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Comparison of Dissolved Oxygen Processes Under Ice in Two Southern Yukon Rivers

YUKON RIVER BASIN STUDY

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Water Quality Report No. 3

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Yukon River Basin Study
Water Quality Work Group Report #3

Disclaimer

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Abstract

Processes affecting the concentration of dissolved oxygen under winter ice cover were studied during the winter of 1982-1983 in the Nordenskiold and Takhini Rivers. Oxygen levels in both rivers became depleted during the winter, with the depletion of oxygen being most severe in the organic rich Nordenskiold River where oxygen concentrations dropped to 50 percent saturation. The development of these depressions appears to be related to both biological and physical processes. The manner in which the ice cover forms on the river affects the development of dissolved oxygen depressions. Inputs of groundwater are important in determining the ultimate level that the depression reaches. Levels of dissolved oxygen decrease most rapidly during the period of ice cover formation. About 80 percent of the total depression which ultimately occurs happens within the first week of ice cover. Levels of dissolved oxygen return to the saturation level prior to the decay of the ice cover. Once the snow cover present on the surface of the ice is gone, allowing light penetration to occur, oxygen levels show substantial increases. The level of organic carbon appears to enhance the depression of oxygen.

RESUME

Les facteurs qui affectent la concentration de l'oxygène sous la surface de glace hivernale ont été étudiés pendant l'hiver 1982-1983 pour les rivières Nordenskiold et Takhini. Les niveaux d'oxygène dissous ont diminué fortement dans les eaux des deux rivières pendant l'hiver; la diminution la plus marquée a été observée dans les eaux riches en matière organique de la rivière Nordenskiold, où la concentration de l'oxygène a baissé jusqu'à 50% du niveau de saturation. Ces dépressions semblent être reliées à des facteurs biologiques aussi bien que physiques, et elles sont affectées par la façon dont la surface de la rivière gèle. Les apports de l'eau souterraine influencent de façon marquée le niveau final de ces dépressions. La diminution la plus rapide du niveau d'oxygène dissous est observée durant la période de formation de la surface de glace: environ 80% de la diminution totale se produit durant la première semaine. Le niveau d'oxygène dissous revient au point de saturation avant la disparition de la glace: quand la neige recouvrant celle-ci disparaît, la lumière peut pénétrer la surface, et le niveau d'oxygène remonte de façon substantielle. Un niveau élevé de carbone sous forme organique accentue la dépression de la concentration d'oxygène.

Introduction

The objective of this study was to improve our understanding of the development of dissolved oxygen depressions under winter ice cover. The approach used in this study was to document the occurrence of these depressions and examine other factors which are related to the development of the depressions.

Depression of dissolved oxygen during winter is a widespread phenomenon throughout the arctic and subarctic regions of Alaska and northern Canada (Schallock and Lotspeich, 1974). The occurrence of depressions within the Yukon Territory has been reported by Schreier et al.(1980), and depressed dissolved oxygen levels have been observed within the Yukon River basin (Whitfield and Whitley, unpublished).

Schreier et al.(1980) show that dissolved oxygen depressions are independent of hydrological differences between the Swift and Ogilvie Rivers. They suggested that dissolved oxygen depressions result from a combination of three factors: (1) inputs of oxygen depleted groundwater; (2) oxidation of organic and nitrogenous material; and (3) biological respiration. It is likely that all three of these factors play some role in the development of winter dissolved oxygen depressions. The study areas chosen were selected on the basis of large differences with respect to these three factors.

Previously Schreier et al.(1980) and earlier Schallock and Lotspeich (1974) collected their data at broadly spaced intervals over the winter period. Their results suggest that the critical periods during the occurrence of the phenomenon were during the formation of the river ice and immediately prior to the decay of the ice cover in the spring. In approaching the problem we placed more of our efforts during these periods. It was felt that this approach would give more information about these critical periods of the year, and by concentrating efforts in these periods the dominant processes could be isolated.

Study Areas

The two study areas were chosen on the basis of real differences with respect to organic content, groundwater inputs, and biological processes. In addition, access to the systems was an important consideration in the planning of winter sampling.

The Takhini River in winter is a groundwater dominated system (Chin, 1966) which is relatively low in organic material. Gould (personal communication) found the Takhini River to have depressed oxygen concentrations which bordered on the severe (less than 3 mg/l). Access to the Takhini River is by road throughout its length, and its close proximity to Whitehorse eased some of the logistic problems associated with winter field work.

Five sampling locations were chosen along the length of the Takhini River. The location of these sites, along with their NAQUADAT station numbers are shown in Figure 1. One of these sites, the Takhini River Campground, proved to be inaccessible during the period of the year when snow was on the ground. Our data, then, comes primarily from the four downstream locations.

The Nordenskiold River is an organic rich basin, in part due tothe profusion of bogs and marshes within the drainage. The refractory nature of this organic material is not known. The logistics of winter field work on this river were eased to a degree by its proximity to the Klondike Highway along the lower 40 kilometers of the river. Five sampling locations were chosen along this portion as shown in Figure 1.

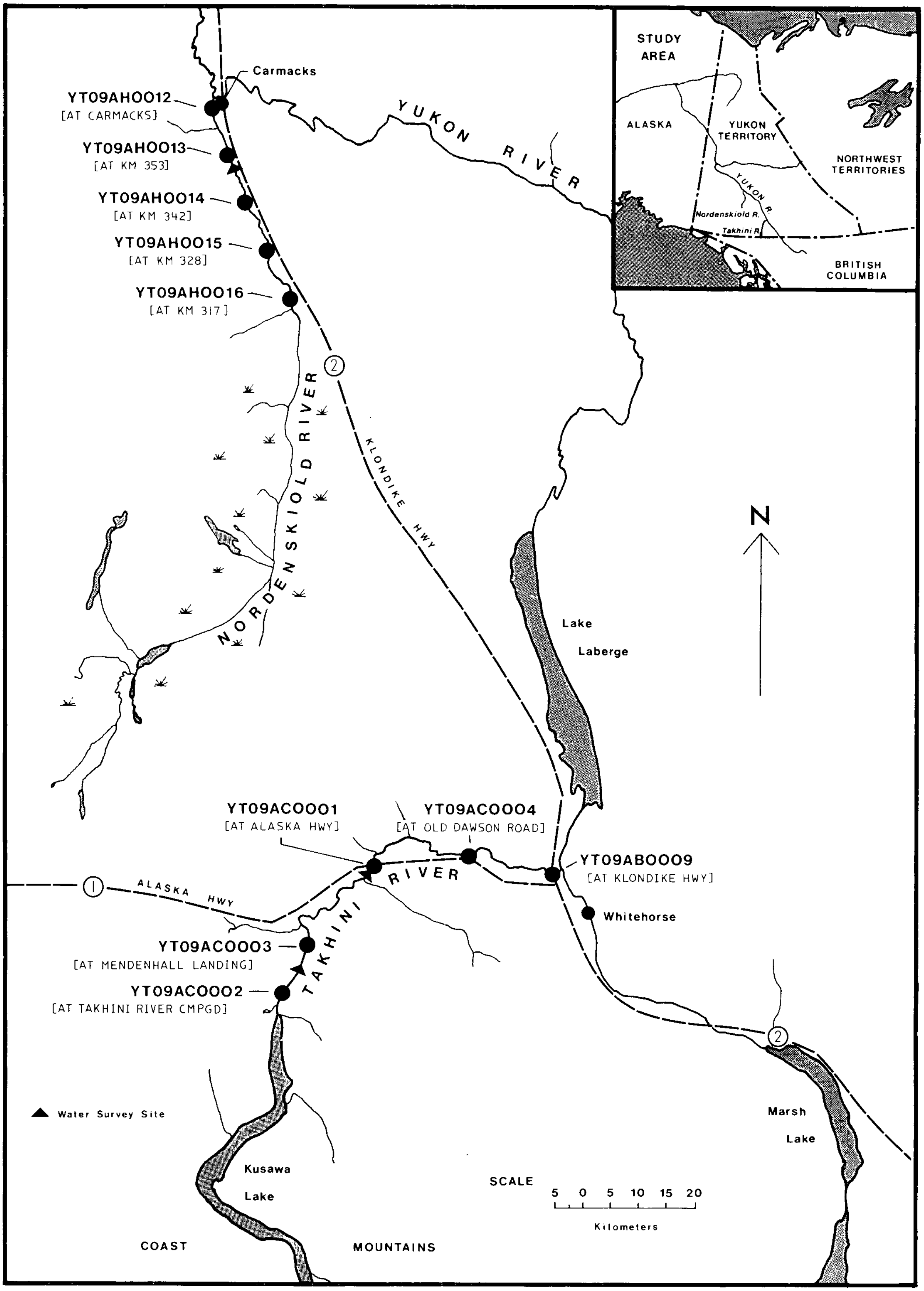

Figure 1
Study Areas Showing Sampling Locations

Another concern was how the physical characteristics of each river affected the formation of ice cover and the subsequent development of the dissolved oxygen depression. The Takhini River descends at a moderately high slope through the upper half of its length, becoming nearly flat through the lower half. Conversely, the Nordenskicld River is a flat meandering stream throughout the upper portion, with a moderately steep gradient in the lower 20 kilometers. Elevation profiles of both rivers are shown in Figure 2.

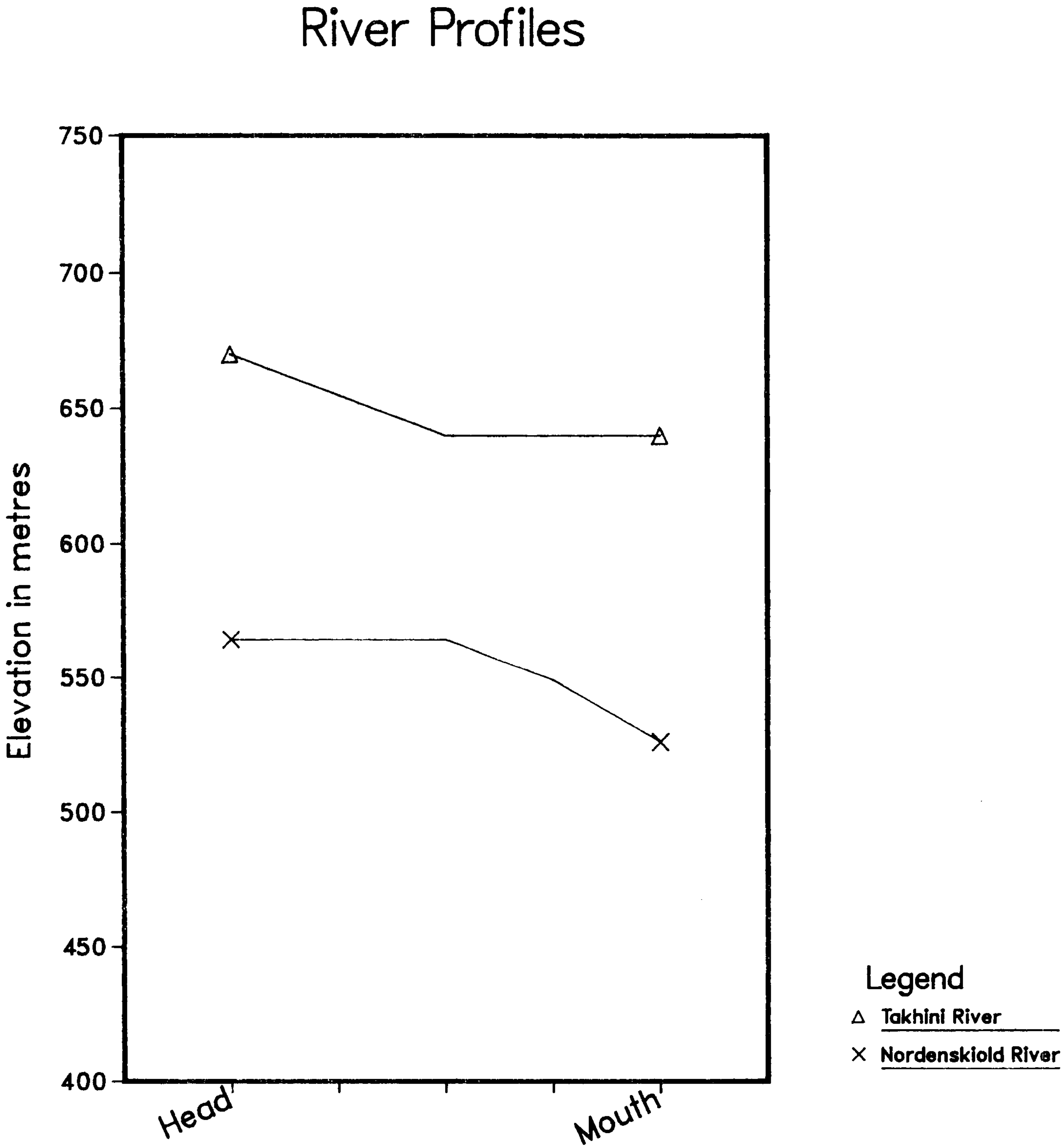

Figure 2
Elevation Profiles of the Nordenskiold and Takhini Rivers

Methods

Selection of Variables

The variables selected for consideration in this study were chosen to reflect aspects of the processes which were potentially active in the depression of dissolved oxygen under ice. Dissolved oxygen determinations were made using the modified Winkler method. This method was selected over electronic methods because of its higher precision and reliability. The variables nitrate plus nitrite, organic nitrogen, ammonia, total dissolved nitrogen, and total organic carbon are indicators of biological activity. Groundwater contributions are indicated by changes in the levels of sodium, calcium, sulphate, chloride, alkalinity, potassium, and hardness.

Sample Collection

During the summer, samples for dissolved oxygen determinations were collected using a "DO Dunker" (A. P. H. A., 1975). Four samples for dissolved oxygen determination were collected and preserved at each site. Additional water samples were collected in sets of six replicates using the IWD replicate sampler (Kleiber and Erlebach, 1977). Two sets of replicates were collected; one set for the determination of total carbon, total inorganic carbon and total organic carbon; and a second set for total dissolved nitrogen, nitrate plus nitrite, ammonia, and organic nitrogen. Two one-liter samples were also collected, these being analysed for major ions. Measurements of water temperature, pH, and conductivity were made in the field within ten minutes of sample collection.

During the winter, the collection of water samples is more difficult. Special methods and equipment were necessary to ensure samples were not subjected to freezing temperatures for more than a few seconds. Collection of samples during the winter involved the following procedure; snow cover on the ice was removed from an area about two meters in diameter using a shovel; a power auger was then used to drill a vertical hole through the ice (approximately 25 cm diameter); slush ice was removed from the auger hole; a specially constructed 'hot-box' was then placed over the hole; the inlet hose from the portable pump sampler within the 'hot-box' was dropped down the auger hole below the undersurface of the ice; samples were then pumped directly into the sample bottles (also within the 'hot-box'). Detailed description of the construction of the 'hot-box' and its use in winter field sampling is described by McNaughton (1984). The same number and type of samples described for the summer sampling were collected using the pump sampler. Field measurements of water temperature, pH, and conductivity were made in the field vehicle.

All samples were stored in coolers and returned to the EPS laboratory in Whitehorse. Determinations of dissolved oxygen concentrations were performed on the day of collection using the azide modification of the iodometric (Winkler) method (A.P.H.A., 1975). The remainder of the samples were shipped by air to the Water Quality Branch laboratory in Vancouver for analysis.

Analytical Methods

Full details of the analytical methods used in the determinations of the variables considered in this study are described in the Analytical Methods Manual (Environment Canada, 1979). Detailed data not presented in this report are available from the Data Systems Section of Water Quality Branch, Inland Waters Directorate, Ottawa.

Quality Control

In all field studies concerns about the quality of the data being gathered must be addressed. In the present study a number of the concerns which we felt pertinent were examined.

Our first concern was the variation in concentration across the width of the river at the sampling sites. To address this question samples were collected at four holes drilled through the ice across the width of the river. From these samples we were able to conclude that no lateral variation existed, indicating that a single hole in a transect was adequate for the collection of data.

The second concern was whether daily and short-term variation would affect the measurements. To address this question, daily samples were collected at one site for a period of five days to examine day to day variations. To examine short-term variations samples were collected from one sampling hole every thirty minutes (in replicates of four) for three hours. The determinations of dissolved oxygen on these samples showed little variation indicating that time of day had no affect on the results obtained.

The last concern which we addressed was related to the process of drilling a hole through the ice for the collection of samples. The physical disturbance of the water which occurs when a hole is drilled has the potential for producing biased results. To determine whether or not this was actually a problem we drilled a hole and sampled from it every two minutes for sixteen minutes from the time the hole was opened. This procedure was followed for two separate holes. The only variation found among these two sets of samples was due to the limits of the analytical method, suggesting that the physical disruption caused by the drilling of the hole through the ice does not affect the results obtained, in the situation under study.

Results

Formation of Ice Cover

The formation of ice cover on the Nordenskiold River begins in mid-October with the development of shore ice. At the time of the field visit on 6th November a nearly complete ice cover existed at the three upper sites (Kilometer 317-342). There were,however,numerous leads in the ice suggesting that the ice cover was just forming. In general, ice forms when water temperatures reach zero degrees Celsius and continues as heat is lost to the atmosphere. At the same time in the lower reach of the river there was only a partial ice cover, with 80-90 percent of the surface being open. At Kilometer 353 the ice appeared to be accumulating and progressing from the right bank. On the left bank the surface velocity appeared to be inhibiting the formation of ice. At the Carmacks site, where flow was very turbulent, ice cover formation was quite irregular. Large amounts of frazil ice were present flowing over and around islands of bottomfast ice. This type of flow results in a building of an ice sheet through freezing on the upper surface rather than on the bottom of the ice as typifies more quiescent waters.

By November 10th a continuous ice cover existed at all five sites along the river. Air temperatures were in the range from -20 and -30 degrees Celsius. By the end of the November field trip (15th) the ice thickness had reached 40 cm in the upper reaches, with about 25 cm present in the lower reach. In January and February ice thickness had increased to 110-125 cm, by March it was 170-185 cm. At the Carmacks site, the earlier situation developed into a moderate aufeis formation. The initial stages of the break-up of the Nordenskiold ice were observed at the end of the April field trip. Warmer air temperatures and melting snow cover resulted in a layer of flowing water on the surface of the ice. Ice cover was present through the upper portion of the river, while the lower portion was beginning to have small areas of open water. Break-up on the Nordenskiold River was estimated to have occurred between April 20th and 29th, 1983.

In early November ice cover formation was in the initial stages at most of the Takhini River sites. Open water still existed at Mendenhall Landing due to warmer water temperatures (three degrees Celsius) resulting from the thermal energy stored in Kusawa Lake. At sites downstream, however, about ten centimeters of shore ice had developed. Bank ice formation at Mendenhall Landing began on November 10th, 1982. By the end of the November field trip small pans of ice forming from frazil ice were covering most of the surface of the river at Mendenhall Landing. Further downstream, at the Alaska Highway crossing bank ice covered 50 percent of the surface area of the river. The open portion of the river was mostly covered with flowing pans of ice. On the right bank these pans were accumulating against the bank ice. Two days later, on November 10th ice cover existed over the entire surface of the river at this site. At the Old Dawson Road crossing of the Takhini River the ice cover was generated through a combination of a small ice jam upstream of the site and extensive development of shore ice downstream of the jam. On the initial visit in November to this site about 80 percent of the rivers surface was covered with ice. On the next day (November 7th) the river was completely covered with ice seven to ten centimeters in thickness.

Ashton (1978) describes an ice jam as an accumulation of floating ice fragments that causes bridging across the surface of a river. Initial bridging is the result of the ice discharge rate, fragment size, and the width of open water between the banks. Three types of jams are described by Ashton (1978): simple surface accumulations, for which the thickness is determined by the flow and ice characteristics at the upstream edge; accumulations that occupy a large fraction of the flow cross section but are still floating; and the 'dry' ice jams, in which the ice accumulation extends to the bottom and is grounded. The jams on the Takhini river were simple surface accumulations.

The lower reach of the river is narrow and to a degree meandering with a substantial increase in flow over that observed at Mendenhall Landing. Ice formation at the Klondike Highway site was similar to the formation at the other two sites in this lower reach. In each case ice jams began to form at constrictions in the river with extensive development of shore ice downstream of the jams. Full ice cover developed in this lower reach by the end of the November field trip.

For the remainder of the winter all four sites had competent ice covers of approximately the same thickness described for the Nordenskiold River. This full ice cover remained through the end of the April sampling. During April the snow cover was nearly gone, and break-up occurred between the April and May sampling trips.

Discharge

The Water Survey of Canada (WSC) have two recording gauges for discharge measurements on the Takhini River. One station located at the outlet of Kusawa Lake (Station No.09AC004) was established in 1952 and relocated downstream in 1981. The second WSC site (Station No.09AC001) was installed in 1948 downstream from the Alaska Highway sampling site (Figure 1). Mean monthly discharge records during the study period for both stations are shown in Figure 3. Figure 3 shows a slight increase in flow at the downstream site. This site differs from the Kusawa Lake site in stream morphology as well as being influenced by groundwater discharge and inflow from the Ibex River. The two stations have similar discharge patterns. In August flows were decreasing and minimum flows occurred from December through April. Minimum daily mean discharge of 9 m^3/s was recorded on 24 April 1983 at Kusawa Lake (Environment Canada, 1983). Streamflow started to increase in May after break-up and by July 1983 a maximum discharge of 197 m^3/s at Kusawa and 207

Takhini River

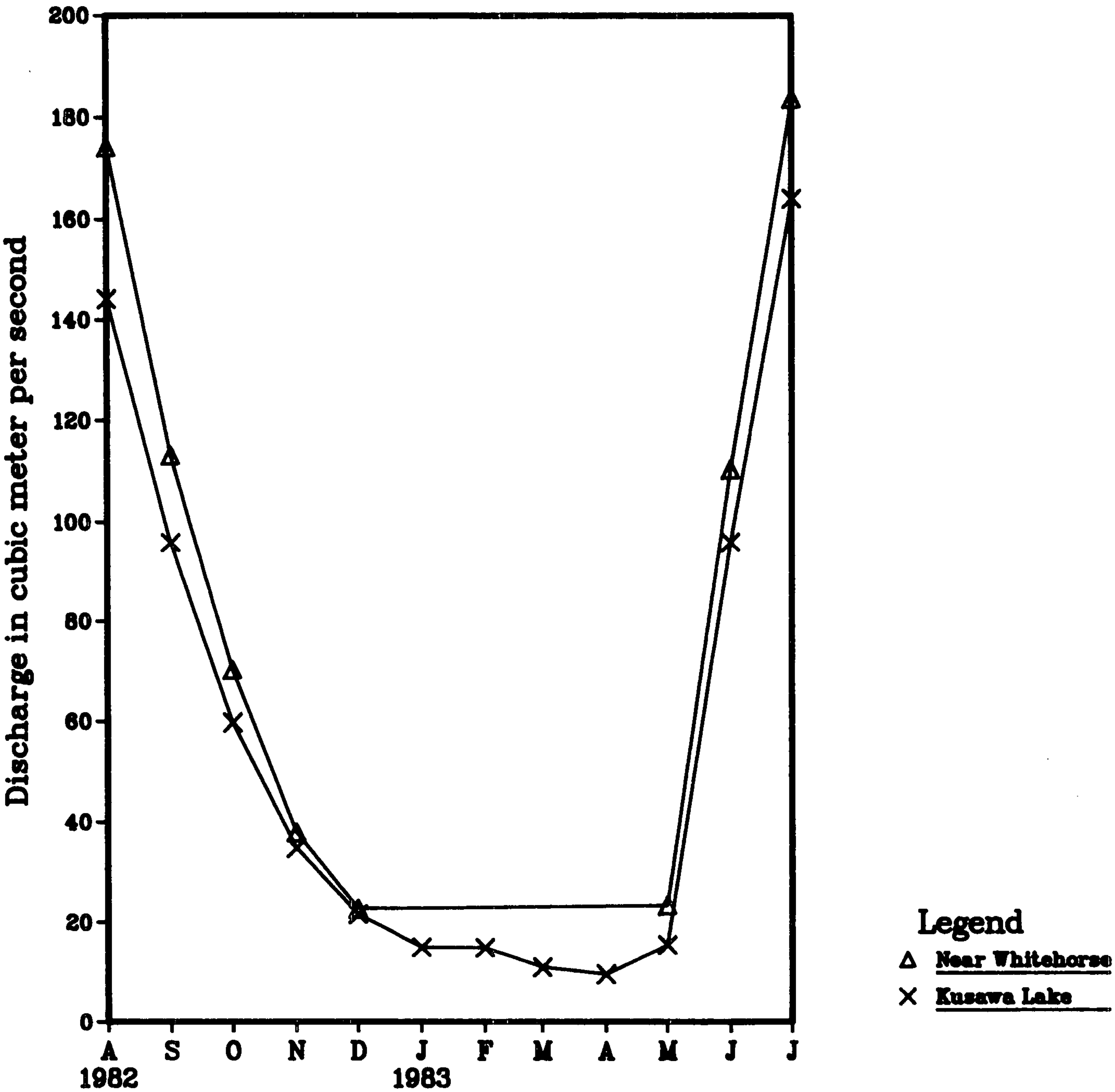

Figure 3
Mean Monthly Discharge for the Takhini River

m^3/s downstream at the Alaska Highway bridge was recorded. Discharge remained relatively high through July and August maintained largely by precipitation, glacial meltwater, storage from Kusawa Lake and groundwater discharge.

The hydrological station on the Nordenskiold River was installed in the spring of 1982, slightly upstream from our Kilometer 353 sampling site. From the gauge recordings maximum discharge of 48 m^3/s occurred on 02 May 1983, two months earlier than recorded on the Takhini River (Figure 4). Minimum discharge was indicated on 25 March 1983, approximately one month earlier than the Takhini, with a discharge of 2.5 m^3/s.

Dissolved Oxygen Depressions

In August both the Takhini and Nordenskiold Rivers were fully saturated with respect to dissolved oxygen. With water temperatures in the range of 10 to 12 degrees Celsius, water saturated with dissolved oxygen would have a concentration of about 11 mg/l. All measurements in August were in excess of this level, averaging about 12.5 mg/l, suggesting a degree of supersaturation. In November concentrations were much more varied, ranging from a high of 15.8 mg/l for the Takhini River, to a low of 8.5 mg/l at one of the Nordenskiold River sites. All sites showed rapid declines with respect to dissolved oxygen concentrations during the November sampling. Figure 5 shows dissolved oxygen concentrations over the study period at the sites on the Nordenskiold and Takhini Rivers.

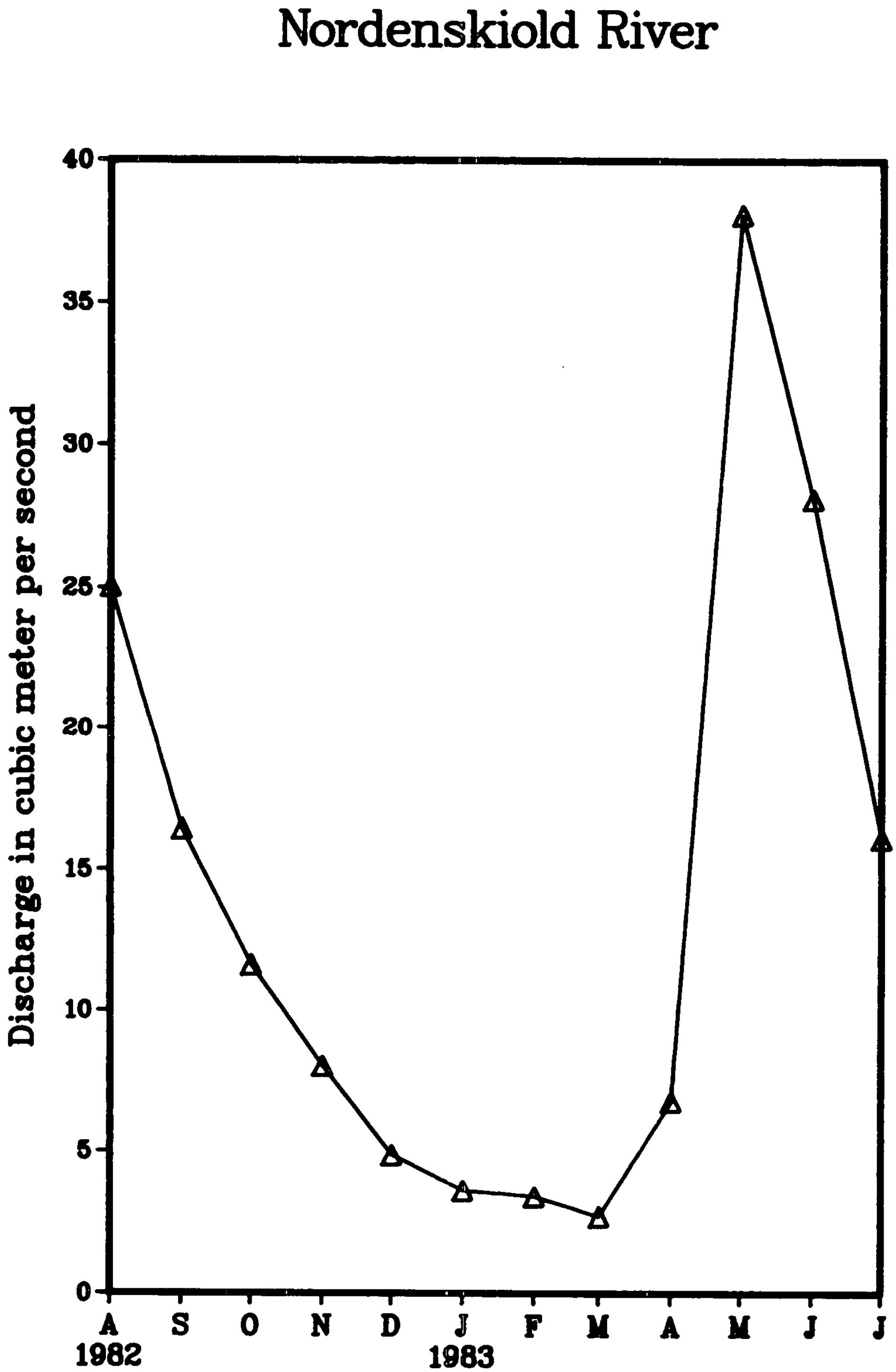

Figure 4
Mean Monthly Discharge for the Nordenskiold River

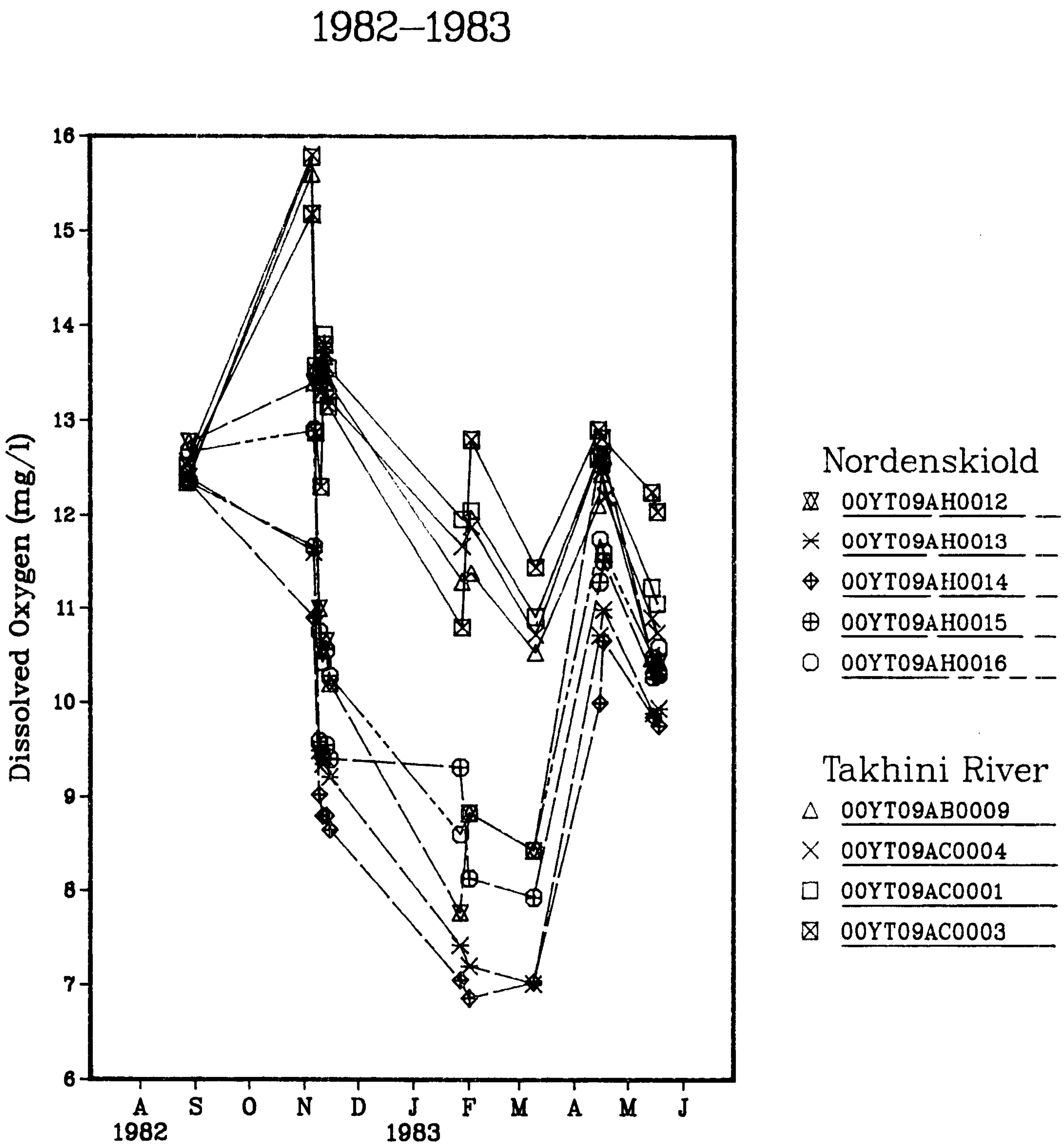

Figure 5
Dissolved Oxygen Concentrations in the Takhini and Nordenskiold Rivers during the Winter of 1982-1983.

The extremely high values of dissolved oxygen measured in the Takhini River at the beginning of November reflect a change in the saturation level which results from the decrease in temperature. At 0.5 degrees Celsius the level of saturation for oxygen is 14.4 mg/l. In this respect dissolved oxygen concentrations were at about the same levels of saturation as observed in August. During the November sampling trip oxygen concentrations decreased between each sampling. This is reflected in Figure 5 by the sharp decline evident among the November samples.

Oxygen concentrations continued to decline from the November levels through January and into March (Figure 5). During April significant increases in dissolved oxygen were observed despite the fact that there was still a full ice cover on both rivers. In May, after the break-up of the ice cover there was still some variation in the dissolved oxygen measurements. These measurements were near to saturation when the increased temperature is taken into consideration.

The results shown in Figure 5 outline some of the features which need further evaluation. These are:

1. Dissolved oxygen became much more depressed in the Nordenskiold River than in the Takhini River. It is important that the reasons for this difference be evaluated.
2. Both the Takhini and Nordenskiold Rivers showed a rapid decline in oxygen concentration during the two week

sampling period in November. Earlier studies failed to observe this phenomenon, largely because of the sampling designs that were used. It is apparent that the period during which ice formation is taking place is critical in the development of the oxygen depressions.

3. The increases in dissolved oxygen concentrations observed during April under a full ice cover is another observation which was not described in previous studies. The mechanism which is responsible for increases in dissolved oxygen concentration during this period also needs to be evaluated.

These evaluations involved considering the observations of dissolved oxygen and the other chemical variables, physical processes and the potential for biological processes relevant to these observations. To examine these related phenomena we chose three distinct strategies:

1. In considering why the Nordenskiold River is distinctly different from the Takhini River, we examined the relationship between all of the variables using correlation analysis. From correlation matrices for each river a group of variables were selected for further consideration, namely; total organic carbon, silicate, total inorganic carbon, sodium,and alkalinity. The first step was to plot each of these variables against

dissolved oxygen concentration. Following this each of the variables was plotted as a function of time over the study period.

2. In considering the rapid decrease in dissolved oxygen concentration observed during November, we followed the same pattern that was described above limiting the analysis to only the November observations.
3. The increases in dissolved oxygen that were observed in April were examined by evaluating the data in the interval from March (prior to the increases) through to May. This approach was necessary because the data set for April was much more limited than the data from November.

Nordenskiold-Takhini Differences

The plot of mean total organic carbon concentration against dissolved oxygen (Figure 6) illustrates differences in both these variables between the two rivers. The difference with respect to total organic carbon was anticipated in the design of the study, and Figure 6 confirms that the Nordenskiold River has a substantially greater concentration of organic carbon. Noting that the 'y-axis' in Figure 6 is a log axis, the Nordenskiold River has a median concentration of about 6.5 mg/l of total organic carbon while the Takhini River has a median value of about 1.5 mg/l.

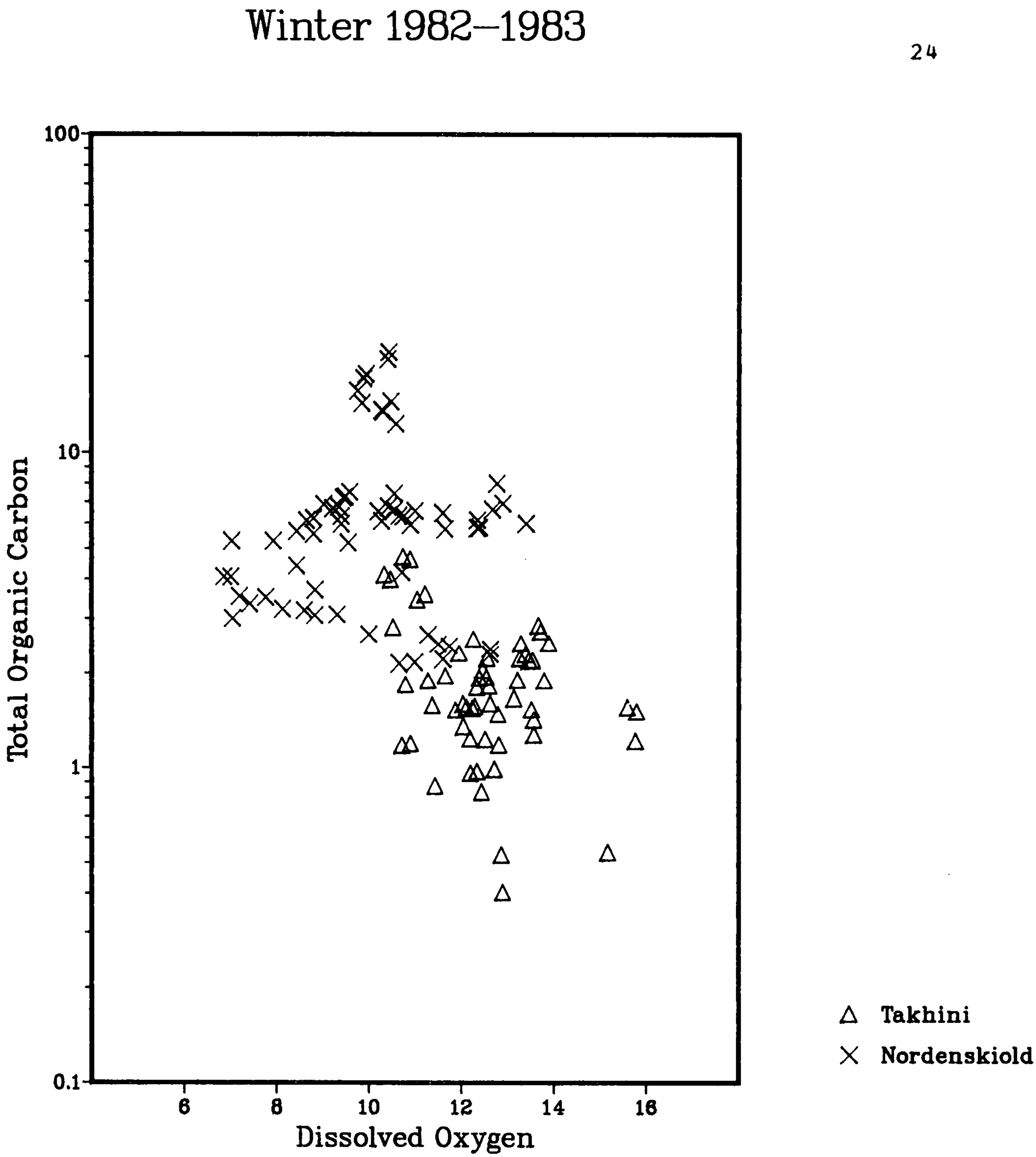

Figure 6
Total Organic Carbon Concentration against Dissolved Oxygen Concentrations

With respect to silicate, shown in Figure 7, the Nordenskiold has a higher concentration than the Takhini River. However, silicate concentrations in the Nordenskiold River showed little variation during the study period, whereas, the Takhini River varied from a low of 3 mg/l to a high of 7 mg/l. It is obvious from Figure 7 that real differences exist between the two rivers with respect to silicate concentration.

Total inorganic carbon demonstrates a similar pattern to silicate. The Nordenskiold River has higher total inorganic concentrations than does the Takhini River. The average for the Nordenskiold was about 30 mg/l, while the Takhini average was approximately 5 mg/l. Similar results were obtained for alkalinity, shown in Figure 9. Again the Nordenskiold River exhibited higher levels ranging from 75 to 150 mg/l than the Taknini River (range from 10 to 55 mg/l).

From the results it is obvious that the Nordenskiold and Takhini Rivers are very different from each other in terms of average concentrations of the variables described. Much greater variability was evident in the Takhini River. Since these variables, as exhibited in Figures 6 to 9, do not appear to be directly related to the concentration of dissolved oxygen an examination of the temporal change in the variables was considered.

Total organic carbon concentrations in the Nordenskiold River do not change by a significant amount between August and November (Figure 10). The levels decrease from the

Winter 1982–1983

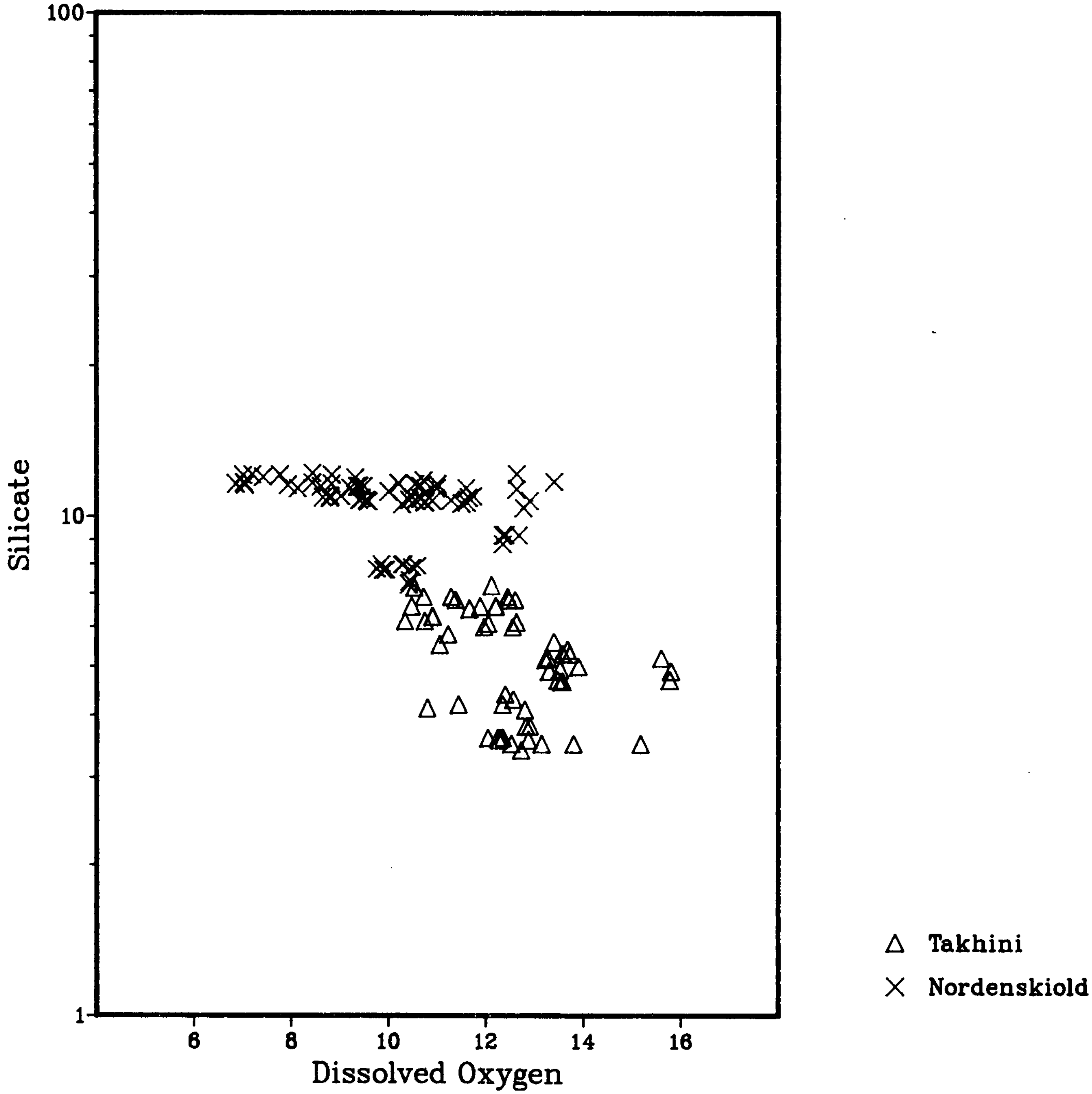

Figure 7
Silicate Concentration against Dissolved Oxygen Concentrations

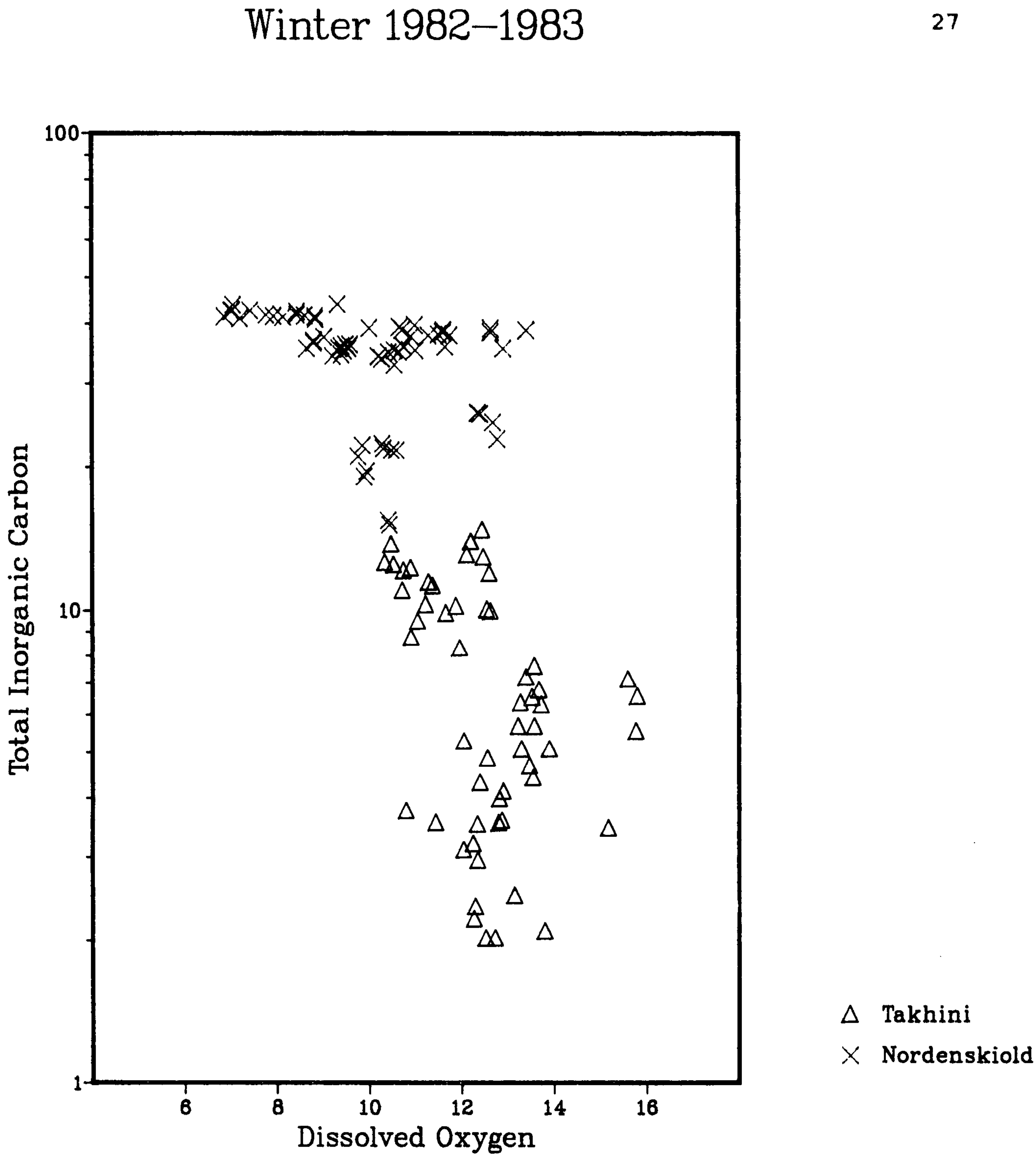

Figure 8
Total Inorganic Carbon Concentration against Dissolved Oxygen Concentrations

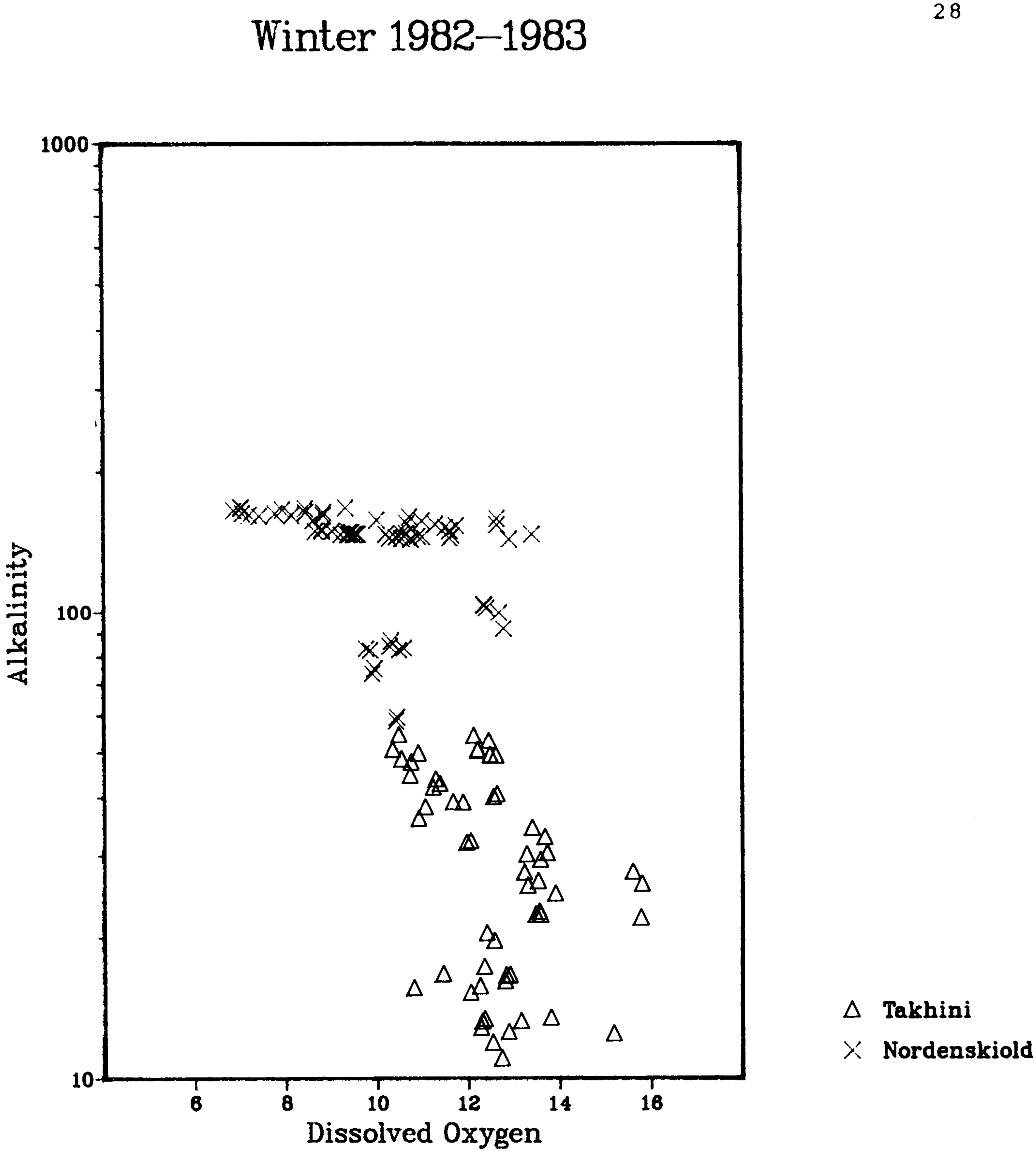

Figure 9
Alkalinity against Dissolved Oxygen Concentrations

November level of about 6 to 8 mg/l to about 3 mg/l in late January. A slight increase in concentration takes place between February and March, followed by a decline to about 2 mg/l in April. In May concentrations are much elevated (20 mg/l). Concentration variation between sites and sampling dates within each sampling trip is small in the Nordenskiold River data. However, the Takhini River behaves in a quite different manner. Concentrations of total organic carbon are generally stable over the study period with values ranging from 0.5 to 5.0 mg/l. There is no evidence of any variation over the winter (e.g. between sampling trips). Most of the variation among the Takhini River samples occurs between sites and/or sampling times within a sampling trip.

Figure 10 and the plots which follow are drawn in log scale. The use of this display has the property of making the variation proportional to the mean. In effect this makes the variation which is evident similar to the coefficient of variation. In the descriptions which follow it is important to note than references to the variation evident in a figure is the relative variation, not absolute variation.

Silicate concentrations in the Nordenskiold River over the study period, shown in Figure 11, reflect differences in the flow regime. The lower concentrations observed in August and May are the result of the higher flows, hence higher dilution, (but not proportionally so) than during the low flow period. The Nordenskiold silicate concentrations are, similar to total organic carbon, relatively invariant between

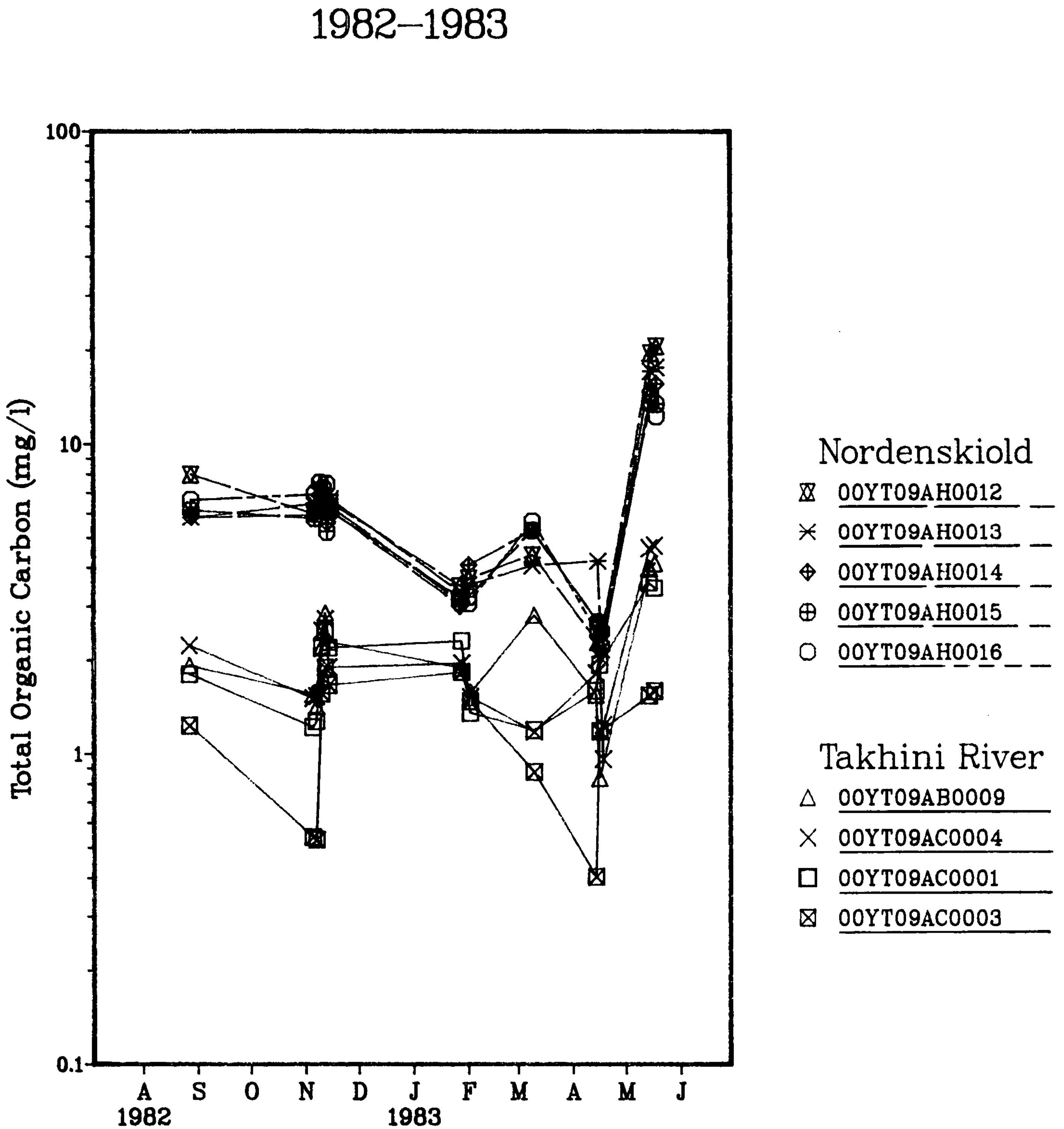

Figure 10
Total Organic Carbon Concentration over the Study Period

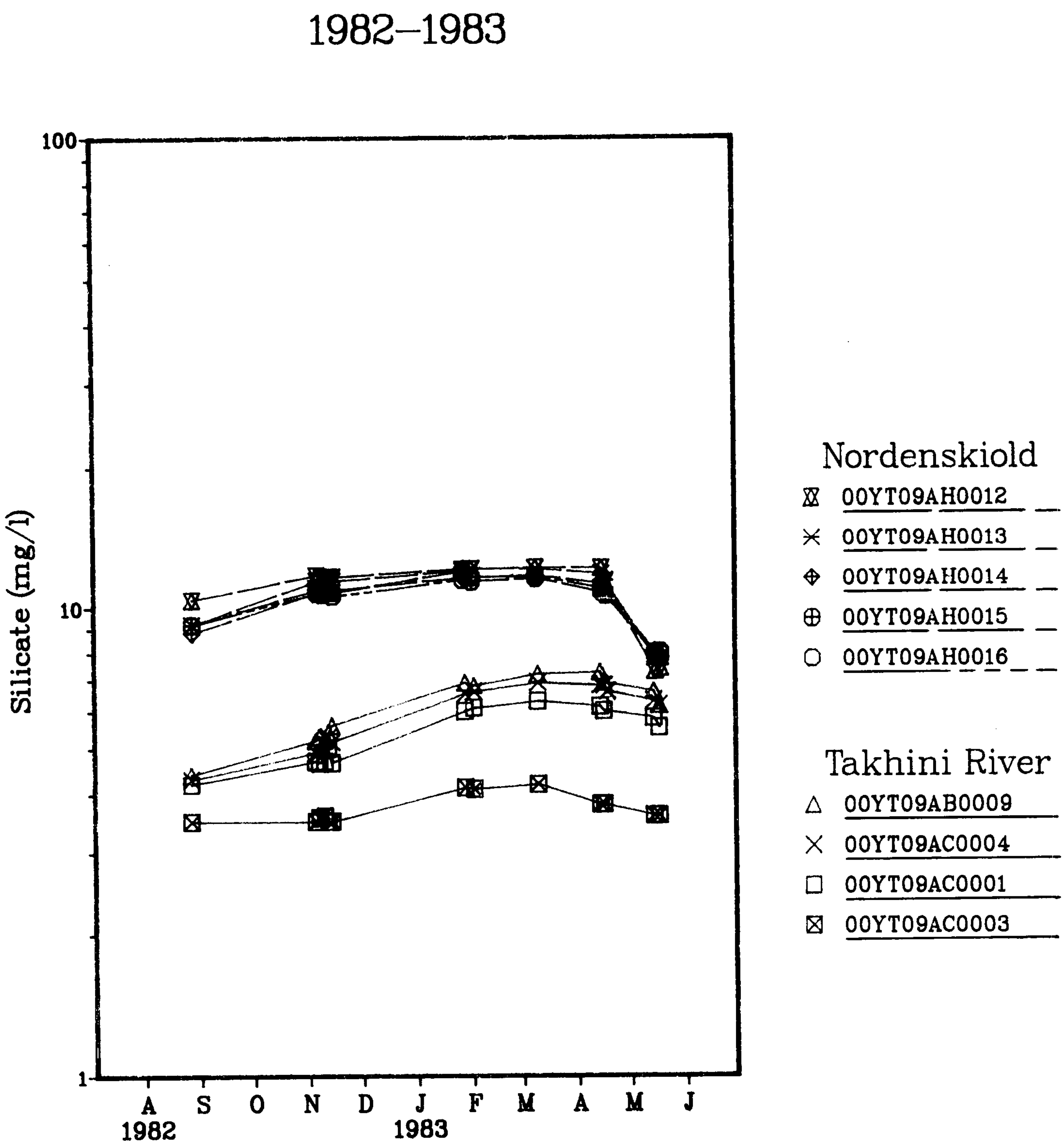

Figure 11
Silicate Concentration over the Study Period

sites and within each sampling trip. Silicate concentrations in the Takhini River vary less than other variables within sampling trips, and increase during the ice covered period. Figure 11 suggests that the data from the upstream site is somewhat lower in concentration than the other sites. The Takhini River also reflects the dilution effect of the higher flows in August and May. This dilution effect is not a linear function of discharge.

The Nordenskiold River also showed little relative variation between sites and samplings within a sampling trip for total inorganic carbon. A similar dilution effect to that noted for silicate was also evident in the August and May total inorganic carbon data (Figure 12). Total inorganic carbon in the Takhini River shows a clearer separation between sites along the river, behaves in a different manner over the winter than the Nordenskiold River. Levels of total inorganic carbon show continuing increases over the winter, whereas the Nordenskiold remained relatively constant over the same period. Levels of total inorganic carbon were substantially greater at the three sites on the lower (flat) portion of the river, than were found at Mendenhall Landing. These data form the lower points on the graph.

Sodium concentrations in the Nordenskiold River also reflect a pattern similar to that observed for the other inorganic variables (Figure 13). There is little variation in sodium concentration between sites, or sampling times within a sampling trip. The dilution effect noted for the other

1982–1983

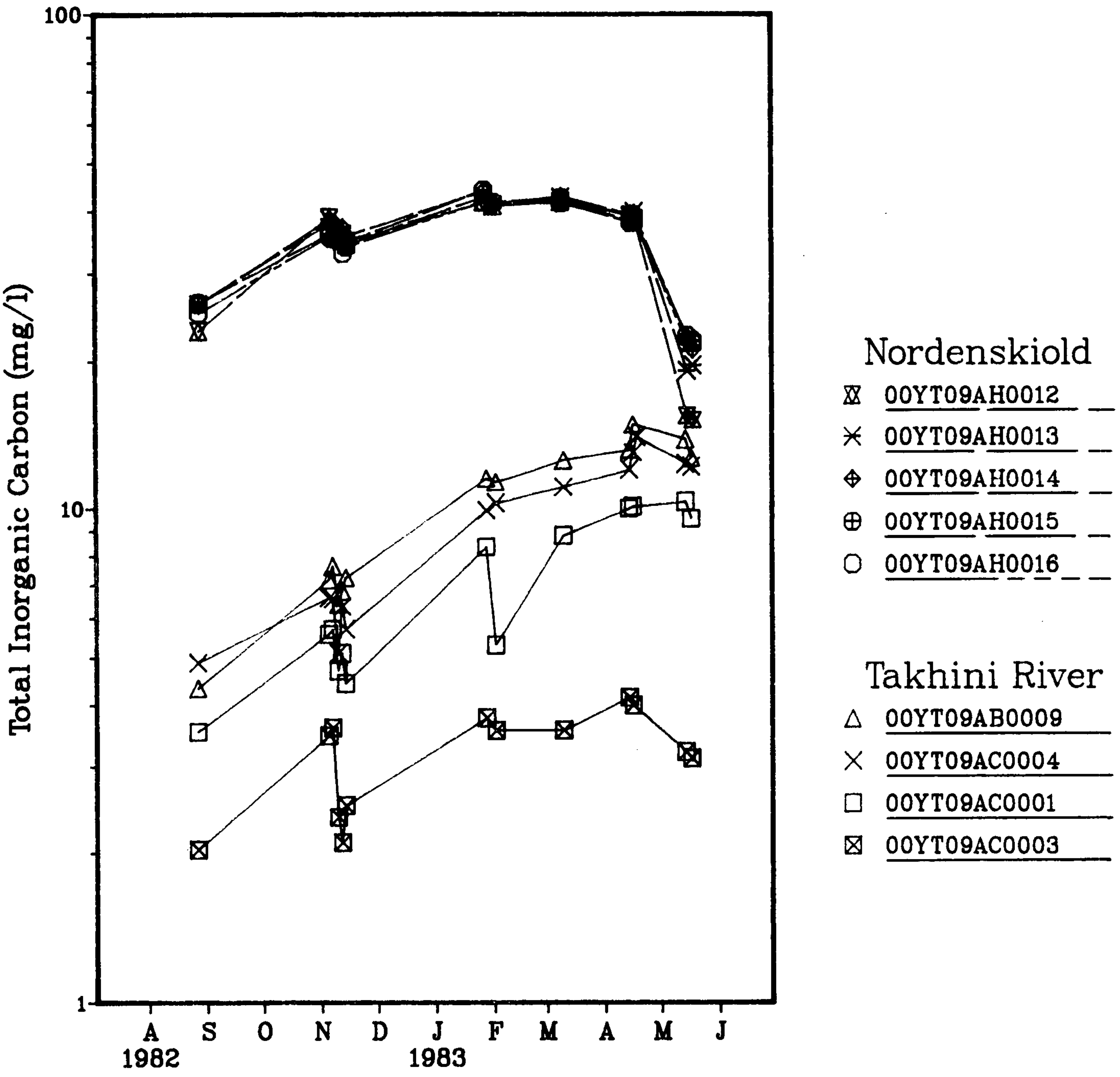

Figure 12
Total Inorganic Carbon Concentration over the Study Period

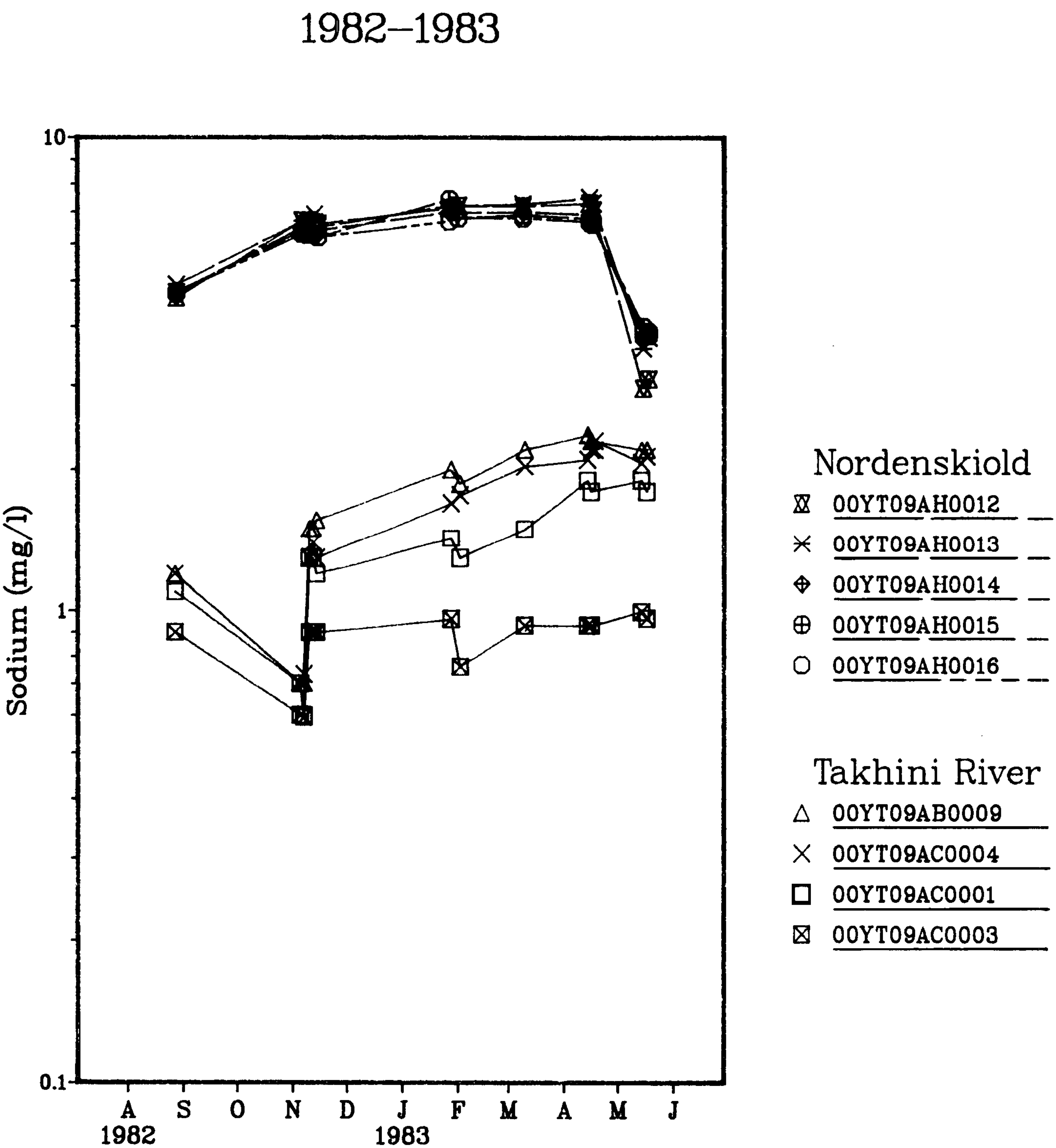

Figure 13
Sodium Concentration over the Study Period

variables is more pronounced for sodium than for the other variables. The lowest sodium concentrations were observed in May when flows were the largest. In the Takhini River sodium concentrations were quite varied between sampling locations, with concentrations increasing between November and April (Figure 13). Overall, sodium concentrations were found to vary in about the same manner as total inorganic carbon in the two rivers. In the Nordenskiold River, sodium concentrations reached a high level in November and remained at this level for the duration of the ice covered period. In the Takhini River, sodium concentration continued to increase throughout the winter ice covered period. The effect of increased flows during May on sodium concentrations in the Takhini River is much less pronounced than the effect observed in the Nordenskiold River, because the increase in discharge was less.

Alkalinity measurements over the study period are shown in Figure 14. In the Nordenskiold River, alkalinity is relatively constant between sites and sampling times within a sampling trip. Alkalinity reaches a maximum level at freeze-up and remains relatively constant for the duration of the winter. The dilution effects noted earlier are again evident in Figure 14. Alkalinity in the Takhini River behaved in much the same manner as sodium and total inorganic carbon. There is a clear separation between the observations at the four sites, and a general increase in concentration over the winter, and there is a moderate dilution effect evident in

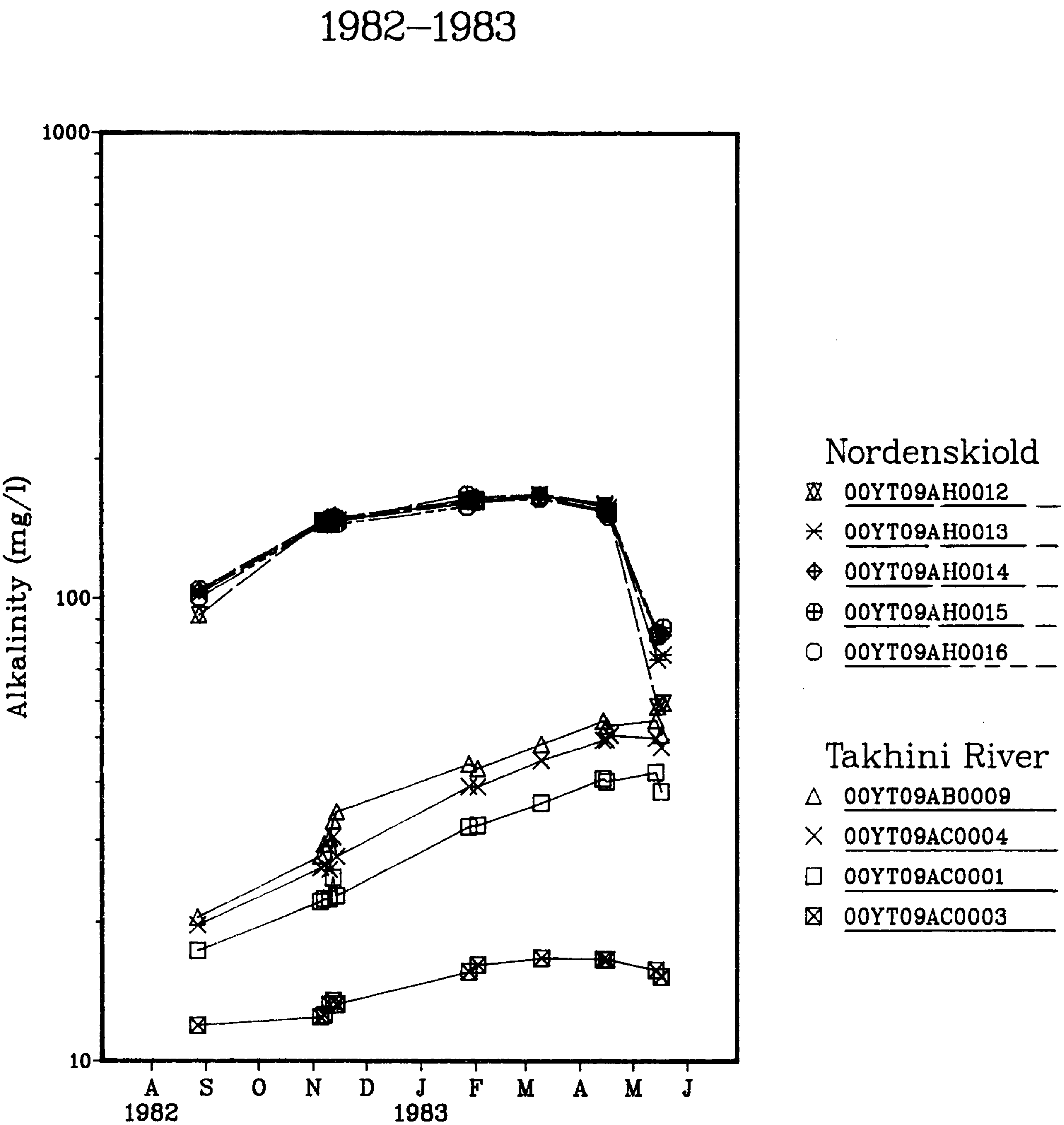

Figure 14
Alkalinity Concentration over the Study Period

May.

The results presented above demonstrate that the Nordenskiold and Takhini Rivers are different from each other in a variety of ways. These differences can be summarized as follows:

1. Dissolved oxygen concentrations become more depressed in the Nordenskiold River than in the Takhini River (Figure 5).
2. Concentrations of all variables, except dissolved oxygen, showed more variation between sites along the Takhini River than along the Nordenskiold River (Figures 6 to 14).
3. Total organic carbon, silicate, total inorganic carbon, sodium, and alkalinity have greater concentrations in the Nordenskiold River than in the Takhini River (Figures 6, 7, 8, 13, and 9).
4. Total organic carbon concentrations in the Nordenskiold River decreased during the ice covered period with a low being reached in April. In the Takhini River there was some variability between sampling sites (Figure 10), but levels did not change over the winter.
5. In the Nordenskiold River, silicate, total inorganic carbon, sodium, and alkalinity remained at a relatively constant level throughout the ice covered period, while the Takhini River showed gradual increases during this period (Figures 11 to 14).

There are also similarities between the two rivers with respect to the variables described, namely:

1. Depressions of dissolved oxygen occurred in both rivers, although to different degrees (Figure 5).
2. Both rivers exhibit a very rapid decrease in dissolved oxygen over the November sampling trip (Figure 5).
3. From November through to March, both rivers exhibited decreases in the concentration of dissolved oxygen (Figure 5).
4. Increases in dissolved oxygen were observed during April, prior to the decay of the ice cover.
5. Both rivers exhibited lower concentrations of inorganic material at higher discharge rates.

Changes at Freeze-up

Dissolved oxygen concentrations decrease very rapidly at the time of the formation of the river ice cover. Figure 15 expands the time scale for the November sampling period, and shows the changes in dissolved oxygen concentration over this period more clearly. The Takhini River was effectively open when sampled on 5 November 1982, and dissolved oxygen

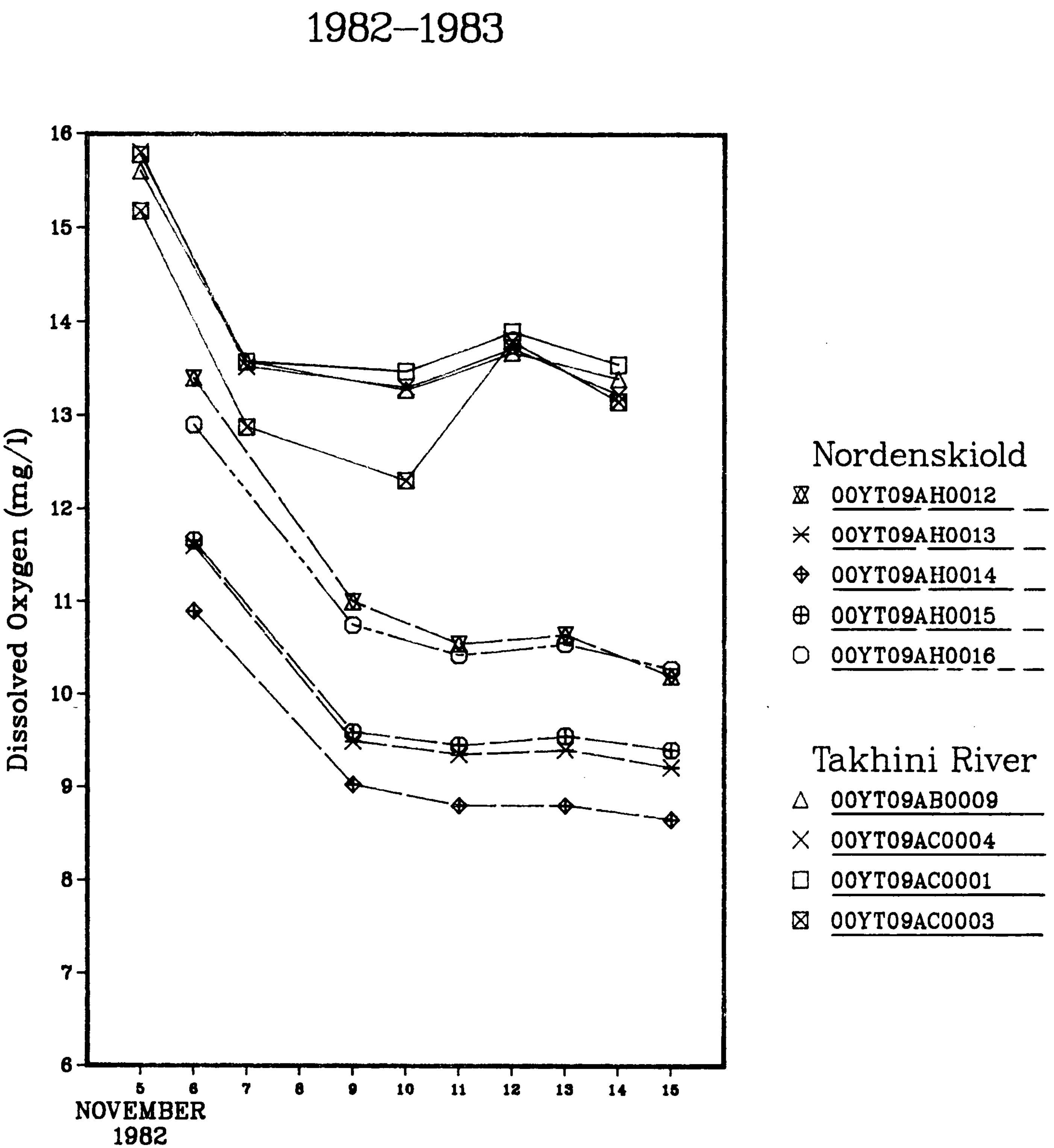

Figure 15
Dissolved Oxygen Concentrations during November

concentration was at saturation. Two days later, the dissolved oxygen concentration had dropped by more than 2 mg/l. During this two-day interval there was extensive development of the Takhini River ice cover. On the following days the ice cover became nearly complete, and dissolved oxygen concentrations stabilized around 13 mg/l.

In the Nordenskiold River, dissolved oxygen concentrations were already somewhat depressed when sampled on 6th November 1982. There was more variation between Nordenskiold River sites with respect to dissolved oxygen concentration than was evident for the Takhini River. During the period between the 6th and 9th of November when the next samples were taken, dissolved oxygen concentrations decreased by about 2 mg/l at each of the Nordenskiold river sites. Similar to the Takhini River, dissolved oxygen concentrations subsequently decreased at a much lower rate.

In the previous section we saw that the concentrations of total organic carbon decreased during the winter in the Nordenskiold River. During the November sampling, total organic carbon concentrations in the Nordenskiold River remained relatively constant,ranging from 5 to 8 mg/l (Figure 16). In the Takhini River, levels of total organic carbon increased from less than 1.5 mg/l on 5 and 7 November to greater than 1.5 mg/l from 10 - 14 November.

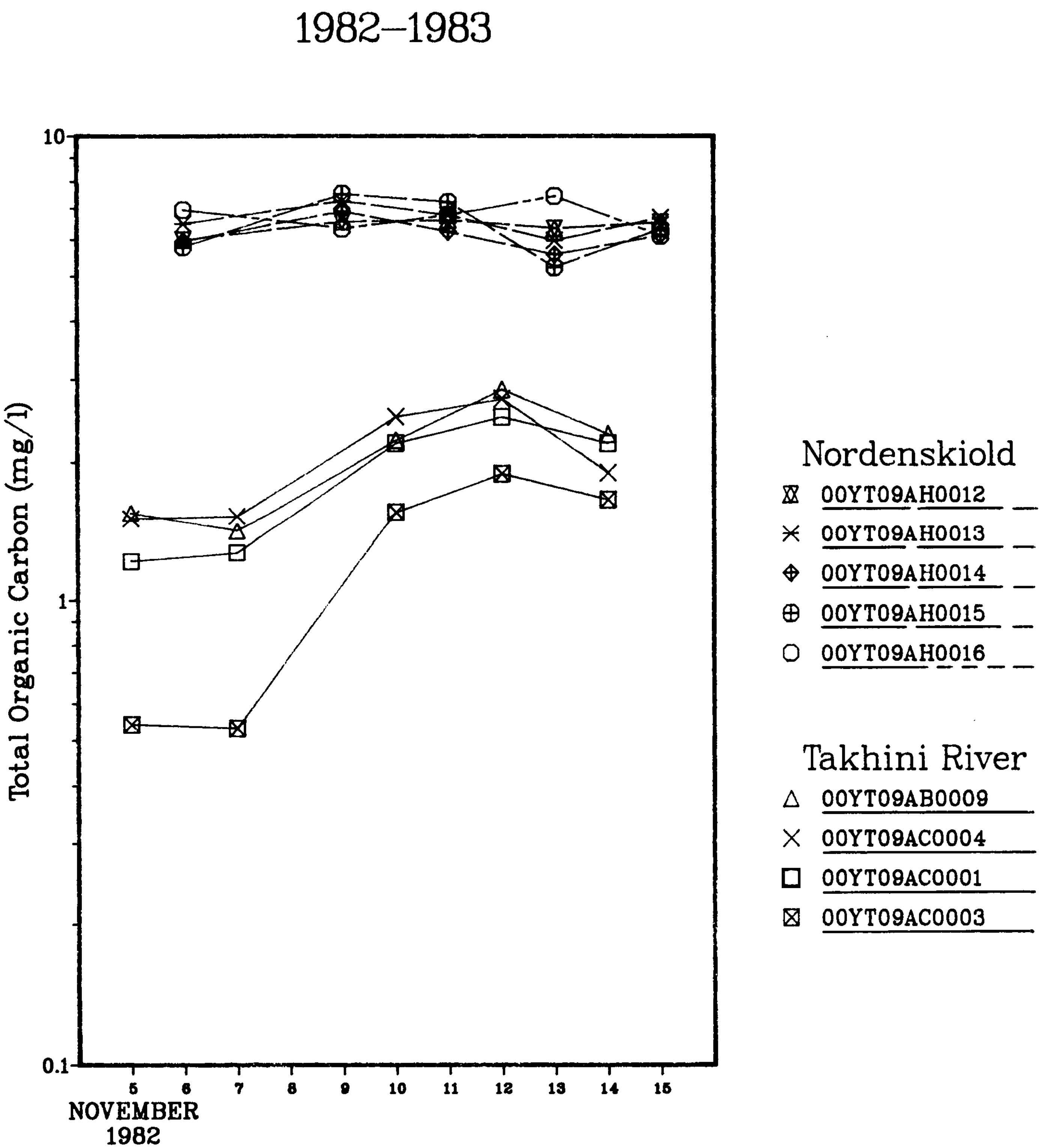

Figure 16
Total Organic Carbon Concentrations during November

Changes Prior to Break-up

In Figure 5 an increase in dissolved oxygen during April was noted. This increase occurs before the break-up of the ice cover and is a phenomenon not previously reported. In Figure 17 dissolved oxygen concentrations over the period from March through May are shown. The expanded time scale used in Figure 17 allows closer examination of the changes in dissolved oxygen concentrations which occur during this critical period. Sites on the Nordenskiold River showed dissolved oxygen concentration increases of about 3 mg/l between March and April. Since no samples were collected in the interim period, we are unable to clearly define when the concentration increases actually began. The samples taken in April from each station on the Nordenskiold River show that increase could be quite rapid. The Takhini River samples also show the same phenomenon, however the amount of the increase is less than that observed in the Nordenskiold River (only about 1.5 mg/l). All the sites on both rivers show individual variation on this general pattern. This suggests that the sites either behave in slightly different ways, or the timing of the phenomenon differs between sites.

Total organic carbon concentrations during the period from March to May are shown in Figure 18. Data from the Nordenskiold River shows a slight decline in total organic carbon concentrations between March and April. After break-up there was a substantial increase in the concentration of

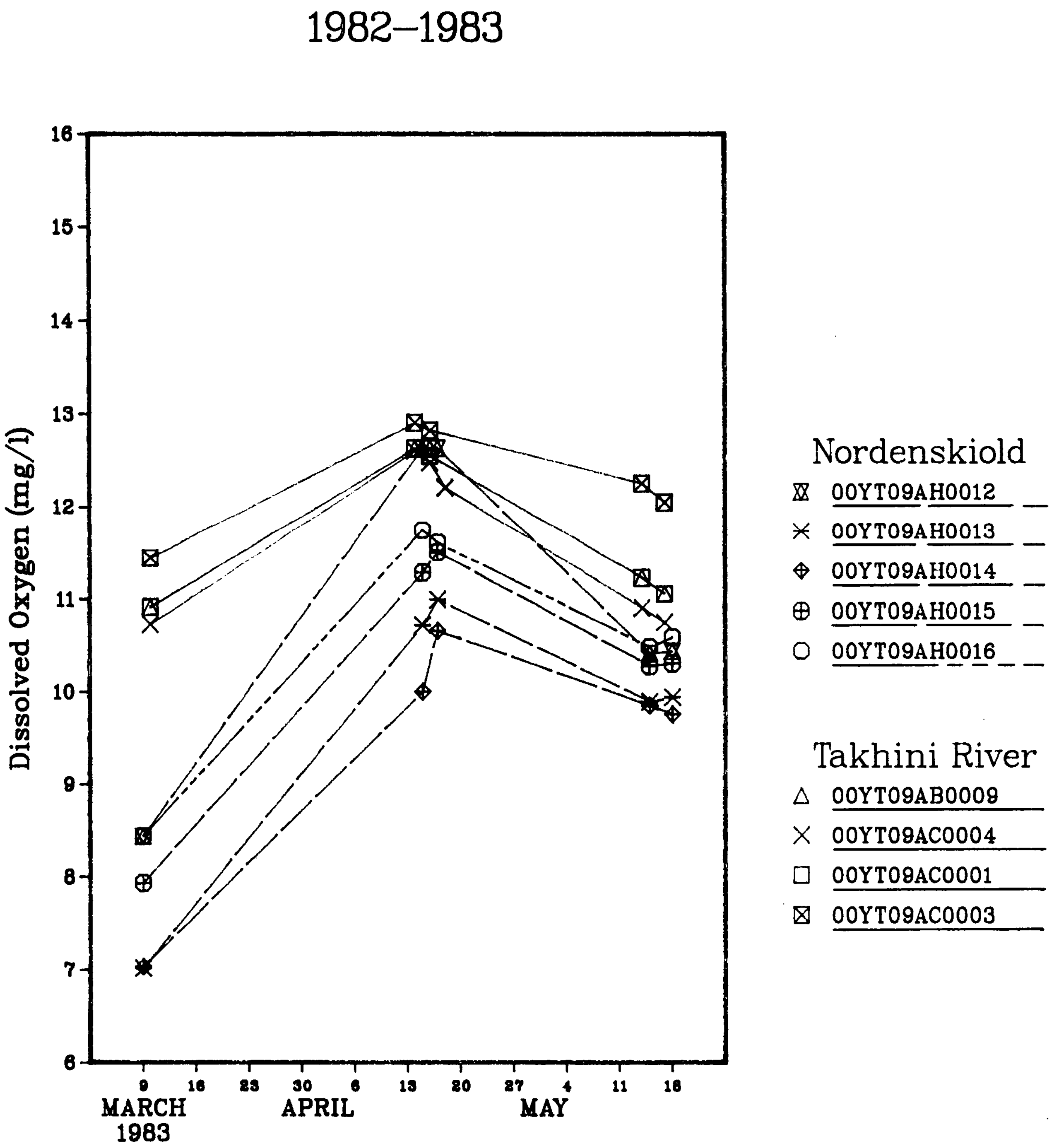

Figure 17
Dissolved Oxygen Concentrations from March to May

total organic carbon in both rivers. For the Nordenskiold River this increase is from 2 to about 20 mg/l. The Takhini changes somewhat less, from a range of 0.5-2.0 to a range of 1.0-4.0 mg/l. All the other variables show substantial decreases during the same period. Those decreases have been attributed to the increase in discharge during this interval.

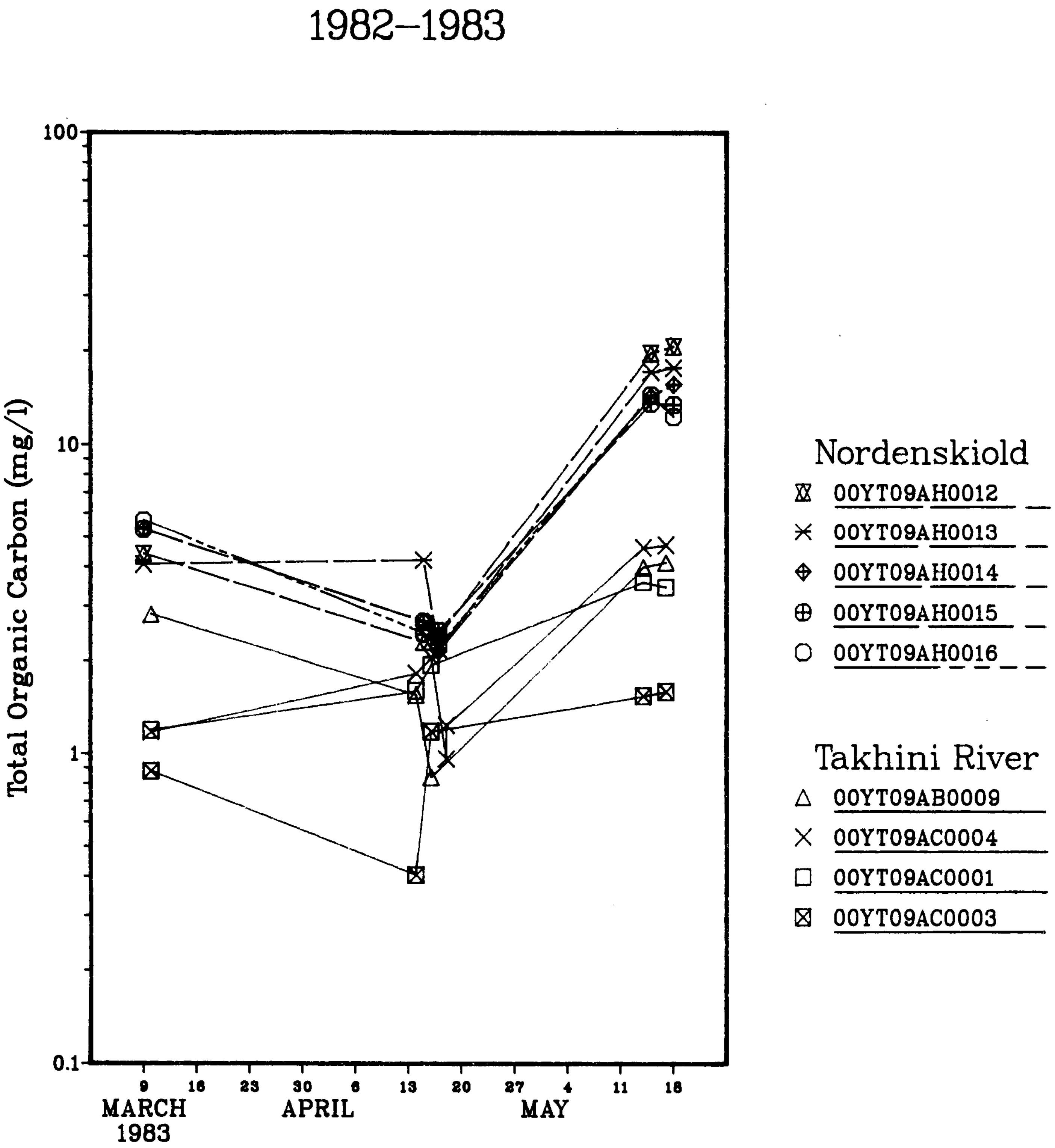

Figure 18
Total Organic Carbon Concentrations from March to May

Discussion

Schallock and Lotspeich (1974) indicated that dissolved oxygen depressions in Alaskan rivers begins in October and continues declining into February. They also found that the magnitude of the depression increased with downstream distance, an observation that was generally true in our study, and has also been reported by Bouthillier and Simpson (1972). They also observed that alkalinity and conductivity increased over the same time-frame. The results of the present study agree with their findings.

Data presented by Bouthillier and Simpson (1972) shows a rapid decline in dissolved oxygen concentration at the time of ice formation and a substantial increase in late February and early March. These results are very similar to those obtained in the present study. Bouthillier and Simpson (1972) did not discuss this aspect of their results.

Schreier et al. (1980) found that dissolved oxygen became depressed in both the Swift River (Southeastern Yukon), and the Ogilvie River (Northcentral Yukon). They found that the lowest concentrations observed occurred during late winter, when ice cover was most extensive. They found no direct relationship between ice thickness or ice type and oxygen concentration. They also suggested that as winter progresses the stream flow increasingly consists of groundwater, which is usually low in oxygen. Schreier et al. (1980) also noted that where open water persisted through the winter, the depression of dissolved oxygen was reduced. They noted that inorganic constituents increased in concentration over the winter, which they attributed to increases in the proportion of the flow contributed by groundwater. The data presented by Schreier et al.(1980) bears a close resemblance to the data presented in Figure 5. However, their sampling times did not coincide with either the period of ice formation or the period immediately prior to break-up.

In those areas where we can compare our results to earlier studies, our findings are very similar, namely:

1. Dissolved oxygen becomes increasingly depressed through the winter reaching its lowest concentrations in February or March.
2. During the same time-frame inorganic constituents increase in concentration. This results from the increasing proportion of the flow which is contributed from groundwater.
3. The magnitude of the dissolved oxygen depression generally increased with distance downstream.

In several other areas, however, our results represent new findings. These new findings are:

1. The absolute magnitude of the depression, and the rate at which it develops is much greater in the organic rich Nordenskiold River than in the Takhini River.

2. The initial depression of oxygen occurs during the formation of ice cover.
3. The concentration of dissolved oxygen increases to near saturation prior to the break-up of the ice cover.
4. These findings do not coincide with changes in any of the other variables that were measured.
5. The depression of dissolved oxygen occurs in two stages, a rapid decline during the formation of the ice cover, and a slower decline with increasing time after the formation of the ice cover.

These findings suggest that current hypotheses of how winter dissolved oxygen depressions develop needs to be expanded to include these new phenomena.

<u>Depletion of Oxygen at Freeze-up</u>

Before the formation of an ice cover on a river a relatively rapid transfer between the atmosphere and the river water occurs. Where oxygen is produced in the water by photosynthesis the concentration increases and the net transfer of oxygen is to the atmosphere. Where oxygen is consumed, either through biological or chemical processes in the river, there will be a net transfer of oxygen from the atmosphere to the water. The solubility of oxygen in water is mainly a function of temperature and pressure (Hem, 1970). The main source of oxygen in water exposed to air is the atmosphere, although some is contributed as a by-product of photosynthesis. At zero degrees Celsius, the solubility of oxygen in water is at its maximum.

The oxygen concentration of a stream is highly transient because of rapidly changing input and consumption rates. At freeze-up the formation of the ice cover affects the rate at which oxygen is transferred to the water, while the active biological processes may continue. The transfer of oxygen to the water is controlled by hydraulic parameters (Langbein and Durum, 1967). The primary controlling parameters are surface area, concentration gradient and vertical mixing. Nearly all rivers are turbulent, because their Reynold's numbers (the product of the velocity and the depth divided by the kinematic viscosity) are considerably greater than the threshold between laminar flow and turbulent water (Ashton, 1979). The turbulence causes mixing of the water, and at the surface there is a continuous interchange of water parcels with the flow below. When the water of a stream reaches zero degrees Celsius several changes occur which affect the exchange with the atmosphere. There may be formation of bank ice which reduces the surface area exposed to the atmosphere, thus reducing the area through which exchange of oxygen can occur. This process, however is likely of less importance than the formation of frazil ice in the water column.

Once the water column of a stream becomes supercooled (slighty below zero) small crystals of ice develop. These crystals, called frazil, are most often disc-shaped, with diameters of only a few millimeters. Frazil crystals immersed in supercooled water are not in equilibrium but are actively growing (Ashton, 1979). These ice crystals , are buoyant, and tend to move to the surface, or attach to objects in the flow. As they collect on the surface they tend to agglomerate, forming small pans. This process tends to restrict the vertical mixing of the water column, and actively impedes the transfer of oxygen from the atmosphere into the water.

Biological processes do not respond as quickly to environmental changes as do physical processes. Of particular interest in this situation is respiration, the process by which living organisms use oxygen to produce energy. Gordon (1970) shows that significant biological activity takes place at zero degrees Celsius in arctic and subarctic bacterial communities. The biological community present in a river is utilizing oxygen at a given rate when the ice begins to form on the surface. This rate will not be immediately affected by the change in the physical situation, but will lag behind by the period of time necessary for the individual organisms to reduce their oxygen demand. During this transition period oxygen utilization will change from the normal state of consumption to the much reduced rate of consumption associated with the overwintering state.

These two processes, occurring simultaneously, would result in rapid decreases in oxygen concentrations during the freeze-up period. This theory would explain the results which we obtained during the November sampling, shown in Figure 15. In November, there was a rapid decline in oxygen concentration during the first days of ice formation. The rate at which oxygen concentrations decreased during the November sampling period became progressively less with increased time after the formation of surface ice, suggesting that the biological community was making the necessary transition with respect to its oxygen consumption.

Effect of Organic Material

The Nordenskiold River has much higher concentrations of total organic carbon than does the Takhini River. The Nordenskiold also becomes more severely depressed with respect to oxygen than does the Takhini River. The difference with respect to dissolved oxygen can be attributed to the difference in the organic content of the two systems. This result agrees with the present understanding of biological utilization of oxygen in arctic and subarctic systems. Gordon (1970) has shown that indigenous bacteria exert a demand on dissolved oxygen under laboratory conditions, and increases in organic material increases the rate of oxygen utilization. Schallock et al.(1970) demonstrate that the rate and extent of oxygen utilization depends on the availability of bacterial substrate and nutrients. Schallock (1979) describes a field situation where disruption of the stream bed enhances the depression of dissolved oxygen.

We are uncertain to what degree the total organic carbon that was measured in this study is of the type which bacteria may utilize as a substrate. From the pattern of total organic carbon concentrations over the study period, it appears that only a small fraction of the organic carbon present was utilized over the winter.

<u>Changes Prior to Break-up</u>

Our results show a substantial increase in dissolved oxygen concentrations during April while the ice cover on the rivers remained coherent. Despite the fact that there was no open water, oxygen concentrations had risen from the winter minimums to near saturation level. In April, air temperatures were warmer than the winter sampling periods. During the day, air temperature were rising above freezing resulting in the melting of the snow cover. By the end of the April trip the ice surface was free of snow. The reduction of the thickness of the layer of snow, along with the increased radiation from the sun accompanying the longer days would result in the increased penetration of light into the water below the ice. Increased light penetration results in increase production by photosynthetic organisms. Many Yukon and Alaskan lakes become photosynthetically productive before the ice goes out in the spring (Woods, personal communication; Gray, personal communication; Shortreed, personal communication). In fact, chlorophyll concentrations often reach their annual maximum in this time period, when nutrient concentrations are high and predation rates are moderately low.

Photosynthesis, likely by periphyton, is thought to cause the observed increases in oxygen concentrations. Both the Takhini and the Nordenskiold Rivers are very shallow during this time period. With adequate light penetration through the ice, both rivers could potentially be very productive.

Conclusions

Several processes are active in the development of dissolved oxygen depressions under the ice in the two rivers studied. The principal processes which affect the depression include biological utilization, inputs of groundwater, and the physical processes associated with the formation of ice cover. It is difficult to separate out the individual effects of each of these processes, since many of the effects are coincident.

The theoretical model of the development of dissolved oxygen depression is extended to include two new 'events' previously not documented. The general model of how dissolved oxygen depressions develop is as follows:

1. In the fall, prior to ice formation, oxygen solubility increases due to the decrease in the water temperature, and concentrations of dissolved oxygen rise. Biological processes which utilize oxygen are active.
2. When the water temperature becomes supercooled frazil ice formation begins. The formation of frazil ice reduces the reaeration of water column by decreasing the vertical mixing and the formation of surface ice pans. Biological utilization of dissolved oxygen continues at a relatively high rate, and the dissolved oxygen concentrations drop at about 1 mg/l each day.
3. After a brief lag, the rate of biological utilization decreases to a minimal level for the duration of the winter.

Most of the total decrease which occurs over the winter happens during this lag period.

4. Oxygen concentrations continue to decline over the following period. These declines are related to the concurrent increases in inorganic materials. Both of these occurrences are believed to result from groundwater contributing an increasing proportion of the total flow of the river over the winter.
5. Dissolved oxygen concentrations reach their minimum concentrations in late winter (February to March).
6. Melting of the snow cover on the rivers results in increased light penetration into the river and provides the energy for increased photosynthesis. Photosynthetic activity produces oxygen, and dissolved oxygen concentrations increase from the winter minimum to near saturation.
7. Break-up of the ice cover returns the water of the river to contact with the atmosphere. Oxygen concentrations during the ice free period are controlled by solubility which is controlled by temperature.

The organic rich Nordenskiold River became more severely depleted with respect to dissolved oxygen than did the Takhini River. Current theories suggested that this would be the case. Decreases in total organic carbon concentrations over the winter of 1982-1983 were very similar to the dissolved oxygen decrease in the Nordenskiold River. In the Takhini River there was no variation in total organic carbon concentration over the study period.

Our results are in agreement with the earlier findings of Schallock and Lotspeich (1974) and Schreier et al. (1980) with respect to the development of the depressions of dissolved oxygen. Our results suggested that the initial development of the depression was much more rapid than had been previously described. Our results also suggest that the level of dissolved oxygen returns to the saturation concentration before the ice cover breaks up. Current research on subarctic lakes in the Yukon and Alaska report similar results.

Recommendations

Management Practices

When management options are being evaluated the following points should be considered:

1. Based on the findings of this study, as well as those of Schallock and Lotspeich (1974), Schallock et al. (1970), and Gordon (1970), we would recommend that no additions of organic material to streams occur between the end of September and the middle of April. Additions of organic material during the formation and existence of the ice cover would have detrimental effects on the biological communities which are already subjected to depressed dissolved oxygen concentrations.
2. Similarly, any disruption of the stream bed should not occur during this same period. Work of this nature re-introduces organic debris, and oxygen depleted material from the stream bed into the water column. Such practices have been shown to have detrimental effects on biota, including fish (Schallock, 1979).

Future Studies of Dissolved Oxygen

Several aspects of the proposed model of dissolved oxygen need futher evaluation, namely:

1. A more detailed study of the changes which occur at the time of frazil ice formation is needed to determine more precisely the physical changes which affect the reaeration process.
2. To determine whether or not organic carbon levels affect the magnitude of the depression a summer (August) winter (late February) comparative study of a larger number of rivers should be conducted. Such a study would measure total organic carbon levels, dissolved oxygen, and some of the inorganic variables. The results from such a study would also improve our ability to predict the severity of dissolved oxygen depressions.
3. A study of the period from March through May examining variables related to photosynthetic activity is needed to validate the proposed mechanism of oxygen generation under the spring ice cover.

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