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GRAPHIC AND ANALYTICAL METHODS FOR ASSESSMENT OF STREAM-WATER QUALITY -- MISSISSIPPI RIVER IN THE MINNEAPOLIS-ST. PAUL METROPOLITAN AREA, MINNESOTA

GEOLOGICAL SURVEY, ST. PAUL, MINNESOTA

PREPARED FOR

METROPOLITAN WASTE CONTROL COMMISSION

ST. PAUL, MINNESOTA

JULY 1976

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Water—Resources Investigations 76—94

Prepared in cooperation with the Metropolitan Waste Control Commission of the Twin Cities area

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16. Abstracts Historical records were analyzed to determine effects of population, pollution-control strategy, and other factors on water quality of the Mississippi River. Isopleths of DO (dissolved oxygen) concentrations and lines of equal stream temperature indicated periodic data could be used to guide sampling of certain critical conditions in time and space.

Long-term records revealed generally mixed changes in quality in the Mississippi River. Several mean-time series were used to show seasonal variation in water quality and effects of initiation of wastewater treatment in 1938. Kendall's tau statistical test indicated a significant increase in DO in the upper reach of the river during the period of record. If only the post-1938 period is considered, DO conditions remained fairly constant below the metropolitan plant and biochemical oxygen demand increased throughout the main-stem reach.

Significant trends in stream temperature were indicated for winter periods using Kendall's tau procedure. The Mann-Whitney statistical test gave estimates of a 98-percent confidence interval of the magnitudes of change.

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By Steven P. Larson, William B. Mann IV, Timothy Doak Steele, and Russel H. Susag [1/]

ABSTRACT

Increasing use of water from the main stem Mississippi River in the Minneapolis-St. Paul metropolitan area has prompted investigation of quantity and quality aspects of the river system. In this study, historical water-quality records were analyzed to determine the effects of population, pollution-control strategy, and other historical factors on stream-water quality.

Data collected periodically from 1971 to 1973 at 14 stations along the main stem Mississippi River were used to construct lines of equal dissolved-oxygen concentrations and lines of equal stream temperature on two- and three-dimensional computer-derived graphs. Results indicated that the available periodic data could be used as guides to future sampling of certain critical conditions in both time and space.

Long-term records at five stations, averaging 40 years in length, revealed generally mixed changes in stream-water quality in the main stem Mississippi River, depending upon the choice of indicator variable. Monthly mean, annual mean, and critical period mean-time series were used to display seasonal variation in stream-water quality and the effects of wastewater treatment beginning in 1938. Kendall's tau statistical test indicated trends (at a significance level of 0.01) for each water quality variable for at least one station for at least one of the three (annual, summer, or winter) time series analyzed. If the entire period of record is considered, including a time interval prior to operation of the metropolitan treatment plant, dissolved-oxygen concentrations in the upper reach of the main stem Mississippi River increased significantly. However, if only the post-1938 period of record is considered, dissolved-oxygen conditions have remained fairly constant below the metropolitan plant and concentrations of biochemical oxygen

[1/] Metropolitan Waste Control Commission, St. Paul, MN.

demand (BOD) have increased significantly throughout the main stem reach. Also, significant increases in coliform-bacteria levels have occurred over the available periods of record at three of the five stations. The trend indicated for BOD and coliform bacteria could be related to increased population in the Twin Cities area serviced by waste-treatment facilities during the period of record.

Time changes in stream temperature of the Mississippi River were not detectable by visual inspection using results of harmonic analysis applied to depict the observed seasonal variability, but significant trends were indicated for winter periods using the Kendall's tau procedure. The Mann-Whitney statistical test substantiated these results for stream temperature and provided estimates of a 98-percent confidence interval of the magnitudes of change.

INTRODUCTION

Water-resources development and demands for pollution control of surface- and ground-water supplies in the Minneapolis-St. Paul metropolitan area have increased rapidly over the past decades. These increases to a large extent can be attributed to a near fourfold population growth since the turn of the century in the seven-county metropolitan planning area (Borchert and Yaeger, 1969). The ratio of urban to total (urban plus rural) population has grown nearly 15 percent over this period, with manufacturing becoming a major contributor to the economy of the area.

Increasing dependence on the Mississippi River for public water supplies and for discharging wastewater effluents (most of which have currently undergone secondary treatment in plants under the jurisdiction of the Metropolitan Waste Control Commission) has placed a stress on the quantity and quality aspects of the stream system. Compounding this stress are substantial annual fluctuations in historical streamflow. (See Norvitch and others, 1973, fig. 26.) These streamflow fluctuations are expected to continue due to the lack of effectively useable reservoirs on the Mississippi River and its tributaries at or upstream from the Minneapolis-St. Paul area.

Efficient operation of wastewater-treatment plants in the metropolitan area is essential for maintaining quality of receiving streams, in accordance with State stream standards and recent Federal legislation.

Purpose and Objectives

This study was made primarily to provide a means to depict and forecast stream quality based on known causative or apparent correlative factors.

The major objectives are (1) to assess the long-term impact of wastewater-treatment-plant installation, expansion, and upgrading; changes in plant and sewer configuration, and other factors affecting quality of receiving waters and (2) to aid in development of a data-management system that will utilize current data to modify operations of treatment plants, delineate problem areas within the system of receiving waters, assess the impact of operational changes, and enable forecasting of resultant water quality.

This study is a cooperative project between the U.S. Geological Survey and the Metropolitan Waste Control Commission (MWCC) of the Twin Cities area. The project was designed to complement an ongoing cooperative data-collection program between the agencies. Based on the results and recommendations of this study, the ongoing program will periodically be reviewed and modified. This should provide a more effective information base both for management of current operations and for evaluation of long-term plans. It also should provide a means for evaluating effects of policy or planning alternatives that comply with regulatory stream-quality standards; also anticipating the consequences of compliance.

Background

Study interest was influenced by the existence of long-term records on streamflow quality. The records were fairly consistent in terms of areal coverage (sampling sites), frequency of sampling, period of coverage (several records extend beyond 45 years), and suites of variables analyzed (with some recent changes and additions in analytical schedules). Moreover, the MWCC was interested in applying the most current graphic and statistical techniques for data analysis to assess past planning and management decisions rationally and objectively. These assessments were to include wastewater-treatment facilities for the metropolitan area and inferences of past performance, considering recent and impending technologic advances, and requirements under regulatory legislation.

An earlier evaluation concerning pollution and recovery characteristics of the Mississippi River was made by the

University of Minnesota (1958, 1961) for the Minneapolis-St. Paul Sanitary District. The current study draws on this earlier evaluation and updates it, utilizing available techniques on data manipulation and statistical analysis aided by digital computer. Relatively recent reports from studies supported by the Minnesota State Planning Agency (1969, 1970a, 1970b) also were useful. A study on water resources in the Minneapolis-St. Paul metropolitan area (Norvitch and others, 1973) provided some insight as to the operation of the overall hydrologic system.

AREAL DESCRIPTION

The Minneapolis-St. Paul (Twin Cities) metropolitan area (fig. 1) includes seven counties in east-central Minnesota and covers 2,968 square miles (7,447 square kilometres). Within this area, two major rivers, the Minnesota and St. Croix, are tributary to the Mississippi. The analytical phase of the study is concerned with a more than 100-mile (160-kilometre) reach of the main stem Mississippi River, extending from Anoka bridge (UM 871.6, see fig. 3) downstream to Read's Landing (UM 764.9, fig. 3). The term, UM, denotes Upper Mississippi River mile location and will be used throughout the report to designate site locations.

Locations of stream-gaging stations in or near the study area having records extending 35 years or more are shown on figure 2. Three long-term stations are on the main stem Mississippi River and one station each on the Minnesota, St. Croix, Rum, and Crow tributary rivers. Information pertaining to the stations shown on figure 2 is given in table 1. Flow estimates at intermediate water-quality-sampling sites are based on these and related records of intervening flows from streams, treatment-plant effluents, or municipal-water diversions.

Locations of historical and current water-quality-sampling stations in the metropolitan area are shown in figure 3. The present network (19 stations) includes map numbers 1, 2, 6, 8, 14, 15, 18, 19, 23-27, 29-33, and 36. Samples are analyzed for a variety of constituents (table 2) and are currently collected monthly. Most of the analyses for this study are based on data from 14 stations (map numbers 1, 2, 4, 6, 8, 14, 15, 18, 19, 23-27, on fig. 3 and table 2) on the Mississippi River. Five stations (map numbers 6, 8, 14, 18 and 19 combined, and 23) were selected for analysis and evaluation of long-term changes in observed stream-quality conditions.

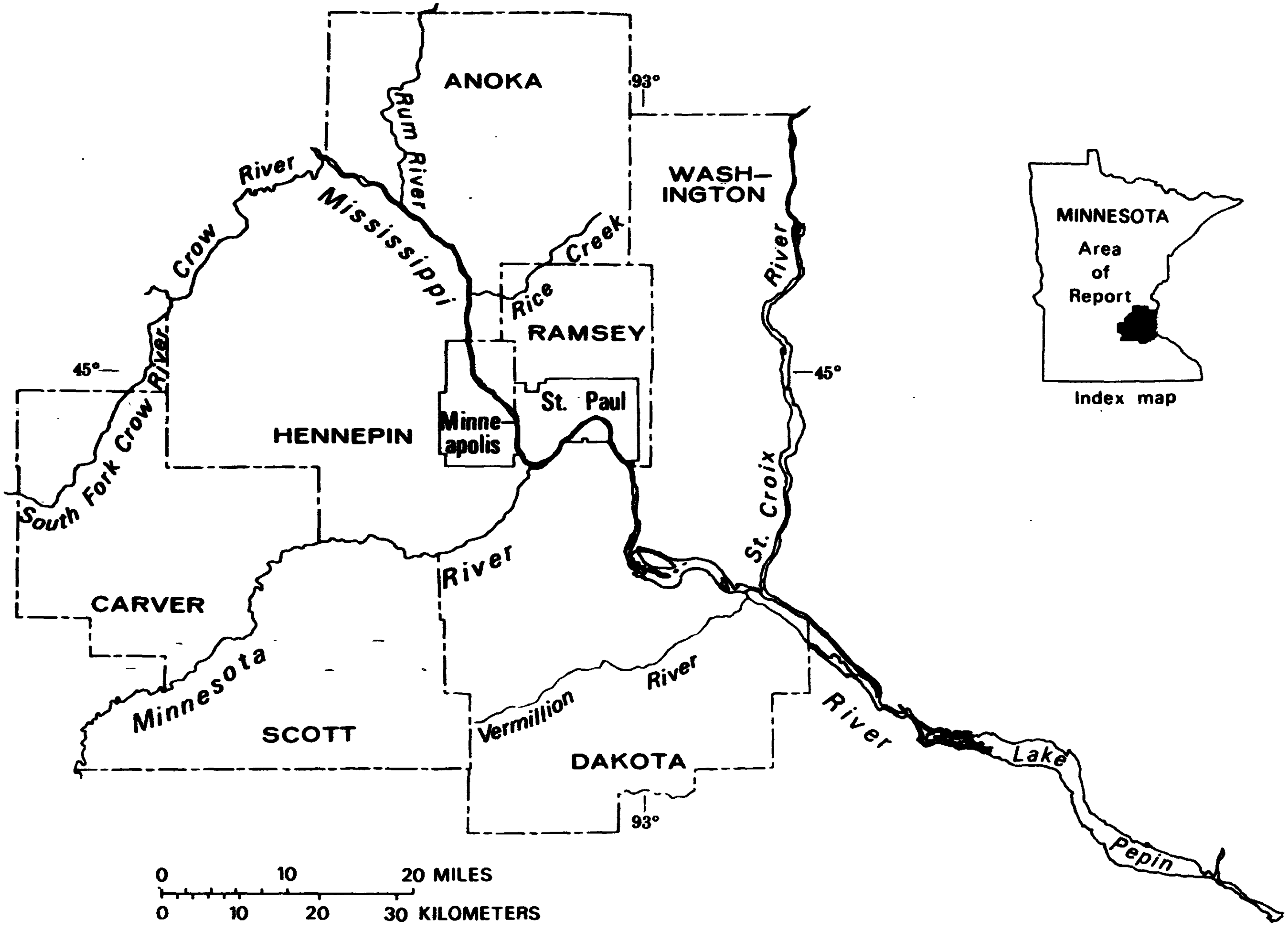

Figure 1.--Location and extent of study area.

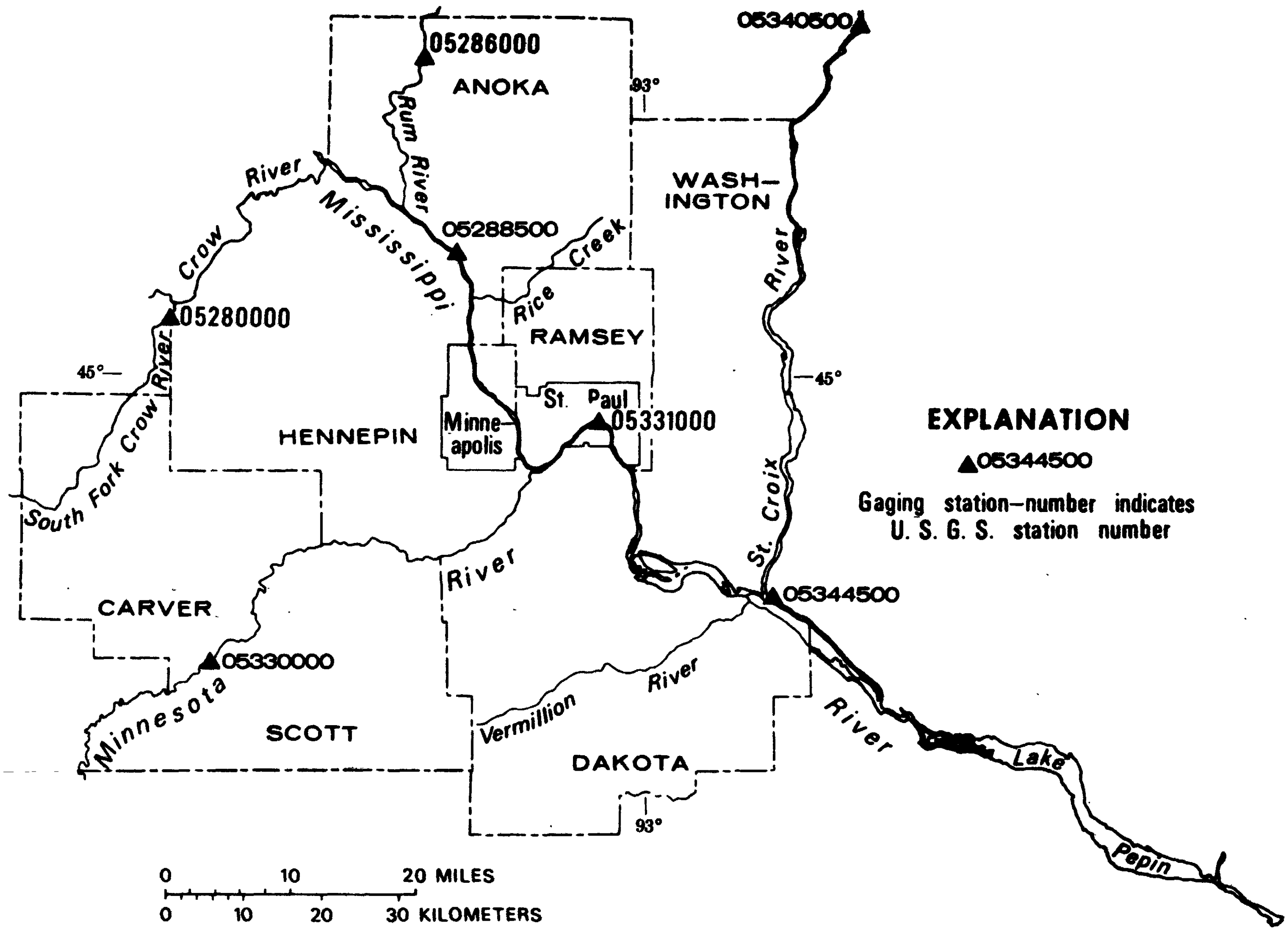

Figure 2.--Location of gaging stations having long-term records.

TABLE 1.—GAGING STATION INFORMATION

River Mile	U.S.G.S. Station Number	Station Name	Drainage Area (mi^2)	Period of Record	Mean Discharge (ft^3/s)	Mean Annual Runoff (in)
—	05280000	Crow River at Rockford, Minn.	2,520	1934[1] -	625	3.37
15.8	05286000	Rum River near St. Francis, Minn.	1,360	1933[1] -	585	5.84
864.8	05288500	Mississippi River near Anoka, Minn.	19,100	1932 -	7,410	5.27
39.4	05330000	Minnesota River near Jordan, Minn.	16,200	1935 -	3,425	2.87
839.3	05331000	Mississippi River at St. Paul, Minn.	36,800	1893 -	10,470	3.86
52.2	05340500	St. Croix River at St. Croix Falls, Wis.	5,930	1903 -	4,158	9.52
811.4	05344500	Mississippi River at Prescott, Wis.	44,800	1929 -	16,011	4.88

[1]/ Discontinuous data available for some prior years.

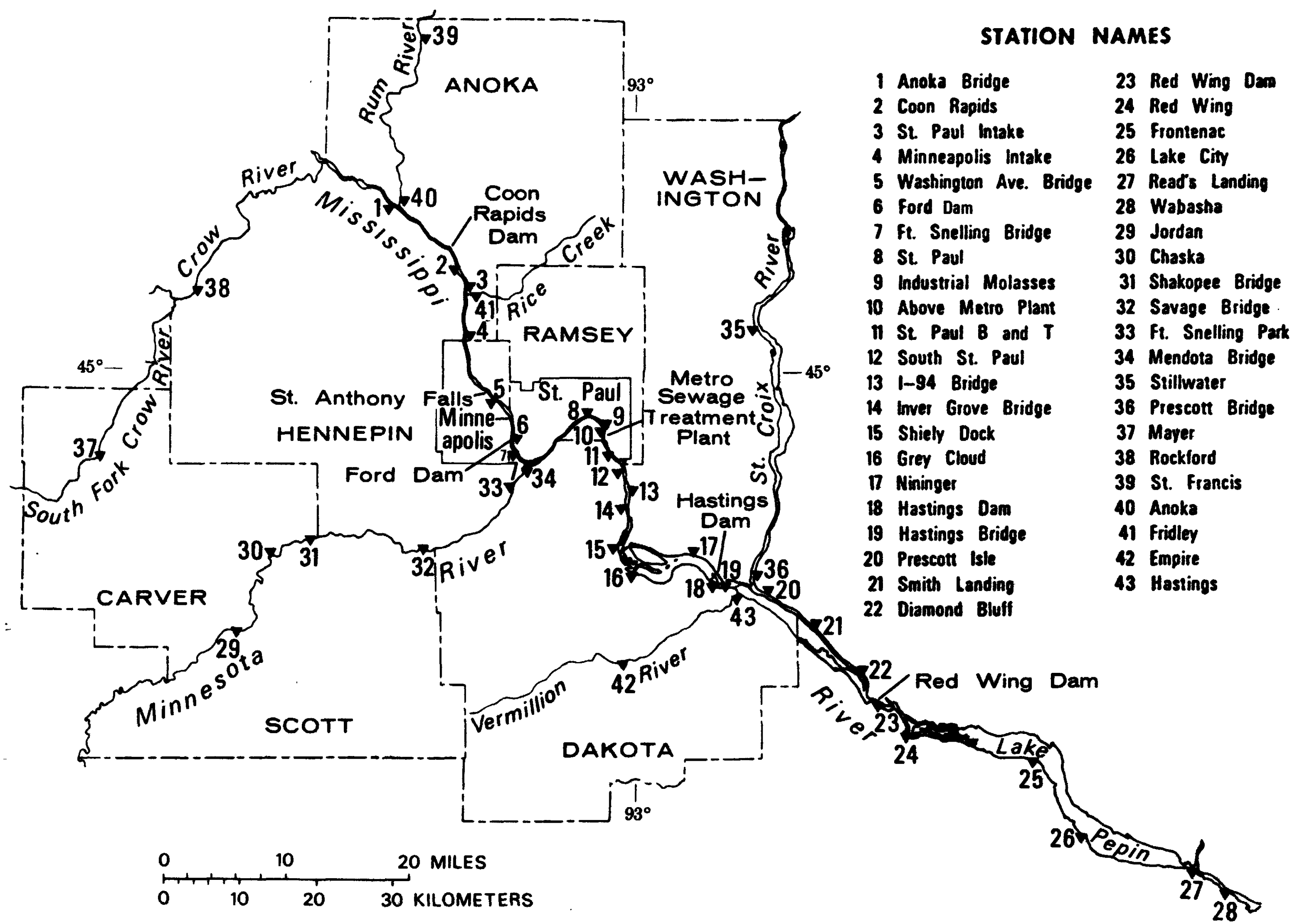

Figure 3.--Location of historical and current water-quality-sampling stations.

TABLE 2.—WATER-QUALITY-SAMPLING INFORMATION

Map No.[1]	River Mile	Station Name[2]	Sampling Record (years) Periodic	Continuous	Turbidity	Suspended Solids	Dissolved Oxygen	Biochemical Oxygen Demand	Kjeldahl Nitrogen	Phosphorus Total P	Coliform MPN	Temperature	pH	USGS-MSB Coop Program	Remarks
		MISSISSIPPI RIVER													
1	871.6	Anoka Bridge (05283500)	1971-		X	X	X	X	X	X	X	X	X	X	
2	864.8	Coon Rapids (05288500)	1972		X	X	X	X	X	X	X	X	X		
3	862.8	St. Paul Water Intake (05288570)		1974-			X					X	X	X	Sp. Cond.
4	858.5	Minneapolis Waterworks	1927-1971	1971-1972	X		X	X	X	X	X	X	X		Camden Ave. bridge 1927-54
5	852.6	Washington Ave. bridge	1927-1970		X		X	X			X	X	X		
6	847.7	Ford Dam (05288950)	1927-	1974-	X	X	X	X	X	X	X	X	X	X	Sp. Cond.
7	845.5	Fort Snelling bridge	1934-1970		X		X	X			X	X	X		
8	839.1	St. Paul (Lampert landing) (05331000)	1938-		X	X	X	X	X	X	X	X	X	X	Robert St. bridge
9	836.8	Industrial Molasses		1968-			X					X	X		Sp. Cond.
10	836.4	Above metropolitan plant	1938-68, 1970		X		X	X			X	X	X		Sampled May-October
11	835.3	St. Paul bridge & terminal	1927-1940		X		X	X			X	X	X		
12	834.4	South St. Paul	1938-1968		X		X	X			X	X	X		Sampled May-October
13	832.5	I-494 bridge	1953-68, 1970		X		X	X			X	X	X		
14	830.3	Inver Grove bridge	1927-		X		X	X	X	X	X	X	X		

TABEL 2.--WATER-QUALITY-SAMPLING INFORMATION (CONTINUED)

Map No.[1]	River Mile	Station Name[2]	Sampling Record (years) Periodic	Sampling Record (years) Continuous	Turbidity	Suspended Solids	Dissolved Oxygen	Biochemical Oxygen Demand	Kjeldahl Nitrogen	Phosphorus Total P	Coliform MPN	Temperature	pH	USGS-MSB Coop Program	Remarks
		MISSISSIPPI RIVER (CONTINUED)													
15	826.6	Shiely dock	1935-	1971-	X	X	X	X	X	X	X	X	X		Sp. Cond.
16	822.5	Grey Cloud landing	1934-68, 1970		X		X	X	X	X	X	X	X		
17	819.4	Nininger	1938-68, 1970		X		X	X			X	X	X		Sampled May-October
18	815.3	Hastings Dam (05331578)	1930-	1973-	X	X	X	X	X	X	X	X	X	X	
19	813.9	Hastings bridge (05331580)	1928-		X	X	X	X	X	X	X	X	X	X	
20	810.2	Prescott Island	1937-68, 1970		X		X	X			X	X	X		Sampled May-October
21	805.2	Smith landing	1937-68, 1970		X		X	X				X	X		Sampled May-October
22	800.5	Diamond Bluff	1937-1970		X		X	X				X	X		
23	796.9	Red Wing Dam (05344980)	1937-		X		X	X	X	X	X	X	X	X	
24	792.0	Red Wing	1928-70, 1971-74		X		X	X	X	X	X	X	X		Sampled May-October
25	779.0	Frontenac	1929-70, 1971-74		X		X	X			X	X	X		Sampled May-October
26	772.8	Lake City	1929-70, 1971-74		X		X	X	X	X	X	X	X		Sampled May-October

TABLE 2.--WATER-QUALITY-SAMPLING INFORMATION (CONTINUED)

Map No.[1]	River Mile	Station Name[2]	Sampling Record (Year) Periodic	Sampling Record (Year) Continuous	Turbidity	Suspended Solids	Dissolved Oxygen	Biochemical Oxygen Demand	Kjeldahl Nitrogen	Phosphorus Total P	Coliform MPN	Temperature	pH	USGS-MSB Coop Program	Remarks
		MISSISSIPPI RIVER (CONTINUED)													
27	764.9	READ'S LANDING	1928-70, 1971-74		X		X	X			X	X	X		SAMPLED MAY-OCTOBER
28	760.2	WABASHA	1928-1940		X		X	X			X	X	X		
		MINNESOTA RIVER													
29	36.0	MINNESOTA R. NR JORDAN (05330000)	1952-1974	1972-	X	X	X	X	X	X	X	X	X	X	SP. COND.
30	29.5	MINNESOTA R. AT CHASKA	1971-1972		X	X	X	X	X	X	X	X	X		
31	25.1	SHAKOPEE BRIDGE	1971-		X		X	X	X	X	X	X	X		
32	14.3	SAVAGE BRIDGE	1971-	PENDING	X		X		X	X		X	X		
33	3.5	FORT SNELLING STATE PARK (05330920)	1971	1967-	X	X	X	X	X	X	X	X	X	X	SP. COND.
34	1.7	MENDOTA BRIDGE	1931-1968		X		X	X			X	X	X		
		ST. CROIX RIVER													
35	23.3	STILLWATER (05341550)	1974	PENDING	X		X	X	X	X	X	X	X	X	MARINE ON ST. CROIX 1973-74
36	0.3	PRESCOTT BRIDGE	1931-68, 1970-		X	X	X	X	X	X	X	X	X	X	

TABLE 2.—WATER-QUALITY-SAMPLING INFORMATION (CONTINUED)

Map No.[1]	River Mile	Station Name[2]	Sampling Record (Year) Periodic	Sampling Record (Year) Continuous	Turbidity	Suspended Solids	Dissolved Oxygen	Biochemical Oxygen Demand	Kjeldahl Nitrogen	Phosphorus Total P	Coliform MPN	Temperature	pH	USGS -MSB Coop Program	Remarks
		MISCELLANEOUS													
37		S. Fork Crow R. nr Mayer (05279000)	1961-					X	X	X	X			X	
38		Crow R. at Rockford (05280000)	1952-					X	X	X	X			X	Sp. Cond. (1971)
39		Rum R. nr St. Francis (05286000)	1967-					X	X	X	X			X	Sp. Cond. (1970)
40		Rum R. at Anoka (05287000)	1972-					X	X	X	X			X	
41		Rice Crk. at Fridley (05288600)	1972-					X	X	X	X			X	
42		Vermillion R. nr Empire (05345000)	1972-	1973-			X	X	X	X	X	X	X	X	Sp. Cond.
43		Vermillion R. nr Hastings (05346000)	1972-					X	X	X	X			X	

[1]/ See figure 3.

[2]/ USGS station number in parentheses

Continuous-recording water-quality monitors at selected flow points in the stream system have either been installed recently, are proposed, or have been transferred over for inclusion or consideration in a USGS-MWCC cooperative data-collection surveillance program. (See fig. 3, map numbers 3, 6, 9, 15, 18, 23, 29, 33, and 42.) Hourly data on the following variables are obtained: pH, temperature, DO (dissolved oxygen), and specific conductance. Details on the availability of continuously-recorded data are given in table 2.

Most of the stations on figure 3 and table 2 are or were part of the stream-quality-sampling program made by the MWCC and predecessor agencies. In 1973, the USGS-MWCC surveillance program included collection of streamflow records, sampling schedules, and laboratory analyses at selected sites on the Mississippi and Minnesota Rivers, as well as on other tributary streams. (See table 2 and fig. 3.) This surveillance program complements the MWCC stream-quality-sampling program mentioned previously.

In the past 40 years, MWCC and predecessor agencies have consolidated wastewater-treatment plants and expanded the treatment of wastewater by interceptor sewers. During 1972, 32 wastewater-treatment plants were operating in the seven-county area (fig. 4). Plant operations during 1972, in terms of treatment process, design capacity, and effluent receiving waters, are given in table 3.

During the past 2 years, plant operations have been consolidated and some plant capacities have been expanded to improve treatment efficiencies and to insure better compliance with State and Federal effluent- and streamwater-quality standards. This has included phasing out several smaller, less efficient plants, implementing new plants at Seneca and Rosemount (physical-chemical-treatment process), and expanding capacities at the Blue Lake and metropolitan treatment plants. At the end of 1973, 23 plants were in operation. Further consolidation of treatment-plant operations is planned, with an eventual plant configuration of 13 by the early 1980's.

APPROACH

Historical water-quality data from five long-term-record stations were entered into the Geological Survey computer files using optical scanning techniques. The stations were selected primarily because of their locations

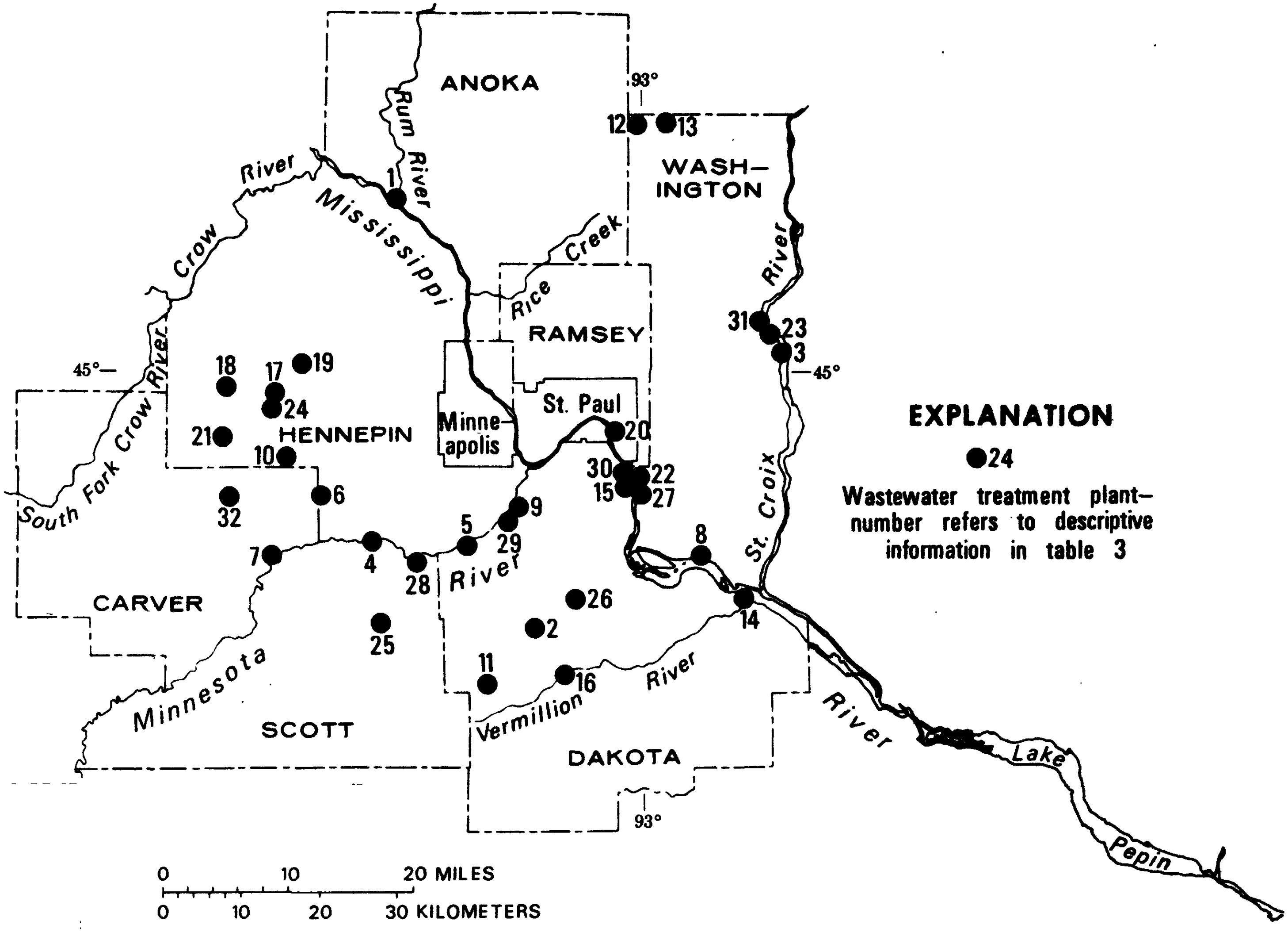

Figure 4.--Location of wastewater treatment plants operated in 1972.

TABLE 3.—WASTEWATER-TREATMENT PLANTS OPERATED BY THE METROPOLITAN SEWER BOARD IN 1972

MAP* NUMBER	TREATMENT PLANT	TREATMENT PROCESS	DESIGN CAPACITY (MGD)	EFFLUENT RECEIVING WATER 1/
1	ANOKA	ACTIVATED SLUDGE	2.5	MISSISSIPPI RIVER (UM 871.5)
2	APPLE VALLEY (1)	ACTIVATED SLUDGE	1.5	DITCH TO VERMILLION RIVER
3	BAYPORT	ACTIVATED SLUDGE	0.65	ST. CROIX RIVER (S 19.4)
4	BLUE LAKE (PHASE 1)	AERATED POND	2.5	MINNESOTA RIVER
5	BURNSVILLE (2)	ACTIVATED SLUDGE	1.5	MINNESOTA RIVER (M 10.5)
6	CHANHASSEN (3)	HIGH-RATE TRICKLING FILTER	0.07	DITCH TO RICE
		ACTIVATED SLUDGE	0.07	MARSH LAKE
7	CHASKA	ACTIVATED SLUDGE	0.70	MINNESOTA RIVER (M 29.4)
8	COTTAGE GROVE	ACTIVATED SLUDGE	0.90	MISSISSIPPI RIVER (UM 819.6)
9	EAGAN TOWNSHIP (4)	POND 1: AERATED POND	0.15	MINNESOTA RIVER
		POND 2: AERATED POND	0.08	MINNESOTA RIVER
10	EXCELSIOR (5)	ACTIVATED SLUDGE	0.54	LAKE MINNETONKA
11	FARMINGTON	HIGH-RATE TRICKLING FILTER	0.54	VERMILLION RIVER
12	FOREST LAKE VILLAGE (6)	ACTIVATED SLUDGE	0.18	HOWARD LAKE TO RICE CREEK
13	FOREST LAKE TOWNSHIP (7)	STABILIZATION POND		SWAMP TO FOREST
14	HASTINGS	ACTIVATED SLUDGE	1.80	MISSISSIPPI RIVER (UM 813.8)
15	INVER GROVE HEIGHTS (8)	ACTIVATED SLUDGE	0.48	MISSISSIPPI RIVER (UM 830.3)
16	LAKEVILLE	HIGH-RATE TRICKLING FILTER	0.25	VERMILLION RIVER
17	LONG LAKE	HIGH-RATE TRICKLING FILTER	0.18	LONG LAKE CREEK
				LAKE MINNETONKA
18	MAPLE PLAIN	HIGH-RATE TRICKLING FILTER		PAINTER CREEK
		ACTIVATED SLUDGE	0.22	LAKE MINNETONKA
19	MEDINA	AERATED POND	0.10	SEEPAGE POND (NO SURFACE DISCHARGE)
20	METROPOLITAN	ACTIVATED SLUDGE	218	MISSISSIPPI RIVER (UM 836.2)
21	MOUND	ACTIVATED SLUDGE	1.25	LAKE LANGDON
22	NEWPORT	ACTIVATED SLUDGE (CONTACT STABILIZATION)	0.3	MISSISSIPPI RIVER (UM 831.0)

TABLE 3.--WASTEWATER-TREATMENT PLANTS OPERATED BY THE METROPOLITAN SEWER BOARD IN 1972 (CONTINUED)

MAP* NUMBER	TREATMENT PLANT	TREATMENT PROCESS	DESIGN CAPACITY (MGD)	EFFLUENT RECEIVING WATER 1/
23	OAK PARK HEIGHTS	ACTIVATED SLUDGE (CONTACT STABILIZATION)	0.25	ST. CROIX RIVER
24	ORONO	ACTIVATED SLUDGE	0.4	FRENCH LAKE LAKE MINNETONKA
25	PRIOR LAKE	HIGH-RATE TRICKLING FILTER	0.2	CREDIT RIVER
26	ROSEMOUNT	HIGH-RATE TRICKLING FILTER	0.1	EFFLUENT POND (NO SURFACE DISCHARGE)
27	ST. PAUL PARK	HIGH-RATE TRICKLING FILTER	0.2	MISSISSIPPI RIVER (UM 830.1)
28	SAVAGE	HIGH-RATE TRICKLING FILTER	0.36	CREEK TO MINNESOTA RIVER
29	SENECA (9)	ACTIVATED SLUDGE	24.0	MINNESOTA RIVER (M 14.4)
30	SOUTH ST. PAUL	HIGH-RATE TRICKLING FILTER	10.0	MISSISSIPPI RIVER (UM 832.4)
31	STILLWATER	ACTIVATED SLUDGE	3.0	ST. CROIX RIVER (S 21.2)
32	VICTORIA	HIGH-RATE TRICKLING FILTER	0.09	DITCH TO LAKE AUBURN

(1) APPLE VALLEY: EXPANDED ACTIVATED SLUDGE PROCESS PLACED IN OPERATION OCTOBER, 1972, DESIGN CAPACITY REPORTED (1.5 MGD) IS FOR EXPANDED PLANT.
(2) BURNSVILLE: PHASED OUT SEPTEMBER 23, 1972, FLOW DIVERTED TO SENECA PLANT.
(3) CHANHASSEN: PHASED OUT JANUARY 10, 1972, FLOW DIVERTED TO BLUE LAKE PLANT.
(4) EAGAN TOWNSHIP: PHASED OUT JULY 21, 1972, FLOW DIVERTED TO SENECA PLANT.
(5) EXCELSIOR: PHASED OUT FEBRUARY 28, 1972, FLOW DIVERTED TO BLUE LAKE PLANT.
(6) FOREST LAKE VILLAGE: PHASED OUT SEPTEMBER 28, 1972, FLOW DIVERTED TO METROPOLITAN.
(7) FOREST LAKE TOWNSHIP: PHASED OUT SEPTEMBER 28, 1972, FLOW DIVERTED TO METROPOLITAN.
(8) INVER GROVE HEIGHTS: PHASED OUT NOVEMBER 3, 1972, FLOW DIVERTED TO SO. ST. PAUL.
(9) SENECA PLANT PLACED INTO OPERATION JULY, 1972.

* SEE FIGURE 4.

1/UM, M, AND S REFER TO UPPER MISSISSIPPI, MINNESOTA, AND ST. CROIX RIVER MILES, RESPECTIVELY.

relative to dominant factors affecting the water quality of the stream system; that is, the Minnesota River, the Metropolitan Wastewater-Treatment Plant, and the St. Croix River. The discharge of the Mississippi River (average discharge about 10,500 cubic feet per second (297 cubic meters per second) at St. Paul), in relation to the discharge of most of the treatment plants and the temporal density of available data (primarily monthly means), makes it improbable that the effects of any individual plant will be detectable. Thus, efforts were concentrated on evaluating the effects of changes in the dominant influencing factors on the water quality of the stream system, including population growth and start of operation of the metropolitan plant.

Data on DO and temperature for the period 1971-73 were assembled independently, as required by the computer program used in the analysis. Also, independent data files for the long-term stations were established to enable efficient abstraction of data for various analyses and graphical displays.

River-Reach Description

DO and temperature in the main stem Mississippi River during the period 1971-73 were displayed by producing isopleth (lines of equal parameter value) maps to depict a given variable as a function of time and position (river-reach location). This enabled changes in DO concentration (and in temperature) with time and location along the river to be displayed concurrently.

A California Computer Products, Inc.[1/] general-purpose contouring package was used to generate isopleth maps on a digital computer from periodic sample data. The contouring procedure is briefly described in the following paragraphs, but further details can be found in the appropriate references (California Computer Products, Inc., 1969 and 1971). The purpose of applying the contouring procedure was to interpolate in time and space (river reach) from point-data values, enabling a generalized depiction of river-reach and temporal variations.

Isopleth maps are developed in two steps. First, values at uniformly spaced grid points in time and space (position along the river) are determined from sample data that are

1/ The use of the brand name in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

relatively uniform in time and space. Second, isopleth lines are drawn on the grid, adhering to parameter values at each grid point. The interpolating scheme is third-order, with respect to the grid dimensions.

Parameter values at grid points also are determined in two steps. First, tangent planes are determined at each sample data point so that the plane passes through the data value at the point, and the angles between the plane and vectors (or lines) from the point to a specified number of neighboring data points are minimized. Second, parameter values at grid points are determined by extending the tangent planes from a specified number of neighboring data points to the grid point and weighting the projected values to reflect the respective distances from the neighboring data points to the grid point.

DO and temperature measured on about a monthly schedule at most of 14 stations (see p. 4 and table 2) from 1971 thru 1973 were used to make the isopleth maps. The contouring grid consisted of a time dimension from January 1 thru December 31 of a given year and a space dimension from river miles UM 875.0 to UM 760.0. The grid spacing was 5 days in the time dimension and 5 miles (8 kilometres) in the space dimension. These spacings were chosen primarily on the basis of computer efficiency and data density. The resulting isopleth maps depict the variation in DO and temperature through the reach of the main stem Mississippi River in the metropolitan area for 1 calendar year, as indicated by the discrete periodic measurements.

Dams along the river represent points of discontinuity with respect to DO because dams tend to produce step-changes in DO concentrations. The magnitude of the change depends upon flow conditions, temperature, biological activity, and the physical characteristics of the dam.

In an attempt to evaluate dam effects, a group of isopleth maps were made by dividing the space dimension (position along the river) into four segments. The divisions between segments represented dams within the study reach. Ford Dam (UM 847.7), Hastings Dam (UM 815.3), and Red Wing Dam (UM 796.9) were chosen as dividing points for the river reach. (See fig. 3.) Each segment was contoured independently and subsequently spliced together to form a map of the entire river reach. Comparisons could then be made between isopleth maps, considering the study reach as a whole and considering segmentation, to evaluate the effects of reaeration at the dams.

Attempts were also made to evaluate the representativeness of the sample data used in the isopleth map generation. That is, was sample-data density sufficient to describe spatial and temporal variations in DO concentrations adequately? Time slices (temporal variation at a specific point along the river) and reach slices (spatial variation at a specific time) were abstracted from the isopleth maps and compared with independent measurements and sample data. The lack of independent data prevented verification.

Three-dimensional drawings of the isopleth surfaces were also produced. A companion computer program to the contouring package was used to make the drawings (California Computer Products, Inc., 1969). The results were evaluated qualitatively as to their use for depicting significant variations in DO concentrations.

Time-Series and Time-Trend Analyses

Five Mississippi River stations: Ford Dam (UM 847.7), St. Paul (UM 839.1), Inver Grove (UM 830.3), Hastings bridge and dam (UM 813.9 and 815.3), and Red Wing Dam (UM 796.9), each having 35 or more years of record, were selected for time-trend analysis. Monthly means of from 1 to 56 samples per month were available for temperature, turbidity, DO concentration, BOD (biochemical oxygen demand), and coliform bacteria. Flow estimates were made at the sampling points from available gage records at or near the sampling site. Data at three of the five stations were available for periods prior to the start of the Metropolitan Wastewater-Treatment Plant (UM 836.2) in 1938.

Various statistical measures were used to evaluate temporal variations in the sample data. Monthly mean-time series, annual mean-time series, and two annual critical-period mean-time series were plotted for each variable. The two annual critical periods selected were a January-February period and a July-August-September period. DO concentration was reported in mg/l (milligrams per litre) and as percent saturation, the latter to remove the effect of temperature. The resulting graphical displays provided for a qualitative assessment of the relationship between historical causative factors and resultant water quality of the stream system.

To supplement the qualitative assessment, certain analytical techniques were used in an attempt to quantify observed historical variations. Kendall's tau non-parametric testing procedure (Conover, 1971) was used to evaluate time trends for the annual, summer, and winter period mean-time series. A significance level of 0.01 was chosen to indicate a trend. That is, a trend was considered to be significant if data values had a 99-percent probability of an overall increase or decrease during the period of evaluation. Temperature data were evaluated further by fitting a simple harmonic function to the annual monthly mean values at 5-year intervals and testing the resulting harmonic coefficients for trend with the Kendall's tau procedure Further discussion and demonstration of the Kendall's tau procedure for time trends and of the harmonic analysis of stream temperatures is given in Steele, Gilroy, and Hawkinson (1974).

RESULTS OF RIVER-REACH ANALYSIS

Isopleth maps of DO (expressed as percent saturation) in the Mississippi River between river miles UM 875.0 and UM 760.0 during 1971, 1972, and 1973 are shown in figures 5 thru 10. In figures 5, 6, and 7, the overall reach is segmented, as discussed on page 18. In figures 8, 9, and 10, the reach is considered to be a single increment; however, the sample data are identical to those used in developing figures 5, 6, and 7.

The isopleth maps provide a means of graphic evaluation of critical points in the river with respect to DO conditions in both time and space (location along the river). The effects of waste-water effluents on the main stem Mississippi River in the vicinity of the metropolitan treatment plant (UM 836.2) are clearly evident during late summer low-flow periods. In 1971 DO was estimated to be less than 15 percent saturation downstream from the treatment facility during this period (figs. 5 and 8). In 1973 it was estimated to be less than 35 percent saturation (figs. 7 and 10). In 1972 relatively higher stream discharge, thus more dilution water, prevented the lower DO conditions observed during 1971 and 1973 (figs. 6 and 9). During spring, the dilution effect of high discharge maintains DO at near 100 percent saturation over the entire study reach for all 3 years.

Qualitatively, only minor differences exist between the segmented (figs. 5, 6, and 7) and nonsegmented (figs. 8, 9, and 10) isopleth maps. Determination of reaeration effects at the three dams in this river reach are apparently controlled by sampling density upstream and downstream from the dams. That is, the spatial sampling intervals adequately reflect changes in DO (saturation) such that the nonsegmented isopleth maps are not distinctly different from segmented maps.

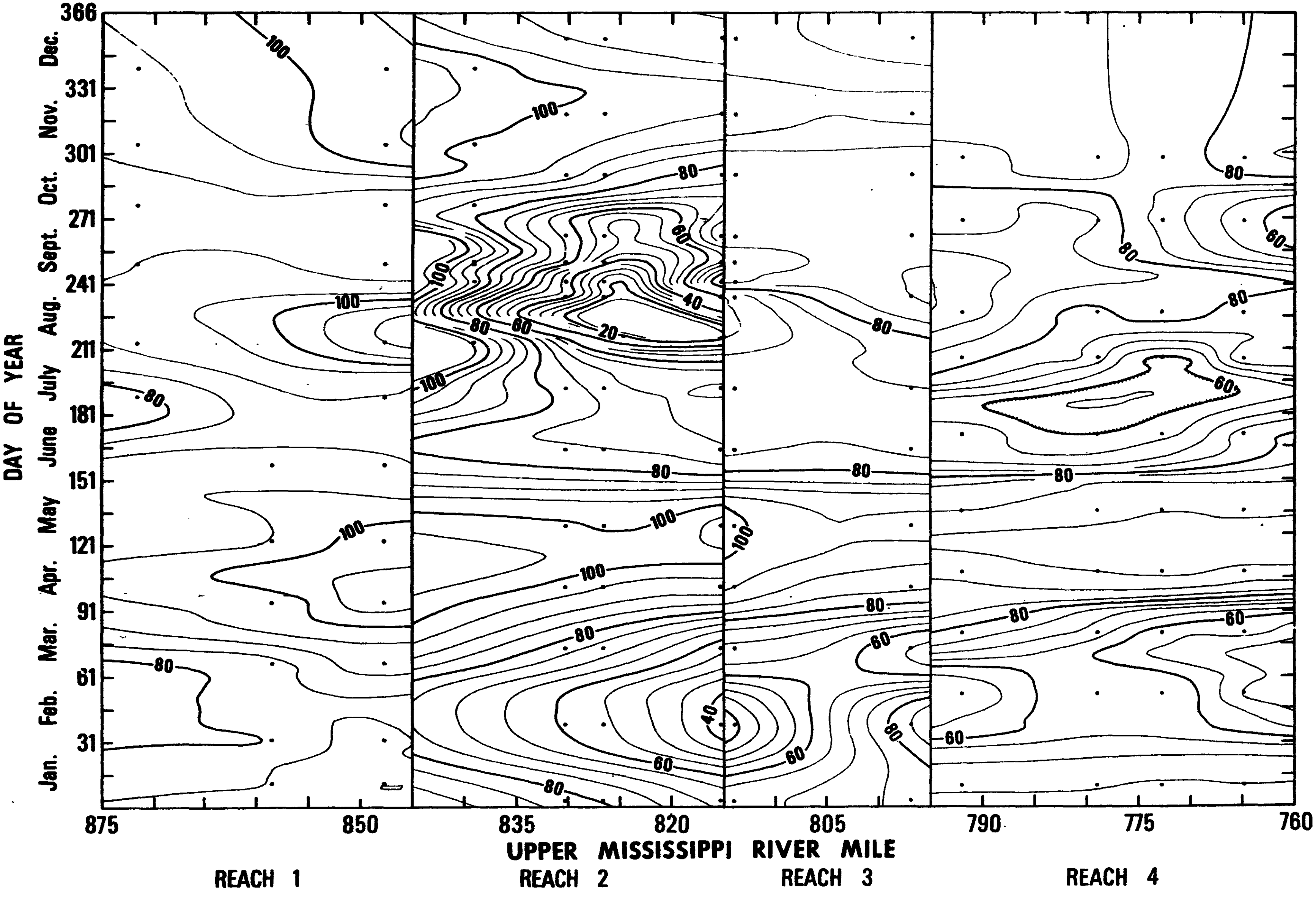

Figure 5.--Isopleths of dissolved oxygen, percent saturation, 1971 (Isopleth interval - 5 percent.)

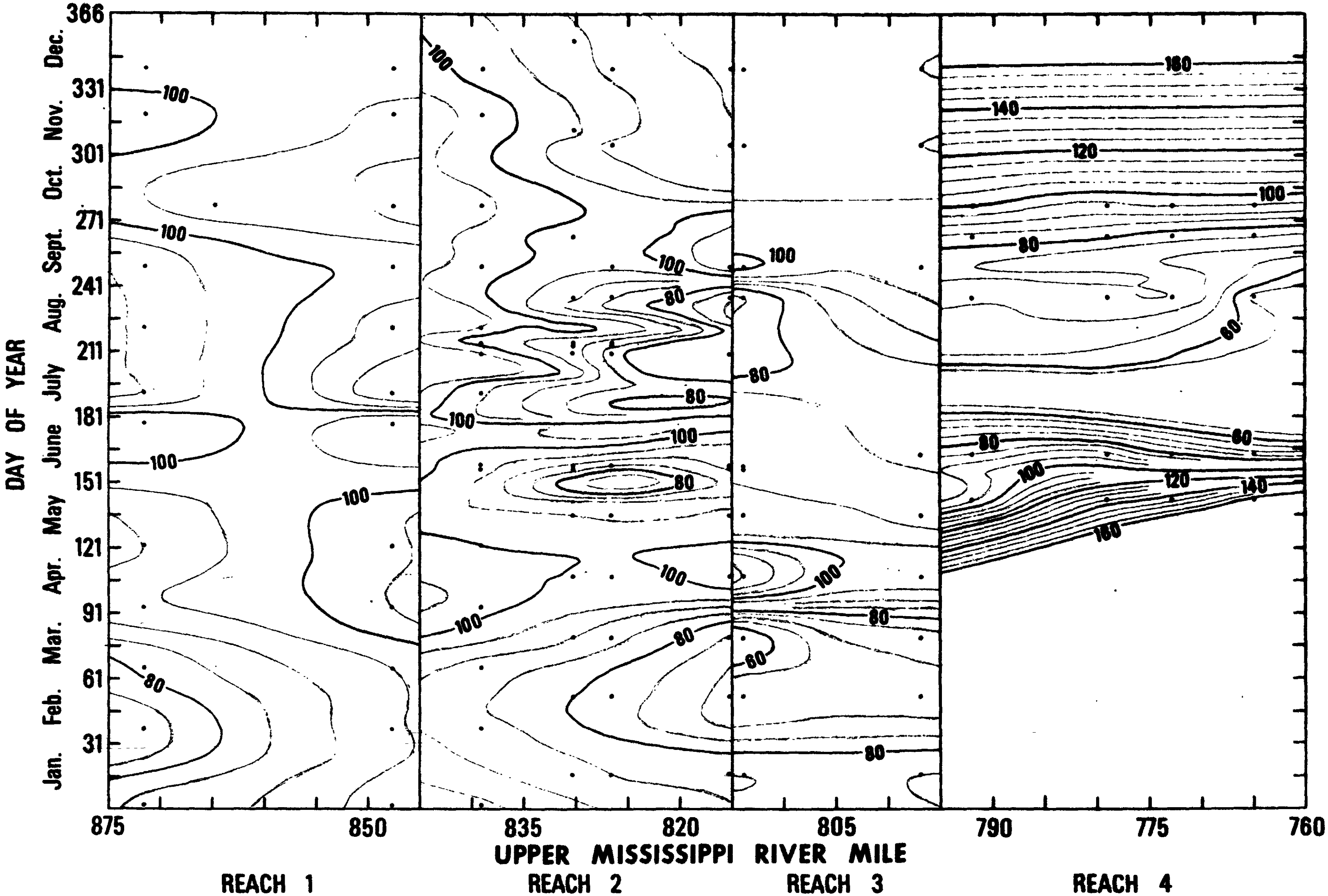

Figure 6.--Isopleths of dissolved oxygen, percent saturation, 1972. (Isopleth interval - 5 percent.)

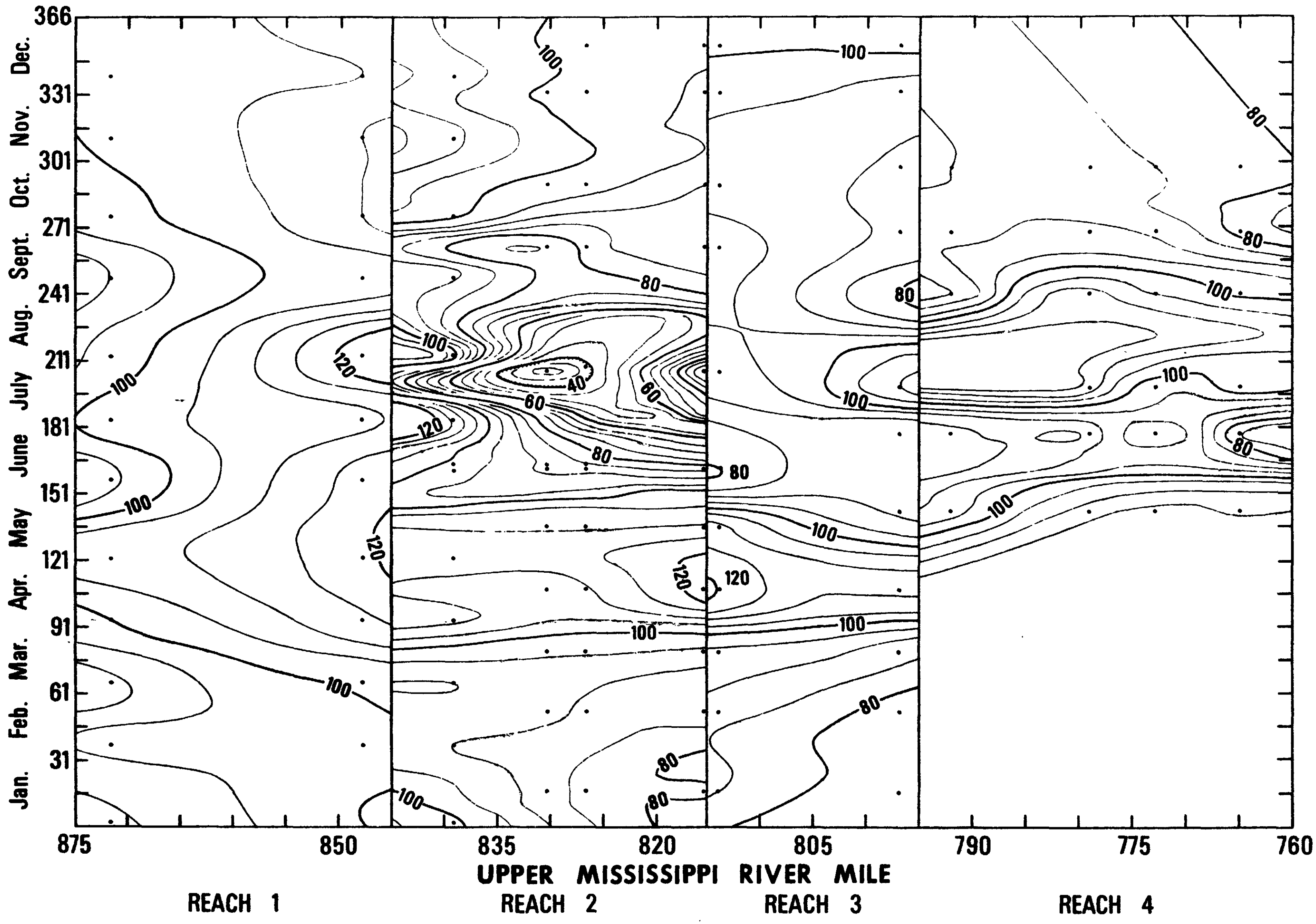

Figure 7.--Isopleths of dissolved oxygen, percent saturation, 1973. (Isopleth interval - 5 percent)

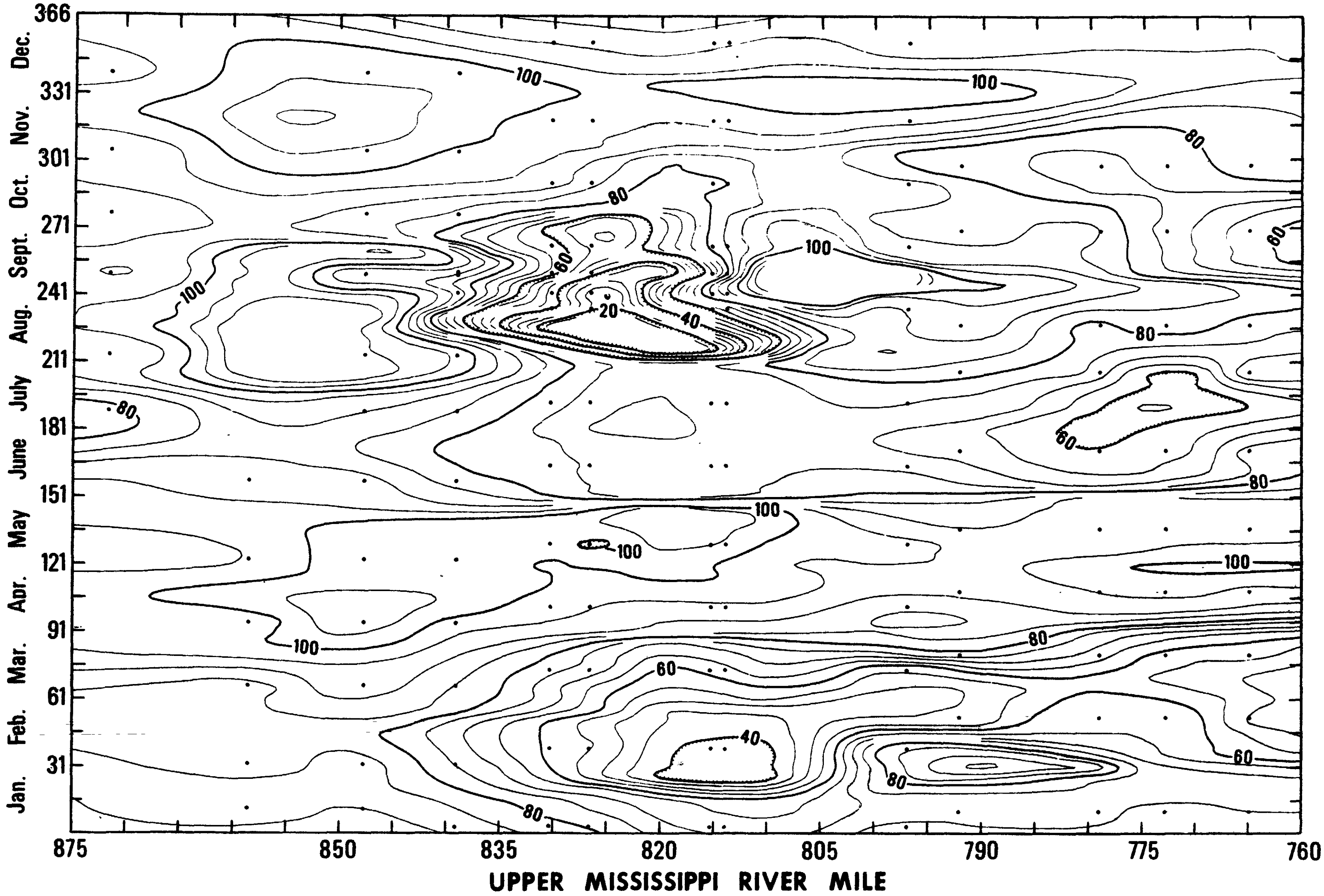

Figure 8.--Isopleths of dissolved oxygen, percent saturation, 1971. (Single continuous reach; isopleth interval - 5 percent.)

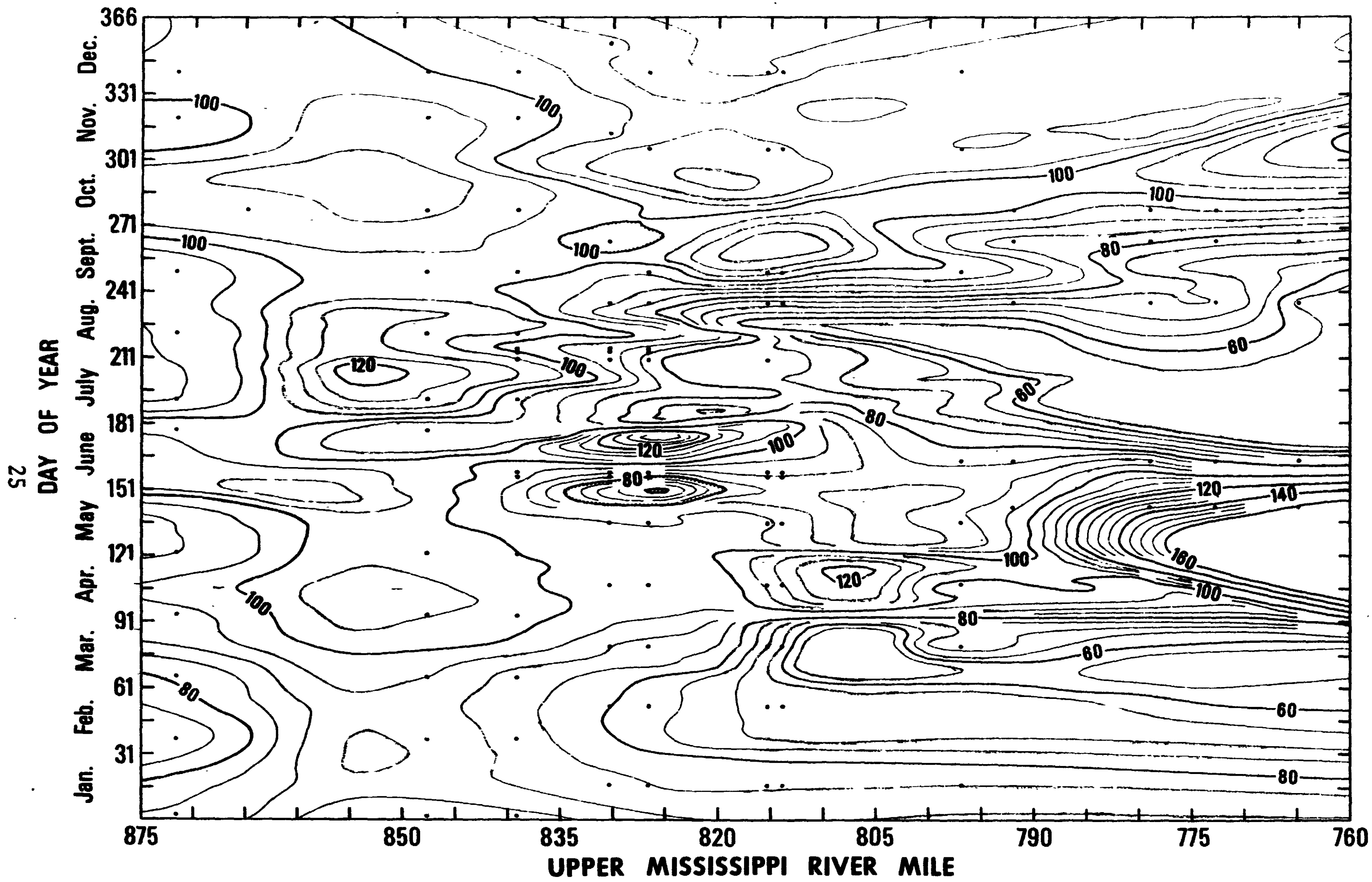

Figure 9.--Isopleths of dissolved oxygen, percent saturation, 1972. (Single continuous reach; isopleth interval - 5 percent.)

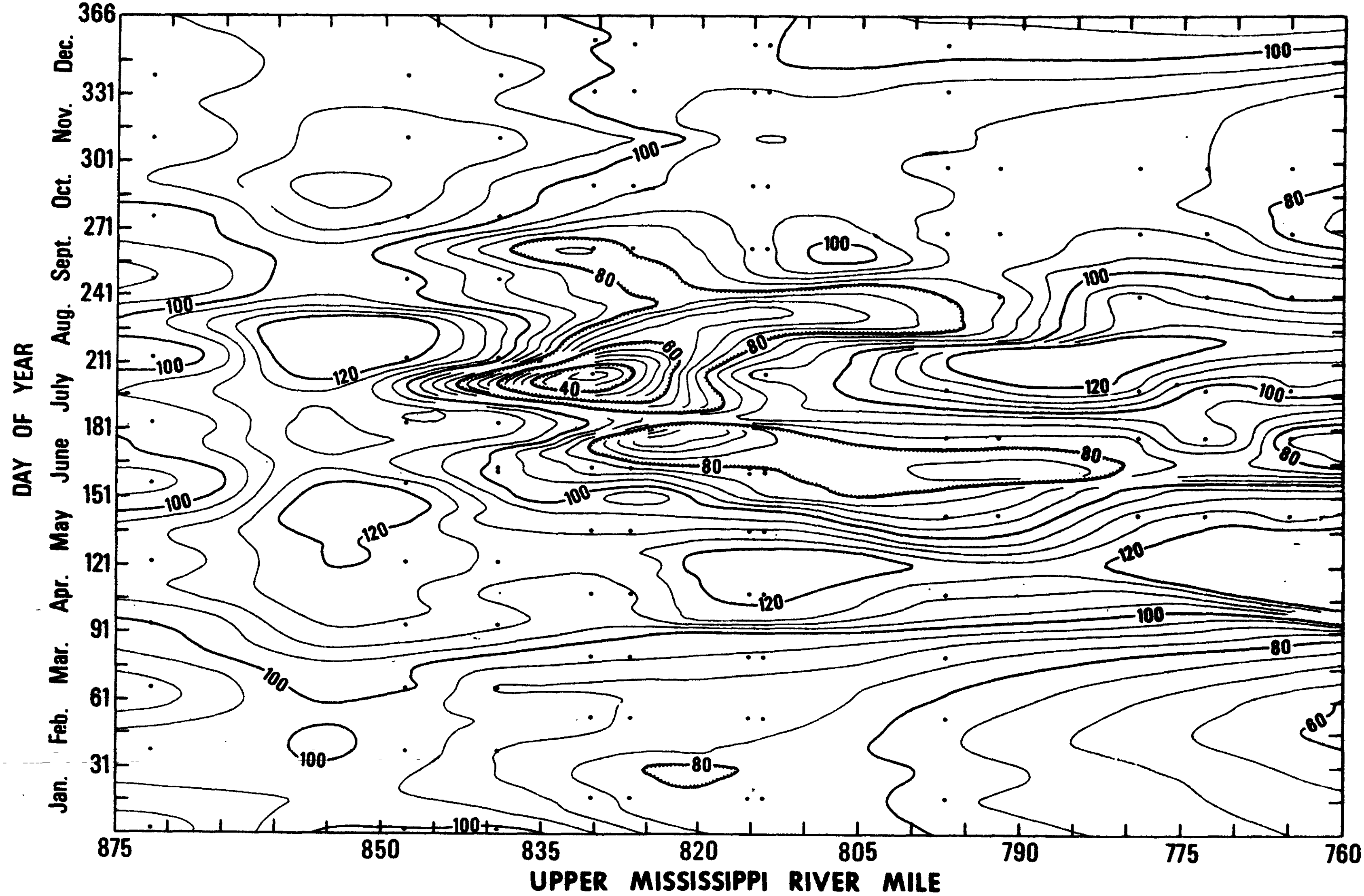

Figure 10.--Isopleths of dissolved oxygen, percent saturation, 1973. (Single continuous reach; isopleth interval - 5 percent.)

Low sample-data density is apparent for certain time-space plotted regions for the 1972 and 1973 segmented maps (figs. 6 and 7). In reach 4, no sample data are available for periods at the first and last parts of the year. For the first period, extrapolated (grid) values exceeded the maximum sample-data value, so isopleths were not drawn in this region (lower part of reach 4, figs. 6 and 7) by the computer program. Thus, the lack of data was obvious. However, during the last period, and on the nonsegmented maps for the same years (figs. 9 and 10), the lack is not as obvious. Interpretation of isopleths in regions of low sample-data density must be done with caution, and a high degree of uncertainty is reflected in the results.

Methods of evaluating the adequacy of sample-data density in a more quantitative manner were investigated. Cross sections of the isopleth maps were constructed at a specified point along the river (time slice) or at a specified time (reach slice). Comparisons were then made with independent data collected from continuous recording instruments or from intensive sampling surveys. Example comparisons are shown in figures 11 and 12, and the locations of the slices are shown in figure 13. Figure 11 is a time slice at UM 835.0 compared with continuous sampling results at UM 836.8. Agreement between the two lines is generally good, with a standard error of estimate of 1.3 mg/l. Deviation during the last half of July may be caused by monitor calibration problems or by BOD load sources between the monitor and the location of the time slice. Ice cover causes a lowering of DO that is not accounted for in the isopleth generation for the last half of December. This is partly a boundary-effect problem, in that, if data collected during January of the following year were used, agreement may have been improved during the December period. Further discussion of boundary effects will be presented in subsequent paragraphs.

Figure 12 is a reach slice of estimated DO for August 19, 1973 (average of August 17-21) compared with the results from intensive sampling at eight stations during the same period. The mean and range of DO in discrete samples collected at 4-hour intervals at each station are shown. The largest deviations in time (between actual sampling and average estimated DO conditions) near UM 830.0 coincide with regions of lower sample-data density along the slice (see fig. 13) and indicate that greater sample-data density in time may improve agreement between observed and estimated values.

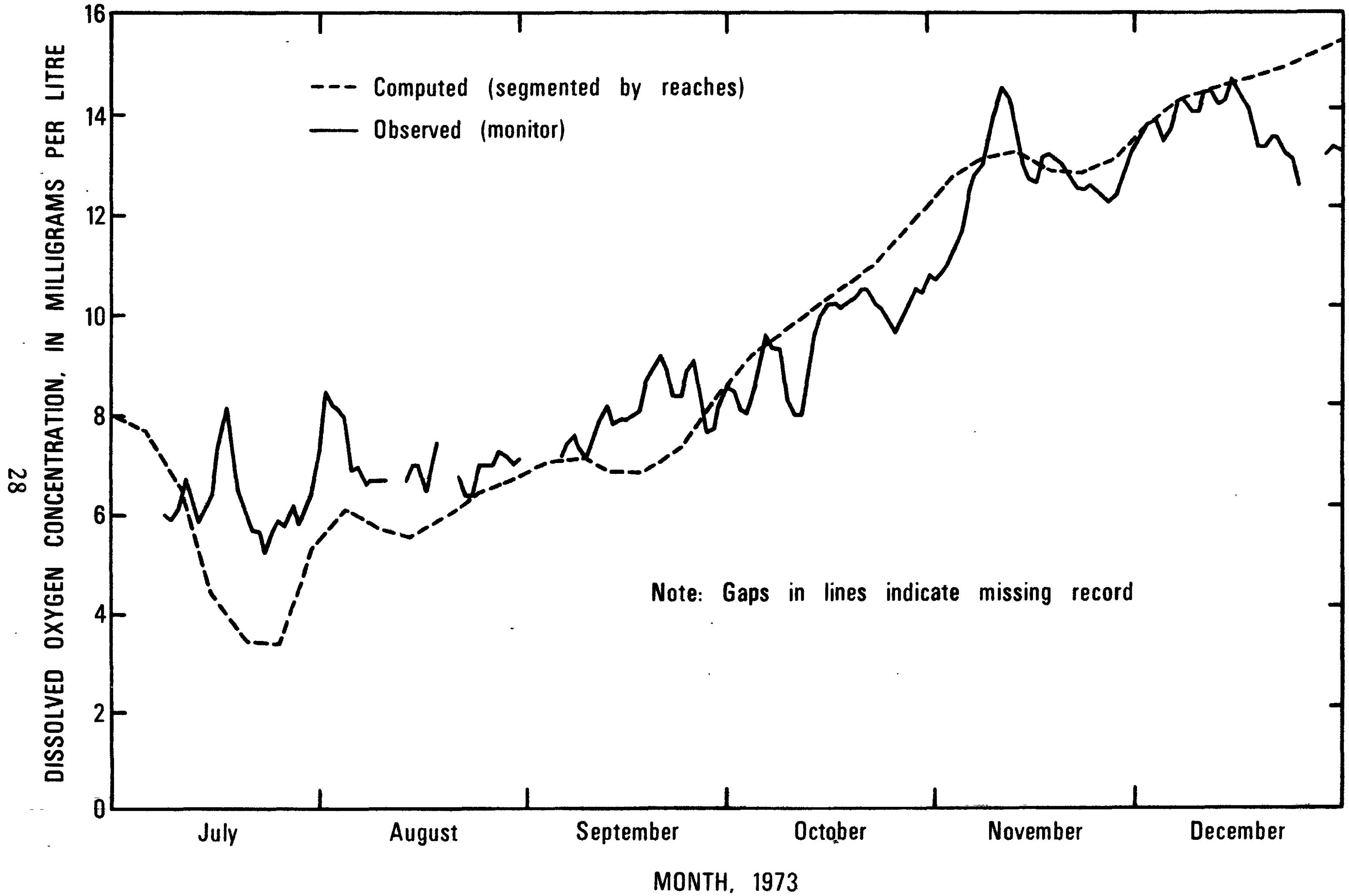

Figure 11.--Computed dissolved-oxygen concentrations (Upper Mississippi River mile UM 835) and observed monitor results (UM 836.8), July-December 1973.

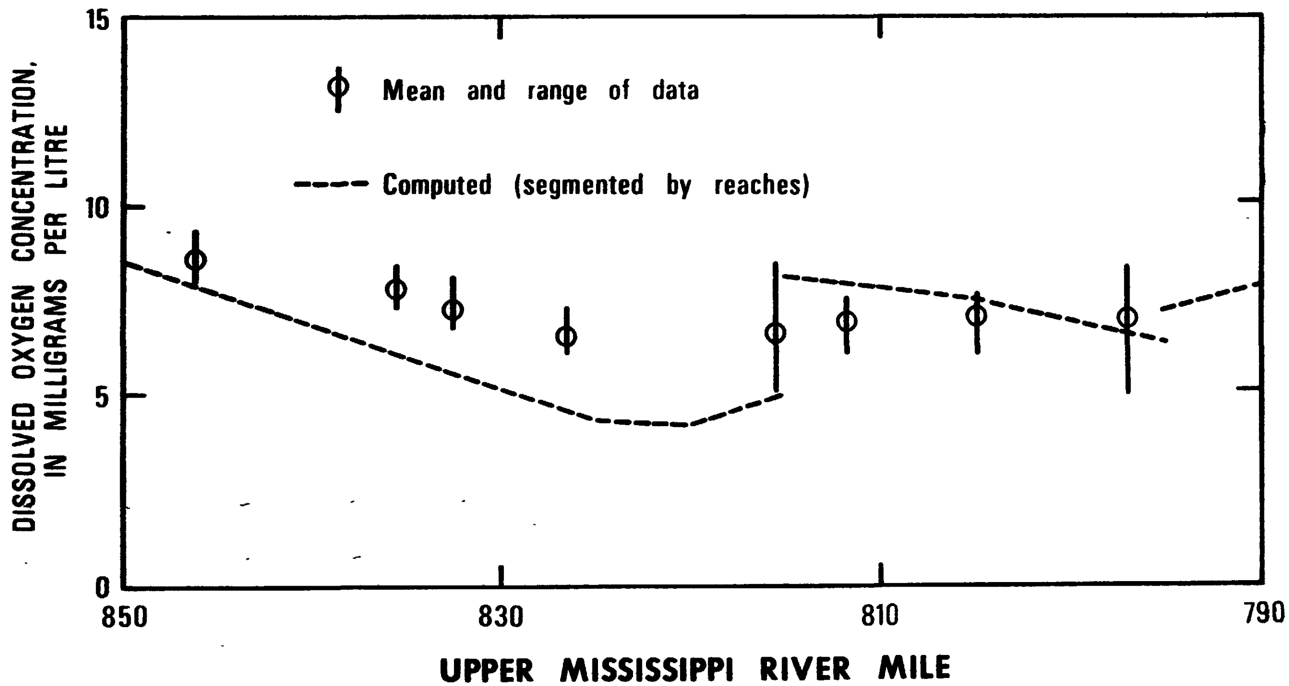

Figure 12.--Computed dissolved-oxygen concentration (August 17-21) and mean and range of sample data collected August 17-21, 1973.

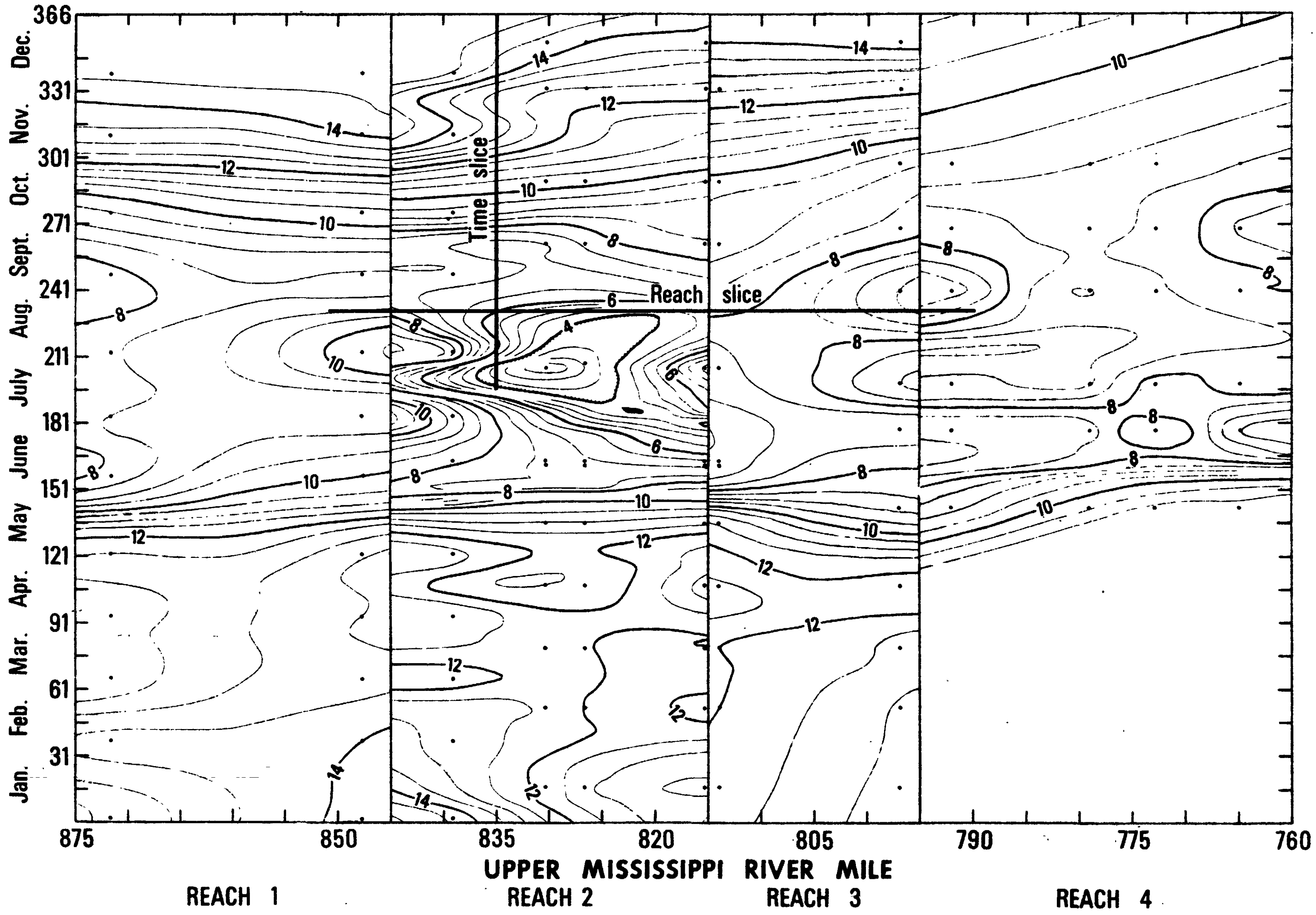

Figure 13.--Isopleths of dissolved oxygen concentration (in milligrams per litre) and location of reach and time slices, 1973. (Isopleth interval - 0.5 milligrams per litre.)

Evaluations of time-related boundary effects on the isopleth maps were investigated by constructing maps for the period July 1 to June 30 (figs. 14 and 15). Qualitative evaluation indicated that any boundary effects were confined to the immediate vicinity of the boundary (vertical time-scale), and use of a calendar-year basis in constructing the isopleth maps did not significantly affect results.

Another important factor was the choice of units of time and space used for constructing the isopleth maps. Days and miles were chosen for convenience. The relationship of these units, however, affects the determination of "neighborhoods" of influencing-data values in the isopleth-generation procedure. It seems that some type of 1-to-1 correspondence between time and space (position) units should have been established. That is, how many time units have an equivalent correlative effect as a given number of space (position) units? One possible relationship might be to define a time unit as that required to traverse one space unit at the average velocity of the river. The relationship selected may significantly affect isopleth generation and warrants further investigation.

A three-dimensional display of the DO (percent saturation) isopleth surface for 1972 is shown in figure 16. Note that the downstream direction is from right to left, rather than left to right, as on the corresponding isopleth map in figure 9. The display is somewhat more illustrative than the isopleth map. However, direct quantitative determination of percent saturation magnitudes is difficult, limiting usefulness of the display.

A map showing lines of equal water temperature for 1973 was also made, using the contouring program (fig. 17). Results indicate that variations in the space dimension are small and that variations in the time dimension follow a seasonal pattern similar to variation in air temperature. major heat-load sources on the Mississippi River are located at UM 856.9, UM 840.5, and UM 789.4. Additional heat loading may come from the Minnesota and St. Croix Rivers, with a major source in the former being 8.4 miles (14 kilometres) above its mouth. The 2°C line during the middle of January near UM 830.0 may be attributable to upstream heat-load inputs. The effect of these heat loadings during warmer periods may be less pronounced because of a smaller temperature difference between the heat load and the receiving water.

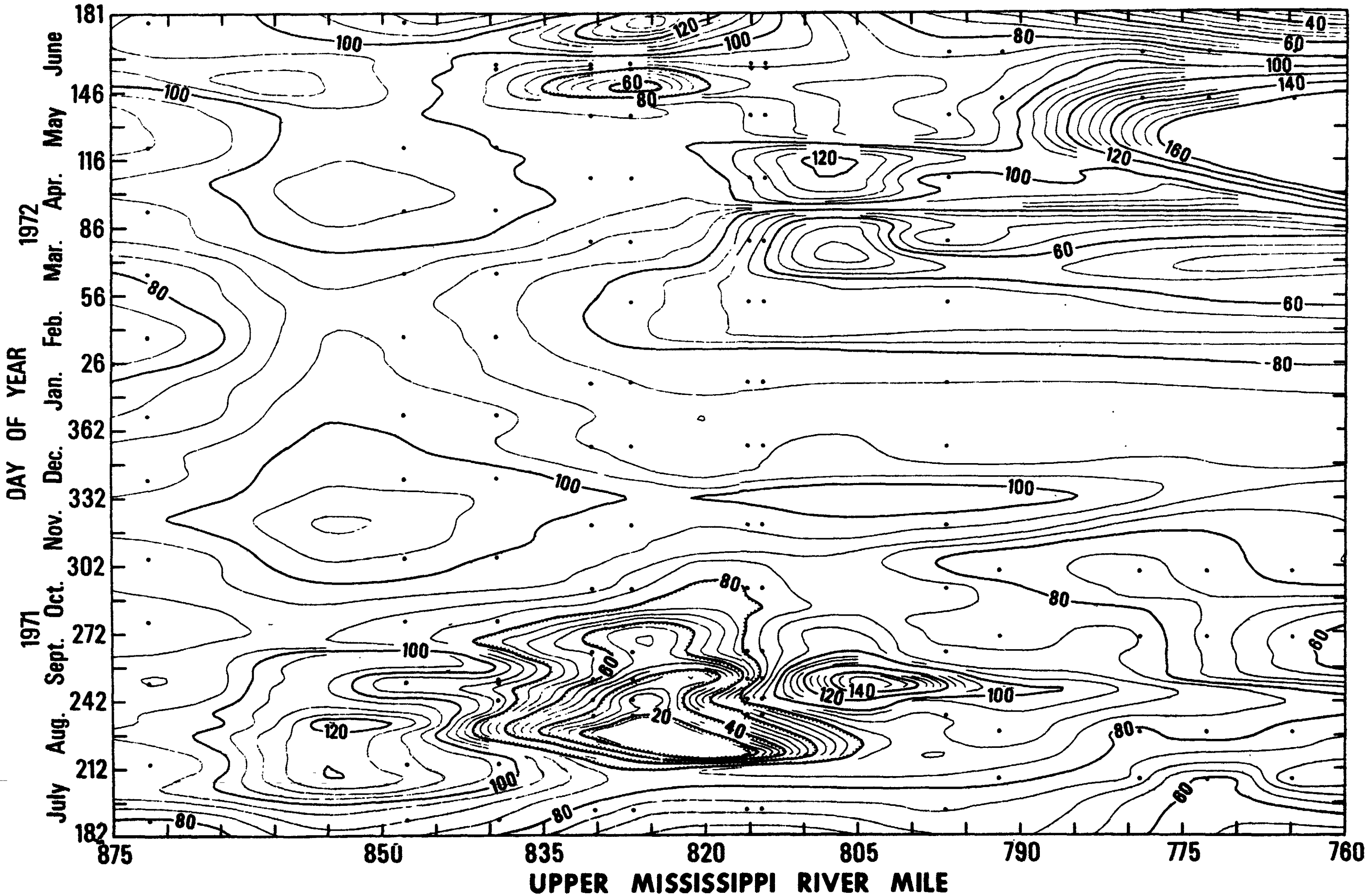

Figure 14.--Isopleths of dissolved oxygen, percent saturation, July 1971 to June 1972. (Single reach; isopleth interval - 5 percent.)

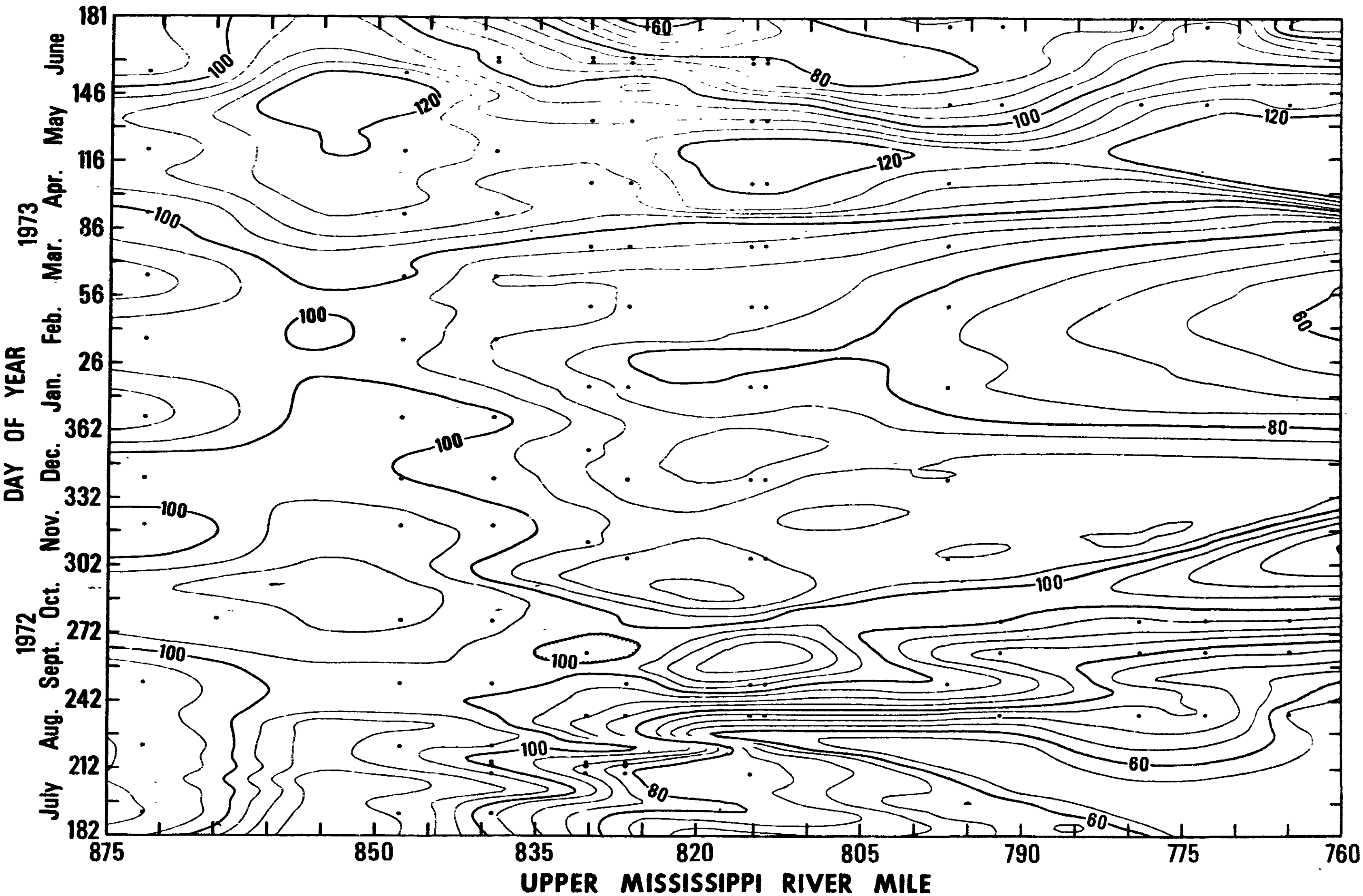

Figure 15.--Isopleths of dissolved oxygen, percent saturation, July 1972 to June 1973. (Single reach; isopleth interval - 5 percent.)

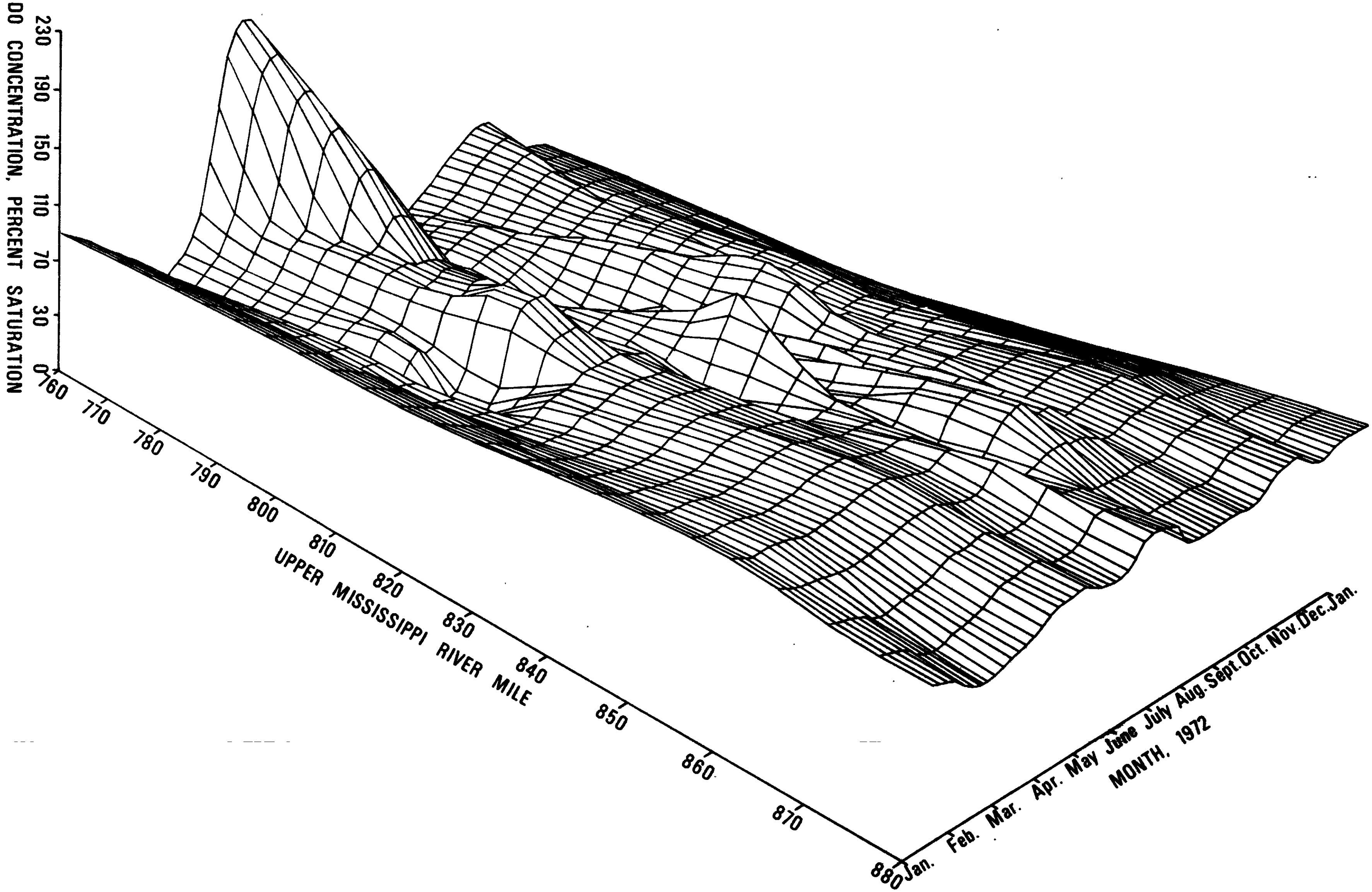

Figure 16.--Three-dimensional graphical display of dissolved oxygen, 1972.

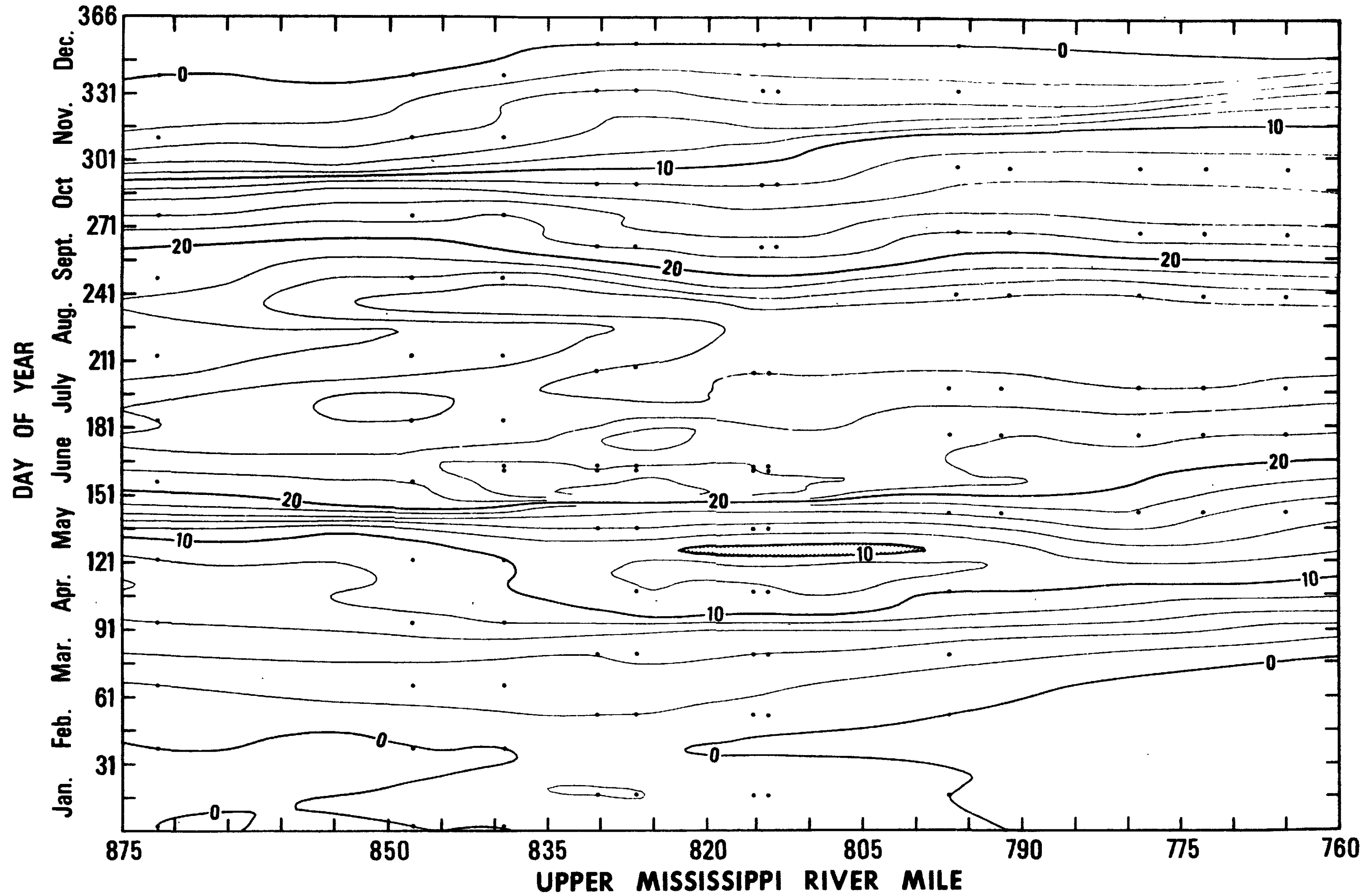

Figure 17.--Lines of equal water temperature, 1973.
(Single reach; line interaval - 2°C.)

RESULTS OF TIME-SERIES AND TIME-TREND ANALYSES

Monthly-mean time-series data were used to evaluate seasonal variations as well as long-term trends. The monthly-mean time series for DO (percent saturation) and BOD (mg/l) for the five selected long-term stations are shown in figures 18 and 19.

Implementation of the Metropolitan Wastewater Treatment Plant (UM 836.2) in 1938 resulted in most of the domestic waste load being diverted from the river above the plant to below the plant. This caused an increase in DO, as percent saturation, and a decrease in BOD concentrations in the Mississippi River above the plant outfall. The change is clearly indicated by time-series data at the Ford Dam station (UM 847.7), beginning in 1938, on figures 18 and 19. Records for the St. Paul station (UM 839.1) prior to 1938 are not available. The remaining stations are downstream from the outfall of the metropolitan plant (UM 836.2), and changes since 1938 are less apparent because of the effluent loadings. However, peak values of BOD concentration seem to be reduced after 1938, especially at the Hastings station (UM 815.3, fig. 19). Coliform bacteria (not shown) also decreased at the Ford Dam station after 1938. Time-series data at these five stations for other variables (temperature and turbidity, not shown) over the 1926-72 period showed no appreciable trends.

Secondary treatment of wastes at the metropolitan plant began, at least partly, in 1966. Subsequent reductions in BOD concentration in the waste effluent has resulted in lower BOD concentrations at the Inver Grove station (fig. 19), especially since 1970, when secondary treatment was fully implemented.

Seasonal fluctuations of the monthly BOD time series are of particular interest at the Ford Dam station. Before 1938, BOD concentrations (fig. 19) were generally at highest levels during winter, a time of relatively low stream discharge. Most of the BOD loads during this early period (pre-1938) can probably be attributed to domestic wastes entering the river through a combined sewer system. After this loading was reduced or eliminated, beginning with operation of the metropolitan plant (post-1938), maximum BOD concentrations occurred during summer and minimums during winter. The bulk of the BOD loads during the period can probably be attributed to surface runoff, which is at minimum during the winter. The conditions at St. Paul station (fig. 19) exhibit a character similar to that of the Ford Dam station for the post-1938 period. The BOD concentrations at stations downstream from the effluent of the metropolitan plant continued to peak during winter in the post-1938 period because reductions in domestic waste loads were not as pronounced as those upstream from the metropolitan plant.

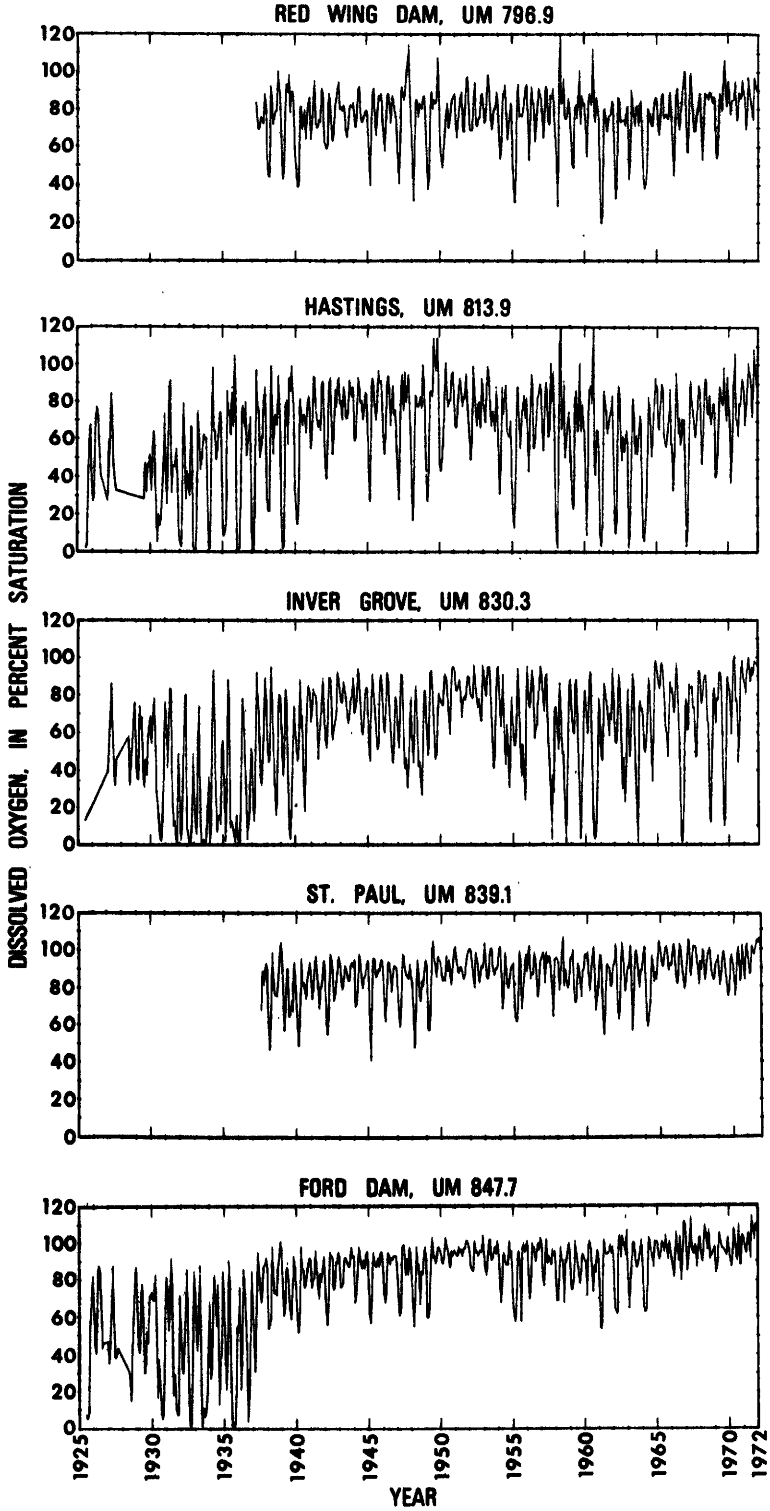

Figure 18.--Monthly mean-time series of dissolved oxygen at selected stations.

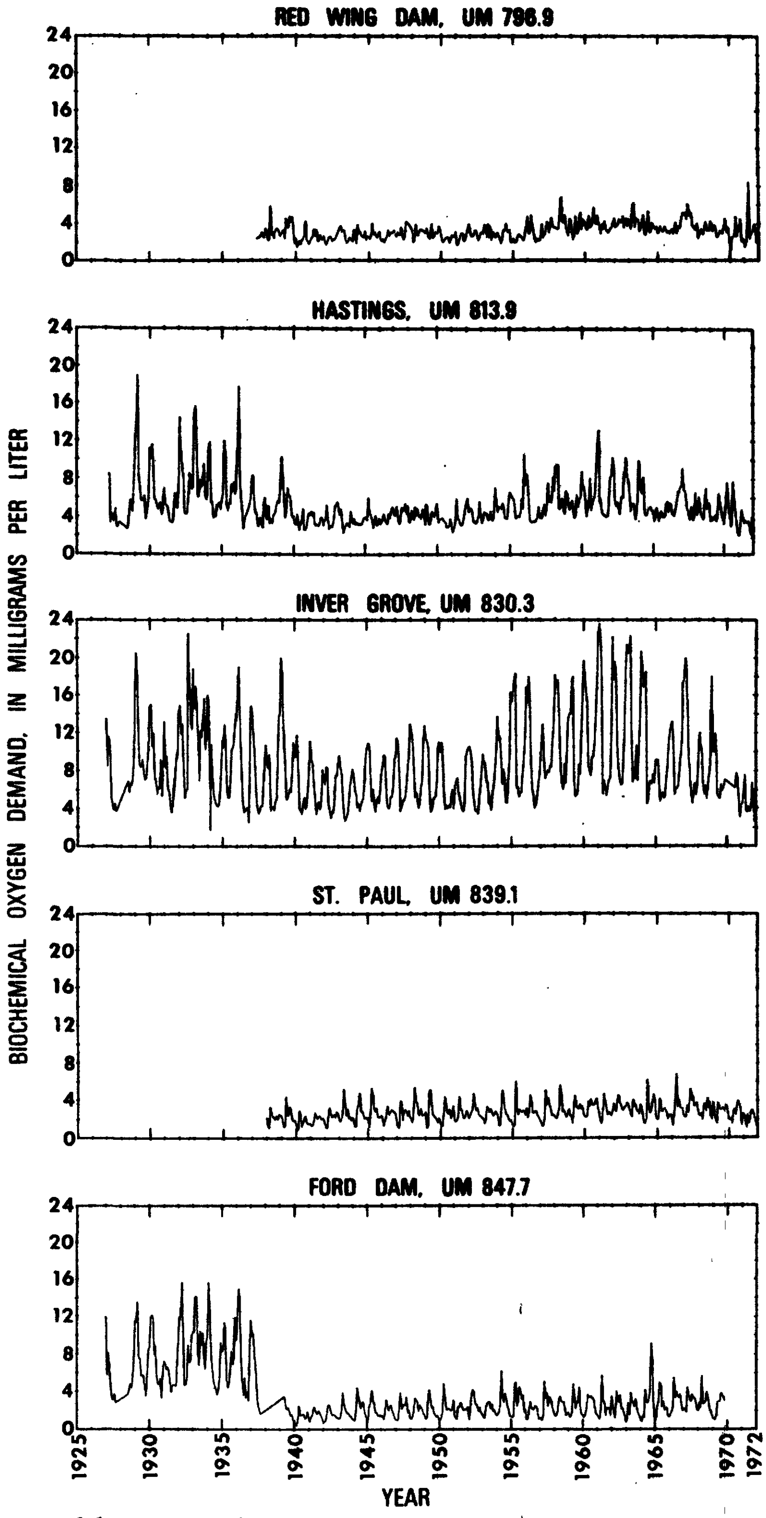

Figure 19.--Monthly mean-time series of biochemical-oxygen-demand concentrations at selected stations.

Reduction of BOD loads in the main stem Mississippi River after 1938 did not affect DO levels in a manner similar to BOD concentrations. Although BOD concentrations (and presumably BOD loads) at the Ford Dam station show seasonal minimums during the winter for the post-1938 period, DO (percent saturation) levels (fig. 18) also show seasonal minimums during winter for the same period. One possible explanation for this is that ice cover reduces reaeration and masks much of the gain from reductions in BOD loads. However, the reduction in BOD loads in the Mississippi River after 1938 has nearly eliminated the high summer DO minimums that were characteristic of the pre-1938 period. Stations downstream from the metropolitan plant continued to exhibit summer DO minimums during the post-1938 period.

Seasonal fluctuations are also exhibited by other variables. Turbidity tends to reach an annual maximum in the summer, and a minimum in the winter. This phenomenon indicates that surface runoff is probably an important factor governing turbidity of streamflow. Water temperatures follow the annual seasonal variation of air temperatures. Monthly time series of coliform bacteria were highly variable, and discernible characteristics were difficult to distinguish. At the Inver Grove staion (UM 830.3), however, maximum concentrations of coliform bacteria consistently occurred during early summer and fall. This is probably the result of a combined effect of dilution of treated wastes and seasonal variations of coliform-bacteria concentrations discharged from the metropolitan plant. This phenomenon seems to be fairly consistent year after year.

Although the effects of population growth of the Twin Cities area on river quality might be determined from monthly time series of water-quality data, annual mean-time series are more illustrative. (See fig. 20.) Statistical measures can be computed to detect and evaluate signicant time trends in the annual mean values. BOD loadings into the metropolitan treatment plant are related directly to population growth in the metropolitan area. BOD influent loadings to the metropolitan plant have more than doubled since 1940, and effluent BOD loads from the plant follow this trend until about 1966 when partial secondary treatment of wastes was begun, thus reducing effluent BOD loads.

The result of increased BOD loads on river quality above and below the metropolitan plant during 1940-72 is illustrated in figure 21. Annual-mean discharge-weighted BOD loads, determined from monthly means of BOD concentration and river discharge, are shown for the St. Paul and Inver Grove stations. Rough mass-balance calculations of BOD loadings between these two stations indicate that effluent load from the metropolitan

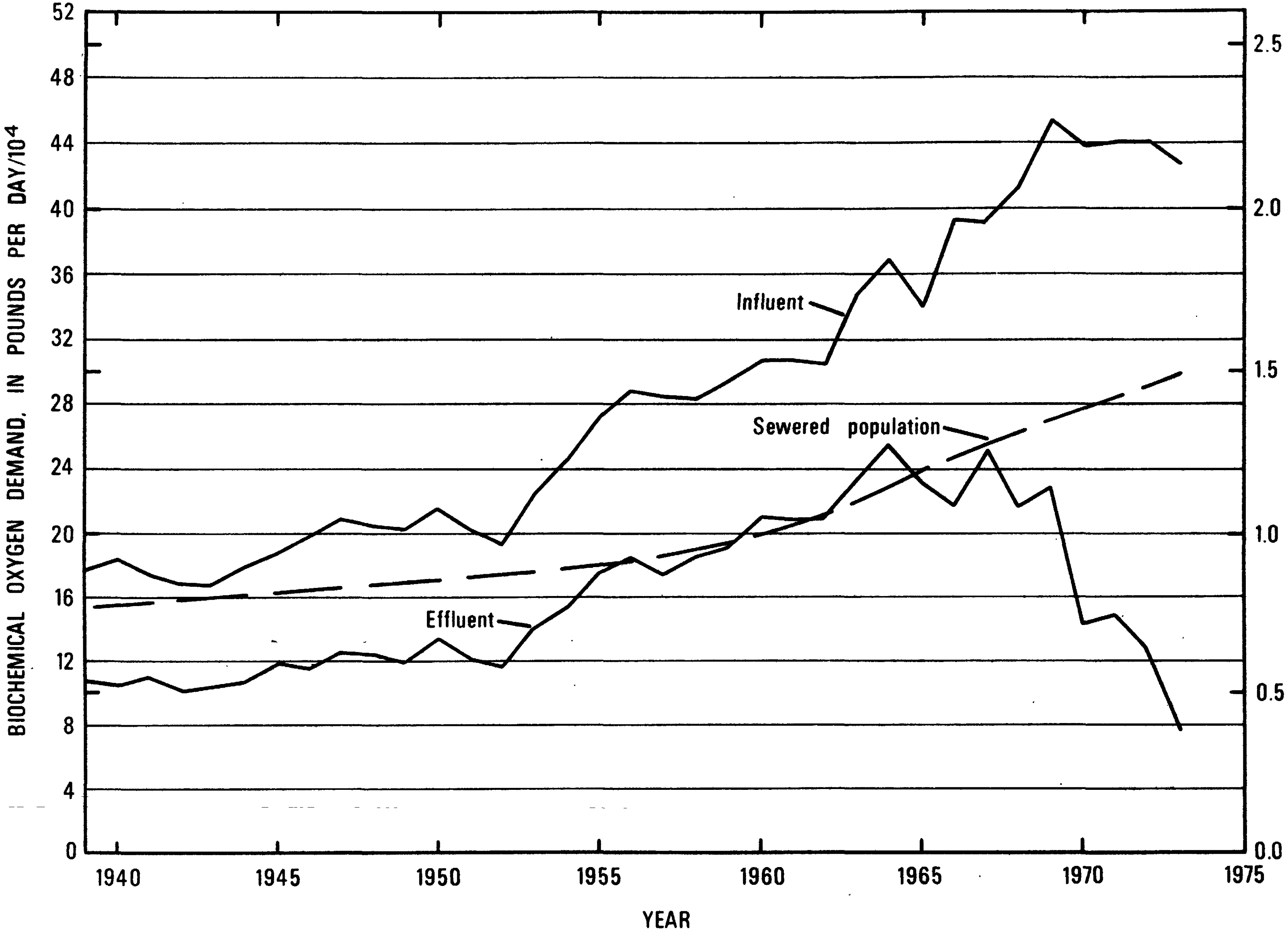

Figure 20.--Annual-mean-time series for influent and effluent biochemical-oxygen-demand load for Metropolitan Wastewater Treatment Plant and tributary population.

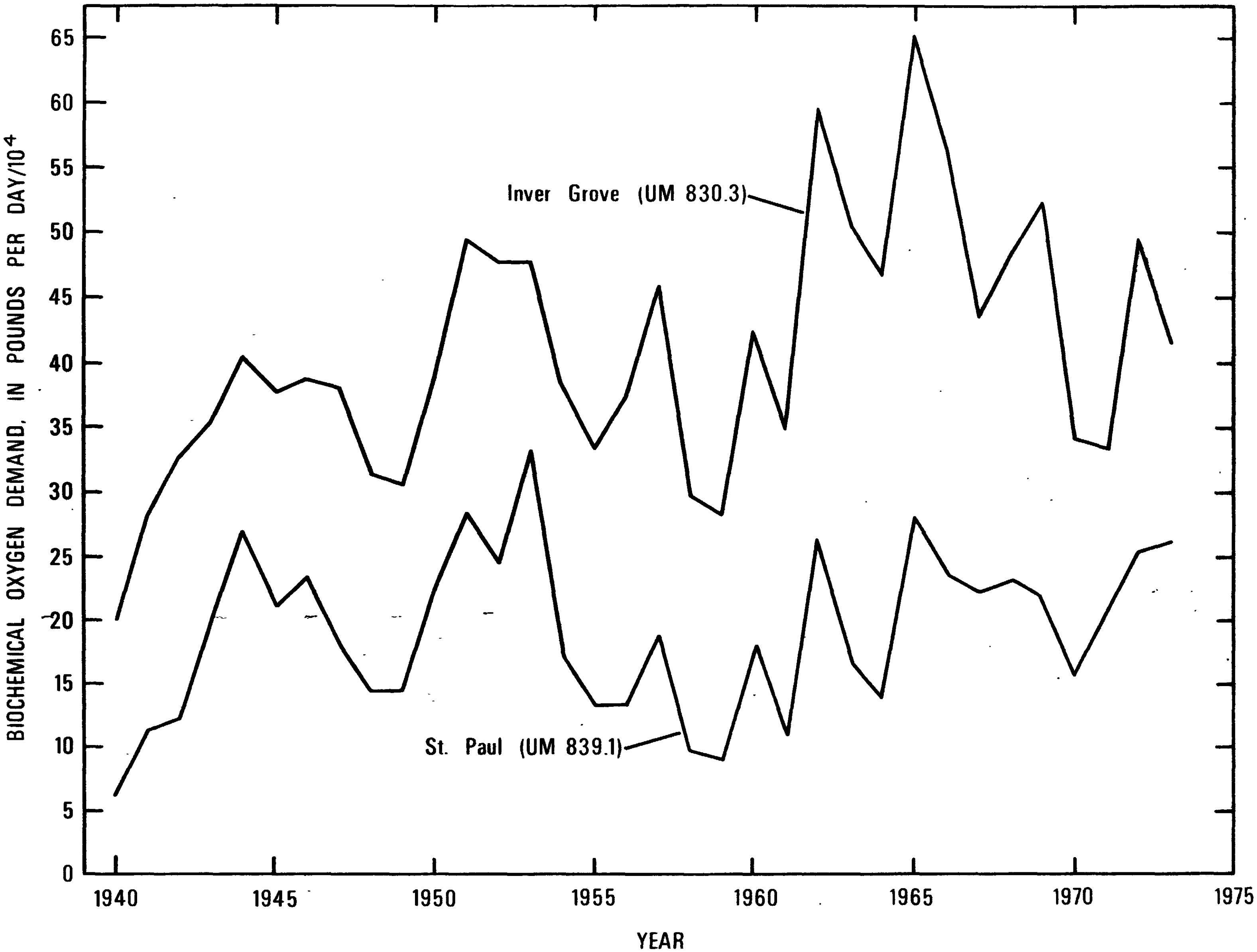

Figure 21.--Discharge-weighted annual-mean-time series of biochemical-oxygen-demand load at selected stations.

treatment plant accounts for an average of 82 percent of the increase in BOD load between these stations. Most of the year-to-year variation in BOD loads observed in figure 21 can be attributed to corresponding changes in annual-mean stream discharge (fig. 22). An increase in the differenece in BOD loads between the two stations (fig. 21) is consistent with the observed increase in the effluent loading from the metropolitan plant (fig. 20) that occurred around 1958.

Long-term trends in water quality in the upper Mississippi River, primarily in response to population growth, can be expressed somewhat more quantitatively using statistical measures. Results of applying the Kendall's tau test to annual-mean-time series, annual summer-period (July-September) mean-time series, and annual winter-period (January-February) mean-time series for the variables of interest are shown in table 4. Each annual time series was computed from values determined at approximately a monthly frequency. The relative ranking numbers indicate that level of significance for any observed change in the time series (annual, summer, or winter) for each variable at each station. The level of significance chosen to indicate a change was assumed to be 0.01, corresponding to a relative ranking of +5 or -5 in table 4. (See Steele, Gilroy, and Hawkinson, 1974.)

At the assumed significance level, trends are indicated (+5 or -5) for each variable at at least one station for at least one of the three time series (annual, summer, or winter). Positive trends in temperature are indicated for three of the winter periods and are considered to be related to the effects of heat loadings from thermal-power-plant effluents during these periods. Additional techniques were applied to temperature and will be discussed later in more detail.

Positive trends in turbidity are indicated for three summer periods, two annual periods, and one winter period. Summer-period trends are probably the result of increased concentrations of suspended material in surface runoff and may be related to increases in population and urbanization or to changes in agricultural practices. Flow contributions having relatively higher turbidity from the Minnesota River (UM 844.0) cause a significant increase in the turbidity observed between the Ford Dam (UM 847.7) and St. Paul (UM 839.1) stations. Thus trends indicated at stations downstream from the Minnesota River may be accounted for principally by concurrent trends in the Minnesota River. In addition, the trends indicated at Hastings Dam (UM 815.3) may be flow-related (noted corresponding trends in discharge); that is, the observed increasing trend in turbidity at this station may result from a corresponding increasing trend in flow.

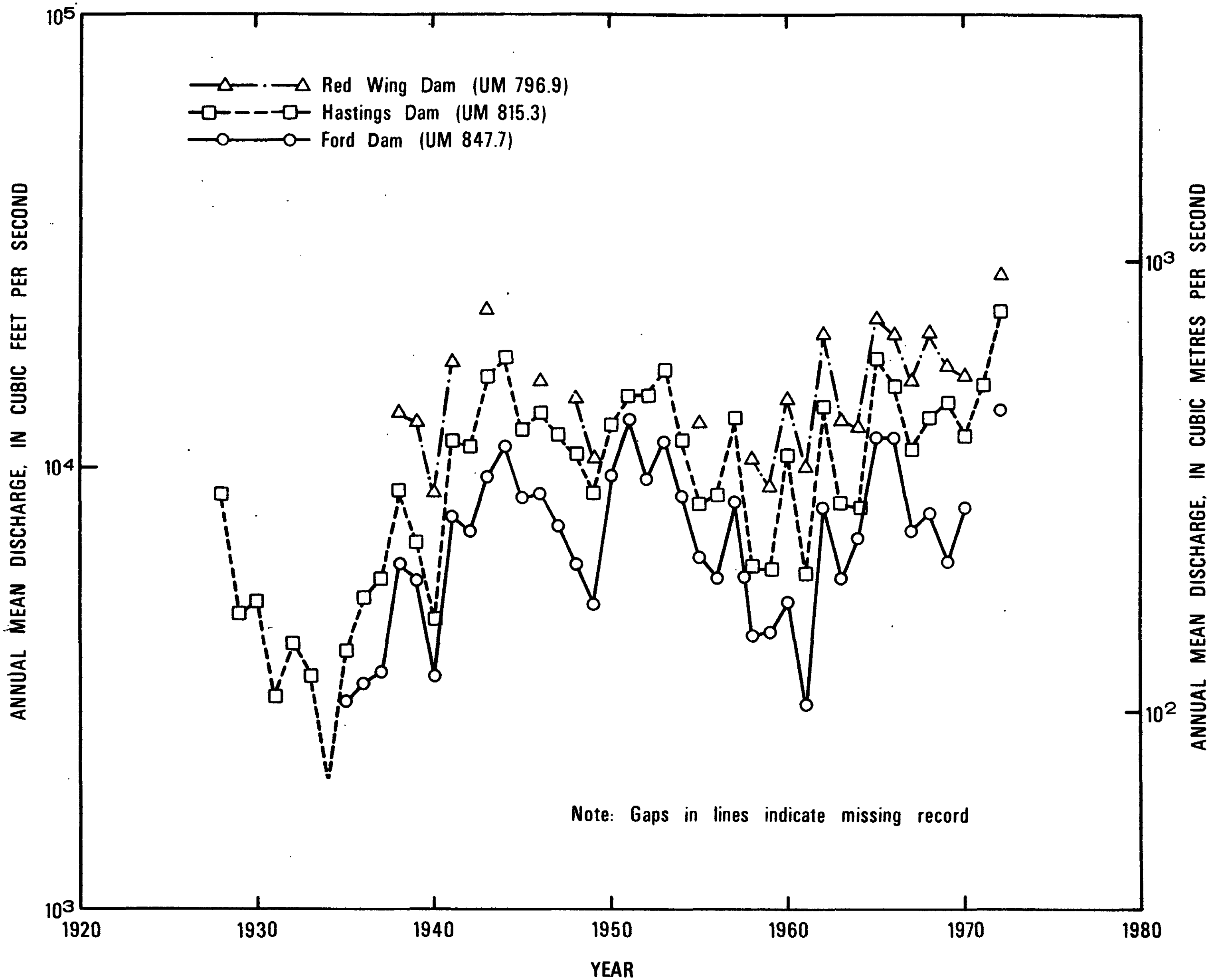

Figure 22.--Annual-mean-time series of discharge at selected stations.

TABLE 4.--LEVELS OF SIGNIFICANCE FOR EVALUATION OF LONG-TERM CHANGES OF STREAMFLOW CHEMICAL QUALITY (1926-1972)

STATION	A,S, OR W[1]	NUMBER OF YEARS [2]	TEMPERATURE	TURBIDITY	DISSOLVED OXYGEN,MG/1	DISSLOVED OXYGEN, PERCENT SATURATION	BIOCHEMICAL OXYGEN DEMAND	COLIFORM	DISCHARGE
FORD DAM	A	47	-2	+3	+5	+5	-0	-1	+2
Do.	S	47	-0	+5	+5	+5	-0	-4	+1
Do.	W	45	+2	-3	+5	+5	-0	-1	+2
ST. PAUL	A	35	+1	+0	+5	+5	+5	+3	+0
Do.	S	35	+1	+1	+1	+3	+5	+0	-0
Do.	W	33	+5	+5	+4	+5	+5	+3	+0
INVER GROVE	A	47	+0	+5	+5	+5	+0	+5	+3
Do.	S	45	-0	+5	+3	+3	+2	+5	+2
Do.	W	44	+5	-0	+5	+5	+1	+5	+4
HASTINGS DAM	A	42	-0	+5	+3	+3	+0	+5	+5
Do.	S	45	-0	+5	+4	+4	+0	+1	+5
Do.	W	44	+0	-0	+2	+2	-1	-0	+4
RED WING DAM	A	35	-0	+1	+1	+1	+5	+1	+2
Do.	S	35	-0	+0	+1	+1	+5	-0	+0
Do.	W	34	+5	+0	+0	+0	+3	+0	+0

NOTATION:
LEVELS OF SIGNIFICANCE OF TRENDS IN TIME SERIES FOR VARIABLES OF INTEREST.

0: TREND WITH A SIGNIFICANCE LEVEL GREATER THAN 0.20
1: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.20 BUT GREATER THAN 0.10
2: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.10 BUT GREATER THAN 0.05
3: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.05 BUT GREATER THAN 0.02
4: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.02 BUT GREATER THAN 0.01
5: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.01

SIGNIFICANCE LEVELS EXPRESSED ABOVE CORRESPOND TO A TWO-TAILED TEST APPLYING KENDALL'S TAU STATISTIC. DECREASING CHANGES ARE INDICATED BY (-) AND INCREASING CHANGES ARE INDICATED (+).

[1]/ A,S, OR W REFER TO ONE OF THE FOLLOWING TIME SERIES: A-ANNUAL MEAN, S-JULY-SEPTEMBER CRITICAL PERIOD MEAN, W-JANUARY-FEBRUARY CRITICAL PERIOD MEAN.

[2]/ MAXIMUM NUMBER OF YEARS OF RECORD AVAILABLE FOR ANY SINGLE VARIABLE.

Computation of trend statistics for DO were made for values expressed both as mg/l and as percent saturation, the latter removing the effect of seasonal temperatures. Results for these two DO measures (table 4) are identical, except for the winter period at the St. Paul station. The positive temperature trend indicated for winter periods might explain part of the difference in the DO trend indications.

Upon initial examination of table 4, it seems that the positive trends for DO can be attributed to reduction of waste loads resulting from start of waste treatment at the metropolitan plant in 1938. Further examination reveals that expected negative trends in BOD do not occur commensurate with increases of comparable significance in DO. In fact, positive trends for BOD are indicated in some places. Evidently a direct inverse relationship between BOD and DO levels in streamflow may not exist.

Some insight into this anomalous situation can be gained by examining only the post-1938 trends (table 5), thereby excluding from the time-trend analysis streamflow-quality conditions prior to operation of the metropolitan plant. Positive trends are indicated for BOD for almost all periods. No significant trends are indicated for three stations in table 5 during the extended periods of record for the same stations in table 4. Thus, the increasing trend in BOD for the post-1938 period (table 5) was obscured by reductions in BOD caused by initiation of wastewater treatment, resulting in an indication of no trend in BOD when the entire period is used in the analysis (table 4).

However, the Ford Dam and St. Paul stations upstream from the point of influx of treated wastes exhibit simultaneous positive significant trends for DO and BOD in the post-1938 period. Although the time series increases in BOD concentrations are relatively low, usually on the order of 1 to 6 mg/l (fig. 19), they may be indicative of increased BOD loads in surface runoff resulting from population growth and increased urbanization. Simultaneous indications of increases in DO are difficult to explain but may be caused by more aquatic-plant activity or by the location of the sampling stations relative to the source of major BOD load inflows. Note that many of the values of DO concentration at the Ford Dam station (fig. 18) exceed 100 percent of saturation in recent years. (Supersaturation if they are the result of aquatic-plant activity during the summer.)

Positive trends are indicated for coliform-bacteria at the Inver Grove and Hastings stations (table 4). Positive trends are also indicated for this variable at the Ford Dam station for the post-1938 period (table 5). Annual mean-time

TABLE 5.—LEVELS OF SIGNIFICANCE FOR EVALUATION OF LONG-TERM CHANGES OF STREAMFLOW CHEMICAL QUALITY FOR THE PERIOD 1939-1972. (LEVELS OF SIGNIFICANCE FOR ST. PAUL AND RED WING, 1928-1972, FROM TABLE 4 ARE INCLUDED FOR COMPARISON.)

STATION	A,S, OR W[1]	NUMBER OF YEARS[2]	TEMPERATURE	TURBIDITY	DISSOLVED OXYGEN, MG/1	DISSOLVED OXYGEN, PERCENT SATURATION	BIOCHEMICAL OXYGEN DEMAND	COLIFORM	DISCHARGE
FORD DAM	A	34	+0	+1	+1	+5	+5	+5	+0
Do.	S	34	+0	+1	+5	+5	+5	+1	-0
Do.	W	34	+5	+2	+5	+5	+5	+5	+0
ST. PAUL	A	35	+1	+0	+5	+5	+5	+3	+0
Do.	S	35	+1	+1	+1	+3	+5	+0	-0
Do.	W	33	+5	+5	+4	+5	+5	+3	+0
INVER GROVE	A	34	+4	+4	+0	+0	+5	+3	-0
Do.	S	34	+0	+1	-0	-0	+5	+0	-0
Do.	W	34	+5	+2	+1	+2	+4	+5	+0
HASTINGS DAM	A	34	+0	+3	-1	-1	+5	+5	+0
Do.	S	34	+0	+3	-1	-2	+5	+0	+0
Do.	W	34	+0	+4	-0	-0	+2	+1	-0
RED WING DAM	A	35	-0	+1	+1	+1	+5	+1	+2
Do.	S	35	-0	+0	+1	+1	+5	-0	+0
Do.	W	34	+5	+0	+0	+0	+3	+0	+0

NOTATION:
LEVELS OF SIGNIFICANCE OF TRENDS IN TIME SERIES FOR VARIABLE OF INTEREST.

0: TREND WITH A SIGNIFICANCE LEVEL GREATER THAN 0.20
1: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.20 BUT GREATER THAN 0.10
2: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.10 BUT GREATER THAN 0.05
3: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.05 BUT GREATER THAN 0.02
4: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.02 BUT GREATER THAN 0.01
5: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.01

SIGNIFICANCE LEVELS EXPRESSED ABOVE CORRESPOND TO A TWO-TAILED TEST APPLYING KENDALL'S TAU STATISTIC. DECREASING CHANGES ARE INDICATED BY (-) AND INCREASING CHANGES ARE INDICATED (+).

[1] A,S, OR W REFER TO ONE OF THE FOLLOWING TIME SERIES: A-ANNUAL MEAN, S-JULY-SEPTEMBER CRITICAL-PERIOD MEAN, W-JANUARY-FEBRUARY CRITICAL-PERIOD MEAN.

[2] MAXIMUM NUMBER OF YEARS OF RECORD AVAILABLE FOR ANY SINGLE VARIABLE.

series of coliform bacteria at three stations are shown on figure 23. A dramatic reduction occurs at Ford Dam subsequent to the start of waste treatment in 1938. At the same time, coliform-bacteria concentrations increase at Inver Grove. During the post-1938 period, coliform-bacteria concentrations tend to increase at Ford Dam, as indicated by the positive trend in table 5. At the St. Paul station, the concentrations are similar to those at Ford Dam, but the levels of significance of the trend are lower for the post-1938 period (tables 4 and 5). This difference may be related to a mixing effect with Minnesota River water. The increase in coliform bacteria in 1938 at the Inver Grove station is probably the result of the start of waste-effluent discharges from the metropolitan plant just upstream. Increased waste-effluent loadings during subsequent years result in greater coliform-bacteria concentrations until around 1969, when post-chlorination of effluent from the plant was implemented. This caused the coliform-bacteria trend indications for the post-1938 period (table 5) to have a lower level of significance than for the overall period (table 4). Trend indications for the entire period of record at Ford Dam (table 4) are similarly affected; that is, reductions in 1938 of coliform bacteria are followed by a gradual increase, resulting in an overall indication of no trend in the analysis. (See results for BOD, p. 39.)

It is expected that for the length of record being considered no trend should be indicated for discharge (streamflow). However, at the Hastings Dam station, trends in discharge are indicated for the annual-mean and summer-period time series. Records of relatively low annual-mean discharges during the late 1920's and early 1930's are included at the Hastings Dam station. The effect of beginning the analysis during this below-average flow period results in a significant positive-trend indication. Discharge records as early as 1895 are available for the St. Paul station, and further analysis of time-series trends in stream discharge could be made with these data.

As mentioned previously, additional analyses of temperature records were made. The results of harmonic analyses of stream temperatures (Steele, 1974) and testing the computed harmonic coefficients for trend with the Kendall's tau technique are summarized in table 6. In order to expedite the analysis, monthly mean values of every fifth year (ending in 1970) were selected from the records for each station. A discontinuity in the sinusodial depiction of the annual seasonal variability in stream temperatures occurs because of prolonged periods of 0°C stream temperatures during the Minnesota winters. Therefore, separate analyses were made with 0°C values included and excluded in the fitting of the harmonic function, in order to assess this effect on the annual-harmonic depiction.

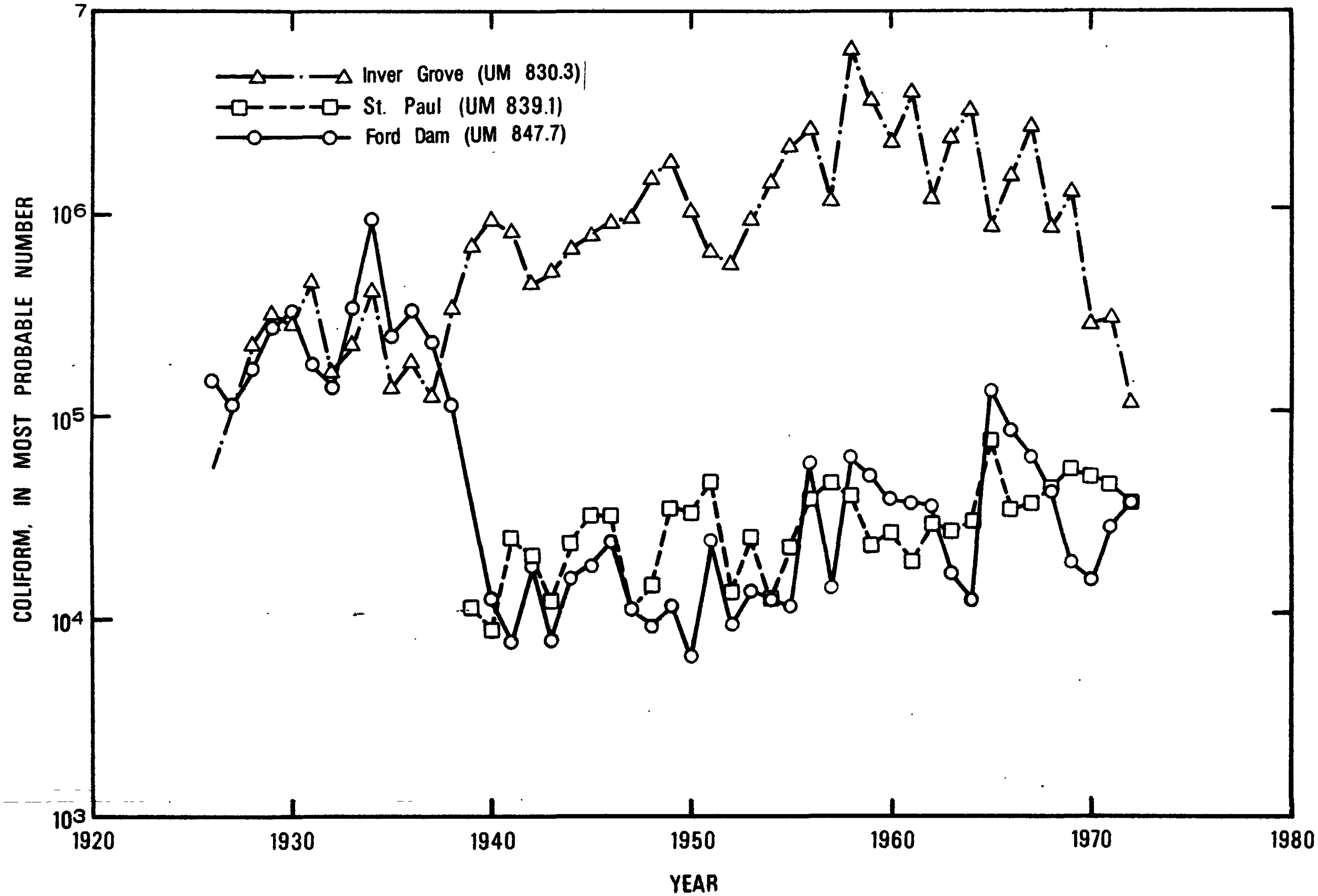

Figure 23.--Annual-mean-time series of coliform bacteria at selected stations.

TABLE 6.--STATISTICAL SUMMARY OF HARMONIC ANALYSIS OF STREAM TEMPERATURE.

STATION	A/B	N	$\bar{A}$	$\bar{C}$	$\bar{M}$	$\overline{A+M}$	A	C	M	A+M
FORD DAM	A	9	12.99	4.32	10.42	23.41	+0	-0	-0	+0
DO.	B	9	14.61	4.33	9.61	24.22	+0	-1	-0	+0
ST. PAUL	A	7	12.86	4.31	11.09	23.94	+0	-0	+1	+1
DO.	B	7	13.49	4.31	10.74	24.24	-0	-0	+2	+0
INVER GROVE	A	9	13.17	4.31	11.07	24.26	-0	-1	+0	+0
DO.	B	9	13.89	4.31	10.69	24.59	-0	-1	+0	+0
HASTING DAM	A	9	13.22	4.32	10.69	23.91	+0	-0	-0	-0
DO.	B	9	14.82	4.32	9.83	24.66	+0	-0	-0	+0
RED WING DAM	A	7	12.76	4.30	10.23	22.97	+0	+0	-0	+0
DO.	B	7	13.93	4.30	9.57	23.51	-0	+0	-0	-0

NOTATION: A/B-A IF ZERO VALUES WERE INCLUDED IN THE ANALYSIS, B IF THEY WERE ELIMINATED.

N - NUMBER OF 5TH YEAR PERIODS ANALYZED.
$\bar{A}$ - MEAN OF THE HARMONIC AMPLITUDES FOR THE N PERIODS.
$\bar{C}$ - MEAN OF HARMONIC PHASE COEFFICIENT FOR THE N PERIODS.
$\bar{M}$ - MEAN OF THE HARMONIC MEAN TEMPERATURES FOR THE N PERIODS.
$\overline{A+M}$ - MEAN OF THE SUM OF THE HARMONIC AMPLITUDES AND THE HARMONIC MEAN TEMPERATURE FOR THE N PERIODS.
A,C,M,A+M - RANKED LEVELS OF CONFIDENCE FOR SIGNIFICANCE OF TRENDS IN TIME SERIES FOR HARMONIC AMPLITUDE, HARMONIC PHASE COEFFICIENT, HARMONIC MEAN TEMPERATURE, AND SUM OF THE HARMONIC AMPLITUDES AND THE HARMONIC MEAN TEMPERATURES, RESPECTIVELY.

THESE ARE CODED AND RANKED AS FOLLOWS:

0: TREND WITH A SIGNIFICANCE LEVEL GREATER THAN 0.20
1: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.20 BUT GREATER THAN 0.10
2: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.10 BUT GREATER THAN 0.05
3: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.05 BUT GREATER THAN 0.02
4: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.02 BUT GREATER THAN 0.01
5: TREND WITH A SIGNIFICANCE LEVEL EQUAL TO OR LESS THAN 0.01.

SIGNIFICANCE LEVELS EXPRESSED ABOVE CORRESPOND TO A TWO-TAILED TEST APPLYING KENDALL'S TAU STATISTIC. DECREASING CHANGES ARE INDICATED BY (-) AND INCREASING CHANGES ARE INDICATED (+).

No significant trends (+5 or -5) are indicated for any of the harmonic coefficients in table 6. Thus, this analysis fails to substantiate the positive trends indicated for winter periods at four of the five long-term stations in tables 4 and 5. Hence, the heat-loading effects are such that they are only detectable (at the assumed level of significance) against the low background temperatures during winter.

Additional analyses of temperature trends noted in tables 4 and 5 were made using the Mann-Whitney test procedure (Conover, 1971). The test was made on winter-period-mean values at all stations for the entire period of record and at some stations for the post-1938 period. Annual-mean stream-temperature values at Inver Grove station were also selected because of the +4 trend indication (table 5) for the post-1938 period.

Using a technique described by Steele and others (1974), the selected time series were divided into two periods (reflecting the change in the time series) by visual inspection. A 98-percent confidence interval was then determined for the significance of difference between the means of the two periods. If the resulting confidence interval includes zero, it is an indication that the expected difference between the means of the two periods may be zero, and thus no true trend exists. If the interval does not include zero, it indicates with a 98-percent probability that there was an incremental change in the mean values between the two periods.

Results of the test are shown in table 7, along with the corresponding trend indication given by the Kendall's tau test (tables 4 and 5). In all cases of trend indication (+5 or -5) by the Kendall's tau test, the 98-percent confidence interval does not include zero. For those cases of no significant trend indication (less than +5 and greater than -5) by the Kendall's tau test, the 98-percent confidence interval included zero 60 percent of the time (3 out of 5). Thus, the results of the Mann-Whitney test corroborate results of the Kendall's tau test and also provide an estimate of the magnitude of change that may have occurred.

The above results show that the effects of heat loadings on stream temperatures are primarily significant during winter. Higher annual-mean and summer-period annual-mean stream temperatures tend to obscure the effects of heat loadings and result in no detectable changes at the assumed level of significance.

TABLE 7.--SUMMARY OF MANN-WHITNEY STATISTICAL TEST APPLIED TO MEAN-TIME SERIES OF STREAM TEMPERATURE AND COMPARISON WITH KENDALL'S TAU TEST STATISTIC.

Station	NYRS	Type of time series, A or W	First period Number	First period Mean	Second period Number	Second period Mean	Estimate of change	98 percent confidence interval	Corresponding Kendall's tau statistic
Hastings Dam	44	W	25	0.1	19	0.3	0.2	0.0,0.5	+0
Do.	34	W	15	0.0	19	0.3	0.3	0.0,0.5	+0
Red Wind Dam	33	W	15	0.0	19	0.3	0.3	0.2,0.4	+5
Inver Grove	44	W	23	0.3	21	1.2	1.0	0.5,1.5	+5
Do.	43	A	25	11.0	18	11.6	0.6	0.1,1.0	+0
Do.	34	W	13	0.2	21	1.2	1.1	0.5,1.5	+5
Do.	34	A	16	10.8	18	11.6	0.8	0.2,1.4	+4
St. Paul	33	W	13	0.1	20	1.3	1.2	0.5,2.0	+5
Ford Dam	45	W	30	0.2	15	0.7	0.5	0.0,1.0	+2
Do.	34	W	19	0.1	15	0.7	0.6	0.5,1.0	+5

NOTATION:

NYRS - Total number of years of record analyzed.
A or W - A = Annual mean, W = winter period (January-February)

KENDALL'S TAU STATISTIC:

0: Trend with a significance level greater than 0.20
1: Trend with a significance level equal to or less than 0.20 but greater than 0.10
2: Trend with a significance level equal to or less than 0.10 but greater than 0.05
3: Trend with a significance level equal to or less than 0.05 but greater than 0.02
4: Trend with a significance level equal to or less than 0.02 but greater than 0.01
5: Trend with a significance level equal to or less than 0.01.

Significance levels expressed above correspond to a two-tailed test applying Kendall's tau statistic. Decreasing changes are indicated by (-) and increasing are indicated (+).

DISCUSSION AND APPLICATIONS

The primary use of time-space contouring with respect to describing river-reach conditions seems to be one of demonstrating a problem (or lack of a problem) to persons unfamiliar with the spatial aspect of the river and the location of discharges. Results of the comparison between observed and computed values for the time slice and reach slice indicate the relative magnitudes of errors involved in using this estimation technique. These errors, combined with costs and timeliness of data collection, will help to determine the accuracy desired for making planning and management decisions. When critical problems occur in time or space, new continuous measuring may be useful to provide the more detailed information. This technique of space-time contouring can be used to determine those locations where new continuous measurements would be most beneficial and the time periods when measuring is most critical.

Time-trend analysis of the long-term records gave a mixed picture of significant changes in water-quality conditions for the main stem Mississippi River, depending upon the choice of indicator variable and of period of record. The total periods of record of the available data at three long-term stations reflect a prolonged period of primary treatment, with changes in treatment strategy occurring only during relatively short periods at the beginning and at the end of the record. Inclusion of more recent data may reflect the positive effects of secondary treatment at the metropolitan plant; but, in general, the only discernible effect of water-pollution control was after the start of wastewater treatment, and this was significant relative to DO only at the Ford Dam station. Seasonal (or short-term) effects are sometimes more dramatic under particular conditions, such as low flows or high temperatures. Data collection during these conditions may be more cost-effective. Seasonal variations are especially apparent and represent one example of the utility of the evaluations.

The statistical measures of the long-term records provide quantitative results, but often the results represent combined effects of more than one factor. Two opposing factors might result in a null net effect despite significant changes in the individual factors. However, given a recognized change, statistical measures provide quantification of the change and an indication of its probability of occurrence.

CONCLUSIONS

This evaluation demonstrates that infrequent (monthly) data are not particularly significant with respect to DO and BOD from a control- or operating-decision basis. Continuous measurements or intensified sampling may be more useful only during critical periods of low-flow or high-temperature conditions, when water quality is affected more appreciably by pollution-control strategies, such as bypassing certain levels of wastewater treatment. Continuous measurements may be warranted only at critical stream sections during critical periods. Periodic sampling, along with the techniques discussed in this report, could provide a basis for making decisions regarding sampling locations and operation of more frequent measurement schedules.

The evaluation also demonstrates the insensitivity of the stream system to many external forces. The physical size (in terms of flow volume) of the upper Mississippi River in the study area is such that changes in pollution-control strategies for most waste dischargers have no observable effect with respect to water-quality measurements; and only the loads from major waste sources, or the cumulative effect over time of loads from many sources, is significant.

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