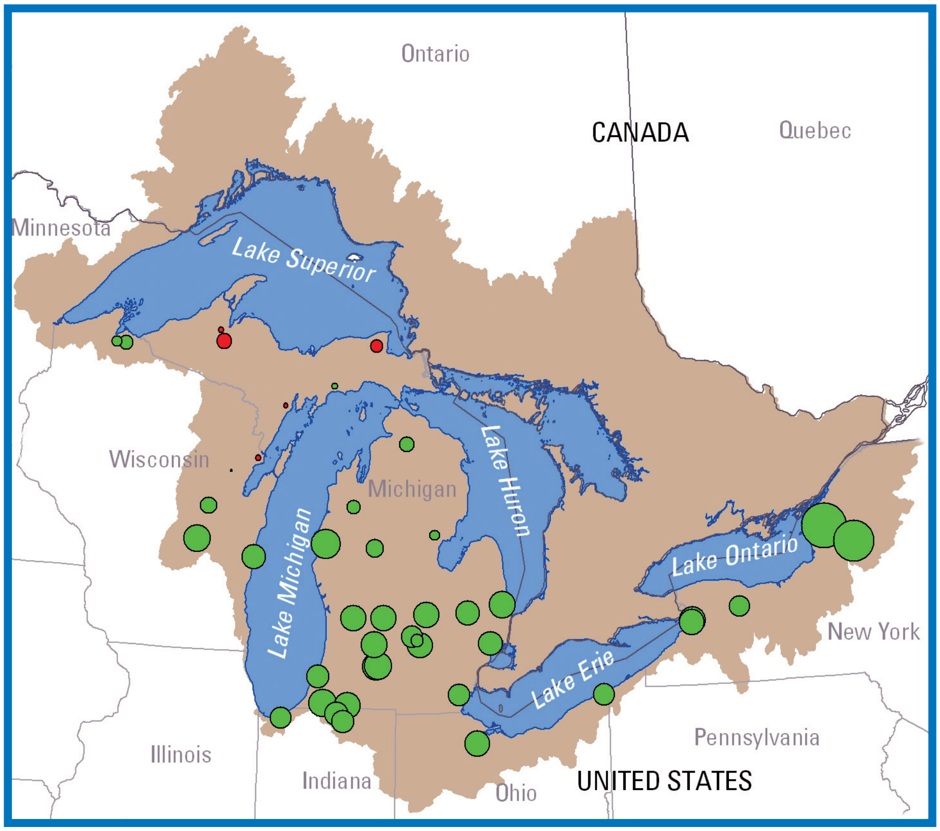
National Water Availability and Use Program

Historical Changes in Precipitation and Streamflow in the U.S. Great Lakes Basin, 1915–2004



Scientific Investigations Report 2007–5118

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
	Volume	
cubic foot per square mile (ft^3/mi^2)	0.01093	cubic meter per square kilometer (m^3/km^2)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Historical Changes in Precipitation and Streamflow in the U.S. Great Lakes Basin, 1915–2004

By Glenn A. Hodgkins, Robert W. Dudley, and Stephen S. Aichele

Abstract

The total amount of water in the Great Lakes Basin is important in the long-term allocation of water to human use and to riparian and aquatic ecosystems. The water available during low-flow periods is particularly important because the short-term demands for the water can exceed the supply.

Precipitation increased over the last 90 years in the U.S. Great Lakes Basin. Total annual precipitation increased by 4.5 inches from 1915 to 2004 (based on the average of 34 U.S. Historical Climatology Network stations), 3.5 inches from 1935 to 2004 (average of 34 stations), and 4.2 inches from 1955 to 2004 (average of 37 stations). Variability in precipitation from year to year was large, but there were numerous years with relatively low precipitation in the 1930s and 1960s and many years with relatively high precipitation after about 1970.

Annual runoff increased over the last 50 years in the U.S. Great Lakes Basin. Mean annual runoff increased by 2.6 inches, based on the average of 43 U.S. Geological Survey streamflow-gaging stations from 1955 to 2004 on streams that were relatively free of human influences. Variability in runoff from year to year was large, but on average runoff was relatively low from 1955 to about 1970 and relatively high from about 1970 to 1995. Runoff increased at all stations in the basin except in and near the Upper Peninsula of Michigan, where relatively small runoff decreases occurred. Changes in annual runoff for the 16 stations with data from 1935 to 2004 were similar to the changes from 1955 to 2004. The mean annual 7-day low runoff (the lowest annual average of 7 consecutive days of runoff) increased from 1955 to 2004 by 0.048 cubic feet per second per square mile based on the average of 27 stations.

Runoff in the U.S. Great Lakes Basin from 1955 to 2004 increased for all months except April. November through January and July precipitation and runoff increased by similar amounts. There were differences between precipitation and runoff changes for February, March, and April, which were likely due to lower ratios of snowfall to rain and earlier snowmelt runoff in recent years. Increases in precipitation were larger than increases in runoff for May, June, August, September, and October. Some of this difference could be due to the different locations of the precipitation and streamflow stations in the basin. Part of the difference may be explained by changes in evapotranspiration.

Some of the few highly urbanized and highly regulated stations analyzed in this report had larger increases in annual 7-day low-runoff from 1955 to 2004 than any of the stations in the U.S. Great Lakes Basin that are on streams relatively free of human influences. This demonstrates the human influence over time on very low streamflows.

Changes—even over periods as long as 90 years—can be part of longer cycles. Previous studies of Great Lakes Basin precipitation and St. Lawrence River streamflow, using data from the mid-1800s to the late-1900s, showed low precipitation and streamflow in the late 1800s and early 1900s relative to earlier and later periods.

Introduction

In 2005, the U.S. Geological Survey (USGS) began a National Assessment of Water Availability and Use at the request of Congress; a pilot phase began that year in the Great Lakes region. The goal of the program is to provide citizens, communities, and natural-resource managers with increased knowledge of the status of the Nation's water resources, trends over recent decades in water availability and use, and an improved ability to forecast the availability of water for future economic and ecological uses (U.S. Geological Survey, 2002). In other words, the assessment will help characterize how much water we have now, how water availability has changed in the past, and how much water we can expect to have in the future (Grannemann and Reeves, 2005).

The Great Lakes (Lakes Superior, Michigan, Huron, Erie, and Ontario) (fig. 1) and their tributaries are essential water-supply, transportation, and power-generating resources that support extensive economic development throughout the region. Some of the world's greatest concentrations of industrial capacity are in the Great Lakes region. Additionally, resources within and around these lakes and tributaries are important to the ecology of the region and to the cultural heritage of the continent (Government of Canada and U.S. Environmental Protection Agency, 1995).

Long-term streamflow changes can give insight into the natural and human processes that control water availability. Streams contribute about 46 percent of the water that goes into the Great Lakes (about 53 percent is through direct precipitation on the lakes, and 1 percent is through diversions) (Government of Canada and U.S. Environmental Protection Agency, 1995). Streamflows are influenced by climatic variables such as precipitation and temperature but also can be influenced by human activities. For example, flows can be affected by storage reservoirs in a drainage basin.

Purpose and Scope

The purpose of this report is to describe streamflow and precipitation changes within the U.S. Great Lakes Basin—in both time and space—to help reveal the ongoing processes that may affect present and future surface-water and ground-water availability. This report compares changes over time for several measures of precipitation and streamflow for sites across the basin with 50 or more years of data. The report includes analyses of monthly and annual precipitation changes, monthly and annual mean streamflows, and 7-day annual low flows. Some air temperature records are analyzed to help explain selected streamflow changes.

Human activities may affect water availability in the streams of the Great Lakes Basin. Changes over time are examined for basins with large amounts of urbanization, reservoir storage, and agricultural land use. Long-term changes that differ from the changes in streams draining basins that are relatively free of human influences may yield insight on the impact of humans on in-stream water availability.

The total amount of water available in streams throughout the year and the water available during low-flow periods are both important. The total amount of water is important in the long-term allocation of water to human use and to riparian and aquatic ecosystems. The future growth of municipalities depends on an adequate supply of water. The water available during low-flow periods is particularly important because short-term demands can exceed the supply.

Previous Studies of Streamflow and Precipitation Changes in the Great Lakes Basin

Many studies have reported on aspects of Great Lakes Basin streamflow or precipitation changes over time at various geographic scales and over various time periods. The scope of previous streamflow studies include: United States from 1948 to 1988 (Lettenmaier and others, 1994); United States from 1914 to 1993 (Lins and Slack, 1999); St. Lawrence River from 1861 to 1994 (Mortsch and others, 2000); Canada from 1947 to 1996 (Xuebin and others, 2001); United States from 1941 to 1999 (McCabe and Wolock, 2002); Lakes Michigan and Huron Basins from 1920 to 1995 (Argyilan and Forman, 2003); Lake Superior Basin from 1948 to 1999 (Lenters, 2004); United States from 1950 to 2000 (Walter and others, 2004); eastern North America from 1913 to 2002 (Hodgkins and Dudley, 2006); Minnesota from 1960 to 2002 (Johnson and Stefan, 2006); and eastern United States from 1948 to 1997 (Small and others, 2006). Results of previous streamflow-change studies are discussed later in this report.

As with streamflow, numerous studies have reported changes in Great Lakes Basin precipitation, for multiple geographic scales and time periods: Great Lakes Basin from 1854 to 1979 (Quinn, 1981); Lake Michigan Basin from 1896 to 1985 (Changnon, 1987); United States from 1948 to 1988 (Lettenmaier and others, 1994); United States from 1910 to 1996 (Karl and Knight, 1998); Great Lakes Basin from 1935 to 1995 (Grover and Sousanis, 2002); Lake Michigan and Huron Basins from 1920 to 1995 (Argyilan and Forman, 2003); Lake Superior Basin from 1948 to 1999 (Lenters, 2004); United States from 1950 to 2000 (Walter and others, 2004); and eastern United States from 1948 to 1997 (Small and others, 2006). Norton and Bolsenga (1993) and Burnett and others (2003) examined snowfall changes in the Great Lakes Basin from 1951 to 1980 and 1931 to 2001, respectively. Results of previous precipitation studies are discussed later in this report.

Physical Description of the Great Lakes Basin

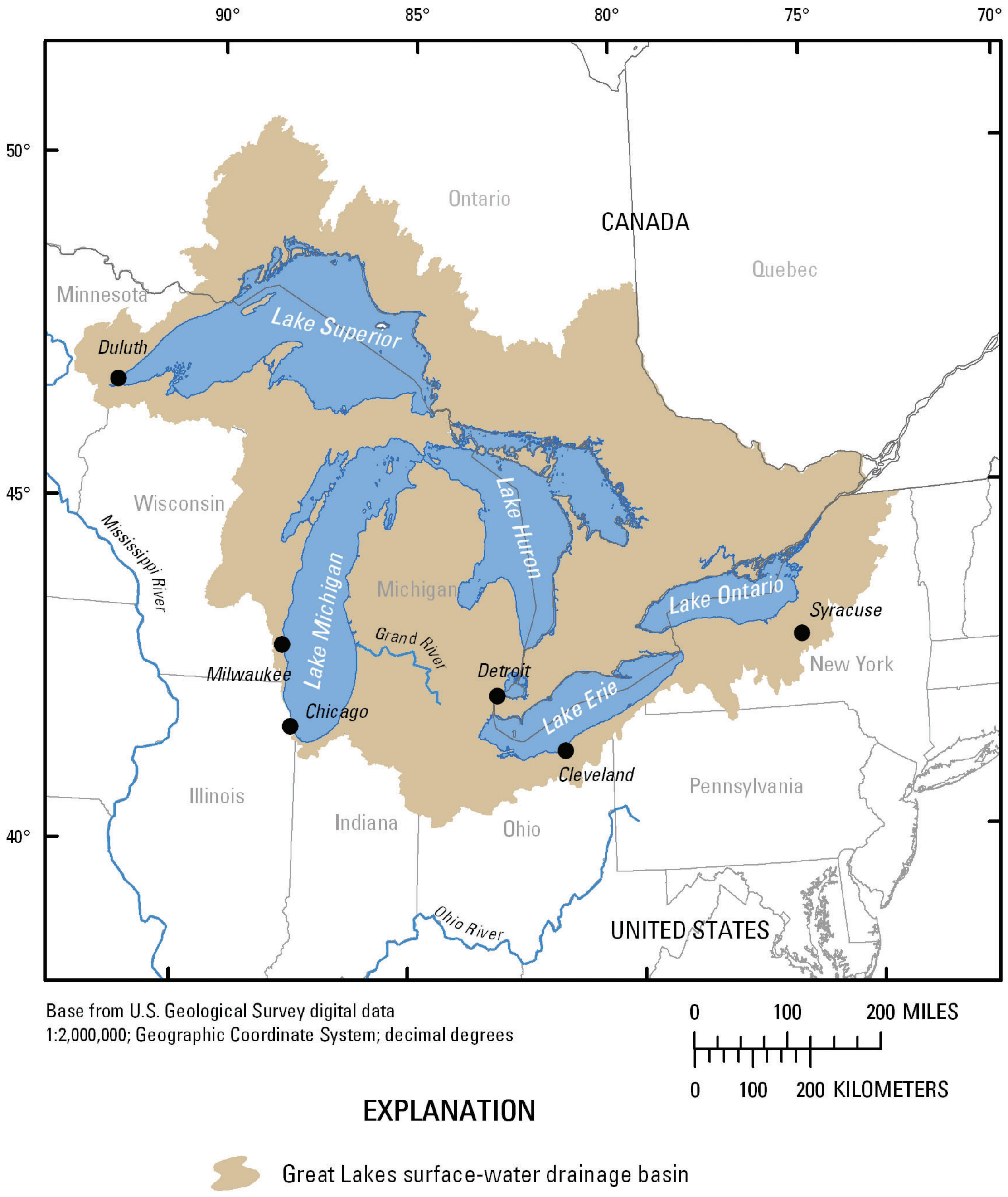
The Great Lakes Basin, including the surface area of the Great Lakes, comprises approximately 296,000 mi^2 in the upper midwestern United States and southeastern Canada (fig. 1). The basin includes parts of eight U.S. states (Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, New York) and one Canadian province (Ontario) (Government of Canada and U.S. Environmental Protection Agency, 1995).

Because of the large size of the basin, its physical characteristics such as soils and topography vary. In the northwestern area of the U.S. part of the basin, the terrain is dominated by very old bedrock under a generally thin layer of soils. In the southern area of the basin, the soils are deeper with layers or mixtures of clays, silts, sands, gravels, and boulders, which were deposited by glaciers. The lands are generally fertile and can be drained for agriculture (Government of Canada and U.S. Environmental Protection Agency, 1995).

Land use in the U.S. part of the Great Lakes Basin varies from the northwest to southeast. Forest dominates the basin in Minnesota and the Upper Peninsula of Michigan, and low-intensity farming and pasture are dominant in Wisconsin. The Lower Peninsula of Michigan contains much forest, low-intensity farming, and pasture in the north and a mixture of low- and high-intensity farming and urban areas in the south. The basin in Illinois, Indiana, Ohio, Pennsylvania, and New York contains much low- and high-intensity farming with some forest and urban areas (Government of Canada and U.S. Environmental Protection Agency, 1995).

Climate of the Great Lakes Basin in the United States

The climate of the U.S. Great Lakes Basin is controlled by the movement of air masses from other regions (warm, humid air from the Gulf of Mexico and cold, dry air from the Arctic), the location of the basin within a large continental



Base from U.S. Geological Survey digital data
1:2,000,000; Geographic Coordinate System; decimal degrees

Figure 1. Drainage area of the Great Lakes Basin, United States and Canada.

landmass, and the moderating influence of the lakes themselves. In summer, most of the U.S. Great Lakes Basin is dominated by warm, humid air from the Gulf of Mexico, and only the most northern part of the basin receives cooler and drier air from the north. Spring and fall are characterized by variable weather corresponding to alternating air masses originating north or south of the basin. In much of the winter, cold arctic air moves across the basin and absorbs moisture from the comparatively warm Great Lakes. The air masses cool and condense as they reach land, creating heavy snowfalls on the leeward side of the Great Lakes (Government of Canada and U.S. Environmental Protection Agency, 1995).

The climate of the U.S. Great Lakes Basin varies seasonally and from a generally northwest to southeast direction. Mean air temperature in January ranges from about 7°F in Minnesota to about 30°F in Indiana and Ohio. Mean air temperature for July ranges from about 63°F in Minnesota to about 75°F in Ohio, Indiana, and Illinois. Precipitation also varies considerably within the study area. Mean annual precipitation ranges from less than 27 in. west of Lake Superior to more than 47 in. east of Lake Ontario. Areas of the Great Lakes Basin to the south and east of the lakes receive about 60 to 140 in. of snow per year (Government of Canada and U.S. Environmental Protection Agency, 1995).

Streamflow and Meteorological Data and Analysis

Long-term (greater than 50 years) changes in streamflow and meteorological data were analyzed by computing annual and monthly statistics at selected locations in the U.S. Great Lakes Basin. Streamflow changes were analyzed at U.S. Geological Survey streamflow-gaging stations on streams that were relatively free of human influences and at stations on streams with substantial amounts of urbanization and storage regulation.

Selection of Stations

Initially, all USGS streamflow-gaging stations in the U.S. Great Lakes Basin were considered for use in this study. The list was culled to eliminate sites that did not meet the minimum criteria for inclusion in this study: a minimum of 50 years of data extending to 2003 or 2004 and no more than 5 percent missing data. Use of these criteria narrowed the list to 113 stations; subsets of these stations that best met study criteria (for example, stations on the most regulated streams) were used in the final analyses.

One class of streamflow-gaging stations used for this study included those appropriate for the study of climate variations—stations on streams where changes should be mostly influenced by natural processes such as precipitation rather than by human influences such as reservoir-storage regulation and urbanization. The starting point for selecting these stations was the USGS Hydro-Climatic Data Network (HCDN), which includes data from 1,659 streamflow-gaging stations across the United States (Slack and Landwehr, 1992). This network contains stations with good-quality data on streams that drain basins that are relatively free of human influences such as regulation, diversion, land-use change, or extreme groundwater pumpage. Data from stations that met HCDN criteria for daily mean flows were used. Historical station information and data were analyzed, and local USGS offices were contacted to ensure the relevant HCDN basins were still considered appropriate for this study and to determine if additional stations would be appropriate for the streamflow statistics used in this study (mean monthly flows and annual 7-day low flows). Several additional stations were identified, and 28 stations made the final cut; the 28 final stations are listed and mapped in the "Streams Relatively Free of Human Influences" section of this report. All of these stations had less than 5.3 percent urban area in their basins. Agricultural land use in the basins ranged from 1 percent to 88 percent.

Numerous streamflow-gaging stations in the basin were not HCDN-type stations because they had minor flow regulation in their basins; they commonly had hydroelectric dams in their basins without substantial amounts of water storage. This level of flow regulation was considered inconsequential for analyzing mean annual flows. Stations were not used if known flow diversions were in their basins or if their basins contained more than 5 percent urban area, except for two HCDN stations with 5.1 percent and 5.3 percent urban area. Forty-four HCDN-type stations and stations on slightly regulated streams, including the 28 stations discussed above, met all the criteria for mean annual flows for streams relatively free of human influences.

The second class of streamflow-gaging stations in this study contains stations on streams draining urbanized basins—referred to in this report as "urbanized stations." The basins for these stations contained relatively large percentages (greater than 10 percent) of industrial, commercial, and residential areas. Land-use percentages were computed by means of geographic information system (GIS) coverages as described in the "Calculation of Basin Land Use" section. Stations were not used if there was known flow regulation in the basin. The one station that met the urbanized-station criteria is described further in the "Highly Urbanized Streams" section.

Stations in the third class were those on streams with high amounts of storage regulation, where dams in the basin control a large amount of water—referred to in this report as "regulated stations." All stations in the basin were searched for ones that had more than 4.5 million ft^3/mi^2 of water storage in their basins (the criterion used by Benson (1962) to indicate substantial storage), less than 5 percent urban area in the basin, and no known diversions. Four stations met these criteria, three in Michigan and one in Ohio. They are listed and described further in the "Highly Regulated Streams" section.

Monthly precipitation (total liquid equivalent) and air-temperature data were obtained from the U.S. Historical Climatology Network (HCN) dataset that was developed and is maintained at the National Climatic Data Center (Karl and others, 1990). The HCN data have been subjected to quality control and homogeneity testing. Precipitation data have been adjusted for bias originating from changes in station location and other station changes (Karl and Williams, 1987). Temperature data have been adjusted for bias originating from changes in observation time (Karl and others, 1986), instrumentation (Quayle and others, 1991), station location and other station changes (Karl and Williams, 1987), and urban heat-island effects (Karl and others, 1988). Thirty-seven HCN stations in the basin met the minimum record length of 50 years and completeness criteria of no more than 5 percent missing data for this study. These stations are listed in the "Precipitation Changes" section.

Calculation of Statistics

Streamflow and precipitation datasets for all statistics were compiled for each of three time periods: 50 years (calendar years 1955–2004), 70 years (1935–2004), and 90 years (1915–2004). Not all of these time periods are reported in the results sections because not all classes of data had adequate amounts of 70- or 90-year data to be representative of conditions in the Great Lakes Basin.

Monthly and annual streamflow statistics were computed, as appropriate, for the classes of data described above for annual mean flow, 7-day annual mean low flow, and monthly mean flows. The 7-day low flow is the lowest mean flow in a year for 7 consecutive days. It is a commonly used measure of low flow. Annual and monthly median streamflows were computed, but their results did not differ enough from mean flows to justify their reporting. If, for any time period, the station record did not meet the 95-percent completeness criterion, statistics for that station were censored for that time period.

The significance of changes is typically computed using linear regression or the Mann-Kendall test. However, there must be no serial correlation for the test results to be correct (Helsel and Hirsch, 2002). A previous study (Hodgkins and Dudley, 2006) and data plots for individual stations from the current study showed extensive serial correlation in the data sets used for this study. Another problem with significance tests occurs when long-term persistence is present (Cohn and Lins, 2005). The concept of statistical significance may be meaningless when discussing poorly understood systems (Cohn and Lins, 2005). The statistical significance of changes is therefore not reported for this study.

The magnitudes of changes were computed using the Sen slope, which is also known as the Kendall-Theil robust line. The existence of serial correlation does not affect the estimated value of the Sen slope (Sheng and others, 2002). This slope is computed as the median of all possible pairwise slopes in each temporal data set (Helsel and Hirsch, 2002). The slope was multiplied by the appropriate number of years of data to obtain changes over time for different time periods. The changes over time in the annual and monthly mean flows were divided by the appropriate drainage basin areas to obtain changes in runoff over time (in inches).

The data were smoothed for plots by use of locally weighted regression (LOESS) (Cleveland and Devlin, 1988) with locally linear fitting, a robustness feature, and a weighting function of 30 years. LOESS, using these parameters, is very similar to LOWESS (Cleveland, 1979). These locally weighted regression techniques allow the data to dictate the shape of the smooth and do not assume linearity (Hirsch and others, 1993).

Calculation of Basin Land Use

Basin land use was calculated for the 113 sites previously identified in the basin with long-term records. Watershed boundaries were delineated using the 1:100,000 scale National Hydrography Dataset (NHD) and a modified version of the 1-arc-second-scale National Elevation Dataset (NED). The NED was modified by use of Hutchinson's algorithm (Hutchinson, 1993) as implemented in a geographic information system (GIS), Arc/INFO version 8.3, to ensure continuous drainage across the surface. This process was necessary to address minor spurious errors in the NED that affect calculation of flow direction across the landscape and to reconcile the locations of channel features from the NHD. The resulting elevation model forces all points on the landscape to drain to a channel mapped in the NHD and ensures that the NHD stream channel coincides with the lowest point in the NED.

Each streamflow-gaging station was then located on the NHD, and the upstream tributary network was traced. Every point on the landscape that contributed flow to any part of the traced network was then identified, and the resulting watershed was saved as a separate feature. Watershed areas were compared to the reported area in the USGS National Water Information System (NWIS) and were visually compared to existing delineations when available.

Land use was calculated by use of the 1992 National Land Cover Dataset (NLCD). Although land use and land cover are not technically the same, they were considered interchangeable for the relatively coarse characterization necessary for this study. Each watershed feature was overlaid on the NLCD, and the various land uses included within the watershed area were tabulated based on the number of 30-m by 30-m cells represented.

Calculation of Basin Population

Assigning population estimates to watersheds is problematic in general because of the irregular density of people on the landscape and the relatively large areal units used for mapping. The issue has been identified as the Modifiable Areal Unit Problem (MAUP) by Openshaw (1983) and several subsequent authors. In other words, the summary characteristics of an irregularly distributed property (such as people) change as one alters the boundary of the area being examined. Approaches to avoid the MAUP include mapping people individually or mapping them in regions with relatively uniform characteristics, which might then be reaggregated in an area-weighted scheme.

The smallest unit of analysis readily available was the census block-level population counts from the 2000 census. However, these data are available only from 1980 forward for the areas of interest in this study. Comparison of estimates created with county-level data (the most available scale of data) to estimates created with block-level data indicated substantial negative bias in the estimates—undercounts of more than 30 percent. A dataset containing subdivisions of counties—minor civil divisions (MCDs)—is available from 1950 to 2000. Comparisons between the MCD-level data and block-level data for 2000 indicated a negative bias of 3 percent for the basin of USGS streamflow-gaging station 04166500 and 6 percent for station 04164000. MCD-level data were used for this study.

Historical census data by MCD were provided by the Southeast Michigan Council of Governments (A. Burns, written commun., 2003). These population counts were converted to densities, and area-weighted totals were generated for each watershed for each census from 1950 through 2000. Some bias is likely included in these estimates, but they are the best that could be derived given the source data available.

Precipitation Changes

Precipitation has increased over the last 90 years in the U.S. Great Lakes Basin. Total annual precipitation increased by 4.5 in. from 1915 to 2004—using the Sen slope estimator on the annual average of 34 HCN stations. Variability in precipitation from year to year was substantial, but there were numerous years with relatively low precipitation in the 1930s and 1960s and many years with relatively high precipitation after about 1970 (fig. 2). Variation in 90-year changes across the basin was also substantial (fig. 3*A*; table 1). The magnitude of changes for 34 stations ranged from -6.0 to 14.8 in. Out of 34 stations, 27 had changes toward increasing precipitation (positive changes). Part of the difference in the changes between stations may be the result of temporal biases at some stations.

Precipitation also increased in the U.S. Great Lakes Basin over the last 70 and 50 years. Total annual precipitation increased by 3.5 in. from 1935 to 2004 based on the average of 34 HCN stations. Precipitation varied across the basin, with changes ranging from -4.7 in. to 14.3 in. Changes at 27 of 34 stations indicated increased precipitation (fig. 3*B*; table 2). Annual precipitation increased by 4.2 in. from 1955 to 2004 based on the average of 37 stations. Changes at individual stations ranged from -2.3 in. to 10.0 in. Changes at 32 of 37 stations indicated increased precipitation (fig. 3*C*; table 3).

Precipitation did not consistently increase for all months over the last 90, 70, or 50 years (table 4). February and March precipitation declined slightly for all three periods, with the largest declines over the last 70 years. April, May, and July through December precipitation increased for all three periods. The largest increases for 1915 to 2004 were in July and August, whereas the largest increases for 1935 to 2004 and 1955 to 2004 were in September and October.

Monthly precipitation changes for the 1955 to 2004 period varied across the basin for the different months (figs. 4*A* and 4*B*; table 5), increasing in some parts of the U.S. Great Lakes Basin and decreasing in others. Precipitation in January, May, June, September, and October increased at most stations in the basin. Many of the January increases were relatively small.

Consistent with this study, other researchers have found increases in U.S. Great Lakes Basin precipitation in the last 70 years—particularly in annual and fall precipitation. Lettenmaier and others (1994) found many significant ($p < 0.02$) increases in annual, August, September, October, and December precipitation, as well as some decreases in February precipitation, from 1948 to 1988. Small and others (2006) reported significant ($p < 0.05$) increases in fall precipitation at 6 of 13 basins in the Great Lakes Basin from 1948 to 1997. Grover and Sousounis (2002) computed an increase of 15 percent in fall precipitation for the entire Great Lakes Basin between the periods 1935–65 and 1966–95.

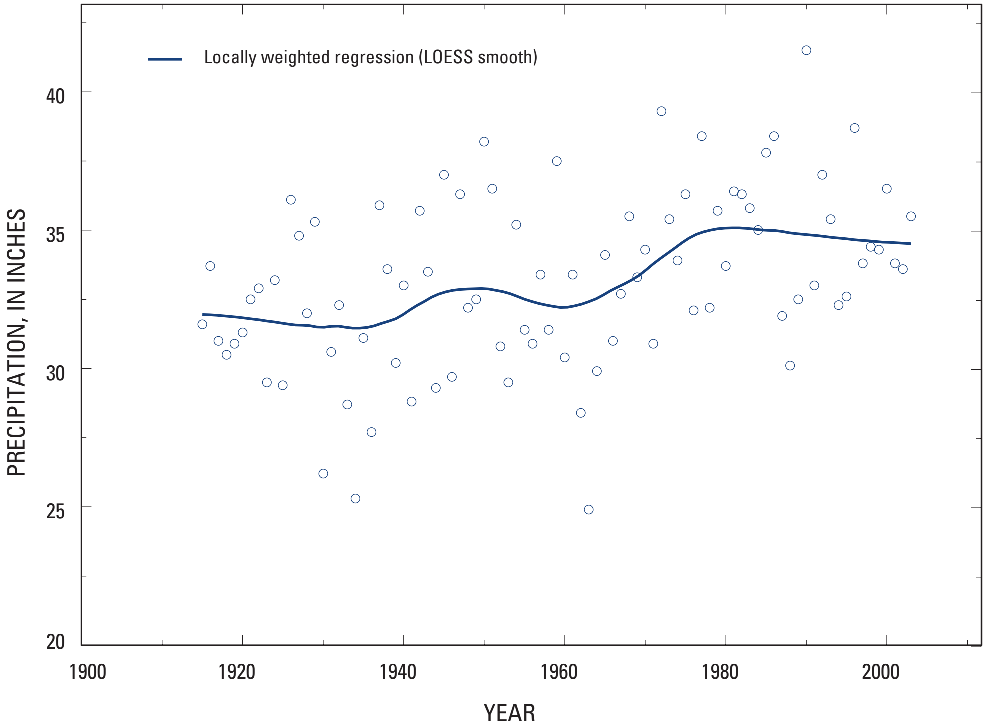
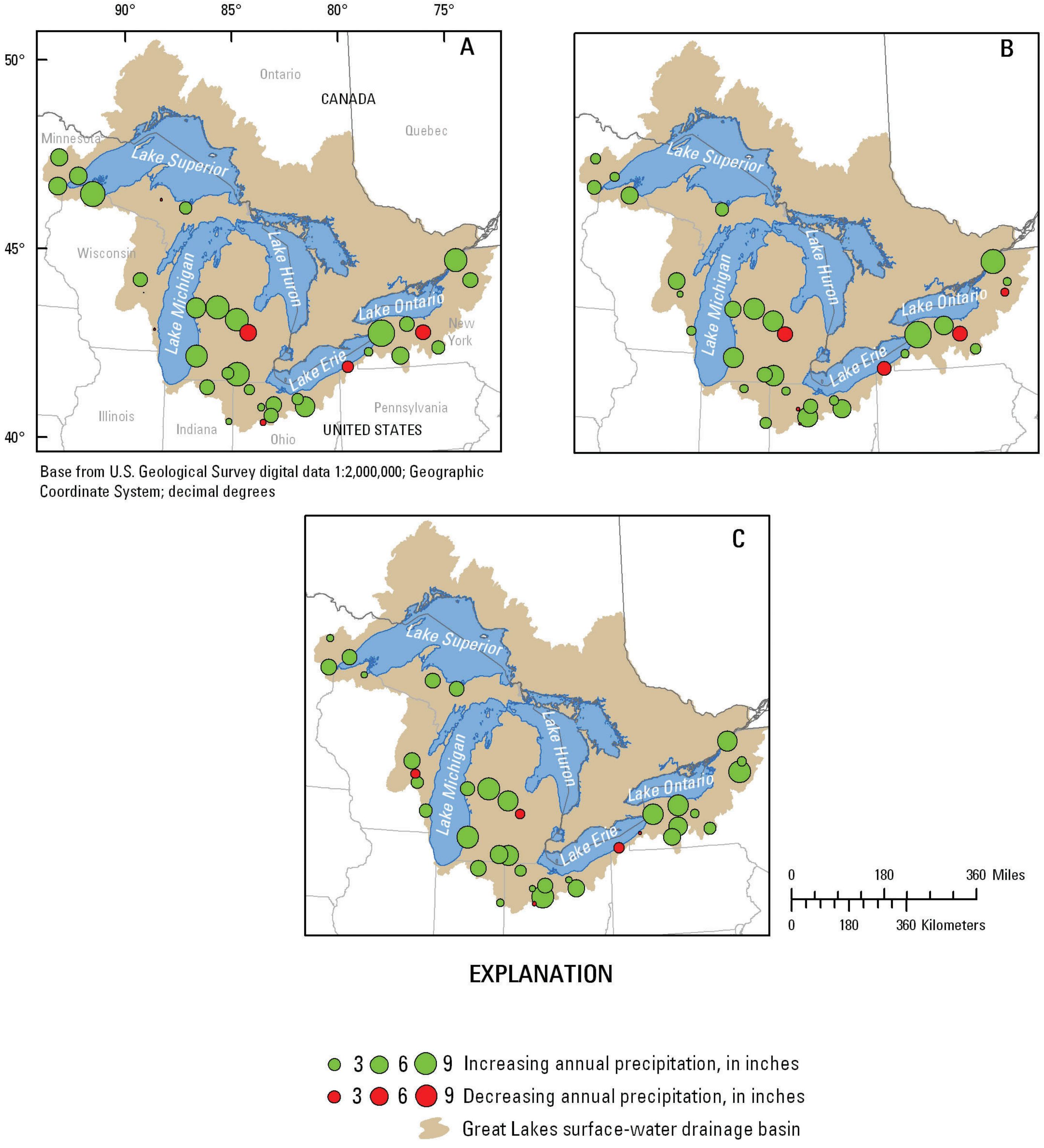


Figure 2. Total annual precipitation for the average of 34 stations in the U.S. Great Lakes Basin, 1915–2004.

Table 1. Annual precipitation changes in the U.S. Great Lakes Basin, 1915–2004.

[HCN, U.S. Historical Climatology Network]

HCN station number	Station name	Latitude, in decimal degrees	Longitude, in decimal degrees	Change, in inches
120676	Berne, Indiana	40.67	-84.95	0.82
123418	Goshen College, Indiana	41.57	-85.83	4.75
200146	Alma, Michigan	43.38	-84.67	10.81
200779	Big Rapids Waterworks, Michigan	43.70	-85.48	10.48
201439	Champion Van Riper Pk, Michigan	46.52	-87.98	-0.13
201486	Chatham Exp Farm #2, Michigan	46.33	-86.92	3.17
201675	Coldwater State School, Michigan	41.95	-85.00	3.01
203632	Hart, Michigan	43.68	-86.35	7.88
203823	Hillsdale, Michigan	41.93	-84.63	10.92
206300	Owosso 3NNW, Michigan	43.03	-84.18	-6.01
207690	South Haven, Michigan	42.40	-86.28	9.65
211630	Cloquet, Minnesota	46.70	-92.52	6.71
212645	Eveleth Waste Water Pl, Minnesota	47.47	-92.57	6.06
218419	Two Harbors, Minnesota	47.02	-91.67	6.77
300183	Angelica, New York	42.30	-78.02	5.75
301012	Buffalo WSCMO AP, New York	42.93	-78.73	14.75
303033	Fredonia, New York	42.45	-79.30	1.41
303184	Geneva Resr Fm, New York	42.88	-77.03	-4.33
304174	Ithaca Cornell Un, New York	42.45	-76.45	3.72
306164	Ogdensburg 4NE, New York	44.73	-75.43	10.27
307167	Rochester Airport, New York	43.13	-77.67	4.72
308944	Wanakena Ranger School, New York	44.15	-74.90	4.80
331541	Chippewa Lake, Ohio	41.05	-81.93	8.34
332791	Findlay WPCC, Ohio	41.05	-83.67	1.19
334189	Kenton, Ohio	40.65	-83.60	-0.95
336196	Oberlin, Ohio	41.27	-82.22	2.77
338313	Tiffin, Ohio	41.12	-83.17	5.21
338534	Upper Sandusky, Ohio	40.83	-83.28	4.22
338822	Wauseon Water Plant, Ohio	41.52	-84.15	2.17
362682	Erie WSO AP, Pennsylvania	42.08	-80.18	-2.70
470349	Ashland Experiment Farm, Wisconsin	46.57	-90.97	11.99
475474	Milwaukee Mt Mary Col, Wisconsin	43.07	-88.03	-0.12
475932	New London, Wisconsin	44.37	-88.72	4.22
476330	Oshkosh, Wisconsin	44.03	-88.55	-0.02



Base from U.S. Geological Survey digital data 1:2,000,000; Geographic Coordinate System; decimal degrees

Figure 3. Changes in annual precipitation, by station, for (A) 1915–2004, (B) 1935–2004, and (C) 1955–2004. Circle sizes proportional to increases or decreases.

Table 2. Annual precipitation changes in the U.S. Great Lakes Basin, 1935–2004.

[HCN, U.S. Historical Climatology Network]

HCN station number	Station name	Latitude, in decimal degrees	Longitude, in decimal degrees	Change, in inches
120676	Berne, Indiana	40.67	-84.95	2.63
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200779	Big Rapids Waterworks, Michigan	43.70	-85.48	8.76
201439	Champion Van Riper Pk, Michigan	46.52	-87.98	0.00
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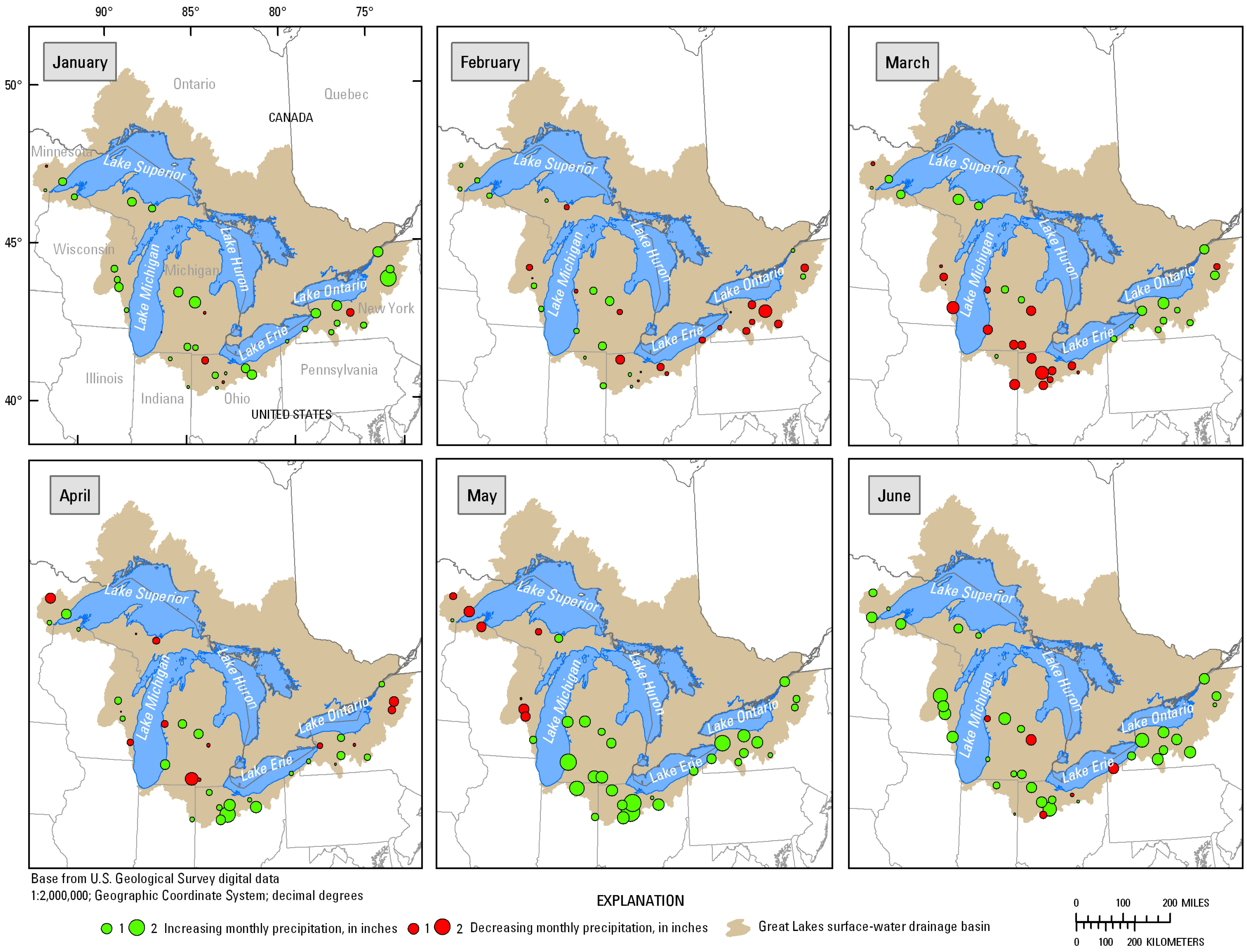
201675	Coldwater State School, Michigan	41.95	-85.00	4.39
203632	Hart, Michigan	43.68	-86.35	5.50
203823	Hillsdale, Michigan	41.93	-84.63	9.16
206300	Owosso 3NNW, Michigan	43.03	-84.18	-4.67
207690	South Haven, Michigan	42.40	-86.28	8.30
211630	Cloquet, Minnesota	46.70	-92.52	4.06
212645	Eveleth Waste Water Pl, Minnesota	47.47	-92.57	2.08
218419	Two Harbors, Minnesota	47.02	-91.67	1.91
301012	Buffalo WSCMO AP, New York	42.93	-78.73	14.34
303033	Fredonia, New York	42.45	-79.30	1.57
303184	Geneva Resr Fm, New York	42.88	-77.03	-4.35
304174	Ithaca Cornell Un, New York	42.45	-76.45	2.00
306164	Ogdensburg 4NE, New York	44.73	-75.43	11.60
307167	Rochester Airport, New York	43.13	-77.67	7.41
308248	Stillwater Reservoir, New York	43.88	-75.03	-1.38
308944	Wanakena Ranger School, New York	44.15	-74.90	1.46
331541	Chippewa Lake, Ohio	41.05	-81.93	6.75
332791	Findlay WPCC, Ohio	41.05	-83.67	-0.24
334189	Kenton, Ohio	40.65	-83.60	-0.11
336196	Oberlin, Ohio	41.27	-82.22	1.89
338313	Tiffin, Ohio	41.12	-83.17	4.22
338534	Upper Sandusky, Ohio	40.83	-83.28	8.14
338822	Wauseon Water Plant, Ohio	41.52	-84.15	1.42
362682	Erie WSO AP, Pennsylvania	42.08	-80.18	-4.29
470349	Ashland Experiment Farm, Wisconsin	46.57	-90.97	5.83
475474	Milwaukee Mt Mary Col, Wisconsin	43.07	-88.03	1.86
475932	New London, Wisconsin	44.37	-88.72	6.10
476330	Oshkosh, Wisconsin	44.03	-88.55	0.85

Table 3. Annual precipitation changes in the U.S. Great Lakes Basin, 1955–2004.

[HCN, U.S. Historical Climatology Network]

HCN station number	Station name	Latitude, in decimal degrees	Longitude, in decimal degrees	Change, in inches
120676	Berne, Indiana	40.67	-84.95	0.99
123418	Goshen College, Indiana	41.57	-85.83	4.96
200146	Alma, Michigan	43.38	-84.67	7.67
200779	Big Rapids Waterworks, Michigan	43.70	-85.48	9.98
201439	Champion Van Riper Pk, Michigan	46.52	-87.98	4.39
201486	Chatham Exp Farm #2, Michigan	46.33	-86.92	4.39
201675	Coldwater State School, Michigan	41.95	-85.00	6.84
203632	Hart, Michigan	43.68	-86.35	3.94
203823	Hillsdale, Michigan	41.93	-84.63	7.84
206300	Owosso 3NNW, Michigan	43.03	-84.18	-1.64
207690	South Haven, Michigan	42.40	-86.28	9.22
211630	Cloquet, Minnesota	46.70	-92.52	5.43
212645	Eveleth Waste Water Pl, Minnesota	47.47	-92.57	0.98
218419	Two Harbors, Minnesota	47.02	-91.67	4.71
300183	Angelica, New York	42.30	-78.02	5.86
301012	Buffalo WSCMO AP, New York	42.93	-78.73	8.52
301974	Dansville, New York	42.57	-77.72	7.55
303033	Fredonia, New York	42.45	-79.30	-0.21
303184	Geneva Resr Fm, New York	42.88	-77.03	1.37
304174	Ithaca Cornell Un, New York	42.45	-76.45	2.86
306164	Ogdensburg 4ne, New York	44.73	-75.43	8.11
307167	Rochester Airport, New York	43.13	-77.67	8.83
308248	Stillwater Reservoir, New York	43.88	-75.03	9.89
308944	Wanakena Ranger School, New York	44.15	-74.90	1.91
331541	Chippewa Lake, Ohio	41.05	-81.93	5.72
332791	Findlay WPCC, Ohio	41.05	-83.67	0.92
334189	Kenton, Ohio	40.65	-83.60	-0.47
336196	Oberlin, Ohio	41.27	-82.22	0.77
338313	Tiffin, Ohio	41.12	-83.17	4.35
338534	Upper Sandusky, Ohio	40.83	-83.28	9.90
338822	Wauseon Water Plant, Ohio	41.52	-84.15	2.51
362682	Erie WSO AP, Pennsylvania	42.08	-80.18	-2.33
470349	Ashland Experiment Farm, Wisconsin	46.57	-90.97	0.86
472839	Fond du Lac, Wisconsin	43.80	-88.45	3.21
475474	Milwaukee Mt Mary Col, Wisconsin	43.07	-88.03	3.38
475932	New London, Wisconsin	44.37	-88.72	5.50
476330	Oshkosh, Wisconsin	44.03	-88.55	-1.70



Base from U.S. Geological Survey digital data
1:2,000,000; Geographic Coordinate System; decimal degrees

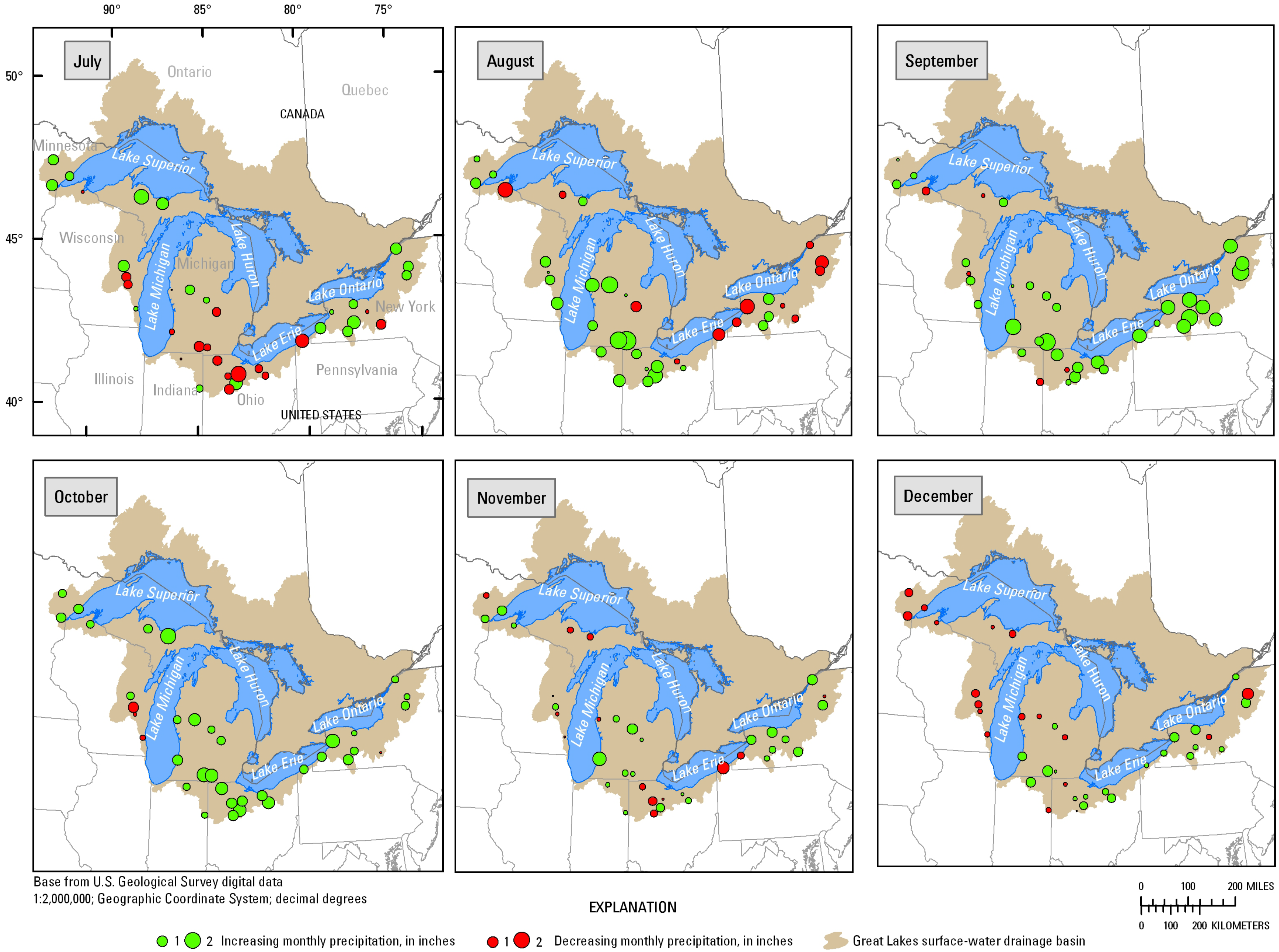
EXPLANATION

1 2 Increasing monthly precipitation, in inches

1 2 Decreasing monthly precipitation, in inches

Great Lakes surface-water drainage basin

Figure 4a. Changes in monthly precipitation for January through June, by station, 1955–2004. Circle sizes proportional to increases or decreases.



Base from U.S. Geological Survey digital data
1:2,000,000; Geographic Coordinate System; decimal degrees

Figure 4b. Changes in monthly precipitation for July through December, by station, 1955–2004. Circle sizes proportional to increases or decreases.

Table 4. Monthly precipitation changes in the U.S. Great Lakes Basin for 1915–2004, 1935–2004, and 1955–2004.

Month	Change, 1915–2004, in inches	Change, 1935–2004, in inches	Change, 1955–2004, in inches
January	0.04	-0.04	0.34
February	-0.03	-0.39	-0.05
March	-0.20	-0.29	-0.05
April	0.55	0.28	0.16
May	0.42	0.28	0.63
June	0.13	-0.04	0.55
July	0.75	0.56	0.14
August	0.93	0.55	0.37
September	0.43	0.83	0.82
October	0.21	0.71	0.64
November	0.66	0.50	0.19
December	0.35	0.28	0.07

Streamflow Changes

The flow of a stream represents the integrated basin response to various climatic inputs, with precipitation and temperature being highly influential. Changes over time in the hydrology of unregulated basins with stable land use generally reflect changes in climatic conditions (Xuebin and others, 2001). For basins with large amounts of storage regulation or land-use changes, such as urbanization, streamflow changes reflect climatic changes combined with human influences.

Streams Relatively Free of Human Influences

Streamflow data from streams not substantially affected by reservoir regulation, diversions, urbanization or other land-use change, or extreme ground-water pumping (see the “Streamflow and Meteorological Data and Analysis” section for details) were available at 43 USGS streamflow-gaging stations for annual mean flows for 1955 to 2004; data were available at 28 stations for monthly mean flows and annual 7-day low flows. For 1935 to 2004, streamflow data were only available for 16 stations for annual flow and 10 stations for monthly flows and annual low flows—not enough to be representative of the entire U.S. Great Lakes Basin. For this reason, most of the flow analyses in this report will focus on the period from 1955 to 2004.

To normalize the flows from all of the different-sized basins used in this study, flows were divided by drainage area. For monthly and annual mean flows, the values were then converted to inches over the time period of interest (month or year). For the 7-day low flows, flows were divided by drainage area to get units of cubic feet per second per square mile ($ft^3/s/mi^2$). When flow is normalized by drainage area, it is normally referred to as runoff.

Annual runoff increased over the last 50 years in the U.S. Great Lakes Basin. Mean annual runoff increased by 2.6 in., based on the average of 43 U.S. Geological Survey streamflow-gaging stations from 1955 to 2004, using the Sen slope estimator. The average drainage-basin area of these 43 stations was 900 mi^2, and the range was from 9.3 to 4,900 mi^2; most drainage areas were between 100 and 1,500 mi^2. Variability in annual runoff from year to year was substantial, but overall patterns can be observed in the data (fig. 5). Runoff was relatively low from 1955 to about 1970 and relatively high from about 1970 to 1995.

Variation in 50-year runoff changes across the basin was substantial. Mean annual runoff changes at 43 stations from 1955 to 2004 ranged from -1.3 in. to 11.1 in. Runoff increased at 38 out of 43 streamflow-gaging stations (fig. 6*A*; table 6). Runoff increased at all stations in the basin, except in and near the Upper Peninsula of Michigan, where relatively small decreases in runoff occurred. Runoff changes for the 16 available stations with data from 1935 to 2004 were similar to 1955–2004 changes (fig. 6*B*; table 7).

Runoff in the U.S. Great Lakes Basin from 1955 to 2004 increased for most months based on the average of 28 stations (table 8); however, runoff decreased in April. Runoff increases were largest in January through March, June, and October through December. The mean annual 7-day low runoff (the lowest annual average of 7 consecutive days of runoff) increased from 1955 to 2004 by 0.048 ($(ft^3/s)/mi^2$), based on the average of 27 stations.

Runoff changes from 1955 to 2004 varied across the basin for different months and for annual 7-day low runoff (figs. 7*A*, 7*B*, and 8; tables 9*A* and 9*B*). In the following discussion, the northwestern part of the basin refers to the following areas of the U.S. Great Lakes Basin: Minnesota, the Upper Peninsula of Michigan, and northern Wisconsin; the southeastern part of the basin refers to the remaining areas of the basin. In the southeastern part of the basin, May through September and November through January runoff increased at all or most stations. In the northwestern part of the basin for these months, there was a mixture of increases and decreases—or all decreases—depending on the month. February and October runoff, and annual 7-day low runoff increased at most or all stations in the basin. March runoff decreased at most stations in southern Michigan, Indiana, Ohio, and New York and increased at all stations to the northwest of southern Michigan. April runoff decreased at 75 percent of stations in the basin.

Consistent with this study, other researchers have found many increases in Great Lakes Basin streamflows in the last 50 years. Lettenmaier and others (1994) found many significant ($p < 0.02$) increases in annual flows and in monthly flows for December through March from 1948 to 1988. Significant increases in April through June flows were observed at many stations in the western part of the basin, and significant increases in September through November flows were observed at several stations in the eastern part of the basin. Some of the changes found by Lettenmaier and others (1994) differ from changes found in this study (changes for

Table 5. Monthly precipitation changes in the U.S. Great Lakes Basin, 1955-2004.

[All trends in inches; HCN, U.S. Historical Climatology Network]

HCN station number	Station name	January	February	March	April	May	June	July	August	September	October	November	December
120676	Berne, Indiana	0.09	0.32	-0.88	0.19	0.40	0.05	0.35	1.12	-0.38	0.29	0.17	-0.23
123418	Goshen College, Indiana	0.10	0.06	0.12	0.00	1.70	0.44	-0.03	0.86	0.52	0.36	0.18	0.69
200146	Alma, Michigan	0.96	0.58	0.33	0.75	0.42	0.40	0.28	0.06	0.62	0.45	0.82	0.24
200779	Big Rapids Waterworks, Michigan	0.77	0.36	0.36	0.63	1.05	1.11	0.70	2.07	0.46	1.06	0.36	-0.18
201439	Champion Van Riper Pk, Michigan	0.60	0.13	0.82	0.02	-0.29	0.65	1.52	-0.43	-0.13	0.56	-0.34	-0.13
201486	Chatham Exp Farm #2, Michigan	0.38	-0.27	0.50	-0.43	0.52	0.25	1.08	0.66	0.65	1.85	-0.29	-0.41
201675	Coldwater State School, Michigan	0.39	0.47	-0.59	-1.28	1.21	0.28	-0.78	2.20	0.57	1.51	0.30	0.90
203632	Hart, Michigan	0.00	-0.12	-0.32	-0.39	0.95	-0.29	-0.01	1.54	0.08	0.49	-0.11	-0.35
203823	Hillsdale, Michigan	0.21	0.00	-0.53	-0.13	1.14	0.59	-0.39	2.69	2.24	1.26	0.18	0.09
206300	Owosso 3NNW, Michigan	-0.09	-0.21	-0.74	-0.13	0.77	-0.88	-0.59	-0.90	0.51	0.60	0.14	-0.28
207690	South Haven, Michigan	-0.02	0.21	-0.68	0.70	2.00	0.18	-0.23	0.75	1.76	0.89	1.59	0.59
211630	Cloquet, Minnesota	0.07	0.15	0.09	0.18	0.07	0.90	0.95	0.80	0.60	0.76	0.47	-0.59
212645	Eveleth Waste Water Pl, Minnesota	-0.03	0.13	-0.10	-0.91	-0.38	0.50	0.84	0.31	0.09	0.53	-0.23	-0.48
218419	Two Harbors, Minnesota	0.47	0.21	0.50	0.67	-0.84	0.11	0.59	0.43	0.31	0.72	0.75	-0.35
300183	Angelica, New York	0.25	-0.39	0.32	0.04	0.37	0.97	0.77	0.73	1.55	0.87	0.25	0.43
301012	Buffalo WSCMO AP, New York	0.72	-0.02	0.67	-0.22	1.87	1.38	0.18	-1.61	1.38	1.43	0.72	0.79
301974	Dansville, New York	0.32	-0.25	0.44	0.48	0.61	0.65	1.22	0.74	2.11	0.49	0.39	0.23
303033	Fredonia, New York	0.22	-0.17	0.13	0.14	0.76	0.48	0.89	-0.61	0.33	0.73	-0.40	0.34
303184	Geneva Resr Fm, New York	-0.54	-1.35	0.26	-0.09	0.95	0.81	-0.09	-0.18	1.45	0.00	0.43	-0.22
304174	Ithaca Cornell Un, New York	0.32	-0.50	0.29	0.34	0.20	0.93	-0.64	-0.38	1.23	-0.03	0.73	0.27
306164	Ogdensburg 4NE, New York	0.89	0.11	0.68	0.27	0.66	0.85	1.00	-0.39	1.45	0.40	0.88	0.37
307167	Rochester Airport, New York	0.72	-0.46	0.96	0.40	1.12	1.06	0.57	0.93	1.56	0.26	0.83	0.73

Table 5. Monthly precipitation changes in the U.S. Great Lakes Basin, 1955-2004.—Continued

[All trends in inches; HCN, U.S. Historical Climatology Network]

HCN station number	Station name	January	February	March	April	May	June	July	August	September	October	November	December
308248	Stillwater Reservoir, New York	2.11	0.26	0.65	-0.47	0.43	0.11	0.66	-0.70	2.22	0.66	0.70	0.77
308944	Wanakena Ranger School, New York	0.47	-0.46	-0.32	-0.69	0.38	0.57	0.77	-1.25	1.44	0.34	-0.09	-1.00
331541	Chippewa Lake, Ohio	0.75	-0.09	-0.06	0.92	0.97	0.09	-0.34	0.21	0.66	1.10	0.37	0.59
332791	Findlay WPCC, Ohio	0.28	0.11	-1.36	0.25	0.67	0.89	-0.27	0.11	-0.20	0.90	-0.65	0.15
334189	Kenton, Ohio	0.08	0.09	-0.66	0.74	1.16	-0.38	-0.63	0.84	0.23	0.81	-0.45	-0.03
336196	Oberlin, Ohio	0.59	-0.42	-0.50	0.18	0.10	-0.10	-0.44	-0.25	1.36	0.84	0.07	0.31
338313	Tiffin, Ohio	0.06	0.02	-0.48	0.97	2.20	0.51	-1.71	1.07	0.89	0.84	-0.03	0.21
338534	Upper Sandusky, Ohio	-0.08	-0.03	-0.28	1.83	2.62	1.54	1.19	1.61	1.01	1.22	0.64	0.46
338822	Wauseon Water Plant, Ohio	-0.36	-0.64	-0.75	0.32	0.96	0.79	-0.63	0.76	1.20	1.14	-0.34	-0.11
362682	Erie WSO AP, Pennsylvania	0.14	-0.28	0.29	0.20	0.64	-0.79	-1.45	-1.17	1.50	0.57	-1.24	0.18
470349	Ashland Experiment Farm, Wisconsin	0.34	0.22	0.63	0.10	-0.73	0.89	-0.08	-1.62	-0.46	0.49	0.23	-0.16
472839	Fond du Lac, Wisconsin	0.66	0.26	-0.01	0.26	-0.78	1.10	-0.61	0.70	0.58	-0.11	-0.13	-0.17
475474	Milwaukee Mt Mary Col, Wisconsin	0.18	0.26	-1.11	-0.30	0.38	1.00	0.15	1.10	0.51	-0.26	-0.06	-0.23
475932	New London, Wisconsin	0.37	-0.29	-0.06	0.41	-0.03	1.66	0.96	0.88	0.52	0.47	0.02	-0.50
476330	Oshkosh, Wisconsin	0.31	0.03	-0.48	-0.02	-0.88	0.94	-0.70	0.05	-0.18	-0.81	0.37	-0.43

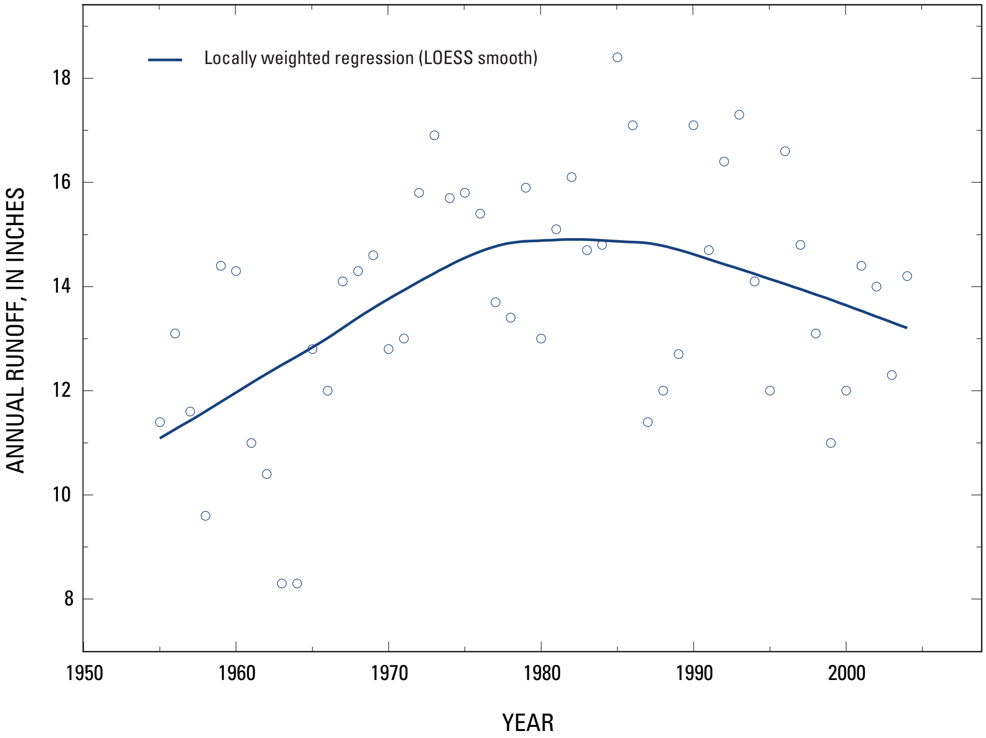


Figure 5. Annual runoff for the average of 43 stations in the U.S. Great Lakes Basin, 1955–2004.

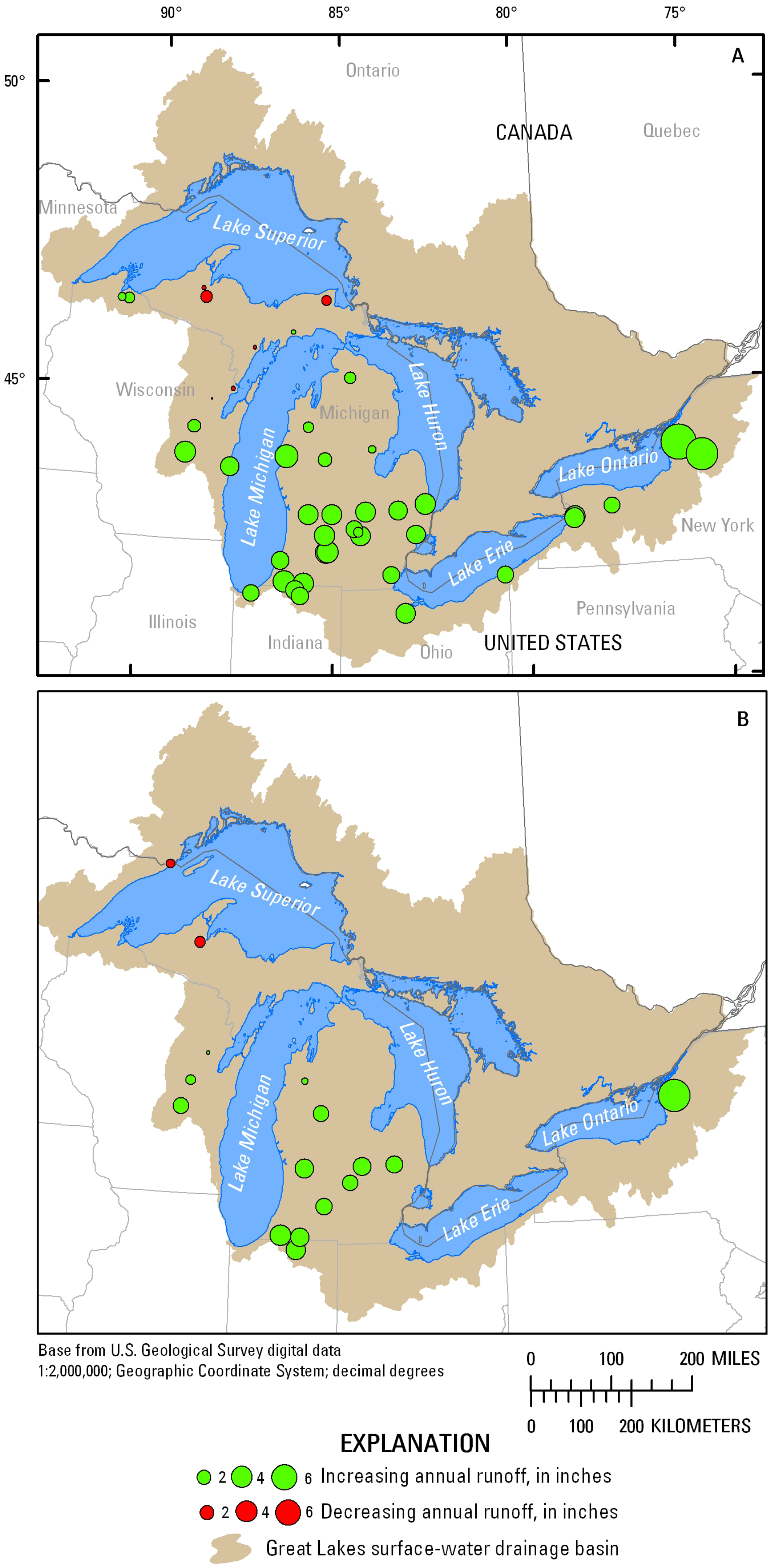
parts of the U.S. Great Lakes Basin in March, April, May, and June). This discrepancy may be due to differences in the time period studied. Lins and Slack (1999) found many significant ($p < 0.05$) increases in annual minimum daily and median daily flows in the basin, and no significantly decreasing flows, for various time periods through 1993. Small and others (2006) reported significant ($p < 0.05$) increases in annual 7-day low flows at 6 of 13 basins and in mean annual flows at 8 of 13 basins in the Great Lakes Basin from 1948 to 1997. In the Canadian Great Lakes Basin, Xuebin and others (2001) reported increasing mean annual streamflows at all five stations between Lakes Huron, Erie, and Ontario from 1947 to 1996. Changes in annual minimum daily flows for these same stations and time period were mixed.

Comparison of Streamflow Changes and Precipitation Changes

The primary cause of any changes in runoff from streams relatively free of human influences in the U.S. Great Lakes Basin is expected to be changes in precipitation. Temperature could affect seasonal runoff through changes in the timing of annual snowmelt runoff. Precipitation changes are compared to runoff changes in the basin in this section, and potential reasons for any difference between these changes are discussed in following sections.

Mean annual precipitation and runoff, based on the average of 37 precipitation stations and 43 streamflow-gaging stations in the U.S. Great Lakes Basin, both increased from 1955 to 2004; annual precipitation increased by 4.2 in. and annual runoff increased by 2.6 in. Precipitation and runoff change patterns for individual stations across the basin were similar (figs. 3*C* and 6*A*). Precipitation and runoff changes are scaled differently on these and other figures because runoff is about 40 percent, on average, of precipitation in the U.S. Great Lakes Basin. The relatively small decreases in runoff in the Upper Peninsula of Michigan are not evident for the two precipitation stations in this area, but they are in different areas than the streamflow-gaging stations. Mean monthly precipitation and runoff changes based on the average of 37 and 28 stations, respectively, in the basin for 1955 to 2004 had similarities and differences (table 10). For November through January and for July, precipitation and runoff increased by similar amounts. For February and March, precipitation decreased slightly, and runoff increased. April was the opposite, with precipitation increasing and runoff decreasing. For May, June, August, September, and October, precipitation increased more than runoff, with the largest differences observed in May and September.

Precipitation and runoff changes for 1955 to 2004 for individual stations across the basin for individual months had similar patterns for many months, given that precipitation and streamflow stations are in different locations (figs. 4*A*, 4*B*, 7*A*, and 7*B*). In February, there were many more precipitation



Base from U.S. Geological Survey digital data
1:2,000,000; Geographic Coordinate System; decimal degrees

Figure 6. Changes in annual runoff, by station, for (A) 1955–2004 and (B) 1935–2004. Circle sizes proportional to increases or decreases.

Table 6. Mean annual runoff changes in the U.S. Great Lakes Basin, 1955–2004.

Streamflow-gaging station number	Station name	Drainage area, in square miles	Change, in inches
04027000	Bad River near Odanah, Wisconsin	597	0.96
04027500	White River near Ashland, Wisconsin	301	0.49
04040500	Sturgeon River near Sidnaw, Michigan	171	-1.33
04041500	Sturgeon River near Alston, Michigan	346	-0.22
04045500	Tahquamenon River near Paradise, Michigan	790	-0.90
04056500	Manistique River near Manistique, Michigan	1,100	0.19
04059500	Ford River near Hyde, Michigan	450	-0.13
04069500	Peshtigo River at Peshtigo, Wisconsin	1,080	-0.19
04071000	Oconto River near Gillett, Wisconsin	705	0.04
04073500	Fox River at Berlin, Wisconsin	1,340	3.78
04079000	Wolf River at New London, Wisconsin	2,260	1.53
04086000	Sheboygan River at Sheboygan, Wisconsin	418	3.24
04094000	Little Calumet River at Porter, Indiana	66.2	2.67
04099000	St. Joseph River at Mottville, Michigan	1,866	4.05
04100500	Elkhart River at Goshen, Indiana	594	2.93
04101000	St. Joseph River at Elkhart, Indiana	3,370	3.08
04101500	St. Joseph River at Niles, Michigan	3,666	4.12
04102500	Paw Paw River at Riverside, Michigan	390	2.84
04105000	Battle Creek at Battle Creek, Michigan	241	4.11
04105500	Kalamazoo River near Battle Creek, Michigan	824	4.29
04111500	Deer Creek near Dansville, Michigan	16.3	3.34
04112000	Sloan Creek near Williamston, Michigan	9.3	0.94
04112500	Red Cedar River at East Lansing, Michigan	355	2.40
04116000	Grand River at Ionia, Michigan	2,840	3.35
04117500	Thornapple River near Hastings, Michigan	385	3.92
04119000	Grand River at Grand Rapids, Michigan	4,900	3.58
04121500	Muskegon River at Evart, Michigan	1,433	1.58
04122500	Pere Marquette River at Scottville, Michigan	681	4.67
04124000	Manistee River near Sherman, Michigan	857	1.06
04127997	Sturgeon River at Wolverine, Michigan	192	1.21
04142000	Rifle River near Sterling, Michigan	320	0.50
04144500	Shiawassee River at Owosso, Michigan	538	3.47
04146000	Farmers Creek near Lapeer, Michigan	55.3	3.08
04159492	Black River near Jeddo, Michigan	464	3.90
04164500	North Branch Clinton River near Mt. Clemens, Michigan	199	3.06
04176500	River Raisin near Monroe, Michigan	1,042	2.51
04198000	Sandusky River near Fremont, Ohio	1,251	3.40
04213000	Conneaut Creek at Conneaut, Ohio	175	2.66
04214500	Buffalo Creek at Gardenville, New York	142	3.75
04215500	Cazenovia Creek at Ebenezer, New York	135	3.34

Table 6. Mean annual runoff changes in the U.S. Great Lakes Basin, 1955–2004.—Continued

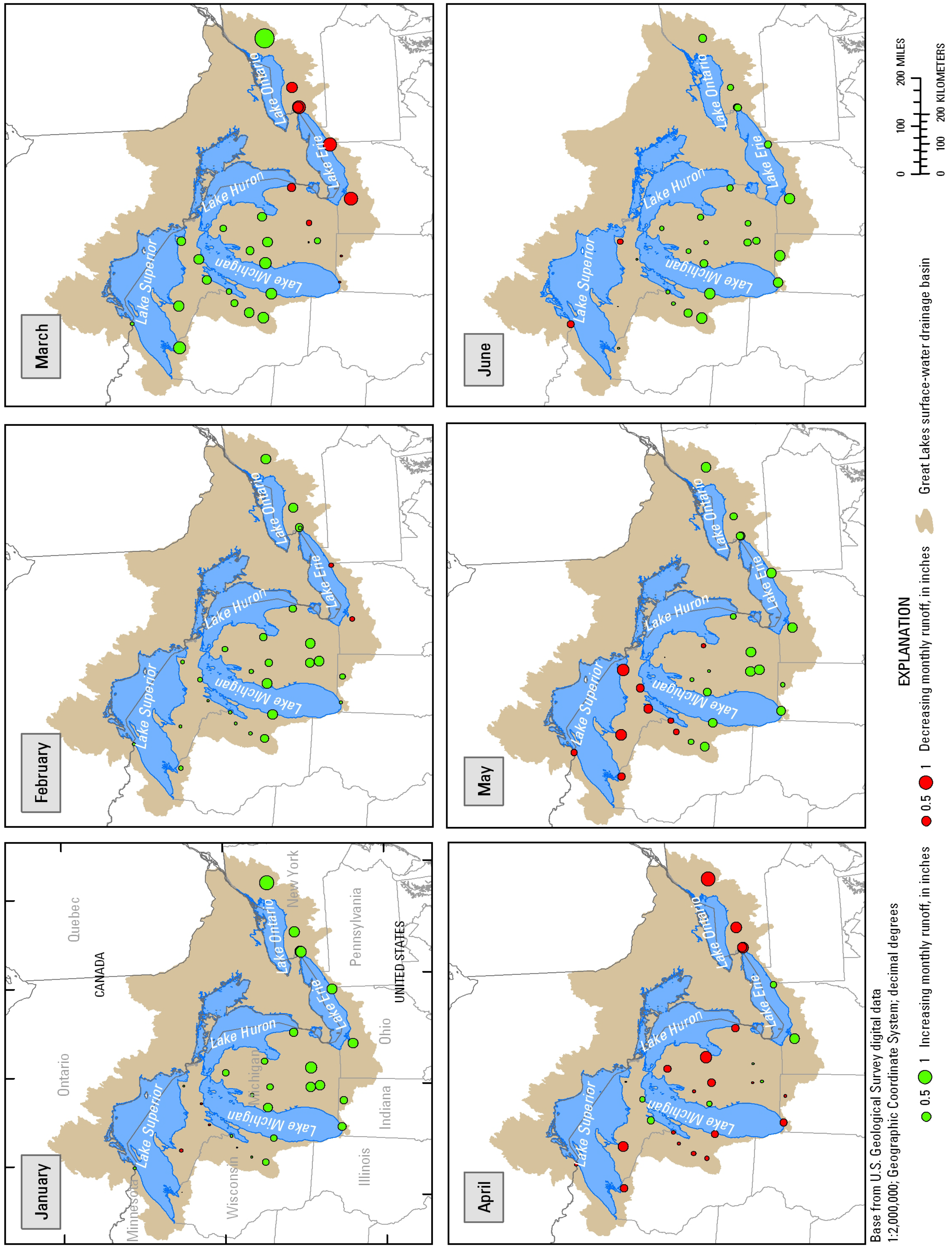
Streamflow-gaging station number	Station name	Drainage area, in square miles	Change, in inches
04230500	Oatka Creek at Garbutt, New York	200	2.29
04256000	Independence River at Donnattsburg, New York	88.7	8.81
04260500	Black River at Watertown, New York	1,864	11.07

Table 7. Mean annual runoff changes in the U.S. Great Lakes basin, 1935–2004.

Streamflow-gaging station number	Station name	Drainage area, in square miles	Change, in inches
04010500	Pigeon River at Middle Falls near Grand Portage, Minnesota	609	-0.66
04041500	Sturgeon River near Alston, Michigan	346	-1.05
04071000	Oconto River near Gillett, Wisconsin	705	0.15
04073500	Fox River at Berlin, Wisconsin	1,340	2.19
04079000	Wolf River at New London, Wisconsin	2,260	0.82
04099000	St. Joseph River at Mottville, Michigan	1,866	3.21
04100500	Elkhart River at Goshen, Indiana	594	3.52
04101500	St. Joseph River at Niles, Michigan	3,666	3.94
04105000	Battle Creek at Battle Creek, Michigan	241	2.59
04112500	Red Cedar River at East Lansing, Michigan	355	2.16
04119000	Grand River at Grand Rapids, Michigan	4,900	3.29
04121500	Muskegon River at Evart, Michigan	1,433	2.14
04124000	Manistee River near Sherman, Michigan	857	0.40
04144500	Shiawassee River at Owosso, Michigan	538	2.97
04146000	Farmers Creek near Lapeer, Michigan	55.3	2.64
04260500	Black River at Watertown, New York	1,864	9.18

Table 8. Mean monthly runoff changes in the U.S. Great Lakes Basin, 1955–2004.

Month	Change, in inches
January	0.30
February	0.22
March	0.18
April	-0.17
May	0.11
June	0.23
July	0.13
August	0.11
September	0.05
October	0.22
November	0.27
December	0.18



Base from U.S. Geological Survey digital data
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EXPLANATION

🟢 0.5 🟢 1 Increasing monthly runoff, in inches

🔴 0.5 🔴 1 Decreasing monthly runoff, in inches

Great Lakes surface-water drainage basin

Figure 7a. Changes in monthly runoff for January through June, by station, 1955–2004. Circle sizes proportional to increases or decreases.

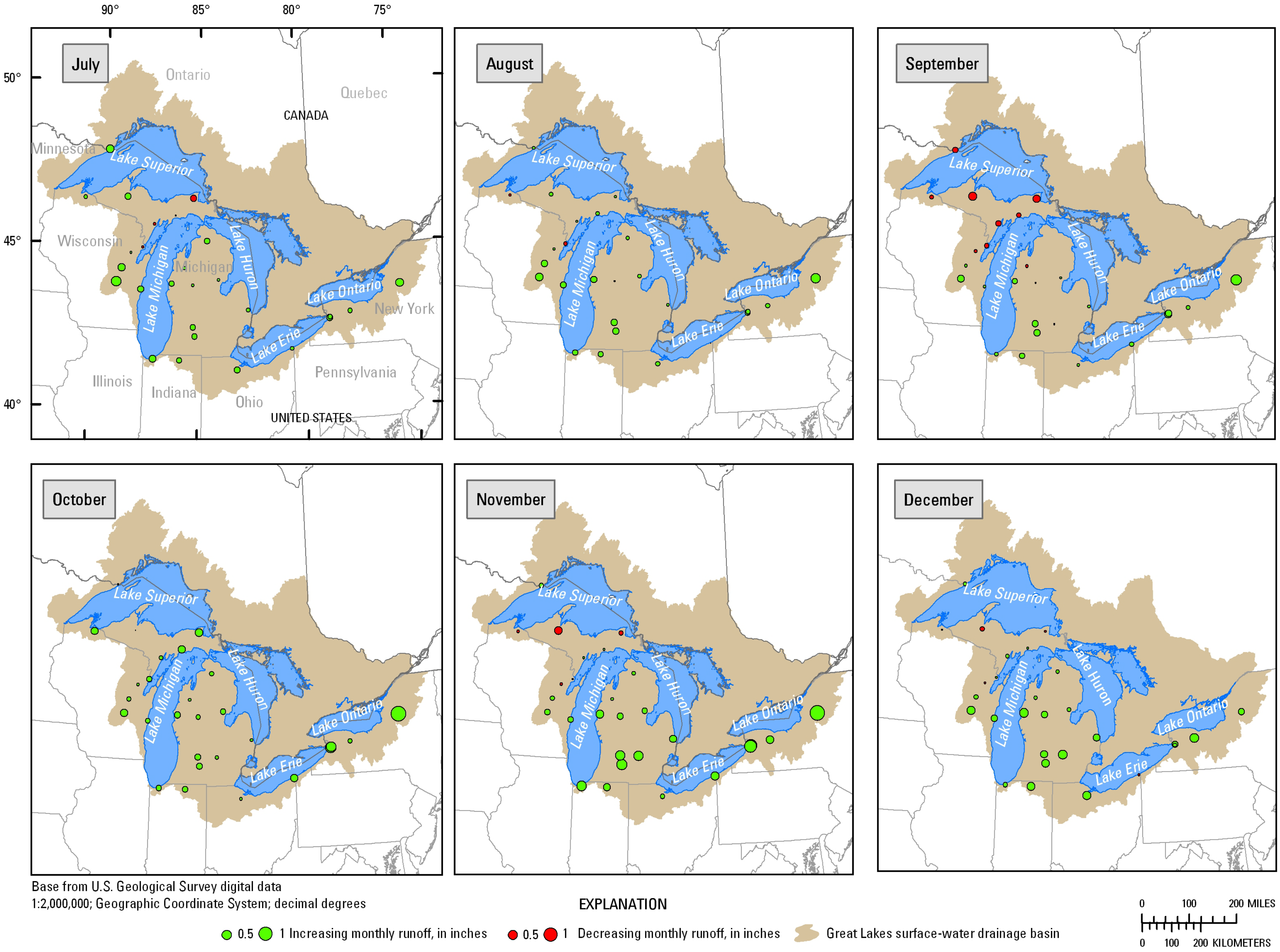

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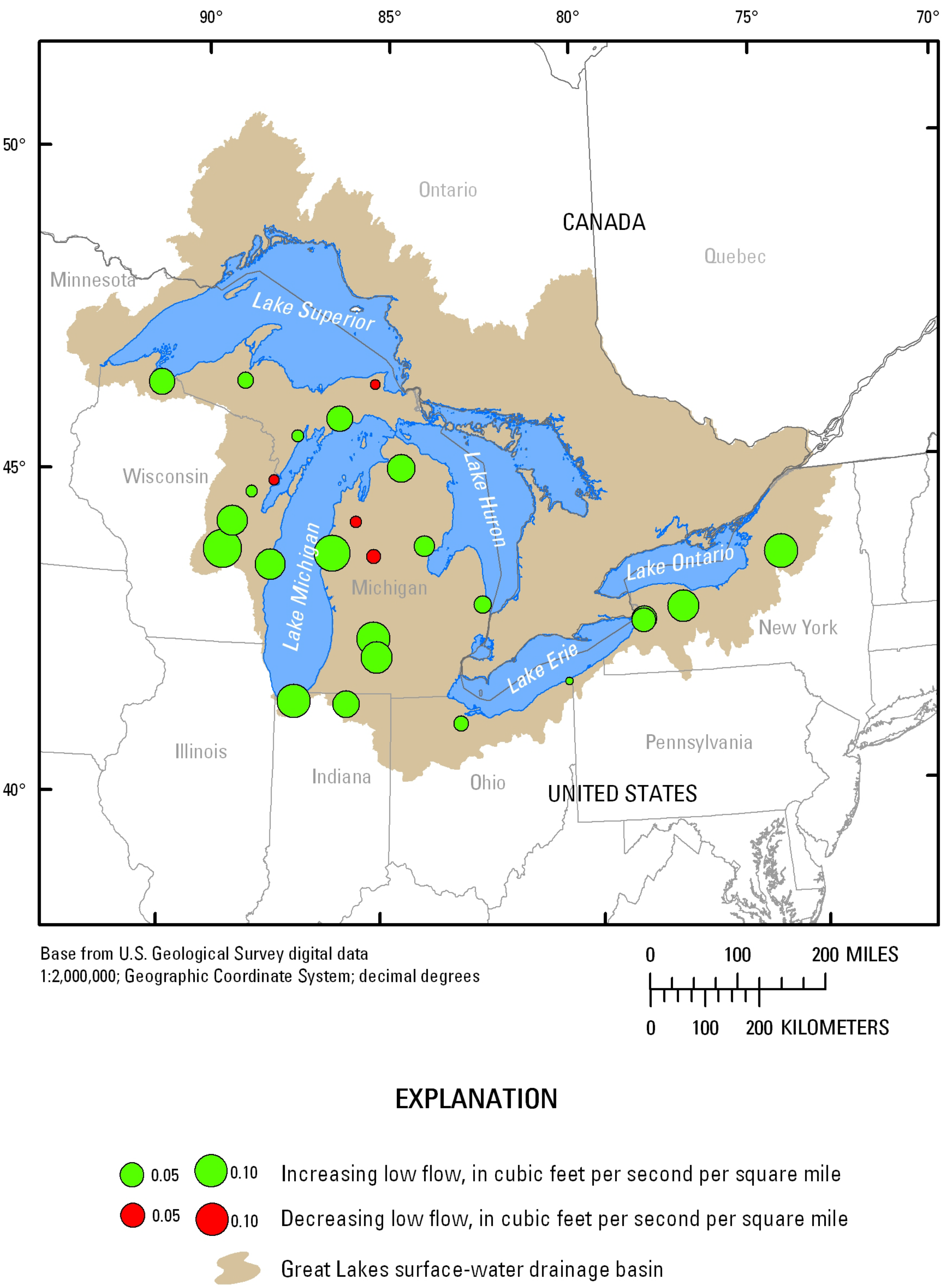
Figure 7b. Changes in monthly runoff for July through December, by station, 1955–2004. Circle sizes proportional to increases or decreases.



Base from U.S. Geological Survey digital data
1:2,000,000; Geographic Coordinate System; decimal degrees

Figure 8. Changes in annual 7-day low runoff, by station, 1955–2004. Circle sizes proportional to increases or decreases.

Table 9a. January through June monthly runoff changes in the U.S. Great Lakes Basin, 1955–2004.

[All changes in inches; USGS, U.S. Geological Survey]

USGS streamflow-gaging station number	USGS station name	Drainage area, in square miles	January	February	March	April	May	June
04010500	Pigeon River at Middle Falls near Grand Portage, Minnesota	600	0.07	0.04	0.10	-0.08	-0.25	-0.30
04027000	Bad River near Odanah, Wisconsin	597	-0.00	0.11	0.80	-0.26	-0.28	0.03
04040500	Sturgeon River near Sidnaw, Michigan	171	-0.07	0.06	0.59	-0.54	-0.61	0.01
04045500	Tahquamenon River near Paradise, Michigan	790	0.03	0.10	0.47	-0.02	-0.75	-0.15
04056500	Manistique River near Manistique, Michigan	1,100	-0.03	0.13	0.53	0.16	-0.38	0.04
04059500	Ford River near Hyde, Michigan	450	-0.03	0.03	0.46	0.27	-0.40	0.00
04069500	Peshtigo River at Peshtigo, Wisconsin	1,080	0.05	0.08	0.18	-0.08	-0.17	0.09
04071000	Oconto River near Gillett, Wisconsin	705	-0.01	0.06	0.27	-0.05	-0.18	0.07
04073500	Fox River at Berlin, Wisconsin	1,340	0.21	0.33	0.59	-0.14	0.44	0.57
04079000	Wolf River at New London, Wisconsin	2,260	0.03	0.10	0.52	-0.14	0.15	0.37
04086000	Sheboygan River at Sheboygan, Wisconsin	418	0.24	0.55	0.61	-0.27	0.47	0.56
04094000	Little Calumet River at Porter, Indiana	66.2	0.33	0.06	-0.02	-0.30	0.45	0.47
04100500	Elkhart River at Goshen, Indiana	594	0.30	0.18	-0.03	-0.05	0.11	0.61
04105000	Battle Creek at Battle Creek, Michigan	241	0.55	0.52	0.24	0.05	0.54	0.31
04111500	Deer Creek near Dansville, Michigan	16.3	0.66	0.52	-0.17	0.03	0.51	0.17
04117500	Thornapple River near Hastings, Michigan	385	0.49	0.43	-0.01	-0.02	0.55	0.29
04121500	Muskegon River at Evart, Michigan	1,450	0.21	0.31	0.55	-0.38	0.06	0.13
04122500	Pere Marquette River at Scottville, Michigan	681	0.47	0.54	0.68	0.15	0.34	0.33
04124000	Manistee River near Sherman, Michigan	857	0.08	0.11	0.32	-0.04	0.10	0.13
04127997	Sturgeon River at Wolverine, Michigan	192	0.24	0.18	0.24	-0.25	-0.00	0.13
04142000	Rifle River near Sterling, Michigan	320	0.20	0.27	0.44	-0.67	-0.10	0.21
04159492	Black River near Jeddo, Michigan	464	0.37	0.31	-0.38	-0.26	0.18	0.22
04198000	Sandusky R near Fremont, Ohio	1,251	0.53	-0.14	-0.88	0.48	0.52	0.60
04213000	Conneaut C at Conneaut, Ohio	175	0.53	-0.11	-0.94	0.25	0.49	0.29
04214500	Buffalo Creek at Gardenville, New York	142	0.65	0.36	-0.60	-0.43	0.27	0.31
04215500	Cazenovia Creek at Ebenezer, New York	135	0.57	0.09	-0.94	-0.64	0.36	0.29
04230500	Oatka Creek at Garbutt, New York	200	0.62	0.44	-0.58	-0.64	0.28	0.25
04256000	Independence River at Donnattsburg, New York	88.7	1.03	0.53	1.92	-1.01	0.47	0.35

Table 9b. July through December monthly runoff and annual 7-day low runoff changes in the U.S. Great Lakes Basin, 1955–2004.

[All changes in inches; USGS, U.S. Geological Survey; ft^3/s/mi^2, cubic feet per second per square mile; --, not available]

USGS streamflow-gaging station number	USGS station name	Drainage area, in square miles	July	August	September	October	November	December	7-day low runoff, in ft^3/s/mi^2
04010500	Pigeon River at Middle Falls near Grand Portage, Minnesota	600	0.36	0.06	-0.17	0.01	0.13	0.07	--
04027000	Bad River near Odanah, Wisconsin	597	0.07	-0.03	-0.09	0.30	-0.07	-0.01	0.059
04040500	Sturgeon River near Sidnaw, Michigan	171	0.19	0.09	-0.38	0.00	-0.37	-0.13	0.023
04045500	Tahquamenon River near Paradise, Michigan	790	-0.22	0.02	-0.28	0.39	-0.14	-0.02	-0.007
04056500	Manistique River near Manistique, Michigan	1,100	-0.01	0.10	-0.14	0.32	0.04	0.03	0.058
04059500	Ford River near Hyde, Michigan	450	-0.05	0.02	-0.17	0.10	0.02	0.07	0.012
04069500	Peshtigo River at Peshtigo, Wisconsin	1,080	-0.02	-0.09	-0.13	0.15	0.01	0.02	-0.010
04071000	Oconto River near Gillett, Wisconsin	705	0.03	0.03	-0.06	0.04	-0.06	-0.03	0.012
04073500	Fox River at Berlin, Wisconsin	1,340	0.51	0.35	0.27	0.30	0.17	0.33	0.127
04079000	Wolf River at New London, Wisconsin	2,260	0.24	0.21	0.04	0.13	0.12	0.13	0.080
04086000	Sheboygan River at Sheboygan, Wisconsin	418	0.21	0.24	0.06	0.14	0.20	0.23	0.081
04094000	Little Calumet River at Porter, Indiana	66.2	0.26	0.17	0.10	0.19	0.51	0.15	0.099
04100500	Elkhart River at Goshen, Indiana	594	0.17	0.16	0.19	0.19	0.33	0.33	0.065
04105000	Battle Creek at Battle Creek, Michigan	241	0.18	0.20	0.21	0.22	0.59	0.40	0.083
04111500	Deer Creek near Dansville, Michigan	16.3	0.00	0.00	0.02	0.07	0.50	0.43	0.000
04117500	Thornapple River near Hastings, Michigan	385	0.15	0.20	0.21	0.21	0.54	0.30	0.095
04121500	Muskegon River at Evart, Michigan	1,450	0.04	0.02	0.01	0.13	0.24	0.26	-0.017
04122500	Pere Marquette River at Scottville, Michigan	681	0.18	0.23	0.15	0.26	0.35	0.44	0.109
04124000	Manistee River near Sherman, Michigan	857	0.06	-0.00	-0.05	0.04	0.07	0.08	-0.011
04127997	Sturgeon River at Wolverine, Michigan	192	0.14	0.10	0.00	0.14	0.09	0.10	0.068
04142000	Rifle River near Sterling, Michigan	320	0.06	0.09	0.03	0.15	0.16	0.09	0.038
04159492	Black River near Jeddo, Michigan	464	0.09	0.04	0.06	0.07	0.27	0.29	0.027
04198000	Sandusky R near Fremont, Ohio	1,251	0.20	0.11	0.04	0.06	0.13	0.40	0.019
04213000	Conneaut C at Conneaut, Ohio	175	0.08	0.00	0.14	0.26	0.34	-0.03	0.004
04214500	Buffalo Creek at Gardenville, New York	142	0.13	0.10	0.25	0.52	0.89	0.20	0.056
04215500	Cazenovia Creek at Ebenezer, New York	135	0.20	0.15	0.31	0.57	0.83	0.09	0.047
04230500	Oatka Creek at Garbutt, New York	200	0.13	0.11	0.10	0.12	0.40	0.46	0.087
04256000	Independence River at Donnattsburg, New York	88.7	0.33	0.48	0.61	1.12	1.20	0.25	0.101

decreases than runoff decreases (figs. 4*A* and 7*A*). In March, southern Wisconsin precipitation decreases contrast with runoff increases; east of Lake Erie, precipitation *increases* contrast with runoff *decreases* (figs. 4*A* and 7*A*). There were fewer decreases in April precipitation than in April runoff (figs. 4*A* and 7*A*). In July and August, there were precipitation decreases in parts of the basin that did not appear in the runoff changes, but increased precipitation at stations tended to be larger than the increased runoff (figs. 4*B* and 7*B*).

Snowmelt-Runoff Changes

The discrepancies between precipitation and runoff changes for February, March, and April in the U.S. Great Lakes Basin are likely due to lower ratios of snowfall to rain and earlier snowmelt runoff in the late winter and early spring. For the entire basin from 1955 to 2004, precipitation decreased slightly in February and March, and runoff increased. In contrast, April precipitation increased, and April runoff decreased. This represents a shift toward earlier runoff; water that was formerly stored in the snowpack in February and March and released in April is now flowing into streams and rivers earlier in the season. February and March air temperatures in the U.S. Great Lakes Basin from the average of 37 HCN stations increased by 5.0°F and 3.0°F, respectively, from 1955 to 2004. Temperatures increased at all stations. Air-temperature increases from 1935 to 2004 were more moderate, 2.3°F in February and 2.6°F in March.

Earlier snowmelt runoff has been documented for a large part of eastern North America, including the Great Lakes Basin. Earlier flows by 5 to 10 days were the most common change in the timing of winter-spring streamflows from 1953 to 2002 in the U.S. Great Lakes Basin (Hodgkins and Dudley, 2006).

Burnett and others (2003) reported significant ($p < 0.05$) increasing lake-effect snowfall from 1931 to 2001, potentially the result of warmer Great Lakes and decreased ice cover; there were no changes in non-lake-effect areas further to the east. This may explain why southern Wisconsin precipitation decreased in March from 1955 to 2004 and runoff increased; but east of Lake Erie in March, precipitation increased and runoff decreased (figs. 4*A* and 7*A*).

Evapotranspiration Changes

Annual precipitation in the U.S. Great Lakes Basin increased by 4.2 in. from 1955 to 2004, and runoff increased by 2.6 in. Some of the difference in the magnitude of the changes could be caused by the different locations of the precipitation and streamflow stations in the basin. Part of the difference, however, may be explained by changes in evapotranspiration (water lost to the atmosphere from the combination of evaporation from water bodies and soil and transpiration from plants).

The differences between monthly precipitation and runoff changes support the idea that changes in evapotranspiration in the basin explain at least part of the difference in the annual changes. Increases in precipitation were larger than increases in runoff for May, June, August, September, and October (table 10). Increasing precipitation, by causing increases in soil moisture, would lead to greater evapotranspiration because the number and duration of periods with soil moisture low enough to significantly restrict evapotranspiration would be reduced (Walter and others, 2004). Walter and others found a larger increase in precipitation than runoff within the U.S. Great Lakes Basin from 1950 to 2000 and attributed the difference to increased evapotranspiration.

Table 10. Mean monthly precipitation and runoff changes in the U.S. Great Lakes Basin, 1955–2004.

Month	Precipitation change, 1955–2004, in inches	Runoff change, 1955–2004, in inches	Difference between precipitation and runoff changes, 1955–2004, in inches
January	0.34	0.30	0.04
February	-0.05	0.22	-0.27
March	-0.05	0.18	-0.23
April	0.16	-0.17	0.33
May	0.63	0.11	0.52
June	0.55	0.23	0.32
July	0.14	0.13	0.01
August	0.37	0.11	0.26
September	0.82	0.05	0.77
October	0.64	0.22	0.42
November	0.19	0.27	-0.08
December	0.07	0.18	-0.11

Relation of Low-Flow Changes to Agricultural Land Use

The basins described and used for analysis in this section of the report are thought to be relatively free of human influences such as land-use change. However, there may be subtle changes associated with land use that have not been considered in the past. One possible change could be changing agricultural practices (Gebert and Krug, 1996). Agricultural land use for basins in the U.S. Great Lakes Basin in this study ranged from 1 percent to 88 percent.

Low flows could be sensitive to changes in agricultural practices. Annual 7-day low runoff changes from 1955 to 2004 for 27 basins were regressed against agricultural land use in those basins (fig. 9). Runoff increases were larger, on average, for basins with higher amounts of agricultural land use than for basins with lower amounts of agricultural land use, although the relation was not significant ($p < 0.10$). Based on the linear regression line shown in figure 9, runoff increases for basins with the highest amount of agricultural land use were more than 50 percent higher than for basins with the lowest amount. This relation may indicate that changing agricultural practices over time have led to an increase in the lowest flows of the year; the increase would be greater for basins with a higher percentage of agricultural land use. This assumes that the percentage of agricultural land use in the individual basins has remained constant over time.

Gebert and Krug (1996) found annual 7-day low-flow increases in southern Wisconsin during the 20th century. The low-flow changes were attributed to changing agricultural practices (contour strip cropping, contour plowing, incorporation of crop residue into the soil, crop rotation, and the filling of eroding gullies) and land-use changes (reversion of steep pasture land to forest) rather than to changes in precipitation. The changing agricultural practices are thought to have increased infiltration of precipitation into the soils, which would cause higher ground-water levels and thus increased base flows, including annual 7-day low flows.

Highly Urbanized Streams

Many studies in the last 40 years have examined the impact of urbanization on hydrology. Leopold (1968) described increased runoff, higher peak flows, and decreased ground-water recharge and thus lower streamflows during low-flow periods due to increased impervious area. Since that time, it has been documented that urbanization also can increase low flows. Flows can increase because of sewerline and water-supply-line leakage, direct discharge of treated sewage, and decreased evapotranspiration and soil-moisture depletion (Brandes and others, 2005). Increases or decreases in ground-water pumping may also decrease or increase low flows (Aichele, 2005a). Researchers have found increased low flows, decreased low flows, and little change in low flows as urbanization has increased (Rose and Peters, 2001; Konrad and Booth, 2002; Aichele, 2005a; Brandes and others, 2005). Dewalle and others (2000) in their analysis of 39 urbanizing and 21 rural basins—mostly in the eastern U.S—found significant positive correlations between annual runoff and population density where higher annual runoff was associated with higher population density for 15 urbanizing basins and significant negative correlations for 2 urbanizing basins.

One station in the U.S. Great Lakes Basin met the criteria of this study for highly urbanized basins; it is located on the River Rouge in the metropolitan Detroit area, and 64 percent of the land use within the station’s drainage basin is urban (table 11). The annual-runoff increase for the River Rouge from 1955 to 2004 was the third highest change in the U.S. Great Lakes Basin when compared to basins relatively free of human influences (table 6; fig. 6*A*). The annual 7-day low-runoff change was the highest low-runoff change in the U.S. Great Lakes Basin when compared to the basins relatively free of human influences (table 9*B*; fig. 8); flows increased through the early 1990s and decreased from the early 1990s to 2004 (fig. 10). The population and population density in the basin roughly doubled from 1950 to 1970 and then remained relatively constant through 2000.

The relatively high increase in low flows over time in the River Rouge Basin may reflect decreased use of ground water and increased use of imported Great Lakes water that is eventually discharged into the basin from wastewater-treatment plants. Higher ground-water levels would lead to greater base flows. The increased use of imported water would increase low flows through pipe leakage and through wastewater discharges. Aichele (2005a; 2005b) found significantly higher ($p < 0.01$) low flows from 1970 to 2003 in two subbasins of the River Rouge Basin where nearly all water demand is met through imported water. One subbasin of the River Rouge Basin had significantly lower flows; in substantial areas of this subbasin, water supply is from ground water.

Highly Regulated Streams

Little has been written about the effects of high amounts of storage regulation on streamflows in the Great Lakes Basin. Reservoirs are designed to alter streamflows for industrial, power generation, water supply, and recreational uses. They typically store water during high flows and release it during low flows.

Four highly regulated basins met the criteria of this study (table 12). The three basins in the Upper Peninsula of Michigan showed decreasing annual runoff from 1955 to 2004, similar to decreases for basins relatively free of human influences in the Upper Peninsula (table 6; fig. 6*A*). The station on the Cuyahoga River in Ohio had a smaller increase in runoff over time than most stations in the southeastern part of the U.S. Great Lakes Basin.

The stations on the Michigamme River in Michigan and the Cuyahoga River in Ohio had higher 7-day low-runoff increases than all 27 basins in the Great Lakes Basin that

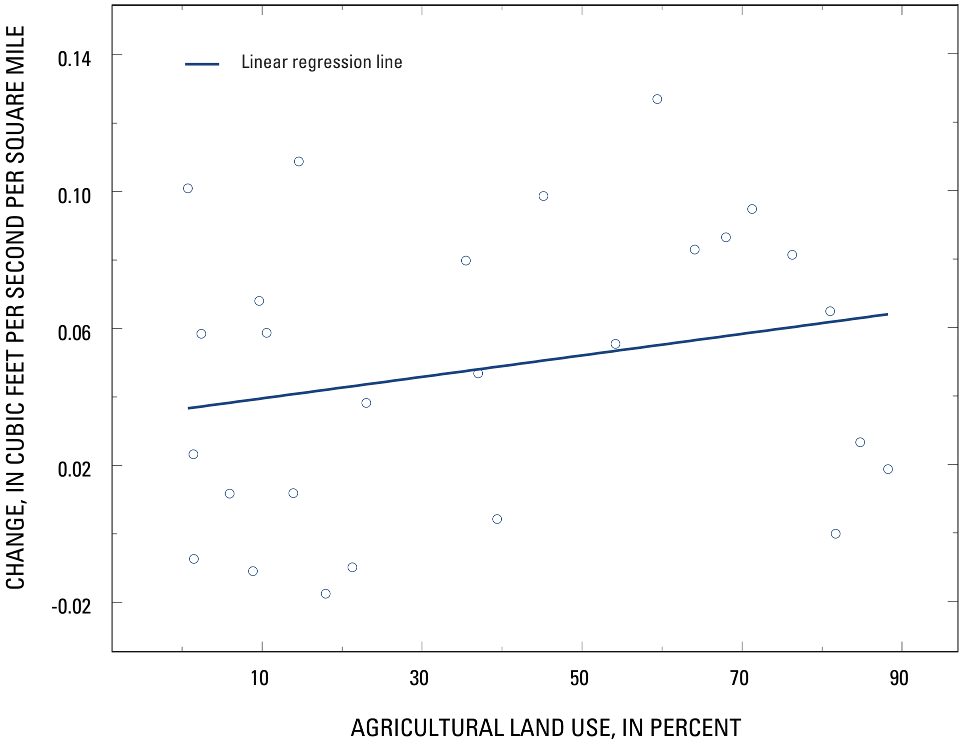


Figure 9. Relation between annual 7-day low runoff change, 1955–2004, and agricultural land use for 27 basins in the U.S. Great Lakes Basin.

Table 11. Mean annual runoff and mean 7-day low-flow changes for a highly urbanized stream in the U.S. Great Lakes Basin, 1955-2004.

[USGS, U.S. Geological Survey; mi^2, square miles; ft^3/s/mi^2; cubic feet per second per square mile]

USGS streamflow-gaging station number	USGS station name	Drainage area, in mi^2	Urban land use, in percent	Annual runoff change, in inches	Annual 7-day low-flow change, in ft^3/s/mi^2
04166500	River Rouge at Detroit, Michigan	187	64.1	4.97	0.134

were relatively free of human influences, from 1955 to 2004 (table 9*B*; fig. 8). The increases at the station on the Michigamme River are likely due to changes in the regulation of the Michigamme Reservoir over time. The increases at the station on the Cuyahoga River may be due to a combination of changes in flow regulation over time and the addition of the LaDue Reservoir in 1961. The stations on the two rivers in the Ontonagon River Basin in Michigan showed small decreases, whereas other streams in and near the Upper Peninsula of Michigan had both increasing and decreasing low-runoff over time.

Long-Term Perspective on Precipitation and Streamflow Changes

Changes—even over periods as long as 90 years—can be part of longer cycles. Quinn (1981) analyzed Great Lakes Basin precipitation from 1854 to 1979 and found (on average) high precipitation from 1854 to the mid-1880s, low precipitation from the mid-1880s to the late 1930s, and high precipitation from the late-1930s to 1979. Precipitation, at least in the U.S. part of the basin, continued to be high from 1979 to 2004.

Mortsch and others (2000) analyzed streamflow changes on the St. Lawrence River at Cornwall, Ontario, from 1861

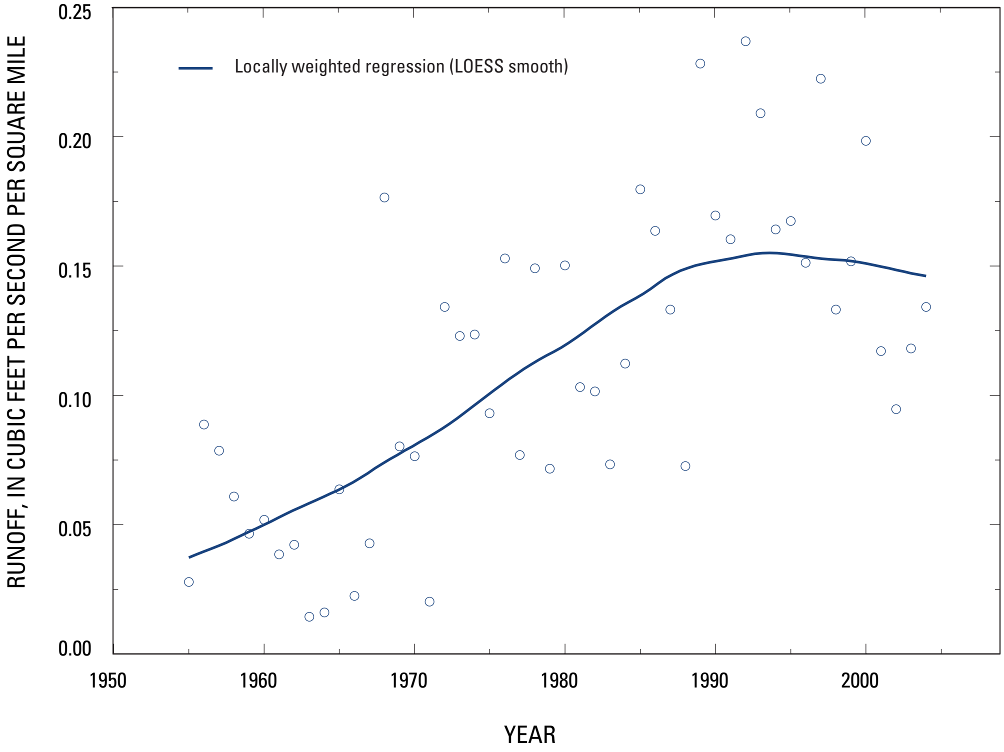


Figure 10. Annual 7-day low runoff for River Rouge at Detroit, Michigan, 1955–2004.

Table 12. Mean annual runoff and mean 7-day low-flow changes for highly regulated streams in the U.S. Great Lakes Basin, 1955–2004.

[USGS, U.S. Geological Survey; mi^2, square miles; ft^3/s/mi^2; cubic feet per second per square mile]

USGS streamflow-gaging station number	USGS station name	Drainage area, in mi^2	Major reservoirs in basin	Date of reservoir completion	Annual runoff change, in inches	Annual 7-day low-flow change, in ft^3/s/mi^2
04036000	West Branch Ontonagon River near Bergland, Michigan	162	Lake Gogebic	1906	-0.82	-0.009
04037500	Cisco Branch Ontonagon River at Cisco Lake Outlet, Michigan	50.7	Cisco Lake	1931	-0.97	-0.012
04062500	Michigamme River near Crystal Falls, Michigan	656	Michigamme Reservoir	1941	-0.50	0.166
04202000	Cuyahoga River at Hiram Rapids, Ohio	151	East Branch Reservoir	1939	1.31	0.131
			LaDue Reservoir	1961		

to 1994. The St. Lawrence River drains all of the Great Lakes and is subject to lake-level regulation on some of the Great Lakes, storage regulation on many of its tributaries, and some diversions into and out of the Great Lakes Basin. Flows were relatively high, on average, from 1861 to about 1890, low from about 1890 to about 1940, and high from about 1940 to 1994 (with the exception of the late 1950s and early 1960s). Despite the human influence on St. Lawrence River flows, the pattern of flows over time mirrors the precipitation results of Quinn (1981).

The precipitation and streamflow changes described in this report are likely part of a longer cycle. What this means for the future is unclear; but in the relatively recent past, precipitation over the land part of the U.S. Great Lakes Basin was lower than at present for several decades. The average precipitation for 1915–34 was 10 percent lower than for 1984–2003. Results from general circulation models used to simulate climate variables disagree on whether the United States and its different regions will receive more or less precipitation in the future. The impacts on specific regions will depend on changes in weather patterns and are certain to be complex (Thompson and others, 2005).

Summary and Conclusions

Long-term streamflow changes can provide insight into the natural and human processes that control water availability. The purpose of this report is to describe streamflow and precipitation changes within the U.S. Great Lakes Basin—in both time and space—to help reveal the ongoing processes that may affect present and future surface-water and ground-water availability. The total amount of water available in streams throughout the year and the water available during low-flow periods are both important. The total amount of water is important in the long-term allocation of water to human use and to riparian and aquatic ecosystems. The future growth of municipalities depends on an adequate supply of water. The water available during low-flow periods is particularly important because short-term demands can exceed the supply.

Data from U.S. Geological Survey (USGS) streamflow-gaging stations and U.S. Historical Climatology Network (HCN) precipitation stations in the U.S. Great Lakes Basin were used to analyze changes over time. The magnitudes of changes were computed using the Sen slope, which is also known as the Kendall-Theil robust line. This slope is computed as the median of all possible pairwise slopes in each temporal data set.

Precipitation increased over the last 90 years in the U.S. Great Lakes Basin. Variability in precipitation from year to year was substantial, but there was an abundance of years with relatively low precipitation in the 1930s and 1960s and many years with relatively high precipitation after about 1970. Total annual precipitation increased by 4.5 in. from 1915 to 2004, based on the average of 34 HCN stations; 3.5 in. from 1935 to 2004, based on the average of 34 stations; and 4.2 in. from 1955 to 2004, based on the average of 37 stations.

Annual runoff increased over the last 50 years in the U.S. Great Lakes Basin. Mean annual runoff increased by 2.6 in., based on the average of 43 USGS streamflow-gaging stations, from 1955 to 2004. Annual runoff varied substantially from year to year; however, runoff was relatively low, on average, from 1955 to about 1970 and relatively high from about 1970 to 1995. There was also much variability in 50-year runoff changes across the basin. Annual runoff increased at all stations in the basin, except in and near the Upper Peninsula of Michigan where relatively small decreases in runoff occurred. Annual runoff changes for the 16 available stations with data from 1935 to 2004 were similar to changes from 1955 to 2004.

Runoff in the U.S. Great Lakes Basin from 1955 to 2004 increased for most months, based on the average of 28 stations; April runoff decreased. Increases in runoff were largest in January through March, June, and October through December. The mean annual 7-day low runoff (the lowest annual average of 7 consecutive days of runoff) increased from 1955 to 2004 by 0.048 $(ft^3/s)/mi^2$, based on the average of 27 stations.

Mean monthly precipitation and runoff changes in the basin for 1955 to 2004 (based on the average of 37 and 28 stations, respectively) had similarities and differences. For November through January, and July, precipitation and runoff increased by similar amounts. For February, March, and April, there were differences between precipitation and runoff changes, which are likely due to lower ratios of snowfall to rain and earlier snowmelt runoff in recent years. Precipitation decreased slightly in February and March and runoff increased; in contrast, April precipitation increased and runoff decreased. February and March air temperatures in the U.S. Great Lakes Basin from the average of 37 HCN stations increased by 5.0° F and 3.0° F, respectively, from 1955 to 2004.

Annual precipitation in the basin increased by 4.2 in. from 1955 to 2004 and runoff increased by 2.6 in. Some of the difference in the magnitude of the changes could be due to the different locations of the precipitation and streamflow-gaging stations in the basin. Part of the difference may be explained by changes in evapotranspiration. The differences between monthly precipitation and runoff changes support the idea that changes in evapotranspiration in the basin explain at least part of the difference in annual changes. Increases in precipitation were larger than increases in runoff for May, June, August, September, and October. Increasing precipitation, through increases in soil moisture, would lead to greater evapotranspiration because the number and duration of periods with soil moisture low enough to significantly restrict evapotranspiration would be reduced.

Low flows could be sensitive to changes in agricultural practices. Annual 7-day low runoff changes from 1955 to 2004 for 27 basins were regressed against the agricultural land-use percentage in those basins. Runoff increases were larger, on average, for basins with higher amounts of agricultural land use, although the relation was not significant ($p < 0.10$). Based on the linear regression line, runoff increases for basins with the highest amount of agricultural land use were more than 50 percent higher than for basins with the lowest amount. This relation may indicate that changing agricultural practices over time have led to an increase in the lowest flows of the year; the increase would be greater for basins with a higher percentage of agricultural land use.

Some of the few highly urbanized and highly regulated stations analyzed for this report had higher annual 7-day low-flow increases from 1955 to 2004 than any of the stations in the U.S. Great Lakes Basin that were relatively free of human influences, thus showing the human influence over time on very low streamflows.

Changes—even over periods as long as 90 years—can actually be part of longer cycles. Previous studies of Great Lakes Basin precipitation and St. Lawrence River streamflow, using data from the mid-1800s to the late-1900s, showed low precipitation and streamflow in the late 1800s and early 1900s relative to earlier and later periods. What this means for the future is unclear; but in the relatively recent past, precipitation over the land part of the U.S. Great Lakes Basin was lower than at present for several decades. The average precipitation for 1915–34 was 10 percent lower than for 1984–2003.

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