University of Minnesota
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OBSERVATIONS OF COOLING WATER DISCHARGE EFFECTS ON ICE COVERS AND DISSOLVED OXYGEN LEVELS IN SELECTED MINNESOTA STREAMS AND LAKES

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I. INTRODUCTION

The impact of cooling water discharges from power generating plants on aquatic environments is usually evaluated and documented for summer conditions. Only a very few studies have dealt with the modification of winter conditions in rivers and lakes by thermal additions. This reflects the defensive approach toward the evaluation of heat addition to streams, rivers, lakes, and estuaries. Preoccupation with the negative effects of heat addition has been so pervasive that the possible benefits from heat addition to streams and lakes in cold regions have been vastly ignored. A number of symposia, including those listed in Table 1, have dealt with rivers and ice, but they usually have not dealt with thermal effluents.

Table 1. -- SYMPOSIA AND CONFERENCES DEALING WITH WINTER CONDITIONS

Univ. of Alaska/ FWQA	International Symposium on Water Pollution Control in Cold Climates, Fairbanks, Alaska, July 1970 (Water Pollution Control Research Series, 16100 EXH 11/71).
IAHR	Symposium on Ice and Its Action on Hydraulic Structures, Reykjavik, Iceland, September 1970, International Association for Hydraulic Research.
Canadian Soc. of Civil Engrs.	Proceedings, First Canadian Hydraulics Conference, Edmonton, May 1973, Univ. of Alberta, Dept. of Extension and Water Resources Centre.
US/IHD	Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Monterey, California, December 1973.
IAHR/PIANC	River and Ice Symposium, Budapest, Hungary, January 1974, International Association for Hydraulic Research.

The Cold Regions Research and Engineering Laboratory of the U.S. Army Corps of Engineers and some Canadian investigators have studied thermal effluent effects on ice cover and water quality to some degree; research on the subject has also been conducted at the Iowa Institute for Hydraulic Research. This work will be referenced where appropriate.

Considerations which center exclusively on "minimal damage" near cooling water outfalls emphasize the detrimental effects of heat on water and ecology. A more positive look at "waste heat" as "energy input" into surface waters in regions with significant cold seasons seems appropriate. In this report, observations made during the winter of 1973-74 and information collected previously in Minnesota surface waters are presented. The findings support the concept of hibernal beneficial effects of cooling water effluents upon water quality, navigation, and maintenance of structures. The study also highlights some possibilities for future winter uses of cooling water in river and lake management. The study has not yet been concluded, as field observations and qualitative interpretations must be expanded into an analytical quantitative analysis.

II. SCOPE OF INVESTIGATION

The objective of the study was to make field observations and a first evaluation of the effects of cooling water discharges on winter conditions in rivers and lakes with emphasis on Minnesota conditions and on actual and potential beneficial effects.

Before the details of the study are presented, the term "beneficial" as used above must be discussed. Thermal discharges from power plants alter natural conditions in portions of the receiving surface waters. Whether such alterations are classified as "beneficial" or "detrimental" depends on the value attributed to certain water characteristics. Water quality criteria and standards are generally defined according to the proposed water usage. Different water uses--domestic water supply, recreation, industrial water supply, navigation, irrigation, etc.--are generally identified. Thermal discharges affect water quality. If they impair water quality for the specified use(s), discharges are classified as pollutants. It follows that if water quality is enhanced with respect to desired use, the effect of the thermal discharge should be considered beneficial. Potential or actual beneficial effects would therefore be those effects which were favorable with regard to the use made of a specific recipient water body. On this basis the following potential beneficial effects of cooling water discharges on surface waters in cold climates can be identified:

1. Facilitation of navigation and prolongation of navigation season by retardation of freeze-over and acceleration of thawing.
2. Enrichment in dissolved oxygen through increased surface aeration and weir aeration at the discharge points, resulting in buffering against oxygen depletion caused primarily by the decomposition of organic materials.
3. Increase in water circulation and mixing of otherwise nearly stagnant water bodies by sinking plumes and wind acting on open water surfaces.

4. Reduction or prevention of ice damage to structures--e.g., bridge piers, stormwater outlets, navigation facilities, and river embankments.

Information on all the above points was obtained in the course of the study described herein.

It should be pointed out that the above is by no means a complete list. There are other, even more obvious potential beneficial effects of cooling water discharges, including

1. Provision of habitat for wildlife, particularly waterfowl.
2. Prevention of the oxygen depletion which results in winter kill of fish.
3. Prolongation of the warm water season, resulting in higher recreational potential, growth of fish populations, etc.

Examples of the last three points can be found in Rochester, Fox Lake, and Colby Lake, respectively. Fish and wildlife experts may conduct further studies on these questions.

III. METHODS OF INVESTIGATION

Investigations were conducted not only in the vicinity of 14 major power plants, but also on stream reaches far beyond the plants for two reasons:

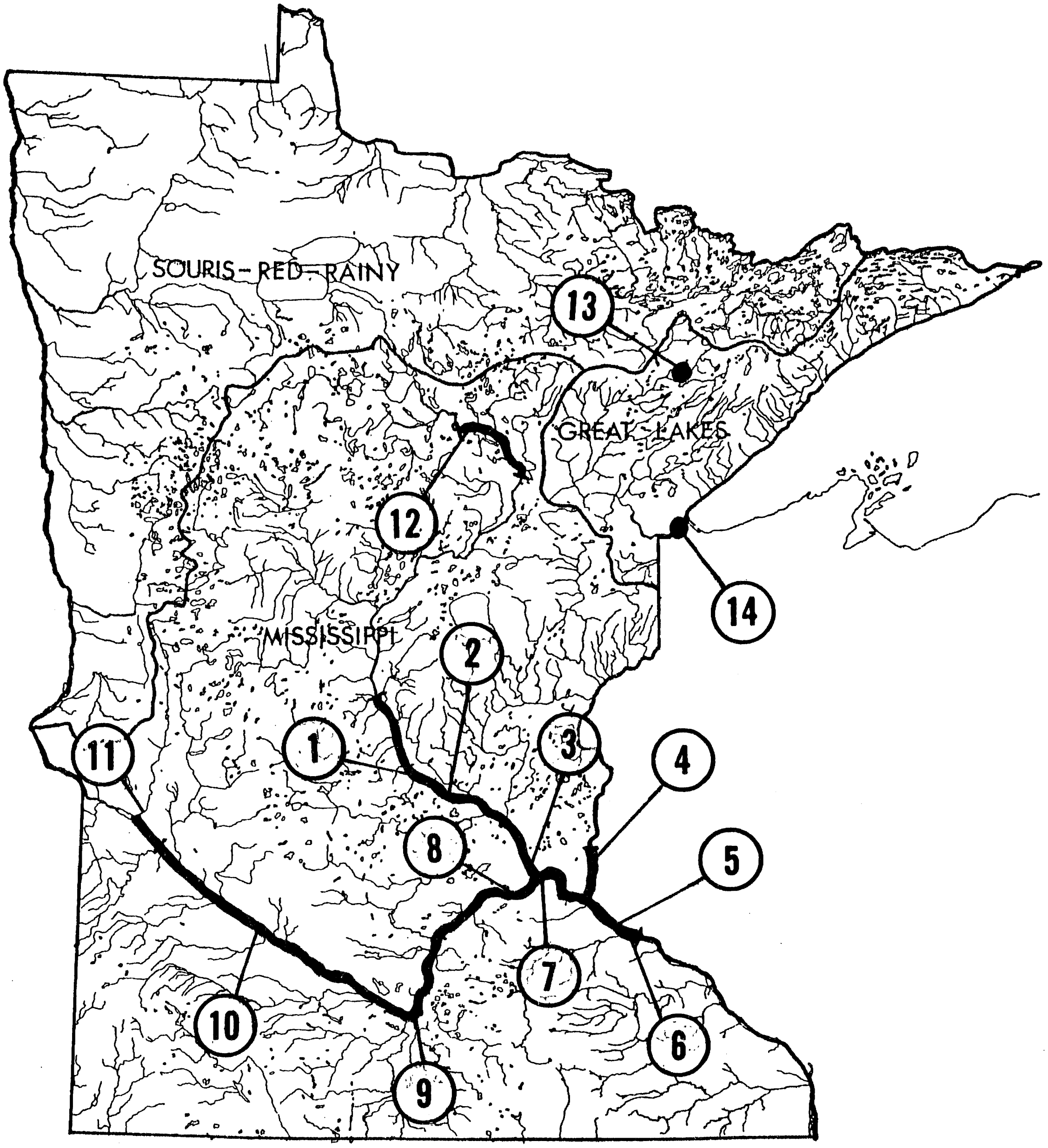
1. The reach of influence of cooling water discharges can be quite long, on the order of miles; and
2. To establish a base for comparison, conditions in areas unaffected by cooling water had to be determined.

Because the overall scope of the study was broad, a large area had to be covered, and only one winter season was available for the study, it was decided that the study objective would best be served by acquisition of the following kinds of information:

1. Samples of ice coverage upstream and downstream from as many power plants as possible.
2. Temporal variation of ice coverage upstream and downstream from power plants located near the Minneapolis-St. Paul metropolitan area during the 1973-74 winter.
3. Samples of dissolved oxygen (D.O.) contents along river reaches, with emphasis on those at power plants, dams, etc.
4. Historical data on ice formation and ice break-up dates, ice jams, ice damage, etc.
5. Water quality data available from other sources for winter periods, e.g., for the Mississippi River.

This selection proved to be practical and useful. Of course, further improvements and additions to the data base are still desirable. However, what is available provides a first assessment of when, where, and what effects of cooling water discharges can be expected.

Extent of ice cover, ice thickness, and dissolved oxygen were measured on several field trips to different streams and plant sites; their locations are shown in Fig. 1. For reference, conditions unaffected by cooling water discharges were investigated as well as those found



KEY

1	Whitney (St. Cloud)	8	Black Dog
2	Monticello	9	Wilmarth (Mankato)
3	Riverside	10	Granite Falls
4	Allen King	11	Appleton
5	Prairie Island	12	Clay Boswell (Cohasset)
6	Red Wing	13	Colby Lake (Aurora)
7	High Bridge	14	Hibbard (Duluth)

Fig. 1 - Locations of Streams and Lake Sites Investigated

downstream from power plants. The extent of ice cover was documented by photographs taken from bridges, high banks, and small aircraft. Ice thickness and dissolved oxygen were measured by local sampling. Water samples were taken through the ice cover or from bridges using a standard sampler and standard BOD bottles. The samples were analyzed indoors using a Yellow Springs Instr. Co. Oxygen Meter No. 54 and a self-stirring BOD probe. Before analysis, samples were stored and transported in an icebath (cooler). This technique is identical to the one used by Schroepfer, Susag, et al. (1965)* in studies on the Mississippi River for the Metropolitan Sewer Board. Appendix A gives a listing of the stations and dates on which D.O. measurements were made. Ice thicknesses were also recorded at several of these sites. Appendix B gives a listing of the river reaches and dates on which ice coverage was surveyed photographically. These surveys covered the following power plants: Whitney (St. Cloud), Monticello, Riverside, High Bridge, Prairie Island, and Red Wing on the Mississippi River; Appleton, Granite Falls, Wilmarth (Mankato), and Black Dog on the Minnesota River; C. Boswell at Cohasset; Colby Lake near Aurora; and the Hibbard plant in the Duluth harbor.

The secondary data retrieval involved searches through records of the U.S. Army Corps of Engineers (St. Paul district), the U.S. Geological Survey (St. Paul District), Northern States Power Company, the Environmental Science Services Administration (NOAA), and the Minneapolis Public Library. Data on ice formation and break-up dates, plant load and effluent temperatures, ice thicknesses, and ice damage were of interest. The data analysis, which involved plotting and interpretation of the data, will be described in the following sections.

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*References are listed alphabetically on pages 84 and 85.

IV. OBSERVED ICE COVERS AND THEIR RELATIONSHIP TO COOLING WATER DISCHARGES

1. Data Collection - Field Surveys

Information on ice coverage during the 1973-74 winter was obtained from photographs taken (a) on field trips, (b) from small aircraft, and (c) from the ERTS 1 satellite. Ground surveys provided detailed information on local forms and textures of ice covers. Only short river reaches could be surveyed in a single day. Aerial inspection and photography gave information over larger areas during periods of only a few hours. Pictorial details were usually quite clear and useful for interpretation. The most synoptic coverage was found in the images taken by ERTS 1, which passed over the area of interest at 18-day intervals. Ice covers were surveyed in the regions delineated by a wide dark line in Fig. 1.

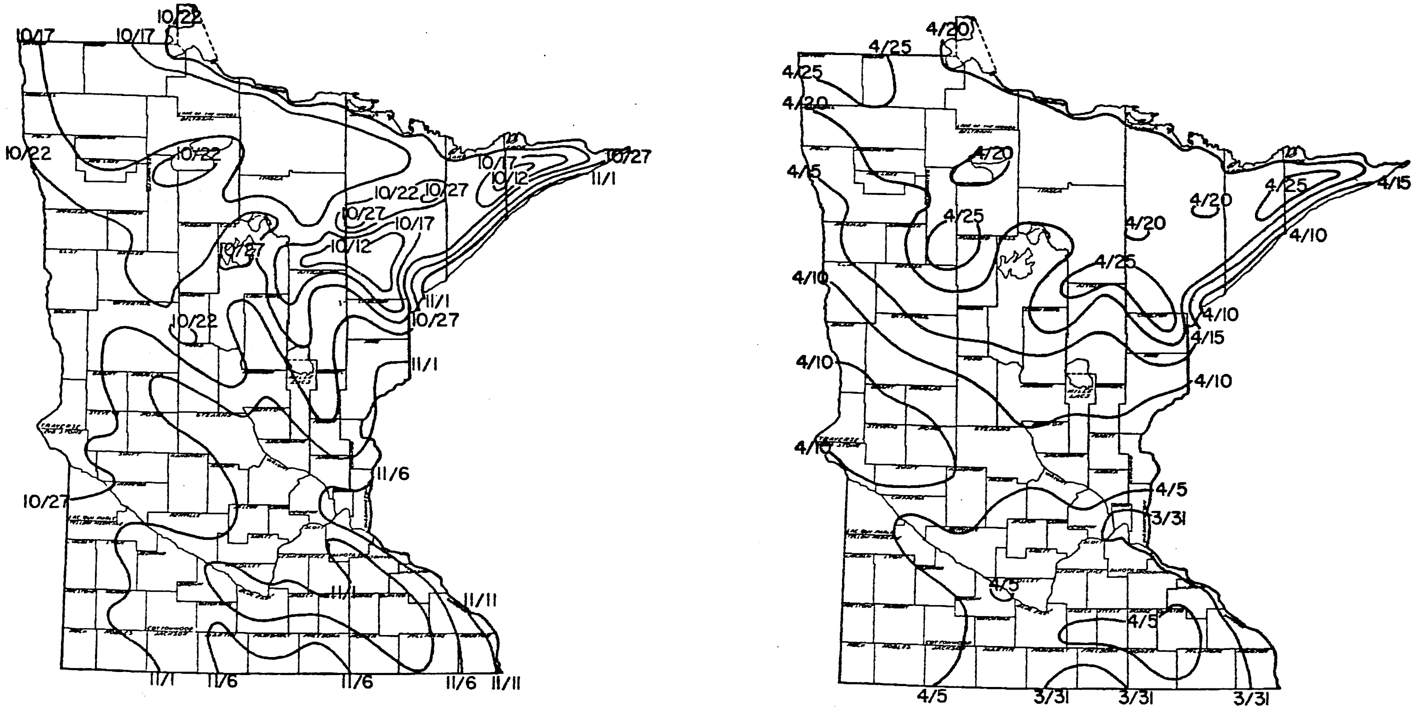
2. Natural Ice Coverage

Under natural conditions the vast majority of Minnesota streams, rivers, and lakes freeze over during the winter. There are a very few exceptions, such as Lake Superior and reaches of fast-flowing streams, which do not always freeze over completely. There are apparently no continuous records of significant length which give periods of ice coverage for streams or lakes in Minnesota. Some fragmentary information for the Mississippi River was found in publications by Schroepfer, et al. (1965) and Ashton (1974), but these were not representative of natural conditions. The U.S. Army Corps of Engineers, St. Paul District, also has some data indicative of the approximate length of the winter season on the Mississippi River. Great Lakes ice covers are published annually by the National Oceanic and Atmospheric Administration's Lake Survey Center in Detroit, Michigan. They indicate that Lake Superior does not usually freeze over completely until February and that it opens in late April.

The period of ice coverage depends, of course, on heat exchange processes between the water in a river or lake and its surroundings, primarily the atmosphere and the soil; deep bodies of water store more heat during the summer and fall and therefore freeze over later than shallow ones. Ice covers on lakes generally last longer than those on rivers and streams. There are not enough water temperature records available to specify the period of ice cover in terms of water temperatures in Minnesota. However, air temperatures are available and have been analyzed by Baker and Strub (1963). Although that study was not related to water temperatures, it is nevertheless of interest to examine the maps reproduced in Fig. 2, which show average commencement dates of winter and early spring from an agricultural viewpoint. There is some indication that the fall dates shown are approximately three weeks before the natural freeze-over and the spring dates are within two weeks of the natural opening of shallow bodies of water, with lakes showing more of a lag. As an additional reference, a study of soil temperatures at St. Paul by Baker (1971) showed that for a period of eight winters--1961-62 through 1968-69--the soil surface was frozen from December 2 through March 16 with a fluctuation of no more than ± 7 days around those dates.

Summarizing all available information, a crude average estimate of the period of natural ice coverage of Minnesota waters can be made as follows: The period of natural ice coverage on the majority of surface waters lasts from approximately December through March in the south (four months) and from approximately November through April (six months) in the far north. With increasing depth of the body of water, the date of the freeze-over is delayed and the period of ice coverage is correspondingly shorter. (Lake Superior, for example, may freeze over in late February and open in April.) Running waters often have a period of ice coverage several weeks shorter than that of standing waters. A delay in the freeze-over or--more frequently--an earlier break-up of the ice cover on running waters accounts for the difference, which can amount to several weeks. For future reference in this study, a set of daily air temperatures recorded at the Minneapolis-St. Paul International Airport weather station for the winter of 1973-74 during which this study was made is given in Fig. 3.

Figures 4 through 9 are photographs of natural ice coverage observed in the course of this study. The completeness of the ice coverage over vast areas of both lakes and rivers needs to be emphasized.



Average commencement date of winter — date on which more than 20 percent of the minimum temperatures are 16° F. or lower. In winter crop plants are dormant.

Average commencement date of early spring — date on which 20 percent or less of the minimum temperatures are 16° F. or lower. In early spring cool season perennial crops, such as bluegrass, begin to grow, and cool season annuals, such as spring oats, are planted.

Fig. 2 - Average Commencement Dates of Winter and Early Spring from an Agricultural Viewpoint

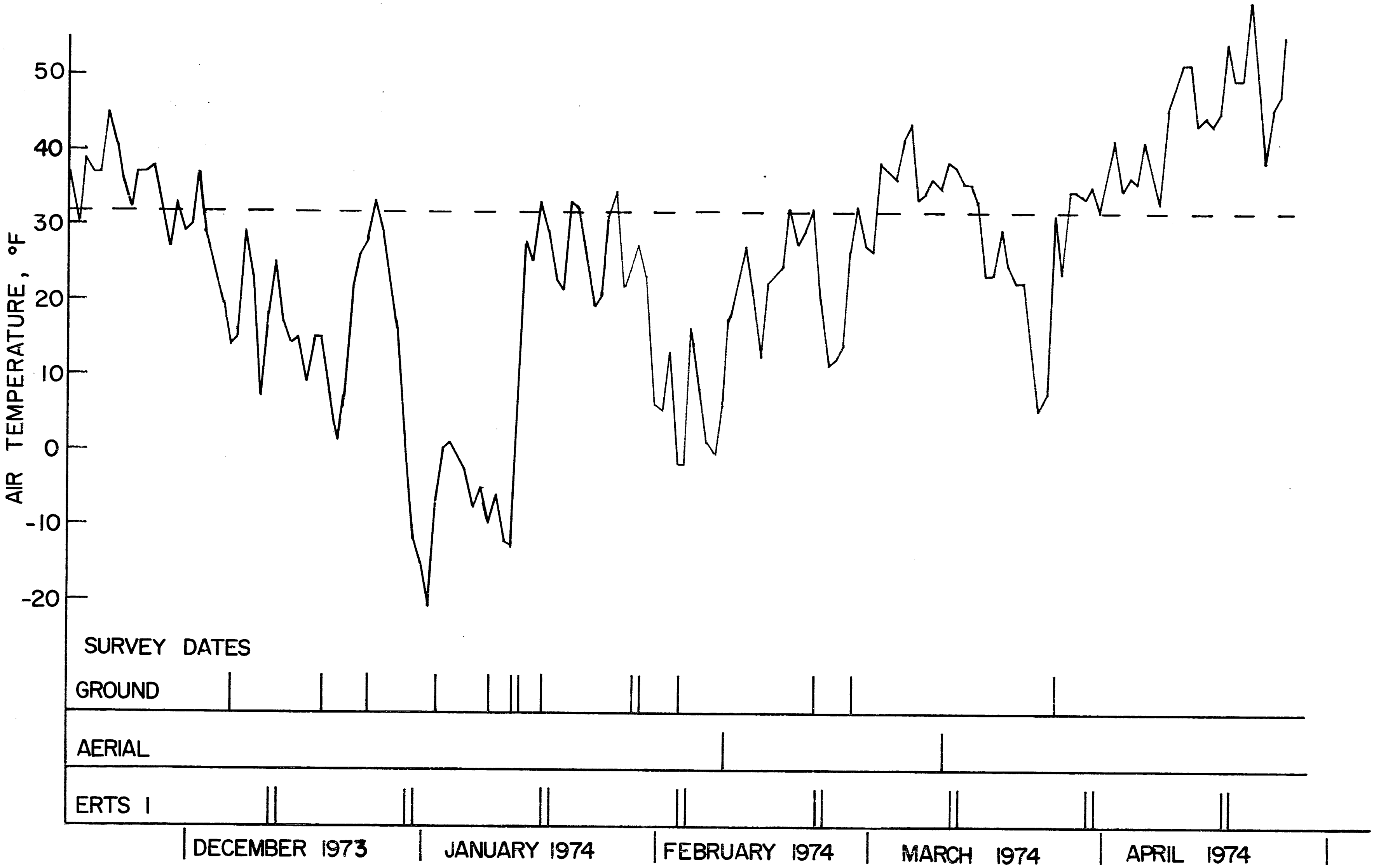


Fig. 3 - Air Temperatures, Minneapolis-St. Paul WSO

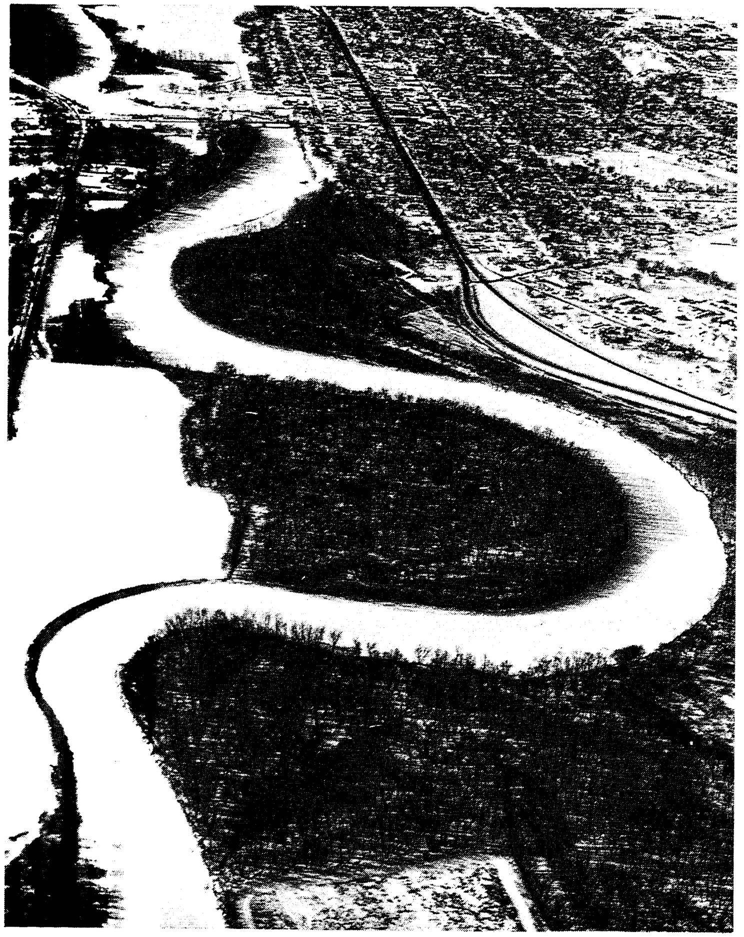


Fig. 4 - Aerial View of Minnesota River Looking Upstream at St. Peter - February 16, 1974

Fig. 5 - Aerial View of Mississippi River Upstream of Sartell, Minnesota - March 10, 1974

Fig. 6 - Ice Cover on Minnesota River near Judson -
February 23, 1974

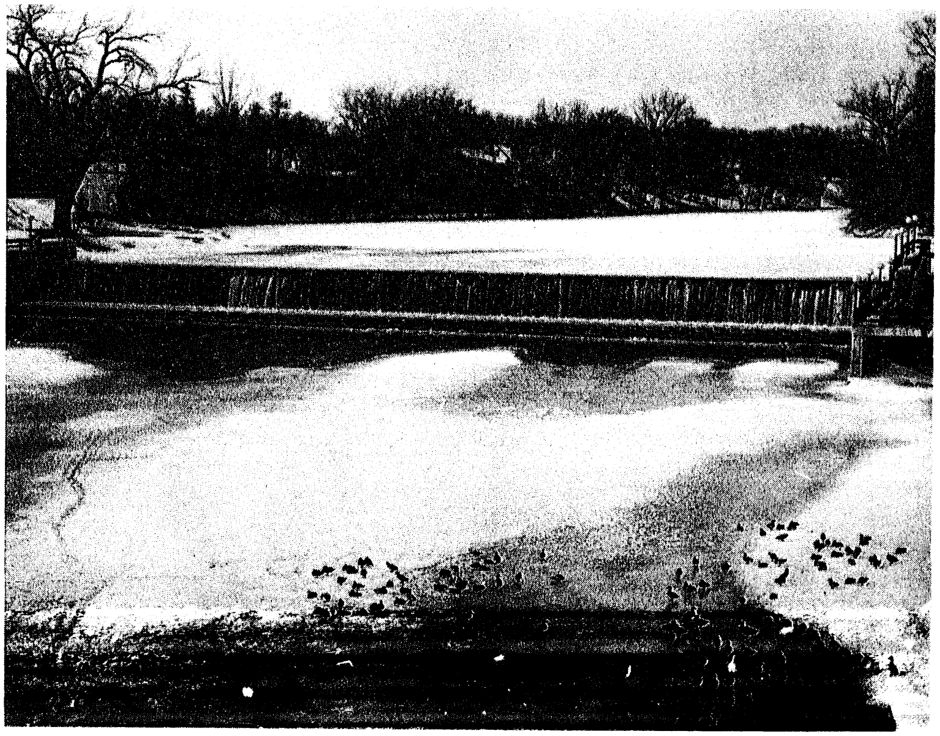


Fig. 7 - Rum River at Anoka - February 26, 1974

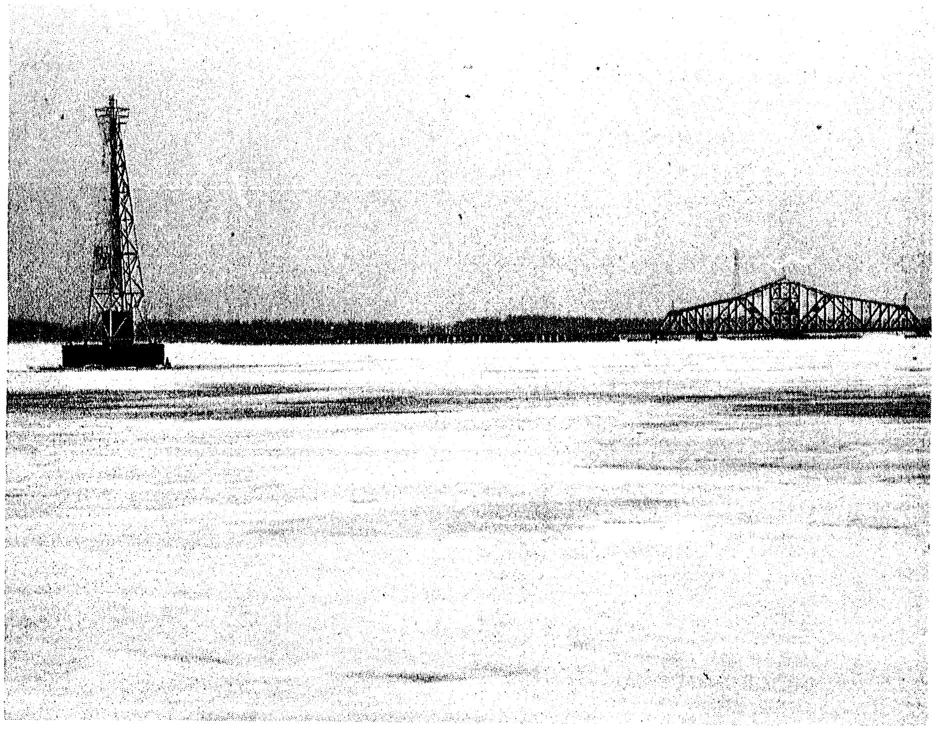


Fig. 8 - Ice Cover on Duluth Harbor Looking Upstream toward St. Louis River - March 3, 1974

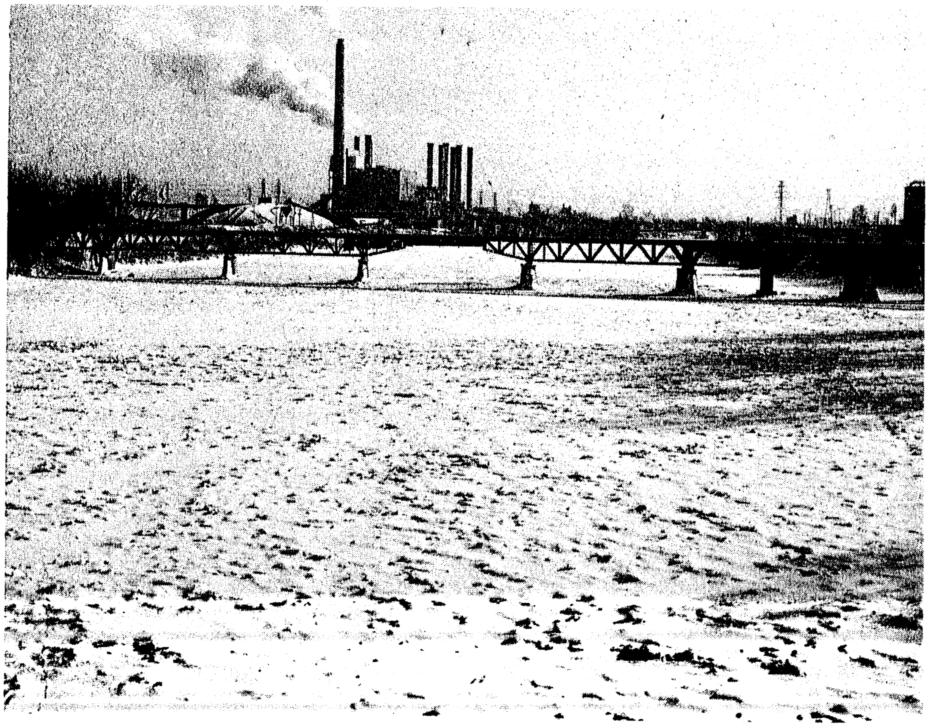


Fig. 9 - Ice Cover on Mississippi River Looking Downstream toward Riverside Plant - January 2, 1974

Significant annual variations exist in the date of freeze-over of or ice break-up on lakes as exemplified by the record given in Table 2.

Table 2. -- DATES OF SPRING ICE BREAK-UP (ICE DISAPPEARANCE) ON LAKE JOHANNA (Minneapolis-St. Paul; surface area 0.87 sq km, mean depth 5.8 m)

Year	1963	1964	1966	1968	1969	1970	1971	1972	1973	1974
Date	4/3	4/12	3/22	3/29	4/13	4/15	4/15	4/21	4/30	4/18

Repeated freezing and melting of ice covers in fall and spring is not uncommon, as is shown by Bilello (1967) for a northern Michigan lake. During the spring of 1974 a period of cold weather in the latter part of March (see Fig. 3) resulted in a refreezing of the Mississippi River in north Minneapolis and above. Warmer weather setting in afterwards caused the ice cover to disappear within four days. The ice cover on the city lakes was then still intact.

3. Ice Coverage near Cooling Water Effluent Sites

a. Near Field and Far Field - Definitions.--Extensive surveys were conducted at numerous sites on a number of dates as shown in Appendix B. The relationship between survey dates and weather conditions is apparent in Fig. 3. Although only a small fraction of the photographic materials collected will be presented for illustrative purposes, the summaries and conclusions will be founded on all the observations made. For the purpose of the presentation we will differentiate between near field and far field observations.

The near field is the flow region in the vicinity of the outfall, where significant mixing between discharged and ambient water occurs and the flow is still perceptibly dependent on the outfall geometry and velocity. A near field region may typically be on the order of 1000 ft long.

The far field is the region in which local temperature gradients have become very small and the observed flow and mixing patterns are those controlled by the river or lake itself rather than by the outfall. Typically, a far field region of a major power plant is on the order of several miles long.

b. Near Field.--Because the near field depends strongly on the type of outfall (channel, mid-stream pipe, onshore pipe, etc.), ice coverage in the near field varies a great deal from one plant to another. Examples are given in Figs. 10 through 13.

Two significantly different modes of behavior of the effluent cooling water plume can be identified. One is as an "open water plume," which means that downstream of the outfall an open-water region of usually increasing dimensions develops, often resulting in a nearly ice-free river. Examples are shown in Figs. 10 and 11. The warm water discharged from the outlet is being mixed into the river water, which results eventually in a very homogeneous temperature over major portions of a river cross section.

A "sinking plume" forms in winter when the cooling water discharge is into a relatively quiescent lake or river. Examples are shown in Figs. 12 and 13. Because water has its greatest specific weight at a temperature of 39.2°F and is slightly lighter at temperatures above and below 39.2°F, water in the temperature range $32^\circ < T < 46.8^\circ F$ will have a tendency to "fall" when brought in contact with ambient water of 32°F temperature unless a turbulent flow process keeps it suspended. A warm water discharge from an outlet into sufficiently quiescent 32°F water will therefore sink, usually after some initial jet-type mixing. The process is shown schematically in Figs. 14 and 15.

c. Far Field.--The far field of a cooling water plume may extend downstream from an outfall for many miles. It usually ends when the excess heat carried by the water has been dissipated to the atmosphere and the water temperature has returned to 32°F. Photographs of portions of the far fields of ten major power plants are shown in Figs. 16 through 36. They show the significant open water areas produced by cooling water discharges.

d. Observed Sinking Plumes.--The existence of a "sinking" plume at the A. S. King site and others had been documented previously. Sinking plumes were also found at several other sites. It should be emphasized that the sinking plume phenomenon depends very much on ambient current velocities and temperatures and very little on outfall design. In fact,

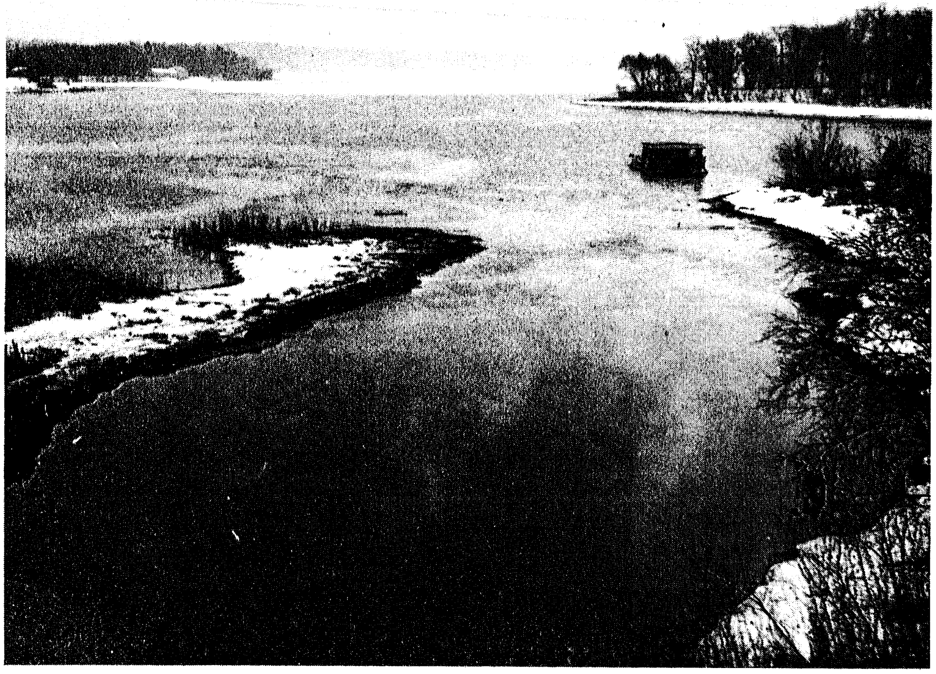


Fig. 10 - Outfall of Clay Boswell Power Plant into Mississippi River - March 2, 1974

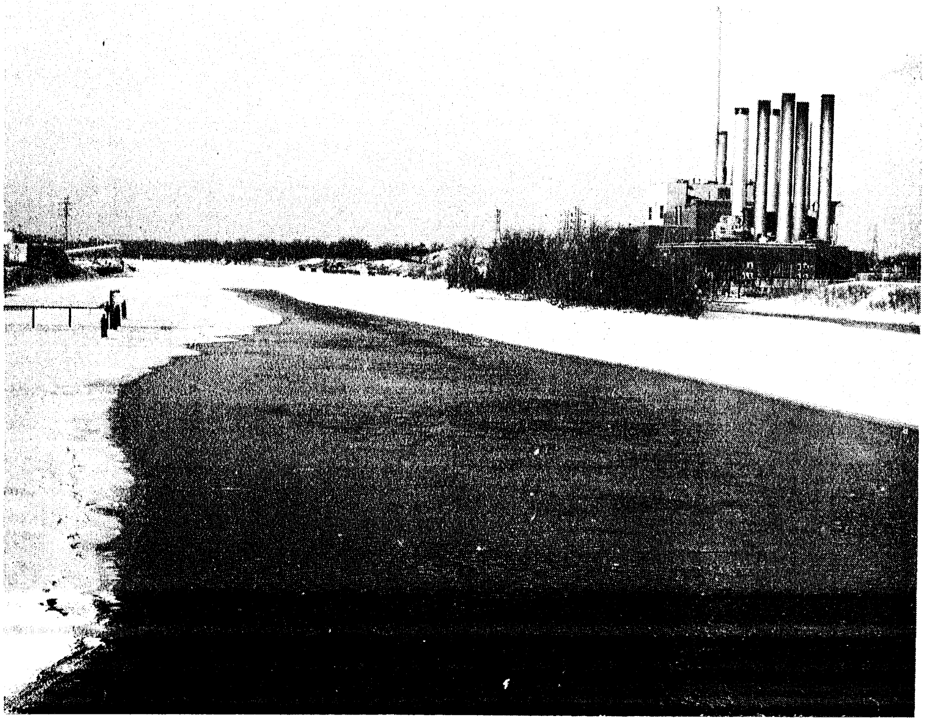


Fig. 11 - Open Water in Mississippi River below Riverside Plant - January 2, 1974

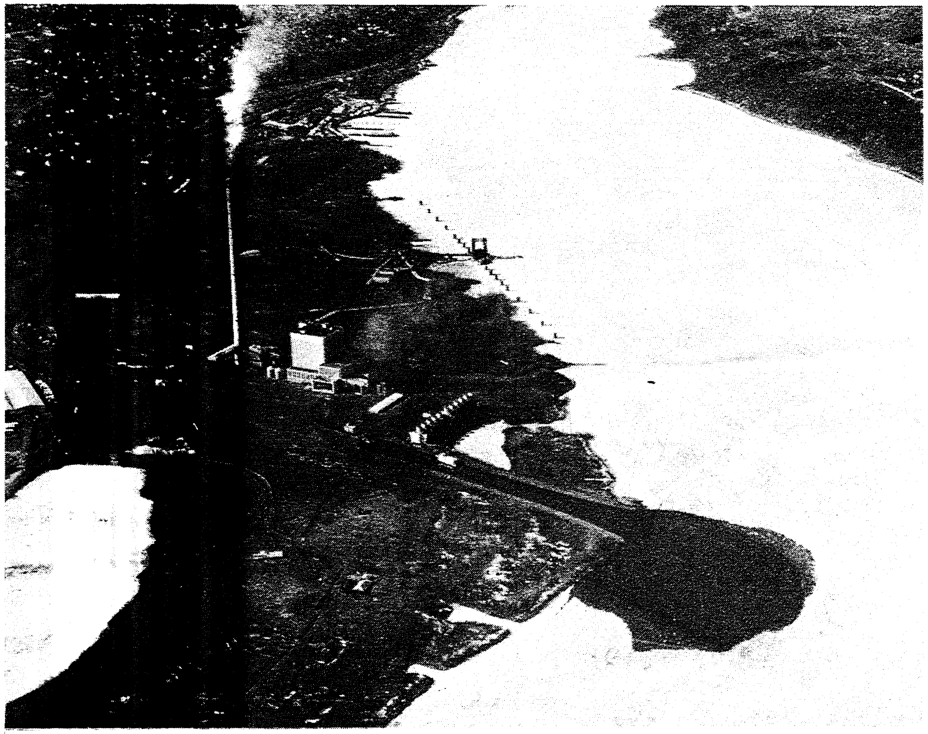


Fig. 12 - Aerial View of Outfall and Open Water at Allen S. King Plant on Lake St. Croix - March 10, 1974

Fig. 13 - Aerial View of Open Water in Minnesota River at Granite Falls Power Plant - February 16, 1974

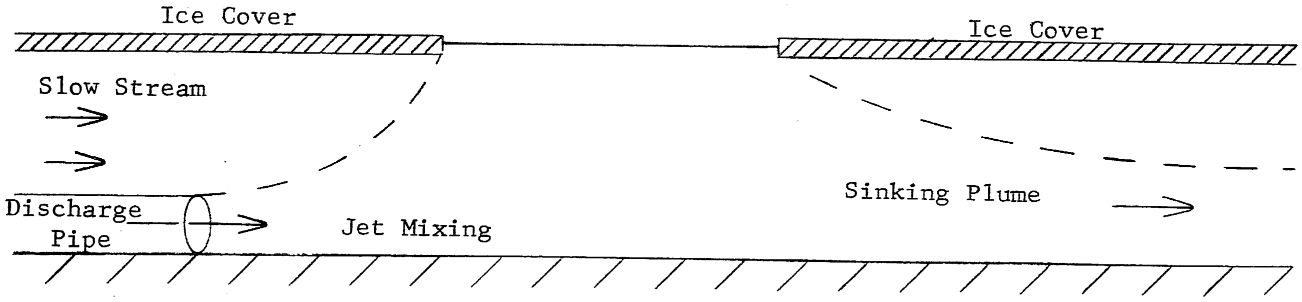


Fig. 14 - Schematic Representation of Sinking Plume in a Slowly Flowing Stream

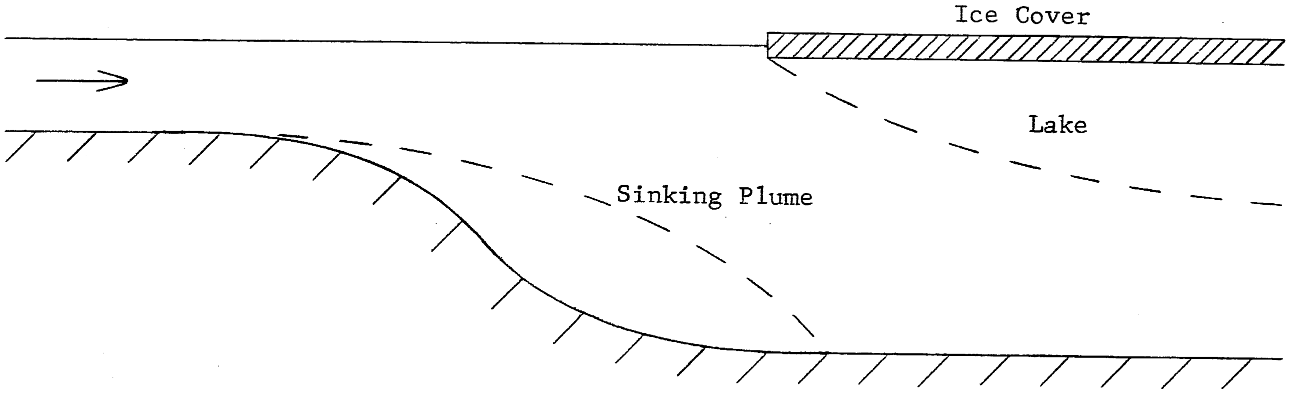


Fig. 15 - Schematic Representation of Sinking Plume in a Lake

Fig. 16 - View of Open Water near Outfall of Hibbard Plant at Duluth - March 3, 1974

Fig. 17 - View Looking across Colby Lake from Beach Area toward Power Plant - March 2, 1974

Fig. 18 - Open Water in Mississippi River at Cohasset Looking Upstream toward Clay Boswell Plant - March 1, 1974

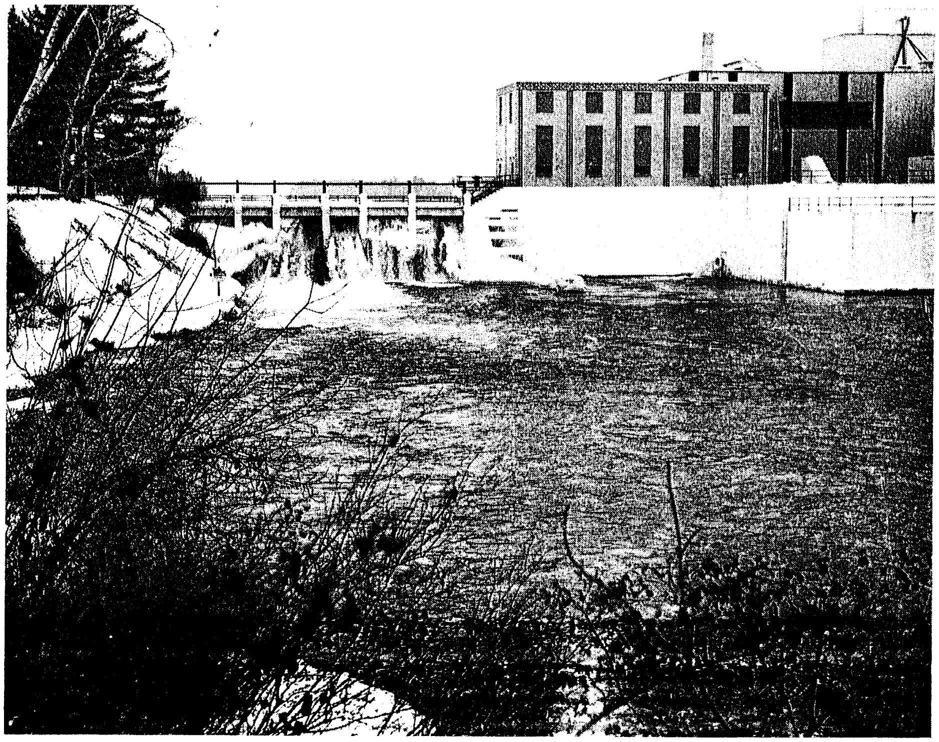


Fig. 19 - Dam on Mississippi River at Blandin Paper Mill in Grand Rapids - March 2, 1974

Fig. 20 - Mississippi River Two Miles Downstream of Grand Rapids - March 1, 1974

Fig. 21 - Aerial View of Mississippi River Looking Upstream toward Elk River - March 10, 1974

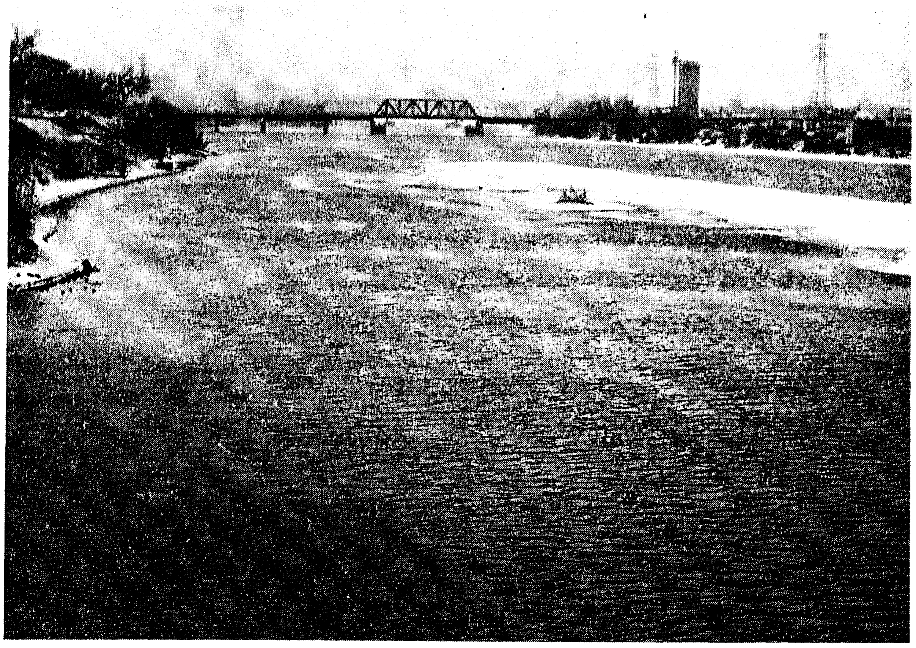


Fig. 22 - Looking Downstream at Mississippi River from Lowry Avenue Bridge toward Downtown Minneapolis - January 29, 1974

Fig. 23 - Isolated Open Patches of Water on Mississippi River Looking Upstream from Franklin Avenue Bridge toward University of Minnesota Campus - January 2, 1974

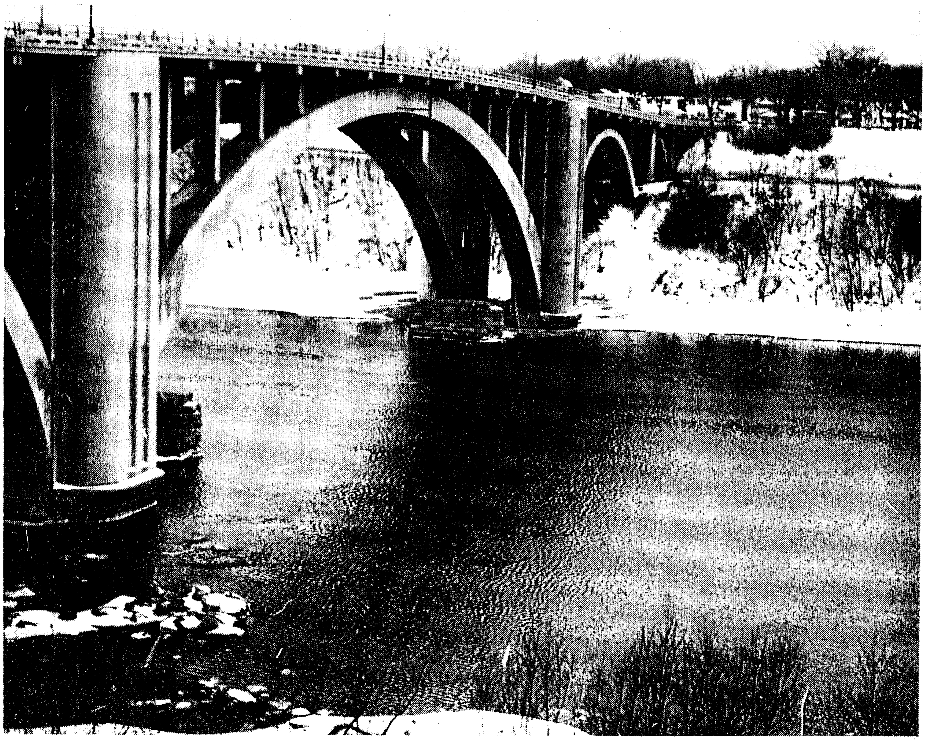


Fig. 24 - Open Water in Mississippi River under Franklin Avenue Bridge - February 21, 1974

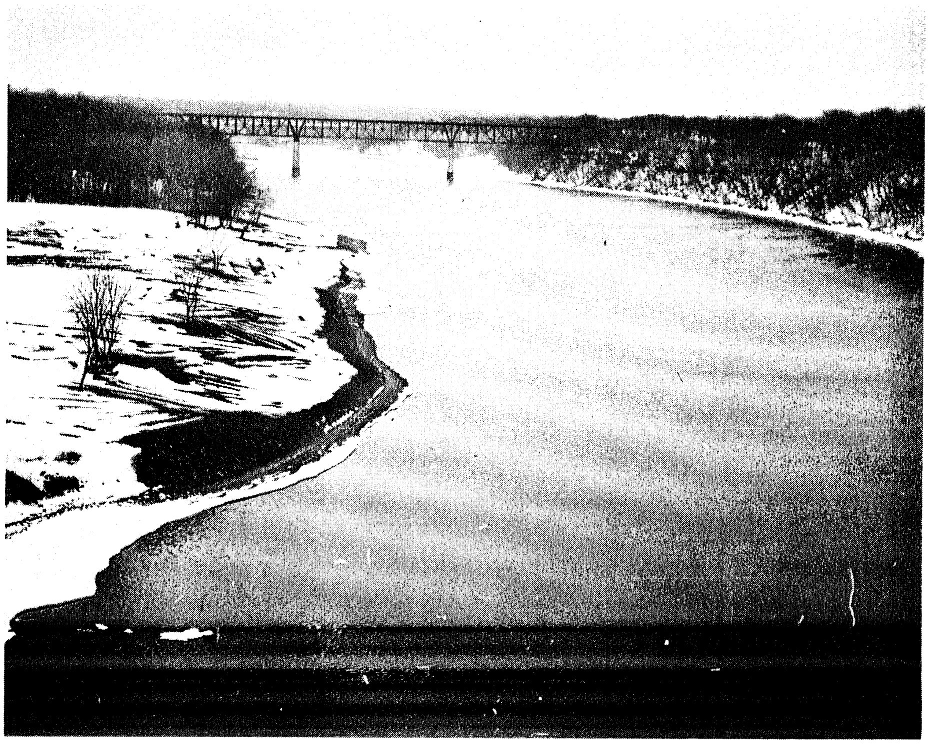


Fig. 25 - Mississippi River Looking Downstream from Franklin Avenue Bridge - February 21, 1974

Fig. 26 - View of Mississippi River near Lake Street
Bridge - February 21, 1974

Fig. 27 - Looking Upstream at Mississippi River toward
Ford Dam - February 21, 1974

Fig. 28 - Aerial View of Open Water on Minnesota River below Granite Falls - February 16, 1974

Fig. 29 - Aerial View of Minnesota River Looking Downstream from Wilmarth Power Plant at Mankato - February 16, 1974

Fig. 30 - Looking Upstream at Minnesota River approximately Two Miles below Wilmarth Power Plant - February 23, 1974

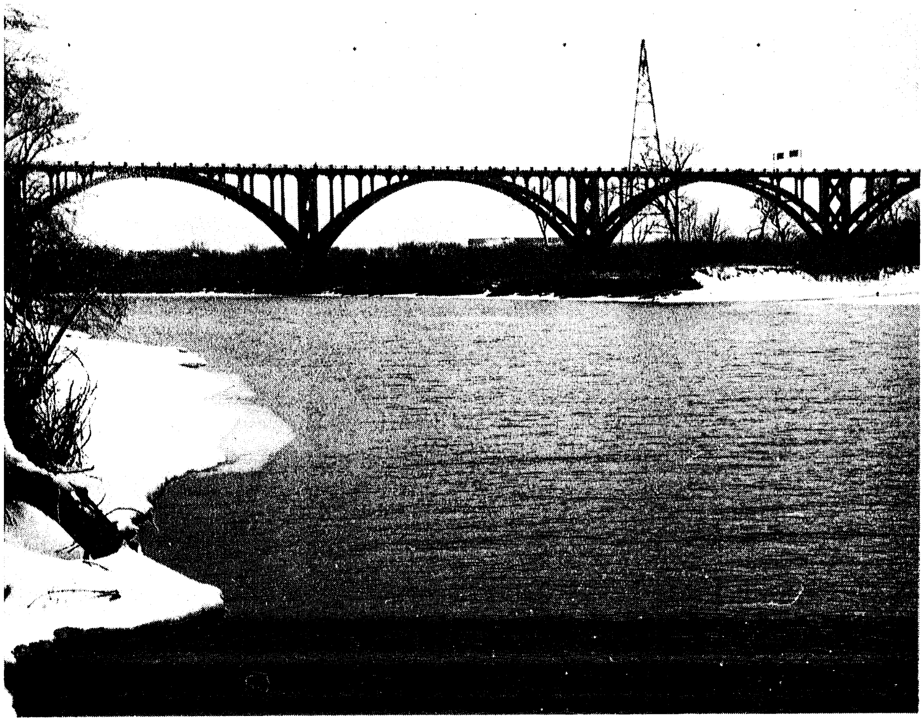


Fig. 31 - View of Minnesota River Looking Upstream toward Mendota Bridge - February 21, 1974

Fig. 32 - View of Mississippi River Looking Downstream from High Bridge toward Downtown St. Paul - January 2, 1974

Fig. 33 - Mississippi River Looking Downstream from Robert Street Bridge in St. Paul - January 2, 1974

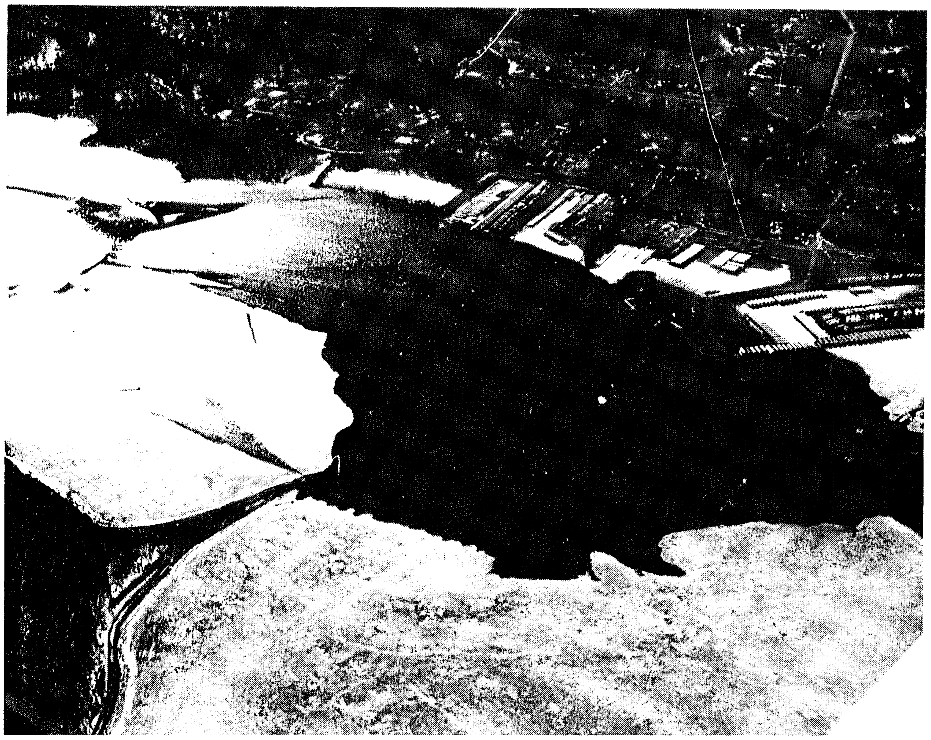


Fig. 34 - Aerial View of St. Croix River near St. Mary's Point - March 10, 1974

Fig. 35 - Aerial View of Junction of Mississippi and St. Croix Rivers at Prescott, Wisconsin - March 10, 1974

Fig. 36 - Mississippi River Looking Upstream from St. Paul Park - January 12, 1974

as a result of changes in ambient water temperatures, open-water plumes and sinking plumes can form at the same outfall at different times.

As a result of sinking plumes, water temperature inversions form in the water. The warmer water temperatures on the bottom are near 39°F and may have potentially beneficial effects on benthic organisms. It appears that the effects of sinking plumes on organisms have not received much attention in the past.

At several sites at which a sinking plume was seen, vertical temperature profiles were also measured. Results of such measurements are reported in Figs. 37, 38, and 39. At the A. S. King plant on Lake St. Croix the temperature stratification is very obvious. The sinking plume forms a pool of 37° to 39°F water near the bottom of Lake St. Croix. This has been shown by water temperature measurements taken during several winters: in January 1969 by Krosch (1970), from January through February 1972 by Hayes and Stefan (1972), and in January 1974 as shown in Fig. 37.

The open-water area at the outfall of the A. S. King plant in January is typically on the order of 600 ft (180 m) long and 300 ft (90 m) wide, covering approximately 140,000 sq ft (three acres or 13,000 sq m). It generally forms with the onset of the ice cover in December and lasts until late March or April. Ice thicknesses surrounding the hole have been found by NSP (1970) to range from 6 to 16 inches, with a mean of 11.5 inches, indicating that the sinking of the plume at the edge of the open-water area must be quite rapid. The warmer water in the St. Croix resurfaces at four different locations downstream where the lake becomes narrow and shallow. One of the locations is shown in Fig. 34. A marina is located in the area. The final emergence is at Prescott, where the St. Croix River flows into the Mississippi.

A similar situation which exists in the Duluth harbor at the Hibbard plant is shown in Fig. 38. The cooling water is discharged into a shallow bay of 4 to 5 ft depth. An open-water area covering an estimated 0.2 sq mi forms in the bay. Heat is dissipated to the atmosphere through the free surface. About 2500 ft from the outlet the cooling water sinks into a trench approximately 18 ft deep and follows it out into the navigation

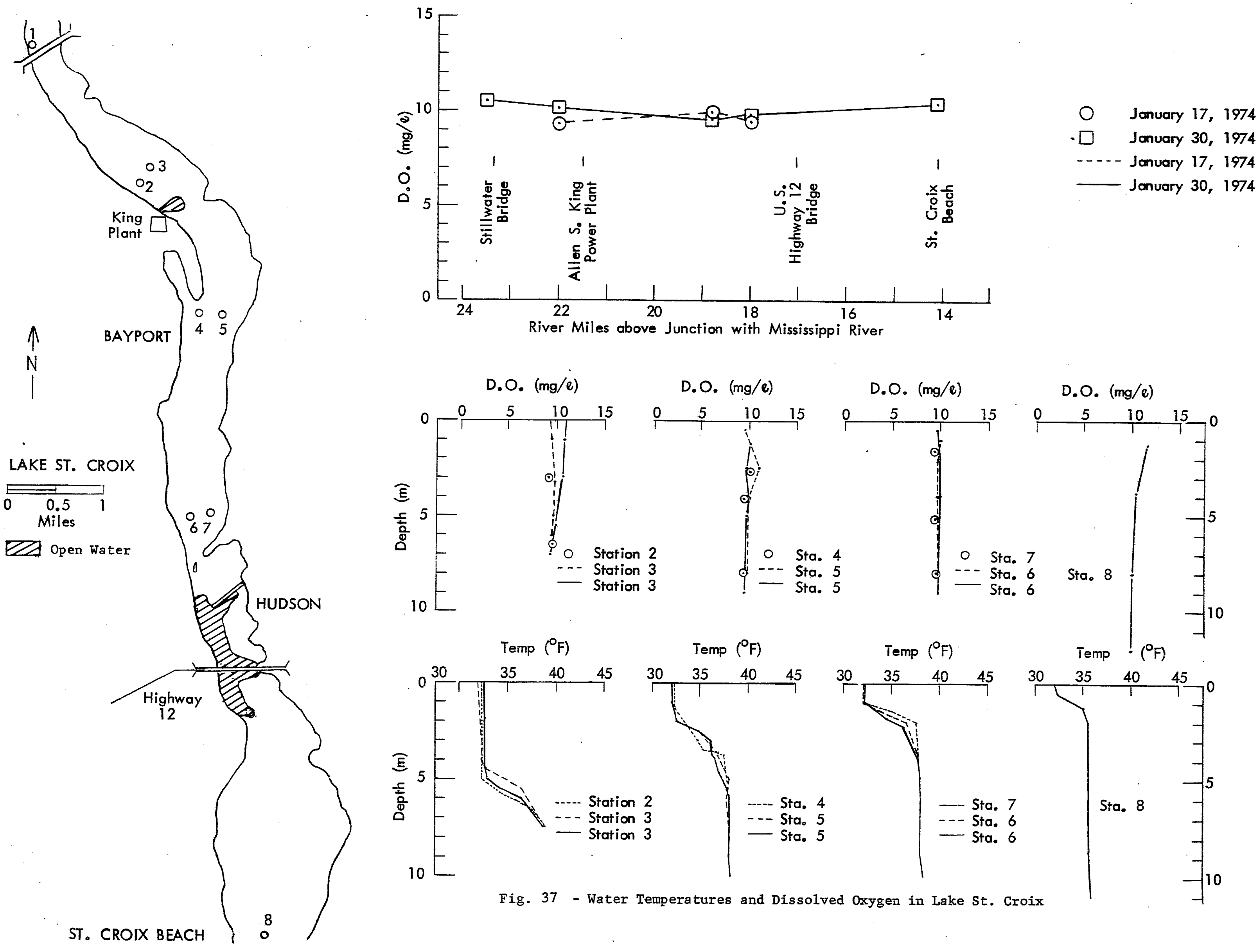
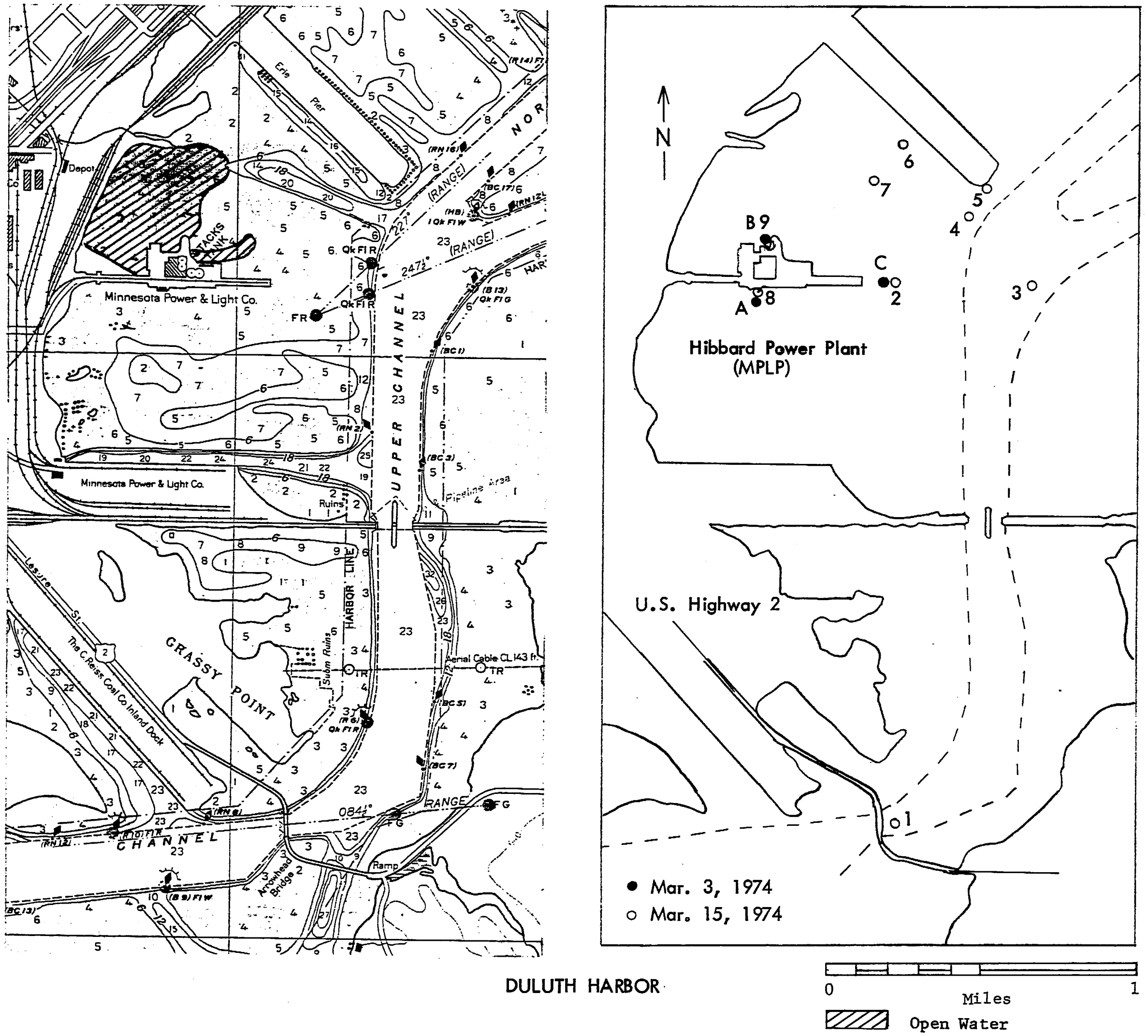
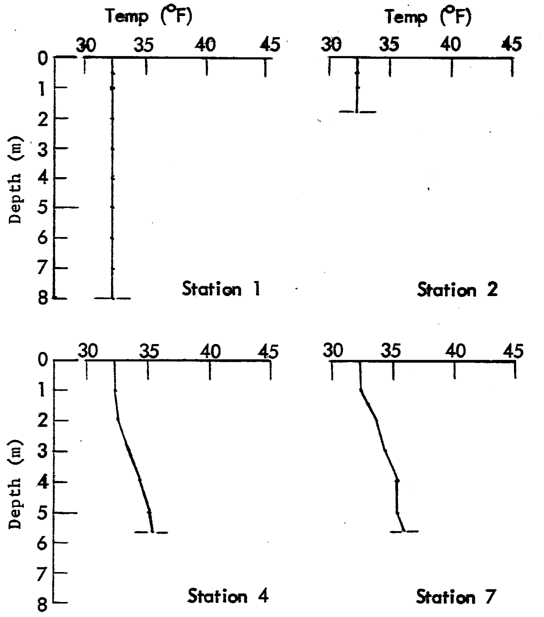


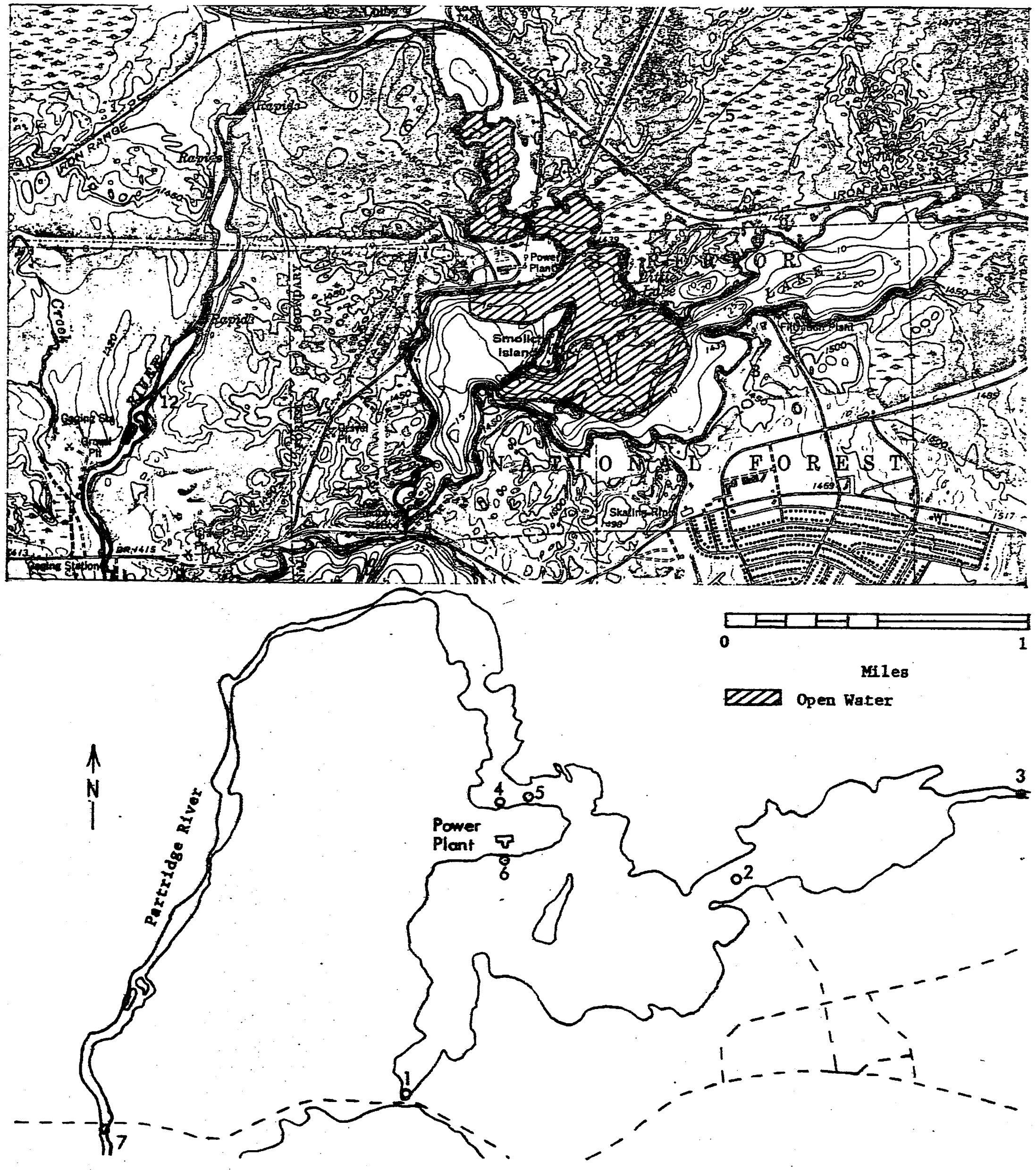
Fig. 37 - Water Temperatures and Dissolved Oxygen in Lake St. Croix

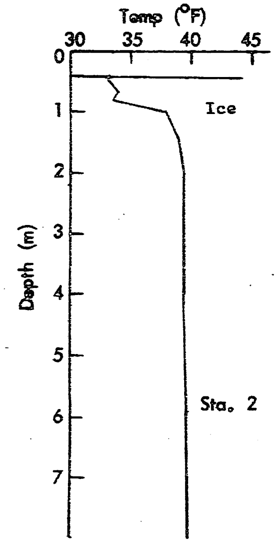




Station	Depth (m)	Temp (°F)	D.O. (mg/ℓ)
A	0.5	33.0	4.15 (Intake)
B	0.5	35.2	7.75 (Outlet)
C	0.5	33.0	4.3
1	2.0	32.3	7.55
1	7.0	32.3	7.5
2	1.5	32.9	5.45
3	3.5	32.3	6.6
4	2.0	32.6	6.15
4	5.0	35.2	5.4
6	0.5	32.7	5.95
7	2.0	33.7	5.8
7	5.0	35.5	5.45
8	1.0	33.0	5.7 (Intake)
9	1.0	37.8	5.75 (Outlet)

Fig. 38 - Ice Coverage, Water Temperatures, and Dissolved Oxygen in the Duluth Harbor near the Hibbard Power Plant





Station	Depth (m)	Temp (°F)	D.O. (mg/l)
1	0.5	37.0°	8.85
1	3.0	37.5°	8.8
2	0.5	33.0°	10.45
2	7.0	39.6°	10.8
3	Surface	32.5°	14.25
4	0.5	50.7°	11.6 (Outlet)
5	0.5	48.5°	11.8
6	0.5	45.0°	11.55 (Intake)
7	Surface	33.0°	13.5

COLBY LAKE
March 2, 1974

Fig. 39 - Ice Coverage, Water Temperatures, and Dissolved Oxygen in Colby Lake

channel. There is some evidence that a small amount of water also recirculates around the point to the water intake. The sinking plume which flows out of the bay area eventually makes its way into the upper channel. It provides a simple and effective mechanism for carrying oxygen into the deeper layers of the Duluth harbor area provided that the discharged water itself has a high oxygen content.

The Colby Lake cooling water circulation system also has sinking plume features. In contrast to the King and Hibbard plant systems, it is not an open circulation system, but a nearly closed one. Most of the cooling water discharged is recirculated to the intake. According to USGS records the Partridge River, which flows through Colby Lake, has the following mean flows:

December	108 cfs
January	56 cfs
February	46 cfs
March	55 cfs

Any cooling water flow above those numbers recirculates. A fairly large open-water area is generated. Through the free surface, heat is dissipated to the atmosphere until the recirculating water reaches maximum density at 39.2°F. It then sinks to the bottom. As a result of this process, most of Colby Lake contains water near 39°F. The continuous inflow of some 32°F water from the Partridge River and a few other small creeks floats on top of the recirculated cooling water. The inflowing water acts as a temperature shield for the ice cover, which would otherwise be much thinner than was observed on the lake (28 inches measured on March 2, 1974). The thin layer of 32°F water can be seen clearly in the temperature profile given in Fig. 39.

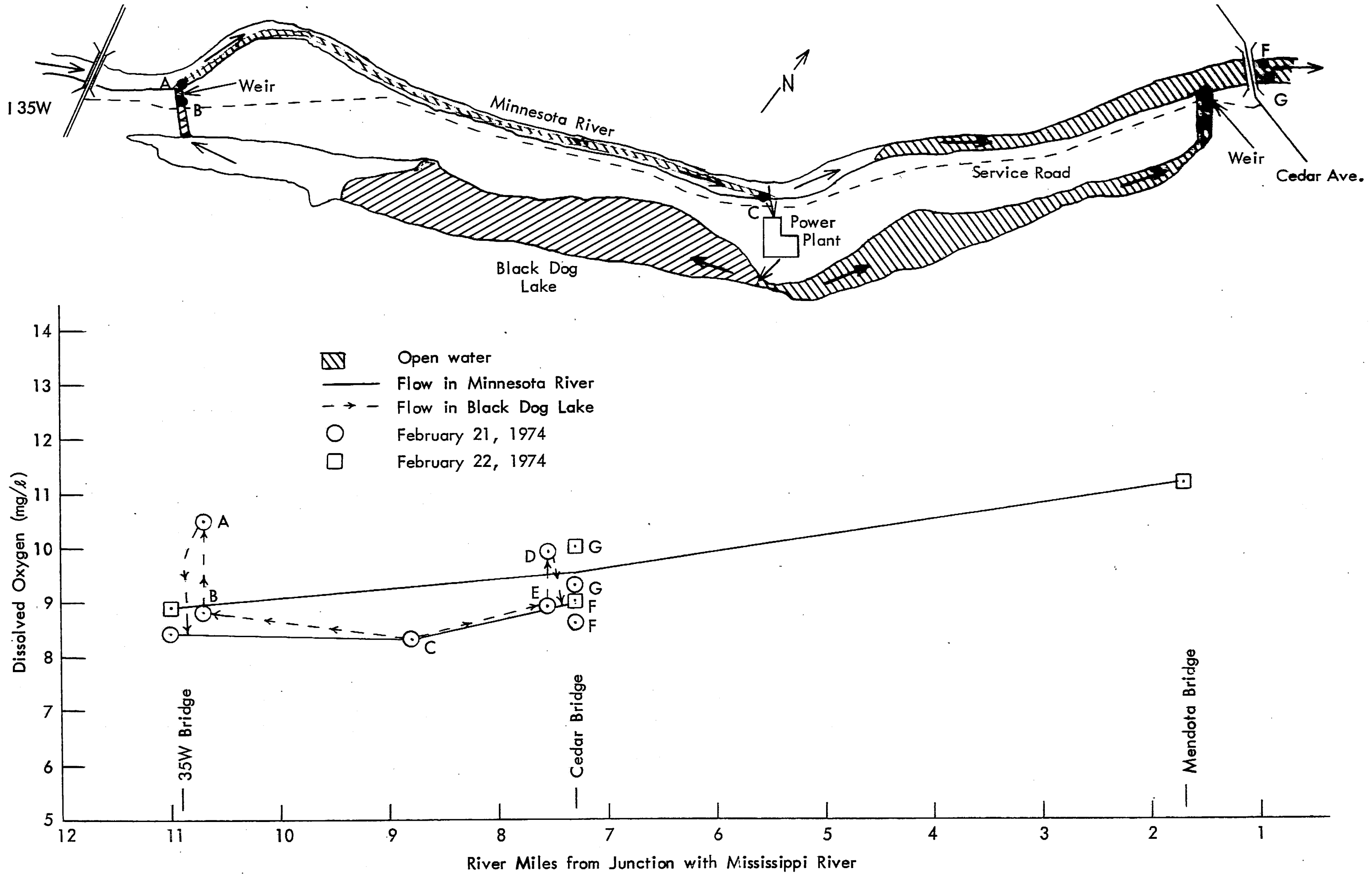
The sinking plume phenomenon enhances the heat transfer process from the discharged water to the atmosphere as long as water temperatures are above 39.2°F. It prevents heat transfer when water temperatures fall below that value. Intake water temperatures are therefore significantly above 32°F during the winter months. Artificial destratification of the lake by air bubbling devices could reduce both the ice cover and the intake water temperatures if that were desirable for plant operation. In this context it should be remembered that ice problems at water intakes both at the power plant and at other pumping stations are prevented or minimized by the availability of water at above-freezing temperatures.

Because Colby Lake is filled with water of nearly constant temperature in the vicinity of 39°F throughout the winter, the annual ice break-up on the lake should be advanced in comparison to that on other lakes, and the swimming season on the Hoyt Lakes beach probably inadvertently benefits from this as well. Similarly, fall cooling should be retarded. The use of a cooling lake for recreational purposes in a naturally cold region certainly seems very logical.

Sinking plumes are natural in lakes, but also occur in river impoundments and in rivers themselves. The Granite Falls power plant provides an excellent example. It is obvious from aerial observation that the cooling water which disappears near the plant site (Fig. 13) resurfaces at a spillway (Minnesota Falls) about 1.5 miles downstream of the plant (Fig. 32) after flowing under the ice cover. Incomplete vertical mixing in the stream--as in lake situations--is the reason for the observation. It was noted that during very cold weather (air temperature below 0°F), open water plumes downstream of river outfalls had a tendency to disappear completely under the ice, indicating that sinking must have a role in the flow and mixing process. This appeared to be the case, for example, at the Riverside and High Bridge plants. The details of the process are not known.

The sinking plume phenomenon also existed at Black Dog Lake, as is shown in Fig. 40. A portion of the cooling water was found to dive underneath the ice cover before resurfacing at the upstream weir.

The same phenomenon occurs in the Mississippi River impoundments downstream from the Clay Boswell power plant and upstream from Grand Rapids. Figure 41 shows the open water areas in the Mississippi River. The location in the Blandin Co. reservoir where the warm water disappeared and the ice cover re-formed is clearly visible. The warm water resurfaces downstream from the dam shown in Fig. 19, and open water over a reach of



BLACK DOG LAKE

Fig. 40 - Ice Coverage and Dissolved Oxygen, Black Dog Lake and Minnesota River

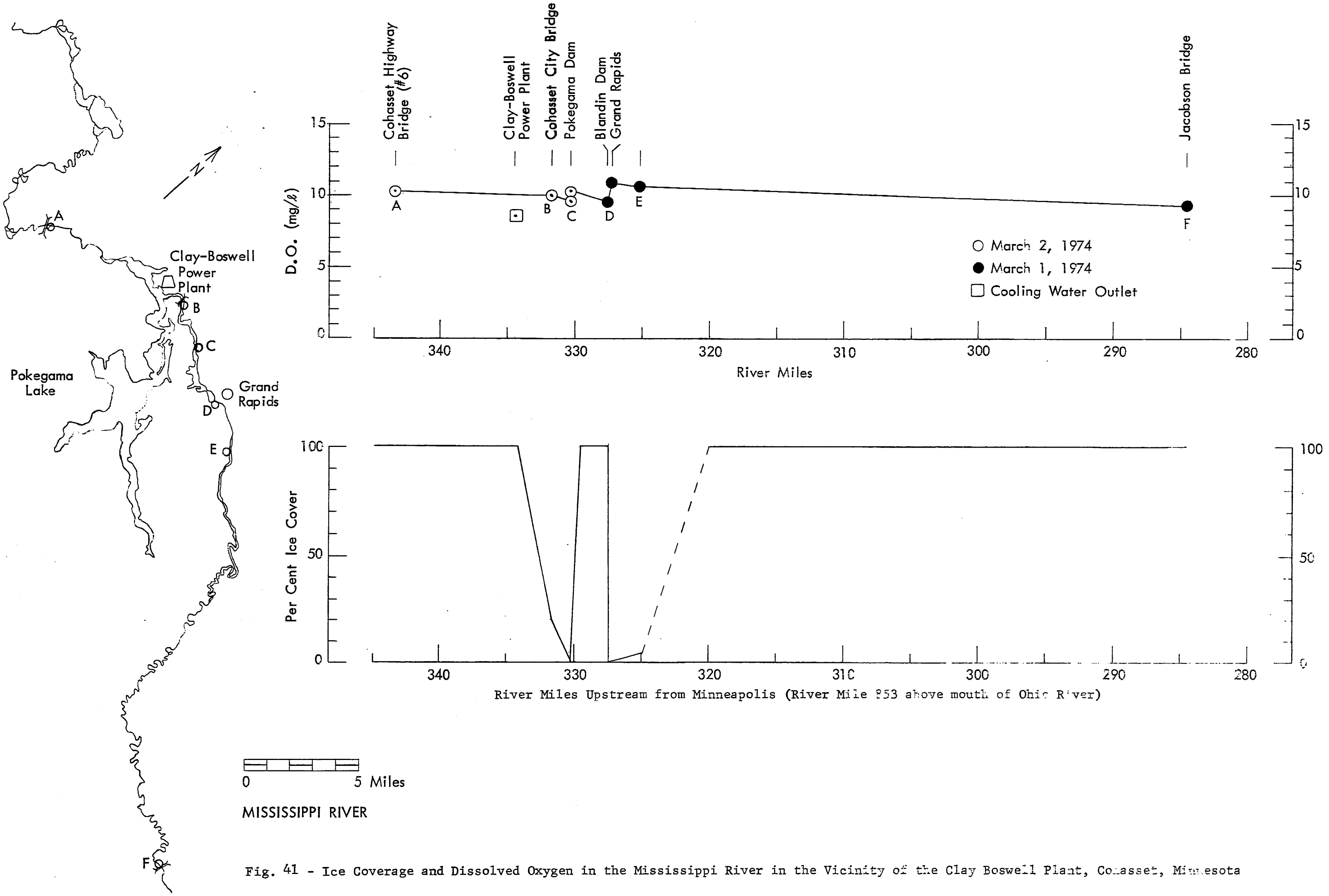


Fig. 41 - Ice Coverage and Dissolved Oxygen in the Mississippi River in the Vicinity of the Clay Boswell Plant, Cohasset, Minnesota

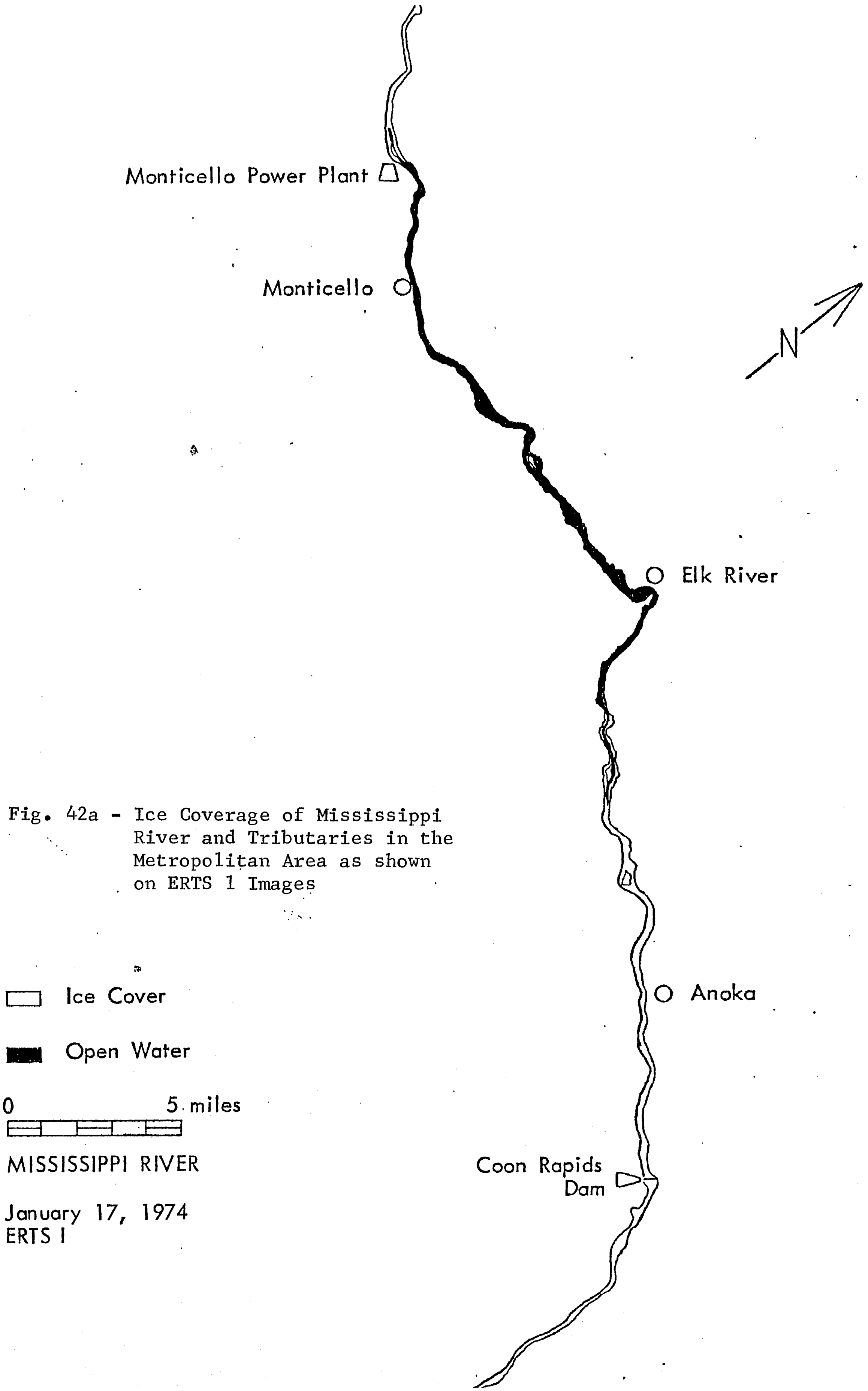


Fig. 42a - Ice Coverage of Mississippi River and Tributaries in the Metropolitan Area as shown on ERTS 1 Images

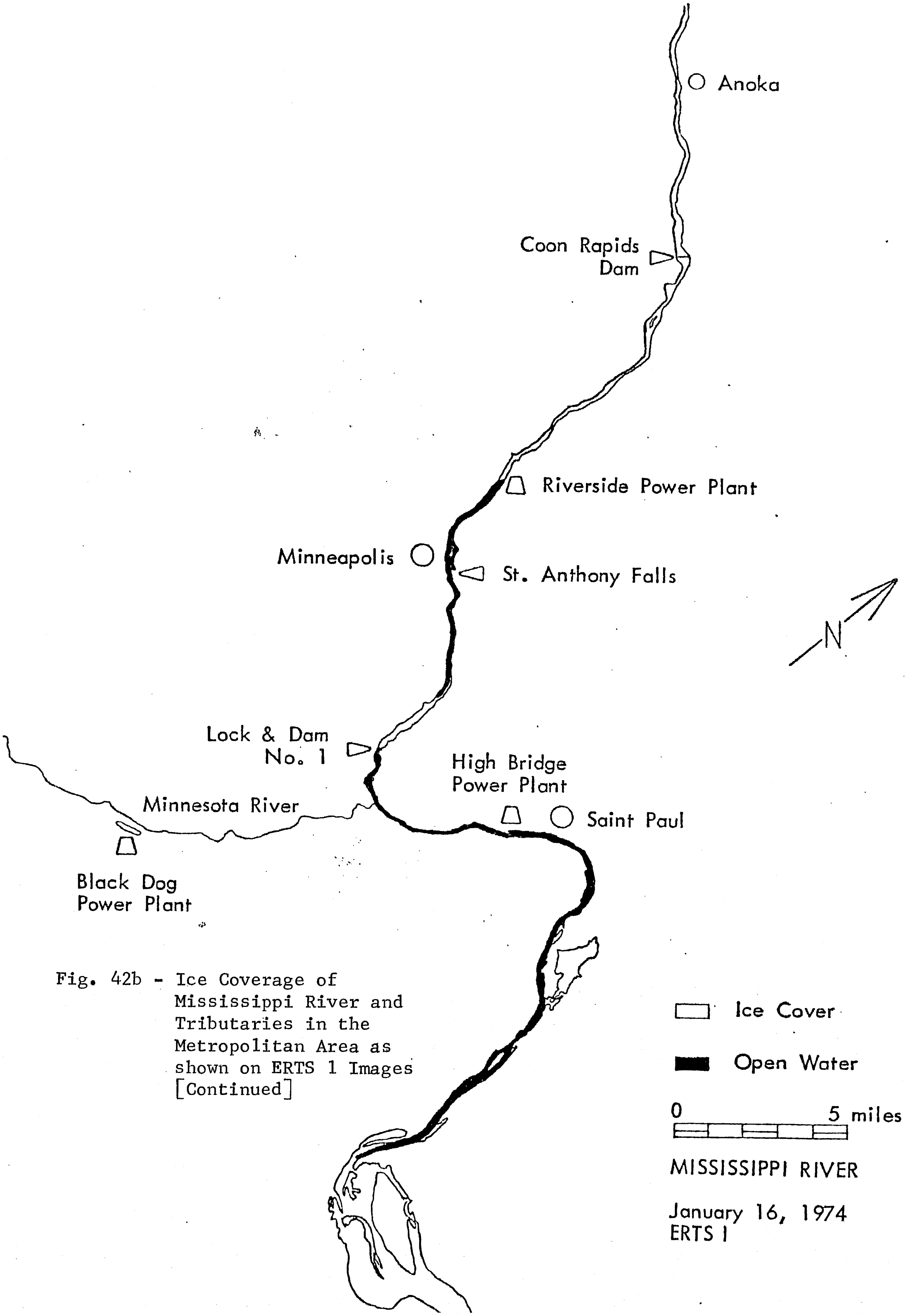


Fig. 42b - Ice Coverage of Mississippi River and Tributaries in the Metropolitan Area as shown on ERTS 1 Images [Continued]

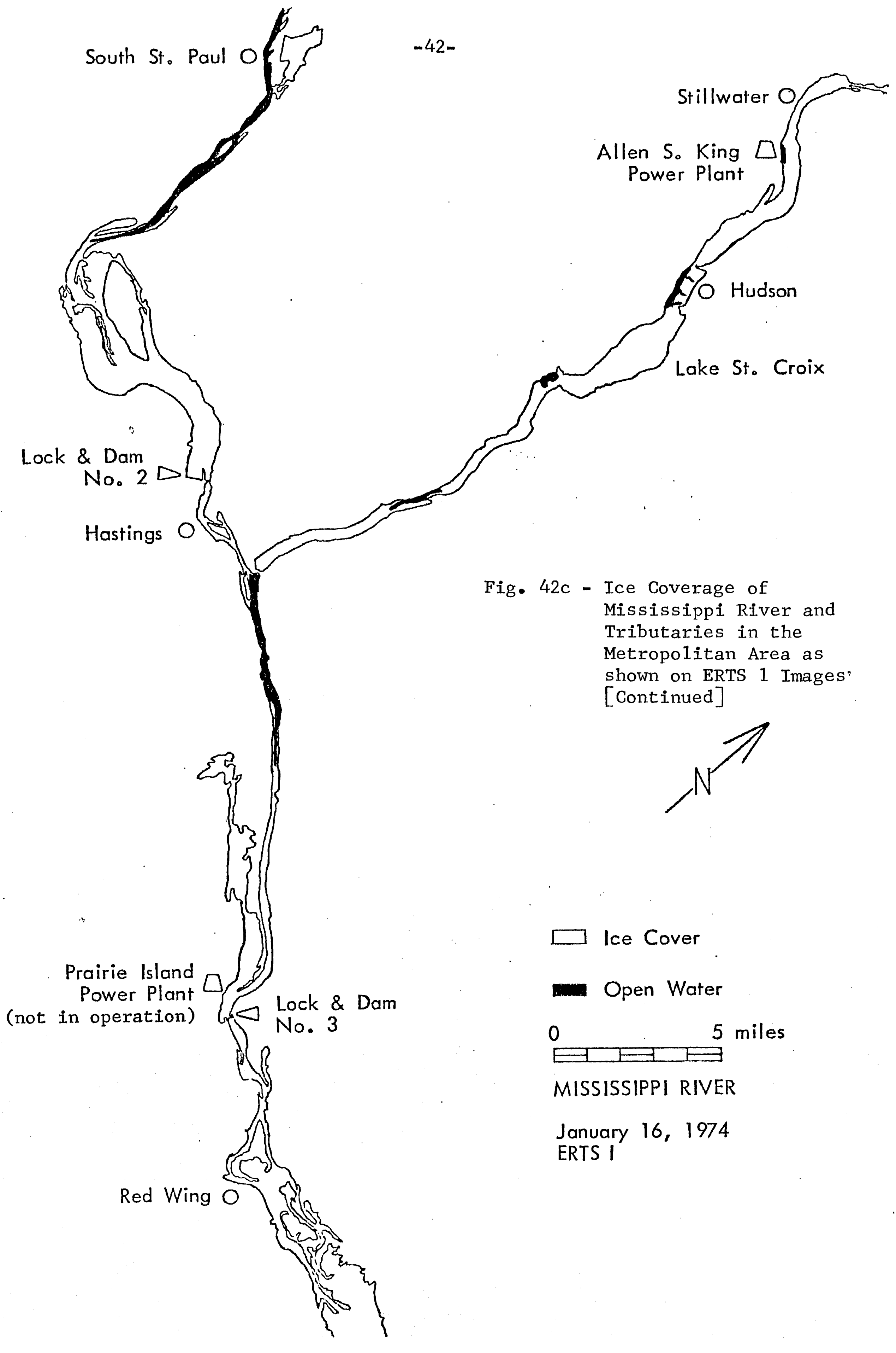


Fig. 42c - Ice Coverage of Mississippi River and Tributaries in the Metropolitan Area as shown on ERTS 1 Images [Continued] reaches. The weather conditions which prevailed during the period of investigation are indicated by the air temperatures in Fig. 3; information on cooling water effluent discharges is also available, but is not shown herein.

ERTS 1 images show changes in ice coverage with time very clearly; the river system quite obviously is a very dynamic system with respect to heat exchange and ice covers. To illustrate this point the percentage of open water length of the river's main stem has been plotted versus time in Fig. 43. The time intervals are rather long, but the fluctuations are nevertheless quite apparent. One hundred per cent is equivalent to a total length of 114 miles. The period of partial ice coverage lasted from December 12 through March 10, a significantly shorter time in spring than for natural conditions. The first Mississippi River tug boats were scheduled to arrive at St. Paul on March 25.

Another noteworthy observation is that at times the Mississippi River as a whole forms a sinking plume at several locations; for example, in Pool No. 1 and Pool No. 2. Changes in the ice coverage of the Mississippi River in the Minneapolis-St. Paul area, where the river not only receives cooling water from several power plants, but also flows through a series of pools and dams, are particularly substantial in terms of both distance and time. Observations made during several ground surveys have been assembled. An example is given in Fig. 44. These data will also be useful for further analysis. Similar data were assembled for the Mississippi River from Sartell to Minneapolis as shown in an example in Fig. 45.

The locations and lengths of the far fields of cooling water plumes on the Minnesota River are shown in Figs. 46a and b. Not enough measurements could be taken within the time and budget allotted for assessment of the dynamic aspects of ice coverage for any of the sites outside the metropolitan area. It is noteworthy that the only significant open water on the Minnesota River is that due to (a) cooling water effluents from power and other plants; (b) effluents from municipal sewage treatment plants; and (c) effluents from lakes and impoundments, primarily Lac Qui Parle.

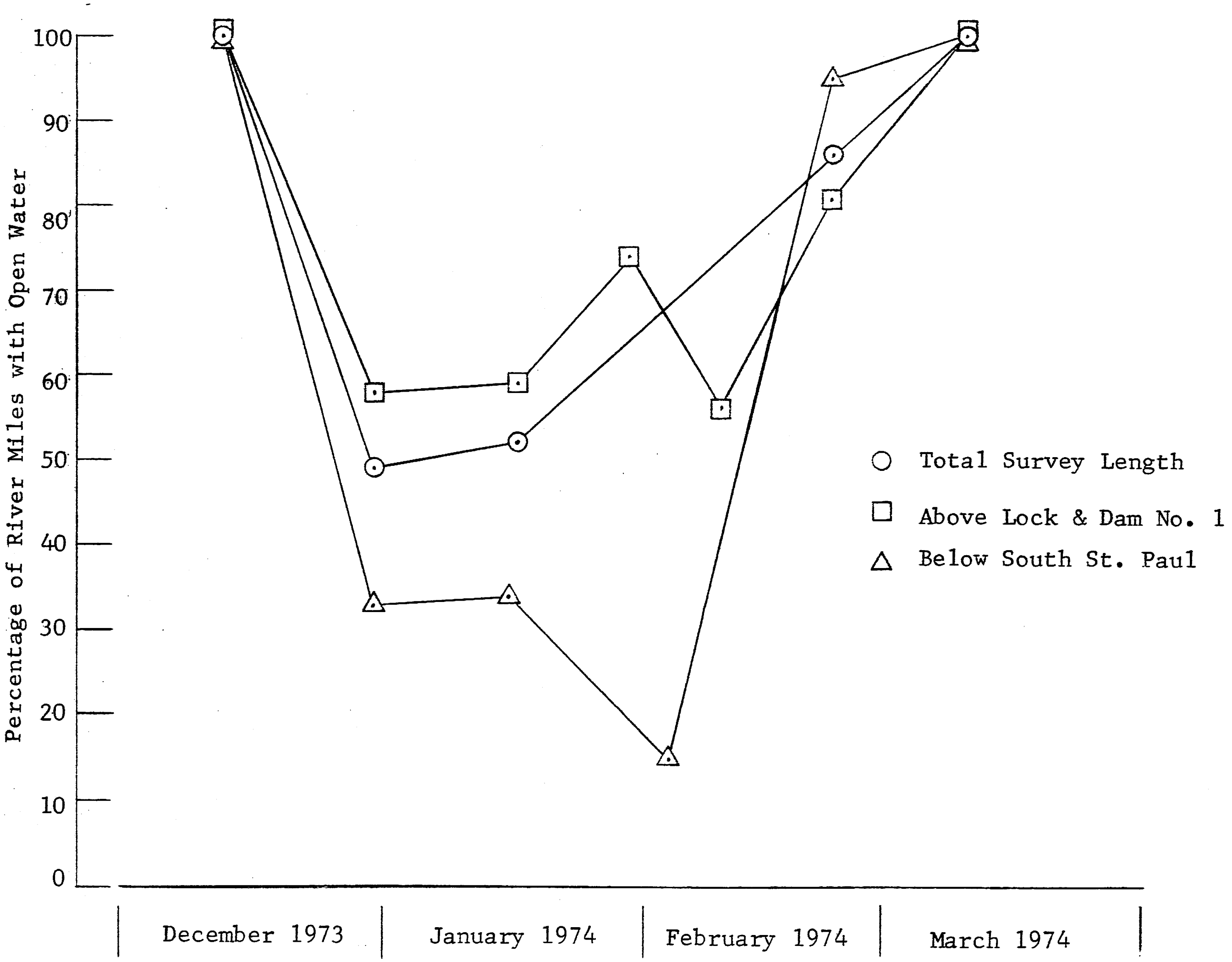


Fig. 43 - Percentage of River Miles with Open Water from Monticello to Red Wing on the Mississippi River

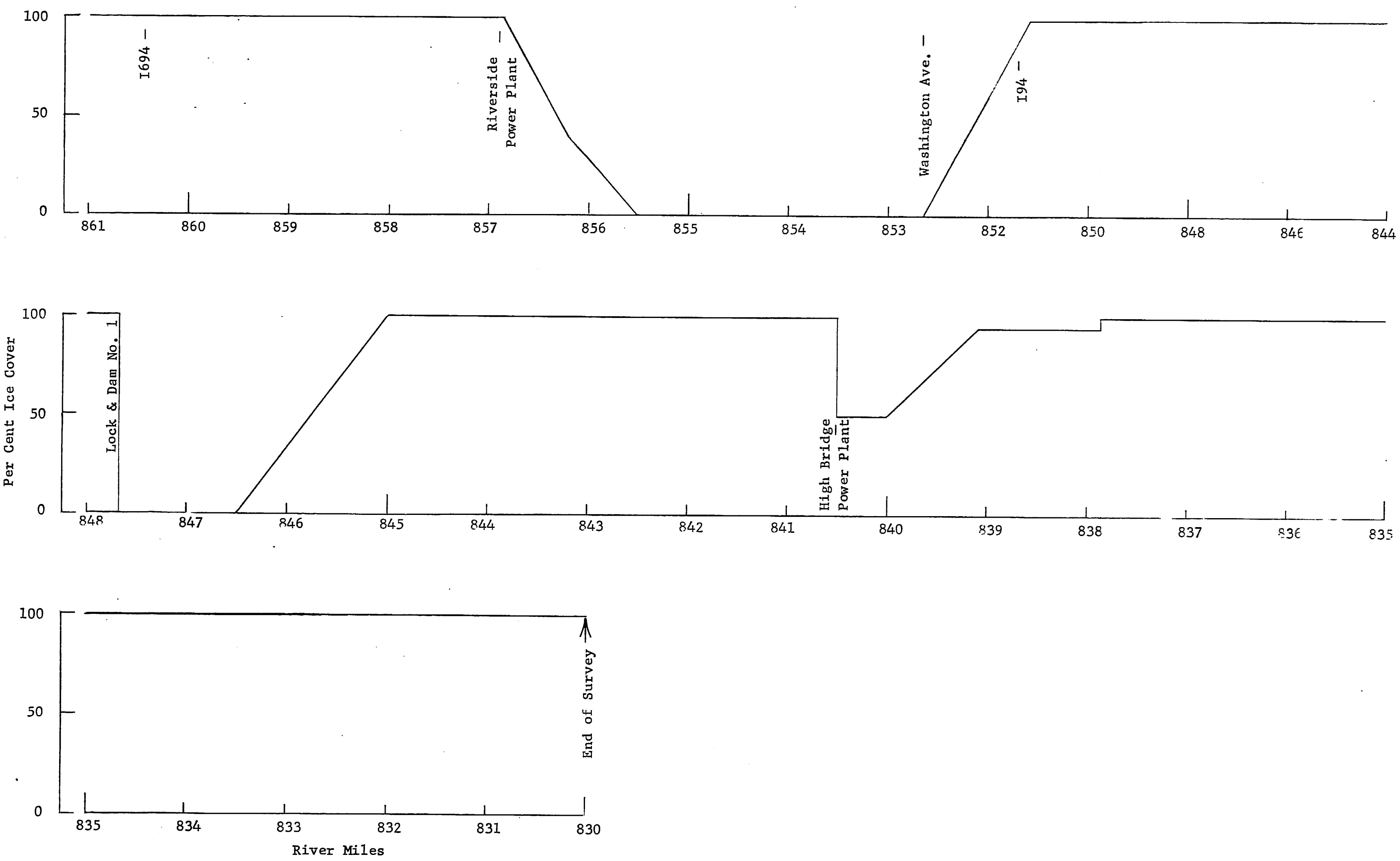


Fig. 44 - Mississippi River, January 2, 1974 - Per Cent Ice Cover

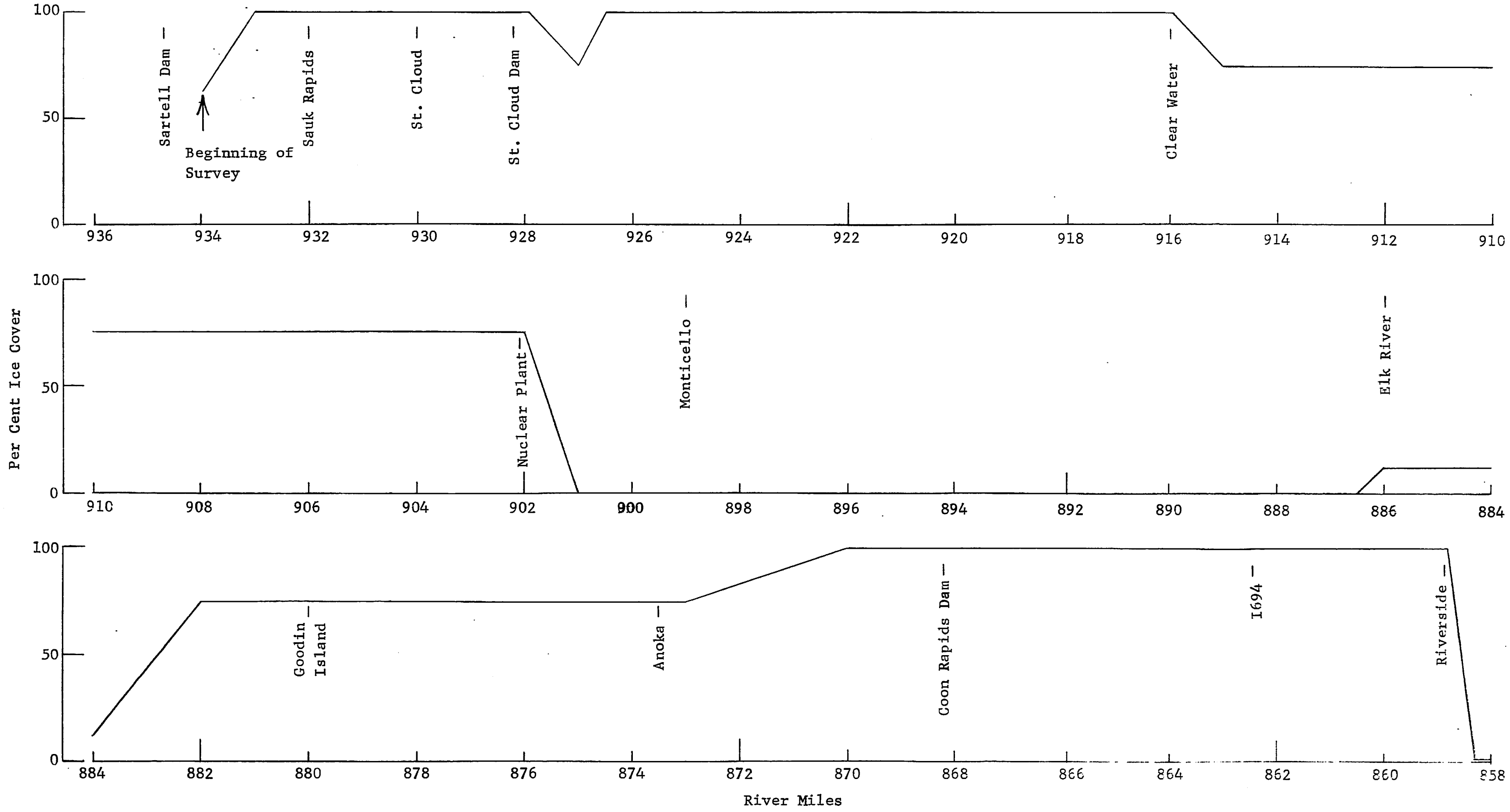


Fig. 45 - Mississippi River, January 29, 1974 - Per Cent Ice Cover

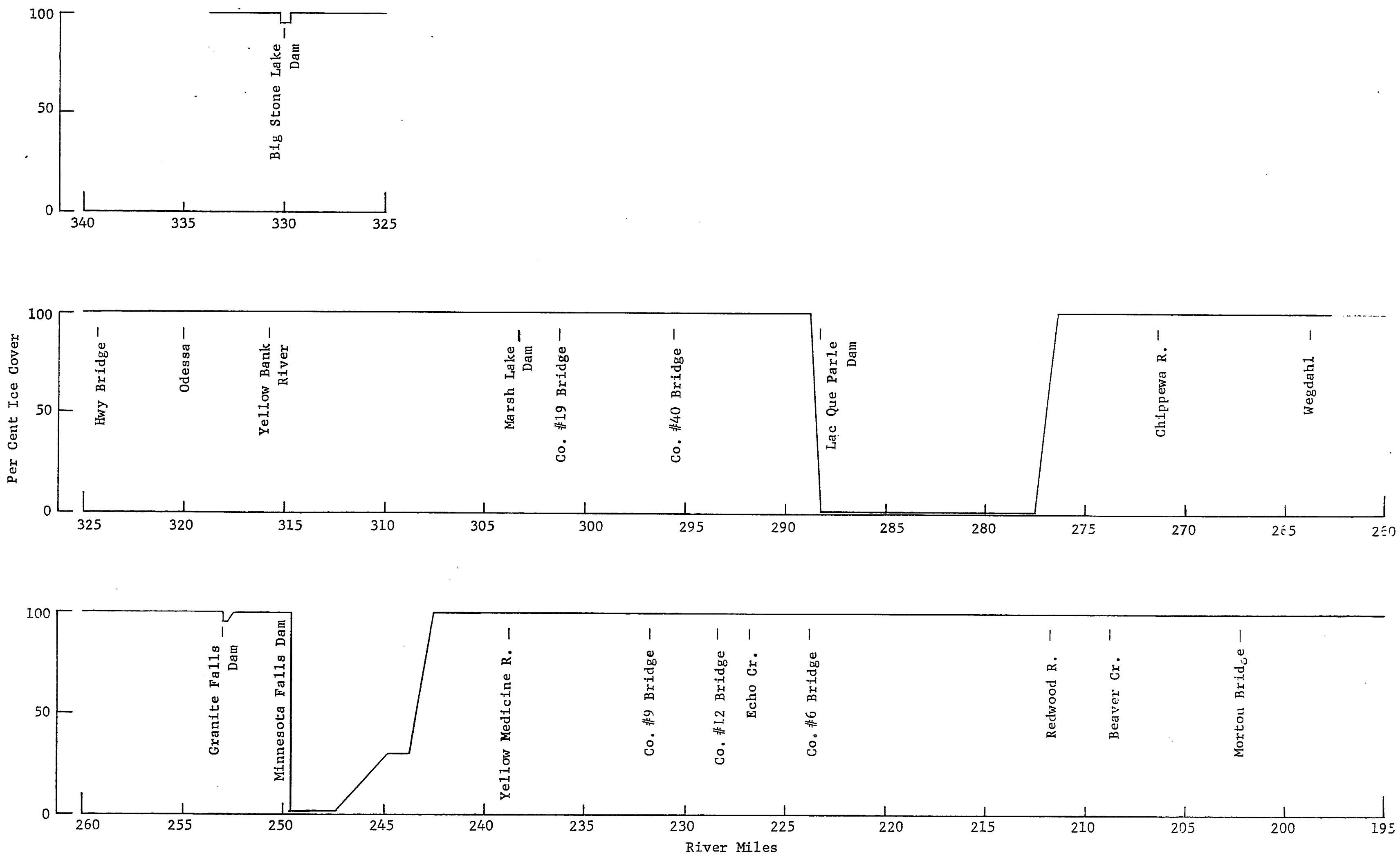


Fig. 46a - Minnesota River, February 16, 1974 - Per Cent Ice Cover

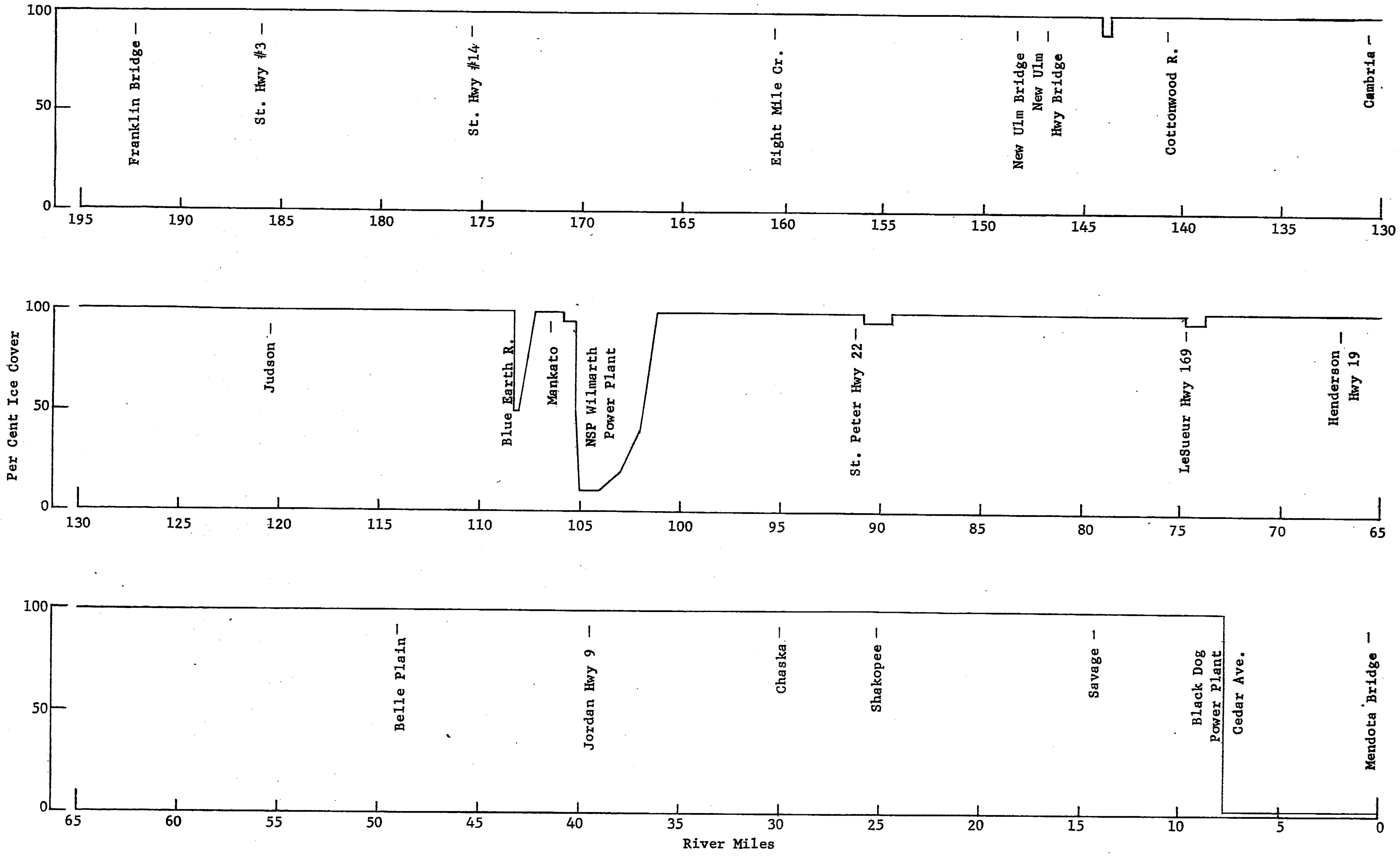


Fig. 46b - Minnesota River, February 16, 1974 - Per Cent Ice Cover [Continued]

V. OBSERVED ICE THICKNESSES

Ice thicknesses measured at various locations and at different times are given in Table 3.

Table 3. -- MEASURED ICE THICKNESSES

Stream or Lake	Location	Date	Ice Thickness (Inches)
Mississippi R.	Red Wing	1/13/74	10
Lake Pepin	Frontenac	1/13/74	17
Lake St. Croix	between Stillwater & Bayport	1/17/74	14
Lake St. Croix	Bayport Park & Beach	1/17/74	16
Lake St. Croix	No. Hudson	1/15/74	15
Mississippi R.	Minneapolis R.R. bridge No. of Riverside power plant	2/7/74	10
Minnesota R.	Minneapolis west of 35W Bridge	2/21/74	11
Minnesota R.	Judson	2/23/74	14
Mississippi R.	Clearwater	2/26/74	18
Mississippi R.	Jacobson	3/1/74	22
Mississippi R.	Hwy No. 6 Bridge upstream of Cohasset	3/2/74	24
Colby Lake	Hoyt Lakes filter plant	3/2/74	28
Duluth Harbor	Hibbard plant, near intake	3/3/74	18
Duluth Harbor	Hwy No. 2 Bridge	3/15/74	14
Duluth Harbor	Hibbard plant, bay receiving cooling water	3/15/74	4 to 16

The measurements given in Table 3 can be summarized in the following way:

1. Along the Mississippi River, natural ice thicknesses during the winter of 1973-74 decreased along the course of the river going from north to south as shown in Table 4.

Table 4. -- SELECTED MISSISSIPPI RIVER ICE THICKNESSES

Location	River Miles above the Mouth of the Ohio River	Date	Measured Ice Thickness (Inches)
Cohasset Hwy No. 6 Bridge	1196	3/3/74	24
Jacobson	1138	3/2/74	22
Clearwater	914	2/26/74	18

According to weather records, natural ice thicknesses should not have varied significantly between February 20 and March 15. The measured gradient in ice thickness from north to south is therefore little affected by the time lag in the measurements.

2. Ice thicknesses on lakes varied from 14 inches to 28 inches (Table 5). A gradient from north to south again existed.

Table 5. -- SELECTED LAKE ICE THICKNESSES

Location	Month	Measured Ice Thickness (Inches)
Lake St. Croix Lake Pepin	January	14 - 17
Duluth Harbor	March	14 - 18
Colby Lake	March	28

3. Mean monthly air temperatures during the 1973-74 winter, as shown in Table 6, were close to normal. The measured ice

thickness can therefore be considered representative for other years as well.

Table 6. -- MEAN MONTHLY AIR TEMPERATURES (^{o}F)

Month	Normal Year	1973-74
November	31.2	34.3
December	18.1	16.7
January	12.4	11.9
February	15.7	16.9
March	27.4	29.5
April	44.3	47.1

Observed ice thicknesses are, of course, directly related to the mechanics of ice formation and ice melting. These mechanics have been studied and described in the literature, e.g., by Ashton, Uzuner, and Kennedy (1970) and by Ashton (1974). With regard to ice distribution downstream from a power plant, an article by Dingman and Weeks (1970) must be referenced. Ice formation requires a heat loss from the water to the atmosphere. After the onset of ice formation this heat loss is by conduction through the ice. Since the ice acts as an insulator, ice growth rates become smaller as the ice becomes thicker. As a rough measure of the potential heat transfer from 32^{o}F water through an ice cover to the atmosphere, degree-days of freezing are often used. Cumulative degree-days of freezing after the onset of ice formation $\sum S_d$ can be related to the ice thickness d_i. It can easily be shown that the relationship is of the following form, assuming constant properties of the ice and no snow cover:

$$d_i = 0.7(\sum S_d)^{1/2}$$

where d_i is measured in inches and S_d in degree-F-days. A comparison of ice thicknesses computed from the above relationship for the winter of 1973-74 with the measurements given in Table 3 is shown in Fig. 47. All the measured values are below the theoretical maximum, as expected.

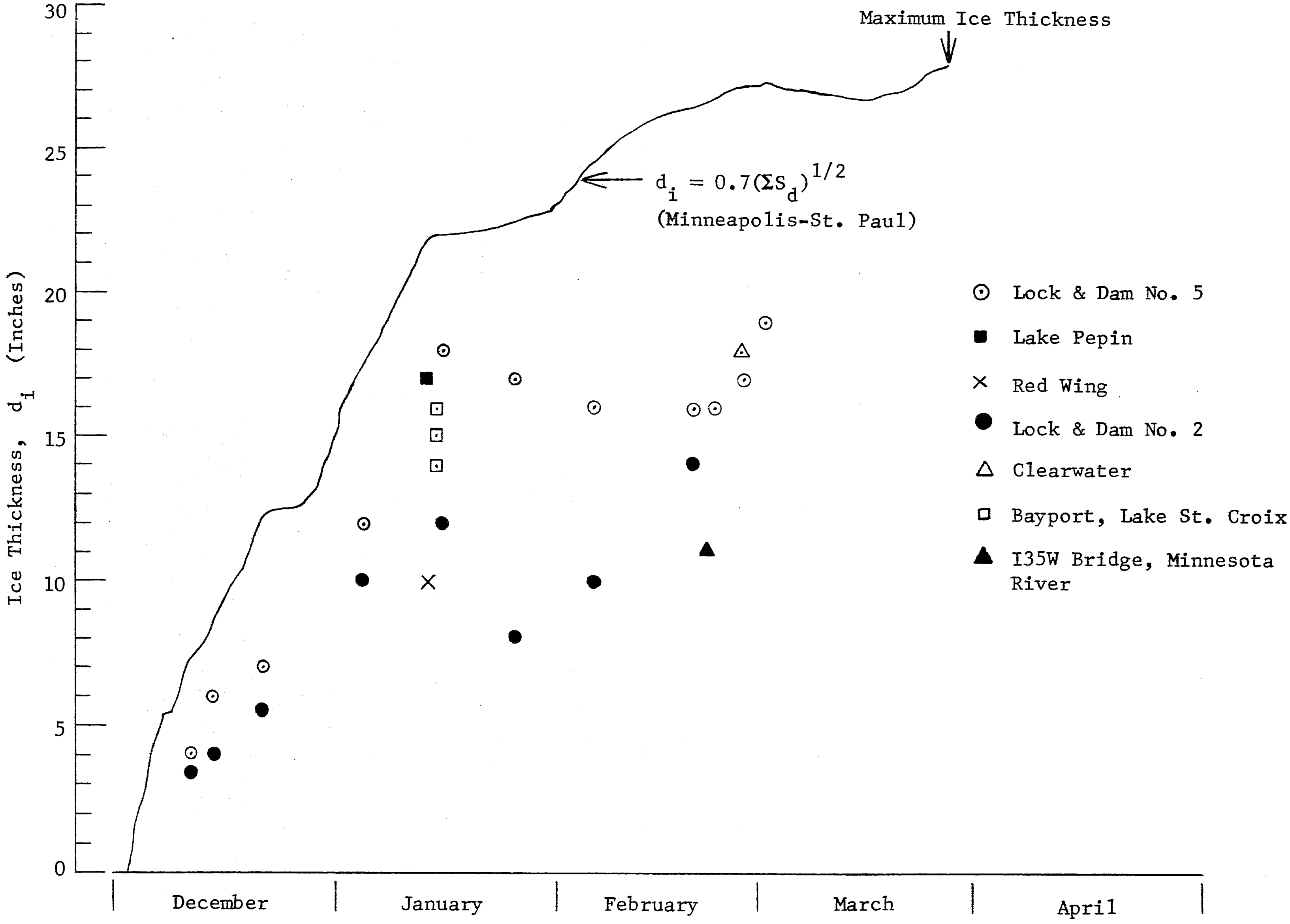


Fig. 47 - Ice Thickness on the Mississippi River and the Theoretical Maximum

VI. LONG-TERM TRENDS IN ICE COVERS

1. Open-Water Period

Records of ice covers or ice thicknesses exist only to a very limited degree and are dispersed among numerous organizations and individuals. Records kept by the U.S. Army Corps of Engineers, St. Paul District, indicate the annual dates of freeze-over and ice break-up for the Mississippi River at Lake Pepin. With interruptions, this information reaches back as far as 1861. There are some fairly consistent records beginning with 1895.

It should be noted that the ice freeze is not necessarily a unique event every year. The dates reported appear to be for the first significant, and often the lasting, event. The existing data were used to prepare Fig. 48, a cumulative plot of the number of days between November 30 and the reported date of ice formation. Through the use of this technique one major change in trend is made readily apparent: Around 1912 the date of ice formation shifted from approximately November 29 to approximately December 5. No other significant changes seem to have occurred.

A similar plot for the reported ice break-up date in Fig. 49 shows a different trend. From the beginning of the record until approximately 1965 the date of ice break-up moved from approximately April 15 gradually to approximately April 6. In 1965 the recorded date of ice break-up receded abruptly to March 17. The general trend of reduced ice coverage in the vicinity of the metropolitan area is also borne out by an analysis of 25 years of data (1938-1962) given by Schroepfer, Susag, et al. (1965). Ice covers downstream of the Pig's Eye Sewage Treatment Plant were measured by the Minneapolis-St. Paul Sanitary District. The analysis presents the frequency of complete ice cover in per cent of sampling days. The results are reproduced in Table 8. It can be seen quite clearly that the incomplete ice cover extended farther and farther downstream as time progressed.

Freezing and break-up of river ice have, of course, direct significance for river navigation. The length of the navigation season

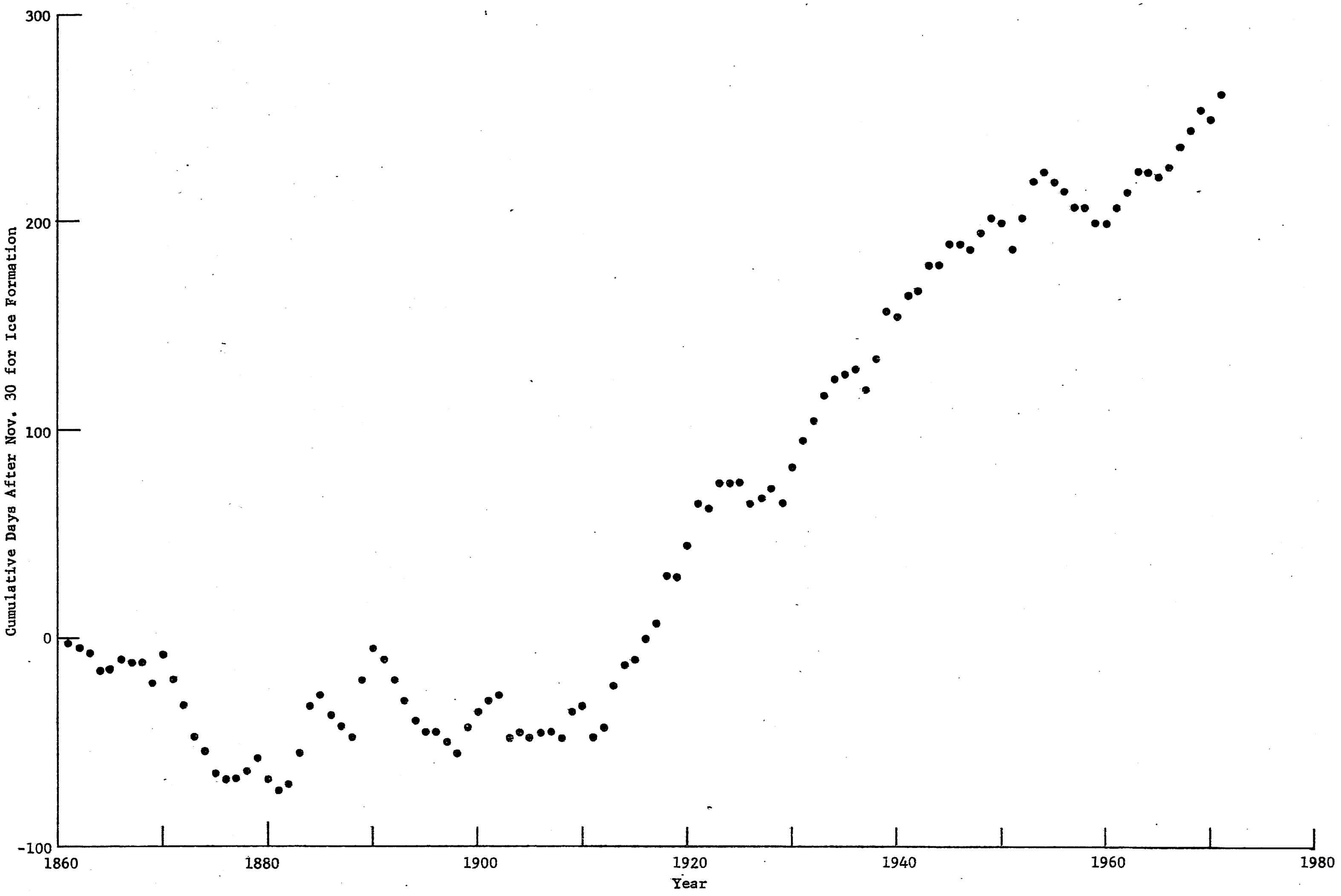


Fig. 48 - Cumulative Yearly Date of Ice Freeze, Lake Pepin (U.S. Army Corps of Engineers, St. Paul, Navigation Records)

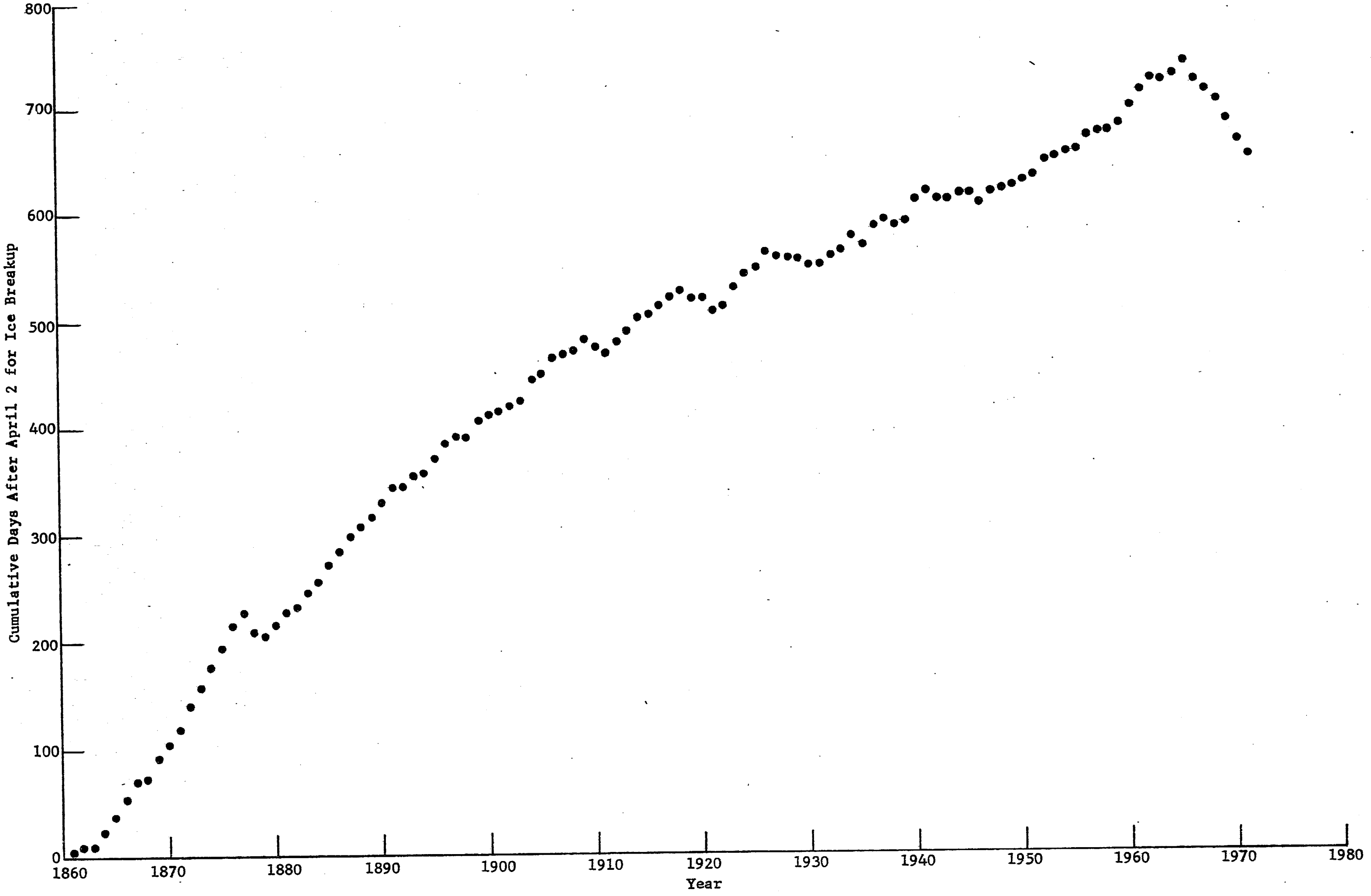


Fig. 49 - Cumulative Yearly Date of Ice Breakup, Lake Pepin (U.S. Army Corps of Engineers, St. Paul, Navigation Records)

Table 8*

Frequency of Complete Ice Cover in Percent of Sampling Days
February 1938 - 62

	Sampling Station									
Year	M 13.8	M 18.0	M 22.7	M 26.5	M 30.5	M 37.8	M 39.1	M 41.7***	M 52.6	M 56.1
1962	0	0*	0	0	50.0	100.0	66.7	100.0	100.0	100.0
61	0	0*	0	0	0	80.0	0	75.0	0	50.0
1960	0	-	0	0	0	100.0	0	100.0	33.3	50.0
59	0	-	0	100.0	75.0	100.0	75.0	100.0	100.0	100.0
58	0	--	0	0	37.5	66.7	50.0	66.7	33.3	100.0
57	0	0	0	0	0	100.0	50.0	100.0	100.0	100.0
56	0	0	0	-	-	100.0	100.0	100.0	100.0	100.0
55	0	0	0	-	-	100.0	100.0	100.0	75.0	100.0
54	0	0	0	-	100.0	100.0	25.0	25.0	33.3	50.0
53	-	0	0	-	-	100.0	0	0	100.0	-
52	0	-	0	-	-	100.0	25.0	75.0	100.0	100.0
51	0	0	33.3	50.0	50.0	100.0	66.7	33.3	100.0	100.0
1950	0	0	40.0	-	100.0	100.0	60.0	20.0	100.0	66.7
49	0	0	25.0	33.3	75.0	75.0	75.0	75.0	100.0	100.0
48	0	0	0	66.7	100.0	83.3	66.7	40.0	100.0	100.0
47	0	0	0	100.0	100.0	100.0	25.0	75.0	100.0	100.0
46	0	0	50.0	-	-	100.0	75.0	75.0	100.0	100.0
45	0	0	0	0	50.0	100.0	25.0	50.0	0	100.0
44	0	50.0	50.0	100.0	100.0	100.0	37.5	77.8	22.2	25.0
43	0	0	0	25.0	66.7	100.0	16.7	50.0	100.0	100.0
42	0	0	66.7	66.7	66.7	66.7	16.7	33.3	66.7	66.7
41	20.0	0	33.3	50.0	100.0	100.0	71.4	75.0	100.0	100.0
1940	22.2	60.0	60.0	50.0	100.0	88.9	30.0	50.0	66.7	100.0
39	25.0	0	20.0	100.0	100.0	87.5	88.9	77.8	100.0	100.0
38	-	57.1**	62.5	71.4	100.0	100.0	66.7	66.7	-	-
Average	3.4	8.0	17.6	45.2	68.5	93.9	48.5	65.6	76.3	87.3
Maximum	25.0	60.0	66.7	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Minimum	0	0	0	0	0	66.7	0	0	0	25.0

* M 20.5 ** M 17.3 *** St. Croix River

*Table taken from Schroepfer, Susag, et al. (1965)

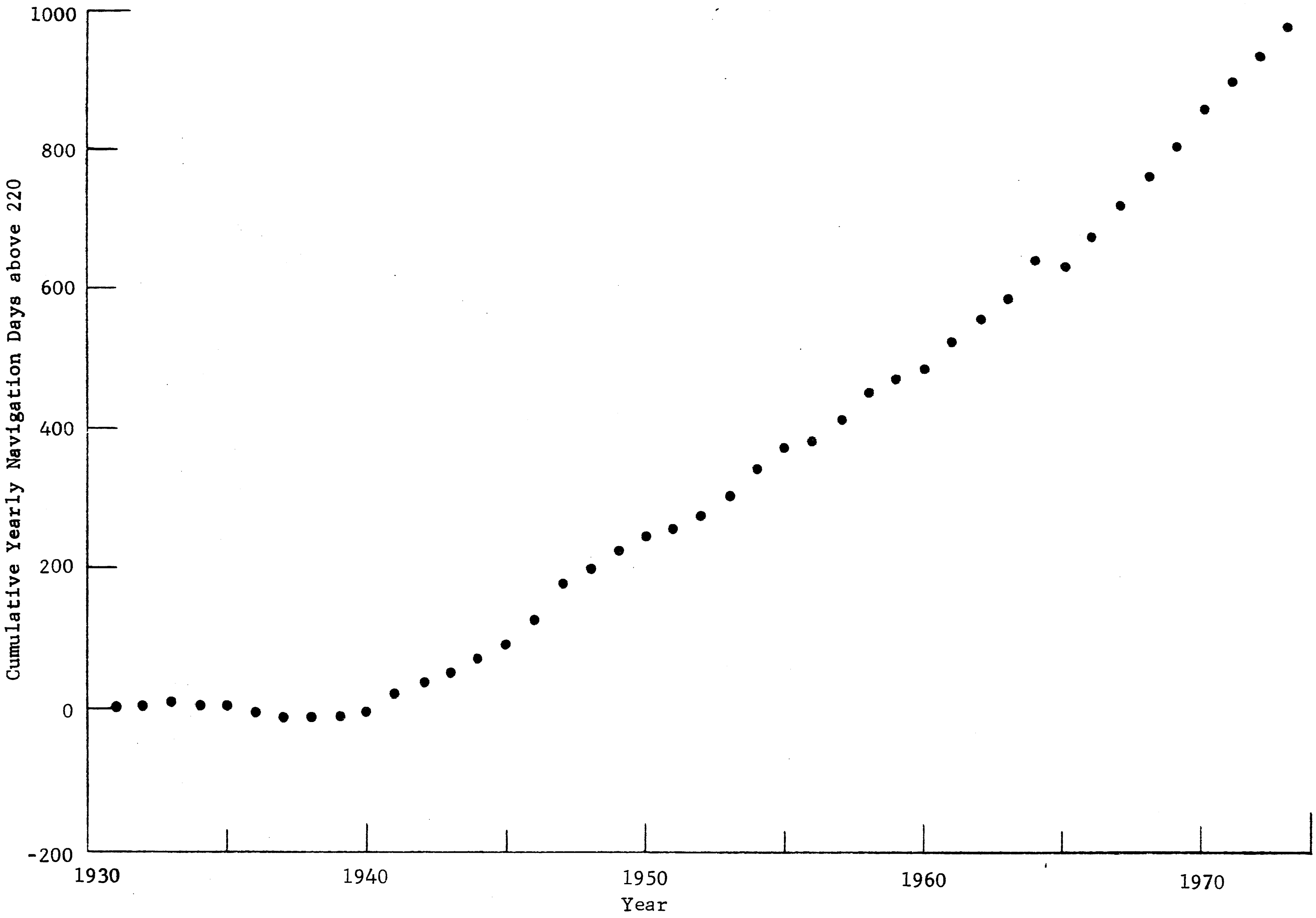


Fig. 50 - Cumulative Length of Navigation Season in St. Paul (U.S. Army Corps of Engineers, St. Paul, Navigation Records)

VII. OBSERVED DISSOLVED OXYGEN LEVELS

The site locations and dates at which dissolved oxygen measurements were taken are shown in Appendix B. Some of the measured values have been shown in Figs. 37 through 41. Additional measurements are given in Figs. 51 through 54. The observed dissolved oxygen concentration in a stream or lake depends on a number of processes, all of which contribute to the dissolved oxygen balance; they are

1. Advective and dispersive transport by the flow in a stream or river.
2. Oxygen uptake due to the biochemical oxygen demand of organic materials in the water.
3. Surface aeration; i.e., oxygen transfer from the atmosphere into the water through a water surface.
4. Photosynthesis and respiration of phytoplankton.
5. Oxygen uptake by decaying organic bottom (benthic) materials.
6. Respiration of zooplankton, Crustacea, fish, etc.

The rates at which oxygen is transferred by these different processes can be estimated. The effect of ice covers is (a) to eliminate surface aeration and (b) to reduce light penetration, which reduces photosynthesis. The net result, then, usually is a reduction in observed dissolved oxygen levels.

The loss in dissolved oxygen through biochemical uptake in an ice-covered stream is apparent in Figs. 51, 52, and 54 for the Mississippi and Minnesota rivers. Schroepfer, Susag, et al. (1965) have illustrated this effect using dissolved oxygen measurements in the Mississippi River downstream of St. Paul; these are reproduced in Fig. 55. The same effect can also be illustrated in terms of time using the D.O. measurements taken at Lock & Dam No. 3 and reported in Water Resources Data for Minnesota by the U.S. Geological Survey; an example is shown in Fig. 56.

That dissolved oxygen is lost through biochemical uptake in an ice-covered stream is clearly borne out by the 1973-74 measurements taken in the

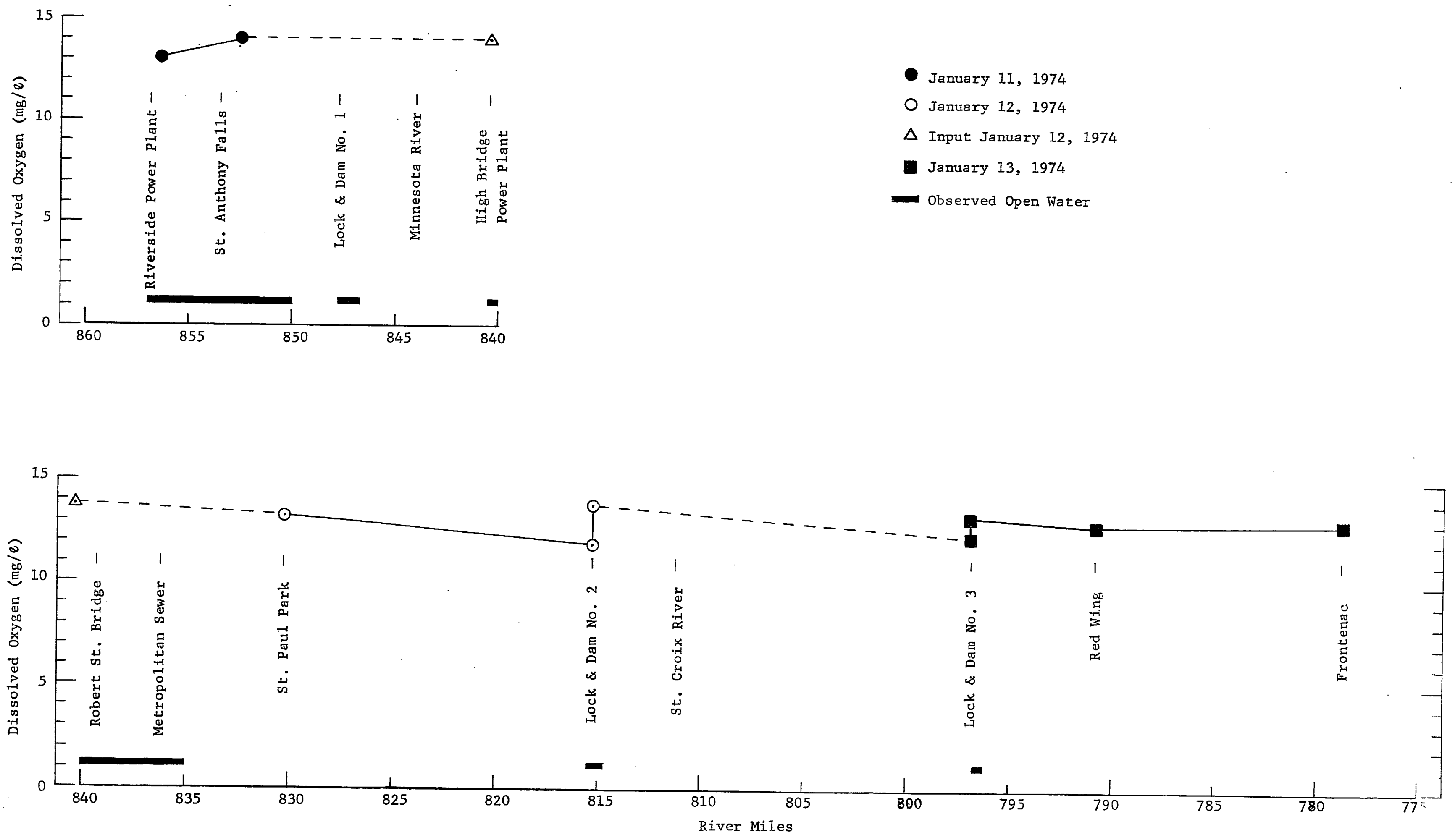


Fig. 51 - Mississippi River, January 1974 - Dissolved Oxygen

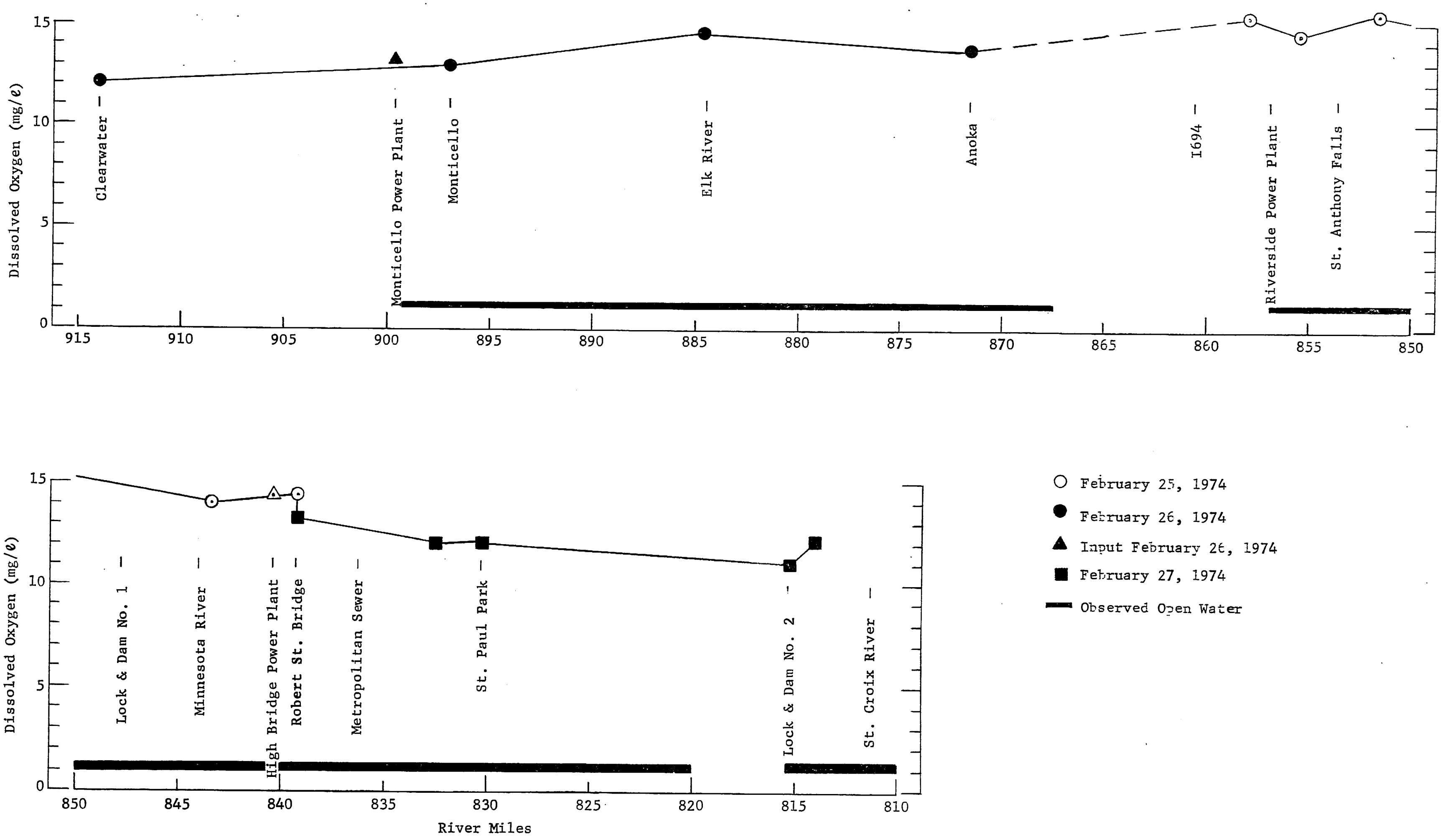


Fig. 52 - Mississippi River, February 1974 - Dissolved Oxygen

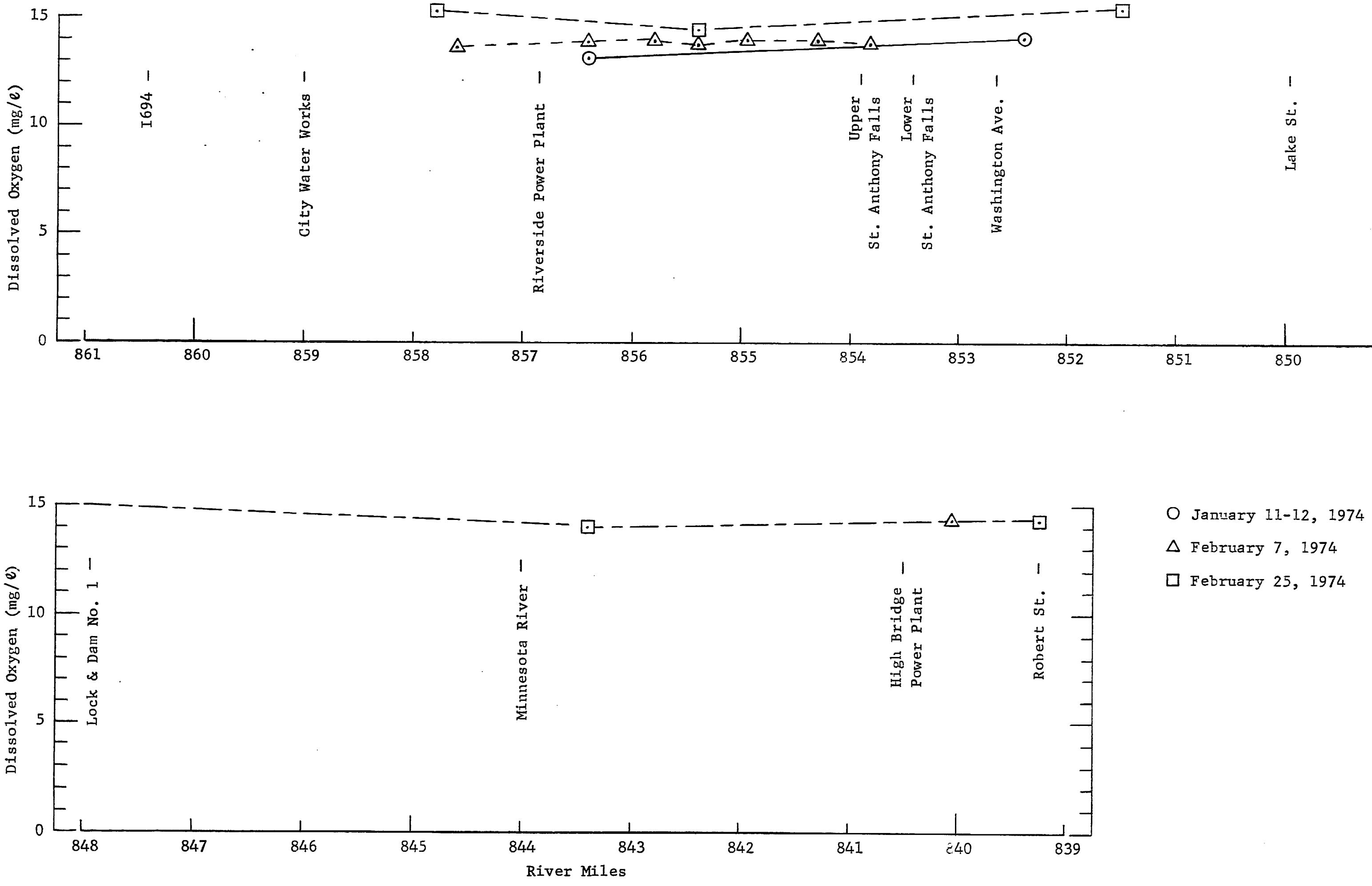


Fig. 53 - Mississippi River, January-February 1974 - Dissolved Oxygen

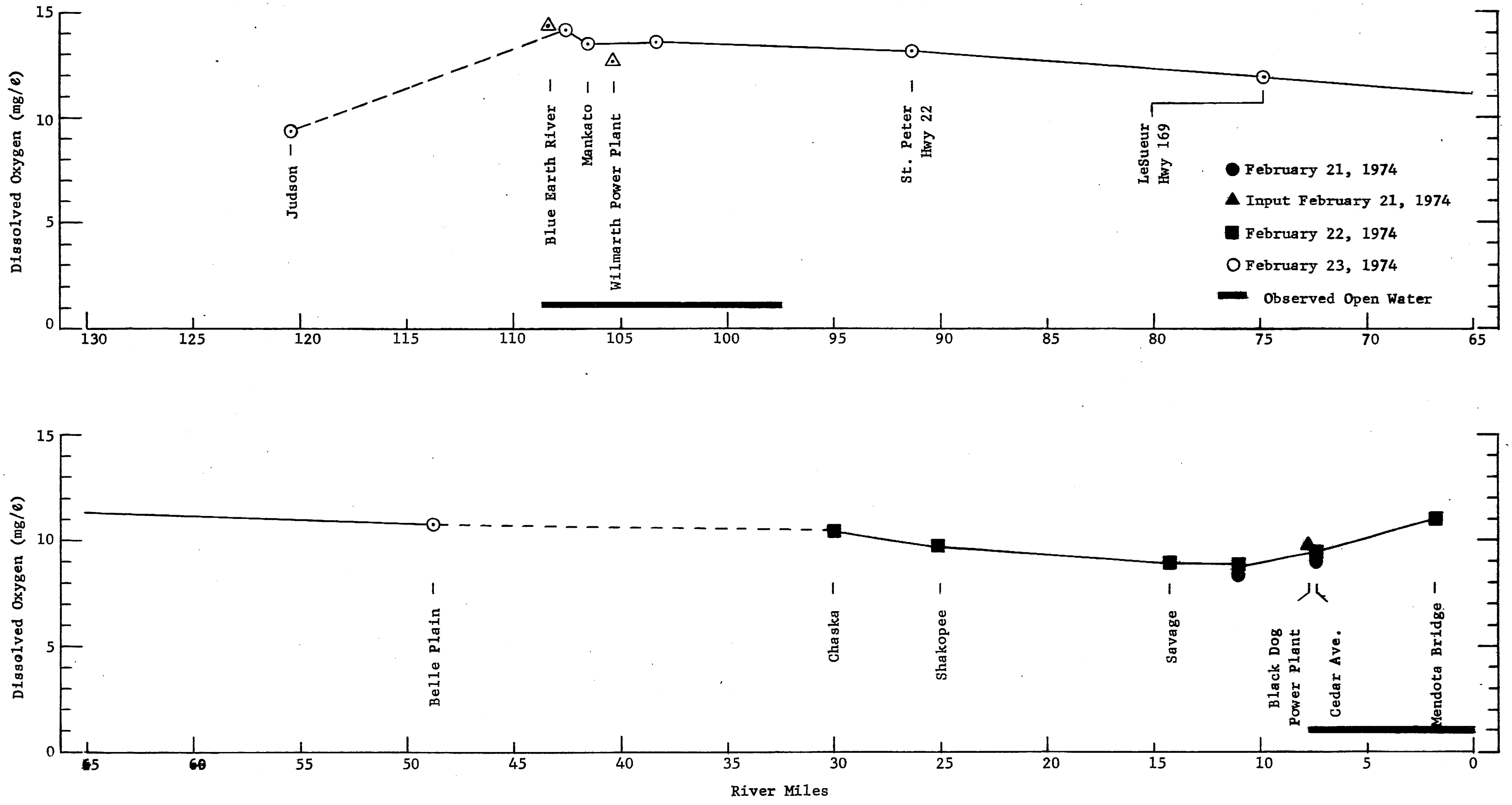


Fig. 54 - Minnesota River, February 1974 - Dissolved Oxygen

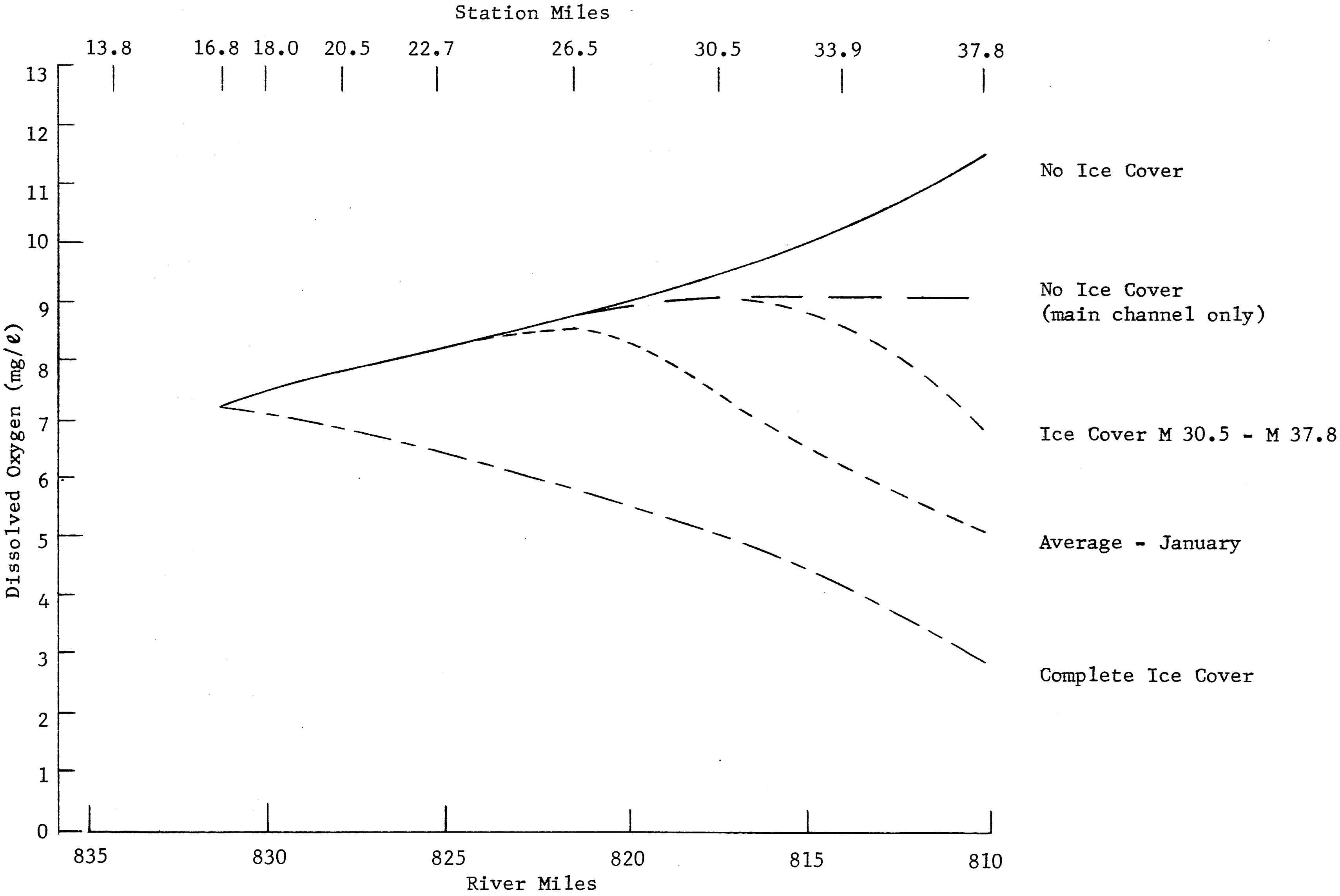


Fig. 55 - Dissolved Oxygen in the Mississippi River in January - Data from Schroepfer, Susag, et al. (1965)

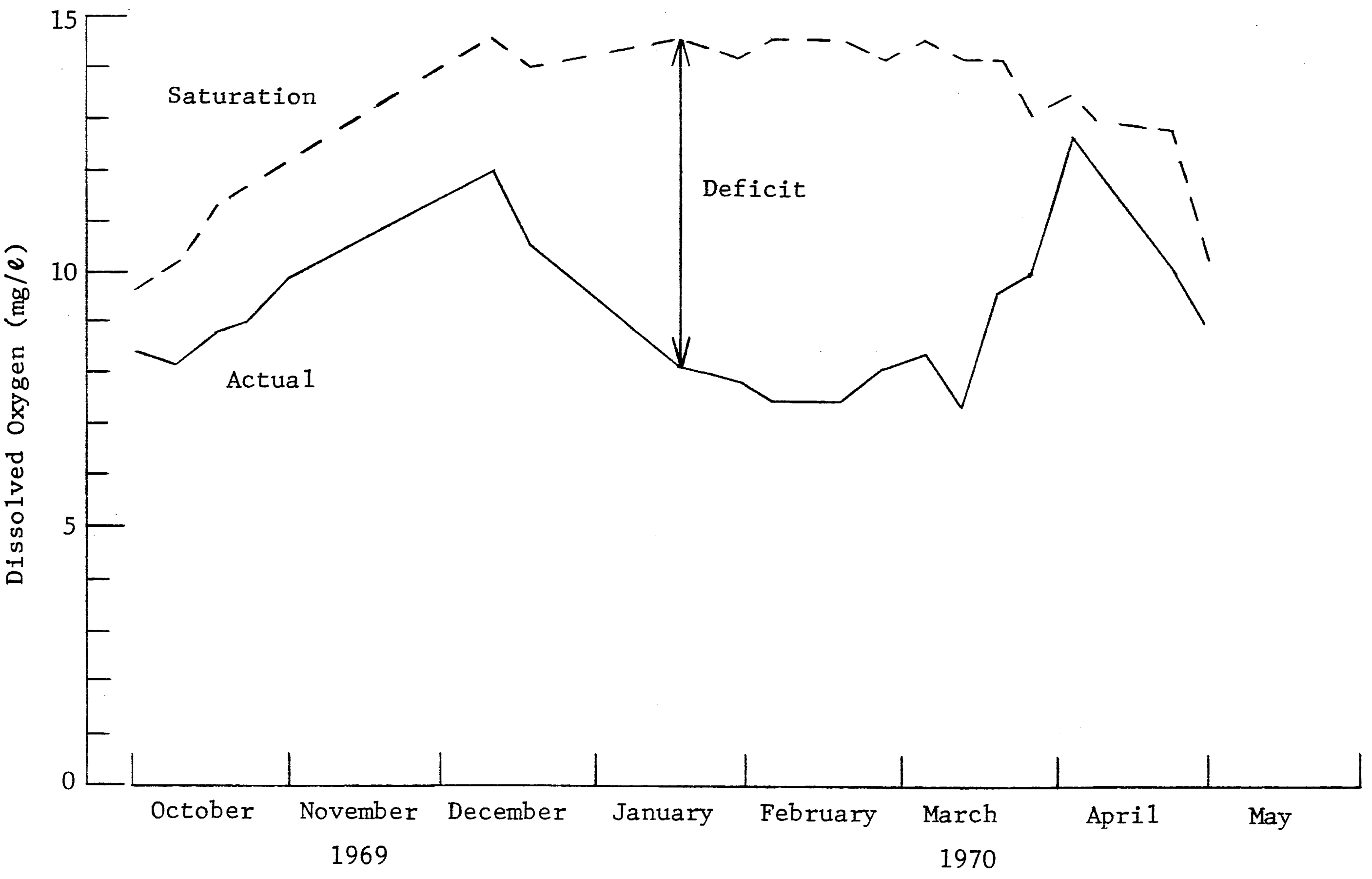


Fig. 56 - Dissolved Oxygen Concentration in the Mississippi River at Lock & Dam No. 3

Minnesota River and shown in Fig. 54. The overall average loss rate from Mankato to Savage is on the order of

$$\frac{14.2 - 9.0}{107.5 - 11.0} = 0.054 \text{ mg}/\ell \quad \text{D.O. per mile}$$

This figure is, of course, related to the biochemical oxygen demand (BOD load), the flow velocity of the stream, and the deoxygenation rate. The latter is temperature-dependent and smaller in winter than in summer. It is quite noteworthy that the D.O. concentrations go up wherever open water is present. At Mankato the Blue Earth River's flowing temporarily (due to bridge construction) through a contracted rapids-like area and over boulders is probably responsible for the D.O. jump from below 10 mg/ℓ to over 14 mg/ℓ. Open water caused to a minor degree by the effluent from the municipal sewage treatment plant and to a larger degree by the Wilmarth power plant is responsible for the constant D.O. level extending several miles downstream from Mankato. Beginning at the edge of the ice cover, D.O. concentrations are seen to drop. Similarly, D.O. levels increase when the river reaches the open water areas downstream of Savage which are primarily due to the cooling water effluent from the Black Dog plant.

The measured dissolved oxygen levels in the Mississippi River reported in Figs. 51 and 52 show features similar to those of the Minnesota River. The first survey was taken early in winter and covered the river from Riverside to Frontenac during a period of very low temperatures and maximum ice coverage. The apparent longitudinal rate of oxygen depletion was on the order of

$$\frac{(13.8 - 11.8) + (13.8 - 12.2) + (13.3 - 12.8)}{(840.5 - 790.7)} = 0.082 \text{ mg}/\ell \quad \text{D.O. per mile}$$

This value is approximately 30 per cent higher than that for the Minnesota River. The difference is most likely due to differences in flow velocities or BOD loadings or both. The actual rate of biochemical oxygen depletion in the Mississippi River must have been higher than 0.082 mg/ℓ per mile, because some open water for surface aeration existed, as indicated. At the dam sites the river picked up several mg/ℓ of D.O.

The rate of oxygen uptake by surface aeration is not directly obtained in these measurements. It can only be estimated indirectly through an oxygen budget analysis using a Streeter-Phelps model or more elaborate mathematical oxygen models. Two D.O. surveys of the Mississippi River were made. The second one, made upstream of the metropolitan area later in winter, is reported in Fig. 52. D.O. levels increase gradually from the ice-covered area near St. Cloud to saturation and near-saturation values as the river encounters the open-water areas downstream of Monticello which were reported on earlier. The river maintains these high D.O. levels all the way to St. Paul. From there on the rate of apparent oxygen uptake comes to be on the order of

$$\frac{14.0 - 11.0}{843.2 - 815.2} = 0.11 \text{ mg}/\ell \quad \text{D.O. per mile,}$$

about 40 per cent higher than the January value.

Oxygen measurements taken at other stream sites provide a similar picture, for example, as shown in Figs. 40 and 41. Dissolved oxygen measurements in slowly flowing bodies of water are reported in Figs. 37 through 39. D.O. values are lower here than those observed in the streams, including an observed minimum of 4.15 mg/ℓ in the Duluth harbor. There appeared to be no significant vertical gradient anywhere. This is most probably due to the circulation induced by the sinking plumes at those sites. The sinking plume phenomenon has a direct bearing on oxygen balances in standing ice-covered waters. Oxygen depletion in lakes or impoundments is usually from the bottom up, because in standing water oxygen is removed by decomposing bottom material. Benthic oxygen demand can be very significant over a period of several months while an ice cover lasts. A bottom density current continuously removes the water which has become low in oxygen and replaces it with oxygen-enriched surface water. Further on-site investigations are desirable.

The results of the observed D.O. measurements can be summarized in the following way:

1. The D.O. concentrations measured ranged from 4.1 mg/ℓ to near saturation (approx. 14.4 mg/ℓ). The lowest value was recorded at the intake of the Hibbard plant at Duluth when the plant was

actually on standby (zero load). The second lowest value was 5.5 mg/ℓ, recorded two weeks later near the intake of the same plant.

2. Differentials in D.O. measured between the intake and the outlet of an operating plant were found to be less than 1 mg/ℓ.
3. Where cooling water is discharged over weirs several feet in height, such as are found at the Black Dog and Monticello plants, appreciable increases in D.O. (more than 1 mg/ℓ) can be produced. The same aeration effect occurs at dam sites such as Lock & Dam Nos. 2 and 3 on the Mississippi River. Cooling water outfalls, if designed for "free fall aeration," contribute to high D.O. levels during the winter, when surface aeration of streams is not possible because of the ice cover.
4. D.O. levels measured appear to be directly related to flow velocities and depths as shown in Table 9 below. Small flow velocities under an ice cover favor oxygen consumption and low D.O. levels. The sinking plume phenomenon is important in those situations.
5. The effect of cooling water effluents is to provide oxygen input by either weir aeration at the outfall or surface aeration in open water reaches produced by the melting of the ice cover in the river or lake. The available data lend themselves to illustrating these effects at several sites.

Table 9. -- RANGE OF D.O. VALUES MEASURED AND DEPTHS AND FLOW VELOCITIES ESTIMATED

	D.O. mg/ℓ	Avg. Depth (est.) ft	Avg. Velocity (est.) fps
Duluth Harbor	4.1 to 7.8	2 - 7	0 - 1
Lake St. Croix	9.3 to 11.4	25 - 35	0 - 1
Colby Lake	8.8 to 11.8	10 - 20	0 - 1
Minnesota River	8.4 to 14.3	1 - 5	1 - 3
Mississippi River	9.5 to 15.4	5 - 10	1 - 3
Partridge River	13.5 to 14.2	1 - 2	1 - 3

VIII. LONG-TERM TRENDS IN DISSOLVED OXYGEN LEVELS

To further substantiate the findings made in the course of this study and broaden the frame of the interpretation, some other sources of D.O. data were consulted. Measurements made between February 12 and 15, 1973, and reported by the EPA are quite similar to the data reported herein for January and February of 1974. The EPA data have been plotted in Figs. 57 and 58 and should be compared with Figs. 52 and 54.

D.O. data collected in Pool No. 3 of the Mississippi River and made available by Dr. E. Miller illustrate the relatively small variability of dissolved oxygen with time during midwinter. The data are for 1971 and 1972 and are reproduced in Fig. 59. This trend was already apparent in Fig. 56 for the winter of 1969-1970. The increase in measured D.O. levels from the 1971 to the 1972 winter season was significant.

It should be mentioned that the Metropolitan Sewer Board (now Metro Wastes Control Commission) has extensive sets of D.O. measurements which are not included in this study.

In the winter of 1963-64 Schroepfer, Susag, et al. (1965) conducted an extensive survey of D.O. conditions in the Mississippi downstream of St. Paul which showed very low oxygen levels in that reach of the river. Since then treatment facilities and methods at the Pig's Eye municipal sewage treatment plant have been largely upgraded and expanded, and more recently D.O. levels in the stream have been much higher than those documented for 1963-64 by Schroepfer, Susag, et al. (1965). In this context it should be noted that the midwinter D.O. levels measured have increased not only downstream of the Pig's Eye sewage treatment facility, but also upstream. This trend is shown in Fig. 60. D.O. levels upstream of the Pig's Eye plant are also significantly higher than those measured by Schroepfer, Susag, et al., as is shown in Fig. 60. One possible interpretation of this observation is that D.O. levels in the Mississippi have improved not only because of a reduction in BOD load, but also because of greater natural oxygen input due to surface aeration upstream. This would be related to cooling water discharges. Figure 60 shows the situation at mile 839.2 (Robert Street Bridge in St. Paul) and at mile 856.7 (Riverside).

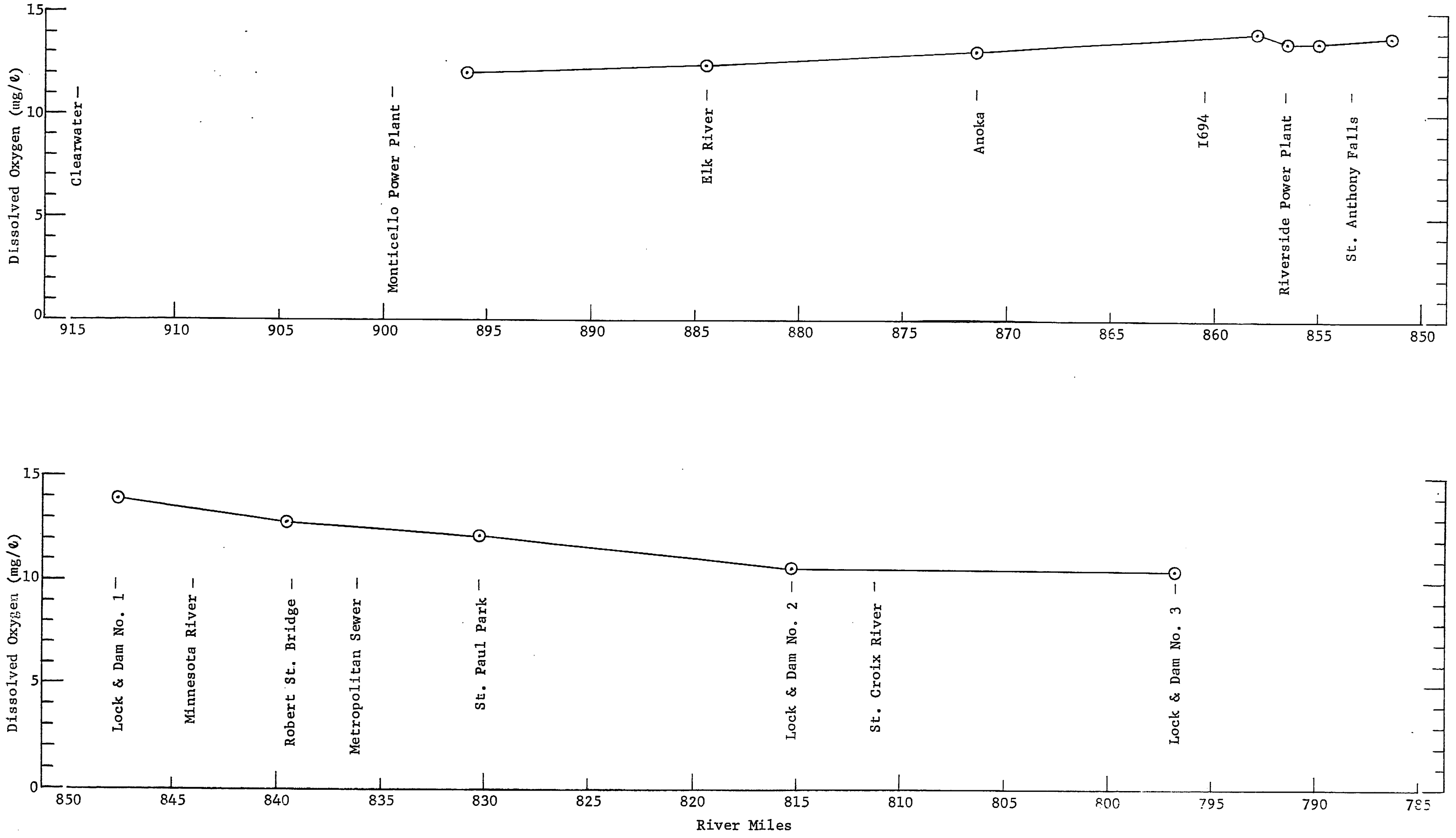


Fig. 57 - Mississippi River, January 12-13, 1973 - Dissolved Oxygen - EPA Data

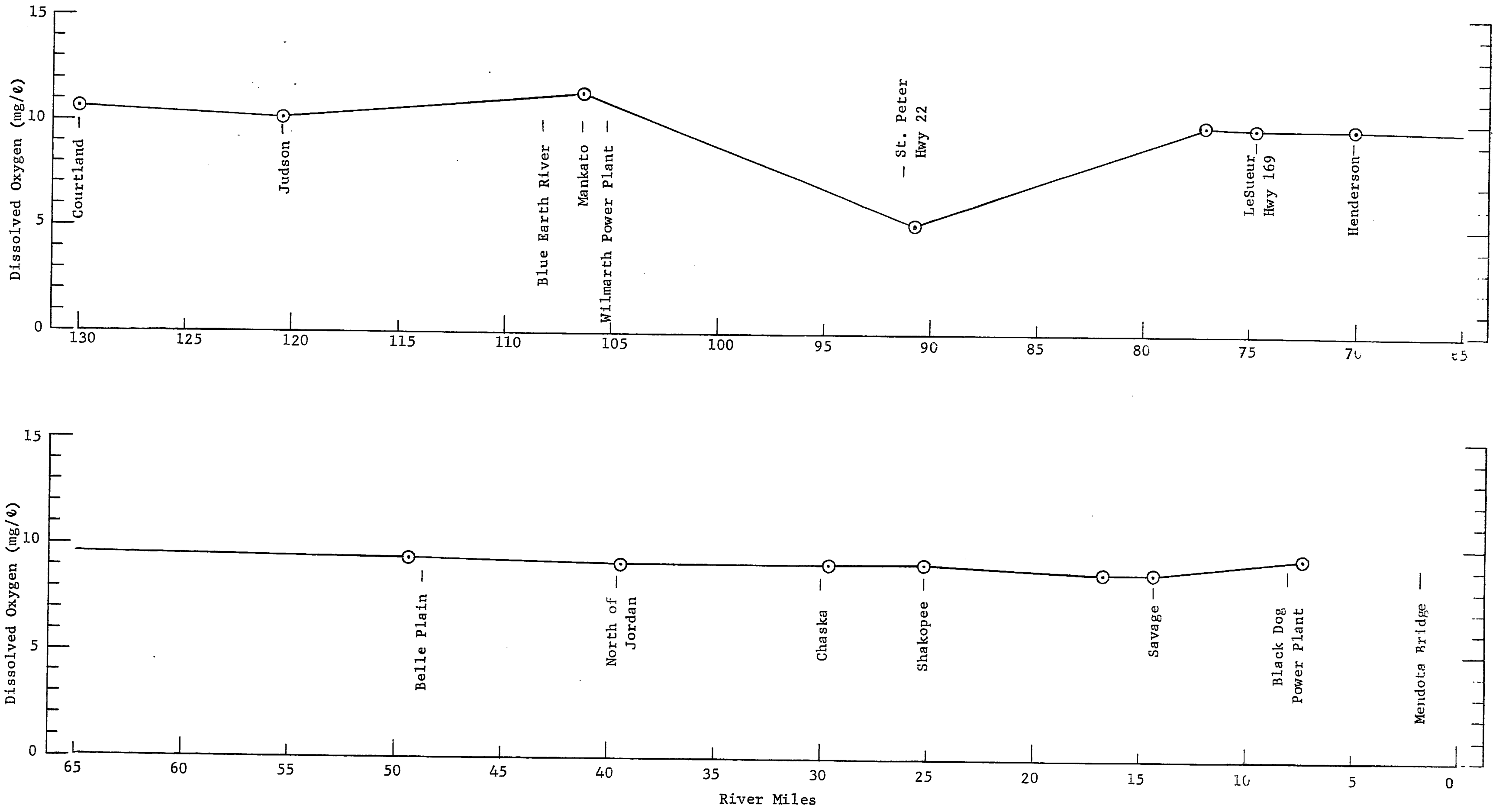


Fig. 58 - Minnesota River, February 12-15, 1973 - Dissolved Oxygen - EPA Data

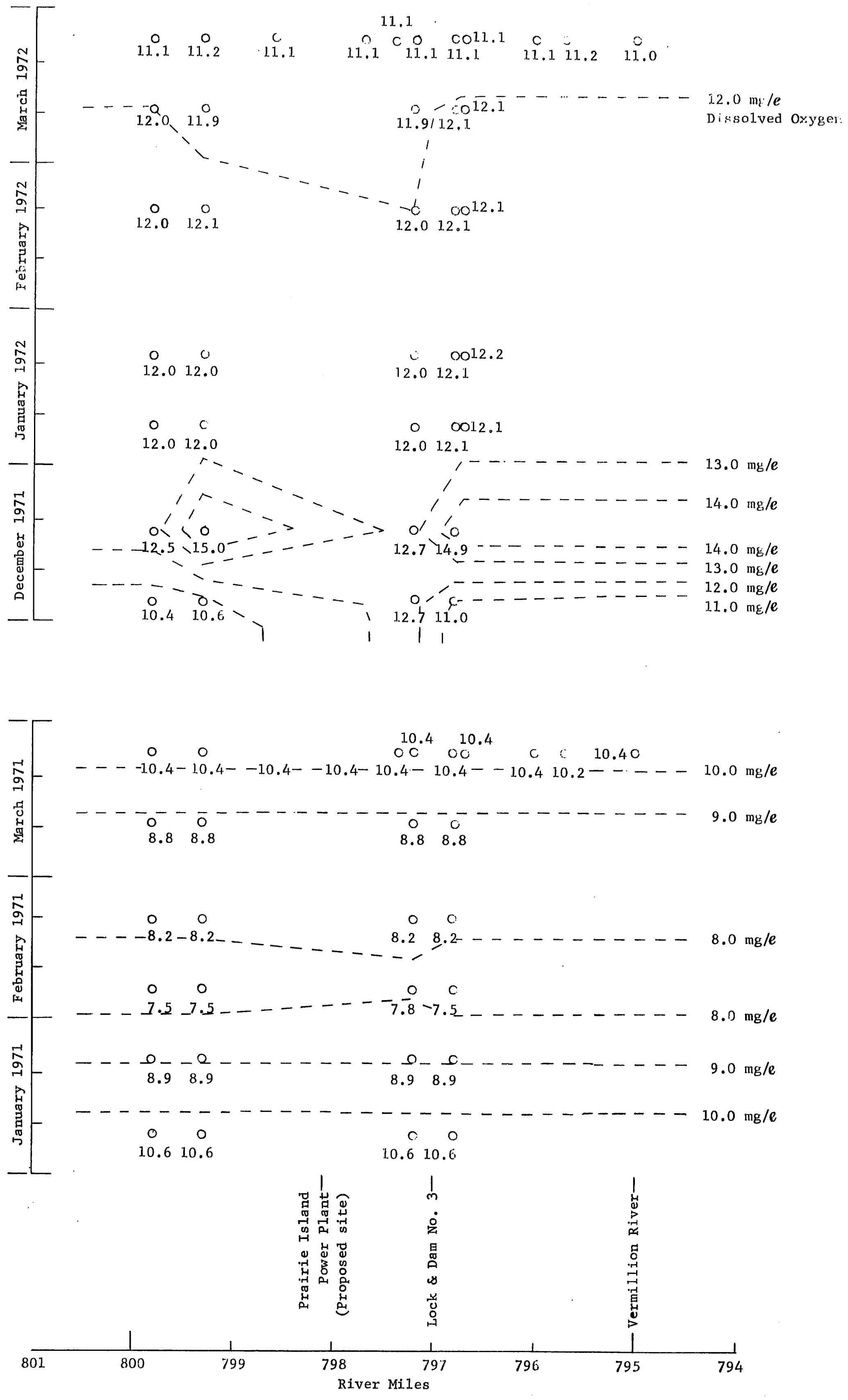


Fig. 59 - Mississippi River, 1971-1972 - Dissolved Oxygen (Data from Dr. Ed Miller, presently with North Star Research and Development Institute, 1974)

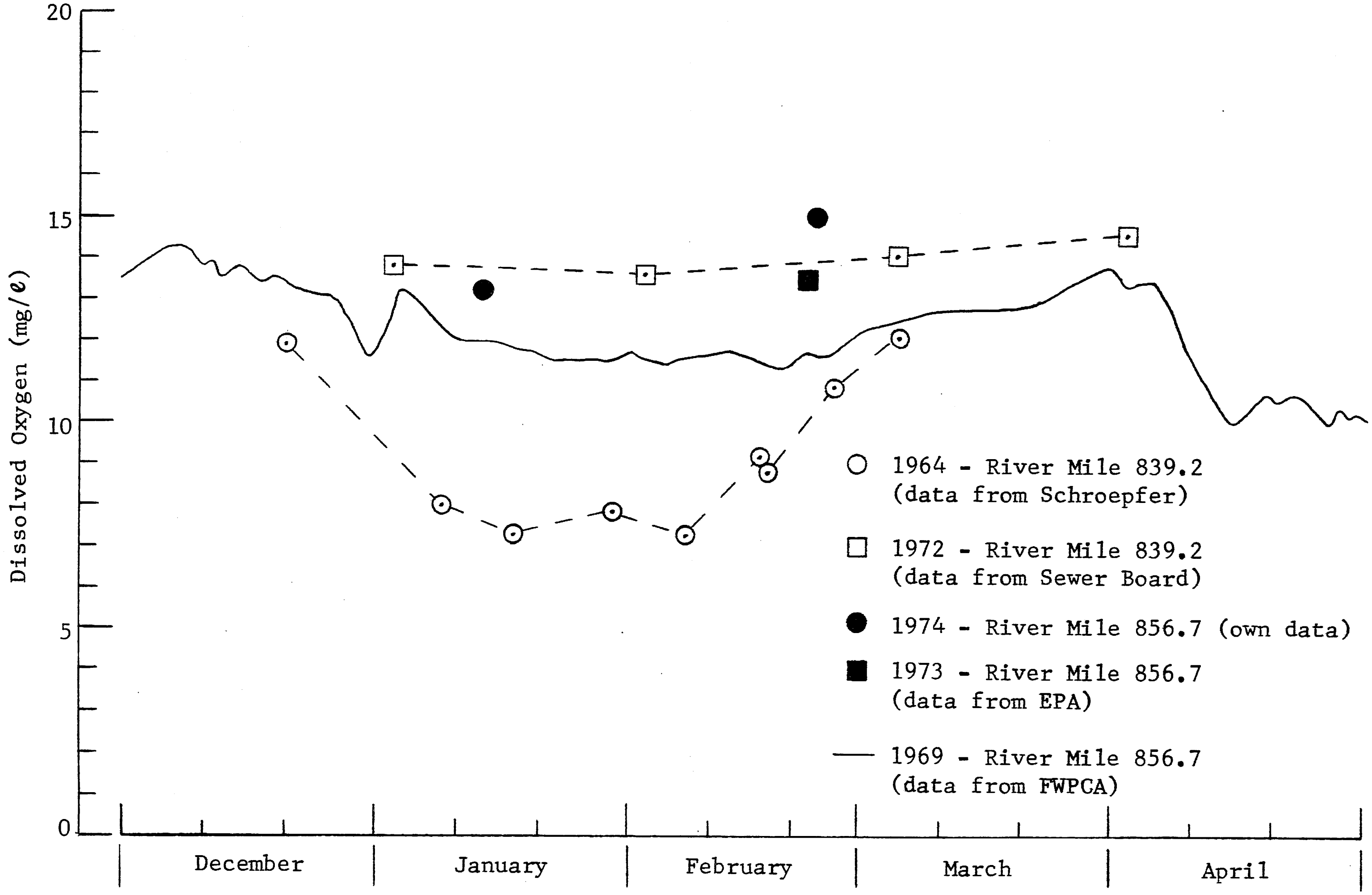


Fig. 60 - Dissolved Oxygen in Mississippi River Upstream from Pig's Eye

A compilation of data covering a 46-year span is given in Fig. 61. The data are from six different sources and are for locations on the Mississippi River within the metropolitan area; they illustrate the general trend clearly. For further correlation and comparison, Fig. 62 shows the development of total midwinter power generation within the metropolitan area. It is hypothesized that the results shown in Fig. 61 are related to the data in Fig. 62 by surface aeration.

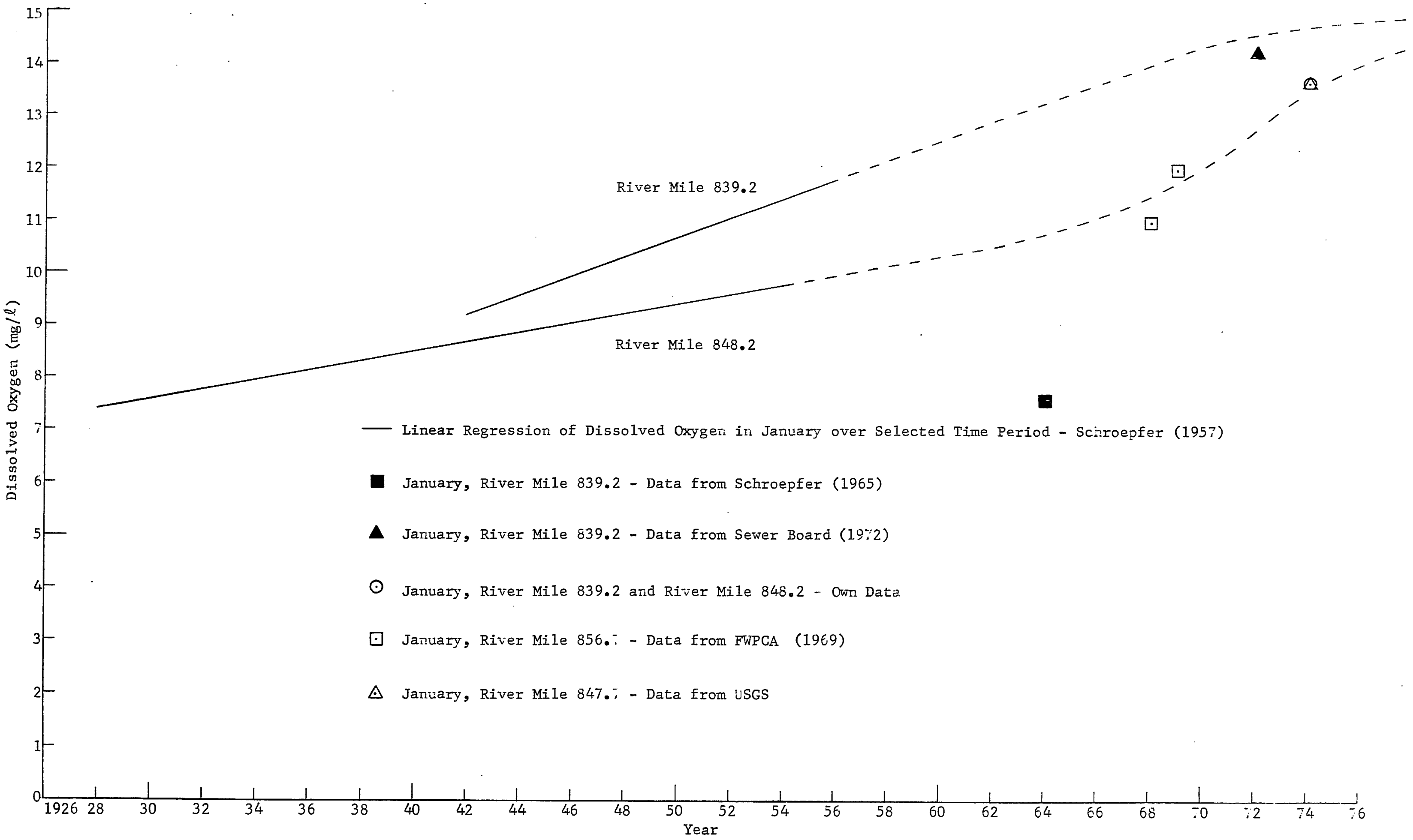


Fig. 61 - Long-Term Trend of Dissolved Oxygen in the Mississippi River Upstream of Pig's Eye under Midwinter Conditions

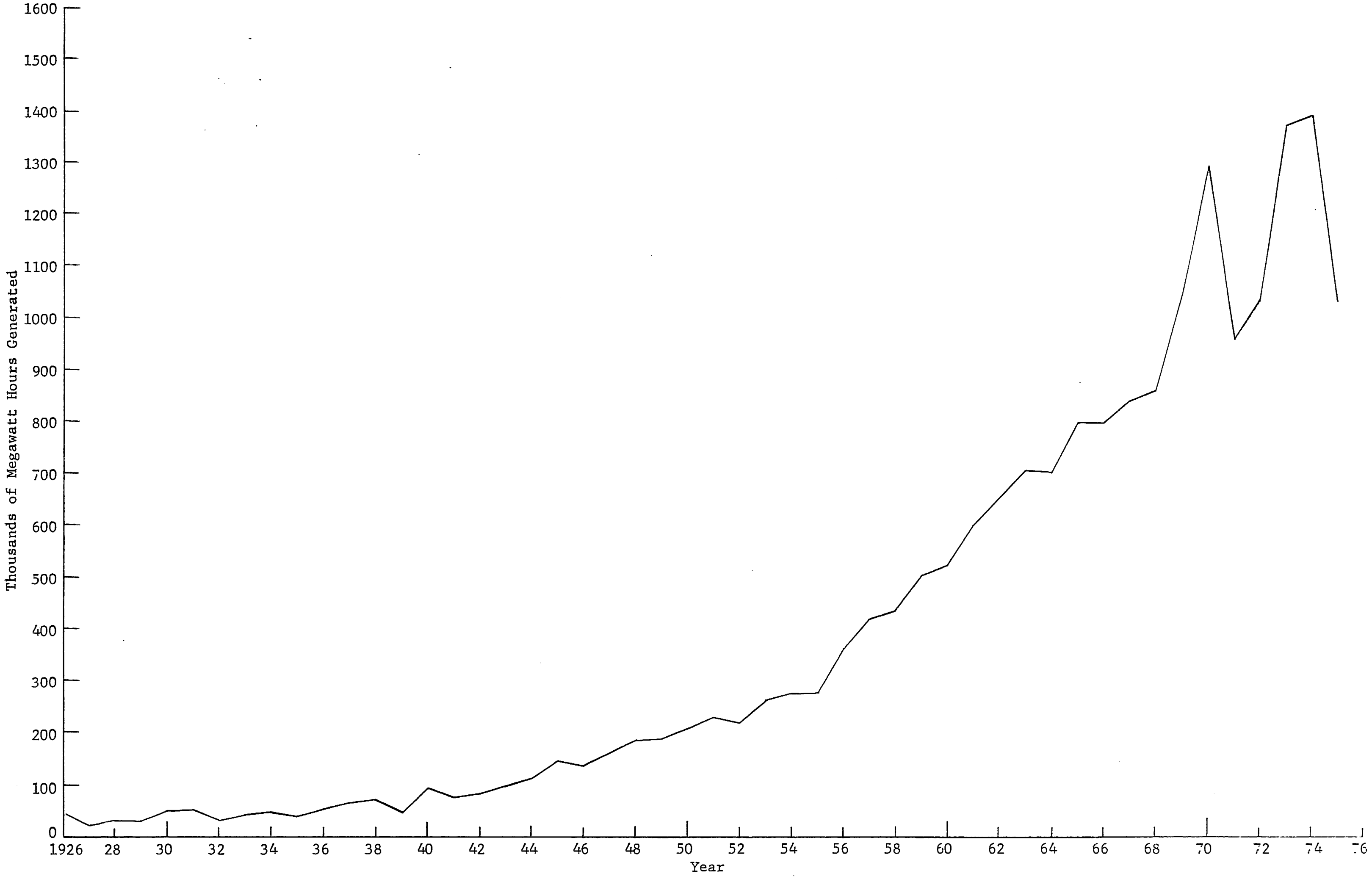


Fig. 62 - Power Output by Thermal and Nuclear Plants in the Larger Metropolitan Area in January (including Monticello, Riverside, Black Dog, High Bridge, and A. S. King Plants)

IX. ASSESSMENT OF SOME BENEFICIAL EFFECTS OF COOLING WATER INPUT ON WINTER CONDITIONS IN MINNESOTA SURFACE WATERS

As was pointed out in Section II, heat addition to a surface water body under winter conditions is termed beneficial if it enhances water uses. Several such benefits have been listed on pages 3 and 4. The data assembled in this report suggest the following observations and conclusions:

One primary effect of cooling water discharges into surface waters under Minnesota winter conditions is to reduce the period and the area of ice coverage. Another, equally important primary effect is to generate flow patterns, particularly sinking plumes, which otherwise would not have existed. Secondary effects are also produced. Some of these can be shown to be beneficial to the receiving water, at least in a qualitative sense. They include advancement of spring ice break-up, which facilitates navigation and spring flood runoff; increases in dissolved oxygen levels through augmented surface aeration; prevention of ice damage; and facilitation of water withdrawal.

1. Advancement of Spring Ice Break-Up and Its Relationship to Navigation and Snowmelt Runoff

Records of ice break-up and aerial and satellite pictures show that the ice break-up on streams receiving cooling water effluents is advanced by up to several weeks. Long river stretches are therefore ice-free early in the season. On the Mississippi, navigation seems to benefit from it. It is not easy to determine the size of that navigational benefit, but data presented herein support the notion that the lengthening of the navigation season and cooling water discharges are related. The primary impact of a longer navigation season is, of course, on commercial navigation, but recreational activities can also be mentioned.

An early ice break-up also clears the river of potentially hazardous ice which might produce problems during the annual spring flood runoff. Where cooling water is discharged into a stream or river, the ice break-up and the spring flood runoff do not usually coincide.

2. Enrichment in Dissolved Oxygen

Dissolved oxygen levels in all the streams and lakes surveyed were frequently increased where cooling water discharges existed. Oxygen addition through surface aeration occurred in the open-water areas and at the free overflow which exists at most outfall sites. The near-saturation levels measured in the Mississippi River in the metropolitan area are directly related to increased surface aeration. The winter oxygen drop due to the ice covers has gradually disappeared over the last ten years. As a result of this effect, in addition to better treatment of municipal sewage, observed dissolved oxygen levels in the Mississippi River have been near saturation upstream of the metropolitan area and significantly above the required minimum downstream of it.

Where cooling water is discharged into a lake or harbor without significant throughflow, oxygen profiles have been found to be uniform with depth and not stratified as is usually the case in lakes and impoundments. The sinking plume which has been observed at those outfalls is the most likely cause for this uniformity. Observed oxygen levels in those lakes and impoundments were also found to be higher than is typical for lakes in winter. Oxygen enrichment by the sinking plume is the most probable reason for the difference. In the near field, discharged water is in contact with the atmosphere (Fig. 63) and often is discharged over a weir or the like (Fig. 64), and therefore the water downstream of a cooling water discharge can be richer in dissolved oxygen than the water upstream.

The sinking plume is a carrier which is, or should be, of significant interest where oxygen levels in a receiving water body are marginal, such as in the Duluth harbor. The sinking plume reaches the lowest portions of the water body. If it is rich in oxygen, the receiving water body's oxygen balance benefits from it. There is potential for the use of sinking plumes in water quality management.

3. Prevention of Ice Damage and Facilitation of Water Withdrawal

Benefits from the elimination of ice damage are difficult to prove. There appear to be no continuous records. Existing information indicates that at least one ice jam which caused significant damage to structures and

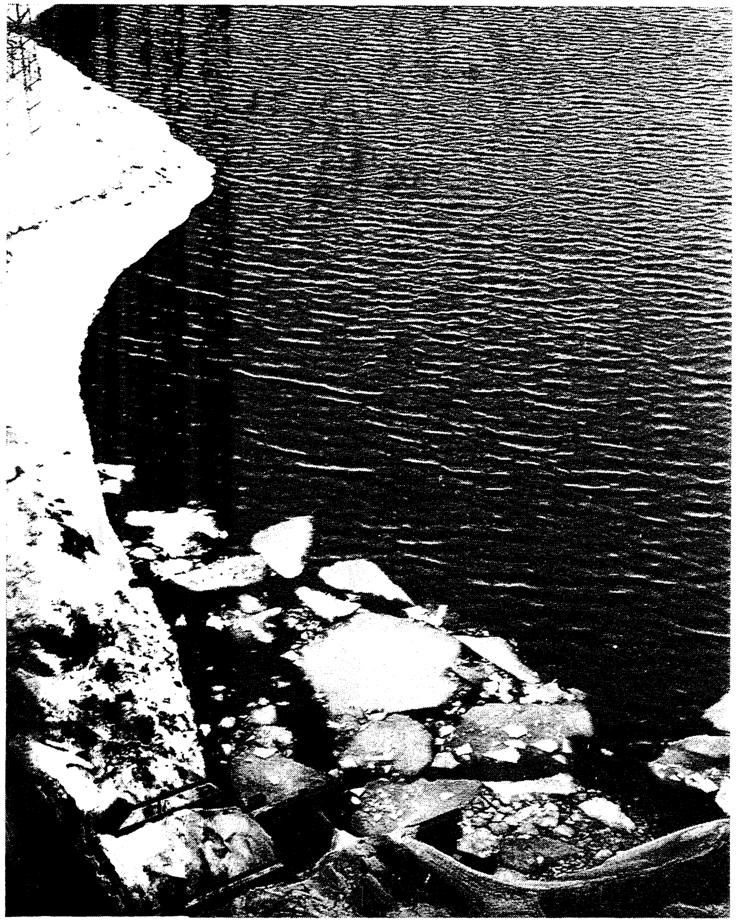


Fig. 63 - Wind Action on a Shallow Open-Water Near Field at Hibbard Power Plant in Duluth Harbor (zero cooling water discharge from channel in foreground at time picture was taken)

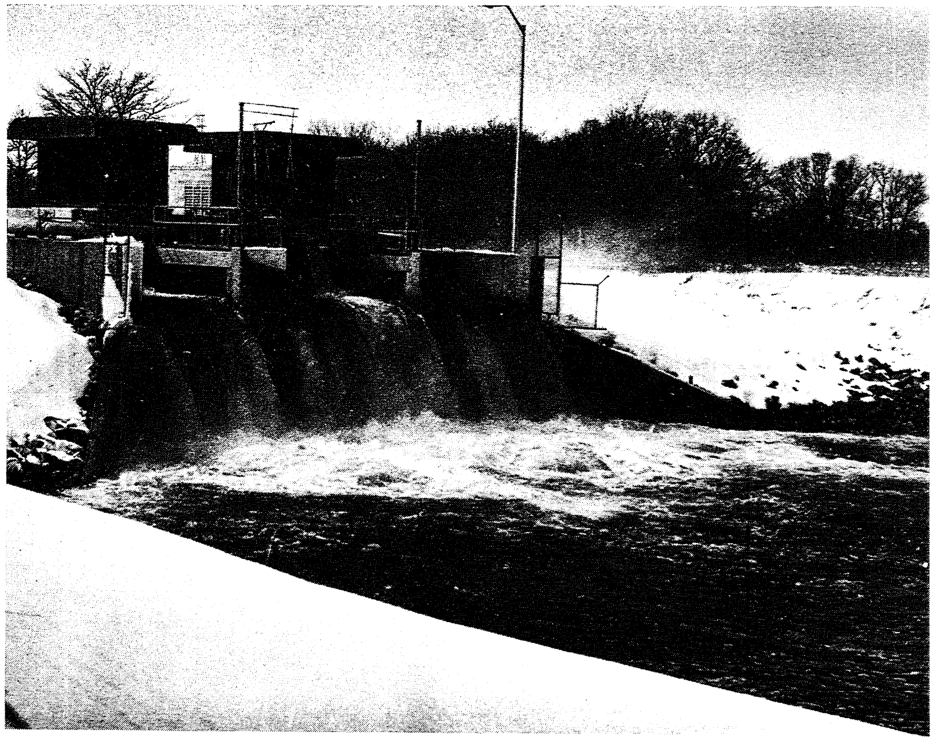


Fig. 64 - Discharge of Cooling Water into Channel at Monticello Power Generating Plant

facilities on the river banks has occurred on the Mississippi (see Appendix C). There are over 30 bridges, numerous marinas and docking and loading facilities, and three major navigation locks on the Mississippi River within the metropolitan area. Last but not least, water intakes for municipal water works or hydroelectric power plants frequently become ice-locked under natural conditions. On an ice-free river, such problems are greatly minimized.

4. Esthetics and Waterfowl Habitat

Open water generated by cooling water effluents may be of esthetic value, particularly in urban areas. It also attracts waterfowl, which people may enjoy seeing. Showing the dependency of open water areas on cooling water discharges has been one major objective of this study. However, the assessment of esthetic values is beyond the scope of the study.

X. CONCLUSIONS

1. The field studies and measurements described in this report were undertaken to determine the effect of cooling water discharges on winter conditions in surface waters with particular reference to possible beneficial effects.

2. Data were collected at 14 different power plant sites and on river reaches connecting several of these sites. The quantitative information collected has been assembled in this report, together with data from other sources, and has been subjected to qualitative interpretive analysis. A quantitative analysis of the processes which led to the observed data needs to be made in the future.

3. The following parameters were observed or measured:

    a. Areal extent of ice covers
    b. Periods of ice coverage
    c. Ice thicknesses
    d. Dissolved oxygen

4. The period of natural ice coverage of surface waters in Minnesota lasts from approximately December through March (four months) in the south and from approximately November through April (six months) in the north.

5. During the winter of 1973-74 the period of ice coverage of the Mississippi River in the metropolitan area lasted approximately from December 6 through March 28, with partially ice-free conditions at times existing in between.

6. More than 60 per cent of the 114-mile reach of the Mississippi River between Monticello and Lake Pepin was ice-free during six surveys taken at 18-day intervals.

7. All cooling water discharges produce at least a small open-water near field.

8. The open-water far field sometimes had no apparent direct connection with the discharge, but occurred farther downstream as an apparently independent stretch of open water.

9. Sinking plumes were seen to exist at several of the sites surveyed.

10. The dissolved oxygen levels measured ranged from 4.1 mg/ℓ to near saturation (approximately 14.4 mg/ℓ). The lowest value was recorded at the intake of the Hibbard plant in the Duluth harbor when the plant was actually on standby (zero load). The second lowest value was 5.5 mg/ℓ recorded two weeks later near the intake of the same plant.

11. Differentials in dissolved oxygen between the intake and the outlet of an operating plant were found to be less than 1 mg/ℓ in most cases.

12. Where cooling water is discharged over weirs several feet in height, appreciable increases in dissolved oxygen (more than 1 mg/ℓ) can be produced.

13. The dissolved oxygen levels measured in ice-covered waters appear to be directly related to flow velocities and depths. This is not an unexpected finding. If the flow velocities are small, biochemical oxygen uptake produces a stronger oxygen sag in a given river reach because the residence times are longer. In shallow water the benthic oxygen demand produces a faster oxygen depletion of the water column than in deep water.

14. Open-water reaches produced by cooling water discharges provide oxygen input through surface aeration. The available data lend themselves to illustrating these effects at several sites.

15. Long-term trends in dissolved oxygen levels in the Mississippi River appear to be directly related to cooling water input and ice coverage.

16. Beneficial effects have been found, at least in qualitative terms. These effects are summarized in Section IX; they include those on navigation, dissolved oxygen, and potential ice damage. Further analysis is necessary to show the quantitative relationship between causes and effects.

REFERENCES

Ashton, George D. (1974), Evaluation of Ice Management Problems Associated with Operation of a Mechanical Ice Cutter on the Mississippi River, Special Report 214, Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, October 1974.

Ashton, G.; Uzuner, M. S.; and Kennedy, J. F. (1970), Two Investigations of River Ice, Report No. 129, Iowa Institute of Hydraulic Research, The University of Iowa, October 1970.

Baker, Donald G. (1971), Snow Cover and Winter Soil Temperatures at St. Paul, Minnesota, Bulletin 37, Water Resources Research Center, Univ. of Minnesota, Minneapolis, June 1971, 24 p.

Baker, Donald G. and Strub, Joseph H., Jr. (1963), Climate of Minnesota, Part II. The Agricultural and Minimum-Temperature-Free Seasons, Technical Bulletin 245, Agricultural Experiment Station, Univ. of Minnesota, June 1963, 31 p.

Bilello, Michael A. (1967), Water Temperatures in a Shallow Lake During Ice Formation, Growth and Decay, Research Report 213, CRREL, Hanover, New Hampshire, December 1967, 20 p.

Bolsenga, S. J. (1968), River Ice Jams - A Literature Survey, Research Report 5-5, U.S. Army Corps of Engineers, Lake Survey District, Detroit, June 1968.

Carey, K. L.; Ashton, G. D.; and Frankenstein, G. E. (1973), Ice Engineering For Civil Works - Baseline Study, CRREL, Hanover, New Hampshire, Aug 1973.

Dingman, S. L.; Weeks, W. F.; and Yen, Y. C. (1967), The Effects of Thermal Pollution on River Ice Conditions. 1. A General Method of Calculation, Research Report 206, CRREL, Hanover, New Hampshire, December 1967.

FWPCA (1969), Data Summary, July 7, 1967 - June 30, 1969, Automatic Monitoring Program, Minneapolis-St. Paul Area, USDI, FWPCA, Great Lakes Region. Upper Mississippi River-Lake Superior Basin Office.

Hayes, Steve and Stefan, H. (1972), Water temperature measurements in Lake St. Croix during January and February 1972, unpublished data.

Krosch, H. F. and Lee, P. (1969), Water temperature measurements made in Lake St. Croix on January 8, 1969; reported in NSP (1970).

Metropolitan Sewer Board (1972), Newsletter.

Miller, Ed (1974), data used in Fig. 59, personal communication.

Northern States Power Company (NSP) (1970), Environmental Monitoring Program Annual Report 1969 (December 1968 through November 1969) for the Allen S. King Generating Plant, Oak Park Heights, Minnesota. July 1, 1970.

Paily, P. P.; Macagno, E. O.; and Kennedy, J. F. (1974), "Winter-Regime Thermal Response of Heated Streams," Jrl. of Hydraulics Division, ASCE, Vol. 100, No. HY4, April 1974, pp. 531-552.

Schroepfer, George; Susag, Russel; et al. (1965) (Department of Civil Engineering, Univ. of Minnesota), Open-file report for Minneapolis-St. Paul Sanitary District, 1965.

Schroepfer, George; Susag, Russel; et al. (1961), Pollution and Recovery Characteristics of the Mississippi River, Appendix I, Part 3, Sanitary Engineering Report 110 S, Department of Civil Engineering, University of Minnesota, September 1961.

Schroepfer, George; Susag, Russel; et al. (1957), Pollution and Recovery Characteristics of the Mississippi River, An Analysis of Available Data for the Period 1926-1955, Vol. I, Part 1, Sanitary Engineering Report 110 S, Department of Civil Engineering, University of Minnesota, October 1957.

Appendix A

SITES AND DATES OF PHOTOGRAPHIC SURVEYS OF ICE COVER

Mississippi River

12/6/73 (ground), Lowry Ave. Bridge in Minneapolis to Robert St. Bridge in St. Paul

12/18/73 (ground), Soo Line R.R. Bridge in Minneapolis to High Bridge in St. Paul

12/24/73 (ground), Highway 24 Bridge to St. Paul Park

1/2/74 (ground), 44th Ave. N. (Webber Park) in Minneapolis to Robert St. Bridge in St. Paul

1/9/74 (ground), 37th Ave. NE Bridge in Minneapolis to Robert St. Bridge in St. Paul

1/12/74 (ground), Highway 24 Bridge at St. Paul Park to R.R. bridge at Hastings

1/13/74 (ground), Lock and Dam No. 3, Red Wing, Old Frontenac (Lake Pepin)

1/16/74 (ground), 37th Ave. NE Bridge in Minneapolis to Robert St. Bridge in St. Paul

1/28/74 (ground), Franklin Ave. Bridge to Robert St. Bridge in St. Paul, Lock and Dam No. 2 at Hastings, Lock and Dam No. 3 at Red Wing, Lock No. 4 at Alma, Wis.

1/29/74 (ground), Bridges in St. Cloud, Monticello, Elk River, Anoka, Coon Rapids Dam, 37th Ave. NE, Minneapolis, and Lowry Ave. in Minneapolis

2/9/74 (air), Sartell to Minneapolis

2/16/74 (air), Coon Rapids Dam

2/21/74 (ground), I-694 Bridge in Minneapolis to Larpenteur Ave. Bridge in St. Paul

2/26/74 (ground), Clearwater Bridge, Monticello Plant, Monticello Bridge, Elk River Bridge, Anoka Bridge

3/1 and 3/2/74 (ground), M P and L Boswell Plant, Cohasset, C. of E. Dam, Grand Rapids, Judson

3/10/74 (air), Royalton to Prescott (exclusive of Minneapolis and St. Paul)

3/25/74 (IDS Tower), NSP Riverside Plant to St. Anthony Falls

St. Croix River

3/10/74 (air), Stillwater to Prescott

Minnesota River

2/16/74 (air), Henderson to Ortonville (Big Stone Lake)

2/21/74 (ground), I-35W Bridge, Black Dog to Mendota Bridge

2/23/74 (ground), Judson, Mankato, St. Peter, Le Sueur, Belle Plaine

Colby Lake

3/2/74 (ground)

Duluth Harbor

3/3/74 (ground), Intake bay and outlet bay of Hibbard Plant

Appendix B

SITES AND DATES OF D.O. MEASUREMENTS

Mississippi River

1/11/74 D.O. measurements at 2 stations

1. Lowry Bridge
2. River Flats (So. of Washington Bridge)

1/12/74 D.O. measurements at 5 stations

1. High Bridge P.P. outlet
2. Outlet downstream of Robert St. Bridge
3. Newport - St. Paul Park Bridge
4. Upstream Lock and Dam No. 2
5. Downstream of Lock and Dam No. 2

1/13/74 D.O. measurements at 4 stations

1. Upstream of Lock and Dam No. 3
2. Downstream of Lock and Dam No. 3
3. Red Wing Park
4. Frontenac (Lake Pepin)

1/22/74 D.O. measurements at 1 station - River Flats

2/7/74 D.O. measurements at 7 stations

1. Railroad Bridge No. of Riverside plant (thru ice)
2. Lowry Bridge
3. Railroad Bridge (between Lowry and Broadway)
4. Broadway Bridge
5. Plymouth Ave. Bridge
6. Hennepin Bridge
7. SAFHL

2/25/74 D.O. and water temperature measurements

1. Park Bridge No. of Riverside Plant
2. Broadway Bridge
3. Franklin Ave. Bridge
4. Interstate 35E Bridge
5. High Bridge plant outlet
6. Robert St. Bridge

2/26/74 D.O. and water temperature measurements

1. Monticello Bridge
2. Monticello plant intake
3. Monticello plant outlet
4. Clearwater Bridge
5. Elk River Bridge
6. Anoka Bridge

Mississippi River (continued)

2/27/74 D.O. and water temperature measurements

1. Robert St. Bridge
2. Interstate 494 Bridge
3. Newport - St. Paul Park Bridge
4. Hastings Bridge (downstream of Lock and Dam No. 2)
5. Upstream of Lock and Dam No. 2

3/1/74 D.O. and water temperature measurements

1. Jacobson Bridge
2. 2.8 mi downstream of Grand Rapids Bridge (Highway 169)
3. Grand Rapids Highway 169 Bridge
4. Above Grand Rapids Dam
5. Discharge of power plant at Grand Rapids Dam

3/2/74 D.O. and water temperature measurements

1. Above Pokegama Dam
2. Below Pokegama Dam
3. Clay Boswell power plant intake
4. Clay Boswell power plant outlet channel
5. Highway No. 6 Bridge upstream of Clay Boswell (thru ice)
6. Cohasset Bridge
7. Discharge at paper mill at Grand Rapids

St. Croix River - through ice

1/17/74 D.O. and water temperature profiles

1. No. of King Plant (2 locations)
2. Bayport park and beach (2 locations)
3. North Hudson (2 locations)

1/30/74 D.O. and water temperature profiles

1. Stillwater Bridge (surface only)
2. No. of King Plant
3. Bayport park and beach
4. North Hudson
5. St. Croix beach

Minnesota River

2/21/74 D.O. and water temperature measurements

1. Sibley House
2. No. outlet channel of Black Dog Plant
   a. Above weir
   b. Below weir

3. So. outlet channel of Black Dog Plant
   a. Above weir
   b. Below weir

4. Inlet to Black Dog Plant
5. West of Interstate 35W Bridge (thru ice)
6. Cedar Ave. Bridge

Minnesota River (continued)

2/22/74 D.O. measurements

1. Mendota Bridge
2. Cedar Bridge (also water temperature)
3. West of 35W Bridge (thru ice)
4. Savage Bridge
5. Shakopee Bridge
6. Chaska Bridge (thru ice)

2/23/74 D.O. and water temperature measurements

1. Judson, Minn. (thru ice)
2. Blue Earth R. Bridge at Mankato
3. Highway 169 Bridge at Mankato
4. Mankato Bridge
5. Wilmarth power plant outlet
6. Approx. 1.5 mi downstream of Wilmarth power plant
7. St. Peter Bridge (Highway 22)
8. LeSueur Bridge (Highway 169)
9. Belle Plaine Bridge

Colby Lake

3/2/74 D.O. and water temperature measurements

1. Erie Mining Co. pumping station
2. Hoyt Lake filter plant (thru ice)
3. Partridge River inlet
4. Colby Lake power plant outlet
5. Colby Lake power plant inlet
6. Colby Lake power plant railroad bridge
7. Partridge River downstream at bridge along road from Aurora to Hoyt Lakes

Hibbard Power Plant

3/3/74

1. Outlet
2. Inlet (thru ice)
3. East of plant toward main channel of St. Louis R. (thru ice)

3/15/74

1. Highway No. 2 Bridge
2. Point A (approx. 400 ft east of peninsula)
3. Point B (approx. 500 ft east of Light 3)
4. Point C (in NE corner of bay area receiving cooling water, approx. 250 ft from shore)
5. Point D (near point C, but on shore)
6. Point E (at the NE rim of the bay receiving cooling water, approx. 650 ft from point C toward the main shore)
7. Point F (approx. 800 ft from the edge of the open water area, toward outflow)
8. Inlet of plant
9. Outlet of plant

Appendix C -- REPORT ON NOVEMBER 1951 FLOOD AND ICE JAM BELOW ST. ANTHONY FALLS

HJL/RC/irk

UMPRT

26 September 1952

SUBJECT: November 1951 Flood on Mississippi River at Minneapolis, Minn.

THRU: Division Engineer
Upper Mississippi Valley Division
Corps of Engineers, US Army
St. Louis, Missouri

TO: Chief of Engineers
Department of the Army
Washington 25, D.C.

1. Authority. - The following report is submitted in accordance with paragraph 4223.05d, Orders and Regulations, inasmuch as the flood was caused by unusual ice-jam conditions warranting documentation of all related data.

2. Prior reports. - During the ice-jam period daily teletype reports were furnished to the Upper Mississippi Valley Division and Office, Chief of Engineers. Later, by letter, UMPVN, 7 December 1951, subject "Emergency Action with Respect to Drifting Barges," this office described existing conditions, the status of affected pieces of floating plant, and possible actions which could be taken to prevent damage to existing structures by barges caught in the ice.

3. Flood causes and related factors. - Above normal precipitation during the latter part of October and early in November had resulted in a flow of about 19,000 second-feet (about 15,000 second-feet above normal) in the Mississippi River at Minneapolis, Minn., on 19 November 1951. By 22 November flows had gradually receded to about 15,000 second-feet with some surface ice in pool No. 1 but no unusual backwater conditions. During the next few days below freezing temperatures, with lows of 11° to -6° F. and highs of 21° to 24° F., appeared to favor the formation of large quantities of frazil which anchored to the surface ice and caused an increasing obstruction to river flows in the reach marked on the inclosed map, generally above the Lake Street bridge. At this time much of the river channel in a 3-mile reach below the lower St. Anthony Falls dam appeared to be blocked by ice. Ice thicknesses of 22 to 24 feet extending to the river bottom were reported. Temperatures remained below freezing up to the morning of 28 November when the temperature rose to a high of 38°. About noon of that date another ice gorge upstream in Minneapolis reportedly broke sending a wave into pool No. 1 and contributing to the record stages noted in the following tabulation.

Location	Minimum damage stage feet	Crest stage 28 Nov. 51 feet	Maximum stage of record Stage feet	Maximum stage of record Year
St. Anthony Falls Upper Dam (mile 853.9):				
Pool	--	99.5	101.2	1916
Tailwater	--	52.6	54.2	1916
St. Anthony Falls Lower Dam (mile 853.5):				
Pool	52.0	51.6	53.3	1916
Tailwater	36.0	49.7	36.4	1916
Minneapolis Barge Terminal (mile 852.6)	34.5	41.2	33.3	1920
Locks and dam No. 1 (mile 847.6):				
Pool	--	25.4	30.7	1920

4. The flash crest was of short duration and was followed by a drop in stage at the St. Anthony Falls Lower Dam tailwater of several feet immediately after the crest reading. Subsequent above-freezing temperatures apparently mitigated conditions so that stages fell rapidly thereafter, reaching normal levels about 4 December. Detailed stage, discharge, and temperature data are shown for the ice-jam period on the inclosed sheet of hydrographs.

5. Efforts made to alleviate conditions. - On 25 November Northern States Power Company shifted all possible steam plant load from generating stations in St. Paul to the Riverside Station above St. Anthony Falls in order to increase the transfer of heat from condenser water to the river above the ice gorge. About that same date the City of Minneapolis diverted sewage flow into the river to assist in raising the temperature of the river water. Also, on 26 November the outflow from the Headwaters Reservoirs was reduced about 2,700 second-feet. However, there were no means of determining the effectiveness of the measures since the rising air temperatures after 27 November appeared to be the major factor in reducing the ice gorge.

6. Extent of damages. - The unusually high stages caused by the ice gorge and the action of the ice resulted in extensive damages to public utility, industrial, navigation, and private developments in the reach from the St. Anthony Falls Upper Dam to locks and dam No. 1. Principal damages are summarized in the following paragraphs.

7. Damages to public utilities. - The high stages in the pool above the St. Anthony Falls Lower Dam threatened the Twin City Rapid Transit

Company steam power plant at mile 853.6 (see photograph No. 1). Shut down of the 35-cycle generating plant would have halted movement of the entire street railway system in the Twin Cities. However, flooding of the power station was prevented by emergency measures involving expenditures of about $1,000. No major damage to the plant resulted. Subsequent conversion to buses of a substantial part of the rolling stock precludes further serious disruption of the transportation system due to a possible repetition of conditions experienced in 1951.

8. Damage to the timber decking of the spillway section of the St. Anthony Falls Lower Dam was disclosed after the high water receded and was estimated at about $125,000 by the Northern States Power Company. Damages to other properties of the power company located in the area and the increased cost of shifting the steam load to the Riverside station were estimated at $5,000 and $3,000, respectively. Damages to the bank in the vicinity of the Minneapolis Gas Company plant at mile 853.4 and necessary protective measures were estimated to total $13,200.

9. Damages to Corps of Engineers project. - During the afternoon of 23 November the high water overtopped the cofferdam of the St. Anthony Falls Lower Lock and Dam (mile 853.4) but caused only minor damage to the partially completed structure. Damages to the contractor's equipment and temporary works and losses suffered through necessary extra labor and cleanup of the area were estimated at about $70,000. A view of the inundated cofferdam area is shown in the accompanying photograph No. 2.

10. Damages to University of Minnesota property. - Sewer lines and steam tunnels connecting with the University of Minnesota steam plant on the left bank of the river (mile 852.9) were flooded. About 1,600 feet of a steam tunnel was flooded creating excessive quantities of steam where the water contacted the steam mains. The steam vented up connecting shafts into buildings above, soaking and loosening plaster and paint and warping woodwork and windows. Emergency sandbag dikes and operation of emergency pumps were constructed and operated to keep the University heated. Total costs of emergency protective measures, repair of damaged facilities, and cleanup of flooded areas are estimated at $30,000.

11. Industrial damages. - The high water and ice caused approximately $3,000 in damages to Western Oil and Fuel Company river terminal facilities located on the right bank at about mile 852.8, carried away about 2,000 tons of the 72,000 tons of coal stored on the municipal coal dock (representing a loss of about $27,600 including the cost of protective measures undertaken and coal salvage operations), and damaged river terminal facilities of the Phillips Petroleum Corporation to the extent of about $1,700. Views of the flooded coal dock and terminal area are shown in photographs Nos. 3, 4, and 5 accompanying this report.

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12. Damages to merchandise and navigation units. - The high water flooded the terminal and warehouse building to a depth of about 3 feet above the floor level and damaged stored merchandise including powdered milk, beans, fiber containers, and other miscellaneous stocks. Damages to the merchandise and the building and sea wall were estimated to total about $30,700 and $6,800, respectively.

13. On 23 November nine barges and the Towboat Harris had broken loose from their moorings at the Minneapolis Municipal Terminal. The towboat and seven barges remained at the terminal but were raised by the ice and thrust up on the dock in various positions as shown in photographs Nos. 6, 7,and 8. These pieces of equipment were secured by cables and lines. However, two of the barges were carried downstream to a point just above the Franklin Avenue bridge (mile 851.5) where they lodged in the ice as shown in photographs Nos. 9 and 10. Damages to the barges and towboat, including costs of protective and rehabilitation measures, were estimated to total $101,000. All of the navigation units were eventually rescued, one sunken barge raised, and the stranded barges returned to the water.

14. Other damages. - Several homes located along the left bank of the river at about mile 853.3 were flooded above first-floor levels. However, in most cases, furniture and appliances were moved in advance of the flood so that such damages were limited to about $10,000. In addition, owners of houseboats moored along the left bank at about mile 852.1 were inconvenienced and put to the expense of securing additional lines and cables to prevent loss of the houseboats. Such costs were estimated to total about $1,000.

15. Damages caused by the ice and high water are summarized as follows:

Type of damage	Estimated damage
Public utilities	$147,200
St. Anthony Falls Lower Lock and Dam Project	70,000
University of Minnesota	30,000
Industrial	32,300
Navigation	138,500
Other	11,000
Total	$429,000

16. Bibliography of pertinent data collected. - The following data have been collected and are on file in this office:

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a. Reports of field reconnaissance in damaged areas.

b. Newspaper clippings covering the flood.

c. Twenty-one photographs of flood conditions.

d. High-water elevations at pertinent locations along the Mississippi River in the affected area.

3 Incl (in trip)
1. Map and profile,
   Miss. R. at Mpls.
2. Temperature, discharge
   and stage graphs
3. Photographs (10)

A. H. BAGNULO
Colonel, Corps of Engineers
District Engineer

Appendix D -- LETTER RELATIVE TO ICE EFFECTS AND DAMAGE RELATED TO WATERWAYS

DEPARTMENT OF THE ARMY
OFFICE OF THE CHIEF OF ENGINEERS
WASHINGTON, D.C. 20314

REPLY TO
ATTENTION OF:
DAEN-RDC

22 November 1974

University of Minnesota
ATTN: Department of Hydraulics
Minneapolis, Minnesota 55455

Dear Sir:

A recent study by the Corps of Engineers has indicated that the yearly costs to the national economy due to ice effects and damage related to waterways are excessive. As part of the continuing program of ice engineering, the Corps of Engineers is addressing ice problems related to the design, operation, and maintenance of Civil Works more positively and more ambitiously than they have in the past.

The ice engineering program is divided into five research subprograms which are summarized below. They are:

Ice Formation - Factors influencing the natural formation of ice, including frazil ice.

Ice Control - Methods of controlling the movement of ice.

Ice Jam Phenomena - Causes and minimization of the effects of jams.

Ice Forces - Criteria to minimize the damage to facilities.

Ice Decay - Techniques for maintaining passable water for shipping on northern navigable waterways.

In order to determine what research facilities (test basins, flumes, and model test areas) are available at the University of Minnesota for ice engineering investigations, we are contacting your department as well as the Department of Civil Engineering. It is requested that you send this office a description of the facilities that you have currently available. It is also requested that you identify other institutions that you feel should be included in this survey.

Sincerely yours,

WILLIAM B. TAYLOR
Chief
Research and Development Office