CHANGES IN HEAVY RAINFALL IN MIDWESTERN UNITED STATES

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ABSTRACT: Characteristics of heavy rainfall events are important in the design of water-handling structures, agriculture, weather modification, and in monitoring climate change. Traditionally it is assumed that the extreme rainfall time series are stationary with no trends. This assumption may not be true for portions of the Midwestern United States. A newly digitized record of precipitation for 304 sites that extends back to 1901 was used to examine this assumption. Results for the entire Midwest show that stations are more likely to experience their heaviest rainfall events in more recent years. An analysis of the geographic distribution of changes in the annual maximum time series shows areas of increases across the Midwest. The impact of the changes in the annual maximum time series can be significant in determining rainfall frequency values and consequent runoff calculations. These results suggest that rainfall frequency studies should be updated on a regular basis for maximum usefulness.

INTRODUCTION

Characteristics of heavy rainfall events are important in the design of water-related structures (e.g., storm sewer systems), agriculture, weather modification, and in monitoring climate change. Traditionally hydrologists have fit various statistical distributions to historical precipitation data to derive the rainfall amounts at selected return periods and storm durations. The assumption underlying the derivation of these values has been that the time series were stationary, without major fluctuations or long-term trends. This assumption allowed the use of all available historical data with equal weight. However, a preliminary study of Illinois by Huff and Changnon (1987) using 1901–80 data for 22 stations investigated the possibility of a climatic trend in the distribution of heavy rainstorms in Illinois. A comparison of one-day and two-day rainfall amounts for two-year to 25-year return periods showed significant changes in the northern two-thirds of the state between two 40-year periods (1901–40 and 1941–80). This was supported by an earlier study of Illinois climate fluctuations (Changnon 1984a) that showed sizable shifts in total precipitation and thunderstorm frequency for 1901–80. Similar results were found for other parts of the Midwestern United States (Huff and Angel 1992), with large areas showing increases in the rainfall amounts at selected return periods between two 40-year periods (1907–46 and 1947–86). The lack of sufficient digital data for many states for those periods prevented a more thorough examination of this change.

In this paper newly available data were used to examine possible changes in heavy rainfall during the 1901–94 period and tested for their statistical significance. The performance of past rainfall frequency studies is reviewed and a possible solution to the problem of nonstationarity is proposed.

STATISTICAL ANALYSIS

Data

The rainfall data for this analysis came from two sources. The first source is the daily rainfall records from the National Climatic Data Center's TD-3200 data set. These records were from the cooperative observer network and were digitized since 1948. While written records exist before 1948, the number of stations with digital records before 1948 varied widely from state to state. To make these pre-1948 records more accessible, the Midwestern Climate Center provided support to the state climatologists in the region to digitize those written records. The precipitation records from TD-3200 and the newly digitized data were combined, yielding 304 stations with digital records from 1901 to 1994 across the Midwest (Fig. 1), after retaining only those stations with ≤10% missing data.

Changes in Extreme Rainfall Events

The change in heavy precipitation in the Midwest was examined in both time and space. For the temporal analysis, a time series was constructed of the number of one-day precipitation events with 50.8 mm (2 in.) or more that occurred in the region for each year (Fig. 2). With random characteristics, one would expect year-to-year variability with no apparent long-term trends in this time series. However, linear regression showed a statistically significant ($\alpha = 0.05$) positive trend in the number of extreme precipitation events over time. This represents an approximate 20% increase during the 1901–94

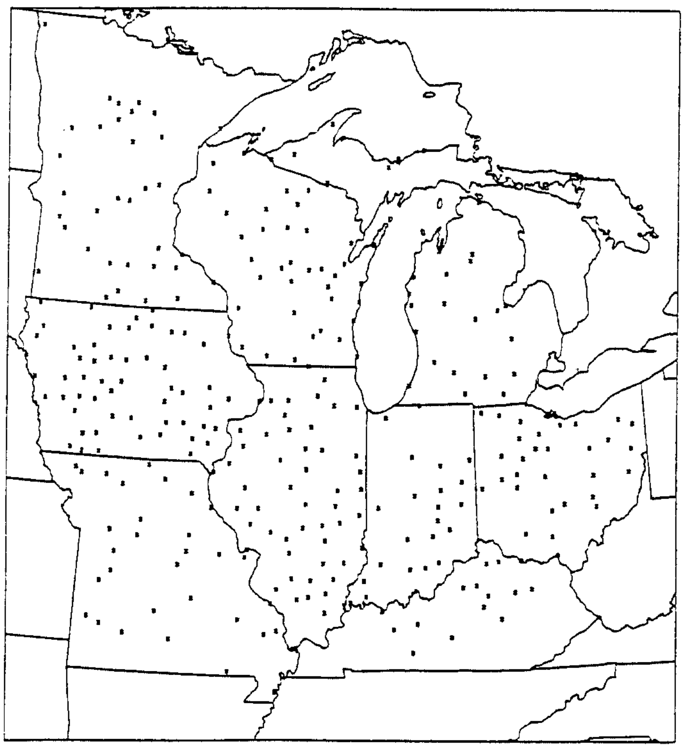

FIG. 1. Available Long-term Climate Stations

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record. Therefore, stations in the Midwest are more likely to experience their larger rainfall events in more recent years.

To find where these significant changes in the heavy rainfall were taking place, the rainfall data were divided into two 47-year periods, 1901–47 and 1948–94. From these two periods, the annual maximum time series were calculated. The annual maximum series was chosen because it is commonly used to determine design rainfall values (e.g., Hershfield 1961; Huff and Angel 1992). For each site the rank sums of the annual maximum series from these two periods were compared using the Wilcox rank sums test (Conover 1980), also known as the Mann-Whitney U test. A nonparametric approach was used because of the skewness in the annual maximum time series. Fig. 3 shows the results for the one-day annual maximum time series. There were 45 sites with a statistically significant (α = 0.05) increase between the two periods. While not statistically significant, an additional 147 sites also showed an increase over time, based on a comparison of the median values of the annual maximum time series for each period. The remaining 112 sites showed a decrease between the two periods, but this was statistically significant at only five sites.

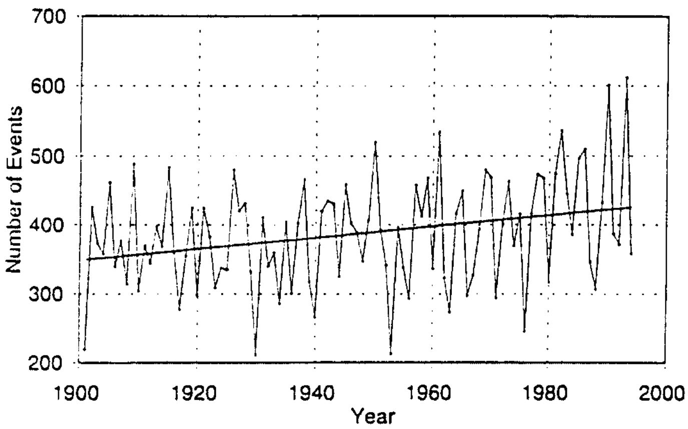

FIG. 2. For the Midwest, Number of One-day Rainfall Events That Equaled or Exceeded 50.8 mm; Linear Regression (Straight Line) Indicates a Statistically Significant Positive Slope at α = 0.05

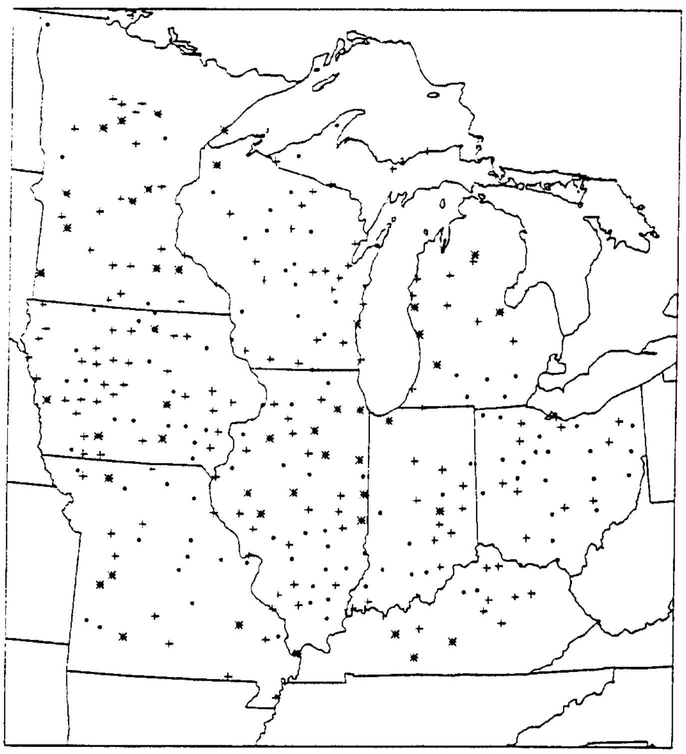

FIG. 3. Changes in Annual Maximum Time Series between Two 47-year Periods (1901–47 and 1948–94) for One-day Storm in Midwest (+ = Stations with Increase Over Time; * = Stations with Significant Increases at α = 0.05 Using Wilcox Rank Sums Test; • = Stations with Decrease Over Time)

An analysis of the 2-, 3-, 5-, and 10-day annual maximum time series yielded similar results over time. For the two-day events, 52 stations showed statistically significant increases, and five stations showed statistically significant decreases. For the three-day events, 44 stations showed statistically significant increases and nine showed statistically significant decreases. For the five-day events, 53 stations showed statistically significant increases and seven showed statistically significant decreases. For the 10-day events, 64 stations showed statistically significant increases and 12 showed statistically significant decreases over time.

In each case the number of stations with a statistically significant increase outnumbered the stations with statistically significant decreases by about five to one. Overall, the percentage of stations showing an increase in the median values between the two periods ranged from 58 to 63% of the 304 stations. In all five storm durations from one to 10 days, the areas with no change were largely confined to four regions: east-central Missouri, southeast Illinois and southwest Indiana, Ohio and southeast Michigan, and central Wisconsin. The remaining areas were dominated by increases over time. These changes in extreme precipitation closely match trends in annual precipitation by climate division found in Karl et al. (1996). For the Midwest, they found increases of 10–20% in Iowa, Minnesota, northern Illinois and Indiana, and Michigan.

Any attempt at a physical explanation for this change is handicapped by a lack of extensive climatological data, such as upper air data or radar data, for the first 47-year period. Because there are areas of the Midwest that do not exhibit an increase in the frequency of heavy precipitation events over time, an explanation involving large-scale processes such as global warming cannot be used. While changes in the observation of precipitation (e.g., changes in gauge exposure, observers, or observing techniques) could cause changes in the reported heavy precipitation over time at individual stations, it is unclear how these changes could be so widespread across the Midwest and primarily favor an increase in observed extreme rainfall amounts over time.

The areas showing an increase did coincide with some major urban areas of the Midwest, St. Louis and Chicago, for example. Huff and Changnon (1973) found that in the Midwest, urban areas enhanced rainfall "downwind," although on a smaller scale (<80 km) than found here. For Chicago in particular, Changnon (1984b) showed increases of 15% on average over the city and 10–20% more rain extending 40 km east over southern Lake Michigan.

Performance of Previous Rainfall Design Studies

An earlier standard for heavy rainfall frequencies for the Midwest was the *U.S. Weather Bureau Technical Paper 40* (Hershfield 1961). That study was based on data from the turn of the century to 1957, which roughly coincides with the earlier 47-year period used in this study. It is expected that areas showing large changes over time (Fig. 3) would also be areas that regularly exceeded the expected rainfall amounts at particular return periods. This was the case with the 100-year, 24-hour storm. The number of times that these values were exceeded in each state is summarized in Table 1 [from Huff and Angel (1992)]. The probability, R, of exceeding a 100-year event, T, in n years can be calculated using

$$R = 1 - \left(1 - \frac{1}{T}\right)^n \quad (1)$$

TABLE 1. Number of Times 24-Hour, 100-Year Value from *Technical Paper 40* Is Exceeded by State

Location (1)	Number of stations (2)	Average length of record (3)	Number of times exceeded (4)	Number of times expected (5)	Ratio[b] (6)
Illinois	61	87	69	36	1.92
Indiana	41	64	17	20	0.85
Iowa	43	80	20	24	0.83
Kentucky	25	67	11	12	0.92
Michigan[a]	46	60	71	21	3.38
Minnesota	25	67	14	12	1.17
Missouri	44	62	4	20	0.20
Ohio	41	60	27	19	1.42
Wisconsin	13	78	13	7	1.86
Midwest	339	70	246	171	1.43

[a]From Sorrell and Hamilton (1990).
[b]Ratio derived from column 3 divided by column 4.

For example, in Illinois, the probability of exceeding the 100-year event 0.583 in the 87 years of records. With 61 stations, one would expect the 100-year event to have been exceeded only 36 times during this 87-year period (column 5, Table 1) rather than the 69 times observed (column 4). The results in Michigan were even more striking, with more than three times the expected number of storms exceeding the 100-year value. For the entire Midwest, 246 storms exceeded the 100-year value against an expected number of 171 storms, a ratio of 1.43. The Table 1 results suggest that the expected 100-year, 24-hour amounts, as presented in Hershfield (1961), are no longer valid for portions of the Midwest.

Design Implications

To illustrate the impact of the significant changes in the annual maximum time series between the two 47-year periods, an analysis of extreme rainfall was made for Chicago. Chicago was chosen because of its statistically significant 39% increase in the median annual maximum between the two time periods. The maximum likelihood method and the generalized extreme value (GEV) distribution (Farago and Katz 1990) were used to estimate the expected rainfall amounts at return periods of 2, 5, 10, 20, and 50 years for the two periods. As Table 2 shows, the expected rainfall amounts increased in the second time period and the differences were larger at the longer return periods. The differences in the rainfall amounts increased from 28% at the two-year event to 60% for the 50-year event. While Chicago represents the largest increase between the two time periods in terms of the median annual maximum, other sites with significant increases showed similar results of larger increases at the longer return periods.

An example of the impacts of these changes in the rainfall frequency amounts can be found from simple runoff calculations using the SCS curve method (USDA 1968). A type B soil under field crop conditions, typical of the Midwest, produced a curve number of 78. The values for the 50-year event were converted from the one-day to 24-hour duration using well-known ratio of 1.13 (Hershfield 1961; Huff and Angel

TABLE 2. Expected One-day Rainfall Amounts (mm) at Selected Return Periods for Two Halves of Record for Chicago, Illinois

Return period (1)	Two-year (2)	Five-year (3)	Ten-year (4)	Twenty-year (5)	Fifty-year (6)
1901–47	52.6	66.6	77.0	86.9	100.1
1948–94	67.3	90.4	110.2	130.3	160.0
Change	+28%	+36%	+43%	+50%	+60%

1992), which yielded 113 mm for the earlier period (1901–47) and 181 mm for the later period (1948–94). These rainfall amounts generated runoff values of 58 and 117 mm, an increase of 102% between the two periods. Therefore, the increase in the rainfall frequency value was reflected and magnified in the runoff calculation. These larger runoff values would require larger and more expensive measures to manage the increased volume of water.

The large changes in the rainfall amounts over time present a challenge to estimating the expected return period amounts. If the entire period of record is used, these large increases over time may lead to an underestimation of expected rainfall amounts because of the lower values in the first part of the record. However, if only the most recent years are used, important information for estimating longer return periods (e.g., the 100-year event) is lost. In an attempt to address this issue in Illinois, Huff and Angel (1989) weighted the expected rainfall amounts for the period 1901–83 by the more recent years. This weighting factor was obtained by calculating the ratio of 1941–80 rainfall to that for the entire 1901–83 period at each of 61 stations in Illinois for the various storm durations and return periods. Mean ratios were then calculated for each of the 10 climatic sections in Illinois, and these average values were used to adjust the station values derived from the 1901–83 data. The average ratios were used instead of station values to reduce the effect of random sampling fluctuations among the 61 individual stations. In this way the 100-year event, for example, could be calculated using all available information while still taking into account the more recent events.

SUMMARY AND CONCLUSIONS

This study examined the change over time of the heavy rainfall distribution in the Midwest. Results for the entire Midwest showed that stations are more likely to experience their heaviest one-day rainfall events (≥50.8 mm) in more recent years. An analysis of the geographic distribution of changes in the annual maximum time series showed areas of increases across the Midwest. The results of an assessment of an earlier rainfall frequency study (Hershfield 1961) reflect the increase in heavy rainfall events in the Midwest. The impact of the changes in the annual maximum time series can be significant in determining rainfall frequency values and consequent runoff calculations.

These findings suggest that the assumption of a stationary time series, for fitting statistical distributions to historical precipitation data, may be invalid for portions of the Midwest. Furthermore, the results suggest those rainfall frequency studies such as Hershfield (1961) need to be updated on a regular basis to provide realistic estimates of rainfall amounts at selected return periods.

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