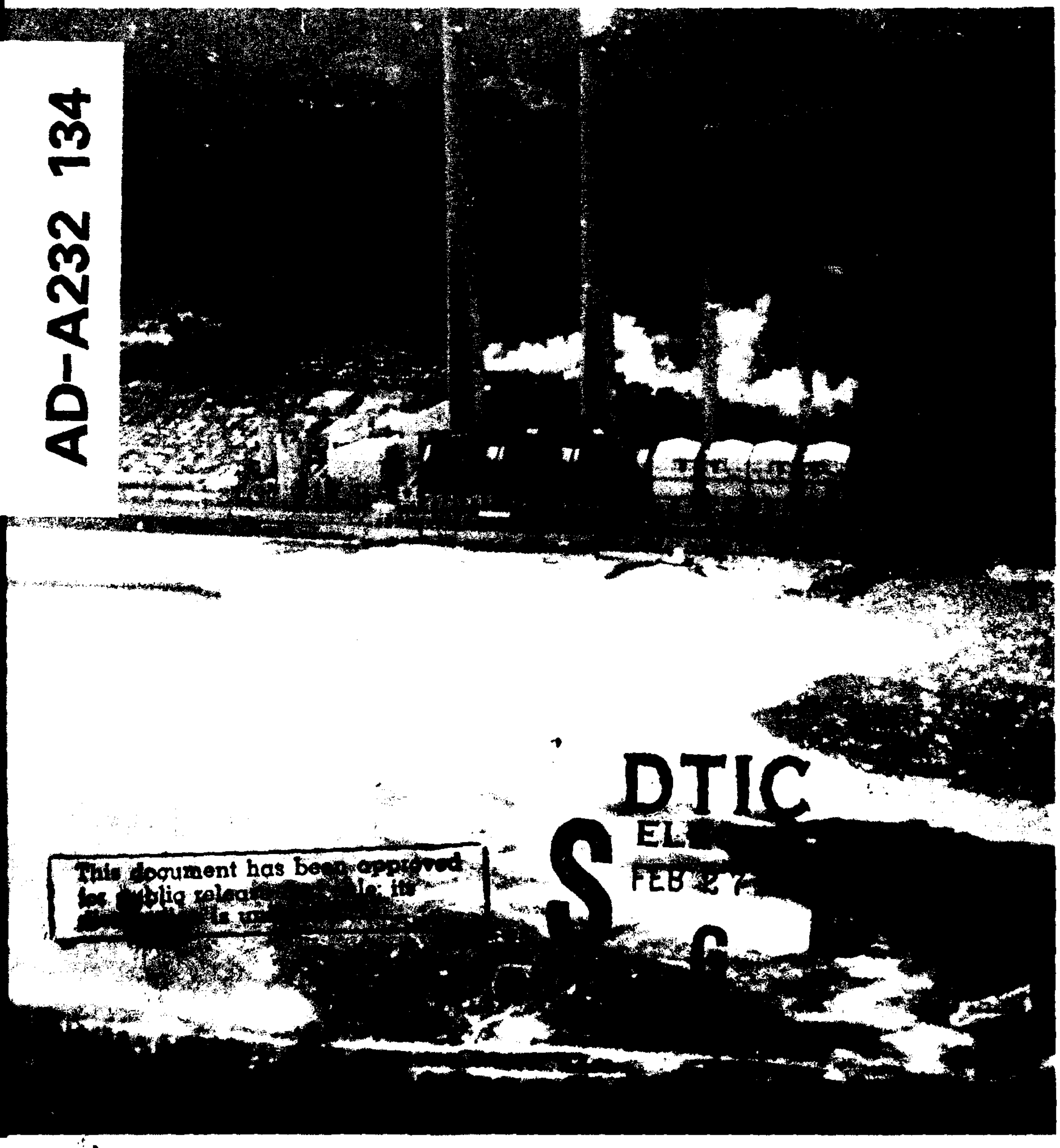
CRREL REPORT 90-12

Winter Environment of the Ohio River Valley

Steven F. Daly, Michael A. Bilello and Roy E. Bates

December 1990



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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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RIM
RIVER ICE MANAGEMENT

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Steven F. Daly, Research Hydraulic Engineer, Ice Engineering Research Branch, U.S. Army Cold Regions Research and Engineering Laboratory, Michael A. Bilello, Meteorologist, Science and Technology Corporation, Hampton, Virginia, and Roy E. Bates, Meteorologist, Geophysical Sciences Branch, U.S. Army Cold Regions Research and Engineering Laboratory.

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The authors thank Guenther Frankenstein, Chief, Ice Engineering Research Branch, for his support during this project; Joyce Putnam, mathematics aid with the CRREL Geophysical Sciences Branch, for extracting and tabulating climatic data during the initial phase of the study; the computer specialists of the Engineering and Measurement Services Branch at CRREL for their programming; Pamela Bosworth of the CRREL Word Processing Center for her contribution; and the CRREL Technical Communication Branch for drafting the figures and preparing the report for publication. The U.S. Air Force Environmental Technical Application Center's section located at the National Climatic Center, Asheville, North Carolina, also merits special recognition and thanks for providing CRREL the necessary NOAA publications.

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These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4	millimeter
foot	0.3048	meter
mile (U.S. statute)	1609.347	meter
$mile^2$ (U.S. statute)	2589669.0	$meter^2$
$foot^3$/second	0.02831685	$meter^3$/second
degrees Fahrenheit	$t_C = (t_F - 32)/1.8$	degrees Celsius

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INTRODUCTION

One of the major objectives of the River Ice Management (RIM) Program was to develop a method of forecasting river ice conditions that can be used as a navigation aid. The initial focus of the RIM program was on the Ohio River, where ice has severely impeded navigation in the past. The formation of ice on any river is governed by the geographic, hydrologic, hydraulic and climatic conditions of a region. These conditions control the heat transfer from river water to the atmosphere, which *in turn* determines the water temperature and ultimately controls the formation of ice. In addition, since these conditions can vary along a river, the distribution of ice along it can vary.

As a first step in developing an ice forecast methodology for the Ohio River, we compiled data on the physical setting, hydrology, river ice conditions and climatology for its region. This report provides a general survey of these data—describing the physical setting and hydrology of the Ohio River Valley and reviewing past ice conditions observed on the river—and analyzes the winter climate for the region. The report is also intended to increase our understanding of ice processes on the Ohio River, and to provide information useful for further studies.

PHYSICAL SETTING AND HYDROLOGY

Geographic setting

The Ohio River is 981 miles long and drains an area of approximately 203,900 mi^2, including parts of New York, Pennsylvania, West Virginia, Ohio, Indiana, Kentucky, Illinois, Tennessee, Mississippi, Alabama, Georgia, North Carolina, Virginia and Maryland. The river begins at Pittsburgh, Pennsylvania, at the confluence of the Allegheny and Monongahela rivers, and flows generally westward to Cairo, Illinois, where it empties into the Mississippi River (Fig. 1). Except for the first 40-mile section, which lies entirely in Pennsylvania, the Ohio River serves as the state boundary between Ohio, Indiana and Illinois on the north, and West Virginia and Kentucky on the south. Major tributaries include the Beaver River in Pennsylvania; the Muskingum, Scioto and Great Miami rivers in Ohio; the Kanawha River in West Virginia; the Big Sandy River in West Virginia and Kentucky; the Licking, Green, Cumberland and Tennessee rivers in Kentucky; and the Wabash River in Indiana and Illinois.

Major population centers along the Ohio include Pittsburgh, Pennsylvania; Wheeling, Parkersburg and Huntington, West Virginia; Covington–Newport and Louisville, Kentucky; Portsmouth and Cincinnati, Ohio; and Evansville, Indiana. The river is the primary source of potable water for over three million people, serving the needs of 51 private and public water supply utilities. Over 100 industries also take water from the river for process use, including cooling water for power plants. Hydropower facilities are either in place or planned at each of the 20 Corps of Engineers navigational lock-and-dam projects along the river.

The Ohio River is considered a vital link in the inland navigation system of the United States. Major commodities transported include coal, refined and crude oil, chemicals, fertilizers, steel and grain. Approximately 170 million tons of goods were transported on the river in 1979 (U.S. Army Corps of Engineers 1981).

The Corps of Engineers operates 20 locks and dams on the Ohio River (Table 1), which allow navigation on the river to proceed throughout the year. A navigation channel of 9-ft depth is maintained on the Ohio and on several tributaries, including the Allegheny, Monongahela, Kanawha, Kentucky, Green, Cumberland and Tennessee rivers.

The lock and dam system along the Ohio River is exclusively operated to maintain the 9-ft minimum depth required for navigation. River discharges are not

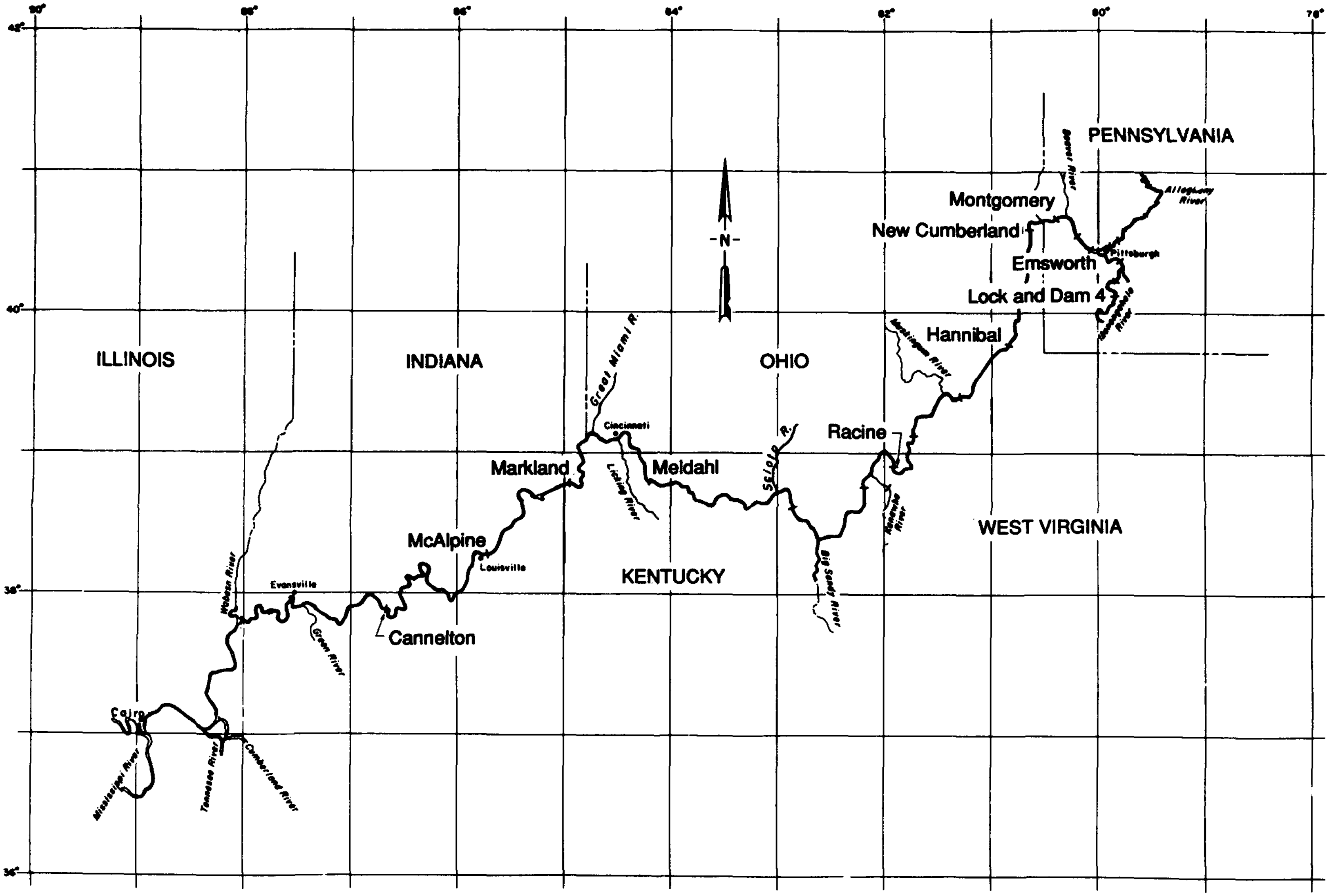


Figure 1. Ohio River and its tributaries.

Table 1. U.S. Army Corps of Engineers lock and dam sites on the Ohio River.

Lock and Dam	First year of operation	River mile	Main lock size (ft)	Auxillary lock size (ft)	Dam gate type	No. of gates	Dam length (ft)	Upper gauge zero elev. (USGS)	Normal pool (ft)	Lower gauge zero elev. (USGS)	Normal pool (ft)	District
Emsworth	1921	6.2	110 × 600	56 × 360	Lift	8	967	694	16	680	12	Pittsburgh
Dashields	1929	13.3	110 × 600	56 × 360	—	—	1585	680	12	670	12	Pittsburgh
Montgomery	1936	31.7	110 × 600	56 × 360	Lift	10	1379	670	12	652.5	12	Pittsburgh
New Cumberland	1959	54.4	110 × 1200	110 × 600	Tainter	11	1315	652.5	12	632	12	Pittsburgh
Pike Island	1968	84.2	110 × 1200	110 × 600	Tainter	9	1306	632	12	611	12	Pittsburgh
Hannibal	1972	126.4	110 × 1200	110 × 600	Tainter	8	1096	611	12	590	12	Pittsburgh
Willow Island	1972	161.7	110 × 1200	110 × 600	Tainter	8	1128	590	12	570	12	Huntington
Belleville	1968	203.9	110 × 1200	110 × 600	Tainter	8	1147	570	12	548	12	Huntington
Racine	1971	237.5	110 × 1200	110 × 600	Tainter	8	1173	548	12	526	12	Huntington
Gallipolis	1937	279.2	110 × 600	110 × 360	Roller	8	1116	526	12	503	12	Huntington
Greenup	1959	341.0	110 × 1200	110 × 600	Tainter	9	1287	503	12	473	12	Huntington
Meldahl	1962	436.2	110 × 1200	110 × 600	Tainter	12	1756	473	12	443	12	Huntington
Markland	1963	531.5	110 × 1200	110 × 600	Tainter	12	1395	443	12	408	12	Louisville
McAlpine	1961	606.8	110 × 1200	110 × 600	—	—	—	408	12	374	9	Louisville
Cannelton	1972	720.7	110 × 1200	110 × 600	Tainter	12	1200	374	9	348	10	Louisville
Newburgh	1975	776.1	110 × 1200	110 × 600	Tainter	9	990	348	10	330	12	Louisville
Uniontown	1975	846.0	110 × 1200	110 × 600	Tainter	10	1100	330	12	312	12	Louisville
Smithland	1980	918.5	110 × 1200	110 × 600	Tainter	11	1210	312	12	290	12	Louisville
Dam 52	1928	938.9	110 × 1200	110 × 600	Wicket	496	1948	283.0	18.7	281.0	9.0	Louisville
Dam 53	1929	962.6	110 x 1200	110 x 600	Wicket	358	1948	273.1	16.9	273.1	—	Louisville

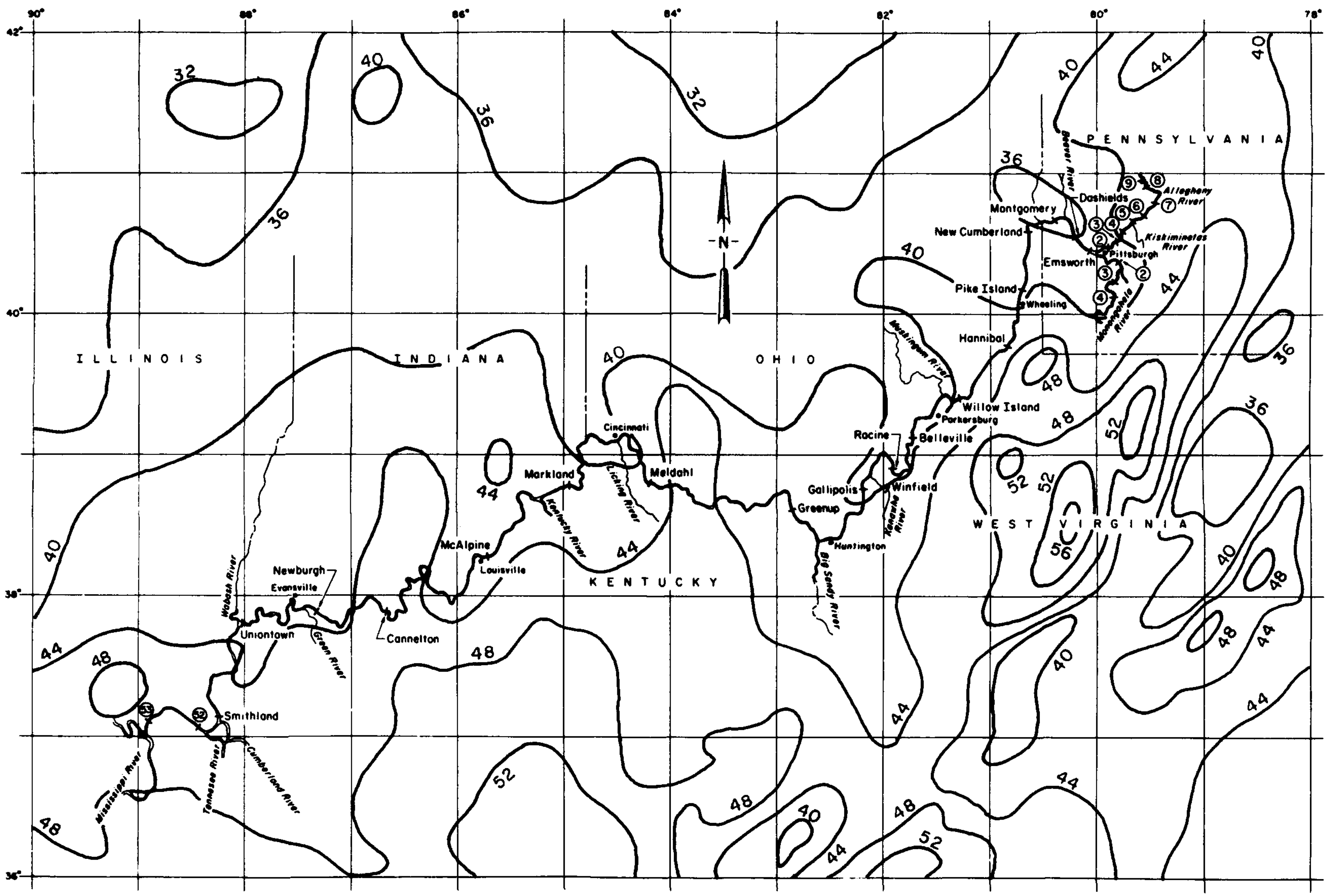


Figure 2. Average annual total precipitation (in.).

regulated at the dams to store water in their upstream pools, but only to maintain navigation depths. The dams therefore are not for flood control. In fact, during high flows, after the gates at a dam are opened as much as possible, the river is said to be "out of control" and is essentially a free flowing, alluvial river (Stoker 1957).

Physiographic setting

There are essentially three major physiographic provinces in the Ohio River watershed (Thornbury 1965): Appalachian Plateau, Central Lowlands and Interior Low Plateau. The Appalachian Plateau extends from the eastern edge of the watershed to about 30 miles downstream of the confluence of the Ohio River and the Scioto River and extends south and west following the heights of the Appalachian Mountains. This area is characterized by rugged topography resulting from the erosion of flat-lying rocks. Moderate groundwater supplies are available from the permeable sand and gravel deposits in the valleys. It has extensive forest cover, poor quality soils, narrow valleys, steep stream gradients and experiences flash floods during the rainy season and low stream flows during dry seasons (Ohio River Basin Commission 1979).

In the northwestern third of the Ohio River Valley, several glaciations have produced the Central Lowlands Province, which extends west from the Appalachian Plateau with the Ohio River as its approximate southern border. The characteristic features of this region, which result from the geologically recent glaciation, are a flat to slightly rolling landscape, a significantly altered drainage system, and some of the richest agricultural soils within the basin. Groundwater is plentiful from buried preglacial streams.

The Interior Low Plateau covers the southwestern third of the Ohio River Valley. Its approximate northern boundary is the Ohio River, although an arm of the Plateau extends into Indiana. Limestone bedrock is predominant. Areas of rolling terrain support farming, while areas of rugged relief are forested with thin soils. Groundwater supplies are variable.

Hydrology

Discharge

The discharge from any watershed is dependent upon the climate, especially the precipitation and evaporation rates, the physical characteristics and vegetation of the watershed, and the influences of any hydraulic structures. Average annual precipitation (U.S. Department of Commerce 1968) over the Ohio River watershed increases from a minimum of 36 in. in the northeast to 48 in. in the southwest. (Fig. 2). Average annual discharges of the Ohio (Table 2) also increase gradually downstream. The gauging stations used in this survey were taken from U.S. Geological Survey (1982) and their locations are shown in Figure 3.

The long-term average discharge $\overline{Q}$ (ft^3/s) for a number of sub-watersheds in the three physiographic regions of the Ohio River watershed shows a consistent relationship with drainage area (Fig. 4). The relationship can be described simply by

$$\overline{Q} = 1.211\,(DA)^{1.019} \qquad (1)$$

where (DA) is the drainage area in square miles. The correlation coefficient is $r = 0.992$. The long-term average discharge for the Ohio River at specific locations follows about the same trend as the sub-watersheds and can be related to the upstream drainage area by the equation

$$\overline{Q} = 4.233\,(DA)^{0.903} \qquad (2)$$

with a correlation coefficient of $r = 0.996$.

Table 2. U.S. Geological Survey gauging stations along the Ohio River (USGS 1982).

Station	*Location*	*Period of record*	*Average discharge (ft^3/s)*	*Remarks*
0308600	Sewickley, Pennsylvania	1934–1983	32,620	
03111534	Martins Ferry, Ohio	1978–1983	37,902	
03150800	Marietta, Ohio	1968–1983	—	Gauge height only
03159530	Belleville Dam, West Virginia	1974–1983	62,370	
03201500	Point Pleasant, West Virginia	1977–1983	—	Gauge height only
03206000	Huntington, West Virginia	1934–1983	75,240	
03216600	Greenup Dam, Kentucky	1968–1983	94,180	
03277200	Markland Dam, Kentucky	1970–1983	124,800	
03294500	Louisville, Kentucky	1928–1983	115,900	
03303280	Cannelton Dam, Indiana	1975–1983	135,600	
03611500	Metropolis, Illinois	1928–1983	269,600	

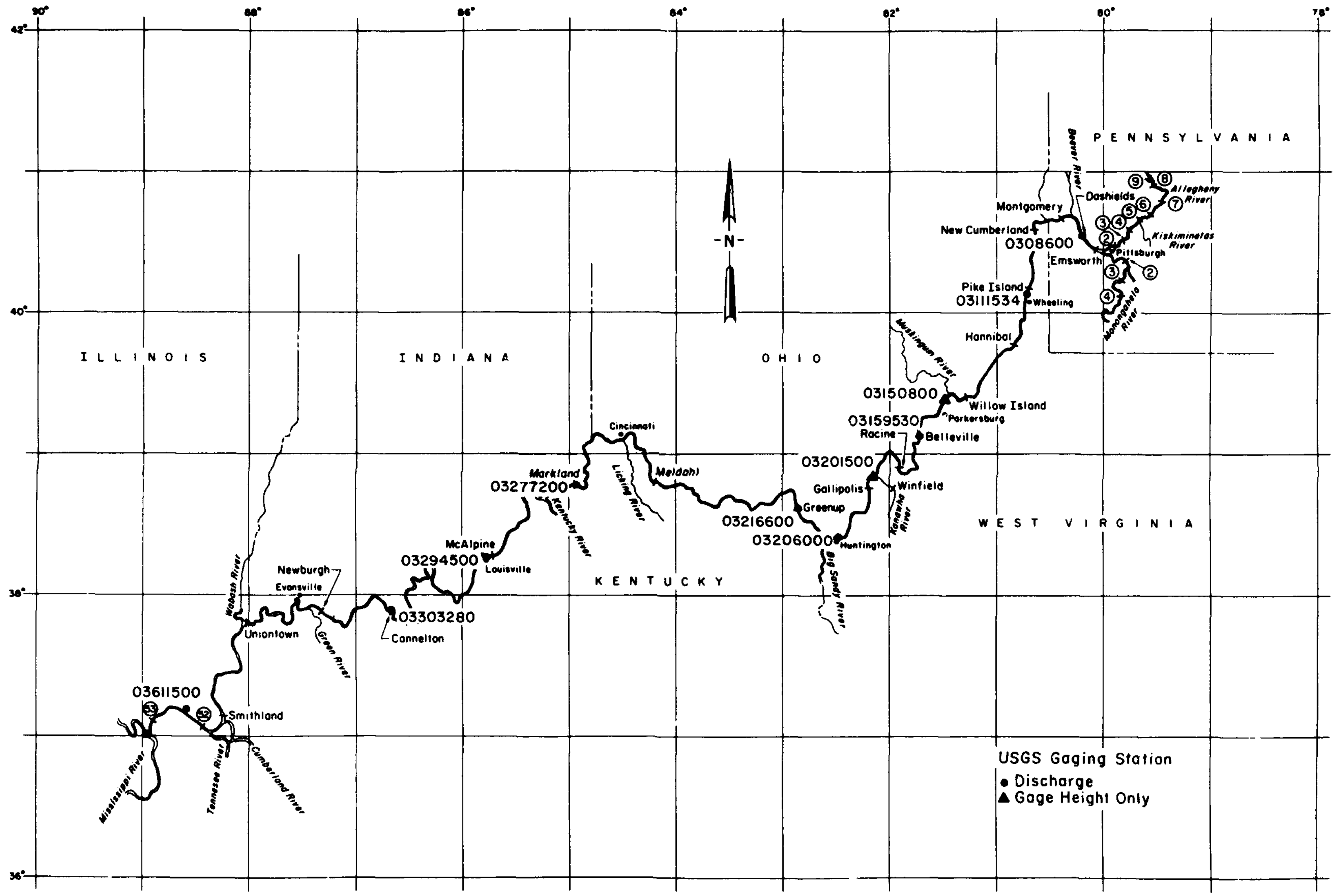


Figure 3. Location of U.S. Geological Survey river gauging stations.

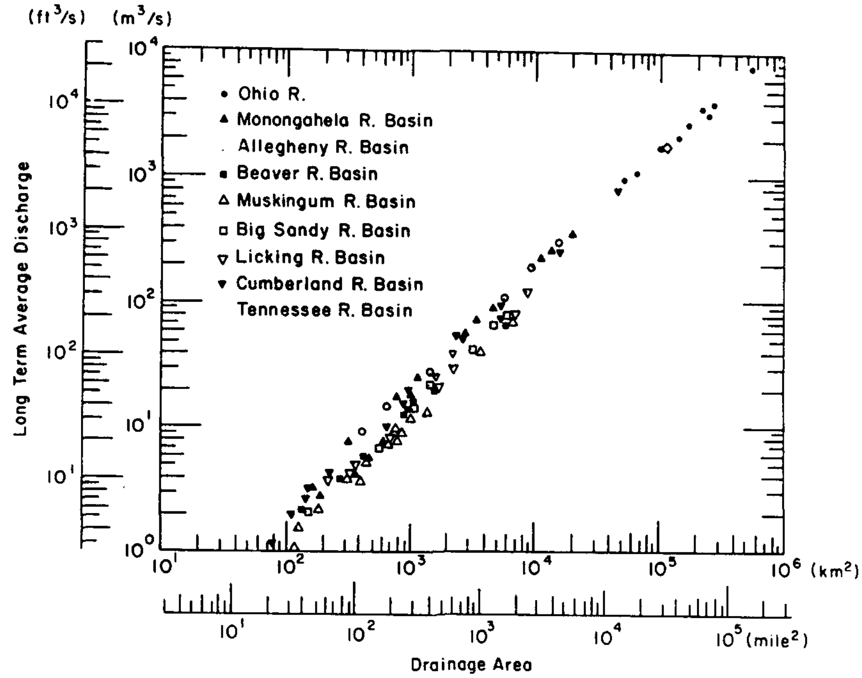


Figure 4. Long-term average discharges for various basin drainage areas.

Average monthly discharges for four selected stations with long records (Fig. 5) show that discharge varies considerably throughout the year. The highest maximum monthly average discharges occur from January to May because of rainfall on frozen or fully saturated ground, snowmelt, and low rates of transpiration and evaporation. The maximum monthly values for this period are two to three times the recorded maximums during the rest of the year and the mean monthly average discharge values from January to May, too. The lowest mean monthly average discharges occur from July through October, a period with high transpiration and evaporation rates.

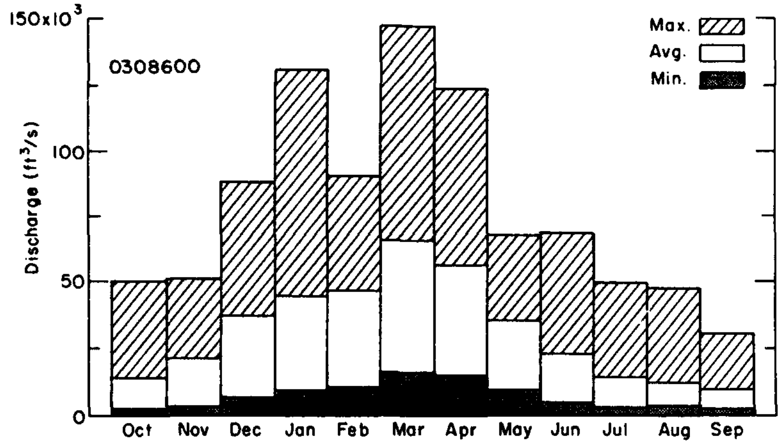
Daily average discharges for Sewickley, Pennsylvania, and Louisville, Kentucky, and air temperatures recorded at Pittsburgh International Airport (3 miles from Sewickley) and Covington (about 90 miles from Louisville) from October to April 1972–73 through 1984–85, are shown in Appendix A. These sites are representative of the upstream and downstream conditions along the river. The graphs show several interesting points. First, they depict the "flashiness" of the river, with several peak discharges each winter from precipitation or snowmelt events. The relationship among timing of the discharge peaks reflects the areal distribution of these events. Most often the peak at Sewickley precedes that at Louisville by several days.

Second, Appendix A shows that the peaks are at least twice the low flow magnitude, and more often four to six times; the trend in the base flow, however, is to increase throughout the winter.

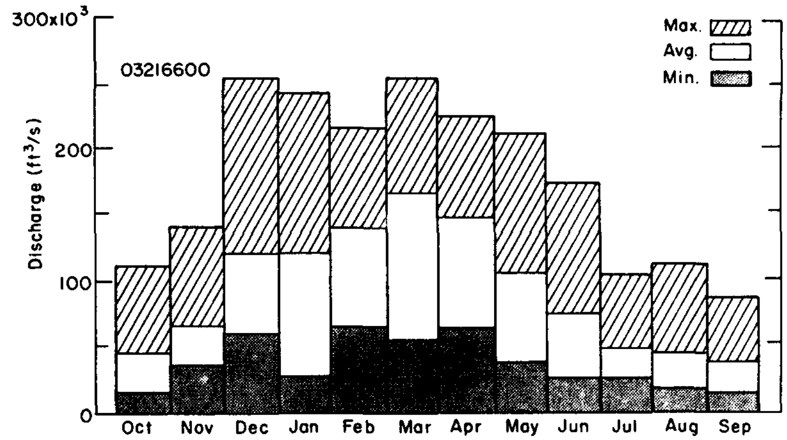
Third, generally, a discharge peak is preceded by an air temperature peak one to ten days before. This correlation is more striking in the Sewickley data, and at both locations it probably is attributable to the arrival of warm fronts. This influx of thawing temperatures would cause snow to melt, contributing to increased river discharges.

At this point, we can look at the effects of discharge variations on river ice conditions. We have observed that the flow in the Ohio River, as shown by the long-term averages, tends to increase throughout the winter season. We have also seen (by inspection of the daily records of discharges for 13 winters) that, in the short term, the flow tends to be quite flashy. The large variability of discharge in the Ohio River probably contributes to a corresponding variability in river ice conditions.

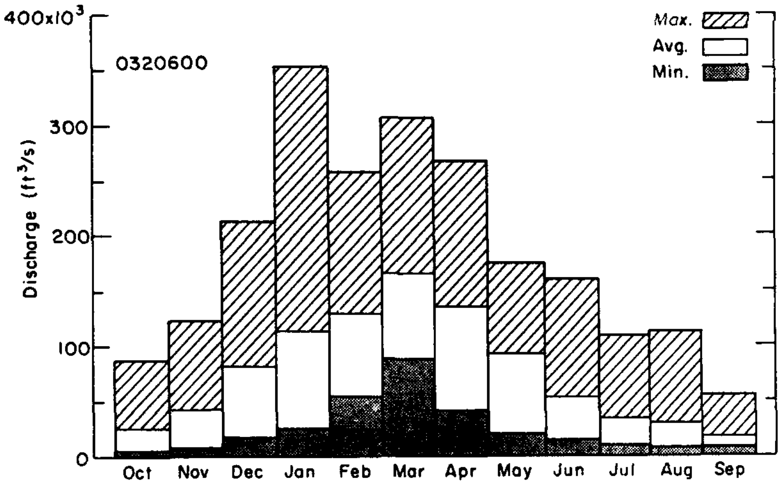
A river ice cover must have sufficient strength to resist the forces that act on it, otherwise the ice cover will start to break up. The forces that act on the ice cover are principally associated with the river's discharge. Low, stable discharges during cold periods promote the formation of ice covers. At low discharges, static ice covers and ice bridges can form, and it is easier for the ice cover to progress upstream by floe juxtaposition. If these ice covers are then subjected to large discharges, especially if the changes in discharge are rapid and associated with warm air, the covers are likely to break



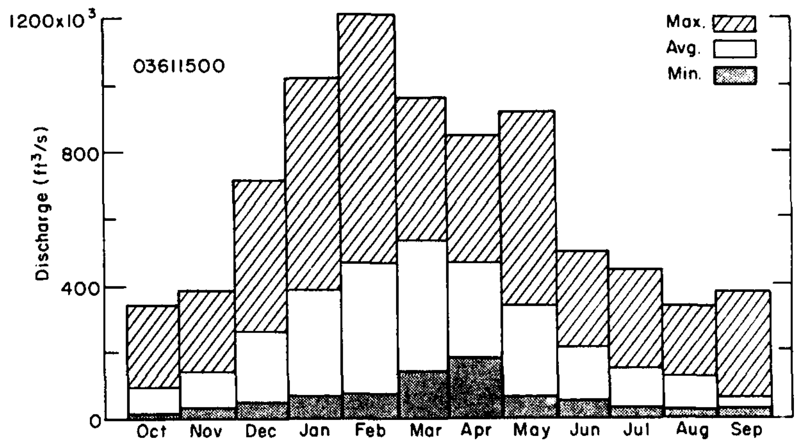
a. Sewickley, Pennsylvania.



c. Greenup, Kentucky.



b. Huntington, West Virginia.



d. Metropolis, Illinois.

Figure 5. Average monthly discharges (each figure shows three histograms that begin at 0).

Table 3. Mean daily average water temperatures (°F) on the Ohio River, and amplitude and phase angle values (for eq 3).

Station	Location	Period of record	Mean daily avg. termed T_m in eq 3	Lowest mean daily average	Highest mean daily average	Amplitude a_l	Phase angle θ
OR 015.2	South Heights, Pennsylvania	7 Mar 63–31 Oct 82	57.9	35.2	81.5	22.3	–2.0407
OR 040.2	East Liverpool, Ohio	2 Apr 75–31 Oct 82	56.7	33.1	82.6	22.7	–2.0371
OR 102.4	Shadyside, Ohio	22 Apr 75–31 Oct 82	59.9	37.2	84.2	21.0	–2.0274
OR 260.0	Addison, Ohio	12 May 75–31 Oct 82	58.3	34.2	82.4	22.7	–2.0551
OR 279.2	Gallipolis Lock and Dam, Ohio	3 Sept 75–31 Oct 82	58.5	33.4	80.8	22.1	–2.0540
OR 306.9	Huntington, West Virginia	16 Sept 75–31 Oct 82	59.9	36.5	82.2	22.5	–2.0679
OR 462.8	Cincinnati Water Works, Ohio	16 Sept 61–31 Oct 82	59.4	36.9	81.5	22.1	–2.1072
OR 490.0	North Bend, Ohio	8 June 64–31 Oct 82	60.6	37.9	82.6	22.1	–2.0869
OR531.1	Markland Lock and Dam, Kentucky	16 May 69–31 Oct 82	60.4	37.8	81.7	21.6	–2.1089
OR 600.6	Louisville Water Co., Kentucky	15 Mar 62–31 Oct 82	60.3	37.2	82.0	22.1	–2.0878
OR 625.9	West Point, Kentucky	8 Apr 75–31 Oct 82	60.4	36.3	83.9	22.7	–2.0661
OR 720.7	Cannelton, Lock and Dam, Indiana	9 Oct 75–30 Oct 82	59.9	34.2	83.5	23.2	–2.0633
OR 791.5	Evansville Water Works, Illinois	10 Oct 68–31 Oct 82	60.6	37.4	82.9	22.7	–2.0735
OR 952.3	Joppa, Illinois	2 July 75–31 Oct 82	61.2	36.9	85.3	22.9	–2.0175

up. A likely pattern for the Ohio River is that during periods when low discharges and low temperatures coincide, a stable ice cover forms on the river. During periods of high discharge, ice sheets are broken up and the ice floes move downstream. Warmer air during these high flow periods would help melt the moving ice floes, causing them to disappear.

Water temperatures

The mean daily average water temperatures (Ohio River Valley Water Sanitation Commission 1982) measured at 14 sites along the Ohio River (Fig. 6) range narrowly from about 56.7°F near the upstream end to 61.2°F at Joppa, Illinois (Table 3). The lowest and highest mean daily average water temperatures recorded in the upstream portions of the river (Fig. 7) are slightly less than those observed downstream, although the difference is less than 5°F in both cases. The lowest mean daily average is 33.1°F, and the highest mean daily average is 85.3°F.

The mean daily minimum, average and maximum temperatures plotted for the 14 sites (Fig. 8) show several features. First, the annual temperature curves follow a sinusoidal pattern, with the lowest temperatures in January and February and the highest in July and August. These high and low periods reveal the slight time lag experienced between air and water temperature peaks.

Second, the water temperature (T_a) variations for the Ohio River Valley Sanitation Commission sites can be described by

$$T_a = T_m + a_1 \sin\left(\frac{2\pi t}{T} + \theta\right) \quad (3)$$

where T_m = long-term average temperature (°F)

a_1 = amplitude (°F)

T = number of days in the year (365 or 366)

t = Julian date (starting on 1 January), and θ is a phase angle (Table 3).

We have discovered that the longer the period of record for a station, the better the above equation can describe the average daily temperature. This can also be seen by comparing those stations with long periods of record with those having relatively short records. The long period records provide smoother curves and smaller daily temperature fluctuations.

Third, although the water temperature records for all 14 locations show a minimum during January, they also indicate a slight rise, which may be the result of the occasional "January thaw." There is a second minimum water temperature during mid-February, after which the temperature in the river tends to increase steadily. This slight warming in January is not well described by the sinusoidal equation above, and would require higher order harmonics to reproduce.

River ice

Ice cover on the Ohio River can be quite dynamic, forming and breaking up very quickly. It is generated principally by the extraction of heat from the river itself, but additional ice also enters the Ohio from its tributaries. Ice can cause many navigation problems, especially at locks and dams, where the ice impedes lockages and the operation of gates, and in general causes hardships to personnel and equipment (Zufelt and Calkins 1985). If the ice becomes excessive or sufficiently thick, it can impede ship passage nearly everywhere during severe winters, especially at river bends and at lock and dam sites.

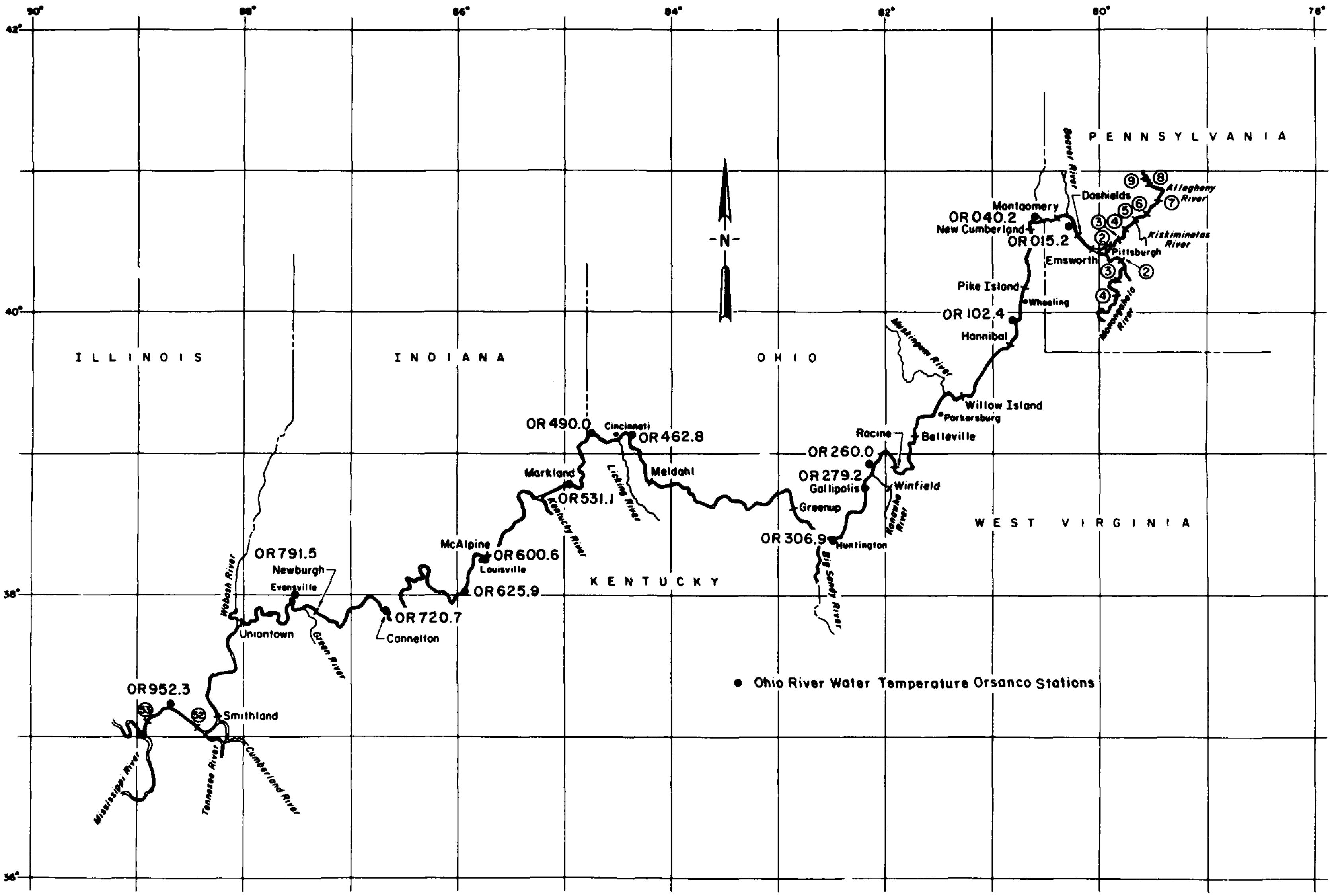


Figure 6. Location of the Ohio River Valley Water Sanitation Commission water temperature sites.

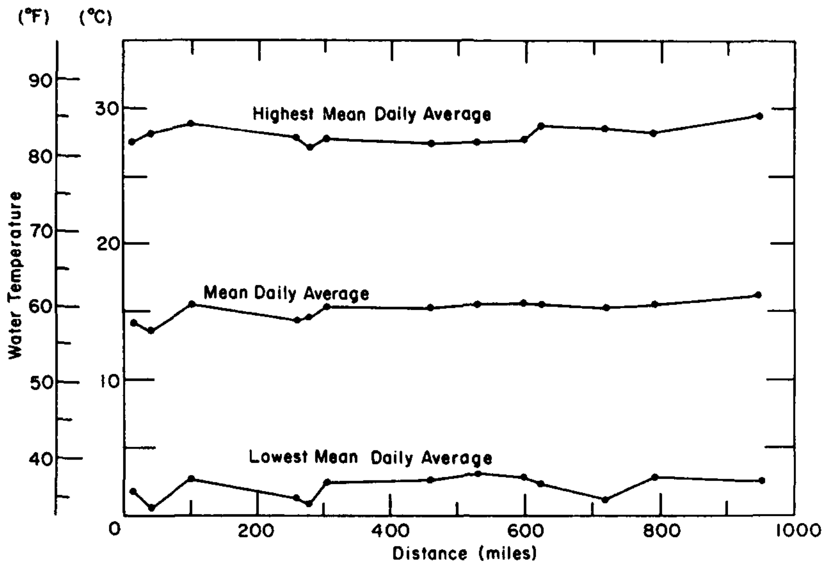
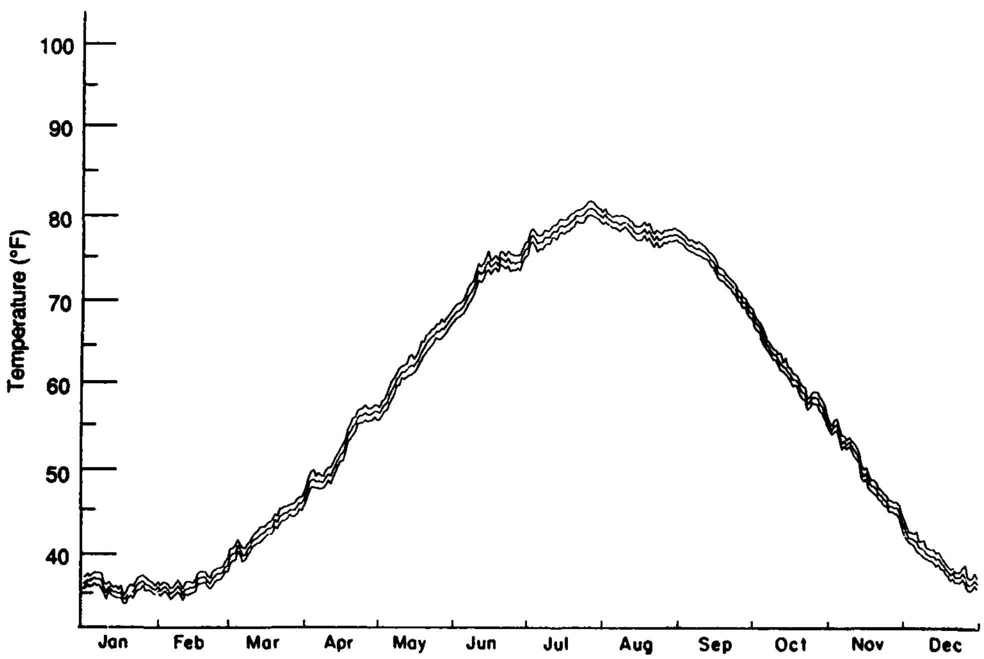


Figure 7. Long-term water temperatures along the Ohio River (distance scale shows miles from Pittsburgh, Pennsylvania).

Descriptions of ice conditions throughout the Ohio River are available from Gatto (1988). Ice information for selected locations is available from daily navigation reports for each lock and dam prepared by the Corps of Engineers (analyzed by Bilello et al. [1988]), from an Ohio River Division summary report (U.S. Army Corps of Engineers 1978) for the Cincinnati area, from newspaper and magazine articles addressing ice conditions, especially during severe flooding, and from unpublished data (e.g., Gatto and Daly 1986).

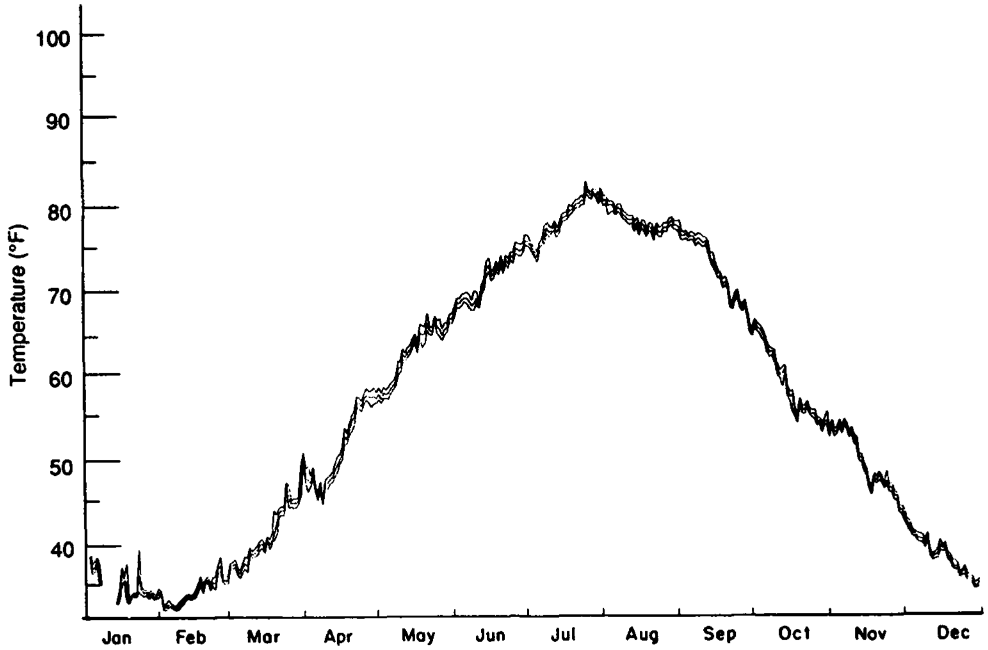
The following review of past ice conditions observed at Cincinnati is based on data from the Corps of Engineers (1978) report, and detailed by Daly and Bilello (1986).

The longest periods of ice on the river each winter (i.e., 40 days or more of observed ice per season) were

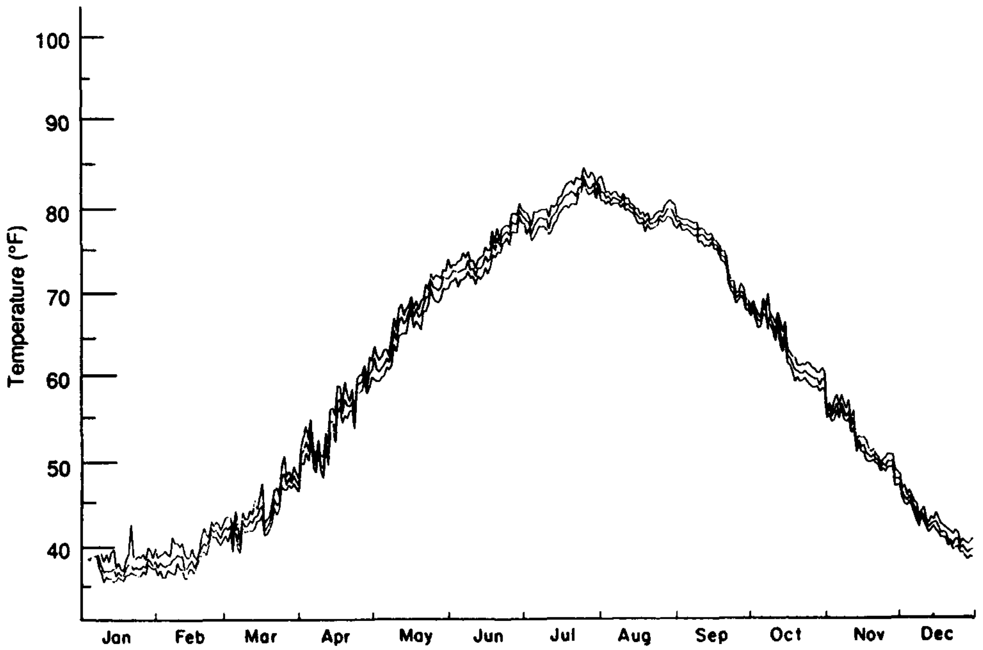


a. South Heights, Pennsylvania (OR015.2).

Figure 8. Annual distribution of mean daily minimum, average and maximum water temperatures at the Ohio River Valley Water Sanitation Commission water temperature sites.

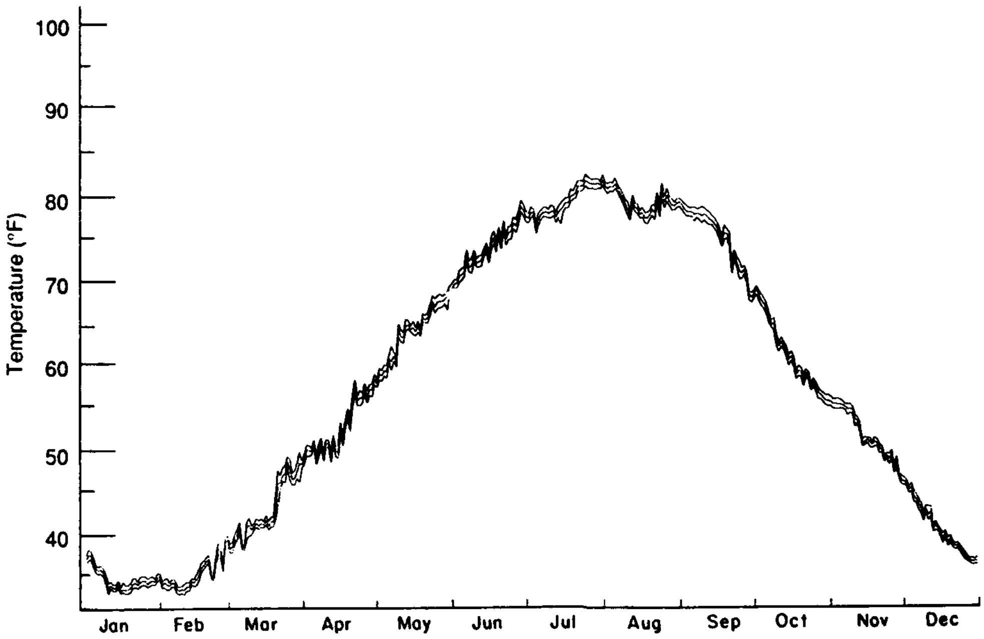


b. East Liverpool, Ohio (OR040.2).

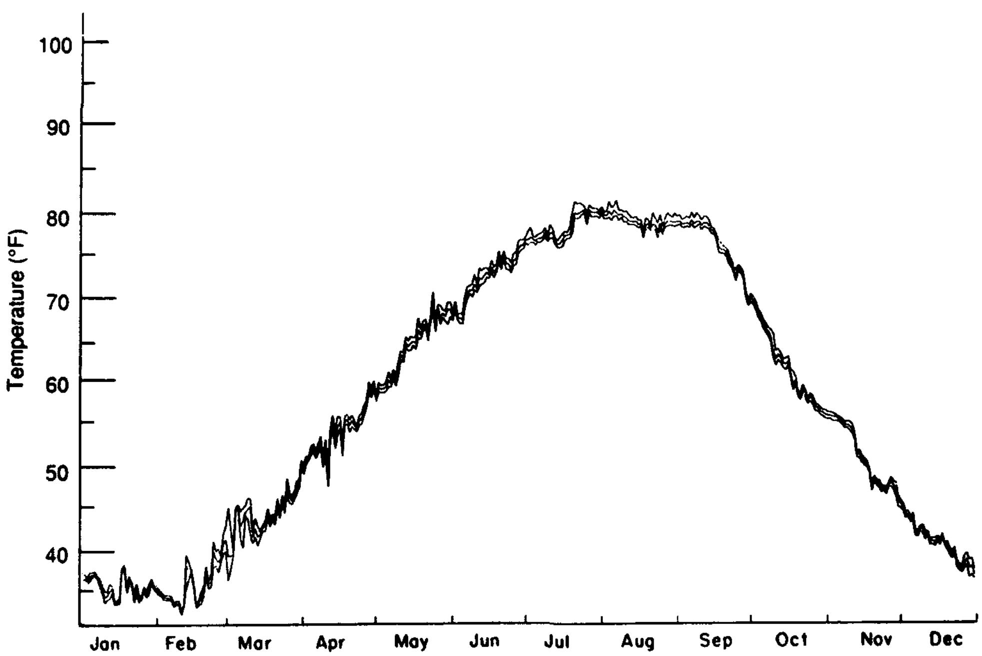


c. Shadyside, Ohio (OR102.4).

Figure 8 (cont'd). Annual distribution of mean daily minimum, average and maximum water temperatures at the Ohio River Valley Water Sanitation Commission water temperature sites.

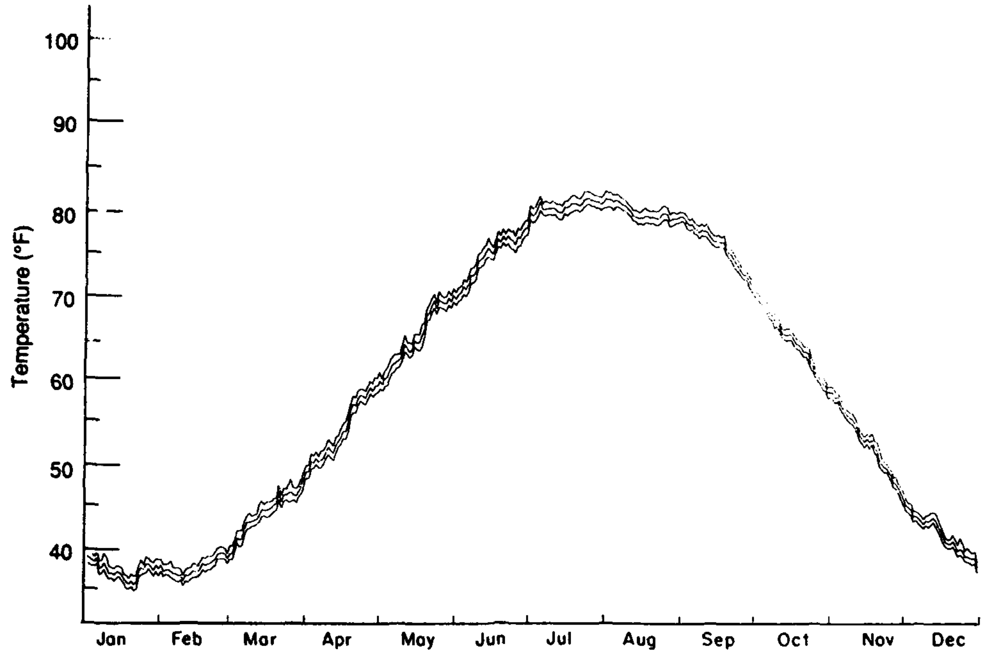


d. Addison, Ohio (OR260.0).

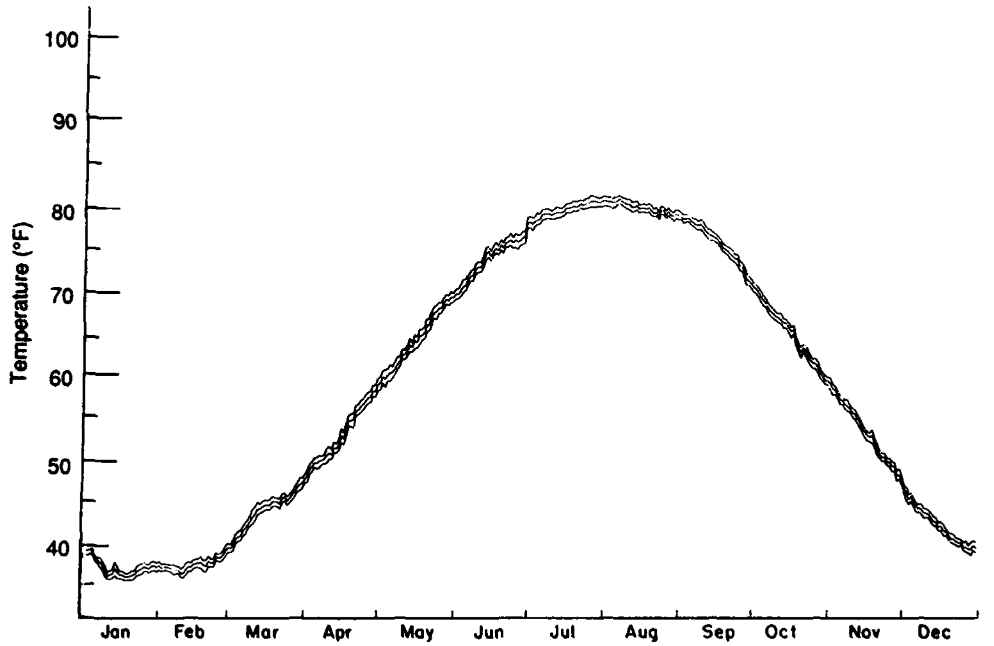


e. Gallipolis Lock and Dam, Ohio (OR279.2).

Figure 8 (cont'd).

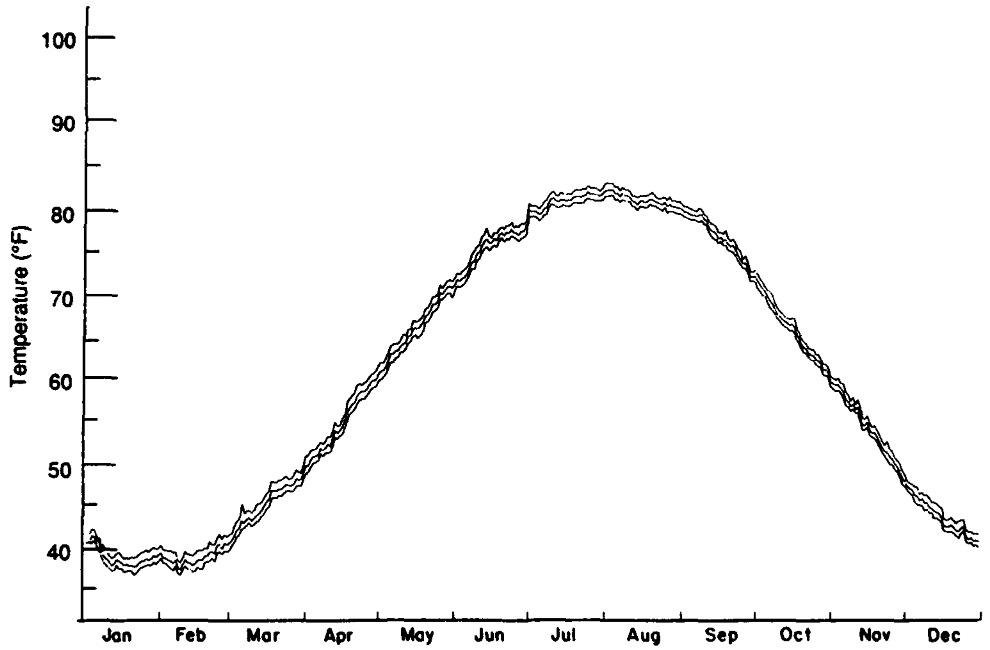


f. Huntington, West Virginia (OR306.9).

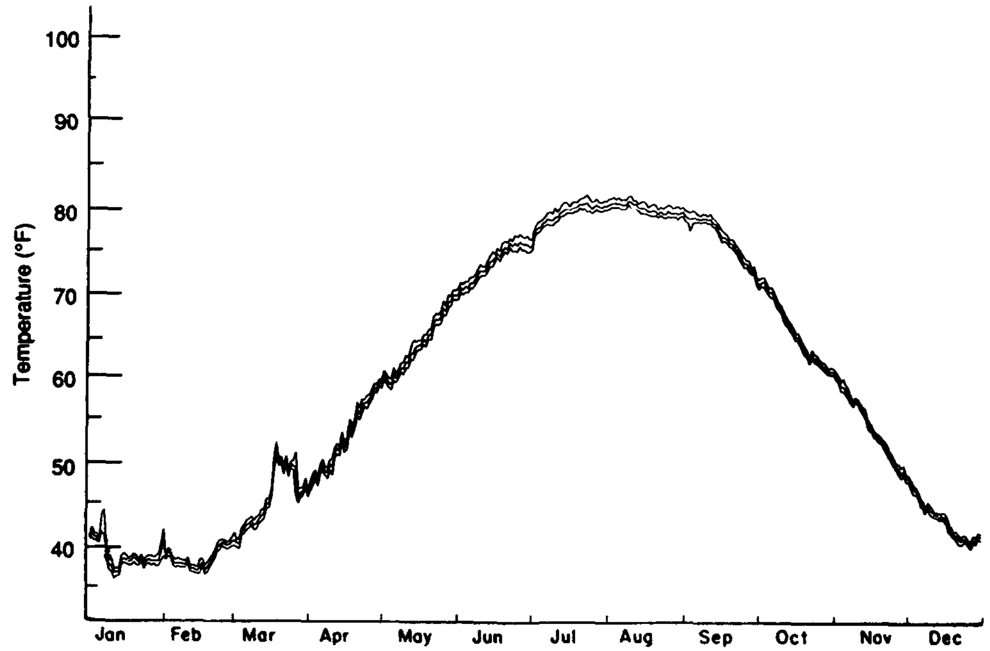


g. Cincinnati Water Works, Ohio (OR462.8).

Figure 8 (cont'd). Annual distribution of mean daily minimum, average and maximum water temperatures at the Ohio River Valley Water Sanitation Commission water temperature sites.

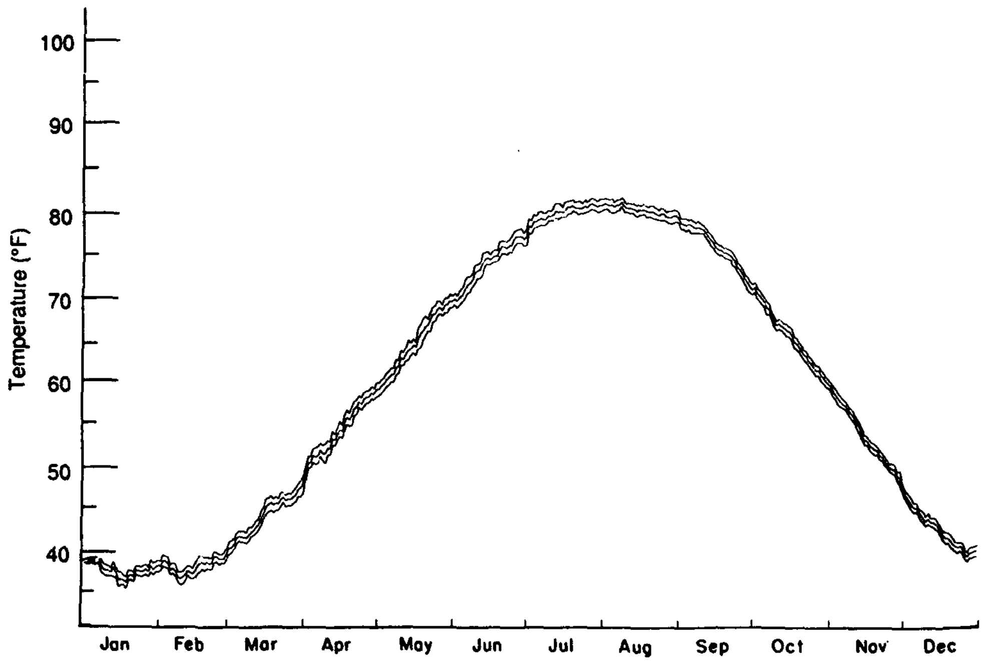


h. North Bend, Ohio (OR490.0).

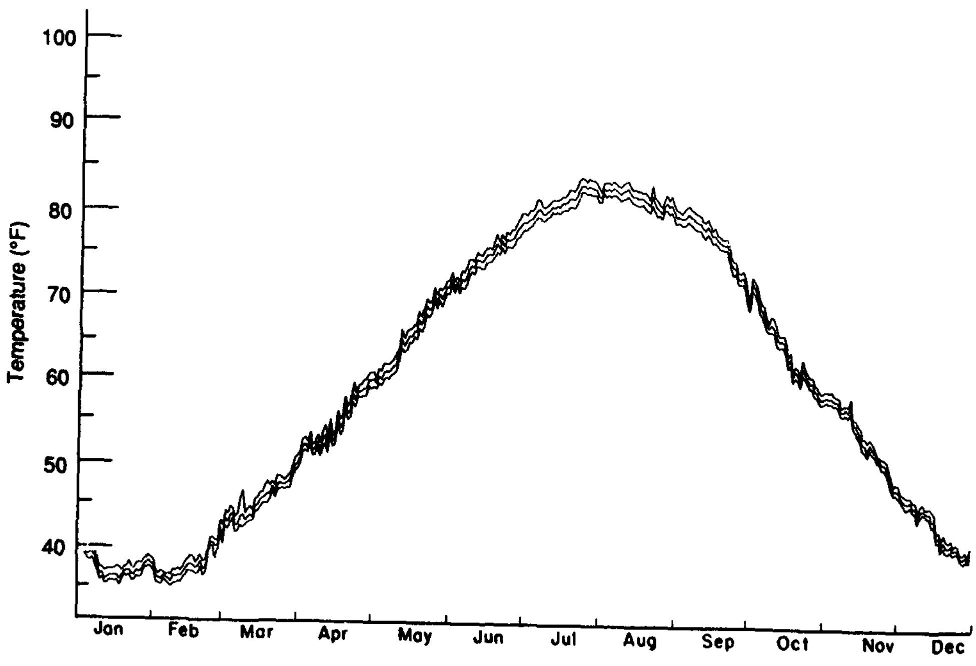


i. Markland Lock and Dam, Kentucky (OR531.1).

Figure 8 (cont'd).

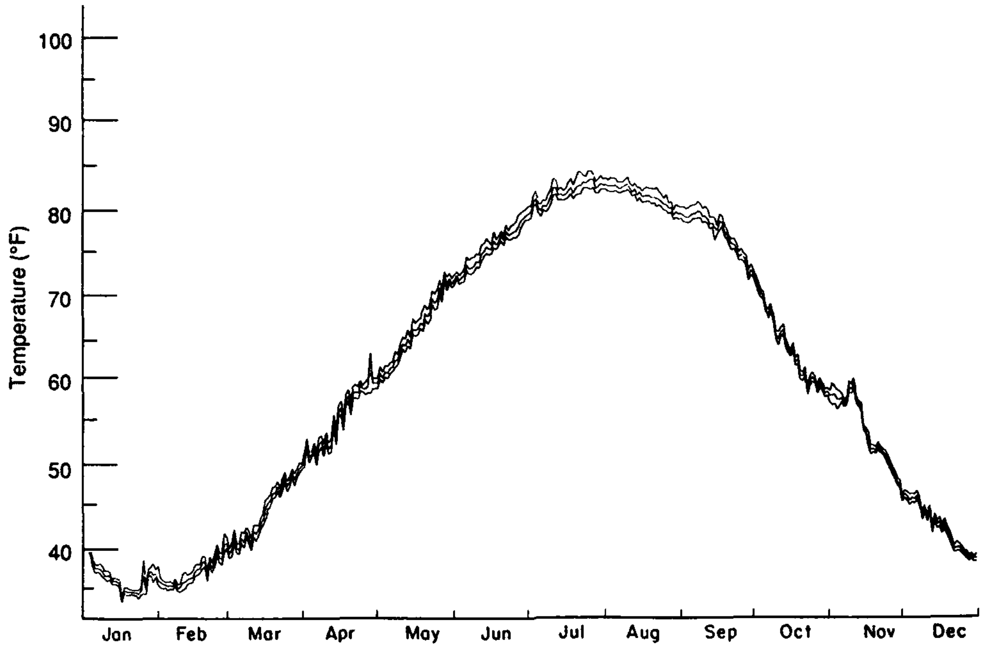


j. Louisville, Kentucky (OR600.6).

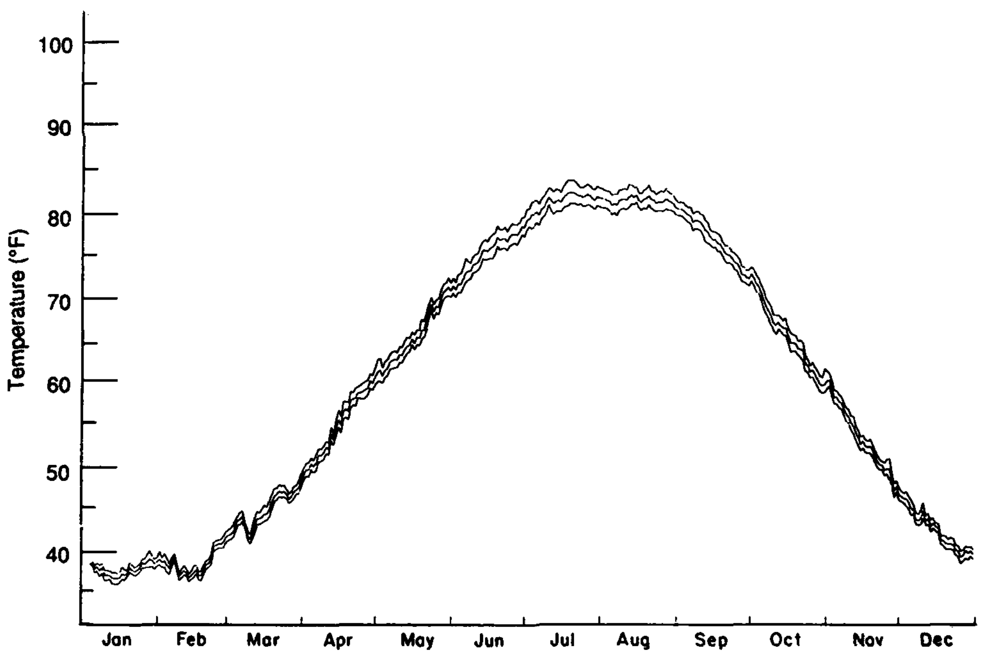


k. West Point, Kentucky (OR625.9).

Figure 8 (cont'd). Annual distribution of mean daily minimum, average and maximum water temperatures at the Ohio River Valley Water Sanitation Commission water temperature sites.

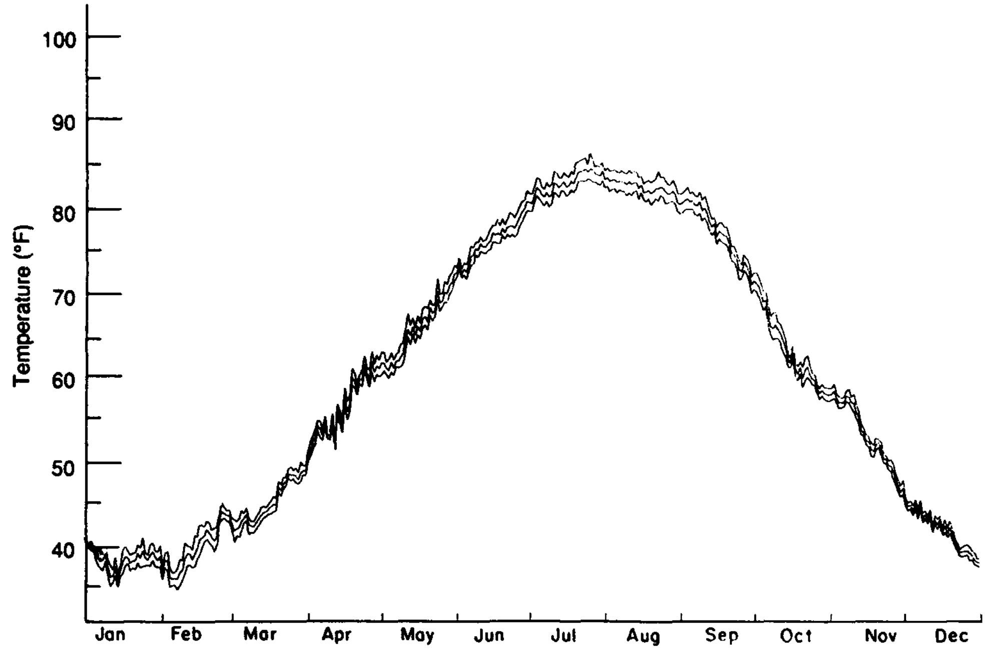


l. Cannelton, Indiana (OR720.7).



m. Evansville, Indiana (OR791.5).

Figure 8 (cont'd).



n. Joppa, Illinois (OR952.3).

Figure 8 (cont'd). Annual distribution of mean daily minimum, average and maximum water temperatures at the Ohio River Valley Water Sanitation Commission water temperature sites.

observed during 13 winters prior to 1940–41, with only two other such events (during the very cold winters of 1976–77 and 1977–78) since that time (Fig. 9 and 10). No ice was observed on the river during 17 of the 66 years of record prior to 1940–41 (or 26% of the time), whereas no ice was noted during 20 of the following 46 winter seasons (or 43% of the time).

A gradual, erratic decrease in ice on the Ohio River at Cincinnati from about 1902 to 1975 is shown by the sequential five-year average ice values (Fig. 10). This general reduction in ice coincides somewhat with warmer winters. Minor variations in the time of the high and low values were noted when the starting point for the five-year averages was shifted two or three seasons forward, but the overall trend for the full record remained similar. When ten-year averages were used, the high and low values became less distinct.

In an investigation of the effect of the winter temperature regimes on the river ice, Daly and Bilello (1986) computed a freezing degree-day (FDD)* index for Cincinnati. This value provides a realistic account of the length or intensity of the freezing regime for an area. The various periods of warmer and colder winters were found to be randomly distributed throughout the entire 112 years of record (Fig 11). Average monthly temperature values greater than or equal to 32°F (i.e., zero FDDs) were recorded during 31 of the 112 winters, as compared to the 15 winters when the total seasonal FDDs exceeded 300 (shown by specific months, D-December, J-January, F-February). During these 15 winters, January most often saw the greatest accumulation of FDDs.

Over longer consecutive periods (i.e., the trend shown by the five-year average increments), the FDDs revealed earlier cold winters between 1874 and 1920 (Fig. 11). Then, except for three or four abnormally cold winters (e.g., December 1935–February 1936), this cold period was followed by a warmer trend that lasted until about 1956. Between 1957 and 1986, the area experienced two significant intervals of cold winters. The first interval extended mostly from 1957 to 1971, and the second from 1976 to the winter of 1985–86. These two cold periods were separated by four consecutive warm winters, 1971–72 to 1974–75.

The relationship between the number of days with ice each winter and the concurrent total seasonal FDDs was determined by computing their ratios. For example, during the winter of 1874–75, ice on the Ohio River at Cincinnati was observed on 43 days, and the total of the FDDs for that winter was 311; 43 divided by 311 results in a ratio of 0.138. Similar ratios were computed for all 112 winters. Included in Figure 12 are 1) those winters when ice was reported but the total FDDs was zero

* The freezing degree-day for any one day equals the difference between the average daily air temperature and 32°F (U.S. Army and Air Force 1966). For example: 32°F–(–3°F) = 35 freezing degree days.

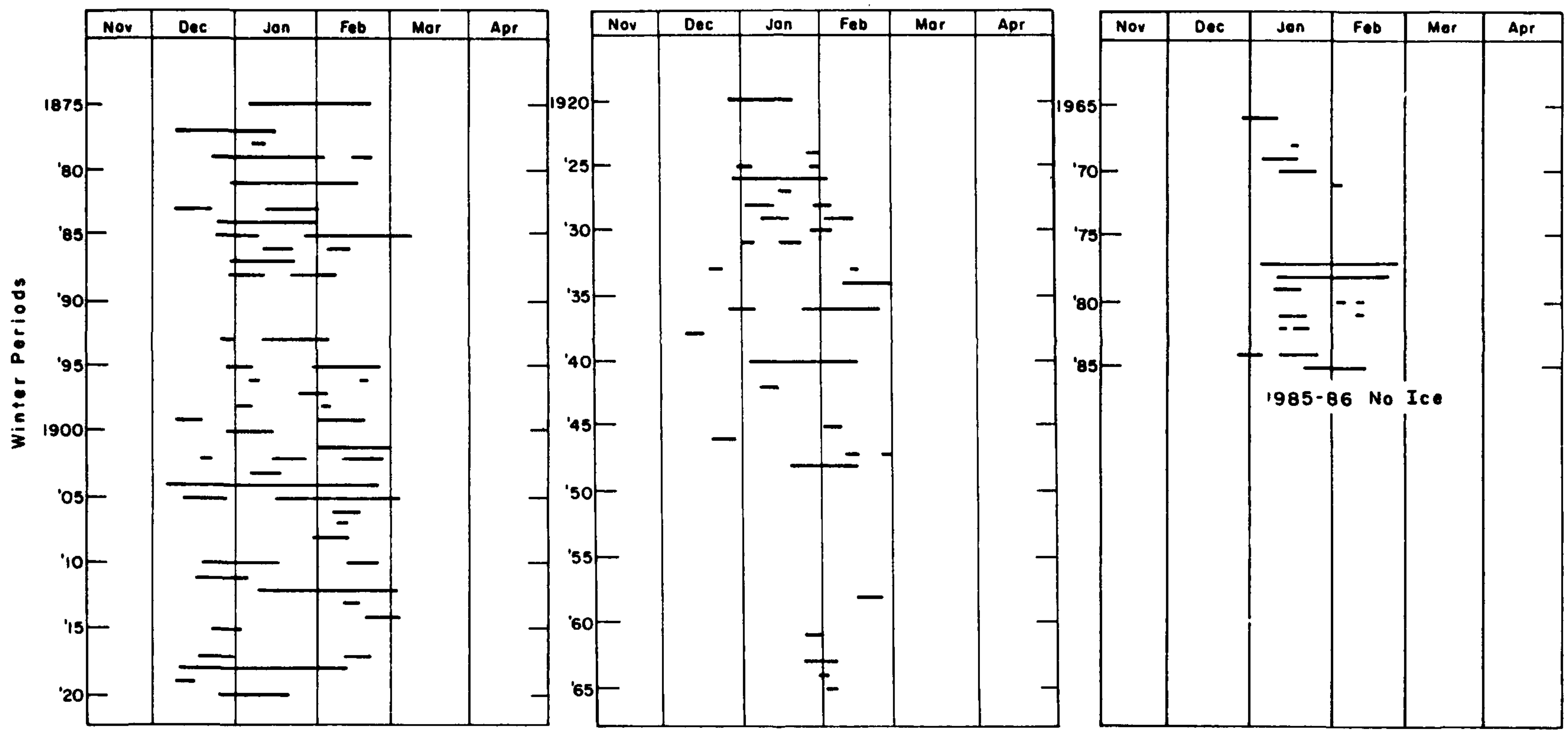


Figure 9. Periods when ice was observed on the Ohio River at Cincinnati during each winter.

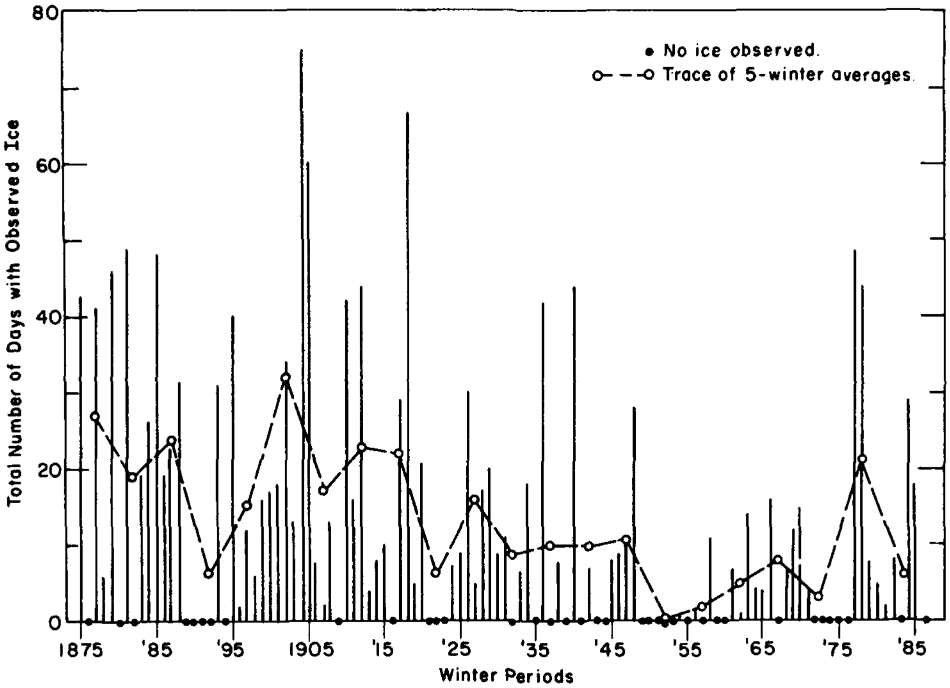


Figure 10. Total number of days when ice was observed on the Ohio River at Cincinnati during each winter.

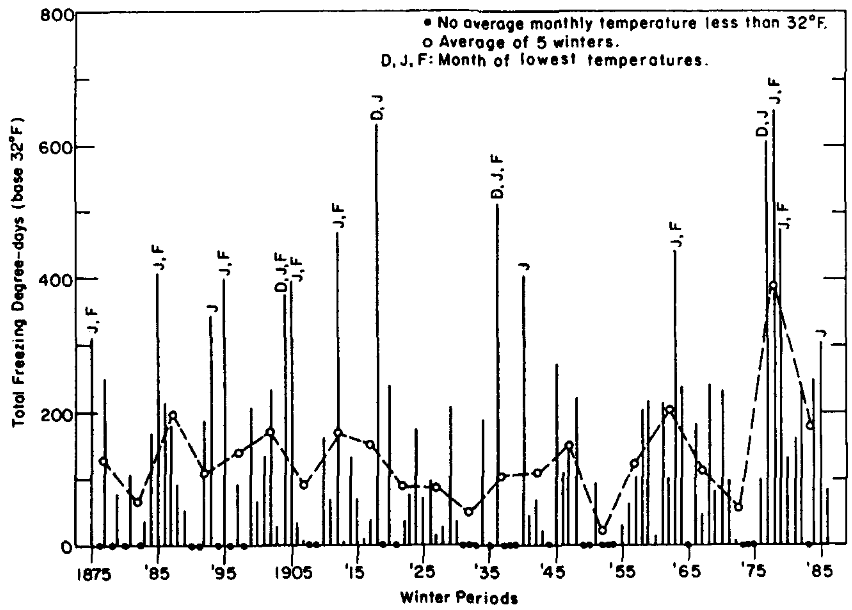


Figure 11. Total seasonal freezing degree-days at Cincinnati during each winter.

(indicated as solid squares), 2) three winters when the ratio value exceeded 0.6 (indicated as open triangles; owing to apparent observation errors, these three values were considered unrepresentative and therefore were not used in the study), 3) those winters with some recorded FDDs but no days with observed ice (indicated as inverted solid triangles), 4) those winters with no observed ice and no FDDs (indicated as solid circles), and 5) a dashed line showing the average ratio of all the values for each consecutive 10-year interval (i.e., starting with 1874–75 through 1883–84).

The winter-to-winter ratios shown in Figure 12 reveal considerable variance. Omitting those winters with symbols, we see that the ratios range from greater than

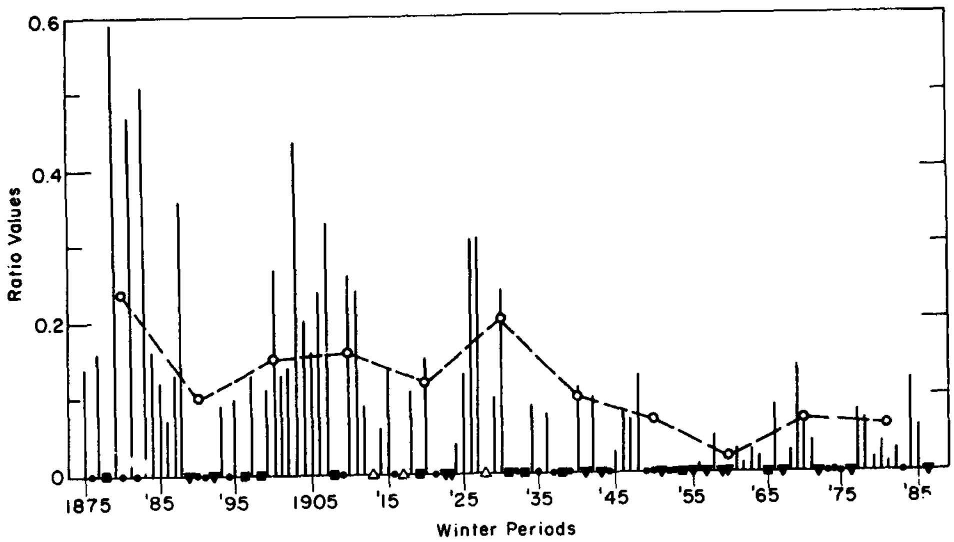


Figure 12. Ratio of total number of days of ice on the Ohio River divided by the total seasonal freezing degree-days for each winter.

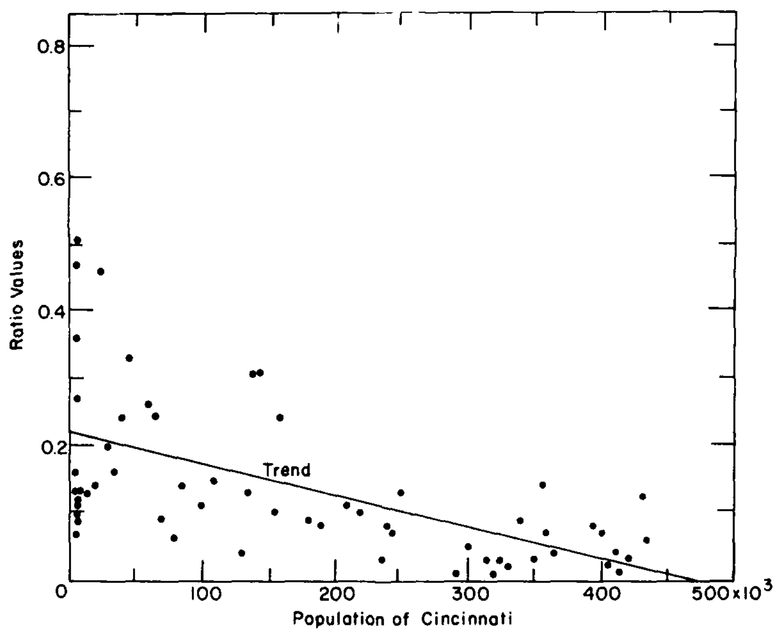


Figure 13. Relationship between ratio values (of observed ice versus freezing degree-days) and population trends at Cincinnati, Ohio, since 1900.

0.4 during the early part of the record to less than 0.1 during the later. The dashed line joining the sequential 10-year average ratios, however, included six consecutive average values of between 0.1 and 0.2 for the winters extending from 1884–85 to 1943–44. Incidentally, an investigation of average five-year ratio values showed a more erratic overall trend. The average value for the 33 winters during which ratios were computed in this period was 0.17, with highest and lowest ratios of 0.46 and 0.04. Of greater significance, though, is the marked decrease in the value, as well as the increase of the number of years with FDDs but no observed ice (indicated by the inverted solid triangles) after the winter of 1941–42. We attribute these reductions in ice on the river in part to the construction of high-lift locks and dams, the increase of navigation on the river, and the general development of the Ohio River valley.

A good index of watershed development can be determined from the region's increase in population. In fact, population can be correlated with several hydrologic parameters (Daly and Peters 1979). As a representative population of the Ohio River Valley, the census records for Cincinnati, Ohio, were examined. The population of Cincinnati has increased more or less linearly since 1900, from about 4000 to 400,000. The decrease in the computed ratios of observed ice to freezing degree-days during this period paralleled this general increase in population (Fig. 13). It is not possible to prove direct cause and effect, other than what we have suggested above. However, the decrease in the ratio of observed ice to the number of freezing degree-days has taken place during the period of watershed development.

Navigation in the Ohio River has increased substantially over the period of record. In 1930, slightly over 20 million tons of freight were shipped over the Ohio River. In 1974, the amount was nearly 140 million tons and was made up largely of coal and coke, with lesser amounts of other commodities such as petroleum, stone, sand, gravel, chemicals, iron and steel (U.S. Army Engineer Institute for Water Resources 1979). Cargo carriers travel the Ohio River during the winter, except during the few times of severe ice conditions. Navigation can influence the ice conditions in a navigable waterway such as the Ohio River (Ettema and Huang 1985). It has generally been reported that navigation tends to increase ice production by repeatedly creating open water areas in which new ice can grow (Sandhurst 1981). Therefore, it is not likely that the increase in navigation itself has caused the decrease in observed ice at Cincinnati.

WINTER CLIMATE

Air temperature regime for November through March

30-year average air temperatures

We used data for 30-year normals (1951–80) from 80 weather stations along the Ohio River Valley adjacent to or within 50 miles of the river (Fig. 14, Table 4) in a survey of the winter climate for the region. Analysis of the monthly average air temperatures (Fig. 15) provided the following observations. As expected, during November through March the temperatures are highest in southern Illinois and lowest in southwestern Pennsylvania, ranging from approximately 48 to 40°F in November, 34 to 24°F in January and 48 to 34°F in March. The increase in average air temperatures down the valley, except for isolated locations (such as at major cities) is quite uniform. The higher temperatures reported in metropolitan areas are reflections of the well documented "heat island" phenomenon (Terjung 1970). Freezing air temperatures along the river normally occur in December (Fig. 15b) at many Pennsylvania and Ohio locations. In January (Fig. 15c), freezing temperatures occur over most of the region, except for the extreme southwest and isolated areas further upstream. In February (Fig. 15d), the average freezing isoline is located slightly northeast of its January location, and melting commences along areas south of the line. The reported air temperatures for Burgettstown and Waynesburg, Pennsylvania (station numbers 15 and 19), appear low and were considered unrepresentative. For example, in January (Fig. 15c) Burgettstown's reported average temperature of 24.8°F is about 2 to 4.5°F lower than nearby stations. Although similar differences in temperature were found during the other winter months, we made no attempt to explain such anomalies, since this would be beyond the scope of this report. Thom's (1968) isoline maps of the standard deviations of monthly average temperature for the Ohio River Valley region range from approximately ±0 to ±3.5°F in November, and from ±0 to ±5.5°F for December through March.

Examination of the average midwinter air temperatures along the valley (Fig. 15c) indicated the existence of the well-documented association between decreasing temperatures and increasing elevation. The numerical relationship, however, for the Ohio River Valley data appeared to differ from the standard atmospheric adiabatic lapse rate of 0.33°F decrease in temperature for every 100-ft increase in height. Consequently, a simplified contour map (Fig. 16) using each station elevation was drawn, which confirmed the generally uniform increase in elevation upriver with decreasing temperatures. The numerical relationship between the 30-year average January air temperature and the elevations for the 80 stations is presented in Figure 17 and shows a decrease of about 1°F in air temperature for every 100-ft increase in elevation. The correlation coefficient r is 0.835, and the standard deviation is ±1.71°F. The calculated line of best fit is

$$y = -0.0095x + 36.6 \tag{4}$$

where x = station elevation (in feet) and y = average January air temperature (degrees Fahrenheit) (i.e., 30-year normal value). The average January air temperature was used because it statistically approximates the duration and intensity of an average freezing season for each location (see Bilello and Appel 1978).

Mean minimum air temperatures

As previously noted, the temperatures for Burgettstown and Waynesburg were consistently low in comparison with surrounding stations, and therefore, were again ignored. Mean minimum air temperature patterns (Fig. 18) were similar to those for the average monthly temperatures. The highest values occur at the Mississippi River juncture and the lowest in the headwaters. They range from approximately 40 to 30°F in November, 26 to 14°F in January, and 38 to 22°F in March. The entire area experiences mean minimum air temperatures below freezing during December, January and February, suggesting that ice will form on the river annually. These data by themselves, however, will not provide reliable predictions of when, where and how much ice can be expected along specific sections of the Ohio River for any particular winter.

Freezing degree-days

A combined measure of the duration and magnitude of below-freezing temperatures occurring during any given freezing season is defined as the freezing index, and is derived from an accumulation of freezing degree-days for the season. A freezing degree-day was defined earlier in the *Physical Setting and Hydrology* section, and since the index provides an evaluation of both the length and intensity of the freezing regime, it is worthwhile to include it here.

The mean freezing index, based on the 30-year monthly normal air temperatures, was computed for 59 of the 80 stations (Table 5, Fig. 19). Three other stations recorded 32.0°F or higher monthly mean normal air temperatures during the winter months. The remaining 18 locations did not record any monthly mean normal air temperatures of 32°F or lower. The 0 and 50 mean freezing index lines (Fig. 19) roughly follow the river valley from Evansville, Indiana, to Parkersburg, West Virginia. The values then increase rapidly from 100 to over 600 mean total freezing degree-days up the valley.

This distribution clearly shows that the valley can be classified into three general winter temperature regimes. The most severe region lies upstream of the confluence of the Ohio and Muskingum rivers, where the mean freezing index values begins to increase rapidly. A moderate zone extends from that confluence to the mouth of the Wabash River. The least severe zone is located downstream of the Wabash, where no mean freezing degree-days are recorded. Although the last region is the mildest, river ice could form there or drift in from upstream during particularly cold winters.

Precipitation regime for November through March

Average total precipitation

Data on precipitation are extremely important in studies of winter floods, river stages, ice levels and ice jams because ice runs in the winter are usually associated with major rainstorms or rain-on-snow events that lead to flooding. Total winter precipitation decreases from over 20 in. at the southwestern end of the Ohio River to less than 13 in. in parts of the northeast section of the river valley (Fig. 20).

A visual comparison of the distributions of precipitation (Fig. 20) and average January air temperatures (Fig. 15c) shows they are similar except for five stations (with mean temperature values below 24°F) located northeast of the Ohio River and in Pennsylvania. This association make sense physically in that lower-air-temperature regimes contain less atmospheric moisture, and have reduced total precipitation.

A linear correlation between the average January air temperature and total winter precipitation for the 75 stations showed an approximate increase of 0.6 in. of precipitation for every 1°F increase in temperature (Fig. 21). The correlation coefficient r is 0.75, and the standard deviation for the water-equivalent precipitation is ±1.44 in. The calculated line of best fit is

$$y = 0.602x - 2.04 \quad (5)$$

where x = average January air temperature (degrees Fahrenheit) (i.e., 30-year normal value) and y = average total water equivalent precipitation (inches) for November through March.

The correlation coefficient for the relationship between elevation and decreasing amounts of the total water-equivalent precipitation recorded from November through March was less than that for the relationship shown in eq 5.

Mean annual and monthly maximum snowfalls

Much of the monthly precipitation amounts for November through March discussed in the previous section include the water-equivalent portions of measured snowfalls. An examination of the distribution of the mean total annual snowfalls and the distributions of monthly maximum snowfalls is therefore of interest.

The mean total annual snowfall amounts increase from approximately 10 in. at the southwest end of the Ohio River Valley to between 25 and 30 in. in the vicinity of the Ohio, West Virginia and Pennsylvania borders (Fig. 22). Annual snowfall amounts then increase very rapidly from 35 in. to as high as 60 in. over a distance of about 60 miles north of the headwaters of the Ohio River.

The monthly maximum snowfall amounts exhibit an interesting reverse distribution along the Ohio River Valley. The 20 in. monthly maximum isoline in the southwestern Ohio River region, for example, is $1\frac{1}{2}$ to 2 times greater than the mean annual total value of 10 to 15 in. An explanation for this is that particular winter storms in the warmer (southern) region often contain

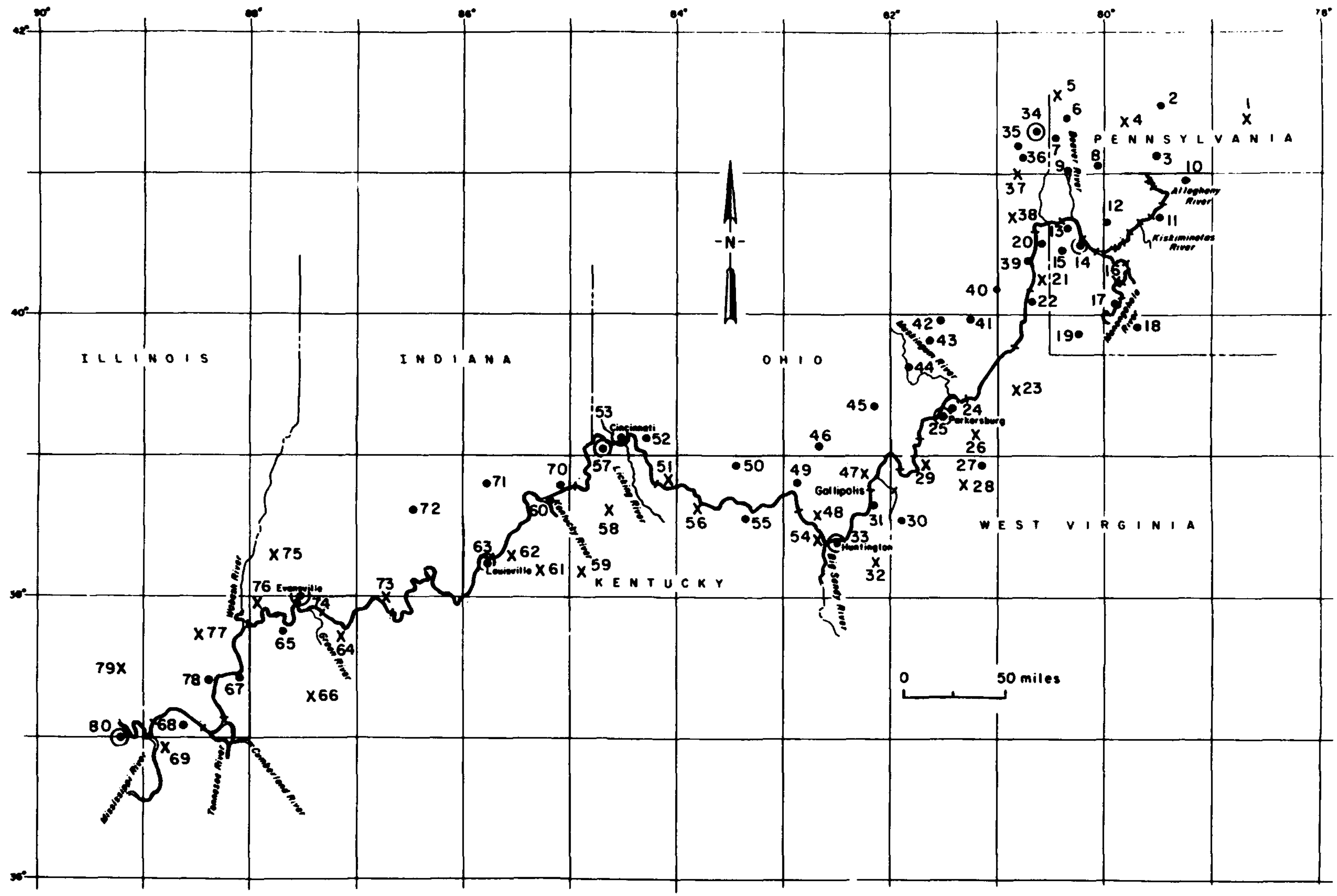
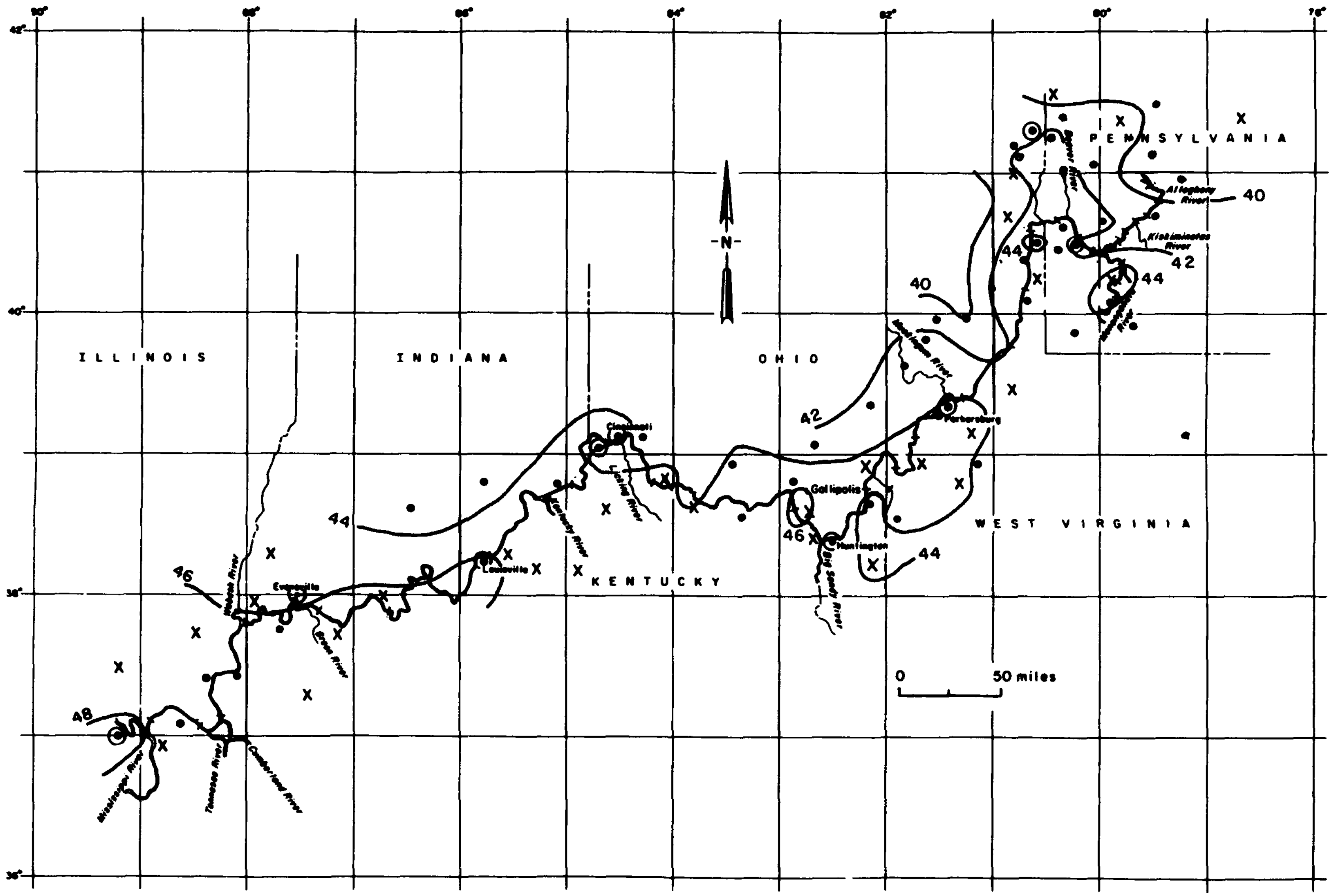


Figure 14. Climatic station number and location map (see Table 4 for station names; solid dot is a co-op station, x is a snowfall climate station, and a circled dot is a first-order weather station).

Table 4. List of Ohio River Valley climatic stations. Sites for each of the six states in the study are listed alphabetically and include the stations' locations, elevation, the type of climatic record, and the station number as given on the location map (see Fig. 14).

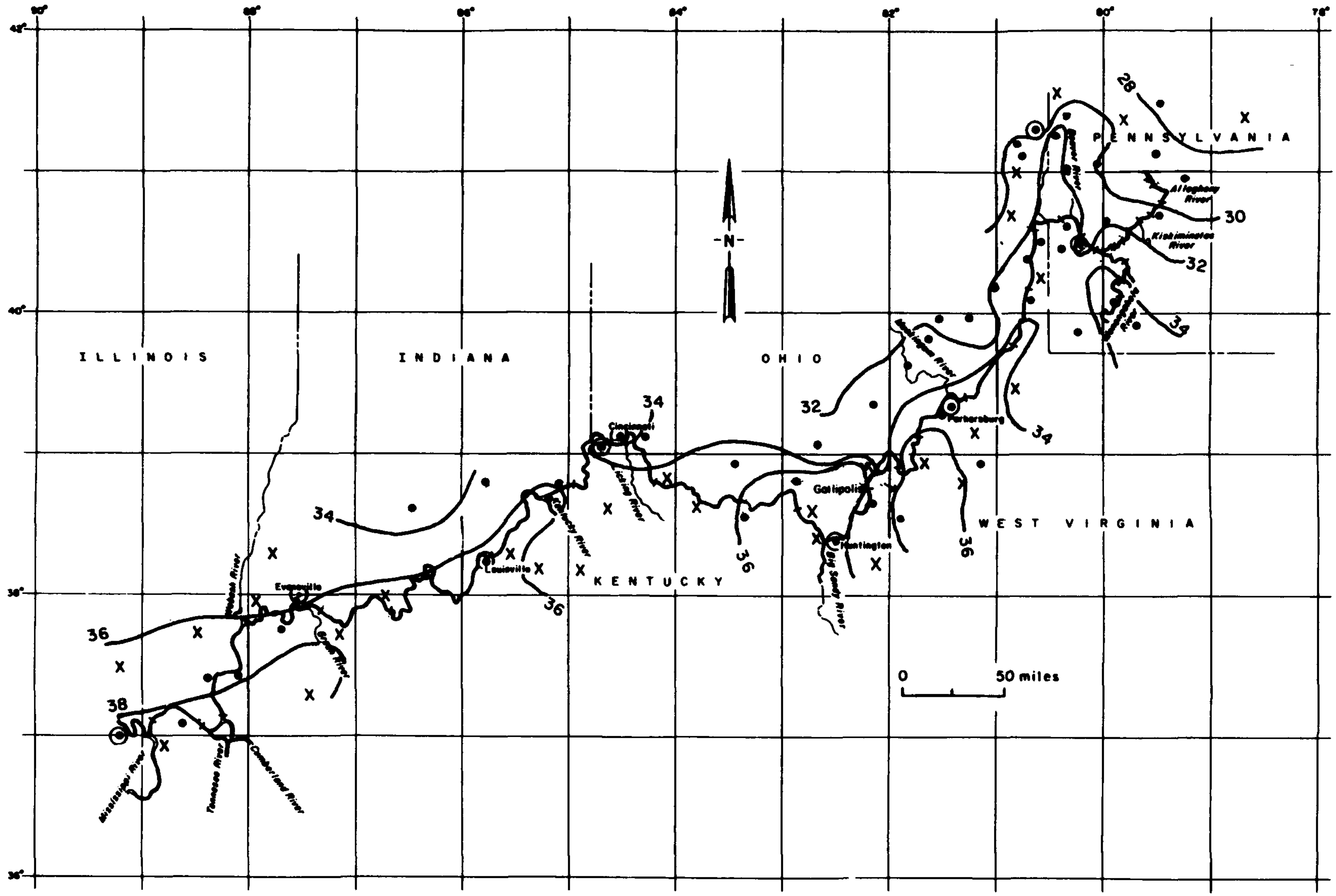
Station name	Location Lat. (N)	Location Long. (W)	Elevation (ft) m.s.e.	Type of record*	Station no. on location map
Pennsylvania					
Bakerstown 3 WNW	40°39′	79°59′	1230	A	12
Burgettstown 2 W	40°23′	80°26′	980	A	15
Clarion 3 SW	41°12′	79°26′	1114	A	3
Donora 1 SW	40°10′	79°52′	762	B	16
Farrell Sharon	41°14′	80°30′	855	A	7
Fort City 4 S Dam	40°43′	79°30′	950	A	11
Franklin	41°23′	79°49′	987	B	4
Greenville	41°24′	80°23′	980	A	6
Jamestown 2 NW	41°30′	80°28′	1050	B	5
Montgomery Lock and Dam	40°39′	80°23′	692	A	13
New Castle 1 N	41°01′	80°22′	825	A	9
Newell	40°05′	79°54′	805	A	17
Pittsburgh AP WSO 2	40°30′	80°13′	1137	C	14
Putneyville 2 SE Dam	40°55′	79°17′	1270	A	10
Ridgway	41°25′	78°45′	1360	B	1
Slippery Rock 1 SSW	41°04′	80°04′	1260	A	8
Tionesta 2 SE Dam	41°29′	79°26′	1200	A	2
Uniontown 1 NE	39°55′	79°43′	956	A	18
Waynesburg 1 E	39°54′	80°10′	940	A	19
West Virginia					
Cairo 3 S	39°10′	81°10′	680	B	26
Grantsville 2 NW	38°56′	81°06′	730	A	27
Hamlin	38°17′	82°06′	642	B	32
Hogsett Gallipolis Dam	38°41′	82°11′	570	A	31
Huntington WSO	38°22′	82°33′	827	C	33
Middlebourne 2 ESE	39°29′	80°52′	750	B	23
New Cumberland	40°30′	80°36′	750	A	20
Parkersburg FAA AP	39°21′	81°26′	831	A	24
Parkersburg (Federal Bldg) WSO	39°16′	81°34′	615	C	25
Ravenswood Lock Park	38°57′	81°46′	584	B	29
Spencer	38°48′	81°21′	964	B	28
Wellsburg 3 NE	40°18′	80°35′	668	B	21
Wheeling Filt Plant	40°07′	80°42′	665	A	22
Winfield Locks	38°32′	81°55′	571	A	30
Ohio					
Athens 5 NW	39°23′	82°11′	685	A	45
Barnesville Water Wks	39°58′	81°10′	1140	A	41
Cadiz	40°16′	81°00′	1260	A	40
Caldwell 6 NW	39°49′	81°36′	980	A	43
Canfield 1 S	41°01′	80°46′	1140	B	37
Meldahl Dam	38°48′	84°10′	500	B	51
Cincinnati Abbe WSMO	39°09′	84°31′	761	C	53
Gallipolis 5 W	38°50′	82°11′	673	B	47
Ironton	38°32′	82°41′	560	B	48
Jackson 2 NW	39°04′	82°39′	700	A	46
McConnelsville Lock 7	39°39′	81°51′	710	A	44
Milford	39°10′	84°18′	570	A	52
Millport 2 NW	40°43′	80°54′	1145	B	38
Mineral Ridge Water Wks	41°09′	80°47′	890	A	36
Peebles	38°57′	83°25′	810	A	50
Portsmouth	38°45′	82°55′	540	A	49
Senecaville Dam	39°55′	81°26′	875	A	42
Steubenville Water Wks	40°23′	80°38′	992	A	39
Warren 3 S	41°12′	80°49′	900	A	35
Youngstown WSO	41°16′	80°40′	1178	C	34
Kentucky					
Anchorage	38°16′	85°32′	730	B	62
Ashland	38°27′	82°36′	555	B	54
Carrollton Lock 1	38°41′	85°11′	480	A	60
Covington WSO	39°03′	84°40′	869	C	57
Fords Ferry Dam 50	37°28′	88°06′	356	A	67
Frankfort Lock 4	38°14′	84°52′	504	B	59
Henderson 7 SSW	37°45′	87°38′	430	A	65
Louisville WSO	38°11′	85°44′	477	C	63
Lovelaceville	36°58′	88°50′	370	B	69
Madisonville 1 SE	37°19′	87°29′	439	B	66
Maysville Sewage Plant	38°41′	83°47′	515	B	56
Owensboro 2 W	37°46′	87°09′	420	B	64
Paducah Sewage Plant	37°96′	88°36′	325	A	68
Shelbyville 3 SSW	38°13′	85°16′	841	B	61
Banceburg	38°35′	83°20′	520	A	55
Williamstown 3 NW	38°39′	84°37′	920	B	58
Indiana					
Evansville WSO	38°03′	87°32′	381	C	74
Johnson Exp Farm	38°16′	87°45′	440	B	75
Mount Vernon	37°57′	87°53′	415	B	76
Paoli Radio WVAK	38°32′	86°29′	640	A	72
Scottsburg	38°41′	85°46′	550	A	71
Tell City Power Plant	37°57′	86°46′	394	B	73
Vevay	38°45′	85°04′	480	A	70
Illinois					
Anna 1 E	37°28′	89°14′	640	B	79
Cairo WSO	37°00′	89°10′	314	C	80
Harrisburg	37°44′	88°32′	366	B	77
Rosiclare	37°25′	88°21′	400	A	78

*A—Cooperative weather stations. Temperature generally taken twice, precipitation once daily (NOAA 1982b).
B—Principal climatological stations. Similar to type A; snowfall data in NOAA (1982a).
C—First-order-stations. Major weather stations, variety of weather data taken throughout the day; data in NOAA (1983).



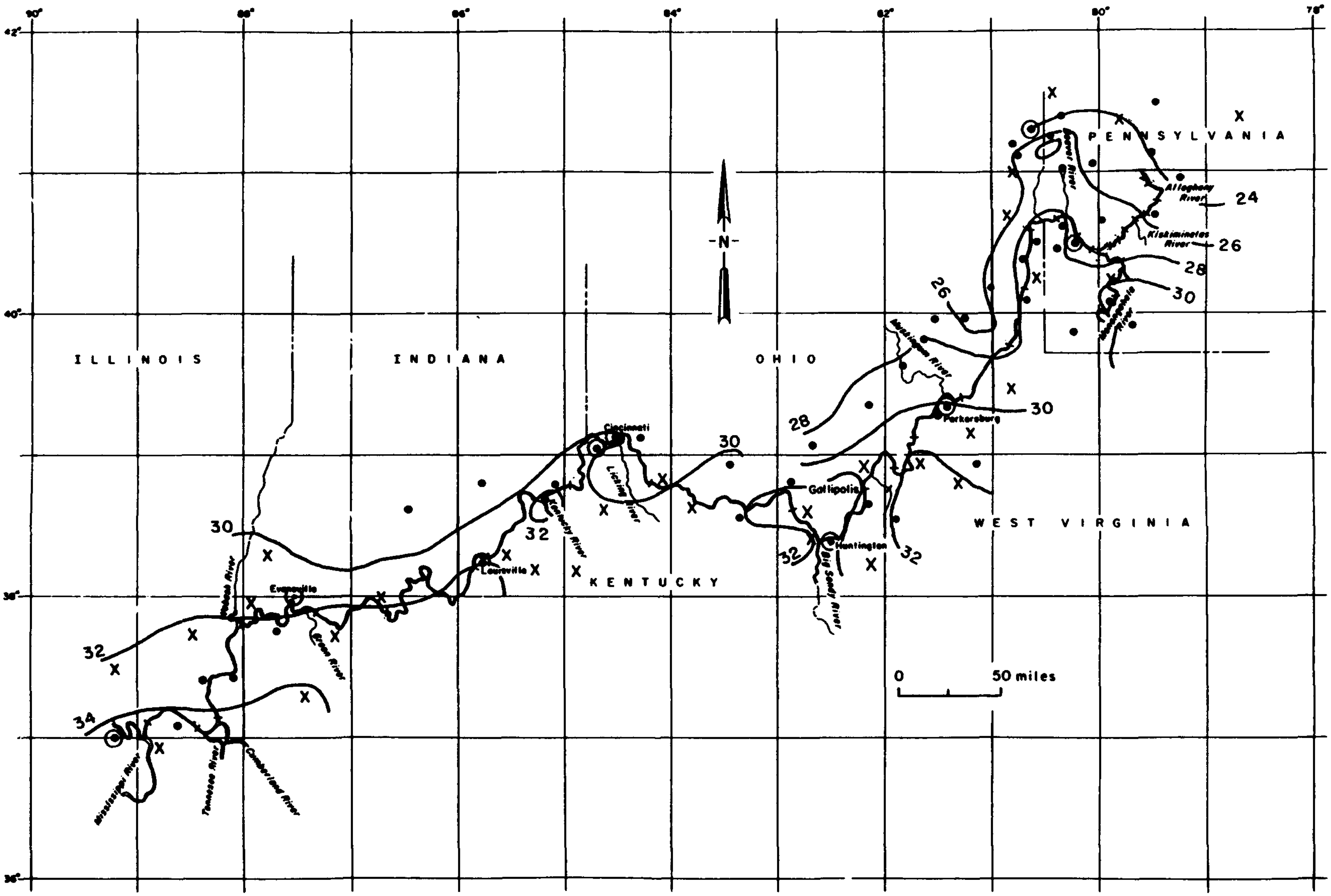
a. November.

Figure 15. Average air temperatures (°F; 30-yr normals).



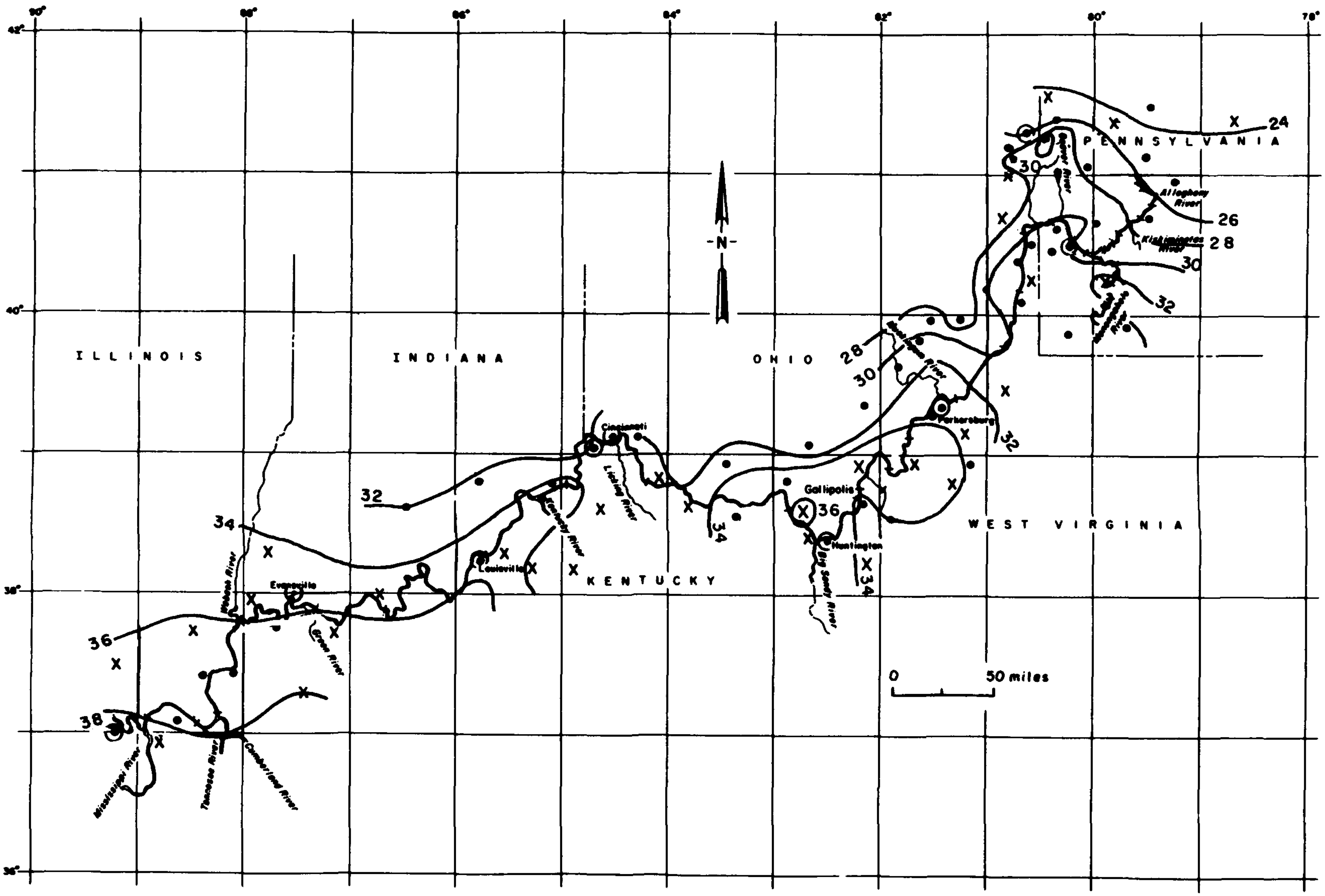
b. December.

Figure 15(cont'd).



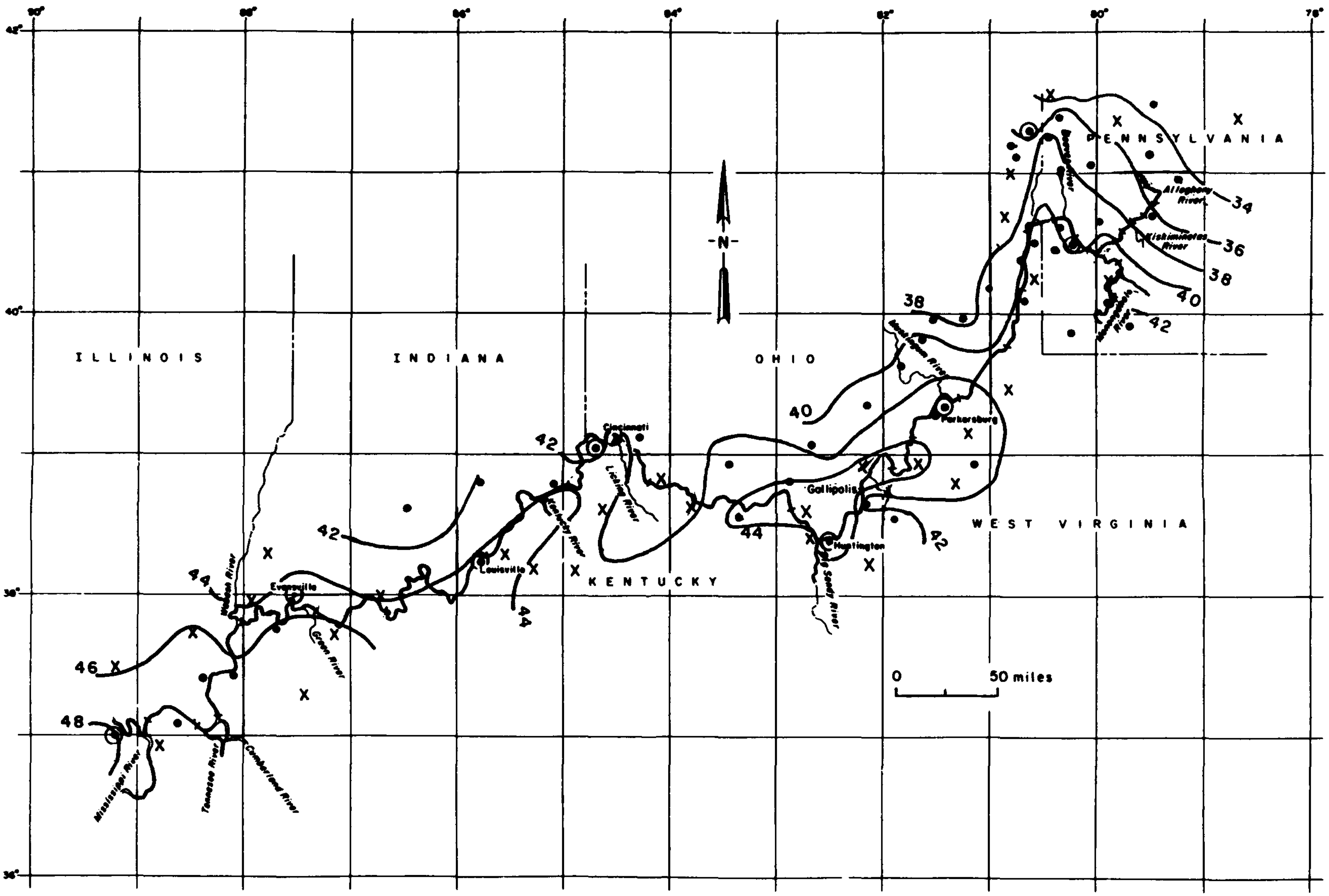
c. January.

Figure 15 (cont'd). Average air temperatures (°F; 30-yr normals).



d. February.

Figure 15 (cont'd).



e. March.

Figure 15 (cont'd). Average air temperatures (°F; 30-yr normals).

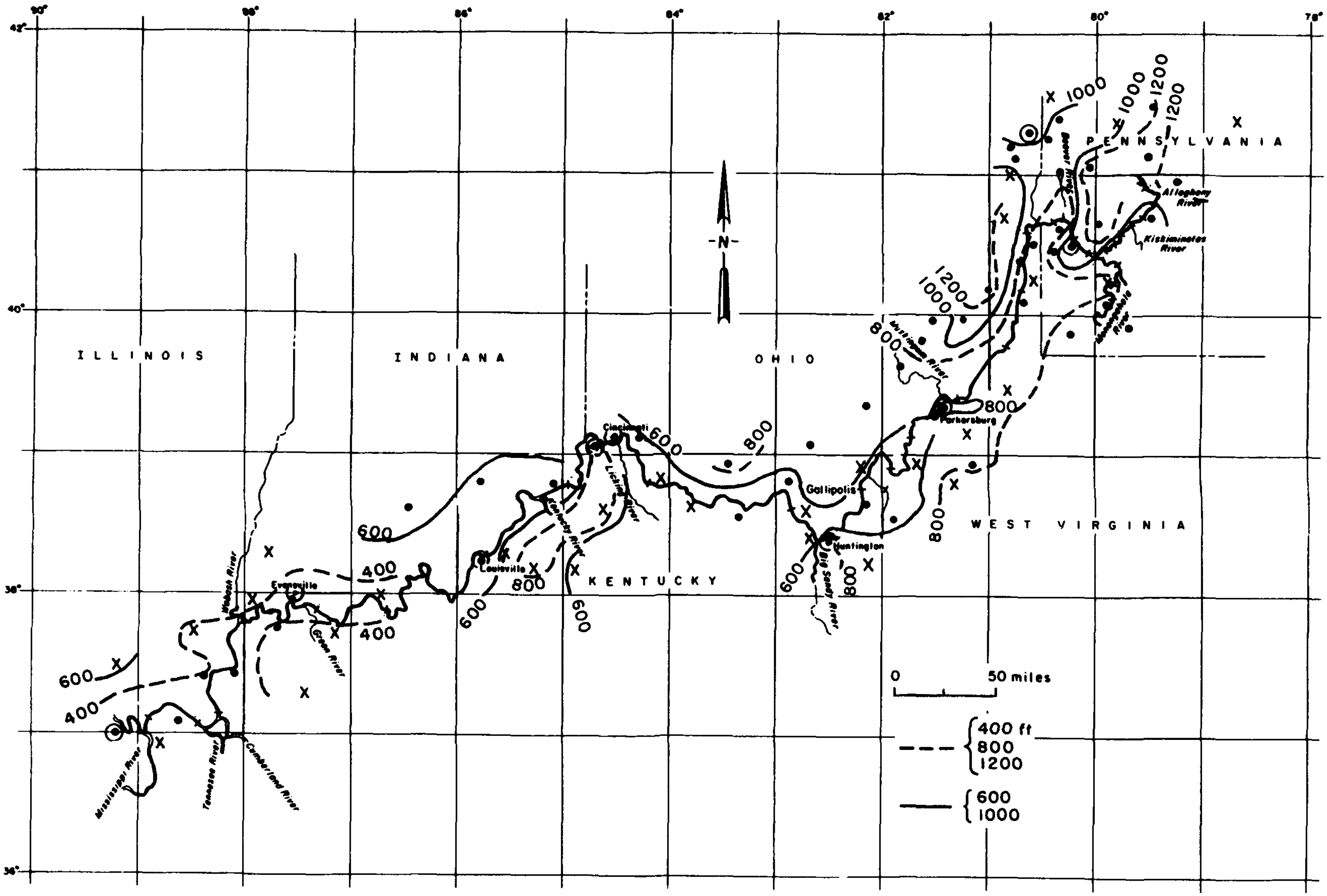


Figure 16. Approximate topographic contour map (ft).

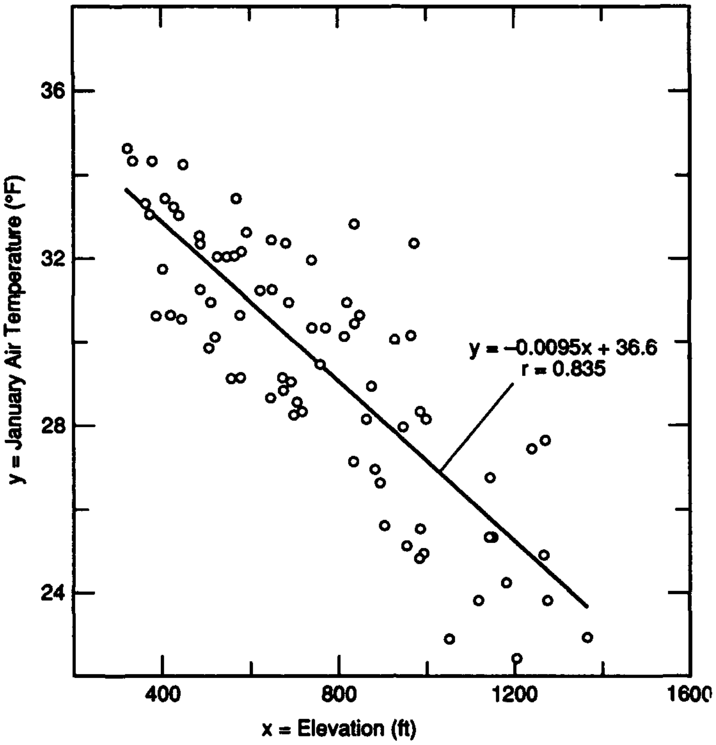


Figure 17. Relationship between station elevation (ft) and average January air temperature (°F).

sufficient atmospheric water vapor to produce substantial snow on a storm-by-storm basis, resulting in occasional high monthly maximum values. But over long periods (i.e., on a seasonal basis), the higher air temperatures in this area bring rain instead of snow, thus total annual snowfall amounts are lower. As described in the following discussion, these climatic conditions are reversed in the northeast region of the river valley.

Both mean annual and monthly maximum snowfall amounts of about 15 to 20 in. are recorded near Louisville, Kentucky, and extend northeastward to Parkersburg, West Virginia (Fig. 22). However, upstream in southwestern Pennsylvania, the ratio of average annual to monthly maximum snowfall amounts is the reverse of that observed at the southwestern end. In this region the monthly maximum values of about 25 to 30 in. are about $1\frac{1}{2}$ to 2 times *less* than the annual amounts of 50 to 60 in. This reversal occurs because of the longer and colder winters experienced in the northeast section of the Ohio River. The numerous individual snowstorms in this area produce greater total amounts of snowfall annually than what is generally recorded during any one month.

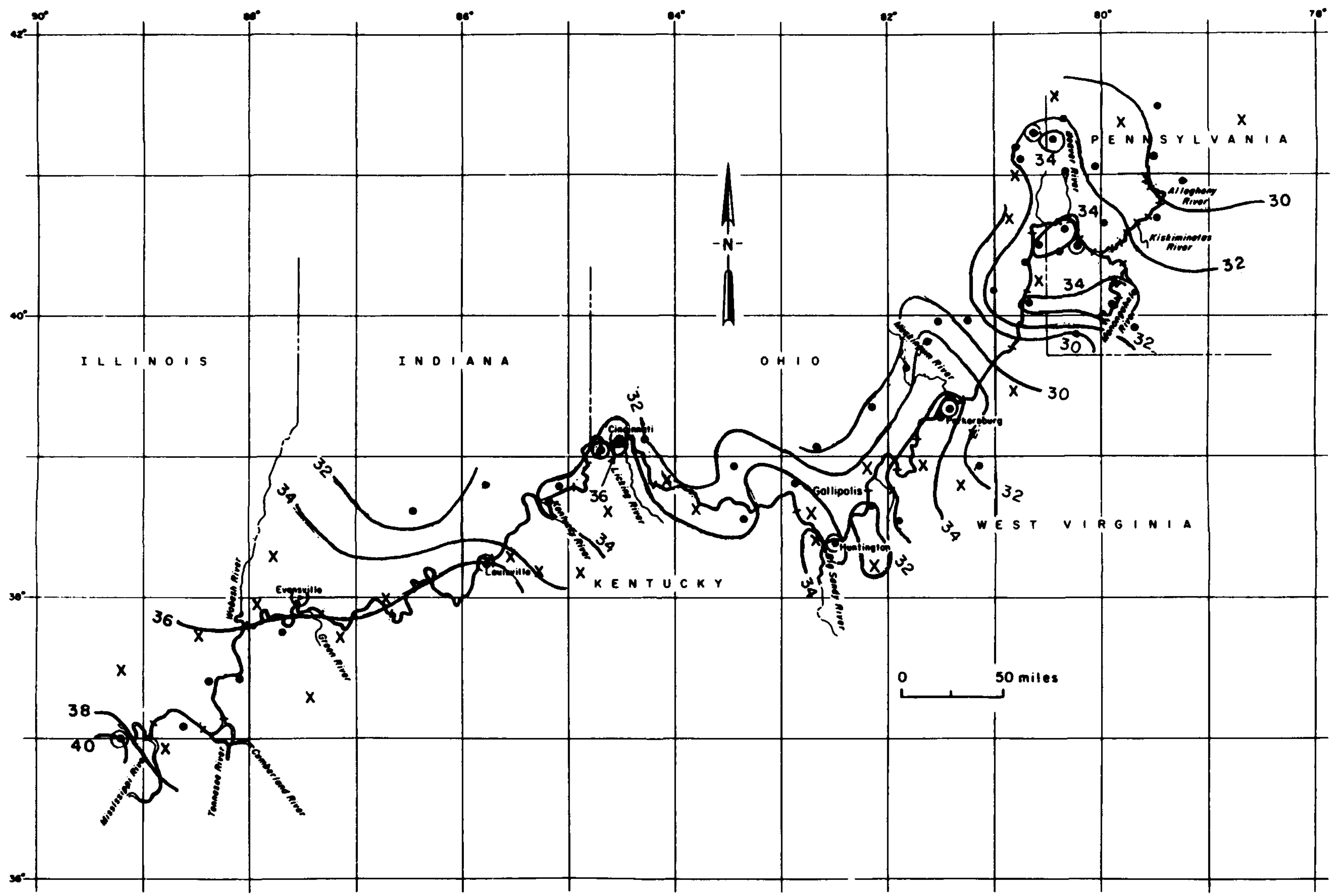
This snowfall information is useful in the calculations of probable river stages and resultant ice jam formations caused by runoff from snowmelt (see, for example, Bates and Brown 1982). It would be particularly pertinent in those areas with "ripe" (near thaw) high-density snow packs, and when rapid above-freezing temperature rises and rain occur simultaneously.

CONCLUSIONS

The Ohio River Valley has three physiographic regions: the Appalachian Plateau, the Central Lowlands and the Interior Low Plateau. Long-term average water discharge values from a particular sub-watershed, however, follows a fairly consistent relationship regardless of the region it is in. This relationship also holds for the Ohio River itself.

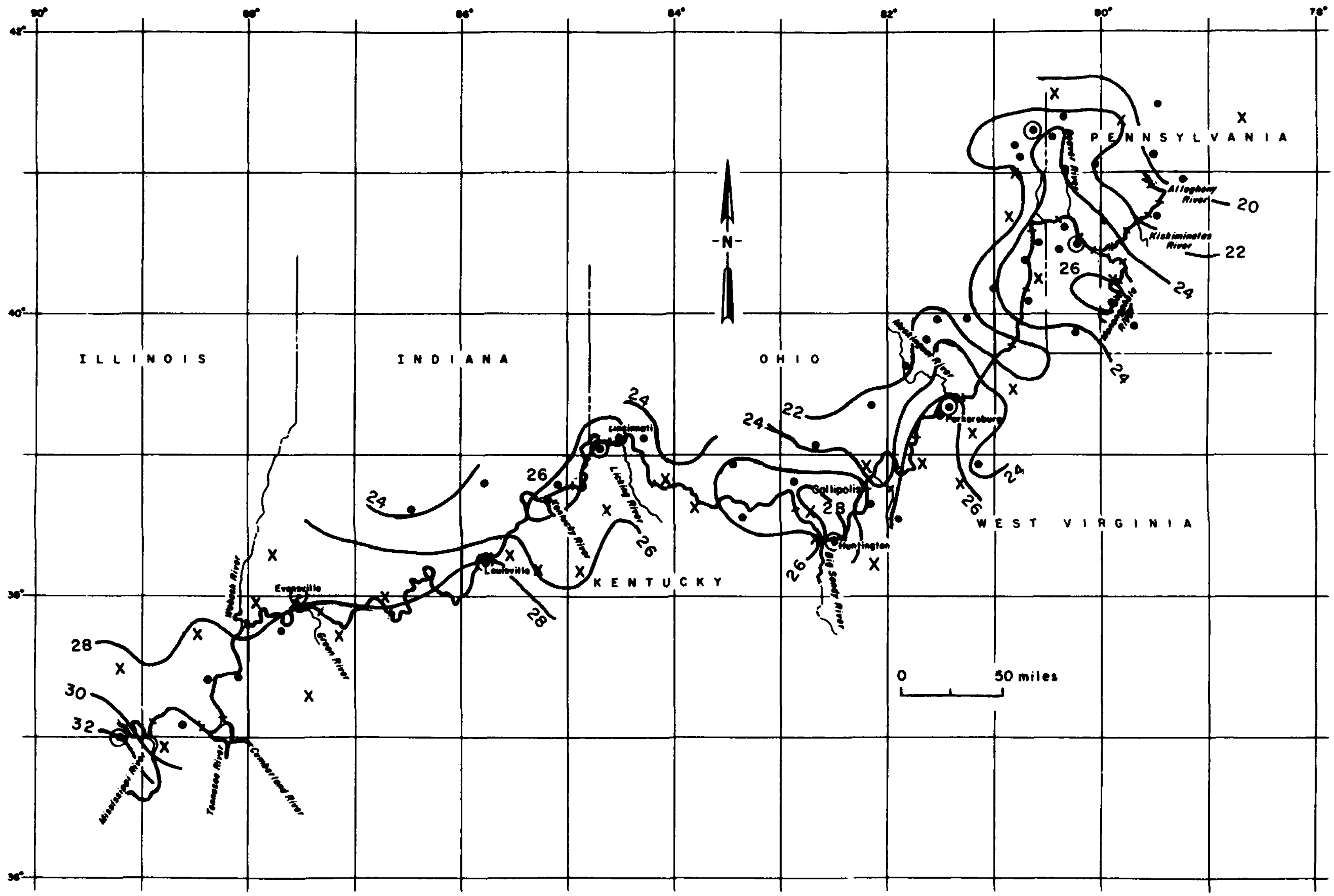
Average discharges for the Ohio River were found to vary considerably during the year. Maximum discharges and minimum water temperatures normally occur in the winter. Frequent and random peak discharges usually come in association with concurrent precipitation or snowmelt, or both. Major changes in ice conditions on the Ohio River, such as ice breakup and rapid movement, occur during these high discharges.

Although the mean minimum and mean maximum daily water temperatures on the Ohio River are as low as 33°F and as high as 85°F, respectively, the long-term



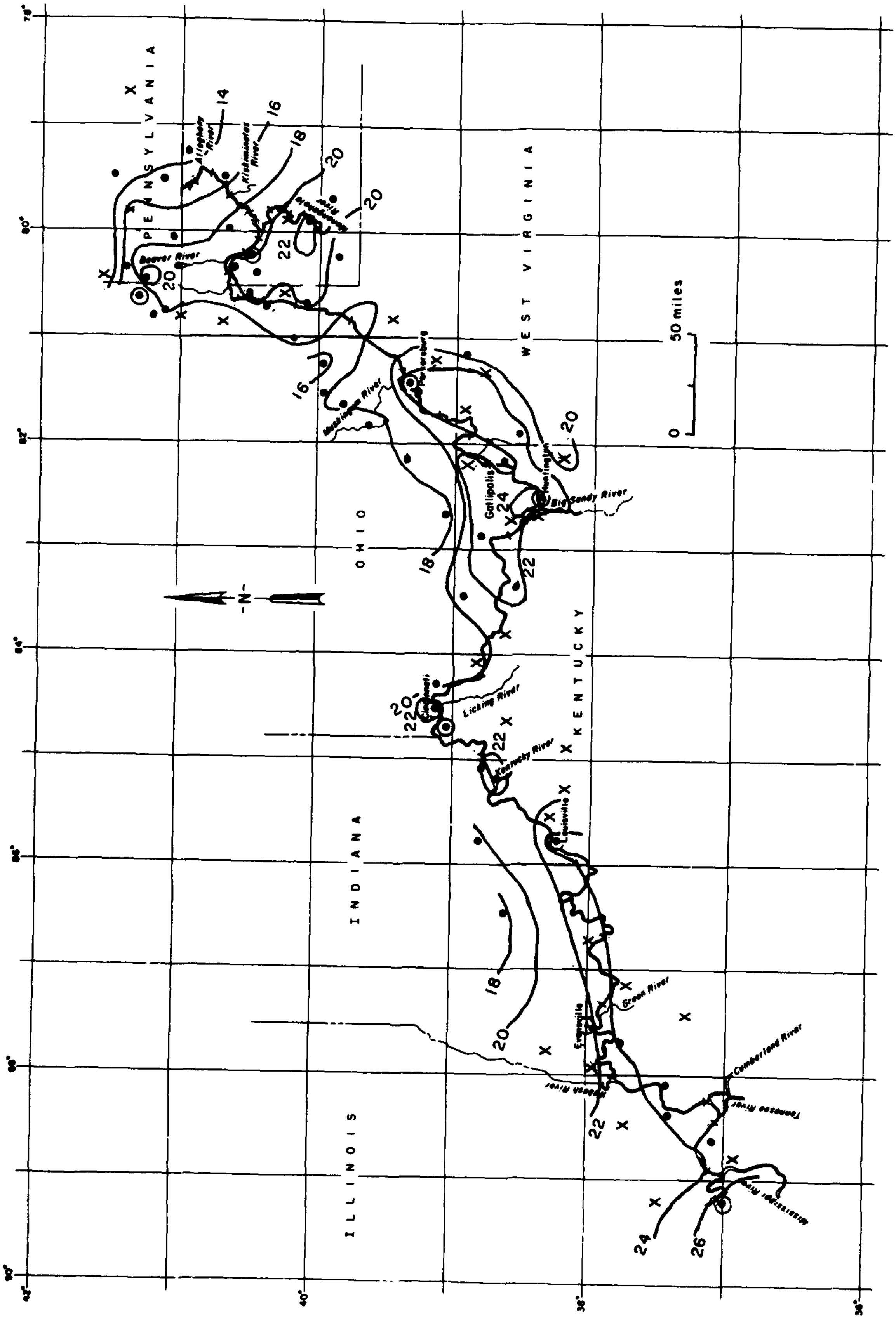
a. November

Figure 18. Mean minimum air temperatures (°F; 30-year normals).



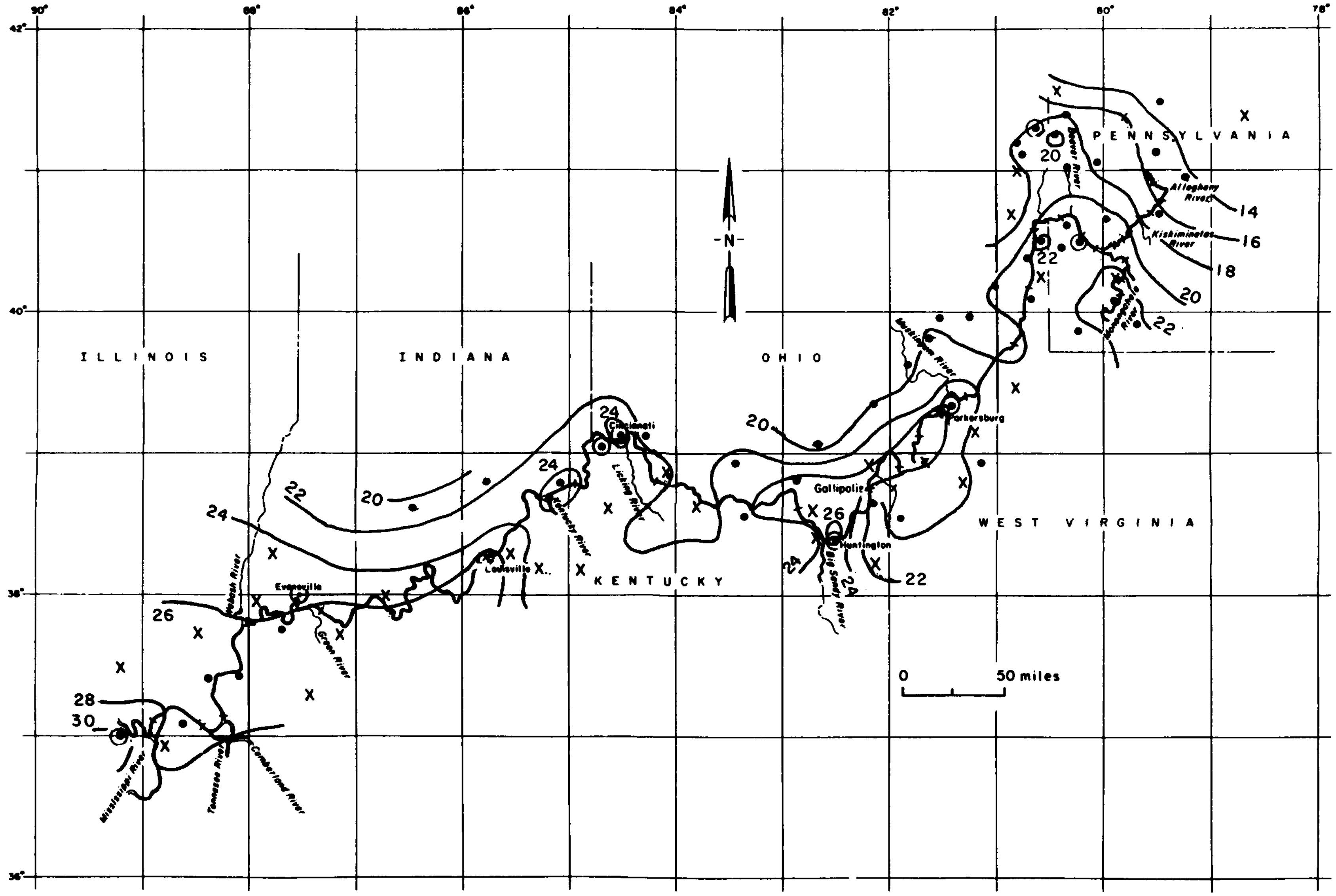
b. December.

Figure 18 (cont'd). Mean minimum air temperatures (°F; 30-year normals).



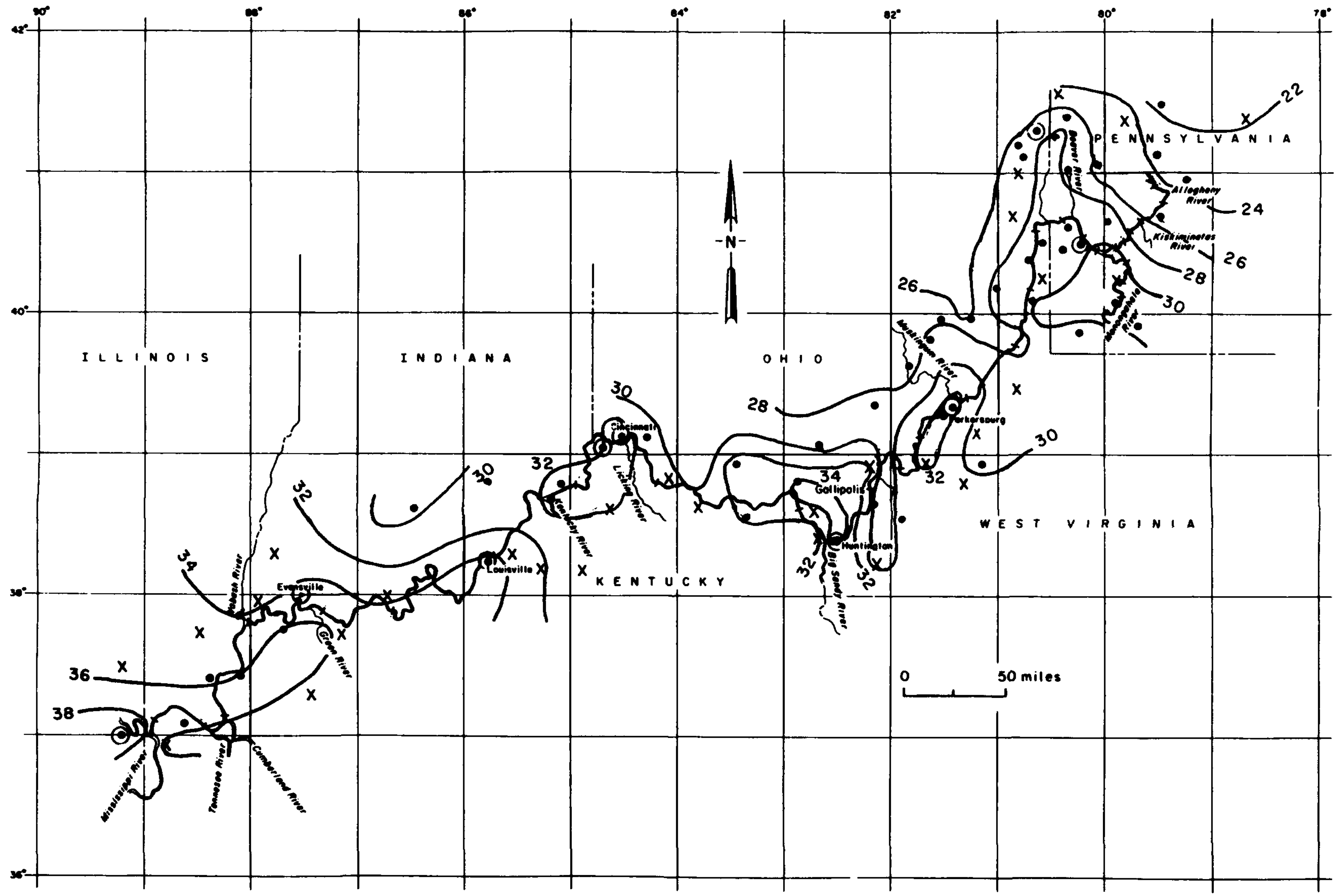
c. January.

Figure 18 (cont'd).



d. February.

Figure 18 (cont'd). Mean minimum air temperatures (°F; 30-year normals).



e. March.

Figure 18 (cont'd).

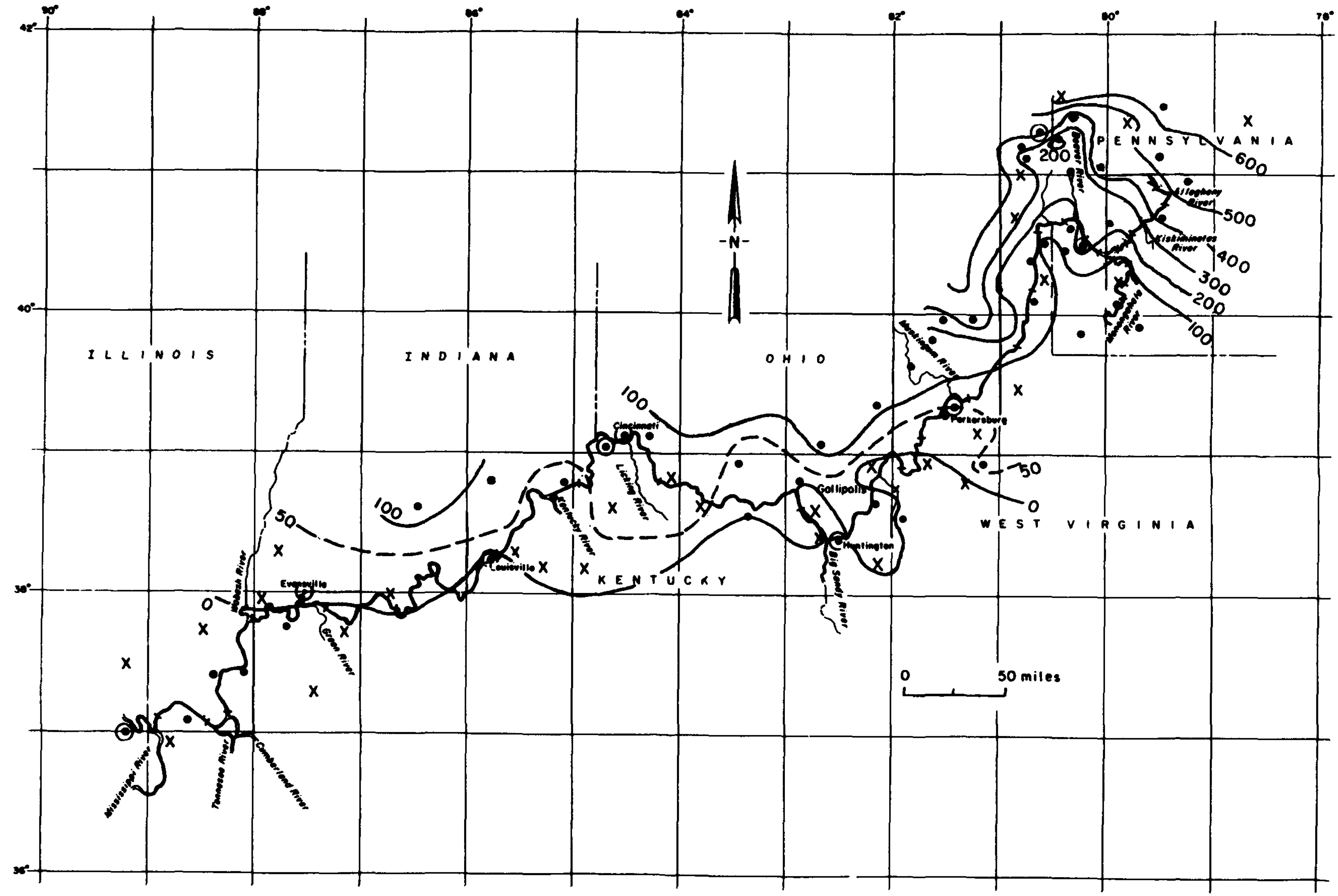


Figure 19. Total seasonal mean freezing degree-days (base 32°F).

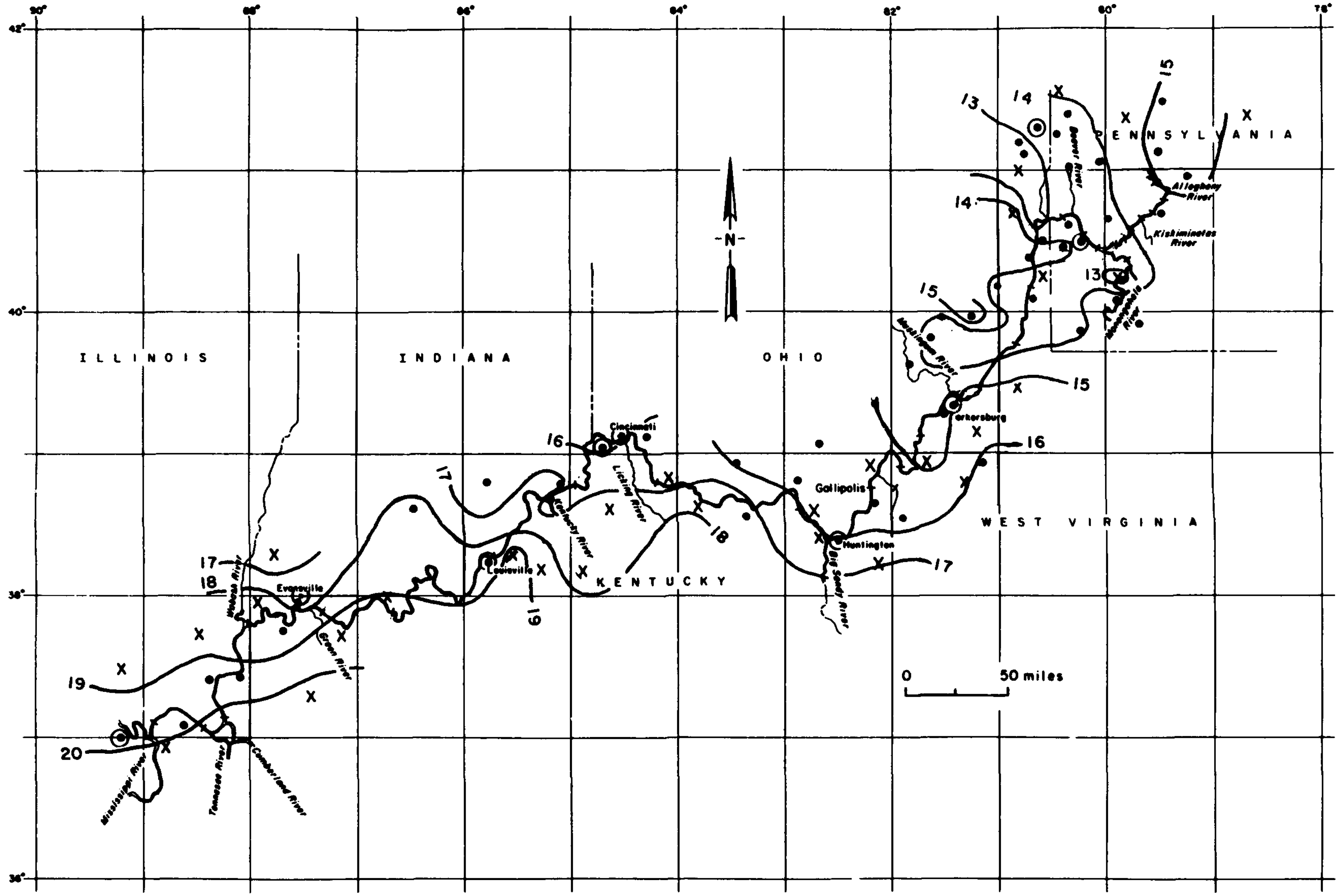


Figure 20. Total water-equivalent precipitation (in.) (November through March).

Table 5. Station summaries of total mean freeezing degree-days for the winter season (base 32°F), total water-equivalent precipitation for the 5-month period November through March, and mean annual and maximum monthly snowfall amounts for type B stations only (NOAA 1982a).

Station name	Total mean freezing degree-days for the winter season (Base 32°F)	5-Months (Nov–Mar) total w/eq. precipitation (in.)	Snowfall amounts (in.) for type B stations: Total mean annual	Snowfall amounts (in.) for type B stations: Observed monthly maximum
Pennsylvania				
Bakerstown 3 WNW	207	13.97		
Burgettstown 2 W	454	14.61		
Clarion 3 SW	545	15.48		
Donora 1 SW	53	12.95	30.3	23.0
Farrell Sharon	174	13.31		
Ford City 4 S Dam	424	14.27		
Franklin	459	14.53	53.8	31.5
Greenville	36	13.54		
Jamestown 2 NW	612	14.01	60.3	32.8
Montomery Lock and Dam	160	13.46		
Newcastle 2 N	236	13.55		
Newell	65	14.94		
Pittsburgh AP WSO 2	273	13.75		
Putneyville 2 SE Dam	555	15.84		
Ridgeway	645	14.89	57.6	34.5
Slippery Rock 1 SSW	428	13.93		
Tionesta 2 SE Dam	687	15.54		
Uniontown 1 NE	65	14.59		
Waynesburg 1 E	86	13.97		
West Virginia				
Cairo 3 S	34	15.90	22.1	24.0
Grantsville 2 NW	53	16.56		
Hamlin	25	16.98	24.0	20.8
Hogsett Gallipolis Dam	43	15.72		
Huntington WSO	—	16.09		
Middlebourne 2 ESE	87	15.26	24.4	22.5
New Cumberland	87	13.08		
Parkersburg FAA AP	50	15.55		
Parkersburg (Federal Bldg) WSO	25	14.15		
Ravenswood Lock Park	—	14.99	16.9	19.0
Spencer	—	15.75	21.9	22.0
Wellsburg 3 NE	119	13.57	23.0	22.0
Wheeling Filt Plant	126	13.74		
Winfield Locks	—	15.91		
Ohio				
Athens 5 NW	104	15.01		
Barnesville Water Wks	390	15.08		
Cadiz	192	13.60		
Caldwell 6 NW	143	13.15		
Canfield 1 S	393	12.04	33.3	20.5
Meldahl Dam	68	16.90	13.7	14.0
Cincinnati Abbe WSMO	53	15.42		

Station name	Total mean freezing degree-days for the winter season (Base 32°F)	5-Months (Nov–Mar) total w/eq. precipitation (in.)	Snowfall amounts (in.) for type B stations: Total mean annual	Snowfall amounts (in.) for type B stations: Observed monthly maximum
Gallipolis 5 W	—	15.76	18.3	15.7
Ironton	—	15.93	17.1	15.1
Jackson 2 NW	129	15.77		
McConnelsville Lock 7	160	14.73		
Milford	90	16.45		
Millport 2 NW	390	14.05	33.5	32.2
Mineral Ridge Water Wks	274	12.17		
Peebles	34	15.92		
Portsmouth	0	15.93		
Senecaville Dam	257	14.00		
Steubenville Water Wks	160	14.82		
Warren 3 S	358	12.50		
Youngstown WSO	494	13.79		
Kentucky				
Anchorage	3	19.44	17.3	16.8
Ashland	0	16.09	14.2	12.9
Carrollton Lock 1	—	16.59		
Covington WSO	96	15.93		
Fords Ferry Dam 50	—	18.29		
Frankfort Lock 4	34	17.38	12.6	15.2
Henderson 7 SSW	—	18.45		
Louisville WSO	—	18.31		
Lovelaceville	—	21.40	10.2	21.0
Madisonville 1 SE	—	20.15	9.4	20.5
Maysville Sewage Plant	59	17.91	13.4	13.0
Owensboro 2 W	—	19.38	12.9	20.5
Paducah Sewage Plant	—	19.47		
Shelbyville 3 SSW	43	18.10	13.9	17.0
Vanceburg	0	17.32		
Williamstown 3 NW	62	17.39	17.7	15.6
Indiana				
Evansville WSO	43	17.40		
Johnson Exp Farm	47	16.49	15.2	18.7
Mount Vernon	43	18.23	12.3	18.8
Paoli Radio WVAK	105	18.68		
Scottsburg	90	16.73		
Tell City Power Plant	9	19.01	12.8	20.0
Vevay	25	17.00		
Illinois				
Anna 1 E	—	18.96	13.6	18.7
Cairo WSO	—	19.98		
Harrisburg	—	18.27	17.3	17.2
Rosiclare	—	19.90		

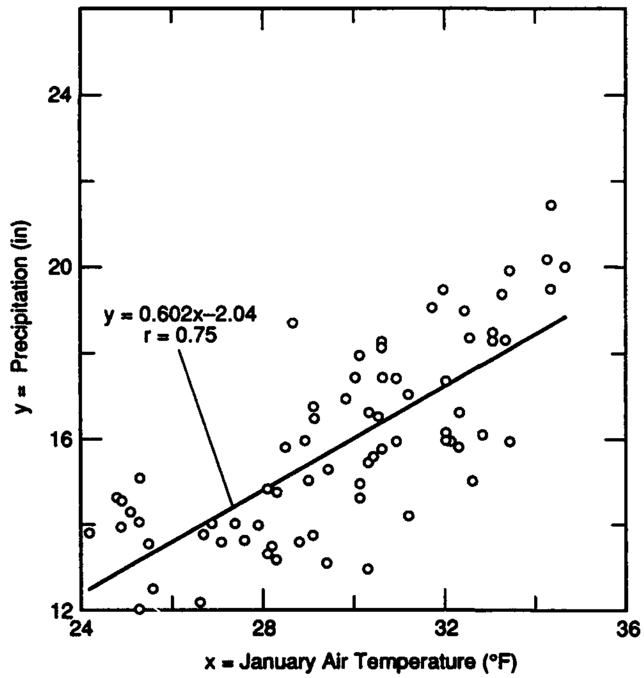


Figure 21. Relationship between average January air temperature and total 5-month (Nov through Mar) water equivalent precipitation.

average value across its entire length only ranges from about 56.7 to 61.2°F. The lower temperatures naturally exist on the upstream portion of the river.

Analyses of river ice conditions at Cincinnati, Ohio, revealed a decline in the amount of ice during the winters from 1902 to 1985. The number of days of observed ice relative to the number of freezing-degree-days has also declined during this period, with the most dramatic decline starting in the 1930s. Reduction in ice amounts corresponds with the basin development. This relationship may result from the changes in the thermal balance in the river brought about by the increase in heated discharges from new power plants along the river banks as population increased, and from changes in the stage and flow regime caused by the construction of locks and dams. Further research is required to quantify the effect of these changes on river ice formation, however.

Additional detailed studies of the winter climate in direct association with records of ice formation, growth and decay and river ice levels, ice jams and blockages are also required. For example, it would be worthwhile to select a particular winter with severe ice conditions on the Ohio River, and gather all available hydrologic, physiographic and environmental data recorded during the entire period. An integrated analysis of all of the contributing parameters could provide some insight into the relative importance of each factor with respect to the chronological and areal distribution of ice on the river. The results would give us an improved capability for predicting ice behavior at specific times and locations on the river.

Future research should also consider investigations of the most severe winters on record, observed short-term periods of extreme cold, and the frequency, intensity and distribution of winter air and water temperatures throughout the area of interest. For example, another form of freezing index that is used in engineering planning and construction work is the "design freezing index." For this index, the average value of the air temperatures for the three coldest winters in 10 years, or the 10 coldest in 30 years, is used. This approach would account for the extremely cold winters, such as 1976–77 and 1977–78, that were experienced recently in the eastern half of the U.S. (Kerr 1985). Such records then could be compared with historical navigation or lock and dam records, or compared with recent aircraft or satellite imagery data of concurrent ice observations on the Ohio River. The ultimate objective would be to develop an accurate river ice forecast model using real time observed weather patterns and the associated river ice conditions.

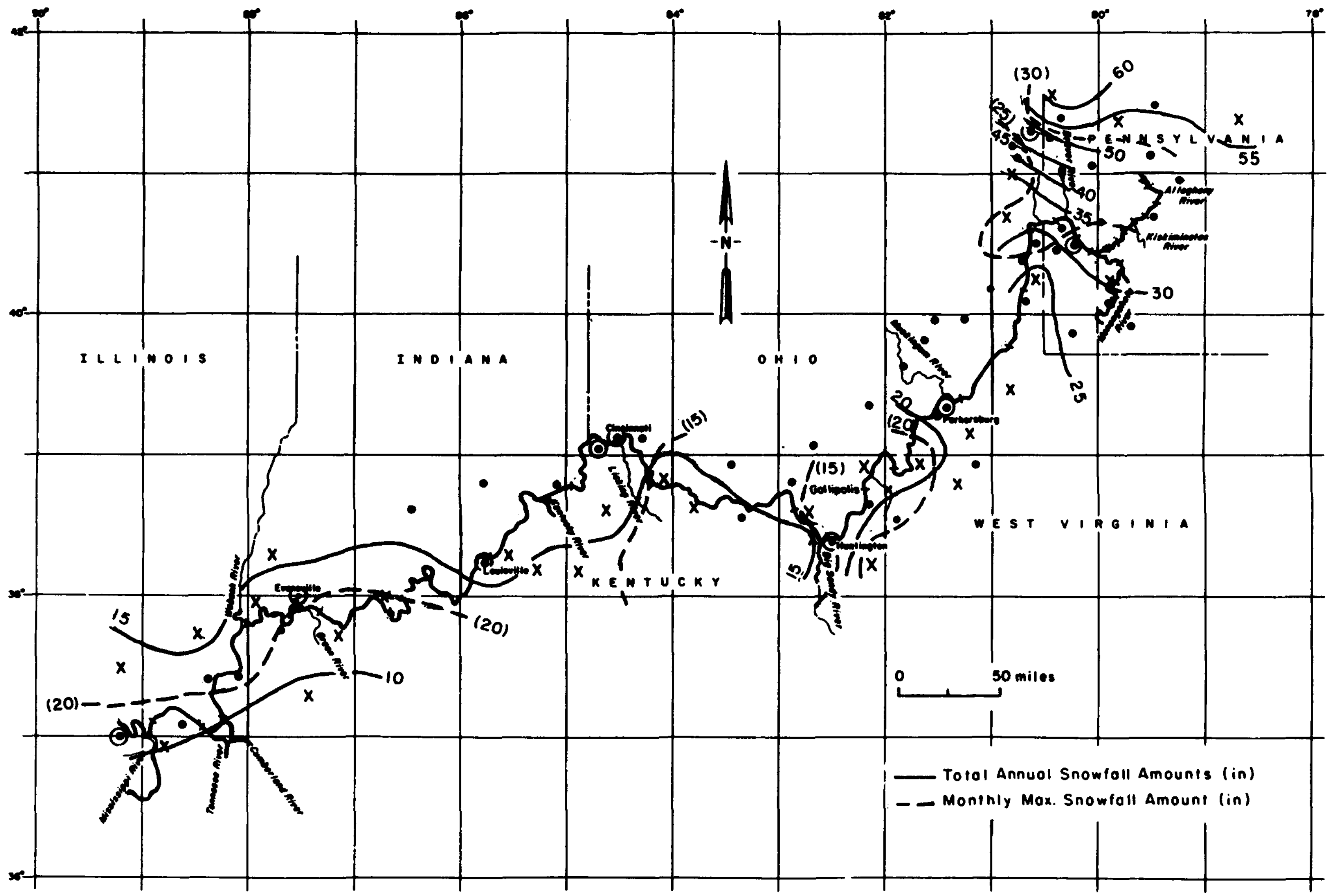


Figure 22. Average total annual and maximum monthly snowfall amounts (in.).

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APPENDIX A: DAILY AIR TEMPERATURES, WATER TEMPERATURES AND DISCHARGES AT TWO LOCATIONS ON THE OHIO RIVER

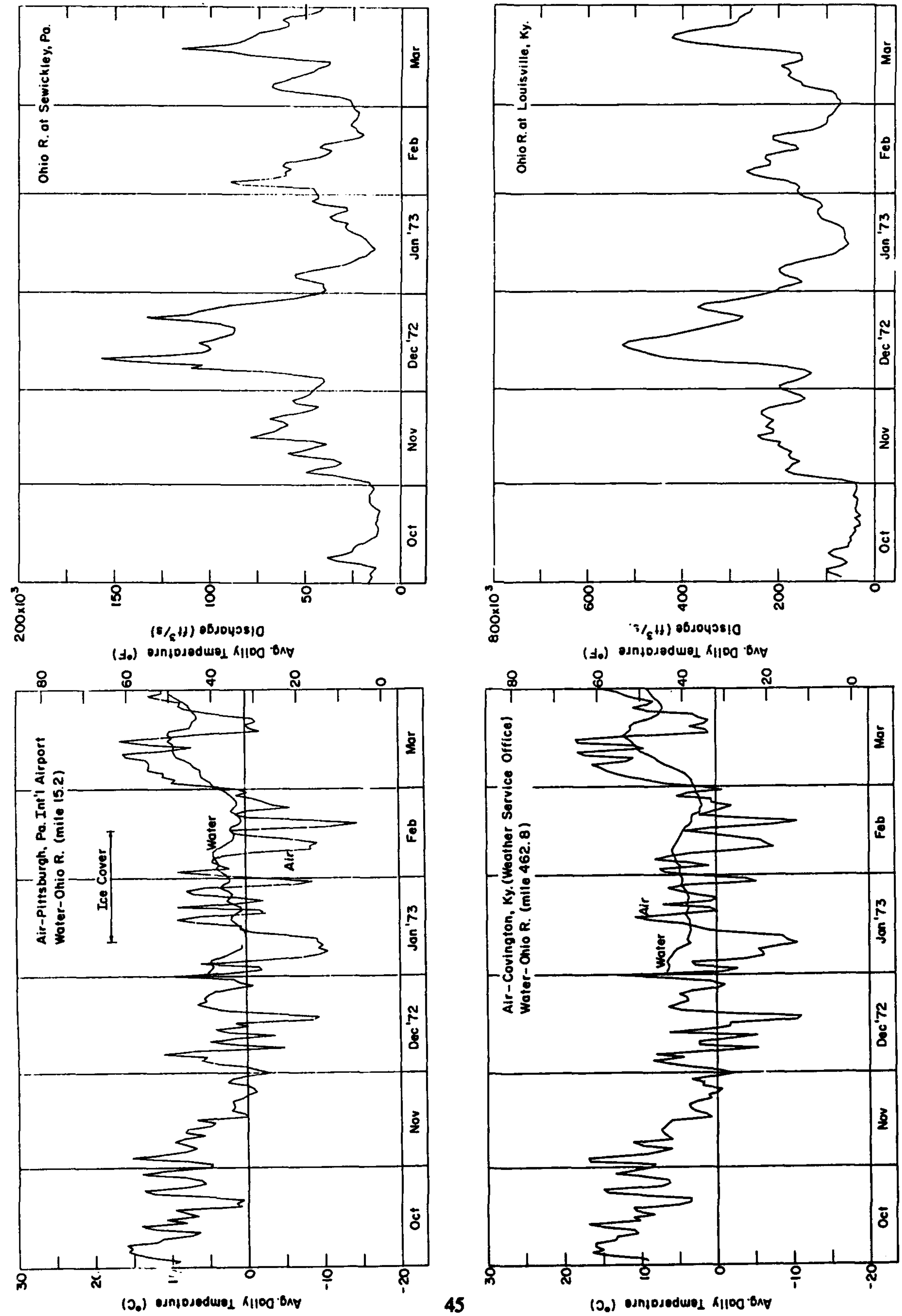


Figure A1. 1972–73.

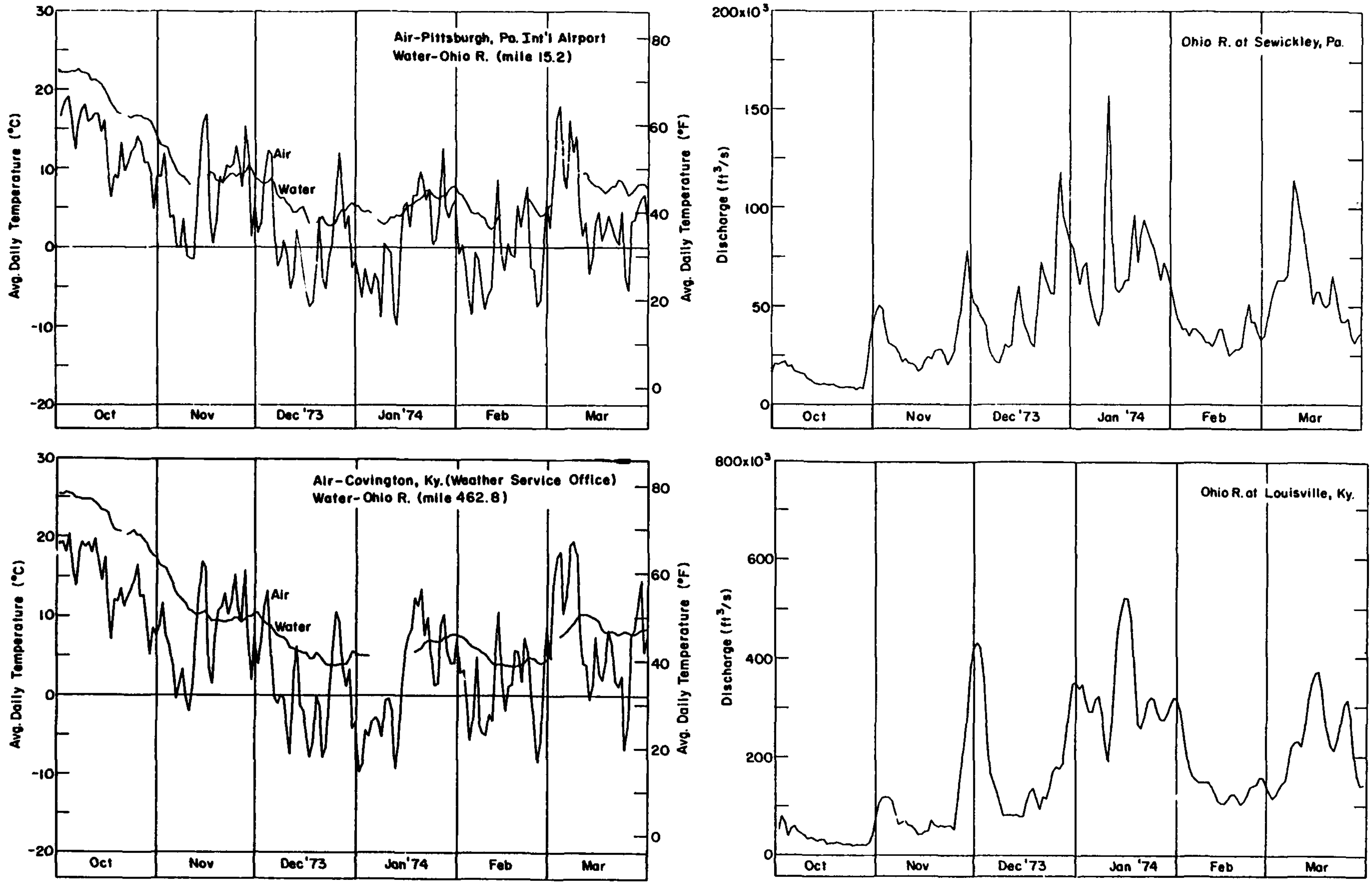
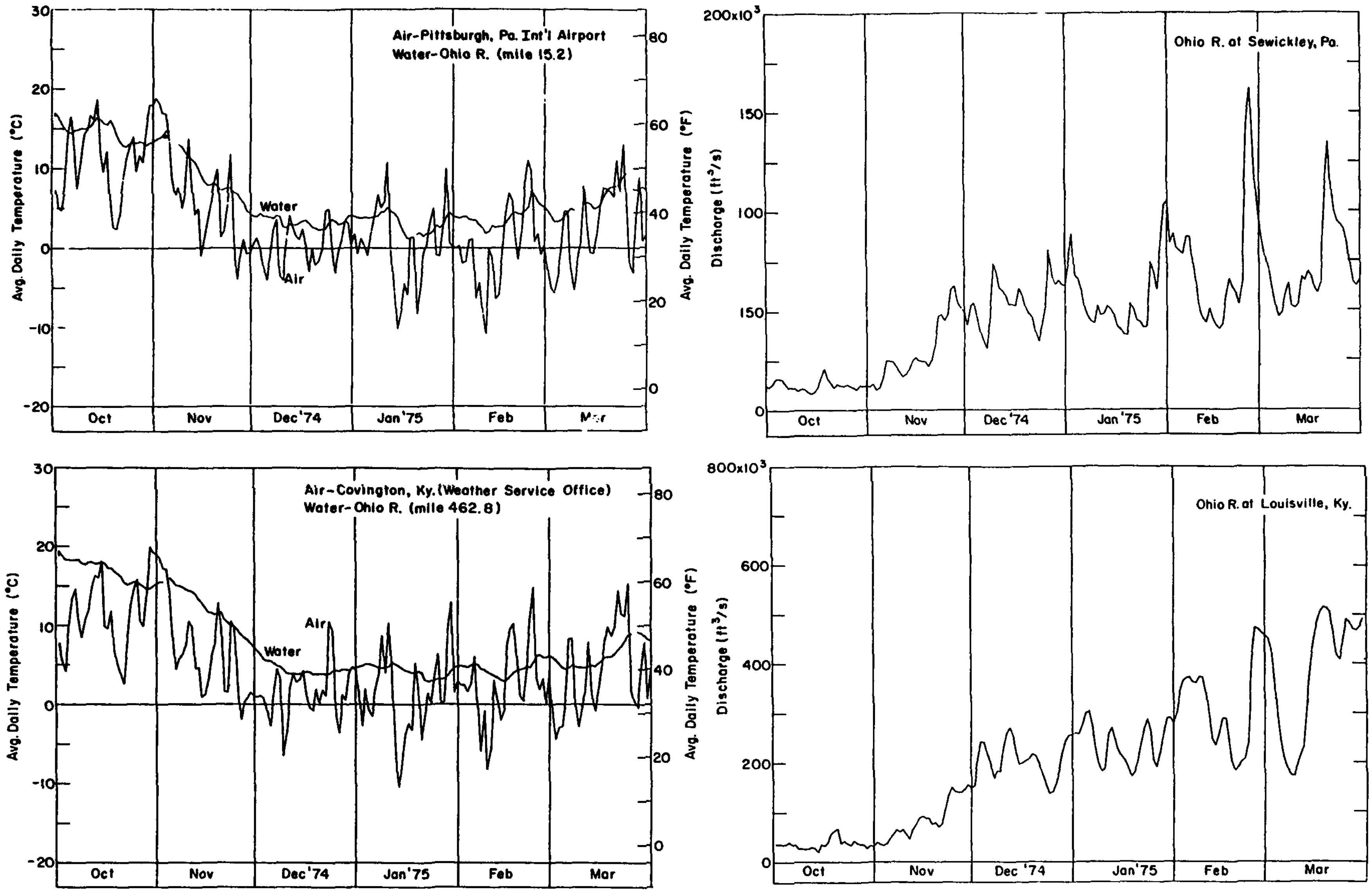


Figure A2. 1973–74.



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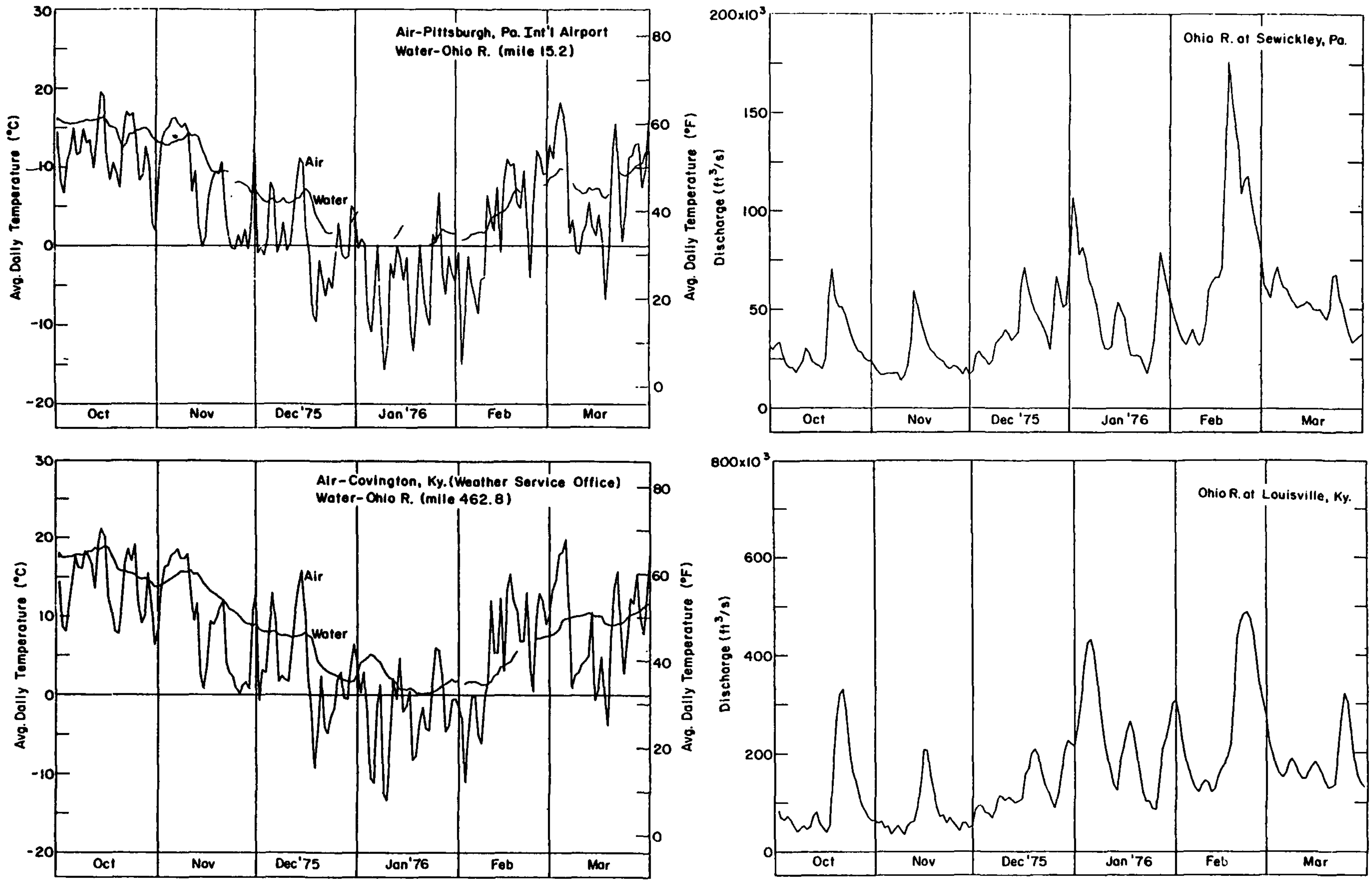
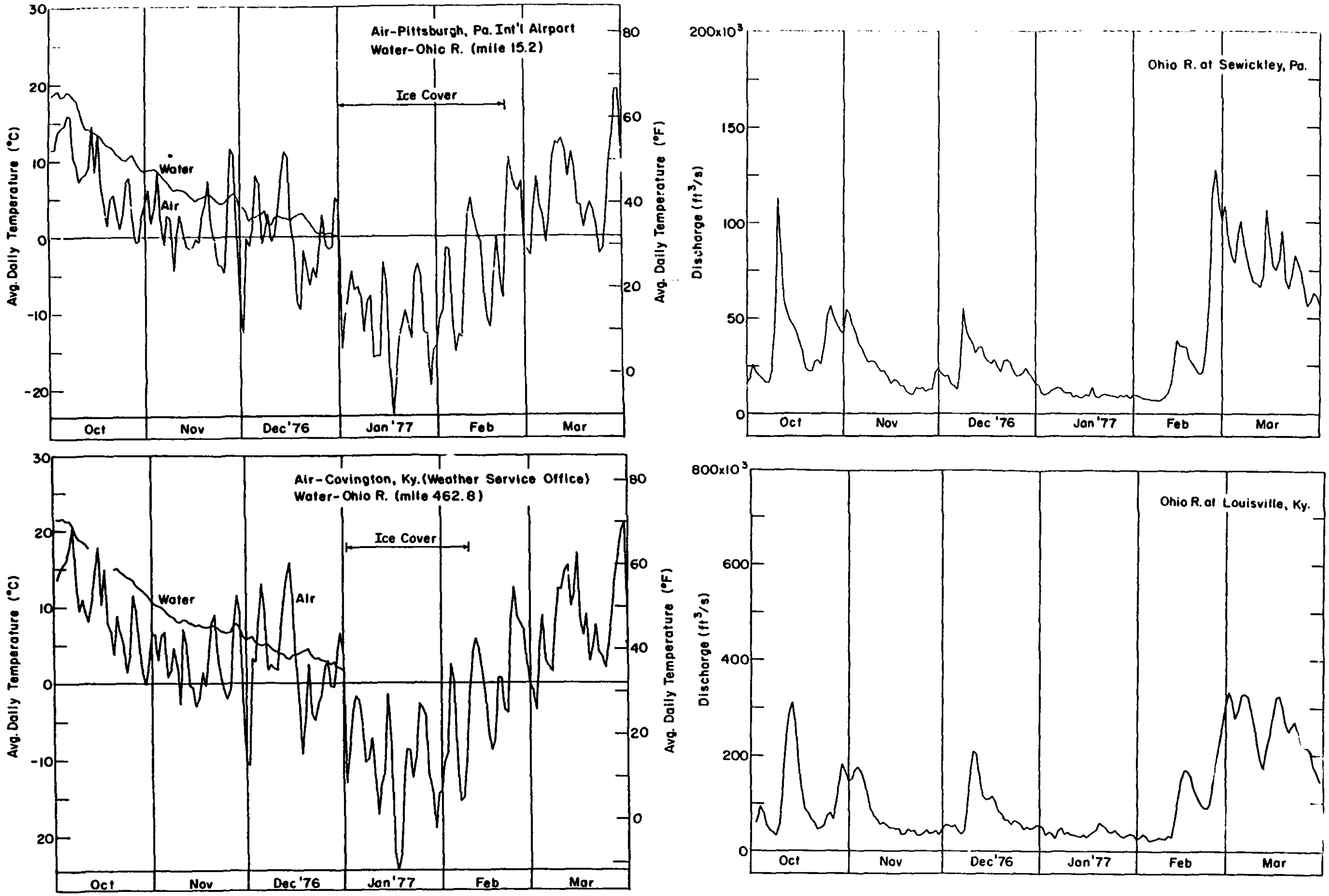


Figure A4. 1975–76.



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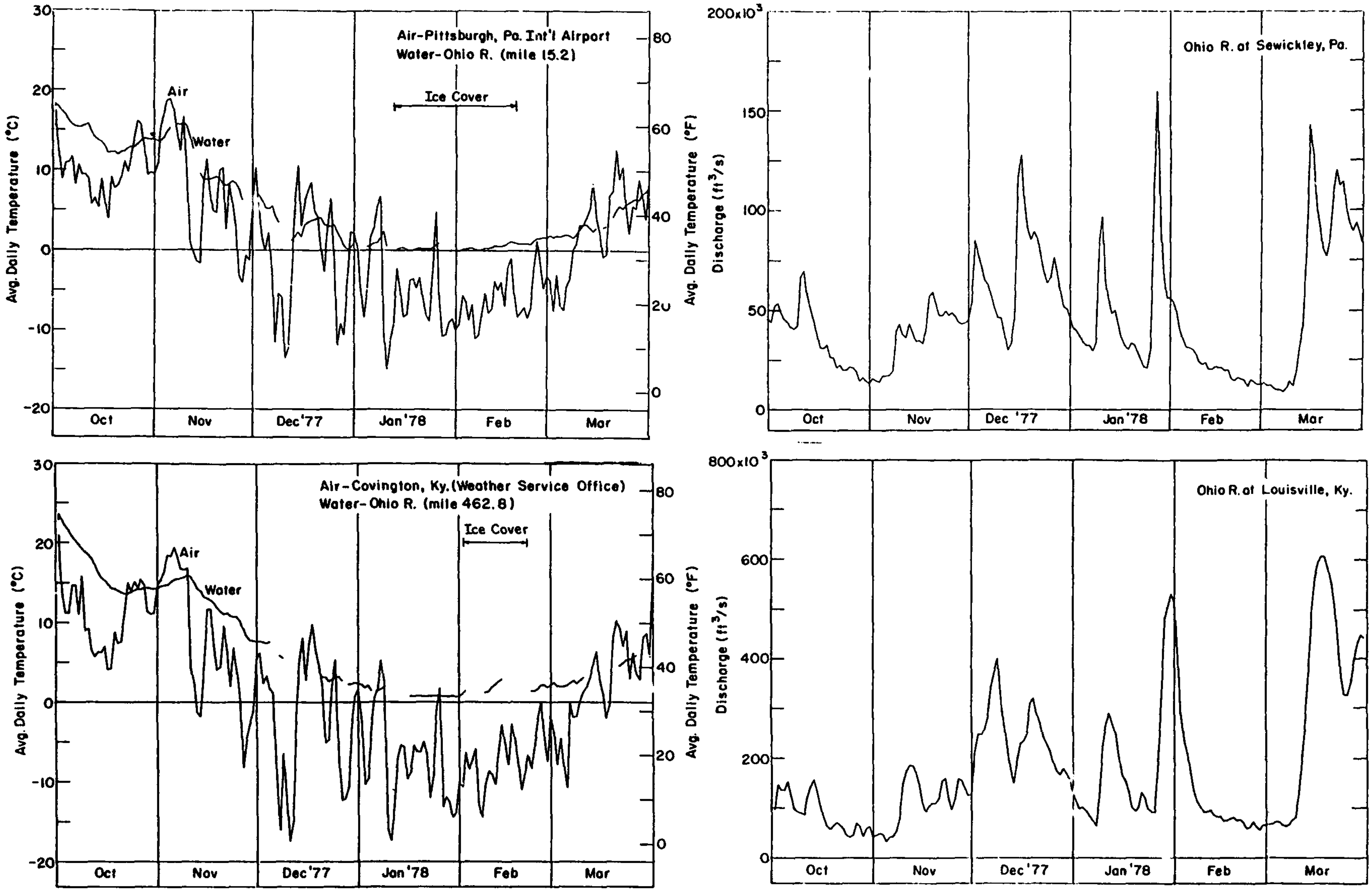

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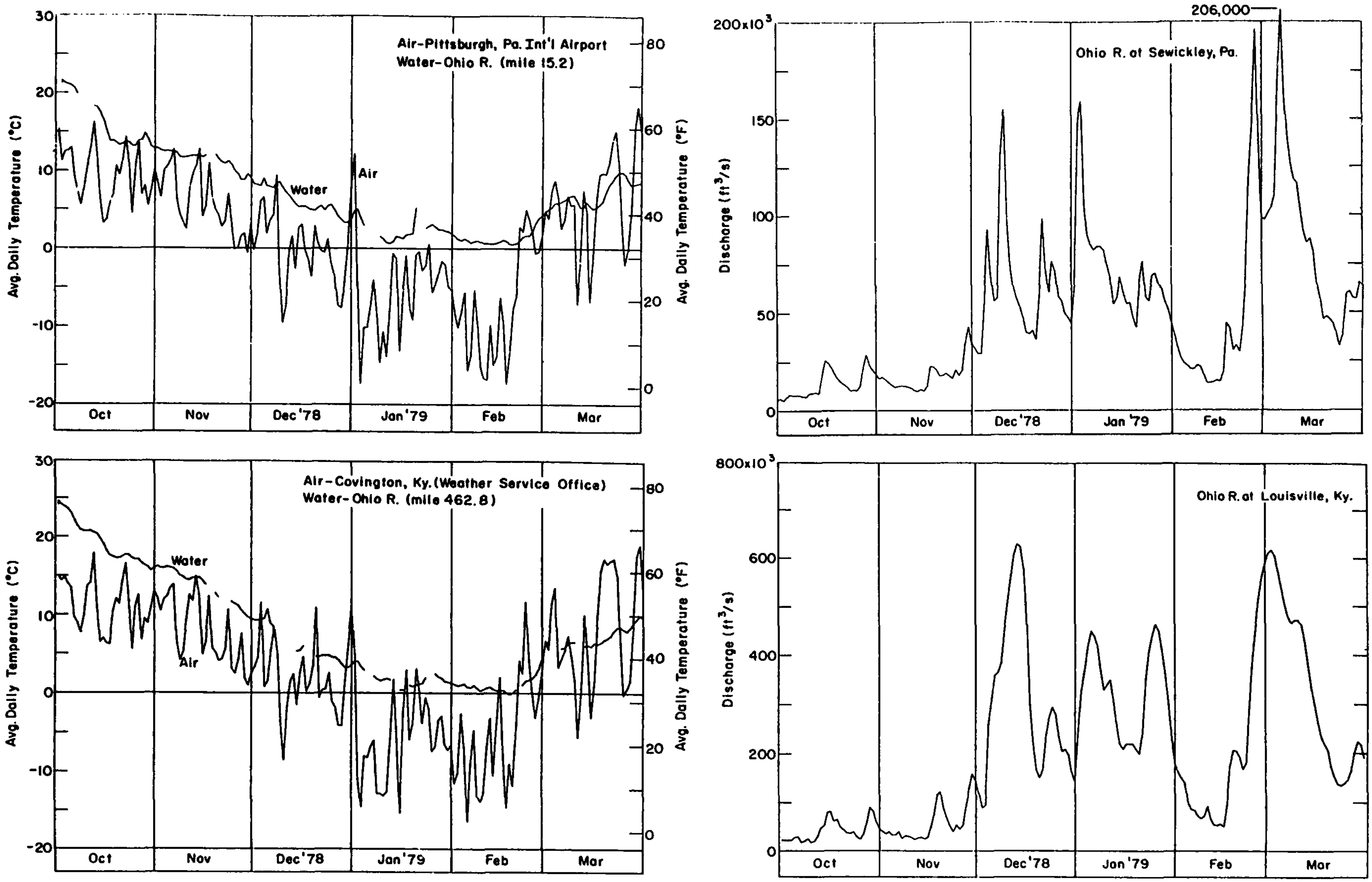

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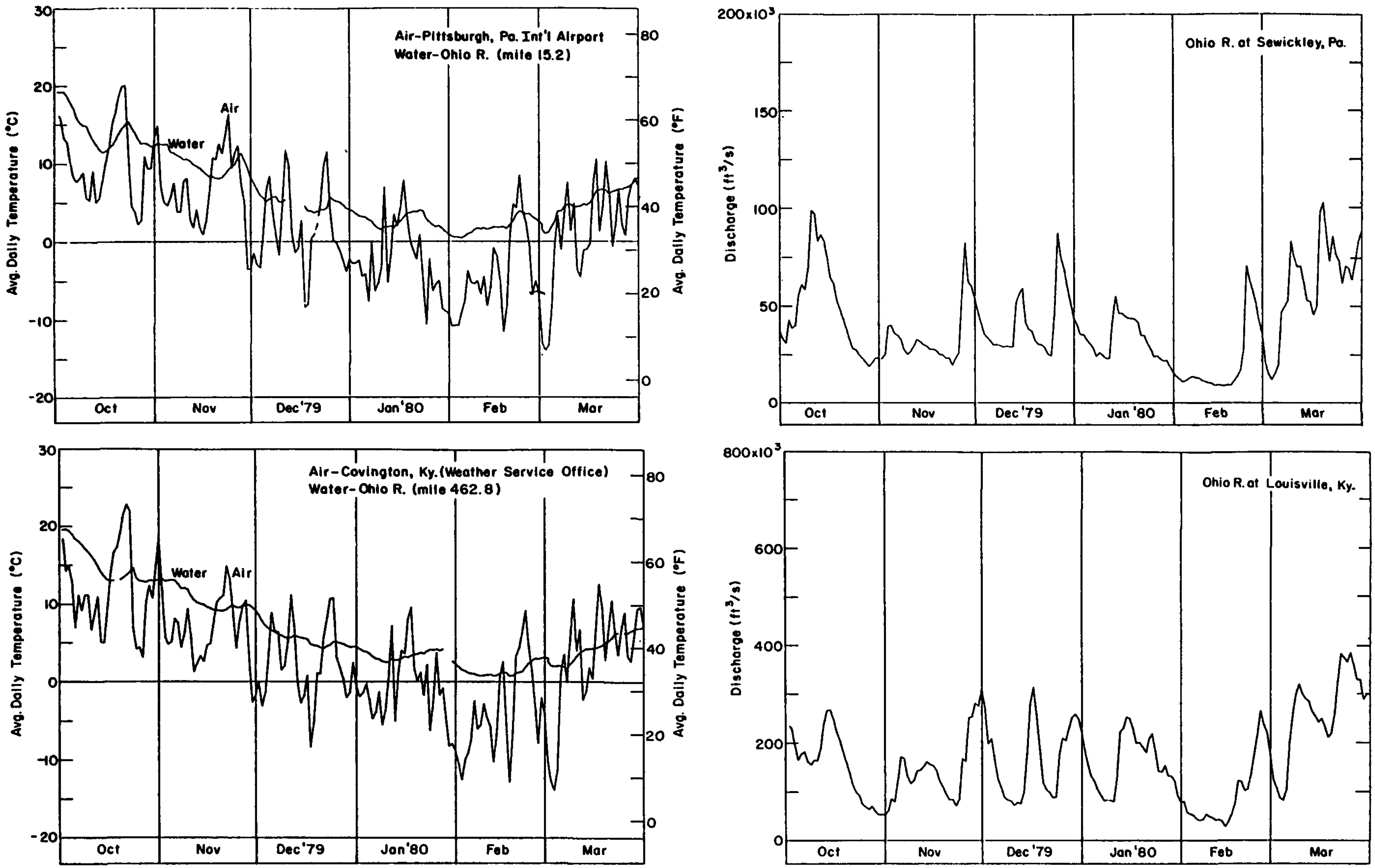


Figure A8. 1979–80.

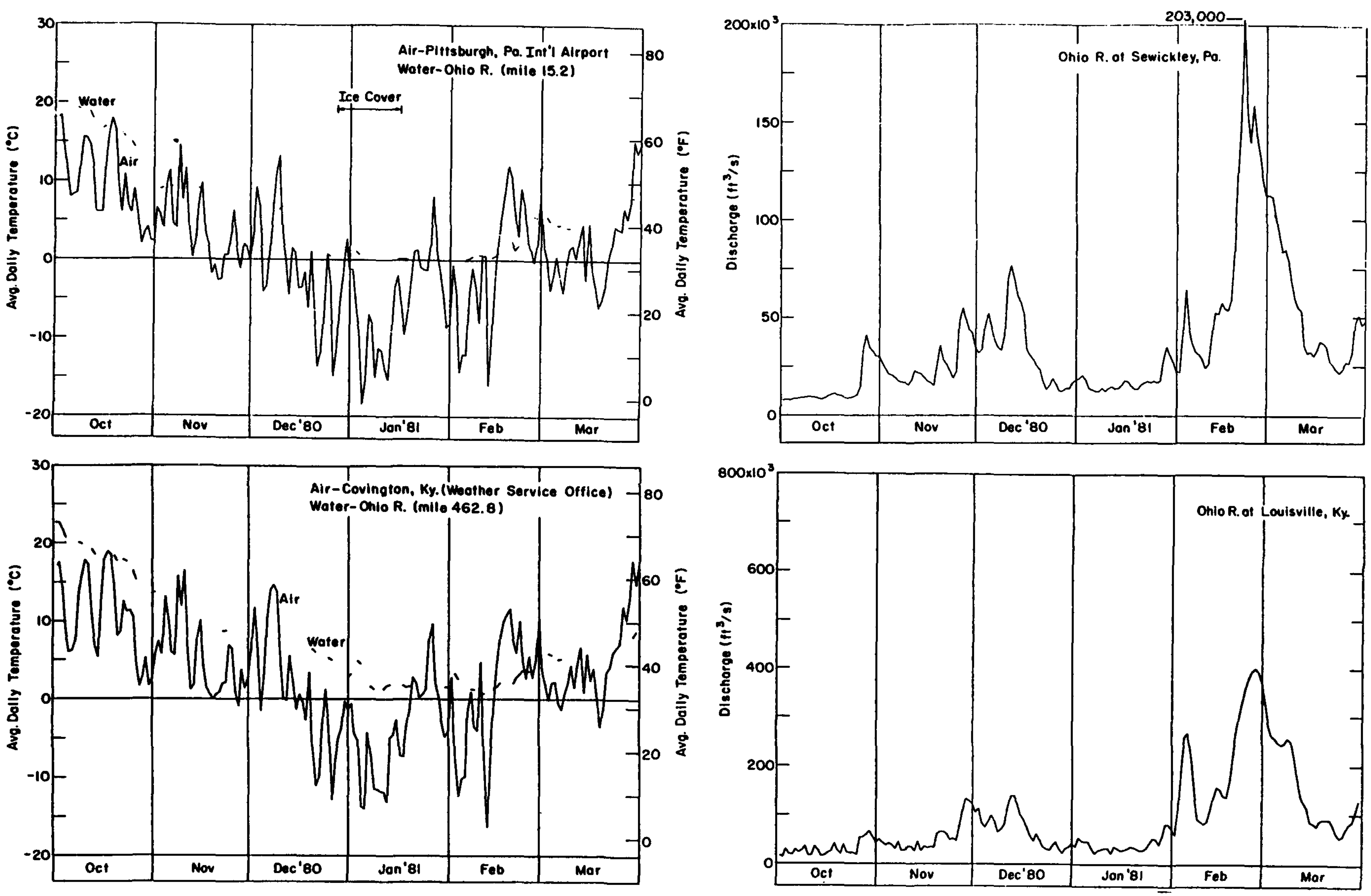


Figure A9. 1980–81.

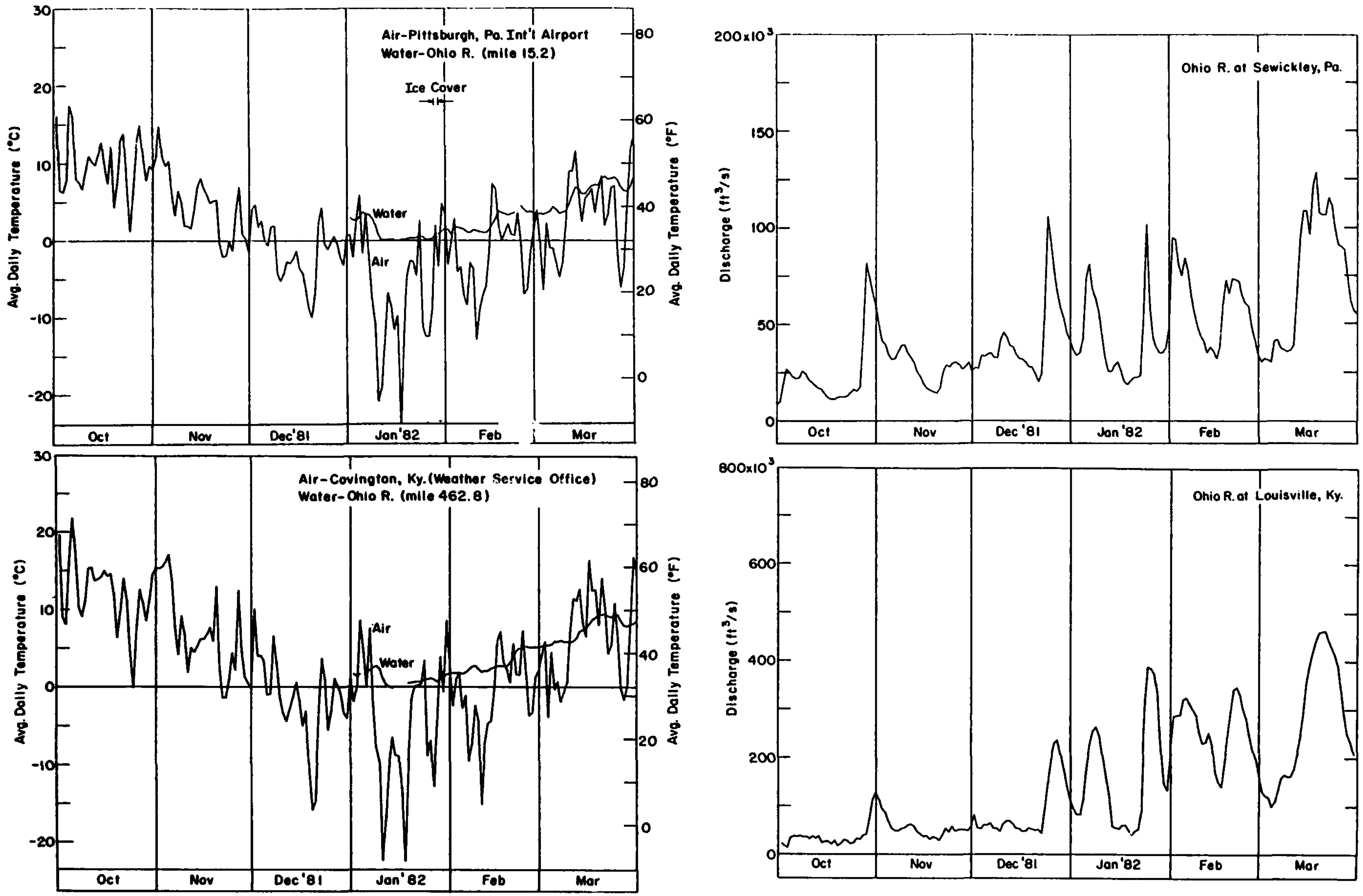


Figure A10. 1981–82.

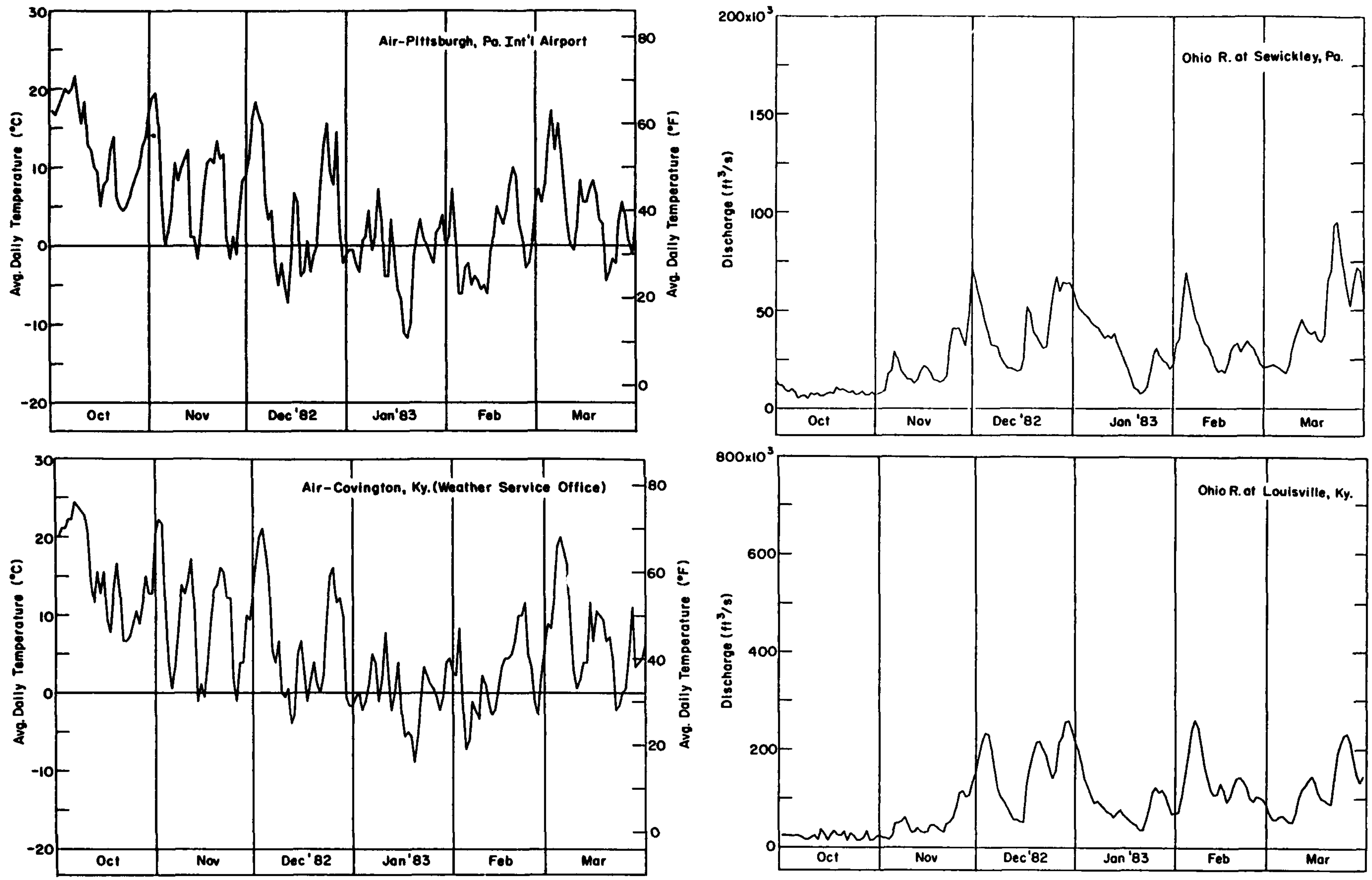
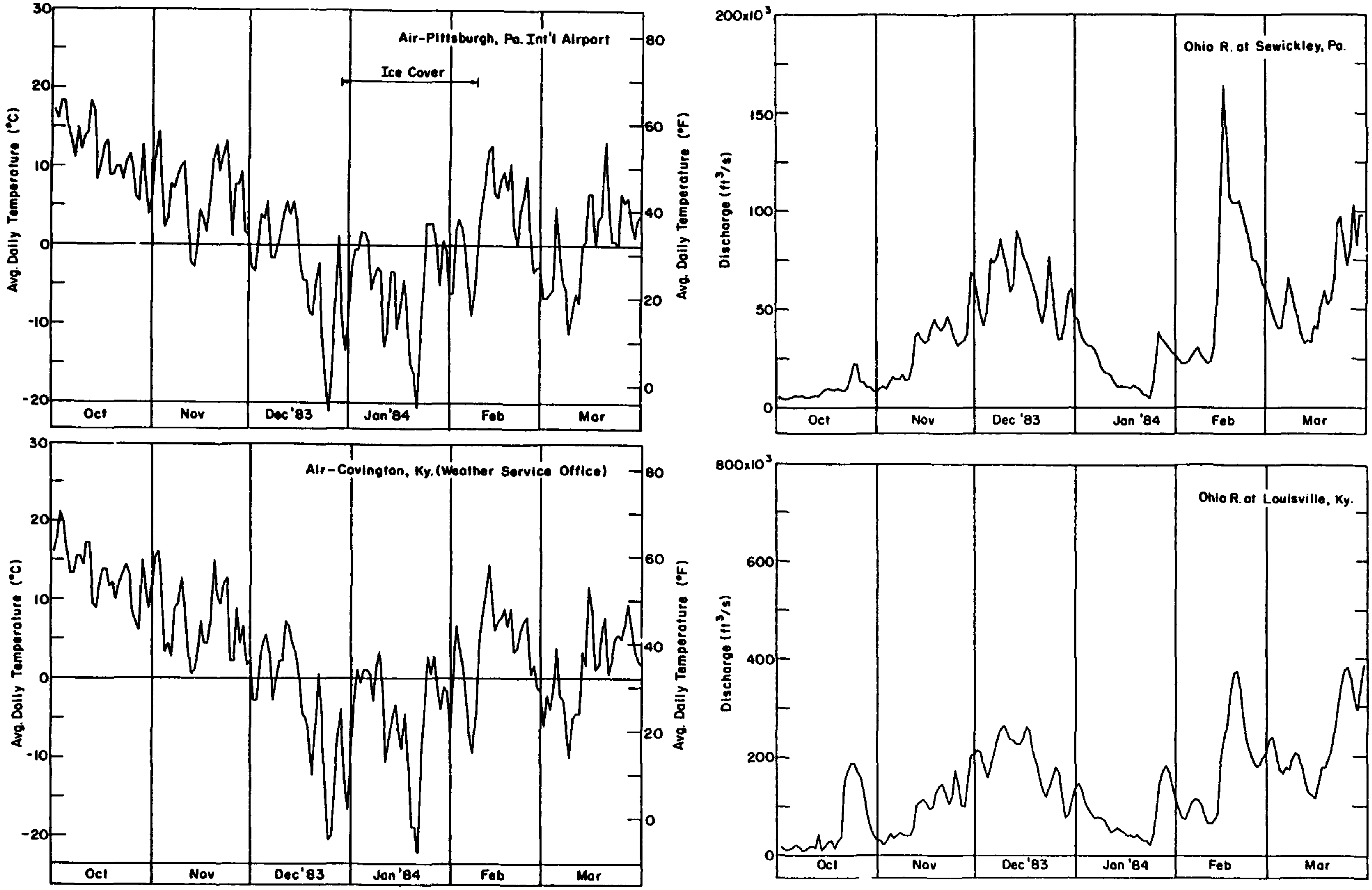


Figure A11. 1982–83.



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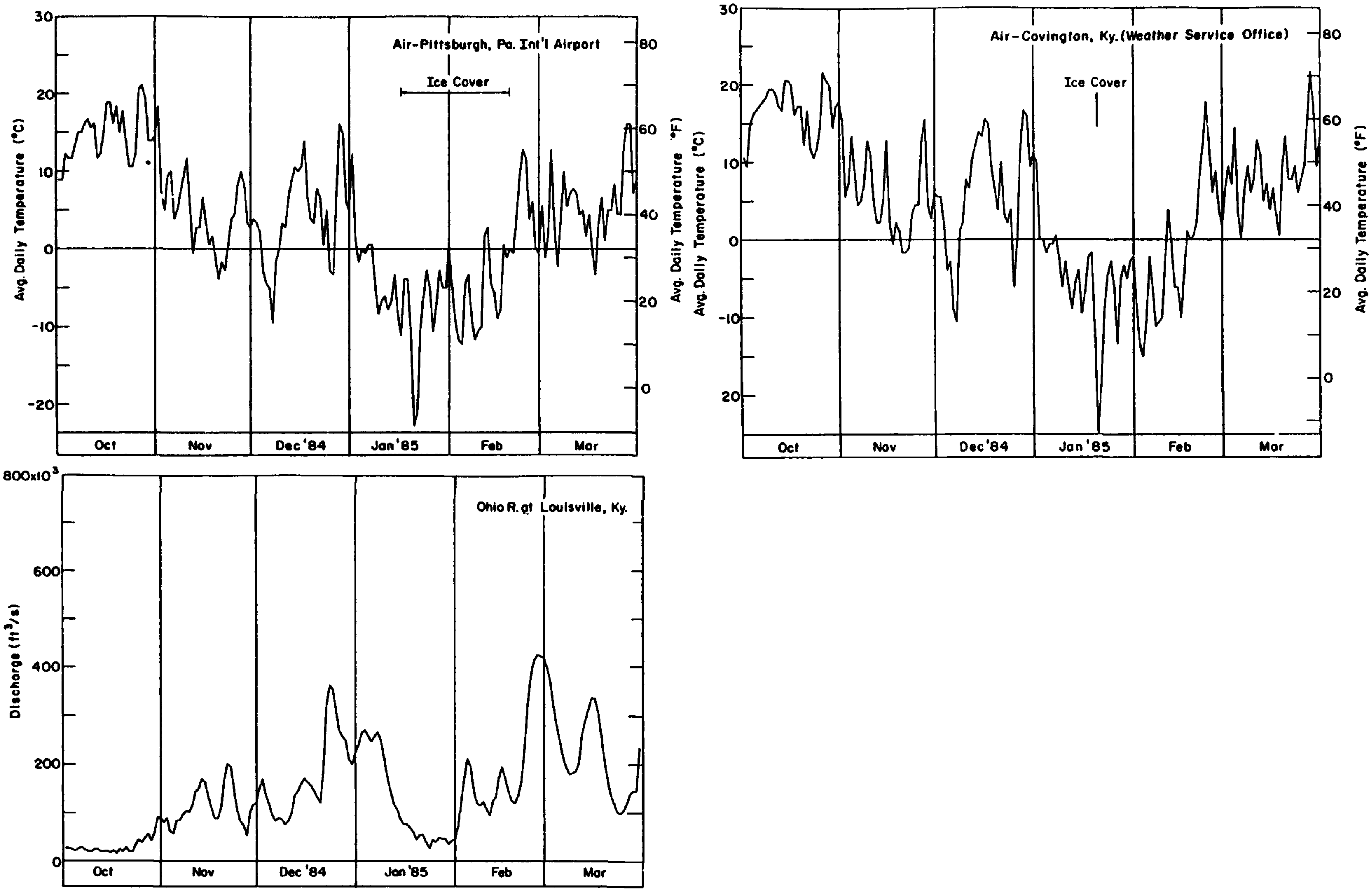

Figure A13. 1984–85.

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13. ABSTRACT (*Maximum 200 words*)

A general survey of the winter environment of the Ohio River Valley that is relevant to river ice formation is described. Included are hydrologic, hydraulic and climatic conditions. The long-term monthly discharges steadily increase on the Ohio River throughout the winter season. Inspection of the discharges for each day shows that it has a large short-term variability during the winter, with peaks being four to six times the base flow, and generally coinciding with higher air temperatures. River water temperatures follow a yearly cycle that is can be closely described by a sinusoidal curve. The river water temperatures have their minimum in January, and also exhibit January "thaws." Ice conditions on the Ohio River are quite variable. The number of days with ice each winter has gradually and erratically decreased from 1902 to 1975. The cause of this decrease cannot be determined, but there is a direct correlation with watershed development, as indicated by watershed population. Average air temperatures show a good correlation with elevation. Other points discussed are mean minimum air temperatures, freezing-degree days and precipitation.

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Winter environment

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