DILUTIONAL PUMPING AT SNAKE LAKE, WISCONSIN

A Potential Renewal Technique for Small Eutrophic Lakes

Technical Bulletin No. 66
DEPARTMENT OF NATURAL RESOURCES
Madison, Wisconsin
1973

UPPER GREAT LAKES REGIONAL COMMISSION

An Inland Lake Renewal and Management Demonstration Project Report

1973

A Cooperative Effort of The University of Wisconsin and the Department of Natural Resources

Sponsored by the Upper Great Lakes Regional Commission

ABSTRACT

Snake Lake, a 12.3-acre (5.0 ha), colored, soft-water lake in northern Wisconsin, received the direct discharge of municipal wastes for more than twenty years. Consequent accelerated eutrophication destroyed the recreational and aesthetic values of Snake Lake; annual dissolved oxygen depletion and nuisance aquatic plant growth have converted a community asset to a liability. Rehabilitation of Snake Lake was attempted by employing a lake flushing scheme by means of dilutional pumping. The local geology and hydrology suggested an innovative flushing method in which nutrient-rich lake water was pumped from the lake to a nearby land disposal area, allowing dilution by influent ground waters. Lake water quality parameters were measured for more than three years during the study. Soil, hydrogeologic (particularly lake–ground water relationships), and bottom sediment nutrient transfer studies were also conducted in conjunction with the lake renewal activity.

Preliminary pumping was conducted for a two-week period in October 1969 in order to test equipment, evaluate water disposal area operations, and assess the response of the hydrogeologic system to stress (pumping). About two-thirds of a lake volume was pumped during this preliminary activity. During July-August 1970, the main dilutional pumping effort took place; about three lake volumes were pumped from Snake Lake and lake level declined about 11 feet (3.4 m).

Dilutional pumping of Snake Lake has not "renewed" the lake; severe dissolved oxygen depletion problems during two winters following pumping continue to prevent the establishment of a sport fishery. However, the 1969-1971 dilutional pumping experiment has shown that flushing of a lake can result in substantial nutrient reduction. At Snake Lake, phosphorus concentrations were diluted and have remained significantly lower than before pumping (although total phosphorus levels are still relatively high). Nitrogen and chloride levels, conductance, and color were also reduced as a result of dilutional pumping; however, these changes were of a short-term nature, and by the following year these parameters had returned to former levels. Other effects of dilutional pumping included the elimination of nuisance blooms of duckweed and deepening of littoral areas due to subsidence associated with dewatering. Bottom sediments appear to be the major source of regenerated nutrients.

DILUTIONAL PUMPING AT SNAKE LAKE, WISCONSIN

A Potential Renewal Technique for Small Eutrophic Lakes

by
Stephen M. Born
Thomas L. Wirth
James O. Peterson
J. Peter Wall
David A. Stephenson

Technical Bulletin No. 66
DEPARTMENT OF NATURAL RESOURCES
Madison, Wisconsin
1973

CONTENTS

INTRODUCTION

The thousands of lakes in the Upper Midwest and their adjacent shorelands form the basis for the recreational and tourist-oriented economy of the region. These valuable natural resources are showing the signs of ever-increasing development and use; many lakes are undergoing accelerated aging. The problems associated with this relatively rapid overfertilization and sediment infilling of lakes—prolific aquatic weed growth, nuisance algal blooms, deteriorating fisheries, impaired water quality—pose a serious threat to our inland lakes.

The Inland Lake Demonstration Project, a joint venture of the University of Wisconsin and the Wisconsin Department of Natural Resources, represents one attempt to address these problems. From its outset in May 1968, Project objectives have included the demonstration of techniques to restore, maintain, and protect a high quality environment within and adjacent to inland lakes in the Upper Great Lakes region. The Project's lake renewal program is concerned with demonstrating various ways to renovate overfertile (eutrophic) lakes.

Lake renewal is in a state of infancy. Our understanding of aquatic ecosystems is incomplete and the technology for lake restoration is only beginning to be developed. Nevertheless, the immediacy and dimensions of lake problems demand that efforts to rehabilitate lakes be undertaken now.*

*P.L. 92-500, Sec. 314 provides for a federal lake restoration program; $300 million was authorized in this act to stimulate and aid state lake rehabilitation efforts.

Renewal projects offer the potential for developing operational lake renewal methods; where unsuccessful, such activities provide direction for new research avenues which may ultimately yield the requisite knowledge for successful efforts.

A variety of approaches to lake restoration have been described (Stewart and Rohlich, 1967; National Academy of Sciences, 1969; Lee, 1970a; Tenney, Yaksich and DePinto, in press). One technique suggested for limiting fertility in eutrophic lakes involves dilution or flushing. The importance of naturally high flushing rates in reducing the productivity of lakes has been demonstrated by McMynn and Larkin (1953), Robertson (1954), Brook and Woodward (1956); Gorham (1958); Rawson (1960); and Dickman (1969). Accordingly, increasing attention has been given to artificial flushing as a potential renewal technology (e.g., Lomax and Orsborn, 1971).

The best documented field experience with dilution/flushing is Green Lake, Washington (Sylvester and Anderson, 1960, 1964; Oglesby, 1968, 1969). At Green Lake, large amounts of nutrient-poor water from the Seattle drinking water supply were diverted into the lake. This flushing produced pronounced improvements in water quality: transparency increased greatly, levels of summer standing crops were lowered, and several nuisance forms of blue-green algae were virtually eliminated from the phytoplankton population (Oglesby, 1968). Flushing has also been recommended or attempted elsewhere (Sketelj and Rejic, 1966; Nunnallee, 1968; Goldman, 1968; Welch, Buckley, and Bush, 1972).

The degree of success of this renewal technology is largely a function of nutrient mass transport processes. Potential sources of nutrients include: rainfall and dry fallout, surface and ground water inflows, and recycle from lake sediments. If the rate of nutrient input from these sources is slow compared to the rate of low-nutrient water movement into the lake (flushing), water quality may be improved by (1) dilution and associated reductions in nutrient concentrations, thereby limiting aquatic plant growth, or (2) "cropping" the bio-mass via algal cell washout. In general, to be successful, nutrient dilution as a means of eutrophication control should be coupled with a program for curbing nutrient inflows to a lake.

This study reports the results of nutrient exclusion/dilutional pumping employed at a small eutrophic lake (Snake Lake) in northern Wisconsin, where nutrient inflows via direct discharge of municipal wastes had been stopped for several years (with little improvement in water quality). Lake flushing requires adequate supplies of nutrient-poor water, which in past situations has been available from either municipal supplies or diversion from a nearby river. At Snake Lake, a different source of flushing water was used; after nutrient-rich lakewater was pumped from the lake, the lake refilled naturally with nutrient-poor water from contiguous ground water reservoirs and from precipitation.

The investigation was undertaken in full recognition that Snake Lake sediments might be a major unarrested source of nutrients, and if so, a dilutional-pumping lake renovation scheme would constitute a large-scale experiment in leaching of nutrients from sediments. Differences of opinion exist regarding the importance of nutrient transfer between sediments and water (Lee, 1970b; Fitzgerald, 1971; and Keeney, 1972), so the role of the sediments in recycling nutrients to lakewater was uncertain. Such uncertainties frustrate efforts at eutrophication control. However, empirical knowledge gained in pilot projects like Snake Lake will ultimately lead to improved management policies and programs for our valuable lake resources.

HISTORY OF SNAKE LAKE WATER QUALITY DEGRADATION

Historical records of limnological observations show that Snake Lake water quality has been degraded by cultural activities (Table 1). The earliest analyses available were those of Juday in 1928. Subsequent water sampling and analysis was undertaken from 1942 through 1967, following the completion of a sewage treatment plant on the west shore of the lake. From its inception, the plant seems to have been plagued by breakdown and substandard operation. State agency reports describe periodic discharges of sewage sludge and plant effluent, frequently of poor quality, directly into the lake. Even given the difficulties of comparing findings of different investigators at varying times, it is apparent that over the years there has been a substantial increase in the concentrations of those parameters available for comparison.

Following the first full year of operation of the treatment plant, a winter-kill of largemouth bass *(Micropterus salmoides)*, bullheads *(Ictalurus* spp.), black crappies *(Pomoxis nigromaculatus)*, bluegills *(Lepomis macrochirus)*, yellow perch *(Perca flavescens)*, northern pike *(Esox lucius)*, and a muskellunge *(Esox masquinongy)* was reported (Flanigon, 1943). The diversity of fish species killed indicated that winter-kill had not been a consistent problem previously. Because of the complaints about sewage plant effluent quality, a sub-soil tile system was installed in 1958 for disposal of the effluent. This system accepted effluent for about three years before the absorptive capacity of the field was exceeded and ponding occurred. Much of the Snake Lake history is contained in state agency records as correspondence, usually complaintive in nature, citing algal blooms, disagreeable odors, general pollution, and health and safety hazards as undesirable qualities.

The deterioration of the quality of Snake Lake created concerns for the residents and property owners on Arrowhead Lake (formerly Little Star Lake), which received drainage from Snake Lake through a man-made canal. The occurrence of algal blooms and deposition of sediment at the southern end of Arrowhead Lake, a prime recreational resource, stimulated riparians to apply for and receive permission to install a gravel-filter structure across the canal to serve as a filtering device in 1962. The structure soon clogged, however, and the water level of Snake Lake rose about two feet. Trees and shrubbery at the lake's edge were subsequently displaced by marsh and bog vegetation. Replacement of the structure yielded no lasting benefit and surface drainage from Snake Lake soon found its way into Arrowhead Lake. Spring runoff and occasional heavy summer rains flooded the low-lying marshy area bordering the length of the canal, and loose debris from the land was flushed into Arrowhead Lake.

In 1964, Woodruff's sewage collection system was connected to a new area sewage treatment plant and the Snake Lake facility was closed. Although highway runoff and runoff from the very small drainage basin have continued to provide some nutrients to Snake Lake, the major source of nutrient inflows was terminated. Duckweed *(Spirodela polyrhiza* and *Lemna* spp.) and algal blooms continued, and the low dissolved oxygen conditions precluded re-establishment of a sport fishery. Property owners on lower lakes in the Snake Lake chain continued to be anxious that nutrient-rich waters flowing from Snake Lake might produce similar eutrophic conditions in their lakes. It was at this time that the Inland Lake Project incorporated Snake Lake into its lake renewal activities.

SITE CHARACTERISTICS

Physical Setting

Snake Lake is situated on the boundary between Vilas and Oneida counties in Wisconsin (T39, 40N; R6E; Sec 35, 36, 1, 2) (Fig. 1). It comprises part of the headwaters of Johnson Creek, a westward-flowing tributary of the Tomahawk River, which in turn is tributary to the Wisconsin River. Surface drainage from Snake Lake flows northward to Arrowhead, Brandy, and Johnson Lakes, and then to Johnson Creek. A channel was dredged about 50 years ago through the natural sand ridge and marsh originally separating Snake and Arrowhead Lakes.

Geology and Soils

Ground-surface elevations in the

TABLE 1. Concentration Ranges of Nitrogen and Phosphorus in Snake Lake (mg/l), 1928–1969

	1928*	1942–43**	1947–48[1]	1967[2]	1968–69[3]
NO_2^-–N	<0.005	<0.005–0.05	<0.005–0.07	0.01–0.03	0.02–0.08
NO_3^-–N	0.03	<0.02 –0.80	0.08 –0.08	0.12–0.20	0.1 –0.4
NH_4^+–N	0.01	0.04 –1.13	0.14 –1.13	0.31–4.00	0.03–1.22
Organic N	0.58	0.47 –1.65	0.49 –6.70	0.91–3.10	0.94–3.18
Total N	0.62	0.65 –2.67	0.92 –7.6	2.5 –7.2	1.1 –3.5
Total P	0.02	0.07 –0.20	0.07 –0.60	0.88–0.96	0.17–1.17
No. of Sampling Dates	1	19	19	3	23

*Surface sample, July (Juday, *In* Mackenthun, 1952).
**Composite or average of 4 samples from 1 meter depth, October 1942–November 1943 (Flanigon, 1943; Malueg, 1972).
[1]Composite of three samples from 1 meter depth, October 1946–September 1948 (Black, 1967).
[2]Epilimnion, June–October (Winter, 1967; includes data of Castagna and Maltbey).
[3]Epilimnion (this study).

area range from approximately 1,590 to 1,620 feet (485 to 495 m) above mean sea level. Glacial deposits, largely pitted outwash deposited during the Wisconsin Stage of Pleistocene glaciation, cover the region. The land surface in the area is relatively flat, with numerous depressions or kettle holes. Snake Lake occupies such a kettle, which formed by the melting of blocks of ice incorporated in glacial sediments. The unconsolidated glacial deposits consist largely of stratified fine- to course-grained sand (Fig. 16, Append. C); the outwash also contains minor clay, silt, and gravel lenses. About 230 feet (70 m) of glacial drift deposits, as measured at Village Well Number 1 in Minocqua, 2 miles (3.2 km) south of Snake Lake, overlie Precambrian crystalline bedrock.

The dominant soil type in the Snake Lake area is a Vilas loamy sand (Soil Conservation Service, 1968). Marsh soils, containing substantial amounts of peat, are present locally adjacent to lakes and streams.

Limnology

Snake Lake is a kidney-shaped 12.3-acre (5.0 ha) brown-water seepage lake, having a maximum depth near 18 feet (5.5 m), a mean depth* of 7.4 feet (2.3 m) and a half-volume depth of about 4 feet (1.2 m) (Fig. 17, Append. C). A shallow saddle separates the north basin (60% of water volume) from the south basin.

In October 1968, a sampling program and data collection effort were begun. Water samples were collected at 3-foot (0.9 m) intervals along the vertical water column at the deepest points in the north and south basins. These samples were analyzed for nitrite, nitrate, ammonium, and organic nitrogen species, as well as dissolved (unfiltered-reactive) and total phosphorus, sulfate, chloride, calcium, magnesium, sodium, and potassium. Field measurements were made of temperature, dissolved oxygen, transparency (Secchi disc), pH and total alkalinity.

Data collected in 1968-69 showed the lake to be typically dimictic (thermally stratified during the summer and winter seasons while displaying both spring and fall mixing periods) (Fig. 18, Append. C). The shallow epilimnion and hypolimnion are well defined during stratification. Dissolved oxygen concentrations in the epilimnion (during daytime samplings) are near saturation during the summer months but the hypolimnion is anoxic except at "turnover". Since 1942-43, Snake Lake has been essentially oxygen-depleted throughout its depth, after the formation of ice cover.

Table 2 presents epilimnetic metalimnetic, and hypolimnetic concentration ranges for the parameters measured. Weighted averages were calculated for total nitrogen, total phosphorus, and chlorides (Appendix A). The ranges of these averages are given in Table 3 for the period October 2, 1968, through October 10, 1969, the year preceding the first dilutional pumping exercise.

In September, 1969, an electrofishing unit netted only fathead minnows *(Pimephales promelas)* and an abundance of western mudminnows *(Umbra lemi)*. No sport fishery exists in the lake.

Information on benthic fauna from 1943, 1952, and 1971 (north and south basin deep areas) is presented in Table 4. While consistency in sampling procedures between the three years cannot be established, there does seem to be a decrease in the diversity of species encountered. The species which are not detected in the latter years represent organisms which are sensitive to low dissolved oxygen conditions. The numbers of organisms recovered in 1971 are considered a very sparse population (Hilsenhoff, 1972). The procedures used by Hilsenhoff would detect all insects, leeches, mites, snails, and clams, and therefore would have noted the organisms found

*Lake volume/surface area.

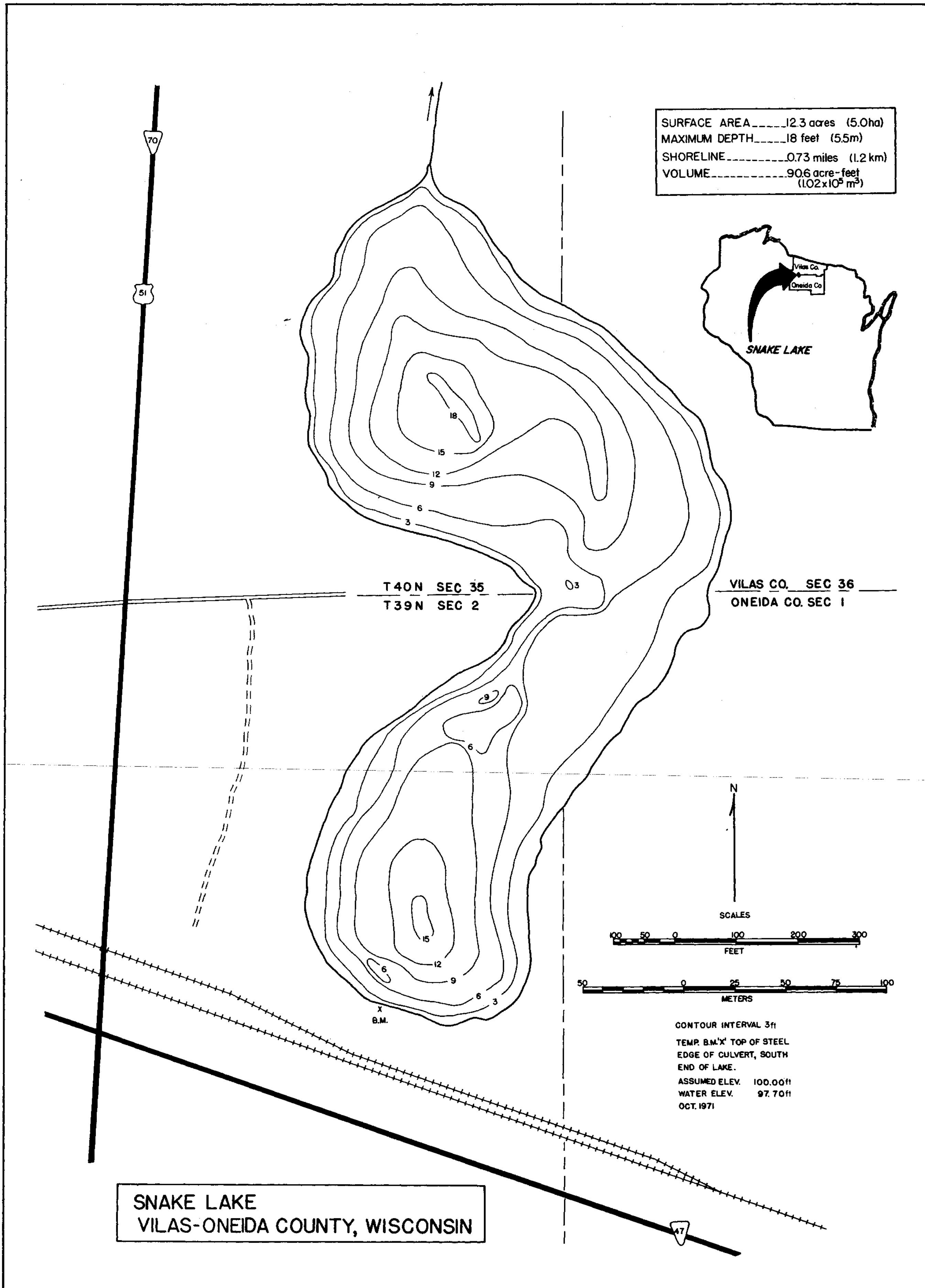


FIGURE 1. *Location and Bathymetric Map*

TABLE 2. Range of Chemical Parameters* (October, 1968–October, 1969)

Parameter	Epilimnion	Metalimnion	Hypolimnion
pH Units	6.3–7.4	6.2–6.9	6.1–6.9
Total Alkalinity ($mg/l\ CaCO_3$)	12–34	16–34	18–76
NO_2^-–N	<0.002–0.76	0.006–0.050	0.004–0.085
NO_3^-–N	0.1–0.4	0.1–0.5	0.1–0.6
NH_4^+–N	0.03–1.22	0.03–1.37	0.04–10.2
Organic N	0.94–3.18	1.28–3.05	1.24–4.96
Reactive P	0.09–1.13	0.19–1.24	0.29–2.95
Total P	0.17–1.17	0.30–5.07	0.33–5.67
$SO_4^=$	10–15	11–16	14–20
Cl^-	22–41	22–49	22–165
Ca^{++}	1.6–4.0	1.6–4.8	1.8–5.5
Mg^{++}	1.2–2.0	1.2–3.0	1.4–3.2
Na^+	7.8–22.0	7.8–22.0	8.0–67.0
K^+	1.8–4.3	2.4–3.8	2.6–4.5

*mg/l except as noted.

TABLE 3. Weighted Average Concentrations of Nitrogen, Phosphorus and Chlorides (October, 1968–October, 1969).

Parameter	Concentration (Weighted Avg.)
Total Nitrogen	1.6 – 3.5 mg/l
Total Phosphorus	0.28– 2.05 mg/l
Chlorides	25. –48. mg/l

TABLE 4. Benthic Organisms in Deep Areas

Date Collected	Collector	Organisms	Density (Org/ft^2)
July, 1943	Flanigon (1943)	*Chaoborus*	–
		Chironomus	–
		Tanypus	–
		Ephemeridae	–
		Hirudinea	–
		Limnodrilus	–
		Hydrachnidae	–
		Tabanidae	–
		Libellulidae	–
September 2, 1952	Mackenthun (1952)	*Chironomus*	–
		Chaoborus	–
		Tubificidae	–
		Hirudinea	–
April 11, 1971	Hilsenhoff (1972)	*Chaoborus*	4.5 (N)* 5.5 (S)*
June 24, 1971	Hilsenhoff (1972)	*Chaoborus*	0.5 (N)
		Chironomus	0.5 (N) 0.5 (S)
		Procladius	0.5 (N)
		Ostracoda	20 (S)
October 23, 1971	Hilsenhoff (1972)	*Chaoborus*	10.5 (N) 39.5 (S)

*North or South Basin.

earlier if they had been present. The procedures would not have detected Tubificidae, however.

Plankton records are sparse, with only a single assessment prior to 1968 (Table 5). Plankton concentrations of 1-7 mg/l (dry weight) were observed, during 1942 to 1943 by Flanigon (1943), using a centrifuge for separation. Field observations indicated that planktonic algae were more abundant during 1971 than in the preceding years, but were not of "bloom" proportions. Following ice cover in 1971, the planktonic organisms included *Cryptomonas*, Desmids and Euglenoid species.

No history of rooted aquatics is available. Observations in 1968-69 noted a sparse distribution of species at the water's edge, and a notable cluster of water lilies in the saddle that connects the two basins of the lake. During 1969, duckweed covered more than 80 percent of the lake surface during late summer. In 1970 large masses of duckweed were present prior to pumping, but in 1971 only scattered individual plants were noted. In 1971 macrophytes present in Snake Lake included small amounts of *Lemna minor* (duckweed), *Nuphar variegatum* (water lily), and *Spirodella polyrhiza* (duckweed) (Nichols, 1971).

Sediments

The surface sediments consisted mainly of noncalcareous muck and peat with small amounts of sand. Dredge samples from about 15 locations indicated that brownish-black, gelatinous muck was present at water depths exceeding approximately 9 feet (2.7 m). Shallow water sediments generally consisted of a fibrous, peaty material except for a few nearshore sandy outcrops.

To more fully describe the sediment column, a series of 5-foot-long (1.5 m) cores (3.5 inch, 8.9 cm, diameter) were taken at six locations in the lake (Fig. 19, Append. C). Physical and chemical data from selected sections of the cores are presented in Table 6. Solids were determined by oven drying at 230 F (110 C); volatile solids by weight loss of dried material upon ignition at 1022 F (550 C). Organic carbon was determined by dichromate oxidation, $NH4^+$-N by distillation of wet sediment, organic nitrogen by Kjeldahl digestion, and inorganic phosphorus was extracted by leaching 1.0 gram of oven-dried sediment with 50 ml of 1N sulfuric acid for 4 hours

(Shah et al., 1968).

Figure 2 shows histograms for inorganic P, organic N, and NH_4^+-N in the sediment profiles. The data show higher levels of P in the muck than in the peat, and consistently higher levels of P in the surface sediments (Table 6). Ammonium-N was more concentrated in the mucks, while organic N was fairly uniform except for being much lower in sections containing large amounts of sand.

Table 7 provides characteristics of some deep, basinal sediments of eutrophic lakes in the region. Snake Lake sediments (Table 6) have much higher organic carbon and nitrogen contents, but are generally similar with respect to total phosphorus. Comparison of chemical characteristics on a dry weight basis is questionable, since relative sedimentation rates, as well as phosphorus-binding capacity of the sediments (Williams et al., 1970) are unknown. Nevertheless, a qualitative difference is suggested between Snake Lake sediments and those from nearby eutrophic lakes.

Probings showed that the sediment thickness varied from 5 feet in the saddle to more than 40 feet (1.5–13 m) in the deep areas of the lake (Fig. 19, Append. C).

Hydrology and Hydrogeology

The Snake Lake area is a part of the larger hydrologic system of the Tomahawk River basin. The average annual precipitation in the area is about 32 inches (81 cm); about three-fourths of that precipitation evaporates or is transpired by plants. The remainder either becomes surface runoff or infiltrates the ground, thereby recharging ground water reservoirs. As noted previously, the only surface drainage in the immediate study area is a small man-made outlet at the northern end of Snake Lake. Seepage below the dam was measured at 17 gpm (64 1/min) on April 17, 1969. Since that time residents of the area, organized as the Four Lakes Improvement Association, have pumped this discharge onto a land disposal area in another effort to keep nutrient-rich Snake Lake water from reaching the lower lakes in the chain.

Review of regional topography indicates that ground water movement* in the area is generally westerly toward the Tomahawk River and its tributaries. In October, 1968, 22 drive-point wells (piezometers) were installed in the area to specifically

TABLE 5. Plankton Composition, October, 1967*

Organism	Percent Composition (Volume)
Volvox spp.	20
Ceratium spp.	5
Aphanizomenon spp.	3
Dinobryon spp.	Trace
Staurastrum spp.	5
Rotifera	5
Tabellaria spp.	2
Daphnia spp.	60

*Winter (1967).

TABLE 6. Characteristics of Snake Lake Sediments*

Core Number and Water Depth	Depth of Sect. (cm)	Appearance	Solids (%)	Volatile Solids (%)	Organic C (%)	Total N (%)	Ammonium N (mg/g)**	Inorganic P (mg/g)**
I (6 ft)	0–5	Brown, fibrous	5.4	71.5	34.8	2.74	0.35	0.64
	45–50	Brown, fibrous	4.3	72.8	35.4	2.95	0.37	0.40
	135–140	Brown, fibrous	6.8	61.5	30.0	2.54	0.07	0.08
II (17 ft)	0–10	Brown muck	4.1	62.2	36.5	2.74	1.61	1.25
	41–60	Brown muck	4.2	71.6	44.8	3.25	1.51	0.72
	140–160	Brown muck	5.2	74.6	38.1	3.31	1.04	0.27
III (8.5 ft)	0–10	Brown, fibrous	3.7	58.5	30.5	1.76	0.43	1.30
	40–60	Brown, fibrous	7.9	51.0	26.0	1.74	0.23	0.32
	120–140	Lt. brown, sandy	21.7	23.0	12.5	0.63	0.10	0.16
IV (7.5 ft)	0–10	Brown, some sand	5.2	58.0	25.8	0.72	0.30	0.76
	40–60	Brown, peaty	5.1	67.7	33.9	2.55	0.24	0.76
	120–140	Brown, peaty	4.9	73.0	35.6	2.86	0.26	0.22
V (16.5 ft.)	0–10	Brown-black muck	1.7	69.8	–	4.00	2.46	2.10
	40–60	Brown-black muck	5.2	61.5	33.6	2.72	1.68	1.19
	100–120	Brown-black muck	5.2	75.6	39.8	3.27	1.54	0.44
VI (8.5 ft)	0–10	Brown, some fibers	2.1	68.0	35.0	3.53	0.61	1.22
	40–60	Brown-black, some fibers	4.4	74.5	39.3	2.84	0.53	0.44
	80–100	Brown-black, some fibers	5.2	76.0	41.7	2.71	0.59	0.20

*All except solids reported on a dry weight basis.
**mg/g x $\frac{1}{10}$ = percent.

TABLE 7. Characteristics of Deep-Hole Surface Sediments From Several Eutrophic, Noncalcareous Northern Wisconsin Lakes.

Lake	Solids (%)	Organic C (%)	Total P (mg/g)*	Inorganic P (mg/g)*	Exchangeable NH_4^+-N (mg/g)*	Organic N (%)	Total N (%)
Little John (Vilas Co.)	3**	23**	4.1[1]	3.4[1]	0.3[2]	2.5[2]	–
Minocqua, N. W. (Oneida Co.)	5**	15**	2.6[1]	2.2[1]	0.1[3]	–	1.6[3]
Little St. Germain, S. (Vilas Co.)	3**	22**	7.5**	–	–	–	–

*mg/g x $\frac{1}{10}$ = percent
**Bortleson (1971).
[1]Williams et al. (1970).
[2]Keeney et al. (1970).
[3]Konrad et al. (1970).

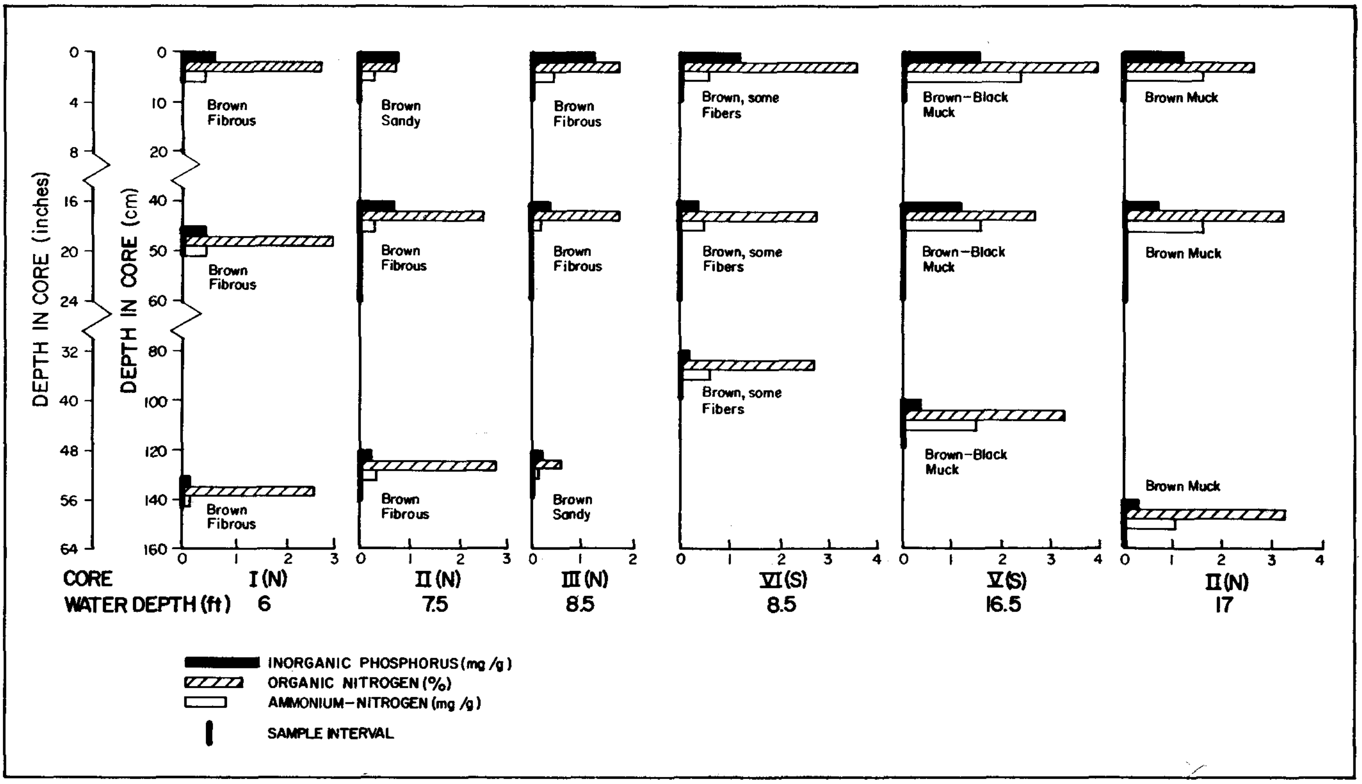


FIGURE 2. *Sediment Analyses–Nitrogen and Phosphorus Profiles*

determine the character and magnitude of water table fluctuations, the rate and direction of ground water flow, and the likely hydrogeologic response to pumping Snake Lake. Thirteen more wells were emplaced in September, 1969, prior to preliminary pump testing, to fill in the hydrologic monitoring network and to provide a ground water surveillance system in the proposed disposal field (Fig. 3). Monthly water-level measurements were taken at water control points.

Ground water occurs here under water table, or unconfined, conditions. As such, the water table itself describes the upper surface of the ground water reservoir, and Snake Lake is nothing more than an "outcrop" of the water table. The ground water flow system at Snake Lake is fairly simple. Water enters the lake from the adjacent aquifer on the east side, mixes with surface waters, and is discharged to the ground water reservoir along the western, southern, and to some extent northern, perimeters of the lake.

Under normal or unstressed conditions (pre-pumping), the Snake Lake area occupies a hydraulic divide which separates ground water movement to Johnson Creek drainage to the west and north from Minocqua Lake drainage to the south. The water table is very flat, and water moves under a gradient of about 3 to 6 feet per mile (0.6–1.2 m/km) (Fig. 6).

Ground water levels fluctuate in response to changes in recharge and reflect the amount of water in storage in the ground water reservoir. Based on the 1944-1969 hydrograph of observation well Oneida 22, located about 8 miles (13 km) east of Snake Lake (DeVaul, 1967), maximum annual fluctuation of the water table has been about 4.5 feet (1.4 m); the average annual fluctuation has been about 2.5 feet (0.8 m). In recent years, water levels in the area have been near maximum.

Ground water levels in the Snake Lake area respond rapidly to recharge because of the permeable nature of the soils and the shallow depth of the water table. Laboratory analyses of Snake Lake outwash deposits yield permeabilities between 150 and 600 gpd/ft^2 (6.1–24.5 cu m/day/m^2) (Fig. 16, Append. C). Field permeability measurements of shallow surficial materials generally corroborate laboratory permeabilities, ranging from 225 to 1125 gpd/ft^2 (9.1–46.0 cu m/day/m^2).

Given the contemplated renovation scheme, the possibility that the lake was hydraulically sealed from the ground water reservoir was an important consideration. The degree of sealing exerts a primary control on the natural rate of lake flushing by ground water. Effective sealing of the lake bottom would have provided for efficient and rapid pumping of lake waters, but would have markedly impeded refilling of the lake. Furthermore, sealing is an important factor in determining what pumping rates are necessary to exceed ground water entry rates.

In spite of the accumulation of more than 40 feet (13 m) of low permeability (k = 1.5–10 gpd/ft^2, 0.06–0.41 cu m/day/m^2), fine-grained organic sediment over outwash sands in the basinal parts of Snake Lake

*Ground water moves along flow paths from areas of high potential (upland or recharge zone) to areas of lower potential (lowland or discharge zone), with potential expressed as elevation of the water table above a mean sea level datum. The pattern of ground water flow from recharge to a discharge area constitutes a dynamic flow system. In a recharge zone, the ground water potential gradient is downward from the water table; in a discharge zone, it is up toward the water table. Between these end members, lateral flow predominates.

(Fig. 19, Append. C), several lines of evidence indicate that Snake Lake is hydraulically continuous with the adjacent unconfined aquifers and that lateral ground water flow predominates. During the preliminary test pumping of October, 1969, water levels in observation wells (piezometers) adjacent to the lake showed essentially no lag in responding to drawdown of the lake. The drawdown exposed numerous seepage zones around the lake, documenting points of hydraulic connection. In addition, lake elevations fluctuate in accord with the regional water tables.

Largely lateral ground water movement is suggested by the low gradient of the water table and by relatively low vertical gradients in piezometer nests on both sides of the lake. These latter wells indicate preferential permeability in a horizontal direction, an anisotrophic condition probably due to stratification of the glacial outwash deposits. Some ground water chemical data further suggest the predominance of lateral flow, and are discussed in a later section. The predominance of lateral flow suggests that ground water moving in deeper parts of the aquifer (perhaps deeper than the maximum water depth, i.e., penetration of the lake into the aquifer, or about 18 feet [5.5 m] for Snake Lake), does not participate in flushing the lake. This condition of underflow would prevent deeper ground waters from being affected by changes in water quality caused by residence in the lake (Fig. 4).

The present ground water flow system has probably existed since the rise of the lake surface due to emplacement of the dam in the outlet in 1962. Prior to that time the lake was probably only slightly above Arrowhead Lake, and, except for the north side, received ground water inflow completely around its perimeter. Because ground water gradients were toward the lake during that period, some effluent from the sewage treatment plant moved into Snake Lake from the west side. The rise in lake level when the dam was built reversed the gradient in the vicinity of the treatment plant, and any residual material from the plant's field now flows away from the lake, rather than toward it.

Water Budget. In order to evaluate the efficacy of the dilutional pumping renovation scheme, it was desirable to know the approximate flushing rate for Snake Lake. An estimate of the flushing period would suffice to insure that the lake was not undergoing continuous rapid dilution naturally, thereby invalidating the proposed renewal scheme.

The lake level appears to have been relatively constant since about 1963, indicating that there has been little change in storage in the lake; the amount of water leaving it equals that which is entering.

Both ground water and surface water flow into Snake Lake. The amount of water, particularly surface water, entering Snake Lake annually is difficult to ascertain, because the topographic control necessary to delineate the drainage basin is lacking.

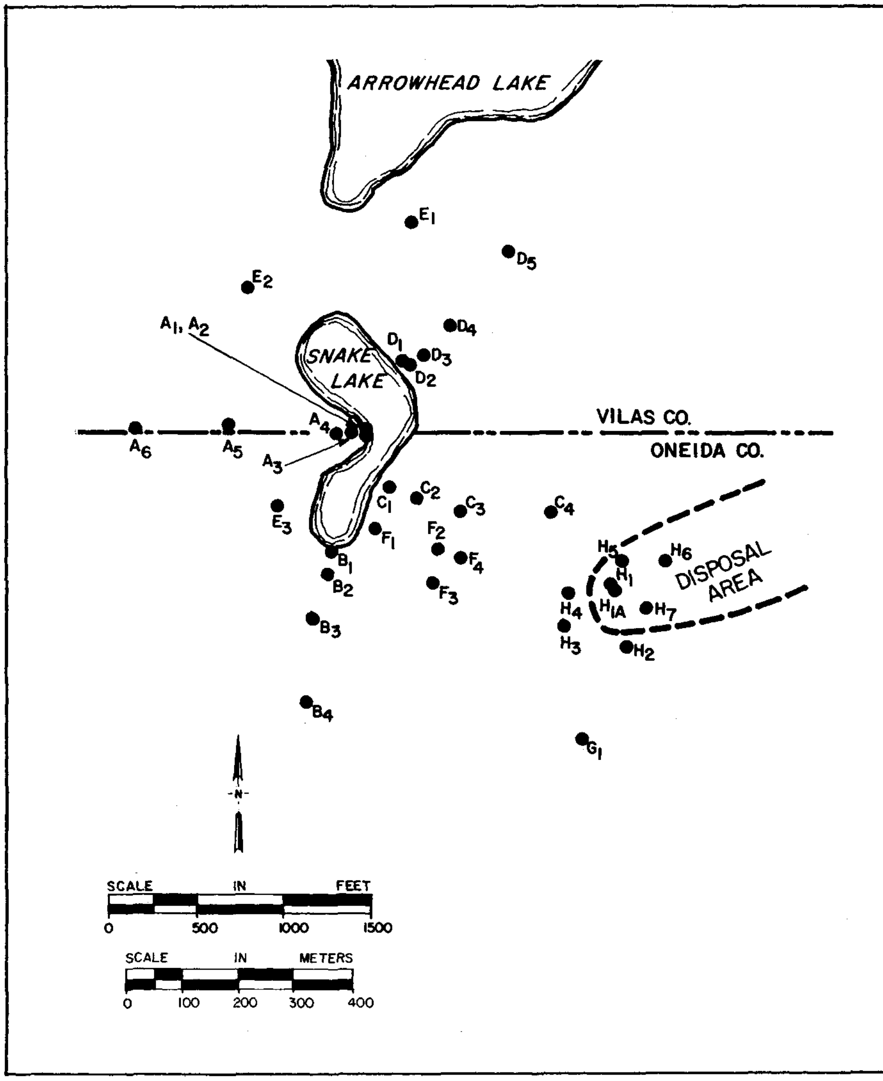


FIGURE 3. *Ground Water Well Index*

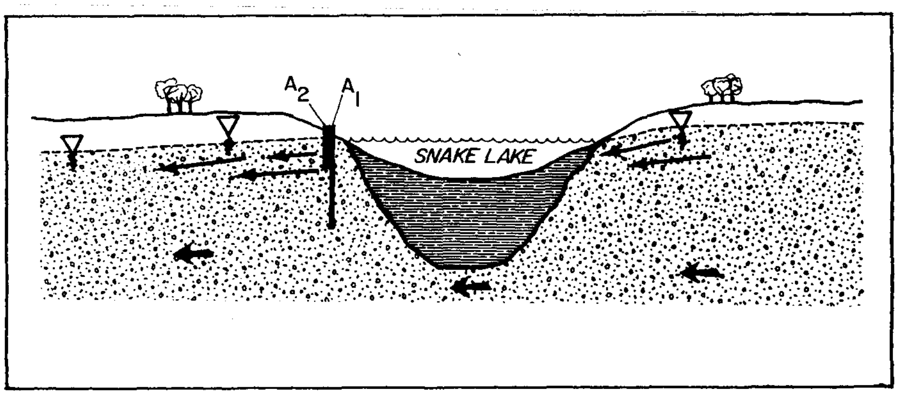


FIGURE 4. *Schematic Diagram of Largely Lateral Ground Water Flow Under Snake Lake*

TABLE 8. Water Quality of Selected Upgradient and Downgradient Wells in the Ground Water Flow System and Snake Lake*

Well No.	Total Nitrogen (mg/l)	Chloride (mg/l)	Calcium (mg/l)	Magnesium (mg/l)	Sodium (mg/l)	Potassium (mg/l)	Phosphorus (mg/l) Reactive	Phosphorus (mg/l) Total
Upgradient								
C_2	0.25 (0.1–0.6)	2 (1–3)	2 (1–5)	1 (1)	1.4 (0.8–2.1)	1.8 (1.5–2.1)	<0.01 (<0.01–0.02)	0.04 (0.03–0.06)
D_5	0.4 (0.3–0.5)	2 (1–3)	1 (1)	1 (1)	0.75 (0–1.8)	1.6 (1.0–2.4)	0.02 (<0.01–0.03)	0.07 (0.04–0.09)
F_1	0.8 (0.8)	2 (1–3)	1 (1)	1 (<1–2)	1.2 (0.1–2.6)	1.4 (0.8–2.7)	0.01 (<0.01–0.03)	0.04 (0.03–0.06)
F_4	1.1 (1.0–1.2)	2 (1–3)	2 (1–2)	1 (1)	1.6 (0.2–3.2)	1.0 (1.0–1.1)	0.02 (<0.01–0.04)	0.04 (0.03–0.06)
Snake Lake**	3.0 (1.9–5.9)	35 (29–54)	3 (1–4)	1.6 (1–2)	26 (21–47)	2.3 (1.6–3.1)	0.35 (0.05–1.13)	0.55 (0.20–1.20)
Downgradient								
A_2	7.7 (5.0–9.8)	14 (2–32)	10 (6–16)	6 (3–9)	58 (38–76)	6.6 (1.0–11)	0.03 (<0.01–0.08)	0.06 (0.03–0.09)
B_1[1]	6.5 (5.7–7.3)	494 (487–500)[2]	41 (37–45)	25 (21–30)	181 (144–218)	7.3 (5.2–9.3)	<0.01 (<0.01)	<0.03 (0.0–0.03)
B_2	1.8 (1.5–2.0)	150 (133–164)[2]	8 (5–11)	8 (5–12)	78 (58–105)	4.2 (2.9–6.4)	<0.01 (<0.01–0.02)	<0.03 (0.0–0.03)
B_3[1]	1.5 (1.2–1.8)	69 (68–70)	11 (11–12)	7 (6–9.5)	18 (3.8–35)	5.4 (3.1–7.8)	<0.01 (<0.01)	0.03 (<0.03–0.03)
E_3[3]	0.7 (0.5–0.8)	2 (1–3)	1 (1–2)	3 (2–4.5)	1.7 (0.5–3.2)	2.7 (1.7–4.0)	0.03 (<0.01–0.07)	0.22 (0.09–0.49)
Downgradient, deep								
A_1	0.9 (0.4–1.5)	1 (1–2)	4 (1–9)	2.3 (2.1–2.4)	1 (<1–1.5)	1.2 (0.3–2.2)	0.02 (<0.01–0.07)	0.05 (0.03–0.09)

*Average and range of monthly values, February–May, 1970.
**Based on surface – 12-foot samples.
[1]Based on 2 sample dates.
[2]See text for explanation of high chlorides in B-series well waters.
[3]Based on 3 sample dates.

Moreover, natural drainage patterns have been altered by man in much of this small watershed. A reasonable estimate of watershed acreage is less than 100 acres (40.5 ha), and probably closer to 50 acres (20.2 ha). Using an empirical precipitation-runoff coefficient generally valid for northern Wisconsin (0.20–0.25 x precipitation), the annual water contribution to Snake Lake would be less than 67 acre-feet (8.3×10^4 cu m). Ground water inflow alone, computed from flow-net analysis, is about 0.1 acre-feet (1.2×10^2 cu m) daily (or 37 acre-feet [4.6×10^4 cu m] annually) under natural conditions. For Snake Lake, with a volume of 90 acre-feet (1.1×10^5 cu m), flushing time to displace one lake volume is estimated at about one and one-half years.

Ground Water Quality. Ground water upgradient of the Snake Lake area generally is acidic, very soft, and contains only small concentrations of dissolved materials. Ground water in that area is relatively low in nitrogen, phosphorus, and chlorides, in comparison to Snake Lake water (Table 8). The distribution pattern of water quality parameters, especially chloride (in that its chemical mobility makes it a good tracer) is closely related to the ground water flow system. Chloride concentrations in wells distant from possible contamination and upgradient (east) of Snake Lake (C_2, D_3, D_5, F_1, F_4) rarely exceeded background levels of 1–3 mg/l (Table 8 and Fig. 3). Downgradient from the lake (A-series wells), chloride levels were generally higher (1–32 mg/l). Constituents other than chloride exhibited somewhat similar, albeit less clearly defined, distribution patterns. It should be noted that well control downgradient from Snake Lake is meager. Consistently high chloride values, particularly in the B-series wells (Table 8) may be related to road salt storage and applications and to the presence of a storm sewer outfall along the south side of Snake Lake; hence, these wells may not represent downgradient water quality. Thus, high quality ground water upgradient from Snake Lake appears to be degraded after residing in the lake, and enters the aquifer on the west side of Snake Lake in a more mineralized condition.

Ground water chemical data tend to corroborate the flow paths determined from purely physical data. Using chloride as a tracer, there was a general pattern of downgradient dilution in the A– and B–series wells. For example, samples from wells A_2 through A_6 collected in March of 1969 showed a downgradient reduction in chloride ion concentration from 18 mg/l in A_2 to 1 mg/l in A_6 (see Table 8 for B–series).

A comparison of samples taken at least quarterly during 1969-1971 from wells A_1 (32 ft; 9.8 m) and A_2 (11.5 ft; 3.5 m) invariably showed a dramatic contrast in chloride levels. A_1, the deeper well, consistently contained 1–2 mg/l in comparison to A_2, which varied from 2-32 mg/l, and suggested lateral flow in the aquifer. This relationship, although by itself inconclusive, supports the argument for ground water flow under Snake Lake based on physical considerations.

LABORATORY INVESTIGATIONS OF SEDIMENT CHARACTERISTICS

In order to estimate the effects of the sediments on the nutritional levels in the lake, N– and P–release characteristics were determined on selected sediment samples under aerobic and anoxic conditions (Fig. 20, Append. C).

Aerobic Leaching

Aerobic batch leaching studies were made on three general types of sediment by agitating and aerating sediment samples in 5 gal (20 l) jugs containing high quality ground water (Table 9) from the nearby aquifer (well C_2). The three types of sediment included (Fig. 2 and Table 6):

1. Peaty surface sediments (core I, surface (0–10 cm) section),
2. Muck surface sediments (core II, surface (0–10 cm) section) and,
3. Muck from 4.9 feet (1.5 m) below the sediment surface (core II, 140–160 cm section).

The sediment (dry weight basis)/ water ratio in the jugs was about 1.7/1000. This ratio would be equivalent to contacting 1 volume of wet sediment with 30 volumes of overlying water.

Well-mixed samples of the sediment-water suspension were withdrawn and analyzed for pH, NH_4^+-N, NO_3^--N, soluble (0.45μ) total P, and soluble organic N periodically for 5 months.

The NH_4^+ in the initial water samples indicated that essentially all of the analytical NH_4^+-N in the sediment had been released immediately. Ammonium levels in the surface-peat jug were depleted within a month, but in the water in contact with muck, about 3 months were required. NO_3^--N levels rose as the ammonia was depleted but attained higher levels than the original NH_4^+-N, indicating a conversion of organic N to nitrate. Soluble total P attained stable concentrations of about 0.25 mg/l in the surface-sediment jugs within a week. The levels in contact with the deeper muck reached about 0.30 mg/l and then dropped off to 0.10 mg/l after a few months.

To summarize the aerobic batch studies: (1) NH_4^+-N in these sediments was released immediately and was converted to NO_3^--N; (2) total P reached a steady state (0,25 mg/l) within a few weeks for surface sediments, but then decreased in the water contacting subsurface mucks, (3) more dissolved colored matter was leached from the subsurface muck (60 units) than the surface sediments (10-15 units). If the sediments currently contribute a substantial portion of the nutrient input to the lake, it is apparent that little could be gained in terms of water quality enhancement by removing only the surface few feet of sediment, i.e., if dredging were to be considered as a renewal technique.

Five sequential aerobic leachings of the sediments (changing water after one month intervals) showed that essentially all of the easily leachable P was released in 3 cycles. About 25 percent of the acid-leachable P (inorganic P) was recovered in the water. Total soluble nitrogen levels in the leachates remained high and variable for 5 water changes, with levels of 0.3–3.5 mg/l being observed. The leachings were not carried through sufficient cycles to deplete the easily leachable nitrogen in the sediments. The data imply that it would take extensive flushings of the lake to substantially reduce potential nutrient contributions from the sediments.

Anoxic Leachings

The anoxic jug studies were run in the same way as the aerobic jugs, except that nitrogen gas rather than air was used to maintain a well-mixed system. An anaerobic system similar to actual Snake Lake conditions was not attained, however. There was no noticeable sulfide production in the jugs, whereas sulfides are commonly noted in the anoxic waters of the lake. The problem may have been the result of traces of oxygen in the commercial grade of nitrogen gas used.

Ammonium-N levels stabilized near 0.4 mg/l in contact with peat and at about 1.5 mg/l in contact with muck within a period of a few weeks. Total soluble P increased to levels of about 0.25 mg/l in all three jugs in a period of 2 months. Nitrates were depleted after 3 weeks and soluble organic N quickly attained stable levels of 0.2–0.3 mg/l. The levels of N and P had reached 90 percent of their stable levels (6 months) within about 3 weeks.

If ground water were to seep uniformly through the sediments of Snake Lake as it refilled, there would not be a substantial improvement in lake water quality in terms of its nitrogen and phosphorus content.

TABLE 9. Composition of Water From Well C_2 Used for Sediment Leaching

Parameter	Composition*
Alkalinity (mg $CaCO_3$/l)	4
Electrical Conductivity (μmho/cm @ 25°C)	30
Color units	< 5
pH units	6.6
Total Phosphorus	0.05
Organic N	0.1
Inorganic N	0.1
Chloride	2
Calcium	2
Magnesium	1
Sodium	2
Potassium	2

*mg/l except as noted.

Based on the results of aerobic sequential leaching, the amounts of readily leachable P would range from 0.06 to 0.13 mg P/cm^2 per cm of sediment depth in contact with the water. That is, a layer of sediment 0.4 inches thick (1 cm) could provide 0.06–0.13 mg P/l in a 33-foot (10 m) column of overlying water. The depth of sediment which can be considered to be in intimate contact with the lake water is estimated to be about 4 inches (10 cm) based on analysis of chlorides in the interstitial waters of several core sections. The sediment sample used for leaching studies was a composite of the upper 4 inches (10 cm) of a sediment core.

PUMPING OPERATIONS

1969 Pumping

Dilutional pumping or "flushing" to exchange water in a lake became practical with the development of a portable irrigation pump* capable of moving large volumes of water at low heads.

Pumping was carried out for a two-week period in October, 1969 to (1) test pumping equipment, (2) evaluate the hydrogeologic response to stressing the system by drawing down the lake, and confirm that the lake could indeed be drawn down, and (3) assess the adequacy of the disposal sites to which Snake Lake water was to be pumped.

Choice of a water-spreading area (disposal area, Fig. 3) was based on (1) location of unoccupied land possessing suitable infiltration characterisitcs, and (2) minimal disturbance to highway or urban developed property. An area beginning about 1500 feet (460 m) east of the south basin of Snake Lake was chosen as the principal disposal site for the October, 1969 pumping. Additionally, a small site 200 feet (60 m) from the lake along the transmission tube pathway was chosen as an auxiliary water-spreading area. The principal disposal site consisted of a 4-acre (1.5 ha) tilled area with pastured boundaries.

Infiltration studies conducted in the disposal areas indicated that infiltration rates for pumped lake water could be increased from 5–7 inches/hour (12–17 cm/hr) to 15–25 inches/hour (37–61 cm/hr) by removing the upper foot (30 cm) of soil cover. Therefore, the channel and terrace network constructed to distribute flows, as well as part of the auxiliary ponding area, were stripped of these less permeable surface soils by contour plowing with a V-plow designed for forest fire-break plowing. In addition a dike was built at the lowest side of the field to pond the overflow and to prevent overflow water from spreading into the yards of nearby neighbors.

*Manufactured by Crisafulli Pump Co., Glendive, Montana.

Thirteen drive point wells were emplaced in the disposal area prior to pumping in order to evaluate the hydrogeology—particularly the storage capacity—of the disposal area, and to monitor changes in ground water levels in the disposal field. This monitoring aided in minimizing water-logging and in managing the pumping schedule. It also provided a check on possible adverse effects to nearby septic-system drainfields and/or domestic wells.

From October 13 through October 24, 1969, a 16-inch (0.41 m) (diameter of outlet) pump was operated from 10 to 12 hours per day, removing approximately 2400 gallons (9100 liters) of lake water per minute (Fig. 5). Pumping to the primary disposal field 1500 feet away created a head at the pump of about 25 to 28 feet (7.7–8.6 m), which included 15 feet of head (4.6 m) due to friction loss in the 16-inch diameter butyl-fabric tubing. Only a small percentage of flow was directed to the auxiliary ponding site. In total, about two-thirds of a lake volume of water (65 acre-feet [8.05 x 10^4 cu m]) was pumped from Snake Lake. During the pumping period, lake levels dropped 3.48 feet (1.06 m) (Fig. 21, Append. C), which is a net loss of some 38 acre-feet (4.7 x 10^4 cu m) of water. The difference represents ground water inflow during pumping.

The response of the ground water system to pumping was classical, and is shown in Figure 6. In short, a substantial ground water mound was created in the disposal area due to the discharge of pumped waters and the lake became influent along its entire periphery. Ground water gradients on the eastern side of the lake increased from 3–6 feet per mile to 32 feet per mile (0.6–1.2 to 6.1 m/km); the increase in the gradient produced a sharp increase in the rate and volume of ground water inflow.

1970 Pumping

The objective of the 1970 operation was full-scale dilutional pumping. The trial in 1969 demonstrated that several lake volumes of water could be moved from the lake to the disposal area in a period of six weeks. The inadequacy of the disposal field as concerns water infiltration rate was taken into account in choosing the size of the pump and preparing a larger disposal area. Summer was chosen as the best period for dilutional pumping because of the high rates of evapotranspiration and nutrient uptake by land vegetation.

A 12-inch (0.31 m) portable pump of the same manufacture as the 1969 pump was employed. It was designed to lift greater volumes of water at heads over 20 feet (6.1 m) than the standard model of same size. In order to facilitate a longer pumping period, the pump was powered with a frame-mounted electric motor (Fig. 7).*

*A single-phase 40 h.p. motor (manufactured by Marathon Electric, Wausau, Wisconsin) with low starting torque and low starting current was used. An electric-powered pump had several advantages over the internal combustion unit. Weight reduction (fourfold in this case) simplified physical installation and subsequent adjustments of the pump in the water. Refueling and lubrication needs were eliminated, as was exhaust noise. The need for attendants at the pump was markedly reduced because of automatic overload features inherent in electrical equipment. Of special advantage was the ability to operate the pump at steep angles on the lakeshore bank that became steeper as lake stage fell. During the 1969 pumping trial the pump frame was equipped with steel drum floats to prevent it from dropping into the water and soft lake bottom sediments at an angle too great for operation; this was unnecessary in 1970.

FIGURE 5. *1969 Test Pumping Operations*

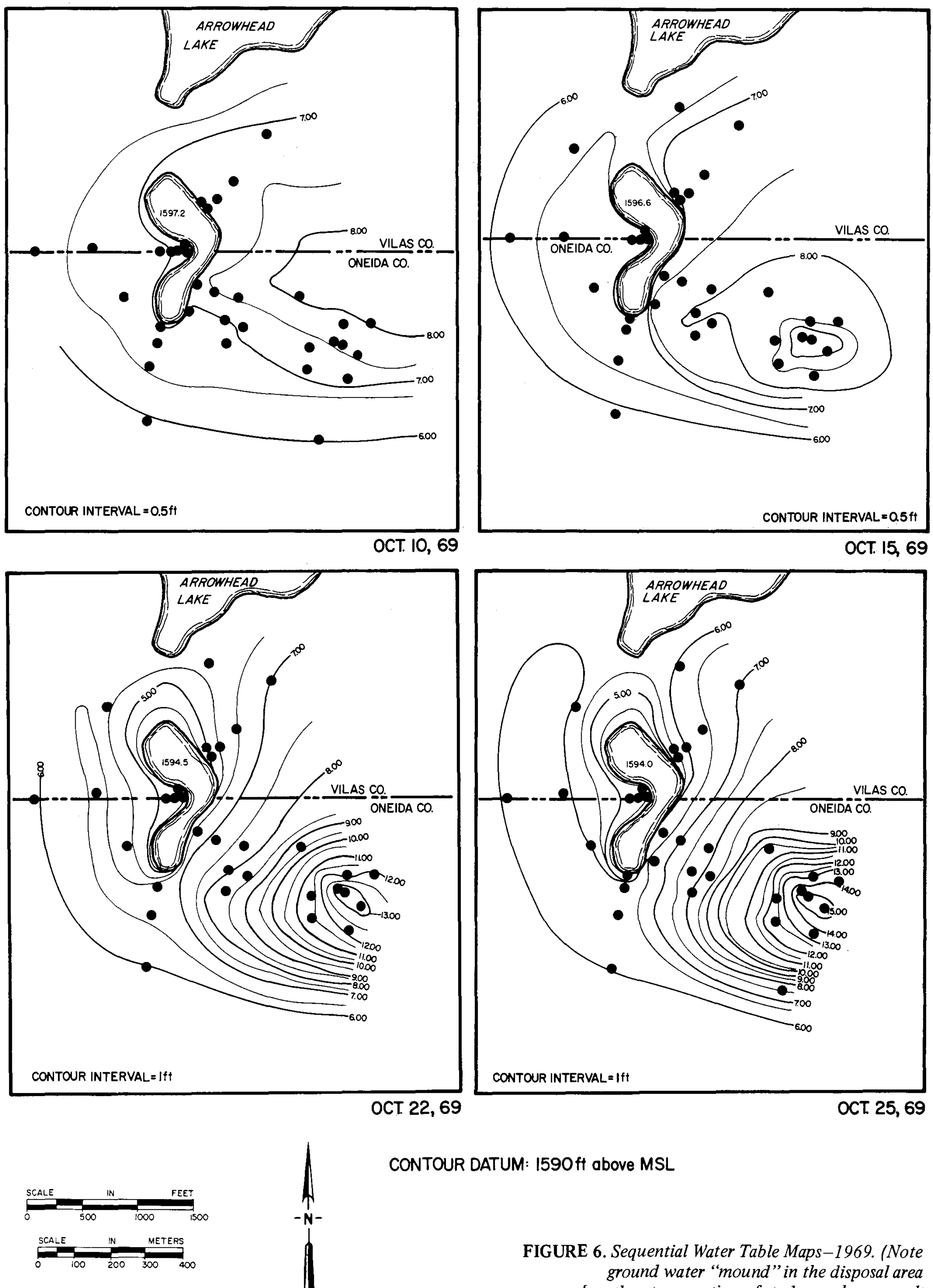


FIGURE 6. *Sequential Water Table Maps–1969. (Note ground water "mound" in the disposal area [southeastern portion of study area] as a result of discharging pumped lake water.)*

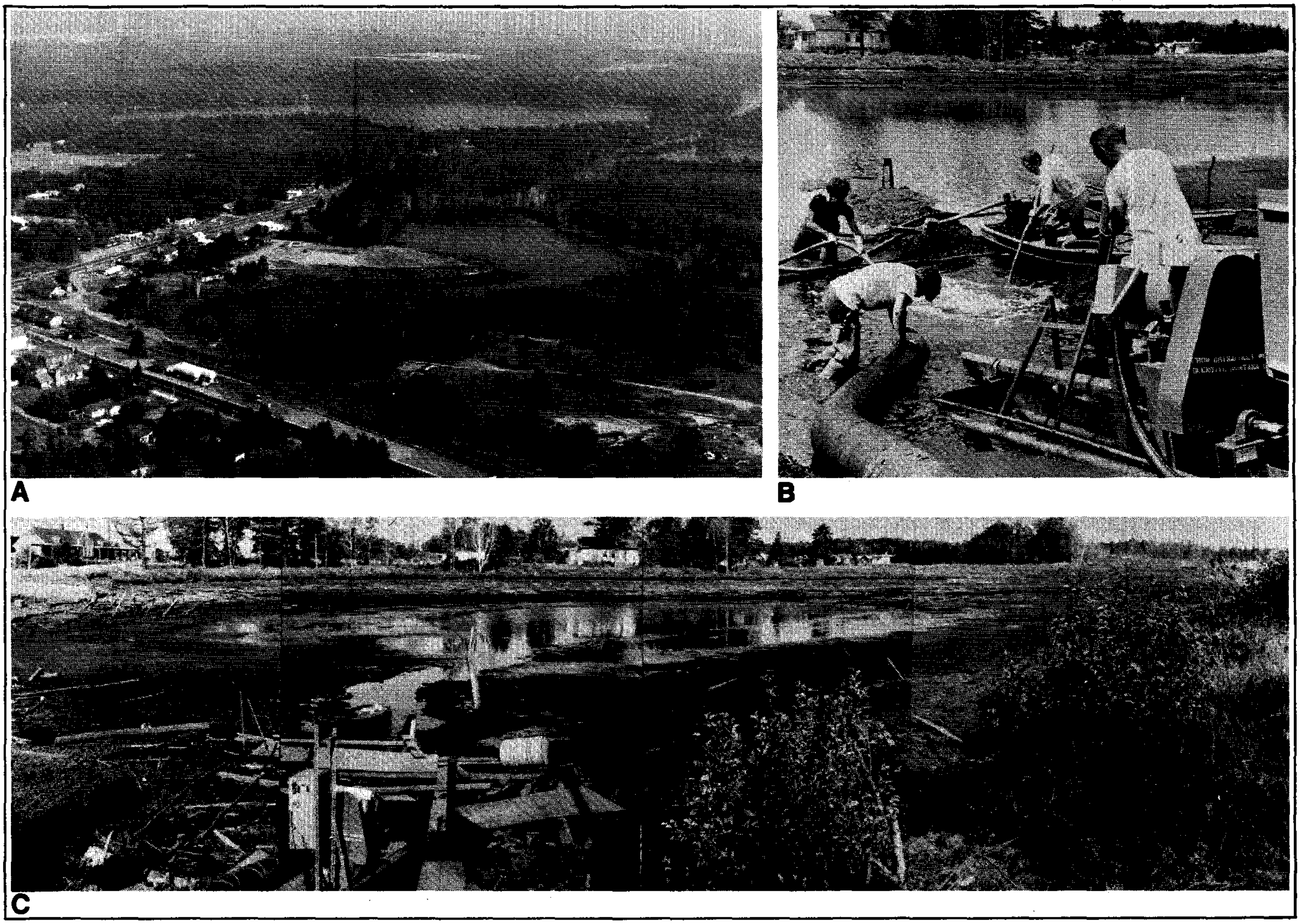


FIGURE 7. *1970 Pumping Operations. (a) Lake during early pumping activity. (b) Jetting and maintenance to keep pump intake open. (c) Snake Lake near maximum drawdown (1970), looking west over south basin.*

In 1970, the disposal area was prepared with a road grader by cutting wide (15 to 20 ft; 4.6–6.1 m) V-shaped channels into an area of about 17 acres (6.9 ha), which incorporated the principal 1969 disposal site (Fig. 8). Water was moved a distance of up to 2,500 feet (780 m) east of the lake by a ditch network which included 1.7 miles (2.5 km) of channels. During the pumping period, constant attention had to be given to maintenance of the channel dikes. During the six-week period, July 17 through August 28, 1970, actual pump operation totaled 878 hours (36.6 days). The 5.4 days of off-time resulted from the need to move the pump as water levels declined, to repair breaks in the disposal field dikes and to repair an electrical wire failure.

During the first week of operations water was pumped to the disposal field at a rate of about 2250 gallons (8850 l) per minute. After this period flows diminished as falling lake stage increased the head. Lake levels dropped until the lake was drawn down 11 feet (3.4 m) at which time the pump rate to the disposal field was 1150 gal/min (4350 l/min). During the last week of pumping the head of water pumped was 42 to 45 feet (13 to 14 m) (including a frictional loss estimate). Actual water level difference between lake and disposal field was 28.5 feet (8.9 m).

As a result of the July-August 1970 pumping, about 250 acre-feet (2.5–3.0 lake volumes) of lake water were circulated through Snake Lake. Lake stratification was completely destroyed; and dilutional flushing of Snake Lake water was complete, based on (1) lake temperatures, which declined to prevailing ground water temperatures, (2) water chemistries, (3) apparent water color, and (4) volumetric considerations. Consolidation of sediments due to de-watering resulted in subsidence. This phenomenon was particularly notable parallel to shorelines, where individual compaction faults (Fig. 9) showed displacements up to 4 feet (1.2 m).

Response of Ground Water System

Under pumping conditions, the ground water flow system changed as shown in Figure 10. Gradients on the west and south side of Snake Lake reversed. On the east side of the lake, steepened ground water gradients caused an increase in ground water discharge (the head differential between the disposal field and Snake

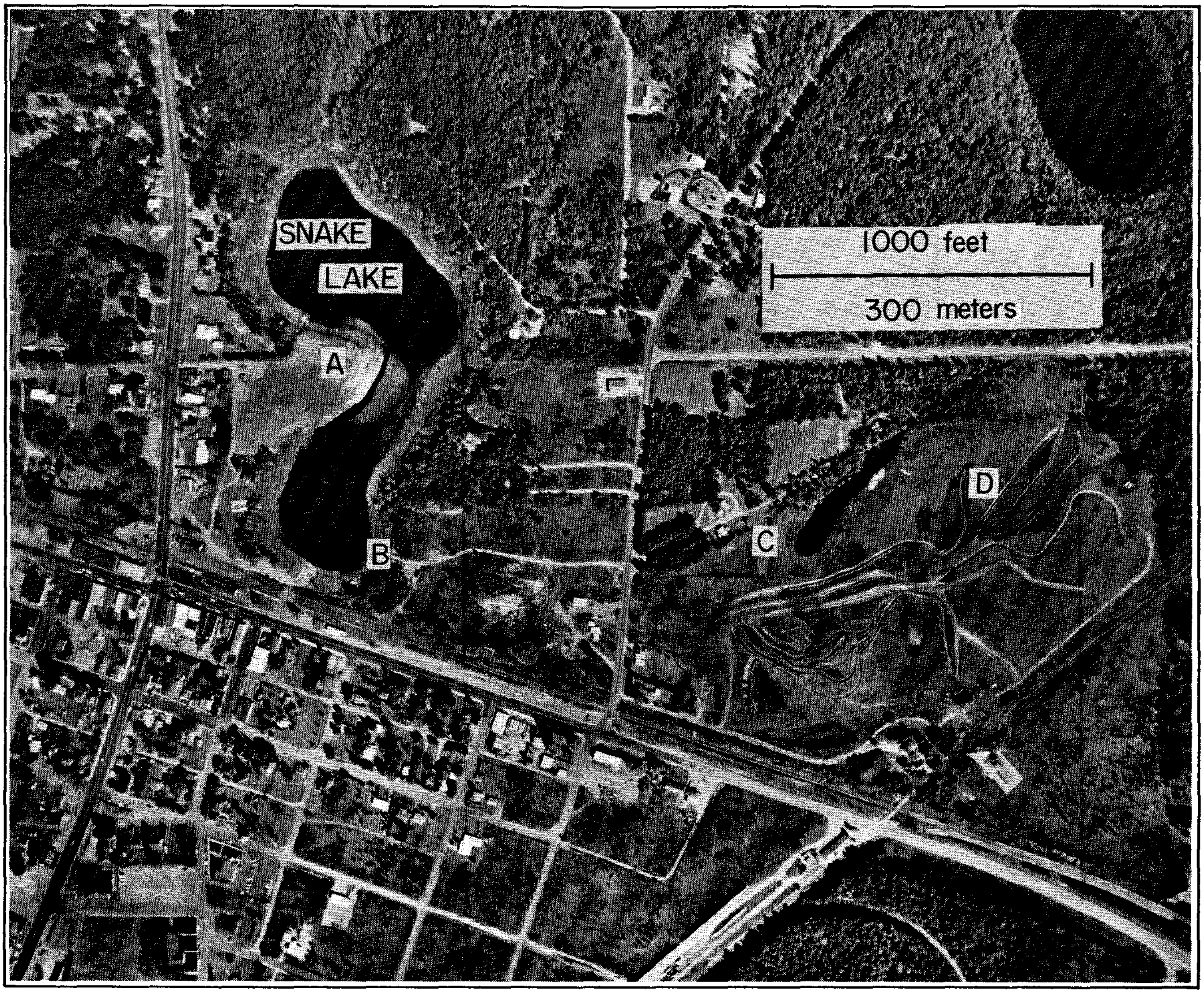


FIGURE 8. *Aerial View of Snake Lake Vicinity Showing Disposal Fields and Pump Location. (a) Site of old sewage treatment plant. (b) Pump location. (c) 1969 Disposal field. (d) 1970 Disposal field addition.*

Lake increased from about 1 foot to 18 feet; 0.31 to 5.5 m).

Under these higher gradients, ground water velocities increased from less than 1 foot per day pre-pumping to about 8 feet per day (0.31 to 2.4 m/day). Actual flow rates determined using chloride as a tracer corroborated these calculated velocities. The measured flow rate between wells H_{1A} and H4 in the disposal field was 9–11 feet (2.7–3.4 m) per day (Fig. 10); less frequent sampling between H_{1A} and well F_1, immediately east of the lake, suggested a rate of ground water move-

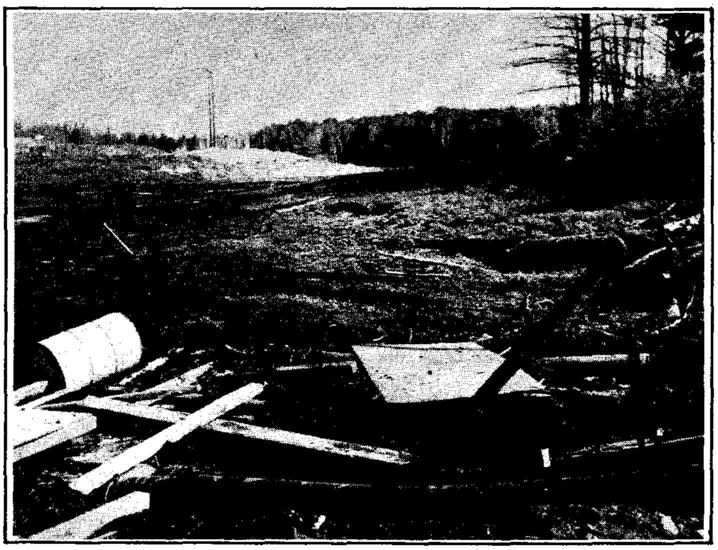


FIGURE 9. *Compaction Faults Along East Shore During 1970 Pumping.*

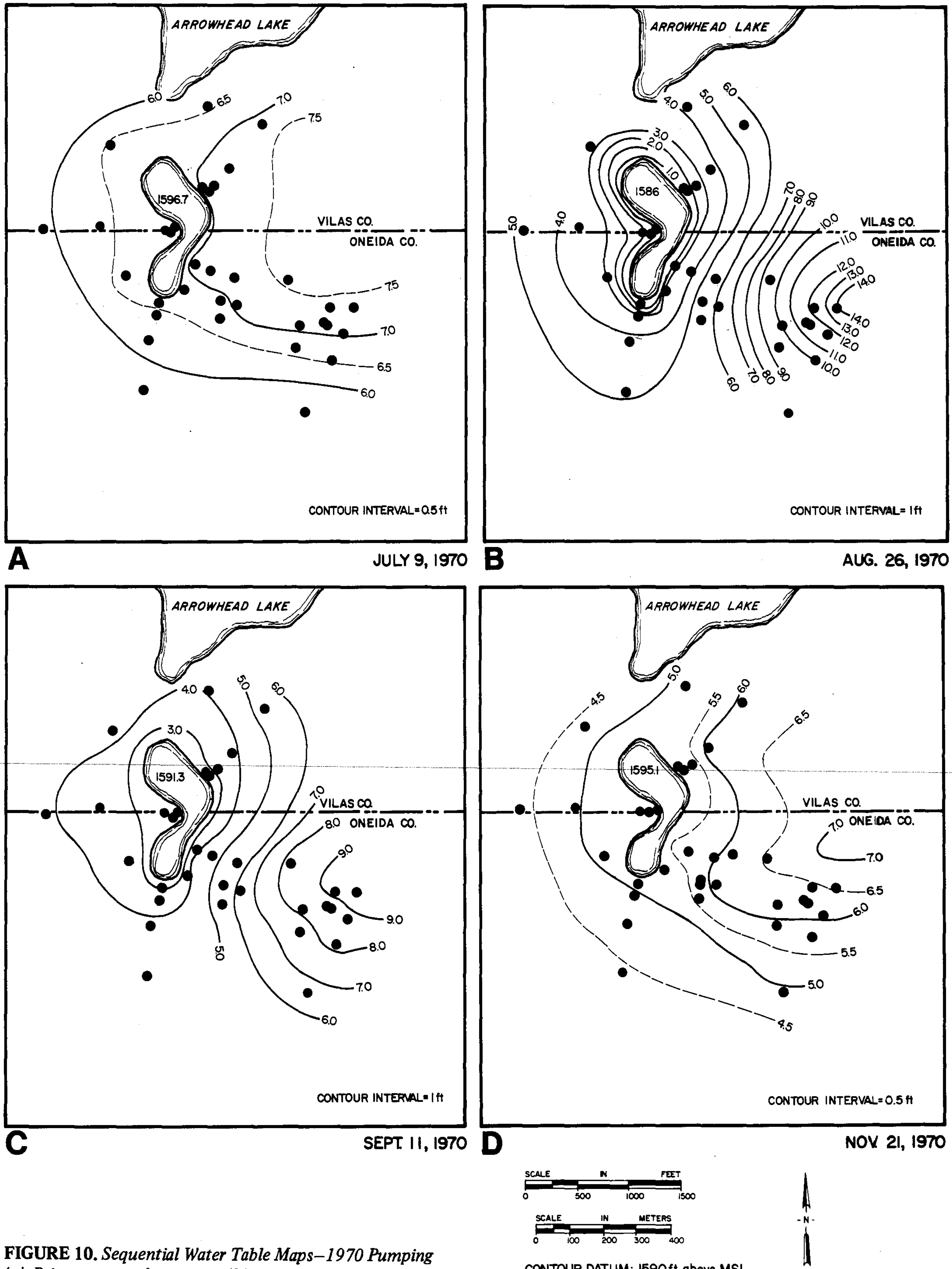
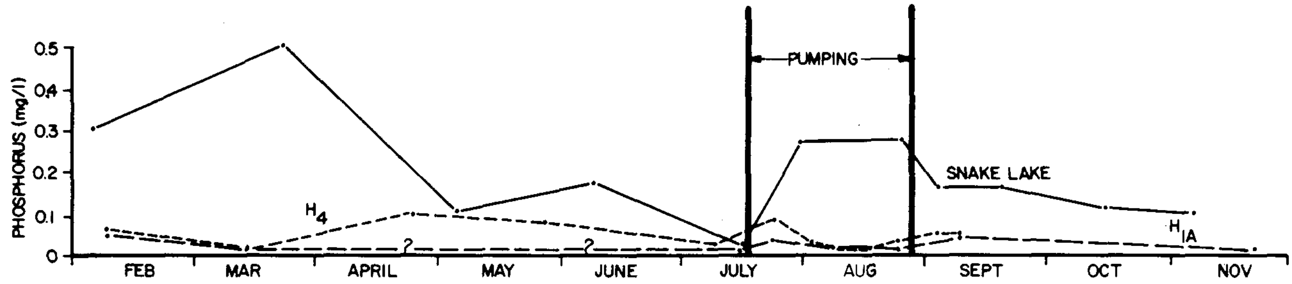
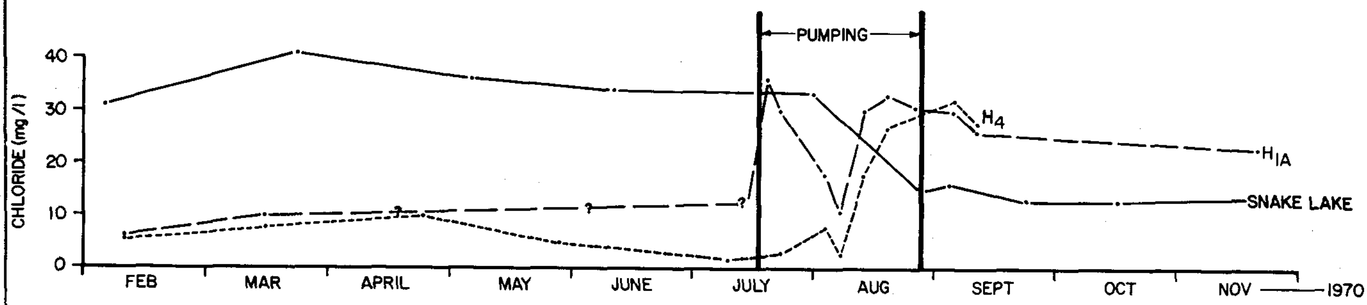


FIGURE 10. *Sequential Water Table Maps–1970 Pumping (a) Prior to start of pumping. (b) Near end of pumping period. (c) 14 days after cessation of pumping. (d) 12 weeks after cessation of pumping.*



(a). Phosphorus (Total P for wells, reactive P for lake water).



(b). Chlorides.

FIGURE 11. *Chloride and Phosphorus Changes in Disposal Field Wells and Pumped Snake Lake Water*

ment of 13–32 feet (4.0–9.7 m) per day. Based on the above data, during stressed conditions pumped waters would recirculate from the disposal field to Snake Lake via the gound water flow system in approximately 4 months.

The phosphorus content of the "return flows" was markedly lower than that of pumped Snake Lake water. Figure 11a shows the concentration of dissolved (unfiltered reactive) phosphorus in the surface lake water plotted along with total phosphorus concentration in two disposal-field wells during the 1970 pumping. The removal of phosphorus would be even more striking if total P values for lake water were used (particulate P would be removed during infiltration and dissolved P furnishes a better measure of removal of phosphorus by adsorption on soil particles). Soil analyses could not show the anticipated changes in soil-P levels, however, due to sampling problems in the ditch system (scouring and sedimentation) (Boyle, 1971, Pers. Comm.). Chloride, in contrast, moves through the soil media, and concentrations in ground waters in the disposal area approximated those of pumped waters (Fig. 11b). No consistent patterns were observed with regard to distribution of nitrogen species in ground water.

The largely lateral nature of ground water flow, even under stressed conditions, was indicated chemically by comparison of chloride levels in nested wells H_{1A} (22 ft) and H_1 (63 ft). The shallow well (H_{1A}) exhibited high chloride levels (6–33 mg/l) continuously, and these concentrations were similar to levels in pumped waters. In spite of being in the center of the ground water mound, well H_1 never exhibited high chloride levels, apparently because of the predominance of lateral vs. vertical fluid movement. During the second pumping, unlike the first, the lake was partially sealed hydraulically, as determined from lags in water level declines in wells vs. lake drawdown. Such a lag effect was not observed during the first pumping. This sealing may be the result of permeability of littoral zone sediments being reduced due to consolidation associated with the October, 1969 pumping and attendant de-watering. Within three months from the cessation of pumping, the pre-pumping ground water flow configuration had been re-established (Fig. 10).

LAKE WATER QUALITY CHANGES

Phosphorus

Phosphorus concentrations remained unchanged as a result of the exploratory 1969 pumping (Fig. 12), although in December, 1969 (several weeks after pumping ceased), there was a substantial short-term increase in phosphorus concentrations. The high values, which occurred throughout the water column, were coincident with a dragline operation on the west shore of the lake. It is difficult to explain the phosphorus increase, however, since there were no apparent changes in nitrogen composition at the same time. Mixing of sediments and asso-

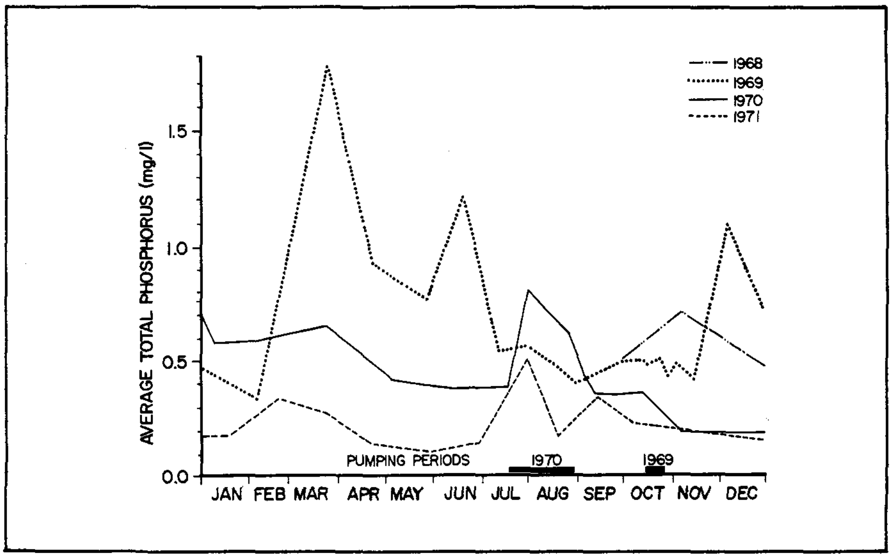


FIGURE 12. *Average Total Phosphorus Concentration*

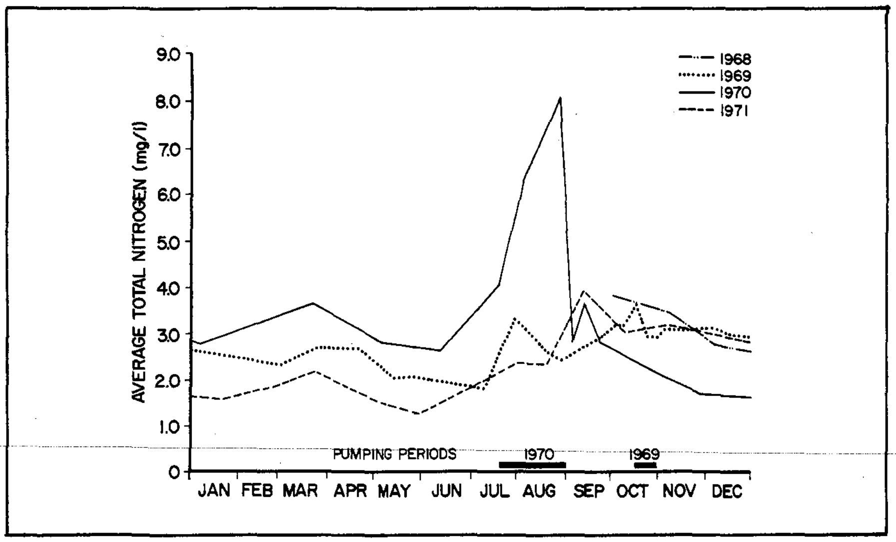


FIGURE 13. *Average Total Nitrogen Concentration*

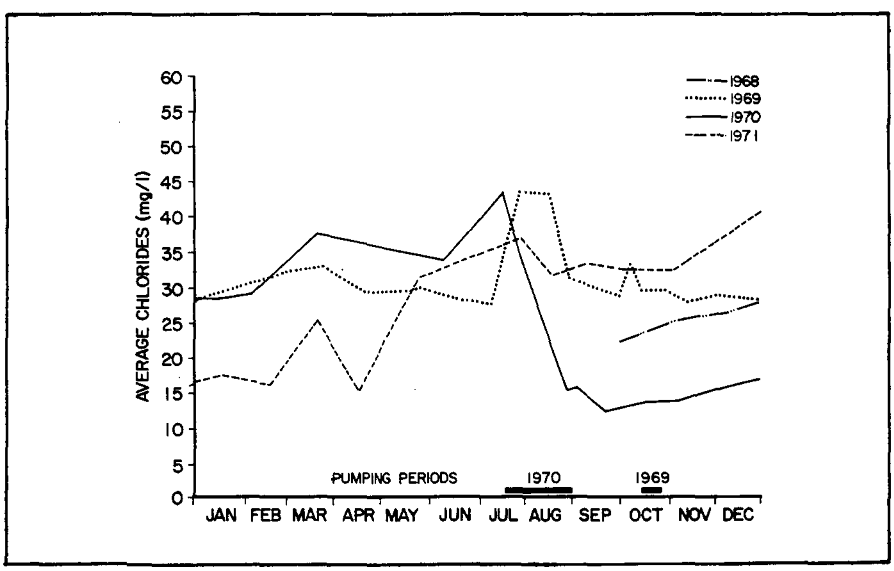


FIGURE 14. *Average Chloride Concentration*

ciated turbidity should show up as an increase in total nitrogen as well as total phosphorus. Phosphorus data from during the 1970 pumping showed an initial increase followed by the apparent effects of dilution. The initial phosphorus increase was principally the inorganic component (reactive P). Upon refilling of the lake, the P concentrations were diluted to substantially less than the 1968-69 levels, and remained generally lower throughout the succeeding year. The levels of P prior to spring turnover in 1971 and 1972 were markedly lower than in 1969 and 1970. The uniparameter figure for P (Fig. 22, Append. C) provides details of the vertical concentration gradients as well as the distribution between reactive and total P in the water column during pumping and refilling.

Nitrogen

Total nitrogen also showed no changes as a result of the brief 1969 pumping (Fig. 13). In 1970, total N increased as pumping began. The increase of the weighted average was due to large hypolimnetic increases in inorganic N (Fig. 23, Append. C), combined with a 1–2 mg/l increase in inorganic N. The organic-N component was in part the result of suspended solids mobilized by pump-induced currents in the lake. The weighted average concentration, however, also responded somewhat to decreases in the volume of the lake, since the surface waters (lower N) were selectively withdrawn from the north basin during pumping. The general decrease in total N upon refilling persisted only through the early spring period of 1971. By late summer, weighted total N concentrations had returned to pre-pump levels.

Chlorides

Chloride concentrations in the lake water are used as a quality parameter (as in ground water) because chloride is highly mobile and the concentration differences between water masses are easily detectable. Figure 14 shows weighted average chloride concentrations in the lake from 1968 through 1971. The 1969 pumping did not result in substantial changes in Cl concentration (given the variability shown in previous data). During the 1970 pumping period, however, Cl showed some initial increase followed by dilution as pumping and refilling continued. By the end of the year, Cl levels were about half of pre-pumping concentrations.

The initial increase may have been due to the induced flow of sediment-associated waters as pumping progressed, although a similar increase in chlorides was noted prior to any pumping in 1969. Chloride levels increased in March, 1971 (attributed to highway runoff and sediment equilibration), and were diluted again in April (due to melting of about 2 feet of lake ice, and concurrent filling of the last 25 percent of the lake volume). The sharp increase in chlorides between April and May, 1971, is more difficult to explain. The concurrent increase in sodium concentration in the lake is equivalent to more than 2/3 of the sodium chloride necessary to contribute the additional chloride, suggesting that NaCl is the source of the large increase.

There are three probable chloride sources: (1) highway and surface runoff, (2) ground water input, and (3) sediment equilibration. There were no road salt applications made after April 4, but melting of the last remnants of plowed snow banks may have contributed some salts. However, the salt increases in the lake are equivalent to about 10–15 salt applications on the roads draining into the lake, and it seems unlikely that melt waters completely account for such high concentrations in the lake. Ground water inflows to the lake are generally of lower chloride concentration than the lake water, with the exception of the B-series wells at the south end of the lake. Since the lake was nearly filled by May, ground water inflows, from the south side of Snake Lake, were not significant. Equilibration of the water with the sediments is a third possible source of chlorides. A jug experiment showed that there was sufficient chloride available in the deep basinal sediments to bring the Cl concentration of a 30:1 water to sediment-volume mixture to about 25 mg Cl/l on a batch basis. The high (>100 mg/l) concentration of chloride noted in the hypolimnion during late summer (Fig. 24, Append. C), when no direct effects of highway de-icing would be expected, further suggest chloride influx from some other source, most likely sediments which have been subjected to high chloride concentrations.

The Cl, N, and P data all suggest that during the initial stages of pumping in 1970, highly mineralized water associated with the sediments was induced to flow into the lake, followed by substantial dilution of lake waters. Although Cl and N have returned to pre-pumping levels, P values remain lower.

Other Parameters

Dissolved oxygen measurement show that pumping had no persistent beneficial effects. The 1969 pumping period was during fall turnover, and any effects were masked. In 1970, after destratification due to pumping, fall turnover allowed oxygen levels to approach saturation, but D.O. was quickly depleted under ice cover as in previous years (Fig. 15). Upon stratification in May (1971), D.O. was again depleted in the hypolimnion within a month.

Color in Snake Lake waters decreased from about 35–40 units prior to pumping to 5–10 after pumping. By May, 1971, color values had returned to near pre-pump levels.

Electrical conductivity of lake water followed a pattern similar to chloride and sodium concentrations, which provided a general check on analyses of the anion and cation composition of the samples.

Transparency measurements (Secchi disc) did not show any improvements, ranging from 1 to 4 feet during the ice free periods of 1969 and 1971.

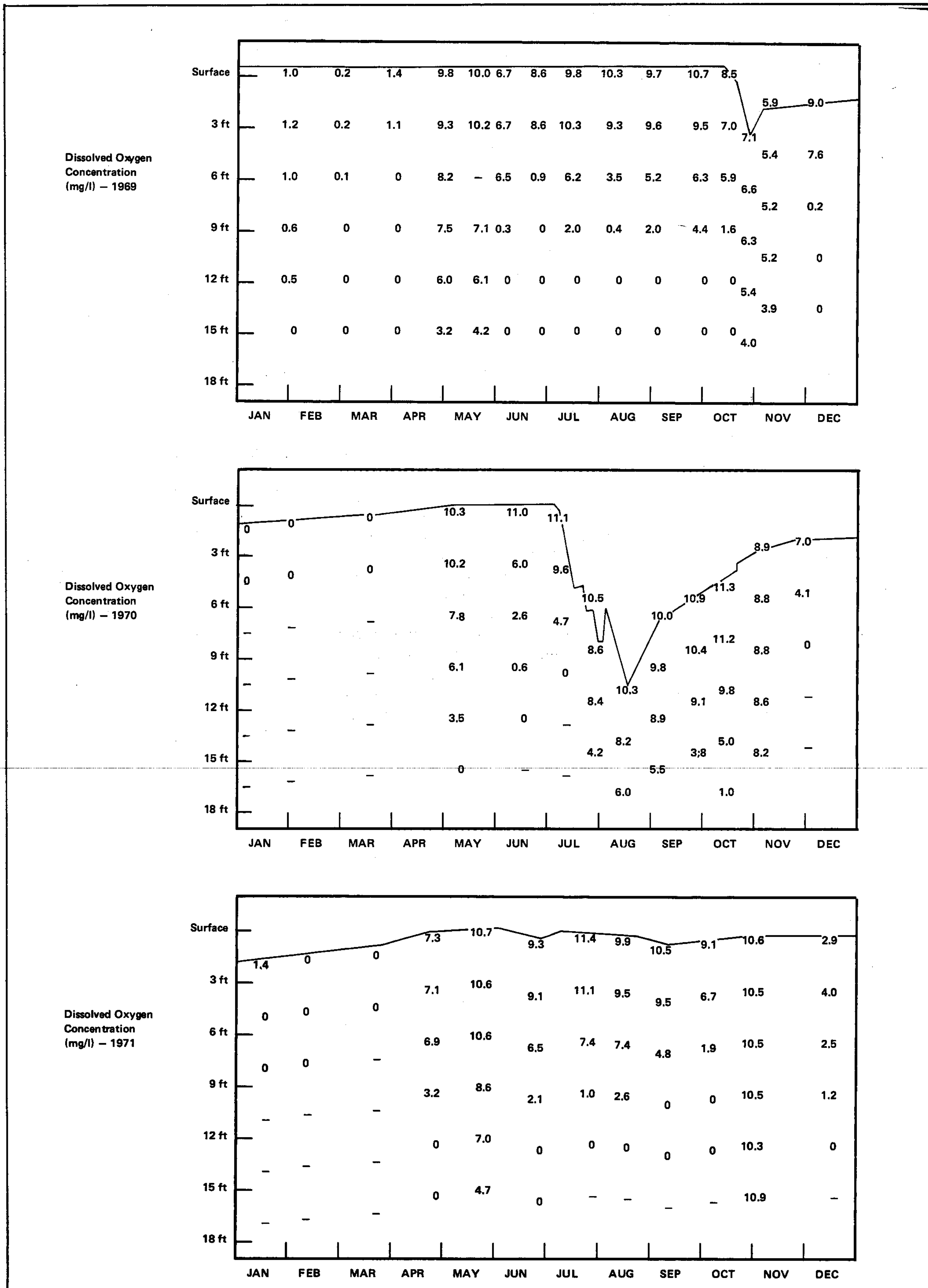


FIGURE 15. *Dissolved Oxygen Data*

CONCLUSIONS

Dilutional pumping of Snake Lake has not "renewed" the lake; severe dissolved oxygen depletion problems continue to prevent the establishment of a sport fishery, and hence general recreational use of the lake.* However, the 1969-1971 dilutional pumping experiment has shown:

1. Irrigation pumps and equipment make rapid pumping of some small lakes technically feasible. At Snake Lake, a supply of high quality water and a suitable method of pumped-water disposal allowed displacement of about three lake volumes of water.

2. Flushing of a lake can result in nutrient reduction. At Snake Lake, phosphorus concentrations were diluted and have remained substantially lower than prior to pumping (total phosphorus levels, however, are still relatively high); post-pumping increases in phosphorus concentrations are attributed to release from bottom sediments. Jar testing indicated that several leaching cycles would be necessary to reduce phosphorus output to a low level, even on a batch basis. Flushing by pumping would be less effective than well-mixed batch leachings, so that an extensive dilution-only scheme would be required to show significant long-term improvements. Snake Lake received sewage for many years and its sediments are rich in nutrients. Dilution may be a more effective means of reducing nutrient levels in a more "normal" lake.

3. Other direct results of pumping are: (a) a reduction in levels of N, Cl, conductance, and color following pumping with a recovery of these parameters to near pre-pumping levels by late the next spring; (b) the preponderance of duckweed growth that occurred prior to pumping has not reoccurred; (c) no apparent effect on dissolved oxygen conditions; and (d) a deepening of part of the littoral zone due to sediment consolidation.

4. The deepening of the littoral zone caused by de-watering is a beneficial side-effect of pumping and drawing down a lake. Such deepening can result in (a) more stable sediment, (b) increased water volume with associated consequences for flora and fauna, and (c) possible hydraulic sealing due to dessication and consolidation of sediments which were de-watered and exposed to air (Smith et al., 1972).

5. The capacity of nutrient sources to provide additional enrichment to a lake must be examined to determine whether other forms of nutrient inactivation – *i.e.*, dredging, sand-blanketing, chemical treatment, diversion, etc.–should accompany dilutional efforts. At Snake Lake, laboratory data suggested that some sediment manipulation activity (facilitated by access to the lake bottom after drawdown) could have been coupled with dilutional pumping to improve lake rehabilitation results. However, given the lack of experience with lake renewal technologies, we wished to constrain the number of stresses acting on the system at one time, and hence focused our efforts only on the consequences of dilutional pumping.

*In June, 1972, Snake Lake was treated with aluminum in order to assess nutrient inactivation (phosphorus removal) as a renewal technique.

APPENDIX A: Calculation of Weighted Average Concentrations in Lake Water

Where average concentrations of a particular constituent in lake water are cited, they were calculated by first assuming that the sample taken for analysis was representative of a definite layer of water in the lake or basin from which it was obtained; i.e, for Snake Lake, where samples were taken at 3-foot (0.9 m) intervals, the surface sample represents the surface 1.5 feet (0.46 m), the 3-foot sample represents the 1.5–4.5 foot strata, etc. The sampler used was 22 inches long, so these composites are a good approximation. Then the volume of each layer of water was determined from the depth-volume relation for the basin, and the percent of total volume calculated. The analytical values were then weighted accordingly to achieve an average concentration. Generally, the results from the two separate basins were coincident, but where they were not, a weighting of the two basins by water volume was used. The average value obtained is equivalent to the total volume of water present, and provides a convenient method for comparing water quality in a stratified lake which is subject to extreme volume changes.

APPENDIX B: Approximate Costs: Snake Lake Dilutional Pumping (1970)

Approximate Costs*
Snake Lake Dilutional Pumping (1970)

Pump, electric motor, and 1500 feet of 12-inch tubing	$10,000**
Electrical service and onsite wiring supplies	650
Disposal field and lakeshore preparation	700
Dredging channel to connect north and south lake basins	750
Electrical power (22,090 kwh)	550
Labor (to operate pumps and manage disposal field)	2,990
TOTAL	$15,640

*Does not include time of Project professional personnel, monitoring, analyses, etc.

**$10,000 is the total capital equipment cost, which was not fully charged against the Snake Lake activity.

APPENDIX C: Supplementary Figures

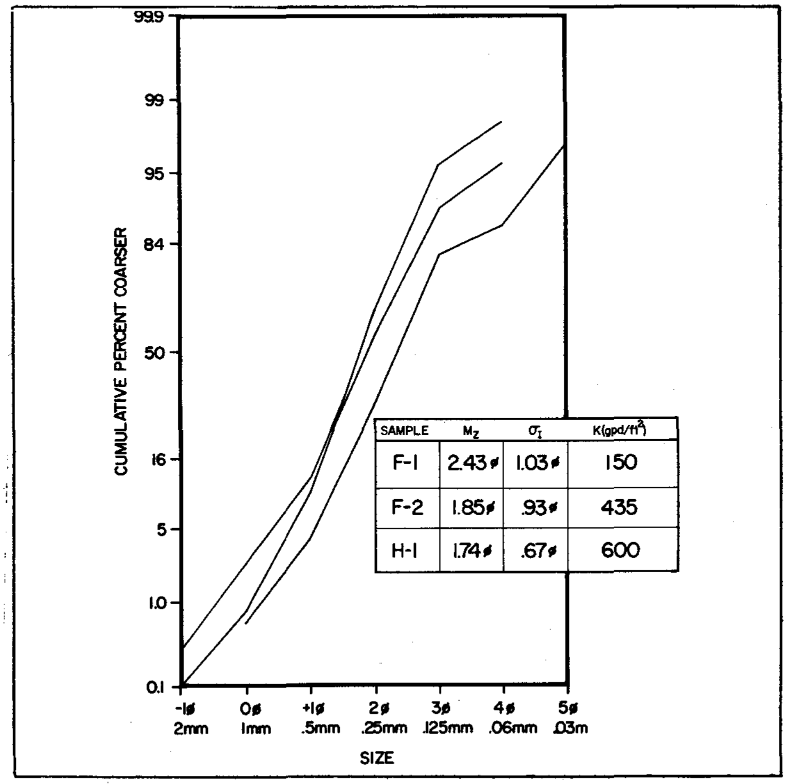


FIGURE 16. *Grain-size Characteristics of Glacial Outwash Deposits (Grain-size parameters after Folk and Ward (1957). Permeabilities (k) determined by constant-head laboratory permeameter. Sample locations refer to observation wells shown in Figure 3. Multiply gpd/ft² by 0.0406 to convert to cu m/day/m².)*

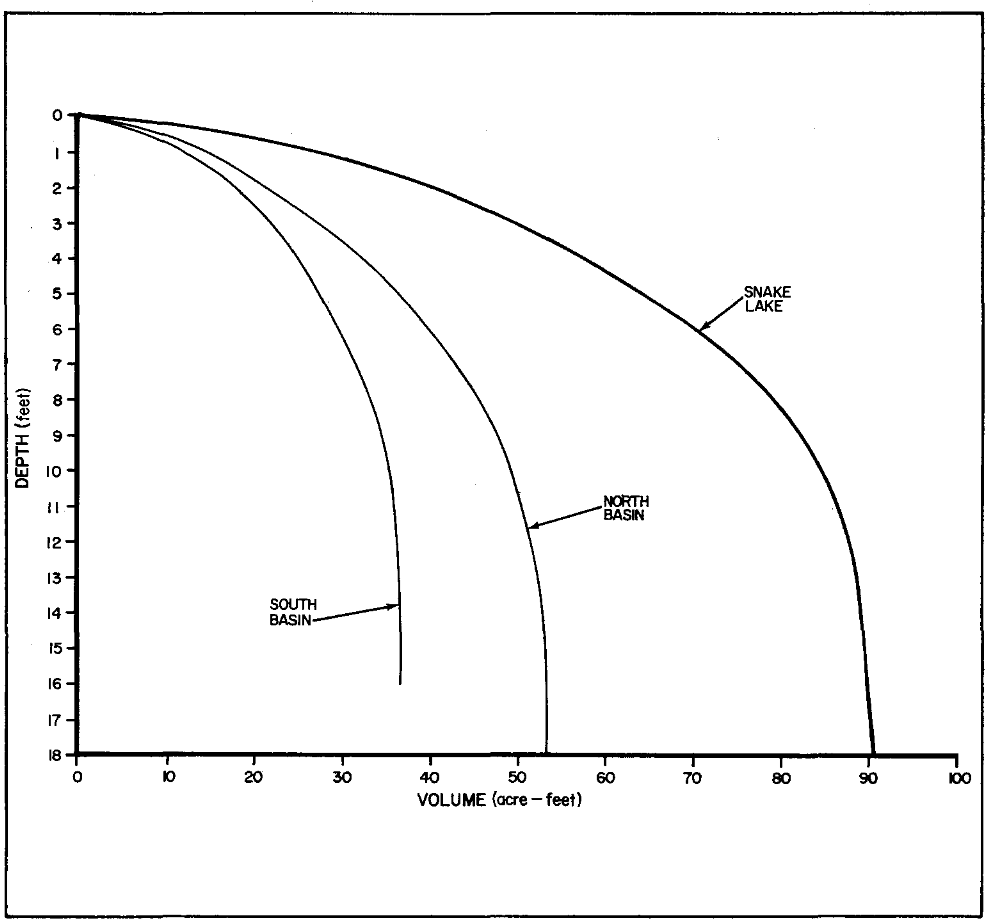


FIGURE 17. *Depth-Volume Relationship (Acre-foot x 1,233.6 = cu meters, feet x 0.305 = meters)*

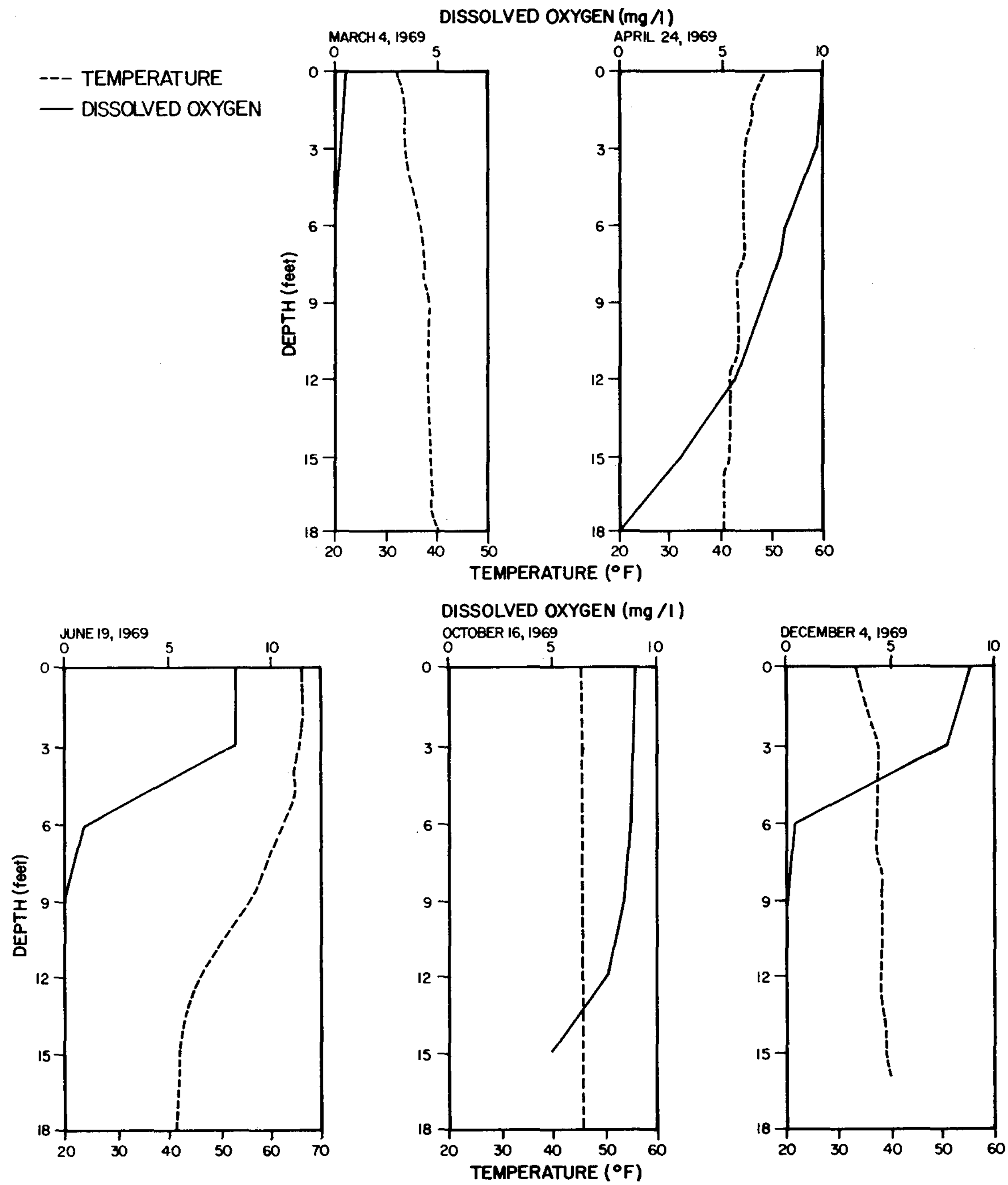


FIGURE 18. *Typical Temperature–DO Profiles*

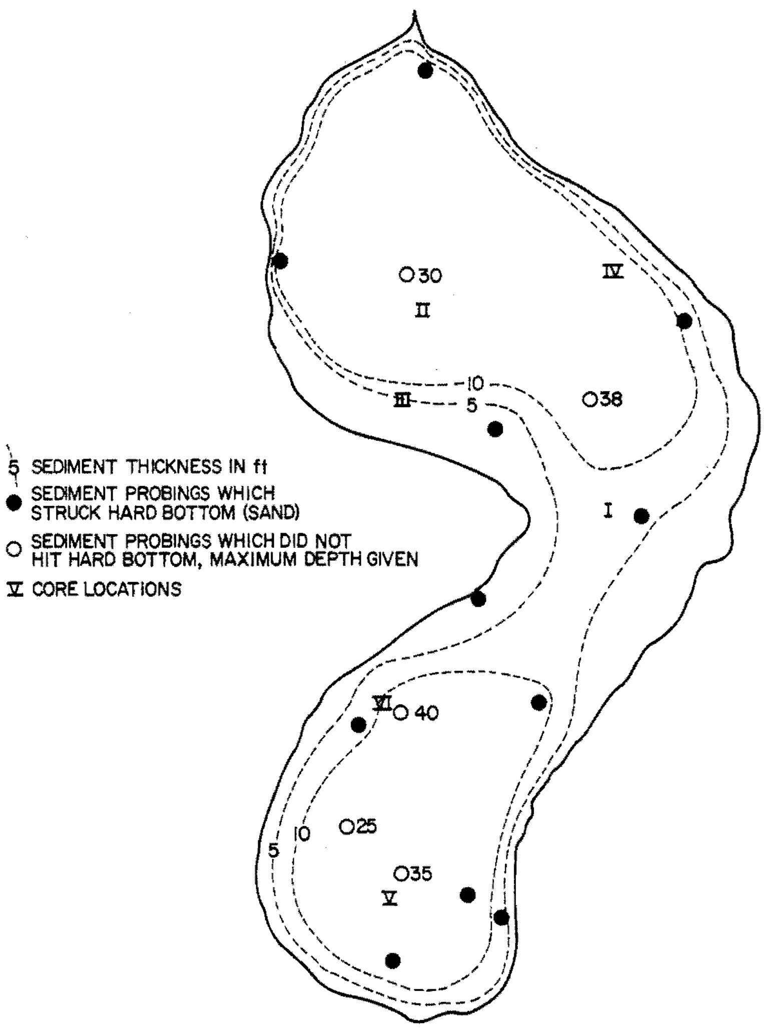
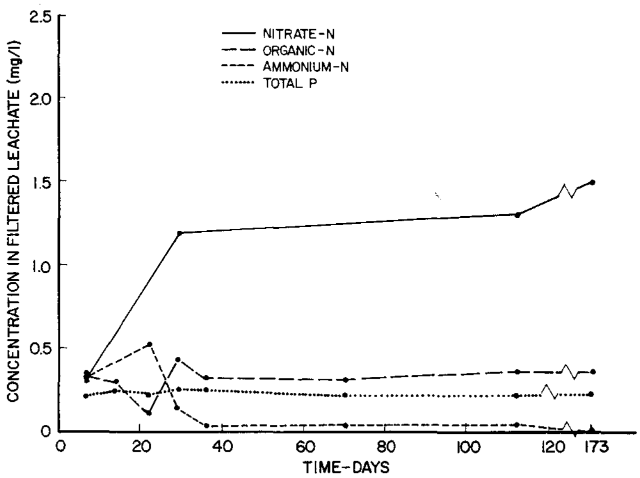
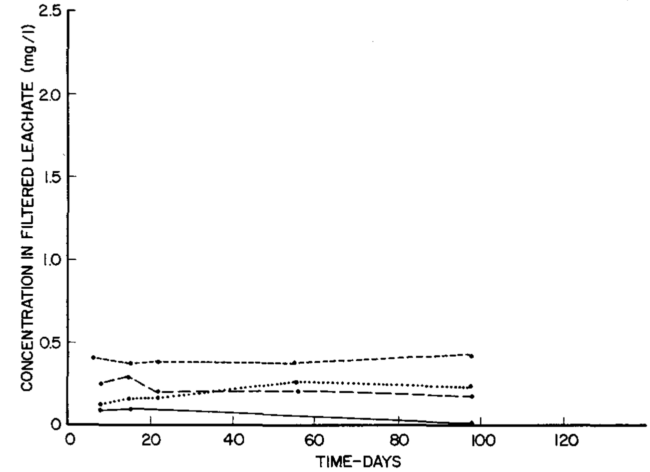


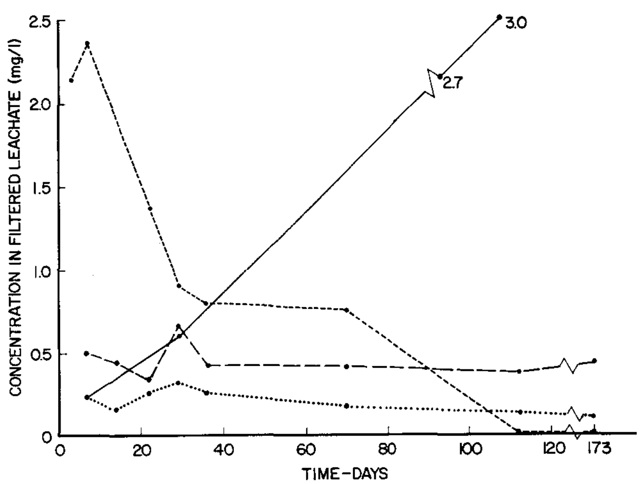
FIGURE 19. *Lake Sediment Thickness and Coring Locations*



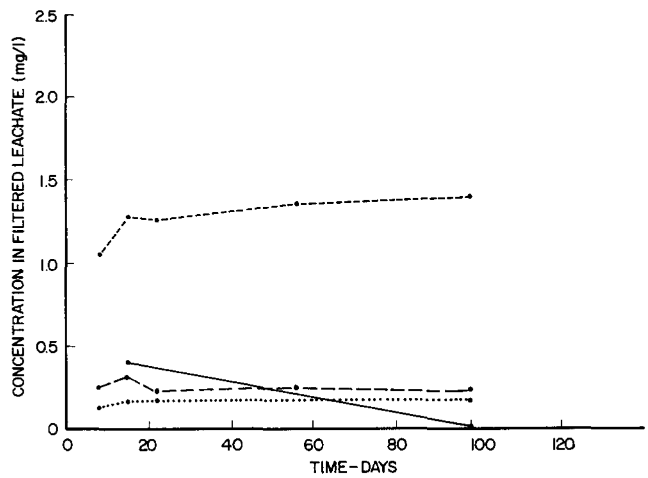
A1. Aerobic Leaching of Surface (Peaty) Sediments (Core I, 0–10 cm)



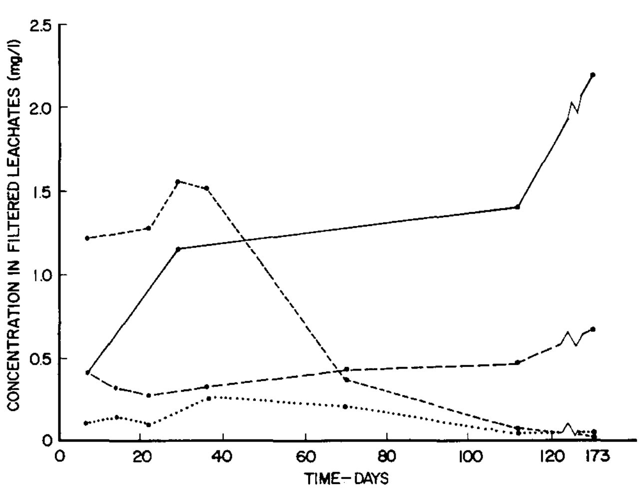
A2. Anoxic Leaching of Surface (Peaty) Sediments (Core I, 0–10 cm)



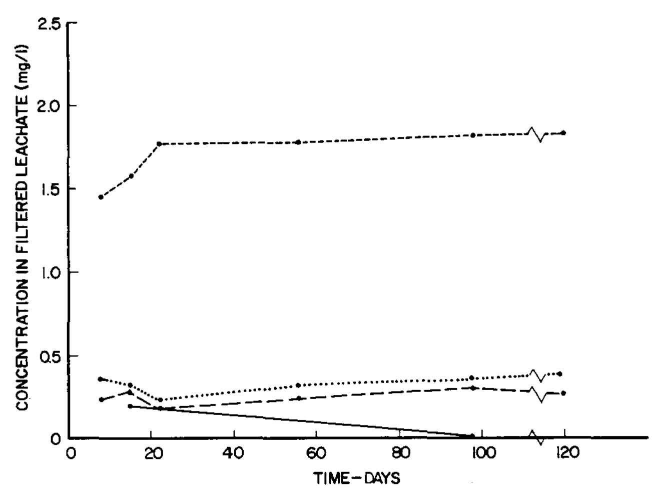
B1. Aerobic Leaching of Deep Hole Surface Muck (Core II, 0–10 cm)



B2. Anoxic Leaching of Deep Hole Surface Muck (Core II, 0–10 cm)



C1. Aerobic Leaching of Subsurface Deep Hole Muck (Core II, 140–160 cm)



C2. Anoxic Leaching of Subsurface Deep Hole Muck (Core II, 140–160 cm)

FIGURE 20. *Nitrogen and Phosphorus in Aerobic and Anoxic Leachates of Snake Lake Sediments*

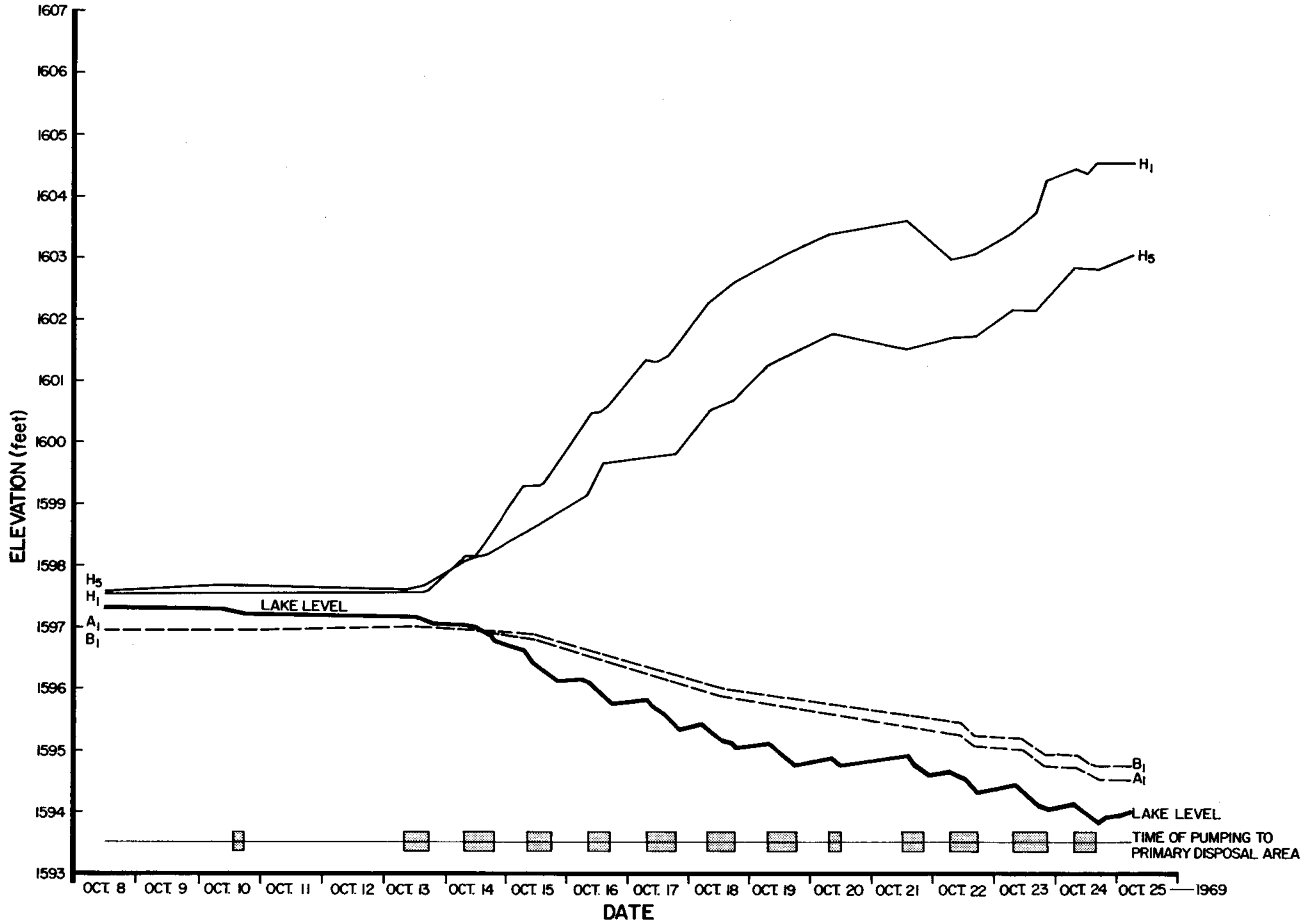


FIGURE 21. *Lake Level Decline and Response of Selected Wells (Wells A_1 and B_1 are next to Snake Lake; wells H_5 and H_1 are in the disposal area (see Fig. 3).*

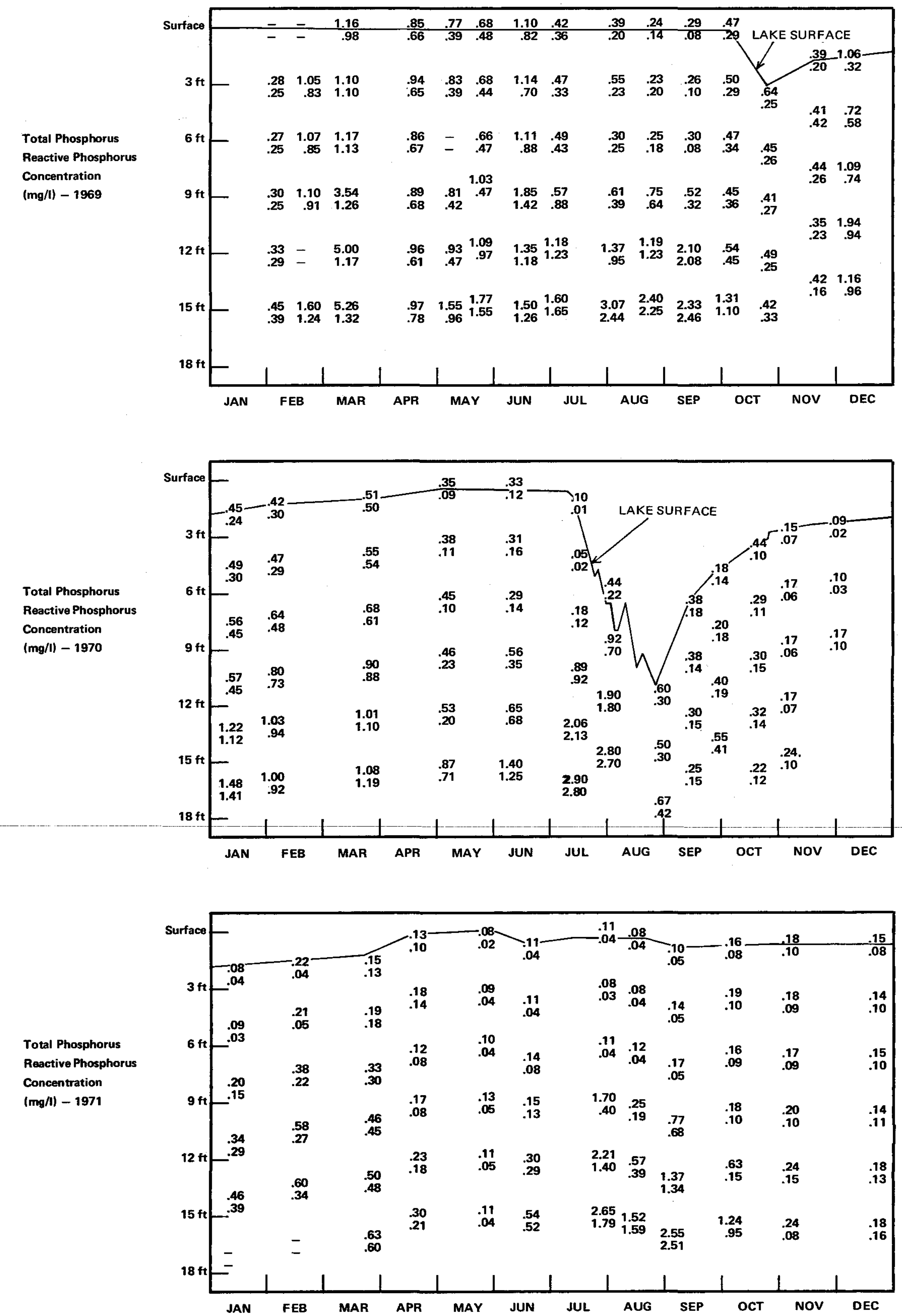


FIGURE 22. *Total and Dissolved Phosphorus Data (Lake level and ice cover are indicated by upper line on figures.)*

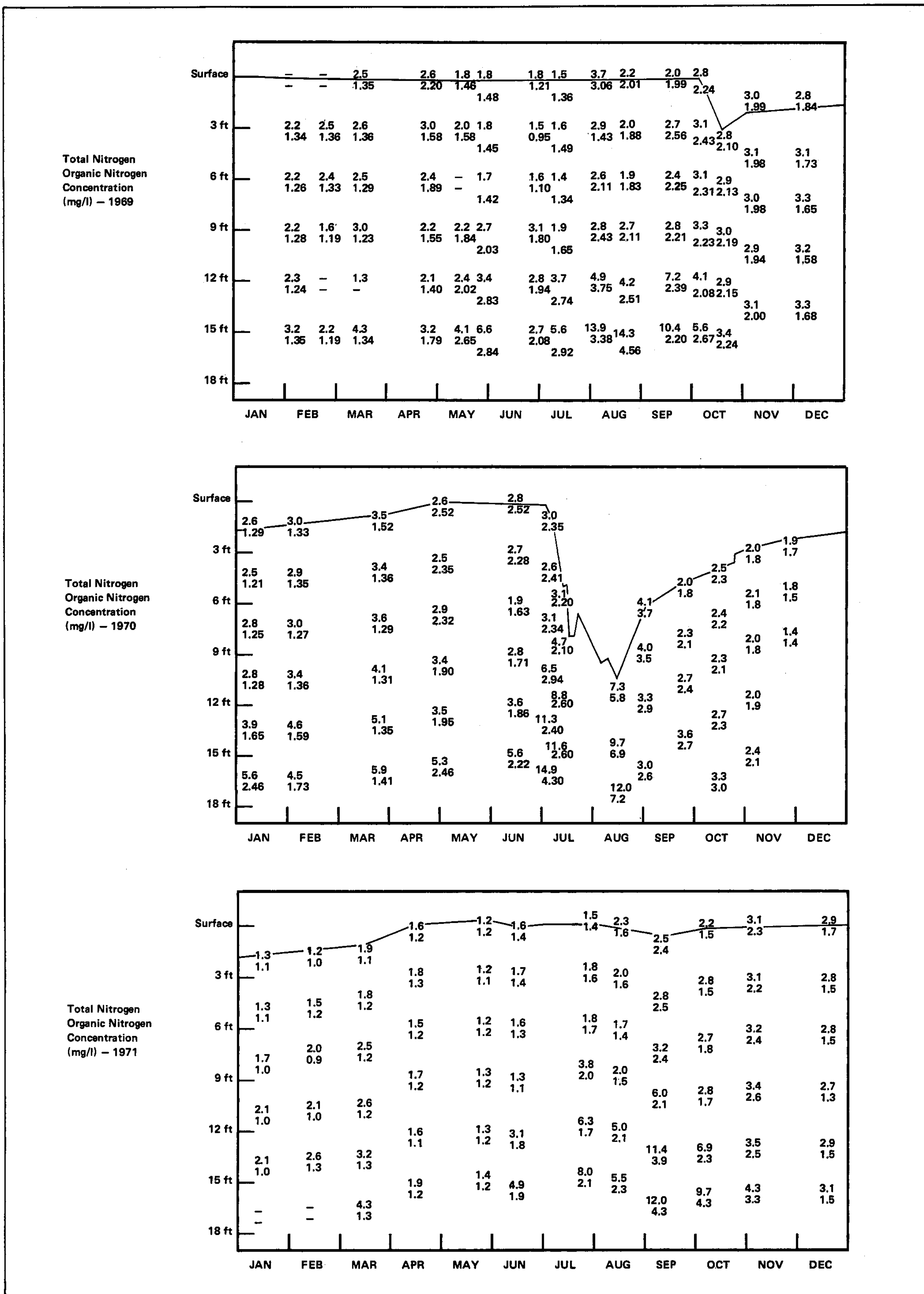


FIGURE 23. *Total and Organic Nitrogen Data*

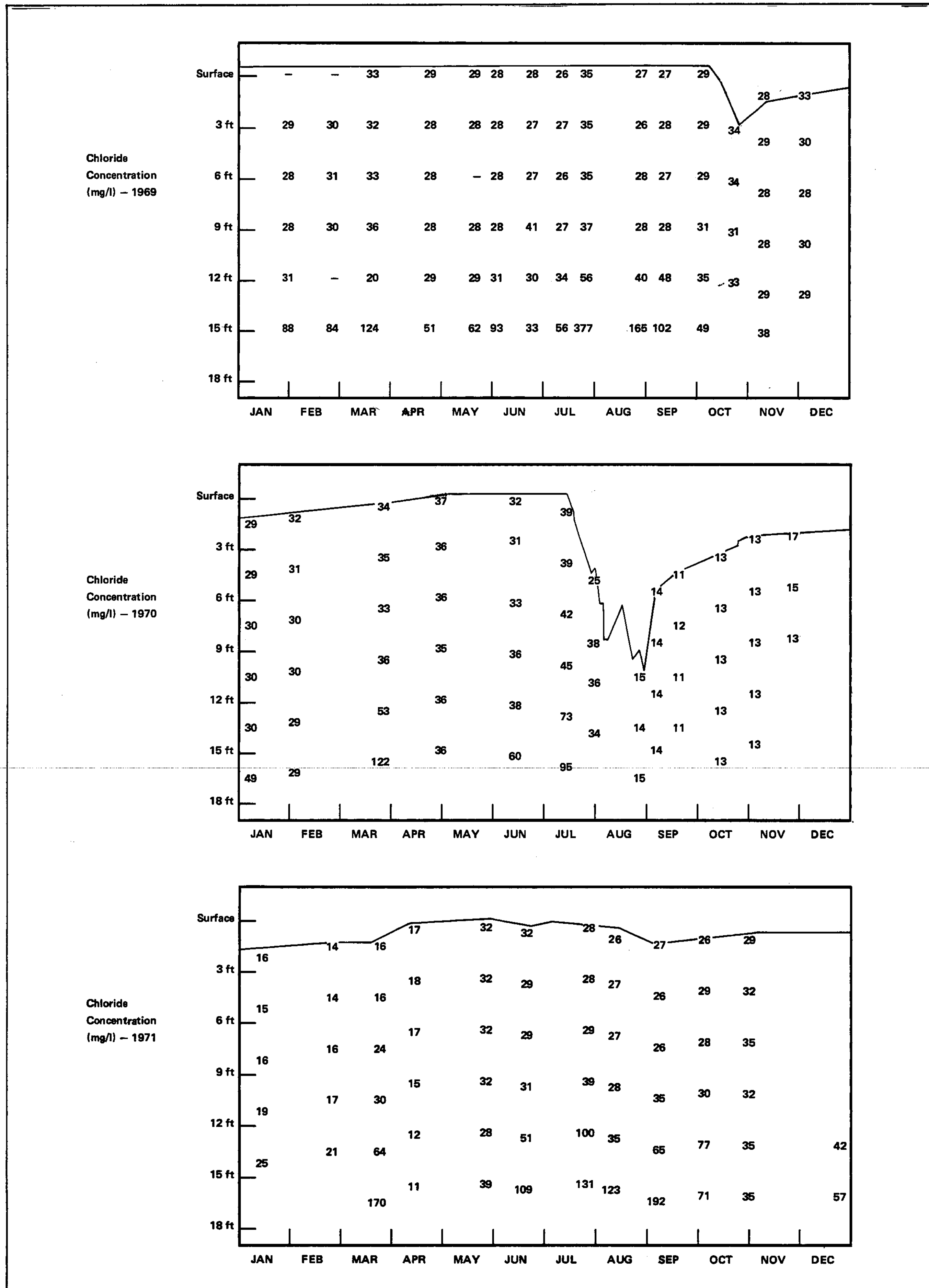


FIGURE 24. *Chloride Data*

LITERATURE CITED

Black, J.
1967. Rep. filed, Dep. Natur. Resour., Water Resour. Res. Sect., Nevin Fish Hatchery, Madison, Wis. (8 p. plus appended tables and figures).

Bortleson, G.C.
1971. The chemical investigation of recent lake sediments from Wisconsin lakes and their interpretation. Env. Prot. Agency Rep., Water Pollut. Contr. Res. Ser. 16010EHR 3/71, 278 p.

Boyle, J.R.
1971. Pers. comm., Univ. Wis., Dep. Soils, Madison, Wis.

Brook, A. J. and W. B. Woodward
1956. Some observations on the effect of water inflow and outflow on the plankton of small lakes. J. Animal Ecol. 25:22-35.

DeVaul, R.W.
1967. Trends in ground water levels in Wisconsin through 1966. U.S. Geol. Surv./Geol. and Natur. Hist. Surv. Inf. Circ. No. 9, Madison, Wis. 109 p.

Dickman, M.
1969. Some effects of lake renewal on phytoplankton productivity and species composition. Limnol. Oceanog. 14:660-666.

Fitzgerald, G.P.
1971. Nutrient sources for algae and their control. Proj. Rep. No. 16010EHR 08/71, Environ. Prot. Agency, Washington, D.C. 77 p.

Flanigon, T.
1943. Progress report on Snake Lake research. Memo to E. Schneberger, Dep. Natur. Resour., July 17, 1943.

Folk, R.L. and W.C. Ward
1957. Brazos River Bar: a study in the significance of grain size parameters. J. Sediment. Petrol. 27:3-26.

Goldman, C.R.
1968. Limnological aspects of Clear Lake, California, with special reference to the proposed diversion of Eel River water through the lake. Rep. to Fed. Water Pollut. Contr. Admin. (EPA), April.

Gorham, E.
1958. The physical limnology of northern Britain: an epitome of the bathymetrical survey of the Scottish freshwater lochs, 1897-1909. Limnol. Oceanog. 3:40-50.

Hilsenhoff, W.L.
1972. Pers. comm., Univ. Wis., Dep. Entomol., Madison, Wis.

Keeney, D.R.
1972. The fate of nitrogen in aquatic ecosystems. Lit. Rev. No. 3, Eutrophication Info. Program, Water Resour. Center, Univ. Wis., Madison. 59 p.

Keeney, D.R., J.G. Konrad and G. Chesters
1970. Nitrogen distribution in some Wisconsin lake sediments. J. Water Pollut. Contr. Fed. 42:411-417.

Konrad, J.G., D.R. Keeney, G. Chesters and K. Chen
1970. Nitrogen and carbon distribution in sediment cores of selected Wisconsin lakes. J. Water Pollut. Contr. Fed. 42:2094-2101.

Lee, G.F.
1970a. Eutrophication. Lit. Rev. No. 2, Eutrophication Info. Program, Water Resour. Center, Univ. Wis., Madison. 39 p.

Lee, G.F.
1970b. Factors affecting the exchange of materials between waters and sediments. Lit. Rev. No. 1, Eutrophication Info. Program, Water Resour. Center, Univ. Wis., Madison. 50 p.

Lomax, J.F. and C.C. Orsborn
1971. Flushing of small shallow lakes. EPA-Water Pollut. Contr. Res. Ser. Rep. 16010DMG 12/71. 39 p.

Mackenthun, K.M.
1952. Biological investigation of Snake and Arrowhead Lakes located in Vilas and Oneida Counties, Wisconsin. Rep. to Wis. Comm. on Water Pollut., T.F. Wisniewski, Director. 5 p. plus appended tables.

Malueg, K.W.
1972. Personal Files, Snake Lake. Right file, No. 3 level, EPA Northwest Water Qual. Lab, Corvallis, Ore.

McMynn, R. and P. Larkin
1953. The effects on fisheries of present and future water utilization in the Campbell River drainage area. Pub. B.C. Game Comm. 2:1-61.

National Academy of Sciences
1969. Eutrophication: Causes, consequences, correctives. Washington, D.C. 661 p.

Nichols, S.A.
1971. File report, Inland Lake Renewal and Shoreland Management Demon. Univ. Wis. Ext., Environ. Resour. Unit, Madison, Wis.

Nunnallee, D.A.
1968. Engineering aspects of nuisance algal control in Moses Lake. M.S. Thesis, Univ. Wash. 83 p.

Oglesby, R.T.
1968. Dilutional effects on nutrients and primary productivity. Dep. Civil Eng., Univ. Wash., Seattle.

1969. Effects of controlled nutrient dilution on the eutrophication of a lake. *In* Eutrophication: causes, consequences, correctives. Nat. Acad. Sci., Washington, D.C., p. 483-493.

Rawson, D.S.
1960. A limnological comparison of 12 large lakes in N. Saskatchewan. Limnol. and Oceanog. 5:195-211.

Robertson, J.
1954. The trophic status of Port John Lake, British Columbia. J. Fish. Res. Bd. Canada 11:624-651.

Shah, R., J.K. Syers, J.D.H. Williams and T.W. Walker
1968. The forms of inorganic phosphorus extracted from soils by N. sulfuric acid. New Zeal. J. Agric. Res. 11:184-192.

Sketelj, J. and M. Rejic
1972. Pollutional phases of Lake Bled. *In* Advances in Water pollution research, Proc. 2nd Int. Conf. Water Pollut. Res. Pergamon Press, Ltd., London, Engl. 1, 345.

Smith, S.A., J.O. Peterson, S.A. Nichols and S.M. Born
1972. Lake deepening by sediment consolidation—Jyme Lake. Inland Lake Demon. Proj. Rep. Univ. Wis. Ext., Madison, Wis. 36 p.

Soil Conservation Service
1968. H. Streblow to S. Born, in litt., Madison, Wis.

Stewart, K. and G.A. Rohlich
1967. Eutrophication: a review. State Water Qual. Contr. Board Publ. No. 34, State of California.

Sylvester, R.O. and G.C. Anderson
1960. An engineering and ecological study for the rehabilitation of Green Lake. Rep. to the Seattle, Washington Park Board. 194 p.

Sylvester, R.O. and G.C. Anderson
1964. A lake's response to its environment. J. Sanit. Eng. Div., Proc. Am. Soc. Civil Eng. 90:SA1,1.

Tenney, M., S. Yaksich, and DePinto
(In Press). Restoration of water bodies. *In* Environmental Engineers' Handbook, B.G. Liptak, ed., Chilton Press, Philadelphia, Pa.

Welch, E.B., J.A. Buckley, and R.M. Bush
1972. Dilutional as an algal bloom control, J. Water Pollut. Contr. Fed. 44:2245-2265.

Williams, J.D.H., J.K. Syers and R.F. Harris
1970. Adsorption and desorption of inorganic phosphorus by lake sediments in a 0.1 M MaCl System. Environ. Sci. Technol. 4:517-519.

Winter, D.R.
1967. Report of investigation on Snake and Arrowhead Lakes—Vilas County, Wisconsin. Rep. filed Dep. Natur. Resour., Nov. 22, 1967.

4000-19-3J30086

ACKNOWLEDGMENTS

Many people aided this investigation. We would like to acknowledge Mr. Edmund M. Brick for helping to initiate this activity, and Drs. G. Fred Lee and Kenneth W. Malueg for their helpful advice during the course of the study. We are indebted to Mr. Perry G. Olcott, Wisconsin Geological and Natural History Survey, for his substantial preliminary hydrogeologic investigations in the study area. We gratefully acknowledge the support of several Department of Natural Resources personnel from the Woodruff, Wisconsin office, particularly Mr. L.E. Morehouse. Thanks are due Drs. David E. Armstrong and Robert C. Ball, and Messrs. Lloyd M. Andrews, William J. Drescher, and Stephen A. Smith for their constructive reviews of this report. We thank the University of Wisconsin–Madison Department of Civil and Environmental Engineering (Water Chemistry Program) for use of laboratory facilities, and several students of the Department of Geology for aid in instrumentation and monitoring in the project area. Finally, we wish to express our gratitude to numerous residents of the Snake Lake area for their support and help in implementing this study—especially Messrs. A. Husak, A. Nicollette, H. Gustafson, L. Schlezewske, J. Branham, and G. Snow.

Dr. Born is project director for the Inland Lakes Demonstration Project and chairman of the Environmental Resources Program for University of Wisconsin–Extension; Mr. Wirth, chief of the Water Resources Research Section in the Bureau of Research, Department of Natural Resources; Mr. Peterson, water chemist and project associate with the Inland Lakes Demonstration Project, University of Wisconsin–Extension; Mr. Wall, project assistant with Water Resources Center, University of Wisconsin; and Mr. Stephenson, Assoc. Prof. with Department of Geology, University of Wisconsin–Madison.

Edited by Ruth L. Hine

TECHNICAL BULLETINS
Currently Available From The Department of Natural Resources

No. 10 Role of refuges in muskrat management. (1954) Harold A. Mathiak and Arlyn F. Linde

No. 13 Seasonal variation in stress resistance and survival in the hen pheasant. (1956) Cyril Kabat, R.K. Meyer, Kenneth G. Flakas and Ruth L. Hine

No. 21 Forest insect surveys within specified areas. (1960) R.D. Shenefelt and P.A. Jones

No. 22 The state park visitor: a report of the Wisconsin park and forest travel study. (1961) H. Clifton Hutchins and Edgar W. Trecker, Jr.

No. 23 Basal area and point sampling: interpretation and application. (1970) H.J. Hovind and C.E. Rieck

No. 26 Effects of angling regulations on a wild brook trout fishery. (1962) Robert L. Hunt, Oscar M. Brynildson and James T. McFadden

No. 31 Evaluation of liberalized regulations on largemouth bass: Browns Lake, Wisconsin. (1964) Donald Mraz

No. 32 Characteristics of the sport fishery in some northern Wisconsin lakes. (1964) Warren Churchill and Howard Snow

No. 35 Production and angler harvest of wild brook trout in Lawrence Creek, Wisconsin. (1966) Robert L. Hunt

No. 36 Muskrat population studies at Horicon Marsh, Wisconsin. (1966) Harold A. Mathiak

No. 37 Life history of the grass pickerel in southeastern Wisconsin. (1966) Stanton J. Kleinert and Donald Mraz

No. 39 Guidelines for management of trout stream habitat in Wisconsin. (1967) Ray J. White and Oscar M. Brynildson

No. 41 Occurrence and significance of DDT and dieldrin residues in Wisconsin fish. (1968) Stanton J. Kleinert, Paul E. Degurse and Thomas L. Wirth

No. 42 Food of angler-caught pike in Murphy Flowage. (1969) Leon Johnson

No. 43 The Lake Winnebago sauger: age, growth, reproduction, food habits and early life history. (1969) Gordon R. Priegel

No. 44 Significance of forest openings to deer in northern Wisconsin. (1969) Keith R. McCaffery and William A. Creed

No. 45 Reproduction and early life history of walleyes in the Lake Winnebago region. (1970) Gordon R. Priegel

No. 47 Evaluation of intensive freshwater drum removal in Lake Winnebago, Wisconsin, 1955-1966. (1971) Gordon R. Priegel

No. 48 Responses of a brook trout population to habitat development in Lawrence Creek. (1971) Robert L. Hunt

No. 49 Growth of known-age muskellunge in Wisconsin and validation of age and growth determination methods. (1971) Leon D. Johnson

No. 50 Harvest and feeding habits of largemouth bass in Murphy Flowage, Wisconsin. (1971) Howard E. Snow

No. 51 A guideline for portable direct current electrofishing systems. (1971) Donald W. Novotny and Gordon R. Priegel

No. 52 Mercury levels in Wisconsin fish and wildlife. (1972) Stanton J. Kleinert and Paul E. Degurse

No. 53 Chemical analyses of selected public drinking water supplies (including trace metals). (1972) Robert Baumeister

No. 54 Aquatic insects of the Pine-Popple River, Wisconsin. (1972) William L. Hilsenhoff, Jerry L. Longridge, Richard P. Narf, Kenneth J. Tennessen and Craig P. Walton

No. 55 Recreation Areas and Their Use. (1972) Melville H. Cohee

No. 56 A Ten-Year Study of Native Northern Pike in Bucks Lake, Wisconsin Including Evaluation of an 18.0-inch Size Limit. (1972) Howard E. Snow and Thomas D. Beard

No. 57 Biology and Control of Selected Aquatic Nuisances in Recreational Waters. (1972) Lloyd A. Lueschow

No. 58 Nitrate and Nitrite Variation in Ground Water. (1972) Koby T. Crabtree

No. 59 Small Area Population Projections for Wisconsin. (1972) Douglas B. King, David G. Nichols and Richard J. Timm

No. 60 A profile of Wisconsin hunters. (1972) Lowell L. Klessig and James B. Hale

No. 61 Overwinter drawdown: impact on the aquatic vegetation in Murphy Flowage, Wisconsin. (1973) Thomas D. Beard

No. 62 Eutrophication control: nutrient inactivation by chemical precipitation at Horseshoe Lake, Wisconsin. (1973) James O. Peterson, et al.

No. 63 Drain oil disposal in Wisconsin. (1973) Ronald O. Ostrander and Stanton J. Kleinert

No. 64 The prairie chicken in Wisconsin. (1973) Frederick and Frances Hamerstrom

No. 65 Production, food and harvest of trout in Nebish Lake, Wisconsin. (1973) Oscar M. Brynildson and James J. Kempinger

No. 66 Dilutional pumping at Snake Lake, Wisconsin: a potential renewal technique for small eutrophic lakes. (1973) Stephen M. Born, et al.

No. 67 Lake sturgeon management on the Menominee River. (1973) Gordon R. Priegel