INVESTIGATION OF IMPACTS OF URBANIZATION ON BASE FLOW AND RECHARGE RATES, NORTHEASTERN ILLINOIS: SUMMARY OF YEAR 2 ACTIVITIES

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ABSTRACT

Base flow and precipitation data from three urbanized watersheds and three urban watersheds in northeastern Illinois and three rural watersheds in northern Illinois have been explored for impacts of urbanization on base flow and groundwater recharge rates. Spearman rank correlation coefficients suggest the correlation between base flow and precipitation rates in the urban streams has become slightly weaker during the period of urbanization of the northeastern Illinois watersheds. Double-mass curves suggest that the ratio of base flow to precipitation in the urban watersheds has increased during the period of urban growth. Time-series and double-mass plots suggest that, in urban McDonald Creek, the base flow rate increased during urbanization, but these increases were exceeded by increases in the base flow rate in the three rural streams. Time-series plots show that base flow in McDonald Creek increased between the late 1970s and 1998, counter to the decreasing precipitation trend during the period. The results of this study are consistent with a conceptual model in which urbanization leads to contributions of water to stream base flow that are unrelated to precipitation events, such as leakage from water distribution systems or sanitary sewers, or the collective runoff from lawn-watering, car-washing, and similar activities that introduce water to storm sewers during dry periods. The base flow rates that have been determined for these watersheds are of dubious value as indicators of groundwater recharge rates since base flow in the urban streams rates may include a component of runoff. The conclusions of this study may not be widely applicable since only a small number of watersheds having suitable streamflow data are available, and since the period of common record between the urban and rural gages is of short duration.

INTRODUCTION

Critically important to understanding groundwater availability from the shallow aquifers of northeastern Illinois is information on groundwater recharge rates and on the interaction between shallow groundwater and surface water in the region. Groundwater recharge rates can impose limitations on long-term groundwater availability. Groundwater withdrawals from shallow aquifers have the potential to reduce base flow in streams and water levels in lakes and wetlands. These constraints, along with public desires and legal mandates to maintain critical streamflows and water levels in surface-water bodies, may limit groundwater withdrawals from shallow aquifers.

Several elements of urban land cover and urban water-management practices may affect recharge rates and base flow. The net effect of these interacting elements may be either an increase or a decrease in recharge and base flow, and prediction of this net effect may not be straightforward since the specific factors affecting one watershed may not affect others (Lerner, 1990). Elements of urban settings affecting recharge rates and base flow include the following:

- **Impervious Surfaces.** Infiltration capacity is reduced in urban areas by widespread impervious surfaces. This effect of impervious surfaces is compounded by the presence of storm sewer systems, which are typically designed to convey direct runoff from impervious surfaces as rapidly as possible to nearby streams.
- **Storm Sewers.** Storm sewers, as mentioned above, convey runoff to stream channels, reducing opportunities for infiltration. However, leakage from storm sewers (where the sewers are positioned above the water table), may offset, at least partially, the reduction of infiltration. On the other hand, leakage of shallow groundwater into storm sewer systems (where the sewers are positioned below the water table) may reduce groundwater discharge to streams (base flow) and leakage to deeper aquifers.
- **Stormwater Detention Basins.** Stormwater detention basins may offset the impacts of storm sewers and impervious surfaces by providing opportunities for infiltration.
- **Groundwater Withdrawals.** Groundwater withdrawals from shallow aquifers may result in capture of groundwater that, under pre-development conditions, would have discharged to streams. Such capture may reduce base flow from pre-development rates.
- **Water Distribution Systems.** Leaks are almost always present in water distribution systems. The leaks could provide recharge to the shallow aquifers that might result in increased base flow.
- **Sanitary Sewer Systems.** In urban watersheds equipped with public water distribution systems and sanitary sewers, groundwater withdrawn by wells is not necessarily returned to the saturated zone via on-site septic systems but is conveyed to treatment plants which typically discharge it to nearby streams. On-site septic systems function as artificial recharge systems and offset the impacts of groundwater withdrawals but may degrade groundwater quality. Leakage of imported water from sanitary sewers may increase recharge rates and base flow.

The preceding list is by no means exhaustive. The goal of the present investigation is to evaluate the net impact of urbanization on base flow and groundwater recharge rates in northeastern Illinois through analysis of base flow in three watersheds in the region. This study will use trend and correlation analysis to characterize temporal changes in base flow and recharge rates accompanying urbanization in comparison to three rural watersheds.

RELATIONSHIP BETWEEN BASE FLOW, GROUNDWATER RUNOFF, AND GROUNDWATER RECHARGE

Under natural conditions, groundwater eventually discharges to surface-water bodies or is removed from the saturated zone by evapotranspiration in areas where the water table intersects the surface or the root zone of plants. Discharge by the process of seepage, often referred to as groundwater runoff, sustains flow from springs, maintains saturated conditions at wetlands, and provides the base flow of streams and rivers.

Groundwater runoff is only one component of the water which may enter a stream channel. The other components include surface runoff, interflow, and artificial discharges. For convenience, it is customary to divide streamflow into two components: direct (or storm) runoff and base flow. Direct runoff is considered to be surface runoff and a substantial portion of interflow, whereas base flow is presumed to consist largely of groundwater (Linsley et al, 1982). The two components are distinguished largely on the basis of their time of arrival in the stream rather than on a strict understanding of the path followed.

For a given time period, the hydrologic budget of an aquifer in a groundwater basin can be expressed by the following relationship (Holtschlag, 1997):

$$\Delta S = R - D_s - D_w - D_a - D_e$$

where:

ΔS = change in groundwater storage
R = groundwater recharge from precipitation, losing streams, and adjacent aquifers
D_s = aquifer discharge to streams
D_w = aquifer discharge to wells
D_a = leakage from the aquifer to underlying aquifers
D_e = aquifer discharge via evapotranspiration

Over a time interval selected so that changes in groundwater storage are negligible (such as one year), and in groundwater basins where withdrawals from wells and leakage to underlying aquifers are negligible, aquifer discharge to streams (D_s), or base flow, approximates net recharge, where net recharge is defined as total recharge minus groundwater evapotranspiration. Thus, under such conditions, the preceding equation reduces to the following:

$$D_s = R - D_e$$

METHODS AND DATABASE

Selection of Watersheds for Investigation

Three gaged watersheds in northeastern Illinois were selected for analysis of the impacts of urbanization on base flow and groundwater recharge rates: (1) Tinley Creek near Palos Park (USGS Gage 05536500), (2) McDonald Creek near Mt. Prospect (USGS Gage 05529500), and (3) Weller Creek at Des Plaines (USGS Gage 05530000). Locations and characteristics of these watersheds are shown in figure 1 and table 1. The Tinley Creek gage is located in southern Cook County, while the McDonald and Weller Creek gages are located adjacent to one another in northern Cook County. The Tinley Creek watershed includes parts of the communities of Oak Forest, Orland Hills, Orland Park, Palos Heights, and Tinley Park. The McDonald Creek watershed includes parts of the communities of Arlington Heights, Buffalo Grove, Mount Prospect, Palatine, Prospect Heights, and Wheeling. The Weller Creek watershed includes parts of the communities of Arlington Heights, Des Plaines, Mount Prospect, Palatine, and Rolling Meadows. The gaged watersheds were selected for study because they are located within the six-county Chicago metropolitan region and because they have a period of record at least 20 years in duration that is substantially unaffected by effluent discharges and flow regulation. No other stream gage data sets from the six-county region meet these criteria. Interpreted satellite imagery (Luman et al, 1996) indicates that urban land cover comprises more than 50 per cent of the McDonald, Tinley, and Weller Creek watersheds. These land cover interpretations are based on satellite imagery acquired in 1992 and 1995.

It is noteworthy that the Tinley and Weller Creek watersheds have received effluent discharges in the past, and the presence of these discharges has disqualified portions of the gage data for these streams from consideration in the present study. Tinley Creek received effluent from a small sewage treatment plant in Orland Hills, but documents on file at the Illinois Environmental Protection Agency (IEPA) indicate that the plant was closed between August and December 1973. For the present study, then, the period of record for the Tinley Creek gage was considered to begin in January 1974. USGS mapping indicates that the plant on Tinley Creek began operations after 1953 and before 1963. Weller Creek received effluent from a sewage treatment plant before November 15, 1958 (Wicker et al, 1998), so the period of record for the Weller Creek gage was considered to begin in December 1958.

Three rural watersheds have been selected for comparison with the urbanized watersheds. The locations of these watersheds are shown in figure 1, and selected characteristics of them are shown in table 2. Singh and Stall (1973), Singh et al (1988a), and Singh et al (1988b) indicate that the three selected rural watersheds did not receive effluent discharges in 1970 and 1984, respectively. Data for other years are not readily available, but, given the rural character of the watersheds and the documented absence of effluent discharges from them in 1970 and 1984, it is likely that the streams did not receive effluent discharges during other portions of their periods of record.

In northeastern Illinois, the shallow aquifer system, consisting of the glacial drift together with the uppermost bedrock, can reasonably be considered to provide all of the groundwater runoff to the McDonald, Weller, and Tinley Creek watersheds. In response to a prevailing downward vertical hydraulic gradient, a small portion of groundwater recharge in the watersheds will leak downward through the Maquoketa Confining Unit (a hydrostratigraphic unit consisting primarily of the Ordovician Maquoketa, Galena, and Platteville Groups) and into the underlying deep bedrock aquifer system. Walton (1962) estimated maximum leakage across the Maquoketa Group in northeastern Illinois at about 0.003 cubic feet per second per square mile (cfs/sq mi). Walton (1965) indicates that groundwater runoff during a year of near-normal precipitation in these areas is 0.1 to 0.2 cfs/sq mi. Comparison of these estimates of leakage and groundwater runoff suggests that leakage to underlying aquifers is about 1.5 to 3 per cent of groundwater runoff during a normal year of precipitation in the selected northeastern Illinois watersheds. This proportion is considered to be small enough to be dismissed as negligible. It is to be understood 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.

Land Cover Mapping

Land cover at selected times in each of the three urban watersheds was mapped from aerial photography using the land cover classification system of Anderson et al (1976). The purpose of the land cover mapping is to characterize the nature and timing of changes in land cover accompanying urbanization of the watersheds. The photography was corrected for distortion by registering each image to points on the surface that are identifiable in both the photographs and USGS mapping. The land cover mapping is based on aerial photographs taken during flights in 1951, 1952, 1962, 1967, 1974, 1975, 1988, and 1998.

Incorporated Area Mapping

The area within each urban watershed lying within incorporated municipalities was determined from 1963, 1973, and 1993 USGS 7½-minute topographic mapping. The purpose of mapping incorporated areas is to characterize the probable area equipped with water-distribution systems, storm sewers, and sanitary sewers.

Estimation of Shallow Groundwater Withdrawals

Groundwater withdrawals from the shallow aquifer system in each of the three urban watersheds were determined from records on file at the Illinois State Water Survey (ISWS). Withdrawals from the shallow aquifers occur from two general categories of wells: (1) domestic wells, and (2) public, industrial, and commercial wells. Withdrawals from domestic wells were based on an estimate of the number of such wells in existence during each year of the period from 1950 through 1998. The estimates assumed that each domestic well served 3.1 people at a rate of 66.2 gallons per day per capita (Illinois Department of Natural Resources Office of Scientific Research and Analysis, 2000). The estimate of the number of shallow wells in existence in the watersheds were multiplied by these factors to estimate average annual withdrawals from domestic wells open to the shallow aquifers in the watersheds. Withdrawals from public, industrial, and commercial wells were estimated from annual withdrawal data reported by water operators and facility managers as part of the ISWS Illinois Water Inventory Program.

Estimation of Water Supplied to Public Water Distribution Systems

Since water distribution systems inevitably leak, their presence can influence base flow and groundwater recharge rates, particularly when the water in circulation is imported to the shallow system that provides base flow. Data on leaks from the water distribution systems present in the three urban watersheds are sparse and inconsistently available. During a given year, only a subset of the public water systems conduct leak detection surveys, and these surveys generally do not cover the entire system. In addition, the leak detection surveys are conducted using differing techniques.

As an indicator of the extent to which leakage from public water systems may have influenced base flow and groundwater recharge rates in the urban watersheds, estimates were developed of the amount of water supplied to public water distribution systems overlapping each of the three watersheds. These estimates were developed from water use data compiled by the ISWS and the Illinois Department of Natural Resources–Office of Water Resources. The estimates are simple annual averages of the amount of water supplied to the distribution systems overlapping the watersheds, even if only a small portion of the distribution system overlapped the watershed. If it is assumed that the amount of water that leaks from the water distribution systems is proportional to the amount of water that is supplied to them, the estimates provide a rough indication of probable temporal trends in distribution system leakage.

Estimation of Base Flow

The computer program HYSEP (Sloto and Crouse, 1996) was used to conduct hydrograph separations of streamflow data from the selected urban and rural watersheds using the *local minimum method* of hydrograph separation. This is the method recommended for use by Pettyjohn and Henning (1979) for use when little is known about the physical conditions governing streamflow in a watershed. The output of the hydrograph separation procedure consists of values of mean daily base flow and direct runoff.

Synthesis of Precipitation Record

A precipitation record for the period of record of each of the six selected stream gage data sets was synthesized from precipitation data available from the Midwest Climate Center at the ISWS. To do this, distances were estimated from each Midwest Climate Center precipitation station to the centroid of each selected watershed. Data from the nearest precipitation station were considered to be representative of precipitation at the watershed. If the period of record of the stream gaging station was not fully covered by the nearest precipitation station, then data from the second nearest precipitation station were chosen to represent precipitation during the time period not covered by the nearest precipitation station, and so on.

DATA ANALYSIS

Characterization of Urban Changes in Selected Northeastern Illinois Watersheds

Tables 3–5 illustrate land cover in the urban watersheds for the years of aerial photograph coverage. The proportion of area within each watershed lying within incorporated municipalities was determined from 1953, 1963, and 1993 USGS 7½-minute quadrangle maps.

Figure 2 illustrates the proportion of each watershed under urban land cover and lying within incorporated municipalities for the period 1950-1998. The plots in figure 2 show that the McDonald and Weller Creek watersheds underwent rapid urbanization between the early 1950s and early 1970s, with urban land cover exceeding 50 per cent of watershed area in the late 1950s and middle 1960s in the Weller and McDonald watersheds, respectively. Urban land cover in both watersheds exceeded 90 per cent of watershed area in the early 1970s. Urbanization of the Tinley Creek watershed began later than in the McDonald and Weller watersheds, with urban land cover exceeding 50 per cent of the watershed area in the middle 1970s and exceeding 90 per cent of watershed area in the late 1990s. The proportion of watershed area lying within incorporated municipalities shows trends similar to that of urban land cover in the northeastern Illinois watersheds. Areas within incorporated municipalities are likely to be served by sewer systems and public water distribution systems.

Groundwater withdrawals from the shallow aquifers within the watersheds show differing trends that reflect shifts in sources of water used by public water systems and the reliance of the local population on domestic wells finished in the shallow aquifers (figure 3). Such withdrawals may affect base flow by reducing natural groundwater discharge. Withdrawals from the shallow aquifers in the McDonald Creek watershed have generally increased and are a reflection of increasing use of domestic wells open to the shallow aquifers. ISWS records show that public water systems in the McDonald watershed obtained no water from the shallow aquifers within the watershed during the 1950-1998 period. Withdrawals from the shallow aquifers within the Tinley Creek watershed strongly reflect use by public water systems, which pumped an estimated 88 to 99 per cent of the annual total withdrawn from the shallow aquifers from 1959 through 1985. Shallow aquifer withdrawals by public water system wells reduced to zero in the Tinley watershed from 1986 through 1998. Withdrawals from the shallow aquifers in the Weller Creek watershed also strongly reflect use by public water systems, which relied in part on withdrawals from shallow aquifers within the Weller watershed prior to 1957, from 1961 through 1963, and from 1970 through 1985.

The public water distributions serving the watersheds obtain water from three principal sources: (1) the shallow aquifers, via wells located both within the watersheds and outside of them; (2) the deep bedrock aquifer system; and (3) Lake Michigan. When it leaks from water distribution systems within the watersheds, water derived from the deep bedrock system and Lake Michigan–and from wells finished in the shallow aquifers outside of the watersheds–may increase groundwater recharge rates and base flow. Figure 4 illustrates trends in the amount of water supplied to water distribution systems that overlap each of the three urban watersheds. Because a link between distribution rate and leakage cannot be clearly established, these data are provided only as an indication of the potential for possible trends in rates of leakage of imported water within the watersheds.

Rates of Base Flow

Table 6 shows the median of mean daily base flow for complete water years within the period of record of the selected stream gages as noted. The base flow rates range from 0.1 to 0.3 cfs/sq mi.

Time-Series Plots of Precipitation and Base Flow

Figures 5 and 6 show time-series plots of monthly precipitation and the monthly median of mean daily base flow, respectively, covering the period of record of the stream gages in the six selected watersheds. The time-series plots include fits to the data that were developed using the weighted low-regression filter LOWESS (LOcally WEigthed Scatterplot Smoothing) (Cleveland, 1979). LOWESS is a computationally intensive smoothing methodology that involves fitting at least 2^n weighted least squares equations, where n = sample size. A smoothness factor between 0 and 1 is selected subjectively by the analyst. A larger smoothness factor leads to greater smoothing of the data set. The smoothed time-series plots shown in figures 5 and 6 were developed using a smoothness factor of 0.3. The time-series plots do not have visually apparent trends in either precipitation or base flow.

Analysis of Correlation Between Precipitation and Base Flow

The degree of correlation between monthly total precipitation and monthly median base flow was evaluated using the Spearman rank-order correlation coefficient. The square of the correlation coefficient is a measure of the total variance accounted for by the relation (Barringer et al, 1994) and reflects the degree to which variability in precipitation, rather than other factors such as changes in land cover and soil moisture, account for variability in base flow.

Spearman rank-order correlation coefficients between monthly median base flow and total precipitation were determined both for the entire period of record of each stream and for common periods of record among the selected gaged streams. Correlation coefficients for the entire periods of record (table 7) do not show a consistent difference between the correlation in rural and urban settings. To assess whether the correlation coefficients had changed with time, correlation coefficients were also computed for common periods of record, at least ten years in duration, for which data from at least one rural and one urban gage were available (table 8). The common periods of record for which correlation coefficients were calculated were selected so that a maximum period of time was considered, in order to account for a range of precipitation conditions in the watersheds. The common periods of record for which these correlation coefficients were calculated are, therefore, irregular in duration. These periods of record also overlap.The Correlation coefficients for common periods of record (table 8) suggest that the correlation between precipitation and base flow was stronger in urban settings for three periods (September 1952–September 1971, December 1958–September 1971, and December 1958– September 1975), equivocal for one period (December 1958-October 1982), and weaker in urban settings for one period (January 1974-October 1982). For example, the coefficients for the urban McDonald and Weller watersheds for the December 1958 - September 1971 period indicate that total precipitation accounts for 9 to 16 per cent of the total variance of median monthly base flow. In contrast, the coefficients indicate the precipitation accounts for only 4 to 6 per cent of the total variance of monthly median base flow at the three rural gages. The correlation coefficients for the period December 1958–October 1982 are not indicative of a systematic difference in the response of base flow to precipitation in urban watersheds as compared to rural watersheds, and the correlation coefficients for the period January 1974–October 1982 indicate that base flow in the urban watersheds was *less* responsive to precipitation than in the one rural watershed for which data are available–precisely the opposite of the relationship suggested by the correlation coefficients for the periods September 1952–September 1971, December 1958–September 1971, and December 1958–September 1975. The correlation coefficients for the period January 1974–October 1982 indicate that total precipitation accounts for 7 to 21 per cent of the total variance of median base flow at the three urban gages and 24 per cent of the variance of median base flow at the rural gage on the East Branch of Panther Creek.

As discussed by Barringer et al (1994) for an urban watershed in New Jersey, an elevated correlation of precipitation with base flow in urban watersheds might reflect leakage from storm sewers and recharge from detention basins. It is, however, not clear that this effect influences the relationship of base flow and precipitation in the northeastern Illinois urban watersheds under investigation in the present study. Overall, the correlation coefficients in table 8 suggest that the correlation between precipitation and base flow has increased in both the urban and rural watersheds, not just the urban watersheds. Moreover, the correlation coefficients in table 8 suggest that the strength of the correlation has increased to a greater degree in the rural watersheds–insofar as they are represented by the watershed of East Branch Panther Creek–than in the urban watersheds.

Double-Mass Curve Analysis

Double-mass curves were constructed to explore for changes in trends in the base flow and precipitation rate data from the urban and rural watersheds. The graphical-statistical method of double-mass-curve analysis (Searcy and Hardison, 1960) is based on the fact that a plot of the cumulation of one property against the cumulation of another property during the same time period will plot as a straight line if the sums are proportional. Slope changes in double-mass curves indicate a change in the ratio of the plotted quantities. Such slope changes may indicate the timing and magnitude of changes that affect only one of the two properties or changes that affect both variables unequally. To better illustrate departures from early data, the double-mass curves in this report include a regression line through the earliest 20 per cent of data points, if the earliest 20 per cent of data points includes a minimum of 3 points. Double-mass curves are a tool for data exploration and to suggest relationships for further exploration. Unfortunately, there is no readily available statistical test of the slope changes indicated by a double-mass curve.

It is noteworthy that a double-mass curve only illustrates relative changes in plotted quantities. Take, for example, a double-mass curve of annual precipitation in watershed X (plotted on the *x*-axis) and watershed Y (plotted on the *y*-axis). A slope decrease in such a plot could indicate either of the following extreme cases (1) that the annual precipitation rate in watershed X has increased, while that in watershed Y has remained unchanged; or (2) that the annual precipitation rate in watershed Y has decreased, while that in watershed X has remained unchanged. Multiple intermediate case are possible. For example, the slope decrease may indicate precipitation rates have increased in watershed X and decreased in watershed Y, or it may indicate that precipitation rates have increased in both watersheds, but more so in watershed X. In the interest of brevity, it will be the convention in this report to describe trends indicated in double-mass curves in relative terms based on the null-case assumption that the rate plotted on the x-axis has not changed. For the example described earlier in this paragraph, then, the double-mass curve trend would be described as indicating that the annual precipitation rate in watershed Y has decreased relative to that in watershed X. It is to be understood that this language could connote any of several possible relationships between the plotted rates, as discussed previously.

Total Precipitation versus Median Base Flow

Figure 7 shows double-mass curves depicting the cumulation of total precipitation versus that of median base flow for annual (water year) accounting periods for the period of record of each of the selected urban and rural stream gages. The slope of these curves indicates the ratio of precipitation and base flow rates. The trend of such a curve would be expected to be linear over a long period of time in an undeveloped watershed. In an urban setting, an increase in slope would suggest greater capture of precipitation or the contribution of imported water to the saturated zone via leakage from distribution systems and/or sanitary sewers. A decrease in slope would suggest less capture of precipitation by the saturated zone. Such a decrease in slope might result from increased impervious surface area or increased coverage by storm sewer systems, or both.

The lefthand column in figure 7 shows data for the selected rural watersheds. The data from East Branch

Panther Creek show that the ratio of base flow to precipitation increased during the 1973 and 1974 water years as compared to the pre-1973 and post-1974 periods. The data for Gimlet Creek show the ratio of base flow to precipitation was relatively low during water years 1953-1959 and 1963-1965. The ratio of base flow to precipitation was higher during water years 1950-1952, 1960-1962, and 1966-1971. The data for Terry Creek generally follow a linear trend, with the ratio of base flow rates to precipitation somewhat reduced during water years 1956-1957 and 1963-1965.

Double-mass curves illustrating the cumulation of total precipitation versus that of median base flow for the selected urban watersheds are shown in the right-hand column of figure 7. The data from McDonald Creek shows a notable break in slope at the data point representing water year 1989, with the 1990-1998 data suggesting that the ratio of base flow to precipitation increased during the post-1989 period. The Tinley Creek data show that the ratio of base flow to precipitation was consistently higher from water year 1990 through 1998 as compared to preceding years. Data from Weller Creek show that the ratio of base flow to precipitation was higher during the post-1976 period than in preceding years.

Double-mass curves comparing precipitation and base flow in the selected watersheds (figure 7) suggest that the ratio of base flow to precipitation has increased in the urban watersheds during the period of urbanization. This suggests that base flow in the urban streams has responded to inflows that are not directly linked to contemporaneous precipitation events.

Total Precipitation

Figures 8 and 9 show double-mass curves comparing total annual precipitation in the six watersheds selected for study. The plots in figure 8 compare precipitation in rural versus urban watersheds, and those in figure 9 compare precipitation in the rural watersheds. Plots comparing precipitation in the Tinley Creek watershed with other watersheds are not included in figure 8 because the common periods of record of the Tinley Creek gage and the East Branch Panther Creek, Gimlet Creek, and Terry Creek gages are of insufficient duration to indicate long-term trends through double-mass curve analysis. The double-mass curves comparing total annual precipitation are included to provide information on whether precipitation amounts have differed between watersheds. If, for example, precipitation has been greater in the urban watersheds than in the rural watersheds, this difference might explain greater rates of base flow in the urban watersheds.

Overall, the data in figure 8 show relatively linear trends, suggesting that annual precipitation amounts have not changed dramatically in any one watershed independent of the others. Small, gradual changes in annual precipitation amounts affecting one watershed independent of another may be indicated, however. The dashed regression line through the earliest 20 per cent of data points provides a reference for comparing the trend of the early data to the entire plot. Plots comparing McDonald Creek data with rural watershed data suggest that, since the early- to mid-1950s, annual precipitation in the McDonald watershed may have decreased slightly relative to that in the rural watersheds. The word *relative* is important: the data may indicate that annual precipitation has increased slightly in the three rural watersheds, and the increase has not affected the McDonald watershed. This trend is indicated more strongly in the double-mass curve comparing precipitation in the McDonald watershed with that in the Terry Creek watershed. The changes in precipitation amounts suggested by the McDonald Creek double-mass curves are not indicated by the plots of Weller watershed data. These plots indicate that annual precipitation amounts in the Weller Creek watershed have increased slightly relative to that in the rural watersheds. Overall, then, the double-mass curve data comparing precipitation in the rural and urban watersheds do not indicate that a single conceptual model explains changes in precipitation amounts in the rural and urban watersheds.

The double-mass curves comparing annual precipitation in the rural watersheds also follow generally linear trends, suggesting that annual precipitation amounts have not changed dramatically in one watershed independent of the others. Slight, gradual changes in annual precipitation amounts may be indicated, however. The plots suggest that annual precipitation at the East Branch Panther Creek watershed has decreased slightly relative to that at the Gimlet and Terry Creek watersheds. The plots suggest that annual precipitation at the Terry Creek watershed has increased slightly relative to that at the Gimlet and East Branch Panther Creek watersheds.

Median Base Flow

Figures 10 and 11 show double-mass curves comparing the median of mean daily base flow in five of the six watersheds selected for study. The plots in figure 10 compare base flow rates in rural versus urban watersheds, and those in figure 11 compare base flow rates in the rural watersheds. Plots comparing base flow rates in the Tinley Creek watershed with other watersheds are not included in figure 10 because of insufficient common period of record, as described previously.

The three plots in figure 10 that compare base flow rates in McDonald Creek with those in the rural streams suggest that the rate of base flow in McDonald Creek has declined relative to that in the rural streams. The plots show that the base flow decline in McDonald Creek relative to East Branch Panther Creek was somewhat gradual from water year 1962 through 1982 except for 1979 and 1980, when base flow in McDonald Creek was dramatically increased relative to East Branch Panther Creek. The plots show that base flow in McDonald Creek occurred at rates that had decreased relative to those in Gimlet Creek during most of the period from water year 1960 through 1971. Relative to Terry Creek, base flow rates in McDonald Creek occurred at decreased rates during most of the period from 1963 through 1975, but that rates were reduced more during 1972 through 1975.

The double-mass curves comparing base flow in Weller Creek with that in the rural streams suggest that rates of base flow in Weller Creek and the rural streams have remained more-or-less proportional during the common periods of record of the gages monitoring the streams, with only very slight decreases in slope suggesting that base flow in Weller Creek occurred at decreased rates during the early- through mid-1970s. The most pronounced feature of the double-mass curves of Weller Creek base flow data is a period of greatly increased base flow during water years 1978-1980 that is indicated in the plot comparing data from East Branch Panther Creek and Weller Creek.

The difference in shape of double-mass curves comparing base flow in McDonald and Weller Creeks with base flow in the rural streams appears to be an artifact, in part, of differing common periods of record between stream gages. The common periods of record between the McDonald Creek gage and the rural gages begin with water year 1953, while those of the Weller Creek gage and the rural gages begin with water year 1960. Water year 1960 post-dates a period of fairly high base flow in McDonald Creek relative to the rural streams, suggesting that base flow in Weller Creek might have occurred at higher rates during water years preceding 1960.

The double-mass curves comparing base flow rates in the rural watersheds (figure 11) suggest that base flow rates in East Branch Panther Creek and Gimlet Creeks remained about proportional during the period 1950-1971. In contrast, base flow in East Branch Panther Creek decreased relative to Terry Creek during the period 1953-1961, returned to approximately pre-1953 rates during the period from 1962-1967, and increased relative to pre-1953 rates during the period 1968-1975. The plot comparing base flow in Gimlet and Terry Creek displays a similar pattern of trends, with base flow in Gimlet Creek occurring at decreased rates relative to Terry Creek during 1953-1959, returning to approximately pre-1953 ratio during the period 1960-1969. Base flow rates in Gimlet Creek increased relative to Terry Creek in 1970 and 1971.

Comparison of the double-mass curves and time-series plots provides insights into the nature of the base flow changes affecting the urban watersheds and suggest possible reasons for these changes. As mentioned previously, double-mass curves show that base flow in McDonald Creek has decreased relative to that in the rural streams. As described earlier, a departure from a linear trend by a double-mass curve is suggestive only of a relative change in the quantities that are plotted. In fact, the time-series plot of base flow in McDonald Creek shows that, rather than decreasing, base-flow rates in the stream generally increased during the entire period from October 1952 through September 1998, except for the early- through mid-1970s (figure 6). Base flow rates in the rural streams were more variable during their respective periods of record. The period of decreased ratio of base flow in McDonald Creek to base flow in East Branch Panther Creek occurred during water years 1962 through 1982, excepting 1979 and 1980. Comparison of the time-series plots of base flow in the two streams (figure 6) suggests that the decreasing slope of the double-mass curve is largely due to the fact that increases in base-flow rates in McDonald Creek have not kept pace with increases in base flow rates in East Branch Panther Creek. During the period of declining base flow in McDonald Creek during the early- through mid-1970s, base flow rates declined proportionally in East Branch Panther Creek. The period of decreased ratio of base flow in McDonald Creek to base flow in Gimlet Creek encompasses most of the period from water year 1960 through 1971 (figure 10). The time-series plots of base flow for the two streams (figure 6) suggest that much of the slope decrease in the double-mass curve can be attributed to the overall lower rate of base flow increase in McDonald Creek during the 1960 through 1971 time period. Likewise, the time-series plots of base flow in McDonald and Terry Creeks suggest base flow rate increases in McDonald Creek did not keep pace with base flow increases in Terry Creek during the period from 1963 through 1975.

The relationship between base flow in McDonald Creek and the rural streams that is indicated by the double-mass curves may reflect a range of influences. Double-mass curves showing precipitation in the watersheds (figure 8) suggest that the ratio of precipitation rates in the McDonald watershed versus the rural watersheds may have declined slightly in comparison to the trend of the early data. Lower precipitation in the McDonald watershed as compared to the rural watersheds may be part of the reason that base flow rates in McDonald Creek have not increased as much as those in the rural watersheds. The double-mass curves comparing precipitation in the watersheds of McDonald Creek, East Branch Panther Creek, and Gimlet Creek (figure 8) and base flow in the same watersheds (figure 9) differ markedly in shape, however, suggesting that influences other than precipitation may have played a role in causing base flow rate increases in McDonald Creek to be less than those in the rural streams. The trend may signify the influence of such features of the urban setting such as impervious surfaces and storm sewer systems–features that would reduce the infiltration capacity of the watershed soils and remove potential recharge from areas that, under undeveloped conditions, would function as recharge areas. It is noteworthy that the reduction in slope of the double-mass curve comparing base flow in McDonald and Terry Creek is more subtle than the reduction in slope in other double-mass curves comparing McDonald Creek base flow data with data from rural creeks. A reduction in slope is apparent, but this slope reduction is similar to that of the double-mass curve comparing precipitation in McDonald and Terry Creeks. The reasons for the dissimilarity of the double-mass curves is not clear.

Increased base flow in Weller Creek relative to East Branch Panther Creek is indicated in the double-mass curve comparing base flow in the streams during water years 1979 and 1980 (figure 10). The time-series plots of base flow in the streams suggest that this increase may be related to two factors: (1) unusually high base flow during March 1979, (2) a series of months in water year 1980 during which base flow was higher-than-average. Because the double-mass curve comparing base flow in McDonald Creek and East Branch Panther

Creek displays a similar relative increase in base flow rates in McDonald Creek in water years 1979 and 1980, the most plausible explanation for the apparent increase in base flow in the urban streams relative to East Branch Panther Creek is that the increase reflects climatic factors. Melting snow, for example, might affect streamflow in such a way the HYSEP would categorize it as base flow rather than direct runoff.

SUMMARY

Few long-term stream gage data sets covering the period of post-war urbanization are available from both urban and rural streams in northeastern Illinois that are not affected by effluent discharges and flow regulation. This comparative scarcity of adequate gage data is underscored by the brevity of the common periods of record of the gages, since the rural gages selected for use in the study ceased operation in 1971, 1974, and 1982. 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:

- The correlation between precipitation and base flow has increased in both urban and rural watersheds in northeastern Illinois, but the correlation has increased to a greater degree in the rural watersheds. That base flow in the urban streams is correlated less strongly with precipitation than it is in the rural streams could be explained by the addition of water to the urban streams from sources unrelated to precipitation events. Such additions might include leakage of water from water distribution systems and water collected and discharged to streams by storm sewer systems from such urban water uses as lawn-watering, car-washing, etc.
- The ratio of base flow to precipitation in the urban streams considered in this study has increased above the ratio indicated by data from the earliest portion of the period of record. In contrast, the ratio of base flow to precipitation in the rural watersheds has generally decreased or remained the same as indicated by the earliest portion of the period of record. Although infiltration of precipitation and its eventual discharge to streams is influenced by several factors, it would be expected in an undeveloped watershed that base flow and precipitation would remain at approximately at the same proportion from year to year. These apparent trends may only be artifacts of the inconsistent periods of record of the data, but the trends are consistent with a conceptual model in which water is contributed to the urban streams by processes unrelated to precipitation, as described in the preceding paragraph.
- Owing to the brevity of the common periods of record between the urban and rural stream gage data, double-mass curves comparing base flow in urban and rural streams that show a change in ratio of base flow rates in the streams are limited in scope. Of the urban base flow data sets examined, only data from McDonald and Weller Creeks, not Tinley Creek, were plotted against data from the rural streams, and double-mass curves involving Weller Creek data cover a period of time that began too late to characterize predevelopment base flow conditions in the Weller watershed. Double-mass curves of base flow in McDonald Creek versus the rural streams, as well as time-series plots of base flow in the streams, suggest that base flow rates in McDonald Creek increased during much of the common period of record of the gages on these streams, but that the increases in rate were less than in the rural watersheds. This can be explained partially by lower precipitation in the McDonald watershed, but it is likely that features of urban development that reduce both infiltration capacity and the availability of water for recharge may play a role in explaining the discrepancy.

Since base flow in the urban streams studied for this investigation appears to be influenced by inflows that may be unrelated to infiltration of precipitation, the base flow rates may not be indicative of groundwater recharge and are probably not indicative of rates of precipitation infiltration. The hypothesized inflows to the streams might originate primarily as subsurface leakage from water distribution systems or sanitary sewers, in which case the base flow rates might be considered indicative of the rate of groundwater recharge, but not that of precipitation infiltration. If the hypothesized inflows are some form of runoff, most likely discharged to the streams through storm sewer systems, the base flow rates are neither indicative of rates of groundwater recharge nor those of precipitation infiltration.

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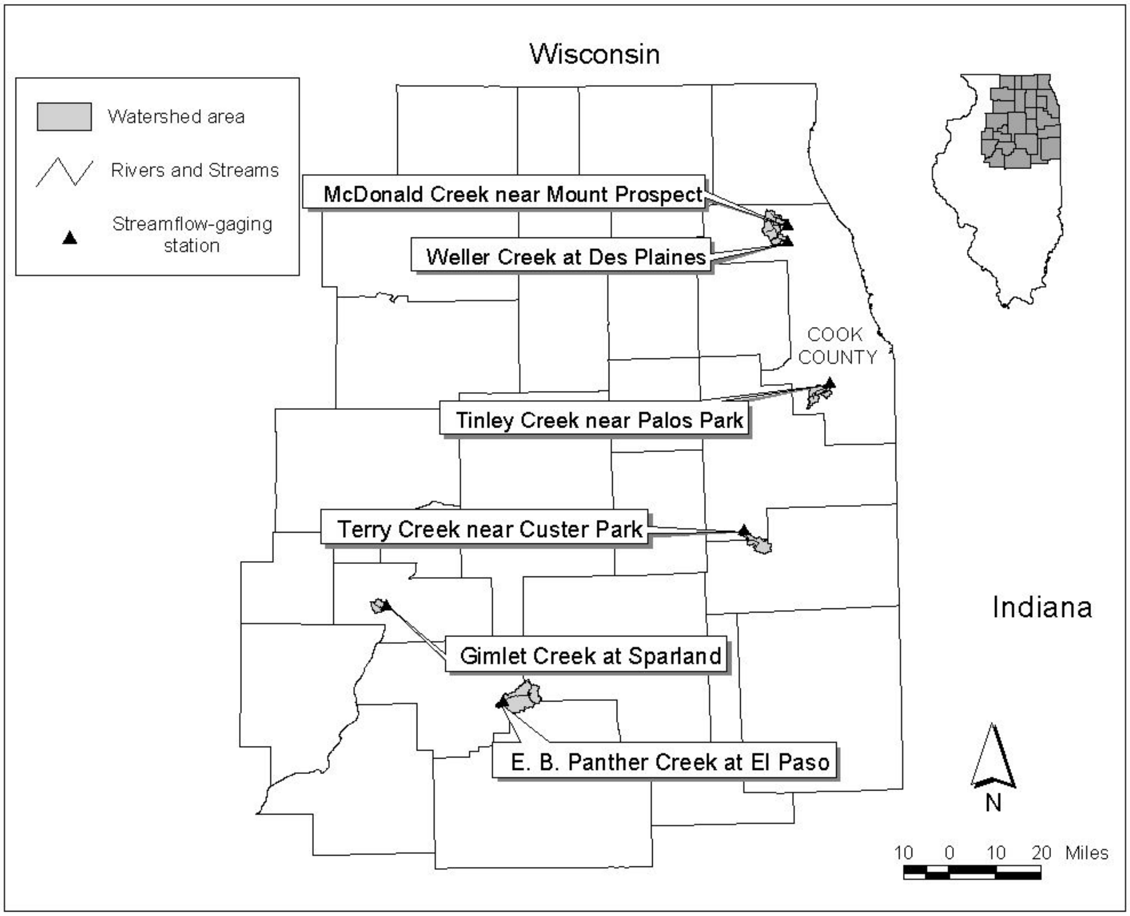

Figure 1. Index map showing locations mentioned in text.

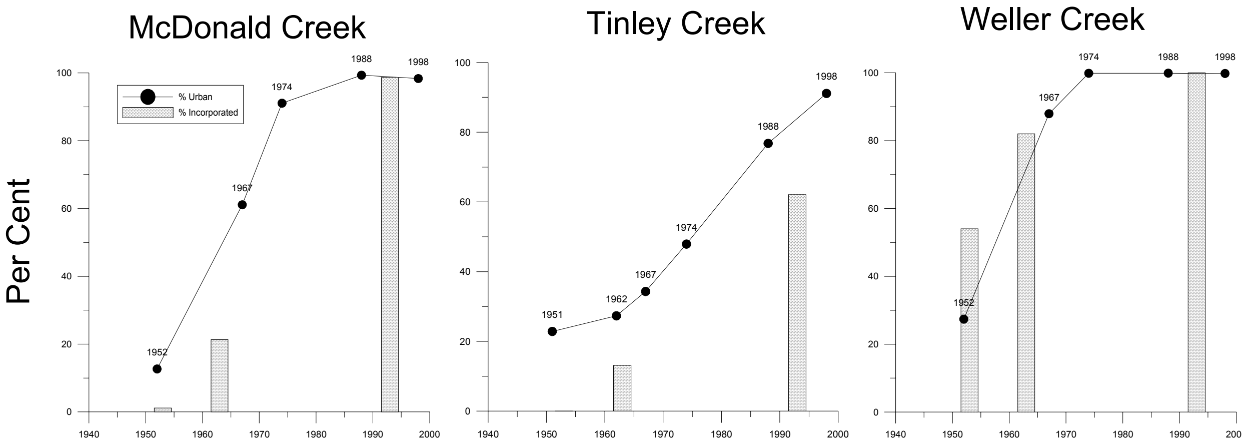

Figure 2. Per cent of watershed occupied by urban land cover and lying within incorporated municipal boundaries.

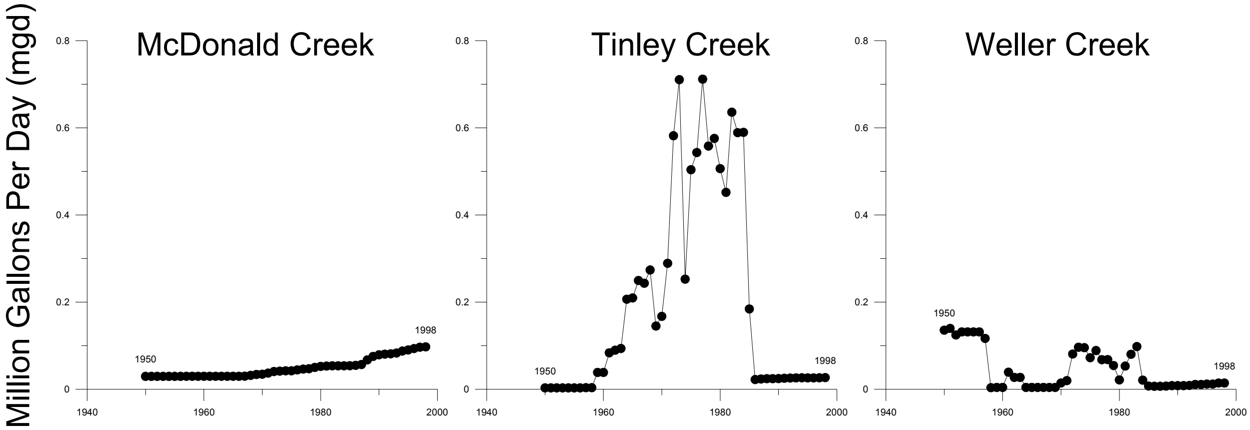

Figure 3. Estimated withdrawals from shallow aquifers within watershed boundaries, annual accounting periods, calendar years 1950-1998.

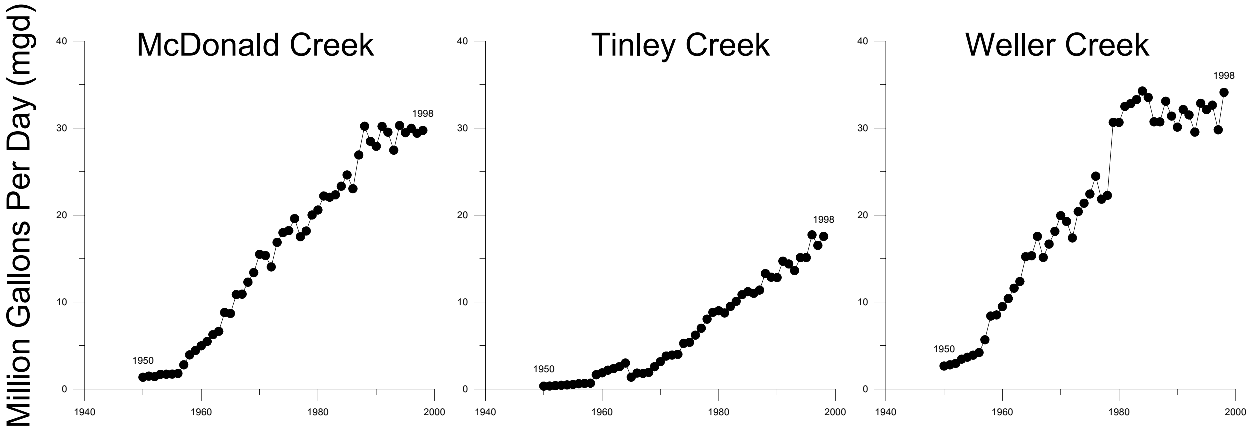

Figure 4. Estimated water supplied to public water system distribution networks partially overlapping watershed, annual accounting periods, calendar years 1950-1998.

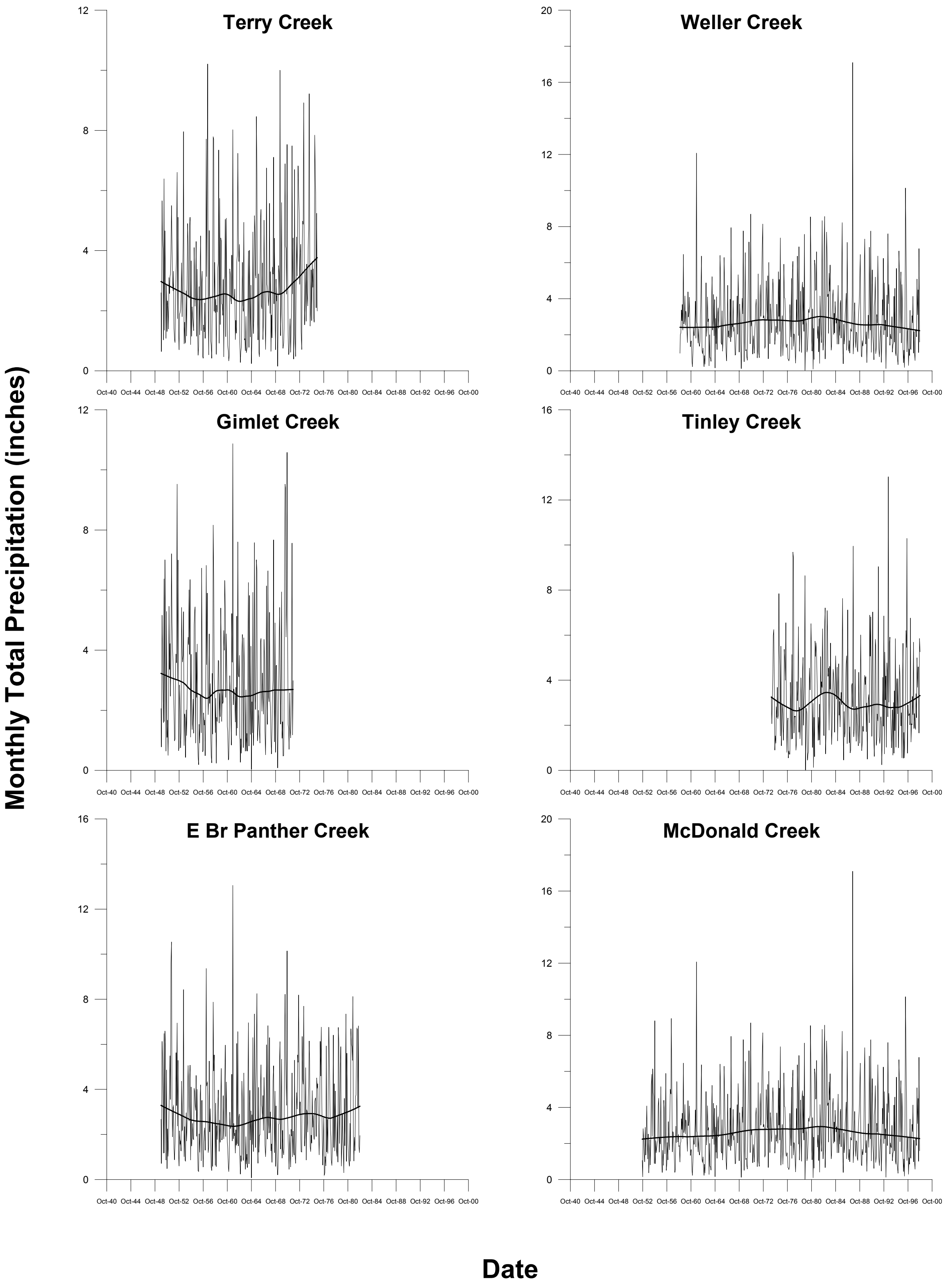

Figure 5. Monthly precipitation (inches) in the six selected watersheds. Heavy line is LOWESS fit to the monthly data.

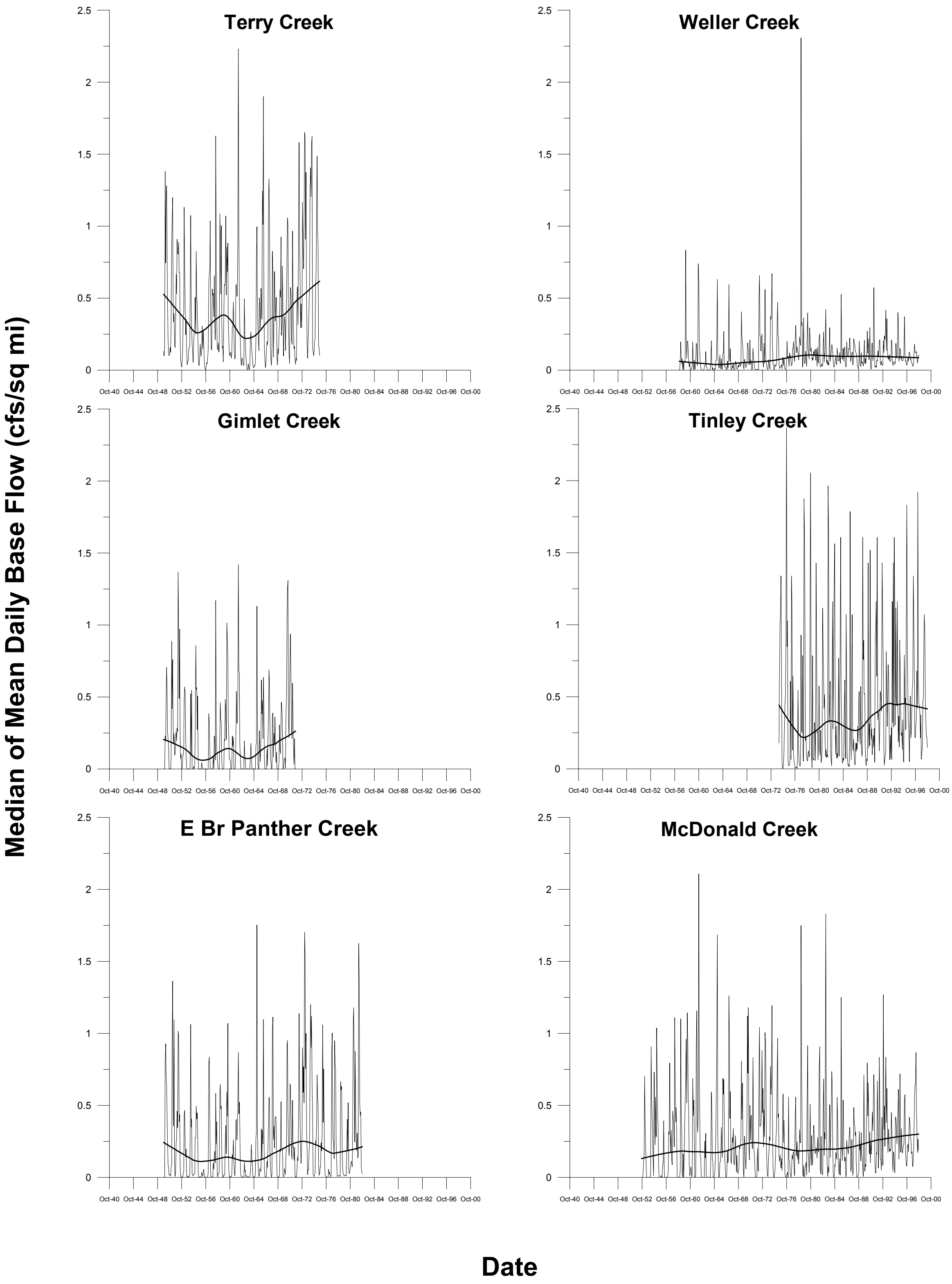

Figure 6. Median of mean daily base flow (cfs/sq mi), calculated for monthly accounting periods, in the six selected watersheds. Heavy line is LOWESS fit to the monthly data.

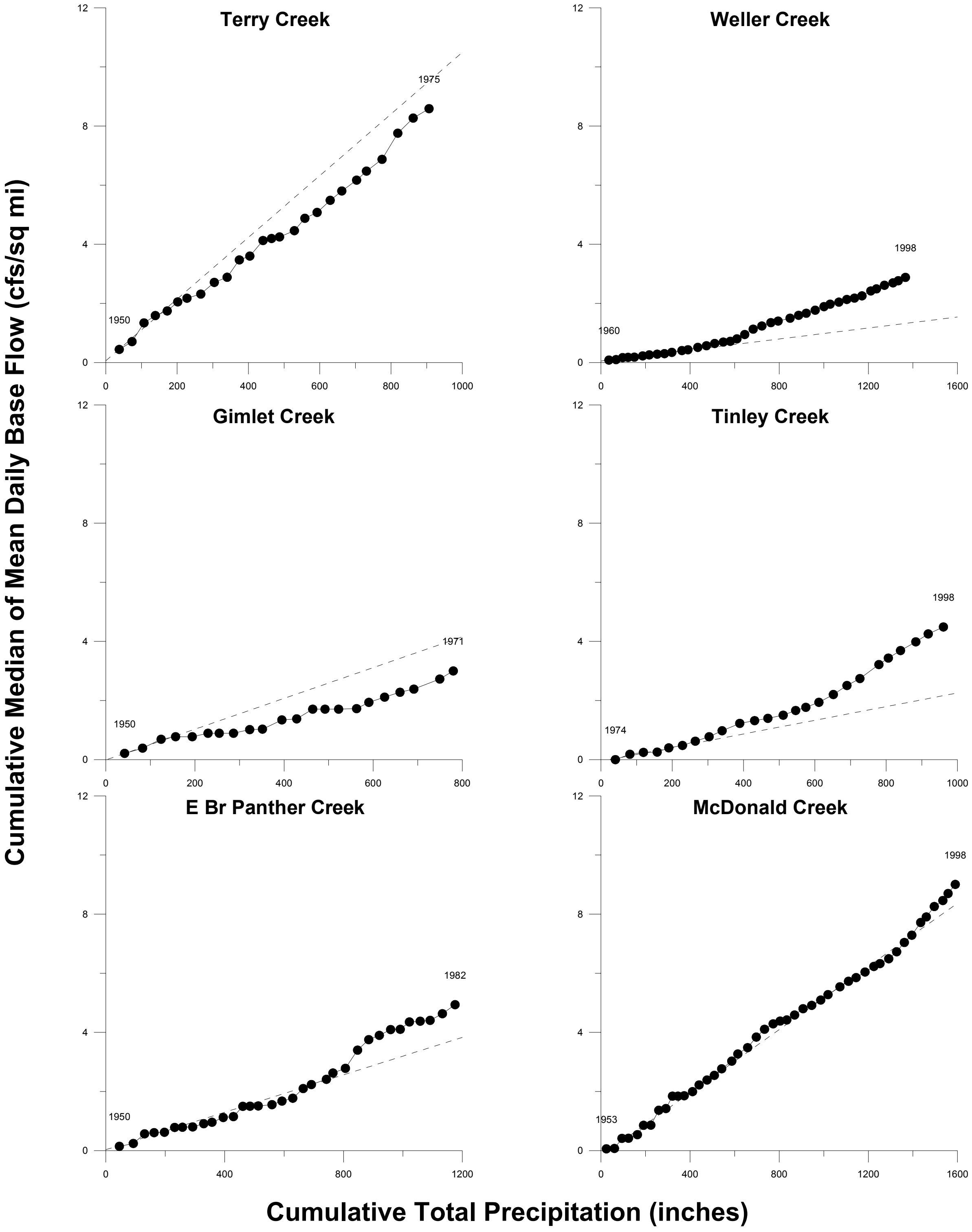

Figure 7. Cumulation of total precipitation (inches) versus median of mean daily base flow (cfs/sq mi) for rural watersheds (left) and urban watersheds (right).Dashed line is regression through earliest 20 per cent of data points.

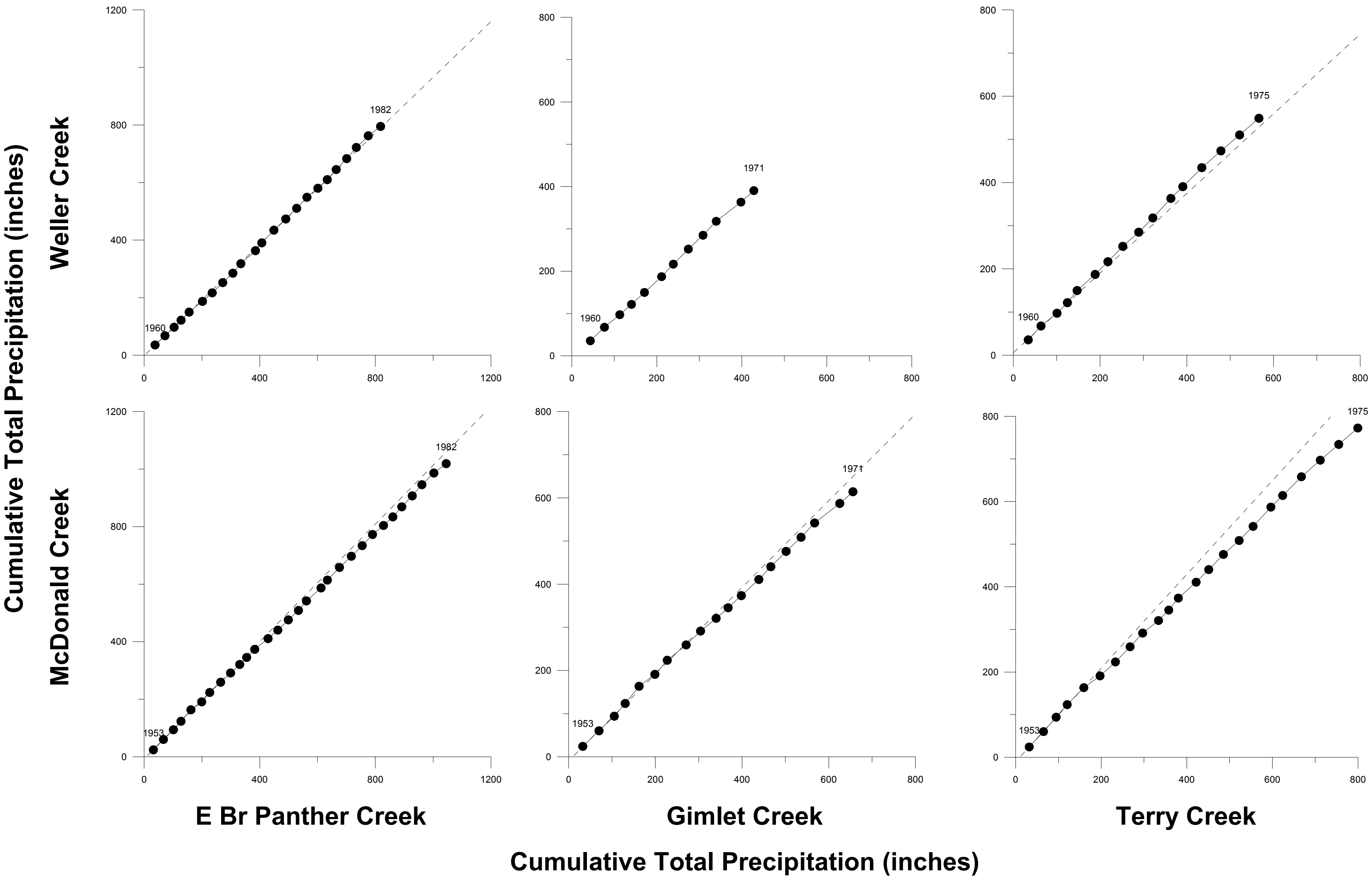

Figure 8. Cumulation of total precipitation (inches) at rural versus urban watersheds for annual accounting periods. Dashed line is regression through earliest 20 per cent of data points.

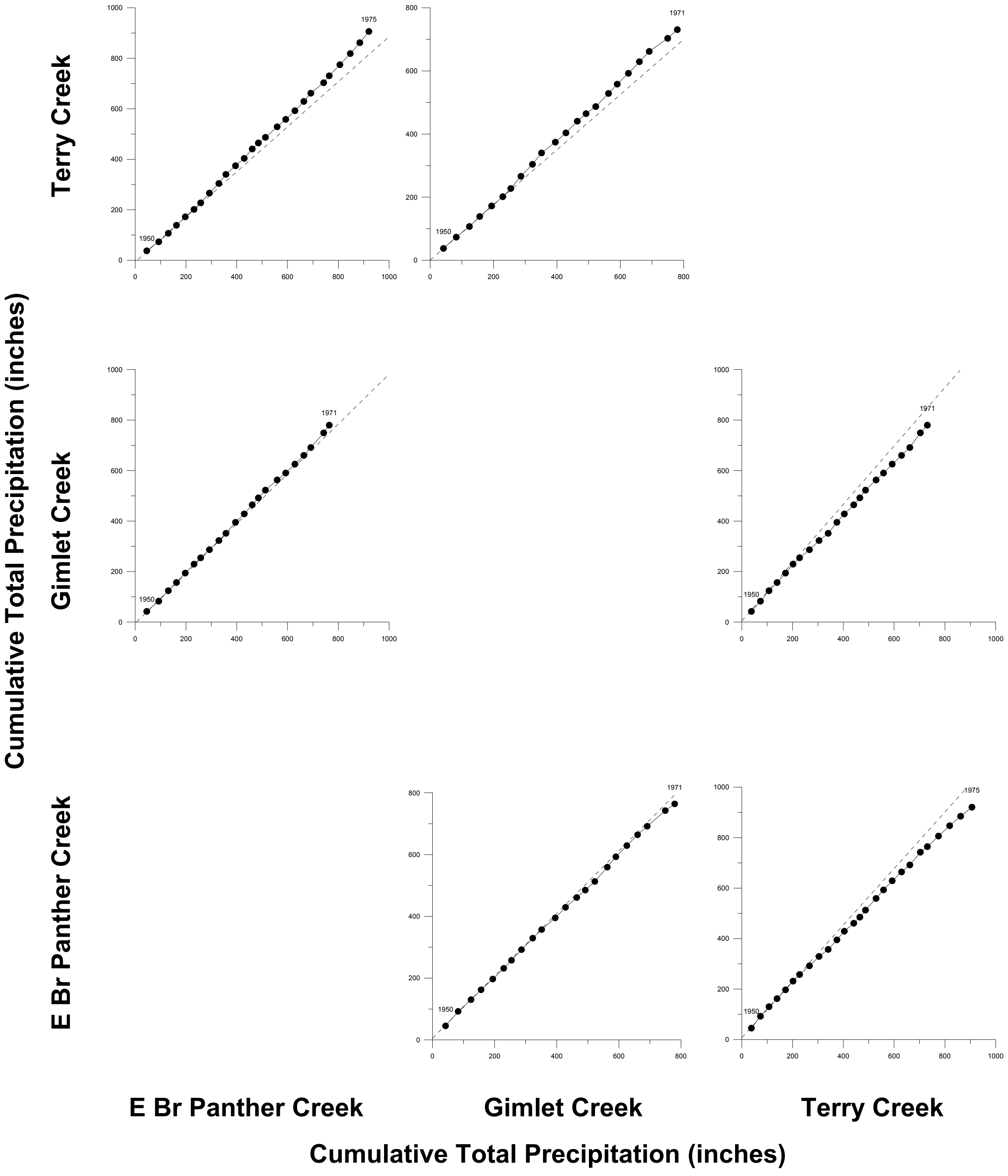

Figure 9. Cumulation of total precipitation (inches) at rural versus rural watersheds for annual accounting periods. Dashed line is regression through earliest 20 per cent of data points.

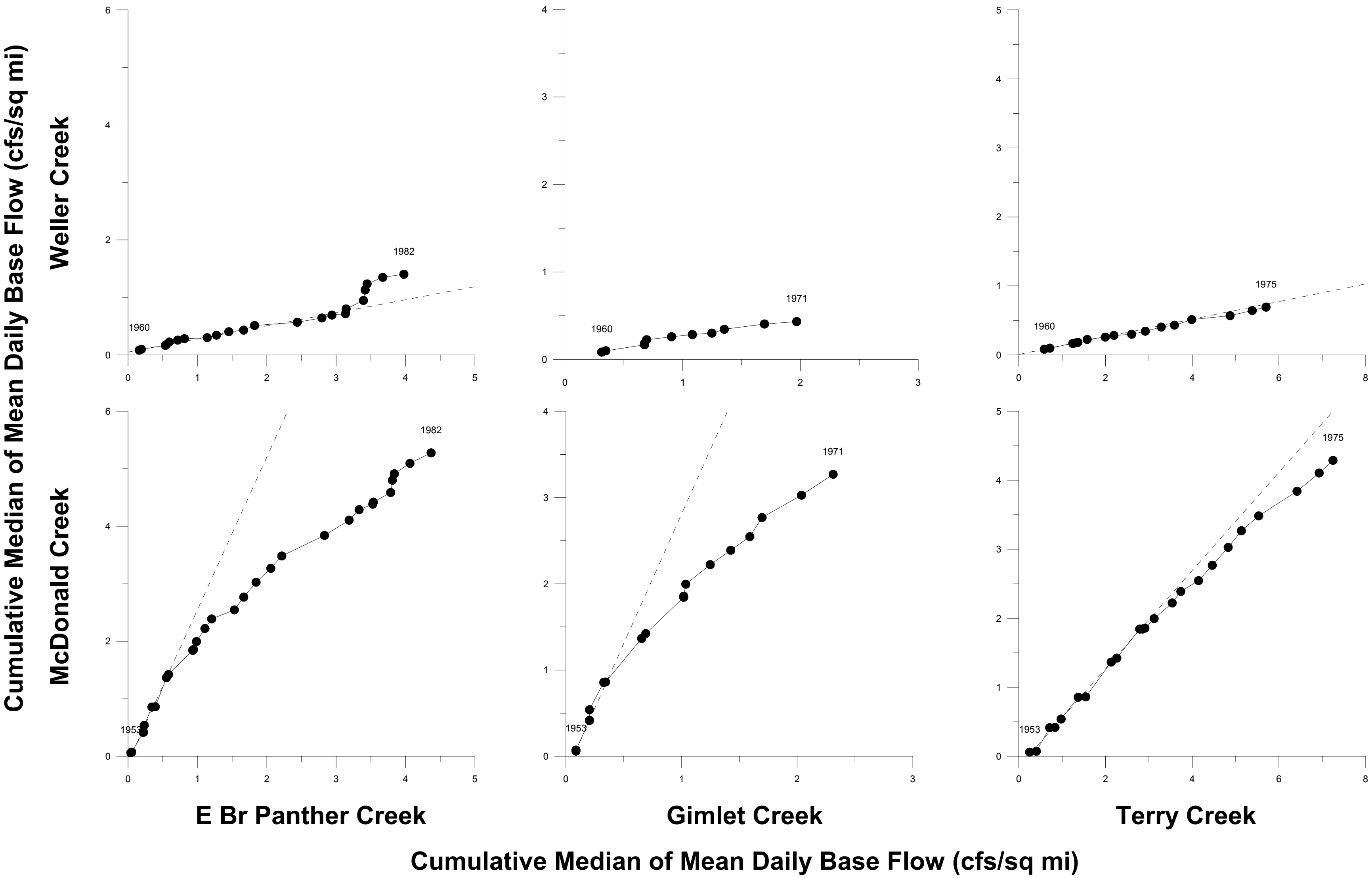

Figure 10. Cumulation of median of mean daily base flow at rural versus urban watersheds for annual accounting periods. Dashed line is regression through earliest 20 per cent of data points.

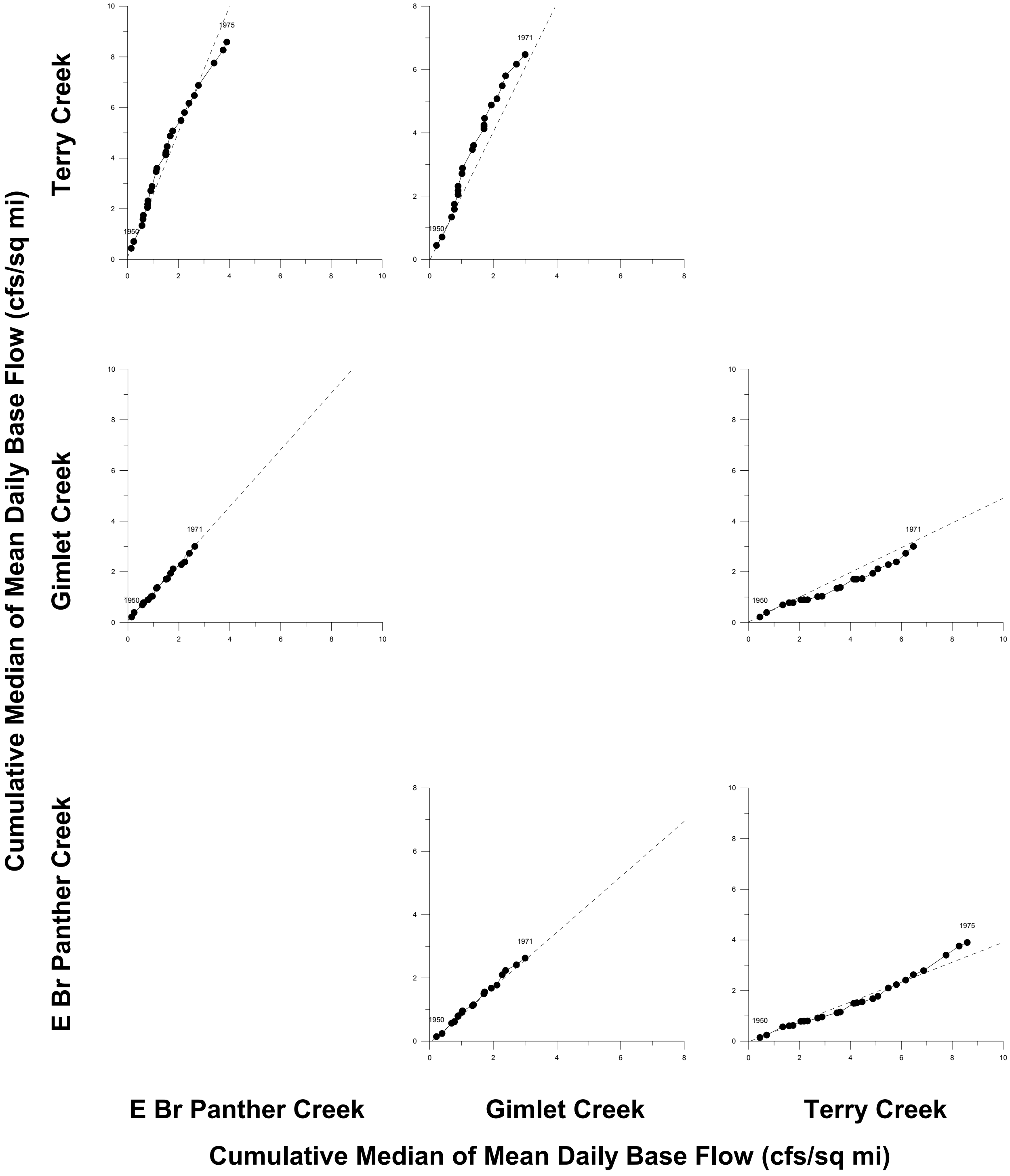

Figure 11. Cumulation of median of mean daily base flow (cfs/sq mi) at rural versus rural watersheds for annual accounting periods. Dashed line is regression through earliest 20 per cent of data points.

Table 1. Gaged Urban Watersheds Selected for Study

Gaged Watershed and USGS Station Number	Area (mi^2) (Wicker et al, 1998)	Period of Record	Per Cent Urban Land Cover (Luman et al, 1996)
McDonald Creek near Mt. Prospect (05529500)	7.93	Sep 1952-Sep 1998	83
Tinley Creek near Palos Park (05536500)	11.2	Jan 1974-Sep 1998	57
Weller Creek at Des Plaines (05530000)	13.2	Dec 1958-Sep 1998	87

Table 2. Gaged Rural Watersheds Selected for Study

Gaged Watershed and USGS Station Number	Area (mi^2) (Wicker et al, 1998)	Period of Record	Per Cent Urban Land Cover (Luman et al, 1996)
East Branch Panther Creek near El Paso (05566500)	30.5	Oct 1949-Oct 1982	2
Gimlet Creek near Sparland (05559000)	5.66	Oct 1949-Sep 1971	2
Terry Creek near Custer Park (05526500)	12.1	Oct 1949-Sep 1975	0

Table 3. Land Cover in McDonald Creek Watershed, Cook County, Illinois

Year	% of Watershed within Land Cover Class					
	Urban or Built-Up Land			Agricultural Land	Forest Land	Water
	Residential	Commercial and Services	Other Urban			
1952	11	0	1	87	0	1
1967	49	1	11	39	0	0
1974	68	5	18	9	0	0
1988	70	10	19	0	0	1
1998	76	10	13	0	0	2

Table 4. Land Cover in Tinley Creek Watershed, Cook County, Illinois

Year	% of Watershed within Land Cover Class					
	Urban or Built-Up Land			Agricultural Land	Forest Land	Water
	Residential	Commercial and Services	Other Urban			
1951	0	1	4	77	18	<1
1962	5	<1	4	72	18	1
1967	9	1	6	63	20	1
1974	19	3	8	49	21	1
1988	41	9	12	14	23	1
1998	47	8	12	1	32	1

Table 5. Land Cover in Weller Creek Watershed, Cook County, Illinois

Year	% of Watershed within Land Cover Class					
	Urban or Built-Up Land			Agricultural Land	Forest Land	Water
	Residential	Commercial and Services	Other Urban			
1952	24	2	1	72	0	0
1967	72	6	10	12	0	0
1974	72	12	16	0	0	0
1988	78	10	12	0	0	0
1998	75	11	13	0	0	0

Table 6. Median of Mean Daily Base Flow

Gaged Watershed and USGS Station Number	Period of Record (Water Years)	Median of Mean Daily Base Flow (cfs/sq mi)
East Branch Panther Creek near El Paso (05566500)	1950-1982	0.11
Gimlet Creek near Sparland (05559000)	1950-1971	0.09
Terry Creek near Custer Park (05526500)	1950-1975	0.29
McDonald Creek near Mt. Prospect (05529500)	1953-1998	0.19
Tinley Creek near Palos Park (05536500)	1975-1998	0.18
Weller Creek at Des Plaines (05530000)	1960-1998	0.07

Table 7. Spearman Rank-Order Correlation Coefficients Between Monthly Total Precipitation and Monthly Median of Mean Daily Base Flow

Watershed		Period of Record of Individual Gage as Noted
RURAL	East Br Panther Creek	0.384 (Oct 1949-Oct 1982)
	Gimlet Creek	0.302 (Oct 1949-Sep 1971)
	Terry Creek	0.320 (Oct 1949-Sep 1975)
URBAN	McDonald Creek	0.332 (Sep 1952-Sep 1998)
	Tinley Creek	0.291 (Jan 1974-Sep 1998)
	Weller Creek	0.286 (Dec 1958-Sep 1998)

Table 8. Spearman Rank-Order Correlation Coefficients Between Monthly Total Precipitation and Monthly Median of Mean Daily Base Flow for Common Periods of Record

Watershed		Period of Record				
		Sep 1952-Sep 1971	Dec 1958-Sep 1971	Dec 1958-Sep 1975	Dec 1958-Oct 1982	Jan 1974-Oct 1982
RURAL	East Br Panther Creek	0.314	0.248	0.298	0.369	0.492
	Gimlet Creek	0.277	0.214			
	Terry Creek	0.274	0.210	0.300		
URBAN	McDonald Creek	0.327	0.306	0.368	0.383	0.453
	Tinley Creek					0.429
	Weller Creek		0.395	0.418	0.358	0.271