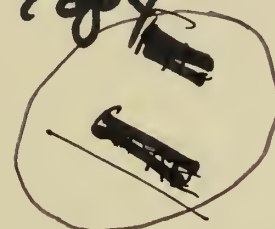


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**Water Quality Inventory and Monitoring—
Gates of the Arctic National Park
and Preserve, 1992–1995**

Jacqueline D. LaPerriere

Alaska Cooperative Fish and Wildlife Research Unit
Biological Resources Division, U.S. Geological Survey

**Final Report
to the
National Park Service**

Unit Cooperative Agreement No. 14-48-009-1582

Research Work Order No. 4

1999

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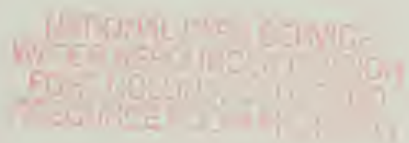
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Executive Summary

Gates of the Arctic National Park and Preserve (GAAR), the second largest national park of the U.S. at 3.4 million hectares, is estimated to contain tens of thousands of lakes. Sixteen lakes in GAAR were studied limnologically in the early summers of 1992, 1993, and 1995. Additionally, the John River near Anaktuvuk Pass and two of its tributaries above the village were studied in summers 1993 and 1994.

Lakes were found to be variable in mixing and chemical types. Lakes to the north in GAAR and shallow lakes to the south do not stratify; therefore, they are discontinuous cold polymictic lakes. Deep lakes to the south in GAAR apparently summer-stratify. These deep, southern lakes may miss some spring overturns as they sometimes had hypolimnetic waters colder than 4°C, the temperature of maximum density, especially in 1992. This phenomenon may also be due to local degradation of permafrost caused by recent climactic warming.

Most of the lakes studied are calcium carbonate lakes, but Pingo Lake, at the head of the Noatak watershed, is a magnesium-calcium carbonate lake, and Chandler Lake, near the headwaters of the Chandler River, is a calcium sulfate-bicarbonate lake. The high sulfate in Chandler Lake may come from the presence of reduced sulfur rocks in the lake's watershed, though this was not established. In 1995, when Chandler Lake was turbid from recent snowmelt and ice-off, total recoverable copper was measured.

All 16 lakes would be classified as oligotrophic on the basis of the total chlorophyll biomass estimates of the phytoplankton. Phosphorus and nitrogen concentrations exceeded the published boundary of oligotrophic-mesotrophic classification in Matcharak Lake. This lake also showed deoxygenation of its deep waters, which typically is due to the degradation of organics. In this lake, however, deoxygenation may instead be due to missed vernal overturns or to intrusion of deoxygenated water from melting permafrost.

Lake nutrient stimulation bioassay experiments all showed that nitrogen and phosphorus when added together were most stimulating to plankton algal growth. Additionally, southern lakes that were tested showed phosphorus limitation as did Chandler Lake, a northern lake, which is dominated by sulfate among the anions. The other northern lakes that were tested showed nitrogen limitation.

Plankton chlorophyll maxima at depth were common in these lakes at light levels between 1 and 4% of surface light. These plankton may be low-light adapted algae that bloom under the ice in spring and seek a lower position with reduced light after ice-off during the summer.

There was no general relation found among all these lakes between nutrients and plankton algal biomass, nor among plankton biomass and Secchi transparency. This may be due to the color and turbidity of many of these lakes, which are caused by dissolved organic and inorganic materials rather than by plankton.

The seasonal growth of benthic algae in the ice-scour zone (≤ 2 m) of Selby Lake was sampled in early July. The whole-lake average standing crop of benthic algae was estimated as approximately equal to the whole-lake standing crop of phytoplankton. Local density of benthic algae was greater near inlets than distant from inlets. Greater density was associated with colder inlets and with those higher in total nitrogen.

All of the lakes sampled in 1993 for counts of zooplankton had cladocerans (water fleas). On that basis, these lakes would be classified among arctic lakes of the highest trophic status, but still oligotrophic.

A model relating fish productivity to the saltiness of lakes and their mean depths developed from four lakes where fish standing crop has been measured ranked two lakes with higher measured standing crops of fish and saltiness per mean depth as more productive than the two lakes with lower standing crops and lower saltiness per mean depth. The model then predicts Pingo, Itkillik, Tulilik, and Matcharak lakes higher in potential fish yield and Kipmik, Walker, Minakokosa, and Narvak lakes lower.

Of the streams in Anaktuvuk Pass that were sampled, Little Contact Creek had the highest conductivity (and associated major ions), Big Contact Creek had the lowest conductivity, and the John River had an intermediate conductivity. Coliform bacteria and total petroleum hydrocarbons were not found to be measurable in these streams, but sampling was very limited over two days in late summer in each of two years.

Introduction

The most recent reviews of limnological studies conducted in the Arctic are by Hobbie (1973 and 1983). Few of the thousands of waterbodies in the western North American Arctic have been studied. Hobbie's reviews cover the findings of the thorough studies of Peters and Schrader lakes (Hobbie, 1962), of Char and Meretta lakes on Cornwallis Island, Canada (Rigler et al., 1974; Schindler et al., 1974a; Schindler et al., 1974b; Welch and Kalff, 1974), and of ponds near Barrow, Alaska (Hobbie, 1980). The long-term, more recent studies of Toolik Lake, Alaska, in the northern foothills of the Brooks Range and just outside Gates of the Arctic (GAAR) National Park and Preserve have recently been summarized by O'Brien (1997). Berger (1977) provides a summary of the Canadian work on the Mackenzie Valley Pipeline studies.

Other papers concerning less intensive studies of aquatic systems near Cape Thompson, Alaska (Watson et al., 1966), near the Beaufort Sea coast (Kalff, 1968), on the Coville River Delta, Alaska (Kinney et al., 1972), and along the Noatak River (O'Brien et al., 1975) were also considered in Hobbie's reviews. Hobbie (1997) has also recently written an interesting history of limnological research in Alaska.

Streams of the north slope of the Brooks Range have been surveyed and classified (Craig and McCart, 1975), and one river, the upper Kuparuk River, has been intensely studied (Peterson et al., 1985) and a synoptic study of the entire river has been conducted (Hershey et al., 1997).

The objectives of the current study were to (1) inventory and characterize the major lakes of GAAR to determine their trophic status and evaluate whether phytoplankton are limited by nitrogen or phosphorus; (2) develop a baseline inventory of water quality characteristics important to aquatic life in major lakes; (3) identify and document the magnitude and direction of changes in water quality of the John River at several sites in GAAR to determine if runoff and leachate from the village of Anaktuvuk Pass alter conditions in the river; and (4) develop a long-term monitoring plan for use by GAAR staff.

Study Site

Gates of the Arctic National Park and Preserve (GAAR) is the second largest national park in the nation at 3.4 million hectares (8.4 million acres) or 34 thousand km² (13 thousand mi²) in area. The number of lakes within GAAR is unknown but is estimated to be in the tens of thousands, calculated from proportion to the area of Alaska at 11.5 million km² (570,833 mi²), which contains approximately 3 million lakes (Bue, 1963). GAAR lies to the

west of the Trans-Alaska Oil Pipeline and its service road, the Dalton Highway. The primary means of access is by small airplane.

Sixteen lakes (Figure 1) were synoptically sampled during this study in summers 1992, 1993, and 1995. Chandler, Kipmik, Matcharak, Takahula, and Walker lakes were sampled all three years. Agiak, Amiloyak, Itkillik, Narvak, Nutuvukti, and Summit lakes were sampled two of the three years. Kurupa, Minakokosa, Pingo, Selby, and Tulilik lakes were sampled only once.

Nine of these lakes were bathymetrically surveyed by Reanier and Anderson (undated), and four of them were surveyed in 1991 by National Park Service personnel (Appendix A). Three of the lakes do not yet have bathymetric maps. Most of these lakes are in glacially eroded troughs (Reanier and Anderson, undated) and therefore are deep (Table 1).

A limited stream study was conducted in late summer 1993 and 1994 on the upper John River and its tributaries, Big and Little Contact creeks (Figure 1), near the village of Anaktuvuk Pass. These waters lie outside GAAR on native lands. The John River enters GAAR below the sampling site and is mostly contained in GAAR.

Methods

General Limnology, Nutrients, and Plankton

Lakes were accessed by Gates of the Arctic National Park and Preserve (GAAR) or charter airplanes on floats during mid-July 1992 and 1993 and about a week earlier in 1995. We landed and anchored at the deepest spot, providing that winds were low enough to allow use of the airplane floats as a steady work platform. We selected a safer site out of the wind effects, in the cases of winds causing large waves or whitecaps at the preselected station.

Secchi disk transparency was measured using a standard 20-centimeter (cm) weighted disk of alternating black-and-white quadrants. It was lowered on a calibrated, unstretchable, braided wire-line until it was no longer visible and retrieved until it could just be seen, and the depth was then read off the line at the surface. This was repeated three times and the average value calculated.

In 1993 and 1995, the penetration of photosynthetically active radiation (PAR) was measured at each lake both sampling periods using a Li-Cor® 185B quantum radiometer photometer with an LI-193SA spherical quantum sensor that measures aquatic quantum scalar (downward plus upward) irradiance. The spherical sensor was held in an

underwater lowering frame which was attached to the calibrated wire-line described above. Data were taken at each meter of depth until values fell to approximately 1% of the irradiance measured immediately under the water surface. Percentage of irradiance was plotted versus depth on semi-log graph paper, and the slope of the best straight line connecting the points was calculated as the vertical attenuation coefficient of downward irradiance, K_d . This coefficient is equivalent whether the sensor used is flat (cosine) or essentially three-dimensional (spherical or scalar) (Kirk, 1994).

In 1992, samples for water color and turbidity, major ions, and nutrients were taken in triplicate with an opaque 2-liter (L) Van Dorn sampler at a depth of 2 meters (m) and delivered into 1-L cubitainers and placed in an insulated cooler. Trace metal samples were taken in the same way and delivered into new, acid pre-cleaned 250-milliliter (mL) Nalgene bottles and stored in a cooler. Also in 1992, phytoplankton samples for biomass estimates (as chlorophyll) were taken with the same sampler and handled the same way as the color and turbidity samples, but triplicate phytoplankton samples were taken at depths of 1 m, the Secchi depth, and twice the Secchi depth. In 1993 and 1995, samples were all integrated through depth with a weighted 13-millimeter (mm) (i.d.) Tygon tube lowered to twice the Secchi depth (Hanna and Peters, 1991).

Depth profiles of physical and chemical characteristics were taken using a YSI Model 3800 multimeter fitted with depth, temperature, pH, conductivity, oxidation/reduction potential, and dissolved oxygen probes. Calibration of the unit was conducted every few days and whenever any sensor maintenance was required. Readings of dissolved oxygen were corrected for the altitude of the lake with a built-in barometer. Conductivity was automatically corrected to 25°C by the electronics of the meter. When the meter flooded and failed in 1993, temperature and oxygen readings were made with a YSI Model 56 meter; Park personnel also used that meter in August and September 1991.

Vertical hauls with a zooplankton net (0.235 m x 1 m) of 20 mesh (0.001 cm) were made in triplicate from the bottom of each lake at the sampling station. These samples were emptied into 60-mL Nalgene bottles, and these were placed into a cooler.

Upon return to the local, temporary laboratory, apparent (unfiltered) color was read at 455 nanometers (nm) on a HACH 2000 spectrophotometer, and turbidity was read on a HACH Model 16800 Portalab turbidimeter (nephelometer) or a HACH Model 2100P hand-held turbidimeter (1995). All samples for planktonic chlorophyll analysis were prepared by filtering 1-L samples through a Gelman GF/C glass-fiber filter. Filters were made alkaline by adding 1 mL of saturated $MgCO_3$ to the last few mL of sample filtered, and were stored frozen over desiccant until processed for chlorophyll at the laboratories of the University of Alaska Fairbanks (UAF).

Alkalinity was titrated using the HACH procedure for the digital titrator (hand-held buret) on 200-mL samples using the more dilute 0.1600 N sulfuric acid cartridges. The endpoint for total alkalinity (usually a pH of 5.1) was sensed with bromcresol green-methyl red indicator. Since the initial pH was always below 8.3, we stopped adding phenolphthalein at the beginning of the titration, because we found that it added significant apparent alkalinity to these low-alkalinity waters by shifting the initial pH of the water.

Chloride was titrated using HACH's digital titrator method on 100-mL samples using their digital-titrator mercuric nitrate method in 1992 and 1993. Lower concentration titrant cartridges (0.2256N Hg (NO₃)₂) were used because of low levels of chloride in the samples. Chloride was not measured in 1995 because all previous measurements were below the detection limit (0.1 mg/L). Sulfate was analyzed using HACH's turbidimetric method using (25-mL) Accuvac Ampules, which were read on the HACH 2000 spectrophotometer.

For phosphorus and nitrogen, triplicate samples were placed into acid-washed screw-cap culture tubes at the field laboratory, and the nitrogen tubes were preserved with 20 microliters (μL) of 50% sulfuric acid. These samples were shipped to the limnology laboratory of Dr. John R. Jones at the University of Missouri, Columbia, where they were analyzed for total phosphorus and total nitrogen as labeled on each tube. Acidic persulfate digestion was carried out in all the tubes, and the molybdate blue species of phosphorus was read on phosphorus samples using a Milton Roy 1201 spectrophotometer. Nitrogen was read for nitrogen samples on the nitrate formed during digestion by the second-derivative spectroscopy method of Crumpton, Isenhardt, and Mitchell (1992).

Chlorophyll filters were extracted in hot ethanol (Satory and Grobbelaar, 1984), and samples were analyzed for total chlorophyll (not corrected for phaeopigments) on a fluorometer (Knowlton, 1984). Zooplankton samples were preserved at the field laboratory with 3 mL of buffered formalin and shipped to our laboratories at UAF. Zooplankton samples were washed to remove the buffered formalin preservative and then analyzed for dry weight and ash-free dry weight (organic content) using pre-ignited and tared glass-fiber filters according to Standard Methods (APHA et al., 1989).

Trace metal samples were refrigerated at the field laboratory and shipped to UAF, where they were preserved with 0.3 mL of Ultrex-grade concentrated nitric acid and shipped to Environmental Trace Substances Research Laboratory (TSRL) in Columbia, Missouri, where they were acid digested for total recoverable metals and analyzed by induced coupled plasma spectroscopy (ICP) scanning for 30 elements.

Data were normalized by log transformations if necessary, and data exploration and statistics were conducted with JMP™ software (SAS Institute, 1994).

Geomorphology and Landscape Characteristics

Altitudes and latitudinal location of lakes were read on topographic maps. Lake surface areas, volumes, and mean depths were measured by Dr. John R. Jones' Limnology Laboratory at the University of Missouri on Reanier and Anderson's (undated) bathymetric maps and by the author on bathymetric maps generated by GAAR personnel and drafted by Betsy Sturm. Watershed areas were measured on U.S. Geological Survey (USGS) topographic maps by Dr. David Swanson of the School of Agriculture and Land Resources Management, UAF. Dr. Swanson also estimated landform, soil, and vegetation cover characteristics from the 1:60,000 color high-altitude infrared photo series, and geology of the basins from USGS geologic maps (Brosge et al., 1979; Chapman et al., 1964; Ferrians, 1965; Grybeck et al., 1977; Kelley, 1990; Patton and Miller, 1966).

Nutrient Stimulation Experiments

Lake planktonic algal stimulation bioassay experiments were conducted on Selby and Narvak lakes in 1993 (LaPerriere et al., 1998), and on Agiak, Chandler, Itkillik, Kipmik, Matcharak, and Summit lakes in 1995. Similar experiments were conducted before this project at Walker Lake in 1988 (Jones et al., 1990) and at Itkillik Lake in 1989 (LaPerriere and Jones, 1991). Near-surface water was sampled and placed into 10-L cubitainers. Triplicate containers were treated with nitrogen, adding 75 micrograms per liter ($\mu\text{g/L}$) using ammonium nitrate, with phosphorus adding 5 $\mu\text{g/L}$ using sodium orthophosphate, with both nitrogen and phosphorus together at the above concentrations, and with no chemical additions as controls.

The cubitainers were attached to an anchored, buoyed line at one-half of the Secchi depth and allowed to incubate at ambient conditions for 4 or 5 days. When retrieved, the cubitainers were returned to the field laboratory in dark containers, and replicate subsamples were immediately filtered through GF-F glass fiber filters and treated as all other chlorophyll samples.

Periphyton

Benthic algae was sampled intensively from random rocks in the ice-scour zone in Selby Lake the second week of July 1993. Biomass was measured as chlorophyll (APHA et al., 1989). The detailed methods are published in LaPerriere et al. (1998).

Streams

In the study in 1993 and 1994 of the John River and its two tributaries, Big and Little Contact creeks, flow was measured by the velocity area technique (Gregory and Walling, 1973) using a Marsh-McBirney electric-field water velocity meter and a top-setting rod. In 1993, anion samples were taken in pre-cleaned polypropylene bottles and transported to the field and UAF labs for analysis. Major ions were measured: alkalinity by the HACH digital titrator method described above for lake work as soon as possible at the field lab. Chloride and sulfate were measured by HACH methods as described above after return to UAF. Trace metal samples were handled and analyzed in the same manner as the lake samples as described above.

Laboratory-prepared bottles were used in both years to obtain coliform bacteria and total petroleum hydrocarbon samples. These were returned within 24 hours to Northern Testing Laboratories, where coliforms were measured by the Colilert method and by fecal coliform membrane filtration. Total petroleum hydrocarbons were analyzed by USEPA method 418.1.

On site, at the streams, a Corning Checkmate hand-held multimeter was used to measure temperature, pH, conductivity, and occasionally dissolved oxygen. Color and turbidity were measured by utilizing extra water from anion samples and using a HACH 2000 spectrophotometer to read color at 455 nm, and using a HACH Model 16800 turbidimeter to read turbidity.

Quality Assurance/Quality Control

Precision of the analytical methods was assured by measurements on replicate (usually triplicate) samples. Accuracy of chemical measurements was assured by the method of standard additions in which increasing concentrations of the appropriate primary standard were added to three subsamples of a sample, and the analytical measurement made on each. Results were plotted on square-matrix graph paper, and the true value of the analyte in the sample was found graphically. This test was conducted on 5% of the samples and whenever a new batch of chemicals was opened for use. Reagent blanks were measured on reagent grade water and subtracted when necessary.

ICP samples were sent to the TSRL as triplicates from each waterbody in totally randomized numbered bottles. The TSRL analyzed duplicate subsamples and blanks, as well as spiking samples with standards and measuring the percentage recovery of the spike. All the above tests showed TSRL results to be acceptably accurate and precise.

Results and Discussion

Landscape and Geomorphology

Because of the location of the Brooks Range and its foothills, southern lakes (~67°N) are at lower altitude than northern lakes (~68°N) in Gates of the Arctic National Park and Preserve (GAAR) (Figure 1, Table 2). As expected, larger lakes are associated with larger watersheds (Table 2).

While all lakes studied had some bare rock plus dry tundra, this landscape classification was more common (40–90%) for the watersheds of northern lakes in GAAR. The notable exceptions were Tulilik Lake, which, surrounded by wetlands, had a somewhat low percentage (33%) for a northern lake; and Walker Lake, which, with a lot of mountainside in its watershed, had a high percentage (60%) for a southern lake (Table 2).

Moist tundra plus sedge classification was more prevalent in northern lakes (10–66%) than southern, where it was often not measurable (0–9%). An exception was Summit Lake (5%), a northern lake with only a small proportion of moist tundra and sedge. This lake was at the highest altitude of all studied and was surrounded by mountains of bare rock. Floodplain forest and deciduous brush had a completely disjunct distribution. Northern watersheds had 5% or less of this classification, and southern watersheds had 30–50% (Table 2). Also, spruce and lichen plus black spruce with moss classification was completely missing from northern watersheds but represented 10–45% of southern watersheds (Table 2). Therefore, with a few exceptions, southern lakes' watersheds were dominated by floodplain forest, deciduous brush, spruce with lichen, and black spruce with moss vegetation. Northern lakes' watersheds were mostly dominated by bare rock and dry tundra and moist tundra and sedge.

Profiles

Lakes were mainly sampled once per year in summer. Preliminary sampling by the NPS was conducted in late summer 1991; sampling for this project in 1995 was about a week earlier in the season than in 1992 and 1993. However, since the investigator had week-long experiences at Walker Lake in 1988 (Jones et al., 1990) and Itkillik Lake in 1989 (LaPerriere and Jones, 1991), physical and chemical lake profiles (Figures 2–15) taken only once per year still yielded much information.

Thermal conditions in these lakes are somewhat unusual and interesting. Lakes to the north in GAAR, and coincidentally at higher altitude (>1000 m), did not summer stratify. Shallower lakes, even those located low and south in GAAR, also probably do not thermally stratify when not ice covered. In the north, we have evidence that this is caused

by frequent, strong winds. When we arrived at Itkillik Lake in 1989 (8 July) it was apparently starting to slightly stratify (Figure 5), but just days later (11 July), strong winds arose and the lake mixed to the bottom (Figure 5). Lakes of this thermal condition are classified as discontinuous cold polymictic (Lewis, 1983). Hobbie (1973) had classified all arctic lakes as continually mixing. The extra heat entering these lakes must add to productivity of aquatic organisms. Deep lakes south of the Brooks Range apparently stratify, which Hobbie (1973) thought a rare event for arctic lakes.

Temperatures colder than 4°C, the temperature of the maximum density of water, were found deep in several of the southern lakes in 1992 (Minakokosa, Narvak, Nutuvukti, Takahula, and Walker; Figures 15, 8, 9, 12, and 14), and this condition was found every time measured in Takahula (Figure 12). Therefore, Takahula may be a monomictic lake, overturning only in autumn. The cold hypolimnion is likely due to missed vernal overturns (Gosink and LaPerriere, 1986; LaPerriere, 1981) during years in which the previous autumnal overturn continued until the water was colder than 4°C before surface freezing occurred. Arctic lakes do not warm significantly during winter from back radiation from the sediments as temperate lakes do (Hobbie, 1973). The vernal overturn is missed because summer stratification begins and strengthens under the ice, and there are insufficient winds at ice-off to overturn the lake (LaPerriere, 1981). Another explanation for cold, hypolimnetic waters being less than 4°C in summer might be the discharge of cold groundwater in the basins. Addition of this cold groundwater may be a deep event. We saw evidence of this in 1988 (Figure 13), measuring at three different depths in a cove of Walker Lake where water colder than 4°C was sensed deep in the center of the cove. Monitoring of temperature through the year would be necessary to fully explain this anomalous thermal phenomenon.

In 1993, we conducted our measurements during and after an unusual arctic heat wave that caused the 12 July air temperature to reach 34°C at Selby Lake where we were sampling phytoplankton and periphyton. During the synoptic survey 16–21 July 1993, maximum surface temperatures were measured: 14.5°C at Agiak, 15.2°C at Amiloyak, 11°C at Chandler, 14°C at Itkillik, 16.3°C at Kipmik, 18°C at Matcharak and Narvak lakes, 23.4°C at Nutuvukti, 21.5°C at Selby, 14.2°C at Summit, 18.5°C at Takahula, and 20°C at Walker. Therefore, Hobbie's (1973) rule that arctic lakes never warm above 15°C was violated, even by more northern lakes (Kipmik and Matcharak) in GAAR. Near-bottom water temperatures for July in some of the polymictic lakes were also highest in 1993: 10°C at Agiak, almost 12°C at Amiloyak, 8°C at Chandler, and nearly 14°C at Itkillik. In other years, about 6°C was typical of Agiak and Chandler lakes.

Dissolved oxygen conditions in these lakes were usually orthograde; that is, increasing with decreasing temperatures at depth, following the ideal gas law. When vernal overturns were apparently missed in 1992, however, some oxygen depletion was seen near the bottoms of some of the otherwise dimictic lakes: Nutuvukti (Figure 9) and Minakokosa (Figure 15). Nutuvukti receives water from a peatland, which is probably anaerobic. This phenomenon might also fit the hypothesis of anomalously cold, hypolimnetic summer water resulting from intrusion of cold groundwater. Such meltwater would probably be deoxygenated from contact with soils anaerobic due to decomposing soil organic matter. Also note that where Takahula Lake had an anomalously cold temperature at and near 50 m on 21 August 1991 (Figure 12), dissolved oxygen was quite reduced (Figure 12). However, deoxygenation at depth may also be due to respiration of deep algal peaks in some of these particular lakes (this will be discussed with the nutrients and plankton results later).

Clinograde oxygen profiles (those in which concentrations decrease at depth despite colder temperatures) in polymictic lakes, such as at Kipmik Lake in mid-August 1991 (Figure 6) and in Matcharak Lake in 1993 and 1995 (Figure 7), may be due to the die-off and settling of rich plankton, or to the phenomenon described by Hobbie (1973) wherein cooling, sinking water from the shallows in autumn is deoxygenated by contact with anaerobic bottom sediments. It may also be due to contact of runoff with organic soil. Subsurface peaks of oxygen were also seen around the thermoclines of some dimictic lakes (Takahula and Walker). These were probably due to algal photosynthesis at deep, peak chlorophyll concentrations, which will also be discussed later in the nutrients and plankton section.

Plankton algae may also be responsible for elevations of pH seen near the surface of many lakes (Agiak, Chandler, Kipmik, Matcharak, Minakokosa, Summit, Takahula, Tulilik, and Walker) and at all depths of the shallow Pingo Lake. All the lakes studied have relatively low conductivity [40-450 microSiemens per centimeter ($\mu\text{S}/\text{cm}$)] and alkalinity and are, therefore, likely to show an increase in pH with active photosynthesis (Wetzel, 1983). Conductivity was lower in 1995 in Agiak (Figure 2), Chandler (Figure 4), and Summit lakes (Figure 11) when measured earlier than in other years, probably due to recent ice- and snowmelt in their basins. Oxidation-reduction potential (ORP) varied between about 200 and 300 millivolts (mV) in these lakes; in other words, they were always in oxidizing conditions measured at all depths in the early summer.

Major Ions

Most lakes of GAAR are so-called calcium carbonate lakes because the dominant cation is calcium and the dominant anion is bicarbonate (Table 3). This was said to be typical of arctic lakes (Kalff, 1968). However, there were two unusual lakes sampled in this synoptic survey. Pingo Lake, at the head of the Noatak watershed, was a magnesium-calcium bicarbonate lake, and Chandler Lake, near the head of the Chandler River drainage, was a calcium-sulfate bicarbonate lake. The condition of Pingo Lake is likely due to local lithography. Chandler Lake was measured to have an alkalinity to calcium-plus-magnesium ion ratio of 0.6, below the normal range (0.8-1.2) of pristine lakes unaffected by acid precipitation (Schindler, 1988). Acid precipitation is not a likely cause of Chandler's unusual chemistry, however, because Amiloyak Lake upstream in the watershed is an ordinary calcium-carbonate lake. It was believed that the high sulfate in Chandler Lake comes from the presence of reduced sulfur rocks in the lake's watershed, though this was not established.

In this study, lakes did not become more saline (higher total major ions) at lower altitudes as was true of the subarctic lakes studied at Katmai National Park and Preserve (LaPerriere, 1996). At Katmai, the lakes studied were connected along two major drainages, so the salinity was expected to increase down gradient. At GAAR, the lakes lie on many drainages, and only Selby and Narvak, and Amiloyak and Chandler, are connected to each other. Surprisingly, Amiloyak was not a sulfate lake, while Chandler, lower in the drainage, was dominated by sulfate. Narvak and Selby were quite similar chemically and are even considered by some to be a single lake with a narrow channel between two basins.

Also, in contrast to Katmai findings, none of the lakes studied had a high proportion of chloride. In fact, it was not measured after the first two years, when it was found below the method's detection limit [0.1 milligrams per liter (mg/L)] in all the lakes sampled. It may be measurable in lakes to the far north in GAAR, but the close ion balances (Table 3) of Itkillik (where it was measured below detection in 1993) and Kurupa lakes, the farthest north lakes studied, do not imply that chloride is a missing major ion. Evaporite rocks, likely to be sodium rich, are not mapped in any of the studied basin. Sodium (logged), in fact, varies only with the major ion (log) magnesium ($r^2_{\text{ADJ}} = 0.552$, $p = 0.0006$). Therefore, the Beaufort Sea, and especially storms moving southward from the Beaufort Sea, do not seem to move much sodium chloride into the northernmost lakes measured. The phenomenon of sodium chloride dominance is, however, known to happen to lakes on the Alaska North Slope (Kling et al., 1992), to the north of GAAR, but reported only in small, shallow (<0.8 m) lakes near the ocean.

Among the study lakes, calcium varied directly with alkalinity ($r^2_{\text{ADJ}} = 0.90$, $p = 0.0000$) as would be expected in lakes that are mainly calcium carbonate, wherein the major component of alkalinity is the bicarbonate ion. Lakes with limestone in the watershed, or in the source area of glaciers that entered the watershed (Dr. David Swanson, 1997, personal communication) (Itkillik, Matcharak, Pingo, Takahula, and Walker), had higher calcium concentration [33.5 ± 12.4 ; ($\bar{x} \pm 95\%$ confidence interval versus 8.05 ± 3.14)] and higher alkalinity (91.5 ± 51.6 versus 22.3 ± 11.2). Magnesium, for most lakes (except Pingo, where it was equally dominant with calcium, as mentioned earlier) was the second most dominant cation. Therefore, as expected, magnesium and calcium varied together ($r^2_{\text{ADJ}} = 0.526$, $p = 0.0009$; Figure 16), and magnesium varied with alkalinity ($r^2_{\text{ADJ}} = 0.775$, $p = 0.0000$) like calcium. The northcentral lakes in GAAR (Agiak, Amiloyak, Chandler, Tulilik, and Kurupa) as well as Pingo, which is to the west of these, have relatively more magnesium versus calcium than the rest of the lakes (Figure 16).

Trace Metals

The method of ICP spectrophotometry used to measure the major cations that were discussed earlier in this report also measured the trace metals (Appendix B). Trace metals detected in particular lakes all three years were few: barium (Ba), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), silicon (Si), strontium (Sr), vanadium (V), and zinc (Zn) (Table 4). Copper, zinc, and nickel, measured in Chandler Lake in 1995 (Appendix B), often occur together in sulfide ore bodies. Such an ore body, as mentioned before, may be present in the Chandler Lake watershed. Of these metals, only copper was found above the freshwater criteria (USEPA, 1984) set to prevent acute and chronic harm to organisms. However, the only year in which this occurred was 1995 when the lake had just cleared of ice. Turbid conditions from recent snowmelt that year (Appendix C) also were associated with measurable aluminum, vanadium, and zinc in Chandler Lake and measurable aluminum in Kurupa and Summit lakes. Aluminum is a dominant component of some clays.

Iron (log) varied directly with (log) color ($r^2_{\text{ADJ}} = 0.805$, $p = 0.0000$). Therefore, the brown color of these lakes cannot probably be entirely attributed to humates, but some is undoubtedly from iron and its oxides (Wetzel, 1983). Additionally, Secchi disk depth was shallower in response to (log) iron ($r^2_{\text{ADJ}} = 0.741$, $p = 0.0000$). This inverse relationship between iron and Secchi depth probably occurred because humates act as complexing agents that keep iron in the water column, and the associated color of both the humates and the iron decreased Secchi transparency.

As the altitude of the lakes increased, the (log) manganese also increased ($r^2_{\text{ADJ}} = 0.612$, $p = 0.0003$). Manganese (logged) also varied directly with the proportion ($\arcsine^{1/2}$) of bare rock plus dry tundra in the watershed ($r^2_{\text{ADJ}} = 0.586$, $p = 0.0003$) and inversely with the proportion ($\arcsine^{1/2}$) of floodplain forest and deciduous brush in the watershed ($r^2_{\text{ADJ}} = 0.522$, $p = 0.0009$). Therefore, manganese was higher in the watersheds of the northern lakes of GAAR, which were at increased altitude and likely to have high amounts of bare rock and dry tundra and lower amounts of floodplain forest and deciduous brush.

Strontium (logged) varied directly with the (log) total major ions ($r^2_{\text{ADJ}} = 0.645$, $p = 0.0001$) and with (log) alkalinity ($r^2_{\text{ADJ}} = 0.599$, $p = 0.0003$). These relationships probably demonstrate that the forces, particularly of weathering, that release the major ions also release strontium into these lakes.

Nutrients and Phytoplankton

All of the studied lakes would be classified as oligotrophic on the basis of the measured total chlorophyll biomass estimates of the phytoplankton (Nürnberg, 1996), which were less than 3.5 µg/L for all measurements of all lakes (Table 5). However, total phosphorus measurements (Table 5) exceeded the oligotrophic-to-mesotrophic limit of 10 µg/L (Nürnberg, 1996) once each in Amiloyak, Matcharak, Kurupa, and Summit lakes. The exceedances in Kurupa and Summit lakes occurred in 1995, when we sampled about a week earlier than the other two years, and we could see the particulates caused by rock material that entered with the recent snowmelt acting as turbidity. Adsorbed phosphorus on the rock material would be measured as total phosphorus but might quickly sediment out of the water column.

The total nitrogen limit of 350 µg/L for the oligotrophic-mesotrophic boundary (Nürnberg, 1996) was exceeded in 1992 and 1993 in Matcharak Lake and once each in Narvak, Pingo, Takahula, and Tulilik lakes (Table 5). We cannot tell if this is a common occurrence in Pingo and Tulilik lakes because we sampled each only once.

As mentioned earlier, Matcharak Lake did have deoxygenation of its deeper water. Because it is richer in nutrients, it may also have more phytoplankton than the other lakes. This could happen as a thin, deep peak of plankton algae that might be missed in discrete sampling and underestimated in integrated sampling. However, there was also some evidence of late-summer deoxygenation of nearby Kipmik Lake (in 1991), which is much less rich in major ions and nutrients. The low oxygen concentration, however, was measured in a small, deep hole near an inlet and may be local and due to allochthonous plant materials being washed in and decomposing there.

Among these lakes, total phosphorus was comparatively low (4–6 µg/L) in the lakes south of the Brooks Range (Table 6), varying (as the log) inversely with the proportion ($\arcsine^{1/2}$) of floodplain forest plus deciduous brush ($r^2_{\text{ADJ}} = 0.480$, $p = 0.0018$) in the watershed (Table 2). There was not a general relationship between total phosphorus and latitude among all the lakes. Manganese (log) and total phosphorus (log) varied together ($r^2_{\text{ADJ}} = 0.671$, $p < 0.0001$), which is an indication that total phosphorus might also (like manganese) be associated with the bare rock proportion in the watersheds, because it was at somewhat higher concentrations at higher elevations (altitude) in GAAR ($r^2_{\text{ADJ}} = 0.462$, $p = 0.0023$).

The total nitrogen-to total phosphorus (TN/TP) ratio varied for particular lakes from year to year (Table 5). The ratios for the two years (1993 and 1995) when water-column integrated samples were taken were not more similar than each compared to the ratios for a particular lake in 1992 when discrete samples were taken. The lack of similarity of ratios of 1993 and 1995 was possibly due to the approximate one week earlier in 1995 that the lakes were sampled compared to 1992 and 1993. The multi-year lake average TN/TP ratio (Table 6) was less than 13, which implies nitrogen limitation (Smith, 1979), for only Kurupa (12; sampled 1995 only) and Summit (11) lakes. The multi-year average ratio (Table 6) was above 21, which implies phosphorus limitation (Smith, 1979), for Amiloyak (24), Chandler (27), Itkillik (35), Kipmik (27), Matcharak (38), Minakokosa (78), Narvak (90), Nutuvukti (57), Pingo (48), Selby (75), Takahula (61), Tulilik (62), and Walker (77) lakes. Agiak Lake had a two-year average ratio of 17, which means it may be limited by nitrogen or phosphorus (Smith, 1979).

We have evidence from nutrient stimulation bioassay experiments (NSEs) that, as expected, Walker (Jones et al., 1990), Selby (LaPerriere et al., 1998), and Narvak lakes, which all had very high TN/TP ratios, were phosphorus limited when we measured them (Table 7), as was Chandler in 1995, which had a much lower TN/TP ratio (14). However, we have NSE evidence that Agiak (TN/TP = 12 in 1995), Itkillik (36), Kipmik (22), Matcharak (36), and Summit (6) lakes were nitrogen limited early in summer 1995 (Table 7). We also have earlier NSE evidence that Itkillik Lake was nitrogen limited in 1989 (Table 7) (LaPerriere and Jones, 1991). Therefore, perhaps a TN/TP ratio of up to 36 can be associated with nitrogen limitation in these lakes. Excluding Chandler Lake, where only one experimental set was retrieved, multi-year ratios above 75 were shown by experiments to be associated with phosphorus limitation. Much more experimentation and multiple nutrient measurements over the open water season to allow calculation of seasonal averages would need to be done to fully determine the pattern of nutrient limitation in GAAR.

The multi-year average TN/TP ratios (Table 6) of these lakes decreased with altitude ($r^2_{\text{ADJ}} = 0.880$, $p < 0.0001$) and with latitude ($r^2_{\text{ADJ}} = 0.688$, $p < 0.0001$), again showing that phosphorus was relatively higher in the northern lakes (in the Brooks Range) and that nitrogen was relatively higher in the southern lakes. The ratio fell with increasing proportion (arcsine^{1/2} transformed) of bare rock plus dry tundra in the watershed ($r^2_{\text{ADJ}} = 0.571$, $p = 0.0004$), typical of northern lakes, and increased with increasing proportion (arcsine^{1/2} transformed) of floodplain forest plus deciduous brush ($r^2_{\text{ADJ}} = 0.544$, $p = 0.0007$) and of black spruce plus moss ($r^2_{\text{ADJ}} = 0.613$, $p = 0.0002$), typical of southern lakes. To sum this up, TN/TP is higher with increased land plant biomass in the watershed.

Among all these lakes, plankton biomass as total chlorophyll was not related to total phosphorus or total nitrogen concentrations. This may be due to some of the lakes being phosphorus limited and others nitrogen limited. These data do not allow definitive separation of all the lakes into these two classes. Another factor that probably affects the nutrient-chlorophyll relationships is the presence of deep peaks of phytoplankton. We had evidence of these deep peaks in several lakes (Table 8), both lakes that stratified and those that mixed throughout summer (Kipmik and Matcharak).

When discrete-depth algal biomass data that demonstrated deep algal peaks (Table 8) were averaged and compared to data obtained with the integrating tube from the same lakes in 1993 and 1995 (Table 5), the values were not close to each other. Thus, the sampling scheme used in 1992 was probably not adequate to characterize the water column, perhaps because peak algal biomass was not consistently at the Secchi depth or twice the Secchi depth and, therefore, was not necessarily sampled. Algal peaks were found in both polymictic and stratified lakes and thus were not necessarily associated with a thermocline.

The peak biomass of plankton algae (as total chlorophyll) was often found at quite low light levels, varying between about 1% and about 4% (Table 9). This phenomenon may be due to low-light adapted algae that bloom under the ice in the spring and seek a lower position with reduced light after ice-off, rather than being associated with the barrier to sinking of a thermocline. Measurements of growth of these deep algae need to be made to help determine why they congregate at these deeper depths.

Light Conditions

While these lakes (Table 10) were not as clear as the lakes of Katmai National Park and Preserve (LaPerriere, 1996), they were among the clearest in the nation in summer 1995, measured as Secchi depth (Carlson, 1996). Light penetration, measured as the 1% light depth, was less in GAAR lakes ($\bar{x} = 12.1$ m versus 29.2 m at Katmai). Correspondingly,

turbidity and apparent (unfiltered) color (Table 10) were higher in GAAR lakes. The relatively high turbidity and apparent color values for Kurupa and Summit lakes were due to the early sampling of 1995 (Appendix C) just after snowmelt, when both lakes were apparently inundated with rock flour. Turbidity is probably high in Kurupa Lake through the ice-free season because it has a glacial source. Turbidity was also higher in Summit Lake in 1993 than in the other lakes measured that year (Appendix C), when we observed a massive debris flow that eventually entered the lake while we were sampling, just after a thunderstorm had ended. Turbidity in the lake at that time may have been due to residual suspended material from snowmelt, as well as from debris flows caused by rainstorms. In this massive national park there are no weather stations; therefore, one could not know the weather with certainty without observing it directly.

Among these lakes, not only was there no relationship found between nutrients and plankton algal biomass (as total chlorophyll), but there was also no relationship found between plankton algal biomass and Secchi depth. Both relationships are typical of most large lake regions (Carlson, 1977; Nürnberg, 1996). Secchi depth, however, had a strong inverse relationship to apparent water color ($r^2_{\text{ADJ}} = 0.789$, $p = 0.0000$), which may include some effects of turbidity because apparent color samples are not filtered. Even so, this was undoubtedly mostly non-plankton turbidity because there was no relationship found between algal plankton and Secchi depth. Therefore, in these lakes, it was color and associated turbidity that scattered light, shallowing Secchi depths. This is expected in colored, turbid systems (Koenings and Edmundson, 1991). Color and iron (both logged) were strongly related to each other ($r^2_{\text{ADJ}} = 0.805$, $p = 0.0000$), so Secchi depth also varied inversely with iron concentration. Therefore, as said before, much of the color in these lakes may be iron oxides and, perhaps, iron complexed by humates.

The ratio between the 1% light depth and the Secchi depth (Table 11) varied widely rather than narrowly around the rule of thumb (Kirk, 1994) of a ratio of 3. The highest ratios appeared to be associated with relatively low Secchi depths caused by scattering materials (turbidity) (Table 10). Another rule of thumb, that the 1% light depth is the lower limit of plant growth (euphotic) zone, may also not hold for these lakes. Many of these lakes had chlorophyll peak concentrations near the 1% light level, indicating that maximum plankton algal biomass was near there (Table 9).

Periphyton

Periphyton (benthic algae growing on rocks) was only sampled at Selby Lake (LaPerriere et al., 1998). Its standing crop measured about equal to the standing crop of phytoplankton. Local standing crop was higher near colder inlets and higher with higher total nitrogen of

the nearby inlets. Periphyton is probably critically important in arctic lakes because the food chain of these lakes may be quite dependent on benthic algae (O'Brien, 1997).

Zooplankton

All of the lakes sampled in 1993 wherein zooplankton were identified and counted, as well as massed (Table 12) as in the other two years, had cladocerans (water fleas) (Table 13). Therefore, these lakes would be classified among arctic lakes of the highest trophic status (but still oligotrophic) according to Hobbie (1973).

Low counts of cladocerans per cubic meter were recorded for Agiak (6), Chandler (6), and Nutuvukti (8) lakes. No rotifers were counted from Chandler or Nutuvukti lakes. This may have been an artifact of sampling if the net mesh (0.001 cm) was too large to capture smaller rotifers that may have been present. Hobbie (1973) concludes that rotifers are in all arctic lakes, even those of the lowest trophic state.

Copepods (Table 13) dominated most of the zooplankton counts and were mostly calanoids (Table 14) when identifiable (i.e., not nauplii or copepodites too small to identify). Therefore, copepod counts were correlated with average ash-free masses of zooplankton among these lakes ($r^2_{\text{ADJ}} = 0.738$, $p = 0.0002$). Cyclopoid copepods were not found in most of these lakes (Table 14).

Zooplankton standing crop (Table 12) was similar for a lake between the years sampled if the depth of the vertical hauls was similar. If the haul depth was different, because the lake was sampled at a different station, the zooplankton sampling crop estimates (as mass per water volume) were different. This probably results from an uneven distribution of zooplankton with depth during the day in at least some of these lakes. This phenomenon is commonly found in lakes. Note that Pingo Lake was not sampled for zooplankton in 1992, the only year it was sampled, because it was too shallow compared to the length of the net. Thick zooplankton, including amphipods (scuds), were, however, visible in Pingo Lake.

Lake Productivity

In general, shallow lakes are more productive than deeper lakes (Rawson, 1952) because nutrients and plankton are kept circulating rather than settling into the depths where they are trapped and light becomes limiting. Three GAAR lakes were not mapped—Pingo, Tulilik, and Summit—but were assessed as shallow. Estimates of the mean or average depths of those three lakes were calculated by assuming the anchor depth was the deepest spot and by dividing that depth by 2.4, which was the average quotient of the maximum

depth divided by the mean depth for the other 13 lakes. Besides the three unmapped lakes, Amiloyak, Agiak, and Itkillik lakes were also shallow (Table 15).

Lakes are also known to vary in productivity with the amount of salts they contain, which can be measured as conductivity, total dissolved solids, or alkalinity (Rawson, 1951). When the lakes were ranked from high to low alkalinity, the six saltiest lakes were Pingo, Takahula, Itkillik, Matcharak, Tulilik, and Walker (Table 15).

An empirical relation between fish yield and both the lake morphometry, as mean depth, and saltiness, as total dissolved solids, was developed and tested in many (mostly temperate) regions (Ryder et al., 1974). This relation is called the morphoedaphic index (MEI) and is here calculated by dividing total ions (mg/L) by the particular lake's mean depth. The estimated MEI of lakes of GAAR (Table 15) is higher for Pingo, Itkillik, Tulilik, and Matcharak lakes, which implies they produce more fish. Pingo Lake probably does not have fish because it is so shallow it freezes to or very near the bottom. We observed large amphipods, which indicated the absence of fish.

The only study lakes in GAAR where fish densities have been evaluated are Amiloyak and Chandler (Troyer and Johnson, 1994), Walker (Johnson and Troyer, 1994), and Itkillik (Patricia Rost, Chief of Natural Resources, GAAR, personal communication). The fish densities were from population estimates and are not yield, which is fish harvested. However, lakes with higher calculated MEI values (Itkillik and Amiloyak) had higher density estimates for top predator fish (lake trout and Arctic char). Lower MEI values for Chandler and Walker lakes were associated with lower density estimates of those fishes (Figure 17).

To use growth of plankton algae and especially zooplankton to evaluate the productivity of these lakes would require expensive and difficult efforts repeatedly over the entire growing season. However, standing crop, in situations where grazing by the next higher trophic level is not intense, may be a good indicator of productivity.

Tulilik, Itkillik, Matcharak, and Amiloyak lakes ranked as the four highest when standing crop as ash-free dry weight of zooplankton (Table 12) was used as an indicator of productivity, which seemed acceptable for these arctic lakes where there are no fish that graze exclusively on zooplankton.

Standing crop of planktonic algae (as chlorophyll) was higher in Pingo and Matcharak lakes, but also in Kipmik, which had a low MEI value. Because zooplankton graze on planktonic algae, the high standing crop of algae in Kipmik Lake may be an artifact of lower grazing pressure there by fewer zooplankton than in other lakes. Therefore, standing crop of algae is probably not a good indicator of productivity for all these lakes.

John River

The flows of the two tributaries of the John River through Anaktuvuk Pass (Contact Creek and Little Contact Creek) were equal to about half the estimated flow of the John River (Table 16), which probably indicates that the John River and its tributaries (Figure 1) are gaining groundwater or hyporheic flow between the sampling stations.

The characteristics of the three sampling stations indicate they were similar when measured both times, with Little Contact Creek having the highest conductivity (or saltiness), Big Contact Creek the lowest conductivity, and the John River an intermediate conductivity (Table 16). These waters were of the normal calcium carbonate type (Table 17).

Big Contact Creek and the John River are chemically similar, and Little Contact Creek is a little more concentrated with regard to the major positive ions (Table 18 and Appendix D). No fecal coliform bacteria were consistently found in any of these streams at the time of sampling (at or above 2 per 100 mL or at or above 1.1 colonies per 100 mL). Total coliforms (Table 19) were slightly higher in the John River (18.4 ± 4.0 colonies/100 mL; $n = 3$) than in either Big Contact Creek (5.2 ± 1.6 colonies/100 mL; $n = 3$) or Little Contact Creek (3.6 ± 1.4 colonies/100 mL; $n = 3$). Three of six samples from the John River had a measurement of total petroleum hydrocarbons above the method detection limit of 0.4 mg/L (Table 20). A much more intense sampling effort on these streams with more sensitive methods for hydrocarbons would be necessary to detect any contamination by bacteria or petroleum products.

Future Research

- The cause of the unusually cold hypolimnia at times on the south slope of the Brooks Range should be investigated. Because Takahula Lake had a cold hypolimnion every time profiled, it should probably be the lake studied.
- The relative importance of phytoplankton, periphyton, and vascular aquatic plants should be investigated by measuring standing crop and growth over the growing season for these three communities in several lakes.
- The viability of plankton algae in deep peak concentrations should be measured by growth experiments conducted by incubating the algae at depth over time.
- Light limitation of plankton algae should be studied by growth experiments.
- Nutrient limitation of plankton algae should be studied repeatedly over the growing season in several lakes that appear from TN/TP ratios to be nitrogen or phosphorus limited.
- The source of the high proportion of sulfate and any association with trace metals in Chandler Lake should be identified.
- The importance of benthic algae and vascular aquatic plants to primary consumers should be investigated.
- An evaluation of the distribution of benthic invertebrates in GAAR lakes and streams should be conducted.
- The importance of the hyporheic zone should be investigated in GAAR streams with deep gravel beds.
- The relative productivity of GAAR streams should be studied.

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Glossary

Accuracy	closeness of measurements to the true value
Alkalinity	the sum of the negative ions of the salts of the weak acids; in freshwater usually mainly bicarbonates, carbonates, and carbon dioxide
Amphipods	small crustacea that are laterally compressed with many-segmented bodies
Anion	negatively charged ions
Attenuation	to lessen in amount
Bathymetry	the science of measuring the depths of water bodies
Benthic	attached to or associated with the bottom sediments
Bioassay	an experiment in which substances are added to measure an induced change compared to the results of no addition
Cation	positively charged ion
Chlorophyll	the enzyme that plants use to capture light energy
Coliform bacteria	indicators of sewage or animal fecal pollution
Conductivity	ease of passage of electrons through water because of salt content
Copepodite	juvenile copepod
Copepods	crustacean microzooplankton that swim with their second antennae and do not have jointed feeding appendages
Detection limit	the lowest value that can be measured reliably
Dimictic	mixing twice during the year usually in spring and autumn
Empirical	a relationship developed from the data
Epilithic	growing attached to rocks
Fluorometer	instrument that induces and measures fluorescence of certain substances
Formalin	38% formaldehyde
Humates	break-down products of vegetation
Hypolimnion	cold, deep water in a stratified lake during summer

Hyporheic	the zone of flow of a stream that is within the sediments and above the groundwater
Irradiance	the amount of light or other radiant energy hitting a given area of surface
Leachate	water that has filtered down through the soil and then might enter a surface waterbody
Lithography	rocks near the ground surface
Major ions	in fresh waters—calcium, magnesium, sodium, potassium, carbonate, sulfate and chlorides
Mesotrophic	medium in concentrations of nutrients and resulting growth of higher trophic levels—plants and animals
Monomictic	mixing only once during a season or year
Morphometry	geometric measurements
Nauplii	larval copepods
Nephelometer	instrument for measuring the turbidity of water
Nutrients	essential substances for organismal growth
Oligotrophic	low in concentrations of nutrients and resulting growth of higher trophic levels – plants and animals
Overturn	complete mixing of a water column top to bottom
Oxidation-reduction potential	proportional to the equivalent free energy change per mole of electrons associated with a given chemical reduction
Periphyton	attached algae that grow on rocks
Permafrost	permanently frozen ground that may be ice rich or ice free
Photosynthesis	production of organic substances from inorganic ones using sunlight
Phytoplankton	plants such as algae that float in the water column
Plankton	plants and animals that float and have little control of their position in the water column
Polymictic	water column mixes several times during a season
Precision	repeatability of measurements
Primary standard	chemical used to test the accuracy of quantitative chemical methods

Reagent	chemical used to detect or measure another substance or to cause a chemical change
Respiration	breakdown of organic substances producing carbon dioxide and water
Rotifers	microscopic animals that feed with cilia or by engulfing particles
Runoff	precipitation that is not intercepted but that runs across the surface into waterbodies
Secchi transparency	clarity of water as measured by a standard Secchi disk on a depth-calibrated line
Spectrophotometer	instrument that selects a wavelength of light and measures its absorption through colored substances
Spike	a known amount of a chemical added while measuring that chemical in a sample to measure percent recovery
Standing crop	measure of biomass of a plant or animal or trophic level at a particular time
Stratify	water column becomes resistant to mixing because of heat or salt content
Synoptic study	sampling (lakes) sufficiently to present the general conditions
Tared	pre-weighed container for weighing contents (or its weight may have been zeroed)
Thermocline	a density gradient caused by differing temperatures
Trophic status	richness of a waterbody for nutrients and resultant plant and animal growth
Turbidimetric	using a turbidimeter
Vernal	of the spring
Zooplankton	animals (usually microscopic) that float in the water column

Table 1. The study lakes, Gates of the Arctic National Park and Preserve.

Lake	Surface Area (km ²)	Volume (m ³ x 10 ⁶)	Mean Depth (m)	Maximum Depth (m)
Agiak	1.5	7.8	5.2	16
Amiloyak	1.1	4.1	3.9	10
Chandler	12.8	181.	14.1	22
Itkilik	3.9	23.	5.8	13
Kipmik	2.9	25	8.6	45
Kurupa	4.6	67	14.6	37
Matcharak	2.8	35	12.5	25
Minakokosa	3.2	114.	35.5	54
Narvak	8.7	543	62.4	114
Nutuvukti	16.2	319.	19.7	49
Pingo	0.7	— ^a	—	—
Selby	9.9	145.	14.6	33
Summit	0.4	—	—	—
Takahula	1.7	55	32.3	55
Tulilik	0.2	—	—	—
Walker	37.5	2297.	61.4	122

^a Dash means bathymetric map not available.

Table 2. Geomorphic and landscape characteristics of lakes of Gates of the Arctic National Park and Preserve.

Lake	Altitude (ft)	Latitude (degrees)	Longitude (degrees)	Watershed Area (km ²)
Agiak	3158	68.08	152.95	51.4
Amiloyak	3182	68.11	152.86	26.9
Chandler	2913	68.22	152.71	341.2
Itkillik	2235	68.40	149.92	26.3
Kipmik	2429	67.95	156.13	43.6
Kurupa	3035	68.34	154.64	173.5
Matcharak	1648	67.75	156.21	32.2
Minakokosa	451	66.93	155.02	94
Narvak	475	66.93	155.63	234.3
Nutuvukti	631	66.98	154.70	75.9
Pingo	1771	67.67	155.41	6.1
Selby	475	66.87	155.68	280.9
Summit	3520	68.07	150.46	4.4
Takahula	810	67.35	153.66	5.5
Tulilik	1821	68.13	154.12	3.2
Walker	637	67.13	154.38	523.6

Lake	% Bare Rock and Dry Tundra	% Moist Tundra and Sedge	% Floodplain Forest and Deciduous Brush	% Spruce and Lichen and Black Spruce and Moss
Agiak	76	15	0	0
Amiloyak	70	30	0	0
Chandler	70	25	0	0
Itkillik	48	52	0	0
Kipmik	66	33	0	0
Kurupa	90	10	0	0
Matcharak	43	53.5	3.5	0
Minakokosa	15	0	38	45
Narvak	20	9	41	30
Nutuvukti	5	10	50	35
Pingo	83	17	0	0
Selby	20	9	41	30
Summit	90	5	5	0
Takahula	33	0	50	17
Tulilik	33	66	0	0
Walker	60	0	30	10

Table 3. Major ion balances, lakes of Gates of the Arctic National Park and Preserve.

	Agiak		Amiloyak		Chandler	
	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	2.00	0.100	3.72	0.186	7.60	0.379
Mg	1.00	0.082	2.08	0.171	4.39	0.361
Na	0.33	0.014	0.63	0.027	2.13	0.093
K	0.12	0.003	<0.05	<0.001	0.36	0.009
Cations		0.199		0.384		0.842
HCO ₃	5.6	0.112	14.2	0.284	21.6	0.432
SO ₄	1.0	0.021	9.0	0.187	22.0	0.458
Cl	<0.1	<0.004	<0.1	<0.004	<0.1	<0.004
Anions		0.133		0.471		0.890
Total Ions		0.322		0.855		1.732

	Itkillik		Kipmik		Kurupa	
	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	37.0	1.846	2.98	0.149	13.7	0.684
Mg	2.08	0.483	0.95	0.078	8.25	0.679
Na	0.63	0.023	0.53	0.023	3.60	0.157
K	0.51	0.013	<0.05	<0.001	0.45	0.012
Cations		2.365		0.250		1.532
HCO ₃	101.3	2.024	7.90	0.158	47.1	0.941
SO ₄	6.0	0.125	0.60	0.012	28.3	0.589
Cl	<0.1	<0.004	<0.1	<0.004	<0.1	<0.004
Anions		2.149		0.170		1.530
Total Ions		4.514		0.420		3.062

	Matcharak		Minakokosa		Narvak	
	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	35.1	1.752	9.37	0.468	12.8	0.639
Mg	5.57	0.458	1.61	0.132	2.22	0.183
Na	4.93	0.214	0.91	0.040	0.61	0.027
K	0.62	0.016	<0.05	<0.001	<0.05	<0.001
Cations		2.440		0.640		0.849
HCO ₃	98.3	1.964	16.0	0.320	25.6	0.512
SO ₄	23.0	0.479	9.0	0.197	20.0	0.416
Cl	<0.2	<0.010	<0.1	<0.004	<0.1	<0.004
Anions		2.443		0.507		0.928
Total Ions		4.883		1.147		1.777

Table 3. Continued.

	Nutuvukti		Pingo		Selby	
	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	8.63	0.431	25.4	1.267	11.90	0.594
Mg	1.51	0.124	20.1	1.654	2.11	0.174
Na	0.69	0.030	20.6	0.896	0.64	0.046
K	<0.05	<0.001	<0.5	<0.005	<0.05	<0.001
Cations		0.585		3.817		0.814
HCO ₃	21.5	0.430	155.	3.098	23.4	0.468
SO ₄	2.30	0.048	1.00	0.021	21.0	0.437
Cl	<0.1	<0.004	<0.1	<0.004	<0.1	<0.004
Anions		0.478		3.119		0.905
Total Ions		1.063		6.936		1.719
	Summit		Takahula		Tulilik	
	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Ca	3.60	0.180	48	2.395	12.30	0.614
Mg	1.30	0.107	7.59	0.626	8.47	0.697
Na	1.05	0.046	0.71	0.031	2.4	0.104
K	0.44	0.011	1.10	0.028	1.3	0.033
Cations		0.344		3.080		1.448
HCO ₃	8.40	0.168	127.7	2.552	54.2	1.083
SO ₄	2.00	0.042	23.0	0.479	1.0	0.021
Cl	<0.1	<0.004	<0.1	<0.004	<0.1	<0.004
Anions		0.210		3.031		1.104
Total Ions		0.554		6.111		2.552
	Walker					
	(mg/L)	(meq/L)				
Ca	21.9	1.093				
Mg	2.59	0.213				
Na	0.47	0.020				
K	0.97	0.025				
Cations		1.351				
HCO ₃	55.1	1.101				
SO ₄	7.2	0.150				
Cl	<0.1	<0.004				
Anions		1.251				
Total Ions		2.602				

Table 4. Trace metal characteristics (ICP) of Gates of the Arctic samples, as total recoverable metals. A dash means criterion (USEPA) is not yet set.

Metal	Laboratory Detection Limit (mg/L)	Acute Criterion (mg/L)	Chronic Criterion (mg/L)	Detected (1992-1995)	Criterion Exceedances
Silver (Ag)	0.01	4.1	0.12		
Aluminum (Al)	0.02	0.75 ^a	0.087 ^a		
Arsenic (As)	0.04	0.360 ^b	0.190 ^b		
Boron (B)	0.02	—	—		
Barium (Ba)	0.0034	—	—	Yes	N/A
Beryllium (Be)	0.0005	0.130 ^c	0.0053 ^c		
Bismuth (Bi)	0.04	—	—		
Cadmium (Cd)	0.002	0.0039 ^d	0.0011 ^d		
Cobalt (Co)	0.01	—	—		
Chromium (Cr)	0.01	0.0016 ^e	0.0011 ^e		
Copper (Cu)	0.003	0.0018 ^d	0.0012 ^d	Yes	Yes ^g
Iron (Fe)	0.005	—	1.000	Yes	No
Lithium (Li)	0.002	—	—		
Manganese (Mn)	0.002	—	—	Yes	N/A
Molybdenum (Mo)	0.005	—	—		
Nickel (Ni)	0.01	1.400 ^d	0.160 ^d	Yes	No
Phosphorus (P)	0.09	—	—		
Lead (Pb)	0.04	0.083 ^a	0.0032 ^d		
Antimony (Sb)	0.04	0.088 ^f	0.030 ^f		
Selenium (Se)	0.04	0.020	0.005		
Silicon (Si)	0.005	—	—	Yes	N/A
Tin (Sn)	0.04	—	—		
Strontium (Sr)	0.001	—	—	Yes	N/A
Titanium (Ti)	0.002	—	—		
Thallium (Tl)	0.08	—	—		
Vanadium (V)	0.003	—	—	Yes	N/A
Zinc (Zn)	0.002	0.112	0.103	Yes	No

^a pH 6.5–9.

^b Arsenic (III).

^c Lowest Observed Effect Level.

^d Hardness dependent criteria (100 mg/L as CaCO₃ used).

^e Cr (VI).

^f Proposed.

^g Chandler Lake, 1995.

Table 5. Mean nutrients and phytoplankton biomass (as total chlorophyll) in lakes of Gates of the Arctic National Park and Preserve.

Lake	1992				1993			
	TN (mg/L)	TP (µg/L)	chl (µg/L)	TN/TP	TN (mg/L)	TP (µg/L)	chl (µg/L)	TN/TP
Agiak	— ^a	—	—	—	0.16	7	1.5	23
Amiloyak	0.19	11	1.7	17	0.28	8	1.6	35
Chandler	0.22	6	1.3	37	0.16	5	1.1	32
Itkillik	—	—	—	—	0.29	8	1.0	36
Kipmik	0.19	6	1.8	32	0.19	6	3.4	32
Kurupa	—	—	—	—	—	—	—	—
Matcharak	0.41	8	1.0	51	0.41	12	2.9	34
Minakokosa	0.47	6	1.7	78	—	—	—	—
Narvak	0.40	5	1.3	80	0.32	4	1.5	80
Nutuvukti	0.30	5	1.5	60	0.27	5	1.6	54
Pingo	0.76	16	2.1	48	—	—	—	—
Selby	—	—	—	—	0.30	4	1.3	75
Summit	—	—	—	—	0.18	6	1.1	30
Takahula	0.35	4	0.7	88	0.21	4	1.2	52
Tulilik	—	—	—	—	—	—	—	—
Walker	0.32	4	0.8	80	0.34	5	0.7	68

Lake	1995			
	TN (mg/L)	TP (µg/L)	chl (µg/L)	TN/TP
Agiak	0.11	9	1.9	12
Amiloyak	—	—	—	—
Chandler	0.11	8	1.4	14
Itkillik	0.25	7	1.2	36
Kipmik	0.11	5	1.4	22
Kurupa	0.13	11	0.5	12
Matcharak	0.32	9	2.9	36
Minakokosa	—	—	—	—
Narvak	—	—	—	—
Nutuvukti	—	—	—	—
Pingo	—	—	—	—
Selby	—	—	—	—
Summit	0.12	21	2.6	6
Takahula	0.15	3	1.3	50
Tulilik	0.44	7	1.4	63
Walker	0.26	3	1.3	87

^a Dash means not measured.

Table 6. Multi-year average nutrients and phytoplankton biomass (as total chlorophyll) in lakes of Gates of the Arctic National Park and Preserve.

Lake	TN (mg/L)	TP (µg/L)	chl (µg/L)	TN/TP
Agiak ^a	0.133	8	1.7	17
Amiloyak ^a	0.235	10	1.6	24
Chandler ^b	0.162	6	1.3	27
Itkillik ^a	0.280	8	1.1	35
Kipmik ^b	0.162	6	2.2	27
Kurupa ^c	0.127	11	0.5	12
Matcharak ^b	0.380	10	2.3	38
Minakokosa ^c	0.471	6	1.7	78
Narvak ^a	0.360	4	1.5	90
Nutuvukti ^a	0.285	5	1.6	57
Pingo ^c	0.760	16	2.1	48
Selby ^c	0.300	4	1.3	75
Summit ^a	0.150	14	1.8	11
Takahula ^b	0.238	4	1.1	60
Tulilik ^c	0.435	7	1.4	62
Walker ^b	0.309	4	0.9	77

^a Two years.

^b Three years.

^c One year.

Table 7. Results of nutrient stimulation bioassay experiments in lakes of Gates of the Arctic National Park and Preserve, expressed as ratio of final to initial total chlorophyll. (C = control, +P = additional phosphorus added, +N = additional nitrogen added, and +N&P = additional nitrogen and phosphorus added). Walker Lake results for 1988 are found in Jones et al. (1990).

Lake and Year	C	+P	+N	+N&P	Duncan's Test Result
Agiak, 1995	1.12	1.11	2.52	6.30	NP>N>C=P
Agiak, 1995	1.16	1.08	2.73	5.88	NP>N>C=P
Chandler, 1995	1.40	1.80	1.33	2.27	NP>P>C=N
Itkillik, 1995	0.82	0.88	1.76	5.94	NP>N>P=C
Itkillik-South, 1989	0.79	0.80	2.42	5.33	NP=N=P=C
Itkillik-North, 1989	1.28	1.14	2.64	6.68	NP>N>C=P
Kipmik, 1995	0.60	0.72	1.73	5.46	NP>N>P=C
Kipmik, 1995	0.50	0.56	1.10	3.64	NP>N=P=C
Matcharak, 1995	0.79	0.80	2.42	5.33	NP>N>P=C
Narvak-North, 1993	0.85	1.93	1.09	2.24	NP>P>N>C
Narvak-South, 1993	0.70	1.26	0.79	1.66	NP>P>N=C
Selby-North, 1993	1.42	2.63	1.46	3.52	NP>P>N=C
Selby-East, 1993	0.78	1.18	0.82	1.43	NP=P=N=C
Summit Lake, 1995	1.07	1.33	1.66	2.79	NP>N=P=C
Summit Lake, 1995	0.97	1.11	1.25	2.44	NP>N≥P=C

Table 8. Discrete total chlorophyll values for specific depths, lakes of Gates of the Arctic National Park and Preserve.

Lake	Depth (m)	chl ($\mu\text{g/L}$)	Lake	Depth (m)	chl ($\mu\text{g/L}$)
1992					
Chandler	1	1.2	Kipmik	1	1.2
	4.5	1.2		6	3.6
	9	1.2		12	1.6
	12	1.3	Minakokosa	1	0.7
Matcharak	1	0.5		6	3.2
	5	0.7		10	2.6
	8	1.2	Nutuvkti	1	1.4
Narvak	1	1.2		6	1.8
	5	1.5		10	1.8
	7.5	1.7		12	0.8
Takahula	15	0.5	Walker	1	0.6
	1	0.3		5	0.8
	6	0.9		12.5	0.8
	12.5	1.1		25	0.6
	25	0.4			
1993					
Narvak (south end)	0	1.0	Narvak (mid-lake)	0	1.0
	2	1.3		2	0.9
	4	1.8		4	0.9
	6	1.8		5	1.2
	7	2.0		6	2.2
	8	2.2		7	1.9
	9	1.9		8	1.9
	10	0.7		10	2.4
	12	1.0		12	1.4
	14	0.6		14	0.9
	16	0.5		16	0.7
	0	0.9	Takahula	1	0.3
Selby	2	0.8		15	1.7
	4	0.8		30	0.8
	6	1.0			
	7	1.2			
	8	1.8			
	10	1.9			
	12	2.0			
	14	1.4			
1995					
Takahula	1	0.34	Walker	1	0.24
	5	0.47		15.6	1.46
	16.4	1.24		31.2	1.90
	32.8	1.05			

Table 9. Light levels at depths of total chlorophyll peaks, lakes of Gates of the Arctic National Park and Preserve.

Lake	Peak Depth (m)	Light Level at Peak Depth (%)
1993		
Narvak (south)	8	3
Narvak (mid-lake)	10	1
Selby	10	2
	12	1
Takahula	15	3
1995		
Takahula	16.4	1
Walker	15.6	4

Table 10. Light conditions (means), lakes of Gates of the Arctic National Park and Preserve. [K_d (PAR) is the extinction coefficient of photosynthetically active radiation].

Lake	K_d (PAR) (m^{-1})	Secchi Depth (m)	1% Light Depth (m)	Apparent Color (Pt-Co Units)	Turbidity (NTU)	Phytoplankton ($mg \cdot m^{-3} chl$)
Agiak ^a	0.464	4.8	10.3	25	1.1	1.7
Amiloyak ^a	0.262	4.6	17.6	19	1.1	1.6
Chandler ^b	0.520	3.6	9.80	25	3.2	1.3
Itkillik ^a	0.290	9.2	16.0	12	0.42	1.1
Kipmik ^b	0.420	7.0	11.1	12	0.52	2.2
Kurupa ^c	1.53	0.6	3.01	83	18.	0.5
Matcharak ^b	0.330	7.8	14.0	9.4	0.56	2.3
Minakokosa ^c	—	5.8	—	14	—	1.7
Narvak ^a	0.433	8.7	10.4	12	0.36	1.5
Nutuvukti ^a	0.433	6.4	10.4	16	0.43	1.6
Pingo ^c	—	—	—	20	—	2.1
Selby ^c	0.404	8.6	11.4	17	0.35	1.3
Summit ^a	0.962	3.8	7.5	56	7.5	1.8
Takahula ^b	0.255	14.6	18.2	5.0	0.32	1.1
Tulilik ^c	0.420	7.3	11.0	8.0	0.44	1.4
Walker ^b	0.252	14.1	18.7	4.3	0.27	0.9

^a Two years.

^b Three years.

^c One year.

Table 11. Composite light characteristics, lakes of Gates of the Arctic National Park and Preserve. (1% = 1% light depth (m), SD = Secchi depth (m), and % PAR at SD = % photosynthetically active radiation at the Secchi depth).

Lake	1%:SD	% PAR at SD
Agiak	2.1	11
Amiloyak	3.8	30
Chandler	2.7	15
Itkillik	1.7	7
Kipmik	1.6	5
Kurupa	5.0	40
Matcharak	1.8	8
Minakokosa	—	—
Narvak	1.2	2
Nutuvukti	1.6	6
Pingo	—	—
Selby	1.3	3
Summit	2.0	3
Takahula	1.2	2
Tulilik	1.5	5
Walker	1.3	3

Table 12. Average concentration of zooplankton as dry weight and as organic material (ash-free dry weight) for lakes of Gates of the Arctic National Park and Preserve.

Lake	1992			1993		
	Haul Depth (m)	Dry Weight (mg/m ³)	Ash-free Dry Weight (mg/m ³)	Haul Depth (m)	Dry Weight (mg/m ³)	Ash-Free Dry Weight (mg/m ³)
Agiak	— ^a	—	—	12	33.8	30.6
Amiloyak	3	75.8	37.1	7	80.0	62.3
Chandler	12	12.5	8.3	12	34.0	22.0
Itkillik	—	—	—	10	106.	99.2
Kipmik	13	15.8	14.2	25	6.7	5.8
Kurupa	—	—	—	—	—	—
Matcharak	9.5	33.7	22.6	17	74.7	70.6
Minakokosa	45	17.4	10.4	—	—	—
Narvak	35	6.6	6.5	8	27.1	24.5
Nutuvukti	30	25.1	20.1	15	13.6	11.4
Pingo	—	—	—	—	—	—
Selby	—	—	—	15	9.4	8.0
Summit	—	—	—	10	26.3	23.7
Takahula	20	48.5	40.1	45	15.3	14.3
Tulilik	—	—	—	—	—	—
Walker	69	6.9	5.1	50	7.1	6.2

Lake	1995		
	Haul Depth (m)	Dry Weight (mg/m ³)	Ash-free Dry Weight (mg/m ³)
Agiak	12	31.7	21.4
Amiloyak	—	—	—
Chandler	12	6.0	2.7
Itkillik	8	164	146
Kipmik	22	18.5	14.7
Kurupa	21	7.8	5.5
Matcharak	14	69.2	61.7
Minakokosa	—	—	—
Narvak	—	—	—
Nutuvukti	—	—	—
Pingo	—	—	—
Selby	—	—	—
Summit	9	13.7	10.2
Takahula	41	20.4	16.8
Tulilik	7	179	167
Walker	70	15.0	11.1

^a Dash means not sampled.

Table 13. Counts of zooplankton ($\#/m^3$), 1993 samples, lakes of Gates of the Arctic National Park and Preserve.

Lake	Copepods	Cladocera	<i>Ceratium</i>	Rotifers	Ciliates
Agiak	3628	6	6	73	0
Amiloyak	3105	56	0	431	299
Chandler	288	6	0	0	0
Itkillik	7407	331	7852	571	0
Kipmik	344	45	9	691	0
Matcharak	1764	125	16	455	0
Narvak	1452	375	389	662	0
Nutuvukti	608	8	0	0	0
Selby	524	148	538	1369	48
Summit	1560	74	0	118	14
Takahula	907	23	57	719	0
Walker	331	34	53	52	0

Table 14. Counts of copepods ($\#/m^3$), 1993 zooplankton samples, lakes of Gates of the Arctic National Park and Preserve.

Lake	Calanoid	Harpacticoid	Cyclopoid	Nauplii	Copepodites
Agiak	134	19	0	3470	4
Amiloyak	602	0	201	2283	20
Chandler	248	8	0	0	33
Itkillik	507	92	2	6442	364
Kipmik	57	3	0	64	221
Matcharak	482	38	0	1068	531
Narvak	110	17	0	741	585
Nutuvukti	112	26	0	3	464
Selby	54	6	2	207	94
Summit	212	44	0	772	532
Takahula	133	18	0	324	432
Walker	47	5	0	190	94

Table 15. Productivity indicator ranking—high to low—of lakes of Gates of the Arctic National Park and Preserve.

Lake	Average Depth (m)	Lake	Alkalinity (meq/L as CaCO ₃)	Lake	Morphoedaphic Index (mg/L total ions/ $\bar{z}$)
Pingo ^a	0.62	Pingo	3.098	Pingo	370.
Tulilik ^a	3.8	Takahula	2.552	Itkillik	25.
Amiloyak	3.9	Itkillik	2.024	Tulilik	21.
Summit ^a	4.2	Matcharak	1.964	Matcharak	18.
Agiak	5.2	Walker	1.101	Amiloyak	7.6
Itkillik	5.8	Tulilik	1.083	Kurupa	6.9
Kipmik	8.6	Kurupa	0.941	Takahula	6.4
Matcharak	12.	Narvak	0.512	Chandler	4.1
Chandler	14.	Selby	0.468	Summit	4.0
Selby	15.	Chandler	0.432	Selby	4.0
Kurupa	15.	Nutuvukti	0.430	Agiak	2.0
Nutuvukti	20.	Minakokosa	0.320	Nutuvukti	1.8
Takahula	32.	Amiloyak	0.284	Kipmik	1.5
Minakokosa	36.	Summit	0.168	Walker	1.4
Walker	61.	Kipmik	0.158	Minakokosa	1.0
Narvak	62.	Agiak	0.112	Narvak	1.0

^a Mean depth estimated as anchor depth divided by 2.4.

Table 16. Stream conditions, John River and tributaries at Anaktuvuk Pass.

	1993	1994
	Flow (m ³ /sec)	Flow (m ³ /sec)
Little Contact Creek	0.39	0.27
Big Contact Creek	1.0	2.6
John River	~6.8	— ^a

	1993				
	pH	Cond. (μS/cm)	Temp. (°C)	D.O. (mg/L)	Turbidity (NTU)
Little Contact Creek	— ^b	323	0.1	11.9	0.18
Big Contact Creek	—	252	0	—	0.25
John River	7.21	240	3.7	11.0	0.34

	1994					
	pH	Cond. (μS/cm)	Temp. (°C)	D.O. (mg/L)	Turbidity (NTU)	Color (cpu)
Little Contact Creek	7.40	286	7.8	—	1.0	5
Big Contact Creek	7.52	168	7.5	—	1.0	8
John River	—	213	7.1	—	2.0	7

^a Too deep for method.^b Dash indicates not measured.

Table 17. Ion balances, John River and tributaries at Anaktuvuk Pass.

	Little Contact Cr.		Big Contact Cr.		John R.	
	(mg/L)	(meq/L)	(mg/L)	(meq/L)	(mg/L)	(meq/L)
Cu	49.3	2.465	31.8	1.587	36.3	1.811
Mg	8.59	0.707	5.06	0.416	5.60	0.461
Na	0.86	0.037	0.51	0.022	0.54	0.023
K	<0.5	<0.013	<0.5	<0.013	<0.5	<0.013
Cations		3.209		2.025		2.295
HCO ₃	112.5	1.84	69.6	1.140	87.3	1.431
SO ₄	70	1.458	48.0	0.999	49.3	1.026
Cl	3.1	0.087	2.6	0.073	3.2	0.091
Anions		3.385		2.212		2.548
Total Ions		6.591		4.237		4.843

Table 18. Trace metal characteristics (ICP) of the upper John River (Big Contact Creek, Little Contact Creek, and the John River at Anaktuvuk) samples, September 1993. A dash means criterion (USEPA) is not yet set.

Metal	Laboratory Detection Limit (mg/L)	Acute Criterion (mg/L)	Chronic Criterion (mg/L)	Detected	Criterion Exceedances
Silver (Ag)	0.01	4.1	0.12		
Aluminum (Al)	0.02	0.75 ^a	0.087 ^a		
Arsenic (As)	0.04	0.360 ^b	0.190 ^b		
Boron (B)	0.02	—	—		
Barium (Ba)	0.0034	—	—	Yes	N/A
Beryllium (Be)	0.0005	0.130 ^c	0.0053 ^c		
Bismuth (Bi)	0.04	—	—		
Cadmium (Cd)	0.002	0.0039 ^d	0.0011 ^d		
Cobalt (Co)	0.01	—	—		
Chromium (Cr)	0.01	0.0016 ^e	0.0011		
Copper (Cu)	0.003	0.0018 ^d	0.0012 ^d		
Iron (Fe)	0.005	—	1.000	Yes	No
Lithium (Li)	0.002	—	—		
Manganese (Mn)	0.002	—	—		
Molybdenum (Mo)	0.005	—	—		
Nickel (Ni)	0.01	1.400 ^d	0.160 ^d		
Phosphorus (P)	0.09	—	—		
Lead (Pb)	0.04	0.083 ^d	0.0032 ^d		
Antimony (Sb)	0.04	0.088 ^f	0.030 ^f		
Selenium (Se)	0.04	0.020	0.00 ⁵		
Silicon (Si)	0.005	—	—	Yes	N/A
Tin (Sn)	0.04	—	—		
Strontium (Sr)	0.001	—	—	Yes	N/A
Titanium (Ti)	0.002	—	—		
Thallium (Tl)	0.08	—	—		
Vanadium (V)	0.003	—	—		
Zinc (Zn)	0.002	0.112 ^d	0.103 ^d		

^a pH 6.5–9.

^b Arsenic (III).

^c Lowest Observed Effect Level.

^d Hardness dependent criteria (100 mg/L as CaCO₃ used).

^e Cr (VI).

^f Proposed.

Table 19. Bacterial analysis, John River and tributaries, late summer 1993 and 1994.

Site	Sample Date	# Colonies/100 mL		
		Total Coliform	Fecal Coliform	Membrane Fecal Coliform
John River	31 Aug 1993	23.0	1.1	<2
		16.1	<1.1	<2
		16.1	<1.1	<2
Big Contact Creek	1 Sep 1993	5.1	<1.1	<2
		6.9	<1.1	<2
		3.6	<1.1	2
Little Contact Creek	1 Sep 1993	3.6	<1.1	<2
		2.2	<1.1	<2
		5.1	1.1	2
John River	16 Aug 1994	POS ^a	ND ^b	
		POS	ND	
		POS	ND	
Big Contact Creek	16 Aug 1994	POS	ND	
		POS	POS	
		POS	ND	
Little Contact Creek	16 Aug 1994	POS	ND	
		POS	POS	
		POS	ND	

^a POS = positive.

^b ND = none detected.

Table 20. Total petroleum hydrocarbons (TPH), John River and tributaries, 1993 and 1994. Three replicates per site per date.

Site	Sample Date	TPH (mg/L)
John River	31 Aug 1993	0.5
		<0.4
		<0.4
Big Contact Creek	1 Sep 1993	<0.4
		<0.4
		<0.4
Little Contact Creek	1 Sep 1993	<0.4
		<0.4
		<0.4
John River	16 Aug 1994	0.6
		0.7
		<0.4
Big Contact Creek	16 Aug 1994	0.6
		0.8
		0.8
Little Contact Creek	16 Aug 1994	0.9
		0.7
		0.7

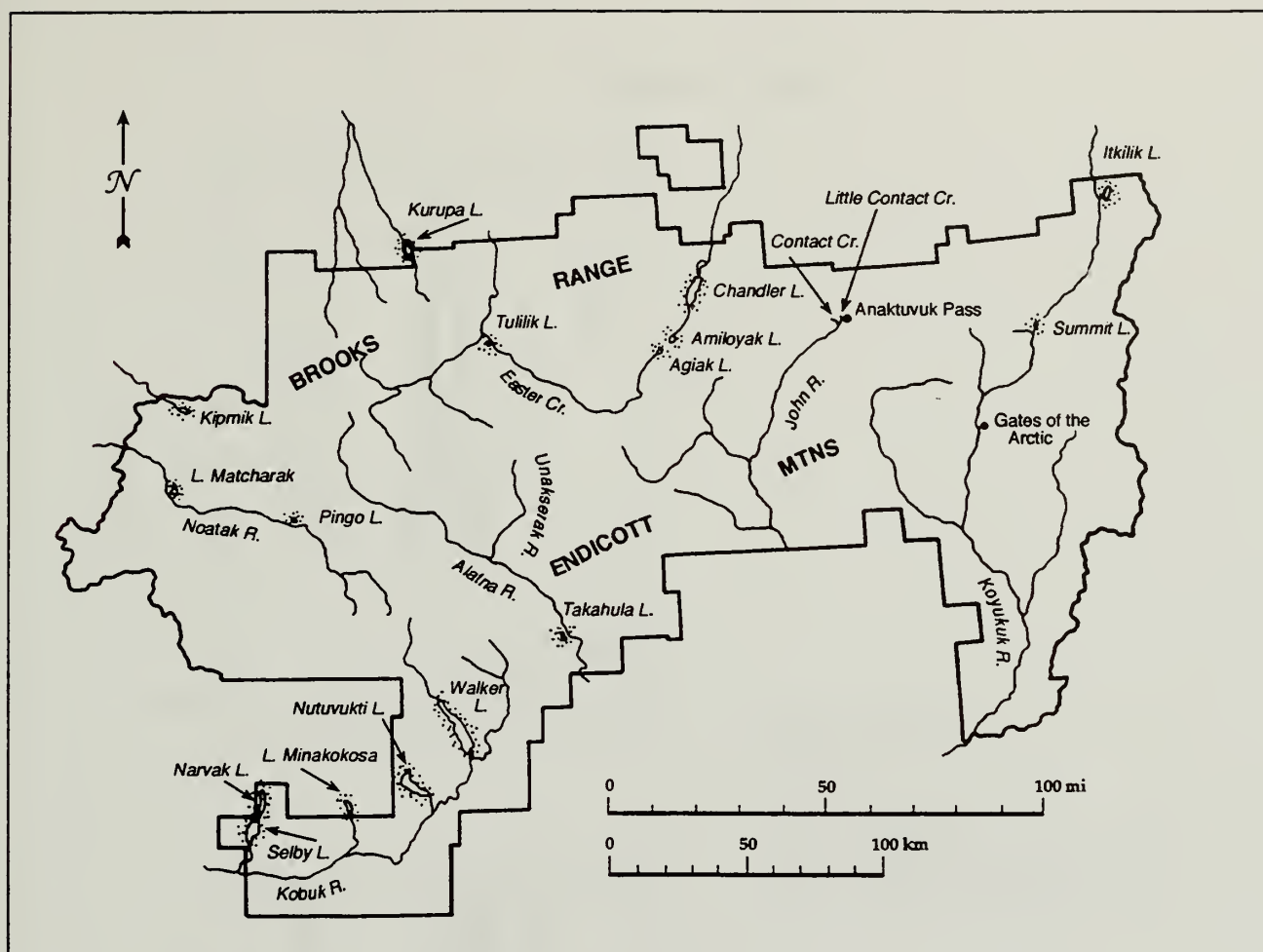


Figure 1. Gates of the Arctic National Park and Preserve with study lakes and streams.

Agiak Lake

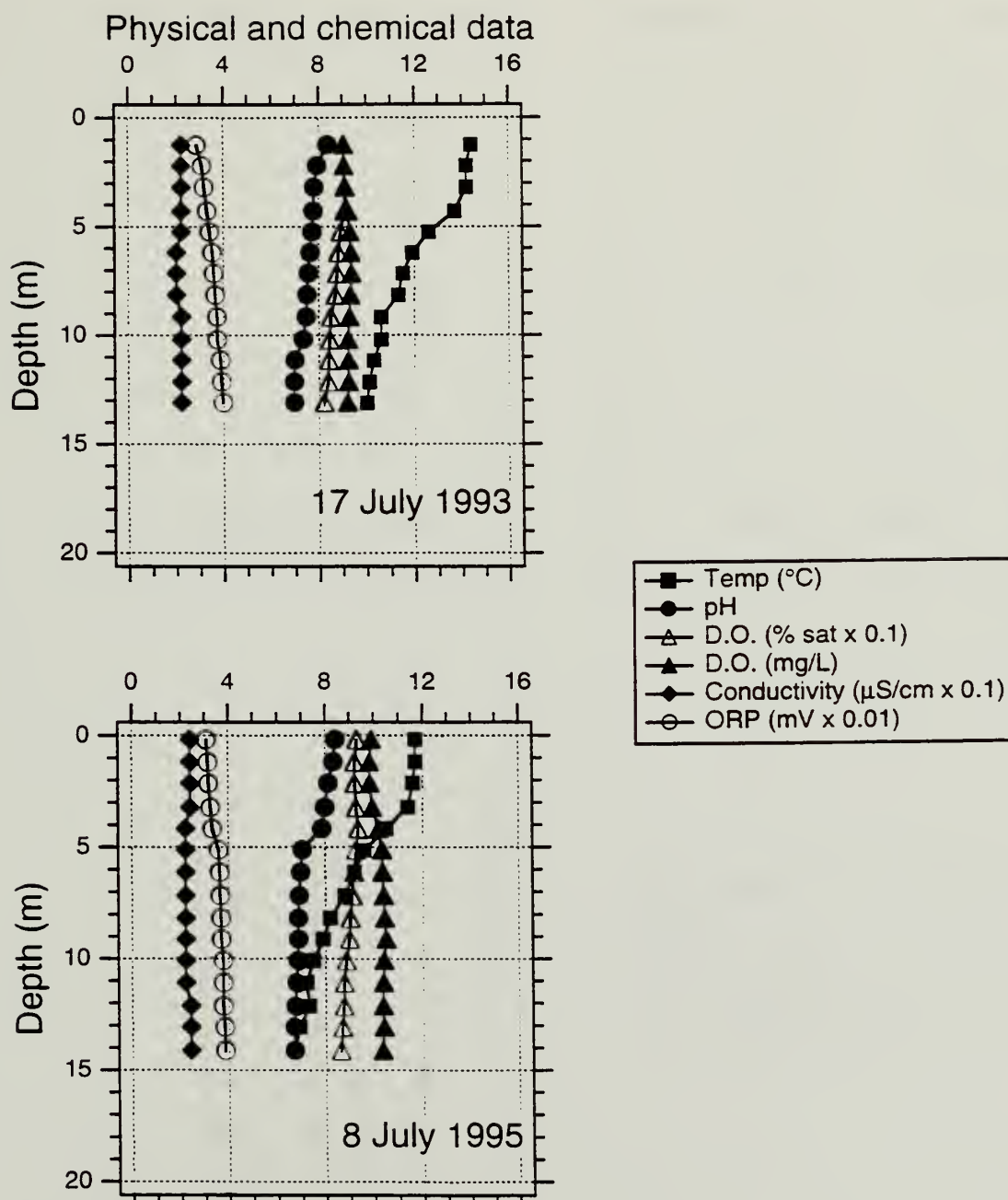


Figure 2. Water quality profiles, Agiak Lake.

Amiloyak Lake

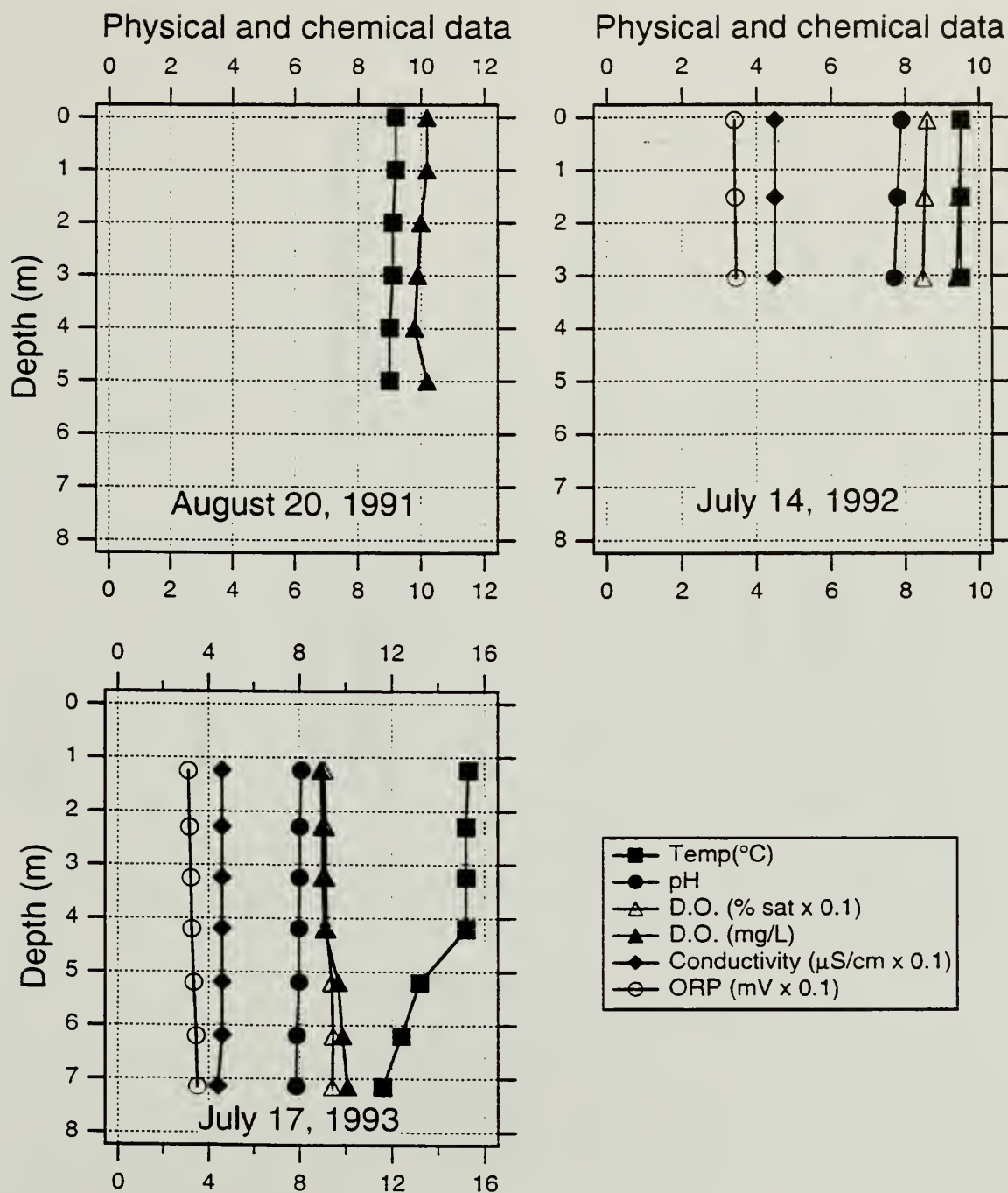


Figure 3. Water quality profiles, Amiloyak Lake.

Chandler Lake

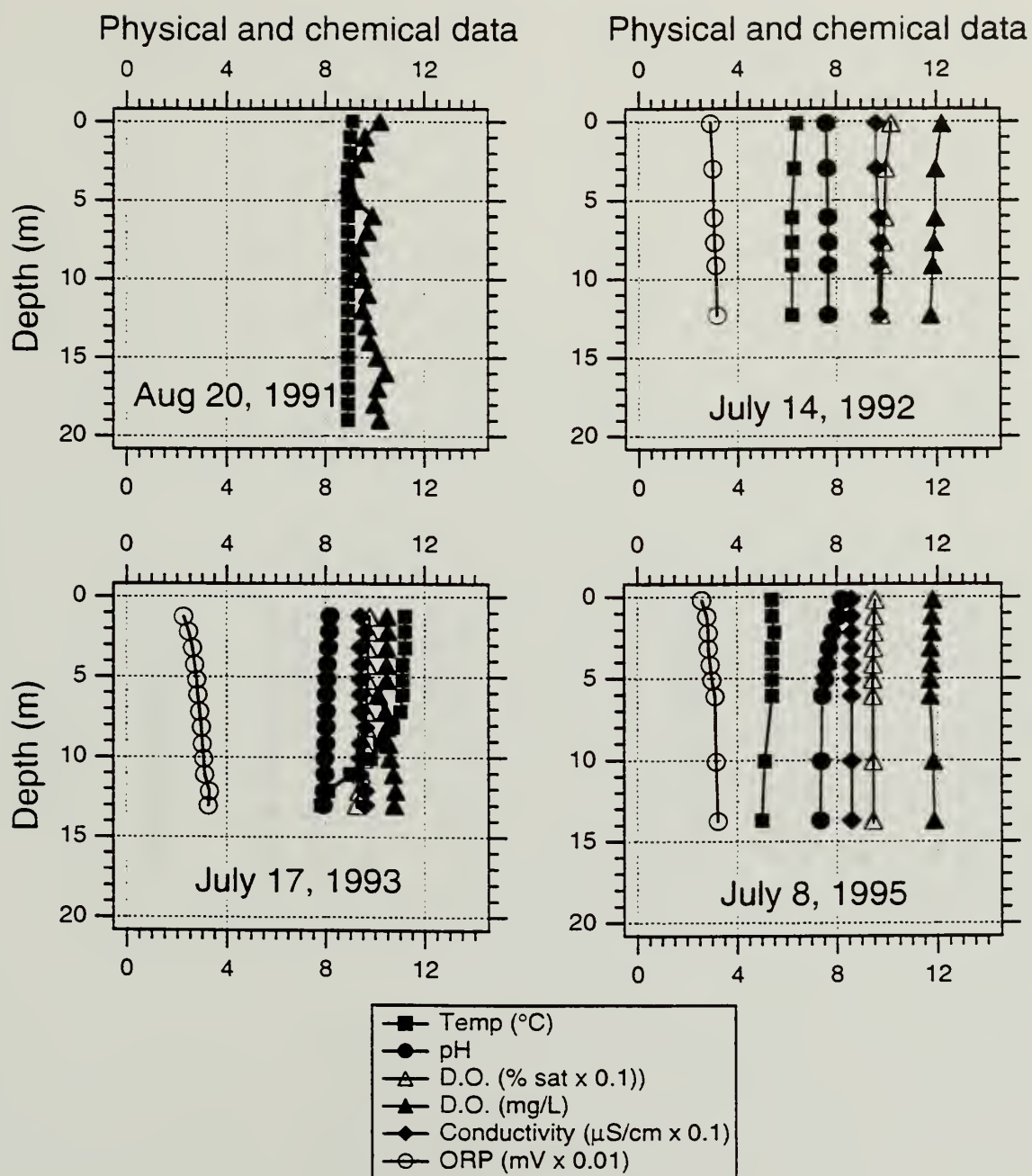


Figure 4. Water quality profiles, Chandler Lake.

Itkillik Lake

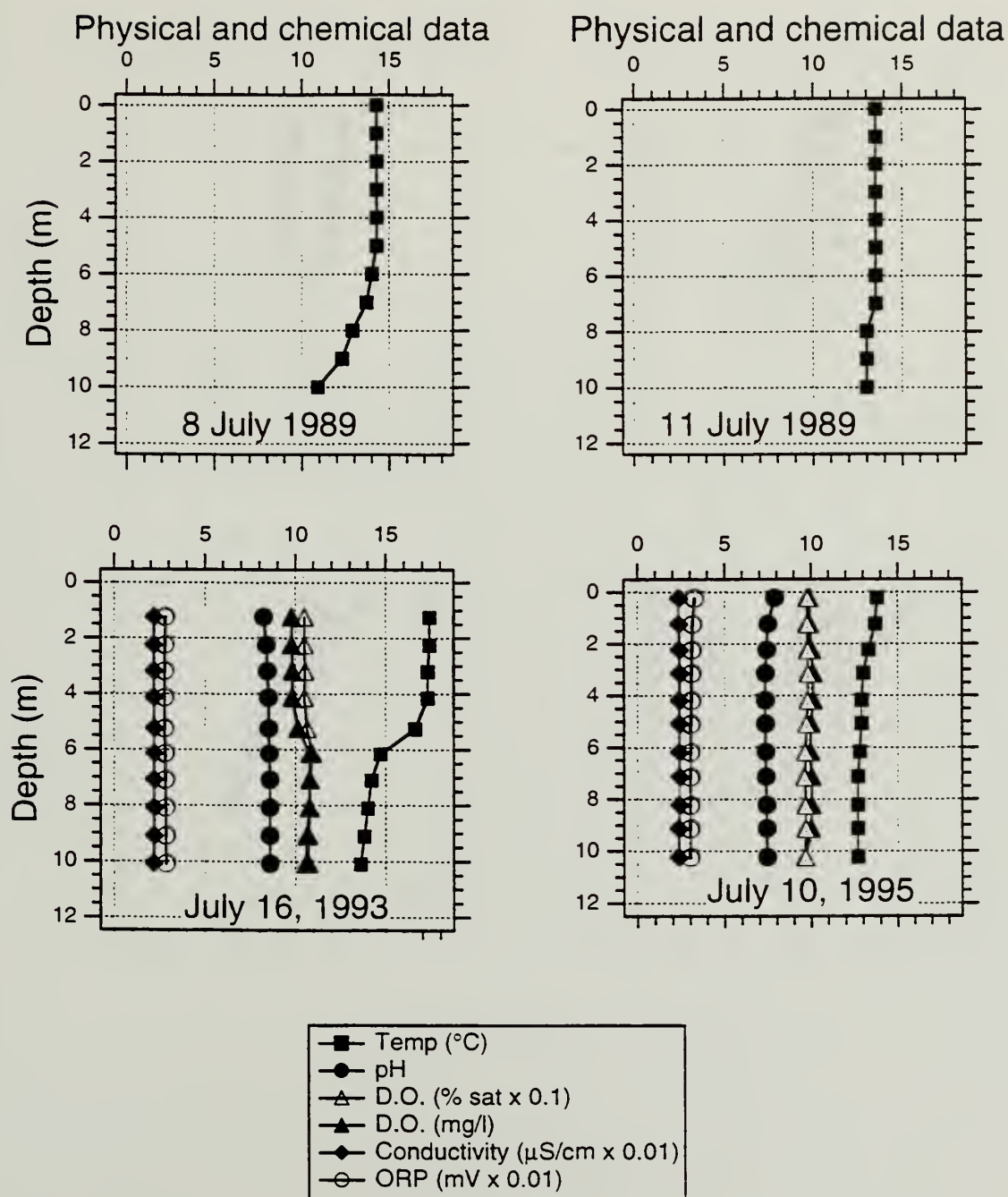


Figure 5. Water quality profiles, Itkillik Lake.

Kipmik Lake

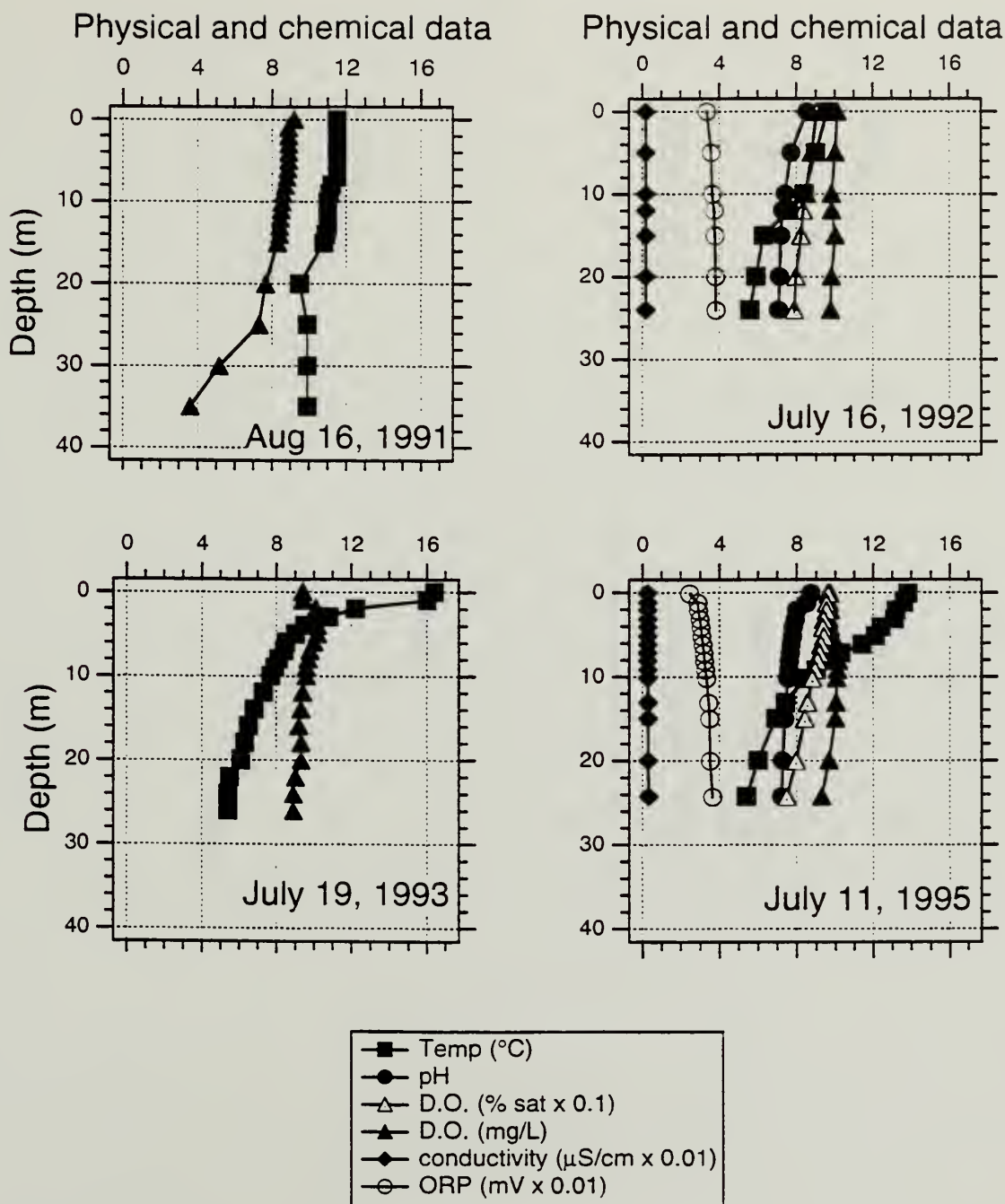


Figure 6. Water quality profiles, Kipmik Lake.

Matcharak Lake

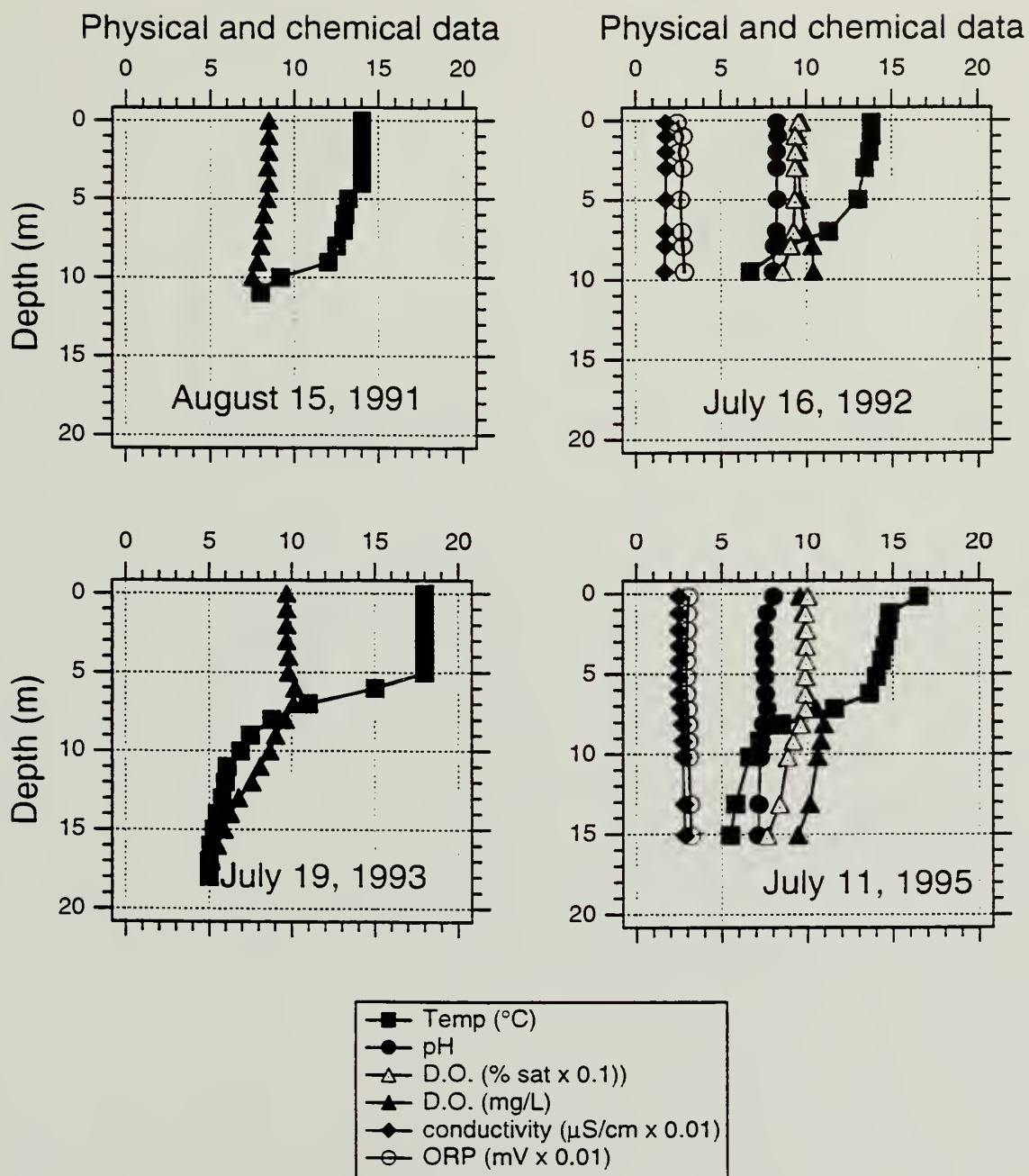


Figure 7. Water quality profiles, Matcharak Lake.

Narvak Lake

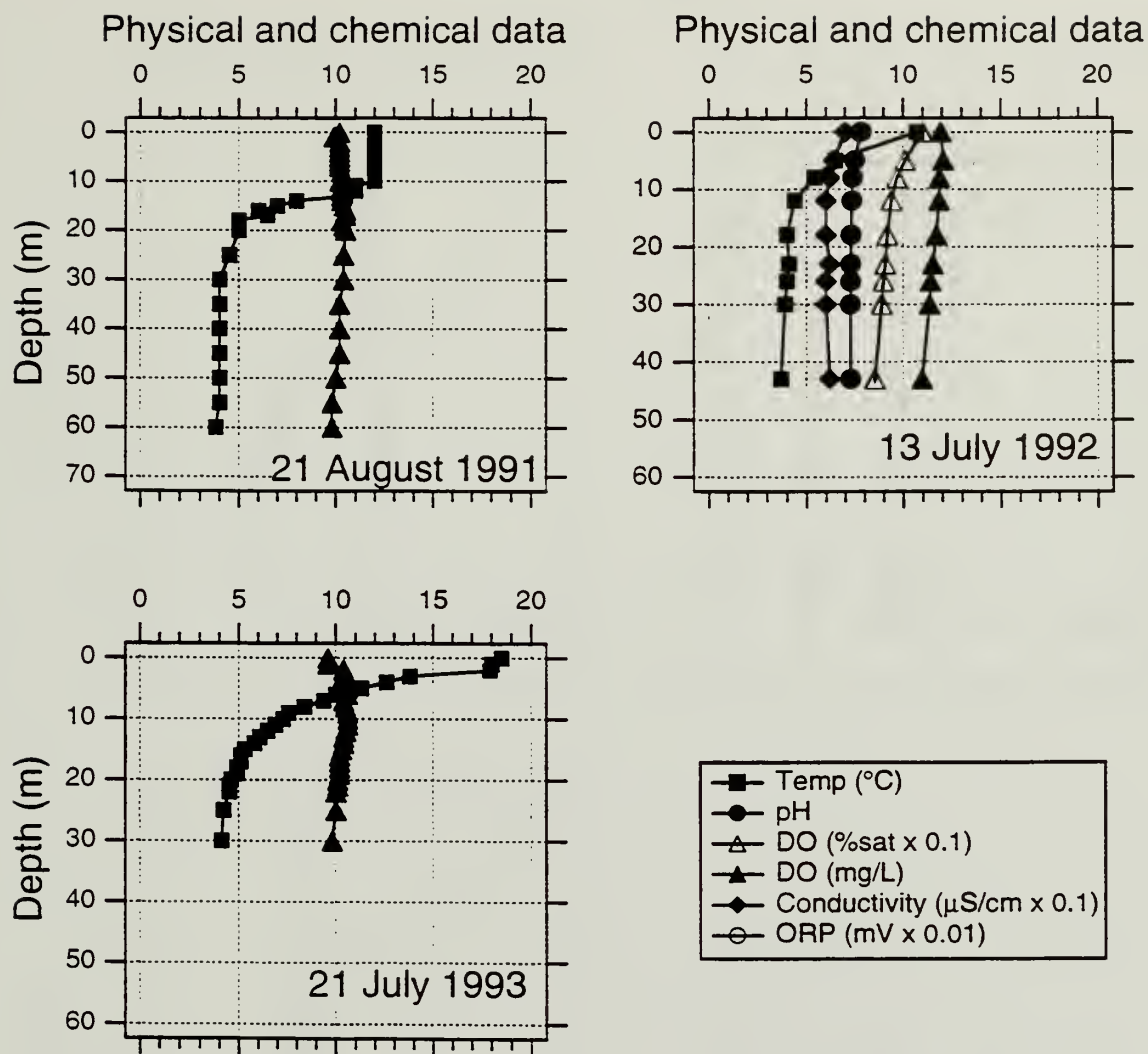


Figure 8. Water quality profiles, Narvak Lake.

Nutuvukti Lake

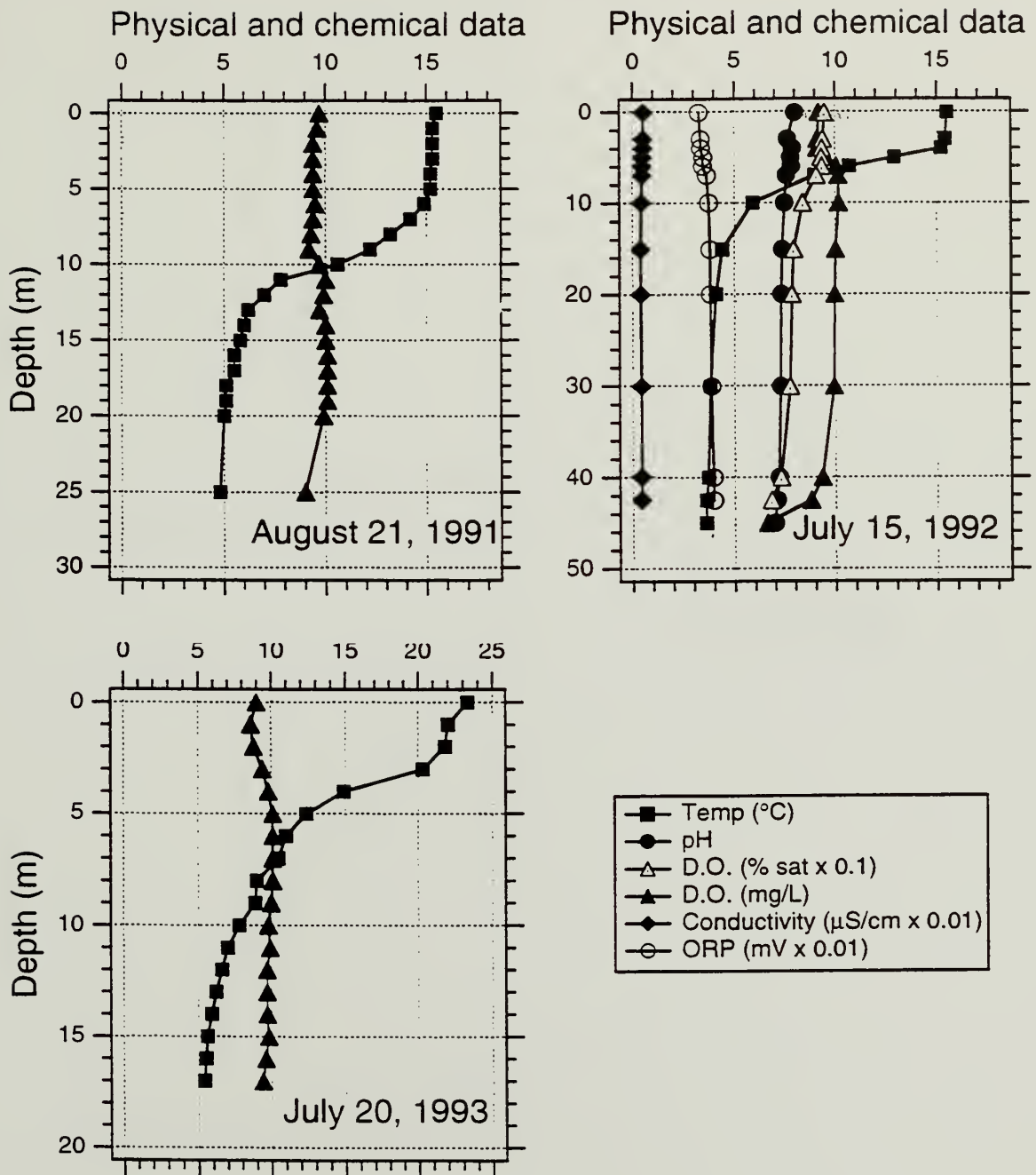


Figure 9. Water quality profiles, Nutuvukti Lake.

Selby Lake

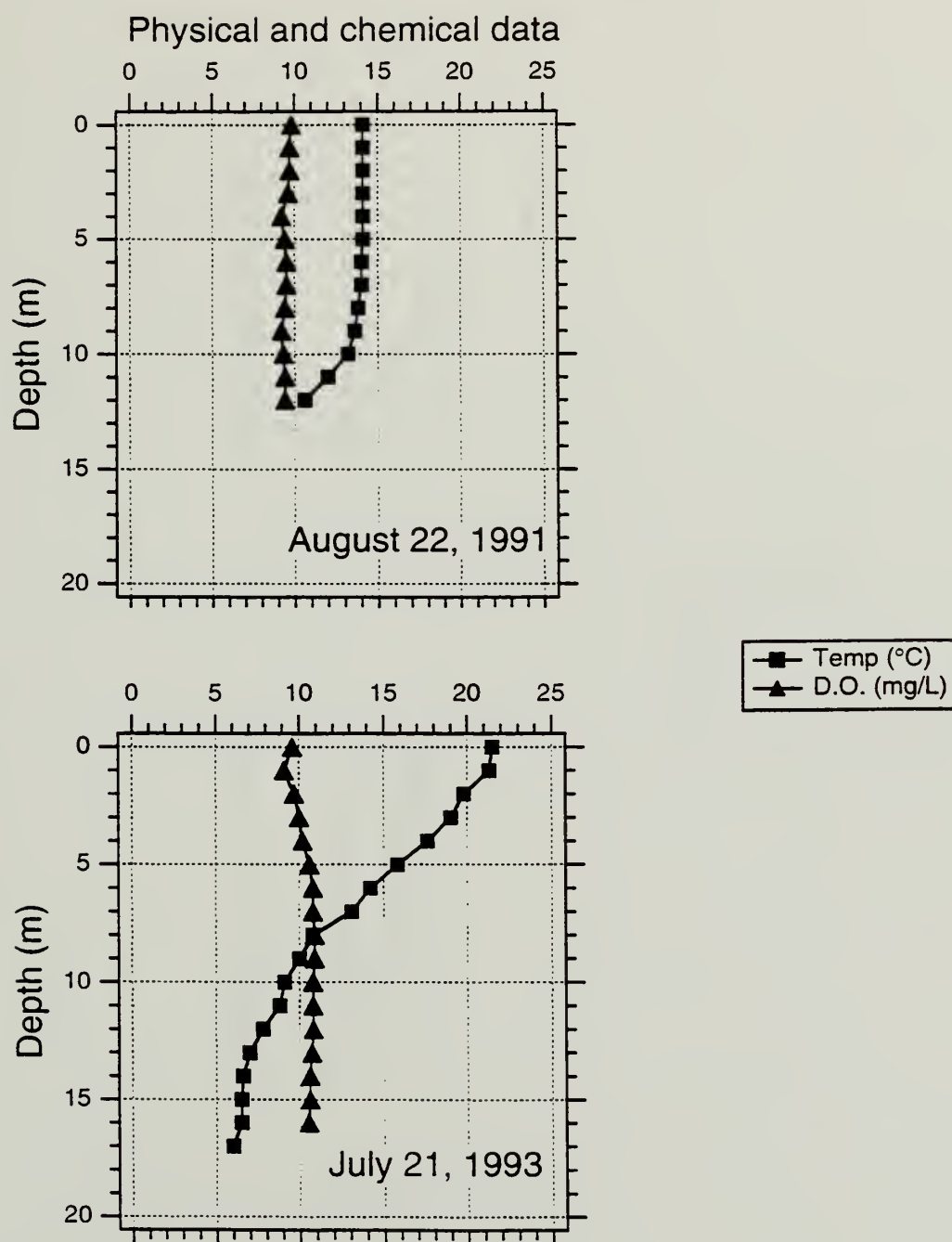


Figure 10. Water quality profiles, Selby Lake.

Summit Lake

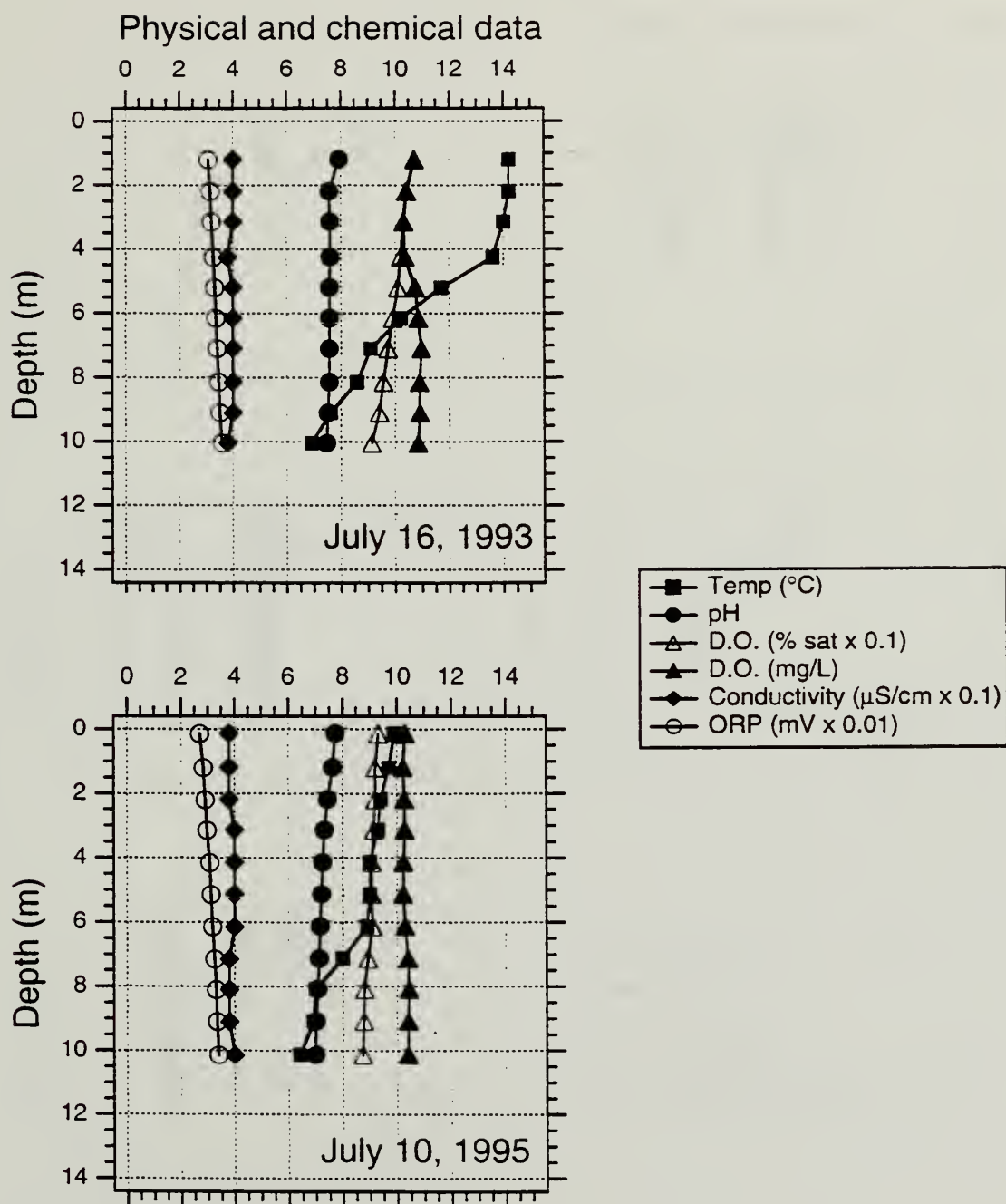


Figure 11. Water quality profiles, Summit Lake.

Takahula Lake

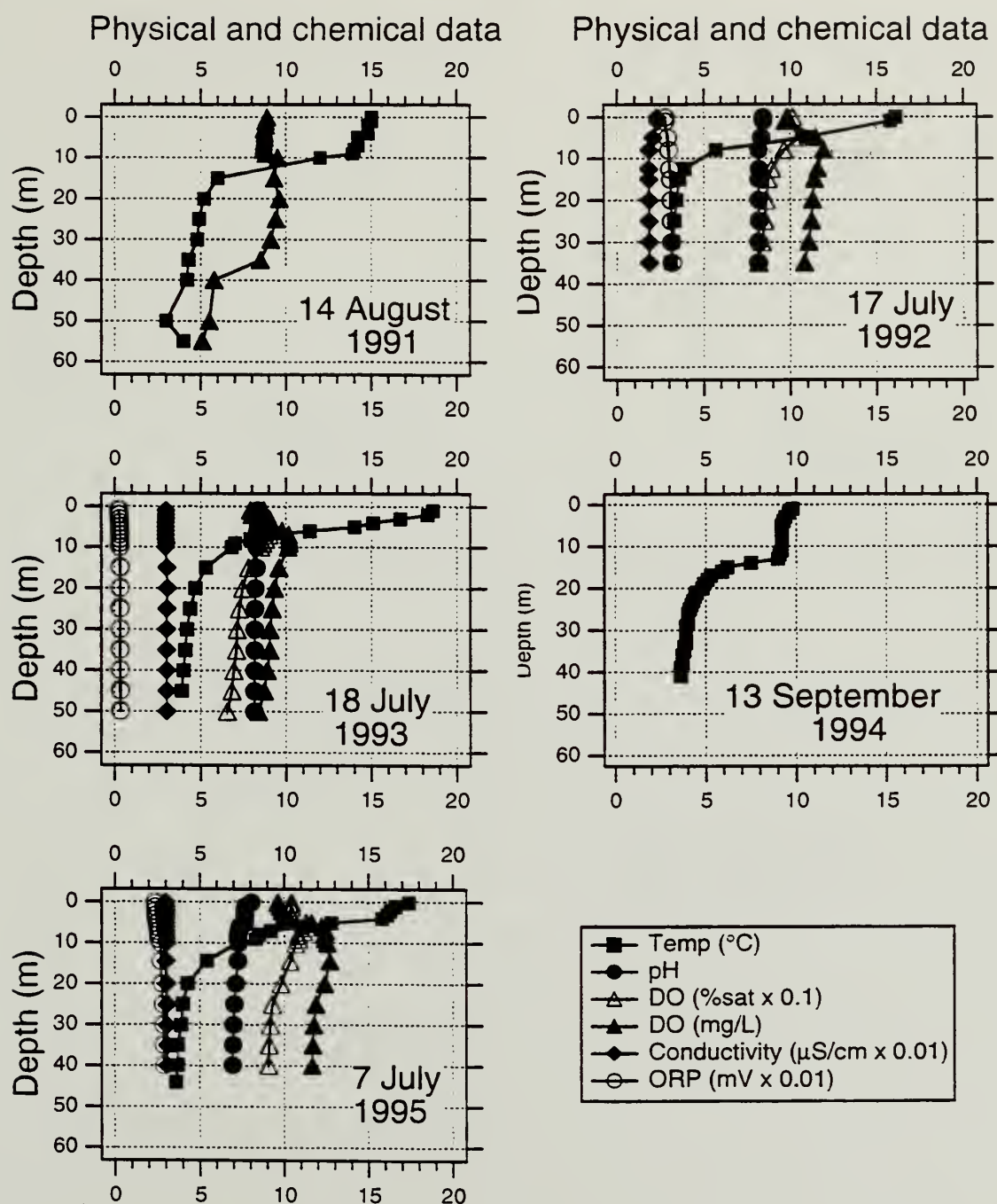


Figure 12. Water quality profiles, Takahula Lake.

Walker Lake-1988

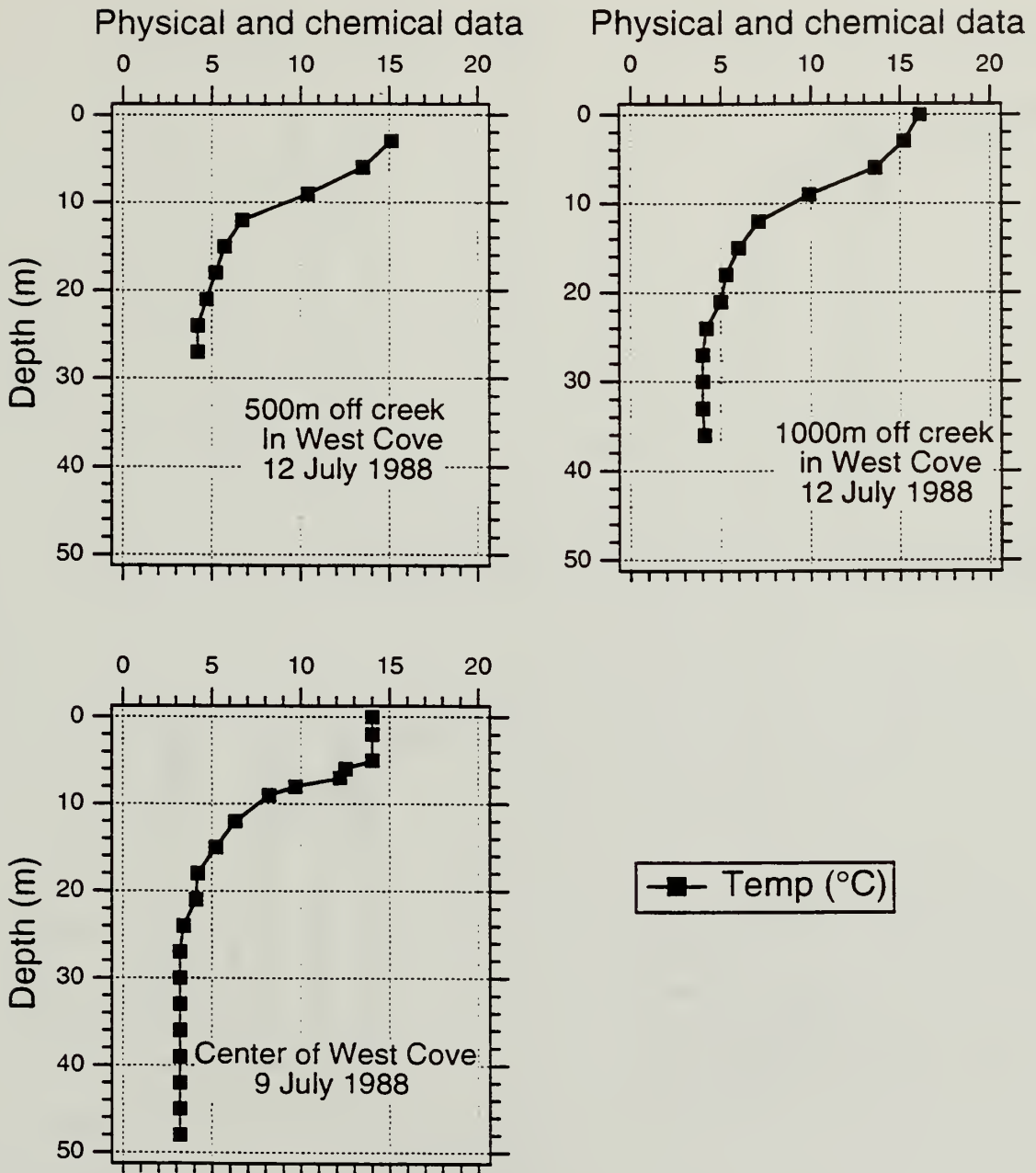


Figure 13. Water quality profiles, Walker Lake, 1988.

Walker Lake

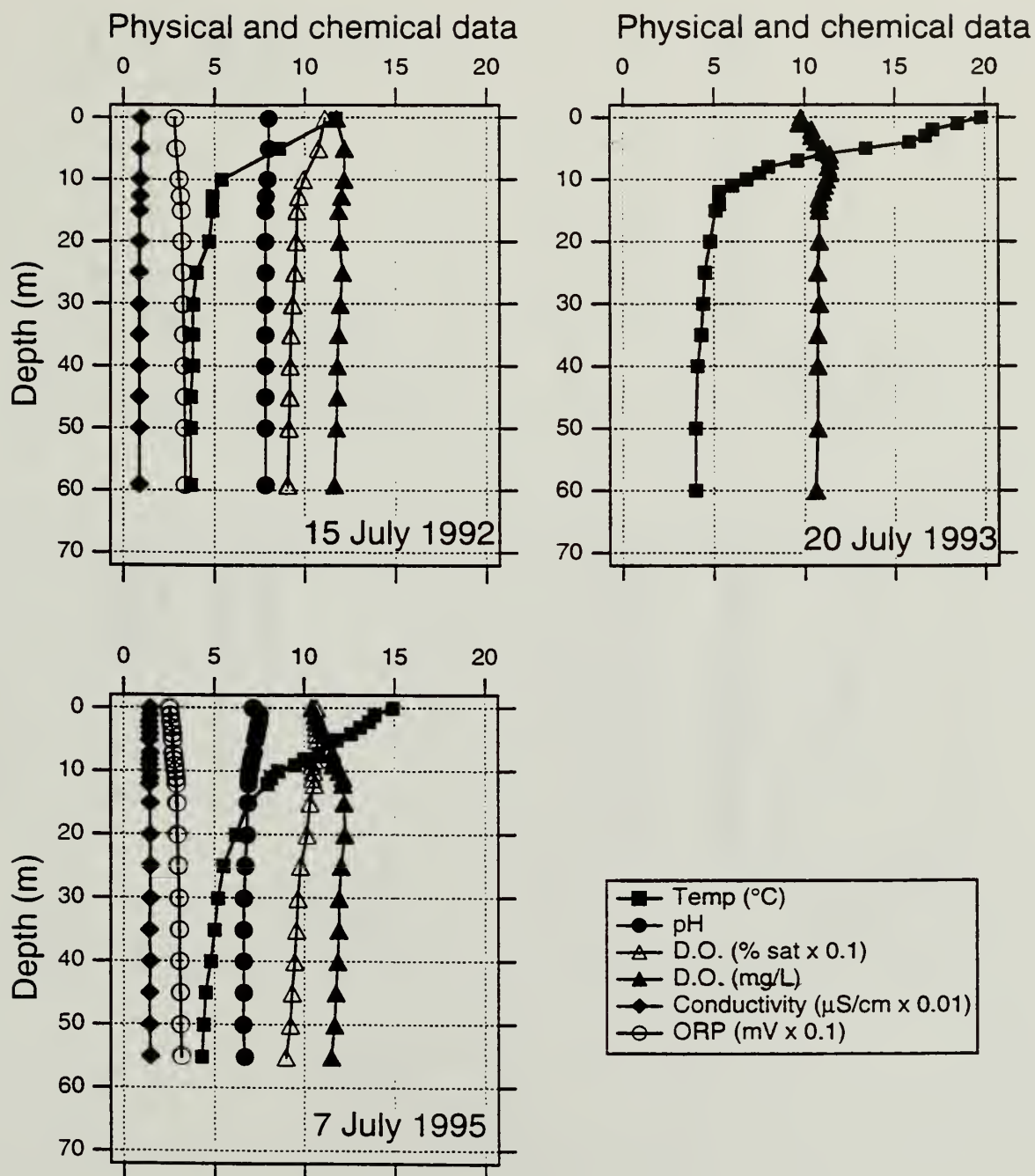


Figure 14. Water quality profiles, Walker Lake.

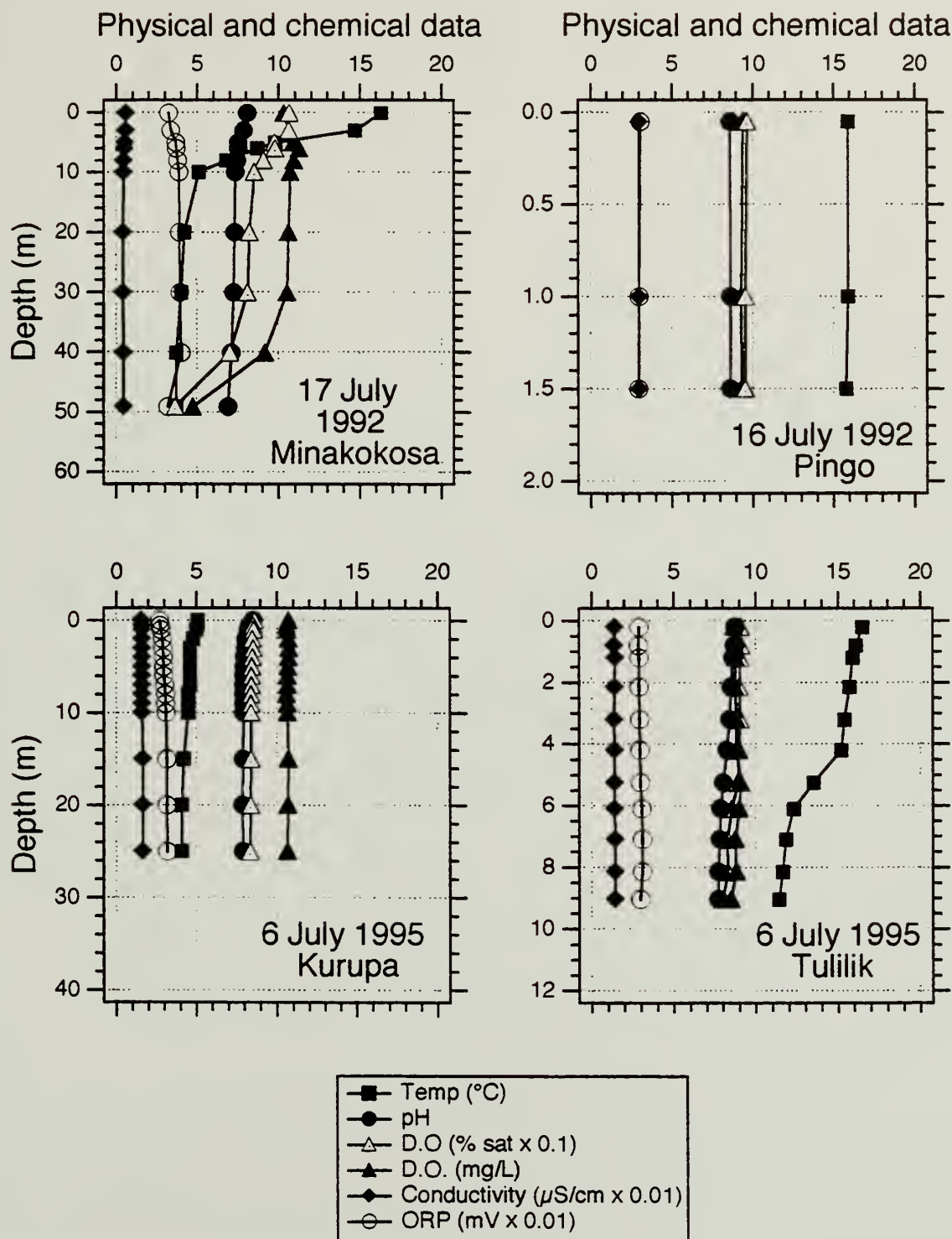


Figure 15. Water quality profiles, Minakokosa, Pingo, Kurupa, and Tulilik Lakes.

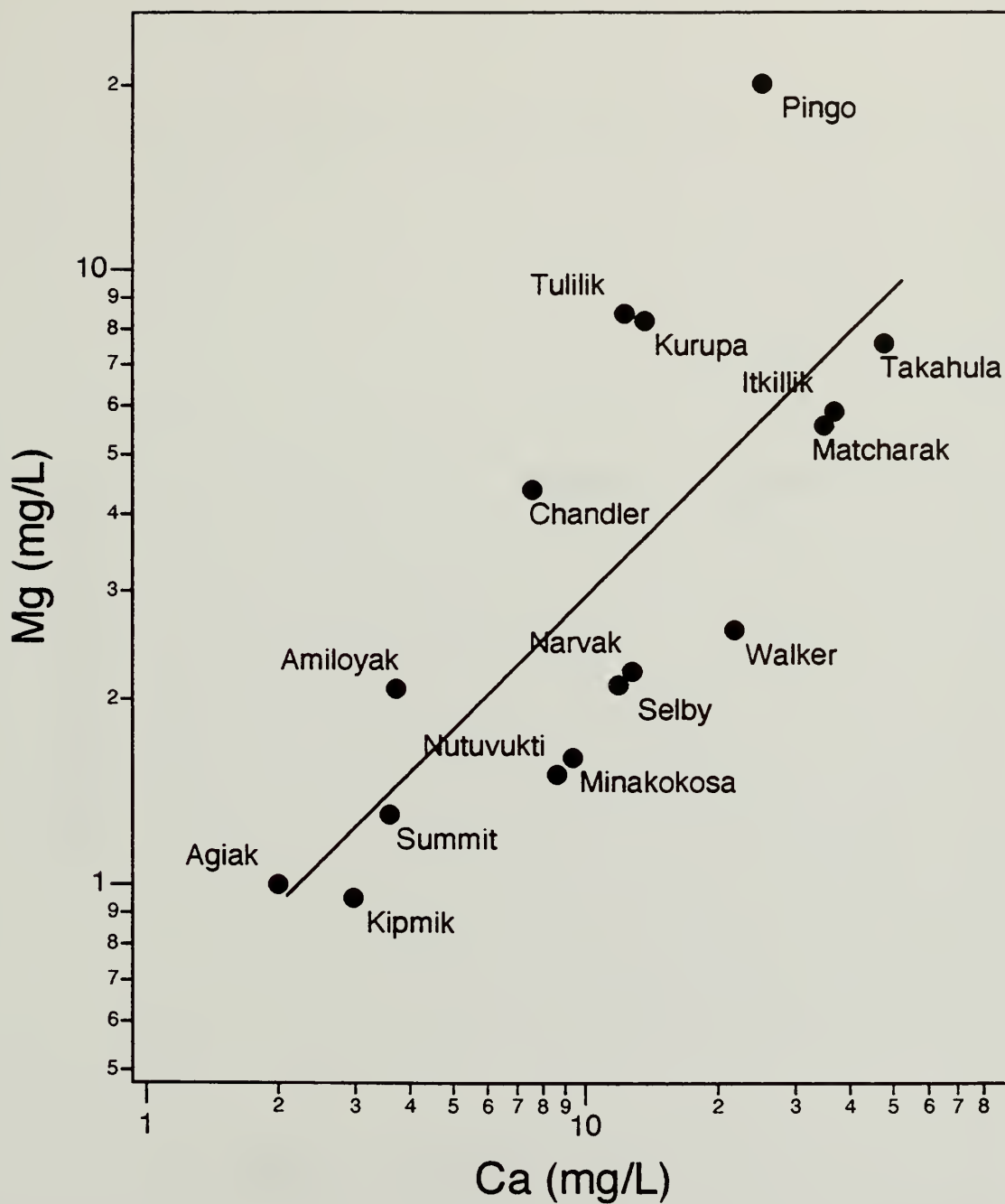


Figure 16. Relation between magnesium and calcium in lakes of Gates of the Arctic National Park and Preserve.

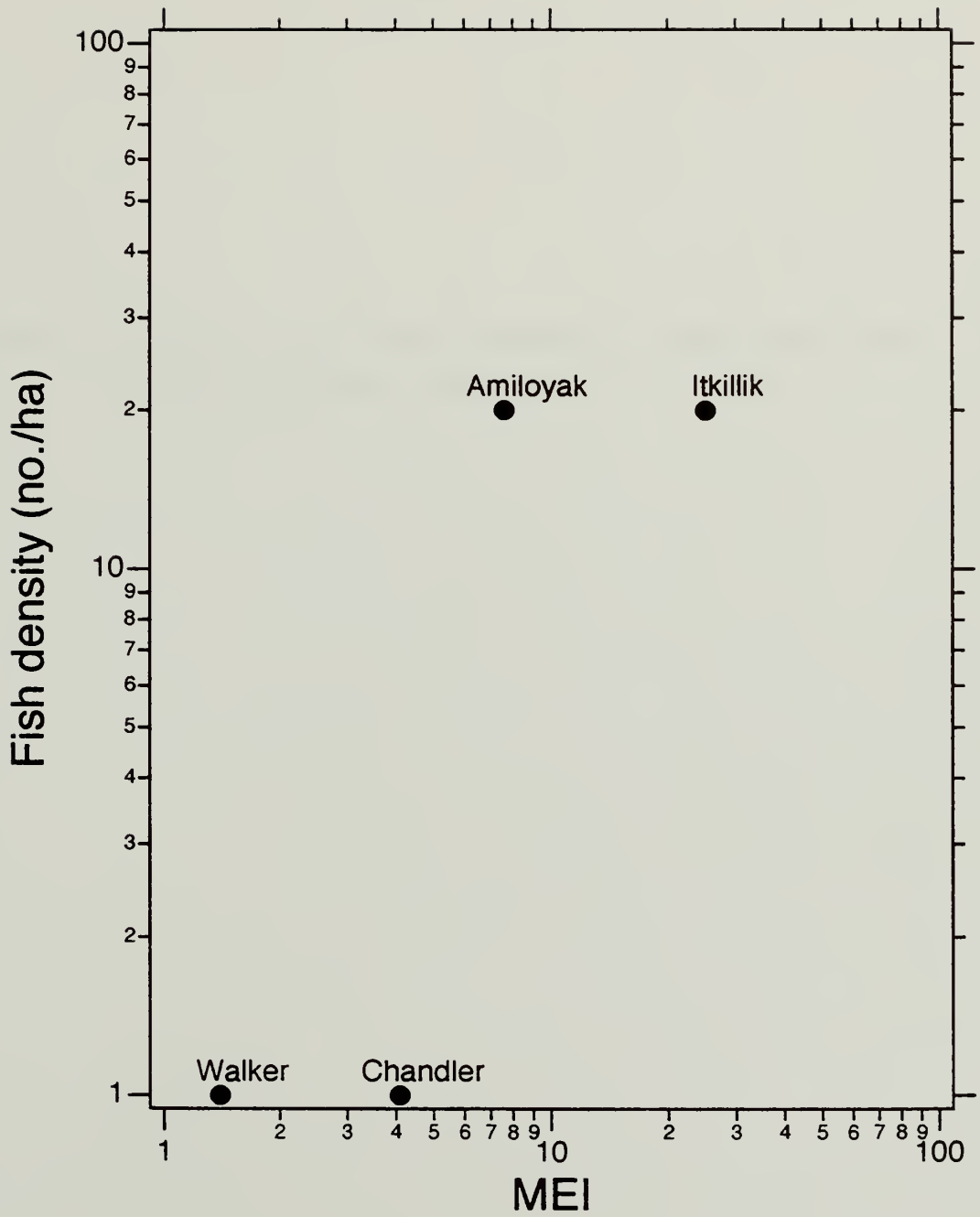
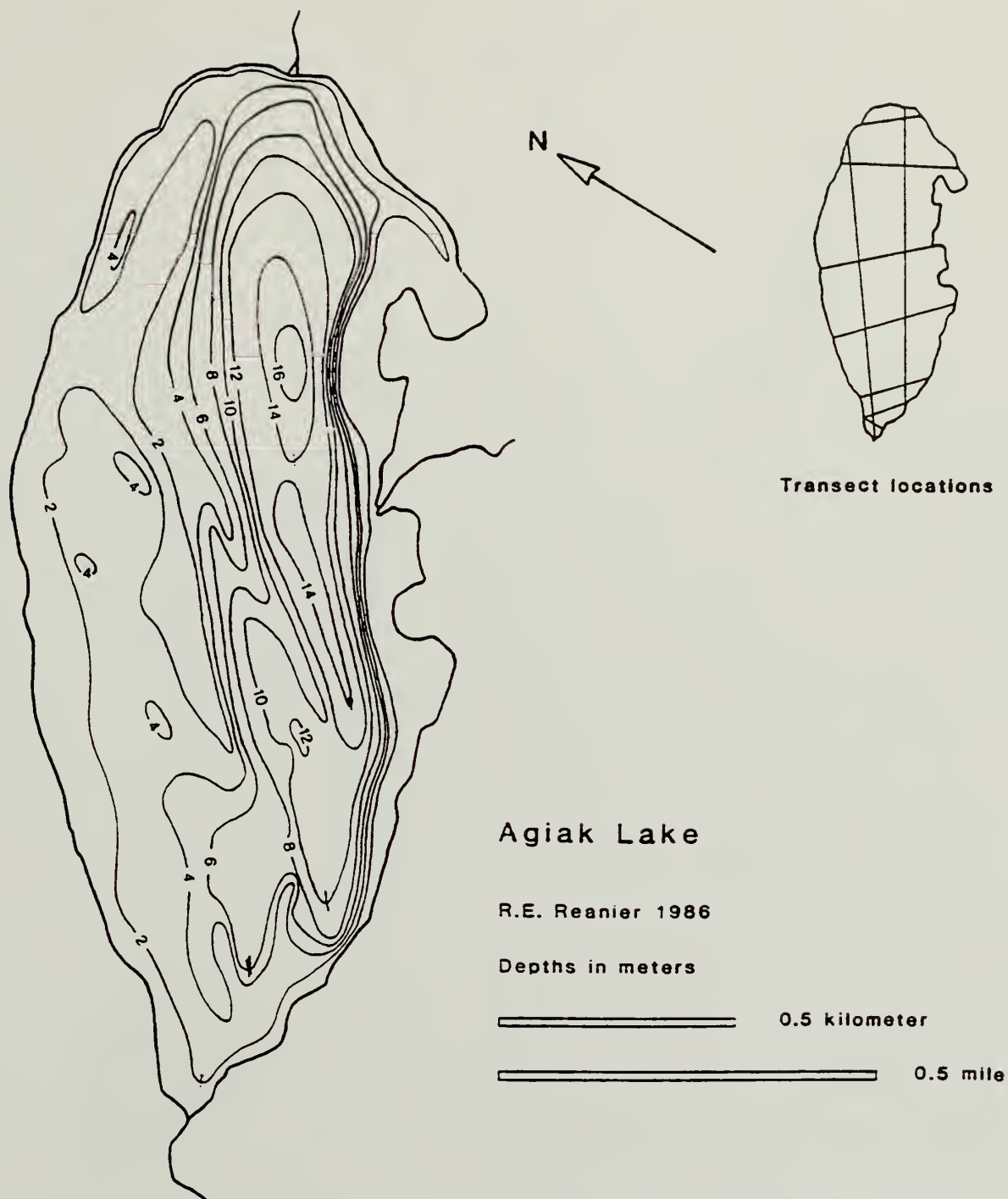
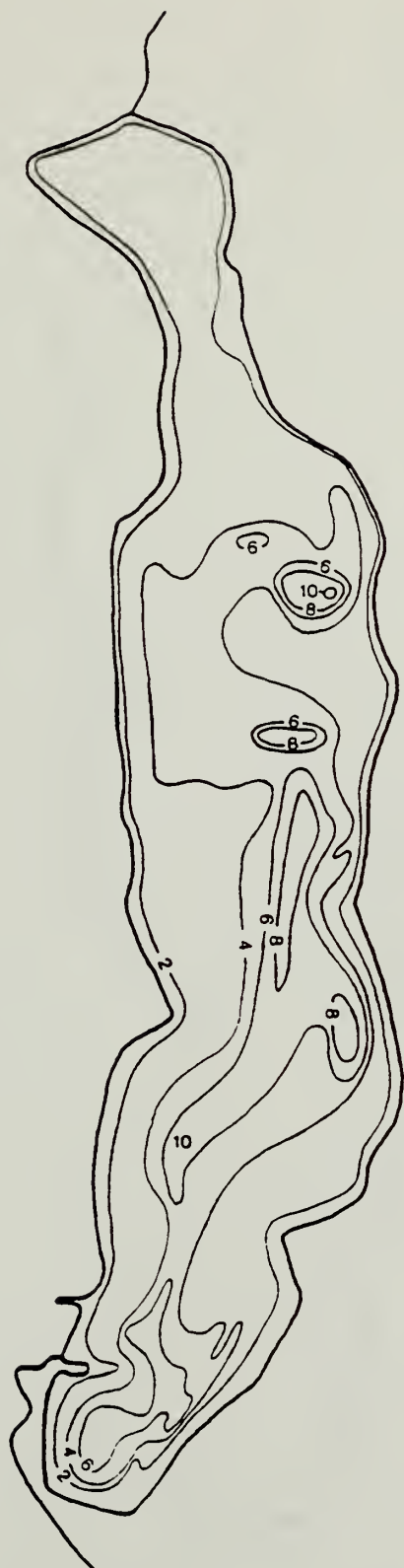


Figure 17. Fish density and the morphoedaphic index of four lakes, Gates of the Arctic National Park and Preserve.

Appendix A. Bathymetric maps of study lakes that are mapped, Gates of the Arctic National Park and Preserve.





Transect locations

Amiloyak Lake

R.E. Reanier 1986

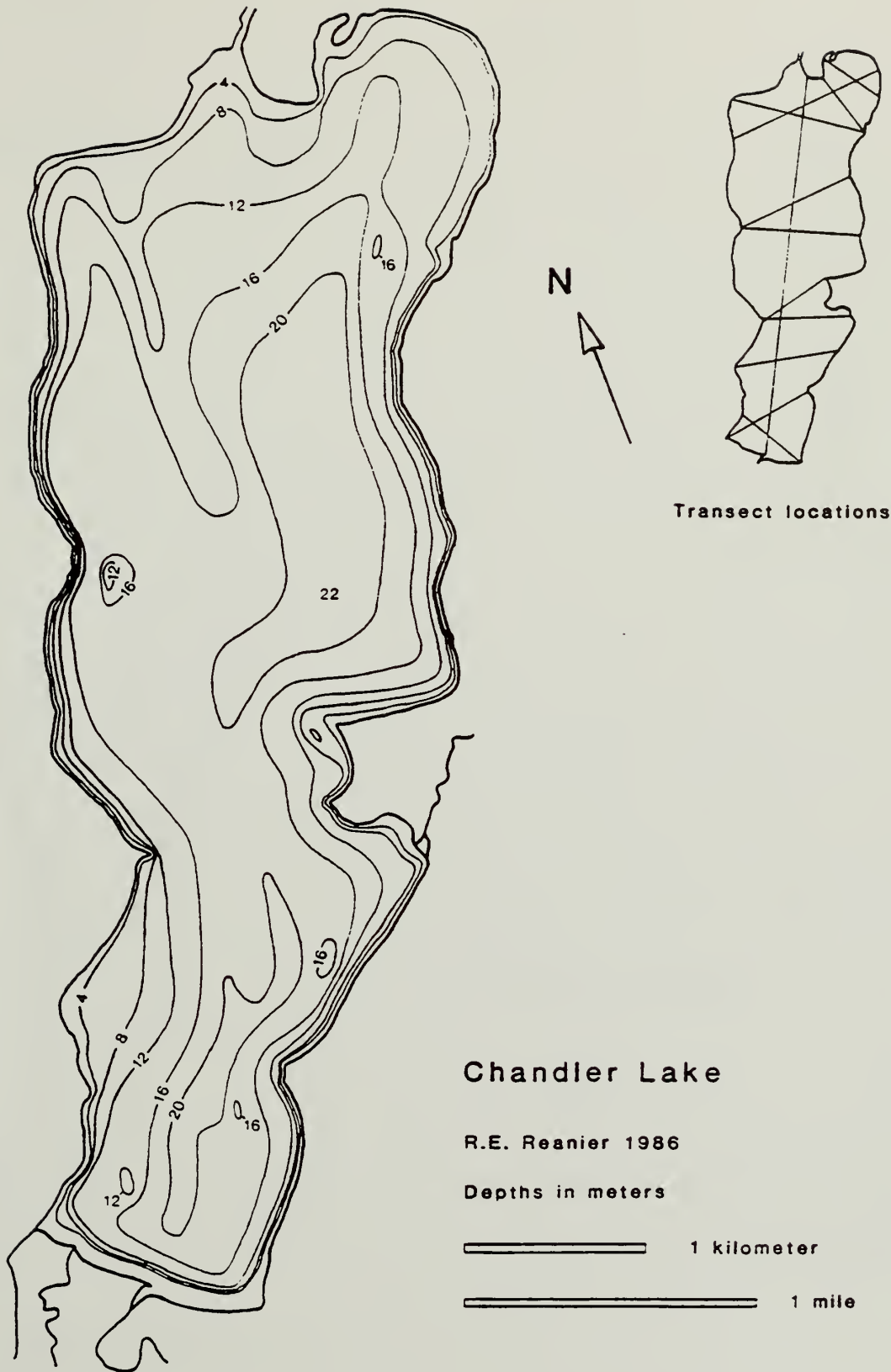
Depths in meters

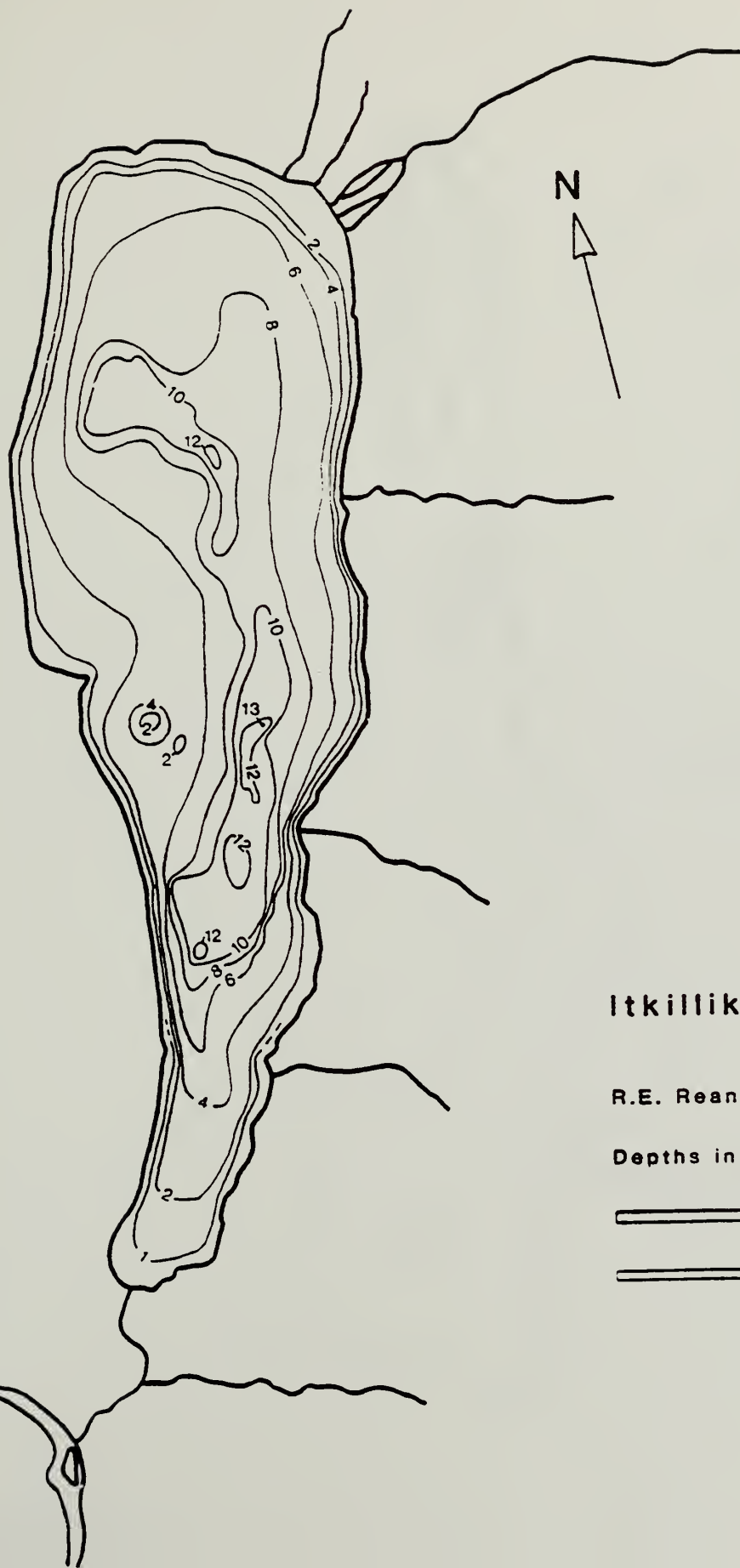


0.5 kilometer



0.5 mile





Transect locations

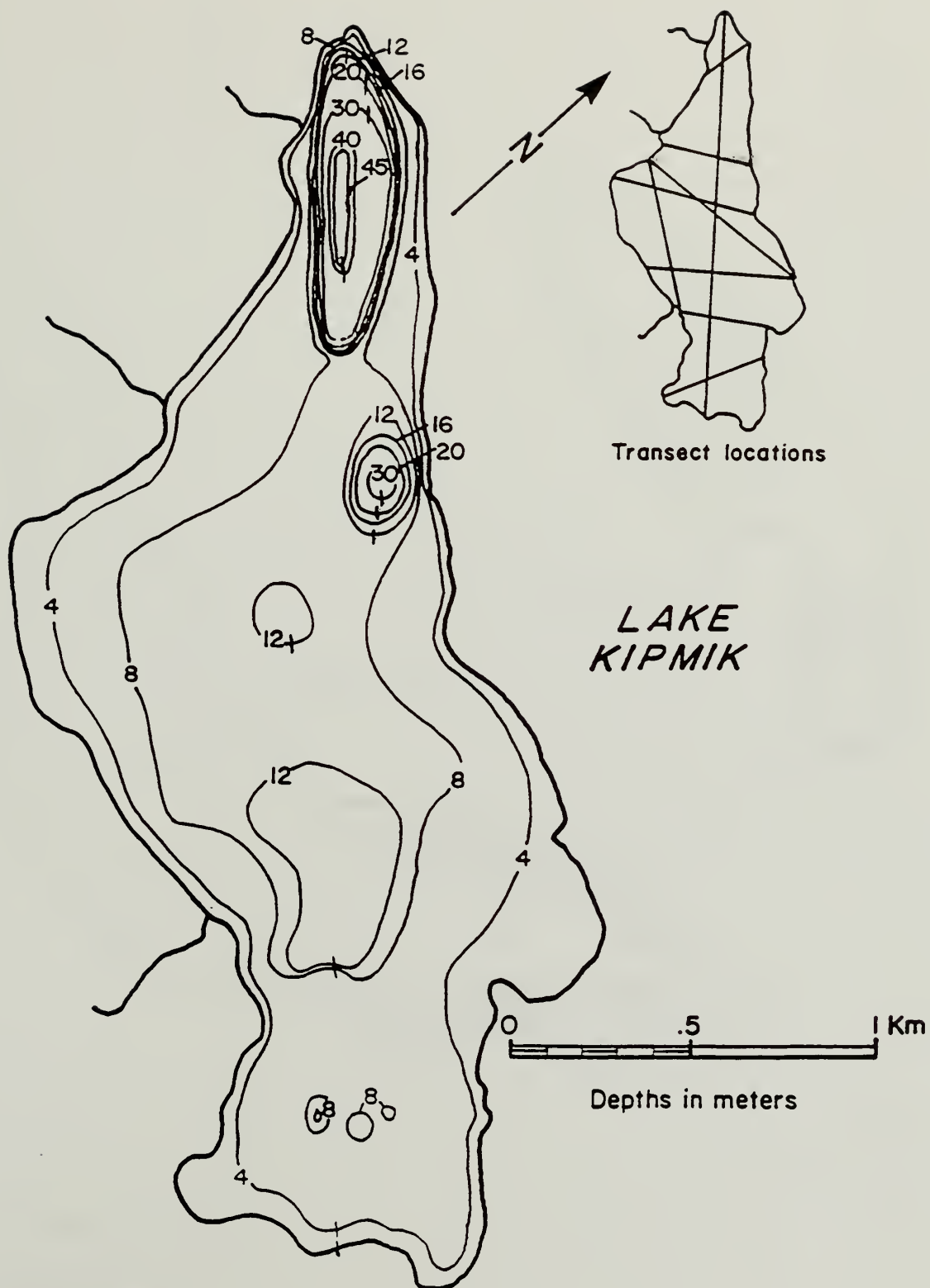
Itkillik Lake

R.E. Reanier 1987

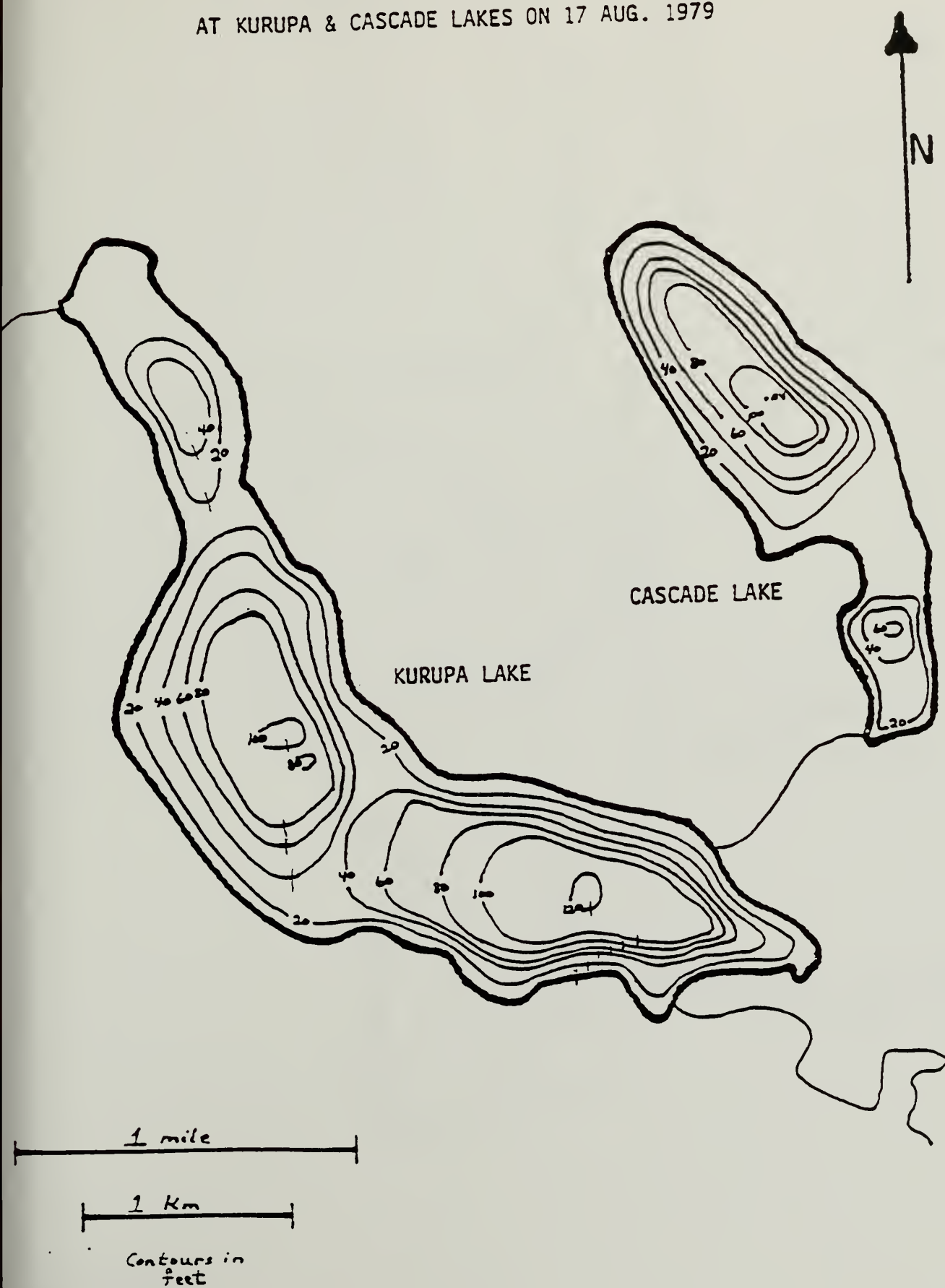
Depths in meters

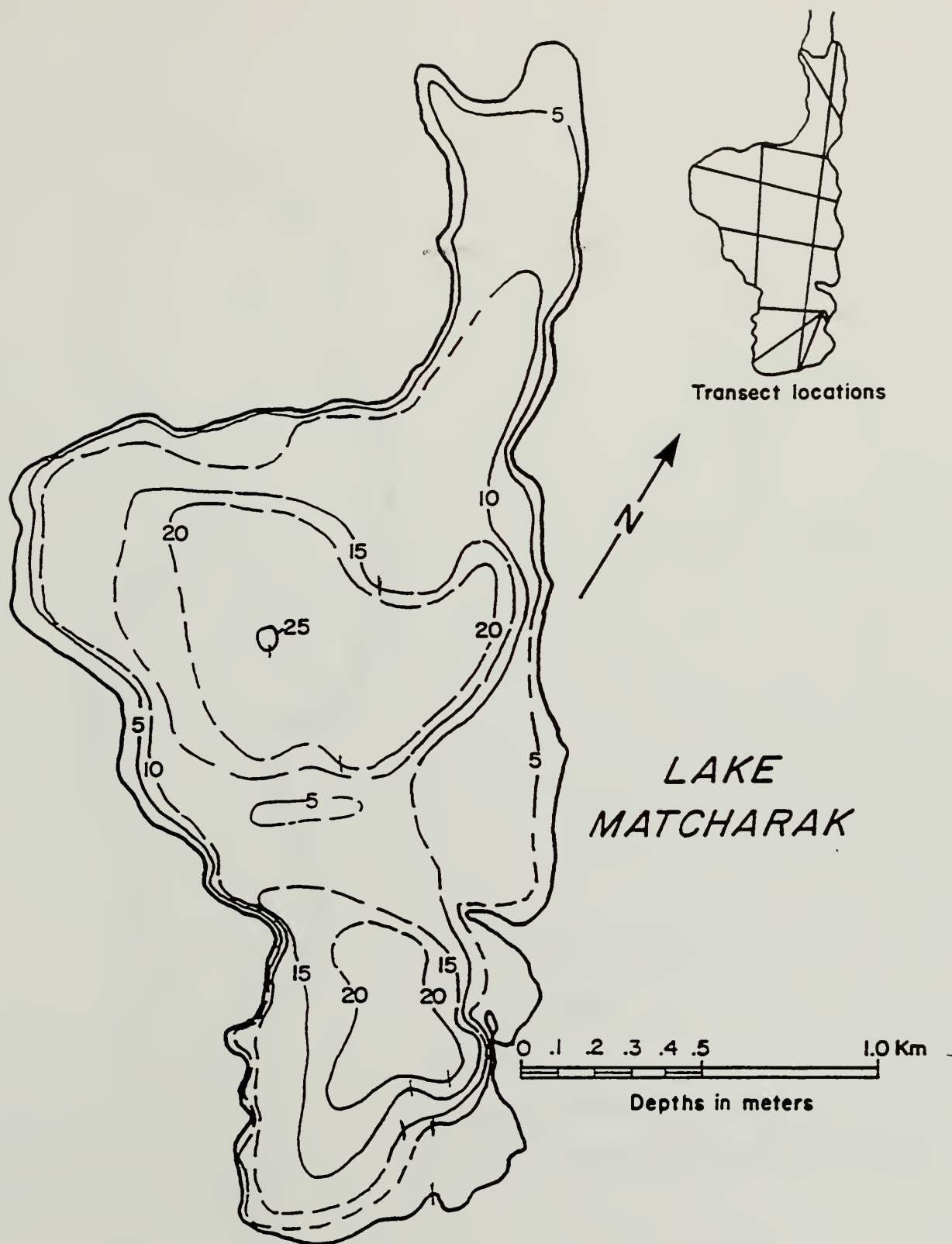
1 kilometer

1 mile



CONTOURS OF LAKE DEPTH APPROXIMATED FROM
SINGLE LONGITUDINAL DEPTH PROFILES TAKEN
AT KURUPA & CASCADE LAKES ON 17 AUG. 1979







Transect locations

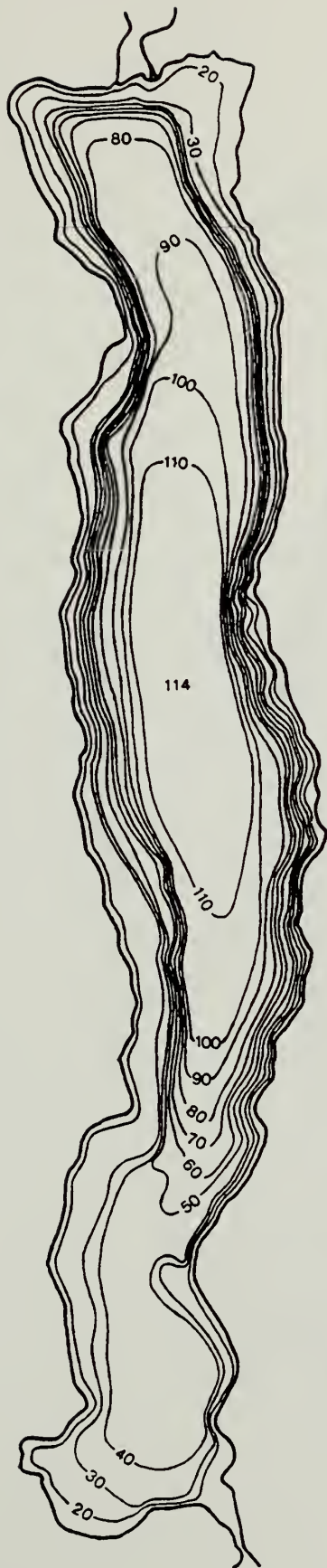
Lake Minakokosa

R.E. Reanier 1986

Depths in meters

————— 1 kilometer

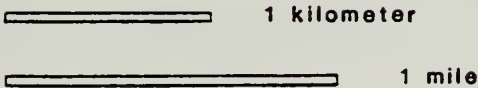
————— 1 mile

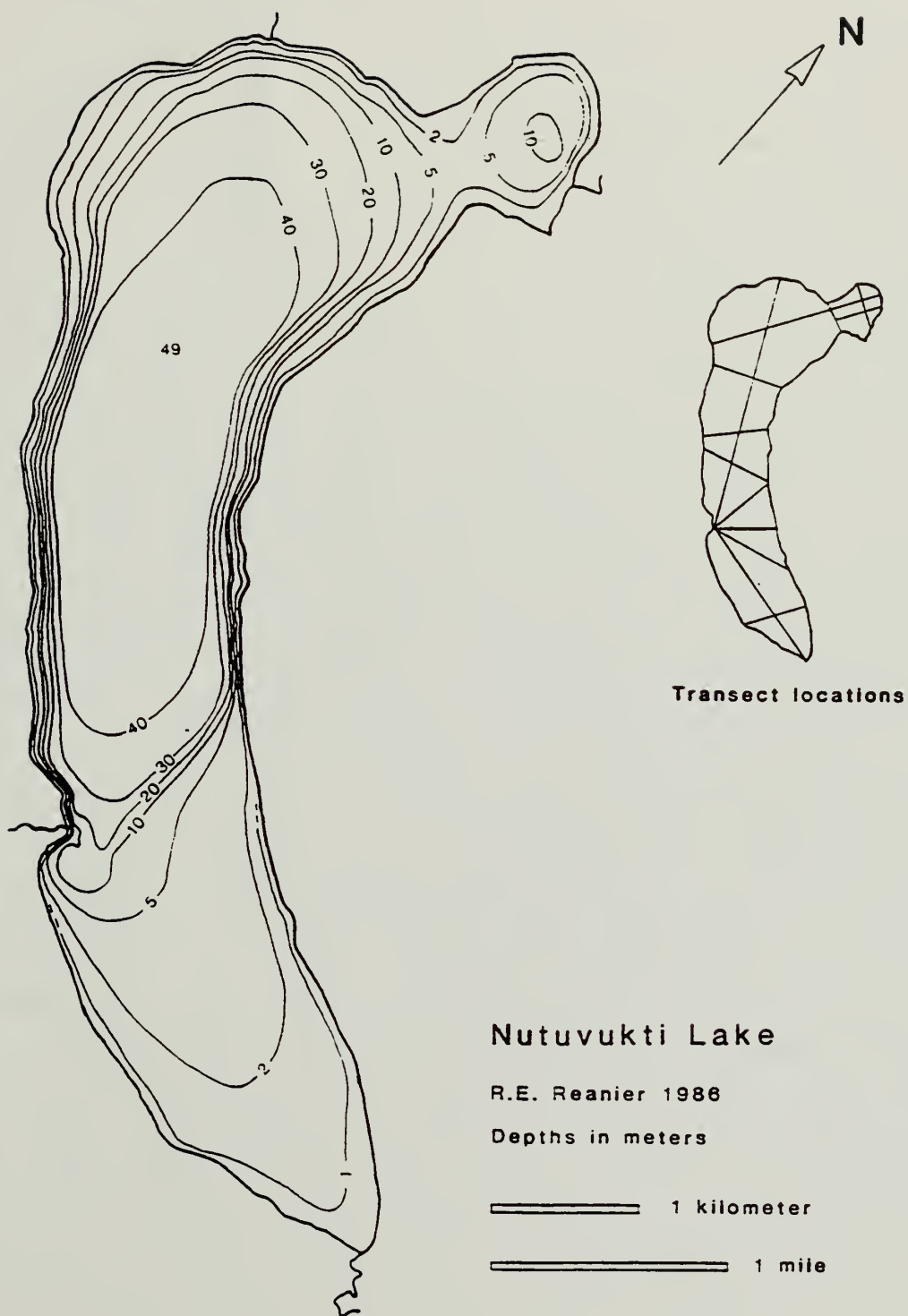


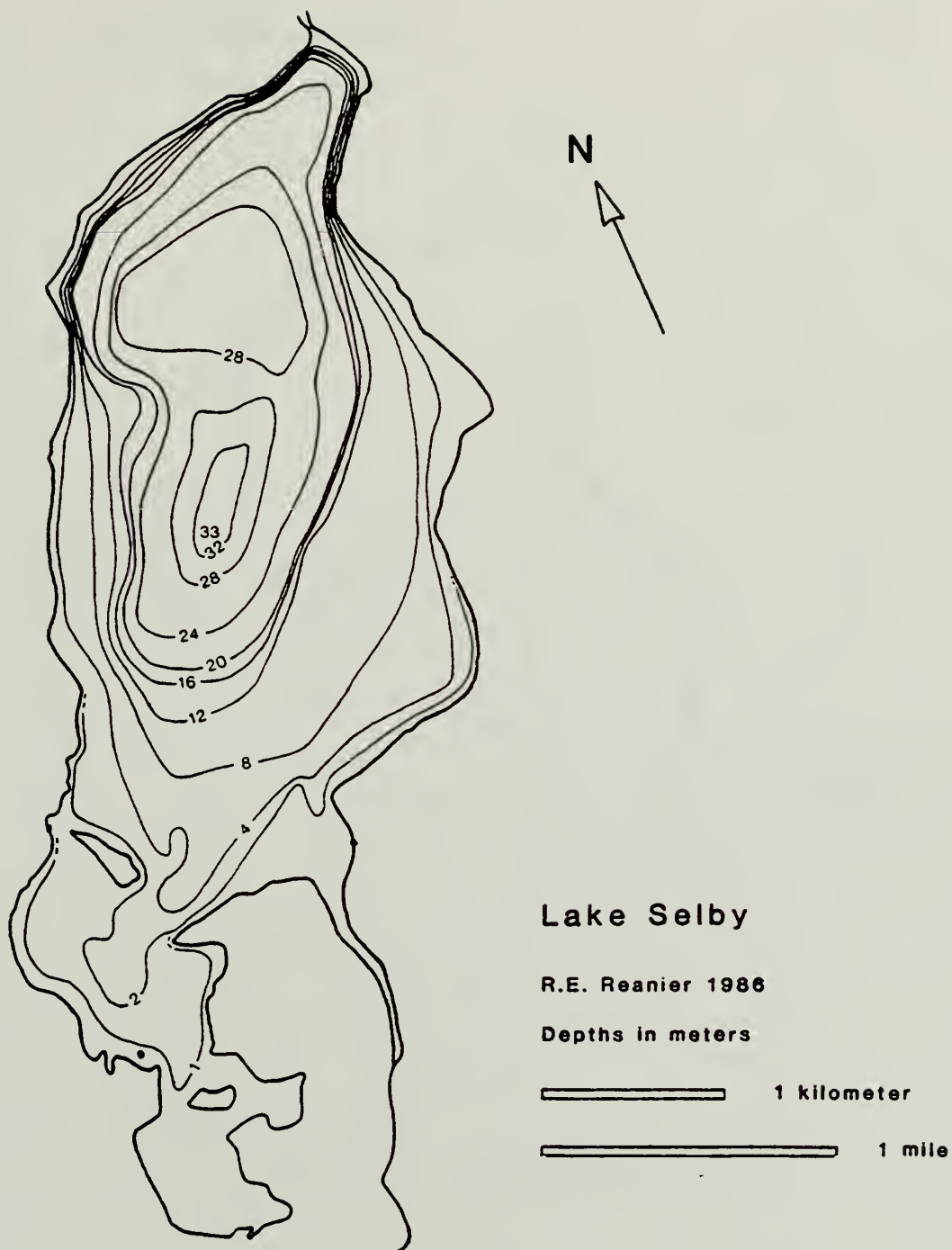
Narvak Lake

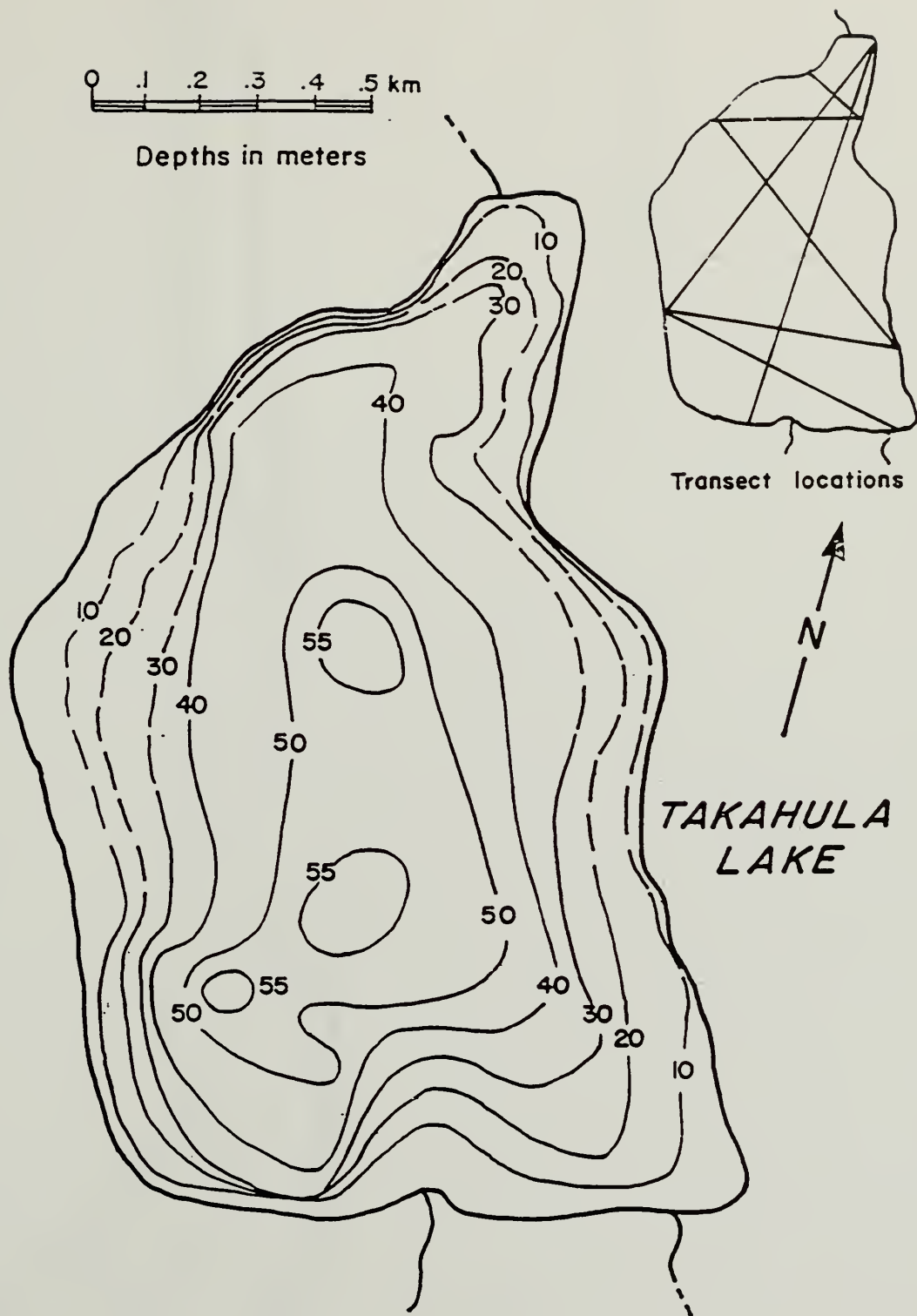
R.E. Reanier 1986

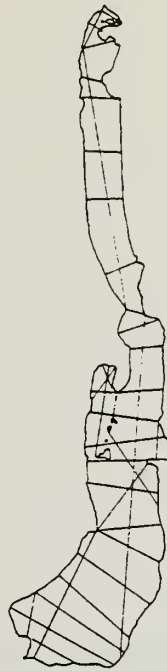
Depths in meters











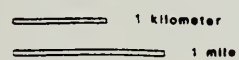
Tresect locations

Walker Lake

R.E. Reenier 1986

Depths in meters

Contour interval 10 meters



Appendix B. Trace and major metals (mg/L) of lakes of Gates of the Arctic National Park and Preserve—1992, 1993, and 1995.

Gates Trace Metals

Rows	names	Ba 92	Ba 93	Ba 95	Av Ba	Ca 92	Ca 93	Ca 95	Av Ca	Fe 92	Fe 93	Fe 95	Av Fe
1	Agiak	•	0.002	0.002	0.002	•	1.9	2.1	2	•	0.061	0.15	0.11
2	Amiolak	0.001	0.001	•	0.001	3.71	3.73	•	3.72	0.079	0.071	•	0.075
3	Chandler	0.01	0.01	0.009	0.01	8.01	7.71	7.1	7.6	0.03	0.038	0.29	0.12
4	Itkilluk	•	0.066	0.075	0.07	•	34	40.1	37	•	0.009	0.01	0.01
5	Kipmik	•	0.001	•	0.001	2.86	2.86	3.22	2.98	0.033	0.035	0.03	0.03
6	Kurupa	•	•	0.05	0.05	•	•	13.7	13.7	•	•	0.5	0.5
7	Matcharak	0.041	0.045	0.042	0.043	32.6	35.6	37.2	35.1	0.011	0.01	•	0.01
8	Minakokosa	0.046	•	•	0.046	9.37	•	•	9.37	0.047	•	•	0.047
9	Narvak	0.032	0.031	•	0.031	13.1	12.5	•	12.8	0.034	0.043	•	0.038
10	Nutuvukti	0.004	0.005	•	0.004	8.63	8.64	•	8.63	0.046	0.055	•	0.05
11	Pingo	0.011	•	•	0.011	25.4	•	•	25.4	0.039	•	•	0.039
12	Selby	•	0.028	•	0.028	•	11.9	•	11.9	•	0.033	•	0.033
13	Summit	•	0.003	0.007	0.005	•	3.45	3.7	3.6	•	0.026	0.4	0.21
14	Takahula	0.01	0.011	0.012	0.011	44.3	•	52	48	0.013	•	•	0.013
15	Tufilik	•	•	0.002	0.002	•	•	12.3	12.3	•	•	0.04	0.04
16	Walker	0.008	0.009	0.009	0.009	20.9	21.8	22.9	21.9	0.005	0.014	•	0.009

Gates Trace Metals

Rows	lake names	K 92	K 93	K 95	Av K	Mg 92	Mg 93	Mg 95	Av Mg	Mn 92	Mn 93	Mn 95	Av Mn
1	Agiak	•	0	0.12	0.12	•	0.93	1.1	1	•	0.017	0.02	0.018
2	Amiolak	1	0	•	•	2.09	2.08	•	2.08	0.01	0.011	•	0.011
3	Chandler	1	0	0.36	0.36	4.53	4.39	4.24	4.39	0.0053	0.003	0.009	0.006
4	Itkilluk	•	0.5	0.52	0.51	•	5.57	6.16	5.87	•	0.004	0.008	0.006
5	Kipmik	0.6	0.3	0	0	0.91	0.89	1.06	0.95	0.02	0.013	0.013	0.015
6	Kurupa	•	•	0.45	0.45	•	•	8.25	8.25	•	•	0.014	0.014
7	Matcharak	3.4	0.4	0.62	0.62	5.27	5.59	5.86	5.57	0.004	0.008	0.008	0.007
8	Minakokosa	0	•	•	•	1.61	•	•	1.61	0.0031	•	•	0.003
9	Narvak	0	0	•	•	2.28	2.15	•	2.22	0.003	•	•	0.003
10	Nutuvukti	0.3	0	•	•	1.52	1.51	•	1.51	0.0031	0.004	•	0.004
11	Pingo	4.8	•	•	•	20.1	•	•	20.1	0.025	•	•	0.025
12	Selby	•	0	•	•	•	2.11	•	2.11	•	0.002	•	0.002
13	Summit	•	0	0.44	0.44	•	1.2	1.39	1.3	•	0.005	0.026	0.016
14	Takahula	2	0.9	1.1	1.1	7.06	7.55	8.16	7.59	0.0031	0.005	0.004	0.004
15	Tulilik	•	•	1.3	1.3	•	•	8.47	8.47	•	•	0.004	0.004
16	Walker	3	0.7	0.97	0.97	2.45	2.52	2.79	2.59	0.002	•	•	0.002

Gates Trace Metals

Rows	lakes	Na 92	Na 93	Na 95	Av Na	SI 92	SI 93	SI 95	Av SI	Sr 92	Sr 93	Sr 95	Av Sr
1	Agiak	•	0.34	0.33	0.33	•	0.46	0.49	0.47	•	0.0062	0.007	0.006
2	Amiolak	0.64	0.62	•	0.63	0.75	0.77	•	0.76	0.015	0.016	•	0.015
3	Chandler	2.3	2	2.1	2.13	0.56	0.46	0.85	0.62	0.0385	0.037	0.36	0.14
4	Itkilluk	•	0.54	0.53	0.53	•	0.93	0.62	0.78	•	0.0586	0.062	0.06
5	Kipmik	0.42	0.78	0.39	0.53	0.62	0.54	0.76	0.64	0.01	0.0098	0.011	0.01
6	Kurupa	•	•	3.6	3.6	•	•	0.98	0.98	•	•	0.048	0.048
7	Matcharak	4.95	5.43	4.4	4.93	1.6	2.06	1.6	1.75	0.0939	0.101	0.1	0.098
8	Minakokosa	0.91	•	•	0.91	2.15	•	•	2.15	0.0537	•	•	0.054
9	Narvak	0.63	0.58	•	0.61	1.7	1.58	•	1.7	0.0569	0.0543	•	0.056
10	Nutuvukti	0.703	0.69	•	0.69	0.66	0.69	•	0.68	0.0505	0.0505	•	0.05
11	Pingo	20.6	•	•	20.6	0.69	•	•	0.69	0.127	•	•	0.127
12	Selby	•	0.64	•	0.64	•	1.56	•	1.56	•	0.0514	•	0.051
13	Summit	•	1.2	0.89	1.05	•	0.42	0.97	0.7	•	0.01	0.011	0.01
14	Takahula	0.68	0.74	0.71	0.71	1.1	1.25	1.4	1.25	0.164	0.174	0.177	0.172
15	Tuillik	•	•	2.4	2.4	•	•	0.69	0.69	•	•	0.39	0.39
16	Walker	0.49	0.48	0.45	0.47	0.92	0.99	1.1	1	0.0654	0.0686	0.072	0.069

Gates Trace Metals

Rows	lake	Al 95	Cu 95	Ni 95	V 95	Zn 95
1	Agiak	•	•	•	•	0.003
2	Amiolak	•	•	•	•	•
3	Chandler	0.2	0.01	0.01	0.01	0.002
4	Itkilluk	•	•	•	•	•
5	Kipmik	•	•	•	•	•
6	Kurupa	0.24	•	•	•	•
7	Matcharak	•	•	•	•	•
8	Minakokosa	•	•	•	•	•
9	Narvak	•	•	•	•	•
10	Nutuvukti	•	•	•	•	•
11	Pingo	•	•	•	•	•
12	Selby	•	•	•	•	•
13	Summit	0.31	•	•	•	•
14	Takahula	•	•	0.008	•	•
15	Tulilik	•	•	0.007	•	•
16	Walker	•	•	•	•	•

Appendix C. Nutrients and total chlorophyll concentrations of plankton of lakes of Gates of the Arctic National Park and Preserve—1992, 1993, and 1995. Total phosphorus as $\mu\text{g/L}$, total nitrogen as mg/L , and total chlorophyll as $\mu\text{g/L}$.

Gates Nutrients and Chlorophyll

Rows	lake	TP 92	TP 93	TP 95	Av TP	TN 92	TN 93	TN 95	Av TN	chl 92	chl 93	chl 95	Av chl
1	Agiak	•	7	7	7	•	0.16	0.112	0.135	•	1.5	1.9	1.7
2	Amiolak	11	8	•	10	0.19	0.28	•	0.235	1.7	1.6	•	1.6
3	Chandler	6	5	8	6	0.22	0.16	0.107	0.162	1.3	1.1	1.4	1.3
4	Itkilluk	•	8	6	7	•	0.29	0.26	0.28	•	1	1.2	1.1
5	Kipmik	6	6	4	5.3	0.19	0.19	0.108	0.163	1.8	3.4	1.4	2.2
6	Kurupa	•	•	11	11	•	•	0.127	0.127	•	•	0.5	0.5
7	Matcharak	8	12	8	9.3	0.41	0.41	0.308	0.376	1	2.9	2.9	2.3
8	Minakokosa	6	•	•	6	0.471	•	•	0.471	1.7	•	•	1.7
9	Narvak	5	4	•	4	0.4	0.32	•	0.36	1.3	1.5	•	1.5
10	Nutuvukti	5	5	•	5	0.3	0.27	•	0.285	1.5	1.6	•	1.6
11	Pingo	16	•	•	16	0.76	•	•	0.76	2.1	•	•	2.1
12	Selby	•	4	•	4	•	0.3	•	0.3	•	1.3	•	1.3
13	Summit	•	6	16	11	•	0.18	0.12	0.15	•	1.1	2.6	1.8
14	Takahula	4	4	3	4	0.35	0.21	0.153	0.238	0.7	1.2	1.3	1.1
15	Tulilik	•	•	7	7	•	•	0.435	0.435	•	•	1.4	1.4
16	Walker	4	5	3	4	0.32	0.34	0.264	0.308	0.8	0.7	1.3	0.9

Appendix D. Light characteristics of lakes of Gates of the Arctic National Park and Preserve—1992, 1993, and 1995. Light attenuation coefficient (k) in m^{-1} , Secchi depths (SD) in m. Depth of 1% light penetration (1%) in m, color in chlorophosphate units (cpu), and turbidity in nephelometric turbidity units (NTU).

Gates Light

Rows	lakes	k 93	k 95	Av k	SD 92	SD 93	SD 95	Av SD	1% 93	1% 95	Av 1%
1	Aglak	0.378	0.55	0.46	•	5.3	4.3	4.8	12.2	8.4	10.3
2	Amiloyak	0.262	•	0.26	•	4.6	•	4.6	17.6	•	17.6
3	Chandler	0.36	0.68	0.52	4.5	4.2	2	3.6	12.8	6.8	9.8
4	Itkillik	0.303	0.27	0.29	•	8.7	9.6	9.2	15	17	16
5	Kipmik	0.47	0.37	0.42	6.1	6.6	8.3	7	9.8	12.4	11.1
6	Kurupa	•	1.53	1.53	•	•	0.6	0.6	•	3.01	3.01
7	Matcharak	0.36	0.3	0.33	7.8	8	7.6	7.8	12.8	15.3	14
8	Minakokosa	•	•	•	5.8	•	•	5.8	•	•	•
9	Narvak	0.344	•	0.344	7.7	8.5	•	8.1	13.4	•	13.4
10	Nutuvukti	0.433	•	0.43	6.1	6.8	•	6.4	10.4	•	10.4
11	Pingo	•	•	•	•	•	•	•	•	•	•
12	Selby	0.404	•	0.404	•	8.6	•	8.6	11.4	•	11.4
13	Summit	0.384	1.54	0.96	•	6.4	1.1	3.75	12	2.99	7.5
14	Takahula	0.23	0.28	0.25	12.4	15.1	16.4	14.6	20	16.45	18.2
15	Tulilik	•	0.42	0.42	•	•	7.3	7.3	•	11	11
16	Walker	0.292	0.21	0.25	13.7	13.1	15.6	14.1	15.8	21.6	18.7

Gates Light

Rows	lake names	color 92	color 93	color 95	Av color	turb 93	turb 95	Av turb
1	Agiak	•	17	33	25	0.8	1.43	1.12
2	Amiloyak	18	19	•	18	1.1	•	1.1
3	Chandler	17	14	44	25	1.3	5	3.2
4	Itkillik	•	11	12	12	0.36	0.49	0.42
5	Kipmik	14	23	0	12	0.42	0.63	0.52
6	Kurupa	•	•	83	83	•	12	18
7	Matcharak	8	6.3	14	9.4	0.43	0.69	0.56
8	Minakokosa	14	•	•	14	•	•	•
9	Narvak	12	20	•	16	0.36	•	0.36
10	Nutuvukti	17	16	•	16	0.43	•	0.43
11	Pingo	20	•	•	20	•	•	•
12	Selby	•	17	•	17	0.35	•	0.35
13	Summit	•	17	94	56	0.86	14.1	7.48
14	Takahula	5	11	0	5.3	0.3	0.33	0.32
15	Tullik	•	•	8	8	•	0.44	0.44
16	Walker	3	10	0	4.3	0.31	0.23	0.27

Appendix E. Trace and major ions (mg/L) of the John River, Big Contact Creek, and Little Contact Creek near Anaktuvuk Pass and Reed River Hot Springs, Alaska, August 1993.

John River		Mean $\pm$ C.I.*		Reed River Hot Spring		Mean $\pm$ C.I.*	
AG:	(mg/L)	(mg/L)	(mg/L)	AG:	(mg/L)	(mg/L)	(mg/L)
AL:	<0.01	<0.01	<0.01	AL:	<0.01	<0.01	<0.01
AS:	<0.02	<0.02	<0.02	AS:	<0.02	<0.02	<0.02
B:	<0.04	<0.04	<0.04	B:	<0.04	<0.04	<0.04
BA:	<0.02	<0.02	<0.02	BA:	0.29	0.29	0.29
BE:	0.0688	0.0681	0.0701	BE:	0.0038	0.0050	0.0044 $\pm$ 0.0076
BI:	<0.0005	<0.0005	<0.0005	BI:	0.0008	0.0008	0.0008 $\pm$ 0
CA:	<0.04	<0.04	<0.04	CA:	<0.04	<0.04	<0.04
CD:	36.4	35.7	36.7	CD:	21.5	22.1	21.8 $\pm$ 3.8
CO:	<0.002	<0.002	<0.002	CO:	<0.002	<0.002	<0.002
CR:	<0.01	<0.01	<0.01	CR:	<0.01	<0.01	<0.01
CU:	<0.01	<0.01	<0.01	CU:	<0.01	<0.01	<0.01
FE:	<0.003	<0.003	<0.003	FE:	<0.003	<0.003	<0.003
K:	0.01	0.01	0.01	K:	<0.005	<0.005	<0.005
L:	<0.5	<0.5	<0.5	L:	9.9	9.9	9.9 $\pm$ 0
M:	<0.01	<0.01	<0.01	M:	0.02	0.02	0.02 $\pm$ 0
N:	<0.002	<0.002	<0.002	N:	0.244	0.240	0.242 $\pm$ 0.025
O:	5.60	5.50	5.69	O:	0.844	0.847	0.846 $\pm$ 0.019
P:	<0.002	<0.002	<0.002	P:	0.072	0.087	0.080 $\pm$ 0.095
Q:	<0.005	<0.005	<0.005	Q:	<0.005	<0.005	<0.005
R:	0.53	0.51	0.57	R:	125	124	124.5 $\pm$ 6.4
S:	<0.01	<0.01	<0.01	S:	<0.01	<0.01	<0.01
T:	<0.09	<0.09	<0.09	T:	<0.09	<0.09	<0.09
U:	<0.04	<0.04	<0.04	U:	<0.04	<0.04	<0.04
V:	<0.04	<0.04	<0.04	V:	<0.04	<0.04	<0.04
W:	<0.04	<0.04	<0.04	W:	<0.04	<0.04	<0.04
X:	0.74	1.01	0.67	X:	31.3	31.2	31.25 $\pm$ 0.6353
Y:	<0.04	<0.04	<0.04	Y:	<0.04	<0.04	<0.04
Z:	0.049	0.048	0.0497	Z:	0.22	0.223	0.2215 $\pm$ 0.0191
AA:	<0.002	<0.002	<0.002	AA:	<0.002	<0.002	<0.002
AB:	<0.08	<0.08	<0.08	AB:	<0.08	<0.08	<0.08
AC:	<0.003	<0.003	<0.003	AC:	<0.003	<0.003	<0.003
AD:	<0.002	<0.002	<0.002	AD:	0.003	<0.002	<0.002

* 95% confidence interval

Big Contact			Little Contact			Mean ± C.I.*
Creek	(mg/l)	(mg/L)	Creek	(mg/L)	(mg/L)	
AG :	<0.01	<0.01	AG :	<0.01	<0.01	0.0601 ± 0.0006
AL :	<0.02	<0.02	AL :	<0.02	<0.02	
AS :	<0.04	<0.04	AS :	<0.04	<0.04	
B :	<0.02	<0.02	B :	<0.02	<0.02	
BA :	0.044	0.044	BA :	0.0604	0.0601	
BE :	<0.0005	<0.0005	BE :	<0.0005	<0.0005	
BI :	<0.04	<0.04	BI :	<0.04	<0.04	
CA :	32.1	31.5	CA :	50.2	48.9	
CD :	<0.002	<0.002	CD :	<0.002	<0.002	
CO :	<0.01	<0.01	CO :	<0.01	<0.01	
CR :	<0.01	<0.01	CR :	<0.01	<0.01	
CU :	<0.003	<0.003	CU :	<0.003	<0.003	
FE :	0.010	0.017	FE :	0.006	<0.005	8.59 ± 0.15
K :	<0.5	<0.5	K :	<0.5	<0.5	
W :	<0.01	<0.01	W :	<0.01	<0.01	
LI :	<0.002	<0.002	LI :	<0.002	0.003	
MG :	5.10	5.00	MG :	8.66	8.56	
MN :	<0.002	<0.002	MN :	<0.002	<0.002	
MO :	<0.005	<0.005	MO :	<0.005	<0.005	
NA :	0.51	0.50	NA :	0.87	0.86	
NI :	<0.01	<0.01	NI :	<0.01	<0.01	
P :	<0.09	<0.09	P :	<0.09	<0.09	
PB :	<0.04	<0.04	PB :	<0.04	<0.04	
SB :	<0.04	<0.04	SB :	<0.04	<0.04	
SE :	<0.04	<0.04	SE :	<0.04	<0.04	
SI :	0.64	0.83	SI :	0.60	0.60	
SN :	<0.04	<0.04	SN :	<0.04	<0.04	
SR :	0.045	0.044	SR :	0.0727	0.0722	0.0723 ± 0.0010
TI :	<0.002	<0.002	TI :	<0.002	<0.002	
TL :	<0.08	<0.08	TL :	<0.08	<0.08	
V :	<0.003	<0.003	V :	<0.003	<0.003	
ZN :	<0.002	<0.002	ZN :	<0.002	<0.002	

• 95% confidence interval

Appendix F. Monitoring Plan

by Patty Rost, Nancy Deschu, and Jacqueline D. LaPerriere.

LAKE MONITORING PLAN

GATES OF THE ARCTIC NATIONAL PARK AND PRESERVE

Gates of the Arctic National Park and Preserve (GAAR) encompasses approximately 8.4 million acres of public land in Alaska. These lands hold uncounted lakes that are isolated from the more common effects of habitat fragmentation, exotic species invasion, urban sprawl, and nearby industrial pollution seen in the other 49 states. The large park and its relative isolation, however, have not left the lakes in the park immune from environmental threats. Climate changes, circumpolar pollutant transport, and nearly 257,000 acres of private lands within the park pose subtle threats that could affect GAAR lakes in the future.

Baseline water quality information in GAAR was collected in 16 lakes through research between 1992 to 1995. Baseline information on GAAR lakes is useful in making sound park resource management decisions. Long-term monitoring of these lakes will provide springboards for further scientific research and alert park management to changes in the resources. Monitoring waters that have not yet degraded can provide the National Park Service and the scientific community with data relating to pristine arctic waters and alert park staff to possible changes in water quality.

This monitoring plan will serve to establish a schedule and sampling scheme to observe changes in lake water quality in future years. This plan will provide park management a means to become ready to protect the water quality of lakes within GAAR. The level of monitoring proposed through this plan assumes that current visitor and local resident activities will remain fairly constant over the next 10 years. It is also assumed that development will not occur within park boundaries and will occur at a minimal level adjacent to the park. As new development activities are proposed near or within the park, individual project-specific monitoring plans will be developed separate from this plan.

MANAGEMENT ISSUES and CONCERNS

Existing or eminent threats to lake water quality within GAAR are minimal at this time. Issues that could arise to change the water quality are as follows:

Increased Visitation: As visitation increases in GAAR, it is expected there will be increased floatplane and boat use on some of the lakes in the park, along with increased camping on the shores of these lakes. Although these activities do not pose major pollution

sources, small cumulative effects from fuel leakage, gray water and human waste from campsites, and riparian vegetation trampling by campers resulting in erosion are of concern.

Associated Lakes—Chandler, Itkillik, Summit, Matcharak, Takahula, Walker, Pingo, and Tulilik

Private Land Development: Development on private land and the potential increase of established commercial operations within GAAR raises concerns regarding changes in water quality, particularly on small lakes. Land clearing, sanitation systems, fuel transport and storage, domestic wastewater discharge, and development of access roads or trails, and non-point runoff from disturbed areas could cause localized changes in water quality.

Associated Lakes—Chandler, Agiak, Amiloyak, and Walker

Road/Trail Development and Increased Road Use: A road is proposed that would cut across the southwest area of GAAR along the upper Kobuk River to access mining districts. This road would open areas of the park that have to date been only accessible by floatplane. This new access may generate increased awareness of Selby, Narvak, Nutuvukti, and Walker lakes in the upper Kobuk drainage. Increased public use of the TransAlaska Pipeline Haul Road along the east side of the park would bring about a greater awareness of the Itkillik Lake area, and perhaps increased floatplane and hiking access to the lake, which is only 20 miles from the road.

Associated Lakes—Walker, Nutuvukti, Selby, Narvak, and Itkillik

Oil and Gas Development: There are existing oil and gas tracts in the Itkillik Lake area as well as on the northern boundary of the park. Itkillik Lake and surrounding tributaries and wetlands water quality could be affected by runoff from an operation in the area. Road construction to and around an oil drilling operation would also be a potential source of pollutants.

Associated Lakes—Killik, Chandler, Amiloyak, Itkillik and Kurupa

Climate Change: Changes in climate over time could affect arctic lakes in several ways: change in the amount of annual precipitation; the ratio of precipitation falling as rain and snow; change in snow pack depth; change in timing of spring melt-off; change in melting rate of permanent snowfields. These changes in hydrologic conditions could affect lake-water quality through increased scavenging of airborne particulate, dilution of the lake

water, and increased watershed input (such as nutrients and sediment) from increased run-off. This information is important to understanding how a pristine ecosystem changes over time.

Associated Lakes—Any with current baseline data

Circumpolar Pollution: There is concern in arctic Alaska for the effects of circumpolar pollution and airborne deposition on water quality. Metals generated by smelting, pesticide application, refining, and auto exhaust (such as arsenic, lead, and mercury) are potential pollutants. In addition, precipitation may carry industrial-produced acidity, as reflected in sulfate measurements. This information is important to understanding possible effects related to human consumptive use of aquatic resources.

Associated Lakes—Chandler, Kurupa, Itkillik, and Walker

MONITORING PROTOCOL and SCHEDULE

Currently, development in and around the park consists of activities within the Alyeska Pipeline corridor along the Dalton Highway; growth within the community of the Anaktuvuk Pass; and development of access routes to private inholding activities. The following schedule and sampling protocol will allow for each lake surveyed through the initial synoptic survey to be revisited every 3 years. It also allows for a repeat of the full synoptic survey described in this report (LaPerriere 1999) every 5-10 years. Duplication of the synoptic survey will be dependent on the level of funding available from park base operating funds or the ability to receive special project funding.

This lake monitoring plan acknowledges that the park will not have a water quality technical specialist on staff. Annual monitoring efforts are planned to be accomplishable by a general science technician employed by the park. The major duplication of the synoptic survey will require contracting or hiring a technical expert to collect and analyze the data.

Annual Cycle

The initial synoptic survey, conducted between 1992 and 1995, focused on 15 lakes split between the north side and the south side of the Brooks Range in the park. The monitoring plan will allow for 5 lakes to be monitored annually making it possible to cover all of the initial baseline lakes over a 3-year period. The following table shows a proposed schedule

Lake Monitoring Schedule

Survey Lake	Monitoring Year										
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Chandler											
Selby											
Kipmik											
Takahula											
Tulikik											
Amiloyak											
Matcharak											
Nutuvukti											
Summit											
Walker											
Kurupa											
Pingo											
Narvak											
Itkillik											
Agiak											

for ensuring coverage of all the original 15 synoptic lakes with representative north/south lakes annually. Walker and Itkillik lakes should be monitored annually to provide year-to-year comparison of north and south lakes.

Monitoring should occur twice during the ice-free season. Allow sufficient time after spring breakup before initiating data collection to allow for settling of sediments washed in with snowmelt. Mid-July through mid-September appears to be the optimum sampling period to develop a representative summertime database. Sampling should occur at one site in the middle of each lake. The park's YSI meter should be used to collect temperature, pH, conductivity, and dissolved oxygen at meter depths of 1, 2, 3, 4, 5, 10, 15, 20, 25, 35, 45, 55, etc., down to the bottom (or as far as cable will allow). Integrated water samples should be collected for turbidity and color measurements. Three separate samples should be collected at twice the Secchi depth for turbidity and color analysis using Tygon tubing. The following parameters should be collected annually:

- Secchi disk – use 50-cm size observed through a viewing scope at water surface to compensate for reflecting light at the surface. Cable should be non-stretching material such as wire cable or polypropylene cord and be calibrated and marked at 0.25-meter intervals. Record depth at which Secchi disk visibility disappears.
- Color – utilize a Hach portable spectrophotometer. Three integrated water samples should be collected at each lake for analysis. Take color measurements down to twice the Secchi depth.
- Turbidity – use a Hach turbidity meter to analyze water samples. Three integrated water samples should be collected to twice the Secchi depth.
- Conductivity – utilize the YSI meter to take conductivity readings from top to bottom following the intervals mentioned above.
- Temperature – utilize the YSI meter to take readings from top to bottom following the intervals mentioned above.
- Chlorophyll – collect three integrated water samples down to twice the Secchi depth.
- MEI – calculate MEI from conductivity data for each lake.

Five- to 10-Year Cycle

Every 5-10 years, a full synoptic survey should be repeated for those lakes that were sampled between 1992 and 1995. Protocols established during LaPerriere's initial synoptic study should be followed to allow for data comparison between years. This level of monitoring cannot be accomplished with general biological expertise. To accurately

collect this advanced level of information the park will need to contract or hire a water quality expert. Parameters include:

Temperature	Chloride	Secchi depth
pH	Total Chlorophyll	Light penetration (photometer)
Dissolved Oxygen	Total Phosphorous	Turbidity
Conductivity	Total Nitrogen	Alkalinity
Sulfate	Trace Metals (including major positive ions)	
MEI (calculated)	Zooplankton (taxonomy/standing crop)	
Color		

DATABASE DESIGN

Data should be input into a Geographic Information System (GIS) interface. The NPS standard is currently Access 2.0. The database should be established prior to field data collection efforts. Field data form should be developed around the database to allow for ease of data entry after field collection. A database should be established that has the following fields:

- ❖ GPS location of sampling site, site number
- ❖ Date, time, lake name
- ❖ Weather at time of sampling
 - Cloud cover
 - Wind speed/direction
 - Precipitation
 - Air temperature
 - Surface (lake) disturbance level due to wind
- ❖ Depth of sample
- ❖ Water temperature
- ❖ Other specific on-site water chemistry results
- ❖ Lab results
- ❖ Environmental changes (i.e. natural landslides, fire, permafrost thaw, etc.)
- ❖ Name of person collecting sample
- ❖ Mode of transportation, pilot name/aircraft

Data entry will occur annually after completion of the sampling period.

REPORTING

An annual report should consist of a brief narrative that focuses on the lake sampled, summarizes results of monitoring, and describes level of effort associated with the project. Information relating to methods and equipment utilized in the project should be documented as well. A copy of the raw data will be attached. In years when full parameter monitoring occurs a report should describe the project and the results and provide a discussion of noticeable water quality differences over time. The report should be written in a standard scientific format and be peer reviewed by at least three technical experts. It will then be finalized and distributed to appropriate institutions and park staff.

DEVELOPMENT DRIVEN MONITORING

Monitoring development activities will be crucial in protecting the park's water resources. Specialized monitoring plans will be developed specifically for each activity as park management learns of proposed development. Development activities that have the potential for threatening water quality will be monitored prior to the start of development and periodically throughout the activity. All threatened waters should have a thorough collection of baseline data prior to the start of the development activity. Focused baseline and long-term monitoring will be initiated in association with world-wide catastrophic pollution events or periods of major climatic change. Even though park management will not be able to effect the impacts to park resources, information gained will be important to understanding these global change effects. Baseline data inventory should follow protocols established by LaPerriere (1999). Suggested parameters to focus monitoring efforts during these specific time periods, for a variety of issues, are as follows:

Increased Visitation

Potential Impacts: Road/trail development

Human waste

Fuel storage/transport

Land clearing

Parameters: Sedimentation (TSS)

Turbidity (aerial monitoring for plumes in lakes)

Hydrocarbons (motorized equipment use)

Fecal Coliform bacteria (septic systems)

Secchi depth (nutrient color or sediment increase)

Road Development

Potential Impacts: Erosion

Stream crossings

Dust

Parameters: Sedimentation (TSS)

Turbidity (aerial monitoring for plumes in lakes)

Hydrocarbons (motorized equipment use)

Oil and Gas Development and Mining

Potential Impacts: Water quantity

Erosion

Hydrocarbon contamination

De-watering

Parameters: Sedimentation (TSS)

Turbidity (aerial monitoring for plumes in lakes)

Hydrocarbons (motorized equipment use)

Metals (drilling muds)

pH

Climate Change

Potential Impacts: Temperature increase or decrease

Runoff increase/decrease

Parameters: Water temperature (at various depths)

Air temperature

Climate data

Circumpolar Pollution

Potential Impacts: Metal concentrations above existing background

Parameters: Metals (deposition from air transport in sediments)

Acid neutralizing capacity

Fire

Potential Impacts: Sedimentation from loss of ground cover

Parameters: Siltation in water from erosion
 Chemicals used in fire fighting
 Sedimentation (TSS)
 Turbidity (aerial monitoring for plumes)
 Total Nitrogen and Total Phosphorous

HISTORIC BASELINE DATA—WATER QUALITY

The following information is a summary of the lake and stream water quality studies that have been conducted in GAAR from 1981 to present.

Synoptic survey of 16 lakes within GAAR between 1992-1995. Specific years for synoptic survey baseline data collection from LaPerriere (1999) are shown in the following table.

LAKE	INITIAL BASELINE
Itkillik	1993, 1995
Summit	1993, 1995
Chandler	1992, 1993, 1995
Agiak	1993, 1995
Amiloyak	1992, 1993
Tulilik	1995
Kurupa	1995
Takahula	1992, 1993, 1995
Walker	1992, 1993, 1995
Nutuvukti	1992, 1993
Selby	1993
Narvak	1992, 1993
Pingo	1992
Matcharak	1992, 1993, 1995
Kipmik	1992, 1993, 1995
Minakokosa	1995

The following parameters were recorded for all lakes surveyed: surface area, latitude, watershed area, altitude, and landscape characteristics (vegetation and geology).

Volume, mean depth, and maximum depth were calculated for all lakes, except Tulilik, Pingo, and Summit. These three lakes did not have bathymetric maps completed and the calculation were not possible.

The following water quality parameters were measured during the lake synoptic survey. However, not all parameters were measured at all lakes surveyed.

Temperature	Trace metals	
pH	Zooplankton	Secchi depth
Dissolved Oxygen	Color	Light penetration
Conductivity	Total Chlorophyll	Turbidity
ORP	Total Phosphorous	Alkalinity
MEI	Total Nitrogen	Sulfate
Chloride		

Bathymetry: Lakes surveyed during the synoptic survey have bathymetric maps ***except*** Pingo, Summit, and Tulilik.

Periphyton samples—Selby 1993: included chlorophyll, taxonomy and standing crop.

Nutrient Stimulation experiments

- Selby and Narvak – 1993
- Chandler, Agiak, Itkillik, and Kipmik, Matcharak, and Summit – 1995
- Walker Lake – 1998
- Itkillik Lake – 1989

National Park Service staff collected water quality data in 1991 on Kipmik, Matcharak, Nutuvukti, Selby, Narvak, Takahula, Florence Creek, Chandler, and Amiloyak lakes. The following parameters were measured: pH, dissolved oxygen, temperature, secchi depth, alkalinity, and hardness.

WATER QUALITY BASELINE INVENTORY

Lake and Stream Selection

Following are parameters considered the most important in stratifying the lakes in GAAR in the future for selecting of addition inventory. GIS will be used to assist in identification and selection of lakes from the hundreds that are in the park.

1. Landscape/Vegetation class type (GIS)
2. Geologic underlay (GIS)
3. Watershed size/Lake surface area (GIS)
4. Fish importance/suspected fish importance (NPS records, ADFG surveys and survey charter operators, local fishing guides)
5. Location in drainage (headwaters, midcourse, etc.)

Other parameters to consider in lake selection for future inventory:

- Location – north or south of continental divide
- Orientation – for wind effects
- Elevation
- Surface area
- Volume (if bathymetry is known)
- Depth (if known)
- Trophic state (if known)
- N or P limited (if known)
- Clarity/light penetration (as of 1999)
- MEI if can be calculated

Snow data for existing synoptic lakes or new inventory lakes would be useful in evaluating pollution effects on water quality. At a minimum, snow data should be collected from a lake on both the north and south side of the park. The lakes chosen for snow data collection should be similar in associated watershed size and maximum depth. Snow sample collection could be arranged in cooperation with the Natural Resource Conservation Service to benefit both agencies.

