Impacts of Urbanization and Climate Variability on Floods in Northeastern Illinois

Momcilo Markus and Sally McConkey, Illinois State Water Survey

Abstract

Annual flood peaks on 12 small urbanizing watersheds in northeastern Illinois increased over the past several decades. This is explained by intensive urbanization and increasing trends of heavy rainfall in the region. Average urbanization of those watersheds increased from 10.6% in 1954 to 61.8% in 1996. In addition to land-cover changes, numerous studies reported increasing frequency and intensity of heavy precipitation in the region. As a consequence, older studies produced lower design rainfall estimates than more recent sources.

In this research, 100-year, 24-hour 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 U.S. 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 effects of various factors on 100-year, 24-hour precipitation at the Aurora College station, particularly effects of selecting different periods of precipitation record, different regions, and different underlying distributions. It was demonstrated that the oldest source, TP-40, published in 1961,

produced significantly smaller 100-year, 24-hour rainfall totals, than Bulletin 70, NOAA-14, and the current study. It also was shown that variability in design rainfall calculated based on different 50-year records was much larger (nearly 200%) than those based on choice of statistical distribution (50%) or selection of region (25%).

It also was demonstrated that present day flood discharges are, on average, at least 15% larger than currently certified estimates. Due to ongoing urbanization, those discharges may become even higher in the future. Those watersheds with largest discrepancies between discharges based on this study and regulatory discharges should have the highest priority for future flood studies.

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). In Northeastern Illinois, intensity and frequency of heavy rainfall events has increased over the past century (Huff and Angel, 1989). Angel and Huff (1997) stated that the assumption of stationarity of extreme rainfall time series may not be true for portions of the Midwest. They further indicated that the number of extreme one-day precipitation events per year (≥ 5 centimeters or 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."

Land-cover information in the Chicago area was obtained from several sources to estimate spatial land-cover distribution of each watershed in 1954 and 1996. Meyer (2005) documented percentages of land-cover types and impervious areas for watersheds of Weller Creek, Tinley Creek, and McDonald Creek in Cook County in 1952, 1967, 1974, 1988, and 1998. Other sources of land-cover and detention storage improvements include previous Federal Emergency Management Agency (FEMA) flood insurance studies (FEMA, 1980; 1986; 2000a; 2000b; 2002; 2005).

In addition, historical aerial photo maps over the vicinity of the watersheds for the years 1954 and 1961, if available. Aerial photo maps were readily available and were used in this study to reflect contemporary urbanization of the region.

This research investigated two main factors contributing to the increase in annual flood peaks on streams in Illinois: precipitation increases and urbanization. The study used 12 watersheds with drainage areas less than 100 square kilometers (km^2) in Northeastern Illinois (Figure 1). It also compared design flood peaks with those published by United States Geological Survey or USGS (Curtis, 1987; Soong et al., 2004) and FEMA (FEMA, 1980; 1986; 2000a; 2000b; 2002; 2005); and determined single and joint contributions of land-use change and climate variability on increasing flood discharges. The proposed methodology easily can be extended to project future flood magnitudes. Such results could be used with existing management practices to reduce flooding impacts; to provide input for flood study prioritization through comparison of published regulatory discharges with flood discharges computed for current conditions; and to investigate potential impacts of future changes in land use and precipitation on flood peaks.

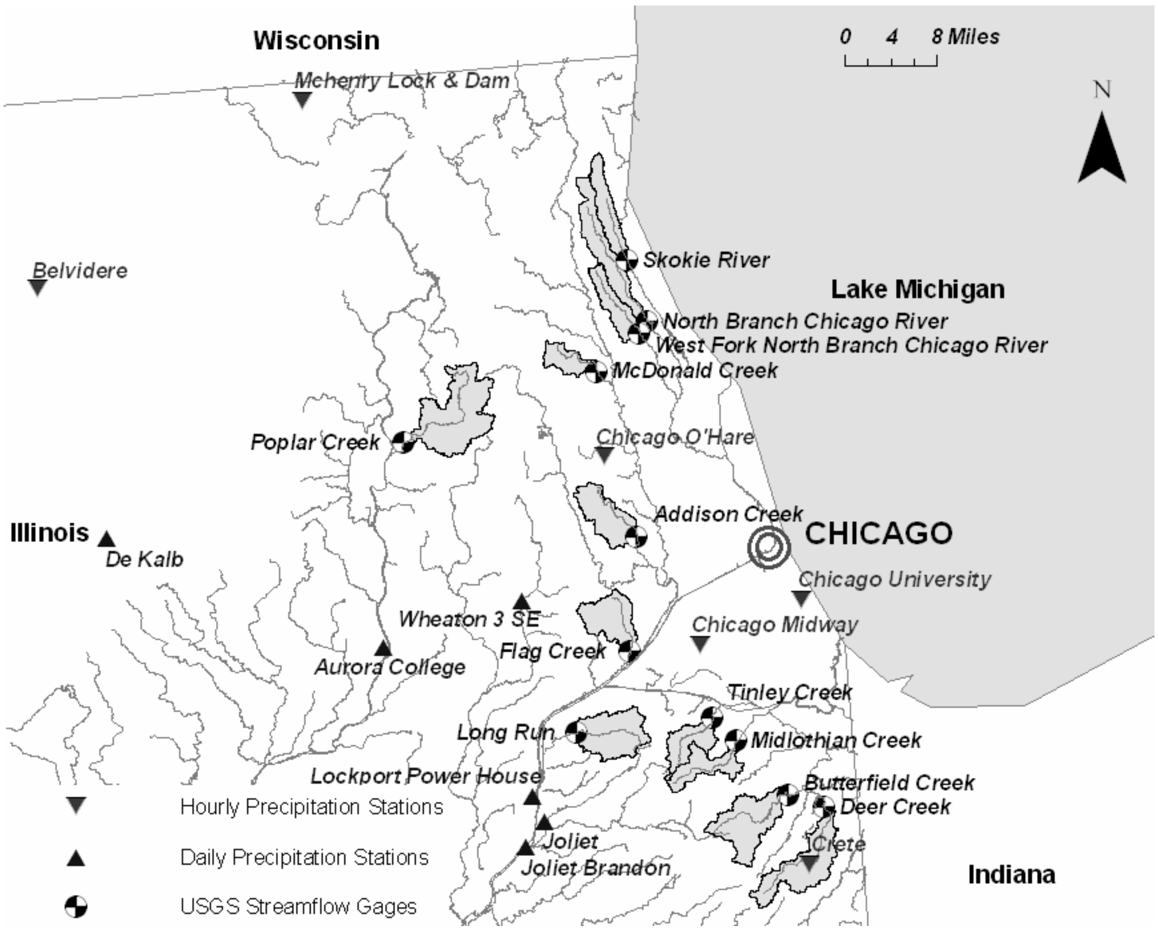

Figure 1. Location of watersheds and raingages

Data

Twelve urbanizing watersheds ranging in size from 20.2 to 90.1 km^2 in northeastern Illinois (Table 1) were selected for rainfall-runoff modeling of two major flood events, in October 1954, and in July 1996. Observed runoff for October 1954 and

July 1996 were obtained from two USGS reports (Daniels and Hale, 1958) and (Holmes and Kupka, 1997), respectively. Precipitation data for hydrologic modeling also obtained from two sources. Observed precipitation data were compiled for the 1954 event from NCDC (2005) and for the 1996 from Holmes and Kupka (1997).

Table 1. Streamflow Gages Used in This Study

Watershed	USGS Station Number	County	Start Year	End Year	Drainage Area (km^2)
McDonald Creek	05529500	Cook	1953	2005	20.2
Tinley Creek	05536500	Cook	1952	2005	28.7
West Fork North Branch Chicago River	05535500	Cook	1953	2005	29.4
Midlothian Creek	05536340	Cook	1951	2005	32.3
Skokie River	05535000	Lake	1952	2005	33.3
Flag Creek	05533000	Cook	1952	2005	42.2
Addison Creek	05532000	Cook	1952	2005	45.8
North Branch Chicago River	05534500	Lake	1953	2005	50.4
Long Run	05537500	Cook	1952	2005	53.5
Deer Creek	05536235	Cook	1949	2005	59.1
Butterfield Creek	05536255	Cook	1949	2005	60.2
Poplar Creek	05550500	Cook	1952	2005	90.1

Methodology

Estimated design precipitation values for each of the 12 watersheds were compiled based on published sources: TP-40 (Hershfield, 1961), Bulletin 70 (Huff and Angel, 1989), and NOAA-14 (Bonnin et al., 2004). Design precipitation totals at all precipitation stations in Northeastern Illinois were estimated using the L-moments (Hosking, 2000). Design precipitation totals then were compared with TP-40, Bulletin 70, and NOAA-14 totals. Sensitivity analysis was used to determine effects of different records, different stations, and different statistical distributions on design precipitation at the Aurora College station.

The schematic (Figure 2) outlines steps of the methodology for this research. Observed rainfall-runoff events (Figure 2, top row) were used to calibrate parameters of the HEC-HMS (USACE, 1998) model for each watershed for both the 1954 and 1996 floods. The resulting set of model parameters described rainfall-runoff relationships at two different stages of development in the watersheds. In particular, the 1954 data described basin development during early urbanization, and the 1996 data described the rainfall-runoff relationship during the advanced stage of urbanization in the 12 watersheds. Calibrated parameters and design precipitation (Huff and Angel, 1992; Hosking and Wallis, 1997) then were used to calculate design runoff (Figure 2, middle row). Calibrating one "historical" and one "contemporary" watershed model facilitated investigation of various urbanization and design storm scenarios (Figure 2, bottom row).

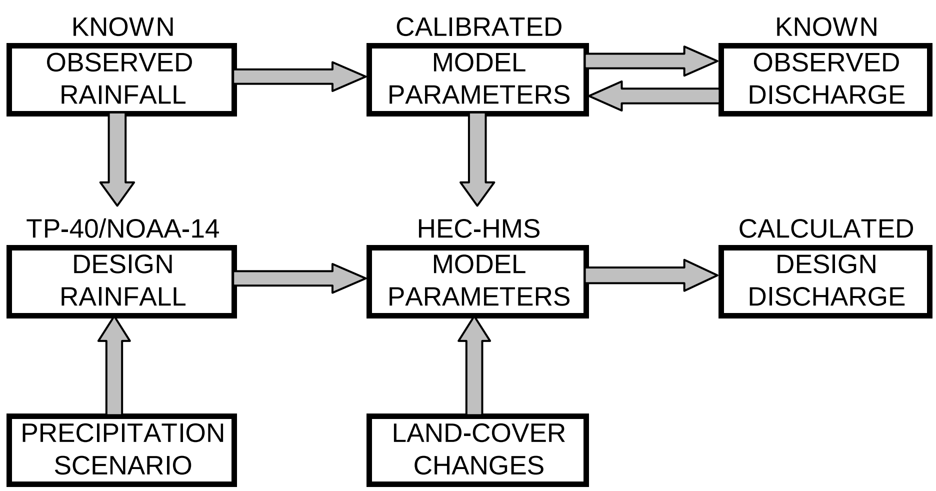

Figure 2. Schematic of the modeling approach

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" with data from several sites with similar features to estimate event frequencies at one site. As opposed to standard methods, such as the method of moments, the L-moments method (Hosking, 2000; Hosking and Wallis, 1997) uses linear combinations of probability-weighted moments (PWMs) 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 then 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), to identify unusual sites in a region and the heterogeneity measure (Hosking and Wallis 1997), to assess the region. 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

$z^{DIST} = \frac{(\tau_4^{DIST} - t_4^R + B_4)}{\sigma_4}$, 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; and $B_4 = \frac{1}{N}\sum_{m=1}^{N}(t_4^{[m]} - t_4^R)$, the bias in the same regional average L-kurtosis, where N is the number of realizations for a region, (N=500 in this calculation). 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 are calculated, design precipitation values could be estimated.

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

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

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

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

Sample L-moment ratios are:

$$t = \frac{\ell_2}{\ell_1}$$
$$t_3 = \frac{\ell_3}{\ell_2} \tag{3}$$
$$t_4 = \frac{\ell_4}{\ell_2}$$

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 the 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. For example, such expressions for the GLO distribution parameters, k (shape), α (scale), and ξ (location) are:

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

Equations 5-7 define the probability density function, the cumulative distribution function, and the quantile function of the GLO distribution, respectively:

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

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

and

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

After parameters are determined (Eq. 4), precipitation totals for 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, 1,000 synthetic datasets with the same statistical features were generated using a Monte Carlo simulation technique (Hosking and Wallis 1997). Each synthetic dataset produced a quantile. The upper confidence limit separated the upper 5% from the lower 95%; and similarly, the lower confidence limit separated the lower 5% from the top 95%.

Analyses

Precipitation Records

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-hour precipitation events occurred at the Aurora College station: 30.0 cm in 1954 and 48.5 cm in 1996 (Figure 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). Data presented in Figure 3 indicate that the 10 largest historical storms recorded at the Aurora College station have been since 1950, and most of these storms appear much larger than any in the previous 50 years. Four of the five largest events at Aurora occurred after 1972, suggesting a shift in the frequency of heavy rain events in that area compared with earlier records.

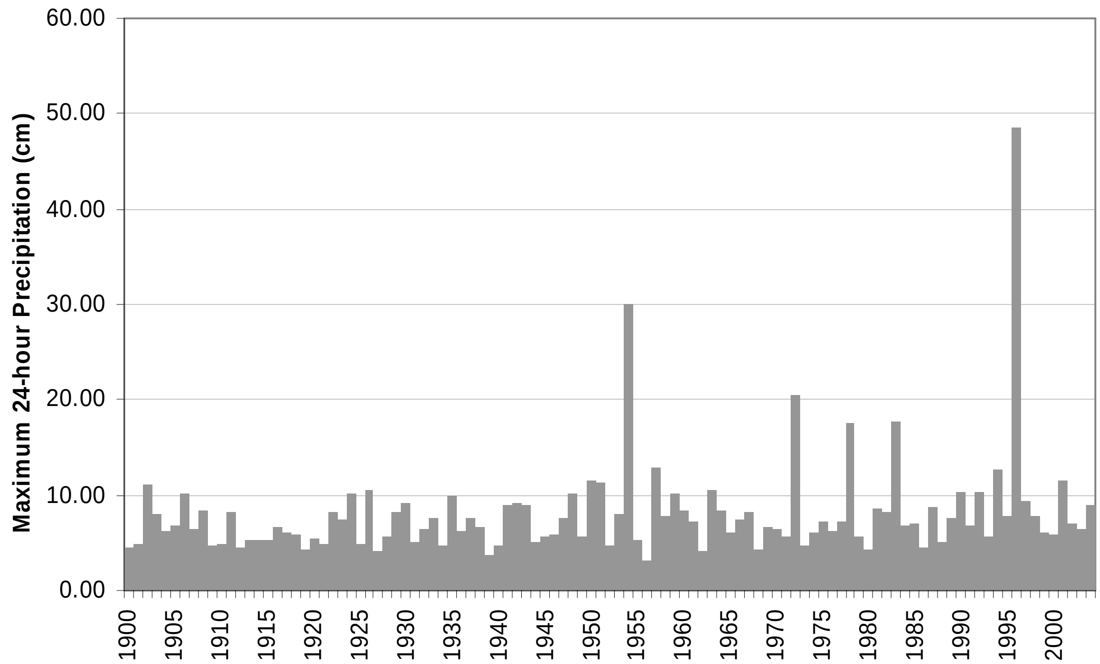

Figure 3. Annual maximum 24-hour precipitation time series (1900-2004), recorded at Aurora College station in northeastern Illinois

Design precipitation calculation for the Aurora College station used daily data and the GLO and WAK distributions for three scenarios: 1 station (Aurora College), 6 stations (Lockport Power House, Aurora College, De Kalb, Joliet Brandon, Joliet, Wheaton 3 SE), and 12 stations (Belvidere, Chicago O'Hare, Chicago University, Chicago Midway, Crete, Mchenry Lock & Dam, Lockport Power House, Aurora College, De Kalb, Joliet Brandon, Joliet, Wheaton 3 SE), also shown in Figure 4. 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 estimates of 100-tear precipitation (P_{100}) than the GLO distribution (the larger number of parameters gives more flexibility in the right tail of the distribution, bending the best-fit curve nearer the two largest observed values); and the P_{100} estimate decreases with increasing numbers of stations in the region, as the Aurora College station had the largest observed daily precipitation for both storms of 1954 and 1996, compared with other stations in the region.

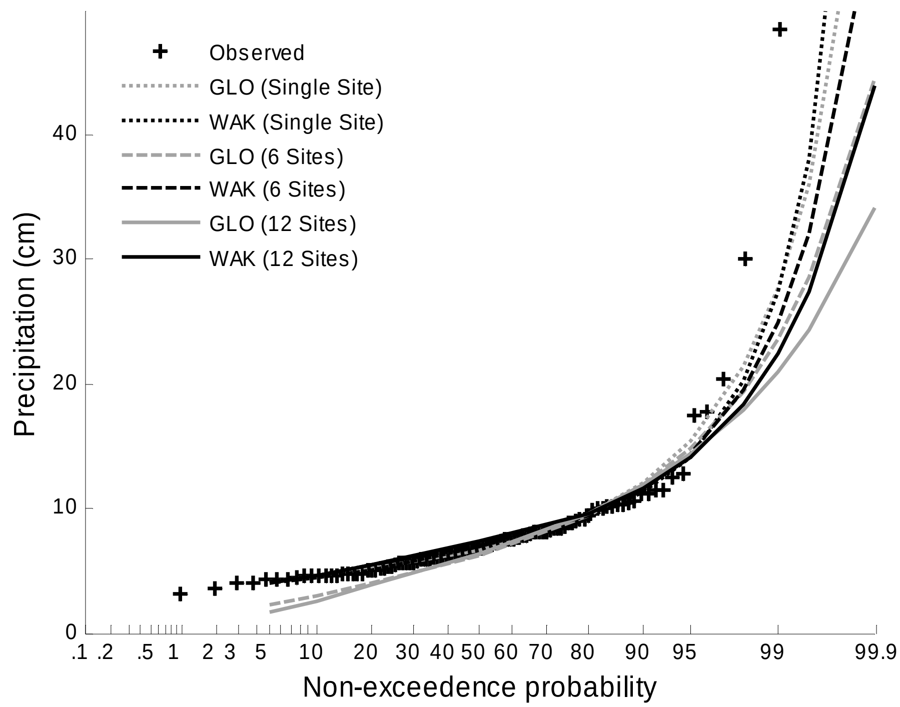

Figure 4. Observed maximum 24-hour precipitation at Aurora College station compared with theoretical best-fit GLO and WAK curves for 1-, 6-, and 12-station regions

Urbanization

Figure 5 compares land-cover conditions for 12 watersheds in the Chicago area between 1954 and 1999. A lumped curve number value for each of the watersheds was estimated based on soil type and land coverage. The average urban areas increased from 10.8% (1954-1961), to 61.8% (1999), while agriculture and forest areas dropped from 54% and 30% to 15% and 18%, respectively. The level of change in land-cover distribution varied between watersheds. For example, McDonald Creek watershed was transformed from predominantly agricultural watershed in 1954 (65% agricultural land, 22% forest, and only 10% urban areas) to highly urbanized watershed in 1999 (86% urban areas, 9% forest and only 1% agricultural land).

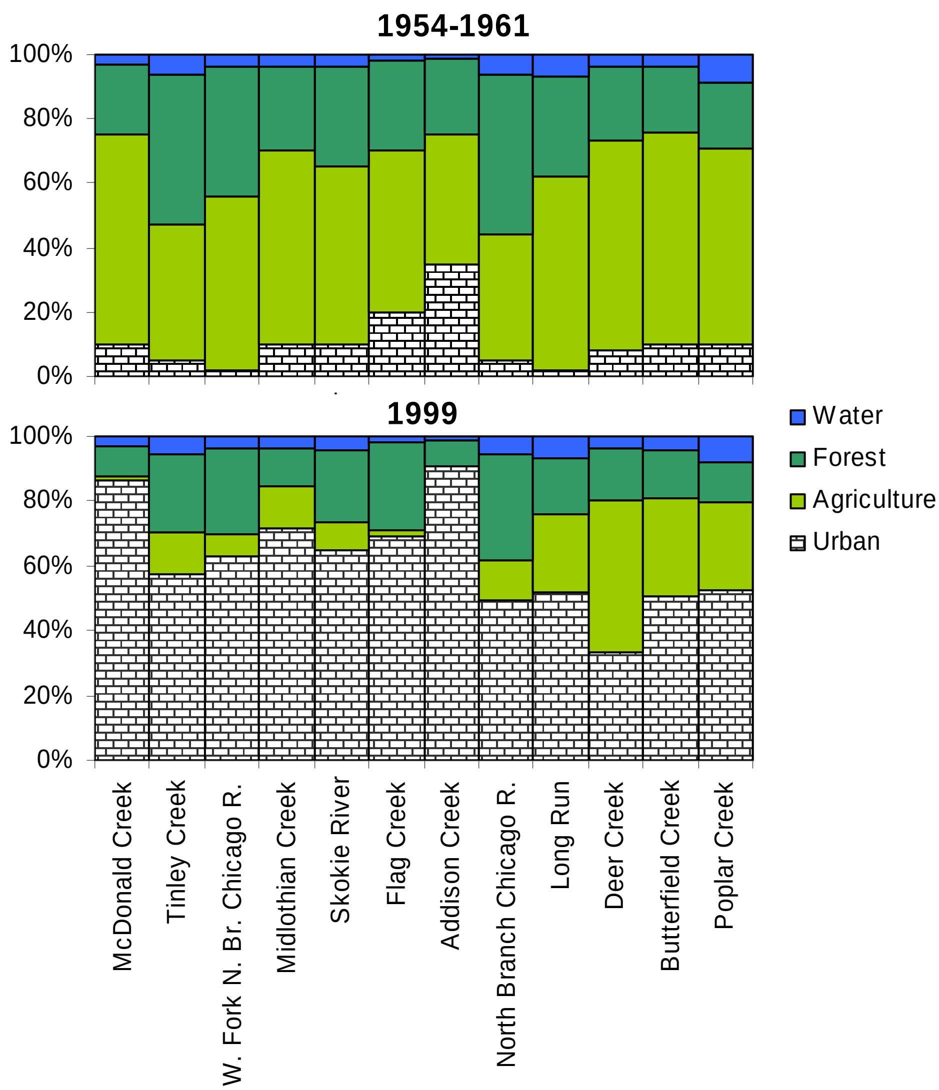

Figure 5. Land-use in 12 watersheds in the metropolitan Chicago area, 1954-61 and 1999

Discharge Trends

Application of the Kendall τ-test (Helsel and Hirsh, 1995) indicated that 10 of the 12 watersheds in this study exhibit statistically significant increasing trends in annual flood peaks, with a significance level of α=90% (Figure 6). The MacDonald Creek and Midlothian Creek annual peaks had no significant trend at the same significance level. Variability in significance of trends could be explained by varying degree of change in land use and in precipitation for each watershed.

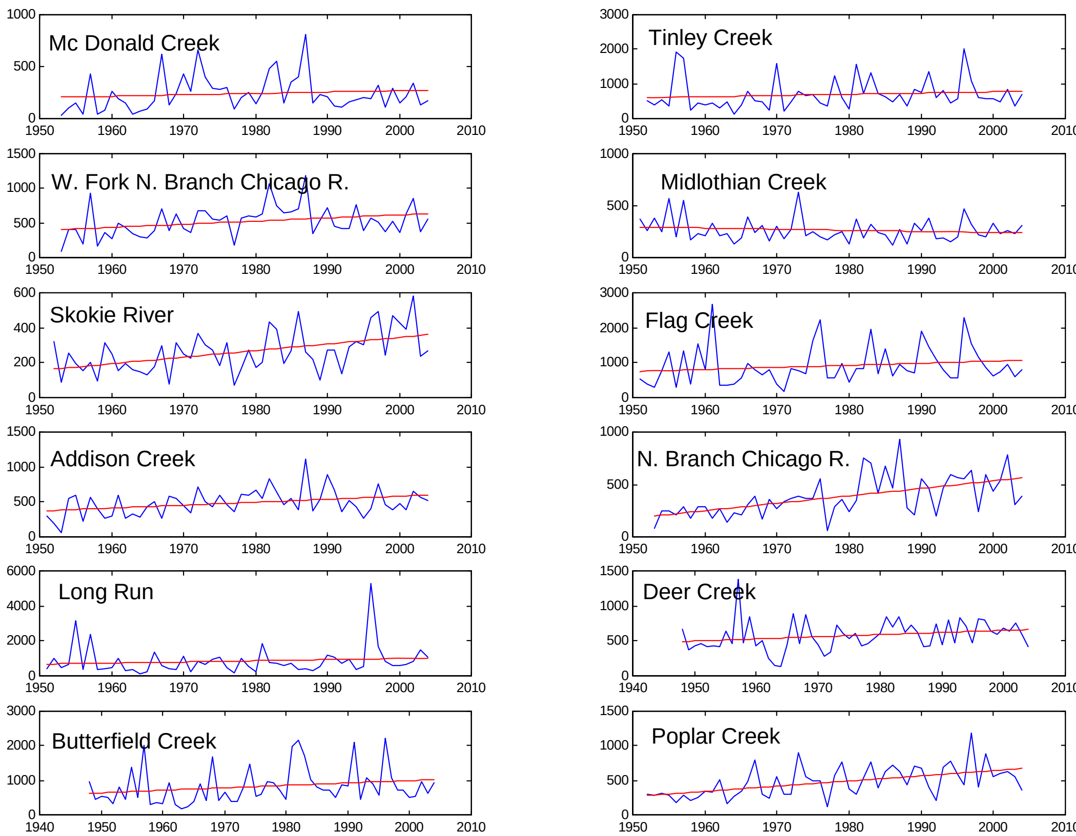

Figure 6 Trends in annual maximum daily discharge at 12 watersheds in this study (the USGS station numbers denote the stations)

Precipitation Sensitivity Analyses

Sensitivity analyses were used to study effects of different periods of precipitation record, different region selection, and different underlying distribution on design precipitation at the Aurora College station. 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 selections of region or 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 the 12-station region.

Relative Contribution of Land Cover and Precipitation Changes

This study also attempted to identify relative contributions of land cover and precipitation changes to the increasing flood peaks in the metropolitan Chicago area. Flood peaks were computed for the 1954 and 1996 periods using the design storm method. The source of design precipitation for the 1954 scenario was TP-40 (Hershfield, 1961). The source of design precipitation for the 1996 scenario was NOAA-14, which was based on data through the year 2000 (Bonnin et al., 2004). Both design precipitation sources were created by the U.S. National Weather Service (formerly U.S. Weather Bureau). The HEC-HMS model parameters for the 1954 scenario were based on 1954-

1961 aerial photos and calibration of the 1954 flood. The HEC-HMS parameters for the 1996 scenario were adopted from the 1996 flood calibration and used the most recent land-cover spatial data.

When comparing contributions of urbanization and precipitation separately, the contribution of urbanization is 29% larger than that of the increase in design precipitation. Changnon and Demissie (1996) reported similar results and concluded that urbanization in northeastern Illinois also has a more dominant effect on flood peaks than the increase in number and frequency of heavy storms.

Comparison with Published Sources

Regulatory floodplain maps for the metropolitan Chicago area, show areas of flood risk based upon discharges reviewed by the Illinois Department of Natural Resources, Office of Water Resources, and published by FEMA. The extent of flooding shown on Flood Insurance Rate Maps guides planning, design, development and insurance purchases. In this study, the 100-year discharges calculated for the 1996-1999 period were compared with those certified by FEMA as of 2005 (FEMA, 1980; 1986; 2000a; 2000b; 2002; 2005). Results also were compared with those published by the USGS (Curtis, 1987; Soong et al., 2004) and shown in Figure 7. On average, flood peaks for the study period are approximately 14.0% higher than those of FEMA, and 13.0% higher than those published by the USGS in 2004 (Soong et al., 2004). Urbanization increases after 1996-1999 may cause current flood peaks to exceed regulatory discharges by more than 14%. This study shows that, in general, regulatory discharges in northeastern Illinois need to be updated. Not all regulatory discharges have large discrepancies with those calculated in this study, but watersheds with largest differences between this study and regulatory discharges (the West Fork North Branch Chicago River, Tinley Creek, Long Run, Addison Creek, and the North Branch Chicago River) should be the highest priority for updating flood studies.

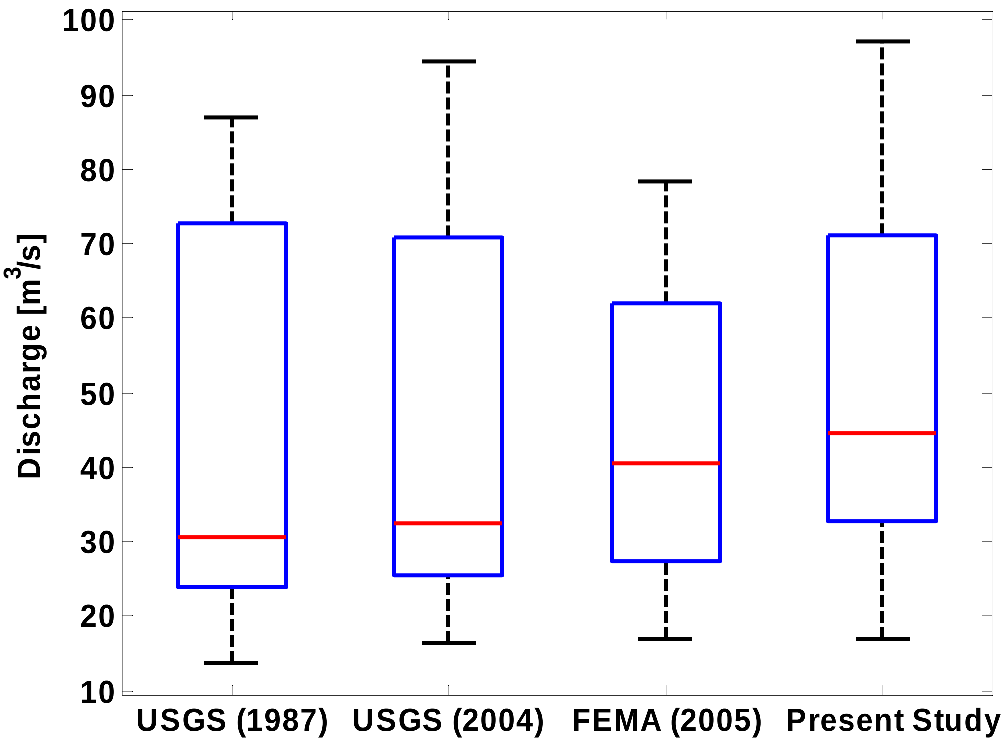

Figure 7. Comparison with other studies

Conclusions

Both urbanization and increase in design rainfall are significant contributors to the increasing flood peaks at small watersheds in the metropolitan Chicago area. On average, urbanization contributed 29% more to these increases than did precipitation increases.

The dominant role of urbanization in flood peak increase for northeastern Illinois is consistent with results of Changnon and Demissie (1996).

Sensitivity analyses for 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.

It also was found that regulatory discharges, on average, underestimate flood peaks in this region by at least 14%. This discrepancy can be used in prioritizing watersheds for future flood studies. The method presented in this study also could serve as a planning tool with the capability to include various future urbanization and precipitation scenarios for small urbanizing watersheds.

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