

INTRODUCTION

The Winter Haven Chain of Lakes consists of 14 interconnected lakes within and around the city of Winter Haven, Polk County, Fla. (fig. 1 and table 1). The lakes comprise a valuable recreational and economic resource. Concern has been expressed by citizens and business interests regarding recent low stages and the deterioration of water quality in the lakes. Lake levels in the spring of 1975 were the lowest in 31 years of record. Both the decline in stage and the deteriorating water quality threaten recreational activity.

This study was made by the U.S. Geological Survey in 1976 in cooperation with the Southwest Florida Water Management District, Peace River Basin Board, and the Winter Haven Lake Region Boat Course District to determine:

1. The quality of water in the lakes.
2. The physical configuration of the lakes and the relation of lake levels to hydrologic factors such as precipitation, inflow, and outflow; and
3. The hydrologic relation of the lakes to the surficial aquifer and to the Floridan aquifer.

Results of the first phase of the study, item 1 above, were published in the report, "Evaluation of chemical, biological, and physical conditions in the Winter Haven Chain of Lakes, Florida, March-June 1976," by R. C. Reichenbaugh and G. H. Hughes. Reichenbaugh and Hughes (1977) found that many of the lakes were eutrophic, particularly Lakes Lulu and Ship. The eutrophication was caused by enrichment of the water with nutrients, principally nitrogen and phosphorus, contained in treated sewage effluent discharged into lakes and in runoff to the lakes from the urbanized watershed.

Results of the second phase of the study, items 2 and 3 above, determining the physical nature of the lake basins and evaluating fluctuations in lake stages and their relation to the hydrology and geology of the area, are contained in this report.

THE LAKES AND THEIR ENVIRONMENT

Winter Haven is in an upland area of hills and ridges that has many deep, internally drained lake basins (fig. 1). The upland part of the Trail Ridge-Lake Wales Ridge system that extends southward into Florida from the Georgia Piedmont. It is the oldest and highest of a series of sand ridges or ridges of ancient sea levels that parallel the present coastlines. Unconsolidated deposits in the area are composed of sand and clay as much as 150 feet thick that mantle limestone. Solution cavities developed in the limestone are reflected at lake surface because of subsidence and collapse of the unconsolidated deposits, forming the many sinkhole basins characteristic of the area.

The drainage area of the Winter Haven Chain of Lakes is 18.6 mi². The 14 lakes in the chain have a combined surface area of 6.79 mi² (4,343.5 acres), table 1, when at a stage of 131 feet above the National Geodetic Vertical Datum of 1929 (see table 1). They are connected by 1.8 miles of canals that are open to small-boat traffic within the chain. Because of the open canals, the 14 lakes are at essentially the same surface altitude.

The Chain of Lakes has two outlets. Both outlets have a concrete dam maintained by the Winter Haven Lake Region Boat Course District (fig. 1) and each discharges to the Peace Creek Drainage Canal. The Peace Creek Drainage Canal, a tributary of Peace River, was dredged in the early 1900s to facilitate cultivation of flat, poorly drained land south and north of Winter Haven. Also, about this same time, many lakes in the Winter Haven area were connected by canals, an outlet canal from Lake Lulu was dredged to the Peace Creek Drainage Canal, and Lake Hartridge was connected through a series of lakes eastward to a tributary of the Peace Creek Drainage Canal.

Most of the lakes occupied individual basins before construction of the canals, and their hydrologic regimes were controlled by rainfall within their drainage areas, by rates of evaporation and transpiration, by subsurface inflow from the surficial aquifer, and by downward leakage to the underlying limestone, the Floridan aquifer. Records of lake stages were not obtained prior to canal dredging, nor for many years thereafter. Under present conditions, the lakes are maintained at a common stage, even though the lakes with large drainage areas contribute most of the lake water, and local geologic conditions may result in greater loss of water by downward leakage from some basins than from others.

Depths and bottom configuration of lakes in the chain are shown in figure 1. Lake Winterset, at the southeastern end of the chain, is the third largest of the lakes and is the deepest. At a surface altitude of 130 feet, a large part of Lake Winterset is between 22 and 26 feet deep. The southeast end, known as Little Lake Winterset, is 8 feet deep. The circular nature of the bottom depressions in some lakes suggests the possibility of relatively recent subsidence, but in more shallow lakes, greater amount of downward leakage, and in some shallow lakes, with passage of time, the clean, well-graded sand of the lake bottom slumps to a relatively low angle of repose, as exemplified in Lake Howard and Lake Ship. Lake Lulu, with depths of 6 to 8 feet, is the shallowest lake in the chain. The bottom is formed by as much as 20 feet of soft organic ooze overlying sand.

Rainfall is the ultimate source of water to the lakes, as well as to the surficial aquifer and to the underlying limestone aquifer. Slightly more than half the annual rainfall occurs during the four summer months, June through September. Figure 2 shows the annual rainfall at Winter Haven for 1946-77. The summer rain occurs as thunderstorms, and, although individual showers cover a narrow swath, their total effect is one of remarkably uniform areal distribution. Precipitation during the winter months is generally less intense but more uniformly distributed; occasional frontal storms commonly cover wide areas with gentle rains that average 2 and 3 inches per month.

Average annual rainfall at Winter Haven for the period 1946-77 is 51.52 inches. The range in annual rainfall is large. Figure 3 also shows departures from average annual rainfall and cumulative departure from average for the same time span. In only 2 years since 1960 has the rainfall been above the 1946-77 average. The cumulative departure from 1960 to 1977 represents a rainfall deficit of 72.34 inches, a deficit equal to nearly 15 years average rainfall. Evaporation from lakes in the Winter Haven area averages about 48 inches per year, according to Kohler and others (1959, plate 2).

RECORD OF LAKE LEVELS

Lake levels rise in response to rainfall on the lake surface, to surface runoff from the surrounding watershed, and, in a more delayed manner, to ground water that seeps into the lake from the surficial aquifer underlying the basin. The Winter Haven lake levels are also augmented by effluent from several food processing plants that pump water from the Floridan aquifer and, until recently, by treated effluent from the Winter Haven sewage treatment plant. In previous years, treated sewage discharged into Lake Lulu accounted for as much as 6 inches of water a year (about 700 MGal/yr) over the Chain of Lakes. Discharge of sewage into the lake was discontinued in 1977. Evaporation from the lake surface averages about 48 inches a year (5.7 billion gallons per year). An unknown amount of water is pumped from the lakes for irrigation of surrounding citrus groves, farmland, and private lawns, and an unknown volume of water moves into the lakes from the surficial aquifer and downward from the lakes to the Floridan aquifer.

Fluctuations in the level of Lake Howard from 1946 through 1977 and of Lake Otis from 1954 through 1977 are shown in figure 3. Lake Howard is representative of the Chain of Lakes. Lake Otis, an isolated lake about a mile east and outside of the Chain of Lakes (fig. 1), is included for comparison. The hydrographs show seasonal variations and a declining trend in lake levels from about 1960 to 1977. However, the range in fluctuation is decidedly different.

The mean level of Lake Howard and the Chain of Lakes for the period 1946 to 1977 is 131.28 feet above NGVD of 1929. The mean level of Lake Otis for the period 1954 to 1977 is 125.01 feet above the datum. The level of Lake Howard has ranged 4.91 feet, whereas the level of Lake Otis has ranged 9.02 feet during their respective periods of record.

Outflow from the Winter Haven Chain of Lakes is partly controlled by concrete structures at the outlets from Lakes Lulu and Hartridge. The Lake Hartridge structure was modified to a fixed crest at an elevation of 132.20 ft in 1974. The Lake Lulu structure remained at an elevation of 132.25, but has flash boards that allow discharge from the lake at a somewhat higher elevation. Records of the manipulation of these control structures are not available. Miscellaneous discharge measurements were made at the outlet from Lake Hartridge between 1954 and 1960; the discharge was generally negligible, except for measurements of 28.9 and 26.8 ft³/s made in 1960. Average annual discharge in the Lake Lulu outlet canal from 1947 to 1971 ranged from negligible to more than 40 ft³/s as shown in figure 4. The maximum recorded discharge was 28.8 ft³/s occurring in June 1959. Rainfall was 21.28 inches above average in 1959. No flow is observed during parts of many years. Although the average discharge for the 25-year period of record is 10.7 ft³/s, the stage of the Chain of Lakes has not been high enough to overflow either control structure in recent years. Discharge of water from the Chain of Lakes has occurred, to an unknown extent, by manipulation of the control. Discharge in the Lake Lulu Outlet Canal also includes wastewater diverted seasonally from ground-water seepage packing plants, as well as seepage through the surficial aquifer from Lakes Lulu and Ship.

A comparison of figures 2 and 3 illustrates the variation of lake stage with rainfall. Total monthly rainfall is shown in figure 2 along with the departure from average for each year. Cumulative departure from average annual rainfall (fig. 2) shows long-range trends more clearly. The relatively short but severe drought that ended in 1967 was followed by 4 years of above average rainfall, culminating with the wettest year of record, 1960. From 1960 to 1977, all but 2 years were below average in rainfall. Fluctuations in the stages of both Lakes Otis and Howard (fig. 3) reflect differences in monthly precipitation and, to a lesser extent, the long-range trends of annual departure from average.

The wide fluctuation in stage of Lake Otis is typical of isolated or landlocked lakes. Fluctuation of Lake Howard is less extreme because of the moderating effect of inflow from the surficial aquifer and the chain and because outflow from the lakes is regulated by manipulation of the outlet control structure.

Annual average lake stages for Lakes Otis and Howard are compared with cumulative departure from average rainfall at Winter Haven in figures 5 and 6. The trend relation of the plotted points shown in figure 5 indicates that rainfall deficiency for several years is a significant factor causing low lake levels.

For Lake Howard, annual average lake stages and cumulative departure from average rainfall are not as well related as similar data for Lake Otis. The data shown in figure 6 for Lake Howard indicates a possible trend similar to the Lake Otis relation shown in figure 5, but

there is a wide scattering of points. Deviation of points from the trend, such as the high stages of 1946, 1947, 1969, and 1970, when cumulative departure from average rainfall is relatively low, and for low stages (1985) when cumulative departure is high, are probably due to the many factors, including the pattern of annual rainfall prior to 1946 and the uneven distribution of rainfall in some years, that affect the lowest in 31 years of record. Both the decline in stage and the deteriorating water quality threaten recreational activity.

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HYDROLOGY

The surficial aquifer in the Winter Haven area is composed of clean, well-sorted sand that grades downward into clayey sand and sandy clay. Thickness of the surficial aquifer ranges from 75 to 100 feet. It is underlain by dense, relatively impermeable clay about 100 feet thick, which is commonly phagitic, sandy, and dolomitic. This poorly permeable material forms a confining bed that retards movement of water from the surficial aquifer in the limestone of the Floridan aquifer. Limestone underlies the surficial deposits to depths of several thousand feet.

Surface drainage in the area is poorly developed because of the highly pervious nature of the sandy soils. Rain that does not fall on the lakes, or is not lost to evaporation, transpiration, and runoff, seeps later downward through the sand. Locally this water may enter an adjacent lake as underflow, but eventually water in the surficial aquifer flows back to the atmosphere or is released as surface flow continuing downward through the sandy clay to the limestone aquifer. An idealized section of the system, as shown in figure 9, illustrates the movement of water in the surficial aquifer.

The water table generally reflects the topography of the land surface. It is highest where the land surface is high and lowest where the land surface is low. The lakes represent areas where the land surface dips beneath the water table. In this respect, a lake may be viewed as a window to the water table. The lakes may also be viewed as the areas of greatest leakage to the Floridan aquifer, inasmuch as they occupy basins that have developed by subsidence of the surficial material into solution cavities in the Floridan aquifer.

Lateral movement of water through the surficial aquifer is generally confined to individual lake basins because of the high water table surrounding the basins. Water from Lake Roy, for example (fig. 1), will not flow through the surficial aquifer to Lake Ring, which is several feet lower in altitude. The water-table divide between the lakes is higher than either lake, thus precluding lateral movement. Lateral leakage between Lake Lulu and the outlet canal is low and markedly it seems likely that water moves through this part of the surficial aquifer from Lake Lulu to the canal, as illustrated in figure 9.

To gain an understanding of the magnitude of leakage from lakes to aquifers, an experiment was conducted at Lake Roy. A recording gauge was installed on the lake and the Winter Haven Canal Commission closed the canal between Lake Lulu and Roy with an earth dam at 10 a.m., November 26, 1979.

The effect of isolating Lake Roy from the Chain of Lakes is illustrated in figure 10. Fluctuations in stage of Lake Roy immediately diverged from those of Lake Howard. In the first 30 days, a period of relatively slight rainfall, Lake Roy declined at a rate of about 0.04 ft/d, compared with a decline of about 0.01 ft/d for Lake Howard. No pumping or other outflow from Lake Roy had been noted during this period, and the rate of evaporation presumably was the same for both lakes, about 0.01 ft/d. The difference in the rate of decline is most likely due to a difference in the rates of leakage through the surficial aquifer underlying the lakes and in rates of ground-water seepage into the lakes. The effect of rainfall and a resultant increase in ground-water flow to the lakes is illustrated by hydrographs for the latter part of December and during January. Following lake-level rises in response to rain, Lake Roy immediately began to decline rapidly, but there is a detectable decrease in the rate of decline, indicating an increase in ground-water inflow. Following the rainfall at Lake Howard, the lake level remained relatively constant, indicating that ground-water flow was sufficient to equal or exceed the quantity of water lost by evaporation and seepage. The Lake Roy experiment illustrates that the rate of downward leakage of water from the lakes is a significant part of the hydrologic regime and does vary from one lake basin, or locally, to another.

The net volume of water lost from Lake Roy to the underlying aquifer, assuming net water outflow from the lake is proportional to its surface area, is 0.03 (ft/d)(0.04 measured loss minus 0.01 foot evaporation loss). The rate of downward leakage is controlled by the hydraulic conductivity of the material between the bottom of Lake Roy and the top of the Floridan aquifer and the difference in head, or hydraulic gradient, between the lake and the aquifer. If the quantity of ground-water inflow to Lake Roy at the time of the experiment is assumed to be negligibly small, the hydraulic conductivity can be determined from the equation

$$Q = \frac{K A \Delta h}{L}$$

where Q = volume of leakage, in cubic feet per day per square foot,
K = hydraulic conductivity of the intervening material, in cubic feet per day per square foot, and
L = hydraulic gradient.

At the time of the experiment, the potentiometric surface of the Floridan aquifer stood at about 114 feet and Lake Roy at about 130 feet above NGVD of 1929. Total thickness of the surficial aquifer and confining layer is about 150 feet. Thus, the hydraulic gradient is $(130 - 114)/150 = 0.11$, and the hydraulic conductivity is $0.03(0.11) = 0.27$ ft/d, assuming that leakage occurs uniformly through the lake bottom. The composite vertical hydraulic conductivity of the material between the bottom of Lake Roy and the top of the Floridan aquifer is 0.27 ft/d.

Water levels in the Winter Haven city wells define the position of the potentiometric surface of the Floridan aquifer in the vicinity of the Chain of Lakes. Water-level records are available for the Fairfax well since 1963. These are portrayed in figure 11 along with the total annual pumpage from all the city wells. The graphs of annual pumpage and water levels in figure 11 follow the same general trend. Use of ground water for citrus irrigation and food processing plants in the area accounts for a large, but unknown, volume of pumpage.

The effects of fluctuation of ground-water level in the Floridan aquifer on lake levels can be estimated from the results of the Lake Roy experiment. Water level in the Fairfax well reached a record low of 102 feet at the end of 1975, according to the hydrograph of figure 11. At that time levels of the lakes in the chain were about 129.5 feet. If the hydraulic gradient then was $(129.5 - 102)/150 = 0.18$, using the vertical hydraulic conductivity of 0.27 ft/d previously calculated and multiplying it by the 0.18 just obtained, yields a leakage of 0.08 ft/d for Lake Roy, an increase of 60 percent over that measured during the experiment and caused by the 60-percent increase in the hydraulic gradient between lake and aquifer.

The potentiometric map (fig. 12) shows the configuration of the water surface in the Floridan aquifer in the Winter Haven area for March 1979. The surface slopes generally toward the south, but the gradient is interrupted in the area east of Lake Howard where a potentiometric high is centered. The high trends southward toward Lake Roy. The potentiometric high indicates local recharge and the downward infiltration of water from the surficial aquifer and lakes at a greater rate than occurs in surrounding areas.

Variations in the rate of recharge are most likely due to local variations in the geology and, consequently, variations in vertical hydraulic conductivity. Study of logs of wells drilled in the area indicates a wide variation in the thickness of the clay confining layer overlying the Floridan aquifer. In areas where the clay layer is thin, sandy or dolomitic, leakage will be greater for a given head difference than in areas where the clay layer is thick and dense.

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SUMMARY

Hydrographs for Lake Howard, representative of the Winter Haven Chain of Lakes, and for Lake Otis, the nearest isolated lake that has a reasonably long record, were compared with graphic representation of various other hydrologic parameters. Analyses relating stage and rainfall records indicate that the annual rainfall has been a major factor in the decline of lake levels in the area. Other factors, such as the regulation of lake levels by control structures, unknown volumes of effluent discharged to the lakes, diversion of lake water for irrigation, changes in surface drainage due to urbanization, and lowering of the potentiometric surface of the Floridan aquifer, have also affected the lake levels, but to a lesser degree.

Water from the surficial aquifer drains to the lakes by ground-water seepage. Water level in the underlying Floridan aquifer is lower than the level of any of the lakes; thus, water moves from the lakes and the surficial aquifer through the confining clay layer to the Floridan aquifer.

The results of an experiment at Lake Roy illustrate that the rate of downward leakage from Lake Roy is significant and that leakage does vary from one lake basin, or locally, to another. Areal differences in the rate of downward leakage from the lakes and surficial aquifer to the Floridan aquifer is also indicated by a mound in the potentiometric surface of the Floridan aquifer in the area from Lake Howard to Lake Roy. The thickness and density of the clay that separates the surficial aquifer from the Floridan aquifer is the principal factor controlling the rate of downward leakage.

Hutchinson, C. B., 1977, Appraisal of shallow ground-water resources and management alternatives in the Upper Peace and Eastern Alafia River basins, Florida, U.S. Geological Survey, Water-Resources Investigation 77-124, 97 p.

Kohler, M. A., Nienow, J. L., and Baker, D. R., 1959, Evaporation maps of the United States: U.S. Department of Commerce, Weather Bureau Technical Paper 37, 13 p., p. 16.

Reichenbaugh, R. C., and Hughes, G. H., 1977, Evaluation of chemical, biological, and physical conditions in the Winter Haven Chain of Lakes, Florida, March-June 1976, U.S. Geological Survey Water-Resources Investigations 77-52, 37 p.

For those readers who may prefer to use metric (SI) units rather than inch-pound units, conversion factors for terms used in this report are listed below:

Multiple inch-pound unit	By	To obtain metric (SI) unit
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi ²)	2.580	square kilometer (km ²)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
(ft ³ /s) million gallons per day (MGal/d)	0.04381	cubic meter per second (m ³ /s)

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."

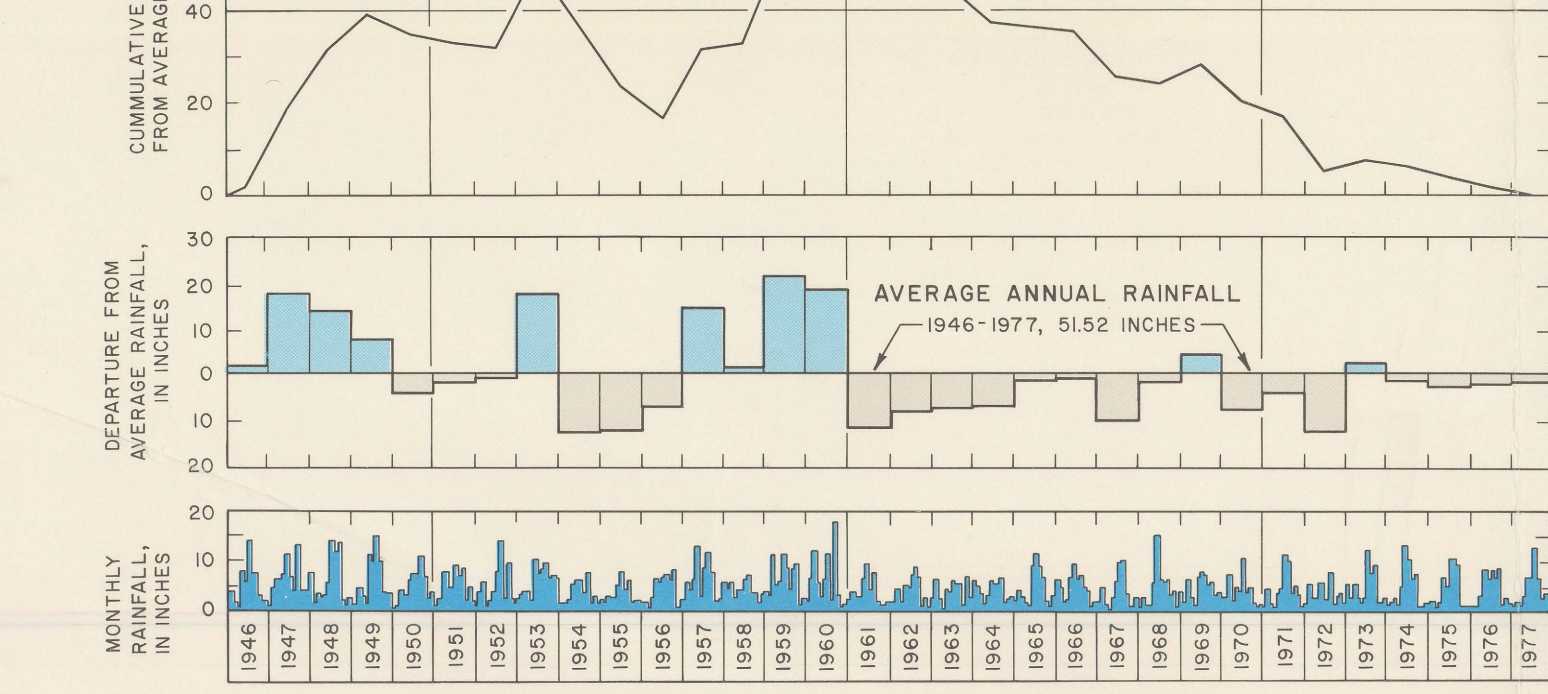


Figure 2.—Rainfall at Winter Haven, 1946-77.

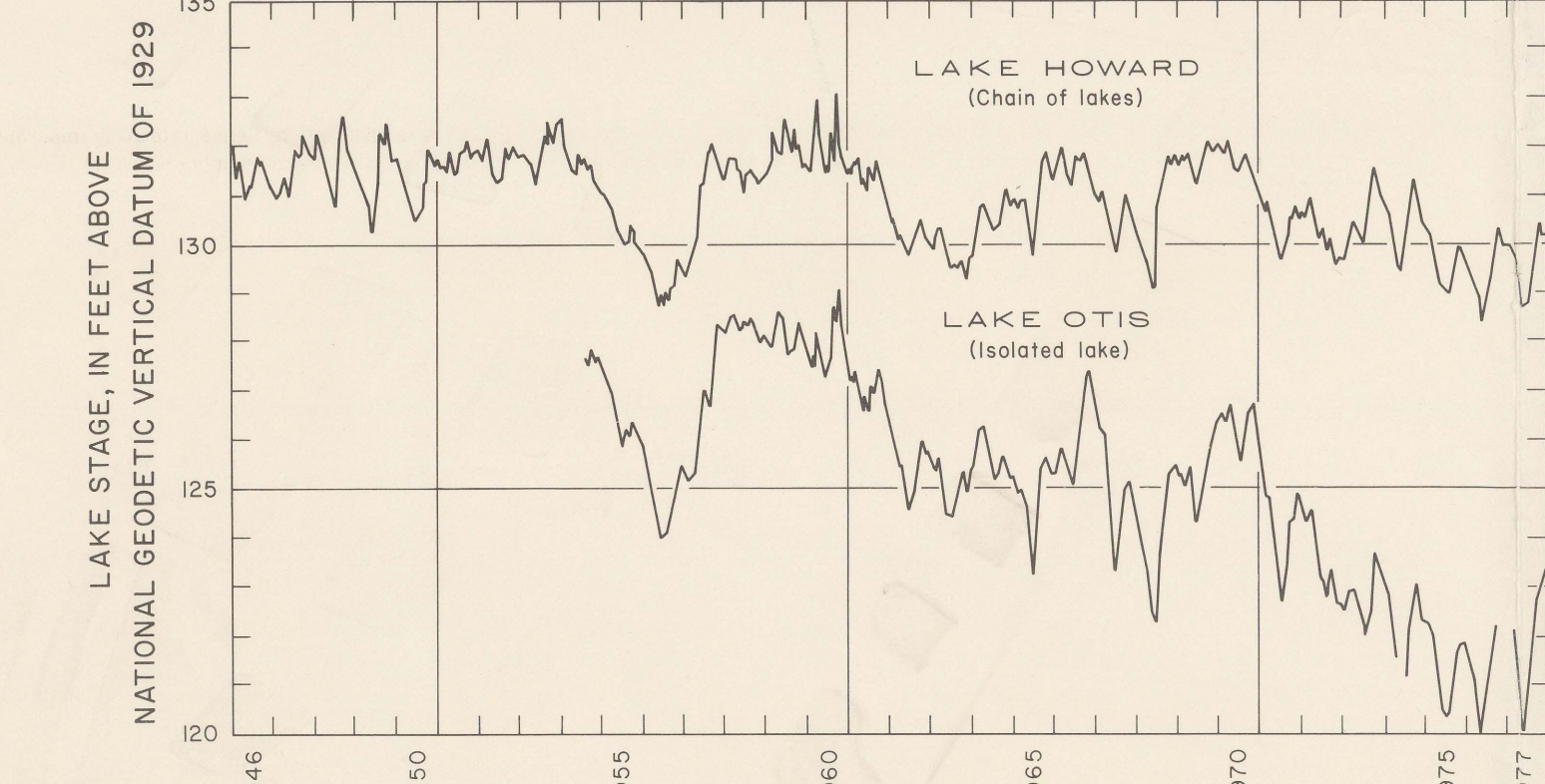


Figure 3.—Hydrographs of Lake Howard and Lake Otis.

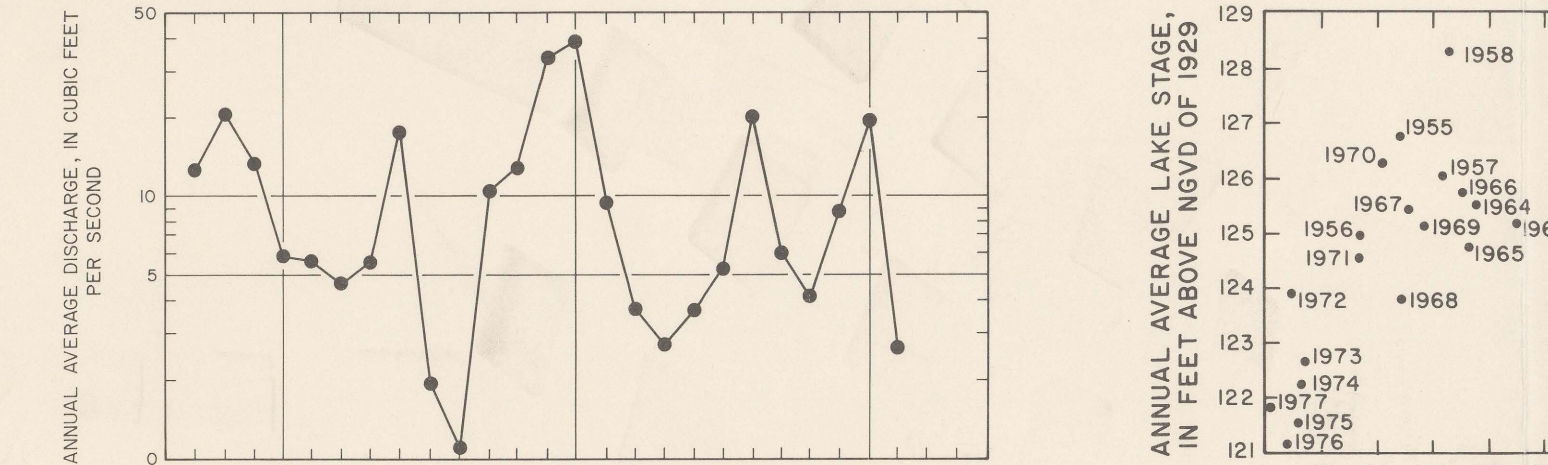


Figure 4.—Annual average discharge through Lake Lulu outlet canal.

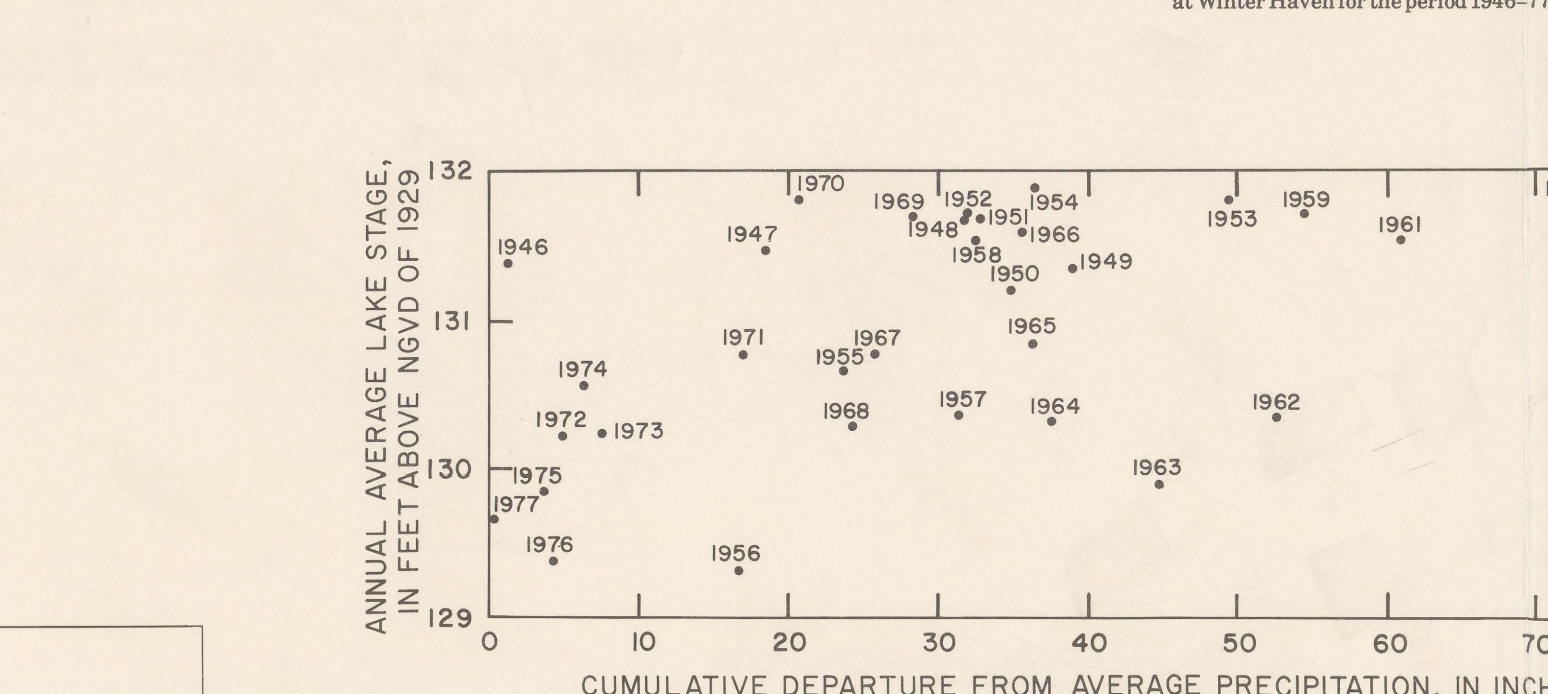


Figure 5.—Stage of Lake Howard versus cumulative departure from average precipitation at Winter Haven for the period 1946-77.

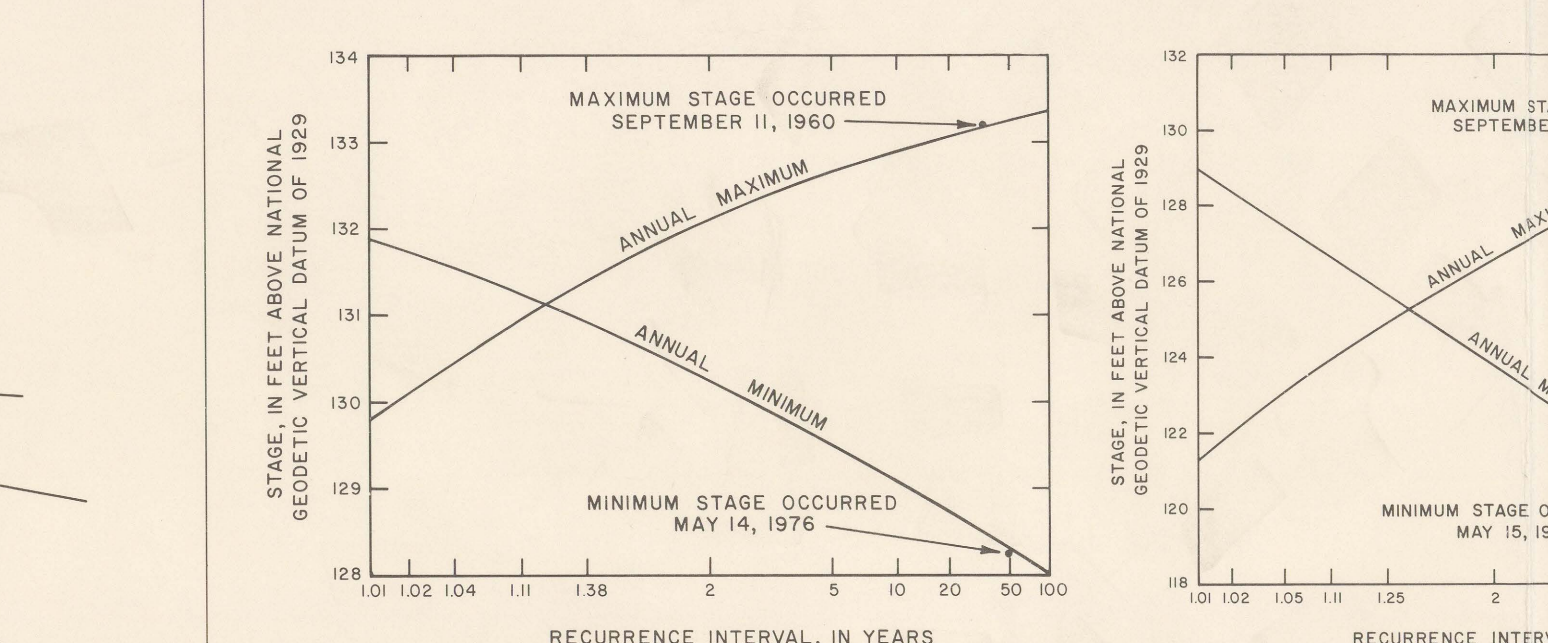


Figure 7.—Magnitude and frequency of occurrence of annual minimum and maximum stages for Lake Howard, 1946-76.

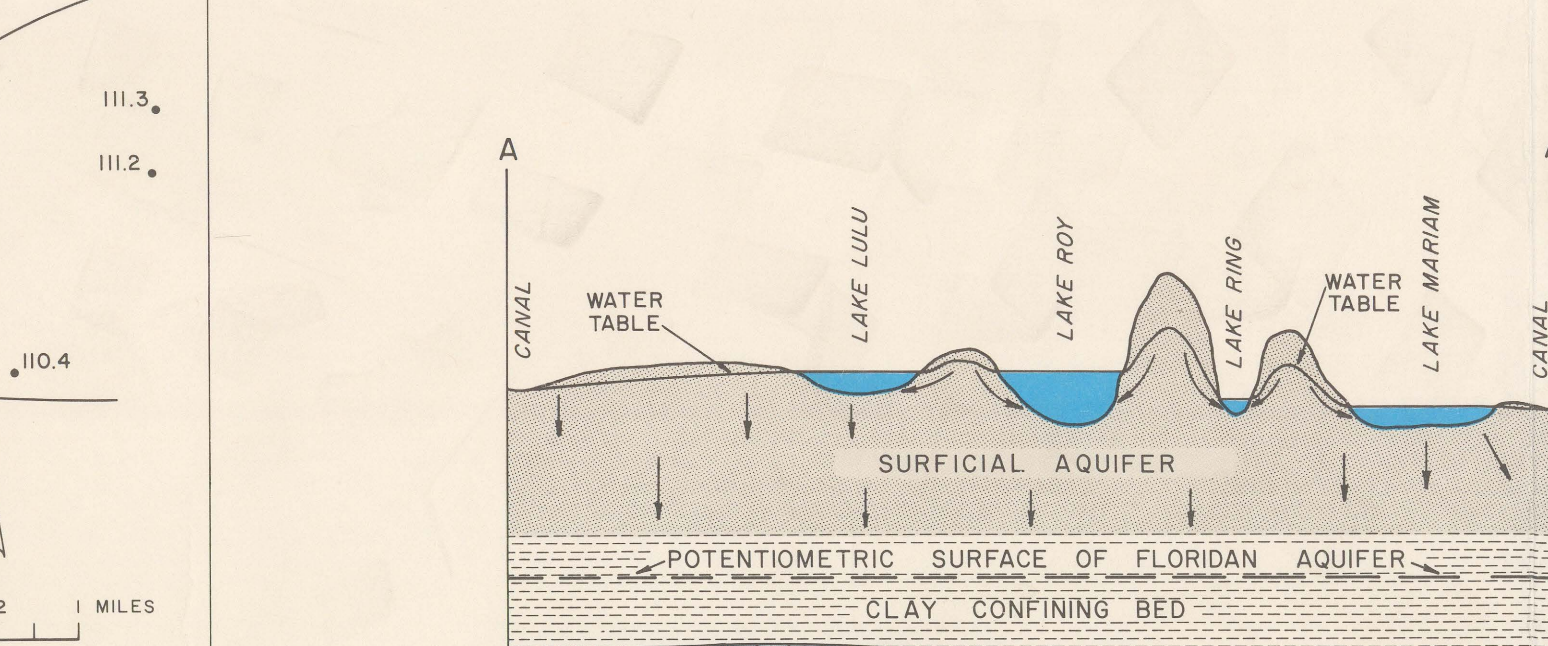


Figure 8.—Magnitude and frequency of occurrence of annual minimum and maximum stages for Lake Otis, 1955-76.

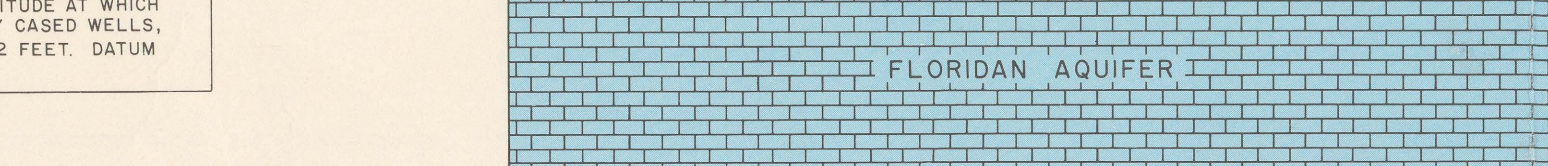


Figure 9.—Idealized section showing inferred direction of water movement in the surficial aquifer. (Location of section A-A' is shown in figure 1.)

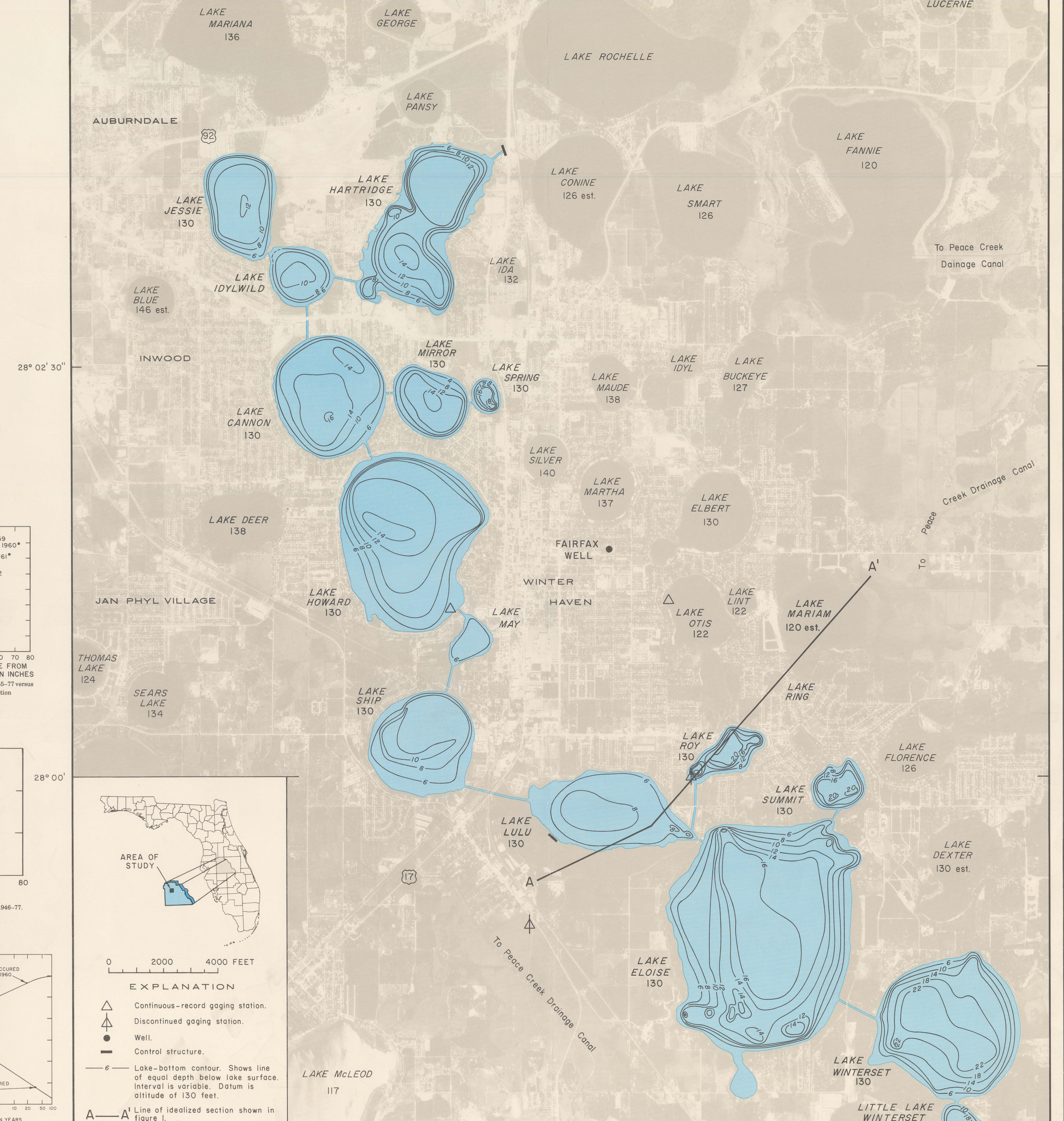


Figure 1.—Bathymetry of lakes in the chain and lake stages in March 1977.

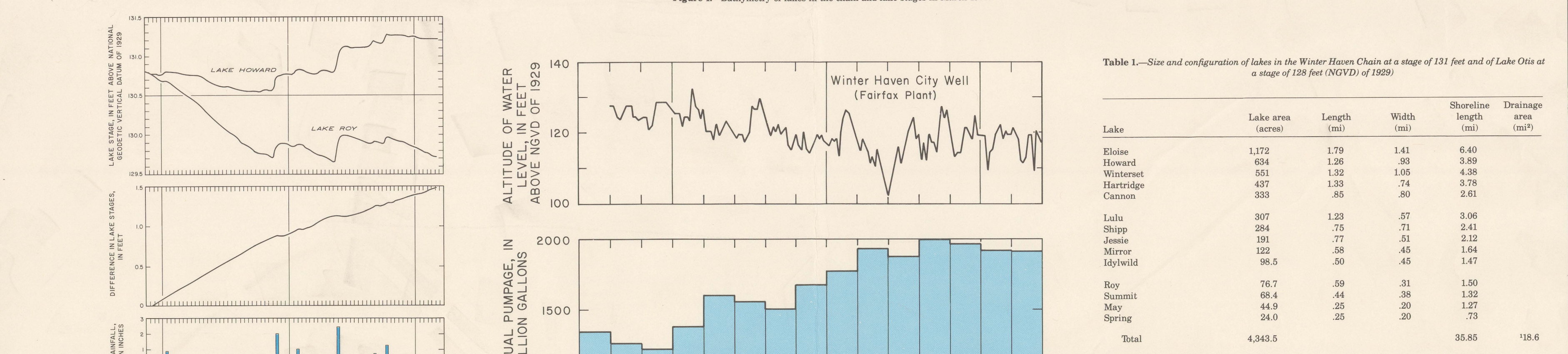


Figure 10.—Hydrographs for Lakes Roy and Howard, difference in lake stages, and daily rainfall at Winter Haven, November 26, 1978 to February 5, 1979.



Figure 11.—Hydrograph of water level in the city of Winter Haven's Fairfax well, and total pumpage of all city wells, 1963-77.

Table 1.—Size and configuration of lakes in the Winter Haven Chain at a stage of 131 feet and of Lake Otis at a stage of 128 feet (NGVD of 1929)

Lake	Lake area (acres)	Length (mi)	Width (mi)	Shoreline length (mi)	Drainage area (mi ²)
Lake Howard	1,172	1.79	1.41	3.49	8.60
Lake Winterset	651	1.32	1.05	4.38	4.38
Lake Otis	487	1.33	0.74	3.78	1.78
Lake Cannon	383	0.85	0.85	2.81	0.85
Lake Lulu	307	1.23	0.57	3.06	0.57
Lake Ship	284	1.76	0.71	2.41	0.71
Lake Hartridge	191	0.77	0.31	2.12	0.31
Lake Mirror	122	0.68	0.45	1.84	0.45
Lake Idylwild	98.5	0.68	0.45	1.47	0.45
Lake Roy	76.7	0.89	0.31	1.50	0.31
Lake Smart	68.4	0.49	0.31	1.32	0.31
Lake May	44.9	0.25	0.20	1.27	0.20
Lake Spring	25	0.20	0.20	0.73	0.20
Total	4,343.5			35.88	18.6
Lake Otis	141	0.99	0.44	2.78	0.97

¹Does not include drainage areas of Lakes Mariana, Blue, and Deer (28.0, 0.5, and 0.9 mi²) that would drain to the Chain of Lakes if control structures were removed. Locations of these lakes are shown in figure 1.

HYDROLOGY OF THE WINTER HAVEN CHAIN OF LAKES, POLK COUNTY, FLORIDA

By
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1981

