
Analysis of base flow trends in urban streams, northeastern Illinois, USA

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Abstract Statistical analysis shows that mean annual base flows in three unregulated urban streams in northeastern Illinois do not display significant trends during periods of substantial watershed urbanization. However, statistically-significant upward trends in median annual base flow (probably emblematic of overall changes in the time-distribution of the base flow), characterized by increases in lower base flow rates, affected the flows in all three streams. The analysis reveals no trends in annual and monthly precipitation during these periods. These results are in contrast to results from studies of other urban streams that have shown decreases in base flow, but these results may be partially explained by the low permeability of the near-surface materials in the watersheds investigated. This study employs formal hypothesis-testing of Kendall tau-a trend statistics computed for monthly and annual base flow and precipitation rates to assess the impact of urban development on base flow rates.

Résumé Une analyse statistique démontre que la moyenne annuelle de l'écoulement de base dans trois rivières urbaines non réglementées du nord est de l'Illinois ne montre pas de tendance significative lors de périodes d'urbanisation massive du bassin versant. Par contre, une tendance statistiquement significative à la hausse de l'écoulement de base médian, probablement représentatif de l'ensemble des changements dans la distribution temporelle de l'écoulement de base caractérisé par une augmentation des faibles taux d'écoulement de base, affecte l'écoulement dans les trois rivières. L'analyse ne révèle pas de tendance dans les précipitations annuelles et mensuelles lors de ces périodes. Ces résultats contrastent avec les résultats d'autres études de rivières en milieu urbain qui ont montré une diminution de l'écoulement de

base. Les résultats obtenus lors de cette étude peuvent partiellement être expliqués par la faible perméabilité des dépôts de surface dans le bassin versant étudié. Cette étude utilise le test d'hypothèse tau de Kendall, une tendance statistique calculée pour l'écoulement de base annuel et mensuel et des taux de précipitation dans le but de déterminer l'impact du développement urbain sur les taux d'écoulement de base.

Resumen El análisis estadístico muestra que el flujo base anual medio en tres arroyos urbanos no regulados en el noreste de Illinois no ostenta tendencias significativas durante los periodos de urbanización sustancial de la cuenca. Sin embargo, el flujo en los tres arroyos fue afectado por tendencias al incremento en el flujo base anual medio. Esto es probablemente emblemático en cambios globales en el tiempo-distribución del flujo base caracterizado por incrementos en las tasas de flujo base bajo y afecta a los tres arroyos. El análisis no revela ninguna tendencia en la precipitación anual y mensual durante estos periodos. Estos resultados contrastan con los resultados de estudios de otros arroyos urbanos que muestran un decrecimiento en el flujo base. Sin embargo, estos resultados pueden explicarse parcialmente por la baja permeabilidad de los materiales cercanos a la superficie en las cuencas investigadas. Este estudio emplea las estadísticas de tendencia tau-a de la hipótesis de prueba formal de Kendall - calculadas según los flujos base mensuales y anuales y las tasas de precipitación. El objetivo es evaluar los impactos del desarrollo urbano sobre las tasas de flujo base.

Keywords Midwestern USA · Groundwater recharge/water budget · Groundwater/surface-water relations · Urban groundwater

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Introduction

Base flow is water that enters a stream from persistent, slowly varying sources and maintains streamflow between inputs of *direct flow* (also known as *event flow*, *storm flow*, or *quick flow*) (Sophocleus 2002). Although the concept of base flow does not imply a strict origin, hydrologists generally agree that most base flow originates largely by saturated flow from groundwater storage,

and long-term base flow rates are, as a consequence, commonly invoked as indicators of basinwide groundwater recharge rates. Base flow may include water derived from sources other than basinwide reduction of groundwater storage, however. These sources include near-surface valley-bottom (or near-channel) storages such as channel bank materials (bank storage), alluvial valley fills, and wetland areas (Smakhtin 2001). Base flow may also include unsaturated subsurface flow, water discharged from lakes and wetlands, and water derived from melting snow and ice. The appropriateness of employing base flow rates as indicators of groundwater recharge is further limited by the fact that base flow may be reduced by direct evaporation from the water surface, by evapotranspiration from the saturated zone in areas bordering the channel, by groundwater recharge from streamflow where the water table is below the channel, by losses to underflow, and by losses to channel bank soils (Smakhtin 2001).

Isotopic studies confirm the polygenetic origins of base flow and, additionally, show that the origins of base flow may change seasonally. Rose (1993) suggested that contributions to base flow in streams in Georgia (USA) from shallow subsurface intervals and from the near-stream zone increase during the season of net water surplus, when precipitation exceeds evapotranspiration, and precipitation is not removed by evapotranspiration prior to flowing through the subsurface and discharging as base flow. During the summer, when evapotranspiration exceeds precipitation, base flow is generated along deep flow paths, most likely originating upslope within the watershed. Isotopic data from one Georgia watershed suggested that much of the annual base flow is generated from the transient saturation and slow release of groundwater from a source in the near-stream zone (Rose 1996).

Base flow rates in urban streams may be altered from predevelopment rates by changes in water management and land use accompanying urbanization. Even in unregulated streams that receive no documented discharges of effluent, base flow in urban streams may be affected by alterations in the watershed due to urbanization, as discussed in the following paragraphs. Considered independently, these alterations may plausibly either increase or reduce base flow rates. The overall effect on base flow of the alterations accompanying urbanization of any single watershed is therefore a function of the number, type, and extent of each alteration of the watershed as well as such basin characteristics as climate, geology, and topography.

Urbanization may reduce base flow by altering predevelopment pathways for the flow of groundwater to surface-water bodies. Groundwater withdrawals create gradients around pumping wells that capture some of the groundwater flow that, in an undisturbed setting, would have discharged as base flow. When pumping rates become sufficiently large, the head declines around pumping wells induce flow out of surface-water bodies in a process known as *induced infiltration* or *induced recharge* (Sophocleus 2002). Such an alteration of

groundwater flow therefore reduces base flow and increases groundwater recharge. Conversely, many researchers have reported, anecdotally, increases in groundwater discharge, such as flooding of basements and low-lying areas, resulting from decreases in groundwater withdrawals. Decreasing groundwater withdrawals are a feature of numerous cities and typically result from the abandonment of local shallow wells in favor of imported water to satisfy increased demand or to avoid pollution of shallow aquifers (Rushton and Al-Othman 1994) or decreased demand connected with economic decline (Riemann 1999) or relocation of industry in outlying areas (Brassington and Rushton 1987; Greswell et al 1994). Predevelopment pathways for the flow of groundwater to surface water may also be altered by storm sewers, which can capture influent groundwater through leaks where the sewers are positioned below the water table and convey it to receiving streams. On the other hand, water can leak from sewers where they are positioned above the water table (Lerner et al 1993).

Urbanization may change base flow rates by altering rates of basinwide groundwater infiltration (Lerner 2002). Predevelopment pathways for precipitation to groundwater may be reduced through impermeabilization of the land surface, particularly where the impermeable surfaces are accompanied by storm sewerage to convey runoff to streams. On the other hand, leaking storm sewers, as mentioned in the preceding paragraph, may contribute water to the subsurface where they are positioned above the water table. Stormwater detention basins may enhance infiltration where they are not lined to reduce leakage (Franke 1968; Barringer et al 1994). Similarly, alteration of pre-existing topography to create closed depressions from natural drainages may result in greater opportunities for infiltration (Ichazo 1999). Rates of predevelopment infiltration may increase with urbanization as a consequence of reduced evapotranspiration connected with removal of pre-existing vegetation, as recognized by Appleyard (1999) in Perth, Australia. Most urban areas import water on a large scale, and the amount of water in circulation in potable water distribution systems is often very significant in relation to available infiltration from precipitation (Foster 1990). Because these distribution systems are constantly pressurized, they are highly prone to leakage. Price and Reed (1989) reported that 20–30% of the water supplied to potable water distribution systems in England and Wales is unaccounted for, and that most of this water is assumed to be leakage. Brassington and Rushton (1987) estimated that leakage from the potable water distribution system under the Liverpool, UK, urban area totaled 65.6 megaliters per day (ML/d). In urban areas that import water but which do not have public sewer systems, infiltration rates can greatly increase due to infiltration through on-site disposal of the imported water, commonly through septic systems. This pattern of development, in which installation of sewer systems lags considerably behind population growth and provision of a potable water distribution system, is common in developing nations (Foster 1990).

Finally, alteration of near-channel and in-channel environments may alter base flow rates in urban areas. Stormwater detention basins may attenuate runoff so much that it appears in urban streams as base flow as a consequence of its slow arrival time in the stream channel. Straightening and deepening of stream channels may increase interception of the water table, increasing groundwater discharge and base flow (Schilling and Libra 2003). Conversion of channel bank areas to urban land cover could reduce evapotranspiration from areas of bank storage, increasing bank-storage discharge and base flow. On the other hand, channel straightening and conversion of valley-bottom wetlands would reduce opportunities for near-channel storage of streamflow, reducing later discharge of this storage as base flow.

This report summarizes research into the base flow trends that accompany watershed urbanization in three streams in Cook County, Illinois, that are substantially unaffected by effluent discharges, flow regulation, and diversion. Trend and correlation analysis are employed to characterize temporal changes in base flow. The polygenetic origins of base flow and seasonal changes in composition of base flow are acknowledged here, but this research does not seek to identify specific influences on base flow in the streams from among the many discussed in the preceding paragraphs or to address how urban development might have altered seasonal changes in base flow composition.

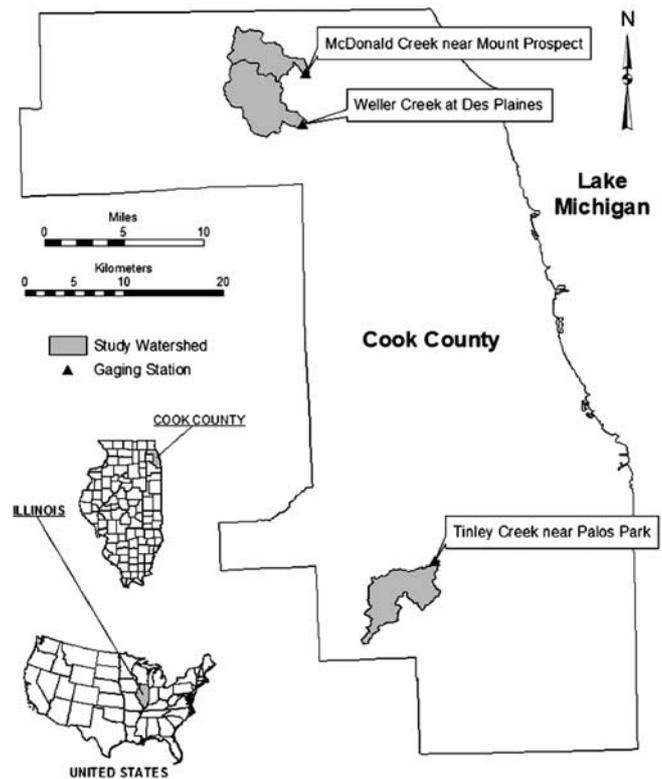


Fig. 1 Index map showing locations of study watersheds in Cook County, Illinois

Methods and database

Three gaged watersheds in northeastern Illinois were selected for this analysis of the impacts of urbanization on base flow: (1) McDonald Creek near Mt. Prospect (USGS Gage 05529500); (2) Weller Creek at Des Plaines (USGS Gage 05530000), and; (3) Tinley Creek near Palos Park (USGS Gage 05536500). The locations and characteristics of these watersheds are shown in Fig. 1 and Table 1. The McDonald and Weller Creek watersheds are located adjacent to one another in northern Cook County, while the Tinley Creek watershed is located in southern Cook County. The watersheds were selected for study because they are located within the six-county Chicago metropolitan region, because they have a period of record at least 20 years in duration that is substantially unaffected by effluent discharges and flow regulation, and because they have undergone substantial urbanization during the period of gage record. No other stream gage data sets from the six-county region meet these criteria.

Table 1 Characteristics of watersheds selected for study

Stream	Area (km ²) ^a	Period of record considered (water years)	Mean slope	Shallow aquifer withdrawals (calendar year) (MI/d)	Water supplied to overlapping potable water distribution systems (calendar year) (MI/d)	Estimated leakage of imported water, calendar year 1990 (MI/d)	% Impervious cover (calendar year)
McDonald Creek	20.5	1953–1998	4.5°	0.1 (1952) 0.4 (1998)	1.2 (1952) 112.4 (1998)	0.9	4.1–5.9 (1952) 31.2–44.7 (1998)
Weller Creek	34.2	1960–1998	4.0°	0.2 (1959) 0.1 (1998)	1.1 (1959) 129.0 (1998)	1.8	12.4–17.7 (1952) 42.1–60.3 (1998)
Tinley Creek	29.0	1975–1998	8.2°	2.3 (1974) 0.6 (1998)	13.9 (1974) 57.0 (1998)	0.8	1.5–2.1 (1951) 28.0–40.2 (1998)

^a Wicker et al 1998

Regrettably, stream gage data from rural watersheds in the region that are comparable in area to the urban watersheds, that cover a period of time coincident and comparable in duration with the urban gage data sets, and that have not been substantially affected by control structures and effluent discharges are not available. It is not possible, therefore, to characterize base flow trends in comparable rural watersheds for the periods of time covered by the urban stream gages.

Available streamflow data from all three gages are limited to an integer-multiple of water years to eliminate seasonal bias. A water year begins on October 1 and concludes on September 30. Water years are designated by the calendar year of the concluding September 30, as is the convention of the USGS. For example, the water year beginning October 1, 1960 and concluding September 30, 1961 is designated as water year 1961. The gage periods of record of Weller and Tinley Creeks were further trimmed to eliminate the effects of discharges of sewage treatment plant eff-

Table 2 Sources of monthly precipitation data

Watershed	Primary source		Secondary source	
	Station name	Distance from watershed centroid (km)	Station name	Distance from watershed centroid (km)
McDonald Cr	Elgin	26.5	Wheaton 3 SE	33.5
Weller Cr	Elgin	24.9	Wheaton 3 SE	29.6
Tinley Cr	Chicago Midway AP 3 SW	11.7	Wheaton 3 SE	30.2

^a Station name used by the Midwest Climate Center, Illinois State Water Survey

fluent to Weller Creek prior to water year 1960 and to Tinley Creek prior to water year 1975.

Estimation of base flow

The definition of *base flow* that is employed in this report is the non-genetic definition of Sophocleus (2002) mentioned previously; that is, that base flow is water that enters a stream from persistent, slowly varying sources and which maintains streamflow between inputs of direct flow. The operational definition of *base flow* is that it is a daily flow value estimated using HYSEP (Sloto and Crouse 1996), a computer program that automates the process of hydrograph separation. *Hydrograph separation* refers to the division of a streamflow hydrograph into base flow and direct flow components. The methods of hydrograph separation offered within HYSEP are not based on the physics of streamflow generation but are instead computer adaptations that consistently apply the manual methods of hydrograph separation documented by Pettyjohn and Henning (1979).

Of the three methods of hydrograph separation available within HYSEP, the *local minimum method* was selected for use in this study. The local minimum method does not assume a time lag, based on basin area, after which direct flow ceases. It is the simplest of the three methods, but Pettyjohn and Henning (1979) recommend its use when little is known about the physical conditions governing streamflow in a watershed. To apply the local minimum method, the duration of direct flow following a storm event is estimated using $N=A^{0.2}$, where N is the number of days following a storm event after which direct flow ceases and A is the drainage area in square miles (mi^2) (Linsley et al 1982). The interval $2N^*$ used in the hydrograph separation algorithm is the odd integer between 3 and 11 nearest to $2N$. For example, the drainage area of the McDonald Creek watershed upstream of gage 05529500 is 7.93 mi^2 (20.5 square kilometers), and the interval $2N^*$ for this watershed is therefore equal to 3. The computer program checks each daily mean streamflow value to determine if it is the lowest daily mean streamflow within an interval between $0.5(2N^*-1)$ days before and after that day. In the case of the McDonald Creek data, the program checks one day before and one day after each day to determine whether that day's mean streamflow is a local minimum. If the daily mean streamflow is the lowest daily mean streamflow within the checked interval, it is identified as a local minimum, and it is connected with straight lines to adjacent local minima. Daily mean base flow values are estimated by linear interpolations between local minima, unless the interpolated value exceeds the observed mean streamflow, in which case the mean streamflow becomes the estimated base flow.

The output of the hydrograph separation procedure consists of values of mean daily base flow and direct flow. These daily mean values, together with mean daily total streamflow, were the basis for calculating percent base flow, mean, and percentile values (including the median) for accounting periods that include one month, one year, five years, and the complete period of record (trimmed to an integer-multiple of years) of each gage. Both mean and median were calculated as central measures of base flow in the streams. The mean permits calculation of the volume of each flow in the stream and the proportion of base flow within the stream. The

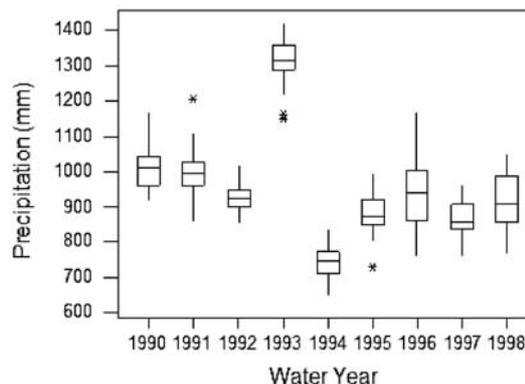


Fig. 2 Annual precipitation at 25 sites in Cook County, Illinois, for water years 1990–1998

median, in contrast to the mean, is indicative of changes in the time-distribution of base flow.

Estimation of precipitation

Monthly precipitation totals from nearby observation stations were employed to represent precipitation in each of the three watersheds. For each watershed, the precipitation record was synthesized mainly from a primary observation station, with monthly precipitation totals from a secondary observation station employed for months when data were not available from the primary station. These monthly precipitation data are available from the Midwest Climate Center at the Illinois State Water Survey (ISWS). Station names and distances from the approximate centroid of each watershed are listed in Table 2.

It is likely that the synthesized precipitation records discussed in the preceding paragraph do not perfectly represent actual precipitation in the watersheds, but owing to the lack of long-term precipitation records from observation stations within the watersheds, the synthesized records, which are based on locally-derived data to the largest extent possible, are a workable solution to the problem of representing watershed precipitation. Nonetheless, it is emphasized that precipitation can vary considerably across the area of a single small watershed.

Box plots of annual precipitation based on 1990–1998 data from the 25-gage Cook County precipitation network are shown in Fig. 2. Locations of the rain gages in the Cook County network are shown in Fig. 3. Although these gages did not operate before water year 1990 and are therefore not used for synthesizing a precipitation record for the study watersheds, the data derived from them are illustrative of precipitation variability in Cook County. The box portions of the plots in Fig. 2 illustrate the values of annual precipitation between the first and third quartiles of the distribution (Q1 and Q3, respectively), with the median marked by a horizontal

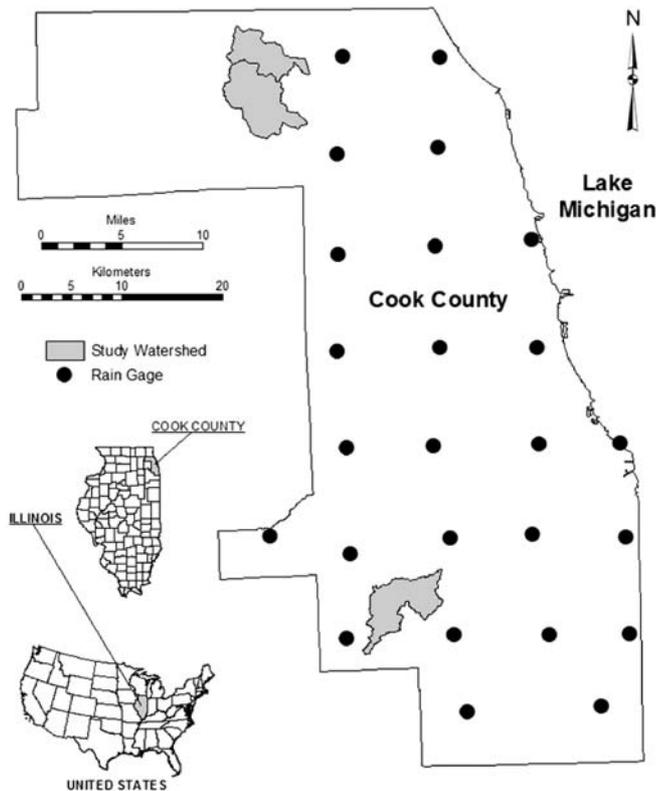


Fig. 3 Map showing the locations of rain gages in Cook County, Illinois, that provided the data shown in Fig. 5

line. The vertical lines, or “whiskers”, show the range of adjacent values within limits given by the following equations:

$$\text{Lower Limit} : Q1 - 1.5(Q3 - Q1)$$

$$\text{Upper Limit} : Q3 + 1.5(Q3 - Q1)$$

Outliers are plotted with asterisks.

Data from the Cook County precipitation network illustrate the variability of precipitation across Cook County and underscore the fact that the assumed precipitation total employed in the present study may not accurately reflect precipitation in the study watersheds. Annual precipitation statistics based on 1900–1998 data from the Cook County network, together with assumed values of watershed precipitation based on nearby observation stations as discussed previously, are shown in Table 3. These data show that numerous assumed watershed precipitation values do not fall within the interquartile range between the first and third quartile values for precipitation calculated from the Cook County network.

Table 3 Comparison of assumed annual watershed precipitation with statistics based on the 25-station Cook County precipitation network, water years 1990–1998. Assumed watershed precipitation values that do not fall between the first and third quartiles based on Cook County network data are in bold typeface

Water year	Assumed watershed precipitation (mm)			Precipitation statistics based on data from Cook County Precipitation Network (mm)		
	McDonald	Weller	Tinley	First quartile	Median	Third quartile
1990	904.0	904.0	1030.0	963.2	1015.2	1045.2
1991	874.8	874.8	969.0	960.4	996.4	1029.2
1992	852.4	852.4	921.3	897.6	927.1	949.7
1993	1009.9	1009.9	1354.8	1287.5	1315.7	1360.2
1994	644.1	644.1	673.4	709.2	747.5	772.7
1995	908.3	908.3	866.9	847.9	872.2	923.5
1996	976.1	976.1	1087.6	859.3	941.1	1005.6
1997	597.9	597.9	884.9	834.1	857.0	905.8
1998	818.6	818.6	1083.3	853.9	909.8	990.1

Statistical analysis of precipitation and base flow data

The nonparametric Kendall tau-a correlation coefficient was calculated in order to look for trends in precipitation and base flow statistics (the term *trend* here referring specifically to a correlation with time). Kendall tau-a correlation coefficients may range from -1 to 1 , with -1 indicating a perfect negative monotonic correlation and 1 indicating a perfect positive monotonic correlation. A perfect negative trend is one in which the values in the series decrease with every time increment. A perfect positive trend is one in which values increase with every time increment. One should recognize that the Kendall tau-a correlation coefficient is an indicator of a monotonic trend—that is, an overall increasing or decreasing trend—and it will not identify U- or V-shaped trends.

The statistical significance of the Kendall tau-a correlation coefficients was evaluated using the hypothesis-testing procedure described by Helsel and Hirsch (2002). Two-tailed tests, employing an assumed value of $\alpha=0.05$, were conducted to evaluate the significance of the calculated Kendall tau-a correlation coefficients with $\alpha=0.05$, for a confidence level of 95%. To reject the null hypothesis of no trend at a given α -level, the hypothesis-testing procedure requires a higher value of tau-a for smaller data sets than for larger sets. Therefore, for shorter periods of record or for sets of annual (as opposed to monthly) data, significant correlation can be more difficult to establish.

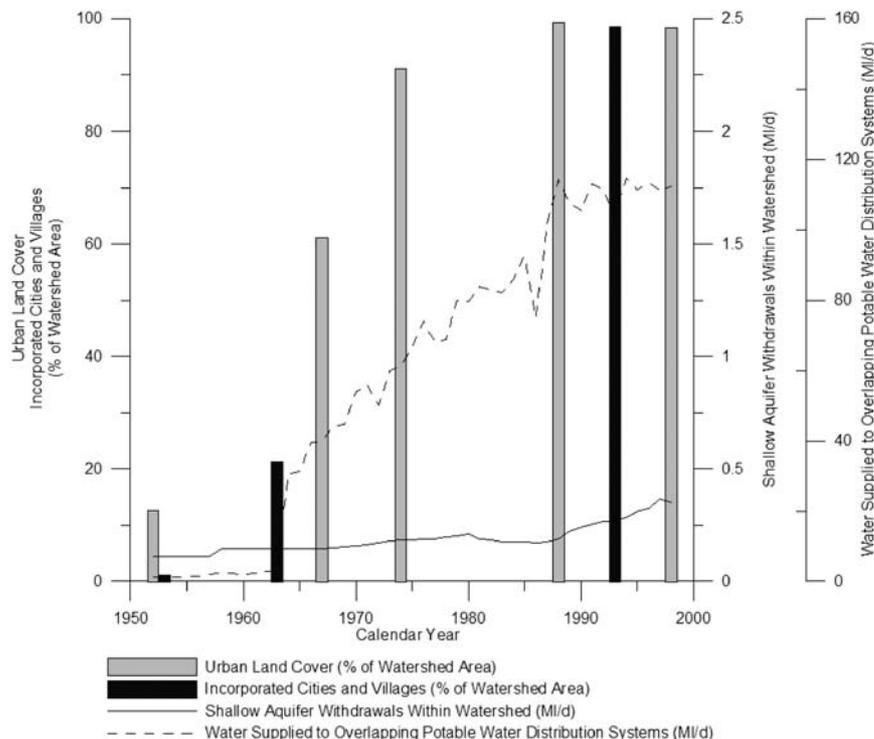
Trends were further characterized by Kendall-Theil robust lines, the equations of which were calculated using procedures described by Helsel and Hirsch (2002). The Kendall-Theil robust line, a straight line related to Kendall's tau-a, offers a nonparametric approach to regression that is resistant to outliers and skewness. The significance at $\alpha=0.05$ of the Kendall-Theil robust line for evaluated data is indicated by the outcome of the hypothesis-testing procedure mentioned previously. The slope of the Kendall-Theil robust line provides an estimate of the rate of change of annual precipitation, mean base flow, and median base flow in the examined watersheds.

Hydrogeology

The near-surface geologic materials in the watersheds are characterized by a continuous sheet of unconsolidated, low-permeability, clay-rich diamicton of the Late Quaternary Wadsworth Formation, with some discontinuous lacustrine silts and clays of the Late Quaternary Equality Formation present in the Tinley watershed. Three-dimensional geologic mapping of the upper 15 m of geologic materials shows that at least 6 m of Wadsworth diamicton is present within this 15 m surficial interval (Berg and Kempton 1988, Hansel and Johnson 1996). Prickett et al (1964) estimated the vertical hydraulic conductivity of materials assigned to these lithostratigraphic units at three locations in southern Cook County and in Lake County, Illinois, which borders Cook County on the north, at 3.3×10^{-4} to 4.5×10^{-4} m/d.

In Cook County as in much of northeastern Illinois, the shallow aquifer system, consisting of the glacial drift and the uppermost 15–30 m of the underlying Silurian dolomite, can, on a regional basis,

Fig. 4 Summary of land cover and water management changes associated with the urbanization of the McDonald Creek watershed



rightly be considered to provide all of the groundwater seepage to streams and to play a significant role in base flow generation. The depth of the portion of the shallow aquifer system that influences base flow generation is poorly understood and varies across the area, however. The glacial drift is heterogeneous in texture, and though it may consist entirely of permeable sand-and-gravel outwash in some areas, it contains impermeable confining units of diamicton or lacustrine silts and clays, at varying depths, in most areas. Where they are present, as in the McDonald, Weller, and Tinley watersheds, these confining units probably limit the role of underlying aquifers in base flow generation. Likewise, the presence of such shallow confining units probably reduces the capture of streamflow by wells pumping from underlying sand-and-gravel aquifers and from the shallow bedrock aquifer, but the effect is not clear.

A small portion of groundwater recharge in the watersheds leaks downward from the shallow bedrock aquifer through an underlying aquitard, often called the Maquoketa confining unit, and into the underlying deep bedrock aquifer system. This confining unit consists of the lower, relatively impermeable portion of the Silurian dolomite together with shales and carbonates of the underlying Ordovician Maquoketa, Galena, and Platteville Groups. Walton (1962) estimated maximum leakage across the shaly Maquoketa Group—the most impermeable portion of the unit—at about 3×10^{-3} mm/d in northeastern Illinois. Walton (1965) indicates that groundwater recharge during a year of near-normal precipitation in these areas is 0.1–0.2 mm/d. Comparison of these estimates suggests that leakage to underlying aquifers is small enough to be dismissed as negligible—about 1–3% of recharge—but we should note that estimates of recharge based on base flow data from the region may slightly underestimate actual groundwater recharge rates owing to this leakage through the Maquoketa confining unit.

Urbanization

All three watersheds underwent significant urbanization during the periods of gage record considered in this investigation. Urbanization of the watersheds is marked by substantial conversion to urban land cover, impermeabilization of land surface, expansion of pipe

networks (sewers and potable water distribution systems), and increases in imported water (Table 1 and Figs. 4, 5, and 6).

Urban land cover exceeded 90% of the McDonald and Weller watershed areas in the 1970s and lagged behind in the Tinley watershed, where it did not exceed 90% of watershed area until the 1990s. Analysis of aerial photographs shows that impermeable surfaces expanded to occupy roughly one-third to one-half of the watershed area in calendar year 1998.

Areas within incorporated cities and villages—an indicator of pipe network area, including sewer systems and potable water distribution systems—expanded with the conversion to urban land cover. Water supplied to potable water distribution networks expanded nearly a hundred-fold in the McDonald and Weller watersheds and grew four-fold in the Tinley watershed. Most of this water was derived from wells outside the watersheds, from Lake Michigan, or from wells open to the deep bedrock aquifer system within the watersheds. This imported water may leak from pipe networks or be introduced to streams via storm sewers, thereby influencing base flow. Estimates of leakage are problematic owing to the lack of data on leakage rates, pipe network locations, and leak locations. Nonetheless, on the basis of 1990 leakage rates reported to the Illinois Department of Natural Resources and 1990 incorporated city and village boundaries, leakage within the watersheds in 1990 from potable water distribution systems is roughly estimated at 0.9 MI/d in the McDonald watershed, 1.9 MI/d in the Weller watershed, and 0.8 MI/d in the Tinley watershed. Estimates of leakage from sanitary sewer systems are not available.

Withdrawals from the shallow aquifers within the watersheds reflect use by domestic and small commercial well owners as well as minor use by public water systems. These withdrawals increased slightly in the McDonald watershed, decreased in the Tinley watershed, and remained about the same in the Weller watershed during the periods of record considered in this study. Most water used in the watersheds in 1998 was derived from the deep bedrock aquifer system and extrabasinal sources.

Fig. 5 Summary of land cover and water management changes associated with the urbanization of the Weller Creek watershed

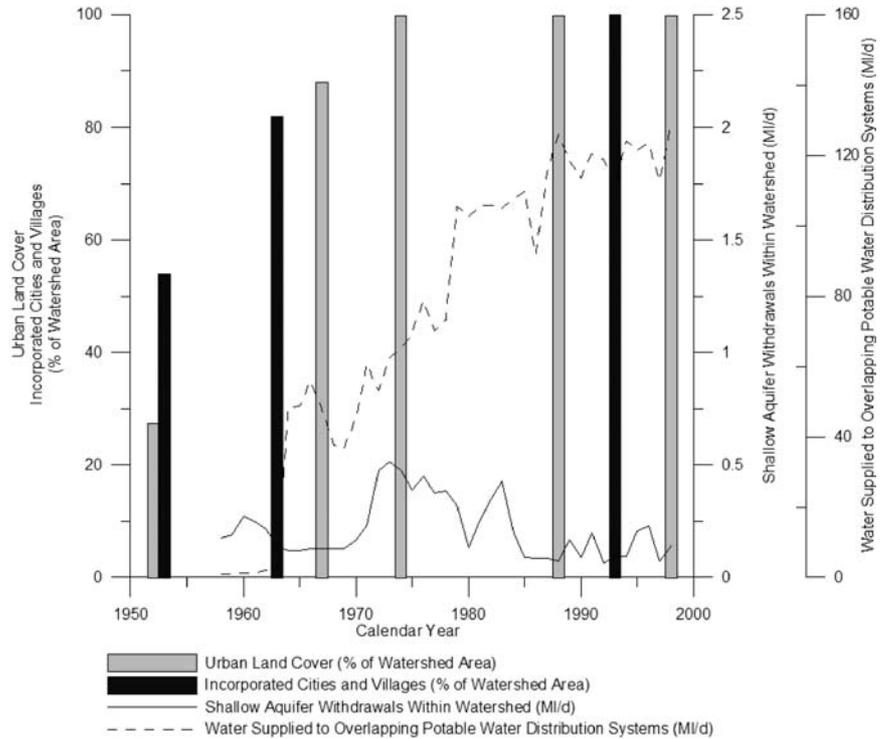
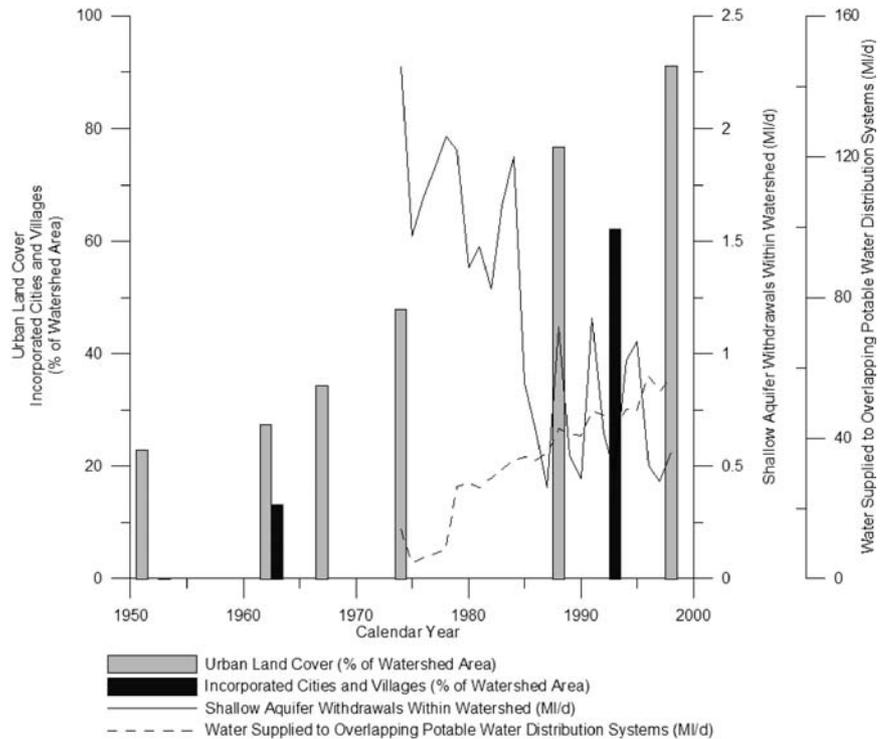


Fig. 6 Summary of land cover and water management changes associated with the urbanization of the Tinley Creek watershed



Results

The null hypothesis of no trend cannot be rejected for annual precipitation data in the McDonald, Weller, and Tinley Creek watersheds on the basis of hypothesis-testing of Kendall tau-a correlation coefficients for the record periods considered (Table 4). That is, the analysis sug-

gests that there was no trend in annual precipitation in the watersheds during the periods of gage record.

For most months, the null hypothesis of no trend cannot be rejected for monthly precipitation in the urban watersheds on the basis of hypothesis-testing of Kendall tau-a correlation coefficients (Table 5). However, the null hypothesis can be rejected at a 95% confidence level for

Table 4 Kendall-Theil slopes (m) and P-values from significance tests of Kendall Tau-a, annual precipitation (Kendall-Theil slope in mm/yr), annual mean base flow (slope in $\text{ML/d-km}^2\text{-yr}$), percent base flow calculated on an annual basis (slope in % per yr), and annual median base flow (slope in $\text{ML/d-km}^2\text{-yr}$)

Watershed	McDonald Cr		Weller Cr		Tinley Cr	
Time period	1953–1998		1960–1998		1975–1998	
Statistics	m	P	m	P	m	P
Annual precipitation	1.62	0.280	-0.33	0.885	-1.33	0.747
Annual mean base flow	<0.01	0.289	<0.01	0.646	<0.01	0.568
Percent base flow, annual basis	-0.3	0.006	0.1	0.358	-0.4	0.063
Annual median base flow	+0.00	0.019	+0.00	<0.001	0.01	<0.001

Slopes and P-values for trends that are significant at $\alpha=0.05$ are shown in bold typeface. The + or – symbols preceding a Kendall-Theil slope of 0.00 denotes whether the Kendall Tau-a statistic suggests an upward (+) or downward (–) trend

Table 5 Kendall-Theil slope (m) and P-values from significance test of Kendall Tau-a, monthly precipitation (Kendall-Theil slope in mm/yr) and monthly mean base flow (B) (slope in $\text{ML/d-km}^2\text{-yr}$)

Month	McDonald				Weller				Tinley			
	Precip		Mean B		Precip		Mean B		Precip		Mean B	
	m	P	m	P	m	P	m	P	m	P	m	P
Oct	0.15	0.733	+0.00	0.017	-0.08	0.781	+0.00	0.175	1.50	0.035	0.01	0.009
Nov	1.14	0.009	0.01	0.001	0.97	0.110	+0.00	0.004	1.65	0.264	0.01	0.004
Dec	-0.05	0.776	0.01	0.011	-0.03	0.898	+0.00	0.001	-0.84	0.346	+0.00	0.472
Jan	0.03	0.962	+0.00	0.038	-0.13	0.727	+0.00	0.035	1.04	0.338	0.02	0.001
Feb	-0.18	0.384	+0.00	0.032	-0.05	0.870	+0.00	0.095	0.25	0.726	0.01	0.244
Mar	-0.41	0.244	-0.00	0.514	-0.79	0.108	+0.00	0.961	-0.89	0.455	-0.02	0.157
Apr	-0.44	0.405	-0.01	0.205	0.71	0.333	-0.00	0.345	-1.85	0.088	-0.01	0.385
May	0.81	0.127	-0.00	0.289	0.89	0.180	+0.00	0.981	-1.40	0.441	+0.00	0.747
Jun	-0.36	0.495	-0.00	0.596	-0.18	0.807	-0.00	0.321	-1.52	0.199	0.01	0.189
Jul	-0.79	0.056	+0.00	0.264	-0.84	0.103	+0.00	0.062	-0.79	0.528	0.01	0.130
Aug	1.47	0.013	+0.00	<0.001	1.88	0.019	-0.00	<0.001	0.46	0.726	0.01	0.031
Sep	0.56	0.184	+0.00	0.001	-0.18	0.771	+0.00	0.110	0.18	0.870	+0.00	0.286

Slopes and P-values for trends that are significant at $\alpha=0.05$ are shown in bold typeface. The + or – symbols preceding a Kendall-Theil slope of 0.00 denotes whether the Kendall Tau-a statistic suggests an upward (+) or downward (–) trend

Table 6 General flow statistics

Stream	Mean base flow (ML/d-km^2)	Median base flow (ML/d-km^2)	% Base flow
McDonald Creek	0.3	0.2	43
Weller Creek	0.2	0.1	21
Tinley Creek	0.3	0.2	30

November and August precipitation in the McDonald Creek watershed, August precipitation in the Weller Creek watershed, and October precipitation in the Tinley Creek watershed. Kendall-Theil slopes indicate upward trends in precipitation during these months, for the periods of record shown in Table 1, in each of the three watersheds.

Mean base flow in McDonald, Weller, and Tinley Creeks, calculated on an annual basis, ranged from 0.2–0.3 ML/d per square kilometer (ML/d-km^2) over the periods of gage record (Table 6). Base flow in the streams was highest during the months of March through May (Figs. 7, 8, and 9). Lowest base flows occurred during late summer and fall, the specific months of lowest base flow differing between watersheds. The percent base flow in the streams ranged from 21 to 43%.

The null hypothesis of no trend cannot be rejected for mean annual base flow in McDonald, Weller, and Tinley Creeks (Table 4). The no-trend hypothesis can be rejected

for percent base flow in McDonald Creek, but not for percent base flow in Weller or Tinley Creeks, although it is worth noting that the correlation statistic for Tinley Creek is nearly significant at the 95% confidence level. The Kendall-Theil slope in Fig. 10 suggests that the proportion of base flow in McDonald Creek declined at an average rate of about 0.3% per year during the period of record considered. The lack of trend in mean base flow in McDonald Creek together with the presence of a negative trend in percent base flow suggests that direct flow has increased in the stream during the period. Hypothesis testing of a Kendall tau-a correlation statistic calculated for direct flow in McDonald Creek confirms that direct flow followed a statistically significant upward trend over the period of record. The equation of the Kendall-Theil robust line calculated for the relationship of time and direct flow in McDonald Creek suggests that direct flow in the stream changed at a rate of about $+0.01 \text{ ML/d-km}^2$ per year during the period. Increased direct flow is a common feature of urban streams and results largely from surface impermeabilization and storm sewers.

The null hypothesis of no trend in mean base flow can also be rejected with 95% confidence for many normally low-base-flow months in the streams (Table 5). This is most clearly shown by the McDonald Creek data, which displays statistically significant trends of up to $+0.01 \text{ ML/d-km}^2$ per year for the months of August through February. Mean base flow data also display statistically

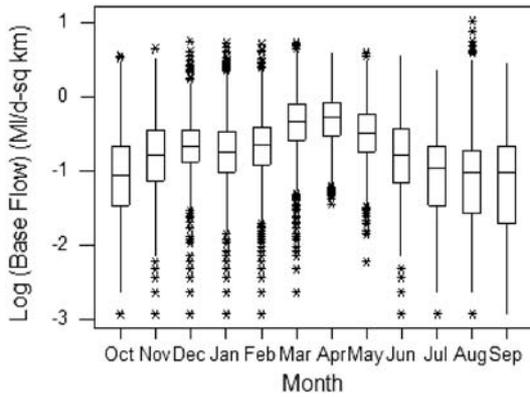


Fig. 7 Log of daily mean base flow, McDonald Creek, water years 1953–1998

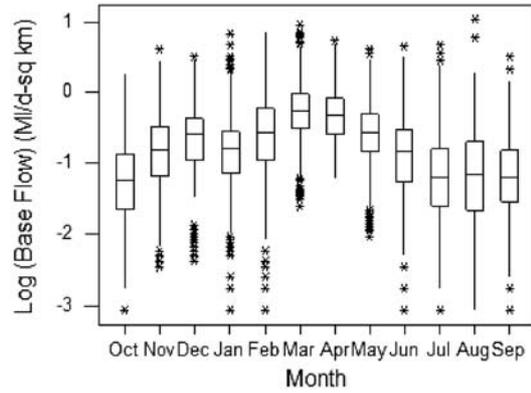


Fig. 9 Log of daily mean base flow, Tinley Creek, water years 1975–1998

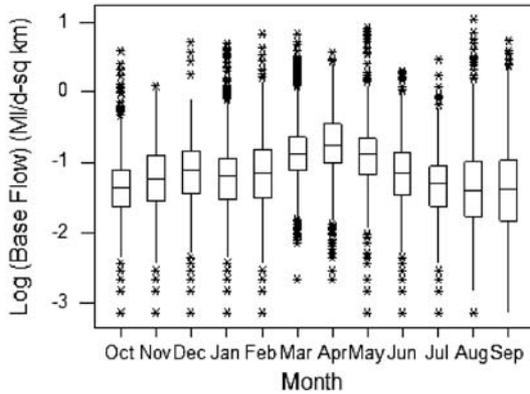


Fig. 8 Log of daily mean base flow, Weller Creek, water years 1960–1998

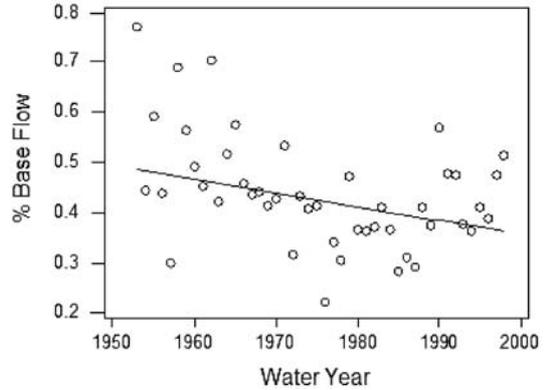


Fig. 10 Percent base flow in McDonald Creek, calculated annually for water years 1953–1998. The Kendall-Theil robust line is superimposed

significant upward trends of less than $+0.01 \text{ MI/d-km}^2$ per year in Weller Creek and $(0.01\text{--}0.02) \text{ MI/d-km}^2$ per year in Tinley Creek during most, but not all, months of August through January. These upward trends may have resulted in part from precipitation increases. Note that months of upward monthly mean precipitation trends were also months of upward monthly mean base flow trends, although it is perhaps meaningful that not all months of upward monthly mean base flow trends were months of upward precipitation trends. It is possible that the small additions of base flow to the streams that are evidenced by the statistically significant positive Kendall tau-a correlation coefficients for mean base flow during low-base-flow months may continue during months of high base flow. Upward trends in mean base flow during these high-base-flow months are not detectable using the Kendall tau-a correlation coefficient, however, because base flow during these months is much more variable than during the low-base-flow months (Figs. 7, 8, and 9).

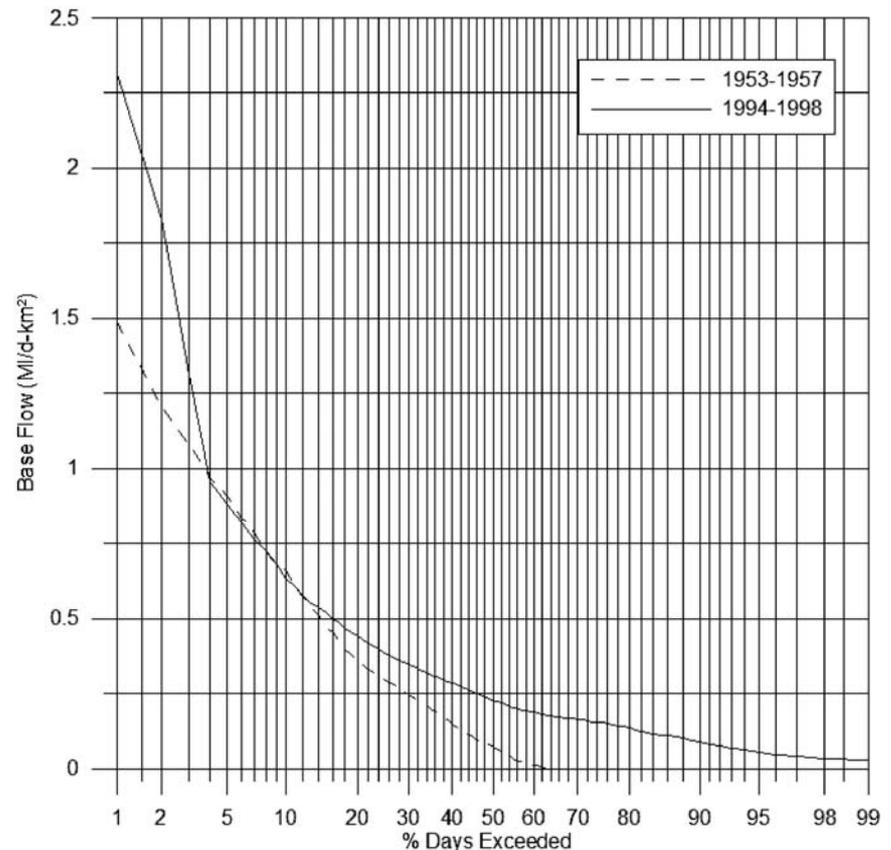
Annual median base flow—the base flow rate exceeded on 50% of days over the course of a year—ranged from 0.1 to 0.2 MI/d-km^2 in McDonald Creek, Weller Creek, and Tinley Creek during the periods considered (Table 6). The null hypothesis of no trend can be rejected at the 95% confidence level for median annual base flow

on the basis of hypothesis-testing of Kendall tau-a correlation coefficients for all three of the urban watersheds for the gage periods of record (Table 4). Kendall-Theil slopes suggest that median base flow in the streams increased at rates of less than $+0.01 \text{ MI/d-km}^2$ per year in McDonald and Weller Creeks and about $+0.01 \text{ MI/d-km}^2$ per year in Tinley Creek during the period of record. Flow duration plots of daily base flow during the first and last five years of the gage periods of record suggest that base flow percentiles representing base flows exceeded on about 20–99% of days increased in all three streams (Figs. 11, 12, and 13). Higher base flows, on the other hand, decreased in Tinley and Weller Creeks but not McDonald Creek.

Discussion

The analysis discussed in the preceding section shows that statistically significant trends in annual mean base flow did not occur in three streams in suburban Cook County, IL, during periods of substantial watershed urbanization (Table 4). More subtle changes in the time-distribution of base flow rates—exemplified by the statistically signifi-

Fig. 11 Base flow duration in McDonald Creek during the first (1953–1957) and last (1994–1998) five-year portions of the period on record



cant upward trends in median base flow—do appear to have affected base flow in the streams, but these changes have not been great enough to result in statistically significant upward trends in mean base flow. The changes in the time-distributions of base flows are characterized by increases in lower base flows, that is, those exceeded on about 20–99% of days (Figs. 11, 12, and 13). Annual precipitation data for the watersheds do not display statistically significant upward trends during periods of record considered, suggesting that the upward trends in median base flow, and the changes in the time-distribution of base flow rates, are related to the process of urbanization.

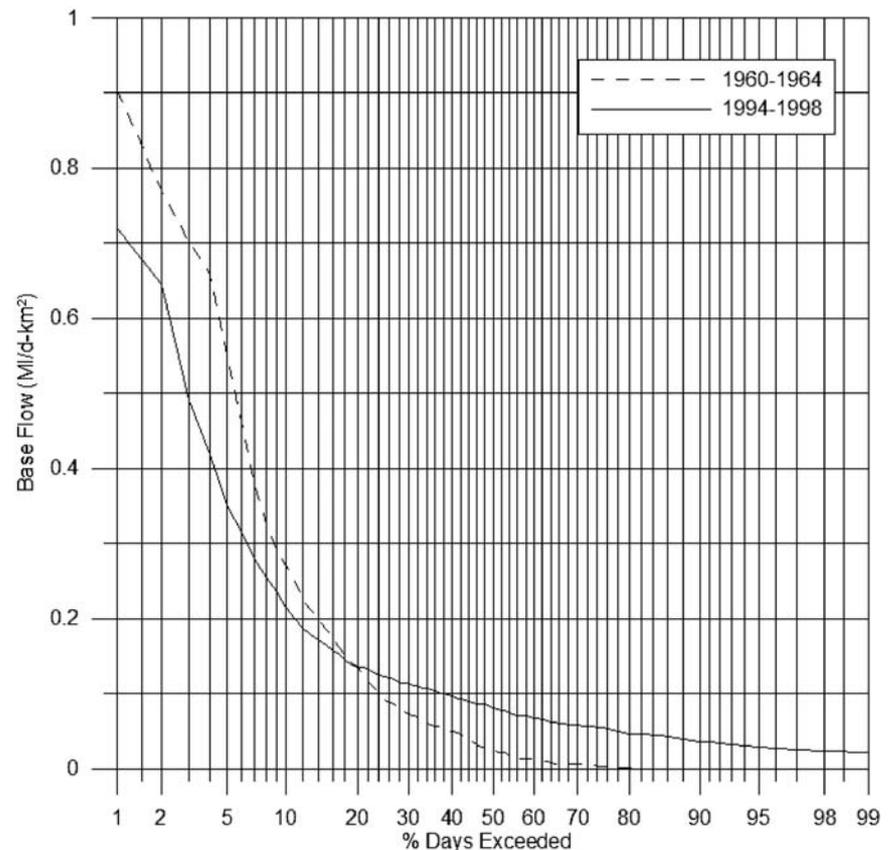
Monthly mean base flow rates in the streams display statistically significant upward trends during most of the low-base-flow months of August through January (Table 5). It is reasonable to conclude that the upward trends in mean base flow during the low base flow months are the same phenomenon that is reflected in the upward trends in annual median base flow and in the overall changes in the time-distributions of base flow rates in the streams. Upward trends in monthly precipitation during some of these months suggest that the upward base flow trends may be partially related to precipitation increases. The absence of statistically significant upward trends in precipitation during most of these months suggests, however, that factors related to urbanization may have resulted in the upward base flow trends. It is entirely possible that the additions to base flow during the low-

base-flow months also occur during high-base-flow months but are not recognizable with the methods employed in this investigation, given the greater variability of base flow during the high-base-flow months.

The specific causes of the changes in the time distributions of base flow rates in the streams cannot be determined from the data and analysis offered in this article. The existence of these changes—and the lack of associated trends in precipitation for the same time interval—is consistent with the effects of any number of alterations of pathways for precipitation to groundwater within the watersheds and with the addition of pathways for imported water to enter the streams, as discussed in the introduction and by Lerner (2002). These alterations need not result in increased recharge in order to generate the observed upward trends. For example, imported water could enter streams as runoff, conveyed by storm sewers, from overwatered lawns and other outdoor water uses without passing through the saturated zone. The mean and median base flow values for the urban streams included in this article should not therefore be considered indicative of groundwater recharge rates.

Stormwater detention basins, which are common in the three urban watersheds examined for this project, may also alter base flow. The attenuating effects of stormwater detention basins on streamflow were noted by Solo-Gabriele and Perkins (1997) in a study of the highly urbanized watershed of the Aberjona River and its principal tributary, Horn Pond Creek, near Boston, MA, USA.

Fig. 12 Base flow duration in Weller Creek during the first (1960–1964) and last (1994–1998) five-year portions of the period on record



In comparison to the Aberjona River, Horn Pond Creek either did not respond to storm events or responded much more slowly. Solo-Gabriele and Perkins (1997) attributed this attenuation of flow to the presence of two reservoirs on Horn Pond Creek. On the basis of its time of arrival in the stream following a precipitation event, both manual and automated streamflow partitioning methods may assign water released from stormwater detention basins to base flow, rather than direct flow. It is possible that HYSEP, the computer program used to quantify base flow for this project, identified some of the direct flow in the urban streams—runoff released from stormwater detention basins long after precipitation events—as base flow. As more stormwater detention basins were constructed in the urban watersheds, the greater volume of direct flow water released by the detention basins—and identified as base flow—could be responsible in part for the apparent increase in base flow affecting the streams.

In addition to releasing runoff slowly, so that it is effectively a component of base flow, stormwater detention basins may provide pathways for precipitation to recharge groundwater and may thereby increase base flow in urban settings. Although they are commonly lined to reduce leakage, leakage from stormwater detention basins could conceivably increase groundwater recharge rates and decrease direct flow in urban watersheds.

It is worth noting that the increases in base flow documented in the streams could be explained by effluent discharges to the streams. As mentioned previously,

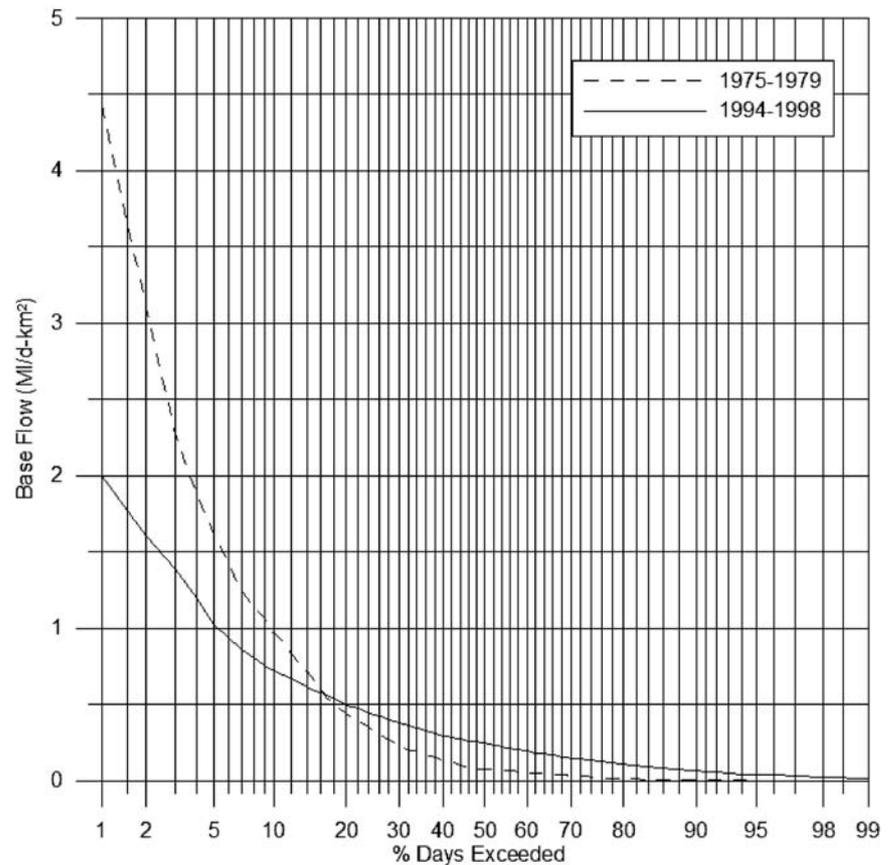
several published references were consulted to determine whether point sources have influenced flow in the streams, and portions of the periods of record of the Weller and Tinley Creek gages were eliminated from consideration because effluent discharge affected the streams during the eliminated time periods. Nonetheless, it is possible that undocumented discharges of effluent to the streams have occurred within the analyzed time periods, and that these discharges are responsible for the observed base flow trends.

Comparison with previous studies

Largely as a consequence of the problem of flooding in urban areas, studies of changes in base flow resulting from urbanization have been of secondary importance to those of changes in direct flow in such areas. An additional reason for this lack of urban base flow studies is undoubtedly the difficulties involved in locating suitable gage records from streams that are not affected by artificial discharges, diversions, and control structures. Nonetheless, a small number of studies of long-term stream gage data sets have examined the base flow response to urbanization.

Numerous studies have examined base flow in urban portions of Long Island, New York (USA). Sawyer (1963) and Seaburn (1969) recognized a reduction in the ratio of base flow to total streamflow in East Meadow Brook

Fig. 13 Base flow duration in Tinley Creek during the first (1975–1979) and last (1994–1998) five-year portions of the period on record



accompanying urbanization of the watershed of the stream during the 1950s and 1960s, and attributed the reduction to coincident increases in the portion of the watershed that was impervious and equipped with sewer systems. Franke (1968) and Sulam (1979) showed that total streamflow in urban streams in Nassau County, as well as the local water-table elevation, declined when local water users began to send wastewater to a regional sewer system and abandoned use of on-site septic systems. Pluhowski and Spinello (1978) showed that base flow in East Meadow Brook, in a sewer district encompassing southwestern Long Island, had declined from 91.2% of total annual stream flow in 1949 to 64.8% in 1974 as a consequence of interception of waste water by the sewer system. Garber and Sulam (1979) showed that streamflow in some Nassau County streams declined from 1940 to 1972 as a consequence of, first, a shift from disposal of waste water through septic systems to disposal through a communal sewer system and, second, to reduced water levels resulting from pumping in neighboring Queens County. These conclusions imply that the overall streamflow reduction is due to a reduction in base flow. Simmons and Reynolds (1982) quantified reductions in base flow as a proportion of stream discharge through 1975 in streams draining urbanized areas on Long Island, and they related the reductions to impervious surfaces and storm—and sanitary—sewerage. They concluded that these factors had reduced base flow from roughly 95% to about 20% of stream discharge in heavily urbanized parts

of Nassau County. Spinello and Simmons (1992) corroborated and extended the research of Simmons and Reynolds (1982) by examining changes in base flow as a proportion of stream discharge through 1985; their analysis therefore examines the impacts of the eastward urbanization of Long Island that occurred subsequent to the study period of Simmons and Reynolds (1982). In addition, Spinello and Simmons (1992) examined temporal changes in flow duration curves of Long Island streams resulting from urbanization. The flow duration curves showed that urbanization had resulted in decreased base flow, increased high flows, and increased flow variability.

An essential distinction between the Long Island and suburban Chicago hydrogeological settings is the difference in the permeabilities of the near-surface materials. Surficial deposits on Long Island consist of permeable sand and gravel with high hydraulic conductivity, permitting substantial infiltration of precipitation (Simmons and Reynolds 1982). These deposits form an unconfined aquifer that is hydraulically connected to the surface waters of Long Island and which is the source of base flow to all streams. The shallow subsurface of the McDonald, Weller, and Tinley watersheds is, on the other hand, marked by a relatively impermeable, continuous layer of clay-rich diamicton that would tend to discharge much less groundwater to streams than would the Long Island sand and gravel. The distinction between these two hydrogeological settings and its significance with regard to base flow is made evident by the percent base flow in

the streams. The mean base flow proportion for the period 1948 through 1970 was over 95% in rural, unsewered areas of Long Island; over 85% in urbanized, unsewered areas; and 61% in an urbanized, sewerage area (Simmons and Reynolds 1982). Mean base flow proportions in the McDonald, Weller, and Tinley Creek watershed are, on the other hand, much lower, ranging from 21% in Weller Creek to 43% in McDonald Creek (Table 6)—much lower than the proportion of base flow in even the most urbanized watersheds on Long Island.

This difference in the character of near-surface deposits has implications for the effects of urbanization on base flow. First, impermeabilization of land surface—one of the factors invoked by the Long Island researchers to explain reductions in base flow there—would be expected to result in a much greater reduction in infiltration on Long Island than in the setting of the McDonald, Weller, and Tinley watersheds of northeastern Illinois. Second, there is a greater potential for capture of streamflow on Long Island, where at least some wells have obtained water from the unconfined shallow aquifer within the time frame of the published studies and caused reduction of base flow (Garber and Sulam 1979). Documented supply wells in the northeastern Illinois watersheds examined in this study obtain groundwater from aquifers that are confined from the surface by the Wadsworth Formation diamicton, and, in comparison with the wells on Long Island, these wells would have a reduced potential to capture streamflow and reduce base flow.

It is also important to note that the Long Island researchers observed a decline in base flow not in relation to undisturbed conditions, but in relation to conditions prior to the use of regional sewer systems in the early 1950s. The pre-existing water-supply/wastewater convention was one in which most of the public water supply of Nassau County was derived from confined deep aquifers, and this water was returned to a shallow, unconfined aquifer, with some evaporative losses, through septic systems and cess pools throughout the county (Franke 1968). In addition, before the regional sewer system was brought into use, storm water in many urbanizing parts of Long Island was routed to recharge basins that were designed to permit rapid infiltration of water, thereby addressing problems of storm water runoff, preservation of recharge capacity, and accommodation of increased water demand. Therefore, in this earlier stage of the urban development of Nassau County and adjacent areas of Long Island, it is plausible that the return of deep groundwater to the shallow aquifer system, together with enhancement of infiltration by way of recharge basins, had increased recharge above predevelopment rates, raised the water table, and caused increased base flow. As regional sewer systems were constructed and began to be used, septic system and cesspool effluent and the water that infiltrated through recharge basins were increasingly conveyed to regional sewer systems and eventually discharged to tidewater. Recharge rates were thereby reduced, and, with them, base flow. The northeastern Illinois watersheds do not seem to have a comparable history marked by re-

duction of widespread, artificially enhanced infiltration, and this historical difference may explain the absence of a downward trend in base flow in the Illinois watersheds.

Barringer et al (1994) evaluated trends in several measures of base flow in an urban stream, Green Brook, and a rural stream, the Neshanic River, in New Jersey, USA, and computed rank-order correlation coefficients with precipitation of monthly base flow, direct flow, and total flow in the streams. Although smoothed base flow and annual one-day low flow in both streams displayed upward trends during a period from around 1960, the smoothed ratio of base flow to direct flow displayed an upward trend in Green Brook and a downward trend in the Neshanic River. The authors concluded, however, that the observed trends in both streams resulted primarily from climatic fluctuations. This conclusion is consistent with the finding of the present study, that mean the base flows in McDonald, Weller, and Tinley Creeks did not increase or decrease during the periods of record considered, all of which were periods of substantial watershed urbanization and during which annual precipitation displayed neither upward or downward trends. An increased correlation between precipitation and base flow in urban Green Brook suggested to Barringer et al that urbanization might have caused the watershed base flow system to become more responsive to precipitation as a consequence of leakage from storm sewers and detention basins. The relationship between monthly precipitation and base flow rates was not investigated as part of the present study.

In another comparative study, Rose and Peters (2001) investigated the effects of urbanization on base flow by comparing streamflow data from urban Peachtree Creek (Atlanta, Georgia, USA) with that from six nearby rural streams. One descriptor of base flow they compared was the base flow recession constant, a calculated value that expresses the change in base flow when it declines from May to September. A strongly positive base flow recession constant indicates a large reduction in base flow during this period and suggests a large reduction in groundwater storage. Although Rose and Peters found that the annual base flow recession constants for Peachtree Creek were low compared with most other non-urban streams in the region, the differences were not statistically significant ($\alpha=0.05$). Rose and Peters also found that annual low-flow values in Peachtree Creek were significantly lower ($\alpha=0.05$) than in the nearby non-urban streams. They hypothesized that this difference reflected decreased infiltration and reduced groundwater storage in the urban watershed in comparison with the non-urban watersheds. To test this hypothesis, Rose and Peters compared groundwater levels in two urban monitoring wells with those in a nearby non-urban monitoring well. They concluded that groundwater levels in the Peachtree watershed had, in fact, declined progressively from the 1960s to the 1990s as compared to those from the non-urban areas, a result consistent with their hypothesis based on low-flow data that groundwater storage had declined in the urban watershed as a consequence of reduced infiltration.

The results of the present study are not based on comparison of urban and rural watersheds, since coincident gage data from comparable, unregulated rural streams in the region are not available, and so they are not directly comparable with those of Rose and Peters' investigation. Mean base flow in the northeastern Illinois watersheds did not decline significantly during the periods of record considered, all of which were periods of substantial watershed urbanization, suggesting that base flow in these urban streams is comparable to that in nearby rural, unregulated streams. This is in contrast to Rose and Peters' finding that low flows in urban Peachtree Creek were significantly lower than in nearby rural streams, but the reasons for this difference are not clear.

Conclusions

Few long-term stream gage data sets covering the period of post-war urbanization are available from urban streams in northeastern Illinois that are not affected by effluent discharges and flow regulation. Analysis of the impacts of urbanization on base flow is further hampered by the lack of suitable data from comparable rural streams in the region for the time period of post-war urbanization. Given these general limitations, it is unclear whether the conclusions of this study are applicable to other watersheds in northeastern Illinois, let alone urban areas in other regions. Nevertheless, the study suggests the following conclusions regarding base flow in urban watersheds in northeastern Illinois:

1. Annual mean base flow rates for the investigated periods of record, each of which encompasses substantial urban development of the watersheds without annual precipitation trends, do not display statistically significant trends. Annual base flow rates have not changed in the streams as a consequence of urbanization in a way that is verifiable by the statistical methods employed in this investigation.
2. Statistically significant monotonic increasing trends are displayed by the annual median base flows in all three of the streams. These trends appear to reflect overall changes in the time-distributions of the base flow rates, characterized by increases in low base flow rates occurring during the months of August through January. These trends indicate either (a) that water is being added to stream base flow specifically during low-base-flow months, or (b) that this water is being added all year round, but that upward trends during high-base-flow months are masked by the high variability of base flow during the high-base-flow months.
3. The changes in the time-distributions of the base flow rates in the streams are consistent with a variety of alterations of pathways for precipitation to groundwater and surface water and with addition of pathways for imported water to streamflow. Specific causes of the trends are not determinable based on the data and analysis included in this report.

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