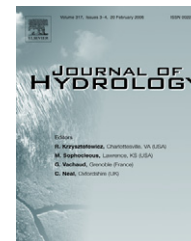




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Changing estimates of design precipitation in Northeastern Illinois: Comparison between different sources and sensitivity analysis

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Summary Recent research points to changing frequency and intensity of heavy rainfall events and consequently, flood flows in Northeastern Illinois. Flood frequency modeling is a key component of managing floodwaters in this highly populated metropolitan area, which includes Chicago and surrounding urban areas, and has enormous economic and environmental significance.

In this research, 100-year 24-h precipitation totals in Northeastern Illinois were quantified using the L-moments method with 1948–2004 hourly precipitation data at six stations in the region for comparison with published results from the US Weather Bureau Technical Paper No. 40 (TP-40), Illinois State Water Survey Bulletin 70 (Bulletin 70) and National Oceanic and Atmospheric Administration Atlas-14 (NOAA-14). Sensitivity analyses were conducted to examine the effects of various factors on 100-year, 24-h precipitation at Aurora College station, in particular the effects of selecting different periods of the precipitation record, different regions, and different underlying distributions. The sensitivity analyses used 1900–2004 daily precipitation data at 12 stations in the region. Finally, the HEC-HMS rainfall-runoff model was used to illustrate relative impacts of changing estimates of design precipitation on flood peaks at 12 small watersheds in the region.

It was demonstrated that the oldest source, TP-40, produced significantly smaller 100-year, 24-h rainfall totals, than Bulletin 70, NOAA-14, and the current study. It was also shown that the variability in design rainfall calculated based on different 50-year records (nearly 200%) was much larger than those based on the choice of underlying statistical

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distribution (50%), or the selection of region (25%). The average relative increase in hydrologic peaks exceeded that of rainfall peaks. This could partly be explained by the non-linear nature of the hydrologic system.

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Introduction

Recent studies have reported statistically significant increases in heavy rainfall at various locations around the world (Adamowski and Bougadis, 2003; Groisman et al., 2005). Hejazi and Moglen (2007) concluded that precipitation variability induced a greater impact on low flows than urbanization in six urbanizing watersheds in the Maryland Piedmont region. Young and McEnroe (2006) found that rainfall depths for return periods greater than 10 years in the metropolitan Kansas City area are higher than those estimated in 1961 (Hershfield, 1961) and 1977 (Frederick et al., 1977). In Northeastern Illinois, the intensity and frequency of heavy rainfall events increased over the past century (Huff and Angel, 1989). Angel and Huff (1997) stated that the assumption of stationarity of the extreme rainfall time series may not be true for portions of the Midwestern United States. They further indicated that the number of extreme one-day precipitation events per year (≥ 5 cm) in the Chicago area showed a statistically significant positive trend over time. More recently Changnon and Westcott (2002) pointed to "... continuing increases in the number of heavy rainstorms in future years, which have major implications for water managers in Chicago and elsewhere."

In this study, rainfall frequencies were calculated using the method described by Hosking and Wallis (1997) and Hosking (2000), herein referred to as the L-moments method. The calculations used available hourly data (1948–2006) and the results were compared with rainfall frequencies based on TP-40; Illinois State Water Survey's Bulletin 70 (Huff and Angel, 1989), referred to as Bulletin 70; and the National Oceanic and Atmospheric Administration, National Weather Service (NOAA, NWS) rainfall frequency Atlas 14 (Bonnin et al., 2006), referred to as NOAA-14. Those sources use the datasets available at various times in the past. Calculated rainfall frequencies from different sources are variable, as the best-fit distribution parameters differ for different datasets.

The TP-40 (Hershfield, 1961) included US rainfall frequency maps for 30-min to 24-h durations and 1- to 100-year return periods. It used the conventional moments method to estimate distribution parameters using the data through 1958. The method was partly empirical and partly theoretical. The Gumbel procedure for fitting the annual series data to the Fisher–Tippett Type I distribution was used for large return periods, such as the 100-year return period.

Bulletin 70 (Huff and Angel, 1989) presents the results of an extensive investigation of the distribution of heavy rainstorms in Illinois based on data for 61 precipitation stations operated during 1901–1983. It shows frequency distributions of point rainfall for periods ranging from 5 min to 10 days and for recurrence intervals of from 2 months to 100 years. The study used graphical analysis of log–log transformed data.

NOAA Atlas 14 (Bonnin et al., 2006) contains precipitation frequency estimates with associated confidence limits for the United States and is accompanied by additional information such as temporal distributions and seasonality. It is based on observed rainfall data through 2000. The approach follows the regional frequency analysis based on the L-moments method (Hosking and Wallis, 1997). The procedure is used for estimating the 2- to 1000-year precipitation totals for 5-min to 60-day durations. A Monte Carlo simulation was used to produce upper and lower confidence limits.

Comparison between the L-moments method and the three published sources, TP-40, Bulletin 70, and NOAA-14 is presented in Fig. 1. One-hundred-year, 24-h precipitation is referred to as design precipitation and denoted as P_{100} . As the rainfall analysis ultimately was applied to hydrologic analyses at watersheds smaller than 100 square kilometers (km^2), for such scale it was deemed appropriate to use only hourly precipitation records (1948–2004). The NOAA-14 source used daily and hourly data ending with the year 2000. Because the region of interest in this study was limited to the small suburban watersheds, only hourly data observed at rainfall gages in the proximity of selected watersheds having continuous records longer than 43 years (Scenario 1 in Table 1 and hourly precipitation stations in Fig. 2) were used.

The Aurora College rainfall gage recorded the highest observed precipitation amounts during the two largest historical storms in the metropolitan Chicago area, one in October 1954 (Daniels and Hale, 1958) and the other in July 1996 (Angel and Huff, 1999; Changnon, 1999; and Changnon and

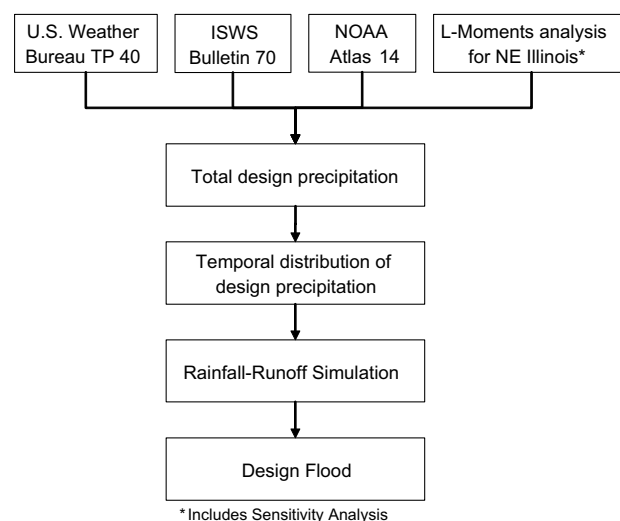


Figure 1 Focus of this research including comparison of different sources for design precipitation, sensitivity analysis based on L-moments, and design flood, with the main emphasis on total design precipitation.

Table 1 Precipitation stations, period of record, and Scenarios^a

NCDC#	Station	Period of record	Years	Increment	Note	Scenarios			
						1	2	3	4
110583	Belvidere	1948–2004	57	Hourly		x			x
111549	Chicago O'Hare	1962–2004	43	Hourly		x			x
111572	Chicago University	1948–1994	47	Hourly		x			x
111577	Chicago Midway	1948–2004	57	Hourly		x			x
112011	Crete	1948–2004	57	Hourly		x			x
115493	Mchenry Lock and Dam	1948–2004	56	Hourly	Missing 1991	x			x
115136	Lockport Power House	1948–1974	26	Hourly				x	x
110338	Aurora College	1900–2004	105	Daily			x	x	x
112223	De Kalb	1969–2004	36	Daily				x	x
114530	Joliet Brandon	1948–2004	57	Daily				x	x
114535	Joliet	1900–1974	75	Daily				x	x
119221	Wheaton 3 SE	1900–2004	71	Daily	Missing 1902-1935			x	x

^a Scenario 1 was used for regional analysis, comparison with published sources, and hydrologic analyses. Scenarios 2–4 compare design precipitation at the Aurora College station for 1- 6-, and 12-stations regions, respectively.

**Figure 2** Location of watersheds and rain gauges.

Kunkel, 1999). Precipitation from these storms far exceeded all other storms in the region during the monitoring history (1990–2004), and many scientists consider them rare values or outliers (D. Martin, NWS, personal communication). Thus, it was of particular interest to examine the sensitivity of the design precipitation at the Aurora College station for different data records, different region definitions, and different statistical distributions used in the frequency analysis.

The goal of this study was also to quantify the relative impact of the change in design precipitation on flood flows at 12 small suburban watersheds in Northeastern Illinois from 20.2 to 90.1 km² in size. This approach first estimated design precipitation totals and their spatial distributions, which served as an input to the hydrologic HEC-HMS model to calculate the corresponding discharge for each of the 12 watersheds. In this study, the discharges obtained based

on the design precipitation are referred to as the design discharges.

Methodology

A schematic of the methodology framework of this research is shown (Fig. 1). Estimated design precipitation values for each of the 12 watersheds were compiled based on published sources TP-40, Bulletin-70, and NOAA-14. Next, the L-moments method, as described by Hosking (2000), was applied to the Northeastern Illinois region to estimate design precipitation at all precipitation stations. Design precipitation totals then were compared with TP-40, Bulletin-70, and NOAA-14 totals. Effects of different records, different stations, and different statistical distributions on design precipitation at the Aurora College station were studied by sensitivity analysis.

For each of the 12 watersheds, the inverse-squared distance method was used to estimate design precipitation magnitude. Those magnitudes then were compared with those of TP-40, Bulletin-70, and NOAA-14. Afterward, the hydrologic HEC-HMS model used the hourly temporal distribution of design precipitation for each watershed following the method described in Huff (1990).

The hydrologic component of this research was based on the HEC-HMS rainfall-runoff model, developed by the US Army Corps of Engineers (HEC-HMS, 1998). HEC-HMS model is commonly used in the United States for engineering design purposes, and for flood insurance (FEMA, 2003). In the recent research, this model was coupled with atmospheric models to predict watershed runoff (Anderson et al., 2002); to predict hydrological extremes under future climate conditions (Cunderlik and Simonovic, 2005); and to assess impacts of urbanization and climatic fluctuations on streamflow magnitude in Southern California (Beighley et al., 2003). Guo (2001) also compared the design storm approach based on the HEC-HMS model with a continuous simulation approach and an analytical approach in the Chicago area and found that the design storm approach provided peak discharge estimates similar to those of the other two methods. Although a detailed hydrologic analysis is beyond the scope of this research, the purpose of using the HEC-HMS model in this study is to assess the relative changes in peak flows based on the changes in precipitation.

To quantify the hydrologic impact of changing precipitation, the hydrologic model was applied to each of the 12 watersheds. The model used design rainfall totals calculated in this study and also those obtained from TP-40, Bulletin-70, NOAA-14. Model parameters were determined through simulations of flooding resulting from a major regional storm in Northeastern Illinois observed in July 1996 (Holmes and Kupka, 1997), the most recent event for which simultaneous rainfall and runoff datasets were published. This was also the largest rainfall event on record. The flood of 1996 was simulated using the HEC-HMS model based on Clark's unit hydrograph and the US Soil Conservation Service (SCS) curve number. The most recent land cover and soil type data available at the time of this study (1999) were used to determine the SCS curve number for each watershed. Initial losses, times of concentration, and storage coefficients were determined through calibrations for each

of the 12 watersheds. The calibrated hydrologic models then were used to predict design runoff for different design precipitation totals and durations. The 24-h rainfall duration was found to be critical for the small watersheds in the study, as it produced maximum peak discharges.

For comparison with TP-40, Bulletin-70, and NOAA-14, only hourly precipitation stations in Northeastern Illinois having records of 43 years or longer were selected. There were six such stations (Table 1), and this dataset is referred to as Scenario 1. Using only stations with hourly data, and thus avoiding a conversion factor for transforming daily to 24-h data, potentially could produce more accurate design precipitation estimates.

Record flood-producing rainstorms of October 1954 (Daniels and Hale, 1958) and of 17–18 July 1996 in the metropolitan Chicago area received a lot of attention (Angel and Huff, 1997; Changnon, 1999; Changnon and Kunkel, 1999) due to their unusually high amounts and relatively limited spatial extent. Two extreme 24-h precipitation events occurred at the Aurora College station: 30.0 centimeters (cm) in 1954 and 48.5 cm in 1996 (Fig. 3). The 1954 observed rainfall amount was close to the NOAA-14 500-year estimate ($P_{500} = 33.7$ cm), while the 1996 amount exceeded the NOAA-14 1000-year estimate ($P_{1000} = 41.1$ cm). The data presented in Fig. 3 indicates that at the Aurora College rain gauging station, the 10 largest historical storms recorded have been since 1950, and most of these storms appear much larger than any in the previous 50 years. In addition, four of the five largest events at Aurora (all exceeding 15.5 cm) occurred between 1972 and 1996, suggesting a shift in the frequency of heavy rain events in that area compared with the earlier records.

This sensitivity analysis for the Aurora College station used daily data and calculated design precipitation for three scenarios (Table 1): one station (Scenario 2), 6 stations (Scenario 3), and 12 stations (Scenario 4). Scenario 2 included only the Aurora College station. Scenario 3 used one hourly station (Lockport Power House) aggregated to daily increments and five daily stations (Aurora College, De Kalb, Joliet Brandom, Joliet, and Wheaton 3 SE). Available records varied from 27 years (1948–1974, Lockport Power House) to 105 years (1900–2004, Aurora College). Scenario 4 used all 12 stations (Table 1).

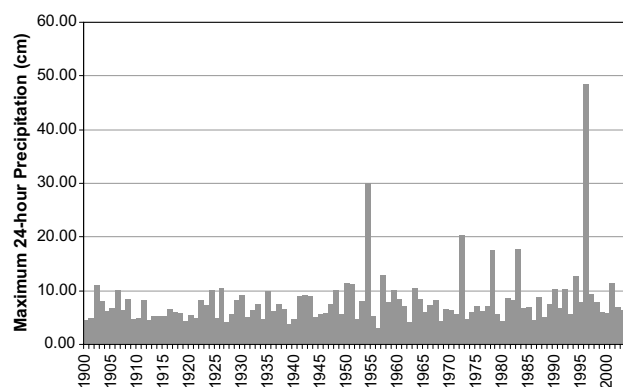


Figure 3 Annual maximum 24-h precipitation time series (1900–2004), Aurora College station, Illinois.

L-moments method

The magnitude of a 100-year event often is calculated based on less than 100 years of observed data. Regional frequency analysis attempts to alleviate this problem by "trading space for time"; i.e., by using data from several sites to estimate event frequencies at one site. As opposed to the standard methods, such as the method of moments, the L-moments method (Hosking, 2000; Hosking and Wallis, 1997) can be estimated by linear combinations of the probability-weighted moments of an ordered sample. Past research results (Vogel and Fennessey, 1993; Hosking et al., 1985; Hosking, 1990) indicate that regional frequency analysis based on the L-moments method has several advantages, such as robustness and better identification of the parent distribution, compared to standard estimation techniques, particularly for regional studies.

The L-moments method is a regional frequency analysis approach to estimate the magnitude of design precipitation. This research followed the detailed work of Hosking and Wallis (1997) using the computer code presented in Hosking (2000). This method uses the discordance measure (Hosking and Wallis, 1997), denoted as D_i to identify unusual sites in a region and the heterogeneity measure (Hosking and Wallis, 1997), denoted as H , to assess if the region is homogeneous. The next step is to find which statistical distribution best fits the region among the following ten distributions (Hosking, 2000): Exponential (EXP), Gamma (GAM), Gumbel (GUM), Normal (NOR), Generalized Pareto (GPA), Generalized Extreme Value (GEV), Generalized Logistic (GLO), Generalized Normal (GNO), Pearson Type 3 (PE3), and Wakeby (WAK). Generally, a distribution with smallest goodness-of-fit-measure z^{DIST} (Hosking and Wallis, 1997) is selected. This measure is defined as $z^{\text{DIST}} = \frac{(\tau_4^{\text{DIST}} - t_4^R + B_4)}{\sigma_4}$, where τ_4^{DIST} is the fitted L-kurtosis for any distribution; t_4^R is the observed regional average L-kurtosis; σ_4 is the standard deviation of t_4^R ; $B_4 = \frac{1}{N} \sum_{m=1}^N (t_4^{[m]} - t_4^R)$ is the bias in the same regional average L-kurtosis. N is a large number of realizations of a region, in this calculation assumed to be $N = 500$. The fit is declared to be adequate if the absolute value of z^{DIST} is less than 1.64 (Hosking and Wallis, 1997). Once the distribution is selected and the parameters calculated, design precipitation values are estimated.

Hosking (1990) defined L-moments as linear combination of probability weighted moments (PWMs), denoted as b_r , as defined by Greenwood et al. (1979). For a probability distribution with cumulative distribution function $F(x)$, unbiased estimators of the first three PWMs are defined by Hosking and Wallis (1997):

$$b_r = n^{-1} \binom{n-1}{r}^{-1} \sum_{j=r+1}^n \binom{j-1}{r} x_{j:n} \quad (1)$$

where $x_{j:n}$ denotes the j th smallest number in the sample of size n . The first few sample L-moments are as follows:

$$\begin{aligned} \ell_1 &= b_0 \\ \ell_2 &= 2b_1 - b_0 \\ \ell_3 &= 6b_2 - 6b_1 + b_0 \\ \ell_4 &= 20b_3 - 30b_2 + 12b_1 - b_0 \end{aligned} \quad (2)$$

The sample L-moment ratios are:

$$\begin{aligned} t &= \frac{\ell_2}{\ell_1} \\ t_3 &= \frac{\ell_3}{\ell_2} \\ t_4 &= \frac{\ell_4}{\ell_2} \end{aligned} \quad (3)$$

where t is the L-CV, t_3 is L-skewness, and t_4 is L-kurtosis (Hosking and Wallis, 1997).

For estimating p unknown parameters of a selected distribution, the method of L-moments obtains parameter estimates by equating first p sample L-moments to the corresponding population quantities, i.e., $\lambda_i = \ell_i$, $i = 1, 2, 3, 4$, $\tau = t$, $\tau_3 = t_3$, and $\tau_4 = t_4$. For various distributions, Hosking and Wallis (1997) provided expressions for distribution parameters in terms of the L-moments. As an example, such expressions for the GLO distribution parameters, ξ (location), α (scale), and k (shape), are:

$$k = -\tau_3, \quad \alpha = \frac{\lambda_2 \sin k\pi}{k\pi}, \quad \xi = \lambda_1 - \alpha \left(\frac{1}{k} - \frac{\pi}{\sin k\pi} \right) \quad (4)$$

The probability density function, the cumulative distribution function and the quantile function of the GLO distribution are given by Eqs. (5)–(7), respectively:

$$f(x) = \frac{\alpha^{-1} e^{-(1-k)y}}{(1 + e^{-y})^2}, \quad y = \begin{cases} -k^{-1} \log\{1 - k(x - \xi)/\alpha\}, & k \neq 0 \\ (x - \xi)/\alpha, & k = 0 \end{cases} \quad (5)$$

$$F(x) = 1/(1 + e^{-y}) \quad (6)$$

$$x(F) = \begin{cases} \xi + \alpha[1 - \{(1 - F)/F\}^k]/k, & k \neq 0 \\ \xi - \alpha \log\{(1 - F)/F\}, & k = 0 \end{cases} \quad (7)$$

After the parameters are determined (Eq. (4)), precipitation with different return periods are calculated using the quantile function (Eq. (7)). Similarly, Hosking and Wallis (1997) provided methods with detailed explanations to calculate parameters for other probability distributions.

To construct confidence limits, 1000 synthetic datasets having the same statistical features were generated using a Monte Carlo simulation technique (Hosking and Wallis, 1997), where each synthetic dataset produced a quantile. The upper confidence limit separated the upper 5% and the lower 95%, and similarly, the lower confidence limit separated the lower 5% from the top 95%.

Data

Hourly precipitation data were obtained from the NOAA National Climatic Data Center Web site (NCDC, 2005). Daily precipitation data were obtained from the Midwestern Regional Climate Center of the Illinois State Water Survey (MRCC, 2005). The NOAA National Weather Service operates and maintains the rain gages used in this study. These sites conform to their standards with regard to the equipment, exposure of the site, and rules for compatible station moves and, hence, it is assumed that the records are homogeneous. The list of precipitation stations used in this study is shown (Table 1). Generally, hourly precipitation data were not available before 1948 while daily data are available in digital form and may date back to 1900. To study hydrologic

impacts of changing precipitation, this study used streamflow gaging stations (Table 2) in urbanizing areas with drainage areas of less than 100 km² and for which hourly rainfall-runoff data were available for the storm of 1996 (Holmes and Kupka, 1997). Fig. 2 shows the study area, including watershed boundaries and locations of precipitation and stream gages.

This analysis used hourly and daily data. Four scenarios (Table 1) included Scenario 1: hourly data at all six selected hourly stations (1948–2004); Scenario 2: daily data observed at the Aurora College station (1900–2004); Scenario 3: daily data observed at six stations not used in Scenario 1 (1900–2004); and Scenario 4: daily and hourly data observed at all 12 gages (1990–2004). Results of Scenario 1 were compared with TP-40, Bulletin-70, and NOAA-14 results. Scenarios 2, 3, and 4, were used for the sensitivity analysis for the Aurora College station.

Results based on six hourly stations – Scenario 1

Daily and 24-h precipitation

Data observed at six hourly precipitation stations (Belvidere, Chicago O'Hare, Chicago University, Chicago Midway, Crete, and McHenry Lock and Dam) were used to estimate design precipitation. Those stations matched streamflow gaging station locations reasonably well (Fig. 2). Record length ranged between 43 and 57 years (Table 1). Using hourly instead of daily data facilitated more accurate estimation of maximum 24-h precipitation for each year. When only daily data are available, maximum 24-h precipitation is calculated as maximum daily precipitation multiplied by a correction factor of 1.13 (Huff and Angel, 1992). This empirical factor varies from station to station and represents an average value for a large number of stations in the region, however. Thus, using hourly data generally produces more accurate estimates of design precipitation.

To investigate the reliability of the correction factor of 1.13, maximum 24-h precipitation values were compared with maximum daily precipitation values at the six selected hourly stations. This resulted in ratios of annual maximum 24-h precipitation to annual maximum daily total precipita-

Table 3 Ratio between 24-h duration precipitation amounts and daily total precipitation amounts

Station name	NCDC #	Ratio	Years
Belvidere	110583	1.20	57
Chicago O'Hare	111549	1.10	43
Chicago University	111572	1.17	47
Chicago Midway	111577	1.14	57
Crete	112011	1.17	57
McHenry Lock and Dam	115493	1.15	56
<i>Average ratio</i>		1.16	

tion (Table 3). Ratios varied between 1.1 and 1.2 for the six hourly sites, with an average of 1.16, somewhat larger than the empirical ratio of 1.13 (Huff and Angel, 1992).

Calculation of 24-h precipitation and comparison with other sources

For the assumed region, including the six hourly stations, the discordance measure for sites ranged between 0.68 and 1.54, indicating that no site was discordant ($Di > 3$), while the homogeneity measure was less than 1 ($H = 0.4$), indicating a homogeneous region. The best-fit distribution of 24-h precipitation first was determined using the L-moments ratio diagram (Fig. 4), which provides an indication of which distribution may be expected to fit a data sample. Both the diagram and the goodness-of-fit z-statistic ($z = -0.66$) demonstrated GLO as the best fit distribution for the annual maximum 24-h duration precipitation data for the six hourly sites. The other nine distributions had $z > 1.64$. Thus, the GLO distribution was selected as the best-fit distribution. The regional average design precipitation total is 17.61 cm.

Fig. 5 compares the estimated design precipitation based on current study with TP-40 (Hershfield, 1961), Bulletin 70 (Huff and Angel, 1989), and NOAA-14 (Bonnin et al., 2006). This comparison also includes two sets of confidence limits, one based on current study, the other based on NOAA-14. The results show that the average design precipitation based on the current study (GLO) was 1.13% lower than precipitation based on NOAA-14. The confidence limits

Table 2 Streamflow gages in this study

No.	Watershed	USGS station number	County	Start year	End Year	Drainage area (km ²)
1	McDonald Creek	05529500	Cook	1953	2005	20.2
2	Tinley Creek	05536500	Cook	1952	2005	28.7
3	West Fork North Branch Chicago River	05535500	Cook	1953	2005	29.4
4	Midlothian Creek	05536340	Cook	1951	2005	32.3
5	Skokie River	05535000	Lake	1952	2005	33.3
6	Flag Creek	05533000	Cook	1952	2005	42.2
7	Addison Creek	05532000	Cook	1952	2005	45.8
8	North Branch Chicago River	05534500	Lake	1953	2005	50.4
9	Long Run	05537500	Cook	1952	2005	53.5
10	Deer Creek	05536235	Cook	1949	2005	59.1
11	Butterfield Creek	05536255	Cook	1949	2005	60.2
12	Poplar Creek	05550500	Cook	1952	2005	90.1

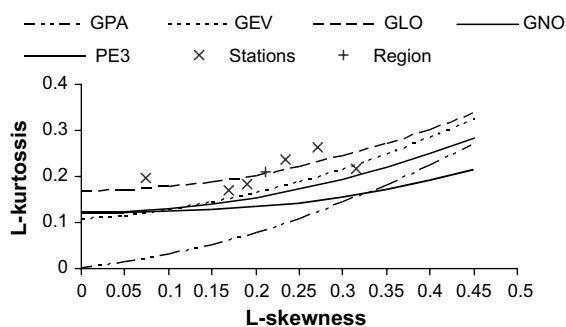


Figure 4 L-moments ratio diagram for six selected sites with hourly data using five distributions.

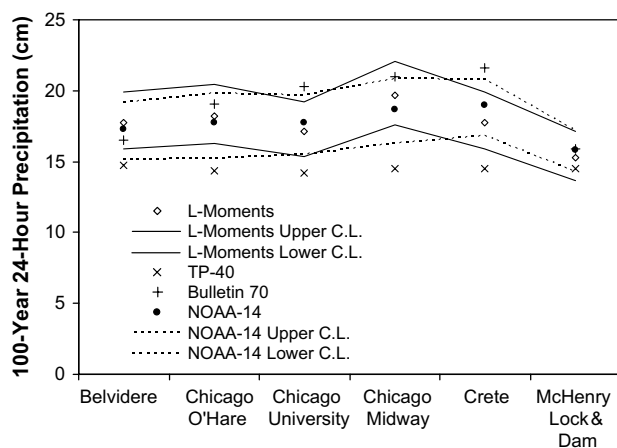


Figure 5 Estimated 100-year 24-h precipitation amounts based on L-moments, TP-40, Bulletin 70, and NOAA-14 methods. The L-moments and NOAA-14 methods also include 90% confidence limits for six hourly precipitation stations (Scenario 1).

based on these two studies were relatively similar (Fig. 5). On the other hand, results of the current study are, on average, 21.83% larger than those of TP-40 and 7.54% lower than those of Bulletin 70. For most locations the design precipitation based on TP-40 falls below the lower confidence limits for the current study. The design precipitation based on Bulletin 70 exceeds the upper confidence limits at Crete and Chicago University locations, while it appears reasonably close to the current study at other locations. These differences reflect different temporal extent of datasets used to calculate design precipitation for different studies.

Sensitivity of 24-h precipitation to selection of temporal range

A sensitivity analysis of the calculated design precipitation based on the period of record also was assessed in this study. Fig. 6 shows the results based on hourly precipitation data from six sites most covering the period 1948–2004, and L-moments method. Fig. 6a shows the results for three 19-year periods: 1948–1966, 1967–1985, and 1986–2004. The lowest 19-year estimates of P_{100} were obtained for the period 1967–1985 and the other two periods each produced an average P_{100} estimate approximately 20% higher than for the period 1967–1985. This could be explained by the occurrence of major storms during the earliest 19 years (storm of 1954) and during the latest 19 years (storm of 1996). Fig. 6b shows design precipitation estimates based on a fixed start year and a sliding end year for four periods 1948–1970, 1948–1980, 1948–1990, and 1948–2000. The estimates of P_{100} based on these periods of record varied, on average, from 17.07 cm for 1948–1980, to 18.21 cm for 1948–1970. Both amounts are within approximately 3% of the 17.60-cm long-term mean of for the period 1948–2004, meaning that shorter records within the entire hourly record (1948–2004) produced a P_{100} estimate relatively consistent with that for the entire record.

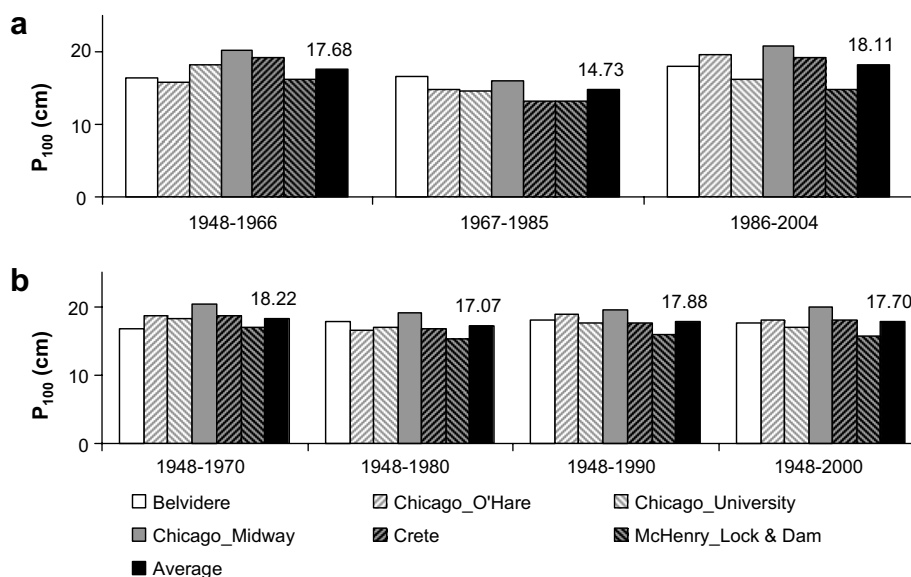


Figure 6 Design rainfall for six selected stations in the region (Scenario 1) showing the results for (a) three 19-year time periods and (b) fixed start year and sliding end year.

Sensitivity analysis for Aurora college station estimates (Scenarios 2–4)

To examine the sensitivity of P_{100} estimates to changing temporal records, Scenarios 2–4 were applied to seven daily time periods: 1900–1925, 1926–1950, 1951–1975, 1976–2000, 1900–1950, 1951–2000, and 1900–2004. Table 4 shows the P_{100} estimate for the three scenarios and the seven time periods. Temporal variability of the P_{100} estimate for Scenario 2 at the Aurora College station shows that design precipitation based on 1900–1950 was approximately three times smaller than that of the period 1951–2004. For shorter record lengths, such as 25 years, the variability of estimates was even larger. For Scenario 2, design precipitation based on the period 1976–2000 was more than four times larger than that of the period 1926–1950. Fig. 7 shows that the variability in design precipitation based on different scenarios (for the entire 105-year period) is smaller than the variability based on different 25-year (or 50-year) periods. The variability in the P_{100} estimate correlates highly with the selected period of data. Design precipitation totals based on periods that include the largest observations (particularly at Aurora College) exceed P_{100} estimates that do not include those observations. Most of the largest observations were observed after the year 1950 and mostly at Aurora College (Fig. 3). In addition, the smallest variability in P_{100} for both 25-year and 50-year records was for Scenario 4, followed by Scenario 3 and Scenario 2. Using more stations in the region (12 stations, Scenario 4) produced a more stable P_{100} estimate than using a smaller number of stations (1 station, Aurora College, Scenario 2) because 24-h totals observed at the single station exceeded 24-h totals observed at other stations. The effect of the extreme observations at Aurora College was reduced significantly by using the six stations (Scenario 3), and even further reduced by using the 12 stations (Scenario 4).

A sensitivity analysis for statistical distributions was conducted for Scenario 3 (Fig. 8). The figure compares different distributions, regardless of goodness-of-fit z-statistics, and includes 90% confidence limits based on the GLO distribution for the entire record, 1900–2004. For the entire record, two-parameter distributions (EXP, GAM, GUM, and NOR) produced smaller P_{100} estimates than three-parameter distributions (GEV, GLO, GNO, GPA, and PE3), and the five-parameter distribution (WAK). For example, GLO and WAK distributions produced nearly 50% larger design precipitation than the NOR distribution. This can be explained by

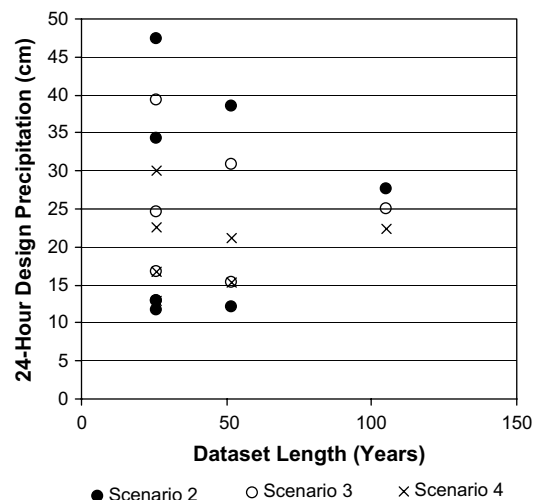


Figure 7 Variability of P_{100} estimates at Aurora College based on record length and scenario including four approximately 25-year records, two approximately 50-year records, and one 105-year record.

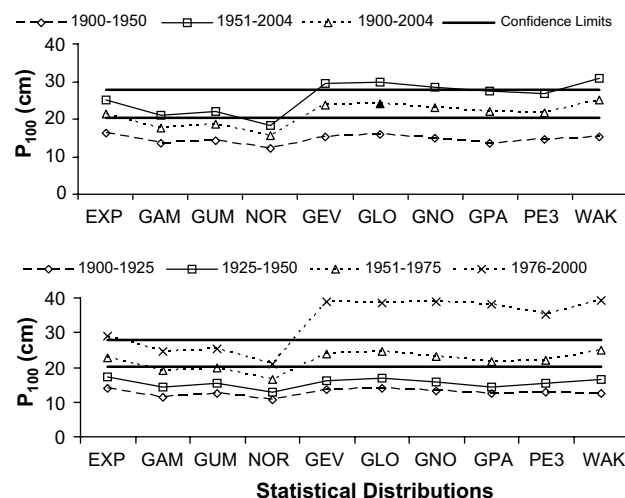


Figure 8 Sensitivity of design rainfall to selected distributions and various periods of record (Scenario 3) at Aurora College station. The confidence intervals are based on the complete available record 1900–2004 period and GLO distribution (solid triangle in the top chart).

Table 4 Point value for P_{100} at Aurora College, Scenarios 2–4 and various periods

Period	Scenario 2		Scenario 3		Scenario 4	
	P_{100} (cm)	Best-fit distribution	P_{100} (cm)	Best-fit distribution	P_{100} (cm)	Best-fit distribution
1900–2004	27.64	GLO	25.10	WAK	22.47	WAK
1900–1950	12.19	GPA	15.24	GEV	15.24	GEV
1951–2004	38.46	GLO	30.89	WAK	21.27	WAK
1900–1925	12.98	GPA	12.95	PE3	12.94	PE3
1926–1950	11.68	GPA	16.71	GLO	16.70	GLO
1951–1975	34.24	GLO	24.51	GLO	22.52	GLO
1976–2000	47.40	GLO	39.29	WAK	30.06	WAK

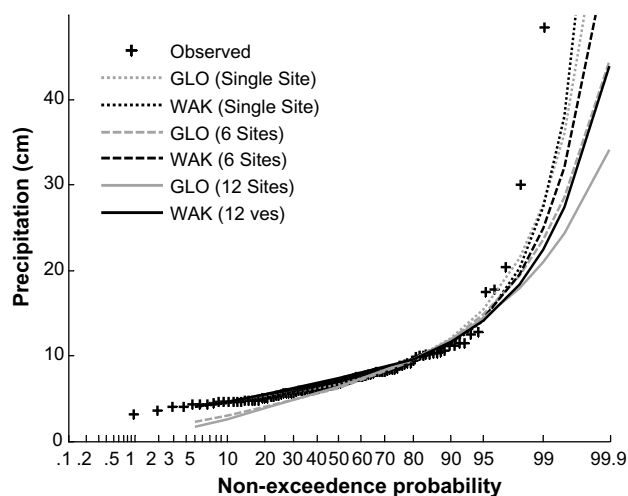


Figure 9 Observed maximum 24-h precipitation at Aurora College station compared with theoretical best-fit GLO and WAK curves for 1-, 6-, and 12-station hypothetical regions (Scenarios 2, 3, and 4, respectively).

the limited ability of two-parameter distributions to fit right-tail extremes, compared to the three- and five-parameter distributions. The results of all three- and five-parameter distributions are within the confidence limits for the GLO distribution. This shows that the selection of distribution does not affect the design precipitation as much as the selection of 25- or 50-year record.

To show the effect of the largest observed daily values at Aurora College, GLO and WAK distributions were compared in Scenarios 2–4 (Fig. 9). The comparison indicates that the two largest observed precipitation events (representing the storms of 1954 and 1996) could be outliers; the five-parameter WAK distribution tends to give higher P_{100} estimates than the GLO distribution (the larger number of parameters gives more flexibility in the right tail of the distribution, bending the best-fit curve closer toward the two largest observed values): and the P_{100} estimate decreases with increasing numbers of stations in the region, as Aurora

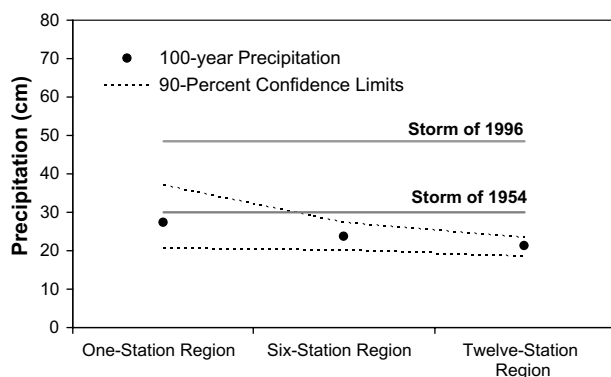


Figure 10 100-year 24-hour precipitation estimates with 90% confidence limits based on GLO distribution, 105 years of observed data (1900–2004) and various numbers of stations. The figure also shows the two historical maximum 24-h observed rainfall amounts, observed in 1954 and 1996.

College was the station with the largest observed daily precipitation for the storms of 1954 and 1996, in the entire region.

Fig. 10 shows the design precipitation for 1-, 6-, and 12-station regions, the confidence limits for the GLO distribution based on the 1900–2004 datasets. It also shows the amounts of the two largest regional storms, observed in 1954 and 1996. The figure indicates that both storms are outside the confidence limits in all cases, except for the storm of 1954 and one-station region.

Hydrologic impact of increased estimates of design precipitation

To illustrate the significance of the observed variability in design precipitation magnitudes among various methods and its translated hydrologic implication, design precipitation was applied to 12 watersheds in the study area using the HEC-HMS model. Design precipitation was distributed according to recommendations of Bulletin 70 and the results are shown (Fig. 11 and Table 5). Fig. 11a compares design

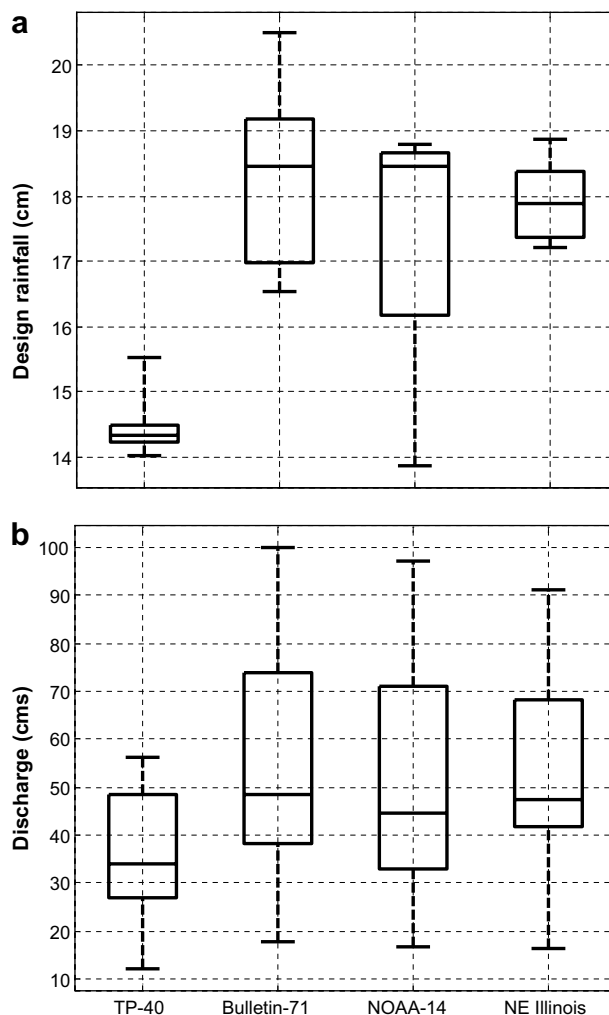


Figure 11 Design precipitation for different sources (a) and the corresponding peak discharges (b) calculated at 12 watersheds in Northeastern Illinois.

Table 5 Design precipitation and peak discharge for each watershed in the study

USGS watershed number	Design 24-h precipitation (cm)				Peak discharge (m ³ /s)			
	TP-40	Bulletin 70	NOAA-14	NE Illinois	TP-40	Bulletin 70	NOAA-14	NE Illinois
05529500	14.35	17.15	16.69	17.91	15.73	20.70	19.88	22.09
05536500	14.55	19.08	18.57	18.57	47.61	69.69	67.20	67.15
05535500	14.17	16.81	15.67	17.73	35.45	47.15	41.99	51.22
05536340	14.53	19.30	18.54	18.24	12.10	17.69	16.79	16.43
05535000	14.15	16.54	13.87	17.30	30.37	38.67	29.40	41.88
05533000	14.45	18.19	18.77	18.49	56.31	78.03	81.40	79.74
05532000	14.30	17.17	18.77	17.88	23.53	37.89	47.23	41.90
05534500	14.02	16.64	14.15	17.30	35.61	49.61	36.26	53.27
05537500	14.38	19.08	18.80	18.24	52.68	99.98	97.13	91.17
05536235	14.33	20.50	18.54	17.22	30.85	57.02	48.52	42.77
05536255	14.33	20.24	18.39	17.42	49.55	87.17	74.80	69.15
05550500	15.52	18.75	17.86	18.87	32.43	43.11	40.10	43.54
Mean	14.42	18.29	17.38	17.93	35.19	53.89	50.06	51.69
Percent difference	24.32	−1.94	3.14	0.00	46.92	−4.08	3.26	0.00
Median	14.34	18.47	18.47	17.89	33.94	48.38	44.61	47.38
Percent difference	24.80	−3.09	−3.09	0.00	39.60	−2.07	6.21	0.00

point precipitation based on various sources and calculated at the center of each of the 12 watersheds in the study, and Fig. 11b shows corresponding design peak discharges calculated at the 12 watersheds in Northeastern Illinois. Spatial variability of TP-40 values was smaller than the variability of other sources, both in precipitation (Fig. 11a) and corresponding discharge (Fig. 11b). As shown in Table 5, on average, design precipitation for each watershed based on the current study was 3.14% larger than the NOAA-14 estimate, 1.94% smaller than the Bulletin 70 estimate and 24.32% larger than the TP-40 estimate. Median design precipitation was 3.09% smaller than the NOAA-14 estimate, 3.10% smaller than the Bulletin 70 estimate and 24.80% larger than the TP-40 estimate. The corresponding mean discharge was 3.26% larger than that based on the NOAA-14 source, 4.08% smaller than the Bulletin 70 report, and 46.92% larger than the TP-40 report. Generally, relative differences in discharge were larger than corresponding differences in precipitation, due to the non-linear nature of the rainfall-runoff relationship.

Discussion

Design precipitation totals for Northeastern Illinois were calculated using the L-moments method and hourly datasets (1948–2004) at six gages in the region. Calculated precipitation totals were compared with those from TP-40, Bulletin 70, and NOAA-14. A significant increase in design precipitation was evident when considering recent data records. Consequently, the oldest source, TP-40, produced smaller design rainfall than Bulletin 70, NOAA-14, and the current study. Average design precipitation totals for the six precipitation stations based on the current study differ by +21.83%, −7.54%, and −1.13% when compared with TP-40, Bulletin 70, and NOAA-14 design totals, respectively. Similarly, average design precipitation totals for all 12 watersheds based on the current study differ by 24.32%,

−1.94%, and +3.14% when compared with TP-40, Bulletin 70, and NOAA-14 design totals, respectively.

Effects of different periods of precipitation record, different region selection, and different underlying distribution on design precipitation at the Aurora College station were studied using sensitivity analysis. This analysis used 1900–2004 daily precipitation data at 12 stations in the region. Research results indicate that design precipitation and design flood discharges are more sensitive to changes in the period of record than to the selection of region or choice of the underlying statistical distribution. For example, design precipitation for the Aurora College station, based on the period 1951–2004, was approximately 200% larger than the corresponding value for the period 1900–1950. Nevertheless, design precipitation based on different two- and three-parameter statistical distributions could differ by as much as 50%; and the one-station region could produce design precipitation up to 25% larger than that of a 12-station region.

As described earlier, the research also quantified impacts of various design precipitation values in the region on flood peaks at the outlets of 12 small watersheds using the HEC-HMS rainfall-runoff model calibrated on the large flood of July 1996. The mean design peak flow for all 12 watersheds calculated in this study differed by +46.92%, −4.08%, and +3.26% when compared to those based on TP-40, Bulletin 70, and NOAA-14 sources, respectively, showing that large increases in design precipitation could result in even larger increases in design discharges.

Conclusions

This study calculated design precipitation totals for the Northeastern Illinois region and compared them with those published in TP-40, Bulletin 70, and NOAA-14. The average design precipitation for 12 watersheds in the study, based on the current study was 24.32% larger than that of TP-40,

which resulted in 46.92% larger design discharges. For the 12 watershed locations, the differences in average design precipitation and average design discharges between the current study and more recent sources (Bulletin 70 and NOAA-14) did not exceed 5%. Generally, the older source of precipitation frequency (TP-40) produced lower design precipitation estimates than newer ones, which could be explained by the increasing trend in annual maximum 24-h precipitation totals in Northeastern Illinois since 1900.

Sensitivity analysis at the Aurora College precipitation station revealed that changes in period of record have the largest impact on estimated design precipitation, and thus the design flood peaks, followed by selection of statistical distribution, and selection of the number of stations in the region.

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