2016

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Recommended Citation

Choi, Woonsup; Nauth, Kathryn; Choi, Jinmu; and Becker, Stefan, "Urbanization and rainfall-runoff relationships in the Milwaukee River Basin" (2016). *Geography Faculty Articles*. 10.
https://dc.uwm.edu/geog_facart/10

Urbanization and rainfall-runoff relationships in the Milwaukee River Basin

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This is an Accepted Manuscript of an article published by Taylor & Francis Group in The Professional Geographer in volume 68 in 2016, available online: https://www.tandfonline.com/doi/abs/10.1080/00330124.2015.1007427

Abstract

To understand the changing rainfall-runoff relationship, the study examined climate and streamflow data in the Milwaukee River Basin in southeastern Wisconsin, of which four catchments with different degrees of urbanization were selected for analysis. This study analyzed temperature, precipitation, and streamflow data with a range of statistical methods, including the Mann-Kendall test, double-mass technique, and quantile regression. Runoff ratios and extreme flow indices were higher in more urbanized catchments. Catchments with long-term data (>40 years) showed significantly increasing runoff ratios and slopes in double mass curves. Overall, there are signs of changes in the rainfall-runoff relationship, but how much they can be attributed to land use changes is uncertain.

Key words: *runoff*, *precipitation*, *streamflow*, *urbanization*, *Milwaukee*

The city of Milwaukee and its suburban communities in southeastern Wisconsin suffered significantly from flash flooding events in July 2010. Particularly, the rainfall of 190 mm over a two-hour period on 22 July 2010 turned many streets and roads impassable and caused sewer backups. In response, the President of the United States issued an Individual Assistance Declaration in response to the damage (FEMA 2010). The severity of the flooding events raised some important questions, such as to what extent they were exacerbated by urbanization, and whether such events will occur more frequently in the future. Not far from Milwaukee, urbanizing catchments in northeastern Illinois experienced increases in design peak flows along with increasing precipitation, but on average urbanization contributed more than the increase in precipitation to the increases in peak flows (Hejazi and Markus 2009). Even though the hydrometeorology of particular flood events in the metropolitan Milwaukee region was investigated (e.g. Elsner, Drag, and Last 1989; Zhang and Smith 2003), little research investigated long-term relationships between climate and streamflow in the region, taking land use changes into account. It is important to detect past trends of hydroclimatic variables for understanding potential future change and its impacts (Claessens et al. 2006; Sahoo and Smith 2009). The present study investigates the long-term relationship between rainfall and streamflow in the Milwaukee River Basin to help better understand the influence of urbanization.

Streamflow (runoff) trends, in response to climate and/or human activity, have been extensively investigated worldwide at various scales, and the literature is well summarized by Sahoo and Smith (2009). With respect to urbanization, which Dow and DeWalle (2000) defined in hydrologic terms as the increase in impervious areas and the loss of vegetation, the literature generally concludes that higher degrees of urbanization lead to higher mean and extreme flows and shorter time to peaks in hydrographs (e.g. Watts and Hawke 2003; Chang 2007; Choi and Deal 2008; Sheng and Wilson 2009; Bhaskar and Welty 2012; Huang et al. 2012; Zhou et al. 2013). However, the effect of urbanization on the rainfall-runoff relationship is not always obvious. A modeling study revealed a logistic relationship between percent impervious cover and runoff ratio (fraction of runoff to precipitation) for the Gwynns Falls Basin in Maryland (Brun and Band 2000). A data-driven study found inconsistent trends in hydrological variables between urban and rural catchments of Maine and attributed it to the low level of urbanization (Martin, Kelleher, and Wagener 2012).

There are a few widely adopted approaches in the literature about streamflow and urbanization. One is to examine and compare long-term trends of streamflow between catchments with different degrees of urbanization (e.g. Sahoo and Smith 2009; Martin, Kelleher, and Wagener 2012; Velpuri and Senay 2013). The non-parametric Mann-Kendall test for trend (Mann 1945; Kendall 1975) is frequently employed in this approach. This approach provides insight into the stationarity and periodicity of the hydrological and climatological variables, and allows one to determine whether these variables significantly changed over time. Attributing the changes to particular causes, e.g. climatic and land cover changes, is often done by examining inconsistencies between the variables or catchments examined. Another approach is to run a hydrological model and examine the runoff characteristics and their changes (e.g. Choi and Deal 2008; Tu 2009; Huang et al. 2012; Zhou et al. 2013). This approach enables one to control for other variables affecting the rainfall-runoff relationship, but it is subject to modeling uncertainty. The other approach is to compare runoff characteristics, such as runoff ratio, recession constant, and time to peak, from observed data between catchments (e.g. Rose and Peters 2001; Watts and Hawke 2003; Chang 2007; Meierdiercks et al. 2010). Such studies generally found significant differences between more and less urbanized catchments. The selection of study catchments is very important when using this approach. The current study adopts both the first and third approaches, considering the availability of streamflow data and different degrees of urbanization across the Milwaukee River Basin.

An interest in long-term trends motivated the present study. Scientists have conducted little research of this sort for streamflow in Wisconsin, even though rivers and streams are among the state's most important natural resources (WDNR 2011). Existing research finds that annual low flows increased significantly, whereas annual flood peaks decreased in southwestern Wisconsin (Gebert and Krug 1996). Average annual streamflow and average annual baseflow were found to show generally increasing trends across the state of Wisconsin, and the Milwaukee River showed increasing trends in both variables significant at the 5 percent level during 1915-1999 (Gebert et al. 2007). However, those studies did not explicitly consider anthropogenic changes in land cover to explain the streamflow trends. In addition, the Milwaukee River Basin is suitable for examining streamflow characteristics between more and less urbanized catchments with at least a couple of decade’s streamflow data. Therefore, the present study (1) analyzed long-term temperature, precipitation, and streamflow data for selected catchments; (2) examined rainfall-runoff relationships in relation to urban growth; and (3) compared streamflow characteristics between catchments with different degrees of urbanization. This study not only provides a detailed picture of the hydrology of the Milwaukee River Basin, but also demonstrates the utility of a range of statistical methods for hydroclimatological analyses.

STUDY AREA

The study area is the Milwaukee River Basin located in southeastern Wisconsin, United States (Figure 1). The areal extent is about 2330 km^2, and it is home to about one million people. The basin includes three primary rivers, Milwaukee, Menomonee, and Kinnickinnic, which meet as they empty into Lake Michigan in the heart of downtown Milwaukee. The estuary formed by this confluence of rivers is highly urbanized, and the United States Environmental Protection Agency has listed it as an Area of Concern (US EPA 2013). The topography of the area is comprised of rolling moraine over bedrock, and slopes downward from the northwest to the southeast with a range of about 250 meters (WDNR 2001).

The southern portions of the basin are highly urbanized, whereas northern portions are much less so, with land cover consisting primarily of agricultural land. The Milwaukee and

Menomonee catchments drain both urban and rural communities, whereas the Kinnickinnic catchment is almost entirely urbanized. Concrete lines the majority of the Kinnickinnic River as a flood-control measure implemented in the 1960s.

DATA

The United States Geological Survey web site (USGS 2014) provided daily mean streamflow data (measured in cubic feet per second) for the four sites listed in Table 1. Site 04087000 MILWAUKEE RIVER AT MILWAUKEE, WI, is located just upstream of the highly urbanized area in Milwaukee, and this station is short-named ‘Milwaukee’. Site 04086600 MILWAUKEE RIVER NEAR CEDARBURG, WI is located upstream of the Milwaukee station, and its drainage area is mostly rural. This site is short-named ‘Cedarburg’. Site 04087159 KINNICKINNIC RIVER @ S. 11TH STREET @ MILWAUKEE, WI (hereafter referred to as ‘Kinnickinnic’) has a small drainage area, and is located in a densely developed area. Site 04087120 MENOMONEE RIVER AT WAUWATOSA, WI (hereafter referred to as ‘Menomonee’) is located in a largely urban drainage area. The unit of the streamflow data was converted to cubic meters per second. When the flow data were aggregated to monthly and annual scales, the unit was converted to millimeters by multiplying by the number of seconds and dividing by the catchment area. It allows for direct comparisons to precipitation and between catchments and is referred to here as runoff, since runoff is defined as the part of precipitation that appears as streamflow (WMO/UNESCO Panel on Terminology 1992).

Serbin and Kucharik (2009) developed gridded data sets of daily maximum and minimum temperatures and precipitation data for Wisconsin. They developed the data sets by interpolating weather station data across the state of Wisconsin for the period 1950-2006. The grid spacing is about 8 km. We downloaded the data from a server located at the University of Wisconsin-Madison and clipped it for our study area (Figure 1). The data points with different symbols correspond to each of the USGS sites. We used averaged data from the grid points with the same symbol to compare to runoff data from the corresponding USGS site. Note that the grid points for Cedarburg were also used for Milwaukee.

Local land use data were obtained from the American Geographical Society Library at the University of Wisconsin-Milwaukee. It was produced by the Southeastern Wisconsin Regional Planning Commission in 2004 as an ArcGIS shapefile, and shows historic urban growth inventory since the late 19th century in southeastern Wisconsin counties every few years up to year 2000 (Figure 2). The dataset does not include two counties that overlap the northern edge of the basin. However, because there has been little urban growth in the area, it is still usable for the study.

METHODS

Land use change anaysis

The Wisconsin Department of Natural Resources divides the Milwaukee River Basin into six catchments (WDNR 2001). Because streamflow data are applicable to the upstream areas of the gauging sites, we further divided the catchments between upstream and downstream parts of the gauging sites. We followed the general procedure to delineate catchment boundaries using a digital elevation model obtained from the National Elevation Dataset. Figure 1 shows the resulting boundaries. Land use data overlaid the catchment boundaries and then clipped accordingly. Their statistics were aggregated for all catchments upstream of each USGS site. This study did not analyze catchments downstream of Milwaukee, Menomonee, and Kinnickinnic sites.

Quantile regression

The interannual variability of annual runoff was analyzed using quantile regression models (Koenker 2005), with year as an explanatory variable and annual runoff as the dependent variable. With quantile regression, it is possible to examine changes in specific parts (quantiles) of the distribution of the data (Linares, Delagado-Huertas, and Carreira 2011). The τ^{th} quantile ($0 < \tau < 1$) represents the value of the data below which the proportion of population is τ. For example, the central location of a distribution is represented by the 0.5^{th}

quantile (median), and the boundary between the top 5 percent and the rest is represented by the 0.95th quantile (Koenker 2005). In this study, we used the `quantreg` package (Koenker 2012) add-on to the R language combined with MATLAB® coding. It is available upon request from the lead author.

Extreme streamflow analysis

To compare the catchments with respect to extreme streamflow, we calculated annual maximum, 99th and 95th percentile flows. We calculated annual maximum flows by choosing the maximum value of each year's daily mean streamflow. To make them comparable between the catchments, we divided annual maximum flows by the catchment area. We calculated annual 99th and 95th percentile flows in a similar way, by choosing the 99th and 95th percentile values of each year's daily flow, respectively. To examine the statistic with respect to the median and to allow for inter-catchment comparison, we divided annual 99th and 95th percentile flows by annual median flows.

Mann-Kendal test for trend

This study analyzed the temporal trends of precipitation, runoff, and runoff ratio data using the Mann-Kendall test for trend. For the Mann-Kendall test, we followed the procedure laid out by Manly (2009, 192), as follows:

For a data series x_n, the test statistic S is the sum of the signs of the differences between any pair of observations,

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \operatorname{sign}(x_i - x_j) \tag{1}$$

where sign(a) is –1 when a is negative, 0 for zero, and 1 for positive. When the order of the series is random, the expected value of S is zero and the variance is:

$$\operatorname{Var}(S) = n(n-1)(2n+5)/18 \tag{2}$$

Z statistic tests whether S is significantly different from zero, shown as follows:

$$\text{if } S > 0, \quad Z = \frac{S-1}{\sqrt{VS}}$$

$$\text{else } \; Z = \frac{S+1}{\sqrt{VS}} \tag{3}$$

Z follows the standard normal distribution, and its significance can be compared with critical values in the distribution. A positive Z value indicates a positive trend and a negative one indicates negative in a two-sided test. For monthly data, the statistics S and Var(S) were calculated for each month of the year and summed for an overall test to account for seasonality (Manly 2009, 192).

Double-mass curve

Double-mass curves for each catchment provided the tool to create and evaluate the relationship between precipitation and runoff over time. The double-mass curve method builds from the idea that there is a proportional relationship between two variables, in this instance precipitation and runoff (Cluis 1983; Zhao et al. 2004; Kliment and Matouskova 2008; Zhang and Lu 2009; Du et al. 2011). This proportional relationship can be plotted as the cumulative value of one variable against the cumulative value of the other, in which the slope of the line that they form represents the relationship between the two (Searcy and Hardison 1960). Any change in slope represents a change in the relationship between precipitation and runoff. This method is useful for investigating the influence of anthropogenic changes upon the relationship between precipitation and runoff.

We made double-mass curves for each of the four catchments by plotting the cumulative annual runoff values (measured in mm) to the cumulative annual precipitation values (measured in mm) of the area. Breaks in the slope of each curve were identified and tested for statistical significance using an analysis of variance test (ANOVA) as outlined in Searcy and Hardison (1960).

RESULTS AND DISCUSSION

Urban growth in the Milwaukee River Basin

Figure 3 shows the fraction of developed area in each catchment. The fraction of developed areas increased in all the catchments, particularly in Cedarburg which saw it more than quadruple. However, it still remains very undeveloped, less than 12 percent in year 2000. Kinnickinnic is the most urbanized catchment throughout the time measured but stays almost flat since the 1980s. On the other hand, Milwaukee and Menomonee saw steady growth. Because Cedarburg is nested in Milwaukee, the increase in Milwaukee is partly due to the increase in Cedarburg.

Summary of temperature, precipitation, and runoff

Table 2 summarizes daily maximum temperature (TMAX), minimum temperature (TMIN), precipitation (PRCP) for the period 1950-2006, and runoff for the time periods for which each catchment's data were obtained. Temperatures are almost identical between the catchments. Precipitation statistics are very similar between Milwaukee, Cedarburg, and Menomonee, whereas Kinnickinnic shows somewhat larger mean and standard deviation of annual precipitation. Kinnickinnic and Menomonee, more urbanized catchments than the others, show the largest mean annual runoff during the available data periods. Interestingly, more-urbanized Milwaukee has lower annual mean and monthly maxima of runoff and smaller variability than Cedarburg.

Figure 4 portrays interannual variability in annual total runoff. Milwaukee's annual runoff (Figure 4A) was relatively low in the 1930s through 1960s and high since then, both for the middle ($\tau = 0.5$) and high ($\tau = 0.9$) ends of the data. Runoff ($\tau = 0.5$) in the 2000s is significantly higher than that in the 1940s, indicated by the non-overlapping confidence intervals. The 0.9th quantile annual runoff also tends to increase since the 1940s, but the confidence intervals overlap. The annual runoff for Cedarburg (Figure 4B) shows a U-shaped trend both for the middle and high ends of the data, with a trough in the late 1990s. Annual runoff for Menomonee increased overall (Figure 4C). It appears to have reached a plateau in the 1990s, both for the middle and high ends of the data. The increasing-then-leveling trend is largely because the measurement began in the 1960s when runoff was low. Runoff in 2008 was particularly high, when a large swath of the state was flooded in June. This is similar in other catchments. The increase in the middle end of the data is significant, but that in the high end is not. Kinnickinnic (Figure 4D) shows no particular trend in annual runoff during the data period, but an increasing variability since the late 1990s. At the same time, it monotonically increased from 1996 to 1999, and then decreased through 2003. Both minimum and maximum runoff values occurred in the 21st century.

Extreme streamflow

The annual maximum of daily mean flow was compared between the catchments for 1983-2008. For comparison, streamflow values were divided by the catchment area. Not surprisingly, it is highest in Kinnickinnic, followed by Menomonee (Figure 5). Those of Milwaukee and Cedarburg are mostly the same. When it comes to temporal trend, none of the catchments show any significant trends during that time. It could be because the time period was too short for urbanization effects to appear, or precipitation patterns held back the annual maximum flow. During 1950-2006, most of the extreme precipitation indices examined by Choi et al. (2013) show no statistically significant increases in much of the study area.

The ratio of annual 99th percentile flow to annual median flow (Figure 6) shows similar inter-catchment differences to the annual maximum of daily mean flow, i.e. lower in Milwaukee and Cedarburg and higher in Menomonee and Kinnickinnic. Assuming that the precipitation characteristics are practically identical between the catchments, the higher ratios suggest larger effects of urban land cover. Interestingly, the ratio of annual 99th percentile to median appears to be increasing in the two highly urbanized basins, whereas the annual maximum of daily mean flow did not reveal significant trends. Increasing ratios suggest that daily streamflow became more extreme, likely either due to extreme rainfall events or high degrees of urbanization, which was not identified from the annual maximum of daily mean flow. The annual maximum of daily mean flow reflects the flow condition of a particular day, whereas the ratio of annual 99th percentile to median reflects an extreme flow condition with respect to a normal condition. Therefore, the ratio better reflects the changes in streamflow characteristics than the annual maximum. The ratio of annual 95th percentile flow to annual median flow shows similar trends to those shown in Figure 6, therefore this this article omits them.

Relationship between precipitation and runoff

Precipitation and runoff generally changed in the same directions but with different strengths (Table 3). Overall, monthly data show stronger trends than annual data. In Milwaukee, monthly precipitation did not increase significantly but runoff did, and monthly runoff ratio increased significantly during 1950-2006. Because runoff increased significantly whereas precipitation did not, it can be speculated that runoff changes are largely due to human causes, such as increased imperviousness of the catchment (Velpuri and Senay 2013). It should be noted that base flow increased in Milwaukee during 1970-1999 (Gebert et al. 2007), also contributing to the runoff increase. Menomonee also shows a significant increase in runoff ratio, as well as in precipitation and runoff during 1962-2006. It indicates that runoff increased more than what is expected from the precipitation increase, thus both anthropogenic and climatic factors played a role. On the other hand, Cedarburg and Kinnickinnic showed decreases in both precipitation and runoff since the early 1980s, although only Cedarburg monthly runoff decreased significantly. Cedarburg shows a significant decrease in runoff ratio, suggesting an anthropogenic factor reducing runoff. Kinnickinnic had been heavily developed by the 1980s, therefore it is speculated that additional development did not result in any significant runoff changes.

Figure 7 shows the double-mass curve for each basin considered in the study. Three of the catchments exhibit a break in slope that is statistically significant. One catchment, Kinnickinnic, does not possess breaks in slope that are statistically significant, although it does appear to have a slight change in slope during the time from 1994 to 1996. Cluis (1983) warns against considering any period of time less than five years as a distinct period of change in the runoff regime due to the variability inherent in hydrological systems. Although the breaks in slope for the Kinnickinnic are not significant, they were included in the double-mass curve figure for consideration by the reader. It also should be noted that the slope changed in Cedarburg only after five years, which is quite short compared to other catchments.

The three remaining catchments illustrate some interesting trends. Both Menomonee and Milwaukee exhibit a statistically significant break in slope in the early 1970s, with *p*-values not exceeding 0.001. In both cases, the slope increased following the break. Before the break point, precipitation was generally below the mean, and it was generally above the mean afterwards. Coinciding with urban growth, runoff ratio generally increased in the two catchments (Table 3), and the double curve slope is steeper than before. Therefore, the break point in the early 1970s is thought to be mainly a result of precipitation trend rather than faster urban growth afterwards. Kinnickinnic, even though insignificant, also shows an increasing slope in recent years. Interestingly, the slope change in Cedarburg does not match those of the other catchments. Cedarburg shows a statistically significant break in slope ($p = 0.002$) around the year 1986. Prior to 1986, the slope of the curve was 0.357, but it decreased to 0.285 following the break, in line with the runoff ratio decrease (Table 3). The reason why it decreased could not be found, but it is speculated that the short (5 years) period before the break point could be a reason. The year 1986 is a break point of annual precipitation in Cedarburg during the time span of 1982-2006, before which annual precipitation was generally above the mean and after which below the mean. The steeper slope of the double mass curve before 1986 occurred during the short wet period and may be seen as an aberration. It should be also noted that Cedarburg is still fairly rural, and signs of urbanization impacts may not be visible yet, as in the case of Martin, Kelleher, and Wagener (2012).

CONCLUSIONS

Climatic and land cover conditions strongly influence the rainfall-runoff relationship of a catchment. At the same time, they do not remain constant either over time. In this study, using the Milwaukee River Basin as a study site, we analyzed land use changes in the basin and the trends of temperature, precipitation, and streamflow statistics for the four selected catchments with varying degrees of urbanization. Then we examined how rainfall-runoff relationships differed between the catchments using double mass curves. Our findings include the following: (1) urban land use in the Milwaukee River Basin as a whole increased substantially during the last few decades; (2) the rainfall-runoff relationships differed between the catchments mostly in line with the literature. In other words, more urbanized ones showed higher mean and extreme runoff than less urbanized ones; (3)

runoff ratio significantly increased, meaning runoff increased more than expected from precipitation increases, in two catchments that have streamflow data for more than forty years.

Overall, it was clear that more urbanized catchments had higher mean and extreme runoff values, which can be regarded as the effects of urban land cover. However, effects of land use *change* were not as clear, and only basins with long-term data showed increasing runoff trends more than expected from increasing precipitation. One of the limitations of the study is that it could not examine long-term data for an undeveloped catchment within the Milwaukee River Basin because of lack of data. A well-calibrated hydrological model could help overcome the limitation.

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Table 1. United States Geological Survey sites selected for streamflow data

Site number	Short name	Latitude (N), longitude (W)	Elevation above sea level	Drainage area	Record obtained for the period
04087000	Milwaukee	43°06'00", 87°54'32"	184.99 m	1802.63 km^2	1915-2008
04086600	Cedarburg	43°16'49", 87°56'30"	199.14 m	1572.12 km^2	1982-2008
04087159	Kinnickinnic	42°59'51", 87°55'35"	179.39 m	48.69 km^2	1983-2008
04087120	Menomonee	43°02'44", 87°59'59"	191.59 m	318.57 km^2	1962-2008

Table 2. Statistics of TMAX, TMIN, PRCP, and runoff by catchment. Climate variables are for 1950-2006 and runoff is for the available data period as shown in Table 1.

	Milwaukee	**Cedarburg**	**Menomonee**	**Kinnickinnic**
Average TMAX (°C)	13.3	13.2	13.6	13.3
Average TMIN (°C)	2.7	2.6	2.9	3.5
Annual PRCP (mm)	808	807	807	841
Standard deviation, annual PRCP	117	116	127	152
Maximum single-month PRCP (mm)	285	294	283	288
Minimum single-month PRCP (mm)	1.5	1.6	0.2	0.6
Mean annual runoff (mm)	219	257	300	461
Standard deviation	83.5	103.7	99.8	103.7
Maximum single-month runoff (mm)	149	210	186	210
Minimum single-month runoff (mm)	0.8	5.9	0.9	5.8

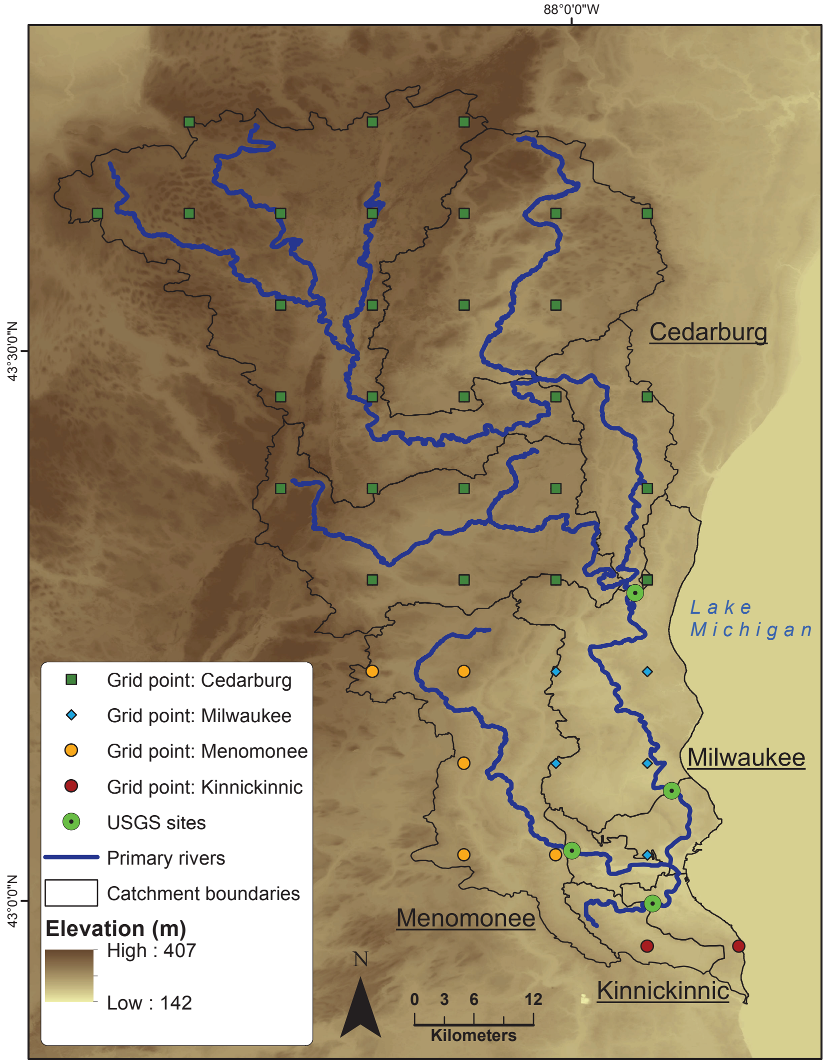
Table 3. Trends of annual (upper) and monthly (lower) PRCP, runoff, and runoff ratio from the Mann-Kendall test by catchment.

	PRCP		**Runoff**		**Runoff ratio**	
	p	Sign	p	Sign	p	Sign
Milwaukee	0.06	+	0.05	+	0.26	+
Cedarburg	0.44	−	0.09	−	**0.03**	**−**
Menomonee	**0.01**	**+**	**0.00**	**+**	0.11	+
Kinnickinnic	0.16	−	0.44	−	0.50	+

Milwaukee	0.14	+	**0.00**	**+**	**0.00**	**+**
Cedarburg	0.20	−	**0.00**	**−**	**0.00**	**−**
Menomonee	**0.02**	**+**	**0.00**	**+**	**0.00**	**+**
Kinnickinnic	0.24	−	0.20	−	0.91	+

The bold fonts indicate that the trends are statistically significant (α = 0.05)

513 **FIGURES**



514

515 Figure 1. Landforms in the study area and locations of streamflow and climate data sources.
516 Larger green circles with a dot in them are United States Geological Survey streamflow
517 gages, and other symbols (circles, squares, and diamonds) indicate the grid points of the
518 climate data for each catchment

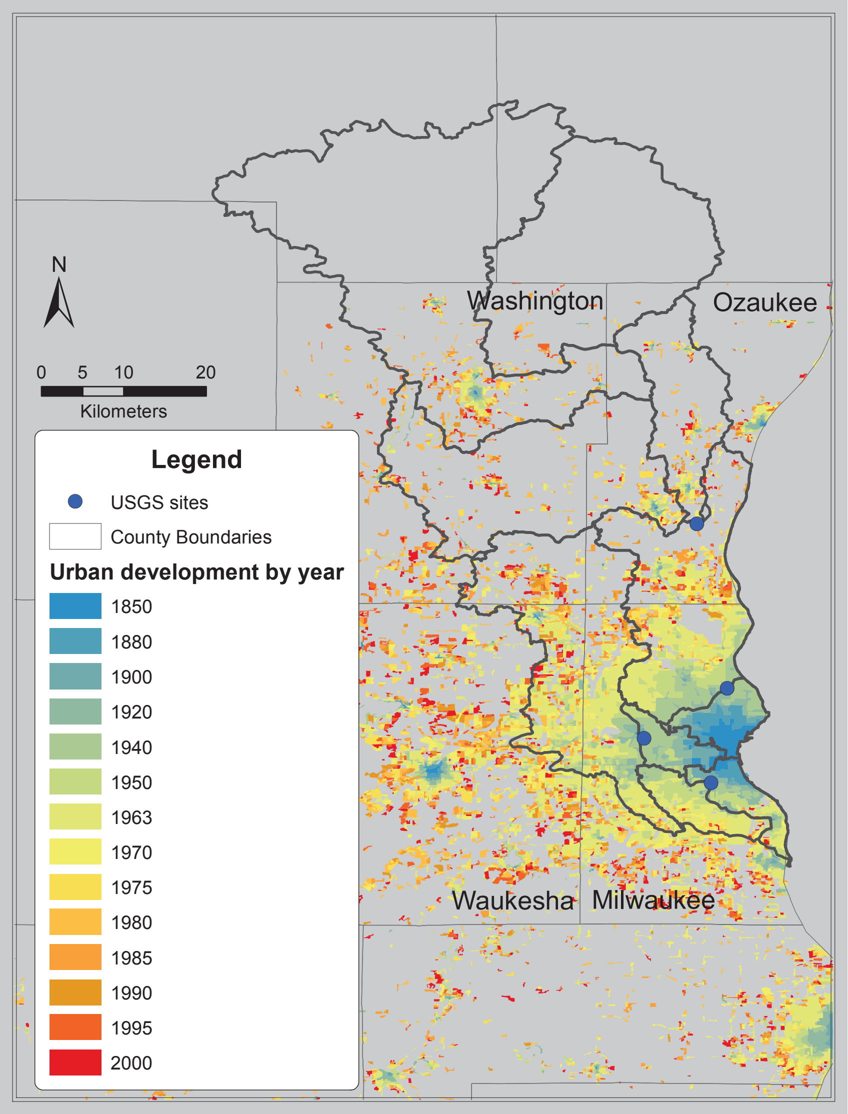


Figure 2. Expansion of developed areas (blue to red for older to newer) in southeastern Wisconsin since the late 19th century (data courtesy of Southeastern Wisconsin Regional Planning Commission)

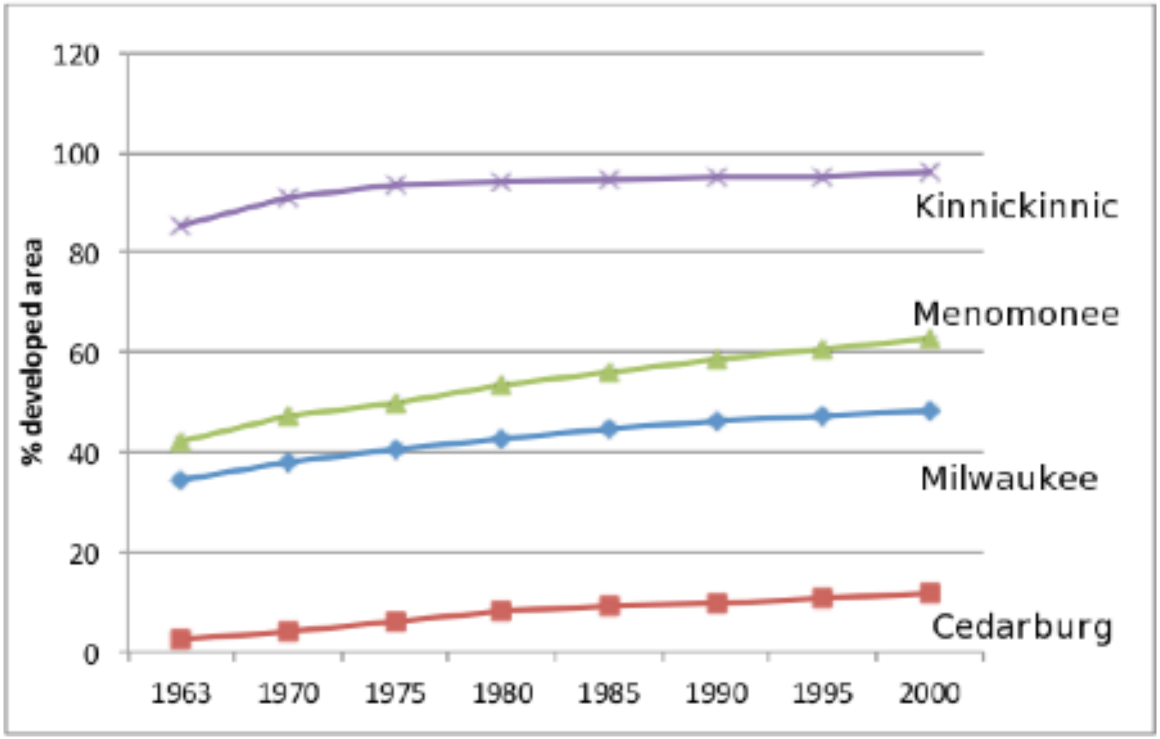
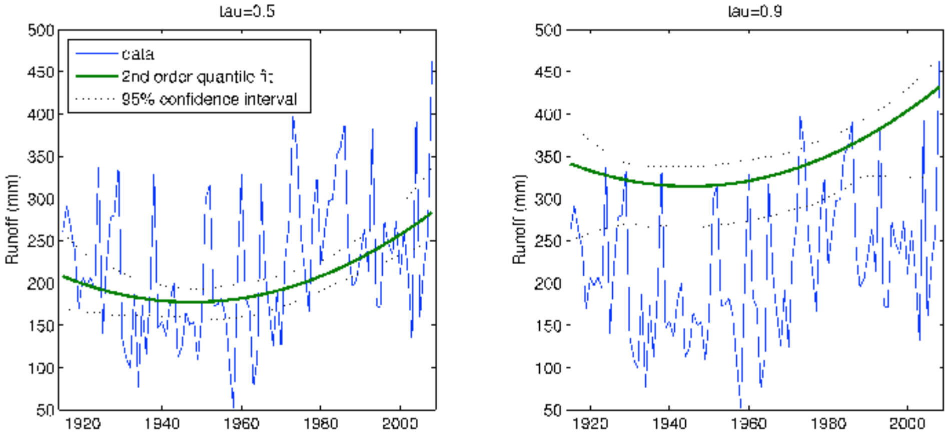
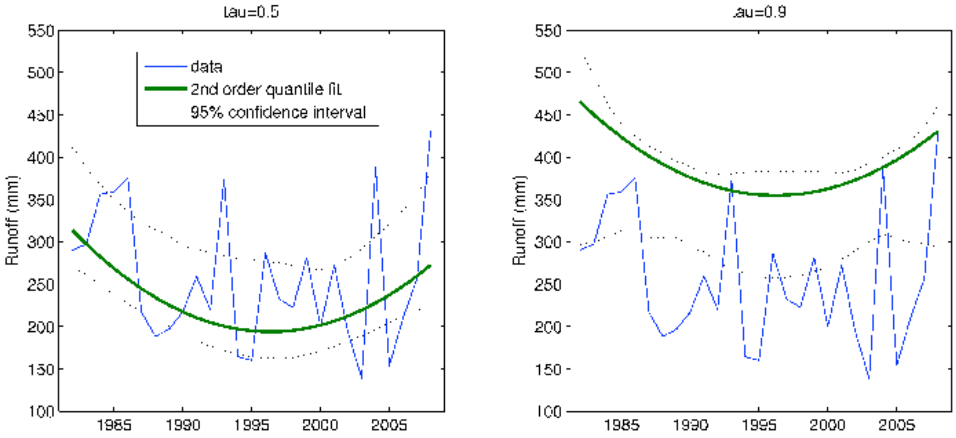


Figure 3. Fraction of developed areas for the four catchments calculated using the Southeastern Wisconsin Regional Planning Commission data

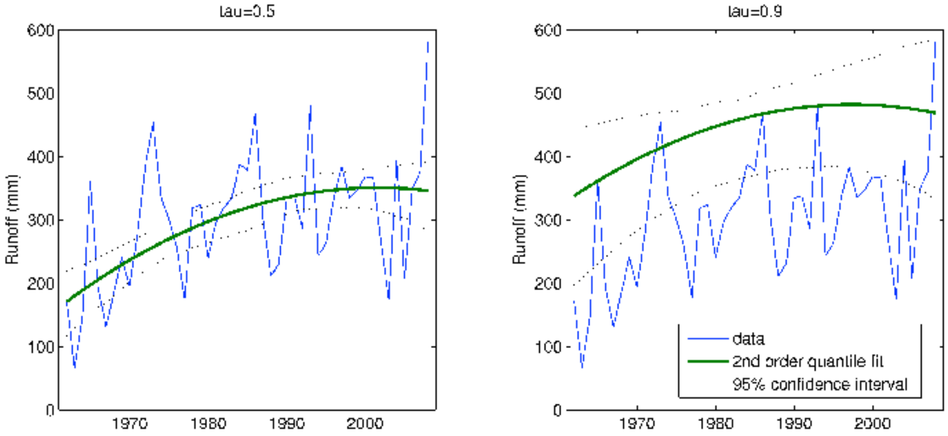
(A)


tau=0.5
tau=0.9
Runoff (mm)
data
2nd order quantile fit
95% confidence interval
500
450
400
350
300
250
200
150
100
50
1920
1940
1960
1980
2000

(B)


tau=0.5
tau=0.9
Runoff (mm)
data
2nd order quantile fit
95% confidence interval
550
500
450
400
350
300
250
200
150
100
1985
1990
1995
2000
2005

(C)


tau=0.5
tau=0.9
Runoff (mm)
data
2nd order quantile fit
95% confidence interval
600
500
400
300
200
100
0
1970
1980
1990
2000

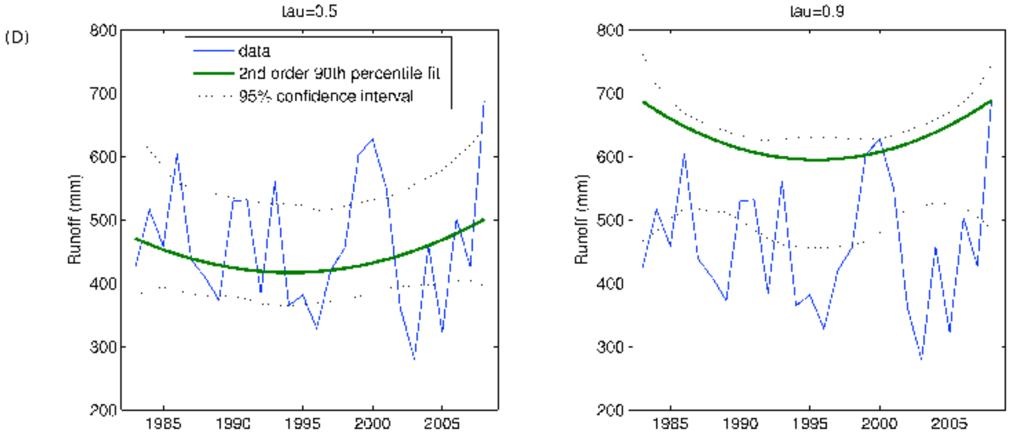


Figure 4. Annual runoff (thin blue line) with second order quantile regression lines (thick green line) for (A) Milwaukee, (B) Cedarburg, (C) Menomonee, and (D) Kinnickinnic. The left panel is for tau = 0.5 and the right for tau = 0.9 for the same annual runoff data.

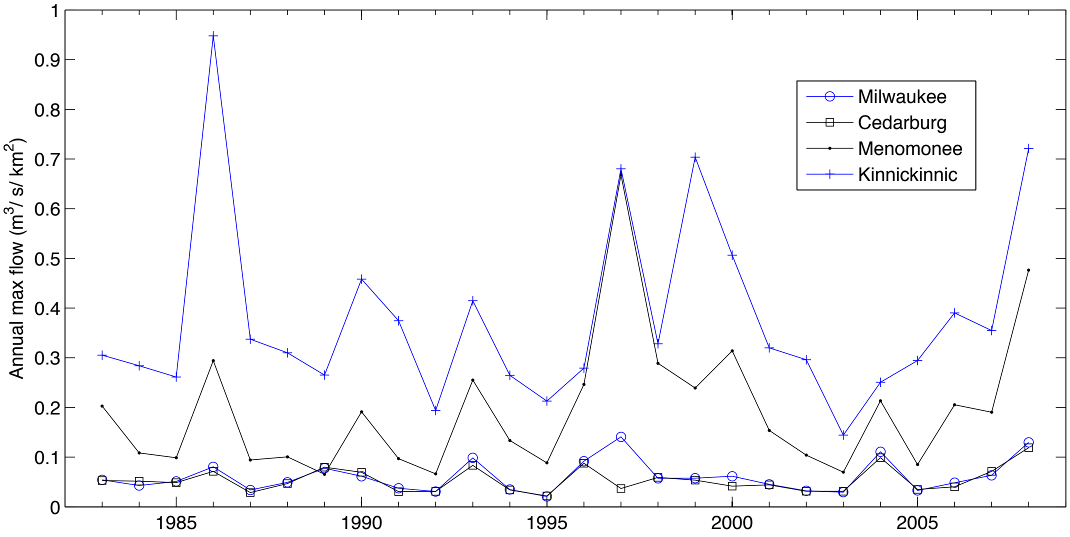


Figure 5. Annual maximum of daily mean streamflow during 1983-2008, divided by the catchment area for comparison between the catchments

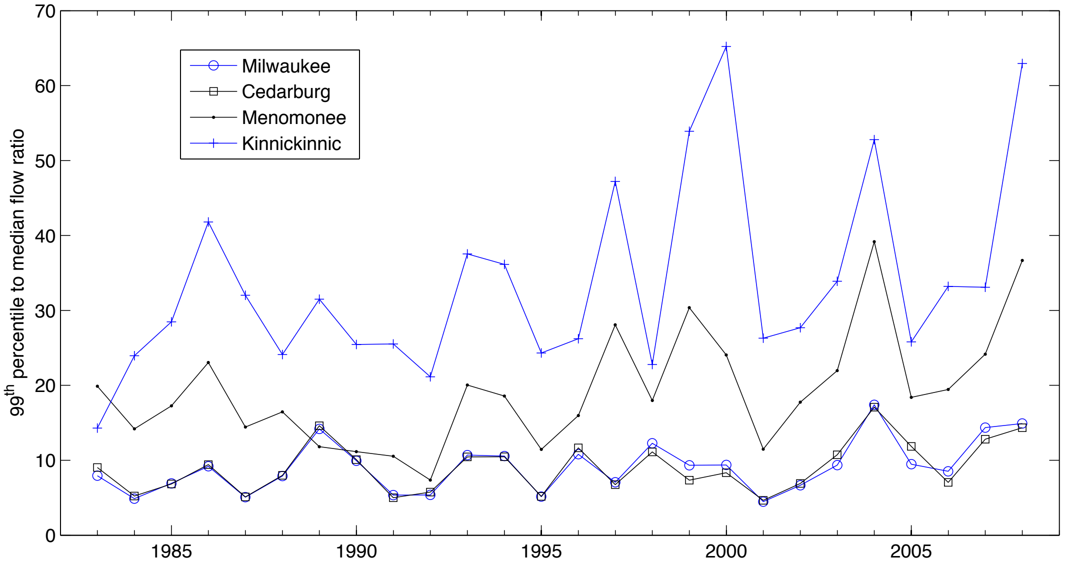
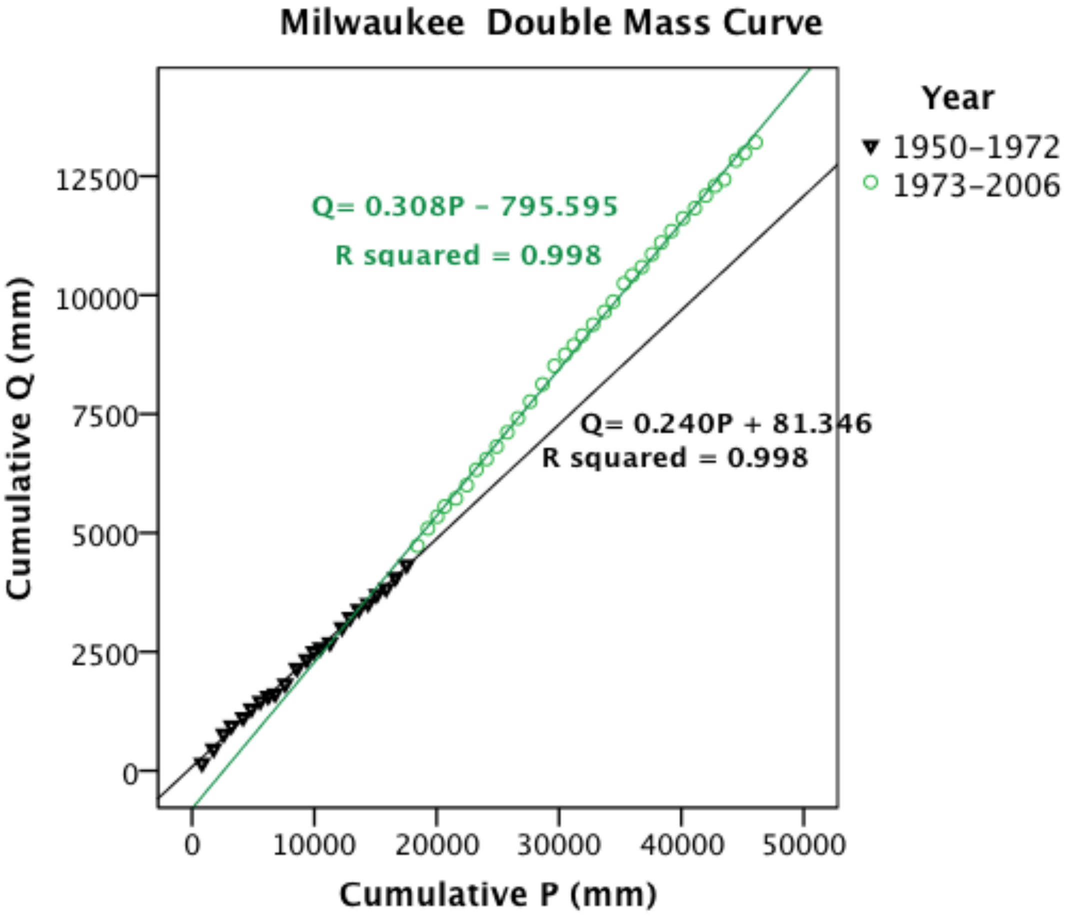
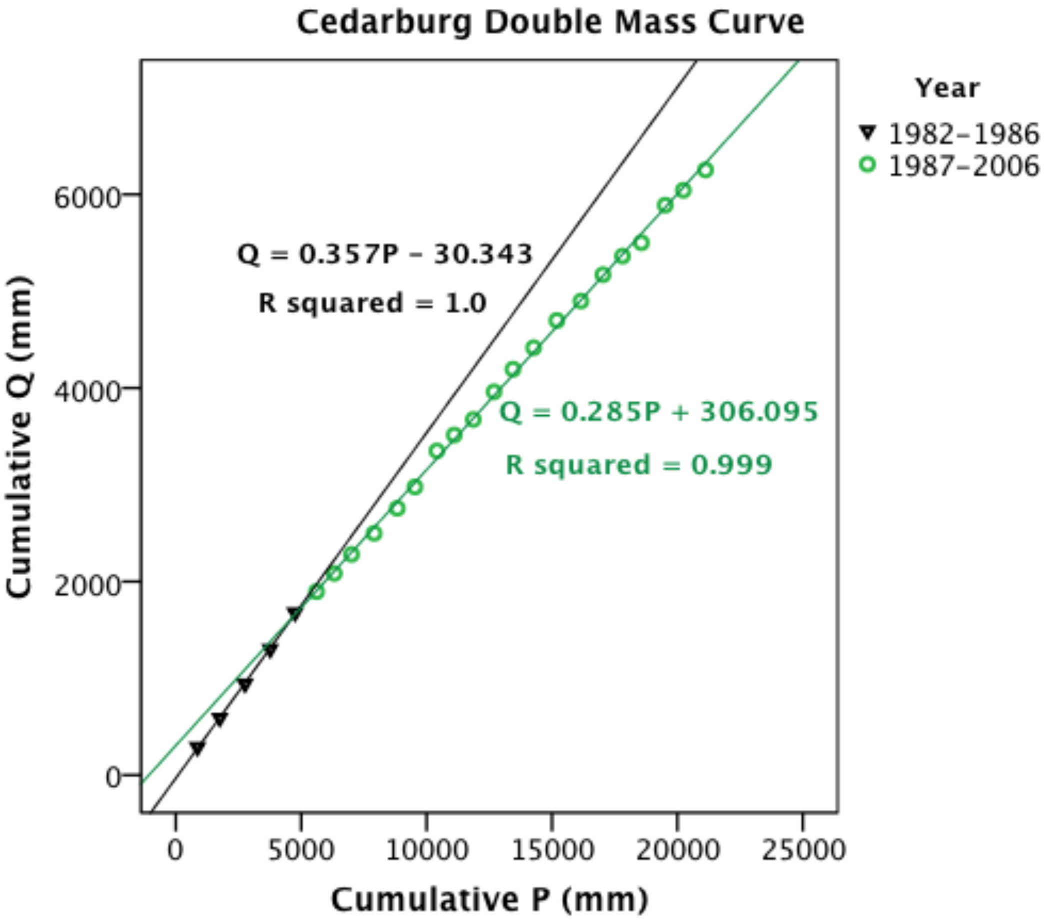
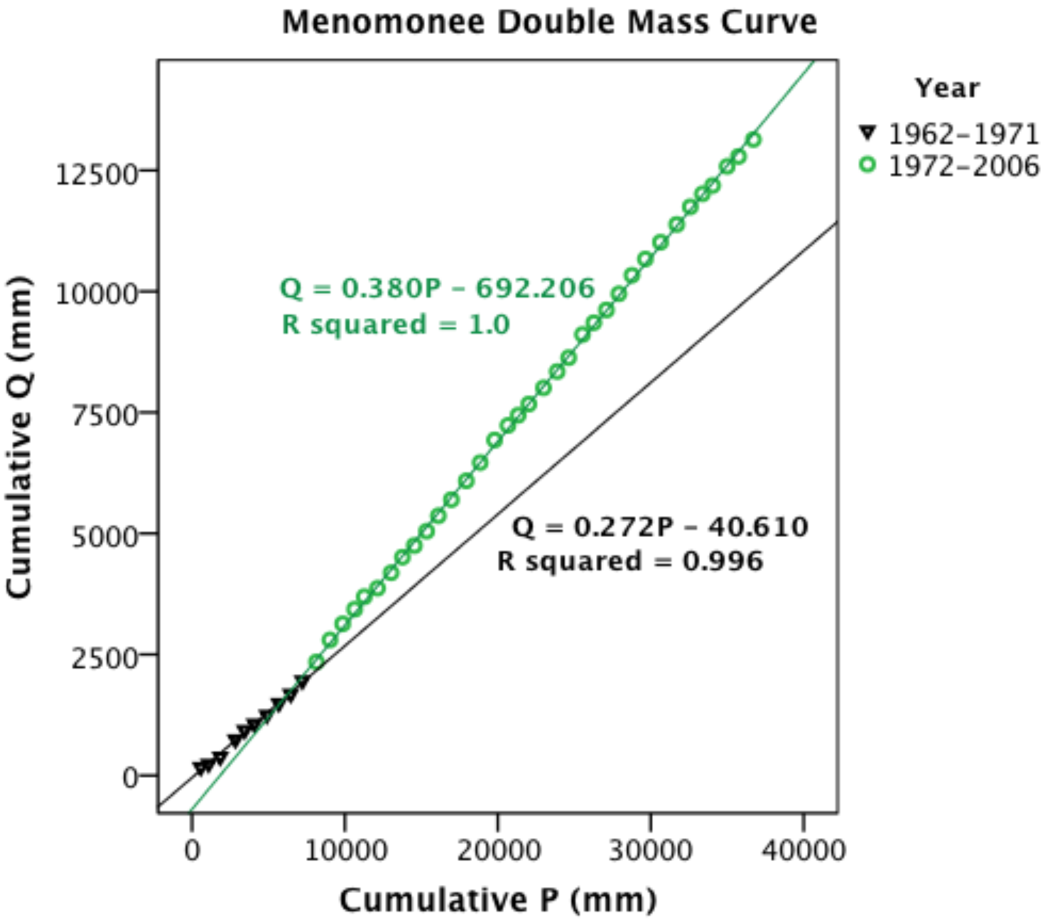


Figure 6. Ratio of annual 99th percentile flow to annual median flow during 1983-2008


Milwaukee Double Mass Curve
Year
1950-1972
1973-2006
Q= 0.308P - 795.595
R squared = 0.998
Q= 0.240P + 81.346
R squared = 0.998
Cumulative Q (mm)
0
2500
5000
7500
10000
12500
Cumulative P (mm)
0
10000
20000
30000
40000
50000


Cedarburg Double Mass Curve
Year
▼ 1982–1986
○ 1987–2006
Q = 0.357P – 30.343
R squared = 1.0
Q = 0.285P + 306.095
R squared = 0.999
Cumulative Q (mm)
0
2000
4000
6000
Cumulative P (mm)
0
5000
10000
15000
20000
25000


Menomonee Double Mass Curve
Year
▼ 1962-1971
○ 1972-2006
Q = 0.380P - 692.206
R squared = 1.0
Q = 0.272P - 40.610
R squared = 0.996
Cumulative Q (mm)
12500
10000
7500
5000
2500
0
Cumulative P (mm)
0
10000
20000
30000
40000

544

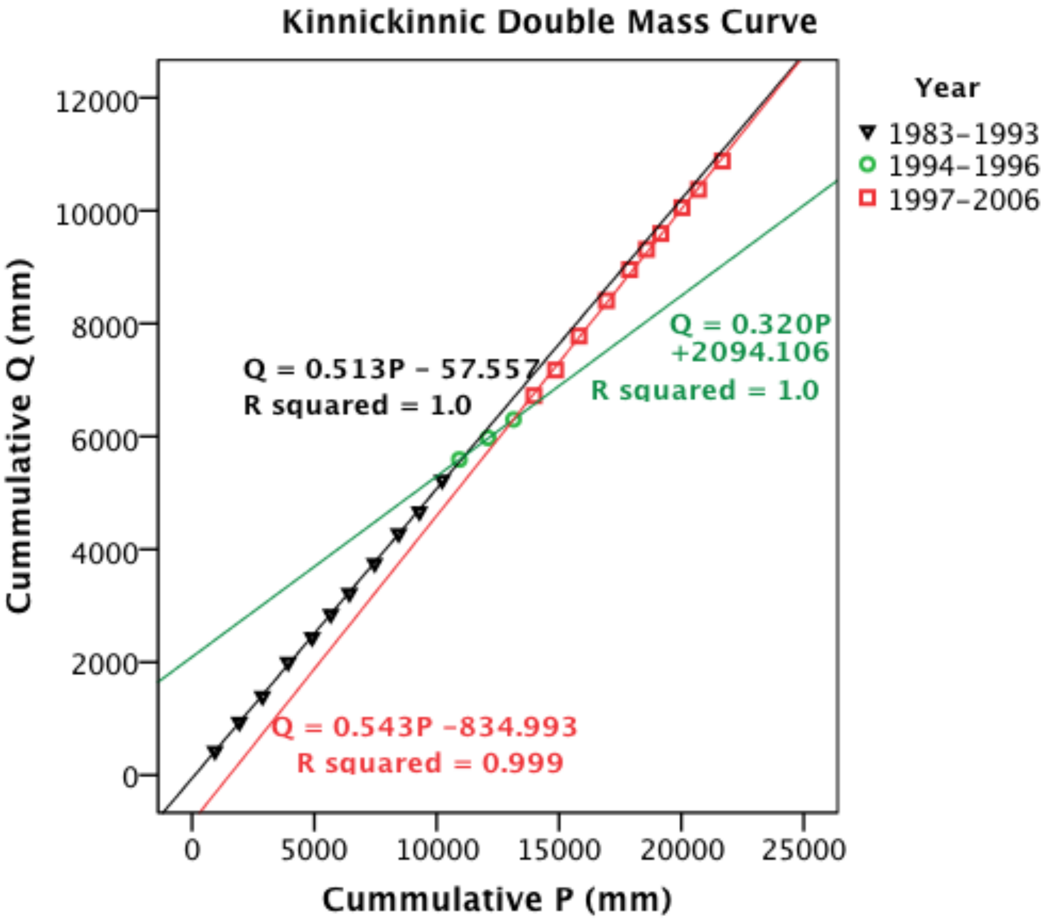


Figure 7. Double mass curves between cumulative precipitation (P) and runoff (Q) for the four catchments