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GEOLOGICAL SURVEY

GENERAL HYDROLOGY AND EXTERNAL SOURCES OF NUTRIENTS AFFECTING PINE LAKE, KING COUNTY, WASHINGTON

By N. P. Dion, S. S. Sumioka, and T. C. Winter

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	1,233.6	cubic meter (m^3)
pound (lb)	0.4536	kilogram (kg)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
degree Fahrenheit (°F)	1.8; then add 32	degree Celsius (°C)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

An adjusted water budget prepared for Pine Lake, a candidate for lake-quality restoration, indicates that of the 790 acre-feet of water that enters the lake in a typical year, 410 acre-feet is from precipitation, 350 acre-feet is from surface inflow, and 27 acre-feet is from ground-water seepage. An equal amount of water leaves the lake, and of this, 130 acre-feet is by evaporation, 660 acre-feet is by surface runoff, and less than 1 acre-foot is by ground-water seepage. On the basis of these amounts of inflow and outflow, the theoretical water-renewal time of the lake is 2.2 years.

The contributions of inorganic nitrogen and phosphorus to the lake in a typical year from precipitation, surface inflow, and ground-water inflow are about 2,500 pounds and 49 pounds, respectively.

INTRODUCTION

Background

Pine Lake is in northwestern King County, Washington, 13 miles east of Seattle, 2.0 miles east of Lake Sammamish, and 4.0 miles north of Issaquah (fig. 1). About 96 percent of the shoreline of the lake is developed residentially, and a public park, operated by King County, is situated on the east shore (see fig. 7). Recreational use of the lake by swimmers, boaters, and fishermen is heavy, especially in late spring and summer.

Previous studies (Dion and others, 1980; Uchida and others, 1976) have indicated that Pine Lake is eutrophic to highly eutrophic. Indications of the lake's advanced trophic state include frequent and severe algal blooms, locally dense growths of aquatic macrophytes (Goodpasture and others, 1978), depletion of dissolved oxygen in the hypolimnion during summer thermal stratification, and the tainting of fish flesh.

Because of its advanced trophic state, the lake is being considered as a candidate for water-quality restoration by the State of Washington Department of Ecology. To select an appropriate restoration technique, however, additional information is needed concerning local hydrologic conditions, the nutrient loads responsible for the trophic state of the lake, and the probable sources of those nutrients.

Objectives

This report presents the findings of a study that was designed to determine (1) the general hydrologic conditions in the immediate vicinity of the lake, and (2) the loadings of inorganic nitrogen and phosphorus from selected external sources that affect the lake.

Acknowledgments

The authors express their appreciation to John Bachman, Ivard Budge, Howard Eastlick, Ralph Gress, Urban Massett, Elizabeth Park, and Robert Riggle for their assistance in collecting hydrologic data, and to personnel of the Water Resources Laboratory, Civil Engineering Department, University of Washington, for performing nutrient concentration determinations. The authors also thank the King County Park Department and the numerous private land owners who allowed access to their property for purposes of installing hydrologic instruments and collecting hydrologic data.

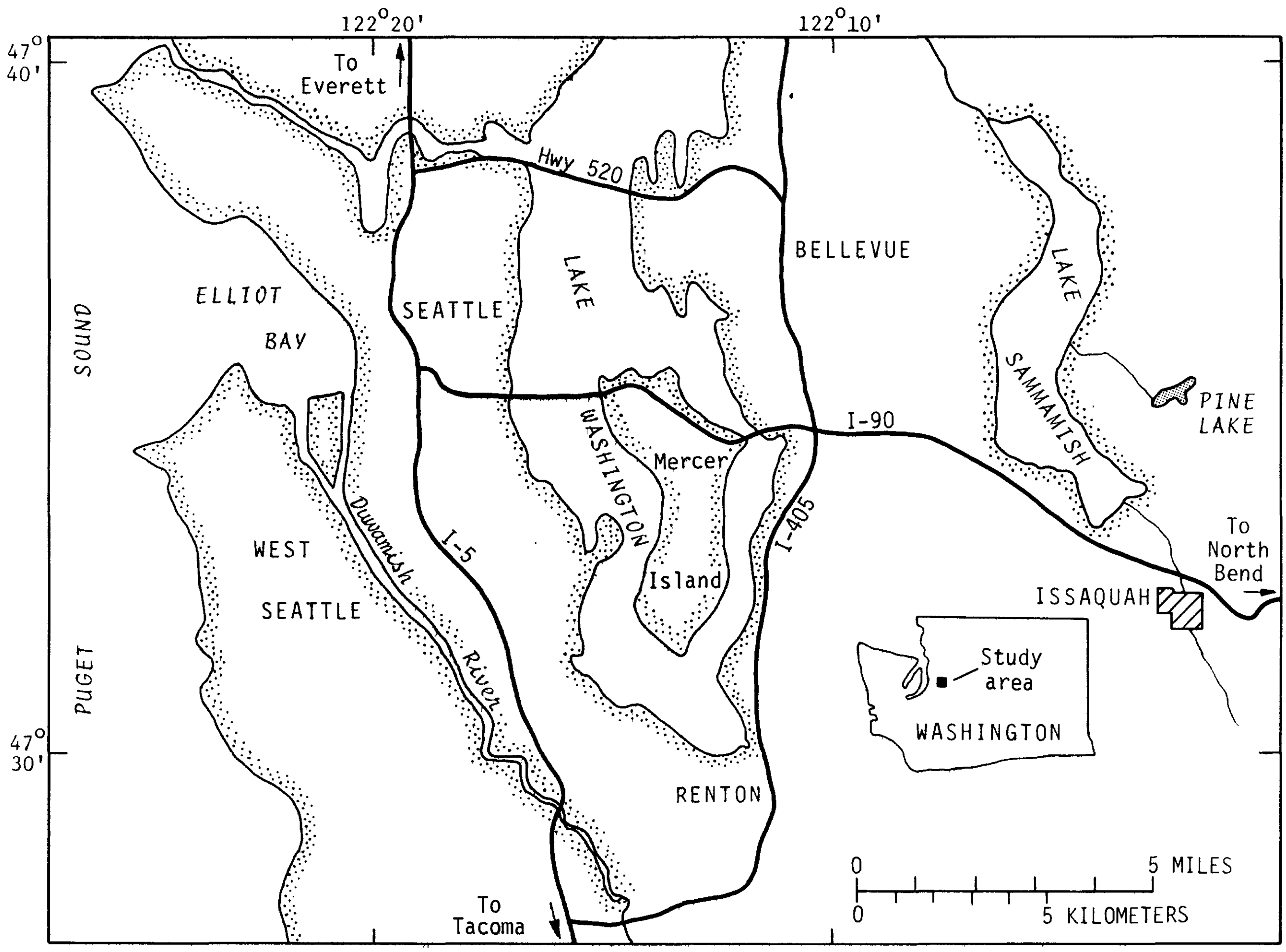

FIGURE 1.--Location of Pine Lake.

CLIMATE

The Pine Lake area has an equable climate. Because of its nearness to the Pacific Ocean and because the prevailing winds blow from the ocean, extremes in temperature are uncommon. The climate is of the mid-latitude, west coast marine-type, characterized by warm, dry summers and cool, wet winters. The mean annual air temperature at Seattle, the point nearest the study area where climatological data are collected, is 11°C, and the mean monthly air temperatures in January and July are 3.3°C and 18°C, respectively (U.S. Department of Commerce, 1979). The mean annual precipitation at Seattle is 39 inches. July has the smallest mean monthly precipitation (0.71 inch) and December the largest (5.9 inches).

DRAINAGE BASIN

The drainage basin of Pine Lake, including the surface of the lake itself, is 1.0 square mile in extent. There is a peat bog on the southwest side of the lake; the exact position of the drainage divide in the bog is not known. The lake surface is about 375 ft above sea level and the highest hills, northeast of the lake, are about 550 ft above sea level.

The surficial geologic materials of the drainage basin, as described by Liesch and others (1963), consist chiefly of glacial till and include local patches of alluvium and peat. The till is a heterogeneous, unstratified, compact mixture of clay, silt, sand, gravel, and boulders, and is part of the Vashon Drift of Pleistocene age. According to Snyder and others (1973), the soils of the drainage basin are chiefly gravelly, sandy loam with minor amounts of sandy loam, peat, and muck. The gravelly, sandy loam, formed on glacial till, has a compact, weakly cemented stratum (hardpan) of low permeability at a depth of 2 to 4 feet below the ground surface.

The drainage basin of Pine Lake, exclusive of the lake, has an area of about 560 acres. Of this total, about 60 percent is developed for private, year-round residences at a medium to high density (fig. 2). The remainder is used for low-density residential, agricultural, and recreational purposes.

About 15 acres on the east side of the lake is occupied by Pine Lake County Park. The park is open year-round and is used extensively for swimming, picnicking, boating, and other sports and recreation. Although no attendance records are kept at the park, it is estimated (John Keizer, King County Parks Department, oral commun., October 23, 1980) that summer visitors total about 500 per weekday and about 1,000 per weekend day. Yearly total attendance, including winter visitors, is about 60,000.

Only a small part of the drainage basin is sewered; most homes, including all nearshore residences, discharge domestic wastes to individual septic tanks. Domestic wastes from Pine Lake County Park are also discharged to a septic tank. Most homes in the basin obtain water from a central water district that pumps water from deep wells outside the basin. A few domestic water supplies are taken from privately owned dug or drilled wells, and a few homes withdraw domestic water directly from the lake.

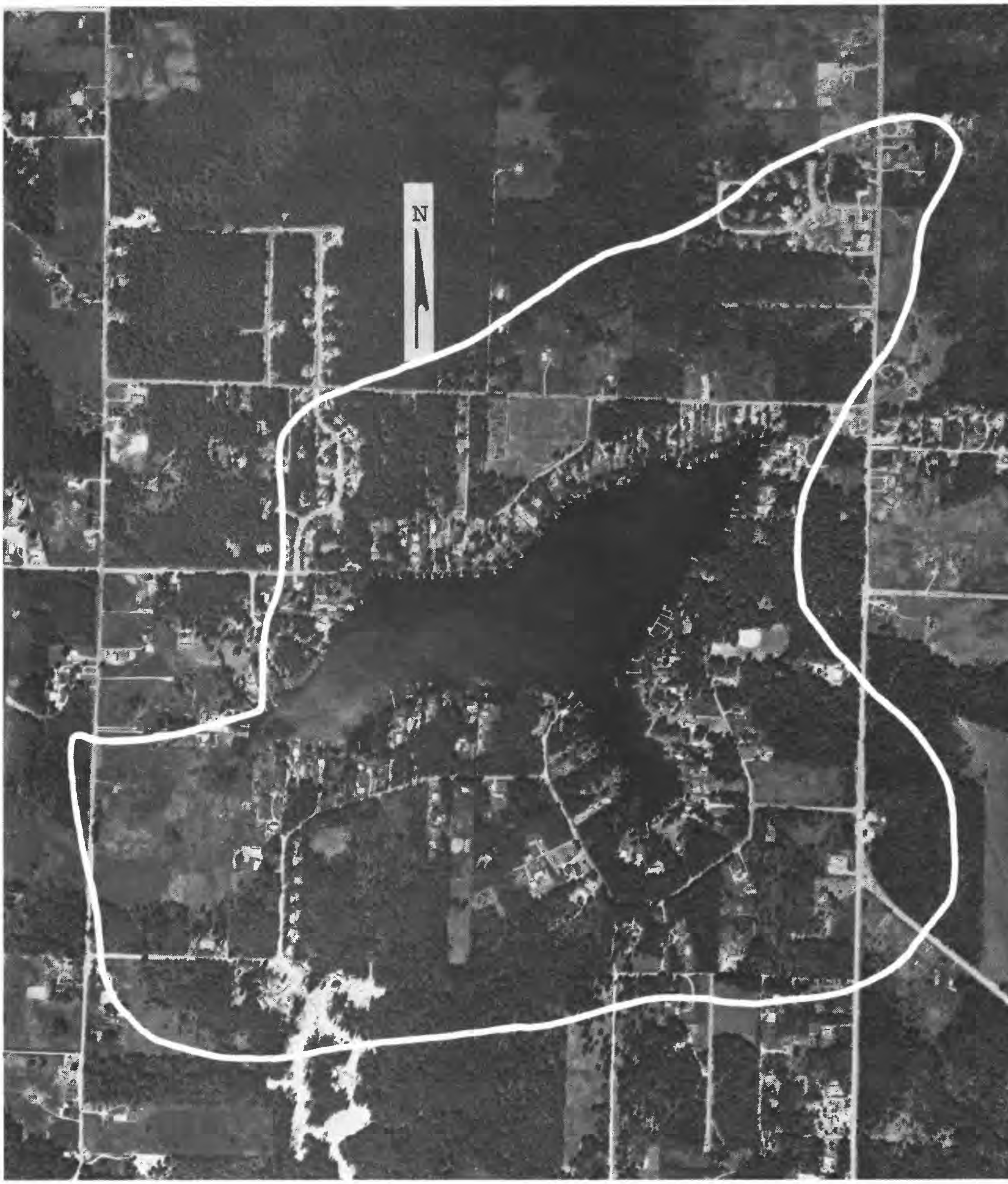

FIGURE 2.--Pine Lake. From Washington Department of Natural Resources, June 4, 1978. (Approximate scale 1:12880.)

CHARACTERISTICS OF THE LAKE

Physical

The shape of the lake bottom is shown by a bathymetric map in figure 3. From the bathymetric map, a number of morphometric characteristics can be obtained that express aspects of the lake shape in numerical terms, allowing quantitative comparisons among lakes. A summary of selected morphometric features of Pine Lake is given below, referenced to a lake stage of 375 ft above sea level; readers desiring a description of how the morphometric features are calculated are referred to a report by Dion (1978).

Maximum depth	39 feet
Mean depth	20 feet
Relative depth	1.8 percent
Surface area	86 acres
Volume	1,700 acre-feet
Shoreline configuration	1.8 (dimensionless)

Chemical

The chemical characteristics of Pine Lake have been described in detail by Uchida and others (1976) and Dion and others (1980) for the years 1973 and 1975, respectively. The following synopsis is taken from the results of those investigations.

The specific conductance of water in the epilimnion and hypolimnion of Pine Lake in 1975 averaged 46 and 52 umho/cm (micromho per centimeter), respectively. This indicates that, with respect to dissolved solids, Pine Lake is similar to other lakes in western Washington.

Vertical profiles of water temperature and dissolved-oxygen concentration for four seasons in 1975 are presented in figure 4. As shown in the graphs, the lake was vertically homogeneous with respect to temperature in February. Thermal stratification had begun to develop in April, and was strongly developed in July and September. The dissolved-oxygen concentrations in the bottom water were above 9 mg/L (milligrams per liter) in February and April, but at or near zero in July and September.

The concentrations of inorganic nitrogen, hydrolyzable phosphorus, and chlorophyll a in samples collected from Pine Lake are shown in figure 5. In the epilimnion, inorganic nitrogen (nitrate plus ammonia) concentrations were generally high in autumn and winter, but decreased as the water temperature increased in spring and summer and dissolved nutrients were assimilated by aquatic plants. Concentrations of hydrolyzable phosphorus in the epilimnion were moderate to high throughout the period of record. In the hypolimnion, inorganic nitrogen concentrations were significantly higher than corresponding concentrations in the epilimnion, largely as a result of high ammonia concentrations. Hydrolyzable phosphorus concentrations in the hypolimnion were slightly higher than corresponding concentrations in the epilimnion.

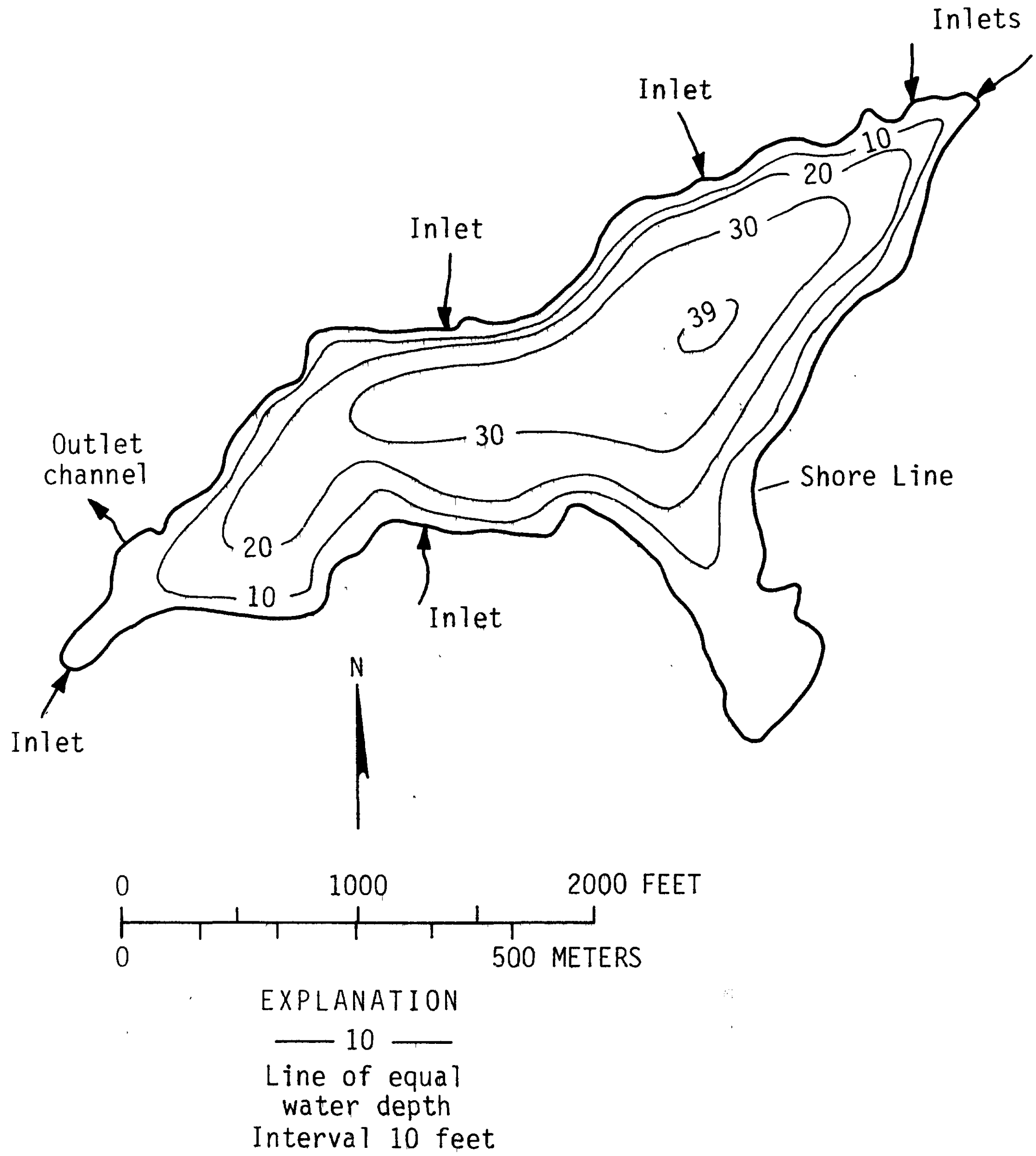

FIGURE 3.--Bathymetric map of Pine Lake. Modified from Wolcott (1965).

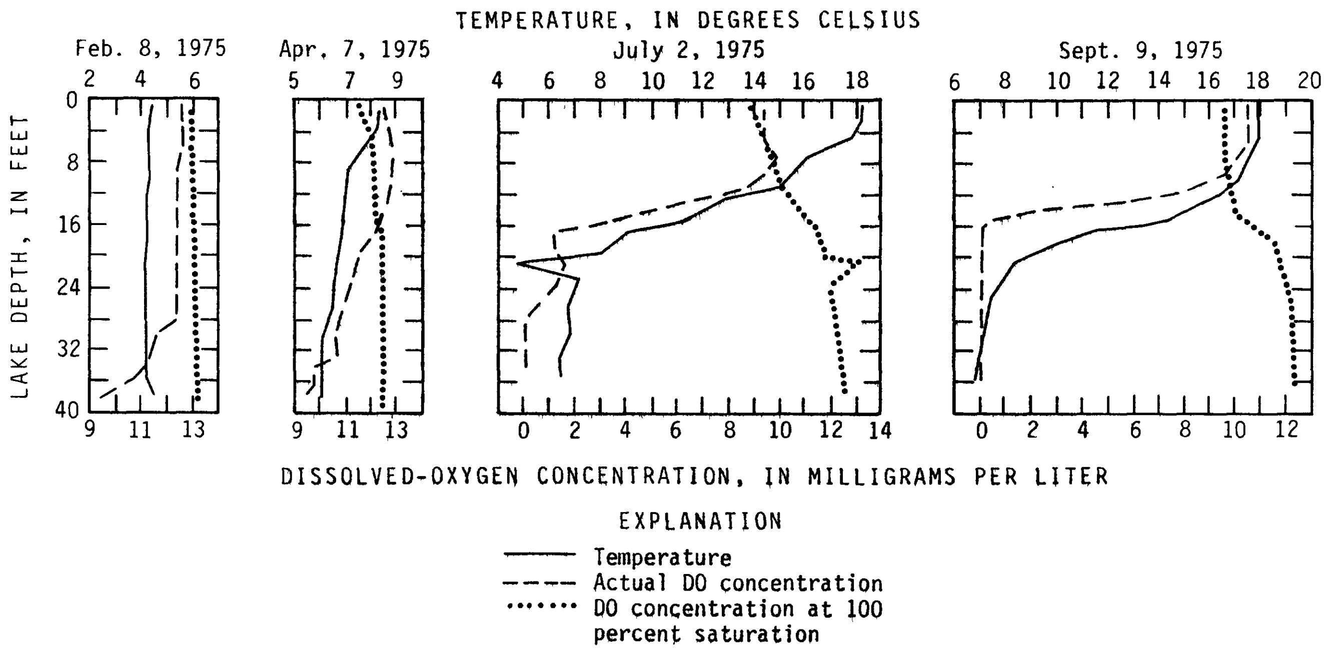

FIGURE 4.--Vertical profiles of water temperature and dissolved-oxygen concentration for Pine Lake (from Dion and others, 1980).

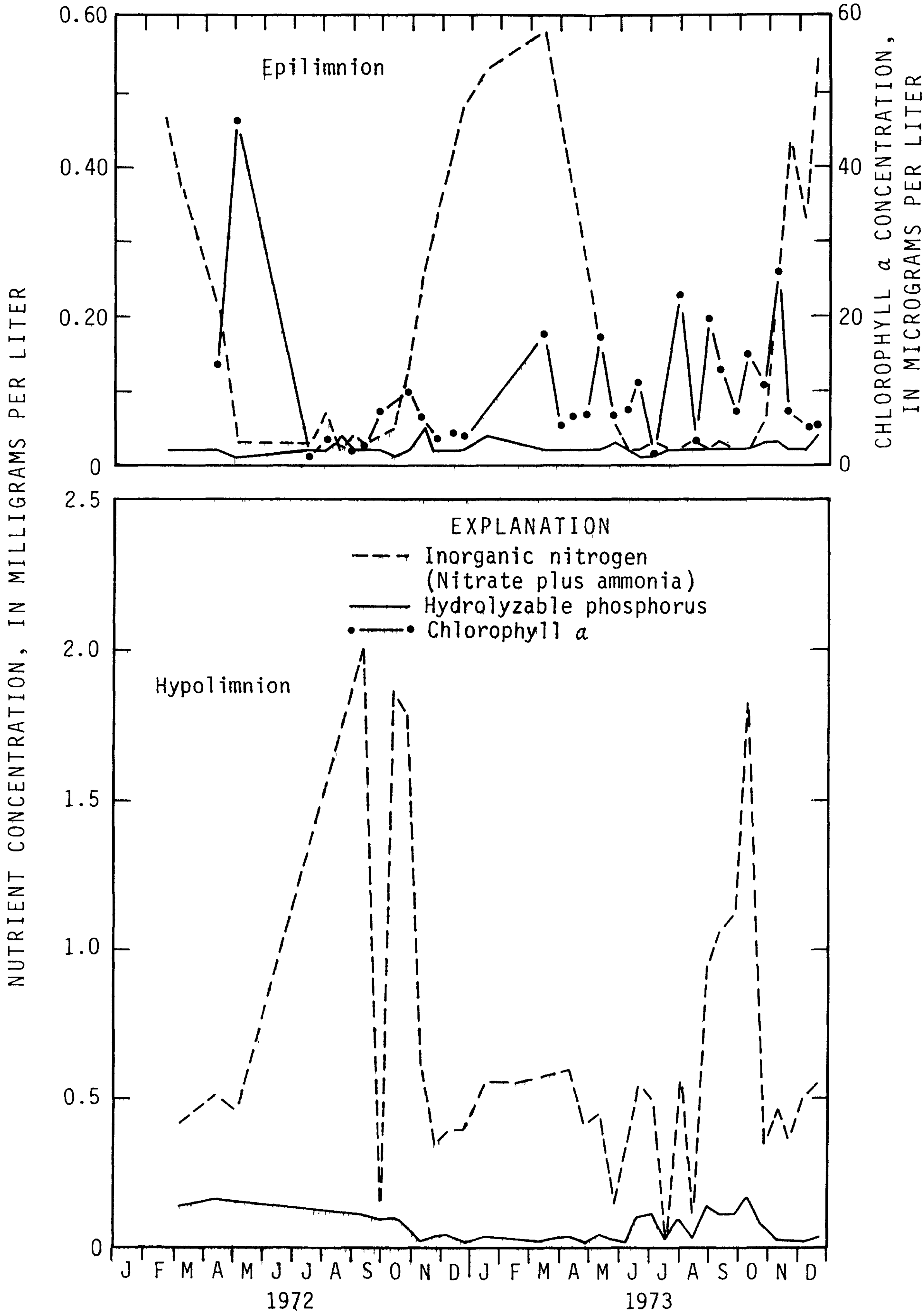

FIGURE 5.--Concentrations of inorganic nitrogen, hydrolyzable phosphorus, and chlorophyll a in Pine Lake. Modified from J. I. Davis, Municipality of Metropolitan Seattle (written commun., Feb. 6, 1980).

Biological

Pine Lake has a history of frequent and intensive algal blooms. The phytoplankton genera found to be dominant in the lake in 1973 (Uchida and others, 1976) are as follows:

Green algae	Blue-green algae	Yellow-brown algae
Volvox	Anabaena	Dinobryon
	Anacystis	Synura
	Aphanizomenon	Tabellaria[1]
	Coelosphaerium	

[1]Diatom.

Chlorophyll *a* concentrations in the epilimnion (fig. 5) in 1972 and 1973 ranged from 1.0 to 46 ug/L (micrograms per liter) and averaged 9.5 ug/L. A mean concentration of this magnitude is generally considered to be high.

Secchi-disc transparency was measured 38 times in the 1972-73 period; the values ranged from 3.6 to 14 ft and averaged 8.1 ft. As might be expected, the transparency values were lowest at times when the algal populations, as represented by the chlorophyll *a* concentration, were highest.

The results of a macrophyte survey in August 1979 are presented in a report by Goodpasture and others (1979). The dominant macrophytes found at the time of the survey were *Nuphar variegatum*, *Nitella* sp., and *Najas flexilis*; these three species were found in water depths of as much as 10 ft around nearly all of the lake. Other plants found in various parts of the lake included *Brasenia schreberi*, *Elodea canadensis*, *Isoetes bolanderi*, *Nymphaea odorata*, and two species of *Potamogeton*. Goodpasture and others (1979) noted that the submersed plant growth they observed in 1979 was somewhat greater than that observed by the same investigators in 1978. In addition, they mention the possible discovery of *Myriophyllum spicatum* (Eurasian water milfoil) in Pine Lake by other researchers. That problem species had not been found in the lake previously.

Concentrations of total- and fecal-coliform bacteria in Pine Lake in 1973 were presented by Uchida and others (1976). Total-coliform bacteria concentrations ranged from 20 to 970 organisms/100 mL (milliliters), and averaged 39 organisms/100 mL. Fecal-coliform bacteria concentrations ranged from 20 to 170 organisms/100 mL, and averaged 20 organisms/100 mL. Officials of the King County Health Department report that the county park is occasionally closed to swimming during the summer because of excessive fecal-coliform concentrations. The closings are not based on specific concentrations of bacteria, but rather on sudden, sharp increases in concentration.

Pine Lake has large populations of resident waterfowl and fish. The State of Washington Department of Game reports that the lake is intensively managed for rainbow trout, but that the 40,000 to 50,000 fingerlings stocked each year also include coho salmon and eastern brook trout. In addition, 3,000 to 6,000 legal-sized rainbow trout are stocked just prior to the opening of the general fishing season. Rotenone was applied to Pine Lake in 1953, 1969, 1974, and 1980 in efforts to eliminate rough fish species and improve the lake habitat for trout and salmon.

The trophic classification of Pine Lake varies according to the classification method used. According to criteria proposed by Carlson (1977), which are based on water transparency and chlorophyll a concentration, the lake would be classified as mesotrophic. As reported by Uchida and others (1976), Pine Lake would be classified as eutrophic according to criteria proposed by the U.S. Environmental Protection Agency (1974), which are based on mean chlorophyll a concentration. However, according to the criteria proposed by Vollenweider (1968), which are based on maximum yearly phytoplankton density, the lake would be classified as highly eutrophic.

LAKE HYDROLOGY

Hydrologic Setting and Methods of Analyses

Pine Lake typically receives water by direct precipitation, surface inflow, and ground-water seepage, and loses water by evaporation, surface runoff, and ground-water seepage. In order to describe hydrologic conditions in the immediate vicinity of the lake and to facilitate the preparation of a water budget of the lake, these hydrologic characteristics, as well as lake-stage altitude, were measured or calculated on a daily or monthly basis for the 1980 water year (October 1, 1979, to September 30, 1980).

Precipitation was collected in a standard (8-inch), nonrecording precipitation gage located in an open field on the north side of the lake (fig. 7); the gage was read daily by a local observer. The distribution of precipitation during the study period is shown in figure 6. During the period of observation Pine Lake received 47.8 inches of precipitation, most of which fell as rain. During the same period, precipitation at Seattle was 36.9 inches, 4.8 percent (1.9 inches) below the long-term (1941-70) average for that city.

Pine Lake has six small, unnamed, intermittent tributaries that flow only in response to extended periods of precipitation. During the period of study, staff gages were installed on the two largest tributaries and read daily by local observers. Periodic discharge measurements of all six tributaries were made at various stages to permit the correlation of discharges at the gaged and ungaged tributaries. This information was then used to calculate the combined daily surface-water inflow to the lake. The hydrograph of surface-water inflow to the lake (fig. 6) indicates that inflow began in early December 1979 in response to very heavy rain and ended in early May 1980.

The outlet stream (unnamed) that drains Pine Lake is intermittent; at a point about 0.8 mile downstream of the lake it flows down a steep wooded slope and discharges into Lake Sammamish (see fig. 1). During the period of study, a continuous-recording gage was maintained on the outlet stream at a point about 400 ft downstream of the lake (fig. 7). A hydrograph of the discharge at that station (fig. 6) shows that discharge began in early December 1979 and ended in mid-June 1980. The beginning and ending of stream discharge from the lake coincided with a lake stage of about 377 ft.

Ground-water conditions in the immediate vicinity of Pine Lake were determined using data collected in wells and piezometers located within about 1,700 feet of the lake. The glacial drift underlying Pine Lake and its drainage basin is a heterogeneous deposit, consisting of a till matrix with many clay, silt, sand, and gravel units randomly distributed in it. Because of the scattered distribution of the sand and gravel units, many of which are aquifers, completion depths of wells for water supplies vary widely. There are many more privately owned domestic wells on the south side of the lake than on the north side because residents of the north side have had central water service available since residential development of the area began. Residents of the south side have had to rely on wells until fairly recently when central water service became available there; at that time, most of the privately owned wells were abandoned. Most of the wells had been drilled to depths of 100-150 ft, although a few had been dug by hand to depths of less than 30 ft.

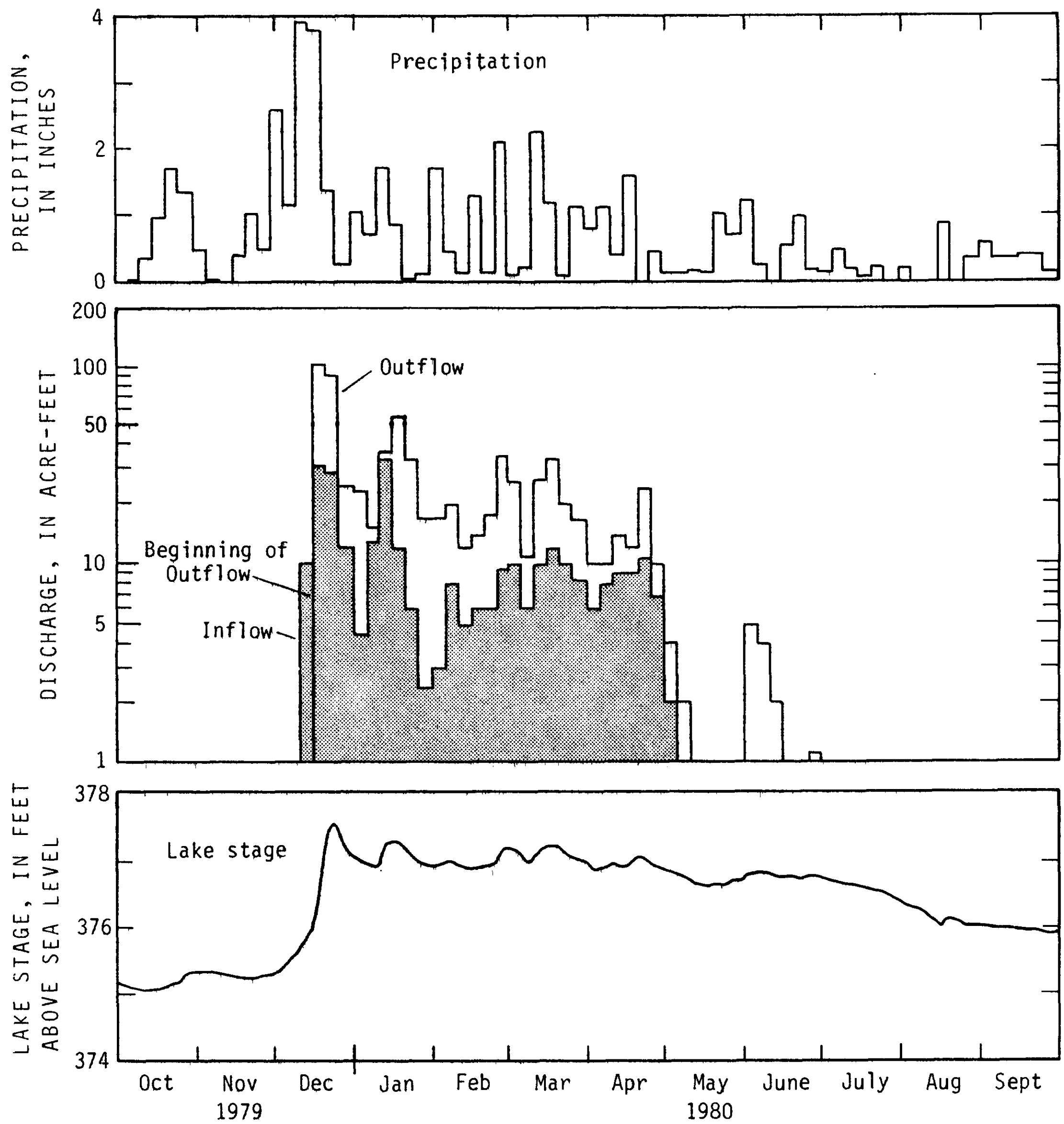

FIGURE 6.--Precipitation, inflow, outflow, and lake stage at Pine Lake. Precipitation, inflow, and outflow values are 5-day increments.

To supplement the ground-water-level measurements made at privately owned domestic wells, 12 piezometers were installed to depths between 10 and 80 ft. Seven additional piezometers were installed to various depths to determine vertical-head gradients. Six of these were installed to depths of 50, 125, 170, 203, 232, and 424 ft at a single site in the county park on the eastern edge of the lake. The seventh was installed to a depth of 425 ft near the southwestern end of the lake. All piezometers were slug-tested to insure that the screens were open to the surrounding geologic materials. The measuring points of all wells and piezometers were referenced to sea level.

In order to determine the lateral direction of flow in the uppermost part of the ground-water system near the lake, a map of the general configuration of the water table (fig. 7) was prepared for January 24, 1980, a time of seasonally high water levels. As shown by the map, the water table near Pine lake has a large amount of local relief; at several locations the water table occurs at depths as much as 70 ft lower than might be expected from projections of water-table levels in nearby wells. However, it has been shown by Lissey (1971) and by Winter and Carr (1980) that in areas where the geologic materials have low hydraulic conductivity, it is not unusual to find relief of the water-table surface of this magnitude.

The water-table map indicates a general movement of ground water into Pine Lake from the north, east, and south, and a general movement of water from the lake into the ground-water system to the west. Seepage into and from the lake occurs through glacial till, and field observations indicate that some of the ground-water inflow probably occurs by way of submerged springs and as interflow (subsurface flow). In the Pine Lake area, temporary perched water bodies 2 to 4 ft below land surface are known to develop locally over cemented strata in the soil during the rainy season (Gilliom and Patmont, 1982; Snyder and others, 1973). These perched water bodies are usually of short duration because the water flows laterally over the cemented layer to discharge points at lower altitudes, and vertically through the cemented layer, but at a much slower rate. Some of the interflow, of course, emerges at land surface before flowing into the lake.

In addition to the lateral direction of flow, the vertical direction of flow in the immediate vicinity of the lake was determined from a series of water-level measurements made in the nest of six piezometers on the eastern edge of the lake and in a pair of piezometers near the southwestern end of the lake. Water levels in these piezometers (fig. 8) showed a consistent downward gradient of as much as 0.5 foot per foot throughout the study period, indicating that the vertical direction of ground-water flow in the Pine Lake area is downward.

As stated previously, most of the drilled domestic wells in the Pine Lake area are located on the south side of the lake and are 100-150 ft deep. These wells are screened at approximately the same altitude, and their water levels (fig. 9) are considerably lower than lake level. As shown in the water-level map, the general direction of ground-water movement for this altitude is to the southwest.

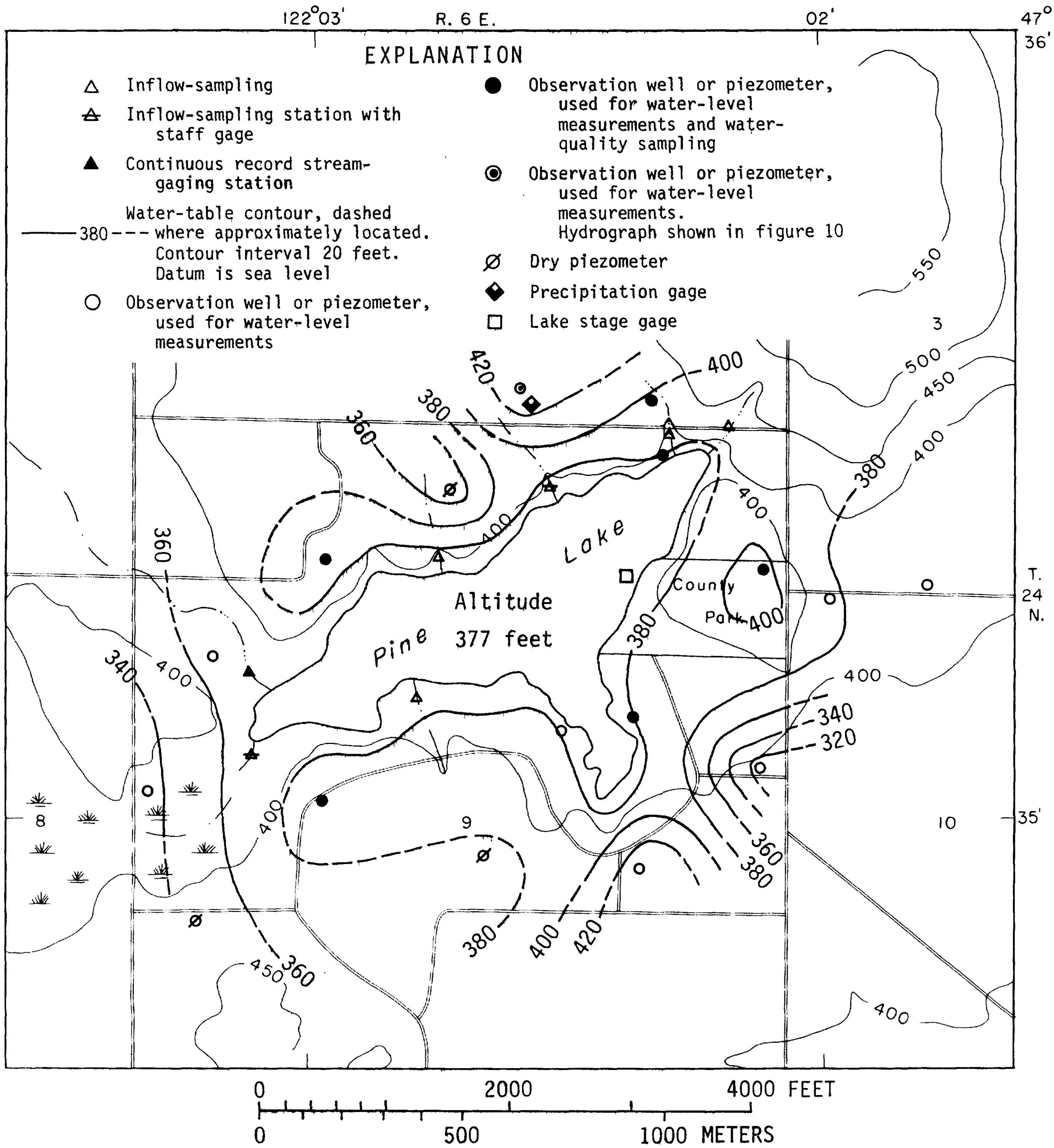

FIGURE 7.--Shallow ground-water conditions near Pine Lake, January 24, 1980.

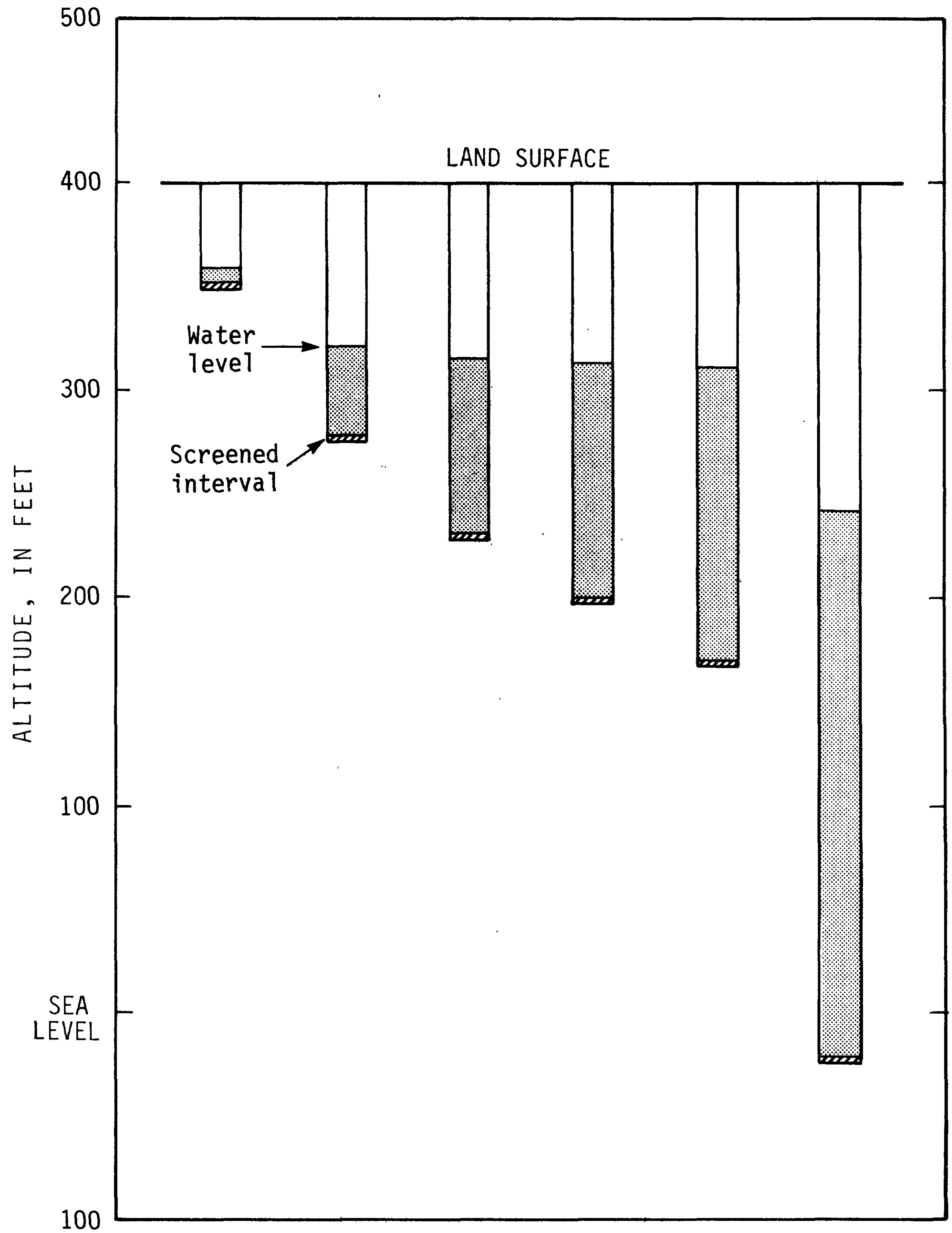

FIGURE 8.--Ground-water levels in piezometer nest on January 24, 1980. See figure 9 for location of piezometer nest.

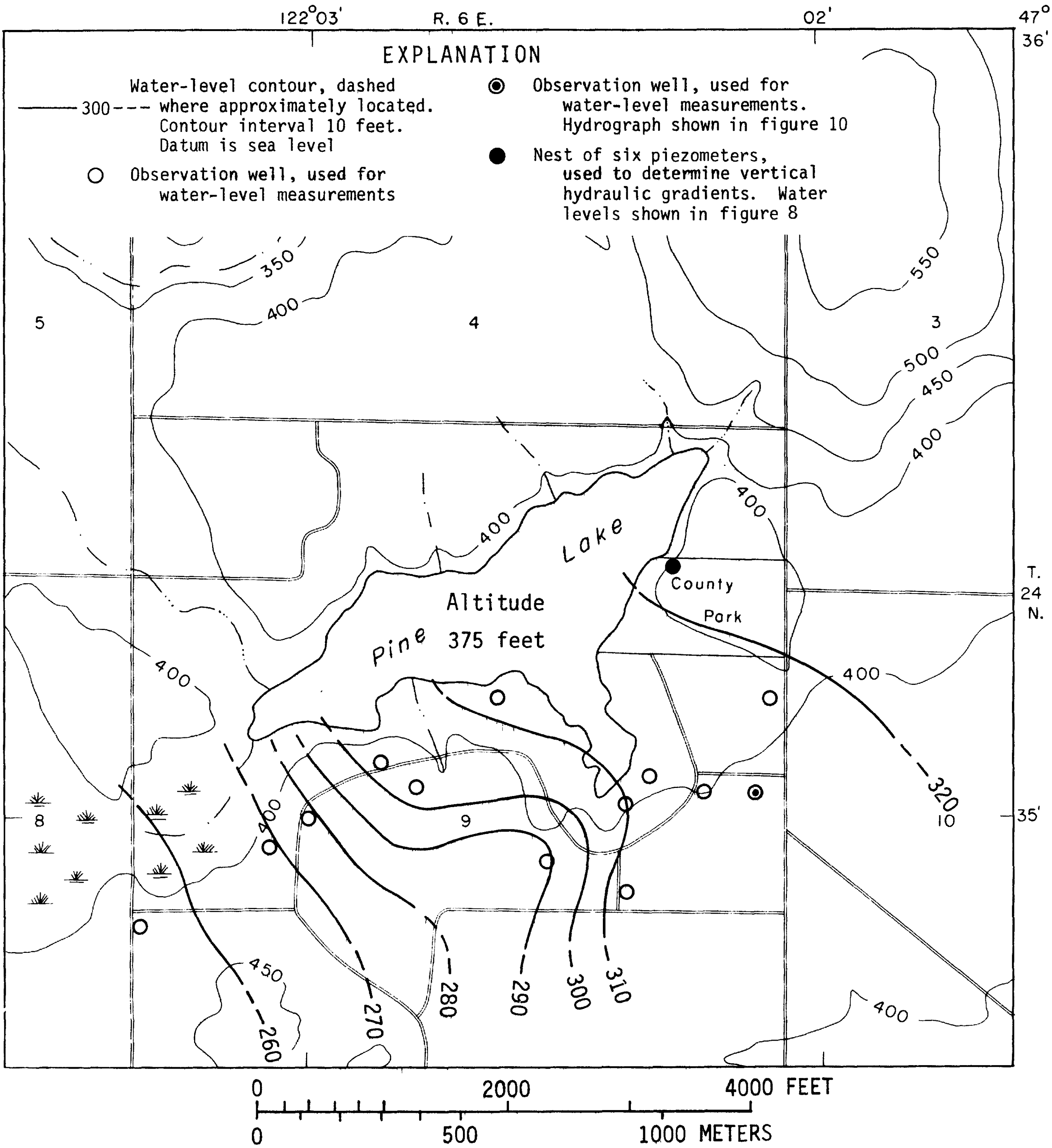

FIGURE 9.--Water levels in deep wells near Pine Lake, October 16, 1979.

Hydrographs of typical shallow and deep wells are shown in figure 10. Water levels in the shallow observation well responded much more quickly to recharge from heavy precipitation in December 1979 than did water levels in the deep obervation well. In addition, the amount of fluctuation was greater in the shallow well. Although water levels in the shallow well peaked in December 1979, peak water levels in the deep well did not occur until about 6 months later. The delay in response time between shallow and deep wells is probably caused by the low hydraulic conductivity of the geologic materials in the area.

To determine ground-water discharge for the water budget of this study, areas of ground-water inflow and outflow were delineated, chiefly on the basis of general water-table gradients. This approach was substantiated with limited measurements of seepage through the lake bottom in the littoral zone using seepage meters described by Lee (1977).

The volumes of ground water seeping into and from the lake were calculated using the hydraulic equation

$$Q = KIA, \tag{1}$$

where

Q = the rate of seepage, in acre-feet per day;
K = the hydraulic conductivity of the water-bearing materials beneath the lake, in feet per day (cubic feet per square foot per day);
I = the hydraulic gradient, in feet vertically per feet horizontally; and
A = the cross-sectional area of lakebed through which seepage occurs, in acres.

The hydraulic conductivity (K) of the glacial till penetrated in nine piezometers was determined using an aquifer test described by Bouwer and Rice (1976). The resulting values for seepage to and from the lake were 0.13 and 0.10 foot per day, respectively. These values compare favorably with values given by Todd (1959, p. 53) for similar geologic materials, and with values used by other investigators (Meyboom, 1966; Sloan, 1972; and Oakes and others, 1975) in similar hydrogeologic settings.

The hydraulic gradients (I) used in the equation were calculated for each month of the study and represent the average differences in altitude between the lake stage and the ground-water levels in nearby observation wells, both upgradient and downgradient of the lake. The month-to-month variations in gradient were small, despite relatively large fluctuations of the water table (fig. 10).

The cross-sectional area (A) of lakebed through which seepage inflow occurs was taken as a zone 10,700 ft long and 50 ft wide (12.3 acres); the outflow zone was 1,440 ft long and 50 ft wide (1.66 acres). Recent studies (McBride and Pfannkuch, 1975; John and Lock, 1977; Lee, 1977; and Lee and others, 1980) have shown that seepage from lakebeds decreases nonlinearly away from the shoreline. Therefore, for purposes of these calculations all seepage into and from the lake was assumed to occur within 50 ft of the shoreline.

In July 1980, officials of the water company supplying domestic water to the Pine Lake area discovered that a leak in the water-distribution system that had eluded detection for several months had in fact occurred in a water main on the lake bottom and was leaking into the lake. The amount of leakage was calculated on the basis of the size of the rupture and the water pressure, and the amount was treated as input to the lake in the preparation of the water budget. The leak was repaired the same month.

Evaporation from the lake surface was calculated using a mass-transfer method (Harbeck, 1962), which requires wind speed, air and water temperatures, and relative humidity data. The temperature of the lake-water surface was recorded on a Marshalltown[1] recorder (model 2200) mounted on a raft near the middle of the lake. Wind speed was measured by a Belfort totalizing anemometer, also mounted on the raft, at a height approximately 7 ft above the water surface. Air temperature and relative humidity were measured by a Belfort hygrothermograph. (The emergent macrophyte growth in Pine Lake is not extensive enough to warrant consideration of transpiration in the water-budget calculations.)

Lake storage is defined as the amount of water stored in the lake at any given lake stage. A change in lake storage, as shown by a change in lake stage, represents the net difference between total lake inflow and total lake outflow. The stage of Pine Lake, which was read daily on a staff gage referenced to sea level, is shown in figure 6. The net change in lake stage from October 1, 1979, to September 30, 1980, was a decline of 0.77 ft.

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[1]The use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

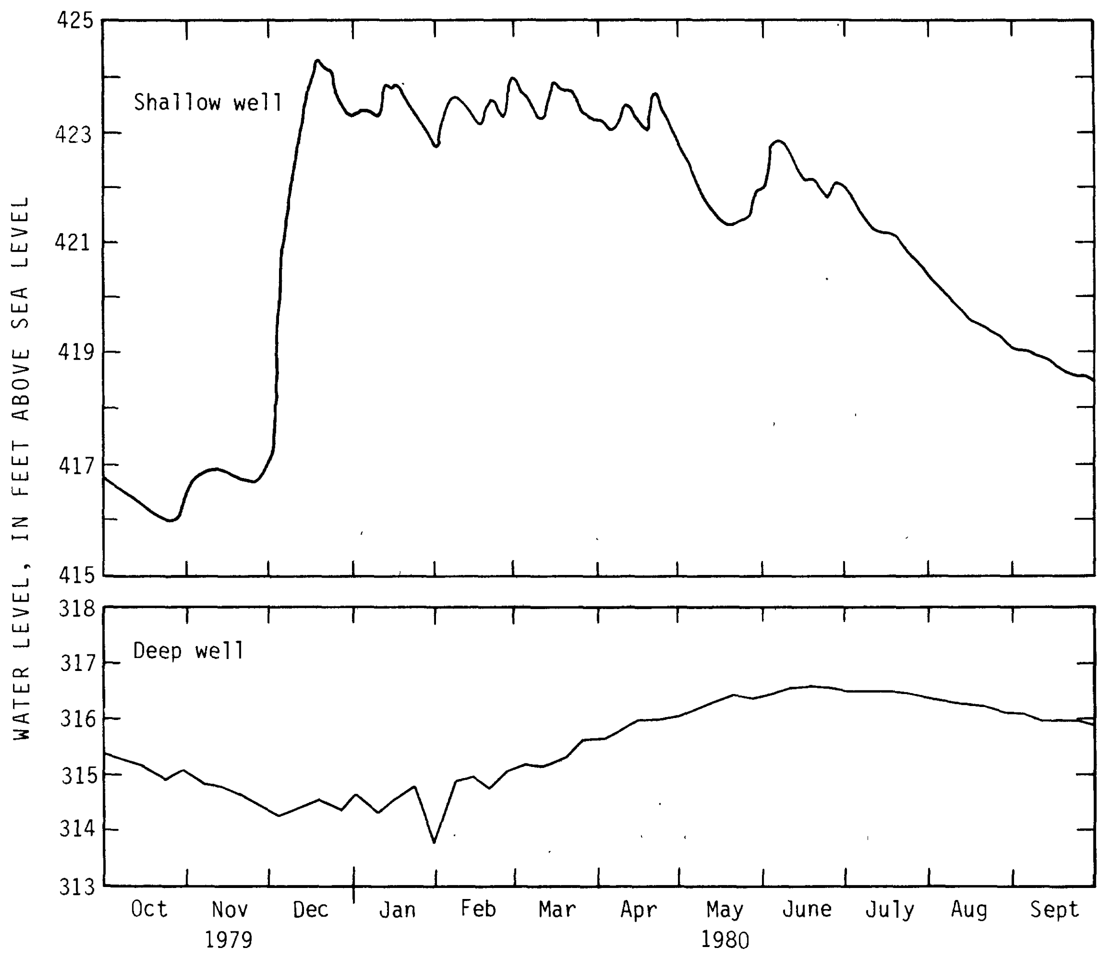

FIGURE 10.--Hydrographs of typical shallow and deep wells near Pine Lake. See figures 7 and 9 for locations of wells.

Water Budget

The basic premise of the water budget used in this report is that the amount of water reaching Pine Lake equals the amount leaving the lake, plus or minus the change in lake storage. The boundaries of the budgeted system are the lake bottom, shoreline, and lake surface. As mentioned previously, in a typical year water enters Pine Lake as precipitation on the lake surface, by surface inflow, and by ground-water seepage, and water leaves the lake as evaporation, surface outflow, and ground-water seepage. During the study year water also entered the lake through a leaky water main (now repaired). The equation used to express this relationship is:

$$Ppt + SW_{in} + GW_{in} + Leak = Evap + SW_{out} + GW_{out} \pm Strg \qquad (2)$$

where

- Ppt = precipitation on lake surface,
- SW_{in} = surface water flowing into lake,
- GW_{in} = ground water seeping into lake,
- $Evap$ = evaporation from lake surface,
- SW_{out} = surface water flowing from lake,
- GW_{out} = ground water seeping from lake,
- $Strg$ = change in lake volume,

and all terms are expressed in identical units.

Because the lake had a net decline in stage over the study period, and therefore a reduction in lake storage, the change-in-storage component was added to the output side of the equation to achieve balance.

The results of the water-budget calculations for the study period are given in table 1, which includes raw monthly and total values as measured in the field or as calculated. The solution of equation 2, using total (12-month) values from table 1, was accomplished as follows:

Total inputs - raw (acre-ft)	
Ppt	350
SW_{in}	300
GW_{in}	24
Leak	120
Total	790

Total outputs - raw (acre-ft)	
Evap	140
SW_{out}	750
GW_{out}	.93
Strg	+64
Total	950

TABLE 1.--Monthly water budget calculated for Pine Lake, October 1979 to September 1980.

[Units in acre-feet]

Component	1979			1980									12-month total
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	
INPUTS													
Precipitation	30	15	94	32	41	35	31	15	22	6.6	9.4	14	350
Surface inflow	0	0	82	72	37	56	51	1.6	1.8	0	0	0	300
Ground-water seepage	1.4	1.5	1.8	2.4	2.2	2.5	2.4	2.2	2.1	1.9	1.8	1.6	24
Leaky water main	13	12	13	13	12	13	12	14	15	4.5	0	0	120
Total inputs	44	28	190	120	92	110	96	33	41	13	11	16	790
OUTPUTS													
Evaporation	8	6.0	5.2	5.0	2.2	6.5	15	15	16	24	22	12	140
Surface outflow	0	0	220	180	120	130	79	6.8	13	.51	0	0	750
Ground-water seepage	.10	.12	.14	.06	.04	.05	.04	.06	.06	.07	.09	.10	.93
Change in storage	+12	-2.4	+140	-11	+20	-15	-8.5	-12	+1.5	-30	-26	-4.6	+64
Total outputs	21	3.7	360	170	140	120	86	9.9	31	-5.4	-3.9	7.5	950

Because of the vagaries inherent in the collection of hydrologic data (Winter, 1981), not all components of the water-budget equation could be evaluated with equal accuracy. Estimates of the likely percentages and magnitudes of error were made for each measured or calculated component and are presented in table 2.

In order to balance the water-budget equation, part of the difference between the total inputs and total outputs (160 acre-ft) was added to the inputs side and part was subtracted from the outputs side. The changes made to each side, and to individual components, were proportional to the magnitudes of the original raw values.

The components of the water-budget equation were adjusted to reflect conditions in an average, or typical, 12-month period. This would in turn allow the calculation of the amount of nutrients that could be expected to reach the lake in a typical year. Had the leak in the water main not occurred (as in a typical year), both the leak and surface-outflow components would have needed to be decreased by the amount of leakage. Similarly, had there been no decrease in storage, the surface outflow component would have needed to be increased accordingly. Although a single 12-month period without a change in lake storage is unlikely, the changes in storage over a number of years would tend to cancel out. Lastly, selected water-budget components (precipitation, surface-water inflow, and surface-water outflow) were adjusted upward to compensate for the departure of precipitation during the study period from the long-term average (see p. 12). With these adjustments, solution of the water-budget equation for a typical year is as follows:

Total inputs - adjusted (acre-ft)		Total outputs - adjusted (acre-ft)	
Ppt	410	Evap	130
SW_{in}	350	SW_{out}	660
GW_{in}	27	GW_{out}	.86
Total	790	Total	790

Based on the values obtained in the adjusted water budget, the theoretical water-renewal time—the amount of time required to completely replace the lake volume—is calculated to be 2.2 years.

TABLE 2.--Estimates of possible magnitude of errors in raw component values of water-budget equation

Component	Source	Value (acre-feet per year)	Possible error (percent)	Possible magnitude of error (acre-feet per year)
INPUTS				
Precipitation	Measured directly	350	±15	±52
Surface inflow	Measured and estimated	300	±100	±300
Ground-water seepage	Hydraulic equation	24	±500	±120
Leaky water main	Calculated	120	±25	±30
OUTPUTS				
Evaporation	Calculated	140	±40	±56
Surface outflow	Measured directly	750	±15	±110
Ground-water seepage	Hydraulic equation	.93	±500	±4.6
Change in storage	Measured directly	64	±5	±3.2

EXTERNAL SOURCES AND MAGNITUDE OF NUTRIENTS

Many elements and compounds act as nutrients to supply the food for aquatic plants. Nitrogen and (or) phosphous, however, are usually considered the limiting nutients for aquatic plant growth, and as such, were the only nutrients measured during this study. In addition, this study concerned itself only with the external sources of selected forms of nitrogen and phosphorus entering (loading) Pine Lake. No consideration was given to the ultimate availability of these nutrients once they reached the lake, nor to the relationship between loadings and in-lake concentrations. Only the inorganic forms of nitrogen and phosphorus were considered, because these forms are most readily utilized by aquatic plants.

The potential external sources of nitrogen and phosphorus for Pine Lake include direct precipitation, surface inflow, ground-water inflow, and such diverse sources as ducks, swimmers, improperly operating septic tanks, fallen leaves, boating activity, and washing-machine effluents discharged directly into the lake.

Only the precipitation, surface inflow, and ground-water inflow were sampled as part of this study, and the expected nutrient loads from these sources (table 3) were calculated on the basis of a typical year (see water-budget section of this report). The nutrient loads from other sources may be significant, but sampling those sources was not considered to be practical or within the scope of the study.

Although the water-budget components were measured throughout a 12-month period, the nutrient concentrations are based on data collected over a shorter period. Samples of precipitation and of surface-water inflow were collected only in December, January, and February, because these components typically peak in the rainy winter months. Samples of ground water were collected on a single date on the assumption that the quality of that water body would change little over the 12-month study period.

Nutrient concentrations in precipitation can vary markedly, both geographically and seasonally. Virtually the entire precipitation for the months of January and February 1980, about 9 inches, was sampled as part of this study and analyzed as six discrete samples. The average concentrations of inorganic (nitrate, nitrite, and ammonia) nitrogen and of inorganic (orthophosphate) phosphorus were 0.16 and 0.003 mg/L, respectively (table 3). Making the very broad assumptions that the precipitation at Pine Lake averages 57 inches per year (the amount calculated in the adjusted water budget) and that there is no seasonal variation in quality, the nutrient loads to the lake annually from precipitation would be 180 pounds of inorganic nitrogen and 3.3 pounds of inorganic phosphorus. Similarly, on the basis of very limited sampling, the average concentrations of inorganic nitrogen and of inorganic phosphorus in the surface inflow were 2.3 and 0.047 mg/L, respectively; the annual loads to the lake from this source would be 2,200 pounds and 44 pounds, respectively. It should be emphasized that the precipitation and surface inflow nutrient loadings are very broad estimates.

Ground water that moves toward Pine Lake was sampled by withdrawing water from wells and piezometers near the shoreline of the lake (fig. 7). The assumption was made that, because of the proximity to the lake, the wells and piezometers contained water that was chemically similar to ground water that seeped into the lake. The average concentrations of inorganic nitrogen and inorganic phosphorus were 2.2 and 0.022 mg/L, respectively. Making the assumption that the ground-water inflow to the lake is 27 acre-ft per year, as calculated in the adjusted water budget, the loads to the lake annually from the ground water would be 160 pounds of inorganic nitrogen and 1.6 pounds of inorganic phosphorus.

The combined annual contributions of inorganic nitrogen and phosphorus from precipitation, surface inflow, and ground-water inflow are in the general order of 2,500 pounds and 50 pounds, respectively (table 3).

TABLE 3.--Concentrations and loads of inorganic nitrogen and phosphorus to Pine Lake from external sources in a typical year

	Source			
Nutrient	Precipitation	Surface inflow	Ground-water inflow	Total load
		Concentration (milligrams per liter)		
Inorganic nitrogen	[a]0.16	[b]2.3	[d]2.2	--
Inorganic phosphorus	[a].003	[c].047	[d].022	--
		Load (pounds per year)		
Inorganic nitrogen	180	2,200	160	2,500
Inorganic phosphorus	3.3	44	1.6	49

[a] Average of six analyses of water collected at one site from January 2, 1980, to February 26, 1980.

[b] Discharge-weighted average of five analyses of water collected at five sites on two dates (December 19, 1979, and March 28, 1980).

[c] Discharge-weighted average of six analyses of water collected at six sites on nine dates during period December 19, 1979 - April 30, 1980.

[d] Average of six analyses of water collected at six sites on February 25, 1980.

SUMMARY AND CONCLUSIONS

Pine Lake receives water by direct precipitation, surface inflow, and ground-water seepage; water loss from the lake is by evaporation, surface runoff, and ground-water seepage.

A generalized water budget of the lake indicates that of the 790 acre-ft of water that enters the lake in a typical year, 410 acre-ft is from precipitation, 350 acre-ft from surface inflow, and 27 acre-ft from ground-water seepage. Of the equal amount that leaves the lake, 130 acre-ft is by evaporation, 660 acre-ft by surface runoff, and less than 1 acre-ft is by ground-water seepage. The theoretical water-renewal time of the lake is about 2.2 years.

Ground water seeps into and out of the lake through glacial till of low hydraulic conductivity. Because of the complex hydrogeologic setting of Pine Lake, a complete understanding of ground-water conditions in the vicinity of the lake would require additional investigation.

Although the potential sources of nutrients to the lake are diverse, only the sampling of precipitation, surface inflow, and ground-water inflow fell within the scope of this investigation. The annual contributions of inorganic nitrogen and phosphorus to the lake are approximated as: (1) from precipitation—180 pounds and 3.3 pounds per year, respectively; (2) surface inflow—2,200 pounds of nitrogen and 44 pounds of phosphorus per year; (3) ground-water inflow— 160 pounds of nitrogen and 1.6 pounds of phosphorus. The combined inorganic nitrogen and phosphorus loads from precipitation, surface inflow, and ground-water inflow in a typical year are about 2,500 pounds and 50 pounds, respectively.

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