with overlapping contributing areas, as in the common circumstance of a series of stations along an individual river. In these situations, records of annual peak discharges for these stations may not be independent because the same flood may be measured (and included in the peak flow files) at several sites. This factor is reduced but not eliminated by excluding basins greater than 26,000 km^2. Nevertheless, the large number and wide distribution of stations presumably overwhelms anthropogenic factors retained in the database that may systematically affect the spatial distribution of large peak discharges, at least for qualitative assessment of the spatial distribution of large flows.

[7] From the final retained records of 35,663 annual peak flows from 14,815 stream gaging stations, a plot of peak discharge versus drainage area shows, as expected, that larger basins typically have larger peak discharges (Figure 2). Nevertheless, some basins produce larger flows than other similarly sized basins. To distinguish the largest of these maximum annual flows with respect to drainage area, we further stratified the data of Figure 2 into the $\sim$90th and $\sim$99th percentile unit discharges (peak discharge divided by drainage area) through use of a pair of power law equations

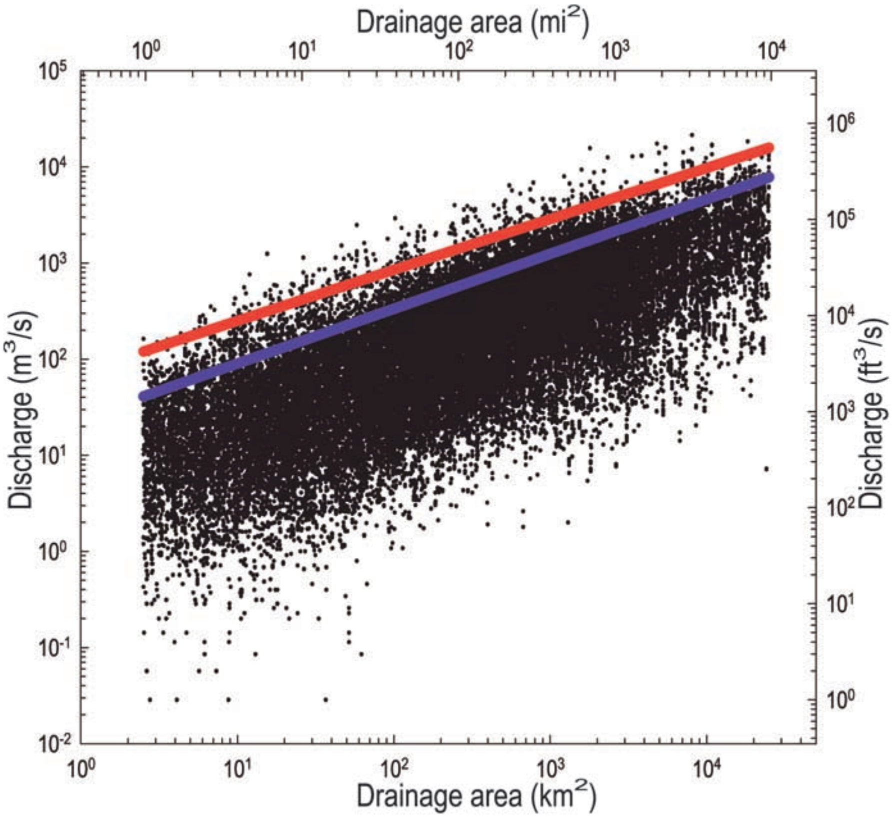

Figure 2. Top 10% of annual peak discharges from each of 14,815 stream gaging stations. These data, comprising 35,663 annual peak discharge values, were further stratified on a unit discharge basis into ~90th and ~99th percentiles by the depicted lines based on the equations listed in Table 1. Drainage areas and discharge values from USGS NWIS data.

(Table 1) formulated to maintain similar overall distributions of drainage basin areas relative to the total population of analyzed stations (Figure 3). Although we refer to these subsets of high unit discharges as the ~90th and ~99th percentiles, they are essentially ~99th and ~99.9th percentile unit discharges with respect to all recorded annual peak discharges because they are derived from only the largest 10% of all annual peak discharges for each station.

2.2. Drainage Basin Delineation

[8] The 3503 flows constituting the ~90th percentile unit discharges are from 2,088 (out of the 14,815) USGS stream gaging stations in the United States and Puerto Rico. For each of these 2,088 stations, contributing drainage areas were delineated within a geographic information system (GIS) using a 1-km-resolution digital elevation model for North America (HYDRO1k elevation data obtained from

Table 1. Relations for Stratification, on Unit Discharge Basis, of the 35,663 Annual Instantaneous Peak Discharges Constituting the Top 10% of Annual Peaks Recorded at 14,815 USGS Stream Gaging Stations in the United States and Puerto Rico

Stratification	Equation	Number of Floods	Number of Stream Gaging Stations
~90th percentile	$Q_{pk90} = 24.3\ [\text{sq km}]^{0.57}$	3503	2088
~99th percentile	$Q_{pk99} = 74\ [\text{sq km}]^{0.53}$	397	284

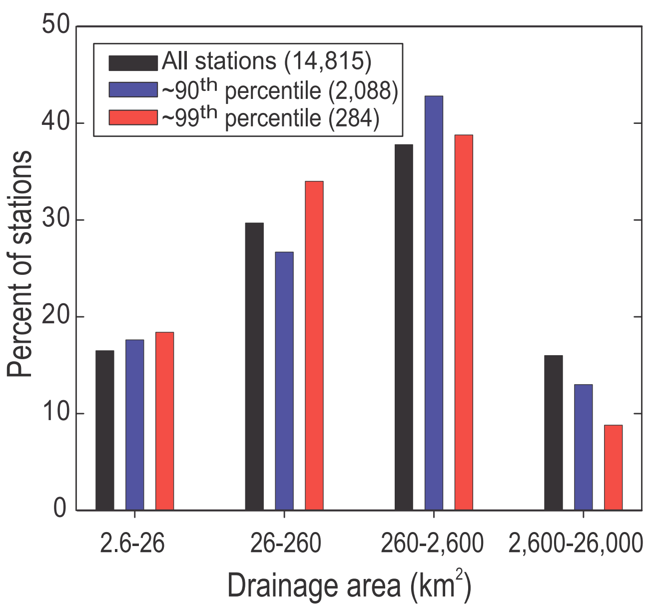

Figure 3. Distribution of drainage areas corresponding with the total collection of analyzed stream gaging stations and the subsets of stations producing the ~90th and ~99th percentiles of high unit discharges.

http://edcdaac.usgs.gov/gtopo30/hydro). The coarse resolution of the elevation model hampers quantitative GIS analyses relating flow characteristics to spatial data. Nevertheless, these approximate delineations allow display of the spatial distribution of areas producing the largest unit discharges on a national basis, rather than just the point locations of the stream gaging stations.

3. Spatial Distribution of the Largest Unit Flows

[9] The resulting maps show that large unit discharges have been recorded throughout the United States and Puerto Rico (Figure 4). All states except Rhode Island and Michigan have areas contributing to ~90th percentile unit discharges (Figure 4a). Seven stream gaging stations had seven of their top 10% annual peak discharges within the ~90th percentile of unit discharges. The 397 measurements composing the ~99th percentile unit discharges were from 284 stream gaging stations recording flow from parts of 30 states and Puerto Rico (Figure 4b). One station, the Eel River at Scotia in northern California (USGS station 11477000), recorded seven flows in this category—the most of any station. The Eel River basin is well known for large floods and extraordinary sediment yield [*Brown and Ritter*, 1971; *Sloan et al.*, 2001].

[10] Despite their widespread occurrence, the distribution of stream gaging stations with the largest unit discharges (Figure 4) differs substantially from the overall distribution of stations used in the analysis (Figure 1). Puerto Rico and Hawaii together comprise 32% of the stations recording flows in ~99th percentile of unit discharges despite accounting for less than 5% of the 14,815 stream gaging stations. Texas accounts for another 20% of the stations with ~99th percentile unit discharges. Also evident on both the ~90th (Figure 4a) and ~99th (Figure 4b) percentile maps are three belts of high unit discharges within the conterminous United States: (1) watersheds draining western or southwestern flanks of mountain ranges near the Pacific coast; (2) watersheds within and flanking the Appalachians along the Atlantic seaboard; and (3) watersheds in a broad northeast trending zone in the southern Midwest extending from southwest Texas to southeast Kansas and southern Missouri.

4. Climatic and Physiographic Factors for Large Unit Flows

[11] Each of these areas of high unit discharges is attributable, qualitatively at this scale, to specific conditions of climate and topography. Puerto Rico and Hawaii both have many basins with high unit discharges because they are in the midst of the trade wind belt, where mountainous islands intercept moisture-laden convective systems, tropical storms, and hurricanes. It follows that a greater proportion of stations with the largest flows are on the windward (eastern) side of these island complexes. The geologically older Hawaiian Islands of Oahu and Kauai have more basins producing high unit discharges compared to the younger islands of Hawaii and Maui, perhaps partly attributable to greater station densities (Figure 1; especially on Oahu), but likely also owing to less permeable soils on the deeply weathered older islands [*Michaud et al.*, 2001].

[12] Along the Atlantic seaboard and southeastern United States, large unit discharges are concentrated along the Appalachians (Figure 4), where they result from the combination of proximity to Gulf of Mexico and Atlantic moisture sources, orographic effects augmenting precipitation, and topographic relief promoting rapid concentration of streamflow [*Sturdevant-Rees et al.*, 2001]. The highest unit discharges (Figure 4b) are along the eastern and western margins of the central and southern Appalachians. Here, high flows result from moisture advected by warm-season hurricanes, tropical storms, and convective storms from the Atlantic Ocean and Gulf of Mexico [*Konrad*, 1994, 2001]. High unit discharges for larger basins are generally from tropical storms, whereas exceptional unit discharges for basins less than 500 km^2, such as along eastern flanks of the Blue Ridge Mountains in Virginia and the western Appalachians of Pennsylvania, owe to supercell thunderstorms and "topographic anchoring" of small convective storms [*Smith et al.*, 1996, 2001; *Sturdevant-Rees et al.*, 2001]. Many peak discharges along the western Appalachians result from interactions between high-relief topography and moisture advected from the west, partly derived from the Gulf of Mexico [*Konrad*, 1994].

[13] The importance of orographic effects and topographic concentration of streamflow for generating high unit discharges along the Atlantic coast is illustrated by the rarity of high unit discharges in Florida and along the Coastal Plain of the southern and eastern tier States. Despite being closest to the moisture sources and subject to frequent landings of major hurricanes and intense rainfall [*Konrad*, 2001], these comparatively flat and permeable areas do not produce large unit discharges.

[14] Within Texas and the southern Midwest states, the distribution of basins with high unit discharges (Figure 4a) broadly corresponds to the decreasing gradient of precipitable water north and west of the Gulf of Mexico [e.g., *Reitan*, 1960; *Ho and Reidel*, 1979; *Bradley and Smith*, 1994]. Many high unit discharges result from mesoscale convective complexes, large, multiple-celled, persistent thunder cell systems supplied largely by moisture from the Gulf of Mexico [*Maddox et al.*, 1979; *Hayden*, 1988; *Hirschboeck*, 1991; *Hirschboeck et al.*, 2000]. In particular, extreme storms and ensuing floods in this region commonly result from a meteorological condition of above-average precipitable water content in the atmosphere coupled with strong dynamic forcing; typically that of a cutoff low centered over the U.S. Southwest [*Bradley and Smith*, 1994]. The largest unit discharges in this region (Figure 4b), however, result from this broad moisture gradient in combination with finer-scale patterns of topography. Orographic effects on precipitation and, perhaps more importantly, runoff at features such as the Balcones Escarpment in south-central Texas [*Dalrymple et al.*, 1937; *Patton and Baker*, 1976; *Baker*, 1977], the Ozark Mountains of western Missouri and Arkansas, and in the Flint Hills of western Kansas [*Zhang et al.*, 2001], result in some of the largest concentrations of exceptional unit discharges in the conterminous United States.

[15] West of about longitude 105° west, moisture from the Pacific Ocean chiefly influences flooding within the conterminous United States and Alaska. Consequently, stream gaging stations with the largest unit discharges are

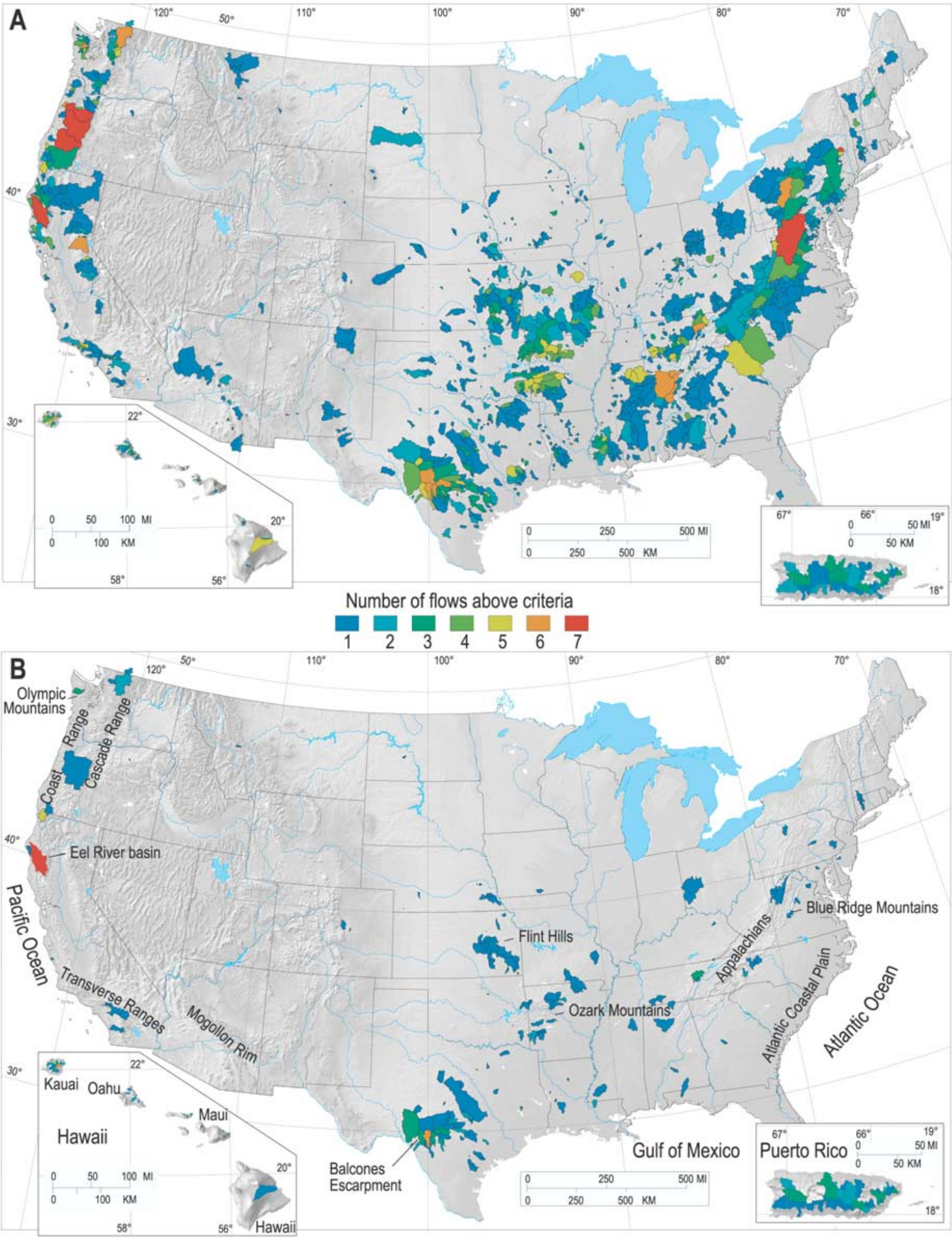

Figure 4. Basins with high unit discharges. Basin boundaries were derived from 1-km resolution digital elevation model (source of base maps). Basin colors refer to the number of individual floods from each watershed meeting the unit discharge criteria. Larger basins are plotted on top of smaller ones. (a) 2088 basins with ~90th percentile unit discharges. Not shown are 12 basins in southeastern Alaska, with basin areas of 21 to 207 km^2, which had flows meeting this criterion. (b) 284 basins with ~99th percentile unit discharges. No stations in Alaska had unit discharges in this category.

concentrated the states contiguous to the Pacific Ocean. Along the western ramparts of the Olympic Mountains of Washington, and the Cascade and Coast ranges of Oregon, Washington, and northern California, many stations have recorded multiple unit discharges within the ~90th and ~99th percentiles. Many of these flows resulted from intense winter cyclonic storms or the combined effects of cyclonic storms and coincident snowmelt, such as the large floods of late 1964 and early 1965 [*Waananen et al.*, 1970]. Because these synoptic systems persist for several days, larger basins (generally greater than 1000 km^2) are preferentially affected by such storms.

[16] The Transverse Ranges of southern California and Mogollon Rim of central Arizona are oriented in particularly favorable directions to intercept moisture from incursions of moist air from the southwest, including extratropical cyclonic systems, dissipating tropical storms moving northward from the Pacific Ocean, mesoscale convective complexes, and local convective thunderstorms [*Maddox et al.*, 1980; *Hirschboeck*, 1991; *Hirschboeck et al.*, 2000]. Consequently, there are distinct concentrations of flooding from a wide range of contributing areas aligned along these features. By contrast, the interior western states of Idaho, Nevada, Utah, Wyoming, and Colorado, as well as interior Alaska, have very few basins with large unit discharges. The few exceptional flows measured at interior western streamflow stations were in small basins flanking prominent mountain ranges and resulted from isolated convective storms. *Maddox et al.* [1980] noted that many flash-flood producing convective storms in the western United States were due to mid-atmosphere short-wave troughs moving northward up the western side of long-wave ridges of high atmospheric pressure during warm-season periods of high atmospheric moisture content.

[17] An overall conclusion that emerges from the distribution of high unit discharges in the United States and Puerto Rico is the combined importance of topography and basin physiography. Certain areas of the United States and Puerto Rico are predisposed to large floods because of their relation to regional climatic conditions, especially those that can produce large rainfall volumes such as Hawaii, Puerto Rico, the Appalachians, and the southern Midwest. However, within these broad areas, the largest unit discharges apparently owe to combined effects of specific topographic conditions, such as basin relief, basin shape and aspect, drainage network structure, and basin substrate, that can influence rainfall volumes and distribution within a basin as well as the speed and efficiency in which the rainfall is routed through the channel network. This observation has been postulated generally [e.g., *Horton*, 1932; *Hoyt and Langbein*, 1939] and demonstrated for individual extreme floods [e.g., *Baker*, 1977; *Smith et al.*, 1996; *Sturdevant-Rees et al.*, 2001], and is corroborated by the national view of high unit discharges provided by extensive USGS flow records.

5. Relation to Previous Studies of the Distribution of Extreme Floods

[18] Earlier studies have also depicted the distribution of large floods for the United States, but with smaller data sets [see also *Michaud et al.*, 2001]. Additionally, no studies that we are aware of depict the basins associated with measured flows. *Jarvis* [1942, pp. 548–549] presented a map showing values closely related to unit discharge for the continental United States compiled from "representative" USGS streamflow stations. This map shows highest unit discharge values in south-central Texas as well as high values in southern California and in the Appalachians. However, because these data are not adjusted for drainage area, it emphasizes measurements from smaller basins, which tend to produce the highest unit runoffs. The map of "relative variation in flood intensities" in the United States produced by *Hoyt and Langbein* [1955, p. 75] depicts areas of relatively high flood intensity that correspond closely with the distribution of ~99th percentile floods shown in Figure 4b, although the southern Midwest area of high unit discharges lacks emphasis in the *Hoyt and Langbein* map. *Crippen and Bue*'s [1977] map of 17 flood regions in the conterminous United States, based on records of 883 stations with basin areas less than 26,000 km^2, identifies many areas that have concentrations of high unit discharges as distinct flood regions, including the Appalachians, the southern Midwest, and the Pacific Coast. However, some areas of high unit discharges in Figure 4 straddle flood region boundaries of Crippen and Bue, including the Balcones Escarpment in Texas and the Transverse Ranges of southern California.

[19] More recently, *Michaud et al.* [2001] analyzed annual peak flow records for 130 USGS stations as well as 88 USGS measurements of "exceptional floods" from ungaged sites in the conterminous United States and Hawaii, all for basins less than 200 km^2. This assessment also corresponds with our results, with the southern Midwest and Appalachians identified as producing comparatively high median and 25-year return interval peaks, as determined from gaged records. They also noted that relatively small peaks were found in the interior western United States, northern Midwest and Great Plains, as well as in the far northeastern United States. *Michaud et al.*'s analysis also showed a concentration of exceptional flows in the southern Midwest and Texas, similar to the distribution of highest unit discharges shown in Figure 4b.

[20] In contrast to broad similarities between the results of this analysis and previous summaries of the spatial distribution of relatively large floods, measurement locations of *maximum* rainfall-runoff floods in the United States (Table 2 and Figure 5) do not correspond as closely with the overall distribution of high unit discharges shown in Figure 4. The thirteen very largest rainfall-runoff floods for basins between 2.6 and 26,000 km^2, defined as those most closely approaching the United States envelope curve of peak discharge vs. drainage area, are all west of longitude 99° west (Figure 5). Some measurement locations for these exceptional flows are in areas of high unit discharges, including six of the seven events from basins >100 km^2 (numbers 7–13 on Figure 5). However, for the 6 envelope-curve floods from basins less than 100 km^2 (1–6 on Figure 5), four are in the interior western United States, which is conspicuous in Figure 4 for the lack of high unit discharges. Most envelope-curve floods for basins smaller than 2.6 km^2 (not shown on Figure 5) are also from the interior western United States [*Costa*, 1987b]. This discrepancy, also noted by *Michaud et al.* [2001], may relate partly

Table 2. Largest Rainfall-Runoff Floods in the United States, Selected on Basis of Flows Defining U.S. Envelope Curve Bounding Peak Discharge Versus Drainage Area[a]

Site Label	Location	USGS Station[b]	Date	Discharge, m^3/s	Drainage Area, km^2	Unit Runoff, m^3/km^2	Source
1	Halawa Stream near Halawa, Molokai, HI	16400000	4 Feb. 1965	762	12	63.5	*Costa* [1987a]
2	Lane Canyon, OR	-	26 July 1965	807	13.1	61.6	*Costa* [1987a]
3	Meyers Canyon, OR	-	13 July 1956	1,540	32.9	46.8	*Costa* [1987a]
4	Bronco Creek, AZ	-	18 Aug. 1971	2,080	49.2	42.3	*Costa* [1987a]
5	S. Fork Wailua River near Lihue, Kauai	16060000	15 April 1963	2,472	58	42.6	*Costa* [1987a]
6	Eldorado Canyon at Nelson Landing, NV	-	14 Sept. 1974	2,152	59.3	36.3	*Costa* [1987a]
7	N. Fork Hubbard Ck. nr Albany, TX	08086150	4 Aug. 1978	2,920	102	28.6	*Costa* [1987a]
8	Jimmy Camp Ck. Near Fountain, CO	-	17 June 1965	3,510	141	24.9	*Costa* [1987a]
9	Mailtrail Ck near Loma Alta, TX	-	24 June 1948	4,810	195	24.7	*Costa* [1987a]
10	Seco Ck. Near D'Hanis, TX	-	31 May 1935	6,510	368	17.7	*Costa* [1987a]
11	W. Nueces R. near Brackettville, TX	08190500	14 June 1935	16,430	1041	15.8	*Dalrymple et al.* [1937]
12	Nueces River below Uvalde, TX	08192000	14 June 1935	17,450	4820	3.6	*Dalrymple et al.* [1937]
13	Eel River near Scotia, CA	11477000	23 Dec. 1964	21,300	8063	2.6	*Costa* [1987a]

[a]Locations are shown in Figure 5.
[b]USGS Station numbers provided for sites of established streamflow gaging stations; other measurements (marked by dashes) at miscellaneous measurement sites not regularly gaged.

to the relative scarcity of measurement stations in the interior west (Figure 1), resulting in underrepresentation in the percentile maps. However, more likely is that rare and exceptionally high-magnitude floods owe to the physiographic setting of these semiarid basins, in which extensive bedrock exposure, high relief, and high drainage densities promote efficient and rapid runoff from intense rainstorms [*Patton and Baker*, 1976; *Costa*, 1987b]. For these extreme floods from very small basins, basin physiography apparently exerts overriding influence, since rainfall volumes and rates for the storms producing many of these floods were not exceptional compared to rainfall amounts and intensities

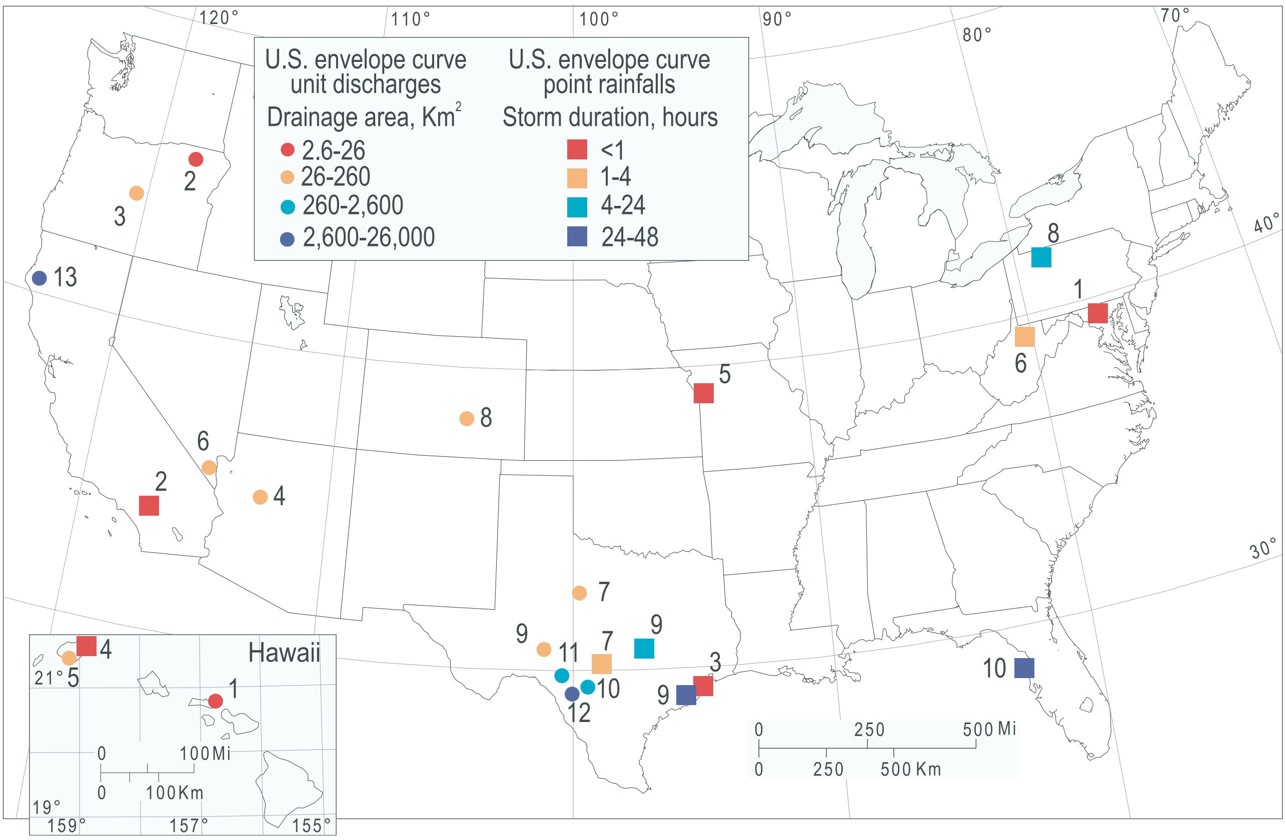

Figure 5. Measurement locations of largest U.S. rainfall-runoff floods from basins between 2.6 and 26,000 km^2 and locations of maximum point rainfall measurements for durations up to 48 hours. Numbers refer to descriptions in Tables 2 and 3. Modified from maps and data given by *Costa* [1987a, 1987b].

Table 3. Largest Point Rainfall Measurements in the United States, Selected on the Basis of Events Defining U.S. Envelope Curve Bounding Rainfall Depth Versus Measurement Duration[a]

Site Label	Location	Date	Duration, min	Depth, mm
1	Unionville, MD	4 July 1956	1	31
2	Haines Canyon, CA	2 Feb. 1976	5	64
3	Galveston, TX	4 June 1871	14	100
4	Kilauea Kauai, HI[b]	24 Jan. 1956	30	152
5	Holt, MO	22 June 1947	42	305
6	Rockport, WV	18 July 1889	130	483
7	D'Hanis, TX	31 May 1935	165	559
8	Smethport, PA	18 July 1942	270	782
9	Thrale, TX	9 June 1921	1080	925
10	Alvin, TX	25 July 1979	1440	1092
11	Yankeetown, FL[c]	3 Sept. 1950	2880	1095

[a]All data, except as noted, are from *World Meteorological Organization* [1986, p. 259]. Locations are shown in Figure 5.
[b]From National Weather Service Records posted at www.nws.noaa.gov/oh/hdsc/.
[c]From maximum 48 hour, 26 km^2 precipitation [*World Meteorological Organization*, 1986, p. 261].

in the eastern United States [*Costa*, 1987b]. Indeed, nine of the 10 maximum point rainfall values for the conterminous United States are east of longitude 99° west (Figure 5 and Table 3). Only in the area of the Balcones Escarpment of Texas and in Hawaii do maximum U.S. precipitation values and optimum flood-producing basin physiography apparently coincide [*Patton and Baker*, 1976; *Baker*, 1977; *Costa*, 1987b], thus producing the prominent region of high unit discharges shown in Figure 4b as well as the envelope-curve-defining floods for the United States, and in the case of the 1935 flood of the West Nueces River [*Dalrymple et al.*, 1937], a discharge defining the world envelope curve of maximum floods [*Costa*, 1987a].

6. Large Unit Flows and Flood Hazards

[21] Areas of large unit flows do not necessarily equate to areas of high flood hazard, since the flood hazard for any particular location is in part due to local forecasting, warning, and communication systems, existing flood protection works, as well as the community's social, political, and regulatory setting. Nevertheless, areas of high unit discharge are likely areas of elevated hazard because of the potential for large flow depths and velocities. This appears to be the case for fatalities directly related to flooding (Figure 6), of which the majority result from "flash floods" (defined by the National Weather Service as those occurring within 6 hours of heavy rainfall). Texas has had by far the most fatalities related to flooding, averaging nearly 17 casualties per year for the period 1960–2002, followed by Puerto Rico and California with about 9 and 8 deaths per year, respectively (1960–1996 Flood and flash flood fatality data from www.ncdc.noaa.gov/oa/climate/sd/annsum96.pdf; 1997–2002 data from http://www.nws.noaa.gov/om/severe_weather/; 2002 data are preliminary). Several other states, primarily those flanking the Appalachians and in the southeastern United States also have high flood-related fatality rates. These areas generally correspond with areas of high unit discharges (Figure 4). Hawaii, despite being a state of exceptional unit discharges, has had relatively few flood related fatalities (Figure 6), probably because of low population densities in affected areas. Colorado and South Dakota have had high fatality rates compared to the incidence of high unit discharges, but for South Dakota, 237 out of the 248 fatalities between 1960 and 2002 were from the 9–10 June 1972 Rapid City

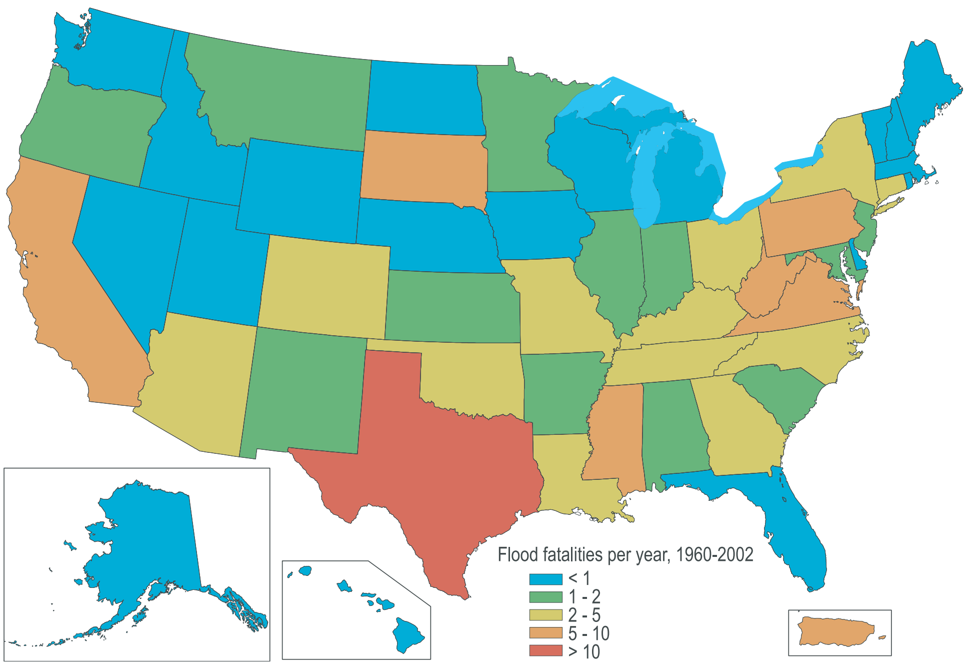

Figure 6. Average annual flood related fatalities for the United States and Puerto Rico for 1960–2002. State averages calculated from a 1960–1996 summary from the National Climatic Data Center (available at www.ncdc.noaa.gov/oa/climate/sd/annsum96.pdf) and 1997–2002 data from the National Weather Service (available at http://www.nws.noaa.gov/om/severe_weather/).

flood, and for Colorado, 144 of a total of 181 deaths resulted from the 1 August 1976, Big Thompson flood. Only Texas has had fatalities every year during 1960–2002.

[22] Monetary damage from floods in the United States does not so closely correspond to basins between 2.6 and 26,000 km^2 producing high unit discharges, mainly because large long-duration floods on rivers draining areas greater than 26,000 km^2 can cause exceptional damage (but without significant loss of life). For example, 1993 flooding in the Mississippi River and major tributaries caused an estimated damage of $23.1 billion (1998 dollars), more than twice the damage of any other flood during 1980–1999 [*Ross and Lott*, 2000] and four times the mean annual U.S. flood loss [*Pielke and Downton*, 2001]. Texas and Hawaii, states of exceptional unit discharges, rank 5th and 48th, respectively in total flood damage between 1955 and 1999 (flood damage data from http://sciencepolicy.colorado.edu/sourcebook/floods.html) [see also *Pielke et al.*, 2002]. The highest ranking states, in order, are Pennsylvania, California, Louisiana, and Iowa, all states subject to high unit discharges but also all large states with population centers affected by one or more exceptionally damaging events.

7. Future Work

[23] Available and developing geospatial data sets offer substantial potential for analysis of hydrologic processes such as flooding [*Tarboton and Maidment*, 2001]. The flow records of the USGS stream gaging program are the most extensive water resource data in the nation and are the logical basis for national and regional scale analysis of factors controlling streamflow. Several such studies have been conducted for small subsets of USGS streamflow stations, either for specific regions or for stations meeting a combination of specific criteria such as size, duration or period of record, or basin characteristics [e.g., *Patton and Baker*, 1976; *Pitlick*, 1994; *Jones and Grant*, 1996; *Sturdevant-Rees et al.*, 2001; *Michaud et al.*, 2001]. These types of analyses are also the basis of regionalization techniques to estimate flood quantiles at ungaged sites [*Thomas*, 1987]. However, no studies have yet systematically analyzed large portions of USGS flow data; the primary obstacle is that contributing basins to most active and discontinued streamflow stations are not yet available in digital form. Once basin boundaries are available in GIS format, the possibilities for understanding climate and drainage basin properties that cause exceptionally large flows on a regional or national basis will be greatly expanded, as will the potential for evaluating relations between flow and human geography. Available geospatial data linked to station locations will also allow for more systematic assessment of some the factors affecting the character of USGS flow data, such as urbanization and regulation, which are only subjectively described by the station coding system.

[24] To conduct these types of analysis, the necessary next step is to develop higher resolution basin delineations within a GIS, not just for the stations recording ~90th and ~99th percentile peak flows but for all stations containing records in the peak flow files. The USGS is now in the process of systematically delineating basins of active and discontinued stations in digital format, in part so such analyses can proceed. Once complete and linked to an updated database with more than 0.5 million USGS-measured peak flows from over 23,000 active and discontinued stations, we plan to assess more quantitatively the connections between climatic, physiographic, and anthropogenic characteristics and peak flows, using similar statistical techniques employed in the previous regional studies. Results from our first assessment, as well as many previous studies, point to (1) the strong importance of various aspects of topography in controlling both precipitation and runoff, and (2) that the importance of basin physiography varies with basin size and possibly with regional climatic regime. These suppositions will be starting points for future quantitative analyses of these flow data.

8. Conclusions

[25] The vast number of measurements of annual flood peak discharges collected and maintained by the USGS over the last 100+ years permits systematic analysis of the spatial distribution of large floods in the United States, which has previously only been attempted with far fewer observations [e.g., *Hoyt and Langbein*, 1955; *Crippen and Bue*, 1977; *Michaud et al.*, 2001]. More than 0.5 million annual peak-flow records from 23,216 active and discontinued USGS stream gaging stations have been distilled into a database composed of the top 10% of annual discharges from 14,815 stream gaging stations recording flow from basins between 2.6 and 26,000 km^2 in the United States and Puerto Rico (Figure 1). These data permit identification of regions that produce the highest unit discharges. Adjusted for drainage area (Figure 2), the 90th percentile unit flows from this database (essentially the 99th percentile of all annual peak flows) are concentrated in Hawaii, Puerto Rico, and three broad bands within the conterminous United States: (1) a northeast trending belt encompassing the Appalachians in the eastern United States, (2) the western flanks of mountain ranges along the Pacific Coast, and (3) a northeast trending zone from central Texas to southern Arkansas and eastern Nebraska (Figure 4a). The 99th percentile unit discharges (essentially the 99.9th percentile of all flows) are concentrated in Hawaii and Puerto Rico, the area of the Balcones Escarpment in central Texas, the southern Midwest (especially the Flint Hills of eastern Nebraska and the Ozarks of Missouri), the eastern and western flanks of the Appalachians, the Transverse Ranges of southern California, and locally along western ramparts of Pacific Northwest coastal mountain ranges and the Cascade Range (Figure 4b). The interior of the western United States, most northern mid-continent states, and the Atlantic Coastal Plain have few basins producing exceptional unit discharges (Figure 4). The distribution of flood-related fatalities corresponds in a general manner with areas that produce relatively high unit discharges (Figure 6).

[26] Extraordinary unit discharges relate to specific topographic and climatologic conditions. In general, basins producing high unit discharges correspond to areas where regional climatic patterns can produce extraordinary precipitation, such as the Appalachians, the Pacific Coast, Texas and the southern Midwest. For basins with areas greater than about 500 km^2, the highest unit discharges are where large storms produce sustained rainfall (and sometimes snowmelt) for multiple days over broad areas, such as tropical storms in the eastern United States and Pacific

cyclonic systems on the west coast. The highest unit discharges for smaller basins are where convective systems deliver substantial rainfall for periods of minutes to several hours. Such events are most common in Texas, the southeastern United States, and along the flanks of the Appalachians, where mesoscale convective complexes and supercell thunderstorms have produced near world-record precipitation rates for durations up to 4 hours [e.g., *Smith et al.*, 2001].

[27] While broad areas of high unit discharges correspond closely with regional climatic patterns, specific basins of high unit discharge are nearly always areas of relatively high topographic relief. Relief increases local precipitation by a variety of orographic effects and increases resulting peak discharges by both increasing runoff and decreasing flow travel times through basins. The combined influence of these factors is qualitatively apparent in the distribution of high unit discharges across the nation but especially evident by the locations of specific basins producing high unit discharges within areas of high rainfall, such as the Balcones Escarpment, the Transverse Ranges, and the eastern and western flanks of the Appalachians (Figure 4b). The Balcones Escarpment is particularly subject to exceptional unit discharges because of the convergence of very high point rainfalls (Figure 5) and flood-producing basin physiography [*Dalrymple et al.*, 1937; *Patton and Baker*, 1976; *Baker*, 1977]. For the largest floods from very small basins (Figure 5), basin topography and other basin characteristics may be the overriding factor, since many of the largest U.S. discharges from small basins were not associated with exceptionally high precipitation, but were all in areas of considerable local relief [*Costa*, 1987a]. Ongoing delineation of basins associated with USGS stream gaging stations within a GIS will allow more quantitative analysis of the relations between basin physiography (and other characteristics), climate, and flow generation.

[28] Areas of high unit discharge are not necessarily indicative of elevated flood hazard. However, the broad correspondence between the distribution of flood fatalities (Figure 6) and areas of high unit discharge does indicate that channels and floodplains in regions of high unit discharge may be more dangerous than channels and floodplains in other areas. Consequently, the areas of high unit discharge shown on Figure 4 may be useful to guide national-level priorities for further studies of flood generation processes, focused flood hazard education, establishment of flood warning systems, as well as for updating floodplain mapping.

[29] **Acknowledgments.** T. Haluska, L. L. Orzol, and R. Viger provided GIS and database assistance. Reviews by Jared Bales, Barry Hill, John Williams, and *Water Resources Research* reviewers improved the manuscript. This work was funded by the USGS Office of Surface Water, as part of the National Streamflow Information Program.

References

Baker, V. R. (1977), Stream channel response to floods with examples from central Texas, *Geol. Soc. Am. Bull.*, *88*, 1057–1071.

Bradley, A. A., and J. A. Smith (1994), The hydrometeorological environment of extreme rainstorms in the Southern Plains of the United States, *J. Appl. Meteorol.*, *33*, 1418–1431.

Brown, W. M., III, and J. R. Ritter (1971), Sediment transport and turbidity in the Eel River basin, California, *U.S. Geol. Surv. Water Supply Pap.*, *1986*, 70 pp.

Costa, J. E. (1987a), Hydraulics and basin morphometry of the largest flash floods in the conterminous United States, *J. Hydrol.*, *93*, 313–318.

Costa, J. E. (1987b), A comparison of the largest rainfall-runoff floods in the United States with those of the People's Republic of China and the world, *J. Hydrol.*, *96*, 101–115.

Crippen, J. R., and C. D. Bue (1977), Maximum flood flows in the conterminous United States, *U.S. Geol. Surv. Water Supply Pap.*, *1887*, 52 pp.

Dalrymple, T., et al. (1937), Major Texas floods of 1936, *U.S. Geol. Surv. Water Supply Pap.*, *816*, 146 pp.

Hayden, B. P. (1988), Flood climates, in *Flood Geomorphology*, edited by V. R. Baker, R. C. Kochel, and P. C. Patton, pp. 13–26, John Wiley, Hoboken, N. J.

Hirschboeck, K. K. (1991), Climate and floods, in *National Water Summary 1988–89*, *U.S. Geol. Surv. Water Supply Pap.*, *2375*, 67–88.

Hirschboeck, K. K., L. L. Ely, and R. Maddox (2000), Hydroclimatology of meteorologic floods, in *Inland Flood Hazards: Human, Riparian and Aquatic Communities*, edited by E. E. Wohl, pp. 39–72, Cambridge Univ. Press, New York.

Ho, F. P., and J. T. Reidel (1979), *Precipitable Water Over the United States*, vol. 2, *Semimonthly Maxima*, NOAA Tech. Rep. NWS 20, 359 pp., Natl. Oceanic and Atmos. Admin., Silver Spring, Md.

Horton, R. E. (1932), Drainage basin characteristics, *Eos Trans. AGU*, *13*, 350–361.

Hoyt, W. G., and W. L. Langbein (1939), Some general observations of physiographic and climatic influences on floods, *Eos Trans. AGU*, *20*, 166–174.

Hoyt, W. G., and W. L. Langbein (1955), *Floods*, 469 pp. Princeton Univ. Press, Princeton, N. J.

Jarvis, C. S. (1942), Floods, in *Hydrology*, edited by O. E. Meinzer, pp. 531–560, McGraw-Hill, New York.

Jones, J. A., and G. E. Grant (1996), Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon, *Water Resour. Res.*, *32*, 959–974.

Konrad, C. E. (1994), Moisture trajectories associated with heavy rainfall in the Appalachian region of the United States, *Phys. Geogr.*, *15*, 227–248.

Konrad, C. E. (2001), The most extreme precipitation events over the eastern United States from 1950 to 1996: Considerations of scale, *J. Hydrometeorol.*, *2*, 309–325.

Lepkin, W. D., and M. M. DeLapp (1979), Peak-flow file retrieval (program 1980), *U.S. Geol. Surv. Open File Rep., 79-1336-I*, 64 pp.

Maddox, R. A., C. F. Chappell, and L. R. Hoxit (1979), Synoptic and meso-α scale aspects of flash flood events, *Bull. Am. Meteorol. Soc.*, *60*, 115–123.

Maddox, R. A., F. Canova, and L. R. Hoxit (1980), Meteorological characteristics of flash flood events over the western United States, *Mon. Weather Rev.*, *108*, 1866–1877.

Michaud, J. D., K. K. Hirschboeck, and M. Winchel (2001), Regional variations in small-basin floods in the United States, *Water Resour. Res.*, *37*, 1405–1416.

Patton, P. C., and V. R. Baker (1976), Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls, *Water Resour. Res.*, *12*, 941–952.

Pielke, R. A., Jr., and M. W. Downton (2000), Precipitation and damaging floods—Trends in the United States, 1932–97, *J. Clim.*, *13*, 3625–3637.

Pielke, R. A., Jr., M. W. Downton, and J. Z. B. Miller (2002), *Flood Damage in the United States, 1926–2000: A Reanalysis of National Weather Service Estimates*, 86 pp., Natl. Cent. for Atmos. Res., Boulder, Colo.

Pitlick, J. (1994), Relation between peak flows, precipitation, and physiography for five mountainous regions in the western USA, *J. Hydrol.*, *158*, 219–240.

Reitan, C. H. (1960), Distribution of precipitable water vapor over the continental United States, *Bull. Am. Meteorol. Soc.*, *41*, 79–87.

Ross, T., and N. Lott (2000), A climatology of recent extreme weather and climate events, *Tech. Rep. 2000-02*, 17 pp. Natl. Clim. Data Cent., Boulder, Colo.

Schildgen, R. (1999), Unnatural disasters, *Sierra*, *84*, 48–57.

Sloan, J., J. R. Miller, and N. Lancaster (2001), Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997, *Geomorphology*, *36*, 129–154.

Smith, J. A., M. L. Baeck, M. Steiner, and A. J. Miller (1996), Catastrophic rainfall from an upslope thunderstorm in the central Appalachians: The Rapidan storm of June 27, 1995, *Water Resour. Res.*, *32*, 3099–3113.

Smith, J. A., M. L. Baeck, Y. Zhange, and C. A. Doswell, III (2001), Extreme rainfall and flooding from supercell thunderstorms, *J. Hydrometeorol.*, *2*, 469–489.

Sturdevant-Rees, P., J. A. Smith, J. Morrison, and M. L. Baeck (2001), Tropical storms and the flood hydrology of the central Appalachians, *Water Resour. Res.*, *37*, 2143–2168.

Tarboton, D. G., and D. R. Maidment (2001), National geospatial datasets for hydrology, *Eos Trans. AGU*, *82*(47), Fall Meet. Suppl., Abstract H42A-0347.
Thomas, W. O., Jr. (1987), Techniques used by the U.S. Geological Survey in estimating the magnitude and frequency of floods, in *Catastrophic Flooding*, edited by L. Mayer and D. Nash, pp. 267–288, Allen and Unwin, Concord, Mass.
Waananen, A. O., D. D. Harris, and R. C. Williams (1970), Floods of December 1964 and January 1965 in the far western states—part 1. Description, *U.S. Geol. Surv. Water Supply Pap.*., *1866-A*, 265 pp.
World Meteorological Organization (1986), Manual for estimation of probable maximum precipitation, *Oper. Hydrol. Rep. 1*, 2nd ed., 269 pp., Geneva, Switzerland.
Zhang, Y., J. A. Smith, and M. L. Baeck (2001), The hydrology and hydrometeorology of extreme floods in the Great Plains of eastern Nebraska, *Adv. Water Resour.*, *24*, 1037–1050.

J. E. Costa and J. E. O'Connor, U.S. Geological Survey, 10615 SE Cherry Blossom Drive, Portland, OR 97216, USA. (oconnor@usgs.gov)