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LIMNOLOGY OF THE UPPER NORTH PLATTE RESERVOIR SYSTEM, WYOMING

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16. ABSTRACT

The baseline limnology of Seminoe, Kortes, Pathfinder, and Alcova Reservoirs, on the North Platte River in Wyoming, was studied by Bureau limnologists during 1976–79. The study period included 2 years of severe drought followed by two of higher than average runoff in the North Platte basin. The reservoirs differ greatly in volume and operating patterns: Seminoe (1.25×10^9 m^3) is mainly for power production; Kortes (5.88×10^6 m^3) and Alcova (2.27×10^8 m^3), flow regulation; and Pathfinder (1.25×10^9 m^3), for storage. The three major system tributaries, the North Platte, Medicine Bow, and Sweetwater Rivers, differ significantly in chemical composition and annual flow volume. Limnology of the Upper North Platte reservoir system is typical in many ways of the High Plains Region of the Western U.S.; i.e., the reservoir waters are dimictic and alkaline, with salinity averaging 369 mg/L and calcium carbonate hardness averaging 184 mg/L. Also, the bluegreen alga, *Aphanizomenon flos-aquae,* blooms in late summer. Study results showed that this annual bloom depends on a shift from phosphorus-limiting conditions in early summer to more nitrogen-limiting conditions by late summer. The study also indicated that nutrient dynamics, and hence primary production in the system, is heavily influenced by the interaction of three main factors: system operating criteria, annual runoff variations in the three major tributaries, and the presence of deep outlets in all four dams.

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UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

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Partial funding for this study was provided by the Lower Missouri Region of the Bureau of Reclamation. The remainder of the support for the study was provided through the Division of Research's ongoing project, "Limnology for the Ecological Management of Reclamation Projects" (DR-409). Chemical analyses were performed by the Chemistry, Petrography, and Chemical Engineering Section of the Applied Sciences Branch. Soil analyses were done by the Soil Testing Section of the Geotechnical Branch.

Valuable field assistance was rendered by personnel of the Casper Office of the Wyoming Game and Fish Department and by personnel of the Seminoe-Kortes Unit of the Bureau. Without the timely help of these people we would have literally been "up the creek" on several occasions.

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APPLICATION

This report is a limnological characterization of Seminoe, Kortes, Pathfinder, and Alcova Reservoirs, done as part of the LM (Lower Missouri) Region's North Platte River Hydroelectric Study. Information in this report will be used by LM Region planners in evaluating possible environmental effects of various power augmentation alternatives, and in determining areas in need of more detailed investigation.

The limnoligical investigations reported here were also done as part of the Division of Research's ongoing study, "Limnology for the Ecological Management of Reclamation Projects" (DR-409). This report is intended as a contribution toward better understanding of the effects of the operation of multipurpose, multireservoir systems on the aquatic ecology of both the individual reservoirs and the system as a whole. To our knowledge, this is the first comprehensive limnological study of an entire Bureau of Reclamation multireservoir system. Information contained in this report should be of interest to anyone involved in resource management on the Upper North Platte reservoir system, in particular, or on multireservoir systems in general.

SUMMARY OF FINDINGS

1. All four Upper North Platte reservoirs may be characterized as alkaline, hard, and somewhat saline bodies of water. Measured hydrogen ion concentrations (pH) were always greater than 7.0, mean calcium carbonate hardness was about 184 mg/L, mean TDS (total dissolved solids) approximately 318 mg/L, mean salinity (sum of anions and cations) about 369 mg/L, and conductivity readings ranged from 240 to 577 μS/cm. The major cations in the system are calcium, sodium, and magnesium, while bicarbonate and sulfate are the major anions.

2. Salinity and TDS were found to be highly correlated ($r = 0.98$) throughout the system. Mass balances of these two parameters, calculated on a mean annual basis, indicated the disproportionate influence of the Medicine Bow River on Seminoe Reservoir. The Medicine Bow accounts for approximately 40 percent of the annual salinity input to Seminoe Reservoir, while contributing only about 15 percent of the annual water inflow. The North Platte, on the other hand, contributes approximately 85 percent of the annual reservoir water inflow and only about 60 percent of the salinity.

3. Summer temperature stratification in the Upper North Platte reservoirs is relatively weak and brief, mainly because the deep outlets rapidly drain off the cool hypolimnetic water. All four reservoirs are dimictic, with isothermal conditions in both spring and fall and ice covers in the winter. Maximum observed summer water temperatures ranged from about 17 to 20 °C at the surface, and 14 to 18 °C at the bottom.

4. Light penetration in the North Platte and Medicine Bow arms of Seminoe Reservoir is greatly reduced by the turbidity of the runoff in early summer. The water clears by midsummer, but a turbid underflow apparently passes through the reservoir, causing reduced light availability in Kortes Reservoir and the "Miracle Mile" in the late summer and fall. There is also evidence of similar density flows of suspended sediments in Pathfinder Reservoir.

5. Bottom dissolved oxygen concentrations reach their minimum at the deepwater reservoir stations by late August; however, the brevity of summer thermal stratification seems to prevent the development of any serious anaerobic, reducing conditions. Minimum observed bottom dissolved oxygen concentrations ranged from 0.2 mg/L in Seminoe to 4.0 mg/L in Kortes.

6. Heavy metals (i.e., iron, manganese, zinc, copper, and lead) do not appear to constitute a biologic hazard in the system, although total concentrations of iron often, and manganese sometimes, exceed EPA (Environmental Protection Agency) quality criteria for domestic water supplies.

7. The percent organic content and the concentration of heavy metals in the bottom sediments of the reservoirs are strongly, positively correlated with the percentage of clay-sized fines (< 5 μm).

8. The benthos of the system shows some difference in composition from upstream to downstream: chironomids predominate in Seminoe Reservoir, while oligochaetes are the major benthic organisms in Alcova Reservoir. Mean depth appears to be the determining factor here, with chironomids making up the larger percentage of the benthos at shallower stations and oligochaetes predominating at deeper stations. No

significant correlation of either taxon with substrate particle size or sediment organic content was found.

9. Supplies of nitrogen and phosphorus in the system are closely related to the volume of annual runoff in the major tributaries. During the dry year (1977), phosphorus was present in detectable concentrations throughout the summer, and seemed to build up in the North Platte arm of Pathfinder. This accumulation of phosphorus contributed to an unusually large production of chlorophyll *a* in Pathfinder Reservoir. During the high-runoff years (1978 and 1979), on the other hand, phosphorus was detected in the reservoirs only in the later summer, and the production of chlorophyll *a* was more evenly distributed throughout the system. In all three summers, however, the presence of detectable amounts of phosphorus seemed to shift the nitrogen-to-phosphorus ratio enough toward relatively nitrogen-limiting conditions to favor a late summer bluegreen algae bloom.

10. In early summer, diatoms are the major component of the phytoplankton in all four reservoirs. By late summer, the bluegreen alga, *Aphanizomenon flos-aquae,* becomes dominant. Zooplankton populations in early summer are dominated by cladocerans and copepods. In late summer, with the onset of the bluegreen algae bloom, these populations decline and rotifiers become an important component of the zooplankton.

11. The trophic state of the Upper North Platte reservoir system ranges from moderately eutrophic, in the river arms of Seminoe and Pathfinder Reservoirs, to mesotrophic, in the deepwater areas of all four reservoirs. The high production of epilithic algae and benthic organisms in the Miracle Mile of the North Platte River seems directly attributable to the deep discharges from Seminoe and Kortes Dams, which supply nutrients and ensure a relatively constant physical environment. This instream production, in turn, appears to provide a food base for trout moving into the Miracle Mile from the North Platte arm of Pathfinder Reservoir.

RECOMMENDATIONS FOR FUTURE STUDY

The present investigations were in support of a systemwide planning study of various hydroelectric power augmentation alternatives (the North Platte River Hydroelectric Study), and was, therefore, rather broad in scope. While this report provides a general overview of the limnology of the entire Upper North Platte reservoir system, more detailed, site-specific studies would be advisable to accompany advanced planning of any given alternative.

Of major importance would be the acquisition of a data base that is more extensive in both temporal and spatial coverage of the particular reservoir affected by the proposed alternative. Specific recommendations to achieve this coverage are:

- Permanent survey stations should be established in each major basin and arm of the reservoir. The present study used only one station in each major tributary arm and one station in the deep water near the dam in any given reservoir (fig. 7). Ideal coverage would require additional stations in the intermediate basins and, perhaps, stations in the upper and lower reaches of the major tributary arms.

- Benthos and sediment sampling should be done on transects, both laterally, at each survey station, and longitudinally, from station to station.

- Sampling should be year-round, including both the ice-free and ice-cover periods.

Depending on available resources and initial survey results, the sampling program could be modified to encompass fewer stations and longer intervals between surveys. As a minimum, however, the affected basin, or basins, should be surveyed in particular detail (i.e., transects, etc.); the reservoir stations established during the present study also should be surveyed to maintain continuity of the baseline data record; and surveys should be performed on a monthly basis for at least 1 year.

To properly evaluate potential environmental impacts, three aspects of reservoir ecology deserve special emphasis during any advanced study. These are:

- The N-P (nitrogen-phosphorus) nutrient budget of the reservoir and its relation to annual primary production.

- Movement of suspended sediments through the reservoir and sediment depositional patterns in the affected basin or basins.

- Population estimates and annual life cycles for plankton, benthos, and fish.

Sediment depositional patterns should be mapped by the Bureau's Sedimentation Section, while fish population estimates and life-cycle studies would have to be developed in cooperation with the Wyoming Department of Game and Fish.

INTRODUCTION

Description of Study

From August 1976 through October 1979, personnel of the Division of Research, E&R (Engineering and Research) Center of the USBR (Bureau of Reclamation) carried out summer limnological surveys on the four uppermost reservoirs on the North Platte River in southeastern Wyoming. The purpose of these surveys was to obtain basic limnological data for the North Platte River Hydroelectric Study, a planning study of different ways of increasing the hydroelectric power production of the Upper North Platte reservoir system.

Preliminary findings of the summer surveys have been reported in two GR (General Research) Reports [1, 2][1] and two Applied Sciences referral memorandums [3, 4]. This is the completion report on the entire limnological study.

Because this was a general study and because surveys were limited to the summer season (i.e., May through October), the results reported here should be considered somewhat preliminary. More detailed and site-specific investigations should be done if and when any of the various power augmentation alternatives are selected for advanced planning.

After the first summer, additional support for the Upper North Platte reservoir system limnological study was provided by the Division of Research's ongoing project, "Limnology for the Ecological Management of Reclamation Projects" (DR-409). This additional funding made possible a more detailed investigation of nutrient dynamics, especially in the Seminoe-Kortes—Miracle Mile section of the system. Results of this particular part of the study are an important contribution toward understanding the effects of USBR reservoir operations on the productivity of tailwater fisheries.

Description of Reservoirs

The North Platte River rises in north-central Colorado, flows through southeast Wyoming, and joins the South Platte River to form the Platte in west-central Nebraska. The four uppermost reservoirs on the North Platte River are all located in Wyoming and from upstream to downstream, they are: Seminoe, Kortes, Pathfinder, and Alcova (fig. 1). Table 1 provides a summary description of these four impoundments, their major tributaries, and functions.

Seminoe Reservoir (fig. 2), located at the confluence of the North Platte and Medicine Bow Rivers, is the first impoundment on the Upper North Platte. Immediately below Seminoe Dam is Kortes Reservoir (fig. 3), a small reregulating impoundment for power releases from Seminoe.

After its release from Kortes Dam, the North Platte River flows freely for a distance of about 6.4 km before entering Pathfinder Reservoir. This free-flowing stretch of river (fig. 4) is a "blue-ribbon" brown trout fishery, locally known as the "Miracle Mile" [5, 6].

Pathfinder Reservoir (fig. 5) receives its inflows from the Miracle Mile and the Sweetwater River. Normally, all releases from Pathfinder Reservoir are routed through a pressure tunnel to Fremont Canyon Powerplant on the upper end of Alcova Reservoir. Only in high-flow years, or when irrigation demands exceed the capacity of the tunnel-turbine complex, does water flow in the 6.4 km historic river channel between Pathfinder Dam and Alcova Reservoir [7, 8].

Alcova Reservoir (fig. 6) is operating primarily to deliver irrigation water to the Kendrick Project via the Casper Canal. The present study of the limnology of the Upper North Platte reservoir system ended with Alcova.

Description of Area

The land surrounding the four Upper North Platte reservoirs lies at elevations ranging from 2727 meters above mean sea level, on Bradley Peak in the Seminoe Mountains west of Seminoe Dam, to 1618 meters, at the town of Alcova on the

[1] Numbers in brackets indicate references listed in the Bibliography.

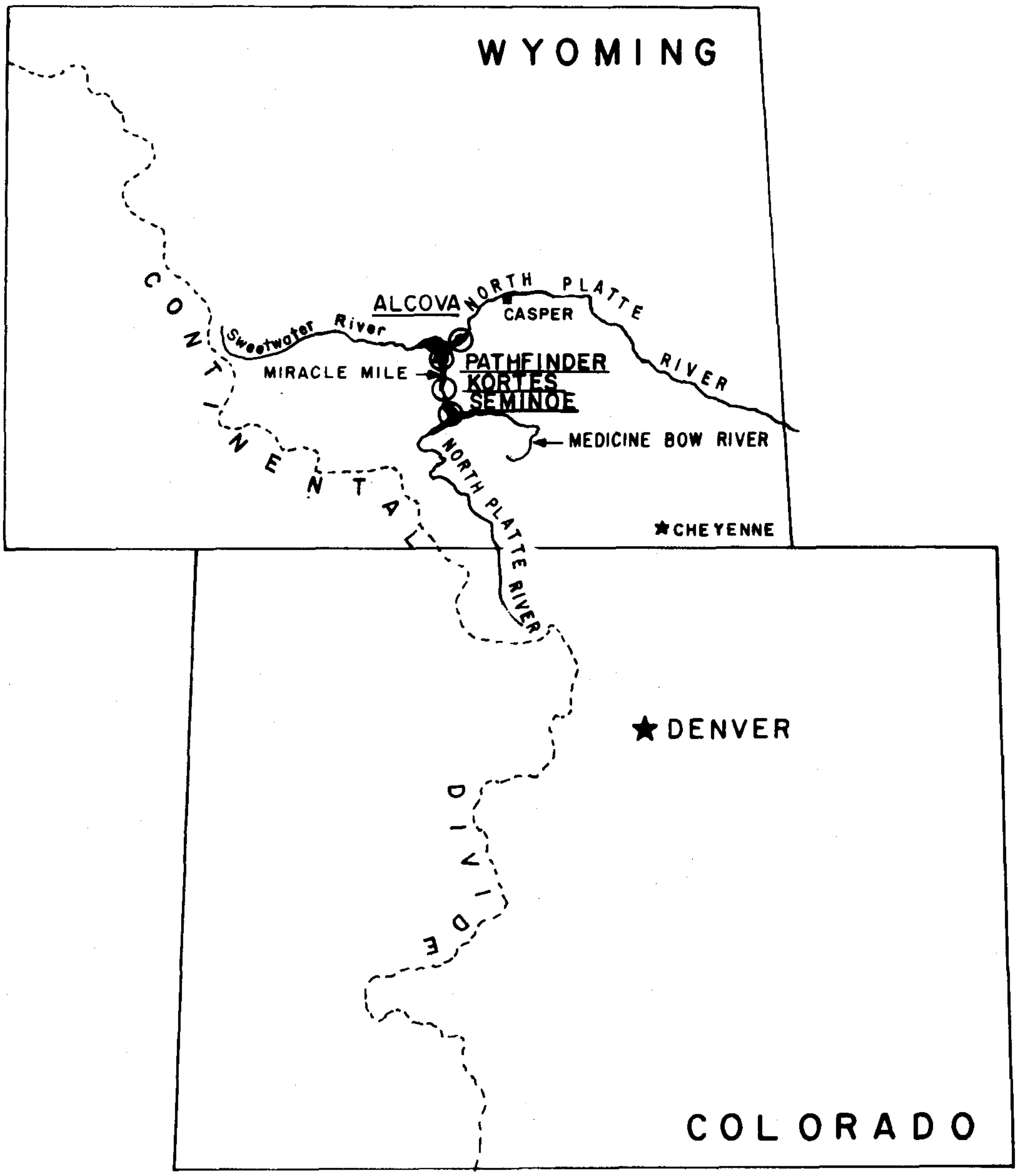

Figure 1.—Map of Wyoming and Colorado showing the location of the Upper North Platte reservoir system.

Figure 2.—Seminoe Reservoir. P801-D-79642.

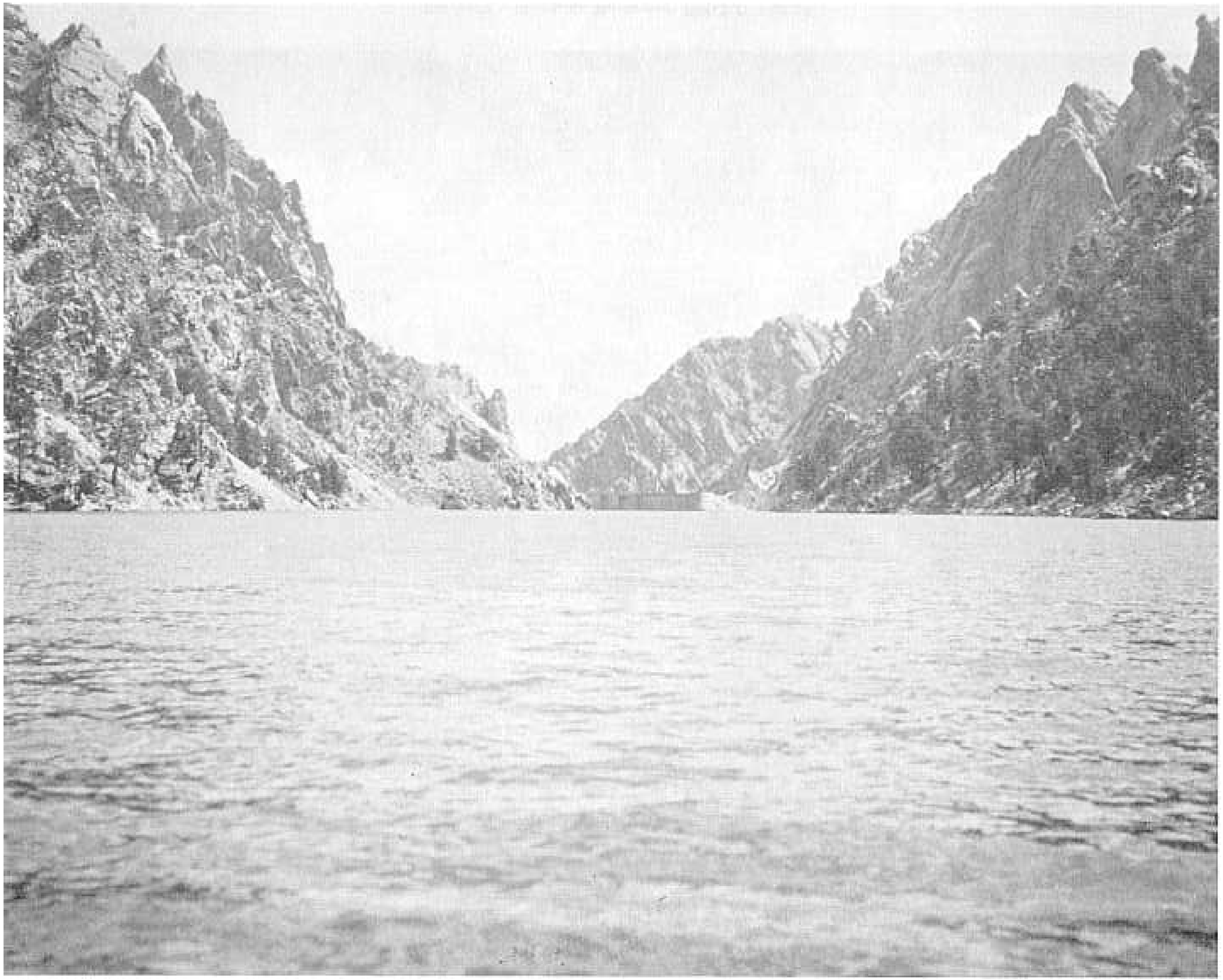

Figure 3.—Kortes Reservoir. P801-D-79643.

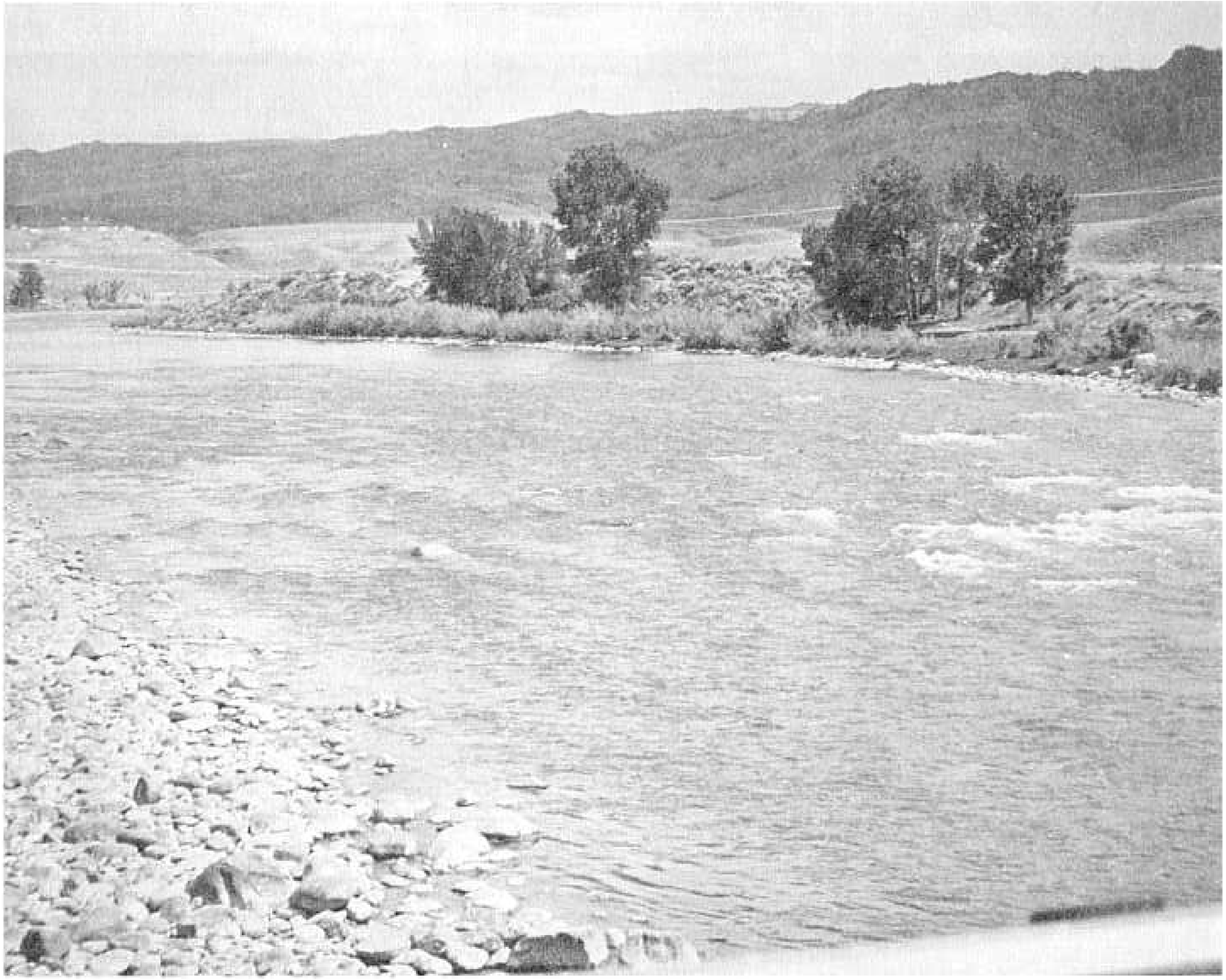

Figure 4. 'Miracle Mile.'' P801-D-79644.

Figure 5. ·Pathfinder Reservoir. P801-D-79645.

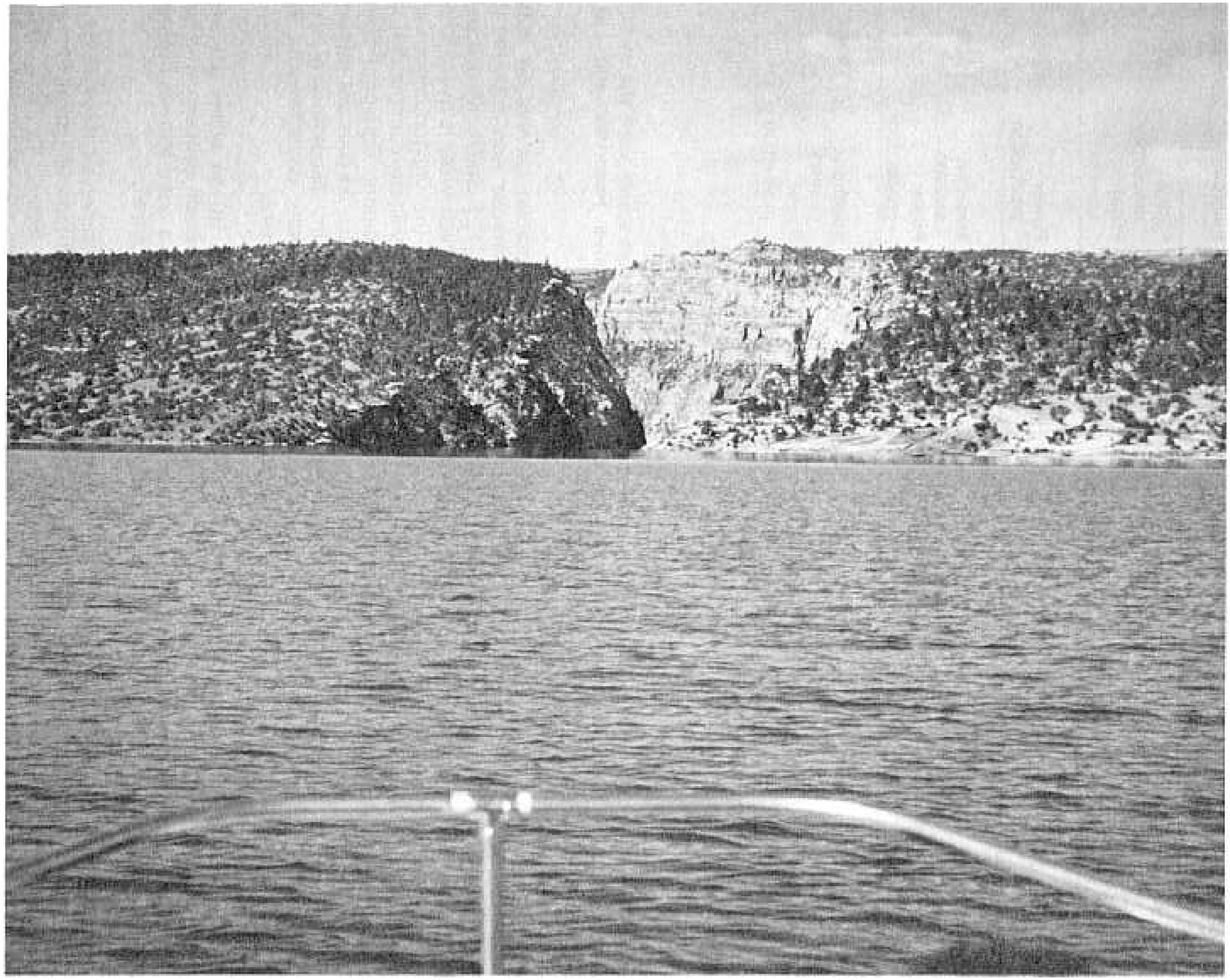

Figure Alcova Reservoir. P80 I-D-

Table 1.—*General description of Upper North Platte reservoirs, Wyoming*

Reservoir	Maximum surface elevation (m)	Maximum surface area (ha)	Maximum volume (m^3)	Mean depth at maximum elevation (m)	Major tributaries	Major functions	Date completed
Seminoe	1937.6	8211.7	1.255×10^9	15.3	North Platte River (85%)[1] Medicine Bow River (15%)[1]	1. Power production 2. Irrigation storage	1939
Kortes	1872.1	33.6	5.878×10^6	17.5	North Platte River	1. Power production	1951
Pathfinder	1783.1	8908.1	1.253×10^9	14.1	North Platte River (90%)[1] Sweetwater River (10%)[1]	1. Irrigation storage 2. Power production[2]	1909
Alcova	1676.4	1000.0	2.274×10^8	22.7	North Platte River	1. Irrigation delivery 2. Power production	1938

[1] Based on USGS long-term average annual flows.
[2] Through Fremont Canyon Powerplant, completed 1961.

North Platte River just below Alcova Dam. Average annual precipitation in the area ranges from about 281 mm at Casper to 265 mm at Rawlins [9]. Mean annual windspeed at Casper is 20.9 km/h [10].

As may be seen on figures 2 through 6, the terrestrial environment is generally arid, windy, sagebrush steppe with scattered ranges of rugged mountains. The dams impounding the four reservoirs were built in steep, river-cut canyons.

Previous Studies

In 1950, the Bureau of Reclamation asked the Public Health Service to do an extensive investigation of the nature, extent, and sources of water pollution in the North Platte River Basin and to make recommendations for improving the situation. The final report [11], issued in 1951, concluded that the river above Casper was "a picture of cleanliness," although the towns of Rawlins, Sinclair, and Medicine Bow were all found to be in need of "adequate sewage treatment" for the wastewater being released to the river via tributaries. An appendix to the report entitled "Limnological Studies of the North Platte River" [11] is concerned solely with the stretch of river between Alcova Reservoir and Lake McConaughy, Nebr.

The results of sedimentation surveys on Pathfinder and Seminoe Reservoirs were reported by Seavy and Illk in 1953 [12]. Sedimentation patterns in Pathfinder Reservoir were reinvestigated in October 1958 when the impoundment was completely drained to facilitate construction of the power tunnel to Fremont Canyon Powerplant [13]. Data from these surveys are referred to later in this report, in the discussions of sediments and possible turbidity underflows in the Upper North Platte reservoirs.

A 1967 report by Clark [9] on water use patterns in the North Platte Basin contains little limnological data, although a good general description of the basin itself is given.

Seminoe Reservoir was surveyed three times in 1975 by EPA's National Eutrophication Survey. The final report [14], issued in 1977, concluded that the reservoir was eutrophic in the North Platte and Medicine Bow arms, moderately eutrophic in the upper basin, and mesotrophic at the two stations nearest the dam. The limiting nutrient was determined to be phosphorus in May and October, and nitrogen in August. It was believed that light might also be a limiting factor during times of high turbidity. A year of monthly tributary sampling indicated that the North Platte River contributed 60.7 percent of the annual phosphorus loading and 62.8 percent of the annual nitrogen loading, while the Medicine Bow River contributed 23.0 percent of the annual phosphorus input and 17.8 percent of the annual nitrogen input.

The fisheries of the four Upper North Platte reservoirs and the Miracle Mile were briefly described by McKnight in 1978 [7] and 1977 [5], respectively. In general, Seminoe Reservoir's game fishery is dominated by stocked rainbow trout and introduced, but self-sustaining, walleye. Because of its difficult access, Kortes Reservoir is not stocked and the trout and walleye populations were probably introduced by spills from Seminoe Reservoir. Cutthroat as well as rainbow trout are stocked in Pathfinder Reservoir, which also hosts self-sustaining populations of walleye and brown trout. In fact, it is partly the fall spawning runs of brown trout from the North Platte arm of Pathfinder Reservoir that makes the Miracle Mile such a popular fishery. A 1976 study and comparison of five Wyoming blue-ribbon trout streams showed the Miracle Mile to be first in all categories considered, including: anglers per mile, average trout length, average trout weight, and trout catch rate per hour [5]. Alcova Reservoir has a stocked trout fishery, but no documented walleye population as of 1978 [7].

In 1978, Rinehart and Kerr [15] reported on their efforts to model the water quality of the Upper North Platte River. They concluded that TDS was "the only pertinent modelable water quality parameter applicable to the Upper North Platte River in Wyoming."

The USGS (U.S. Geological Survey) reports [16] some water quality data from the following seven sites included in the present study:

- North Platte River above Seminoe Reservoir – since WY (water year) 1961
- Medicine Bow River above Seminoe Reservoir – since WY 1965
- Seminoe Reservoir (three stations) – since WY 1972
- North Platte River above Pathfinder Reservoir – since WY 1969
- Sweetwater River near Alcova (i.e., above Pathfinder Reservoir) – since WY 1965
- Pathfinder Reservoir (two stations) – since WY 1972
- North Platte River at Alcova (i.e., below Alcova Dam) – since WY 1966

Data from these USGS reports have been used in the present study to fill gaps and to provide long-term comparisons for some parameters.

METHODS AND MATERIALS

General

Figure 7 is a schematic map of the Upper North Platte reservoir system, showing the locations of the main stream and reservoir sampling stations used in this study. Table 2 gives a complete listing of all stations established during the study and the dates on which they were sampled. These tables also provide a good outline of survey strategies during the 4-year limnological study.

After a single reconnaissance survey of Seminoe Reservoir in August 1976, the Lower Missouri Region's Division of Planning requested that the limnological study be expanded to cover all four Upper North Platte reservoirs and be continued for the next three summers. In 1977, the study approach was to survey all four reservoirs twice: once in June, at the beginning of the summer season, and again at the end of August, when summer productivity could be expected to be at or near its peak. This same approach was followed in 1978, with the addition of three extra surveys on Seminoe and Kortes Reservoirs and two on Alcova Reservoir. These surveys were added to obtain more data on the limnological relationship between Seminoe and Kortes Reservoirs and the Miracle Mile, and to elucidate the effect of flushing on the productivity of Alcova Reservoir. By 1979, it was decided that more data were needed at two critical times of the year: at the onset of the main spring runoff and at the end of the irrigation season; consequently, the entire system was surveyed in May, August, and October of that year.

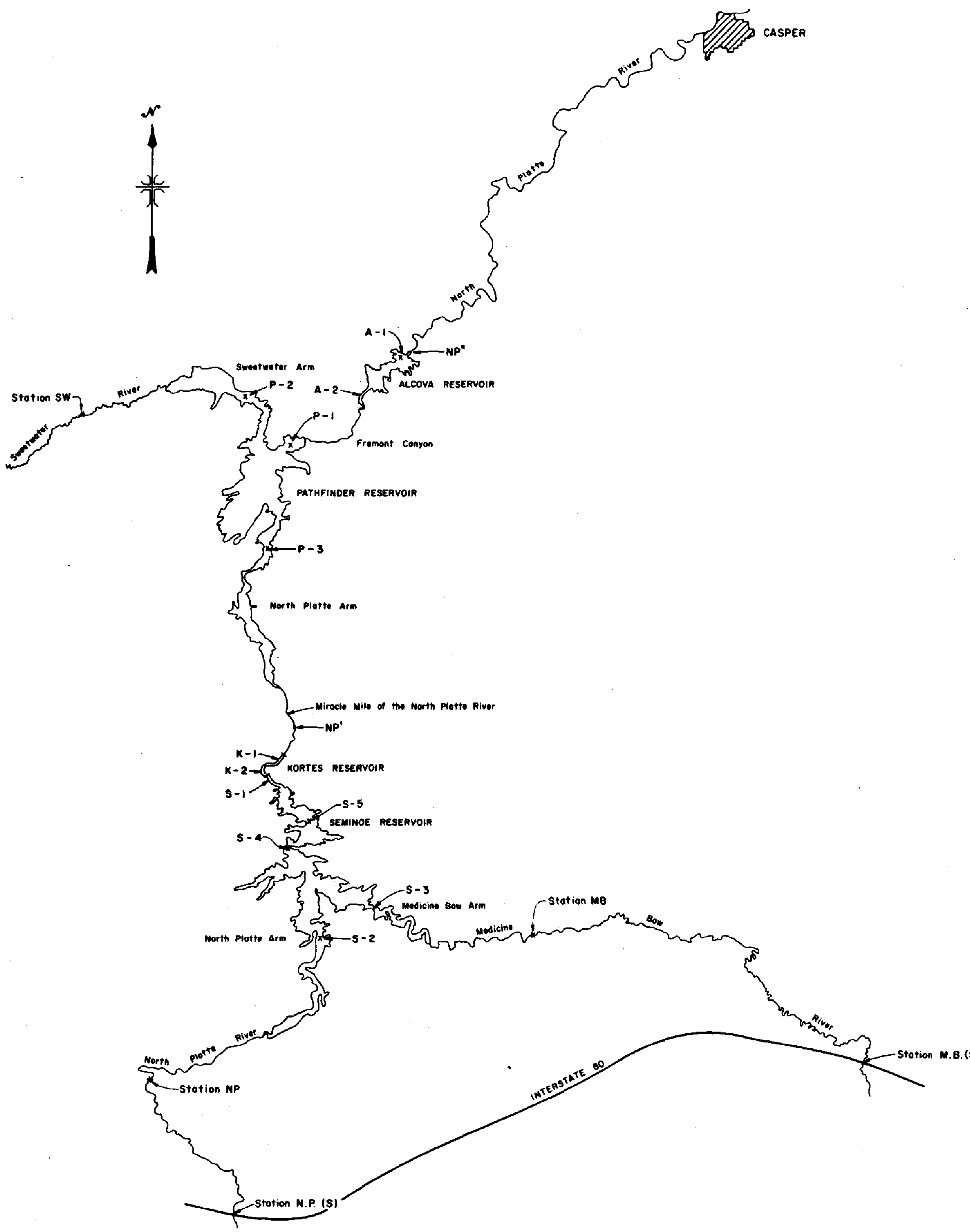

Figure 7.—Map of Upper North Platte reservoir system showing sampling locations.

Table 2.—*Sampling dates*

Station symbol	Station location	Dates sampled 1976	1977	1978	1979
	Seminoe Reservoir stations				
NP(S)	North Platte at I-80	Sept. 3	June 9 June 24 Sept. 2	June 2 June 14 July 19 Aug. 30 Sept. 29	
NP	North Platte at USGS gage above Seminoe			June 1 June 14 July 19 Aug. 30 Sept. 28	May 23 Aug. 29 Oct. 24
MB(S)	Medicine Bow at I-80	Sept. 3	June 9 June 24 Sept. 2	June 2 June 14 July 19 Aug. 30 Sept. 29	
MB	Medicine Bow at USGS gage above Seminoe			June 2 June 14 July 19 Aug. 30 Sept. 29	May 25 Aug. 28 Oct. 24
	Dry Creek at Carbon County Hwy 291			June 2 June 14 July 19 Aug. 30	
	Austin Creek at Carbon County Hwy 291			June 2 June 14 June 19 Aug. 30	
	Saylor Creek at Carbon County Hwy 291			June 2 June 14 July 19 Aug. 30	
S-1	Lower end of Seminoe in canyon leading to dam	Aug. 31	June 22 Sept. 1	May 31 June 15 July 20 Aug. 31 Sept. 28	May 24 Aug. 30 Oct. 25
S-2	North Platte arm of Seminoe	Aug. 31	June 23 Sept. 1	June 15 July 20 Aug. 31 Sept. 28	May 24 Aug. 30 Oct. 25

Table 2.—*Sampling dates*—Continued

Station symbol	Station location	Dates sampled 1976	1977	1978	1979
S-3	Medicine Bow arm of Seminoe	Sept. 1	June 23 Sept. 1	June 15 July 20 Aug. 31 Sept. 28	May 24 Aug. 30 Oct. 25
S-4	Boat Club Basin of Seminoe near large sand dune	Sept. 1	June 22		
S-5	Lower basin of Seminoe just down reservoir from Saylor Creek	Sept. 2			
	Kortes Reservoir stations				
K-2	Inflow to Kortes from Seminoe Dam		June 9 June 23 Aug. 31	June 1 June 14 July 19 Aug. 30 Sept. 27	May 23 Aug. 29 Oct. 24
K-1	Kortes Reservoir near dam		June 9 Aug. 31	June 1 June 14 July 19 Aug. 30 Sept. 27	May 23 Aug. 29 Oct. 24
	Pathfinder Reservoir stations				
	Lost Creek at Carbon County Hwy 291			June 14 July 19 Aug. 30	
NP′	North Platte at Miracle Mile Bridge		June 9 Aug. 31	June 1 June 14 July 19 Aug. 30 Sept. 27	May 23 Aug. 28 Oct. 24
SW	Sweetwater River at State Hwy 220			June 12 Aug. 28	May 23 Aug. 28 Oct. 24
P-1	Pathfinder Reservoir near dam		June 7 Aug. 30	June 12 Aug. 28	May 22 Aug. 28 Oct. 23
P-2	Sweetwater arm of Pathfinder		June 8 Aug. 30	June 12 Aug. 28	May 22 Aug. 28 Oct. 23
P-3	North Platte arm of Pathfinder		June 7 Aug. 30	June 12 Aug. 28	May 22 Aug. 28
	Alcova Reservoir stations				
A-1	Alcova Reservoir near dam		June 6 Aug. 29	June 13 July 18 Aug. 29 Sept. 26	May 21 Aug. 27 Oct. 22

Table 2.—*Sampling dates*—Continued

Station symbol	Station location	Dates sampled 1976	1977	1978	1979
A-2	Upper end of Alcova in Fremont Canyon		June 6 Aug. 29	June 13 July 18 Aug. 29 Sept. 26	May 21 Aug. 27 Oct. 22
NP''	North Platte below Alcova Dam		June 6 Aug. 31	June 14 July 19 Aug. 30 Sept. 27	May 23 Aug. 28 Oct. 24

Physical/Chemical

The following physical/chemical survey was routinely performed at each reservoir station throughout the period of this study.

1. Depth profiles of water temperature, dissolved oxygen concentration, conductivity, hydrogen ion concentration, and redox (oxidation-reduction) potential were obtained by taking readings with a Hydrolab water quality probe at 2-meter depth intervals from surface to bottom.

2. Light penetration was measured with both a Secchi disk and a limnophotometer.

3. Water samples for laboratory chemical analyses were collected with a Van Dorn water sampler, generally from the 1-m, bottom, and middepth levels of the water column. Analyses included:

   a. Major anions and cations

   b. Five heavy metals: iron, manganese, zinc, copper, and lead

   c. Nitrogen and phosphorus nutrients

   Heavy metals samples were spiked immediately after collection with about 1 mL of concentrated nitric acid per 250-mL sample to fix the sample by keeping the metal salts in solution. Samples for N-P nutrient analysis were preserved by freezing.

Chemical analysis of water samples were carried out according to the National Handbook of Recommended Methods for Water-Data Acquisition [17] by the Bureau's Chemistry Laboratory at the E&R Center in Denver, Colo. Detection limits for the heavy metals and N-P nutrient analyses, as of October 1979, are listed in table 3.

Table 3.—*Analytical detection limits*

	HEAVY METALS				
	Iron	Manganese	Zinc	Copper	Lead
Detection limit (mg/L)	0.05	0.01	0.01	0.0005	0.0005

	NITROGEN-PHOSPHORUS NUTRIENTS					
	Phosphorus		Nitrogen			
	Total	Orthophosphate	Ammonia	Nitrite	Nitrate	Organic + ammonia[1]
Detection limit (mg/L)	0.001	0.001	0.01	0.01	0.01	0.03

[1] i.e., TKN (total Kjeldahl nitrogen)

Bottom sediment samples for physical analyses were collected from each of the nine main reservoir stations in June 1977. Samples were obtained with either Ponar or Ekman dredges. The Soil Testing Section of the Division of Research, E&R Center, analyzed each sample to determine gradation, standard physical properties, engineering classification, and organic content [18].

Tributary and effluent streams were usually surveyed by collecting water samples for laboratory analyses of major ions, heavy metals, and N-P nutrients. These samples were sometimes supplemented with in situ measurements of water temperature, dissolved oxygen concentration, conductivity, hydrogen ion concentration, and redox potential. Data not appearing in this report are available in the files of the E&R Center's Environmental Sciences Section.

Chlorophyll

Two replicate samples for chlorophyll were obtained from water collected at the 0.1-, 1.0-, 3.0-, 5.0-, 9.0-, and 15.0-m depths at each station. Following their collection, 800- or 750-mL samples were filtered through millipore glass filter pads and individually frozen until chlorophyll extraction and analyses were performed.

In the laboratory, each filter was crushed in a test tube containing 10 ml of 90 percent acetone. The test tube was allowed to stand for 18 to 20 hours at 4 °C in the absence of light. At the end of this extraction period, each test tube was centrifuged at 2000 r/min for 60 seconds to compact filter fragments into the lower portion of the tube. A 1-mL subsample was analyzed in a Beckman model 25 spectrophotometer with a clinical sipper attachment. Wavelength readings were taken at 663, 645, and 630 nanometers for each sample. Concentrations of chlorophyll *a, b,* and *c* were then calculated from these readings using equations developed by Parsons and Strickland [19].

Plankton

Plankton samples were obtained by two different methods. From 1976 through 1978, zooplankton were collected by towing a metered Clarke-Bumpus plankton sampler having a No. 10 (158-μm mesh net openings) silk net and bucket. Tows were made in a zigzag fashion from the surface to 5 m, 5 to 10 m, 10 to 20 m, and from 20 m to the bottom, as limited by the water depth at the station being sampled. The 1979 plankton samples were collected, additionally, with a closing net sampler having a No. 20 (876-μm mesh net openings) silk net and bucket. Vertical hauls were made from the surface to 5 m, 5 to 10 m, and 10 to 20 m. Samples were preserved with a 2-percent formalin solution for laboratory analyses.

In the laboratory, three replicate subsamples were counted from each sample, using a Sedgewick-Rafter counting cell for zooplankters and a Palmer counting cell for phytoplankton. Organisms were identified at least to genus.

Benthos

The benthic environment of the Upper North Platte reservoirs was sampled using Ponar and Ekman dredges. The Ekman dredge (232 cm^2) was used in 1978 on Kortes Reservoir, and the Ponar dredge (523 cm^2) was used for the remainder of the sampling. Samples were taken at each of the nine reservoir stations. In 1979, samples were also taken at intermediate stations to give a longitudinal transect in each reservoir.

After obtaining the bottom sediment dredge samples, the material was placed in a large littoral bucket with a No. 30 (600-μm opening) mesh screen. By agitating the bucket in the water, the fine sediments were eliminated, leaving the organisms. The organisms were then handpicked, placed in a bottle, and preserved with 5 to 10 percent formalin.

In the laboratory, the samples were again sieved through a 600-μm screen, and the organisms placed in a white porcelain pan. The two major taxa that were found (family Chironomidae, class Oligochaeta) were then separated, counted, and placed in vials. Once in vials, the wet mass for each was obtained. The samples were then dried at 90 °C for 20 hours, and the dry masses were obtained. Finally, the benthic abundance (number of individuals/m^2), and the wet and dry biomass (g/m^2) for each taxon were calculated.

RESULTS

Hydrology

Although the four Upper North Platte reservoirs are operated as a system to store and release water for irrigation and power generation, their individual operating cycles are quite different, reflecting their particular functions within the system (table 1). Figure 8 shows the operational patterns of the four reservoirs on an average monthly basis, while figure 9 shows how these operating patterns and the variation in annual runoff affected reservoir storage volumes during WY's 1976 through 1979.

As the first impoundment on the system, Seminoe Reservoir receives the uncontrolled spring runoff from the North Platte and Medicine Bow Rivers. Over 75 percent of the total annual flow of the North Platte enters Seminoe Reservoir during the period from April through July, with peak flows usually occurring in June. The Medicine Bow River inflows peak in May or June, with over 70 percent of the annual total arriving in Seminoe in the period from April through June. Seminoe Reservoir impounds this spring flood, and releases it at a relatively even monthly rate for power generation. The result of this operating pattern is that Seminoe Reservoir fills rapidly during spring runoff, usually reaching its maximum storage in July, and then is drawn down gradually to late winter minimum storage levels.

The primary function of Kortes Reservoir is to regulate the day-to-day fluctuations of power releases from Seminoe Dam. On an average monthly basis, inflow and outflow curves for Kortes are identical to the Seminoe release curve. Storage in Kortes, therefore, remains relatively constant at approximately 5.678×10^6 m^3 throughout the year, with a mean annual flushing rate of about 2 days.

Nearly 90 percent of the total annual inflow to Pathfinder Reservoir is contributed by the North Platte River, after release from Kortes Dam. The Sweetwater River contributes the remaining 10 percent, according to a spring runoff-type pattern, with nearly 65 percent of its total annual flow reaching Pathfinder from April through July and runoff peaking usually in May. Because of the North Platte's much greater volume, the combined inflow to Pathfinder arrives at a generally even monthly rate and spring flushing effects are probably confined to the Sweetwater arm of the reservoir. Releases from Pathfinder follow an irrigation demand curve, with 55 percent of the annual total being discharged from June through September. This rather complex inflow/outflow regime usually results in maximum storage levels by June, rapid drawdown during the irrigation season, and gradual refilling through the winter months.

Alcova Reservoir regulates power releases from the Fremont Canyon Powerplant and delivers water to the Casper Canal during the irrigation season. Alcova's monthly inflow and outflow curves are thus nearly identical with the release curve from Pathfinder. The resulting storage pattern is a seasonal "step" curve. From May through September, Alcova is maintained at a storage capacity of about 2.214×10^8 m^3 in order to make irrigation deliveries to the Casper Canal. In October, the reservoir is drawn down to about 1.924×10^8 m^3 and maintained at this level until the following April, when it is raised to its irrigation season capacity. Summer flushing rates average about 46 days, while winter flushing rates average 89 days.

The operational regime described above is but one of two major hydrologic factors affecting the limnology of the Upper North Platte reservoir system. The second factor is the annual variation in runoff from the basin watershed.

Table 4 summarizes the total annual inflow and outflow for the reservoirs of the system during

Table 4.—*Reservoir system inflows and outflows, water years 1976–79*

Reservoir	Total annual flow, m^3 × 10^9							
	WY[1] 1976		WY 1977		WY 1978		WY 1979	
	In	Out	In	Out	In	Out	In	Out
Seminoe	1.068	1.007	0.572	0.827	1.473	1.196	1.382	1.239
Kortes	1.007	1.007	0.827	0.827	1.196	1.195	1.239	1.238
Pathfinder	1.210	1.321	0.954	1.229	1.366	1.026	1.430	1.289
Alcova	1.321	1.309	1.229	1.218	1.026	1.015	1.289	1.277

[1] WY = water year (October–September)

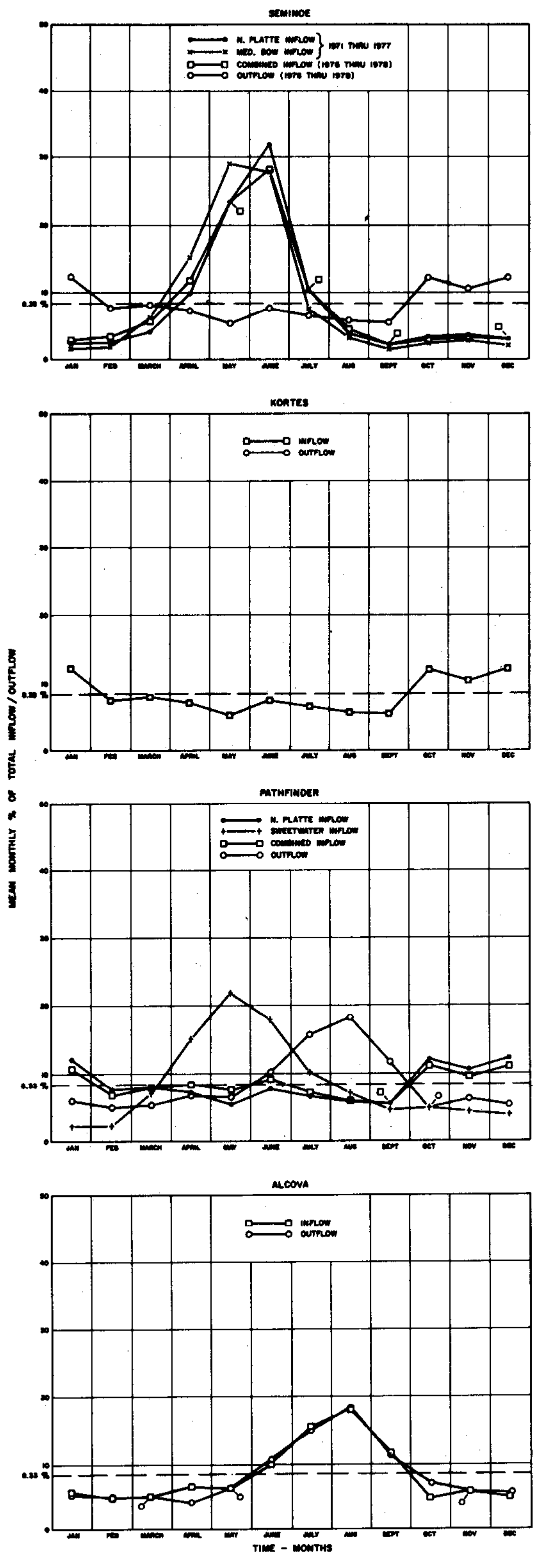

Figure 8.—Operational patterns - Upper North Platte reservoirs, Wyoming.

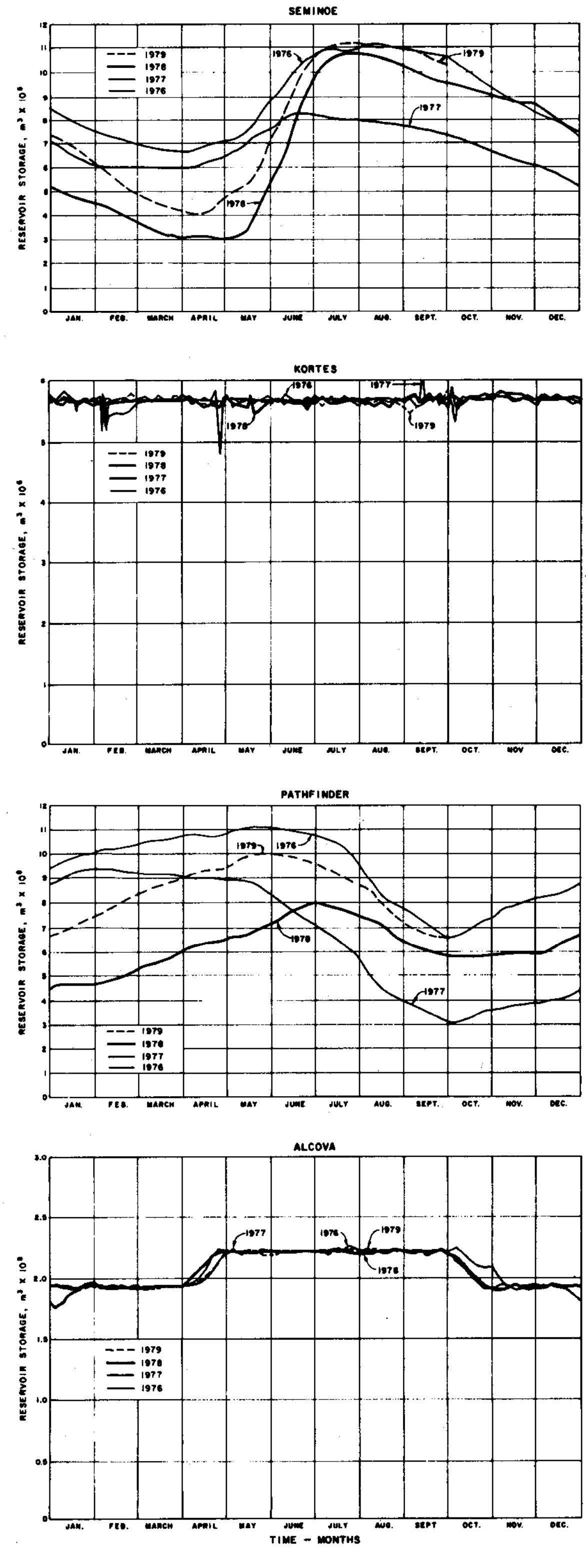

Figure 9.—Annual storage patterns - Upper North Platte reservoirs, Wyoming.

this study period. Figure 10 graphs recent total annual inflow to Seminoe Reservoir as a percentage of the 39-year mean [16]. It is evident from table 4 and figure 10 that WY 1977 (October 1976 through September 1977) was an unusually dry year in the Upper North Platte Basin. The effect of this drought on reservoir storage levels is apparent in figure 9. Seminoe Reservoir was only partially refilled by the low runoff during the spring of 1977; thus, less water was available for release through Kortes to Pathfinder Reservoir through the remainder of the year. In the meantime, Pathfinder was drawn down to extreme lows to meet irrigation demands and, because of low releases from Seminoe, was only partially refilled by the next spring. It was not until the spring of 1979, 1 year after the drought ended, that storage in Pathfinder rose to near predrought levels. Therefore, because of system operating criteria, storage levels in Pathfinder lagged Seminoe by about 1 year in responding to the return of wetter conditions. The two reregulating reservoirs, Kortes and Alcova, on the other hand, were maintained at nearly constant storage levels throughout the study period.

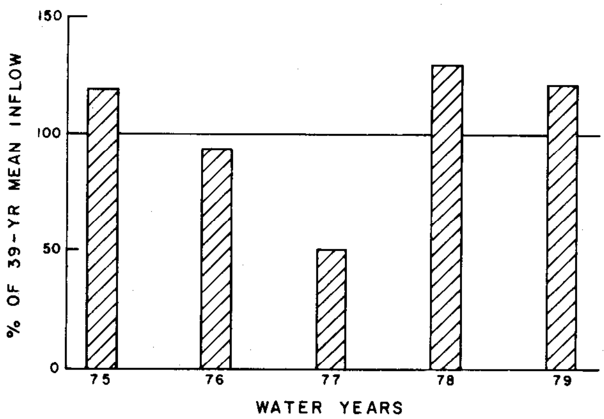

Figure 10.—Annual inflow as percent of long-term mean – Seminoe Reservoir, Wyoming.

Annual runoff variations have a direct, major effect on Seminoe and Pathfinder, the two larger storage reservoirs, and little or no effect on Kortes and Alcova, the two smaller reregulating reservoirs. This situation is emphasized by table 5, which lists the mean depths, calculated on the basis of average annual reservoir elevations, for all four reservoirs for WY's 1976–79.

Light

Energy for photosynthesis in a body of water is provided by sunlight penetrating into the water column. The depth to which sunlight can penetrate is a function of the water's clarity and is measured in terms of η, the light extinction coefficient. This coefficient is defined by the following equation:

$$\phi_Z = \phi_o e^{-\eta Z} \qquad \text{Eq. (1)}$$

where: ϕ_o = light intensity at zero depth

ϕ_Z = light intensity at any given depth Z

η = coefficient of light extinction or attenuation

From equation (1), it can be seen that η is inversely related to the clarity of the water; that is, η becomes smaller as the water becomes clearer, thus increasing the light available at any given depth, Z.

Light extinction coefficients for the Upper North Platte reservoirs at selected times during 1976-79 are plotted on figure 11. Very different patterns of early and late summer water clarity are evident in 1977, as opposed to 1978 and 1979.

In June 1977, light extinction coefficients were uniformly low throughout the system, with somewhat higher values in Seminoe Reservoir

Table 5.—*Reservoir system mean depths, water years 1976–79*

Reservoir	Mean depth, m			
	WY[1] 1976	WY 1977	WY 1978	WY 1979
Seminoe	14.4	13.9	13.6	14.1
Kortes	17.3	17.3	17.3	17.3
Pathfinder	13.0	12.4	12.1	12.5
Alcova	22.1	22.1	22.1	22.1

[1] WY = water year (October–September)

and the Sweetwater arm of Pathfinder Reservoir, reflecting spring runoff turbidity in the North Platte, Medicine Bow, and Sweetwater Rivers. Runoff volume was extremely low during 1977, so the "turbidity peaks" in the June light extinction patterns are only slightly higher than the system mean. By August 1977, algae blooms in the river arms of Seminoe and Pathfinder caused the very pronounced peaks in the light extinction pattern at stations S-2, S-3, P-2, and P-3.

By contrast with the dry year, 1977, the wet years of 1978 and 1979 show a very different pattern of water clarity. The high volume of turbid spring runoff in the North Platte and Medicine Bow Rivers in 1978 and 1979 resulted in extremely large values of η at S-2 and S-3 in the river arms of Seminoe. By August, the turbidity had cleared and light extinction coefficients were relatively low throughout the system, except for algae bloom-caused peaks in the river arms of Pathfinder and Seminoe. Light measurements at fall overturn in October 1979 complete this cycle, with decreased clarity caused by wind mixing of the now destratified and lowered reservoirs.

The major exception to the seasonal cycle outlined above is station K-1, near the dam in Kortes Reservoir. At K-1, water clarity decreases steadily from spring through fall, regardless of wet or dry years. Throughout the period of this study, it could be observed that releases from Seminoe Dam became markedly turbid by late August, even though spring runoff turbidity had cleared in the upper basins of the reservoir and fall overturn had not yet begun; Seminoe Reservoir itself appeared relatively clear. At the same time, Kortes Reservoir became extremely turbid, a condition which persisted through the fall months. Releases from Kortes Dam to the Miracle Mile also became quite turbid in the fall [6]. The cause of this phenomenon appears to be that some of the suspended sediment load carried by the spring runoff into the upper reaches of Seminoe Reservoir becomes a turbid underflow which reaches the dam in late summer and is then flushed through Kortes Reservoir into the Miracle Mile in the fall. It may be noted on figure 11 that light extinction coefficients at K-1 showed a sharper increase during the high-runoff year 1978, and this fact lends some weight to the hypothesis that the increase in turbidity is ultimately related to the turbidity of the spring inflow to Seminoe Reservoir.

The 1958 sedimentation survey of Pathfinder [13] found evidence of possible turbid underflows in that reservoir. This evidence is discussed in more detail in the section on sediments.

Observed ranges of light extinction coefficients at the four deep reservoir sampling stations are listed in table 6.

Table 6.—*Observed summer ranges of light extinction coefficients at deep reservoir stations*

Reservoir	Station	η max. (m^{-1})	η min. (m^{-1})
Seminoe	S-1	1.71	0.48
Kortes	K-1	2.84	0.56
Pathfinder	P-1	1.30	0.46
Alcova	A-1	1.50	0.45

Physical/Chemical Profiles

A major part of the routine survey at each of the reservoir stations was the measurement of temperature, dissolved oxygen concentration, pH (hydrogen ion concentration), conductivity, and E_7 (redox potential) at various depth intervals from the surface to the bottom of the water column. These physical/chemical profiles for the nine major reservoir stations are included in this report as appendixes A through D.

Temperature profiles at all nine reservoir stations indicate a typical dimictic cycle: summer and winter thermal stratification, separated by isothermal conditions (overturn) in fall and spring. Only the spring-to-fall (May through October) conditions were actually surveyed in this study, but it is known that at least partial ice covers form on all the reservoirs during the winter.[2]

Temperature profiles in appendix A show the onset of summer thermal stratification by late May,

[2] Personal observation and personal communications from Ron McKnight, Wyoming Game and Fish Dept. Casper, and Jerry Mathews, Seminoe Powerplant Foreman, Bureau of Reclamation.

with maximum stratification usually developing by mid-July at the deep reservoir stations. Surface cooling and weakening of stratification is evident by the end of August, and isothermal conditions, with complete water column mixing, prevail by late October. The fact that all four reservoirs release cool, hypolimnetic[3] water through low outlets probably accelerates the onset of isothermal conditions by lowering the thermocline and thus increasing the depth of mixing.

The river arms of Seminoe and Pathfinder Reservoirs deviate from this pattern somewhat in that maximum thermal stratification at these stations often occurs in May or June and again in September or October. (See 1978 and 1979 profiles in appendix A). In the spring, this stratification is caused by warmer river water flowing over the surface of the cooler reservoir water. The situation is reversed in the fall, when the rivers cool more rapidly than the impoundments so that inflows plunge under the warmer reservoir water.

Dissolved oxygen profiles (appendix B) indicate a depletion of hypolimnetic oxygen through the summer stratification period, with minimum concentrations usually occurring in late August, especially at the deepwater stations S-1, K-1, P-1, A-2, and A-1. This depletion was most pronounced at station S-1 in 1978, when the bottom dissolved oxygen concentration dropped to 0.2 mg/L, the lowest concentration observed during this study.

Dissolved oxygen conditions in the river arms of Seminoe and Pathfinder are more variable and appear to be more directly linked to primary productivity levels. For example, the minimum observed oxygen concentration at P-3, in the North Platte arm of Pathfinder, occurred in August 1977 and coincided with the largest algae bloom observed at that station during this study. (See "Primary Production" section.) In 1978, the minimum oxygen concentration at S-3, in the Medicine Bow arm of Seminoe, was not observed until late September, which coincided with an algae bloom that was also about a month later than usual.

[3] Hypolimnion = bottom zone in a thermally stratified impoundment.
Epilimnion = upper zone in a thermally stratified impoundment.
Thermocline = level of maximum temperature change in a thermally stratified impoundment; often considered the boundary between the epliminion and the hypolimnion.

Late spring and fall profiles indicate that the reservoirs are completely recharged with dissolved oxygen during the isothermal mixing periods. No evidence of permanent anoxic zones was found in any of the impoundments.

Hydrogen ion concentration (pH) profiles are contained in appendix C. The range of measured pH during this study was 7.10 to 9.05, with most values falling between about 7.8 and 8.6. The waters of the Upper North Platte reservoir system may, therefore, be classified as alkaline or basic (i.e., pH > 7.00). Seasonal cycles, as indicated by the profiles, however, show some variation between the deep reservoir and river arm stations. Profiles of pH at the deep reservoir stations usually show high values at all depths at the beginning of summer and decline, especially in the lower depths, as the season progresses. This overall decline in pH may be the result of increased early summer inflows diluting impoundments which had become chemically concentrated during the winter. Typical late August pH profiles at these stations are highly stratified, with peak values near the surface, caused by photosynthesis, and low values near the bottom, reflecting a hypolimnetic oxygen sag. Fall overturn usually results in uniform profiles at or below the early summer pH values. River arm stations, on the other hand, with the exception of P-3, usually begin the summer with low pH values because of the dilute nature of the spring runoff. As the season progresses, pH values rise and reach extremely high values at all four river arm stations during the late summer algae bloom. Station P-3 is something of a "hybrid" between river arm and deep reservoir conditions, because it is not subject to a spring runoff pulse (fig. 8), but it does support a strong late summer algae bloom.

Conductivity for the system ranged from 240 to 577 µS/cm during the surveys made from 1976 to 1979. Conductivity profiles (appendix D) display seasonal trends that are generally consistent with those noted above for temperature, dissolved oxygen, and pH. Early summer conductivity profiles at S-2 and P-2 reflect the relatively dilute nature of the North Platte and Sweetwater Rivers, respectively, with relatively warm, low-conductivity water flowing in over cooler, more concentrated reservoir water. The situation is different at S-3, because of the consistently higher conductivity of the Medicine Bow River, which manifests itself as a somewhat higher conductivity in the upper, warm layers during the early summer. Station P-3 and the deepwater stations in all four reservoirs begin the summer season in a chemically concentrated condition that is responsible for their nearly vertical, high-conductivity profiles.

By late August, all reservoir stations in the system are characterized by conductivity readings that have been lowered as a result of dilution by the spring runoff. From this point on through the fall, a conductivity anomaly begins to become apparent in the river arms of Seminoe. River inflows become more saline as flows decline and this, coupled with the rapid fall cooling in streams, results in cooler, higher conductivity inflows plunging under the now warmer, more dilute reservoir water. This situation is reflected in the highly stratified late season conductivity profiles at S-2 and S-3. A second conductivity anomaly appeared in Seminoe in 1978, with the development of a high-conductivity "bulge" at the bottom of the S-1 profiles in the late summer and fall. This bulge reflects chemical releases from the sediments under the low dissolved oxygen conditions prevailing at that time.

By late October, fall overturn is well advanced, and conductivity profiles at all deep reservoir stations are generally uniform at conductivity levels equal to or less than those observed at the beginning of the ice-free season. The rivers, however, become even more saline as flows approach their minimum, so that the high-conductivity peaks at the bottom of the river arm profiles are still very much in evidence at this time.

The preceding discussion of seasonal trends exhibited by the physical/chemical profile data in appendixes A through D is, of course, somewhat tentative, since these data cover only a limited period of time. Table 7 summarizes this information and lists maximum and minimum observed values of the different parameters at representative depths at each of the deep reservoir stations during this study period. Although significant differences in trends have been noted between the river arm and deep reservoir stations, the latter have been used here for summary purposes because they are probably more representative of each reservoir.

Looking at yearly trends for the entire system is facilitated by the fact that early and late summer data are available at all reservoir stations for the years 1977-79. Figures 12 through 15 are systemwide plots of selected early and late summer

Table 7.—*Observed summer ranges of physical/chemical profile data at deep reservoir stations*[1]

Depth (m)	Temperature (°C)		Dissolved oxygen concentration (mg/L)		pH		Conductivity (µS/cm)		E_7 (mV)		Dissolved oxygen saturation %	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
					Seminoe Reservoir (station S-1)							
1	20.2	11.0	8.8	5.5	8.4	7.6	525	240	[2]	[2]	—	—
19	17.1	9.1	9.4	4.8	8.3	7.6	527	250	[2]	[2]	—	—
Bottom	14.2	7.5	8.8	0.2	8.6	7.4	534	360	539	171	93	1.8
					Kortes Reservoir (station K-1)							
1	17.1	9.1	9.3	5.3	8.4	7.8	511	240	[2]	[2]	—	—
15	15.3	8.3	9.4	4.6	8.3	7.6	514	246	[2]	[2]	—	—
Bottom	15.1	8.1	9.2	4.0	8.3	7.6	518	244	563	422	96	49
					Pathfinder Reservoir (station P-1)							
1	19.0	12.1	9.6	6.7	8.8	8.1	554	443	[2]	[2]	—	—
19	18.1	8.7	10.1	5.4	8.7	8.0	565	441	[2]	[2]	—	—
Bottom	16.7	7.8	8.6	2.5	8.4	7.6	565	446	471	271	89	30
					Alcova Reservoir (station A-1)							
1	19.8	12.6	11.1	6.7	8.7	8.3	577	456	[2]	[2]	—	—
19	18.4	8.5	10.6	5.7	8.6	8.0	577	456	[2]	[2]	—	—
Bottom	17.7	7.2	8.5	1.3	8.3	7.5	564	468	508	269	87	5

[1] The dates of observation of the various depth and maximum and minimum values do not necessarily coincide.
[2] Only bottom values are limnologically meaningful.

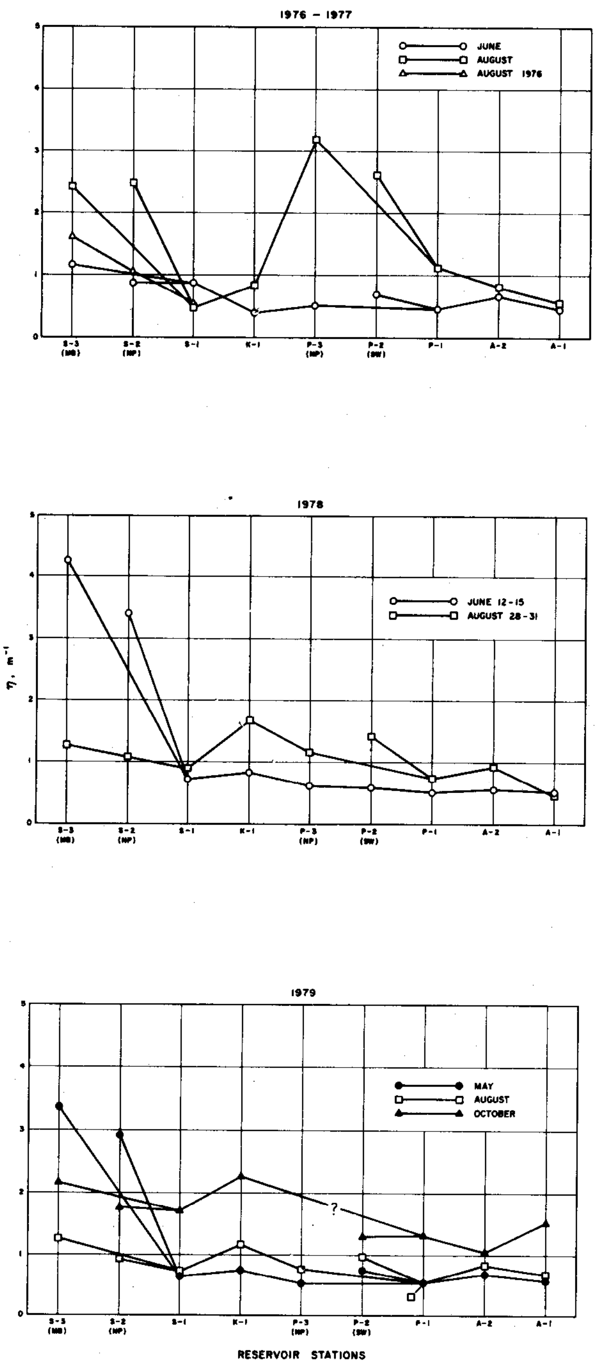

Figure 11.—Light extinction coefficients - Upper North Platte reservoirs, Wyoming.

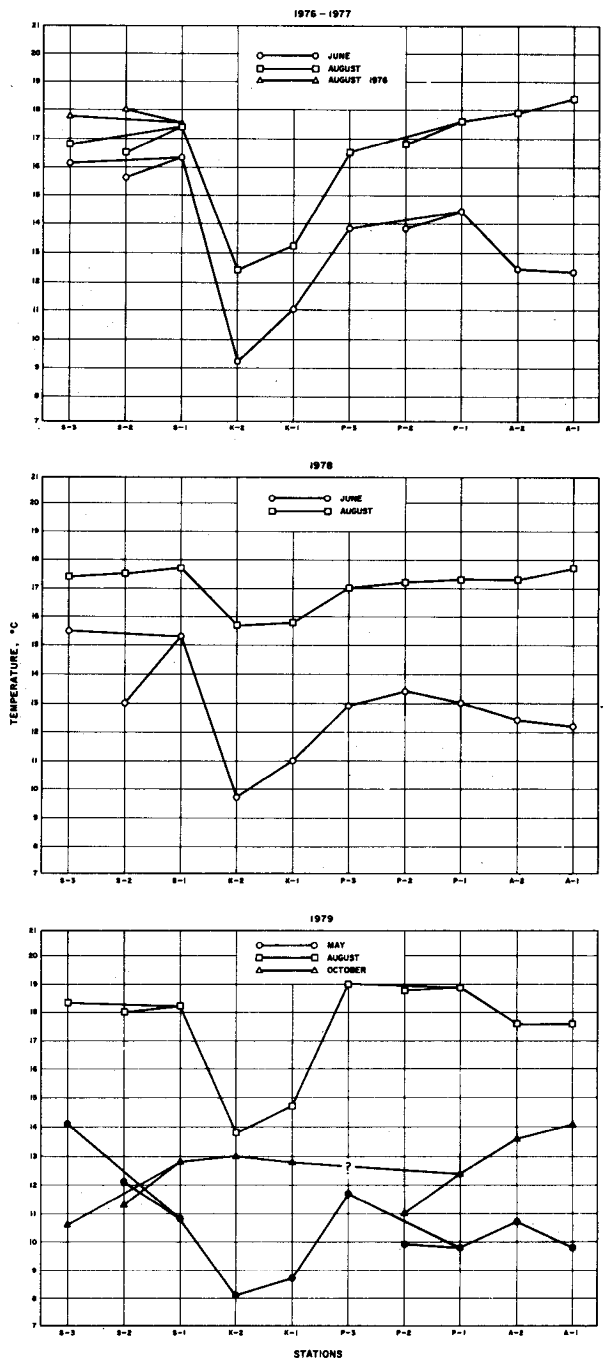

Figure 12.—Mean water temperature of upper 15 meters - Upper North Platte reservoirs, Wyoming.

data over these 3 years. Figure 12 is a plot of the mean water temperature of the upper 15 m at each reservoir station. These data are indicative of the temperature of the trophogenic, (productive) zone at each station from summer to summer. Seasonal patterns here are generally similar, regardless of dry or wet years. By August, temperatures of the trophogenic zone are well into the 17 to 19 °C range, except in Kortes. Lower temperatures in this reservoir at almost all times during the ice-free season reflect bottom withdrawals from Seminoe. Exceptions to this general rule, in August 1978 and October 1979, arose from conditions of weak thermal stratification, and lack of stratification, respectively, at station S-1.

Mean pH of the upper 15 m at each station from summer to summer are plotted on figure 13. These data are indicative of the alkalinity of the productive zone, and, again, there is little evident variation between dry and wet years. The general seasonal trends in pH noted earlier are also apparent here. Dilution by spring runoff in May and June causes lower pH's in the river arms of Seminoe (S-2 and S-3), while pH's throughout the rest of the system are higher, reflecting winter concentrated conditions. By August, some dilution has occurred at the downstream stations and pH's are generally somewhat lower. The trend is opposite at S-2 and S-3, where the annual algae bloom is beginning and pH's have risen accordingly. This was also the case in the river arms of Pathfinder in August 1977, when, as noted above, the algae bloom was particularly large. The relatively low pH noted at station K-2 in August 1978 was due to withdrawal from the bottom zone of S-1, which was experiencing greater than usual oxygen depletion at the time, with consequent low pH's in the hypolimnion.

In general, figures 12 and 13 indicate favorable conditions for primary production in the upper 15 m at all stations in the system by August of each year. Water in the trophogenic zone at this time is warm and alkaline, both of which are conducive to algal growth.

Figures 14 and 15 illustrate systemwide conditions in the bottom, or tropholytic, zone, where decomposition rather than production takes place. Early and late summer bottom dissolved oxygen saturation levels (fig. 14) show oxygen depletion, especially at deep reservoir stations, as the summer progresses. Except for the anoxia observed at the very bottom of station S-1 in August 1978, oxygen depletion does not usually reach severe proportions. Recharge of the bottom waters with dissolved oxygen appears to be complete at spring and fall overturns, as evidenced by the May, June, and October traces on figure 14.

Bottom E_7 (oxidation-reduction potential adjusted to pH 7.0) values systemwide are summarized on figure 15. This parameter is a semiquantitative indicator of the intensity of chemical reduction near the sediment/water interface. Thus, bottom E_7 indicates the possibility of chemical releases from the sediments, and particularly the release of heavy metals, if it falls much below 300 mV. Such an extreme reducing situation was only observed once—at S-1 in August 1978—and it was accompanied by a significant release of manganese from the sediments into the bottom of the hypolimnion. In general, though, extreme reducing conditions (i.e., very low E_7) with problem releases of heavy metals, appear to be rare in this system, probably because the relatively high volume of flow through the hypolimnia of the reservoirs limits the duration and severity of bottom stagnation.

In summary (table 7), all four Upper North Platte reservoirs are dimictic, run-of-the-river impoundments that experience brief and relatively weak summer temperature stratification, which usually reaches its maximum in July and begins to break down by late August. Although there is some hypolimnetic oxygen depletion as the summer progresses, this occurrence rarely reaches extreme anoxia, and severe reducing conditions (i.e., $E_7 < 300$ mV) are unusual. Bottom recharge of dissolved oxygen appears to be complete at both spring and fall overturn. Waters of the system are consistently alkaline (i.e., pH > 7.0), with pH's averaging from 8.0 to 8.5 in the trophogenic zone by late summer. Temperatures in this zone average between 17 and 19 °C during the same period, creating a favorable environment for algal production. Conductivity during the ice-free season ranges from about 240 to 577 μS/cm.

On a systemwide basis, Kortes and Alcova, the smaller reregulating reservoirs, tend to be hydraulically stable, rapidly flushed impoundments whose physical/chemical profiles mainly reflect low withdrawal from the deep reservoir stations immediately upstream, i.e., S-1 and P-1, respectively. However, the physical/chemical profiles

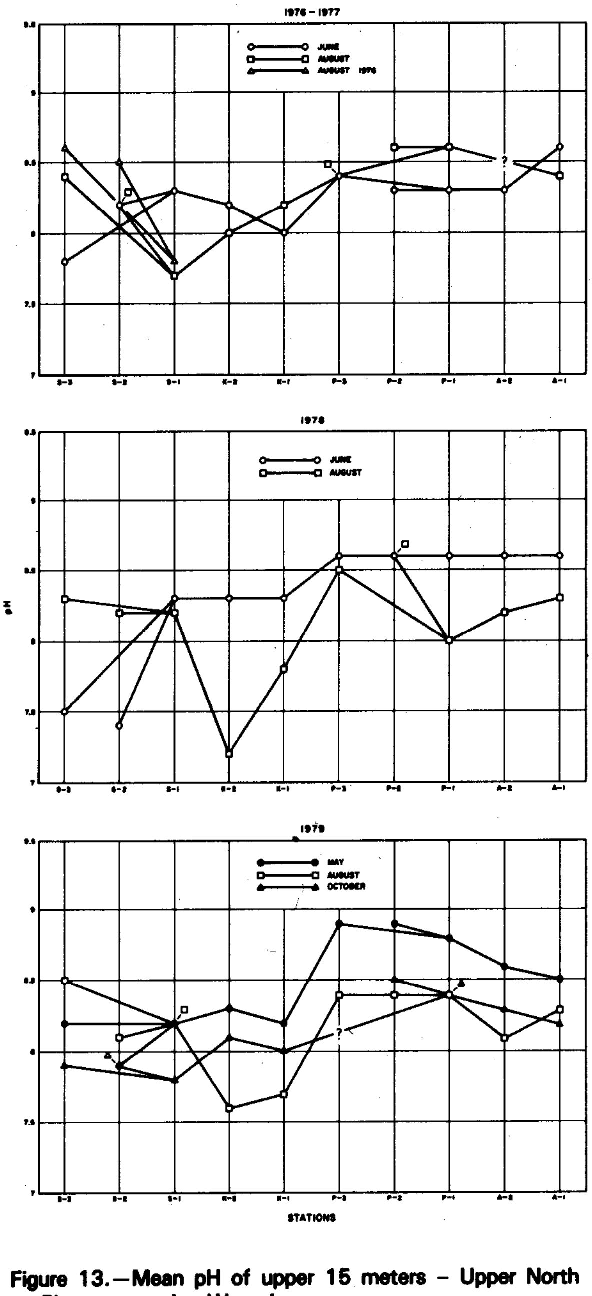

Figure 13.—Mean pH of upper 15 meters - Upper North Platte reservoirs, Wyoming.

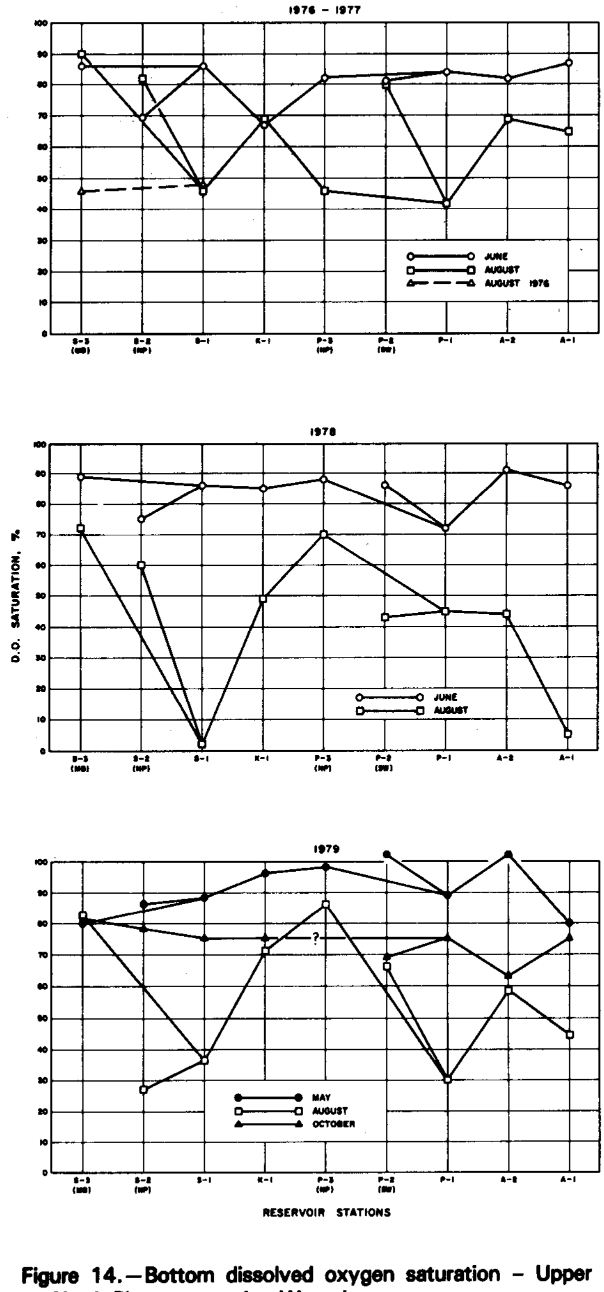

Figure 14.—Bottom dissolved oxygen saturation - Upper North Platte reservoirs, Wyoming.

in the two larger storage reservoirs, Seminoe and Pathfinder, are strongly influenced by runoff volume and inflow conditions. From fall through early spring, both inflow volume and reservoir storage levels tend to be low; thus, the reservoirs become cool and chemically concentrated. With spring runoff, come surface inflows of warmer, more dilute water in the river arms of Seminoe and the Sweetwater arm of Pathfinder. By early to midsummer, the reservoirs reach maximum annual storage levels, and become chemically dilute, relatively homogeneous impoundments. In late summer and fall, the tributary rivers cool rapidly and decline in discharge, so that the river waters enter the reservoirs as plunging inflows of cooler, more saline water. The intensity of this cycle varies, of course, with the volume of the annual runoff, which is in turn dependent upon winter snowpack conditions in the Upper North Platte River Basin. Station P-3, in the North Platte arm of Pathfinder, deviates slightly from the scheme outlined above in that inflow from runoff is controlled by Kortes Dam.

Major Ions

May through October mean concentrations of the major ions in the waters of the Upper North Platte reservoir system are presented, with standard deviations, in table 8. Calcium is the most abundant cation at all stations, followed by sodium, magnesium, and potassium. Major anions, in order of decreasing abundance, are: bicarbonate, sulfate, and chloride, at all stations except the Medicine Bow River (MB) and S-3, where sulfate and bicarbonate are reversed in importance. Carbonate was rarely detected during this study, and then only in very small concentrations in the spring or late summer and early fall. This is to be expected, considering that the average pH of the system is about 8.0 to 8.2 [20]. Together, calcium, sodium, bicarbonate, and sulfate account for 88 to 91 percent of the sum of anions and cations at all stations.

May through October mean TDS concentrations, and standard deviations, for each station are also included in table 8. Tabulated values range from a low of 209 (±97.5) mg/L, in the North Platte River above Seminoe Reservoir (NP), to a high of 810 (±346) mg/L, in the Medicine Bow River.

Table 8 shows a significant variation in water chemistry among the three major rivers tributary to the system. All three have mean TDS concentrations well above the 120 mg/L suggested by Cole [20] as the average for rivers worldwide. The Medicine Bow River, however, has the highest mean ion and TDS concentrations in the entire system. Next in mean concentration of TDS and all ions, except magnesium and sulfate, is the Sweetwater River (SW). The North Platte River, above Seminoe, is the least concentrated of the three, except for magnesium and sulfate ions, where it ranks second.

Rinehart and Kerr [15] used TDS to model water quality changes in the Upper North Platte River of Wyoming, partly because of its conservative nature and ease of tracking as opposed to that of individual ion concentrations. It should, therefore, be possible to elucidate the influence of the three main tributary rivers on the water chemistry of the system by calculating simple mass balances for each reservoir, using the mean TDS concentrations from table 8 and the mean inflow volume percentages from table 1.

For example, if the mean annual volume of inflow to Seminoe is taken as V_T, then an approximate TDS mass balance for the reservoir would be:

$$0.85\, V_T (\mathrm{TDS})_{\mathrm{NP}} + 0.15 V_T (\mathrm{TDS})_{\mathrm{MB}} = V_T (\mathrm{TDS})_{\mathrm{K\text{-}2}} \qquad \text{Eq. (2)}$$

where: V_T = mean annual volume
TDS = TDS concentrations

Equation (2) assumes that average annual inflow is approximately equal to average annual outflow, which is generally true of the Upper North Platte reservoir system [16]. Station K-2 is taken here as being representative of the outflow from Seminoe Dam (fig. 7).

Substituting appropriate mean TDS concentrations from table 8 into equation (2), and dividing through by V_T gives:

$$0.85(209) + 0.15(810) = (\mathrm{TDS})_{\mathrm{K\text{-}2}}$$

$$(\mathrm{TDS})_{\mathrm{K\text{-}2}} = 299 \text{ mg/L}$$

This result agrees closely with the observed value of 297 mg/L for the mean TDS concentration at station K-2 (table 8).

Table 8.—*Upper North Platte reservoir system water chemistry – May through October – Mean ion concentrations and TDS*[1]

	Stations							
	MB	S-3	NP	S-2	S-1	K-2	K-1	NP′
	(mg/L)							
Cations								
Ca^{+2}	102	47.6	36.3	36.4	42.2	44.3	43.3	45.4
	(39.6)	(8.52)	(15.6)	(7.99)	(7.75)	(9.47)	(8.76)	(10.7)
Mg^{+2}	44.3	17.2	10.4	12.2	16.4	16.5	17.0	16.7
	(17.4)	(4.67)	(4.09)	(2.97)	(7.24)	(5.05)	(6.46)	(4.68)
Na^{+1}	91.1	32.0	21.5	21.6	29.1	29.8	30.8	30.4
	(42.5)	(8.13)	(11.8)	(5.03)	(7.21)	(7.63)	(8.03)	(8.56)
K^{+1}	9.00	2.52	2.73	2.25	2.45	2.72	2.84	3.60
	(16.9)	(0.66)	(1.30)	(0.77)	(0.82)	(0.80)	(0.79)	(1.96)
Anions								
CO_3^{-2}	1.09	0.21	0	0	0.24	3.12	3.40	1.53
	(3.62)	(0.66)			(0.57)	(7.16)	(7.23)	(4.06)
HCO_3^{-1}	171	128	124	121	126	129	125	130
	(43.2)	(11.9)	(37.7)	(18.0)	(19.4)	(26.6)	(27.8)	(24.8)
SO_4^{-2}	421	138	58.7	73.6	111	116	116	116
	(190)	(50.7)	(33.2)	(26.3)	(35.9)	(39.8)	(39.0)	(44.4)
Cl^{-1}	33.8	13.6	10.3	11.0	15.8	13.6	14.8	13.0
	(13.9)	(6.34)	(7.19)	(4.73)	(8.46)	(8.67)	(9.60)	(8.83)
Sum[2]	873	379	264	278	343	355	357	357
TDS	810	341	209	245	317	297	302	299
	(346)	(63.8)	(97.5)	(48.5)	(80.9)	(75.3)	(81.2)	(78.9)

	Stations						
	P-3	SW	P-2	P-1	A-2	A-1	NP″
	(mg/L)						
Cations							
Ca^{+2}	49.4	37.6	45.4	45.7	48.3	51.6	52.0
	(5.27)	(10.8)	(4.87)	(9.50)	(8.31)	(6.26)	(5.12)
Mg^{+2}	18.3	9.83	15.1	18.8	20.0	18.8	17.0
	(2.81)	(3.65)	(4.41)	(7.65)	(4.90)	(5.47)	(5.49)
Na^{+1}	33.8	34.4	30.6	31.8	34.2	34.5	36.4
	(4.31)	(16.8)	(3.45)	(5.23)	(5.48)	(5.74)	(5.94)
K^{+1}	3.41	6.16	3.99	3.42	3.58	3.60	3.65
	(1.35)	(2.33)	(1.56)	(1.33)	(1.26)	(1.30)	(1.22)
Anions							
CO_3^{-2}	0	0	1.07	0.80	0.36	0.36	0
			(2.83)	(1.53)	(1.07)	(1.07)	
HCO_3^{-1}	154	153	144	150	159	160	156
	(11.5)	(42.3)	(16.5)	(13.0)	(17.4)	(17.5)	(12.9)
SO_4^{-2}	124	54.8	104	115	123	125	126
	(19.5)	(27.8)	(18.0)	(24.1)	(23.2)	(22.6)	(15.2)
Cl^{-1}	15.4	21.6	16.2	16.9	16.4	17.2	16.3
	(7.54)	(9.38)	(5.94)	(6.87)	(6.06)	(9.62)	(6.30)
Sum[2]	398	317	360	382	405	411	407
TDS	337	274	309	331	340	351	348
	(37.2)	(94.3)	(30.1)	(37.8)	(44.2)	(42.0)	(48.4)

[1] Standard deviations of the data are shown in parentheses.
[2] Sum of cations and anions (salinity).

Murphy[4] found the TDS and salinity (i.e., sum of anion and cation concentrations) of water samples from the Upper North Platte reservoir system to be highly correlated (correlation coefficient, $r = 0.98$). Substituting the appropriate mean salinities from table 8 into equation 2, instead of mean TDS concentrations, gives a sum of 355 mg/L at station K-2, which agrees exactly with the observed value for this parameter.

It is evident, then, that the average water chemistry of Seminoe Reservoir is the result of mixing the smaller, but more saline, Medicine Bow River with the much larger, but much more dilute, North Platte River. On an average basis, station S-2 clearly reflects the ionic composition of the North Platte River. Whereas, station S-3 more closely resembles station S-1 than the Medicine Bow River in mean ionic composition. This situation is probably caused by rising reservoir water levels and the much larger North Platte inflow which push the Medicine Bow-Seminoe Reservoir mixing point farther up the Medicine Bow arm, relative to station location, as the summer progresses.

A comparison of major ion concentrations, salinity, and TDS at stations K-2, K-1, and NP′ (table 8) emphasizes the flow-through nature of Kortes Reservoir: there is no significant change in mean concentrations from the outlet of Seminoe Dam (K-2) to the Miracle Mile (NP′).

Calculating a mass balance for Pathfinder Reservoir is difficult because the data are sparse: the Sweetwater River was only sampled during the wet years of 1978 and 1979, and there was no stream sampling station immediately below the outlet of Pathfinder Dam. Station A-2, below Fremont Canyon Powerplant, is already a deep-water station in Alcova Reservoir, and thus reflects mixing within that impoundment. The following balance is, therefore, very approximate, and is included solely for rough comparison with the other reservoirs of the system.

The general form of a TDS mass balance for Pathfinder Reservoir, using flow volume percentages from table 1, is:

$$0.90 V_T (TDS)_{NP'} + 0.10\, V_T (TDS)_{SW} = V_T (TDS)_{P\text{-}OUT} \qquad \text{Eq. (3)}$$

[4] A. P. Murphy, Bureau of Reclamation Chemistry Laboratory, E&R Center, Denver, personal communication.

Equation (3) assumes that the average annual reservoir inflow and outflow are approximately equal, and calls this value, V_T.

Substituting the appropriate mean TDS concentrations from table 8 into equation (3), and dividing through by V_T gives:

$$0.90\,(299) + 0.10\,(274) = (TDS)_{P\text{-}OUT}$$

$$(TDS)_{P\text{-}OUT} = 296 \text{ mg/L}$$

Using station P-1 as an approximation of "P-OUT," the above result falls below the observed mean TDS concentration (table 8) by a little more than 10 percent. If the mean salinities are used in equation (3) rather than mean TDS concentrations, the resultant sum would be 353 mg/L, which is about 8 percent below the observed value at station P-1. Considering the approximations noted earlier, these mass balance estimates agree fairly well with the observed values.

The overriding influence of the North Platte River on the chemistry of Pathfinder Reservoir is obvious here. It should be noted that by the time this river reaches Pathfinder, mean TDS has increased by 43 percent over that observed above Seminoe, while mean salinity has increased by about 35 percent in the same distance (table 8). Even granting some underestimation of Sweetwater River ionic concentrations, it is apparent that the much smaller flow volume of the North Platte River greatly limits its influence on reservoir chemistry, even in the area of station P-2, in the lower end of the Sweetwater arm (table 8).

Finally, comparisons were made of mean ionic, TDS, and salinity concentrations among stations P-1, A-2, A-1, and NP″ (table 8). Results showed that Alcova Reservoir was similar to Kortes in that mean ionic composition is essentially determined by releases from the reservoir immediately upstream, while the short hydraulic residence time allows for little change in chemical composition between inlet and outlet.

Turning from the average to the particular, figures 16 through 20 show seasonal and annual variations, on a systemwide basis, in TDS, calcium, sodium, bicarbonate, and sulfate concentrations, respectively. The general trends displayed in all five plots are similar, and may be summarized under two main headings: dry years and wet years.

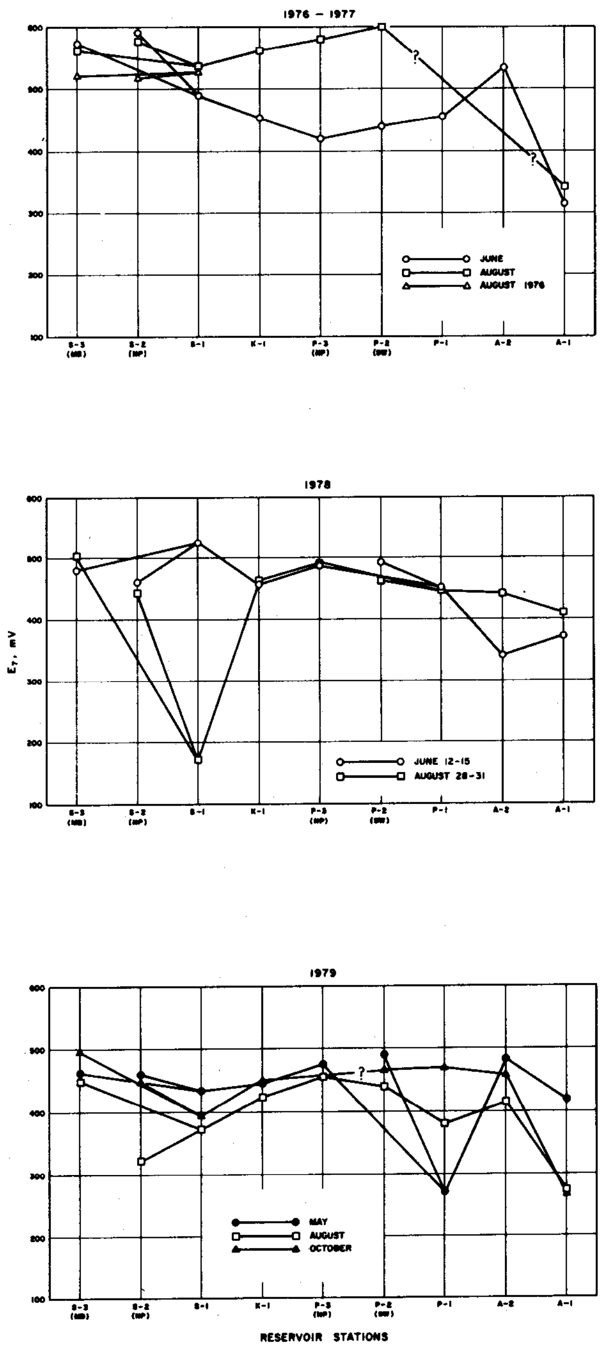

Figure 15.—Bottom redox potentials (E_7) – Upper North Platte reservoirs, Wyoming.

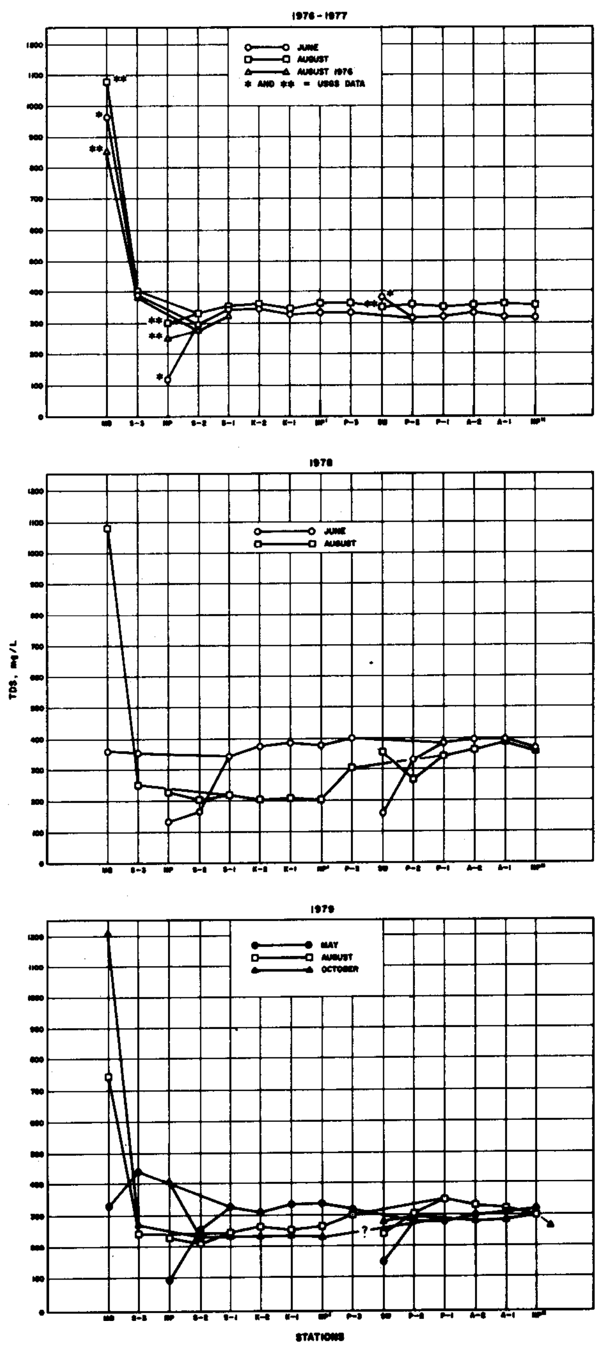

Figure 16.—Total dissolved solids (TDS) – Upper North Platte reservoirs, Wyoming.

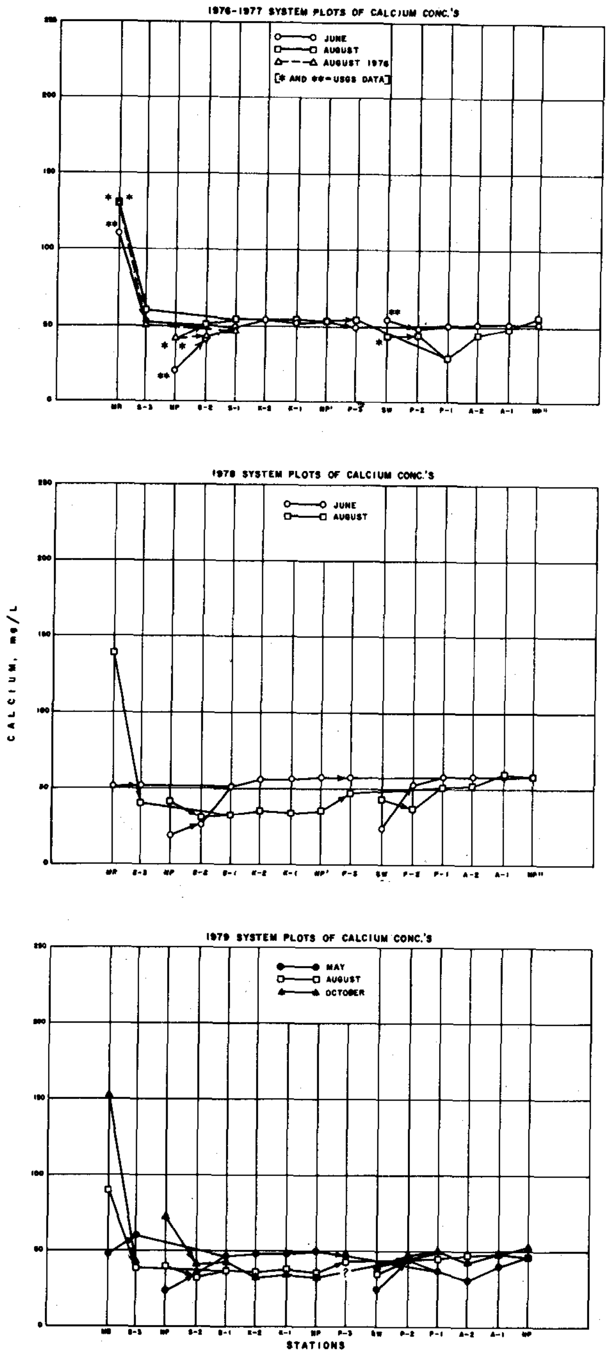

Figure 17.—Calcium concentrations - Upper North Platte reservoirs, Wyoming.

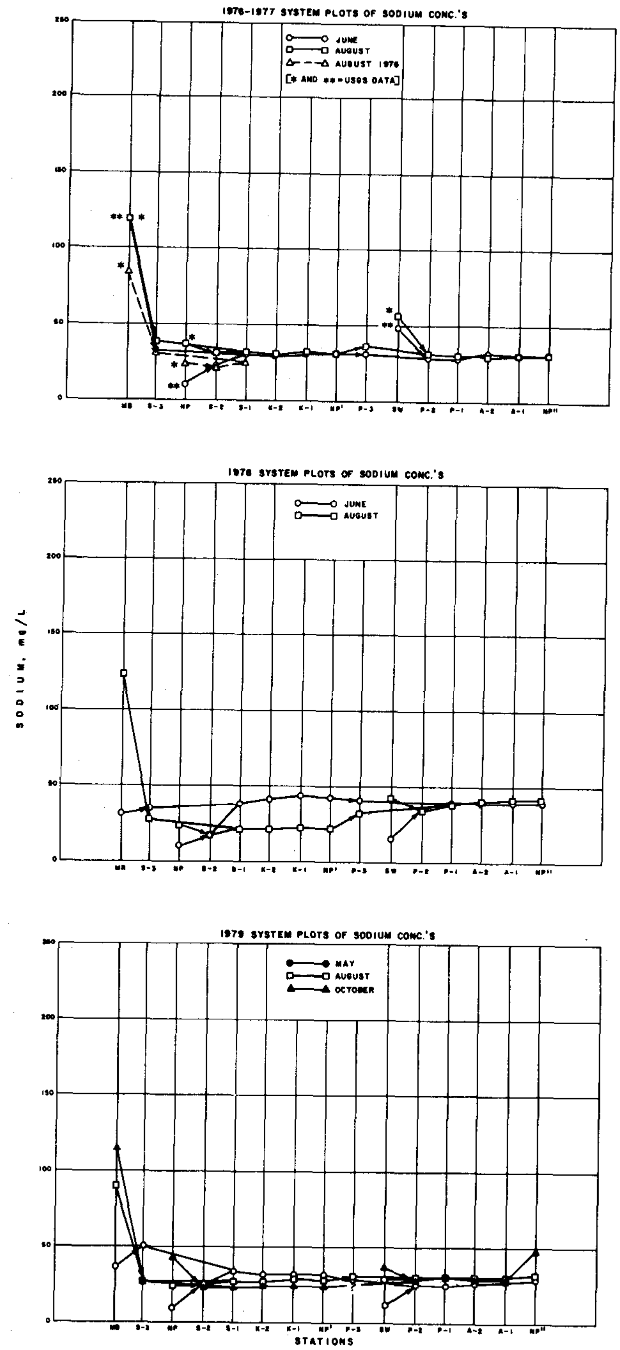

Figure 18.—Sodium concentrations - Upper North Platte reservoirs, Wyoming.

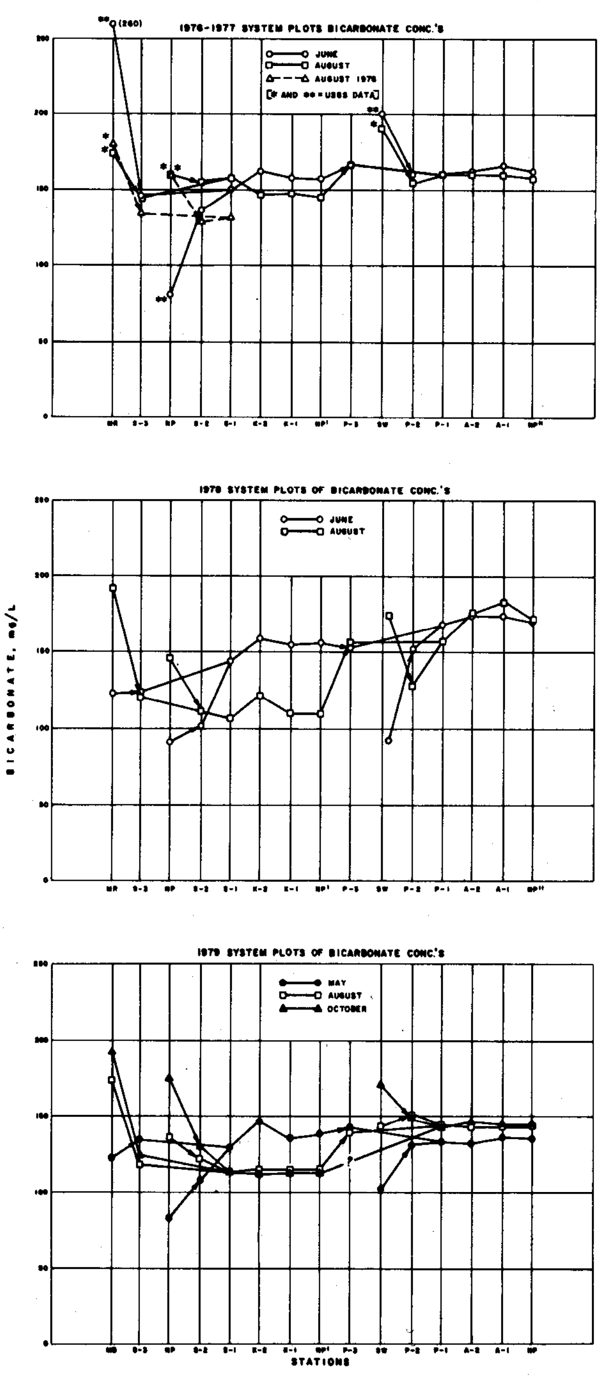

Figure 19.—Bicarbonate concentrations - Upper North Platte reservoirs, Wyoming.

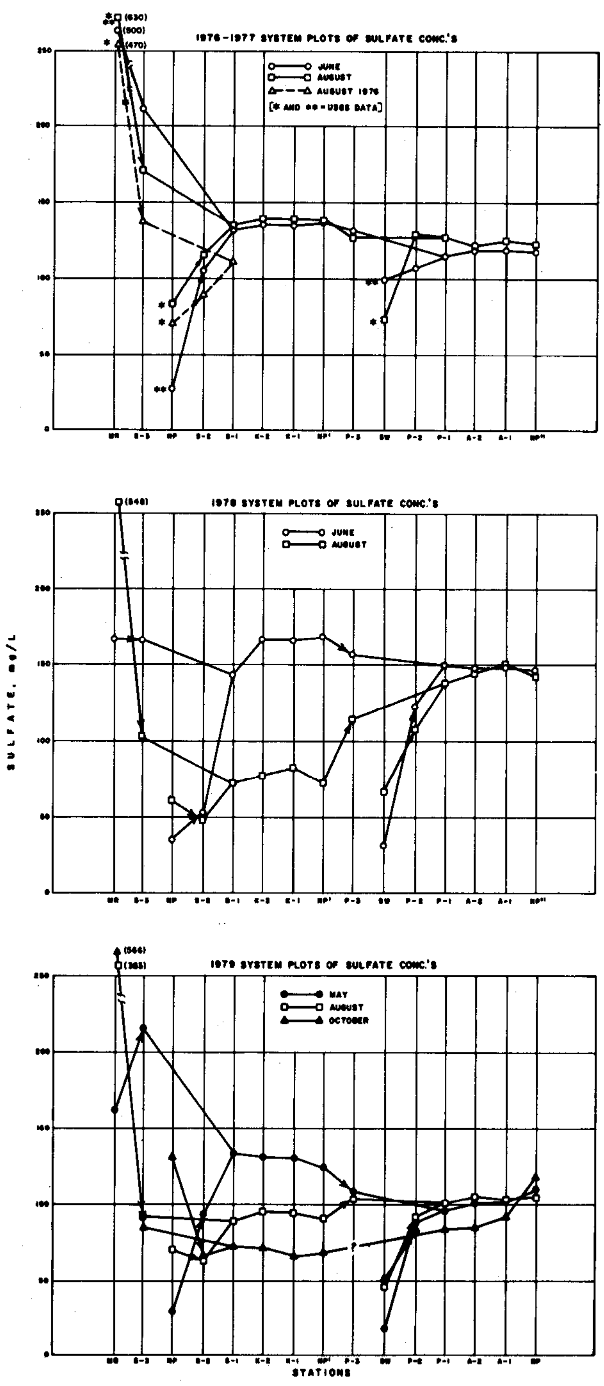

Figure 20.—Sulfate concentrations - Upper North Platte reservoirs, Wyoming.

Considering first the wet years of 1978 and 1979, it can be seen that the three main tributary rivers (i.e., stations MB, NP, and SW) tend to be relatively diluted at the beginning of summer, and become more concentrated as the season progresses and streamflows decline. This increasing ionic concentration with decreasing river discharge is especially apparent in the position of the October 1979 trace on figures 16 through 20. The rest of the system, especially down through the North Platte arm of Pathfinder, tends to become more dilute through the summer and into the fall. As discussed in the previous section, this is probably due to the dilutional effect of the spring runoff. In 1979, in Alcova and the main body of Pathfinder, ionic concentrations were generally lower in May than in August. This apparent anomaly can probably be explained by the fact that maximum reservoir elevation, and thus maximum dilution, occurred in May of that year in Pathfinder (fig. 9). At any rate, the general rule on this system seems to be that during wet years, the tributary rivers become more chemically concentrated through the summer, while the rest of the system tends to become more dilute.

A visual inspection of the 1977 patterns on figures 16 through 20, however, reveals little significant difference between the June and August traces. During this extremely dry year (figs. 9 and 10), both the tributary rivers and the rest of the system remained highly concentrated from June through August, because runoff was insufficient to dilute the rivers in the spring, or the rest of the system through the summer. This drought-year pattern of high ionic concentration throughout the Upper North Platte reservoir system may also be the characteristic winter pattern in any year.

Heavy Metals

Heavy metal concentrations for each station on the system are listed in table 9, along with their standard deviations. The major heavy metals sampled for during this study, in order of decreasing importance, were: iron, manganese, zinc, copper, and lead. It should be noted that the concentrations shown in table 9 are total concentrations; i.e., the total amount of metal detected per unit volume of water, without regard to whether the metal is in a dissolved or particulate form. However, considering the generally high redox potentials measured during the study (fig. 15), and the hard (table 8), alkaline (appendix C) nature of the system waters, it is unlikely that these metals are often in the dissolved, ionic form, except perhaps for such rare occurrences as the large manganese release noted at the bottom of station S-1 in August 1978 [21, 22, 23]. Therefore, these metals do not appear to constitute a significant hazard to aquatic life.

Because of the extreme variability of the measured heavy metal concentrations and several changes in laboratory detection limits during this study, some basic assumptions were necessary in computing the means and standard deviations shown in table 9. First, surface, middepth, and bottom sample concentrations were averaged to

Table 9.—*Upper North Platte reservoir system water chemistry – May through October – Mean heavy metal concentrations*[1]

Metals	Stations				
	MB	S-3	NP	S-2	S-1
			(mg/L)		
FE	3.59	0.62	1.10	0.62	0.40
	(4.34)	(0.46)	(1.34)	(0.33)	(0.30)
Mn	0.09	0.02	0.05	0.04	0.07
	(0.09)	(0.02)	(0.05)	(0.03)	(0.07)
Zn	0.02	0.01	0.01	0.01	0.01
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Cu	0.006	0.002	1.003	0.002	0.002
	(0.007)	(0.002)	(0.004)	(0.002)	(0.002)
Pb	0.0017	0.0004	0.0004	0.0007	0.0014
	(0.0021)	(0.0005)	(0.0005)	(0.0013)	(0.0034)
	K-2	K-1	NP′	P-3	SW
FE	0.50	0.44	0.49	0.63	3.20
	(0.43)	(0.40)	(0.40)	(0.54)	(3.62)
Mn	0.06	0.07	0.05	0.04	0.08
	(0.07)	(0.08)	(0.06)	(0.04)	(0.09)
Zn	0.01	0.01	0.02	0.01	0.01
	(0.02)	(0.01)	(0.03)	(0.004)	(0.01)
Cu	0.001	0.002	0.002	0.002	0.003
	(0.003)	(0.002)	(0.002)	(0.002)	(0.003)
Pb	ND[2]	0.0009	ND[2]	0.0004	0.0012
		(0.0013)		(0.0003)	(0.0018)
	P-2	P-1	A-2	A-1	NP″
FE	0.51	0.40	0.30	0.28	0.38
	(0.22)	(0.36)	(0.25)	(0.24)	(0.38)
Mn	0.03	0.02	0.02	0.02	0.02
	(0.02)	(0.01)	(0.02)	(0.02)	(0.02)
Zn	0.01	0.01	0.02	0.01	0.01
	(0.01)	(0.005)	(0.03)	(0.01)	(0.01)
Cu	0.002	0.003	0.002	0.002	0.002
	(0.002)	(0.003)	(0.002)	(0.002)	(0.002)
Pb	0.0004	0.0013	ND[2]	0.0004	ND[2]
	(0.0005)	(0.0025)		(0.0002)	

[1] Standard deviations of the data are shown in parentheses.
[2] ND = Not detected during this study.

obtain a mean reservoir station concentration for each sampling date. In the calculation of these station means, ND (nondetectable) results were set equal to one-half the detection limit used in each particular analysis. This approximation was introduced to avoid either overestimating the mean, by setting ND equal to the detection limit, or underestimating the mean, by setting ND equal to zero.[5] Reservoir stations at which all three depth samples were ND, and stream stations with ND results, were assigned a sampling date mean of ND. Then, in the calculation of the overall means and standard deviations listed in table 9, these remaining ND's were set equal to one-half the detection limit listed in table 3, i.e., the detection limit in effect at the end of the study. This somewhat arbitrary assumption was introduced to simplify the final computations and, considering the small values involved, should not significantly affect the accuracy of the results for overall summary and trend analysis purposes.

Iron.—Overall mean iron concentrations at all stations of the Upper North Platte reservoir system, except A-1 and A-2 (table 9), exceed the 0.30 mg/L recommended by EPA as the criterion for domestic water supplies [24]. The main source of iron is the Medicine Bow River, followed by the Sweetwater and North Platte Rivers, respectively. Iron concentrations in the rivers vary directly with discharge, so that maximum concentrations usually occur during spring runoff. It appears likely that most of this iron is adsorbed onto particles of suspended sediment carried by the flow. In the reservoirs, much of this material settles out in the river arms, but some may pass through the reservoirs as turbid underflows, as previously discussed. Such through-flushing of particle-associated iron may be responsible for the close agreement in mean iron concentrations between stations K-2 and NP', below Seminoe and Kortes Dams, respectively.

There was also some evidence of iron releases into the lower portion of the hypolimnion from the bottom sediments during the late summer oxygen sag in 1978 at the deepwater stations S-1 and A-2. These elevated hypolimnetic iron concentrations disappeared, however, when bottom dissolved oxygen levels began to rise in September.

[5] Dr. Thomas J. Keefe, Envirostat Associates, Fort Collins, Colo., personal communication.

In summary then, although iron is usually present in the waters of the system, and concentrations often exceed EPA recommended drinking water criteria, most of this metal appears to be associated with suspended sediment particles and thus not biologically active.

Manganese.—Manganese is next in occurrence in the system. The highest overall mean concentrations were found in the Medicine Bow and Sweetwater Rivers, but an examination of the means and standard deviations listed in table 9 indicates that high manganese concentrations usually occurred as isolated "spot shots." These spot shots of elevated manganese concentration often appear to be the result of releases from the bottom sediments under low dissolved oxygen conditions. The largest such release noted during this study was 0.63 mg/L in the hypolimnion at station S-1 at the end of August 1978, when the bottom dissolved oxygen concentration dropped to 0.2 mg/L and the corresponding E_7 was 171 mV. This release at the bottom of S-1 was reflected in elevated manganese concentrations in Kortes Reservoir and the Miracle Mile through late September 1978. Similar, but much smaller, manganese releases were evident at most reservoir stations in late summer when bottom dissolved oxygen was depleted, but disappeared when the hypolimnia were recharged with oxygen in the fall. Such a cycle is not unusual in productive lakes and reservoirs, and it should be noted that manganese is usually the first metal to be reduced to a soluble form and released from bottom sediments under anoxic conditions [20, 25]. The EPA recommended domestic water supply criterion for manganese is 0.05 mg/L [24]. Three reservoir stations, S-1, K-2, and K-1, exceed this limit on a mean basis, but it should be remembered that the high mean values at these stations are mainly the result of the single large manganese release at S-1 in August 1978.

Zinc.—Overall mean zinc concentrations in the system display no particular trends. This metal is usually present at all stations in quantities at, or slightly above, detection limits. Highest spot concentrations were found at station A-2: 0.21 mg/L at middepth in August 1978, and in the Miracle Mile: 0.10 mg/L, also in August 1978. Thes two anomalous concentrations are an order of magnitude greater than any other observed during the course of the study, and may, therefore, be due to some sampling error or concentration in organisms collected in the water sample. In any case, no observed zinc concentration anywhere in the system ever exceeded the EPA recommended domestic water supply criterion of 5.00 mg/L [24].

Copper.—Copper was detected on occasion at all stations in concentrations usually ranging from 0.001 to 0.003 mg/L. The three major tributary rivers, and especially the Medicine Bow, sometimes contributed concentrations of copper in the range of 0.01 to 0.02 mg/L. These elevated concentrations appeared to be somewhat conserved throughout the system. This increased input of copper usually coincided with high spring runoff, and may have been associated with suspended sediment particles [22]. The domestic water supply criterion for copper recommended by EPA is 1.00 mg/L [24].

Lead.—Lead was rarely detected during this study, and then usually in concentrations at, or near, detection limits. Four stations, K-2, NP', A-2, and NP'', never yielded detectable concentrations of lead. It is perhaps interesting to note that stations K-2, NP', and NP'' are located immediately below the outlets of Seminoe, Kortes, and Alcova Dams, respectively, while station A-2 could be considered representative of the outflow from Pathfinder Reservoir. Whether or not their positions in the system coincide with the fact that lead was never detected at these stations is, at present, a provocative but moot question, given the sparsity of the data. Relatively high overall mean lead concentrations were found in the Medicine Bow and Sweetwater Rivers, at the deepwater stations, S-1, P-1, and K-1, and at station S-2, in the North Platte arm of Seminoe. In each of these cases, the relatively high means are the result of one or two isolated concentrations in the range of 0.001 to 0.007 mg/L. The remaining five stations all had overall mean concentrations of 0.004 mg/L, which are indicative of rare, barely detectable occurrences of lead. The EPA criterion for lead in domestic water supplies is 0.05 mg/L [24].

Nitrogen-Phosphorus Plant Nutrients

During this study, water samples were analyzed for total and orthophosphate (PO_4) phosphorus, and total Kjedahl, ammonia (NH_3), nitrite (NO_2), and nitrate (NO_3) nitrogen (table 3). Only the inorganic forms of phosphorus and nitrogen, however, are immediately useful to autotrophic plants [20, 25, 26, 27].

TKN (total Kjeldahl nitrogen) includes both the ammonia and organic forms [17], and is thus an indicator of the amount of organic input to a system as well as the rate of ammonification or bacterial decomposition of nitrogeneous organic material to inorganic ammonia. The succeeding steps whereby ammonia is oxidized to nitrite and then to nitrate are called "nitrification." These last three forms of nitrogen are all inorganic, and thus immediately available as plant nutrients [25, 26]. Under aerobic conditions, however, only the NO_3 form is stable. While NO_2 is usually present in small quantities in lake water, it is rapidly oxidized to NO_3 except under anaerobic conditions [26]. In this report, the term TIN (total inorganic nitrogen) will be used to mean the combined concentration of the NH_3, NO_2, and NO_3 forms.

Orthophosphate is the phosphorus form that is immediately available for algal growth [20, 27]. Total phosphorus (TP), on the other hand, includes various soluble and insoluble, organic and inorganic forms of phosphorus [17]. Lambou et al. [28] point out, however, that due to the "high mobility and short turnover times of phosphorus * * * within the general 'phosphorus pool'," TP is often "a good approximation of bioavailable phosphorus."

Some limitations of these data should be mentioned. First, there are no N-P data for 1976 because analytical methods adequate to detect the relatively low concentrations involved were not available until 1977. Second is the temporal sparsity of the data: early and late summer in 1977; monthly, from June through September in 1978 (except at Pathfinder, which was only surveyed in June and August); and May, August, and October in 1979. Finally, the May 1979 phosphorus data were lost through a laboratory accident, and it is thus difficult to compare early summer 1979 with the two previous years.

The relatively complete N-P record from the summer of 1978 represents a "wet year" following 2 years of drought, and it may therefore be somewhat anomalous. However, these data are presented in some detail (table 10) because they display seasonal cycles that are at least representative of wet, or high-water, years.

The first evident cycle in table 10 is that of PO_4-P. In early summer 1978, PO_4-P was detectable at

Table 10.—*Mean 1978 nitrogen and phosphorus concentrations*

Station	Date	(PO_4-P) Orthophosphate phosphorus	(NO_3-N) Nitrate nitrogen	(NH_3-N) Ammonia nitrogen	(TKN) Total Kjeldahl nitrogen[1]
		(μg/L)			
		Seminoe Reservoir stations			
MB	2 June	5	15	ND[2]	1050
	14 June	ND	25	20	120
	19 July	ND	7	ND	150
	30 Aug.	ND	3	ND	ND
	29 Sept.	ND	3	10	90
S-3	15 June	4	58	27	320
	20 July	ND	8	ND	230
	31 Aug.	ND	7	33	310
	28 Sept.	1	48	43	300
NP	1 June	5	10	ND	480
	14 June	10	7	10	420
	19 July	ND	1	ND	240
	30 Aug.	ND	160	ND	330
	28 Sept.	ND	3	ND	300
S-2	15 June	ND	53	8	510
	20 July	ND	3	ND	90
	31 Aug.	5	25	43	240
	28 Sept.	2	85	10	270
S-1	31 May	ND	172	20	390
	15 June	ND	132	60	340
	20 July	ND	68	12	270
	31 Aug.	9	144	17	410
	28 Sept.	5	238	7	290
		Kortes Reservoir stations			
K-2	1 June	ND	195	35	300
	14 June	ND	130	ND	150
	19 July	ND	25	ND	300
	30 Aug.	10	228	10	240
	27 Sept.	10	149	ND	270
K-1	1 June	ND	187	22	390
	14 June	ND	113	53	350
	19 July	ND	2	ND	320
	30 Aug.	13	235	7	290
	27 Sept.	10	140	7	320
		Pathfinder Reservoir stations			
NP'	1 June	ND	175	ND	300
	14 June	ND	56	ND	180
	19 July	ND	2	ND	240
	30 Aug.	5	163	ND	360
	27 Sept.	5	100	ND	240
P-3	12 June	ND	32	32	330
	28 Aug.	4	107	5	200
SW	12 June	10	3	ND	150
	28 Aug.	ND	2	ND	ND

Table 10.—*Mean 1978 nitrogen and phosphorus concentrations*—Continued

Station	Date	(PO_4-P) Orthophosphate phosphorus	(NO_3-N) Nitrate nitrogen	(NH_3-N) Ammonia nitrogen	(TKN) Total Kjeldahl nitrogen[1]
			(μg/L)		
P-2	12 June	ND	6	35	490
	28 Aug.	4	18	58	290
P-1	12 June	2	11	20	570
	28 Aug.	2	119	7	250
			Alcova Reservoir stations		
A-2	13 June	ND	61	17	660
	18 July	ND	ND	ND	320
	29 Aug.	ND	190	13	240
	26 Sept.	2	70	8	160
A-1	13 June	ND	58	32	590
	18 July	ND	34	ND	280
	29 Aug.	ND	90	13	290
	26 Sept.	9	73	13	230
NP''	14 June	ND	64	20	300
	19 July	ND	3	ND	120
	30 Aug.	ND	250	ND	240
	27 Sept.	5	85	14	270

[1] TKN (total Kjeldahl nitrogen) includes both the ammonia (NH_3) and the organic nitrogen forms.
[2] ND = Not detected during this study.

only two reservoir stations, S-3 and P-1, and, more importantly, in the three main tributary rivers. By July, there was no detectable PO_4-P at any stream or reservoir station sampled. Then, in late August, PO_4-P was present in detectable concentrations at S-2 and S-1 in Seminoe Reservoir, at all the stations in Kortes and Pathfinder Reservoirs, and in the Miracle Mile (NP'). By late September, PO_4-P was detected at every station in the system except the three main tributary rivers, where it had not been found since peak runoff in June.

Apparently, the 1978 spring runoff in the Medicine Bow, North Platte, and Sweetwater Rivers contributed PO_4-P to a reservoir system that had perhaps become depleted of its supplies of bioavailable phosphorus by through-flushing and/or uptake during the drought and the previous winter. The spring phosphorus input probably settled out with the suspended sediment load once it reached the reservoirs. By July 1978, Seminoe's water level was the highest since 1976 (fig. 9) and thermal stratification was at its maximum throughout the system (appendix A). Under these conditions it would not be unreasonable to think that PO_4-P was being both released from the sediments brought in by the spring runoff, and desorbed from the newly inundated littoral areas that had been exposed since 1976 [25]. As thermal stratification began to break down in August, these newly liberated phosphorus supplies would be mixed throughout the water column and become available for algal production. The rather sudden appearance of detectable concentrations of bioavailable phosphorus in late August to late September 1978 did coincide with the onset of the annual bluegreen algae bloom at all the reservoir stations in the system.

Mean NO_3-N concentrations at the various reservoir stations (table 10) also display a definite summer pattern, with high values in June, greatly reduced values in July, and elevated values again in late August. Hutchinson [25] writes that "maximal amounts of nitrate tend to be present [in lakes] at the end of winter or at the vernal circulation period [i.e., spring turnover]." He attributes this to ammonification of organic material during winter stagnation, with subsequent nitrification and mixing during spring turnover. In the Upper North Platte reservoir system, the cause of this early summer NO_3-N peak is probably also related to an accumulation of the stable NO_3 form [26] from the tributary inflows, and a lack of sufficient biological activity during the winter to use it up. The midsummer NO_3-N "sag" here, however, seems well explained by Hutchinson [25] who writes, "In more productive lakes with clinograde [i.e., concentration decreasing with depth] oxygen curves, nitrate is usually removed by assimilation in the trophogenic layer and by reduction [i.e., denitrification] near the bottom of the lake, producing a marked dichotomic distribution with a nitrate maximum in the middle water." This pattern of low NO_3-N concentrations in the upper and lower layers of the water column and a higher concentration in the middle was actually observed at S-1 and K-1 in July and at A-1 in August 1978. Finally, the higher mean NO_3-N concentrations observed throughout the system beginning in late August are probably explained by the predominance of nitrogen-fixing, bluegreen algae in the trophogenic zone and by oxidation of NH_3 and NO_2 in the bottom zone caused by weakening of thermal stratification.

Mean NH_3-N concentrations (table 10) were generally highest in June 1978 at the dam stations (S-1, K-1, P-1, and A-1), while in the three main tributary arms (S-2, S-3, and P-2), they were highest in August or September. In both cases, these higher NH_3-N concentrations were probably the result of ammonification of organic deposits: (1) of internally produced organic material during winter stagnation near the dams, and (2) of runoff-deposited debris during summer stratification in the three main river arms. Concentrations of NH_3-N at stations P-3 and A-2 approach the same levels as those at stations P-1 and A-1, respectively, which follows the above reasoning in that neither P-3 or A-2 are subject to direct spring runoff loading.

Mean TKN concentrations (table 10) followed a general trend of relatively heavy loading from the three major tributaries during the runoff season, followed by declining concentrations as flows diminished. After a low period in July, TKN concentration rose again in August or September throughout most of the system, probably due to late summer algal production in both reservoirs and streams.

Pathfinder and Alcova Reservoirs appear to have deviated somewhat from this pattern, showing a general decline in TKN concentrations from early through late summer. While the data are sparse on Pathfinder, the Alcova concentrations should be a good reflection of events immediately upstream, and they bear out this generally declining trend. Perhaps a combination of increased irrigation season flushing of Pathfinder and Alcova, and a retention and utilization of nutrients further upstream limited the internal production of organic matter in the two reservoirs in the late summer of 1978.

A comparison of mean NH_3-N and TKN concentrations in table 10 indicates that most of the TKN observed in the three main tributaries, the Miracle Mile, and the releases from Seminoe and Alcova were in organic form during 1978. In fact, all the TKN in the Sweetwater River and the Miracle Mile was apparently in organic form since NH_3-N was never detected in either stream. This observation fits well with the fact that these are all well-oxygenated streams and that, therefore, any NH_3 should be rapidly oxidized to NO_3. Early summer TKN peaks in these streams were probably due to overland runoff, while the later season peaks, particularly in the North Platte above Seminoe (NP), the Miracle Mile (NP′), and the North Platte above Alcova (NP″), were probably due to instream algal production. The Miracle Mile, especially, is often observed to produce large amounts of algae in mid- to late summer [6]. Detectable concentrations of NH_3-N in the Medicine Bow and North Platte Rivers above Seminoe would indicate that some ammonification took place instream, while those in the releases from Seminoe and Alcova are most likely due to NH_3 being produced in the bottom deposits behind the dams.

Figures 21 and 22 are early and late season plots of mean TIN and PO_4-P concentrations, respectively, at the various system stations for 1977-79. The main trend evident on figure 21 is a bimodal distribution of TIN within the Upper North Platte reservoir system. Roughly, the trend consists of a general buildup of TIN concentrations through Seminoe to a peak in Kortes, a sharp drop in the Miracle Mile, a general low through Pathfinder, and a second buildup in Alcova. In August 1977, however, the overall pattern was very different in that there were dramatic TIN peaks in the river arms of Pathfinder Reservoir, instead of the midsystem "sag" evident in the other 2 years, and even in June of the same year. These high TIN concentrations coincided with an extremely large bluegreen algae bloom in Pathfinder.

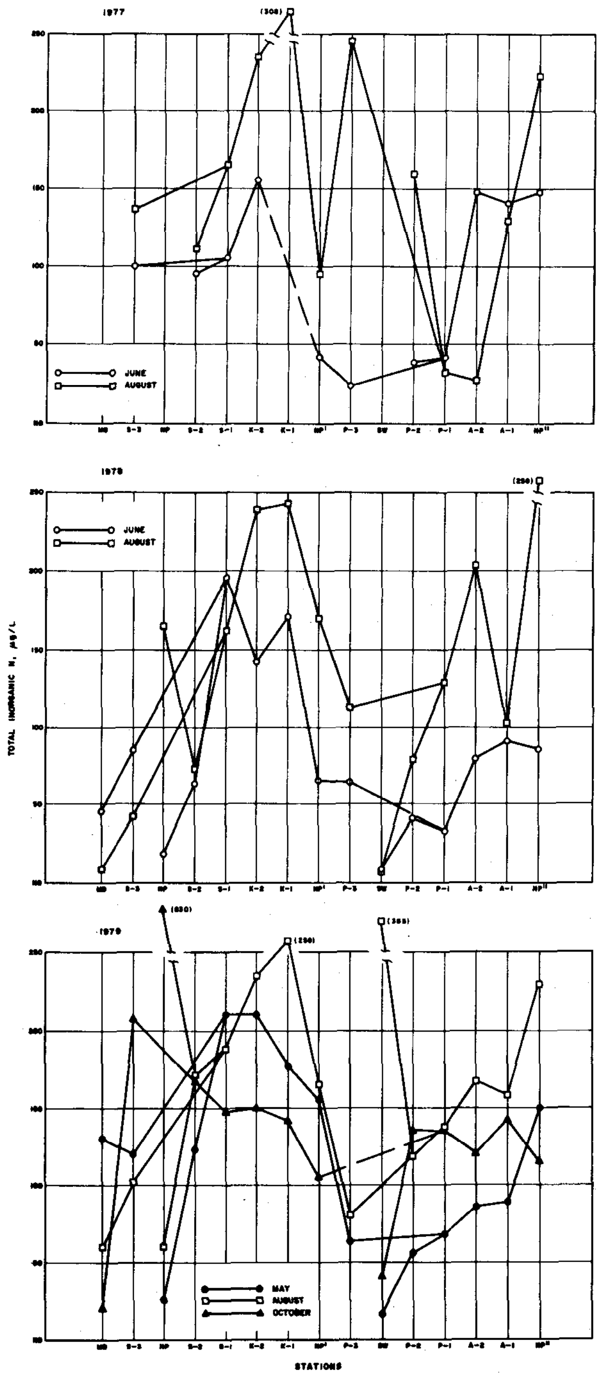

Figure 21.—Total inorganic nitrogen concentrations - Upper North Platte reservoirs, Wyoming.

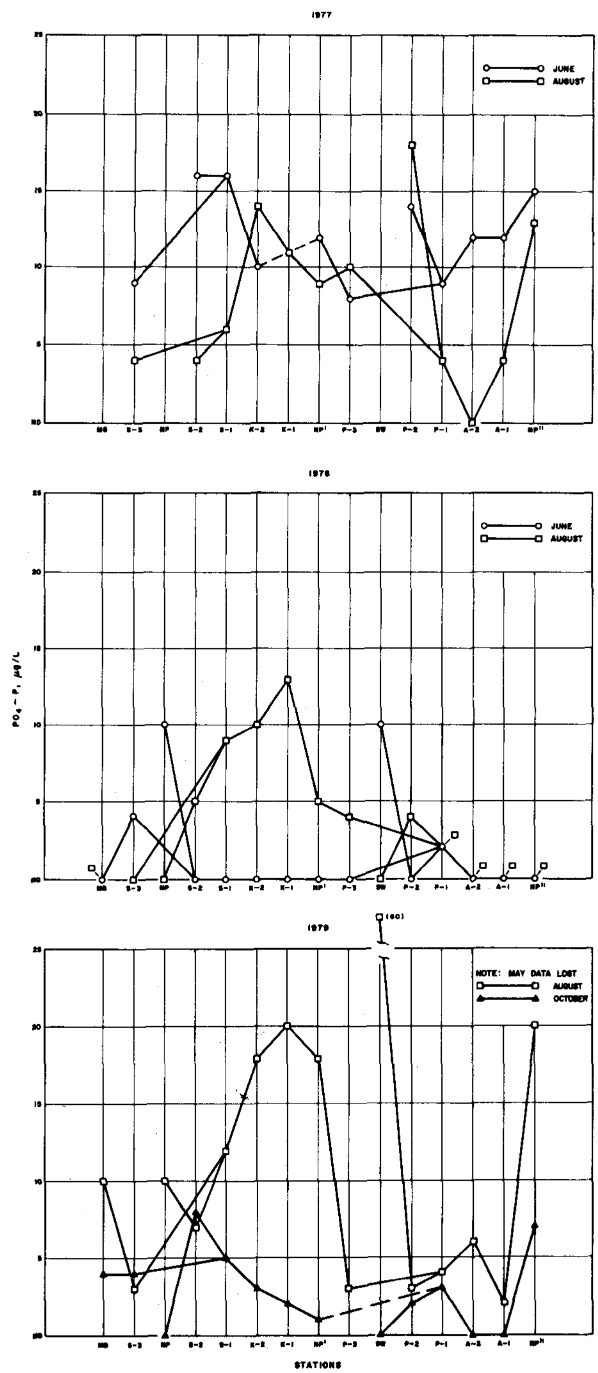

Figure 22.—Orthophosphate phosphorus concentrations - Upper North Platte reservoirs, Wyoming.

The sharp decline in TIN concentration that was evident at station NP′ throughout this study may reflect utilization of available nitrogen for algal production in the Miracle Mile. As mentioned earlier, this stretch of river often supports large quantities of epilithic algae in mid- to late summer [6], and there is some evidence from studies done in Montana that algal communities immediately below deep reservoir discharges are mainly nitrogen limited [29, 30]. The extent of nitrogen utilization in the Miracle Mile and any export of instream-produced organic material could, in turn, affect primary production at station P-3 in the North Platte arm of Pathfinder Reservoir.

The loss of the May 1979 phosphorus data makes identification of seasonal trends on figure 22 somewhat speculative; however, certain important differences between the drought year, 1977, and the high-runoff years, 1978-79, are evident. In 1977, the drought year, there was an early availability of PO_4-P throughout the system. By August, PO_4-P concentrations in Seminoe at P-1, and at Alcova had all declined significantly due to the flushing action of continuous power releases from Seminoe and irrigation releases from Pathfinder and Alcova. At the same time, PO_4-P concentrations rose at K-2 and at P-3 and P-2 in the river arms of Pathfinder. This increased PO_4-P in the "middle" of the system was apparently contributed by releases from Seminoe and by the Sweetwater River. Seminoe Reservoir was by this time extremely low for late summer, and thus approaching a quasi-riverine state in which nutrients would be more likely to pass through rather than be stored in the impoundment.

In 1978, the first high-runoff year after the drought, there was an early tributary input of PO_4-P to a depleted, flushed reservoir system. (See also table 10 and the discussion of the 1978 data earlier in this section.) By late August, PO_4-P concentrations at most reservoir stations, especially from S-2 through Kortes to P-1, had increased significantly. This late season increase in PO_4-P availability affected Alcova by late September, while concentrations upstream at S-2 and S-1 began to decline (table 10). The early season PO_4-P conditions in 1979 can only be guessed at, but the late August trend appears to be a similar, though more pronounced, version of that observed in August 1978. By October 1979, a general decline in PO_4-P concentration from S-1 on down through the system seems to support the idea of a winter depletion of phosphorus stocks to a low level in the following spring.

In summary then, the system began the drought year, 1977, in a chemically concentrated state, as discussed in the section on major ions above, and this chemical concentration included PO_4-P in relatively high concentrations. During that summer, Seminoe, the deep end of Pathfinder, and Alcova were being flushed, and PO_4-P was being concentrated in the river arms of Pathfinder. In August 1977, the largest bluegreen algae bloom of this study was observed in the river arms of Pathfinder Reservoir. By June 1978, PO_4-P concentrations throughout the system were low to below detection limits due to depletion and flushing since the previous August and perhaps to dilution by the heavy spring runoff. This high runoff contributed enough PO_4-P to raise concentrations to significant levels in all the reservoirs by late August or September. At the same time as bioavailable phosphorus began to appear in detectable amounts, bluegreen algae began to bloom at the various stations. The incomplete 1979 data seem to support the idea that PO_4-P then became depleted through the winter months to low levels in the following spring when, once again, heavy runoff increased the supply.

Figures 23 and 24 recapitulate the preceding discussion, showing mean reservoir TIN and PO_4-P concentrations, respectively, for early and late summer of 1977-79. The relatively low June TIN concentrations in Pathfinder in all 3 years are clearly evident on figure 23. Possibly this annual phenomenon is related to nitrogen utilization by algal communities in the Miracle Mile, since they begin growing in the spring [29, 30]. Also evident on figure 23 is the comparatively high TIN concentration in Pathfinder that accompanied, and probably resulted from, the large bloom of nitrogen-fixing, bluegreen algae in August 1977.

Figure 24 shows the high concentrations of PO_4-P present throughout the system in the low-runoff spring of 1977, and the late summer accumulation of this bioavailable phosphorus in the "middle" of the system. Mean reservoir PO_4-P concentrations in the high-runoff years, 1978-79, appear to follow the seasonal cycle outlined earlier: low to undetectable concentrations in early summer, relatively high concentrations appearing in late August and September,

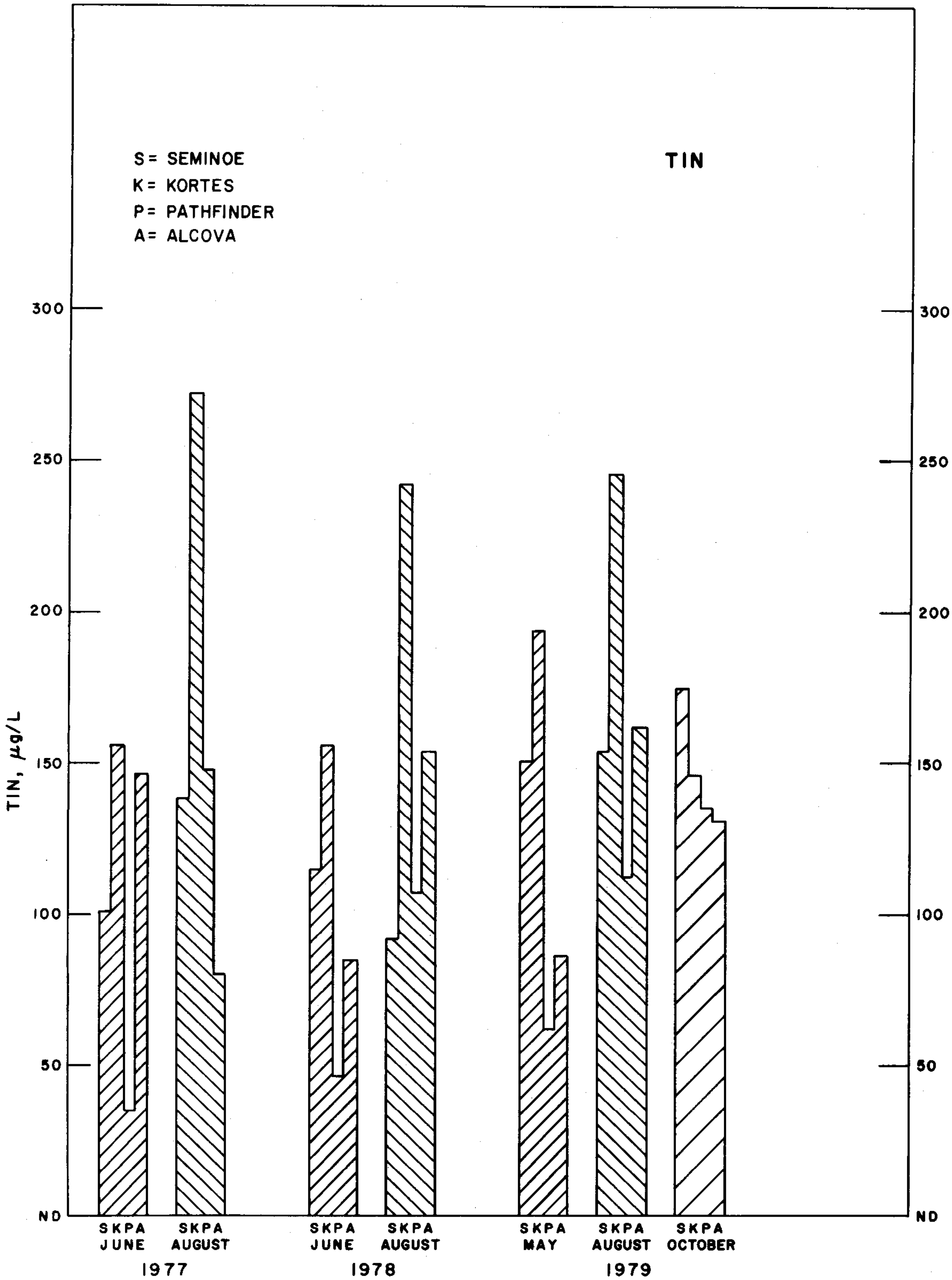

Figure 23.—Mean TIN (total inorganic nitrogen) concentrations - Upper North Platte reservoirs, Wyoming.

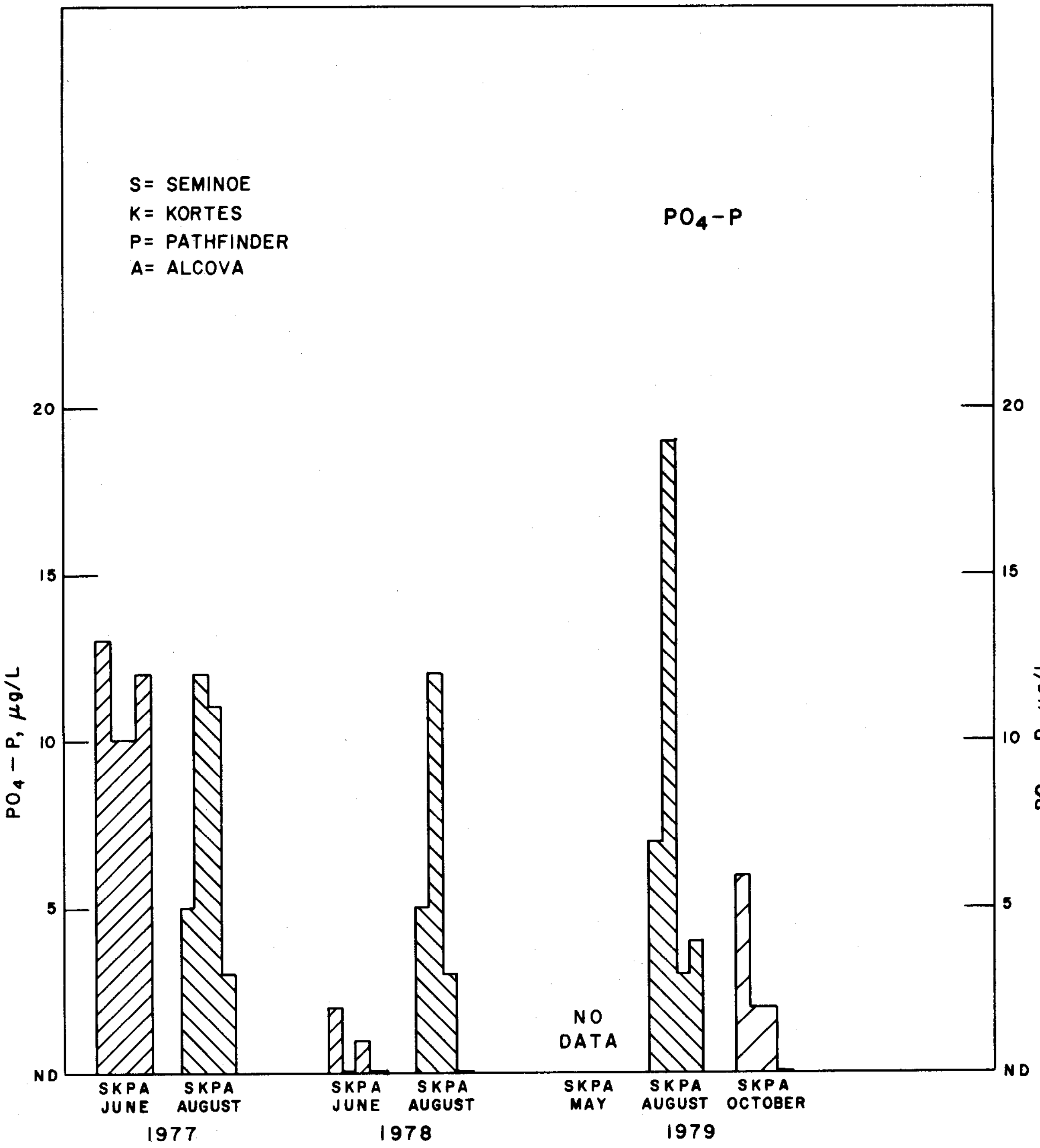

Figure 24.—Mean PO_4-P (orthophosphate phosphorus) concentrations – Upper North Platte reservoirs, Wyoming.

and a general decline in concentrations in the fall.

Figure 25 synthesizes the data from the previous two figures to elucidate the interaction between the two critical plant nutrients. Nitrogen and phosphorus are, of course, utilized together by autotrophic plants, but some diatoms, for example, compete best under conditions where phosphorus is relatively scarce, while bluegreen algae, being able to fix nitrogen from the atmosphere, compete well where nitrogen is the limiting nutrient [20, 25]. The ratio of nitrogen-to-phosphorus concentrations, or N/P ratio, is often used to indicate which nutrient is more limiting in a given situation. There are many approaches to this ratio in the limnological literature, both as to the chemical forms of nitrogen and phosphorus used in the computation and the cutoff points between nitrogen- and phosphorus-limiting conditions. Here, the approach developed by Lamboue et al. [28] was used. The immediately bioavailable forms of nitrogen and phosphorus, TIN and PO_4-P, respectively, were used to compute the N/P ratios on figure 25. Suggested cutoff points established by Lambou et al. [28] are as follows:

- $N/P > 14$ indicates a largely phosphorus-limited environment
- $N/P < 10$ indicates a largely nitrogen-limited environment
- $10 \leq N/P \leq 14$ indicates a "transition," or "co-limited," environment

In regard to the last, "transition," category, Lambou et al. [38] state, "This group contains a number of lakes whose N/P ratios * * * suggest seasonal shifts from one dominant limiting nutrient to the other across a transition zone in which pronounced interaction is likely."

On figure 25, it can be seen that because of the high concentrations of PO_4-P present in the system (fig. 24), both Seminoe and Pathfinder were well into the "largely nitrogen-limited" category in June 1977. By August 1977, due to the accumulation of PO_4-P in the "middle" of the system (fig. 24), Pathfinder was still in the "transition," or "co-limited," zone, while Seminoe had moved into the "largely phosphorus-limited" category. While these ratios are only general indicators of relative nutrient limitation, it is evident that Pathfinder, in 1977, presented a favorable environment for bluegreen algae throughout the summer season.

Conditions in 1978 were rather different. In this year, the late summer appearance of detectable concentrations of PO_4-P (fig. 24) caused a dramatic downward shift in the N/P ratio for Seminoe Reservoir, from high in the phosphorus-limited range to near the "transition" zone. The corresponding N/P ratio shift in Pathfinder was hardly significant, although the initial ratio here was less than half that in Seminoe. In both cases, however, the mere appearance of detectable concentrations of bioavailable phosphorus seemed to be enough to "trigger" the late summer bluegreen algae bloom in both reservoirs. The 1979 data on figure 25 are somewhat inconclusive, although the August N/P ratios for both Seminoe and Pathfinder are close to those observed in 1978. In both 1978 and 1979, bluegreen algae "bloomed" in Seminoe and Pathfinder in late August, but none was of the magnitude of the Pathfinder bloom of August 1977.

Finally, the case of Kortes Reservoir should be noted. Figure 25 indicates that N/P ratios for this reservoir were often the lowest in the system because of relatively high PO_4-P concentrations in the water being released from the hypolimnion of Seminoe Reservoir (fig. 24). It would seem that Kortes should, therefore, support large populations of bluegreen algae. In fact, it does not, probably because its rapid flushing rate precludes the development of large indigenous algal populations.

The ultimate source of nutrients in the Upper North Platte reservoir system is, of course, the basin watershed. Nutrients are transported from the watershed into the reservoirs by the tributary streams, especially the three major tributaries: the North Platte, Medicine Bow, and Sweetwater Rivers.

Figure 26 shows an estimate, based on USGS discharge and water quality data [16], of the annual NO_3-N and TP loading of Seminoe Reservoir by the North Platte and Medicine Bow Rivers during this study period. Only NO_3-N and TP concentrations were available [16] for this estimate; however, considering the fact that NO_3 is the only stable inorganic form of nitrogen under well-oxygenated conditions [26] and the

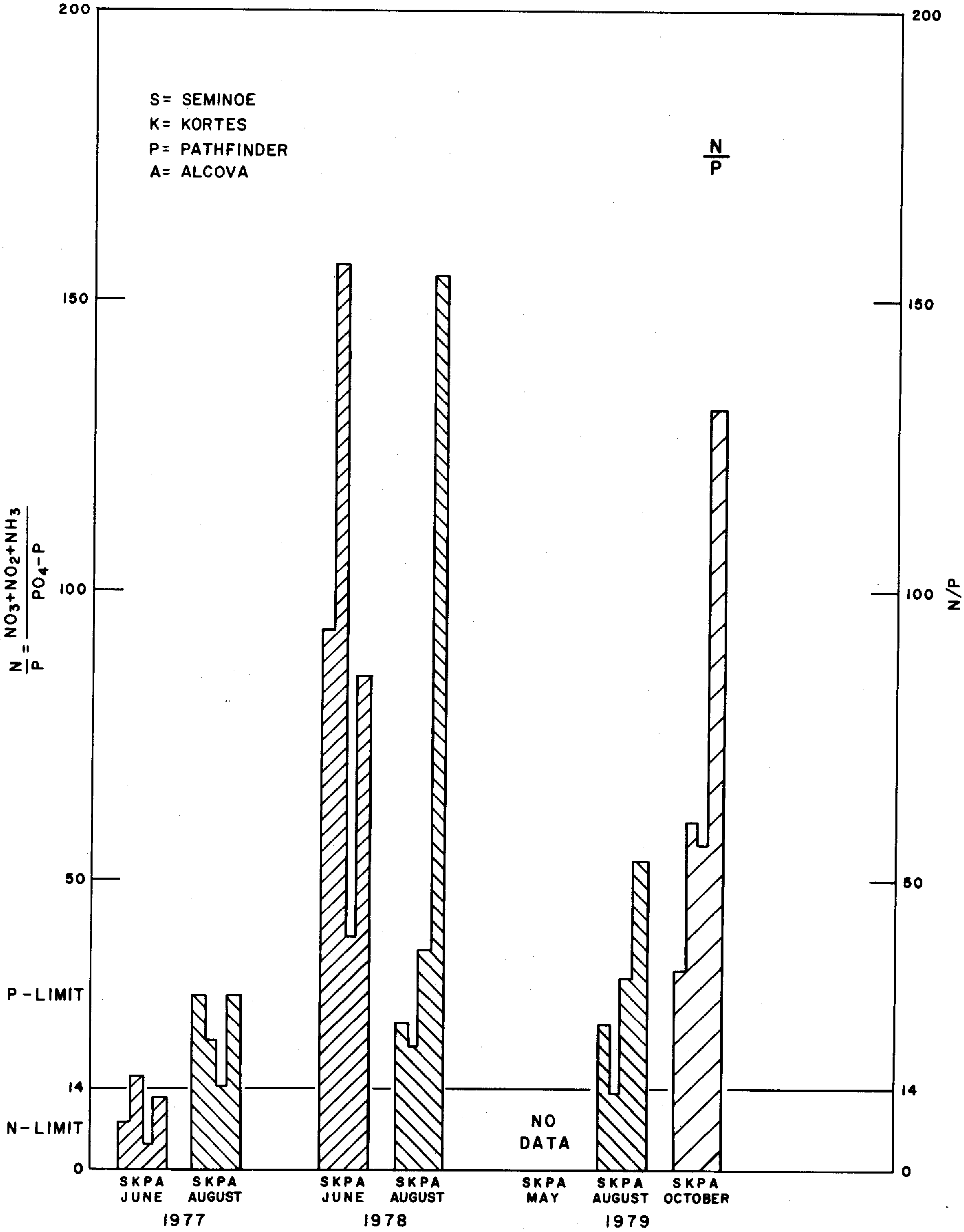

Figure 25.—Mean N/P (nitrogen/phosphorus) ratios – Upper North Platte reservoirs, Wyoming.

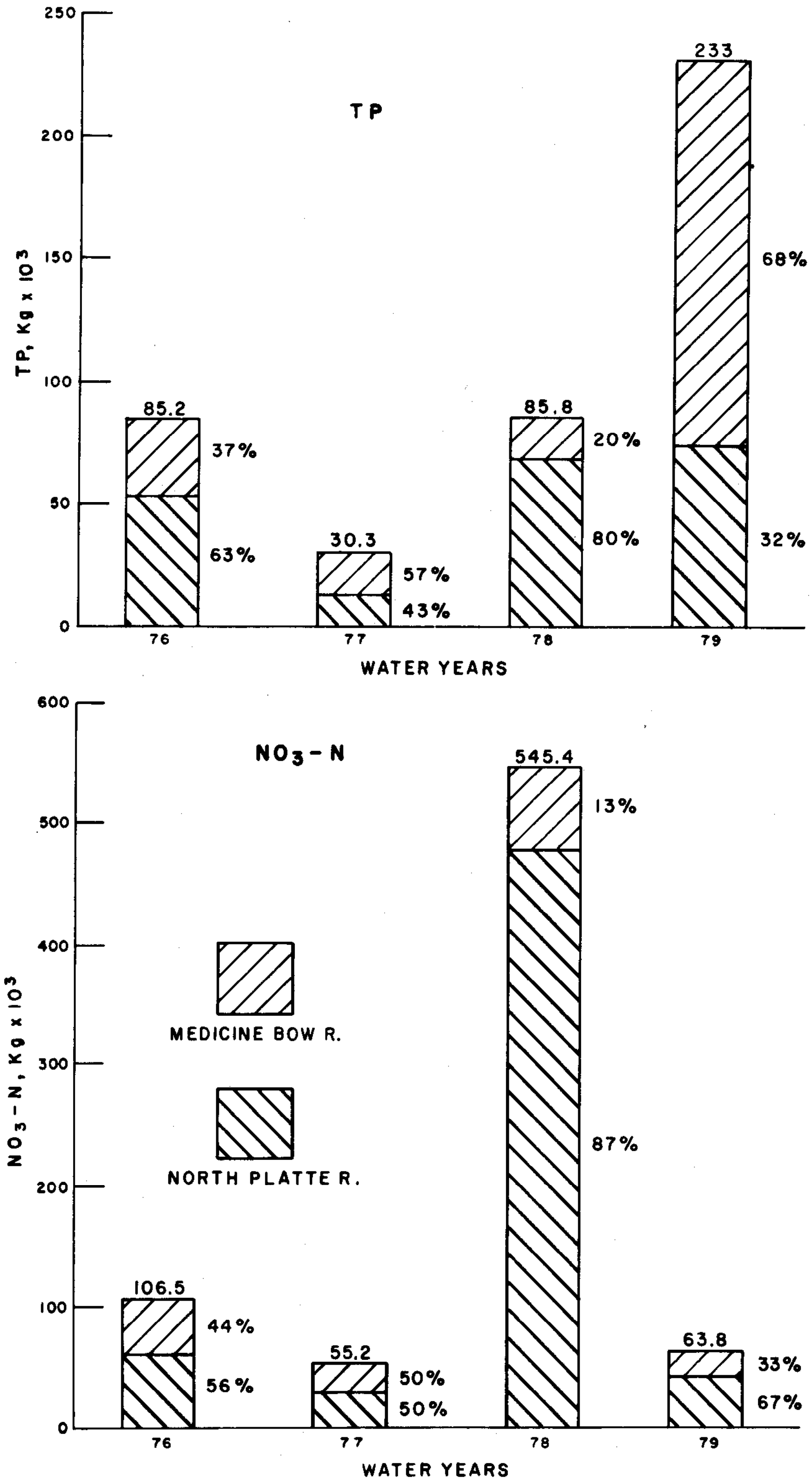

Figure 26.—Estimated annual tributary loading of NO_3-N (nitrate nitrogen) and TP (total phosphorus) - Seminoe Reservoir.

rapid turnover rate of TP [28], these two forms should closely approximate the total amount of bioavailable nitrogen and phosphorus contributed by the two rivers.

There are several recent articles on field studies of nutrient yield/runoff relationships [31-35], and the general consensus seems to be that nutrient yield from a watershed varies directly with runoff volume. In particular, Knight and Harrison [31] found that nutrient losses by leaching from a lodgepole pine forest in the Medicine Bow Mountains of Wyoming occurred only during years of heavier than normal snowfall. Lewis and Grant [32] also noted that the export of "biologically sensitive substances" from the watershed of Como Creek in the Front Range of Colorado seemed to depend upon the flushing of the biological compartments of the watershed ecosystem by increased runoff.

Comparing figures 26 and 10, it is evident that the nitrogen and phosphorus loading of Seminoe Reservoir dropped significantly during the low-runoff year, 1977, and then increased during the high-runoff years that followed. However, the nutrient yield/runoff relationships displayed by the North Platte and Medicine Bow Rivers during the two high-runoff years were more complex than a simple "yield-directly-proportional-to-runoff" model would predict.

Table 11 lists the observed runoff volumes and estimated NO_3-N and TP yields for all three major system tributaries for WY[6] 1976 through WY 1979. The North Platte River showed a direct relationship between TP yield and runoff for WY's 1976 through 1978, but TP yield in WY 1979 increased somewhat over WY 1978, even though runoff volume during the same period decreased. This was even more evident in the Medicine Bow River, where TP yield did not seem to be affected by the dramatic runoff increase in WY 1978, but then increased by an order of magnitude in WY 1979, when runoff was significantly lower.

The Sweetwater River displayed different trends from the other two major tributaries in runoff volume and TP yield. While the Sweetwater was also subject to a sharp decline in runoff and phosphorus load in WY 1977, runoff only gradually increased during the next 2 years to a WY 1979 volume that was still slightly less than that of WY 1976. At the same time, TP yield in WY 1978 returned to a level about equal to that of WY 1976 and then dropped somewhat in WY 1979.

In summary, phosphorus loads carried by the three major system tributaries followed runoff volumes consistently throughout WY 1977; i.e., as runoff decreased dramatically in the drought year, so did phosphorus yield from the watershed. However, the pattern of return to higher yields with increased runoff in WY's 1978 and 1979 was not a clear, directly proportional increase, but varied according to the particular river and its watershed.

Patterns of NO_3-N loading in relation to runoff volume were more uniform among the three major tributaries (table 11). Yields of NO_3-N dropped in WY 1977, increased dramatically in WY 1978, and then in WY 1979, fell to levels below those of the drought year in the Medicine Bow and Sweetwater and lower than the WY 1976 level in the North Platte. Apparently, the return of high streamflows in WY 1978 had the effect of flushing out a large amount of NO_3-N from all three watersheds. Perhaps this "big flush" left the watersheds relatively depleted of NO_3-N in the following year.

The nitrogen and phosphorus loading estimates discussed here (table 11) are very approximate, but the trends identified should be valid, since the basic data were consistent from year to year. Nutrient yields for the three major tributary watersheds showed a direct relationship to runoff through the drought, but recovery in the succeeding high-runoff years was more complex. The reasons for this complexity are probably due to the nature of the biological sequestering mechanisms in the individual watersheds [31, 32, 33] and in the streams themselves [34].

Primary Production

Chlorophyll data are widely used to categorize lakes and reservoirs. Likens [36] uses mg/m³ of chlorophyll *a* to classify lakes and reservoirs into three trophic states: oligotrophic (low productivity), 0 to 3 mg/m³; mesotrophic (average productivity), 2 to 15 mg/m³; and eutrophic (high productivity), 10 to 500 mg/m³. Table 12

[6] The water year begins on October 1 and continues through the following September 30; e.g., WY 1976 = October 1, 1975 through September 30, 1976.

Table 11.—*Tributary annual inflows and estimated nutrient loadings*

Water year	North Platte River[1]			Medicine Bow River[2]			Sweetwater River[3]		
	Total inflow	Estimated loading ($kg \times 10^3$)		Total inflow	Estimated loading ($kg \times 10^3$)		Total inflow	Estimated loading ($kg \times 10^3$)	
	($m^3 \times 10^8$)	NO_3-N	TP	($m^3 \times 10^8$)	NO_3-N	TP	($m^3 \times 10^8$)	NO_3-N	TP
1976	8.253	59.2	53.5	1.494	47.3	31.6	2.024	21.4	11.1
1977	4.362	27.8	13.1	0.917	27.5	17.2	1.269	10.9	2.90
1978	12.240	474.9	69.0	2.087	70.5	16.8	1.707	67.9	11.5
1979	12.074	42.5	74.1	1.600	21.2	159.0	1.917	10.4	9.77

[1] Watershed area = approximately 13 048 km² [12]
[2] Watershed area = approximately 5938 km² [12]
[3] Watershed area = approximately 5879 km² [12]

compares June and August chlorophyll *a* data from all four reservoirs for the years 1977-79. The four North Platte reservoirs show several interesting trophic trends when considered on a yearly basis (fig. 27). Alcova, Kortes, and Seminoe could all be classified according to their chlorophyll *a* biomass as oligotrophic in 1977. Pathfinder was the exception: At a mean chlorophyll value of 22.5 mg/m³ for all three stations in 1977, it was well into the eutrophic category. By comparision, all four reservoirs were in the mesotrophic range during 1978, although Kortes was low-borderline. During 1979, Kortes fell into the oligotrophic range, while the other three reservoirs were still classified as mesotrophic.

Data on phytoplankton species composition and abundance are available only for 1979. In previous years, plankton samples were collected

Table 12.—*Mean Chlorophyll* a

Reservoir	Year	June	August	October
			(mg/m³)	
Seminoe	1976	–	3.53	
	1977	1.22	3.33	
	1978	7.53	15.62	
	1979	4.62	12.82	1.97
Kortes	1977	1.09	1.09	
	1978	4.48	1.35	
	1979	1.53	1.80	1.11
Pathfinder	1977	1.45	41.78	
	1978	5.55	10.15	
	1979	2.12	8.02	4.35
Alcova	1977	1.08	2.53	
	1978	6.52	5.55	
	1979	6.68	3.78	1.98

with a Clarke-Bumpus sampler equipped with a No. 10 net. Most of the planktonic algae species pass through apertures of this size. Samples were collected with a No. 20 closing net during the 1979 surveys. More of the zooplankters (i.e., rotifers and nauplii) and planktonic algal species between 0.158 and 0.076 mm were retained by the No. 20 net.

Chlorophyll *a* concentrations throughout the system were generally derived from a phytoplankton population of diatoms in the early spring, and an abundance of the filamentous bluegreen alga, *Aphanizomenon flos-aquae,* later in the summer. *Tabellaria* was the dominant diatom species in all four reservoirs in the early spring, although *Asterionella, Synedra,* and *Melosira* were also found. By mid-July, most of the chlorophyll *a* was directly attributable to the onset of the annual bloom of *Aphanizomenon flos-aquae.*

Profiles of chlorophyll *a* concentrations (fig. 28) reflect this difference in species composition between June and August. June profiles of chlorophyll *a* may show peak concentrations occurring at 9 or even 15 meters. Maximum chlorophyll *a* concentrations during August usually occur at or near the surface. This difference in the depth at which maximum chlorophyll *a* concentrations occur can be attributed to the light and temperature requirements of the currently dominating algal species. Diatoms dominate algal populations in early spring. They are less buoyant and more competitive at lower light intensities and cooler temperatures. Therefore, maximum abundance is often observed further down in the water column. Bluegreen algae, however, require the warmer temperatures and high light intensities which are found at the water's surface,

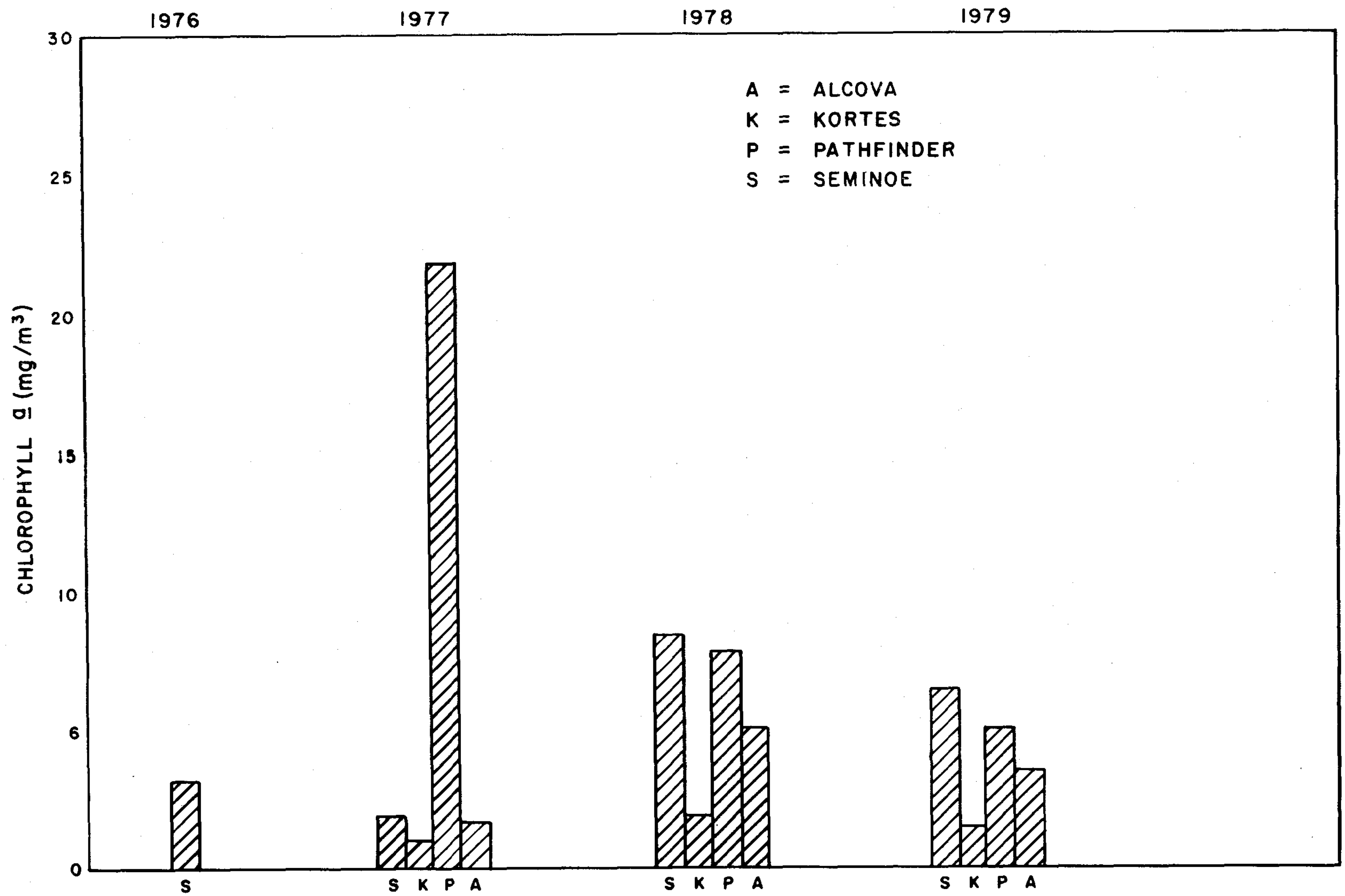

Figure 27.—Mean chlorophyll *a* by reservoir and year.

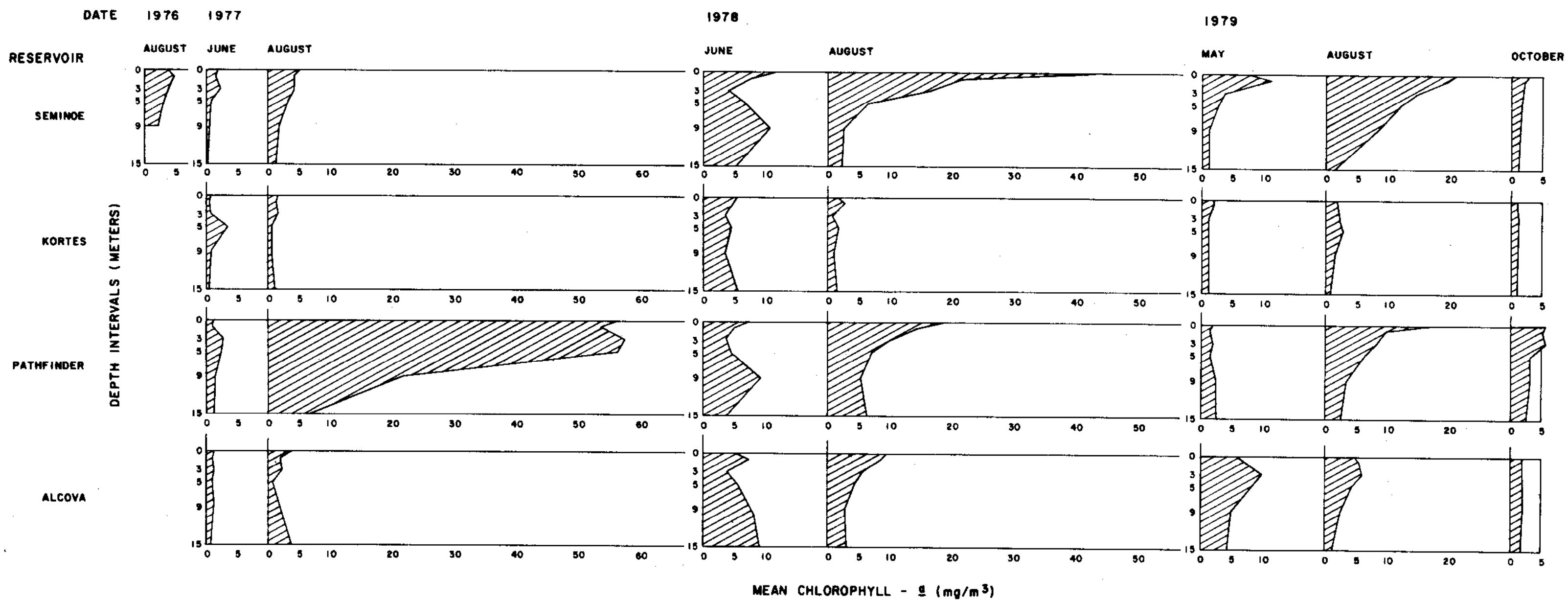

Figure 28.—Chlorophyll *a* concentration - Upper North Platte reservoirs, Wyoming.

although this seems to be dependent upon the degree of wind mixing of the water column. This peak in productivity usually occurs in late August, but can be delayed by sediment-caused turbidity (table 13). During 1978, maximum chlorophyll *a* concentrations seem to have been delayed in the Medicine Bow arm of Seminoe Reservoir (S-3) for about a month. (See appendix E.) This phenomenon was mentioned in a previous section.

The magnitude of the *Aphanizomenon* bloom largely precludes significant multispecies algal populations because this alga produces an alphan toxin, which has been shown to inhibit growth of other biota [37]. Zooplankton populations also decrease because of sensitivity to the toxin. In addition, *Aphanizomenon* fouls the mouth parts of zooplankton and is difficult for them to digest [38]. U.S. Geological Survey data [16], which reports phytoplankton populations in cells per milliliter indicate that after the onset of the bloom, *Aphanizomenon flos-aquae* virtually comprises the total population and its concentration can exceed 85 000 cells/mL.

As discussed in other portions of this report, the magnitude of runoff has a tremendous influence on the ecology of the four reservoirs. Data in table 14 illustrate the change in runoff between years of relatively low runoff and those of relatively high runoff. Seminoe Reservoir is most heavily influenced by runoff. Operational patterns modify the influence of runoff on the three reservoirs downstream from Seminoe. For example, if an increase in nutrients occurred during a low-water year, extreme eutrophic conditions may exist. Because of operational patterns, these eutrophic conditions may be initially manifested in Pathfinder Reservoir due to rapid flushing of the nutrients through Seminoe and Kortes Reservoirs. This may partly explain the very high productivity found in Pathfinder in August 1977 (fig. 28), which is discussed later. Inflows to Seminoe Reservoir during 1977 were approximately half those in 1976. During the winter of 1977-78, the volume of the reservoir was drawn down to very low levels (fig. 9) to meet power generation demands. Inflows further downstream at Kortes and Alcova indicate that the overall system was operated at near normal levels despite low inflows to Seminoe in the spring of 1977. Inflows in 1978 increased greatly, reflecting larger accumulations of snow in the watershed during the winter of 1977-78. Seminoe inflows increased 2½ times over 1977. This resulted in increased flushing of the watershed accompanied by inundation of previously dry shoreline in the reservoir basin. Chlorophyll *a* concentrations were generally higher during 1978. This was a reflection of the increased runoff. Data in table 15 indicate the influence of increased runoff on primary productivity as expressed in concentrations of chlorophyll *a*.

Seminoe Reservoir seems to have exhibited a "new reservoir" pattern in 1978, with a threefold increase in chlorophyll *a* concentrations (fig. 29). Kortes and Alcova also showed significant increases in chlorophyll *a* concentrations (figs. 30 and 32). However, average chlorophyll *a* concentration during 1979 declined, again following the "new reservoir" pattern. This indicates a significant increase in production, followed by a gradual decline as nutrients become less available for algal growth.

Pathfinder Reservoir was the exception to this pattern. The maximum chlorophyll *a* concentration was observed in 1977, followed by a 61-percent decline in 1978 and a 45-percent decline in 1979 from 1978 concentrations (fig. 31). While direct evidence is sparse, it is possible to speculate about physical conditions in Pathfinder which may have enhanced algal production in 1977. The overall volume of the reservoir was relatively low in 1977 (fig. 9) due to low inflow to the system (table 14). This resulted in early spring water temperatures which were warmer than usual. *Aphanizomenon flos-aquae* blooms are favored when water temperatures are 16 to 20 °C and pH values are 7.5 to 8.0 [38]. The entire reservoir system lies within this range in August, but early spring temperatures in high-inflow years can be below 16 °C. Since water levels were low, and remained so throughout 1977, Pathfinder Reservoir functioned as a nutrient trap, storing phosphorus entering from upstream reservoirs throughout the previous winter. A combination of events were apparently responsible for greater productivity in this low-water year in Pathfinder Reservoir: (1) a mild winter in 1976-77, (2) low spring runoff in 1977, (3) overall decreased reservoir volume, (4) warmer spring water temperatures, and (5) nutrient flushing from upstream reservoirs.

Zooplankton

Zooplankton populations in all four North Platte reservoirs are composed of representatives of

Table 13.—*Comparison of areal chlorophyll* a *and light extinction coefficient, June–August*

Reservoir	Station	Date	Areal chlorophyll *a* (mg/m²)	Light ext. coeff. (m^{-1})
		1976		
Seminoe	1	Aug 8	12.42	0.55
	2		22.22	1.04
	3		74.64	1.60
		1977		
Seminoe	1	June 6	12.23	0.86
	2		13.01	4.02
	3		15.11	5.31
	1	Aug. 8	9.10	0.48
	2		38.99	1.90
	3		70.84	1.87
Kortes	1	June 6	17.92	0.38
	1	Aug. 8	14.10	0.83
Pathfinder	1	June 6	14.10	0.46
	2		25.14	0.68
	3		44.91	0.51
	1	Aug. 8	65.88	1.12
	2		649.52	2.61
	3		825.11	3.19
Alcova	1	June 6	14.09	0.45
	2		16.38	0.67
	1	Aug. 8	53.92	0.55
	2		15.86	0.81
		1978		
Seminoe	1	June 6	46.50	0.74
	2		95.97	3.41
	3		119.34	4.28
Seminoe	1	Aug. 8	101.99	0.91
	2		164.64	1.10
	3		65.19	1.29
Kortes	1	June 6	61.78	0.83
	1	Aug. 8	17.45	1.69
Pathfinder	1	June 6	45.86	0.52
	2		109.61	0.60
	3		110.16	0.62
	1	Aug. 8	81.13	0.76
	2		138.07	1.44
	3		125.57	1.18
Alcova	1	June 6	112.66	0.52
	2		98.14	0.57
	1	Aug. 8	76.49	0.48
	2		47.87	0.94
		1979		
Seminoe	1	June 6	13.41	0.63
	2		38.64	2.90
	3		64.88	3.36
	1	Aug. 8	61.81	0.72
	2		86.84	0.92
	3		292.97	1.25

Table 13.—*Comparison of areal chlorophyll a and light extinction coefficient, June–August*—Continued

Reservoir	Station	Date	Areal chlorophyll *a* (mg/m²)	Light ext. coeff. (m^{-1})
Kortes	1	June 6	20.90	0.73
	1	Aug. 8	25.74	1.15
Pathfinder	1	June 6	25.28	0.53
	2		40.73	0.73
	3		34.41	0.51
	1	Aug. 8	24.48	0.53
	2		138.22	0.95
	3		86.00	0.75
Alcova	1	June 6	92.53	0.57
	2		93.25	0.67
	1	Aug. 8	56.96	0.67
	2		33.11	0.81

Table 14.—*Reservoir inflows*

Reservoir	Inflow 1976	Inflow 1977	Percent change	Inflow 1977	Inflow 1978	Percent change
	(m³)			(m³)		
Seminoe	1.07×10^9	5.72×10^8	−46	5.72×10^8	1.47×10^9	258
Kortes	1.01×10^9	8.27×10^8	−18	8.27×10^8	1.20×10^9	145
Pathfinder	1.21×10^9	9.54×10^8	−21	9.54×10^8	1.37×10^9	144
Alcova	1.32×10^9	1.23×10^9	− 7	1.23×10^9	1.03×10^9	−17

Table 15.—*Mean annual chlorophyll* a *concentrations*

Reservoir	1977 (mg/m³)	1978	Percent change	1978 (mg/m³)	1979	Percent change
Seminoe	13.62	49.47	+363	49.47	38.56	−22
Kortes	6.54	12.06	+184	12.06	8.88	−26
Pathfinder	120.69	47.13	− 61	47.13	26.10	−45
Alcova	10.71	31.22	+292	31.22	21.07	−33

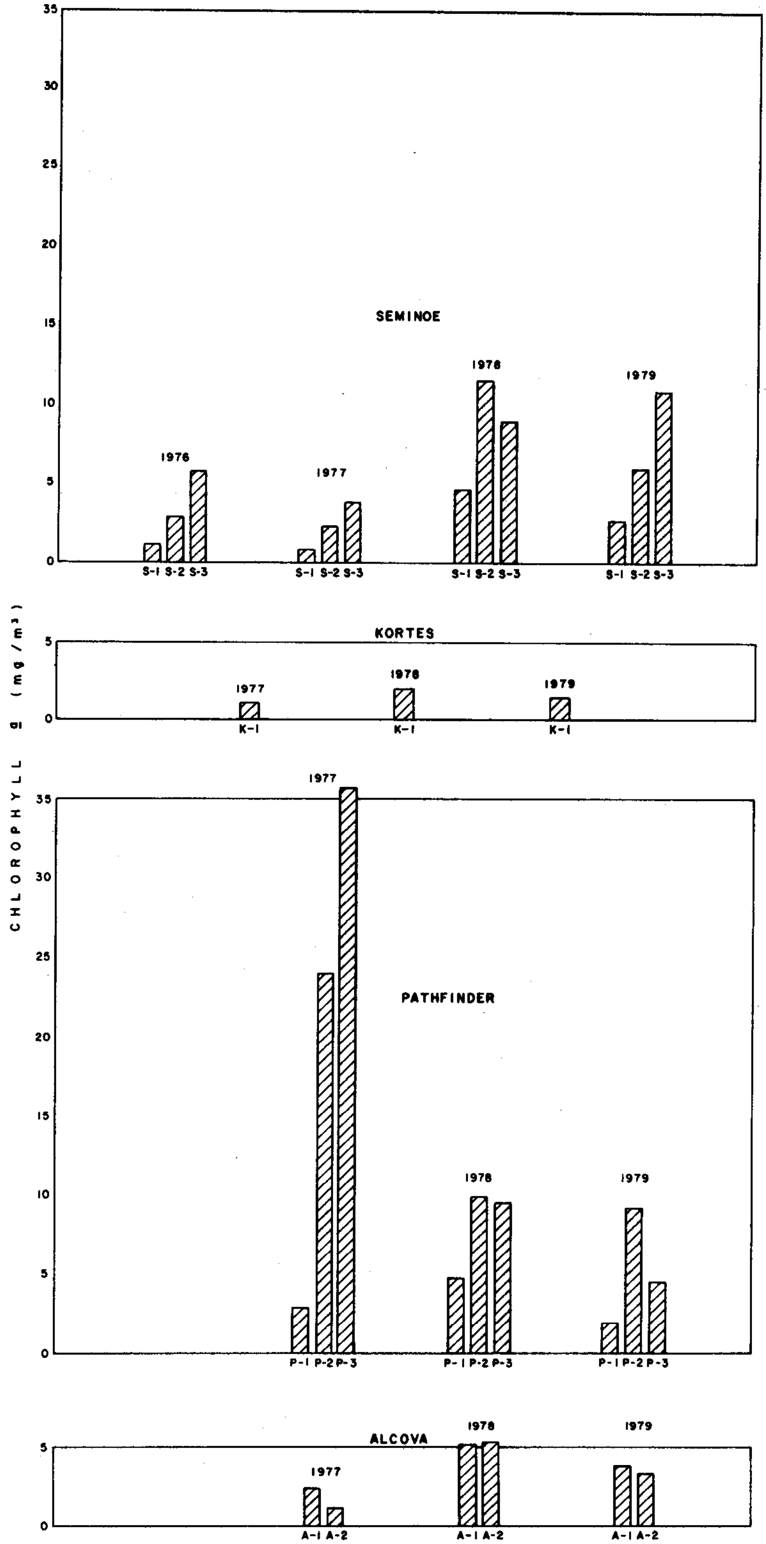

Figure 29.—Mean chlorophyll *a* by station at any depth.

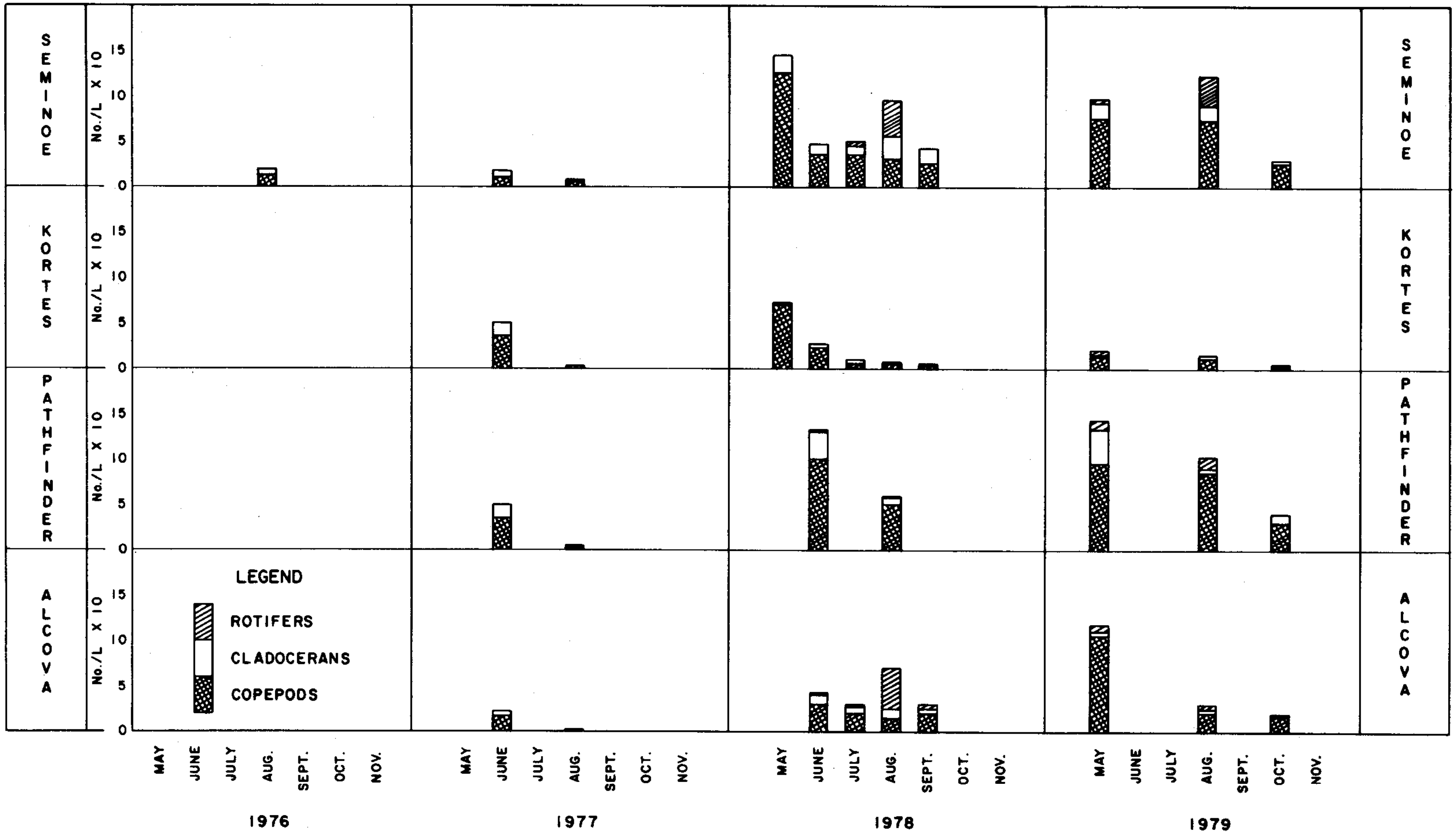

Figure 30.—Zooplankton abundance - Upper North Platte reservoirs, Wyoming.

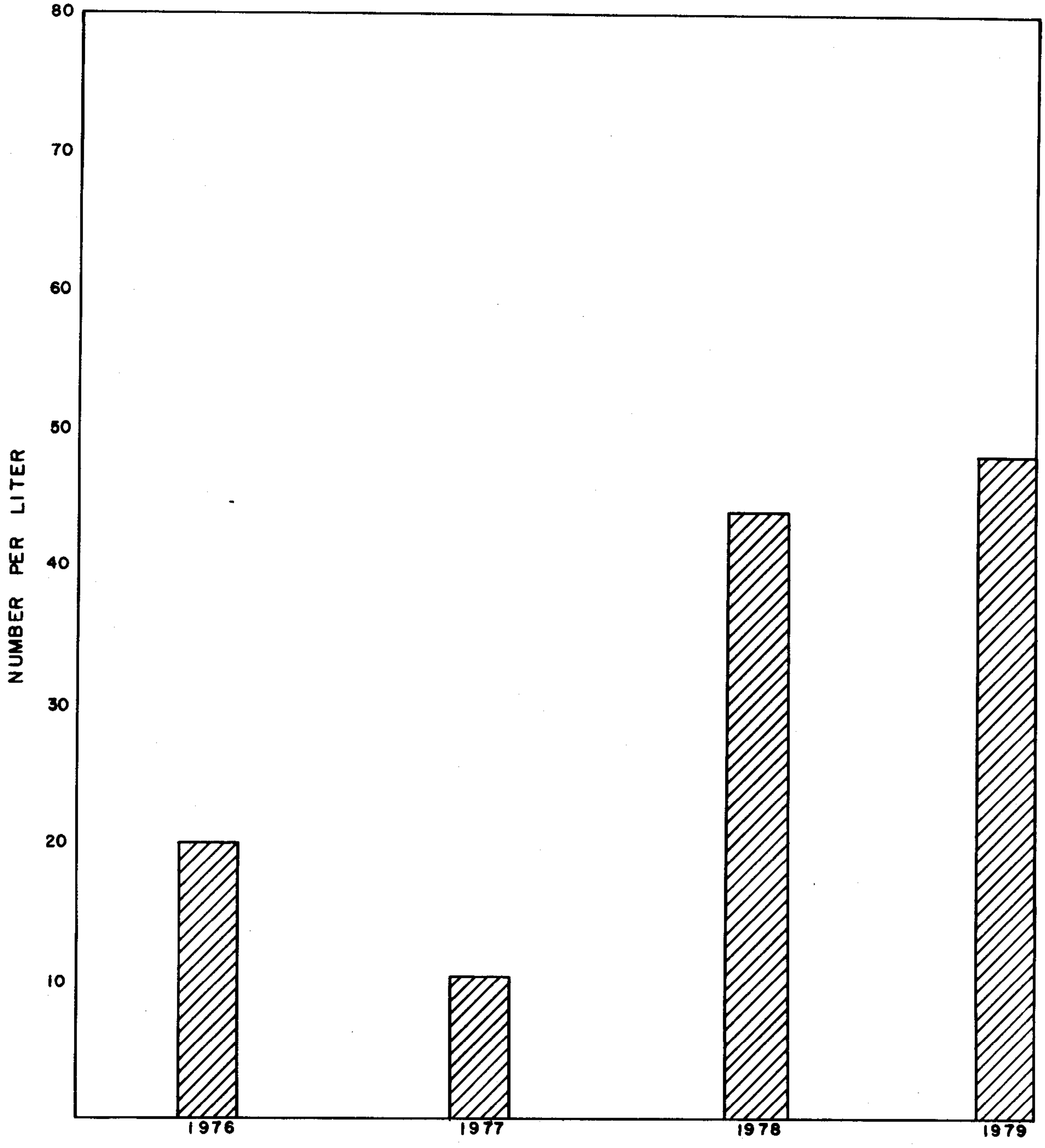

Figure 31.—Mean zooplankton abundance - Seminoe - All stations, North Platte reservoirs.

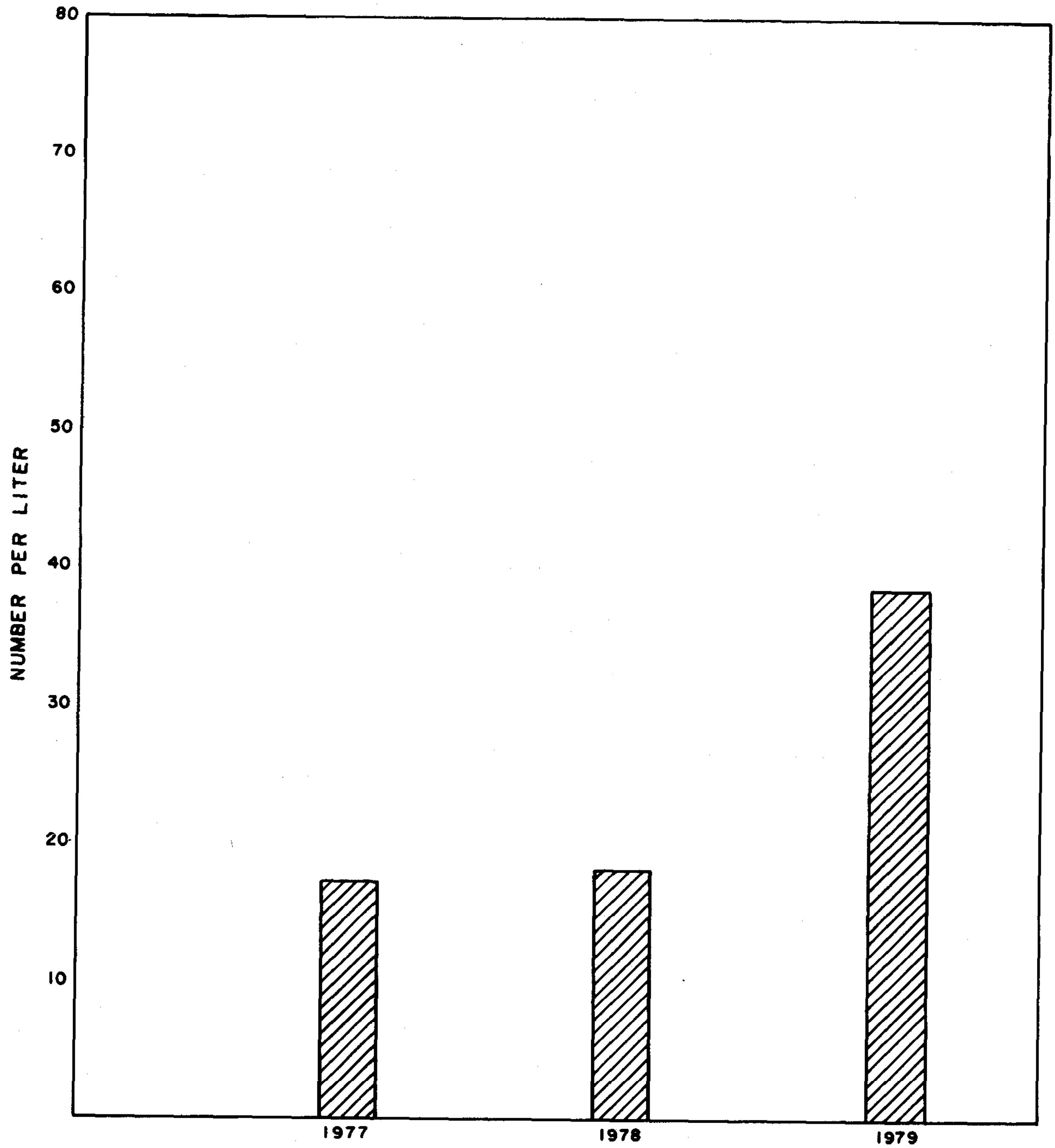

Figure 32.—Mean zooplankton abundance - Kortes - All stations, North Platte reservoirs .

three major groups: copepods, cladocerans, and rotifers.

There are two types of copepods: (1) Calanoid copepods, which are generally filter feeders, and (2) Cyclopoid copepods, which are usually predaceous. Both types are present in the Upper North Platte reservoirs. The cyclopoid copepods tend to be found in greater abundance because they prey on copepodite juveniles or nauplii of both types.

Copepods tend to be the dominant zooplankter during most of the sampling season (May–October, fig. 30). Wetzel [39] states that this may be due to the ability of copepods to successfully overwinter as adult instars and begin reproducing more quickly in the spring. Rotifers and cladocerans have not been found to overwinter in significant numbers in the Upper North Platte reservoir system. They hatch from resting eggs as water temperatures increase during spring.

The overall abundance of zooplankton is generally highest in the spring (fig. 30). Increases in August are usually due to a rise in rotifer populations. Rotifers often increase when algal populations are at a maximum or on the decline because they feed on bacteria and detritus which develop intensively as algae decay [39]. Maximum bluegreen algal populations are frequently observed in late August to early September, which tends to support this fact. However, zooplankton abundance generally decreases from 30 to 50 percent (fig. 30) after the July onset of the *Aphanizomenon* bloom. This decline may be due to fouling of the mouth parts of filter feeding organisms and/or the presence of toxic substances released by bluegreen algae, which can inhibit growth and reproduction of both algal and pelagic zooplankton species [38].

The overall abundance of zooplankton increased during the 4 years of study due to an increase in food supply and living space in wet years (figs. 31-34). Collections from 1976-78 were made using a Clarke-Bumpus sampler with No. 10 net and are generally comparable (table 16). The 1979 data were obtained using a No. 20 closing net. As previously mentioned, data using these two methods may not be comparable. The hypothesis that Seminoe is manifesting a "new reservoir" pattern—an increase followed by a decline—is not clearly illustrated by zooplankton abundance data because of this difference in sampling procedures.

The influence of runoff and the operation of the reservoir system has been found to significantly affect zooplankton populations. Seminoe is the upstream-most reservoir and is operated for power generation. Therefore, water levels in Seminoe Reservoir are lowest in early spring and highest in midsummer. Spring plankton populations initially may be favored by warmer inflows entering Seminoe when it is at its lowest water level. A more rapid warming may provide an early advantage to an overwintering copepod population. The early spring plankton population dominance by copepods is not sustained in Seminoe. Increasing volume of water and turbidity resulting from spring runoff may be responsible for the decrease in numbers of copepods observed in this reservoir (fig. 30).

Kortes does not support a large plankton population. This deep, narrow canyon reservoir may be light limited as well as being significantly cooler than either Seminoe or Pathfinder (see appendix A). The topography of Kortes, the fact that it is continually cooled by bottom releases from Seminoe, and the short water retention time may be responsible for the generally low plankton population observed.

Copepod populations in Pathfinder seem to increase as the season progresses. This reversal of observed plankton dominance with respect to Seminoe fits well with the difference in the operation of the two reservoirs. Pathfinder is at its greatest volume in early spring and decreases throughout the irrigation season. To a large extent, Pathfinder is free from turbidity caused by uncontrolled runoff. The clear, warming conditions which are maintained in Pathfinder as the season progresses may be favorable to increasing copepod populations.

Both copepods and cladocerans serve as food sources for game fish populations, especially rainbow trout. Increased turbidity or nutrient loading which amplifies the annual bluegreen algae bloom (*Aphinozomenon flos-aquae*) may decrease this available food source. Cladocerans are particularly susceptible to increased turbidity because it fouls their filter feeding apparatus and decreases feeding efficiency. Bluegreen algae are not a preferred food source for either copepods or cladocerans because the gelatinous sheath surrounding each strand of algae prevents digestion. As a result of this difficulty in digestion, the algae may pass through the gut intact, picking up essential phosphorus-nitrogen

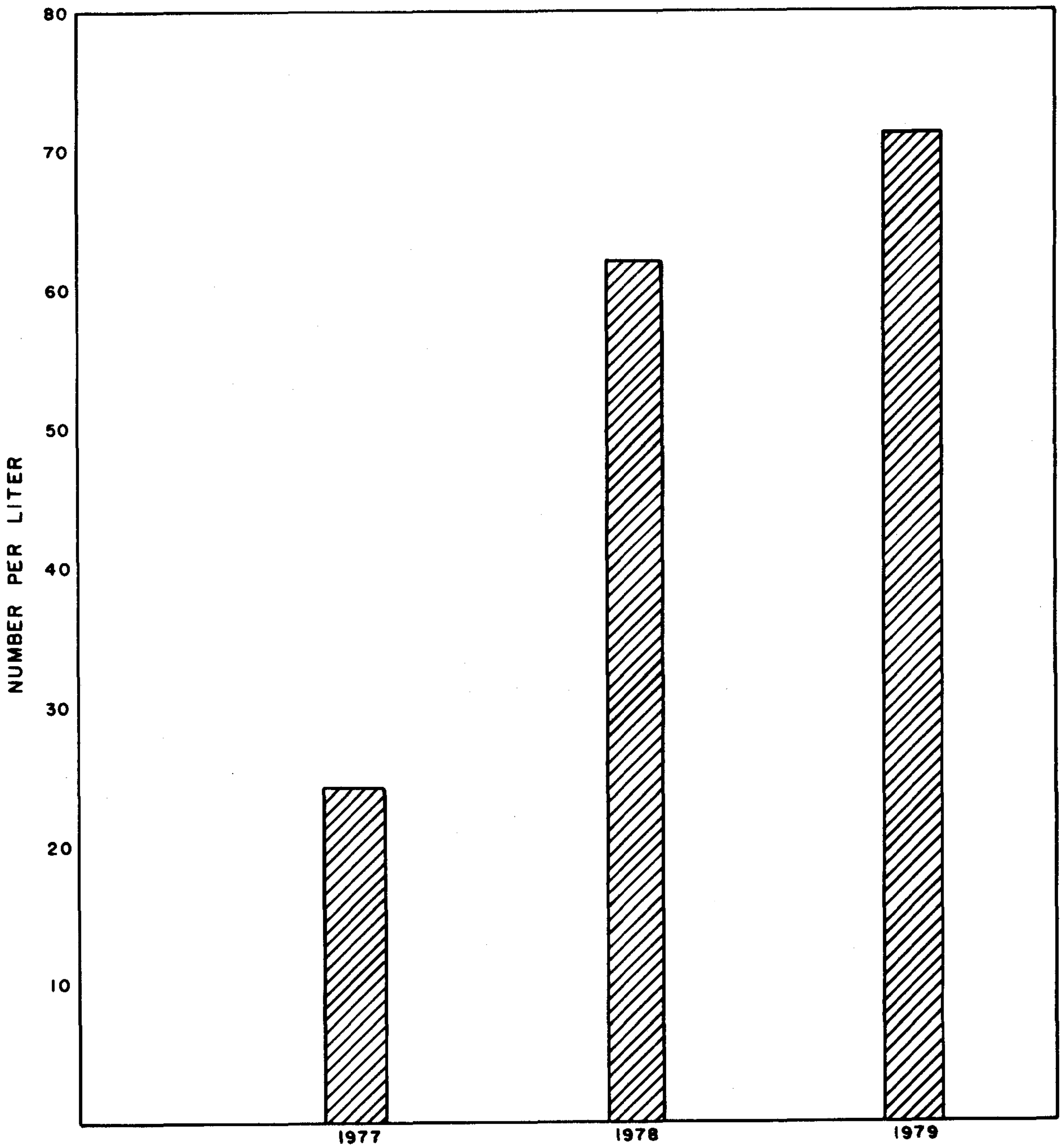

Figure 33.—Mean zooplankton abundance - Pathfinder - All stations, North Platte reservoirs.

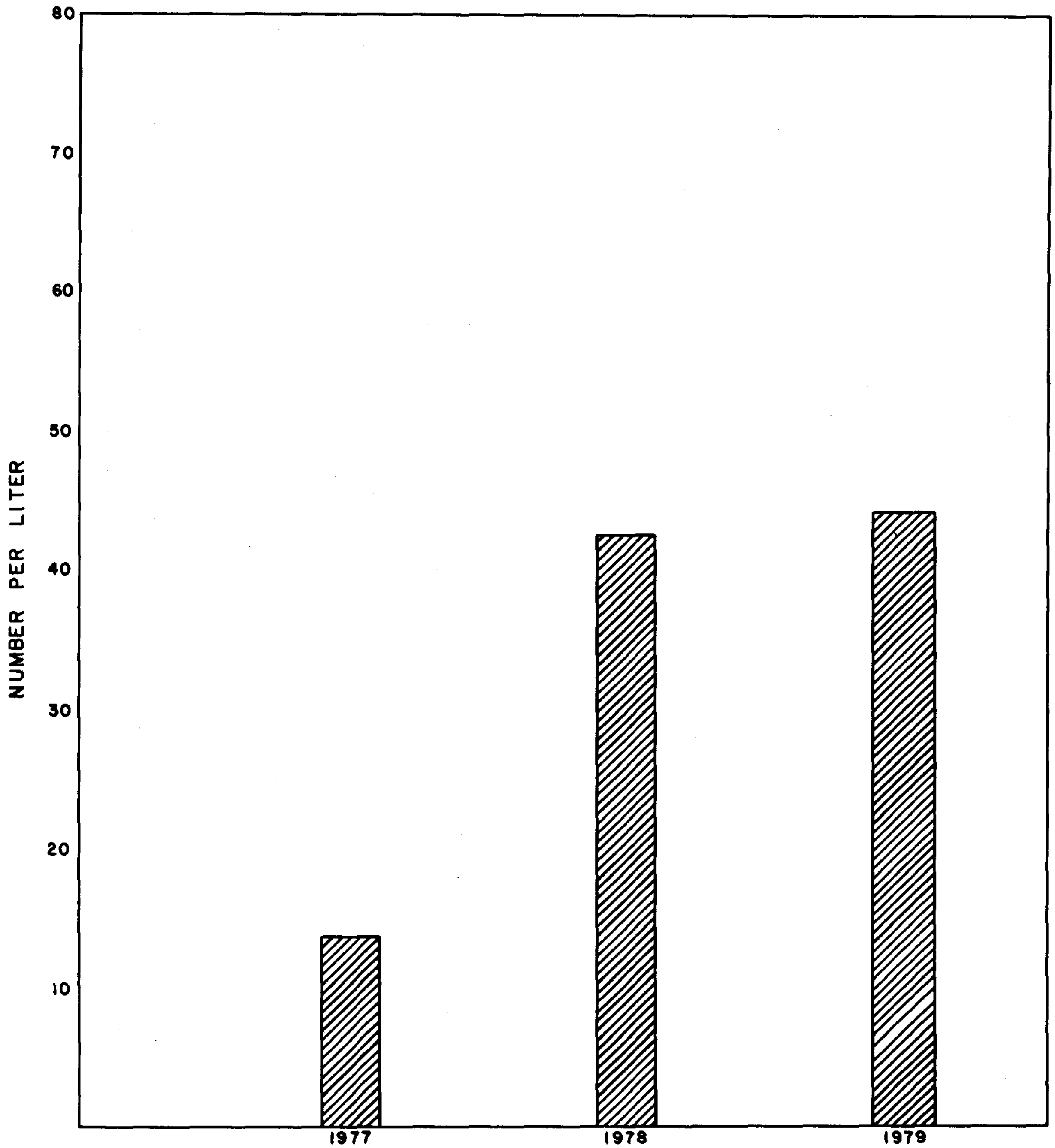

Figure 34.—Mean zooplankton abundance – Alcova – All stations, North Platte reservoirs.

Table 16.—*Zooplankton abundance*

Lake	Station[1]	Number depth intervals sampled	Date	Copepods	Rotifers	Caldocerans	Total Zooplankton	Average	Sampler[2]
					(Number/L)				
			1976						
Seminoe	1	3	Sept. 1	7.0	0.0	6.5	13.5	4.5	CB
	2	1		20.0	0.0	24.3	44.3	44.3	CB
	3	2		20.0	0.0	17.4	37.4	18.7	CB
	4	3		28.2	0.0	16.8	45.0	15.0	CB
	5	3		30.8	0.0	19.3	50.1	16.7	CB
			1977						
Seminoe	1	2	June 15	7.0	0.0	2.7	9.7	4.9	CB
	2	3		12.8	0.0	20.9	33.7	11.2	CB
	3	2		31.6	0.0	24.3	55.9	30.0	CB
	1	4	Sept. 1	9.4	1.0	3.9	14.3	3.6	CB
	2	2		6.4	0.9	5.5	12.8	6.5	CB
	3	2		4.8	0.0	4.5	9.3	4.7	CB
Kortes	1	3	June 15	87.6	0.0	11.8	99.4	33.1	CN
	1	3	Aug. 30	1.4	1.0	0.1	2.5	0.8	CN
Pathfinder	1	3	June 15	80.2	0.0	54.1	134.3	44.8	CB
	2	2		52.9	0.0	14.4	67.3	33.7	CB
	3	2		81.3	0.0	36.4	117.7	58.9	CB
	1	2	Aug. 30	2.7	1.4	0.7	4.8	2.4	CB
	2	2		2.1	0.7	0.0	2.8	1.4	CB
	3	3		3.5	0.0	0.5	4.0	1.3	CB
Alcova	1	3	June 3	47.5	0.0	30.0	77.5	25.8	CB
	2	3		62.9	0.0	14.3	77.2	25.7	CB
	1	3	Aug. 30	0.4	0.0	0.4	0.8	0.3	CB
	2	3		0.5	0.0	2.7	11.2	3.7	CB
			1978						
Seminoe	1	3	May 31	226.8	0.0	57.2	283.2	94.4	CN
	1	4	June 15	283.0	0.0	92.9	275.9	94.0	CB
	2	3		0.0	0.0	1.0	1.0	0.3	CB
	3	2		10.9	0.0	7.5	18.4	9.2	CB
	1	4	July 20	90.7	18.2	7.9	111.8	28.0	CB
	2	3		36.2	4.8	23.7	64.7	21.6	CB
	3	3		140.4	1.0	34.3	175.7	58.6	CB
	1	4	Aug. 31	52.6	39.1	48.9	140.6	35.2	CB
	2	3		100.9	160.2	78.4	339.5	113.6	CB
	3	3		36.4	43.5	31.0	110.9	37.0	CB
	1	4	Sept. 28	26.3	3.7	13.0	43.0	10.8	CB
	2	3		40.4	8.8	51.2	100.4	33.5	CB
	3	3		44.8	3.4	45.1	93.3	31.1	CB
Kortes	1	4	June 1	207.2	0.0	6.5	213.7	53.4	CN
	1	4	June 14	70.4	0.0	14.1	84.5	21.1	CB
	1	4	July 19	18.8	0.0	14.9	33.7	8.4	CB
	1	4	Aug. 30	9.8	4.2	8.7	22.7	5.7	CB
	1	4	Sept. 27	7.7	1.0	1.5	10.2	2.6	CB
Pathfinder	1	4	June 12	359.9	13.5	82.8	456.2	114.1	CB
	2	3		173.4	6.7	55.3	235.4	78.5	CB
	3	3		168.6	4.5	39.0	212.1	70.7	CB
	1	4	Aug. 28	36.8	4.6	5.8	47.2	11.8	CB
	2	3		136.9	2.6	2.2	141.7	47.2	CB
	3	3		122.7	2.1	26.5	151.3	50.4	CB

[1] See figure seven for location.
[2] Sampler - CB = Clarke-Bumpus, CN = closing net.

Table 16.—*Zooplankton abundance*—Continued

Lake	Station[1]	Number depth intervals sampled	Date	Copepods	Rotifers	Caldocerans	Total Zooplankton	Average	Sampler[2]
					(Number/L)				
Alcova	1	4	June 13	120.4	7.3	49.2	176.9	44.2	CB
	2	4		93.0	4.8	40.0	137.8	34.5	CB
	1	4	July 18	86.6	15.7	17.7	120.0	30.0	CB
	2	4		66.8	6.3	27.7	100.8	25.2	CB
	1	4	Aug. 28	95.7	207.6	24.0	327.3	81.8	CB
	2	4		100.1	100.4	26.9	227.4	56.9	CB
	1	4	Sept. 26	31.2	8.6	9.7	49.5	12.4	CB
	2	4		181.7	18.2	19.5	219.4	54.9	CB
			1979						
Seminoe	1	3	May 24	184.8	1.7	39.3	226.8	75.6	CN
	2	3		83.1	2.9	14.2	100.2	33.4	CN
	3	2		39.0	35.9	2.4	77.4	38.7	CN
	1	4	Aug. 30	47.6	34.4	27.6	109.7	27.4	CN
	2	3		139.9	19.1	16.2	176.0	58.7	CN
	3	3		181.4	150.4	81.8	414.1	138.0	CN
	1	4	Oct. 25	25.4	0.0	0.4	25.9	6.5	CN
	2	3		61.6	3.2	5.0	69.6	23.2	CN
	3	3		60.1	1.1	3.3	65.2	21.7	CN
Kortes	1	4	Aug. 29	34.5	2.5	15.0	57.4	14.4	CN
	1	4	Oct. 24	17.9	0.3	0.6	19.8	5.0	CN
Pathfinder	1	3	May 22	218.8	12.0	97.1	327.3	109.1	CN
	2	3		178.1	45.0	38.0	261.0	87.0	CN
	3	3		139.8	47.0	52.9	244.9	81.6	CN
	1	4	Aug. 28	107.3	2.6	1.9	111.8	28.0	CN
	2	3		230.5	9.1	11.6	251.2	83.7	CN
	3	3		107.5	4.0	4.9	115.4	38.5	CN
	1	4	Oct. 23	73.7	0.3	17.8	91.8	23.0	CN
	2	2		52.0	0.6	23.4	76.0	38.0	CN
Alcova	1	3	May 21	134.6	46.4	3.7	184.1	61.4	CN
	2	3		251.7	17.7	27.8	297.3	99.1	CN

[1] See figure 7 for location.
[2] Sampler - CB = Clarke-Bumpus, CN = closing net.

nutrients from the zooplankter enroute [40]. Besides reducing the reproductive capacity of zooplankters, this activity may also enhance algal growth. However, inhibition of growth and reproduction of other algae and zooplankters by alphan toxin which is secreted by *Aphanizomenon flos-aquae* appears to be the main factor in reducing the overall abundance of zooplankton in the Upper North Platte reservoirs.

Benthos

The benthos of the Upper North Platte reservoirs consists primarily of two kinds of organisms: oligochaetes (aquatic worms of the Oligochaeta class) and chironomids (larvae of nonbiting midges of the Chironomidae family). Both organisms play an important role in the exchange of substances between the bottom sediments and the adjacent waters. They also play an important part in the food chain of a lake, being fed upon by bottom-feeding fishes such as suckers, who are in turn fed upon by more traditional game fishes such as walleye and trout.

In 1976, the two kinds of organisms were combined when counted and weighed. Seminoe Reservoir, the only reservoir sampled in 1976, averaged 406 organisms/m² and 0.1369 g/m² dry mass (table 17).

All four reservoirs were sampled during 1977; however, abundance and biomass data for the two kinds of organisms were again combined.

Results for the two dates sampled are found in table 17.

The scope of benthic work increased during 1978 and 1979: more dates were sampled, and oligochaetes and chironomids were enumerated and weighed separately. Abundance and biomass values of chironomids and oligochaetes are in tables 18 and 19, respectively, for all four reservoirs on the dates sampled. Table 17 combines the values of the two organisms for purposes of comparing the 1978 and 1979 data with those from 1976 and 1977.

The abundance of benthos in Seminoe Reservoir ranged from a high of 758 chironomids/m² in May 1979 to a low of 105 chironomids/m² in July 1978. The oligochaete abundance ranged from 2602 in July 1978 to a low of 554 in May 1978. Dry mass ranged from 1.0353 g/m² in May 1979 to 0.0432 g/m² in July 1978 for the chironomids, and from 1.6519 g/m² in July 1978 to 0.1648 g/m² in May 1978 for oligochaetes. The highest total dry biomass of 3.7828 g/m² was measured in June 1977 when the two kinds of benthic organisms were combined, so a breakdown by type is not possible (table 17).

The average number of chironomids per square meter found during the 1978-79 surveys was 384/m² versus 1363/m² oligochaetes. The dry mass averaged 0.3671 g/m² for the chironomids and 0.9919 g/m² for the oligochaetes (table 20).

The abundance of benthos in Kortes Reservoir ranged from 753 chironomids/m² in August 1979 to 71 chironomids/m² in May 1978 and from 1997 oligochaetes/m² in July 1978 to 57 oligochaetes/m² in June 1978. The dry biomass of chironomids ranged from 0.1757 g/m² in June 1978 to 0.0017 g/m² in September 1978. Ranges for oligochaetes (dry mass) were 0.3458 g/m² in July 1978 to 0.0069 g/m² in June 1978 (tables 18 and 19).

The 1978-79 average abundance and dry biomass for Kortes Reservoir were 320 chironomids/m², 603 oligochaetes/m², 0.0561 g/m² for the chironomids, and 0.1306 g/m² for the oligochaetes dry mass (table 20).

Abundance of benthos in Pathfinder ranged from 356 chironomids/m² to 51 chironomids/m² and 1255 oligochaetes/m² to 401 oligochaetes/m². Benthic dry biomass ranged from 0.3266 g/m² to 0.0360 g/m² for the chironomids and 0.9161 g/m² to 0.2740 g/m² for oligochaetes (table 18 and 19).

The average abundance and dry biomass of benthos in Pathfinder during 1978-79 was 207 individuals/m² and 0.1773 g/m², respectively, for chironomids and 786 individuals/m² and 0.5396 g/m², respectively, for the oligochaetes (table 20).

The abundance of benthos in Alcova ranged from 96 to 0 chironomids/m², and 5487 to 2342 oligochaetes/m². The dry biomass ranged from 0.0708 to 0 g/m² for the chironomids and 3.1822 to 1.0880 g/m² for oligochaetes (tables 18 and 19). The averages for the 1978-79 surveys were 37 chironomids/m² and 4231 oligochaetes/m²; dry mass averages were 0.0261 g/m² for chironomids and 2.3102 g/m² for oligochaetes (table 20).

It is recognized that there is only limited value in characterizing the benthic communities of reservoirs with limited numbers of sampling sites and dates. Despite this fact, several conclusions and observations are made from these data. The most noticeable observation of the data is the complete dominance of the Alcova benthos by oligochaetes. Over 99 percent of the organisms surveyed during 1978 and 1979 were oligochaetes compared to 65 to 79 percent for the other reservoirs (figs. 35 and 36). The high oligochaete concentration is further exaggerated by the very low number of chironomids, which is only 23 percent of the next lowest chironomid population (in Pathfinder Reservoir).

Reservoir chironomid populations decrease downstream (figs. 35 and 36). In other words, the largest population is found in Seminoe and the lowest in Alcova. Seminoe Reservoir not only had the largest population of chironomids, but was also second to Alcova in abundances of oligochaetes. This reflects the diversity of habitats in terms of depth, light, nutrients, and substrate, that are found in Seminoe.

From table 20, two different generalities are made. By comparing the percent abundance of chironomids with the percent biomass of chironomids, a relative individual size for the chironomid population can be shown. A larger percentage of the benthic biomass in Pathfinder, Alcova, and Seminoe Reservoirs was made up of chironomids. In other words, the per unit mass of the chironomids in these three reservoirs was

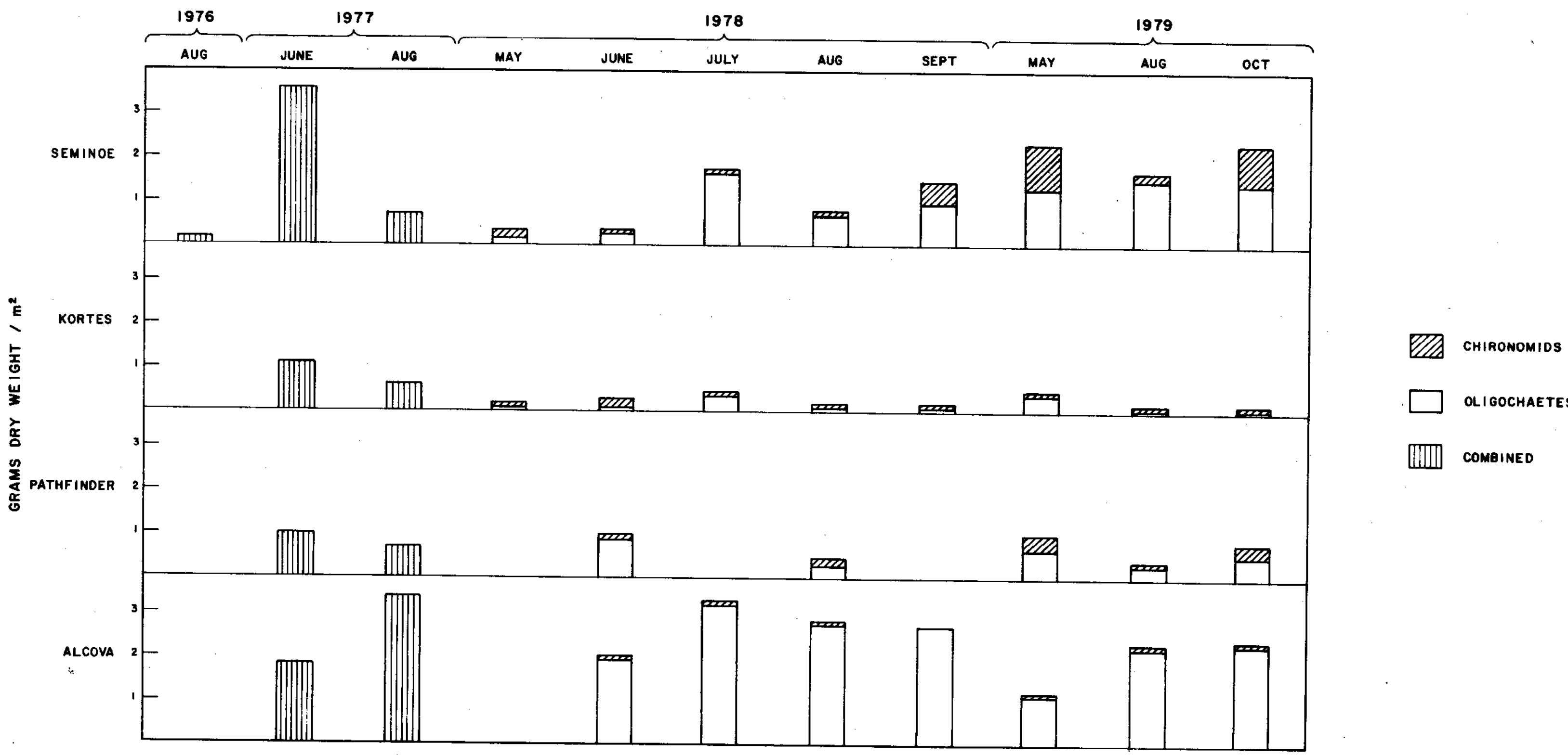

Figure 35.—Benthos biomass - Upper North Platte reservoirs, Wyoming.

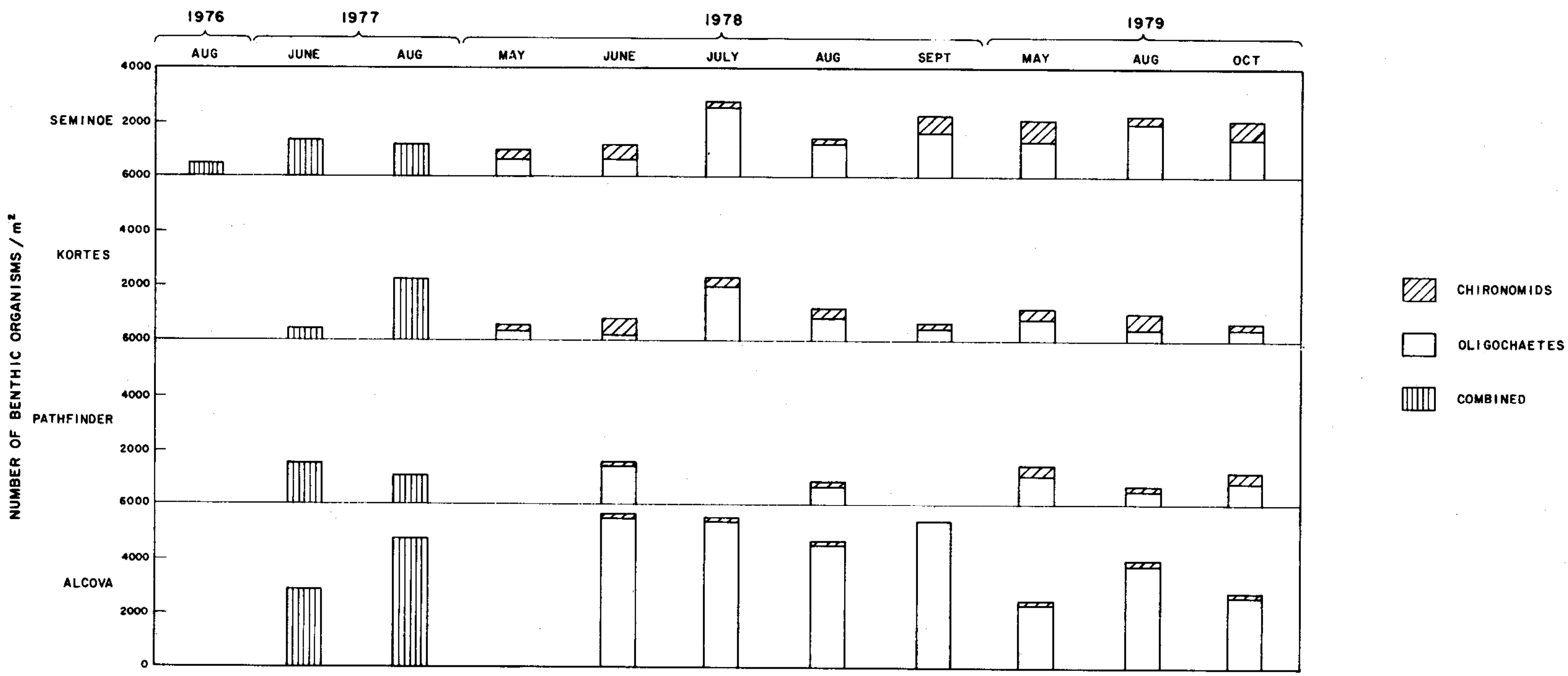

Figure 36.—Benthos abundance - Upper North Platte reservoirs, Wyoming.

Table 17.—*Chironomids and oligochaetes, 1976-79*

	1976	1977		1978					1979		
Reservoir	Aug. 31	June 23	Aug. 31	May 31	June 12	July 28	Aug. 28	Sept. 26	May 21	Aug. 27	Oct. 22
						(Organisms/m²)					
Seminoe	406	1278	1038	853	993	2707	1267	2165	1981	2134	1872
Kortes	—	370	2327	300	588	2370	1020	545	1034	936	592
Pathfinder	—	1362	984	—	1306	—	763	—	1337	490	1071
Alcova	—	2981	4716	—	5497	5340	4640	5293	2409	3939	2763
						(Dry mass g/m²)					
Seminoe	0.1369	3.7828	0.7143	0.3350	0.3703	1.6951	0.7672	1.4423	2.3603	1.6411	2.2609
Kortes	—	1.0715	0.6108	0.0624	0.1826	0.4084	0.1073	0.0674	0.4238	0.1292	0.1126
Pathfinder	—	0.9639	0.6933	—	0.9787	—	0.4118	—	0.9937	0.3239	0.8763
Alcova	—	1.7992	3.3825	—	1.9439	3.1999	2.7580	2.6965	1.1413	2.2013	2.4132

Table 18.—*Chironomids, 1976-79*

	1976	1977		1978					1979		
Reservoir	Aug. 31	June 23	Aug. 31	May 31	June 12	July 28	Aug. 28	Sept. 26	May 21	Aug. 27	Oct. 22
						(Organisms/m²)					
Seminoe				299	422	105	131	580	758	184	592
Kortes				71	531	373	316	143	344	753	210
Pathfinder				—	51	—	185	—	356	89	354
Alcova				—	10	50	10	0	67	96	29
						(Dry mass g/m²)					
Seminoe				0.1702	0.1222	0.0432	0.0641	0.4876	1.0353	0.1394	0.8750
Kortes				0.0200	0.1757	0.0626	0.0174	0.0017	0.0944	0.0585	0.0187
Pathfinder				—	0.0626	—	0.1378	—	0.3233	0.0360	0.3266
Alcova				—	0.0020	0.0177	0.0036	0	0.0533	0.0350	0.0708

Table 19.—*Oligochaetes, 1976-79*

	1976	1977		1978					1979		
Reservoir	Aug. 31	June 23	Aug. 31	May 31	June 12	July 28	Aug. 28	Sept. 26	May 21	Aug. 27	Oct. 22
						(Organisms/m²)					
Seminoe				554	571	2602	1136	1585	1223	1950	1280
Kortes				229	57	1997	704	402	690	363	382
Pathfinder				—	1255	—	578	—	981	401	717
Alcova				—	5487	5290	4630	5293	2342	3843	2734
						(Dry mass g/m²)					
Seminoe				0.1648	0.2481	1.6519	0.7031	0.9547	1.3250	0.5017	1.3859
Kortes				0.0424	0.0069	0.3458	0.0899	0.0657	0.3294	0.0707	0.0939
Pathfinder				—	0.9161	—	0.2740	—	0.6704	0.2879	0.5497
Alcova				—	1.9449	3.1822	2.7544	2.6965	1.0880	2.1663	2.3424

Table 20.—*Average benthos values*

Reservoir	Average Values 1978-79							1976-79
	Chiron./ m²	Oligo./ m²	Chiron. dry mass, g/m²	Oligo. dry mass, g/m²	Percent chiron.		Total avg. dry mass, g/m²	Total avg. dry mass, g/m²
					Abundance	Biomass		
Seminoe	384	1363	0.3671	0.9919	22	27	1.3590	1.4097
Kortes	320	603	0.0561	0.1306	35	30	0.1867	0.3176
Pathfinder	207	786	0.1773	0.5396	21	25	0.7169	0.7488
Alcova	37	4231	0.0261	2.3102	0.87	1.1	2.3363	2.3929

larger than the per unit mass of oligochaetes. Conversely, Kortes shows the opposite phenomenon. Oligochaetes were, on the average, larger than chironomids. This may be related to the operation of Kortes Reservoir and its very short retention time.

The second observation made from gleaning the data in table 20 involves a comparison of the total dry mass. The first value listed in table 20 is from the years 1978 and 1979. The second is from late study years, 1976-79. The two values are very close for Pathfinder, Alcova, and Seminoe, implying that the total average biomass values during the 1976-77 period were very close to those of the 1978-79 period. This denotes stable populations. Kortes again is different. The average total dry biomass of benthos collected from Kortes nearly doubled when data collected from 1976-77 were added to that collected during the 1978-79 period. The average biomass for the samples collected during the 1978-79 period was therefore lower than during 1976-77. The assumption is then that the benthic population had declined between 1977 and 1978.

Sediments

Bottom sediment samples were collected at nine reservoir stations in June 1977 for physical and chemical characterization. The samples were analyzed for physical properties and organic content by the Soil Testing Section of the Geotechnical Branch [41]. Results of these analyses are summarized in table 21. Portions of the samples were also submitted to the Division of Research's Chemistry Laboratory for analysis of heavy metals content; these results are shown in table 22.

No sample was classified as an organic soil per se [41], although the organic content of these soil samples was strongly, positively correlated with the percentage of fines smaller than 5 µm (correlation coefficient, $r = 0.92$). It may be seen in table 21 that the percentage of organic matter also increases as the silts and clays pass from "lean" to "fat." ("Lean" denotes fines of low plasticity and compressibility, while fines of high plasticity and compressibility are called "fat.") These observations are not unexpected since the fine particles of a soil, particularly clay-sized particles, have much higher ion and water-holding capacities than coarser particles, because of their larger surface area per unit mass and the presence of surface charges which tend to attract ions [42]. The same phenomenon accounts for the fact that the total heavy metal content of these sediments (table 22) is also strongly, positively correlated with the percentage of fines smaller than 5 µm ($r = 0.91$).

The data presented in tables 21 and 22 should be interpreted with some caution, because of the limited number of samples collected and the extreme heterogeneity of bottom conditions throughout the reservoir system. For example, at each station the field crew tried to sample the main river channel; it is therefore possible that sediment conditions at other points of the station cross section may be very different.

There are two sets of earlier data on bottom sediment-size characteristics in Pathfinder Reservoir that may be usefully compared with the present data. In 1931, the Corps of Engineers did mechanical analyses of bottom sediments at 10 different locations in Pathfinder [12]. While it is difficult to relocate exactly these 1931 stations, three that appear to have been near the stations used in the present study were chosen for comparison in table 23. In October 1958, while the reservoir was drained for construction of the power tunnel to Fremont Canyon Powerplant, Bureau personnel inspected the exposed sediments and had size analyses done on samples from six different locations [13]. Two

Table 21.—*Sediment classification and organic content*

Sampling station	Soil identification	Classification symbol	Percent organic matter by ash mass	Particle-size fractions in percent		
				Fines		Sand
				(< 5 μm)	(5 to 75 μm)	(75 μm to 4.75 mm)
S-3	Fat clay	CH	11.7	74	26	0
S-2	Fat clay	CH	6.2	64	35	1
S-4	Clayey sand	SC	1.5	21	5	74
K-1	Lean clayey silt	ML-CL	3.6	25	54	21
P-3	Fat clay	CH	7.9	73	25	2
P-2	Silty sand	SM	1.1	8	15	77
P-1	Lean silt	ML	2.4	19	45	36
A-2	Lean-fat silt	ML-MH	3.8	23	70	7
A-1	Lean clay	CL	3.1	32	39	29

Table 22.—*Heavy metals content of bottom sediments*

Sampling station	Percent fines (< 5 μm)	Heavy metals					Total
		Cu	Pb	Fe	Mn	Zn	
		(mg/g)					
S-3	74	0.021	0.038	16.50	0.690	0.085	17.33
S-2	64	0.016	0.035	13.50	0.405	0.080	14.04
S-4	21	0.005	0.008	7.00	0.560	0.030	7.60
K-1	25	0.016	0.035	14.00	0.605	0.060	14.72
P-3	73	0.021	0.044	15.50	0.910	0.070	16.55
P-2	8	0.002	0.010	2.30	0.150	0.005	2.47
P-1	19	0.007	0.020	6.00	0.220	0.025	6.27
A-2	23	0.011	0.022	7.30	0.405	0.045	7.78
A-1	32	0.010	0.020	7.50	0.430	0.040	8.00

of these locations were approximately the same as stations established for the present study, and are therefore also included in table 23.

Comparisons between the 1958 and 1977 analyses at stations P-1 near Pathfinder Dam, and P-2 in the Sweetwater arm are quite close. Unfortunately, the area around station P-3 in the North Platte arm was too soft to be sampled in October 1958 [13]. It would appear, however, that the general conclusions drawn on sedimentation patterns in Pathfinder in 1958 are still valid [13]: "Three types of sediment action influence the pattern of deposition taking place in Pathfinder Reservoir: (1) deposition of bed material particles, (2) settlement of suspended particles, and (3) particle movement by density flow action. * * * At the head of both arms the larger bed load material has deposited. From the head on down through the middle of the reservoir, deposition is mostly the result of suspended sediment particle settlement. In the reservoir area upstream from the dam, evidence points to density flow action as the cause of deposition."

The 1958 investigators [13] pointed out that the "narrows areas" in both river arms appeared to be "instrumental in forming the density flows in the lower reservoir by trapping larger sediment particles above and aiding in the collection of the smaller particles into a current or flow." These two "narrows areas" are located approximately at station P-2 near Bishop's Point in the Sweetwater arm, and just above station P-3 in the North Platte arm, which explains the "silty sand" deposits at station P-2 and the "fat clay" at P-3 (tables 21 and 23).

Comparison of the 1931 data with those from 1958 and 1977 is affected by two major points of difference: (1) difficulty in relocating the oldest stations, and (2) the fact that both Seminoe and Kortes Dams were built between 1931 and 1958. The first point is especially evident at station P-2, where the nearest 1931 station was actually located somewhat below the "narrows area" [12], and thus shows a finer composition than the 1958 and 1977 samples (table 23). The second point is more evident at stations P-1 and P-3, which were similarly located in all three studies [12, 13]. After the construction of Seminoe Dam in 1939, and Kortes Dam in 1951, the Sweetwater River became the main sediment contributor to Pathfinder Reservoir [13]. It was probably the trapping of coarser particles from the North Platte River in the Seminoe and Kortes Reservoirs that was responsible for the shift toward finer sediments at stations P-1 and P-3 between 1931 and the two later surveys (table 23).

Table 23.—*Comparison of sediment particle-size analyses – Pathfinder Reservoir*

Present sampling station	Size fractions[1]	Percent by mass		
		1931[2]	1958[3]	1977
P-1	G	0	0	0
	S	46.8	34	36
	M	14.2	51	45
	C	39.0	15	19
P-2	G	0	0	0
	S	19.1	79	77
	M	36.4	15	15
	C	44.5	6	8
P-3	G	0	No	0
	S	7.8	sample	2
	M	38.5	taken	25
	C	53.7	here	73

[1] G = gravel, S = sand, M = silt (particle size approximately 5 to 75 μm), C = clay (particle size smaller than 5 μm).
[2] Corps of Engineers data [12].
[3] Bureau of Reclamation data [13].

The evidence of "density flows" of sediment into the lower part of Pathfinder Reservoir [12, 13] bears some similarity to the evidence of "turbid underflows" in Seminoe Reservoir, presented earlier in this report. Particle-size analyses of the sediments at stations S-2 and S-3 in the river arms of Seminoe also compare closely with that at station P-3 in the North Platte arm of Pathfinder (table 21). All three of these stations are similarly located with respect to their individual river arms and the main bodies of the reservoirs (fig. 7). (In comparing sediment particle-size distributions between the Seminoe and Pathfinder stations, it should be noted that the "clayey sand" sediment at station S-4 is mainly the result of eolian deposition from the large sand dunes that occupy the west bank of the reservoir in this area.) It therefore seems likely that sedimentation patterns in Seminoe Reservoir are much the same as those observed in Pathfinder [12, 13].

DISCUSSION

Study Limitations

As mentioned at the beginning of the report, this limnological study of the Upper North Platte reservoir system was subject to some important limitations. Surveys were carried out only during the season from late May through late October, so that no winter data are available. Although the investigations spanned four summers, 1976-79, the level of temporal and spatial detail varied from year to year. Only the early summer (late May to early June) and late summer (end of August) sampling periods in 1977, 1978, and 1979 were common to all four reservoirs (table 2). Sampling, counting, and analytical methods varied somewhat from year to year. (See Methods and Materials section.) Surveys were limited to nine reservoir and six stream stations during most of the study (fig. 7), and undoubtedly this tends to oversimplify the picture of the system.

The above limitations should be kept in mind during the following discussion which first characterizes the reservoirs and then outlines systemwide relationships. This is a preliminary overview of the functioning of a large, complex limnological system. More detailed site-specific studies would be required to quantitatively assess the environmental impact of any given modification of the system. (See Recommendations section.)

Reservoir Characterization

The four Upper North Platte reservoirs usually become thermally stratified by June. Because of the continual withdrawal of cool hypolimnetic water through the low dam outlets, however, this stratification does not last beyond late August. All four reservoirs are dimictic; i.e., they are ice covered in the winter, become isothermal in spring and fall, and develop direct thermal stratification in the summer.

In high-runoff years, the river arms and upper basin of Seminoe Reservoir are extremely turbid throughout the early summer. The water clears after peak runoff in June, but a turbid underflow apparently develops and passes through the reservoir. This underflow reaches the dam outlet in late summer, and its release causes Kortes Reservoir and the Miracle Mile to become turbid in the fall. During low-runoff years, reservoir turbidity is mainly a function of wave action on exposed littoral areas rather than suspended sediments carried by runoff. During late summer, light penetration in the river arms of both Seminoe and Pathfinder is limited by blooms of bluegreen algae.

Sediment patterns in Pathfinder Reservoir indicate the existence of density flows of fine sediment from the river arms into the lower basin, with the narrow portions of the arms functioning as traps for coarser sediment particles [13]. In all four reservoirs, the organic and heavy metals content of the bottom sediment is directly correlated with the percentage of clay-size fines.

The waters of the reservoir system can all be classified as being alkaline, hard, and relatively saline. Salinity (i.e., sum of anions and cations) of the reservoir waters averages 369 mg/L, calcium carbonate hardness averages 184 mg/L, TDS averages 318 mg/L, and the pH always exceeds 7.0. Calcium, sodium, and magnesium are the major cations, while the major anions are bicarbonate and sulfate.

The brief summer stratification period generally precludes the development of serious anaerobic or reducing conditions in the hypolimnia of the reservoirs. Some manganese releases from bottom sediments at deep reservoir stations have exceeded EPA recommended domestic water supply criteria, but these quickly disappeared with the reoxygenation that accompanied the early breakdown of thermal stratification. Iron is often present in the waters of the system in concentrations that exceed EPA recommended domestic water supply criteria; however, it appears to be mainly associated with suspended sediment particles rather than being in the bioavailable ionic form. In fact, given the hard, alkaline nature of the water, it is unlikely that heavy metals in the ionic form ever constitute a hazard to reservoir biota.

Mean total inorganic nitrogen concentrations in the reservoir system ranged from less than 50 μg/L to over 250 μg/L during this study (fig. 23). Mean orthophosphate phosphorus concentrations, on the other hand, ranged from less than detectable to less than 20 μg/L (fig. 24).

The N/P ratios (fig. 25) for Seminoe and Pathfinder seem to indicate a "wet-year" pattern of early summer phosphorus limitation, shifting to more nitrogen-limiting conditions in late summer, and a "dry-year" pattern of nitrogen limitation throughout the summer. Both patterns led to late summer bluegreen algae blooms, but the dry-year conditions favored an accumulation of phosphorus in Pathfinder that contributed to the largest such bloom observed during this study.

As a final point, EPA [14], in 1975, found Seminoe Reservoir to be phosphorus limited in May and October and nitrogen limited in August. Figure 10 shows that 1975 was a higher than normal runoff year, so the EPA results would seem to support at least the wet-year nutrient limitation pattern outlined above.

Phytoplankton populations in the reservoirs are usually dominated by diatoms in early summer, and the bluegreen alga, *Aphanizomenon flos-aquae,* in late summer. Early summer zooplankton populations are mainly composed of cladocerans and copepods, while rotifers appear in significant numbers in late summer. Zooplankton populations in general decline as the bluegreen algae becomes dominant.

Species composition of the benthos populations changes from upstream to downstream in the reservoir system. The benthos of Seminoe is made up largely of chironomids, while that of Alcova is almost entirely composed of oligochaetes. This difference may reflect the fact that Seminoe is both shallower (table 5) and more subject to inputs of detritus from the watershed (fig. 11) than is Alcova. Oligochaetes feed mainly on bacteria [20], while chironomids seem to depend more directly on the detrital material that settles out of the water column [43]. Brinkhurst [43] points out that mean depth is an important factor in the production of benthic macroinvertebrates because detritus is subject to bacterial action as it settles, and thus less food energy remains in the detrital material with increasing depth. In this study it was found that the overall mean percentage of the benthos made up by chironomids at each of the nine reservoir stations was negatively correlated with mean station depth (correlation coefficient, $r = -0.83$). The opposite held true for the percentage of oligochaetes versus station mean depth. No significant correlation with substrate particle size or sediment organic content was found for either chironomids or oligochaetes.

The EPA National Eutrophication Survey [14] classified Seminoe Reservoir as being eutrophic in the river arms, moderately eutrophic in the upper basin, and mesotrophic in the lower basins. This separate trophic classification for the river arms and the deeper basins would probably also apply to Pathfinder, where the major centers of primary production are the North Platte and Sweetwater arms. However, on the basis of a recent report by Taylor et al. [44], which lists trophic classification criteria in exhaustive detail, the Upper North Platte reservoir system should be classified as being generally mesotrophic, with somewhat more eutrophic conditions in the river arms of Seminoe and Pathfinder.

System Overview

Three main factors influence the limnology of the Upper North Platte reservoir system: (1) system operating criteria, (2) flow variations in the three major tributaries, and (3) deep outlets in all four dams. Each factor is discussed below.

System operating criteria.—The operating criteria of the Upper North Platte reservoir system dictate the storage and release patterns of the individual reservoirs. Seminoe Reservoir stores runoff and releases water for power production; hence, it fills quickly in the spring and is drawn down gradually as water is released at a relatively even rate throughout the year. Kortes Reservoir is maintained at a constant elevation and, because of its small size relative to the flows it passes, it is flushed on the average of once every 2 days. Pathfinder Reservoir receives about 90 percent of its inflow at an even rate from Seminoe and Kortes and the remaining 10 percent is uncontrolled runoff from the Sweetwater River. Releases from Pathfinder peak in late summer in response to irrigation demand. Reservoir elevations in Alcova are raised rapidly in April, held at a constant elevation until the end of September, dropped quickly in October, and then held constant at a lower elevation through the winter. This stepwise elevation pattern results in flushing rates that average about 46 days during the summer and approximately 89 days in the winter. Between summer and winter are a rapid April dilution and an equally rapid October flushing.

Annual runoff variations.—Superimposed upon the system operating pattern are the effects of seasonal and annual variations in tributary flow. The limnology of Seminoe Reservoir is essentially determined by the interactions of the North Platte and Medicine Bow Rivers. Low flows in these two tributaries result in more riverine conditions in Seminoe, including increased salinity, increased flushing rate, decreased sediment load, and decreased nutrient input. High river flows result in more lacustrine conditions, with the opposite attributes of those listed above.

Nutrient dynamics in particular seem affected by annual runoff variations in the two major tributaries of Seminoe. Under low-flow conditions, nutrients seem to be flushed through Seminoe and Kortes and accumulate in the North Platte arm of Pathfinder, where they contribute to larger than average bluegreen algae blooms.

During high-runoff years, a larger proportion of the increased nutrient loading seems to be retained in Seminoe, and production of algae is more evenly distributed between this reservoir and Pathfinder. The summer pattern becomes one of early phosphorus limitation and late nitrogen limitation.

Increased sediment loading during high runoff may be a key factor. Early phosphorus inputs could be associated with sediment particles and thus unavailable for immediate utilization. Release of this phosphorus from the newly deposited sediments would then cause the late summer switch to nitrogen-limiting conditions. Low runoff, however, means less sediment input, so that even though overall nutrient loading is reduced, phosphorus inputs could be in a more immediately available form. They would also be flushed through the reservoir more rapidly and, given the system operating regime, would tend to accumulate in Pathfinder, at least until late summer when irrigation releases peak.

The relative influence of the two tributaries on the water chemistry of Seminoe Reservoir also varies somewhat with runoff volume, since the salinity of both rivers is inversely proportional to their discharge. About 85 percent of the total annual inflow is contributed by the North Platte River, with a mean TDS of 209 mg/L. The Medicine Bow River contributes only about 15 percent of the total annual inflow, but the mean TDS of this water is 810 mg/L. Thus, the Medicine Bow, on the average, is responsible for approximately 40 percent of the TDS in the main body of the reservoir.

At the same time, the point of river-impoundment mixing moves up and down the river arms in response to the volume of river inflow and the reservoir pool elevation. This is especially the case in the Medicine Bow arm because of its smaller discharge relative to the North Platte. A high runoff after a drought period, for example, moves the mixing point downstream, and the arm becomes more of an extension of the Medicine Bow River. Conversely, at high reservoir pool elevations, the mixing point moves farther upstream as river inflow declines through the summer. In this situation, the Medicine Bow arm becomes more like an embayment of the reservoir, with chemical concentrations approximating those measured at the dam.

The limnology of Kortes Reservoir reflects conditions in the deep water immediately behind Seminoe Dam, modified only by some aeration in the Seminoe tailrace. Because of rapid flushing, Kortes has no significant effect on water chemistry between Seminoe and the Miracle Mile. Development of plankton populations in this small reregulating reservoir is probably limited by shading from the steep canyon walls, low temperature releases from Seminoe, rapid through-flushing of nutrients, and late summer turbidity.

Pathfinder Reservoir resembles Seminoe in that its limnological conditions are basically determined by the interaction of its two large tributaries: the North Platte and Sweetwater Rivers. One important difference lies in the fact that the North Platte River, which supplies approximately 90 percent of total annual inflow to Pathfinder, is controlled by Seminoe and Kortes Dams. As discussed earlier, runoff variations upstream from Seminoe ultimately influence the quantity and quality of the North Platte contribution to Pathfinder, while sediment loading and discharge extremes are largely eliminated.

A second major difference is that the mean TDS of the Sweetwater River is approximately the same as that of the North Platte as it enters Pathfinder (274 and 299 mg/L, respectively). Consequently, the Sweetwater River does not have a strong chemical effect on Pathfinder Reservoir as the Medicine Bow has on Seminoe. The difference is one of degree, however, and the same general principles apply to the Sweetwater arm of Pathfinder as were discussed for the Medicine Bow arm of Seminoe.

Alcova Reservoir, like Kortes, is essentially a flow-through system in which limnological conditions largely reflect those in the impoundment immediately upstream. However, some internal cycling of materials and development of plankton populations does take place in Alcova because of its larger volume and longer retention times. On the other hand, these plankton populations are much reduced by late summer, apparently by flushing into the Casper Canal at the height of the irrigation season. The rapid October drawdown also serves to flush the reservoir and prevent much retention of nutrients for internal cycling.

Deep reservoir outlets.—The third major factor affecting overall system limnology is the fact that the main outlets of all four dams are located near the bottom of the impoundment (table 24). This holds true even for Alcova, which also has a high level outlet for irrigation releases to the Casper Canal.

Table 24.—*Major outlet locations – Upper North Platte reservoirs*

	Seminoe	Kortes	Pathfinder	Alcova
Maximum water depth at dam (m)	61.0	43.6	55.5	54.9
Distance from bottom of major outlet (m)	8.6	11.1	14.3	4.3[1]

[1] Casper Canal outlet, utilized from May through September, is located approximately 4 m below maximum water surface elvation.

These low outlets affect both the reservoirs and the receiving waters downstream.

Wunderlich [45] points out the possibility of a "short-circuiting" effect in a reservoir where a low outlet is combined with an underflow. That is, the inflow tends to pass through the reservoir with a relatively short retention time and with relatively little alteration of its inflow-quality characteristics, if reservoir density stratification is sufficiently stable.

At the same time, there is an increase in epilimnion depth as cold water is withdrawn from the hypolimnion through the low outlet [45, 46]. This is because a density gradient tends to restrict vertical mixing while enhancing horizontal movement. Thus, the stratified layers resist mixing as the hypolimnetic waters are drawn off, which results in a lowering of the thermocline.

Density gradients in the Upper North Platte reservoirs are mainly the result of summer temperature stratification, although tributary sediment load at high flows, or salinity at low flows, probably compounds the situation, particularly in Seminoe and Pathfinder. Rapid flushing of Kortes and Alcova seems to override any density effect in these reservoirs.

The turbid underflow in Seminoe and the density flows of sediment in Pathfinder [13] are one illustration of the short-circuiting effect described by Wunderlich [45]. Short-circuiting of incoming nutrients through the bottom of these reservoirs may also account for the lower production of algae at the deepwater stations relative to the river arm stations [46]. Finally, the rapid decay of summer temperature stratification in late summer in both Seminoe and Pathfinder is caused by loss of the cool hypolimnion through the deep outlets.

The deep discharge from all four reservoirs exercises an important influence over nutrient dynamics in the Upper North Platte system. Deep reservoir outlets tend to release mineral nutrients rather than organic detritus, and maintain the downstream receiving waters at relatively constant, cool temperatures. This combination of nutrient enrichment and environmental stability often leads to high production of benthic algae and macroinvertebrates in the tailwaters of deep discharge reservoirs [29, 30, 47-51].

The Miracle Mile is a classic example of the enrichment effect of deep discharge reservoirs. Nutrients released from the bottom of Seminoe Reservoir combined with flow regulation at Kortes Dam provide the basis for the high production of benthic algae and invertebrates observable in the Miracle Mile. Pathfinder Reservoir provides the trout, which move upstream to feed and spawn [5-7]. The result is a blue-ribbon trout fishery.

The deep discharge from Pathfinder Reservoir may also have a "subsidizing" effect on the fishery in Alcova Reservoir. Facciani[6] developed the following relationship between fish yield, in lb/acre and MEI (morphoedaphic index)[7], in (p/m)/ft on the basis of purse seine data from several Wyoming lakes and reservoirs.

$$\log \text{yield} = 0.7171 + 1.0251 \log \text{MEI} \quad \text{Eq. (4)}$$

Both Pathfinder and Alcova Reservoirs were included in the sample. The MEI of Pathfinder was calculated as 7.32 (p/m)/ft and the measured fish yield was 34.19 lb/acre, which is slightly less than the 40.12 lb/acre that would be predicted from equation (4). The MEI at Alcova was calculated to be 4.43 (p/m)/ft, but the measured yield of fish was 36.75 lb/acre, which is slightly more than that measured in Pathfinder and 53 percent more than the 23.97 lb/acre that equation (4) would predict.

This larger than expected fish yield in Alcova may reflect a "nutrient subsidy" from Pathfinder Reservoir in the form of nutrients released through the deep outlet in Pathfinder Dam. On the basis of information contained on figures 23 and 24 and the reference on Hyalite Reservoir, Montana [29, 30], the major nutrient involved here is probably total inorganic nitrogen. The addition of nitrogen would also account for the general trend, best seen on figure 25, for Alcova, alone among the four reservoirs to become more phosphorus limited from early to late season in all 3 years where data were available. Maintaining relatively phosphorus-limiting conditions in Alcova through deep release of nitrogen from Pathfinder could affect the species composition of the phytoplankton populations in the lower reservoir, and thus, perhaps, maintain zooplankton populations that contribute to increased fish growth.

[6] Steve Facciani, Wyoming Department of Game and Fish, personal communication.

[7] MEI = mean TDS/mean depth [52, 53].

Two final questions on this line of reasoning concern MEI's and relative fish stocking rates. Morphoedaphic indexes calculated on the basis of the present study for Alcova and Pathfinder, respectively, were 4.77 and 7.94 (p/m)/ft, which compare favorably with those calculated by Facciani. The theory behind the MEI is explained in some detail by Ryder [52] and Ryder et al. [53]. There may be some question as to why nutrients added to Alcova by Pathfinder are not already reflected by the MEI, by way of TDS. The answer is that any contribution to TDS by nitrogen and phosphorus nutrient concentrations, measured in μg/L, are entirely masked by the much larger magnitude of the major ion concentrations, measured in mg/L. Thus, the respective MEI's would not necessarily account for any total inorganic nitrogen added to Alcova by the deep discharge from Pathfinder, but this "nutrient subsidy" would be sufficient to have an important effect on N/P ratios (fig. 25).

The final question is more difficult: Is the greater than expected fish yield in Alcova due to a nutrient subsidy from Pathfinder, or is it merely caused by higher stocking rates in Alcova? Alcova Reservoir is primarily a stocked trout fishery, but it does not seem likely that stocking alone could account for a fish biomass per unit surface area that rivals that of Pathfinder, which hosts resident as well as stocked populations [7]. A good food source, with consequent high growth rates, would also seem to be necessary to account for the increased fish biomass.

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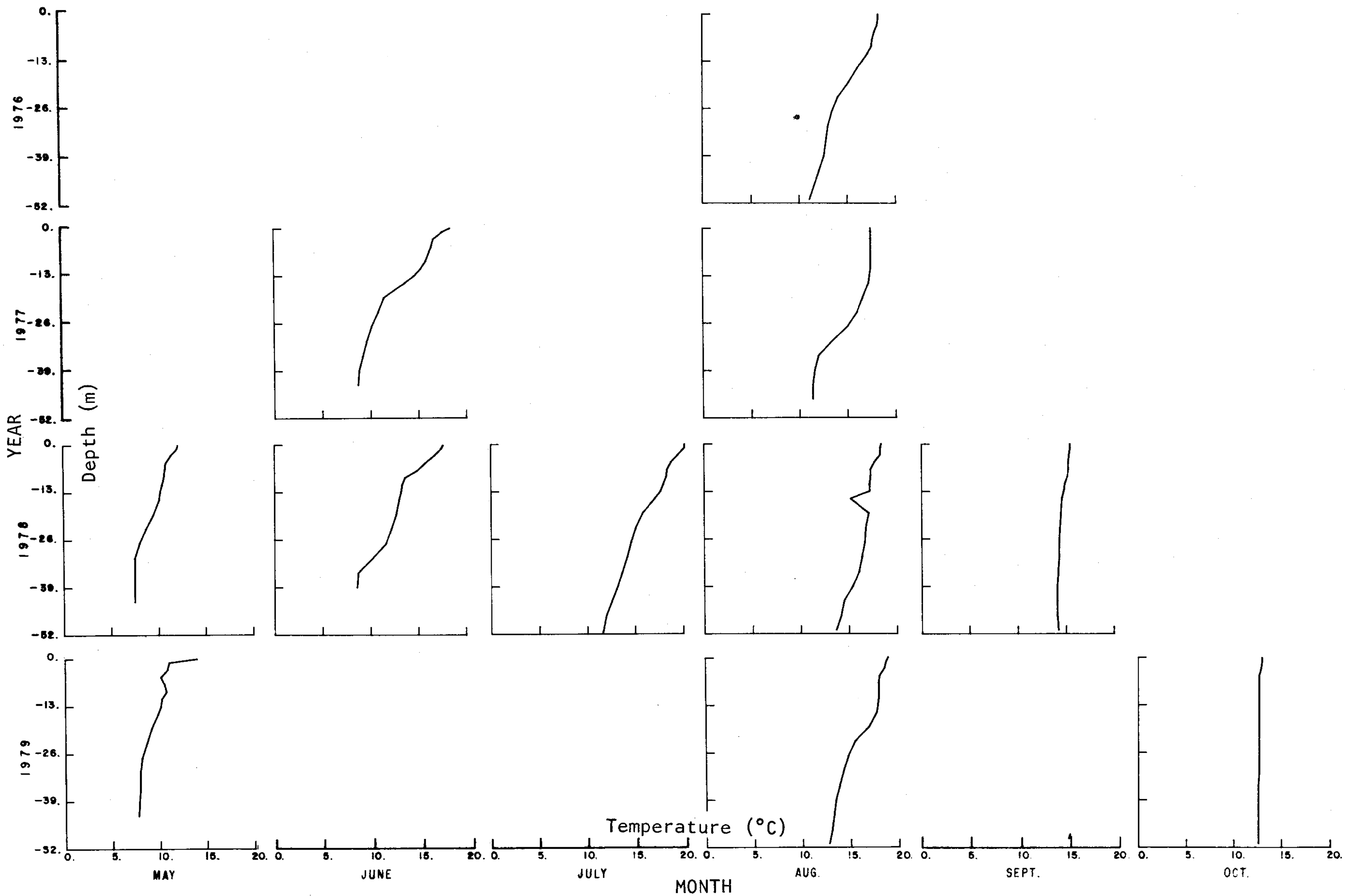
APPENDIX A
TEMPERATURE PROFILES



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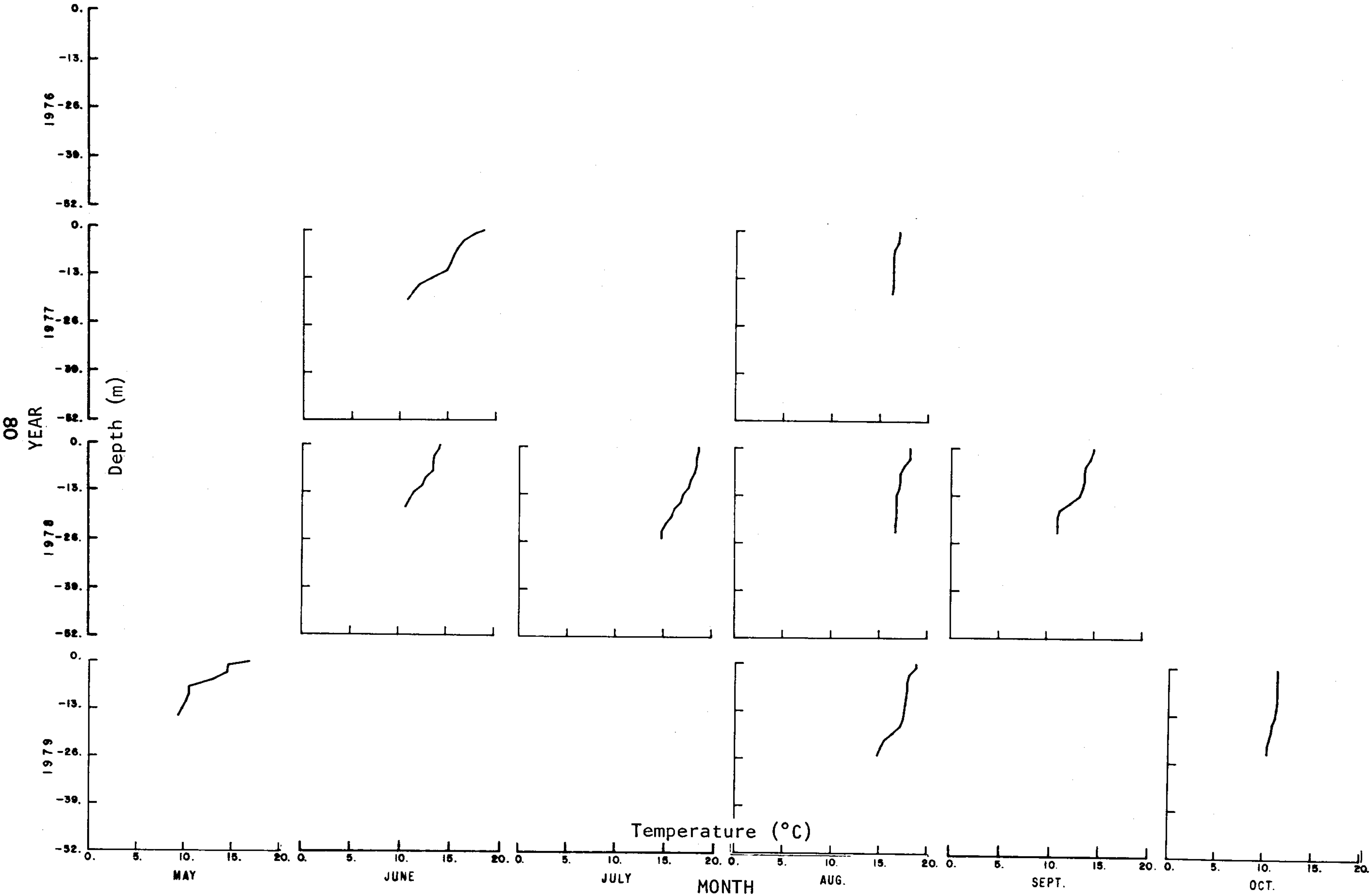

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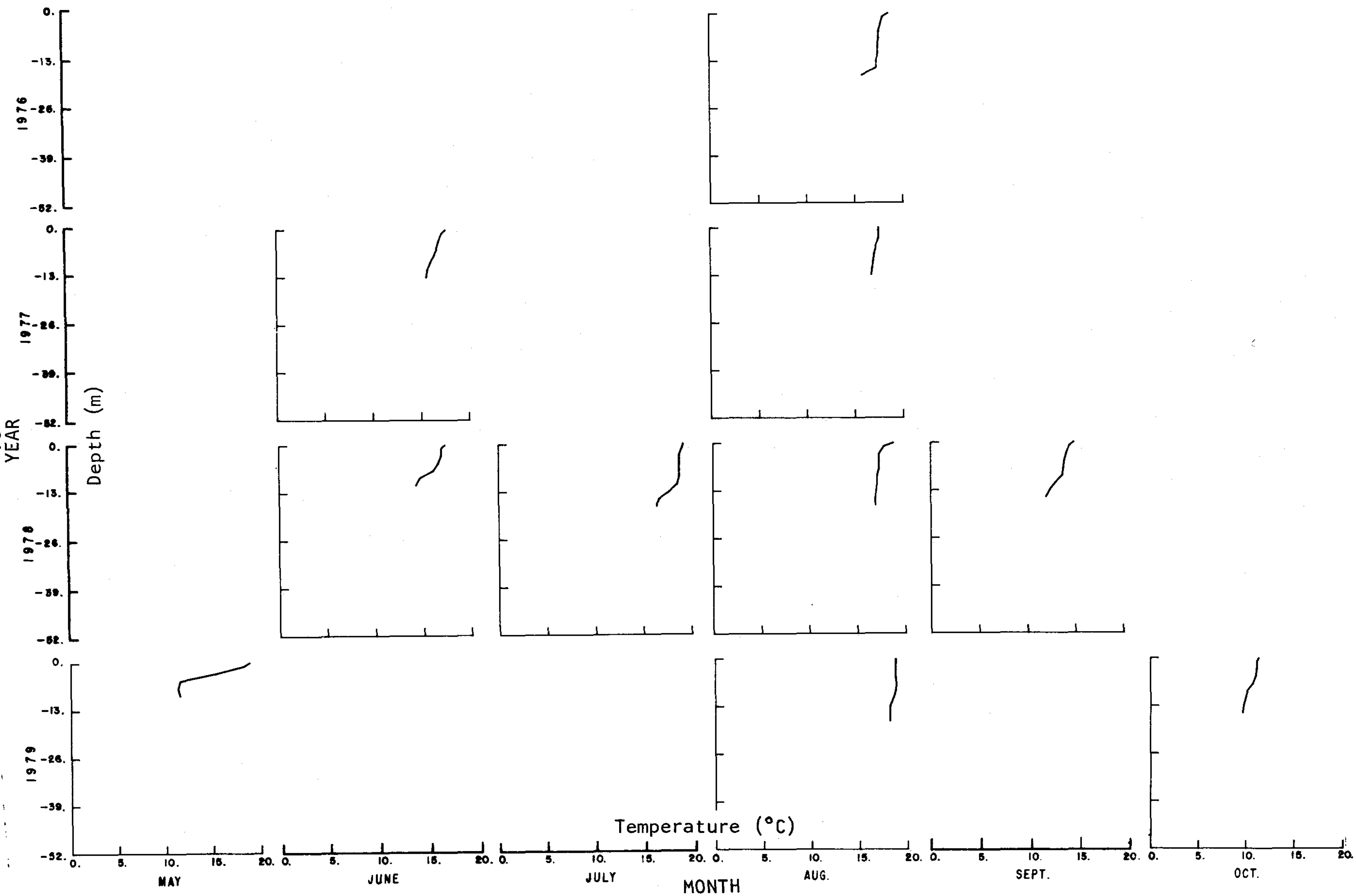
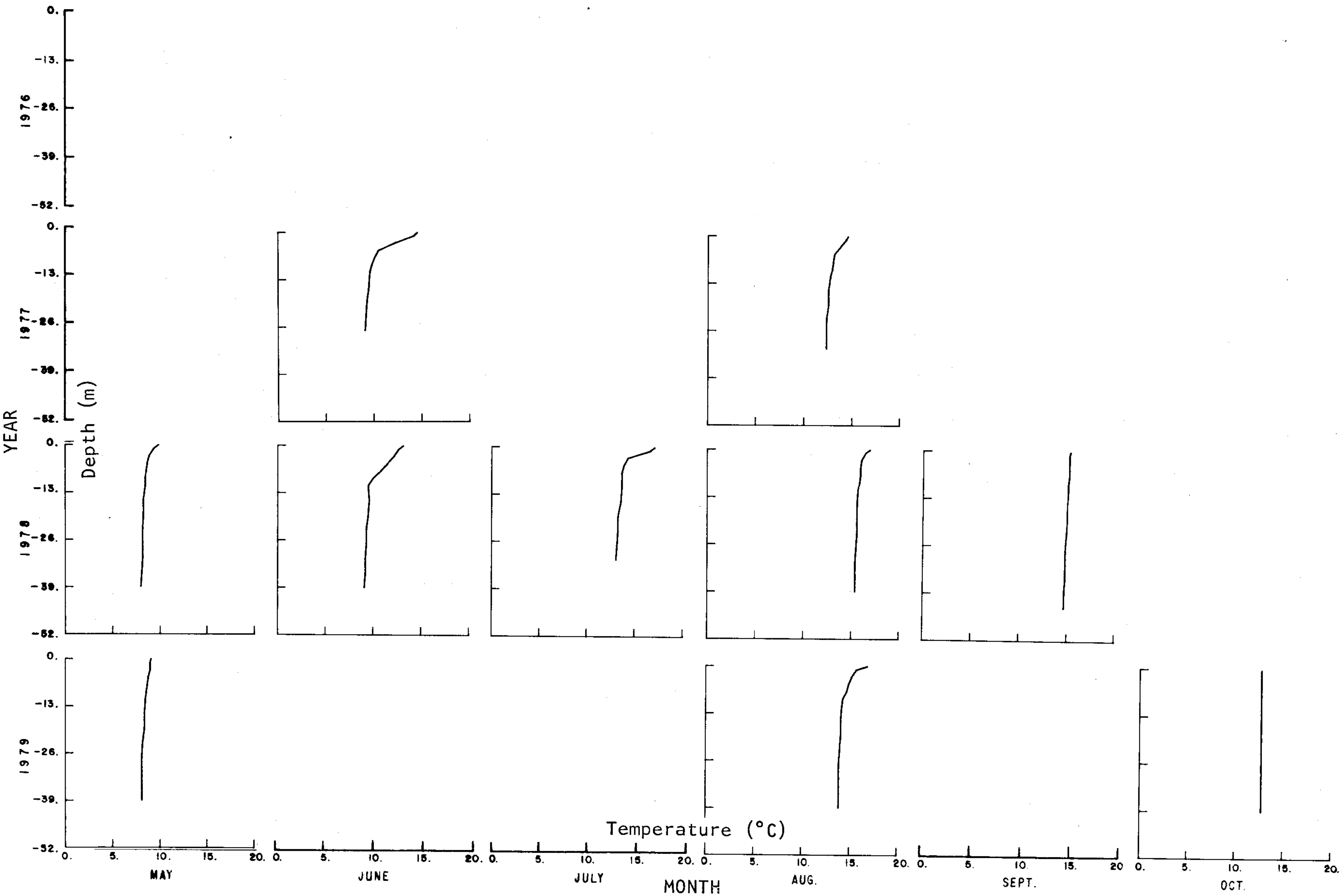


STATION S-3, MEDICINE BOW ARM OF SEMINOE RESERVOIR



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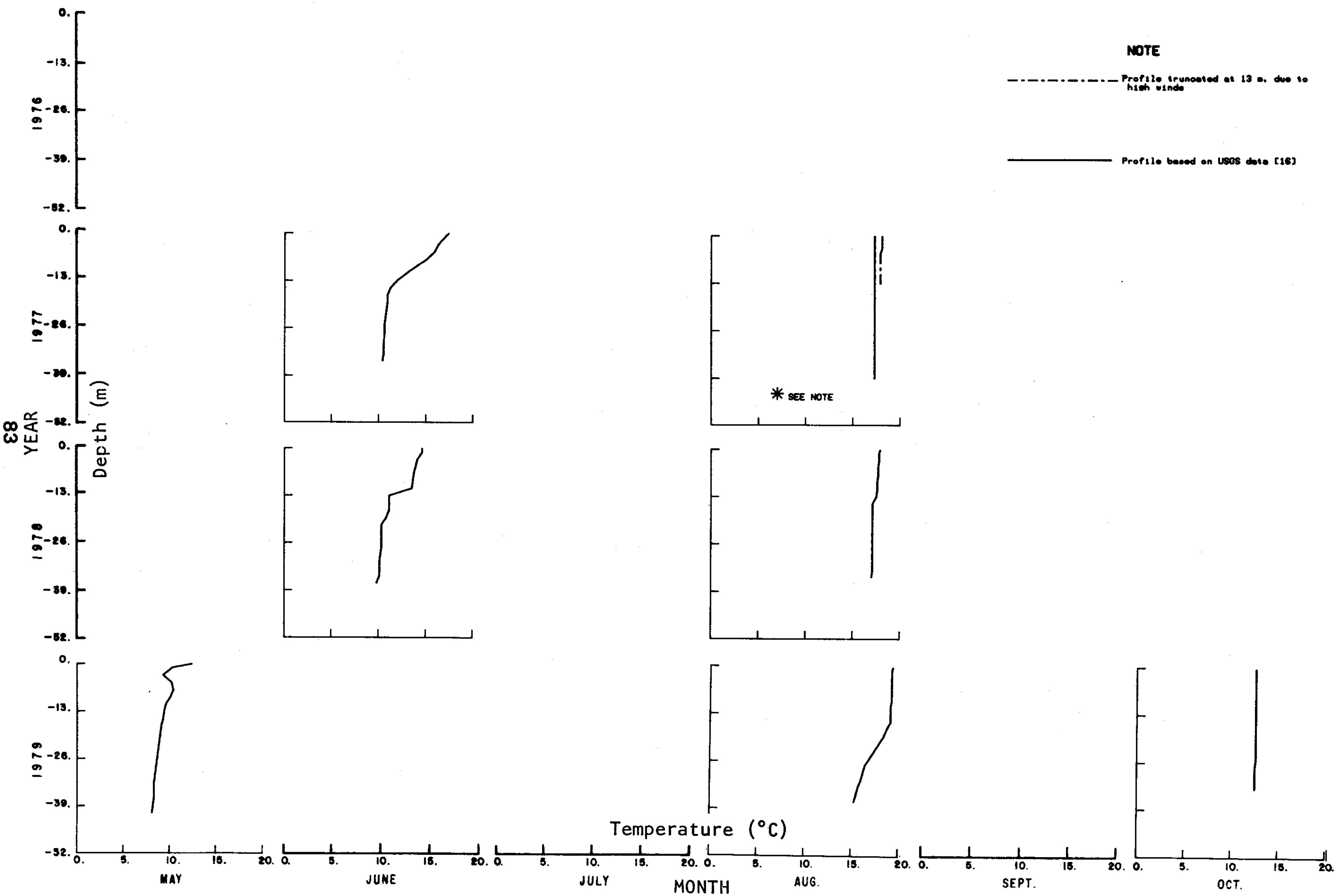

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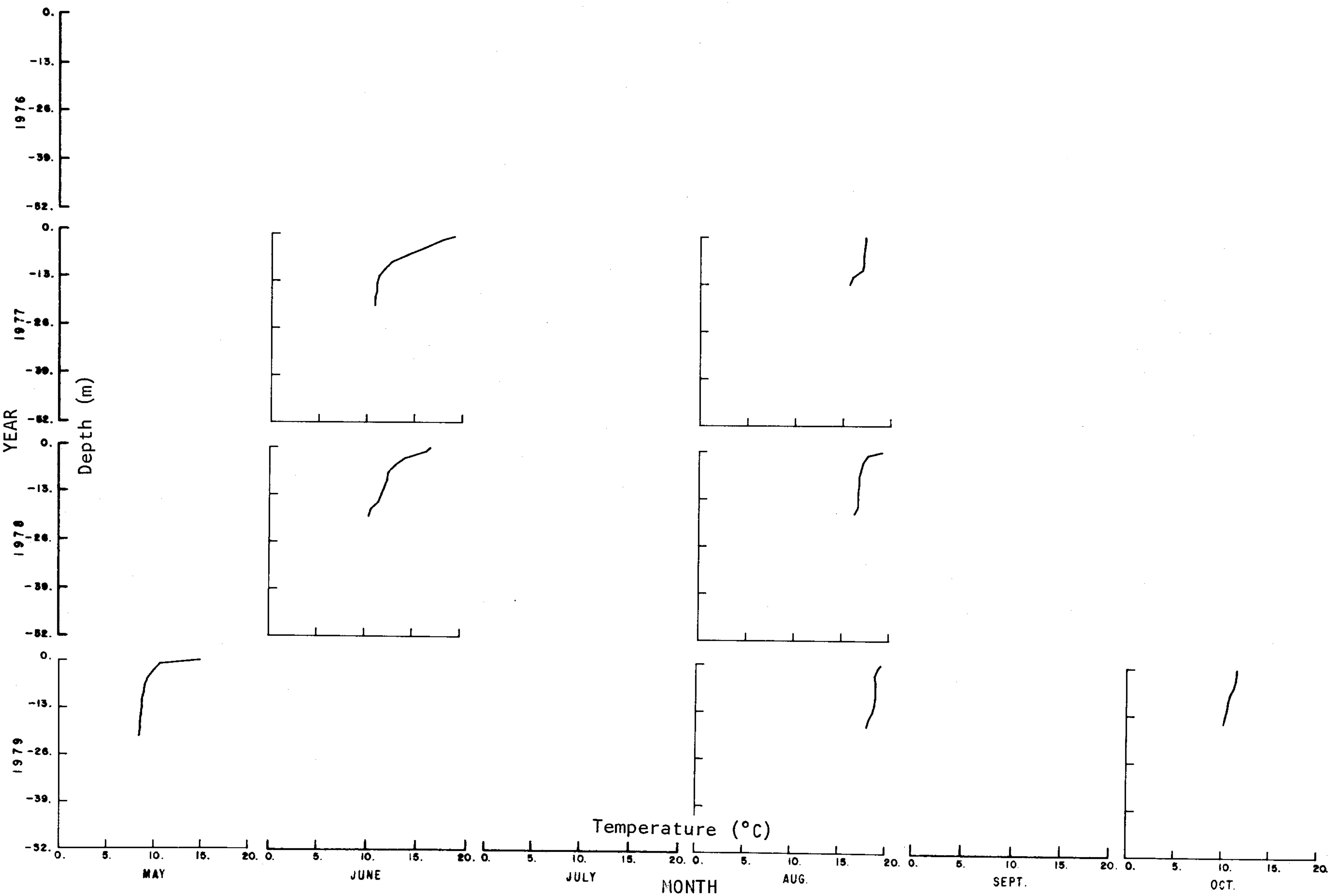
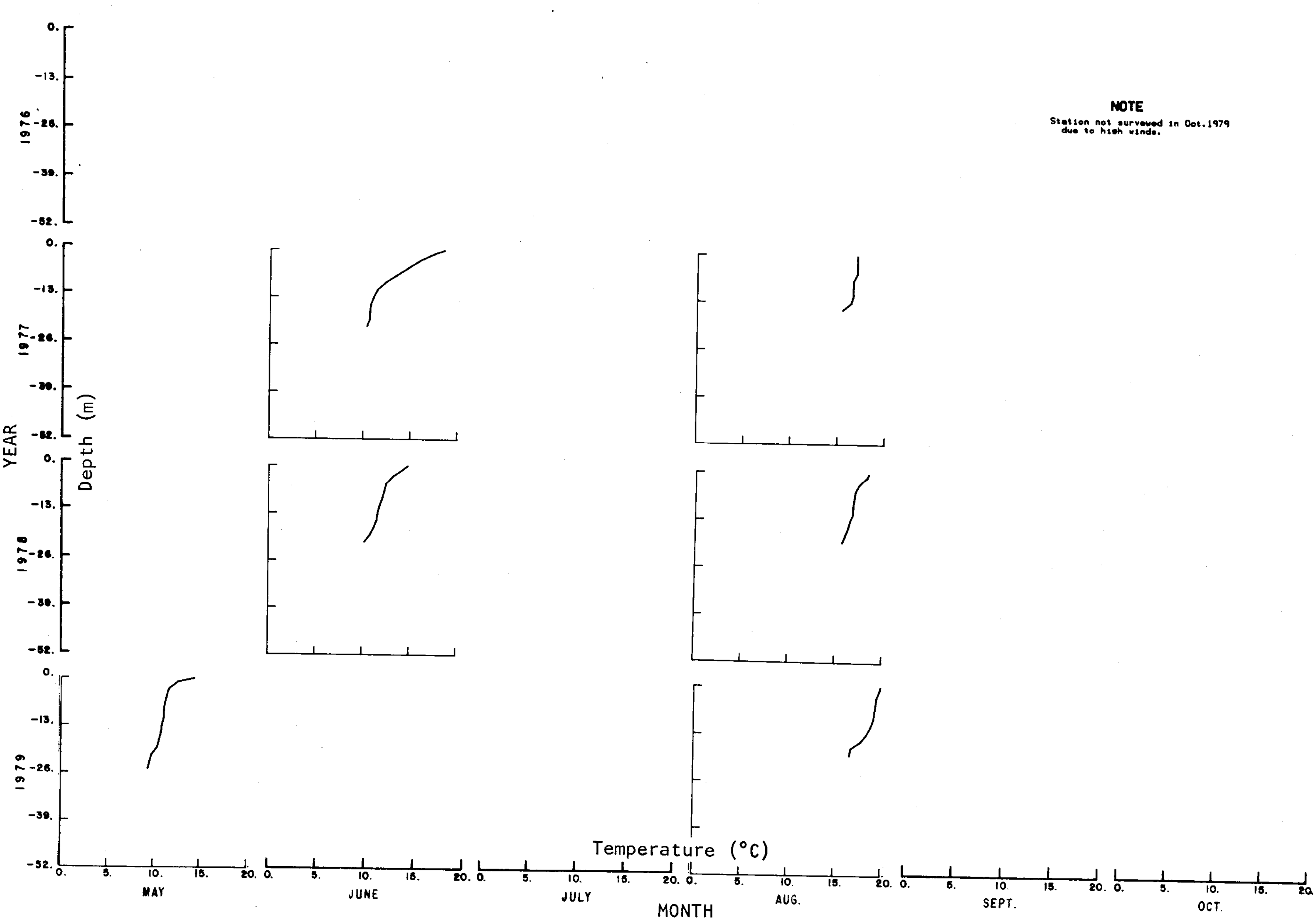
STATION P-1, PATHFINDER RESERVOIR



STATION P-2. SWEETWATER ARM OF PATHFINDER RESERVOIR



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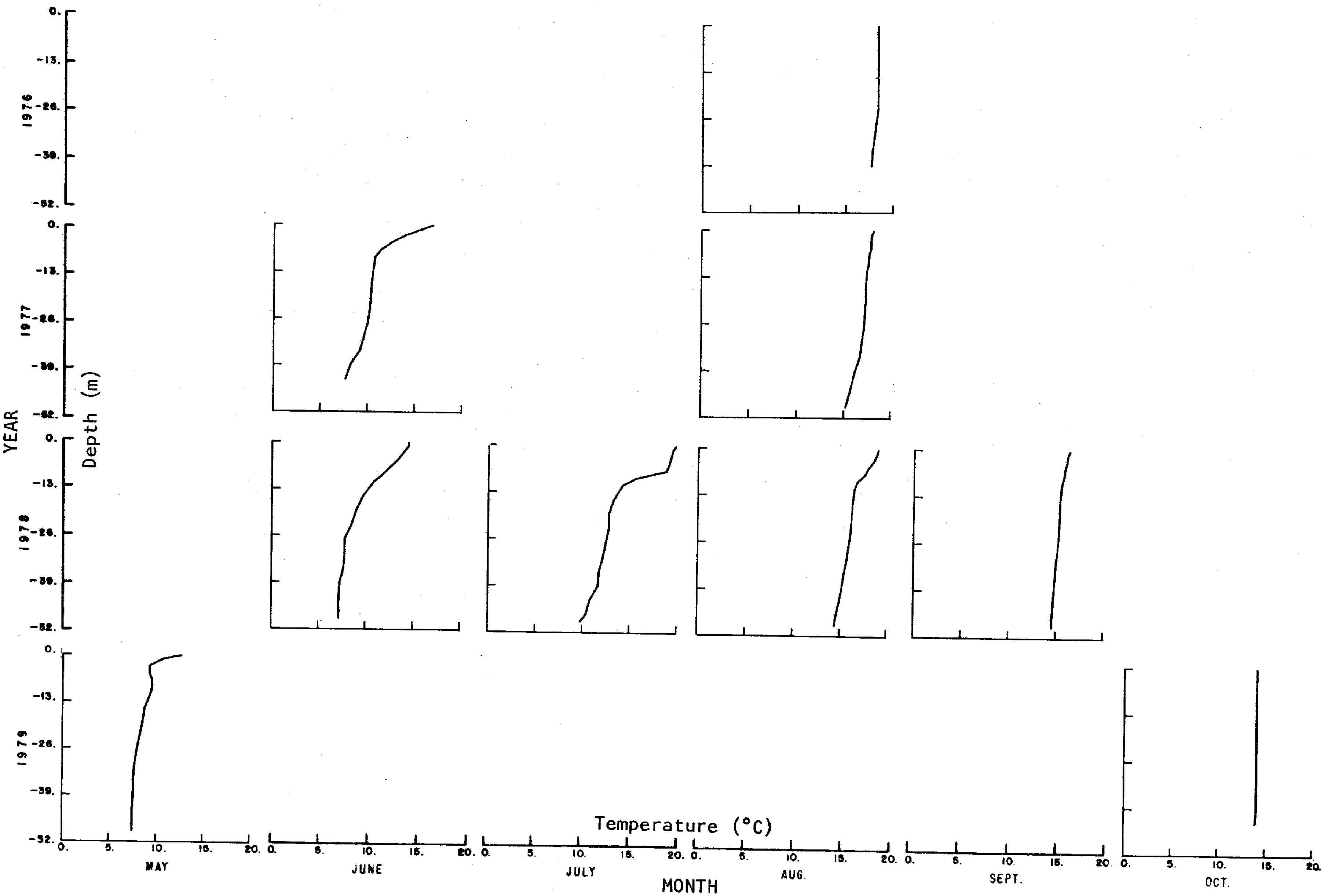

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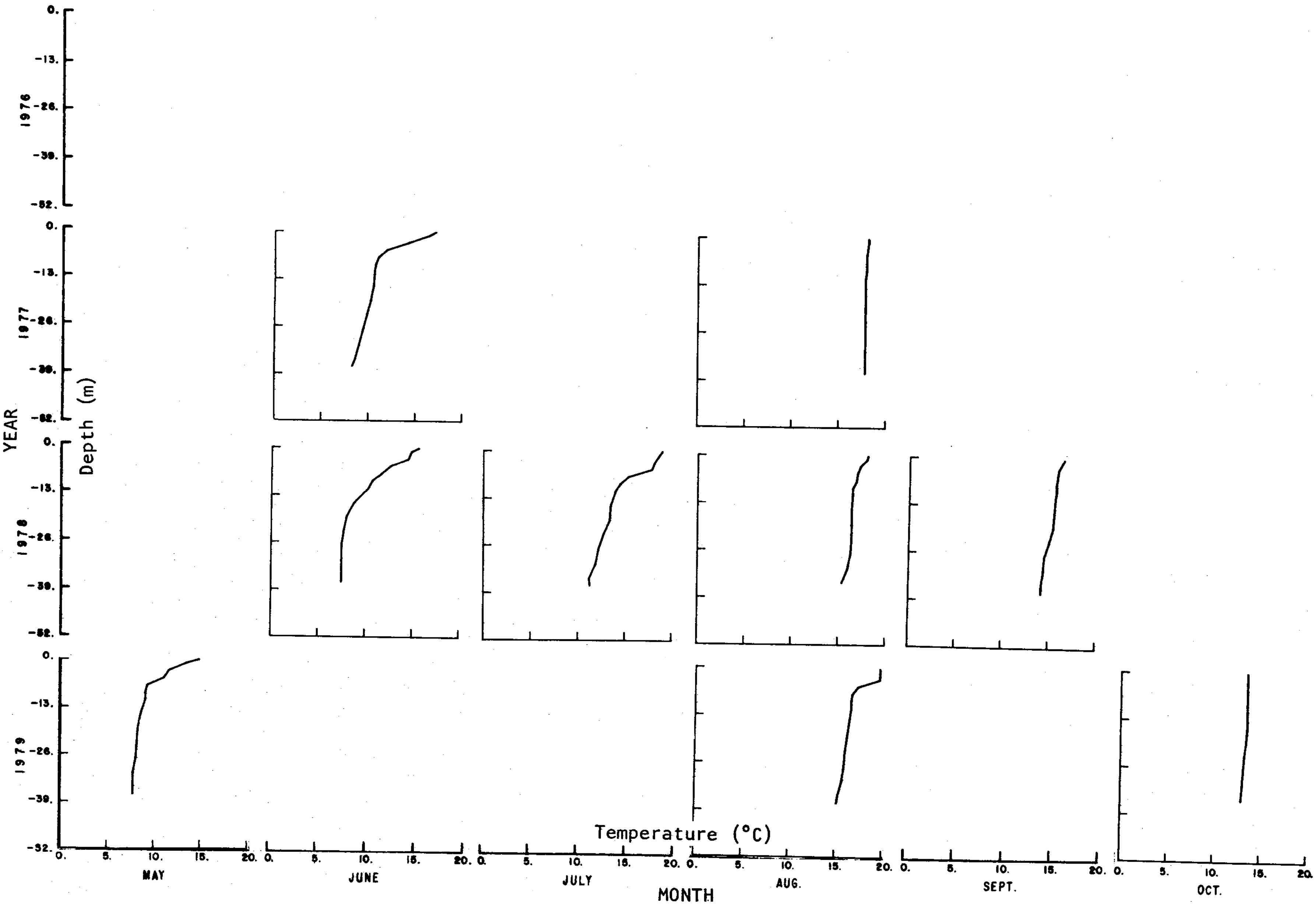
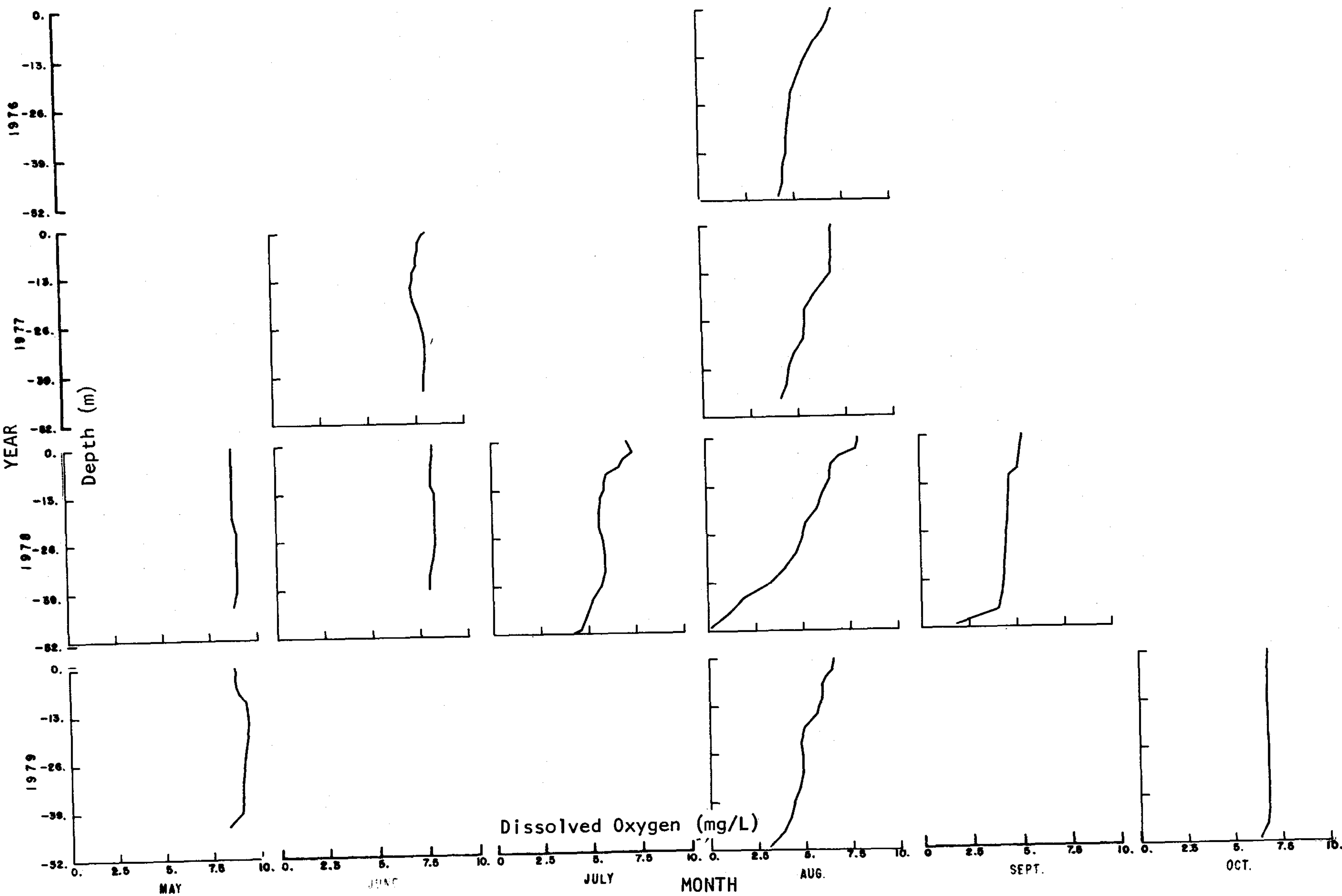


STATION A-2, FREMONT CANYON SECTION OF ALCOVA RESERVOIR

APPENDIX B
DISSOLVED OXYGEN PROFILES



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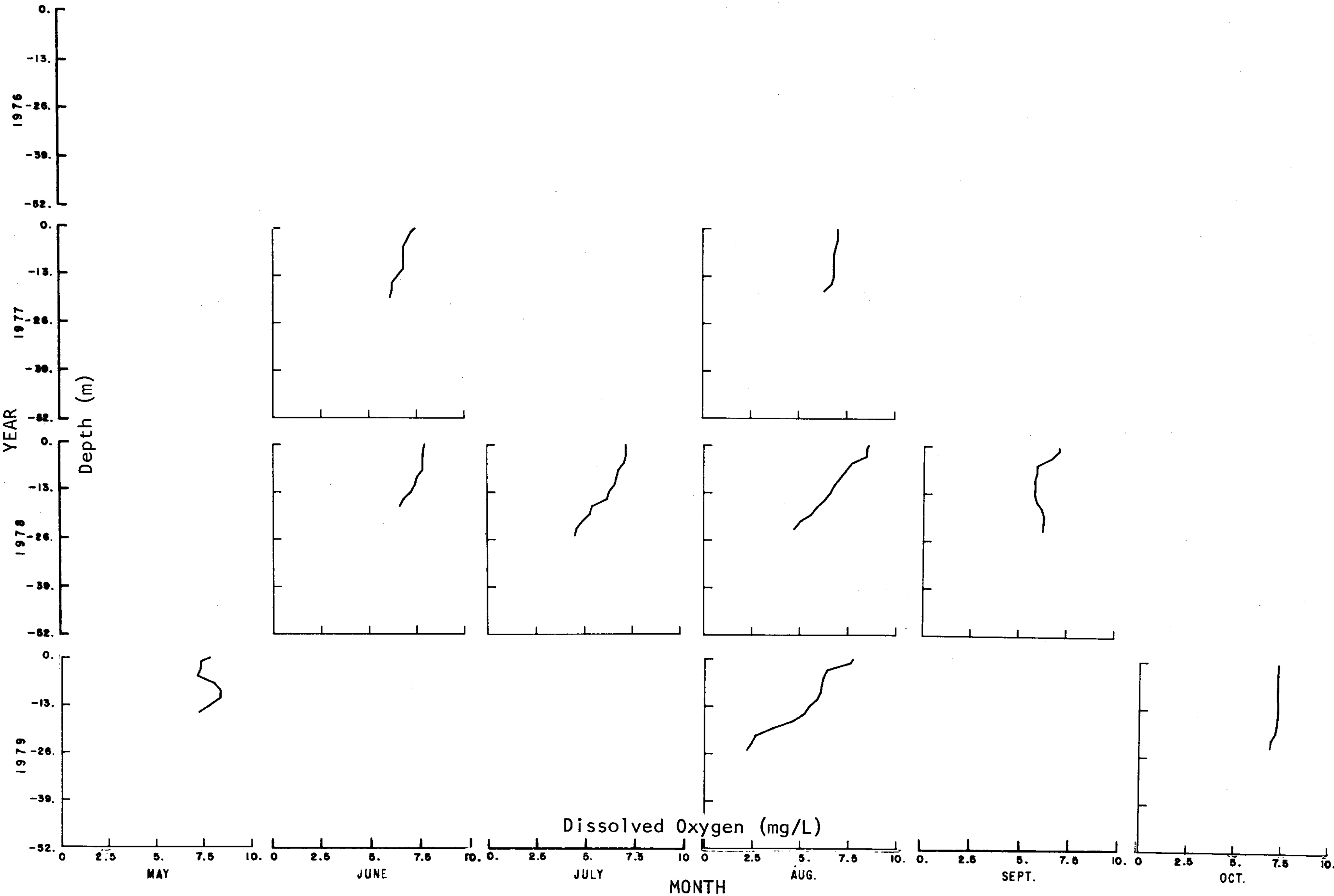

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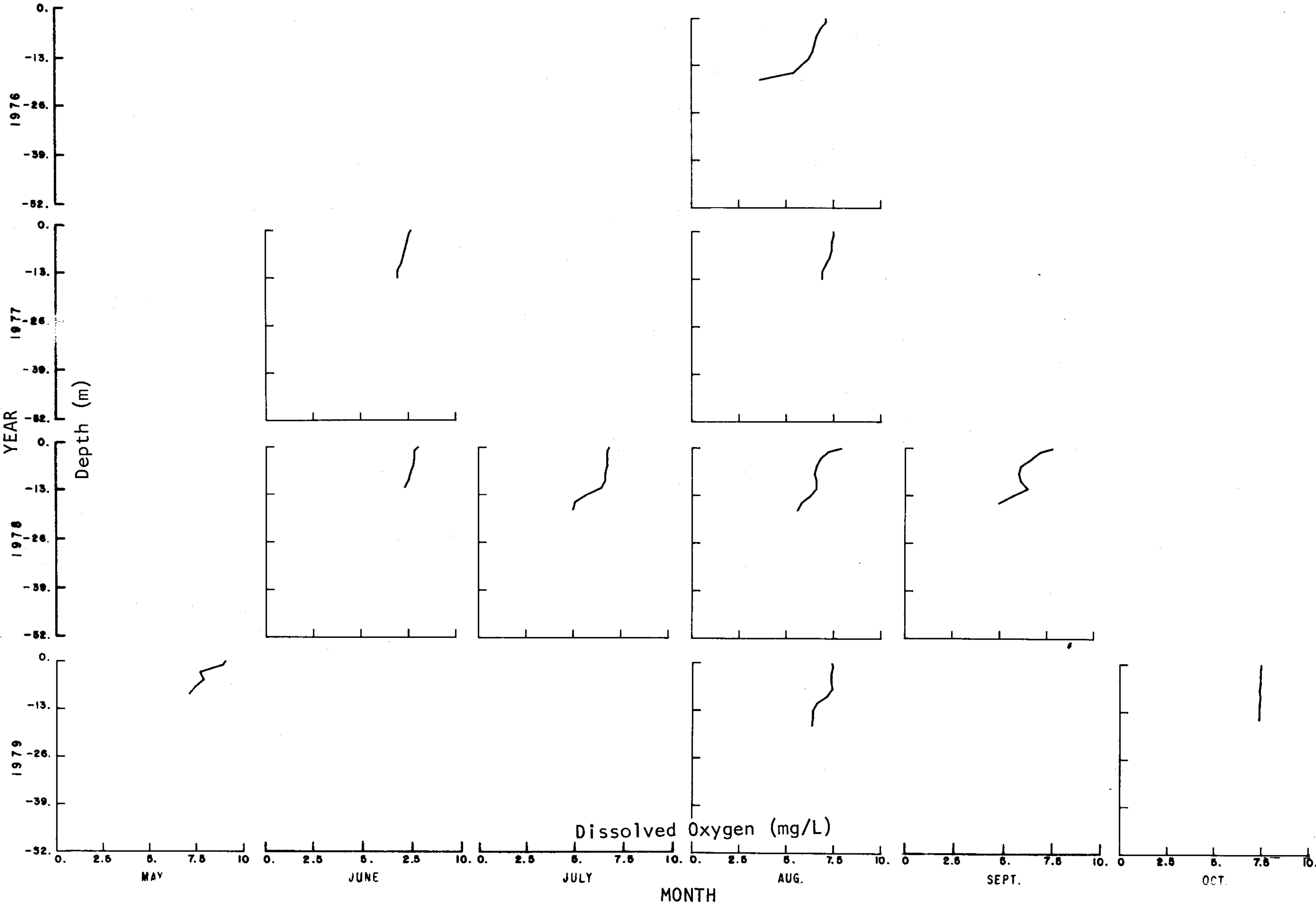

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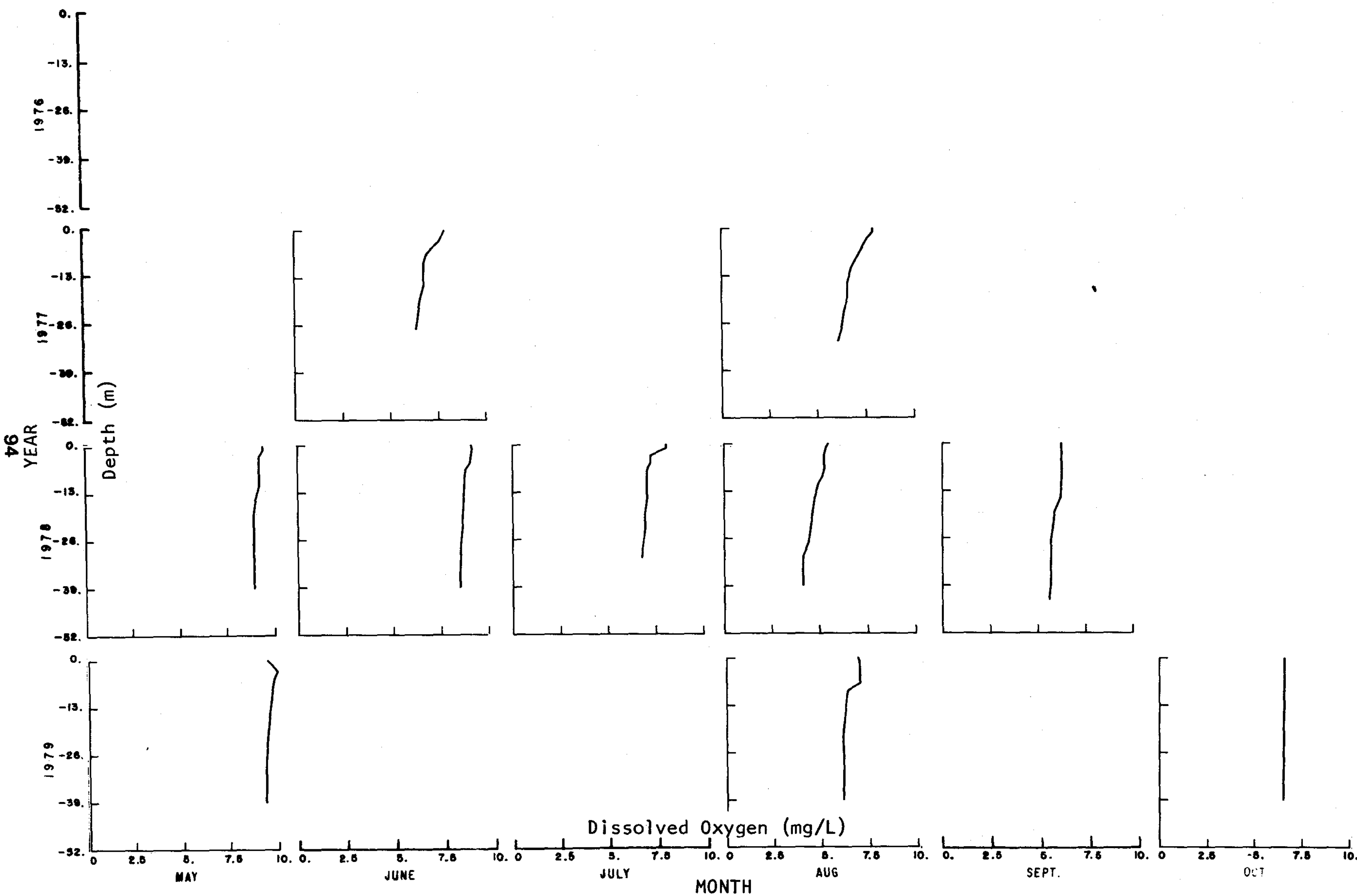

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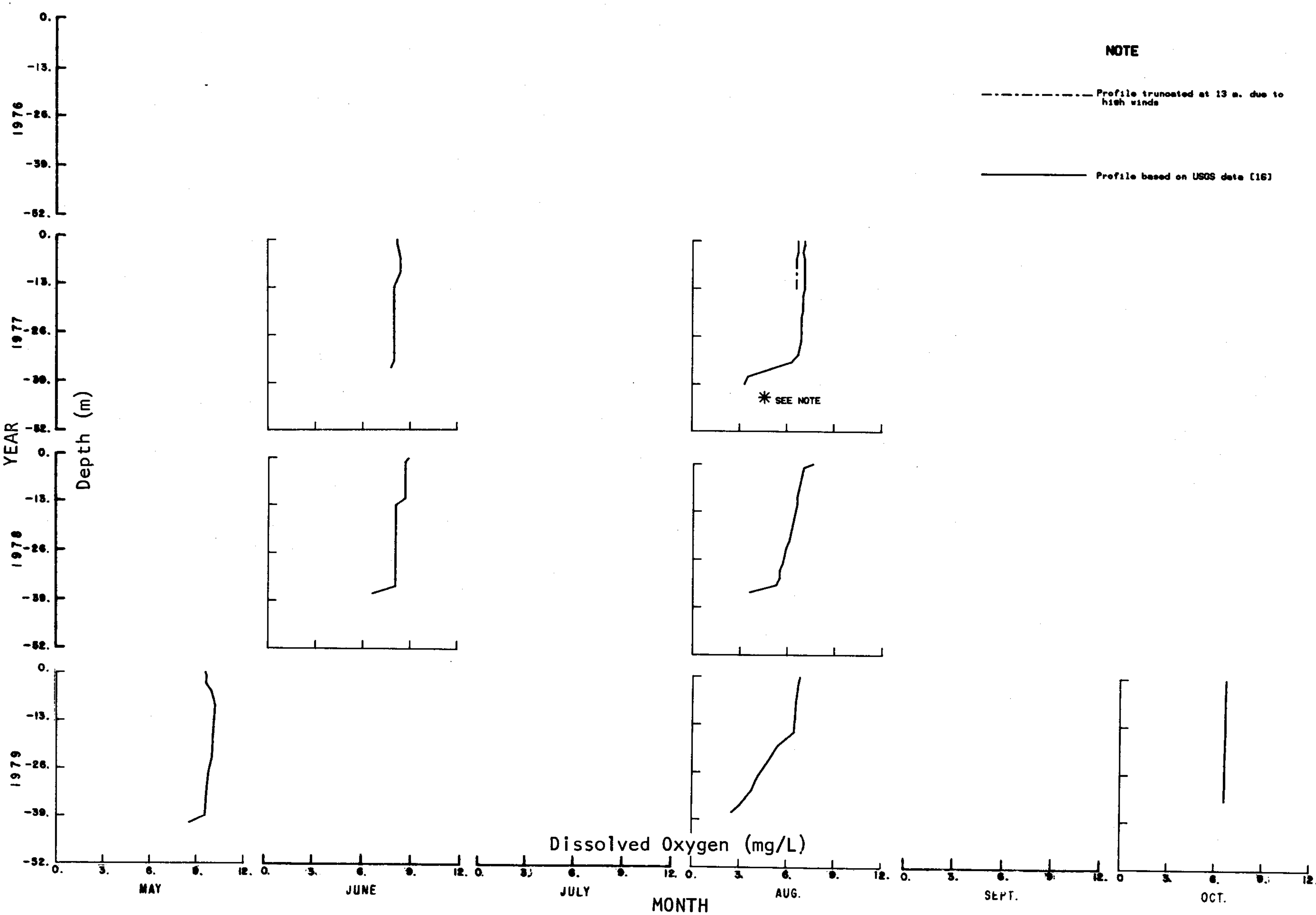

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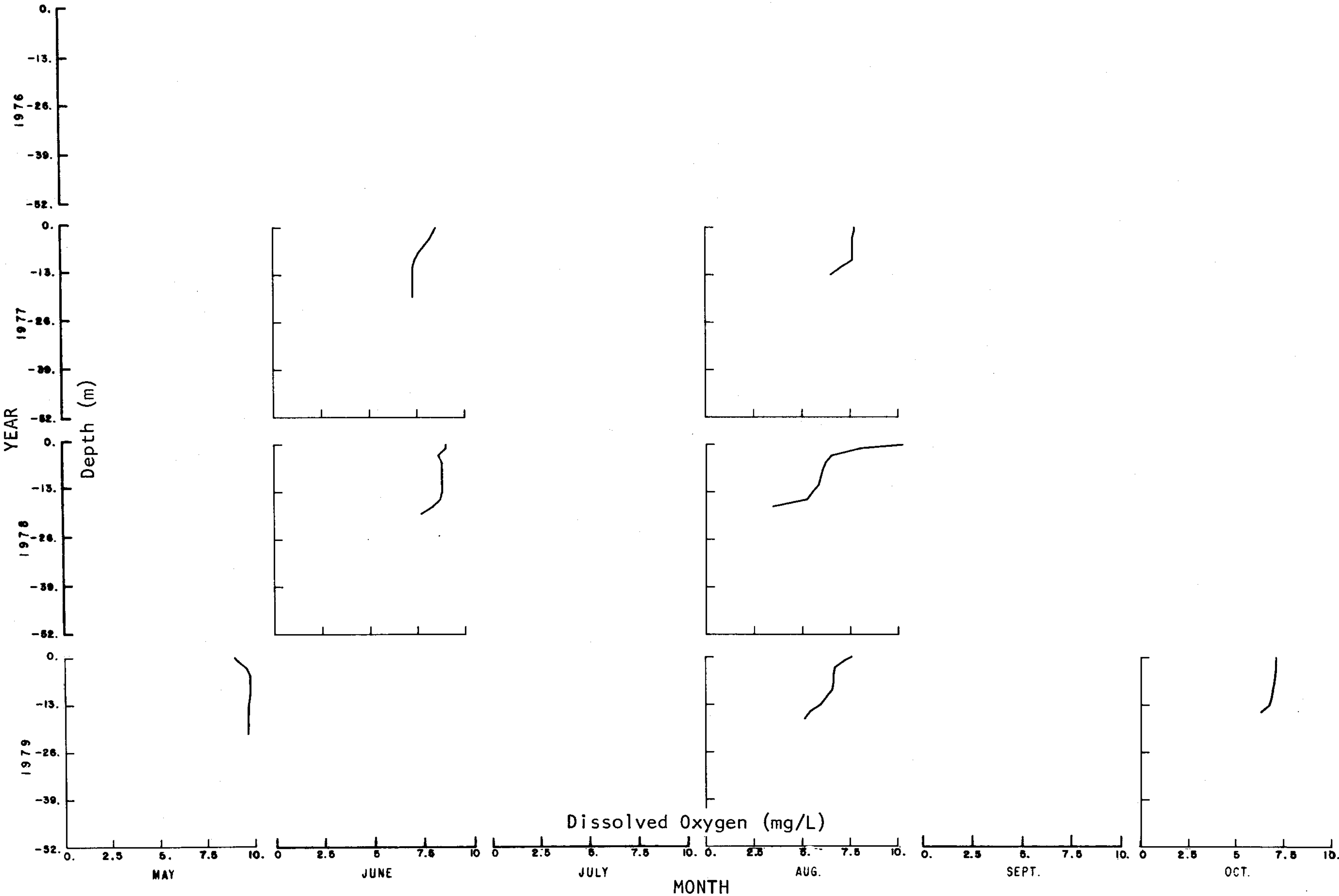
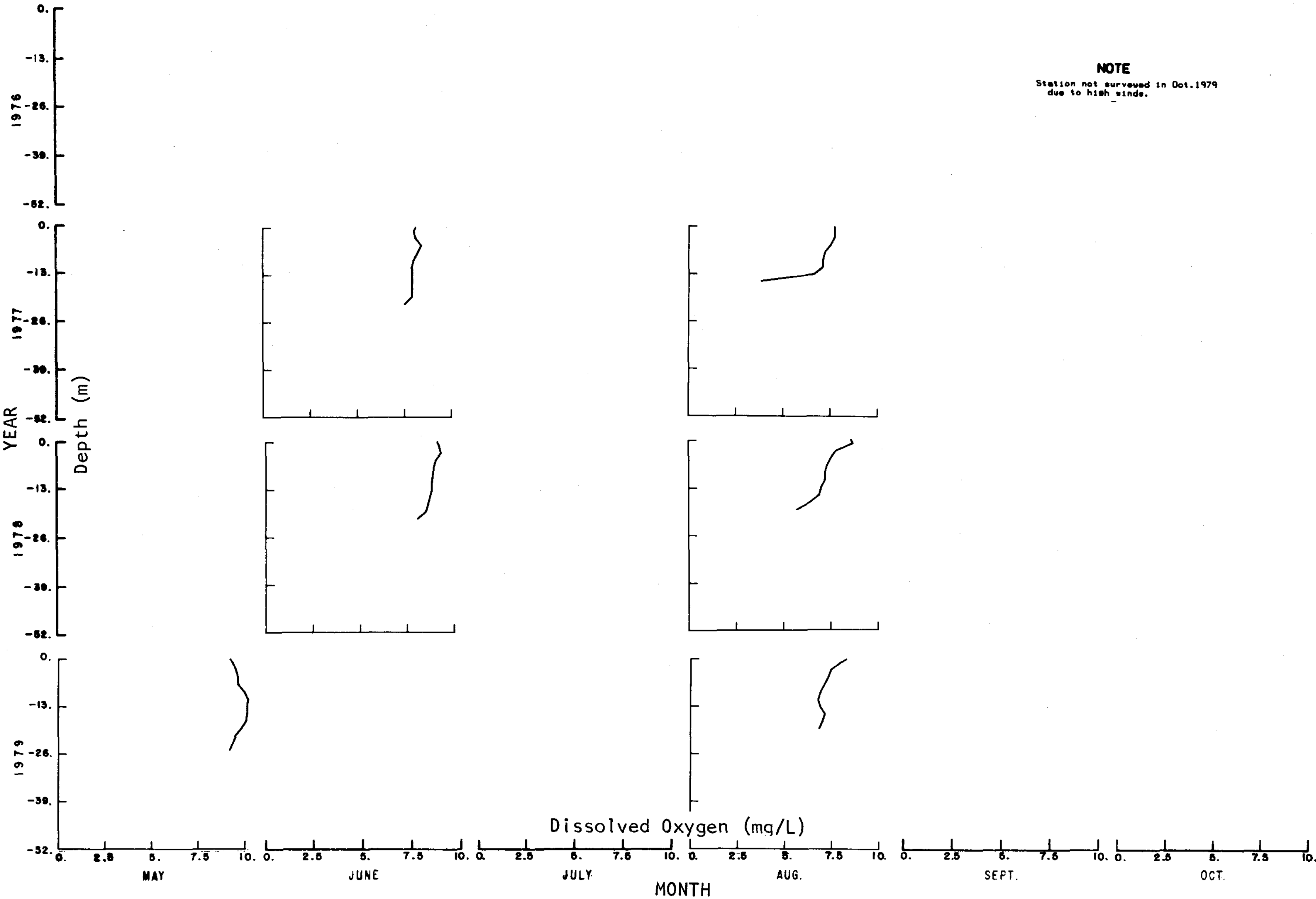


STATION P-2. SWEETWATER ARM OF PATHFINDER RESERVOIR



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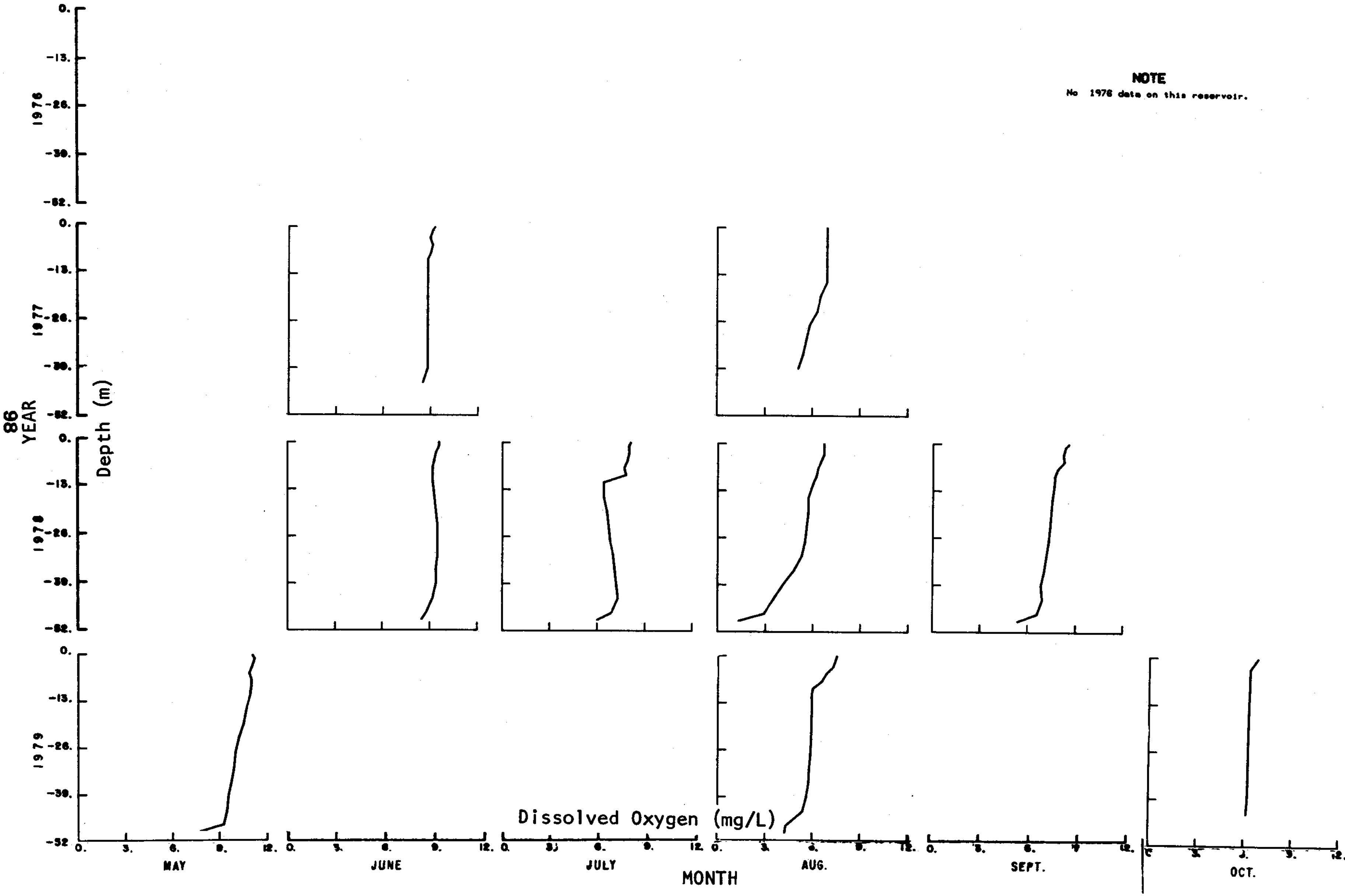

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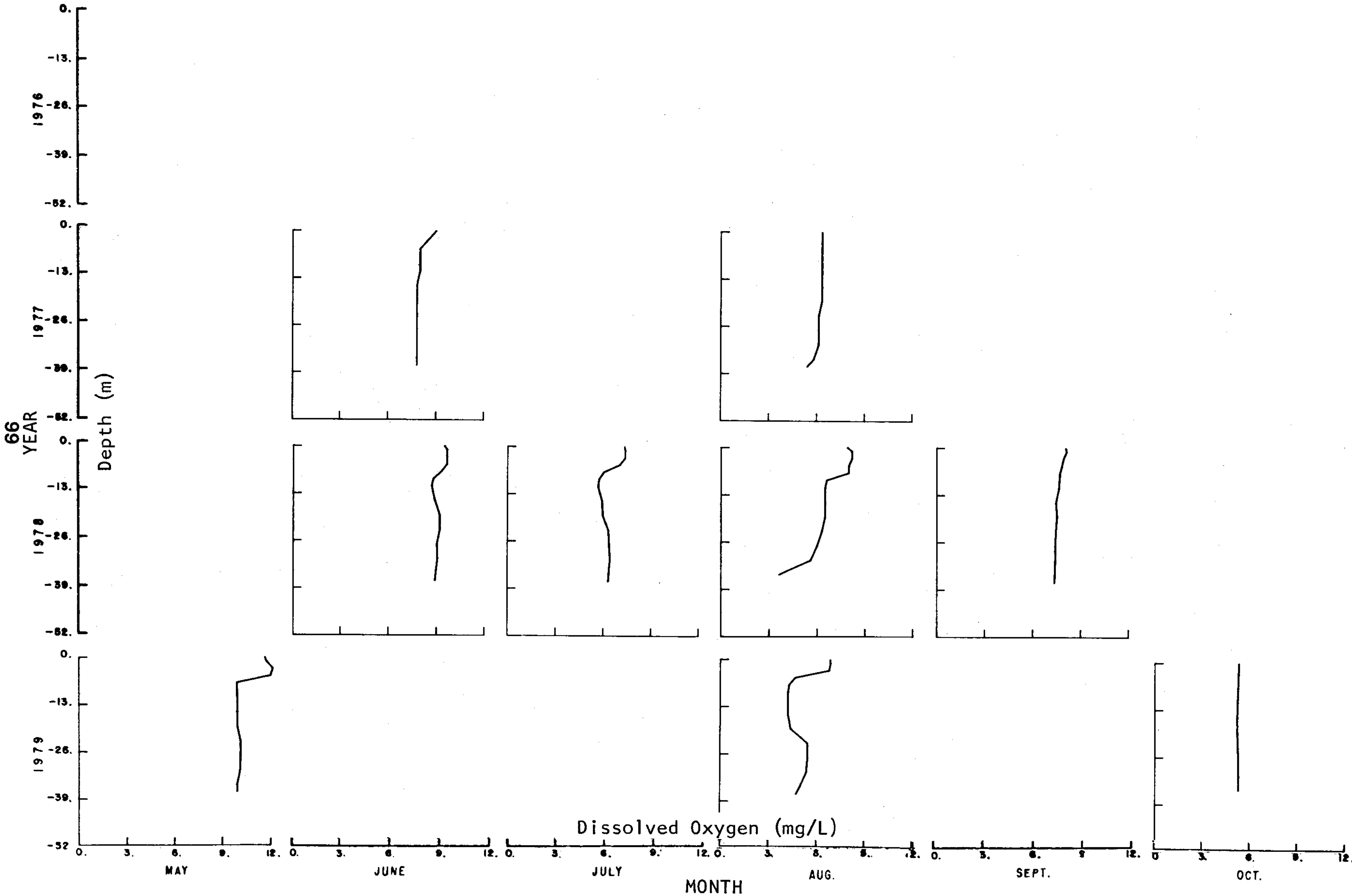

STATION A-2, FREMONT CANYON SECTION OF ALCOVA RESERVOIR

APPENDIX C
pH PROFILES

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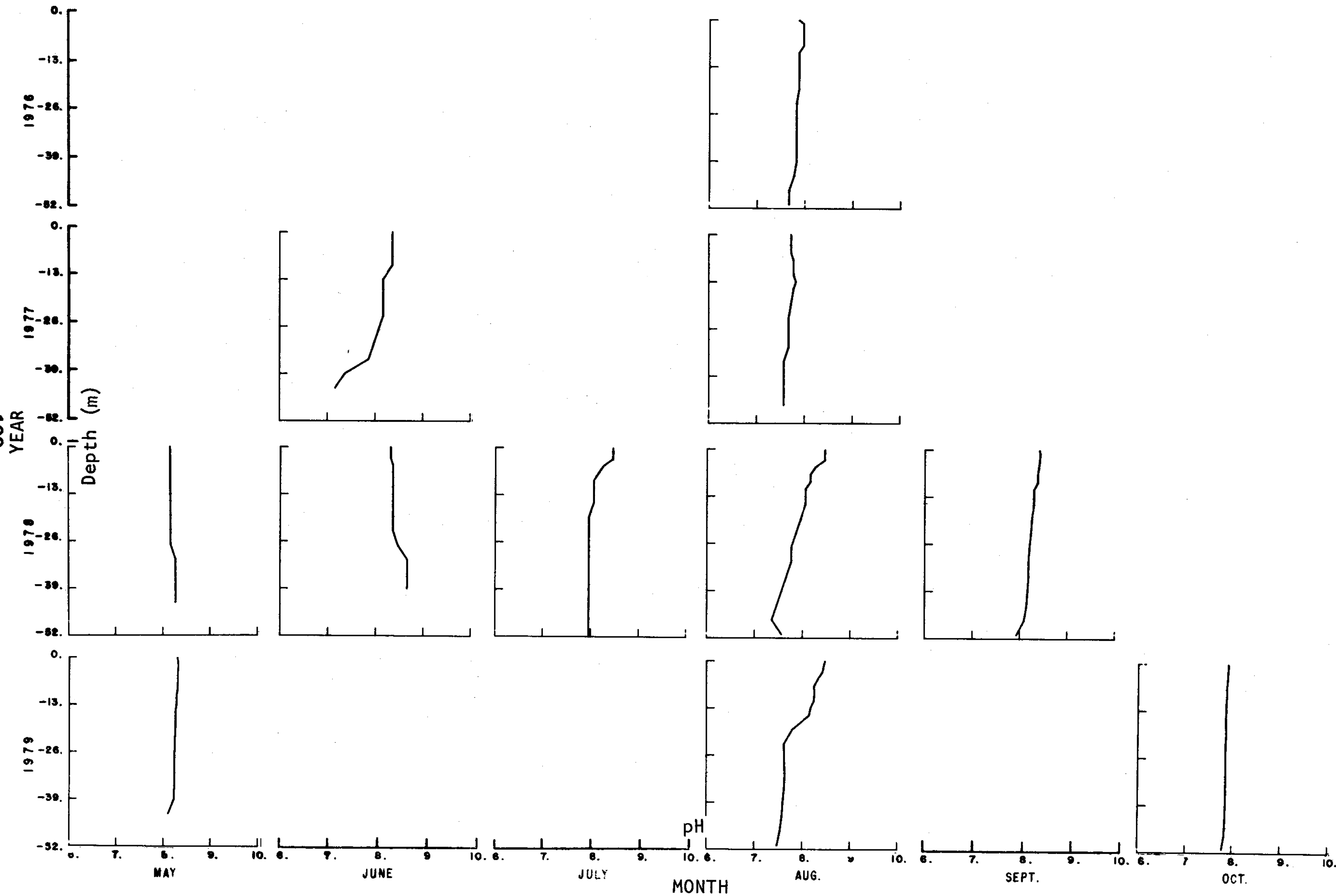

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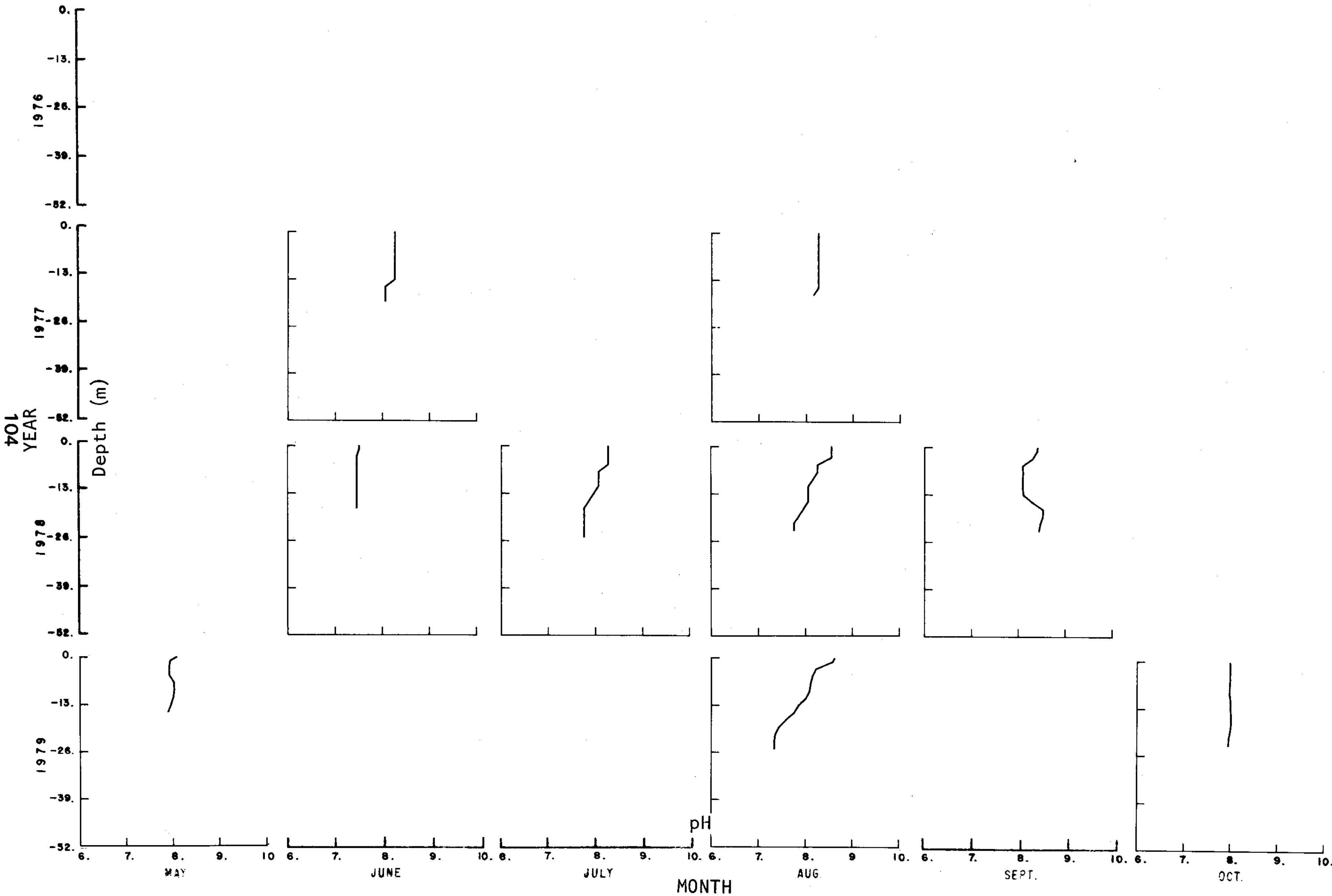

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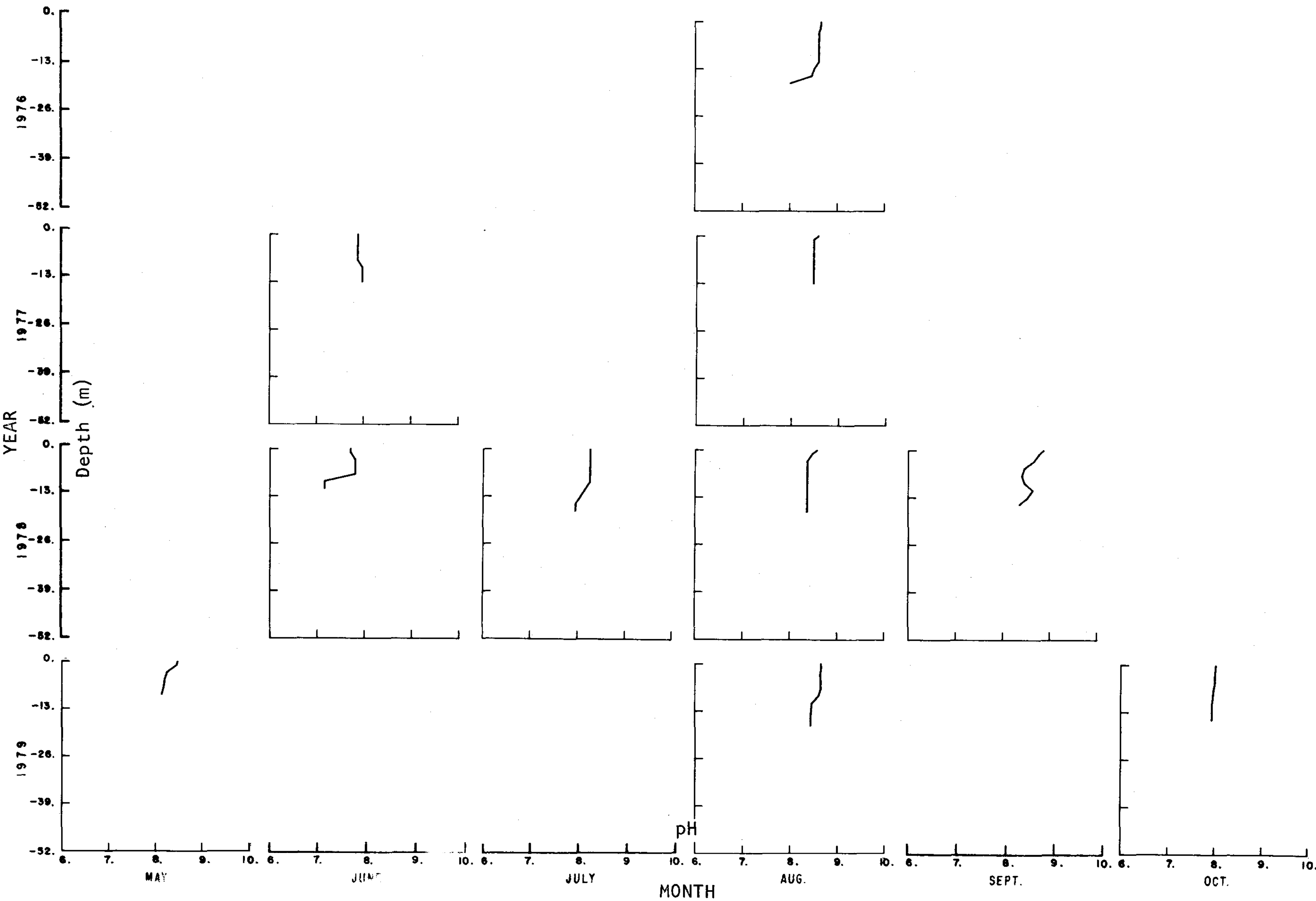

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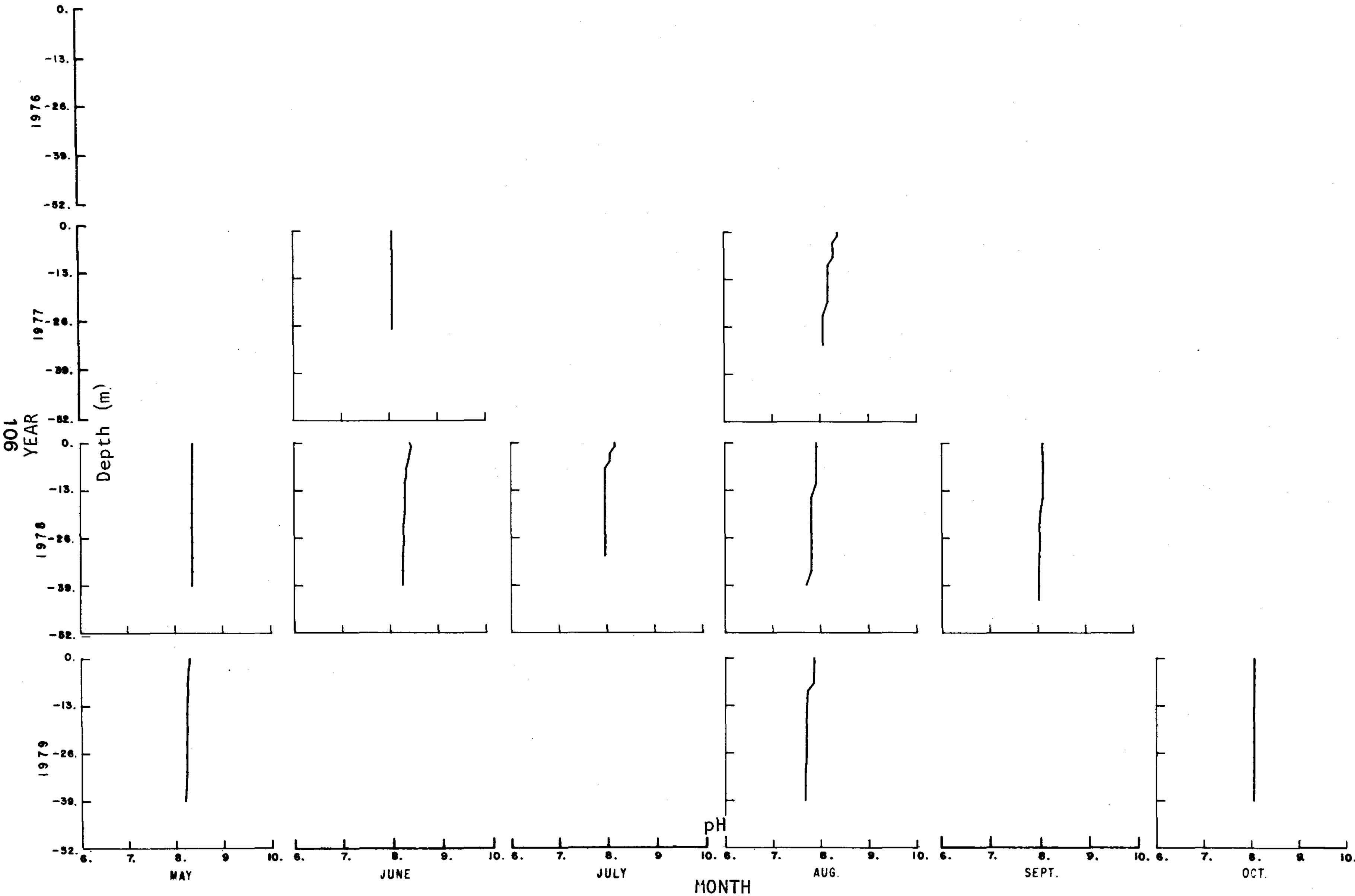

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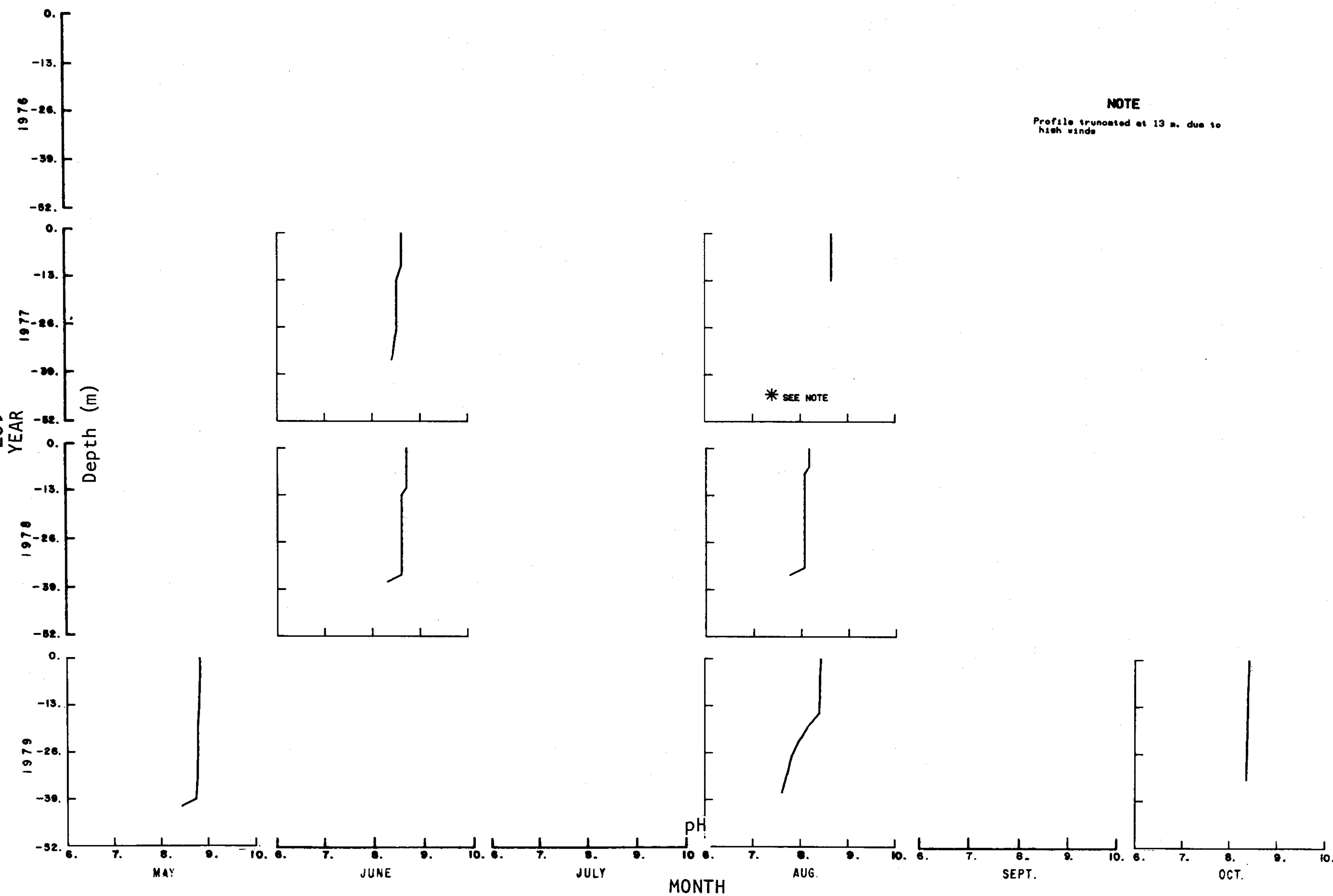

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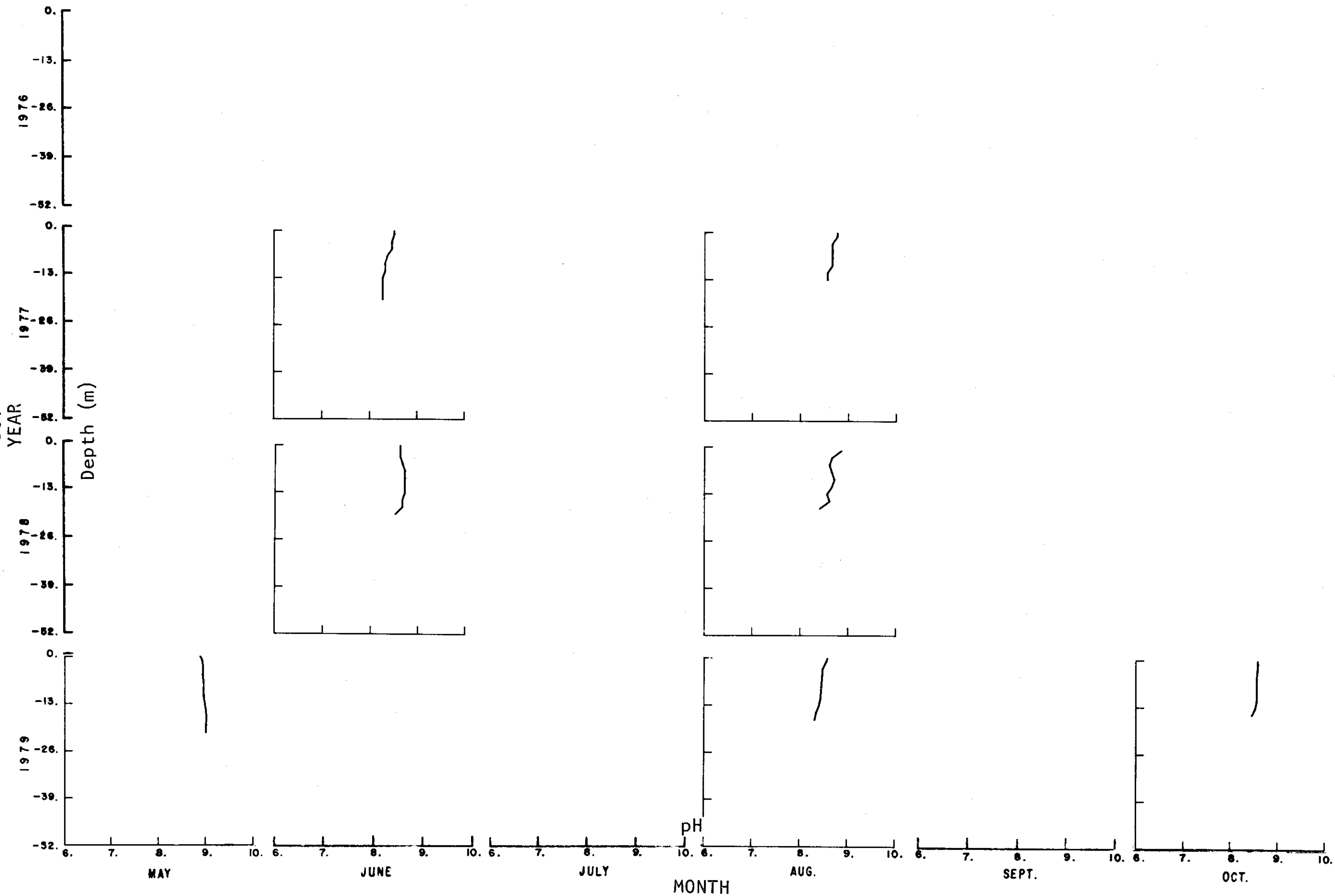

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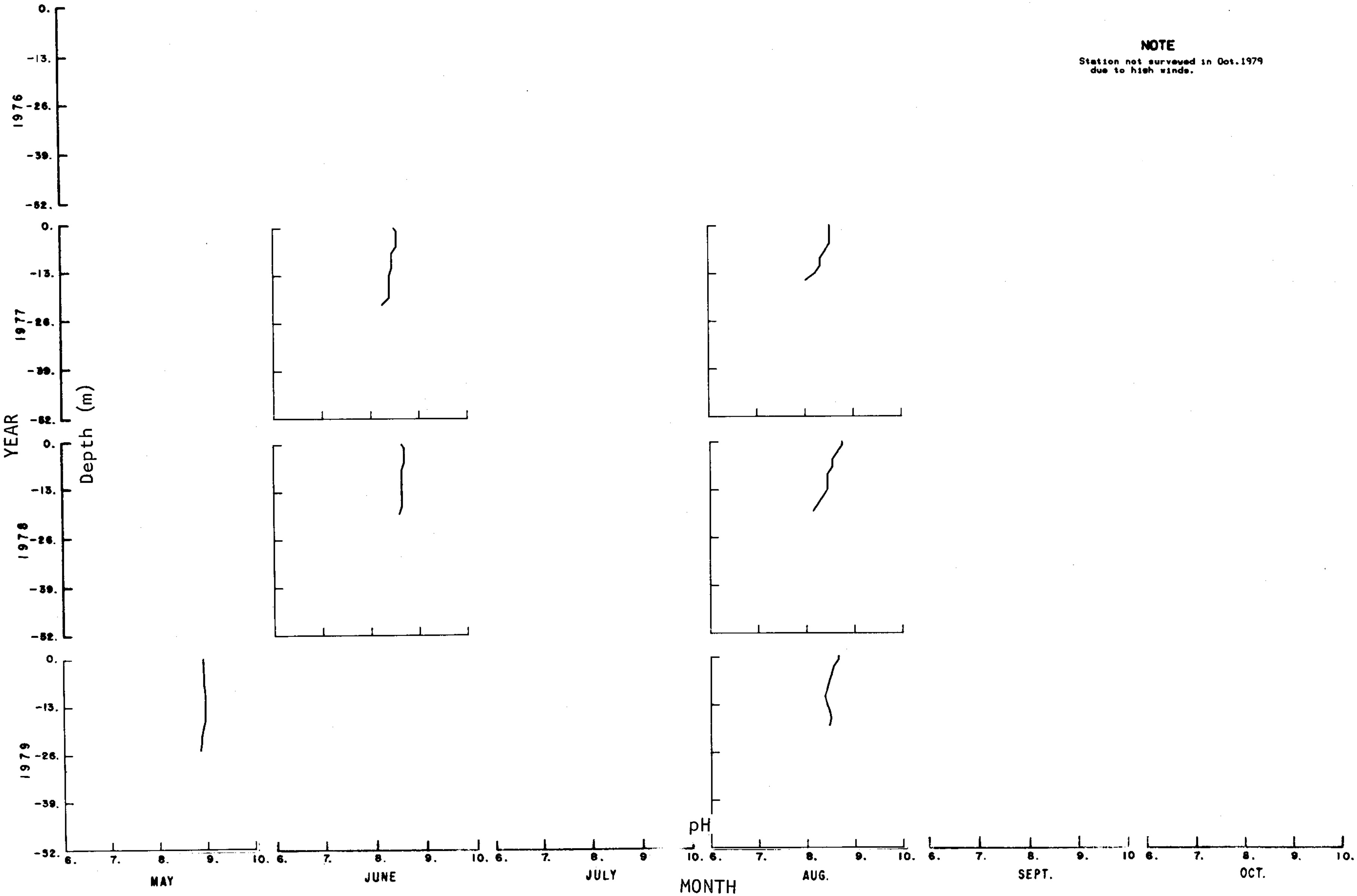

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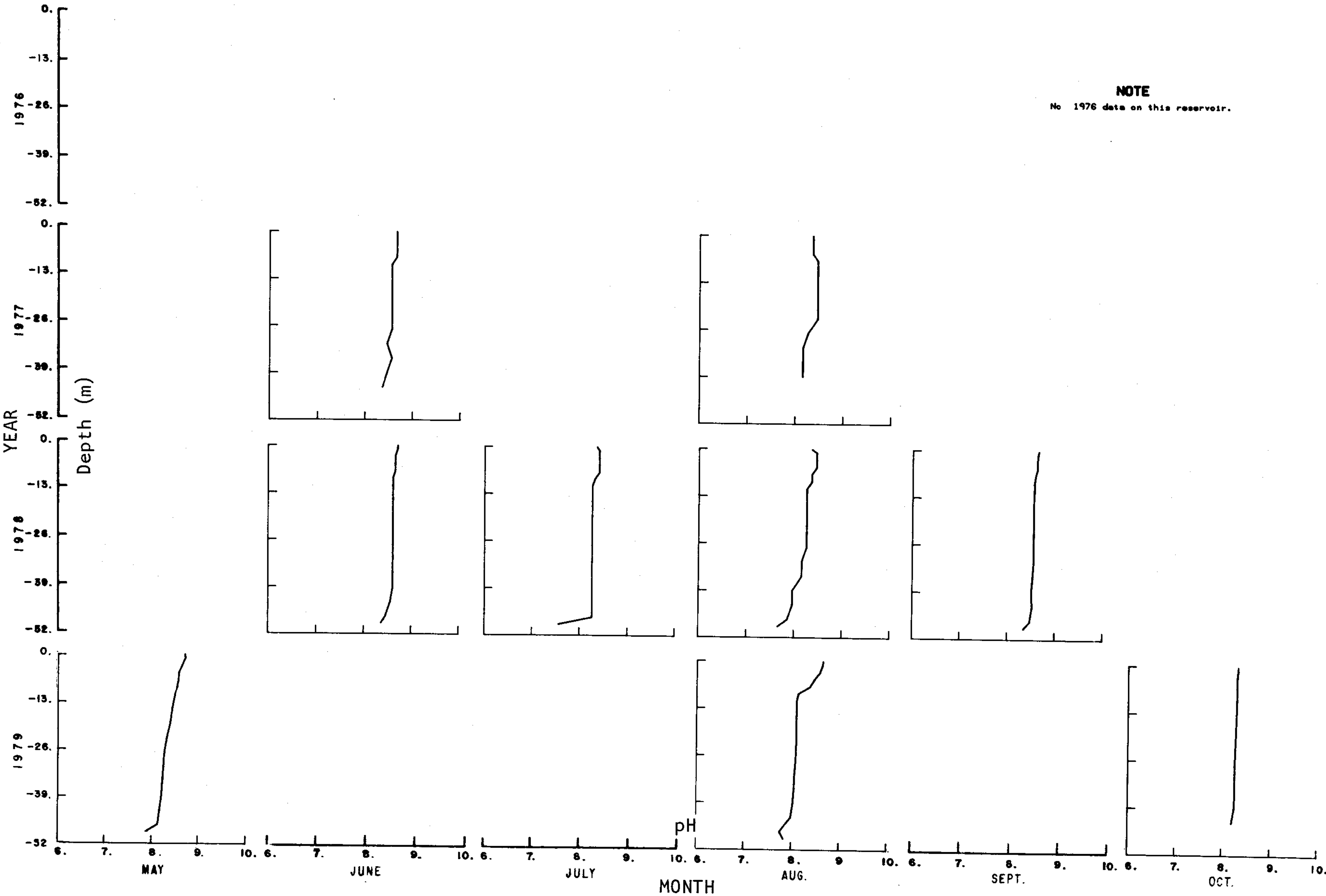

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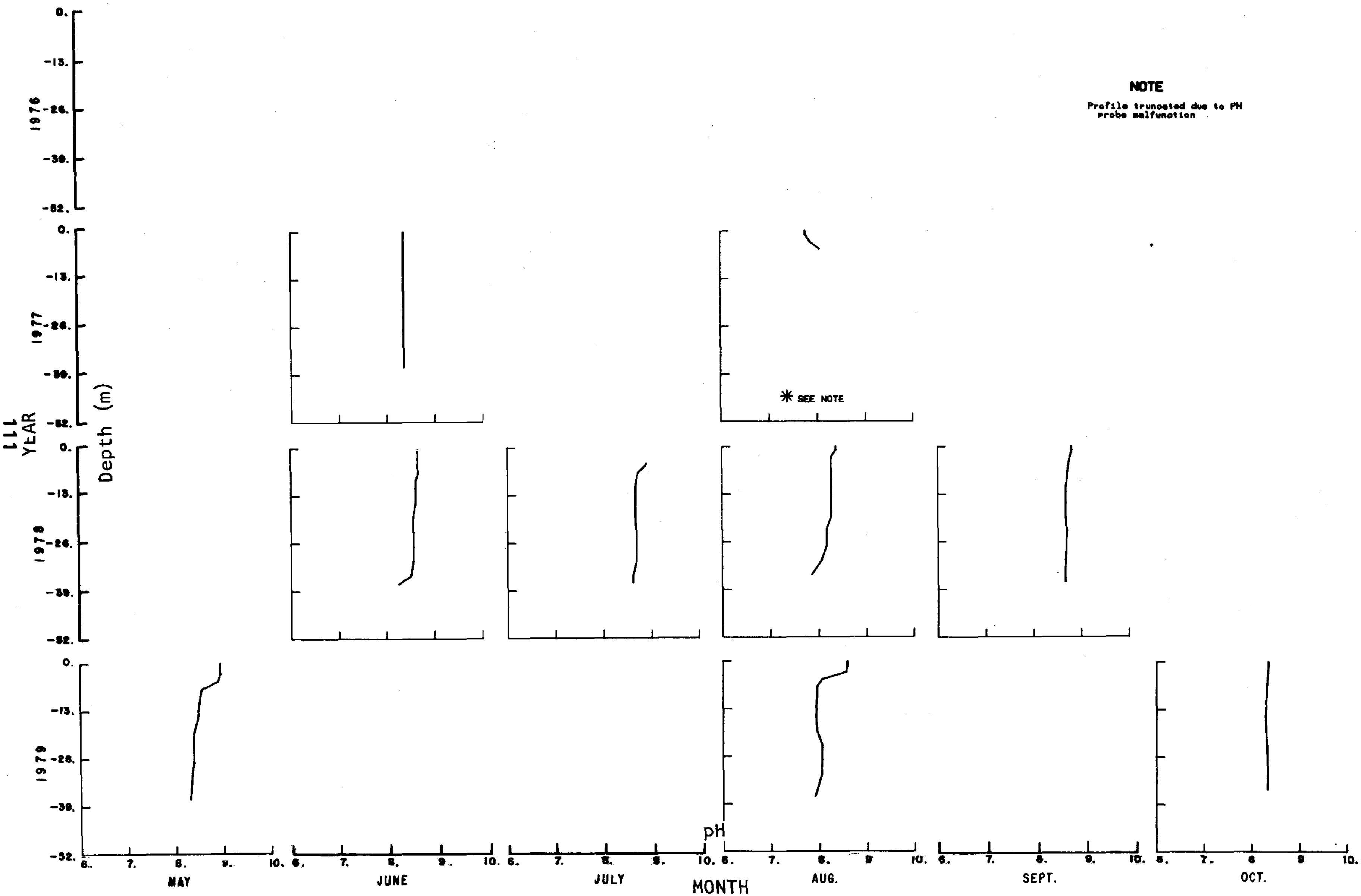
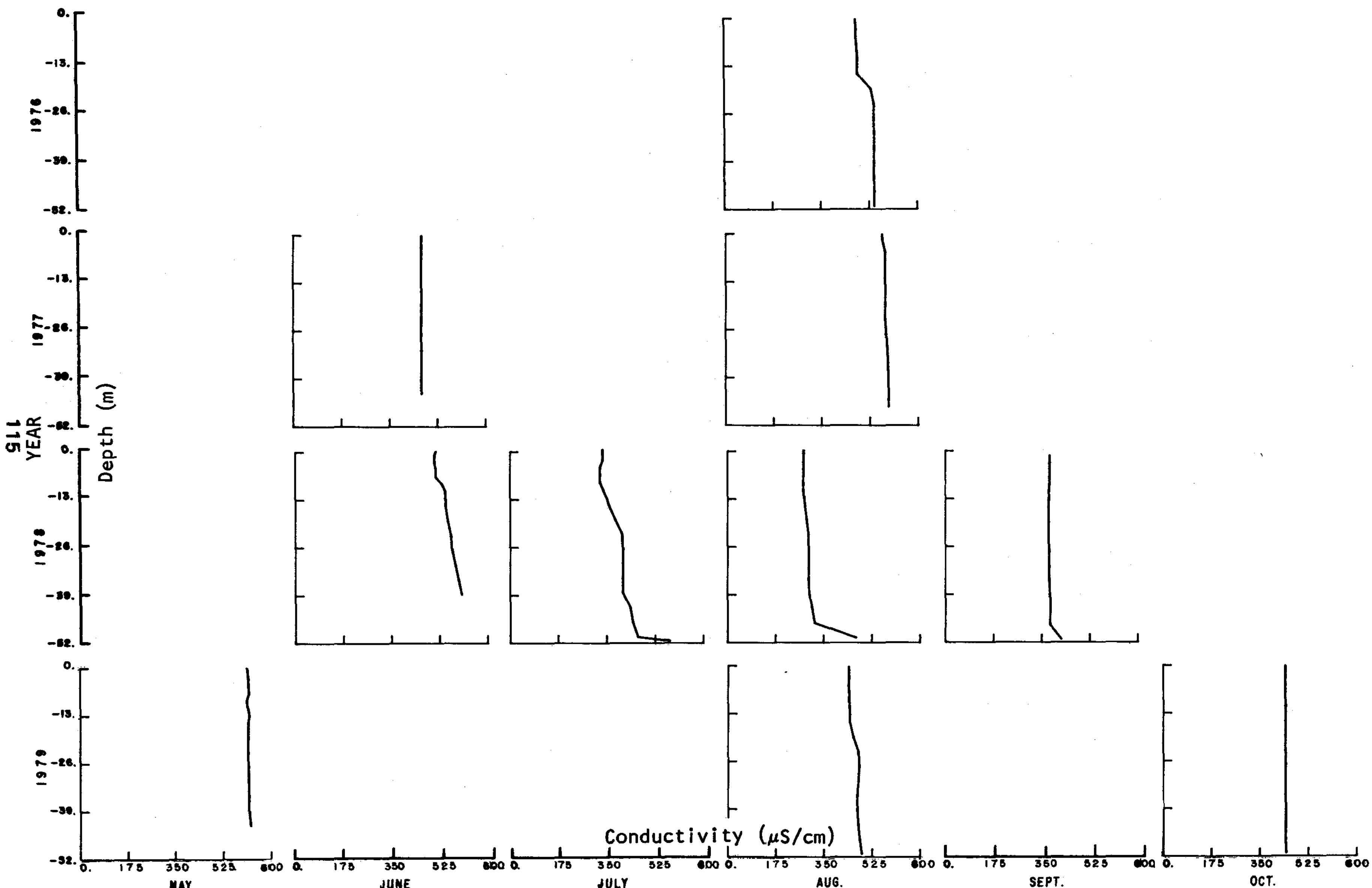


STATION A-2, FREMONT CANYON SECTION OF ALCOVA RESERVOIR

APPENDIX D
CONDUCTIVITY PROFILES



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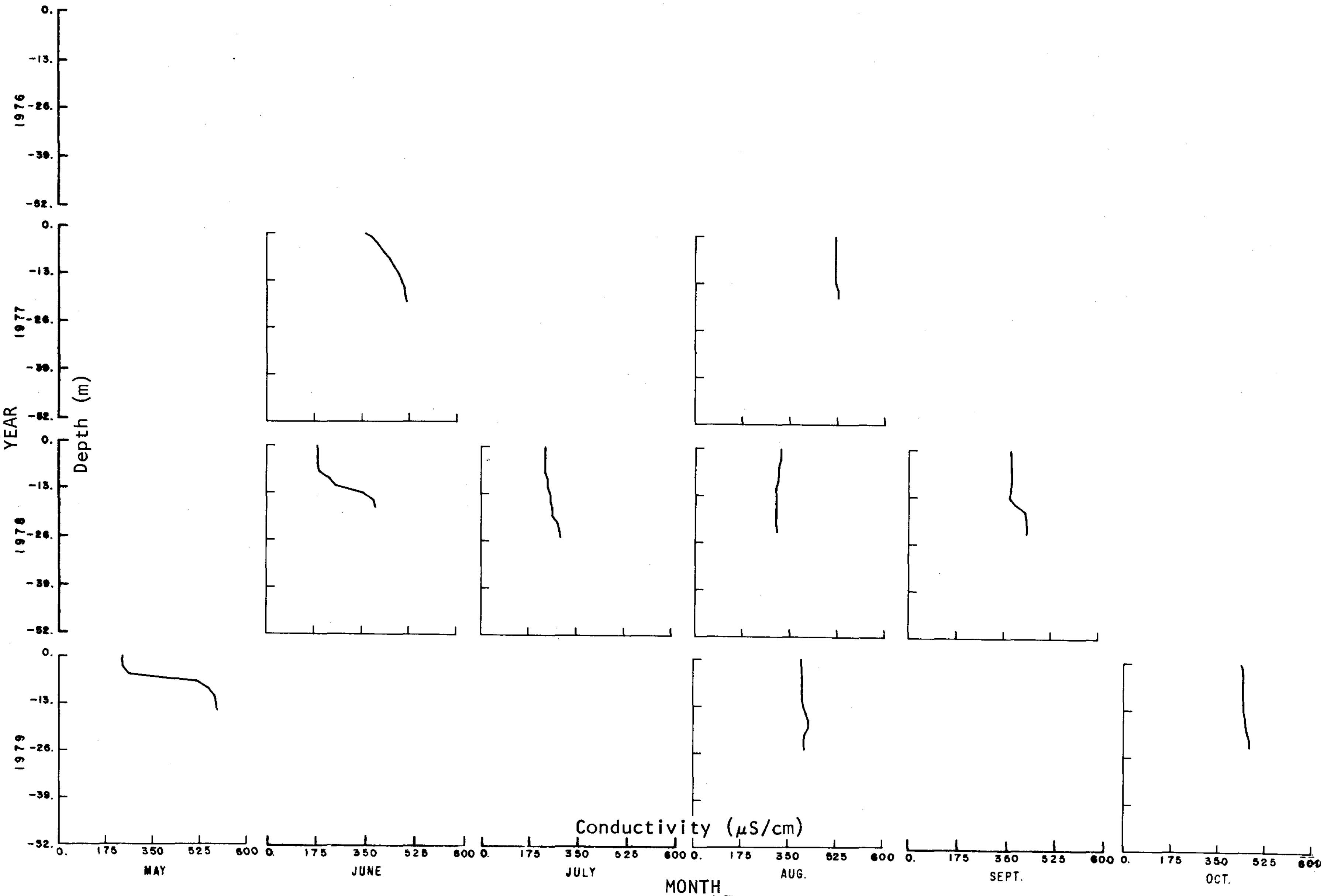

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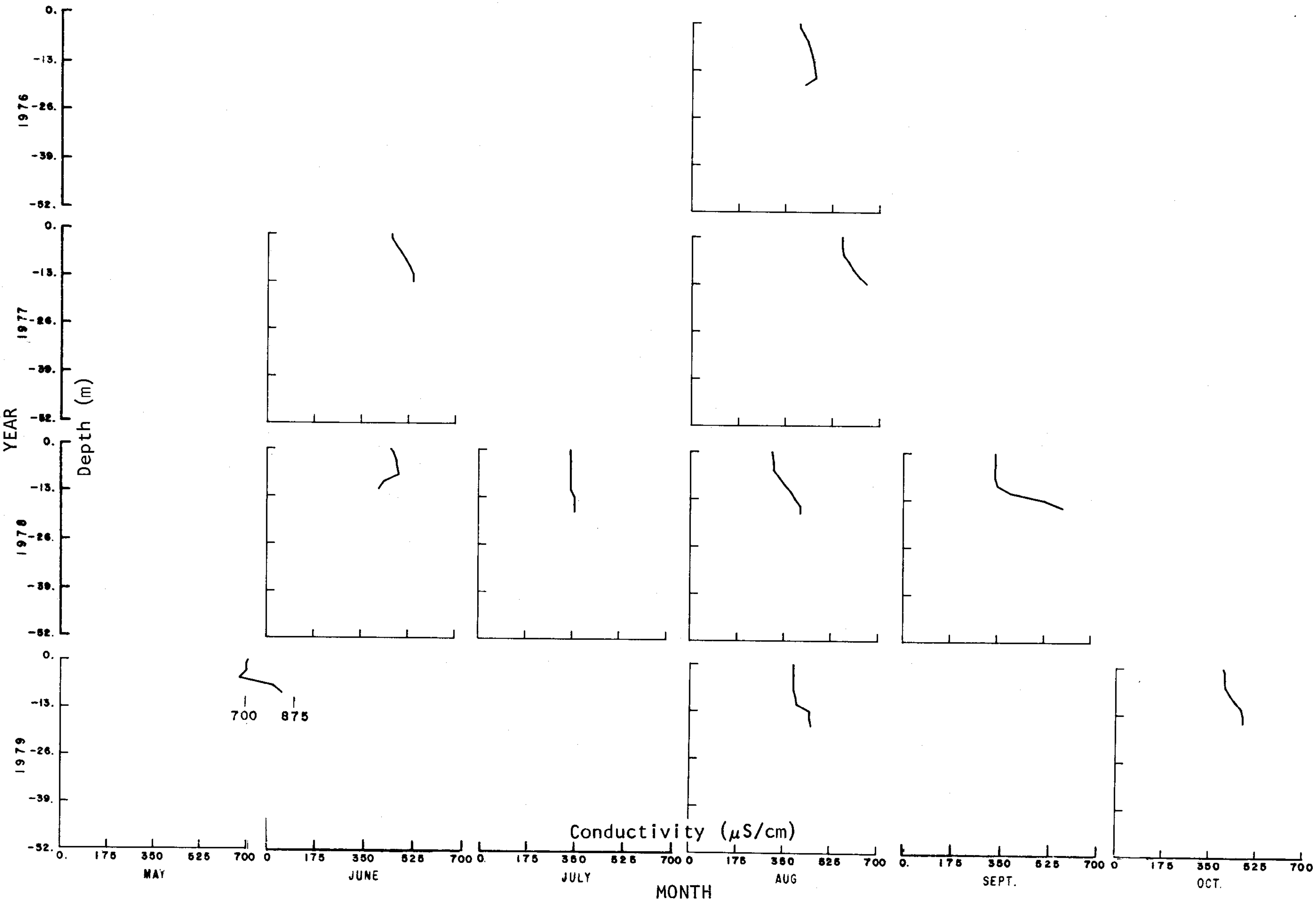

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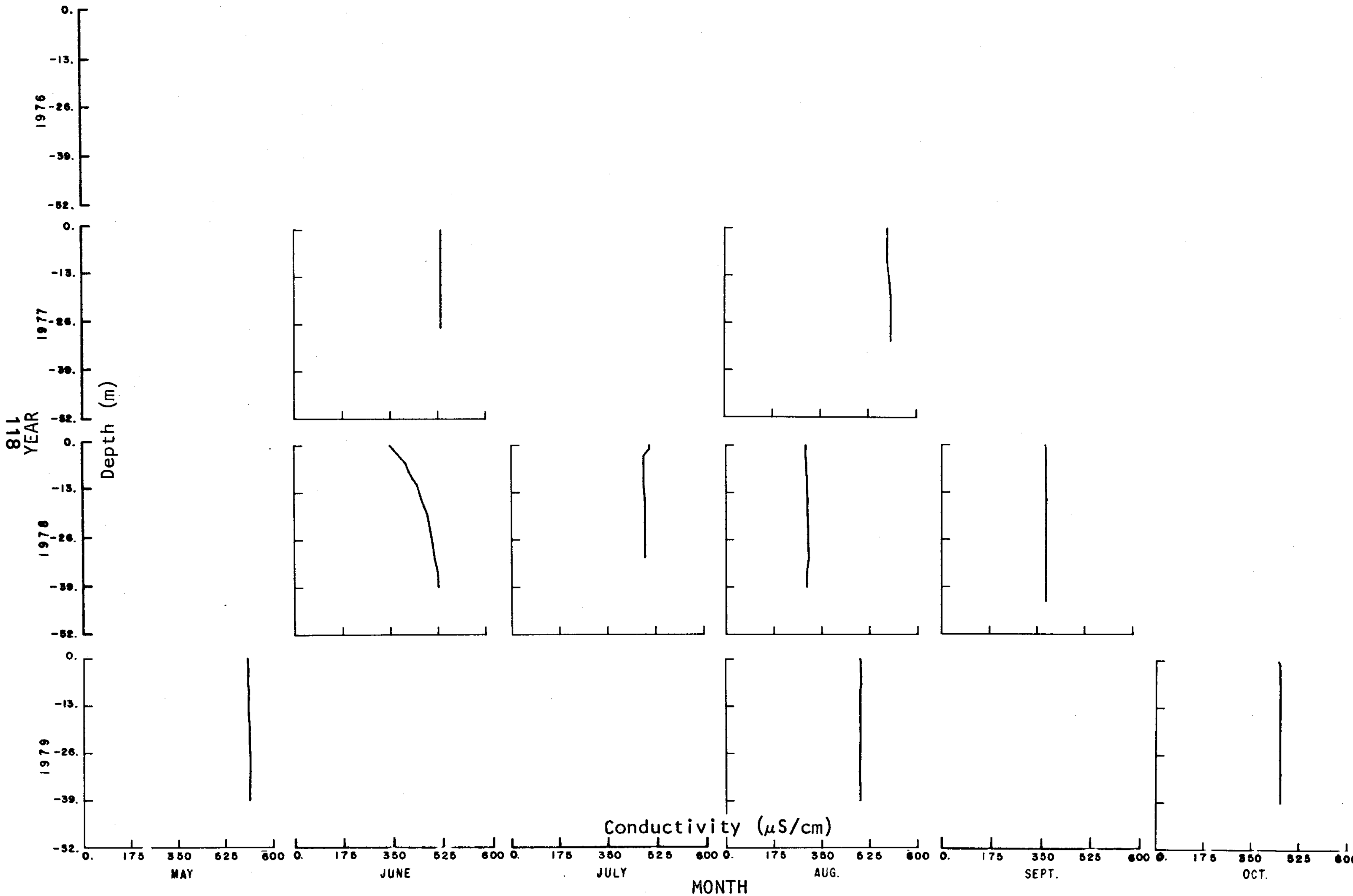

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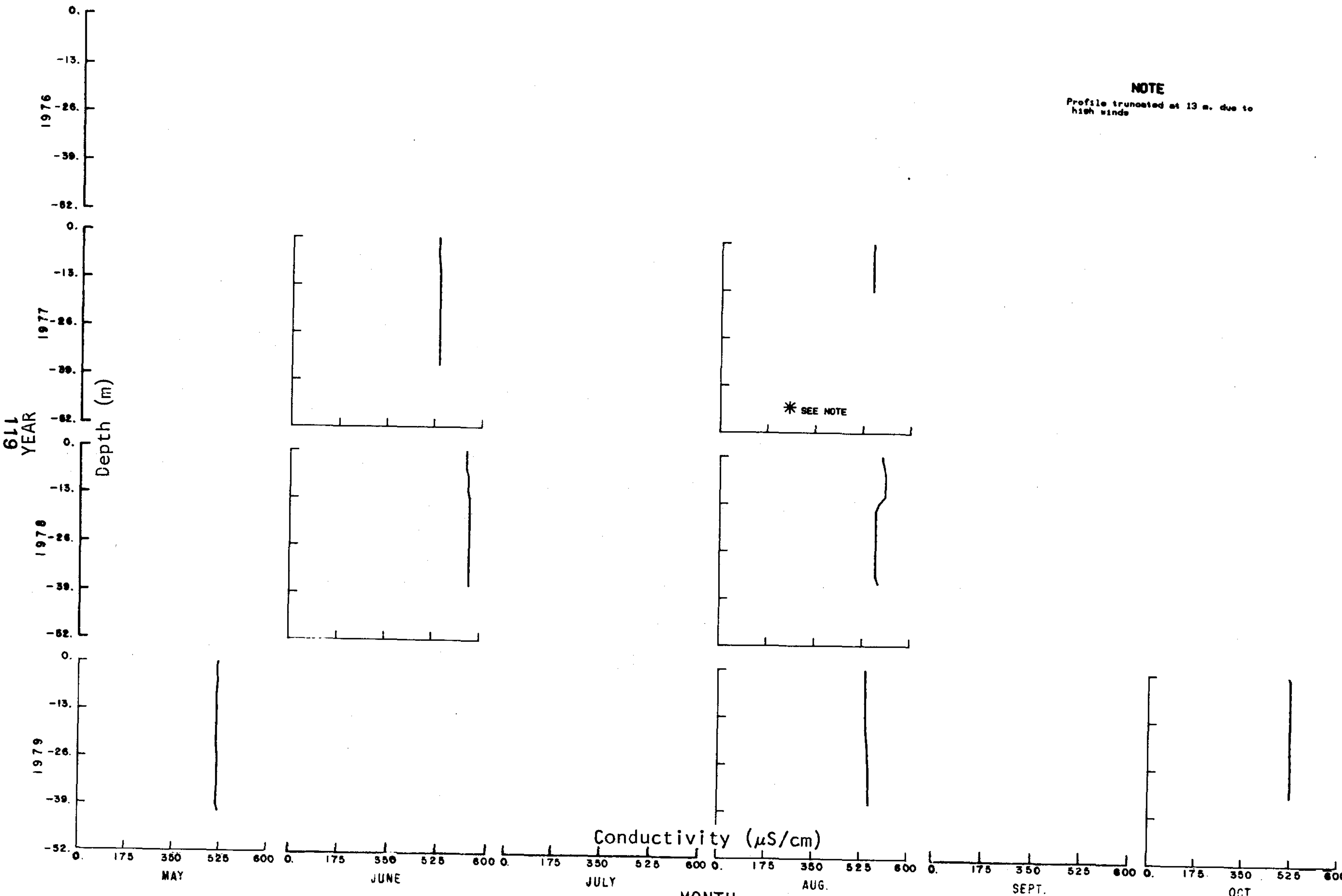

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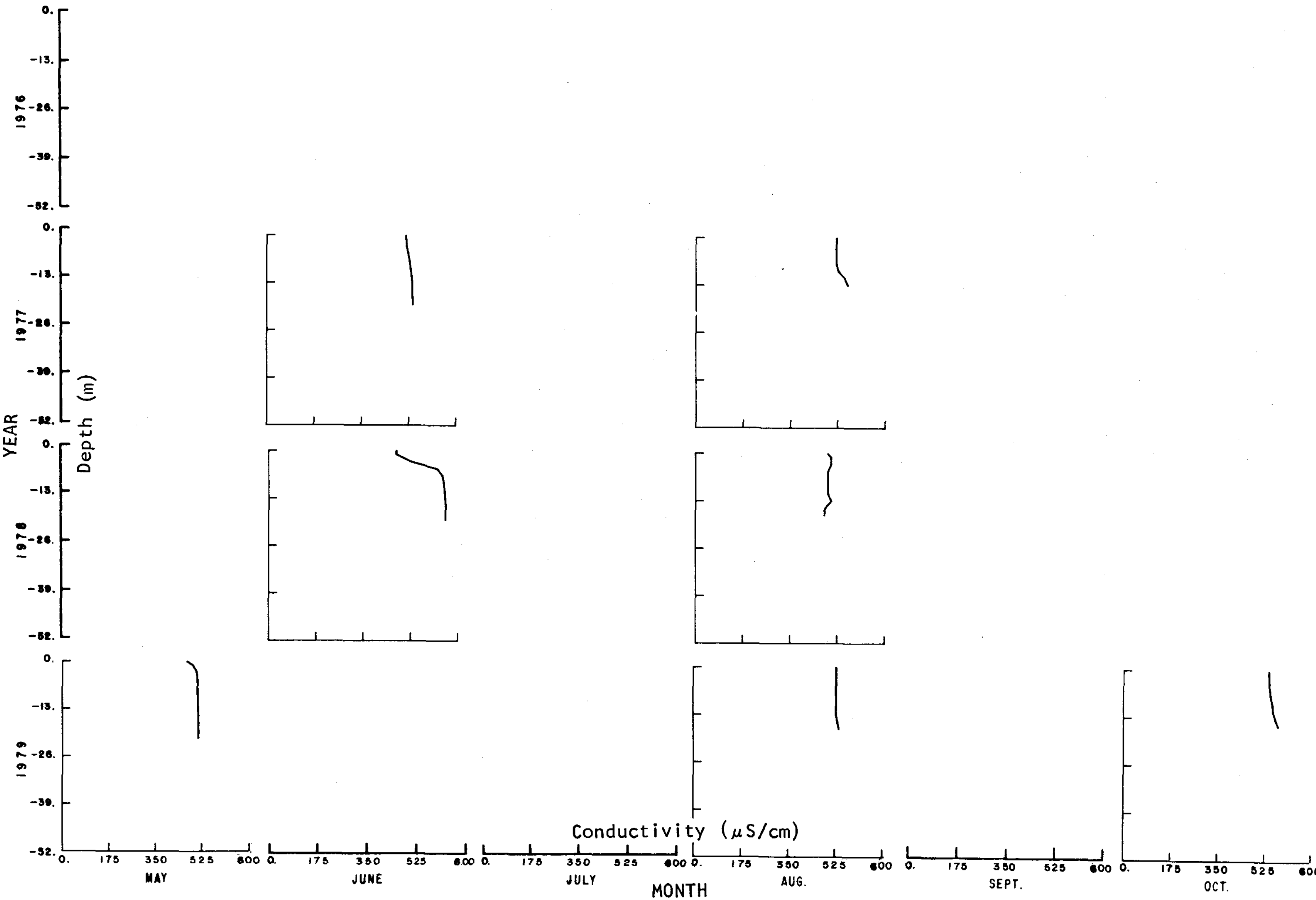

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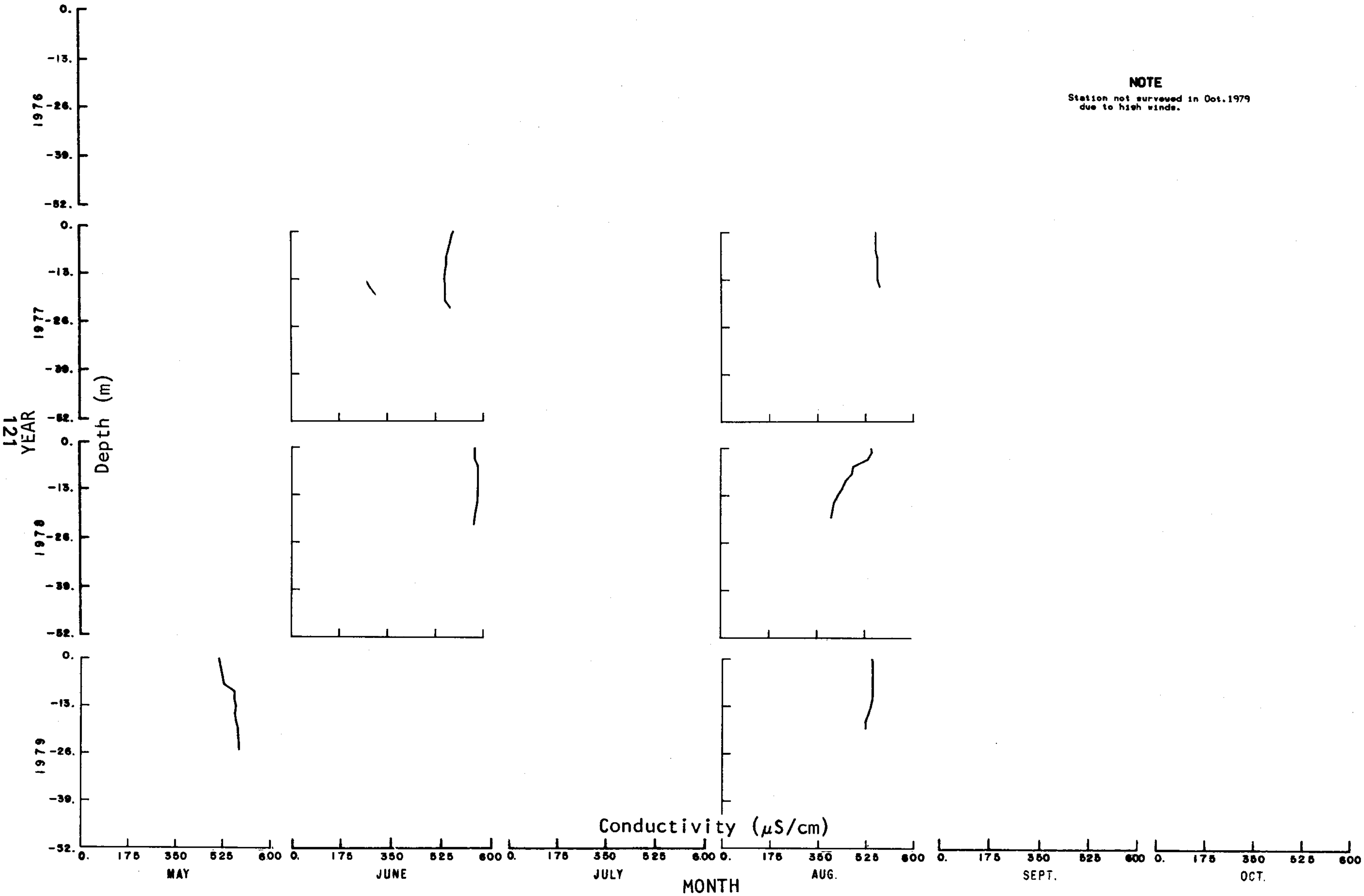
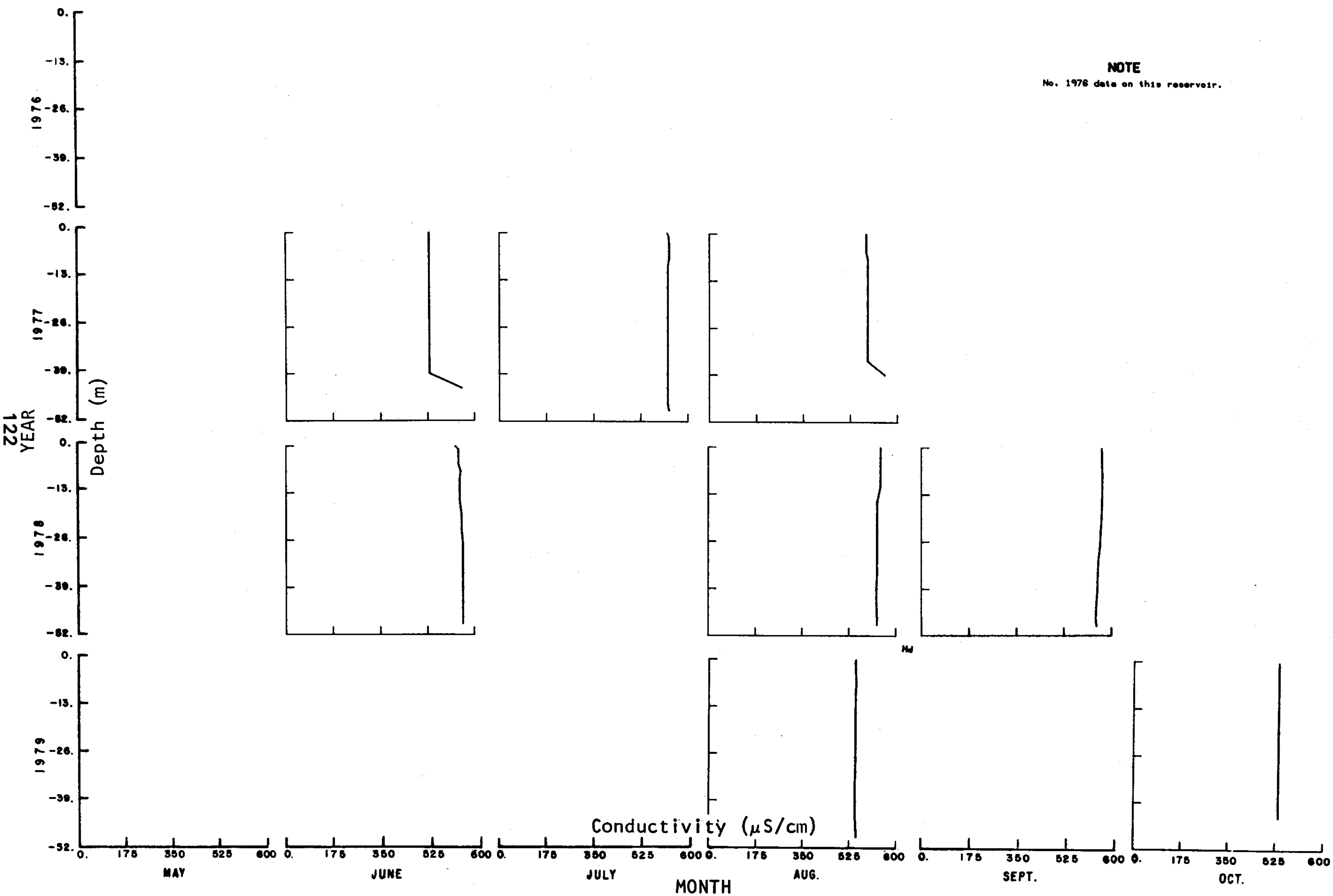
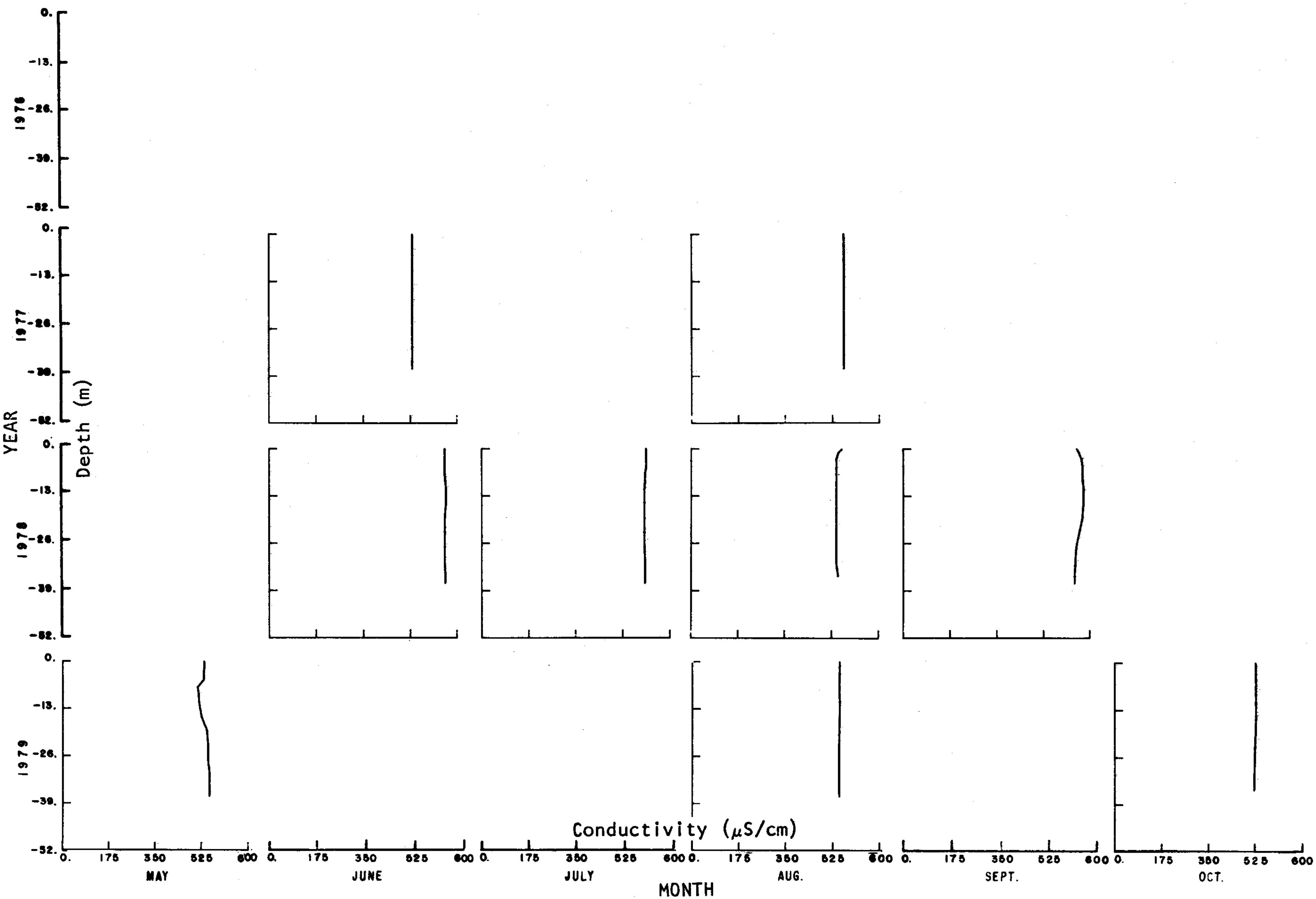


STATION P-3, NORTH PLATTE ARM OF PATHFINDER RESERVOIR



STATION A-1, ALCOVA RESERVOIR



STATION A-2, FREMONT CANYON SECTION OF ALCOVA RESERVOIR

APPENDIX E
CHLOROPHYLL *a*

Table E-1.—*Chlorophyll* a – *1977*

Reservoir	Station[1]	Date	Depth (m) 0.1	1.0	3.0	5.0	9.0	15.0
					(mg/m³)			
Seminoe	1	June 23	0.90	1.12	1.40	1.07	0.55	0.48
	2	23	2.66	2.09	2.47	0.44	0.33	0.29
	3	23	2.08	1.46	2.45	0.78	0.69	0.49
	1	Sept. 1	0.71	0.57	1.07	0.64	0.49	0.48
	2	1	4.55	3.72	3.71	2.58	2.03	2.08
	3	1	9.66	9.00	8.46	6.38	2.93	0.91
Kortes	1	June 9	0.58	0.51	0.95	3.21	0.73	0.58
	1	Aug. 31	1.30	1.14	1.61	0.89	0.63	0.94
	2	31	1.07	—	—	—	—	—
Pathfinder	1	June 8	0.66	0.29	0.87	1.54	1.23	0.29
	2	8	0.44	0.66	1.44	2.65	1.67	1.60
	3	8	2.31	2.09	6.11	3.71	2.16	2.23
	1	Aug. 30	6.68	5.79	5.49	4.60	4.33	2.68
	2	30	55.10	46.83	62.32	60.72	42.57	12.39
	3	30	104.08	108.60	105.15	103.18	17.93	3.77
Alcova	1	June 6	0.41	0.44	0.95	1.02	1.44	0.37
	2	6	1.87	1.64	1.56	1.01	0.79	1.02
	1	Aug. 29	6.36	2.92	3.40	2.48	2.70	6.36
	2	29	0.91	1.06	0.91	0.91	1.23	1.07

[1] See figure 7 for location of sampling station.

Table E-2.—*Chlorophyll* a – *1978*

Reservoir	Station[1]	Date	Depth (m) 0.1	1.0	3.0	5.0	9.0	15.0
					(mg/m³)			
Seminoe	1	May 29	0.9	1.4	3.6	4.5	4.5	4.1
	1	June 15	3.4	5.7	2.6	3.6	1.5	4.4
	2	15	2.0	6.6	1.5	1.7	12.0	5.8
	3	15	17.7	9.5	7.5	15.0	18.8	[2]
	1	July 20	3.1	4.5	3.6	2.5	2.7	1.6
	2	20	3.9	5.4	5.6	5.4	3.0	2.8
	3	20	4.5	3.7	3.3	3.6	2.3	1.6
	1	Aug. 31	17.9	15.4	14.5	7.3	2.9	2.1
	2	31	96.7	35.3	29.5	9.4	2.4	3.7
	3	31	17.4	14.8	4.5	3.5	2.5	1.3
	1	Sept. 28	5.8	2.9	1.9	3.5	4.3	2.2
	2	28	9.4	9.6	5.5	6.7	3.7	2.2
	3	28	50.7	17.8	4.1	2.3	2.4	1.8
Kortes	1	June 1	0.9	0.8	1.1	1.1	0.4	0.8
	1	June 14	5.5	4.9	3.5	4.4	3.1	5.5
	1	July 19	2.2	2.4	3.1	2.2	2.3	1.7
	1	Aug. 30	1.5	2.6	0.6	1.4	0.8	1.2
	1	Sept. 27	0.9	0.9	0.9	1.5	0.9	1.2
Pathfinder	1	June 12	12.5	1.4	2.0	3.4	3.0	3.0
	2	12	6.2	9.6	5.3	5.1	11.3	3.5
	3	12	2.9	3.9	4.1	5.1	13.3	4.4
	1	Aug. 28	2.8	4.5	6.7	5.2	5.0	6.4
	2	28	26.5	21.2	8.9	7.1	7.3	6.6
	3	28	25.8	16.8	13.9	8.7	3.9	5.4
Alcova	1	June 13	2.2	4.6	5.0	5.7	10.9	7.8
	2	13	8.0	10.3	2.4	5.0	5.9	10.1
	1	July 18	2.0	2.8	2.2	2.7	2.2	2.6
	2	18	3.2	2.8	2.2	1.8	2.1	2.6
	1	Aug. 29	7.0	8.3	7.1	6.5	4.2	2.2
	2	29	11.9	8.7	3.5	1.8	1.1	4.0
	1	Sept. 26	6.9	7.6	7.0	5.2	4.8	5.1
	2	26	9.2	8.4	7.5	5.4	4.5	4.8

[1] See figure 7 for location of sampling station.
[2] No sample value obtained.

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Table E-3.—*Chlorophyll* a – *1979*

Reservoir	Station[1]	Date	Depth (m) 0.1	1.0	3.0	5.0	9.0	15.0
			(mg/m³)					
Seminoe	1	May 24	1.00	0.87	1.00	0.88	0.98	0.72
	2	24	5.53	5.33	3.24	3.46	1.44	1.52
	3	24	16.98	27.21	7.00	3.78	—	—
	1	Aug. 30	8.92	9.86	9.40	5.08	1.64	0.42
	2	30	31.02	25.53	12.79	1.47	0.80	0.63
	3	30	23.10	23.27	21.98	29.46	21.90	3.33
	1	Oct. 25	1.50	1.00	0.80	0.79	0.86	0.86
	2	25	2.27	2.63	2.26	2.17	1.96	1.36
	3	25	4.82	3.68	2.80	2.65	1.44	1.59
Kortes	1	May 23	1.85	1.86	1.54	1.45	1.28	1.18
	2	23	1.30	—	—	—	—	—
	1	Aug. 29	1.75	1.98	2.20	2.66	1.52	0.70
	2	29	1.04	—	—	—	—	—
	1	Oct. 24	1.05	0.95	1.07	1.27	1.29	1.04
	2	24	1.17	—	—	—	—	—
Pathfinder	1	May 22	1.5	0.98	1.43	1.47	1.88	2.22
	2	22	3.92	3.63	3.63	2.46	2.75	1.77
	3	22	0.79	0.88	0.87	1.28	3.25	3.65
	1	Aug. 28	1.89	2.16	2.21	1.54	1.47	1.37
	2	28	41.72	15.94	12.17	9.87	5.89	4.31
	3	28	9.56	10.84	10.62	7.37	3.46	1.81
	1	Oct. 23	2.64	2.50	2.56	2.71	3.07	2.70
	2	23	8.77	7.66	9.18	7.45	3.39	2.91
	3[2]		—	—	—	—	—	—
Alcova	1	May 21	4.84	5.53	8.66	7.68	5.64	5.59
	2	21	6.57	8.57	11.23	8.59	4.29	2.73
	1	Aug. 27	5.49	6.61	7.46	5.78	2.03	0.83
	2	27	3.90	3.99	4.29	2.34	1.13	1.44
	1	Oct. 22	1.39	1.54	1.61	1.54	1.54	1.53
	2	22	2.50	2.52	2.38	2.51	2.50	2.28

[1] See figure 7 for location.
[2] Not surveyed in October 1979.