Effect of Irrigation Withdrawals on Stage of Lake Washington, Mississippi

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1460-I

Prepared in cooperation with the Mississippi Board of Water Commissioners

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By G. EARL HARBECK, JR., HAROLD G. GOLDEN, *and* EDWARD J. HARVEY

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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EFFECT OF IRRIGATION WITHDRAWALS ON STAGE OF LAKE WASHINGTON, MISSISSIPPI

By G. EARL HARBECK, JR., HAROLD G. GOLDEN, and EDWARD J. HARVEY

ABSTRACT

The increase in the amount of water pumped from Lake Washington, Miss., for supplemental irrigation caused concern among residents of the area over the possible effect of the irrigation withdrawals on the stage of the lake, which is used for recreation. Records of the stage of Lake Washington, ground-water levels in the area, and meteorological data were used to determine the seasonal variation in the amount of seepage into and out of the lake. In spring, the nearby Mississippi River is high, and the net seepage into Lake Washington is much greater than the out seepage during fall, when the river is low.

Irrigation withdrawals in 1957 were small compared with both rainfall on the lake and seepage into the lake. If the rate of irrigation withdrawals ever became large enough to lower the lake level by more than a few inches, those withdrawals would be partly balanced by an increase in the amount of seepage into the lake when the ground-water level in the area is high. Thus an increase in the amount of water withdrawn would not result in lowering the lake level by an equivalent amount.

INTRODUCTION

This report describes an investigation of the effects of irrigation withdrawals on the level of Lake Washington, Washington County, Miss. The increase in the amount of water pumped from the lake during the drought period 1951–56 caused concern among residents of the area over the possible effects of the withdrawals on the level of the lake, which is an important recreation center. This concern led local people to request a study of the problem. The Mississippi Geological Survey, W. C. Morse, director, assisted in an earlier preliminary investigation in late 1954. The present study was conducted between October 1956 and September 1958 in cooperation with the Mississippi Board of Water Commissioners, Sam A. Thompson, chairman. The results of the observations and the conclusions derived from analyses of the data are the basis of this report. The report was prepared in the Water Resources Division of the U.S. Geological Survey, L. B. Leopold, chief hydraulic engineer.

The lake-level, meteorological, and streamflow data were obtained by personnel of the Surface Water Branch, Jackson, Miss., under the administrative supervision of I. E. Anderson, district engineer, succeeded by W. H. Robinson, and under the technical supervision of G. Earl Harbeck, Jr., research engineer, General Hydrology Branch. The data on ground-water conditions in the Lake Washington area were obtained by personnel of the Ground Water Branch, Jackson, Miss., under the administrative supervision of J. W. Lang, district geologist.

The summer and fall of 1954 were extremely dry throughout Mississippi. Many streams receded to new minimum flows of record. The water surface of Lake Washington was lower than it had been for several years, according to local residents who were concerned that the low level of the lake was the result of withdrawal of water for supplemental irrigation of cotton, corn, soybeans, and pasture, rather than from the drought. Withdrawals for irrigation during the 1954 growing season probably totaled less than 1,000 acre-feet. They were estimated to total about 600 acre-feet in 1957, a year of more seasonal rainfall.

Lake Washington is a popular resort and fishing site. Consequently, the low water level of the lake caused concern among recreational interests, who assumed that the irrigation withdrawals were largely to blame. In 1954, supplemental irrigation was a comparatively new practice in the area. Landowners anticipated that irrigation withdrawals from Lake Washington might expand within a few years to perhaps 10 to 20 times the amount used in 1954.

ACKNOWLEDGEMENTS

Many persons living in the vicinity of Lake Washington contributed to this study. W. F. McKamy, Jr., served as rain-gage observer, and made observations of maximum-minimum water temperatures prior to the installation of the recording thermograph. W. H. Caffey, Roy Shanks, and Wayne Reed served as rain-gage observers. The Highland Club permitted the installation of a water-stage recorder on its pier. Rife Wade permitted the installation of meteorological equipment on his private pier. The irrigators making withdrawals from Lake Washington maintained logs of their operations. The cooperation and assistance of these people were evidence of the keen local interest in the problem, and were greatly appreciated.

DESCRIPTION OF THE AREA

Lake Washington is an oxbow lake in the "Delta" area of northwestern Mississippi about 25 miles south of Greenville. The crescent-shaped lake (fig. 33) whose surface area is about 3,300 acres, occupies

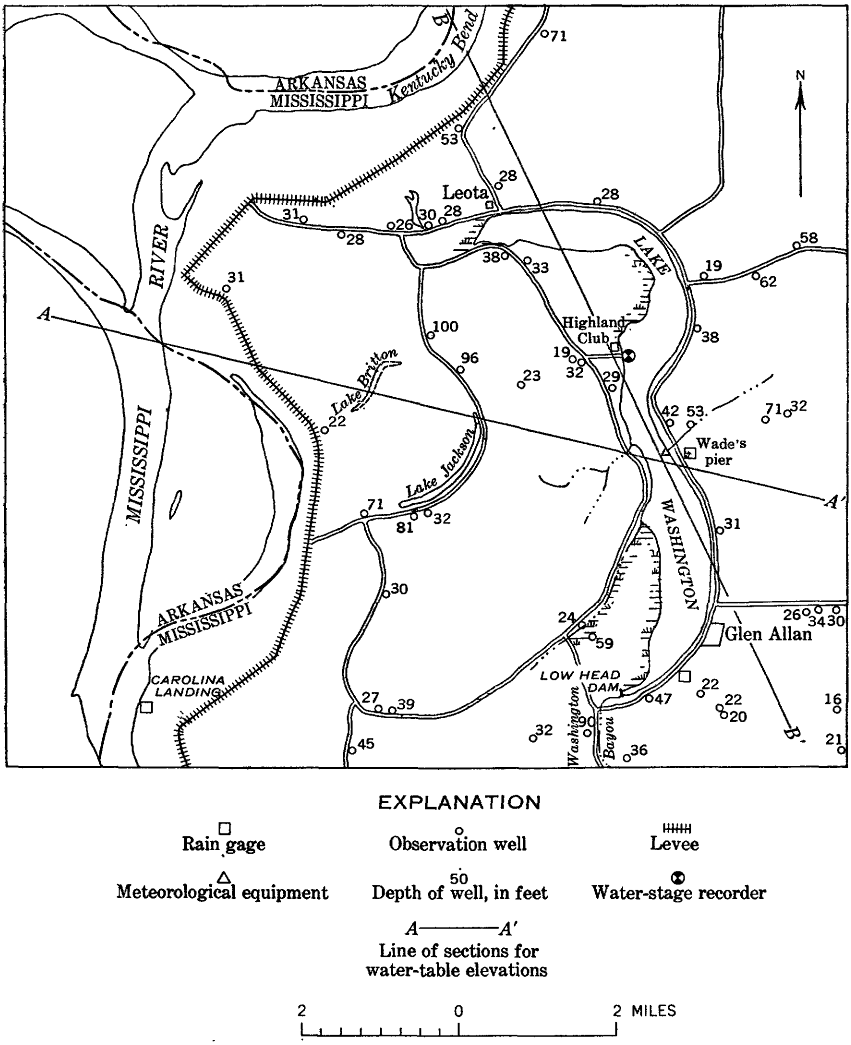

FIGURE 33.—Map of Lake Washington, Miss., and vicinity showing location of instruments.

1 or possibly 2 old meanders of the Mississippi River and is about 1½ miles from Kentucky Bend on the north and 5½ miles from Carolina Landing on the south. The lake is about 8 miles long, lying generally north-south, and ¼ to ¾ mile wide. The shoreline, except for the north and south ends, is composed of high banks with a few drainage ditches sloping into the lake. The north and south ends of the lake are low marshy areas that are inundated during winter and spring. The elevation at the lowest point of the lake bottom is estimated to be about 75 feet above mean sea level. The drainage area trib-

utary to the lake is small compared to the area of the lake surface. A low-head dam, with the spillway crest at an elevation of 96.9 feet, is located at the lake outlet to Washington Bayou. Maximum and minimum water-surface elevations during the 1955–58 water years are given in table 1.

TABLE 1.—*Maximum and minimum water-surface elevations of Lake Washington, Miss., for the water years 1955–58.*

Water year	Maximum elevation (in feet above mean sea level)	Date	Minimum elevation (in feet above mean sea level)	Date
1955	99. 19	Mar. 24	[1] 95. 10	Oct. 24–27 Nov. 2, 3
1956	98. 68	Mar. 17	95. 42	Sept. 30
1957	98. 96	Mar. 6	95. 26	Oct. 20
1958	102. 72	May 11	97. 17	Oct. 14

[1] May have been less prior to recorder installation Oct. 20, 1954.

CLIMATOLOGY

The climate at Lake Washington is humid. The mean January temperature is 46°F, the mean July temperature is 82°F, and the mean annual rainfall is 51.9 inches at Greenville, Miss., according to U.S. Weather Bureau records. The maximum temperature recorded during 1902–41 is 110°F, the minimum, —5°F. A comparison of monthly observed rainfall during 1951–57 with the mean monthly rainfall at Greenville (fig. 34, based on U.S. Weather Bureau records), indicates that rainfall in 1951, 1953, and 1957 was about normal or above, but rainfall in 1952, 1954, 1955, and 1956 was below normal. Greenville is located near the Mississippi River about 20 miles north of Lake Washington. There is little or no difference in the climate at Greenville and at Lake Washington.

GROUND-WATER CONDITIONS

Oxbow lakes such as Lake Washington are abandoned meander loops of the Mississippi River. Older lakes are filled with fine-grained material such as clay, silt, and fine sand. Where the material is relatively impervious it forms a seal or barrier to water movement and is referred to as a clay plug. Younger lakes are partly filled. On the inside of the meander loops are the point-bar deposits. In these, sand occurs commonly at or near the ground surface and extends down to the top of the Tertiary bedrock. The upper part of the sand is more or less silty. The sand occurs at shallow depth as indicated by the depths of driven wells, which range from 19 to 38 feet. The location and depth of wells in the vicinity of Lake Washington are shown on

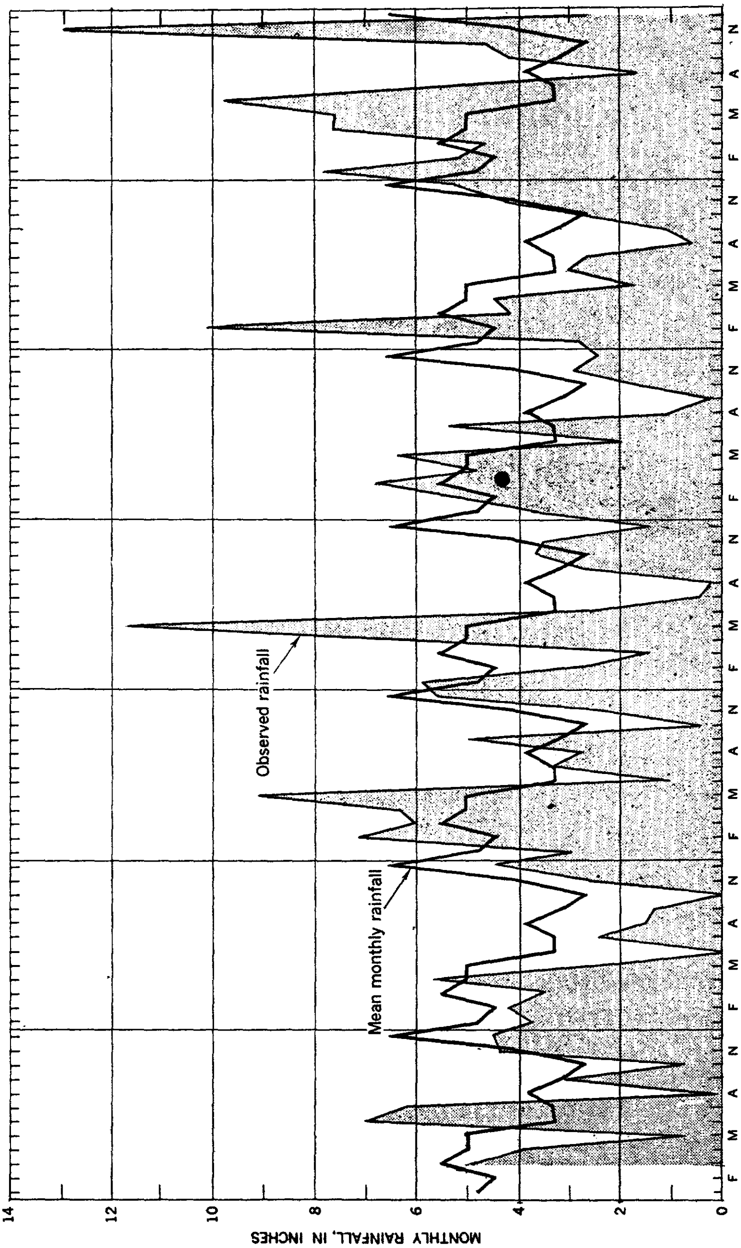

FIGURE 34.—Variation in monthly rainfall at Greenville, Miss.

figure 33. On the outside of the meander loop are the backswamp deposits consisting of clay and silt with some sand. Although there are some shallow wells in this area, the wells tend to be deeper (19 to 71 feet) than in the inside of the meander loops.

The clay plug underlying Lake Washington and other oxbow lakes is the abandoned filled-in channel of the river; it is crescent shaped, conforming to the lake bottom, and the fine-grained sediments may reach depths of 60 to 80 feet below the land surface. Cross sections of other oxbow lakes in the alluvial plain show that the clay plug generally has steep sides and underlies the lakes along their entire lengths. Fine-grained materials consisting of clay, silt, and lenses of sand probably underlie both Lake Jackson (fig. 33) and Lake Washington. Wells located on the bank and along the extension of Lake Jackson, and at the lower end of Lake Washington, were driven to depths of 71 to 100 feet, probably because they could not be completed at shallower depths for lack of sand. A short distance from the edge of Lake Washington shallow wells are also present, indicating that the belt of impermeable deposits does not extend landward far beyond the shores of the lake.

During the nongrowing season and periods of favorable rainfall the area of point-bar deposits will allow recharge to the water table. The backswamp area will allow recharge also, but to a lesser extent than that in the point-bar area. Recharge will be the least in the clay-plug area as the clay extends deeper, and the clay-plug area is narrow in contrast to the backswamp area.

The water-level contour maps, figures 39–47, are based on elevations established in the summer of 1955 by instrumental leveling to 67 driven wells and 1 irrigation well in the vicinity of Lake Washington. Well depths and water levels were measured in November 1954, and water levels in many of the wells have been measured on many occasions since then.

Water-table conditions should exist in the point-bar area and artesian or semiartesian conditions probably occur in the backswamp area. Water under water-table conditions will stand at the height at which it is first tapped in a water-bearing stratum. Water under artesian conditions rises in a well to some height above the top of the water-bearing stratum. Semiartesian conditions exist where water-table and artesian conditions are known to exist at different times of the year in the same place. This has been observed in other parts of the delta where continuous records are obtained of water levels in abandoned irrigation wells.

The water in the ground-water reservoir comes from several sources; rainfall on the land and lake surface in the general area of Lake Washington, seepage from the Mississippi River, and probably upward movement of water from the underlying artesian aquifers in the Tertiary formations. The source of water in the area of Lake Washington is largely rainfall, although a part of the water available must be derived from the river, because the annual rise of the river prevents loss of water to the river, and a small amount probably infiltrates to the ground-water reservoir.

A large amount of water is in storage in the shallow sand and gravel deposits that extend to depths of 100 feet or more. Although more water is stored in clay and silt per equivalent volume of material (because of higher porosity) than in sand and gravel, this water is not readily available because of the much lower permeability of the fine-grained material. In sand and gravel the ground water is readily available. Pumping tests of wells so far made in the delta have yielded storage coefficients ranging from values characteristic of water-table conditions (0.1) to values characteristic of artesian conditions (0.005). The coefficient of storage of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. It is expressed as the decimal fraction of a cubic foot of water discharged from each vertical column of the aquifer having a base 1 foot square as the water level falls 1 foot. For water-table conditions the storage coefficient is practically equal to the specific yield of the material drained or filled; for artesian conditions it is equal to the water obtained from storage by the compression of a column of water-bearing material whose height equals the thickness of the water-bearing material and whose base is 1 foot square, plus a small amount derived by expansion of the water itself as the pressure head declines.

Ground water in the alluvium is in continuous movement from places where the elevation of the water table is high to places where it is lower. The point-bar deposits west of Lake Washington constitute a recharge area. Ground water drains in all directions from this area where the water table is high. Although Lake Jackson lies within the recharge area, it is doubtful that in a short time much water sinks to the water table through the lake bottom, as it is underlain by the plug of relatively impervious silt and clay. Over a long period of time, however, the amount of water added to the water table would be great.

Much of the rainfall available for recharge probably soaks into the sandy area surrounding the lake after soil moisture depleted during the growing season has been replenished during the nongrowing season, and begins its movement to the lake, river, or tributary streams. Late in the year when the lake is low, water seeps into the lake from its flanks and discharges through the ground northward and southward to the river. In spring the reverse is true (figs. 37–48). Water movement is perpendicular to the contour lines on the water-table maps.

The volume of water per unit cross-sectional area that seeps into or out of the lake is proportional to the product of the permeability and the hydraulic gradient. This is in accord with Darcy's law, expressed in the form $Q=PIA$, in which Q is the quantity of water discharged in gallons per day, P is the permeability in gallons per day per square foot, I is the hydraulic gradient measured in a direction perpendicular to the contour lines of the water table on piezometric maps, and A is the cross-sectional area, in square feet, through which the water percolates.

The permeability of the alluvial deposits under the land surface surrounding Lake Washington is much higher than the permeability of the deposits beneath the lake itself if the lake is mostly underlain by a clay plug. Since Lake Washington is not entirely filled with mud, as Lake Jackson is, there probably is a fringe of moderately permeable material surrounding the lake reaching from the shoreline out into the lake to some unknown depth. Water may move more freely through this material than it can through much of the bottom farther from shore. Test holes would show the relationships. However, a gravel-washing plant located several years ago on the west shore of Lake Washington is evidence of the presence along that reach of shoreline of permeable deposits through which ground water might move freely in either direction.

According to Darcy's law the quantity of water seeping into or out of the lake is directly proportional to the hydraulic gradient. If the hydraulic gradient doubles owing to lowering of the lake level, the seepage should likewise double. However, the validity of Darcy's law may be questionable when applied to deposits such as this where the entire section is not completely saturated. The possible variability in permeability of the sides and bottom of the lake precludes the possibility of using Darcy's law with any assurance of accuracy in computing the amount of water draining into or out of the reservoir, without a certain amount of test drilling and extensive permeability tests.

INSTRUMENTATION

A continuous record of the level of Lake Washington has been obtained since October 20, 1954, except for periods when the recorder clock was stopped. Several water-stage recorders were operated in a wooden shelter over a 30-inch corrugated steel-pipe well attached to the south side of the Highland Club pier (fig. 33). The stilling-well intakes were eight ¼-inch diameter holes in the pipe wall. All gage-height record is referred to mean sea level, datum of 1929. A weekly recorder with a 10:12 gage-height ratio (10 inches on the chart equals 1 foot of water) was in use October 8 to December 24, 1956, and May 20 to August 19, 1957. A continuous recorder with a 4:12 gage-height ratio and a 4.8-inches-per-day time scale was in use December 24, 1956, to May 20, 1957.

The temperature of the lake water at the surface was measured with a maximum-minimum thermometer located near the recorder site. The temperature record was not complete because wave action moved the slugs in the thermometer and the entire thermometer several times. A recording thermometer was installed at Wade's pier on June 17, 1957, to assure a more accurate measurement of the average lake-surface temperature.

All the meteorological equipment was located at Wade's pier (fig. 33). Wind speed was measured by two anemometers (airways type, 3-cup) located 100.5 feet and 103.0 feet above mean sea level (2.5 feet and 5.0 feet above the water surface on April 30, 1957). An operations recorder was used to record the wind-speed data. The electrical circuit for the upper anemometer frequently failed to operate, and this record was discarded.

Temperatures and humidities were measured with a weekly recording hygrothermograph. The humidity was checked once weekly, when the hygrothermograph chart was changed, with a sling psychrometer.

Four nonrecording standard U.S. Weather Bureau rain gages were located near the lake (fig. 33). The observers measured rainfall amounts once each day.

Surface outflow from Lake Washington was measured weekly by current meter at a low-water control downstream from the low-head dam. These discharge measurements defined a rating curve relating discharge to lake stage. Daily discharges were taken from the rating curve, using daily mean gage heights obtained from the recorder charts.

Withdrawals from Lake Washington were measured by current meter where possible. Estimates of rate of withdrawals were made using the rated capacity of pumps and other methods. Irrigators kept logs of their time of operation so that the volume of withdrawals could be computed.

THEORY AND ANALYSIS

The basic technique used in measuring the net seepage into and out of Lake Washington was first developed by Langbein and others (1951, p. 13–15). After allowance has been made for surface inflow and outflow, the change in reservoir stage consists of two components, evaporation and seepage. In the mass-transfer theory of evaporation, the exchange of water vapor between a water surface and the atmosphere is calculated from measurements of certain factors affecting the removal of water vapor from a lake by processes of turbulent diffusion and transport. Many equations have been suggested for this purpose. A discussion of the differences between the different equations is beyond the scope of this report but has been given elsewhere (Marciano and Harbeck, 1954, p. 46–70; Harbeck and others, 1958, p. 29–35). All the mass-transfer equations can be expressed in a form similar to the following:

$$E = N\, u\, (e_o - e_a) \tag{1}$$

in which

E = evaporation

u = wind speed, in miles per hour

e_o = saturation vapor pressure corresponding to the temperature of the water surface, in millibars

e_a = vapor pressure of the air, in millibars

The equations differ primarily in the mathematical expressions used to compute the value of the coefficient N. In the Langbein technique the the value of N is of no consequence; it is merely assumed that evaporation is proportional to the product $u\,(e_o - e_a)$.

In the complete absence of wind, evaporation occurs only by molecular diffusion, an extremely slow process. Using an equation developed by Yamamoto (1950, p. 354) it can be shown that evaporation in still air is very small, even if vertical convection currents exist. Evaporation is also very small when the vapor-pressure difference, $(e_o - e_a)$ is almost zero, for then the layer of air over the lake is saturated with water vapor. For the present study, it is assumed that evaporation is zero as a result of either u or $(e_o - e_a)$ being zero, as stated in equation 1.

The application of the foregoing theory to the measurement of seepage is straightforward. For several selected periods, the change in stage in the lake, the wind speed, the water-surface temperature, and the humidity of the air were measured. The change in stage for each period (ΔH) was plotted against the product $u\,(e_o - e_a)$. The intercept on the ΔH axis represents the net seepage loss or gain, for at this point evaporation is zero.

The length of period to be used was determined primarily by the accuracy with which changes in lake stage could be measured. Preliminary studies at Lake Washington were made using a stage-gage reading directly to 0.0001 foot. Stage observations were made at 5-minute intervals during a 6-hour period on October 5, 1956. The results indicated that wind-induced seiches in the lake were sufficiently large to obscure the changes in stage caused by evaporation and seepage, at least for periods as short as a few hours. The record obtained with a continuous water-stage recorder did not permit measuring changes in stage as precisely as did the above-mentioned direct-reading gage; therefore, it was necessary to increase the length of the time interval to obtain a change in stage of comparable accuracy. Moreover, as there was only one recording gage, it was necessary to select periods so that the beginning and end of each period fell at times when the lake was calm, to avoid errors resulting from the water surface not being level or from surges in the stilling well. The data were divided into two groups, one consisting of periods in October, November, and December 1956, when the Mississippi River was at a low stage, and the other of periods in May and June 1957, when the river was at a high stage.

The periods selected in each group were of different lengths, ranging from 24 to 153 hours (table 2). Rainy periods were excluded because surface inflow to the lake was not measured, and because average rainfall on the lake surface could not be determined with sufficient accuracy from the few rainfall records available. Changes in stage were taken from the water-stage-recorder chart and adjusted, if necessary, for outflow from the lake. For each of the priods, average air temperature and relative humidity were taken from the hygrothermograph record; average water-surface temperature was computed from the readings of the floating maximum-minimum thermometer, and average wind speed was obtained from the anemometer record. The anemometers were rigidly mounted at the end of a pier, therefore the height of an anemometer above the water surface varied with the lake stage. During the periods in the fall of 1956, the lower anemometer was 4.8 feet above the water surface and in the spring of 1957, it was 2.9 feet above the water surface. Assuming a logarithmic variation of wind speed with height and using a surface roughness parameter estimated from vertical velocity profiles obtained at other lakes, the recorded wind speeds during spring were increased by 5 percent to make them comparable with those recorded during the previous fall. An error in this adjustment would only change the slope of the regression slightly.

In this analysis the slope of the line is unimportant; the intercept provides the desired answer. From these data the product $u\ (e_o - e_a)$ was computed for each period and the results plotted against ΔH, the change in stage (fig. 35).

A similar analysis was made for selected periods in July and August 1957, but the correlation was poor, probably because the seepage rate was changing rapidly at that time.

In a preliminary statistical analysis, the October–December data and the May–June data were considered to be completely independent. A regresssion coefficient was computed for each set of data; there was no significant difference between the two regression coefficients, and an average of the two was therefore used for both groups. The

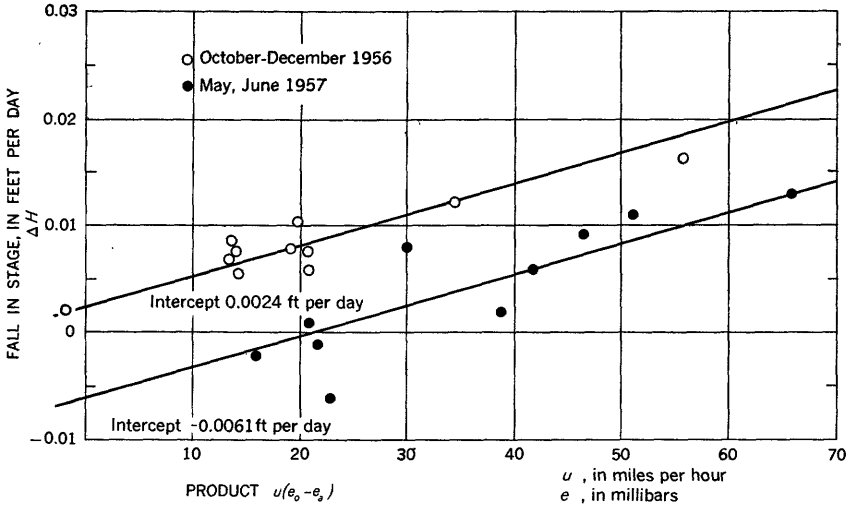

FIGURE 35.—Relation between fall in stage of Lake Washington and the product $u\ (e_o-e_a)$ for spring and fall periods.

intercepts were, of course, not the same. That there was no statistically significant difference between the regression coefficients is in accord with the results of other studies of mass-transfer theory. Only at lakes much larger than Lake Washington is the seasonal effect of changes in atmospheric stability noticeable. Such an effect would cause significantly different regression coefficients for the two groups of data.

The average intercept of 0.0024 foot per day during October, November, and December 1956, indicates that the stage would have fallen that amount each day if there had been no evaporation. In other words, there was an average net seepage loss from the lake of 0.0024 foot per day. During May and June 1957, there was an average net seepage gain of 0.0061 foot per day. At these rates there would be a net loss of 430 acre-feet during a 60-day period in fall and a net gain of 890 acre-feet during a 44-day period in spring, assuming an approximate surface area of 3,000 acres in fall and 3,300 acres in spring.

The seepage losses and gains for the two periods represent the average loss or gain during those periods, not necessarily the peak rates. Little is known concerning seepage rates between the two periods; there is probably a gradual seasonal change from inseepage to outseepage. An idealized sinusoidal seasonal variation is shown in figure 36. Planimetering the areas above and below the horizontal line of zero seepage shows that, during October 1956 to January 1957, net seepage out of Lake Washington totaled about 650 acre-feet and that, during February to September 1957, seepage into the lake

TABLE 2.—*Hydrologic and meteorologic data at Lake Washington for selected periods in the 1957 water year*

Period: From	Period: To	Length of period (hours)	Observed fall in stage (feet)	Correction for surface outflow (feet)	Adjusted fall in stage (feet per day)	Average water-surface temperature (°C)	Average air temperature (°C)	Saturation vapor pressure e_o (millibars)	Vapor pressure of the air, e_a (millibars)	e_o-e_a (millibars)	Wind speed, u (mph)	Product $u\,(e_o-e_a)$
1956												
Oct. 11 (7:00 p.m.)	Oct. 13 (5:00 p.m.)	46	0.0235	0	0.0123	22.5	21.6	27.2	19.4	7.8	4.4	34.3
Oct. 13 (5:00 p.m.)	Oct. 14 (5:00 p.m.)	24	.0085	0	.0085	22.3	21.5	26.9	19.4	7.5	1.8	13.5
Oct. 15 (12:00 p.m.)	Oct. 17 (12:00 p.m.)	48	.021	0	.0105	23.2	21.6	28.4	18.5	9.9	2.0	19.8
Oct. 17 (12:00 p.m.)	Oct. 20 (6:00 a.m.)	54	.018	0	.0080	22.8	21.1	27.8	19.1	8.7	2.2	19.1
Oct. 22 (12:00 p.m.)	Oct. 23 (12:00 p.m.)	24	.006	0	.0060	22.2	20.6	26.8	19.9	6.9	3.0	20.7
Oct. 23 (12:00 p.m.)	Oct. 25 (4:00 a.m.)	28	.008	0	.0069	22.0	19.2	26.4	18.0	8.4	1.6	13.4
Oct. 27 (10:00 p.m.)	Oct. 28 (10:00 p.m.)	24	.0075	0	.0075	22.0	16.4	26.4	14.2	12.2	1.7	20.7
Oct. 31 (9:00 p.m.)	Nov. 1 (9:00 p.m.)	24	.0075	0	.0075	20.3	14.7	23.8	13.3	10.5	1.3	13.6
Nov. 3 (12:00 p.m.)	Nov. 5 (6:00 a.m.)	30	.007	0	.0056	20.8	19.4	24.6	18.9	5.7	2.5	14.2
Nov. 7 (12:00 p.m.)	Nov. 11 (10:00 p.m.)	94	.064	0	.0163	15.7	10.9	17.8	7.5	10.3	5.4	55.6
Dec. 3 (12:00 p.m.)	Dec. 10 (9:00 a.m.)	153	.014	0	.0022	13.2	15.0	15.2	15.5	−.3	5.9	−1.8
1957												
May 13 (12:00 p.m.)	May 14 (12:00 p.m.)	24	0.030	0.028	0.0020	25.6	23.3	32.8	27.2	5.6	6.9	38.6
May 14 (12:00 p.m.)	May 15 (12:00 p.m.)	24	.020	.026	−.0060	27.0	26.1	35.6	28.7	6.9	3.3	22.8
May 15 (12:00 p.m.)	May 17 (12:00 m.)	36	.048	.036	.0080	27.8	26.7	37.4	29.7	7.7	3.9	30.0
May 17 (12:00 m.)	May 18 (12:00 m.)	24	.027	.021	.0060	28.6	26.7	39.1	29.4	9.7	4.3	41.7
May 29 (7:00 a.m.)	May 30 (7:00 a.m.)	24	.021	.010	.0110	29.2	22.2	40.5	19.3	21.2	2.4	50.9
May 30 (7:00 a.m.)	May 31 (7:00 p.m.)	36	.027	.013	.0093	29.4	26.7	41.0	23.8	17.2	2.7	46.4
June 5 (12:00 p.m.)	June 6 (12:00 p.m.)	24	.015	.017	−.0020	27.2	25.0	36.1	26.8	9.3	1.7	15.8
June 6 (12:00 p.m.)	June 7 (12:00 p.m.)	24	.015	.016	−.0010	28.0	26.1	37.8	28.4	9.4	2.3	21.6
June 14 (9:00 p.m.)	June 16 (9:00 p.m.)	48	.045	.019	.0130	29.0	28.3	40.1	30.0	10.1	6.5	65.6
June 25 (6:30 a.m.)	June 26 (6:30 a.m.)	24	.017	.016	.0010	28.9	24.4	39.8	22.5	17.3	1.2	20.8

totaled about 3,100 acre-feet. These estimates are subject to error, but they indicate that seepage into the lake was much greater than seepage out of the lake. Moreover, seepage into the lake was probably much greater than the amount of water pumped for irrigation during the summer of 1957. During July 18 to August 19, pumping records and estimates of nonrecorded pumping indicate that about 425 acre-feet of water was used for irrigation. Presumably, irrigation began in July and continued until the rains began in September. The total volume of water used during the summer probably did not exceed 600 acre-feet, which is equivalent to a depth of about 2 inches over the lake surface area.

Net seepage into Lake Washington during the year that ended September 30, 1957, was about 2,500 acre-feet. The discharge of the Mississippi River at Vicksburg was in the normal range during

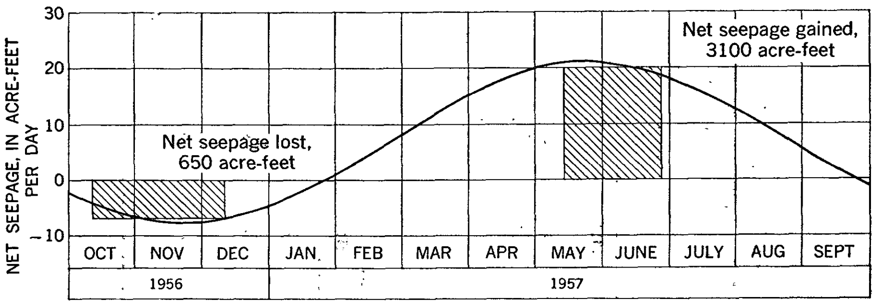

FIGURE 36.—Estimated seasonal variation in seepage losses and gains at Lake Washington, Miss. Net seepage lost from October to January and gained from February to September. Hatched areas represent loss of 430 acre-feet during period of meteorological observation, October 11 to December 10, 1956, and gain of 890 acre-feet during period of observation, May 13 to June 26, 1957.

that same period, and the seepage amount was reasonably representative of normal conditions.

During the 1957 water year, surface outflow from Lake Washington was about 3,500 acre-feet, which agrees with the outflow that might be expected. Average annual rainfall at Greenville is 51.9 inches. If this amount is applicable to Lake Washington, rainfall on the lake surface is about 14,000 acre-feet. According to U.S. Weather Bureau records, gross evaporation from Lake Washington is about 44 inches, or 12,000 acre-feet. The difference of about 2,000 acre-feet would become surface outflow. Adding the net seepage of 2,500 acre-feet calculated for 1957, the total surface outflow (neglecting surface inflow) would be 4,500 acre-feet. Thus, the outflow from Lake Washington as measured in 1957 (3,500 acre-feet) and as estimated from climatological data (4,500 acre-feet) agree reasonably well, and in normal years the outflow from the lake should be about 4,000 acre-feet. The period of maximum outflow from the lake is several months earlier than the period of irrigation demand. Raising the outlet structure only 4 inches would provide an additional 1,000 acre-feet of storage, which is much more than the volume of water withdrawn for irrigation in the summer of 1957.

HYDRAULIC CONSIDERATIONS

During July and August 1957, the volume of water withdrawn for irrigation was about half as great as the surface outflow from the lake. Because the period of maximum lake level does not coincide with the period of maximum irrigation demand, raising the level of the dam that controls the outflow would provide additional storage for irrigation use. Irrigation withdrawals have not yet greatly lowered the lake level. Withdrawals in 1957 were equivalent to a depth of only about 2 inches over the lake-surface area. Moreover, about two-thirds of the water pumped during 1957 was pumped prior to mid-August, when outflow ceased.

Although the lake was spilling much of the time when water was being pumped for irrigation, it cannot be assumed that the irrigators were merely using water that would otherwise have been wasted. This argument would be valid if Lake Washington spilled at all times. But if the lake ceases to spill in summer, the date at which it ceases to spill would be later if no water had been withdrawn previously for irrigation. However, if 500 acre-feet (equivalent to a depth of 1.8 inches over the 3,300-acre lake) were withdrawn in a month, the month-end stage would not necessarily have been 1.8 inches higher if there had been no pumping. The outflow from the lake depends only on the lake stage, and the volume of flow over the broad-crested weir is proportional to the hydraulic head raised to some power greater than unity.

During May 1957, no water was withdrawn for irrigation. The lake stage fell 0.6 foot during the month, and total outflow was about 2,700 acre-feet. Using the close approximation of a simple exponential rating curve and assuming that the natural fall of 0.6 foot per month and the irrigation withdrawals both occurred at a uniform rate, a mathematical analysis was made to determine the effect of the withdrawal on the lake stage. A withdrawal of 500 acre-feet is equivalent to 1.8 inches over the lake surface. But pumping reduced the hydraulic head on the discharge weir, and therefore decreased the outflow from the lake. The net effect was that the lake level would have been lowered only an additional 0.4 inch if 500 acre-feet had been withdrawn for irrigation.

SEEPAGE AS INDICATED BY WATER-TABLE ELEVATIONS

Observations of water levels in wells in the Lake Washington area were made at irregular intervals during November 1954 to September 1958. A map showing water-table contours was prepared for each set of measurements (figs. 39–47). To investigate the possible relation between the stage of the nearby Mississippi River and seepage to and from Lake Washington, two sections were selected, *A–A'* and *B–B'* (fig. 33). From the topographic map and the maps of water-table contours, sections were constructed to show the gradient of the water table in October 1956, December 1956, and April 1967. In October 1956 Lake Jackson was nearly dry, and there was a gentle gradient from that area toward both Lake Washington and the Mississippi River (fig. 37). Section *B–B'* indicates that the water-table gradient was away from Lake Washington and in the direction of Kentucky Bend to the northwest (fig. 38).

The December 1956 sections (figs. 37 and 38) show that gradients were similar to those in October, but were not as steep in the direction of the Mississippi River. Lake Washington was still losing water by seepage in December, which is in agreement with the estimated seasonal variation in seepage illustrated in figure 36.

During April 1957 the river was at a higher elevation than Lake Washington, indicating net seepage into Lake Washington (figs. 37 and 38). Section *B–B'* shows that there may have been also some seepage out of the lake toward the southeast. The net seepage, however, was into the lake, which is corroborated by figure 36.

Figure 39 shows the general relation between the level of Lake Washington and the stage of the Mississippi River. During late summer, fall, and early winter, the river elevation was below the lake elevation. During most of February to July, the reverse was true. The seasonal variation in the relation between these two water levels is in reasonable agreement with the sinusoidal variation postulated in figure 36.

Changes in water-level elevations in 27 wells in the vicinity of Lake Washington and the previously computed figures of seepage losses and gains may be used to approximate the storage coefficient of the alluvium in the area. During August 2 to October 8, 1956, the decline in water levels in the 27 wells ranged from 0.17 to 3.66 feet, averaging 0.023 foot per day. The seepage analysis indicated that during October, November, and December 1956, the net seepage loss was 0.0024 foot per day. If the seepage loss during this period is associated with the decline in water levels during the antecedent months of August to October, the computed storage coefficient is 0.10.

During December 28, 1956, to April 18, 1957, the rise in water levels in the 27 wells ranged from 1.30 to 12.48 feet, averaging 0.033 foot per day. The computed net seepage into Lake Washington dur-

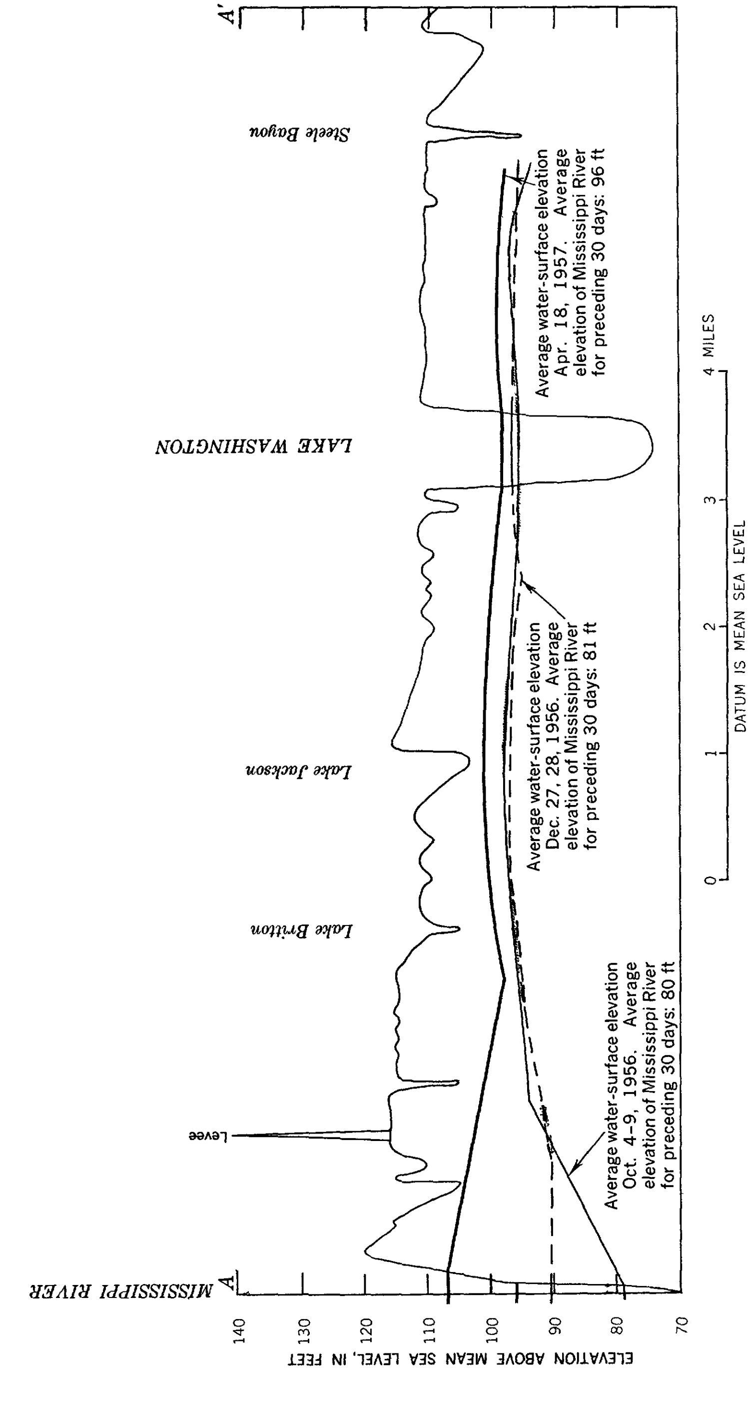

FIGURE 37.—Section *A-A'* showing water-table elevations in the Lake Washington vicinity during October and December 1956 and April 1957.

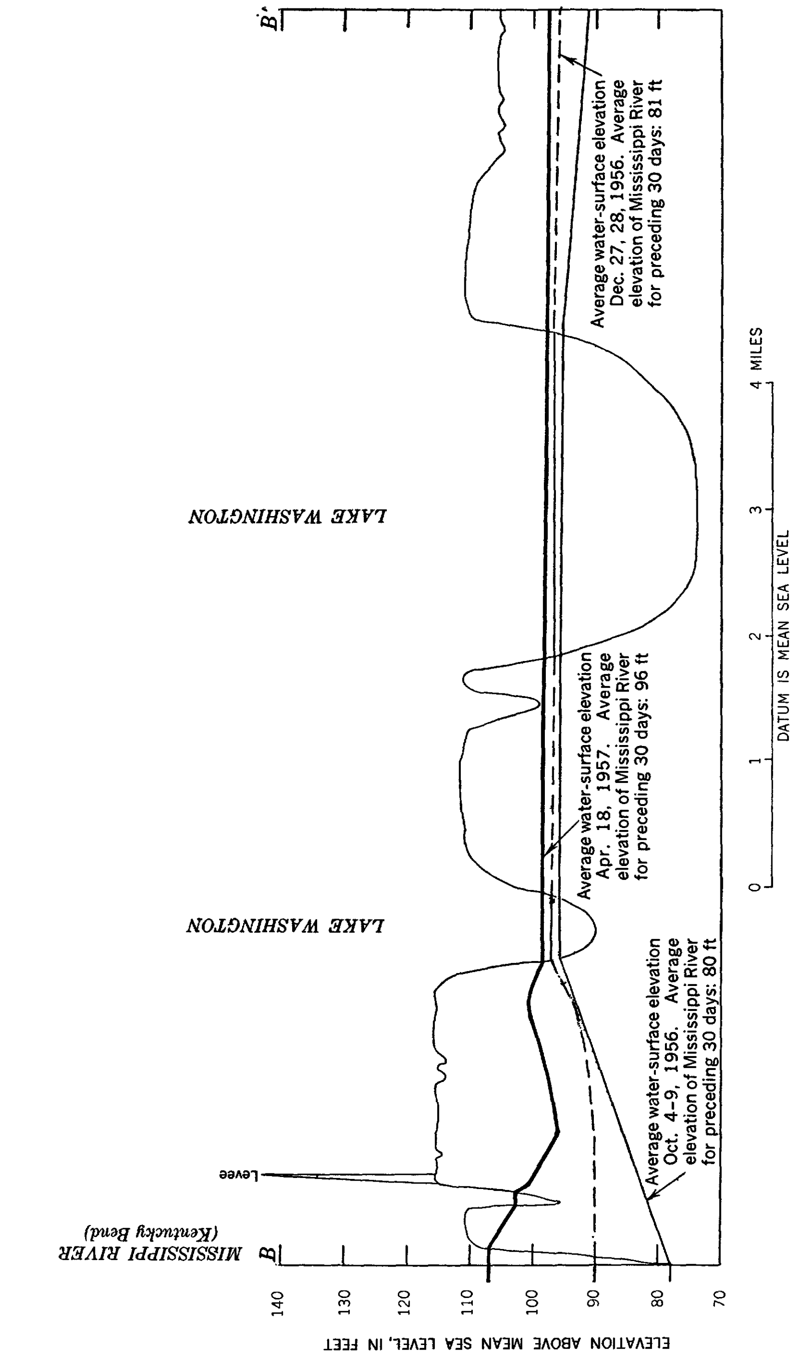

FIGURE 38.—Section B-B' showing water-table elevations in the Lake Washington vicinity during October and December 1956 and April 1957.

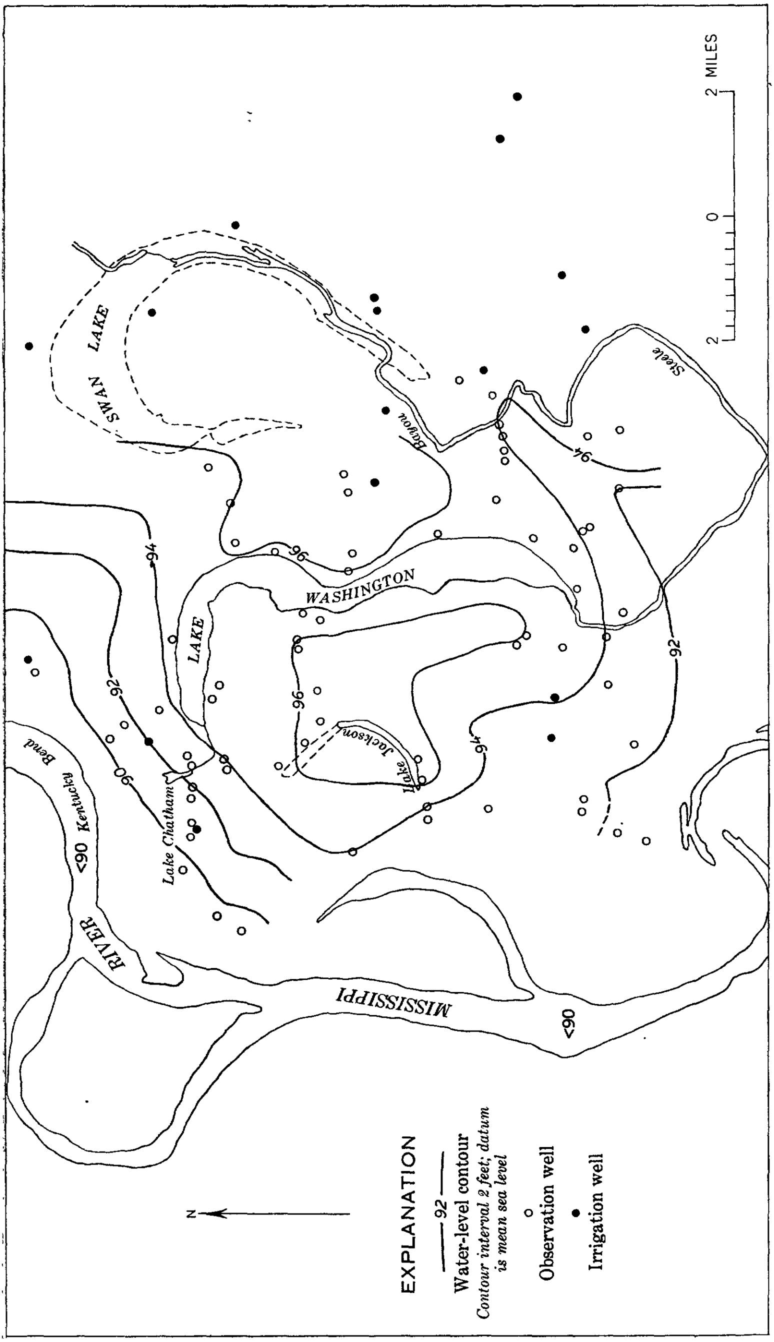

FIGURE 39.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium on November 11–23, 1954.

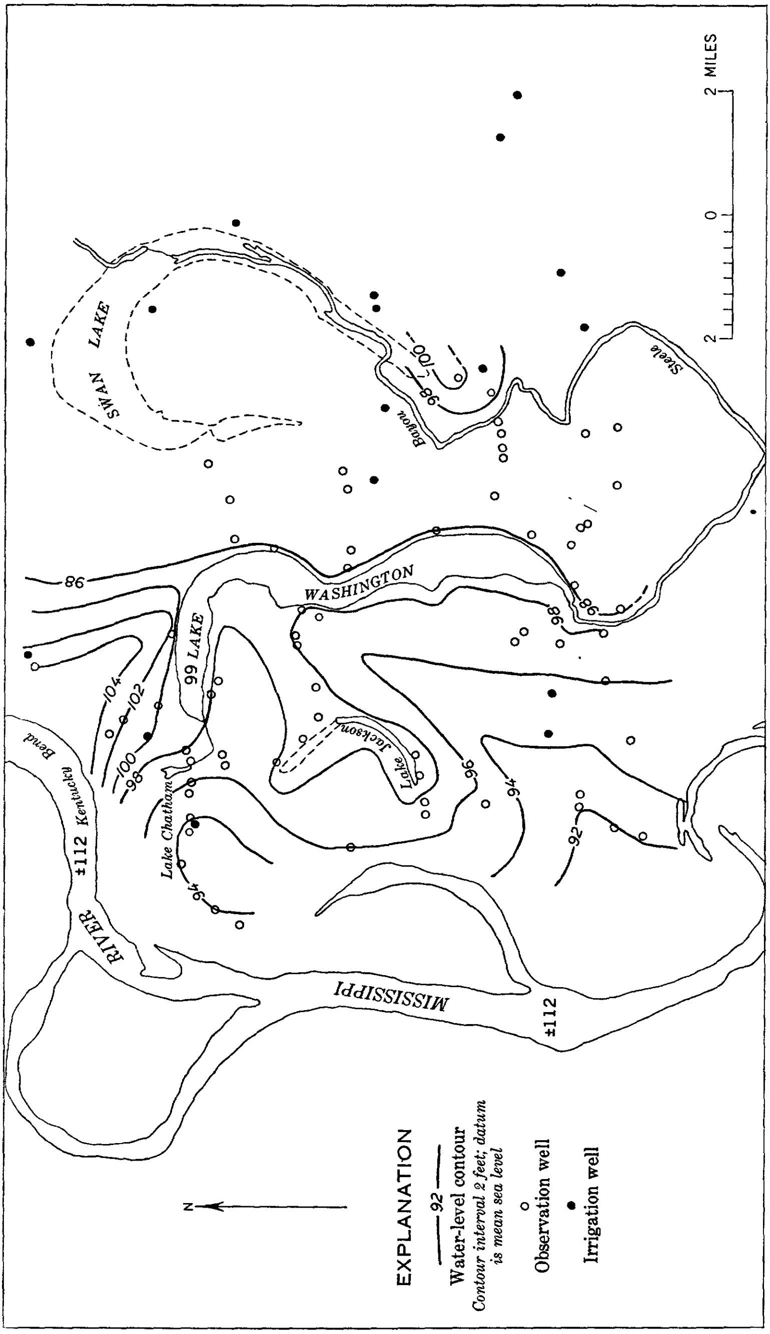

FIGURE 40.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium in April 1955.

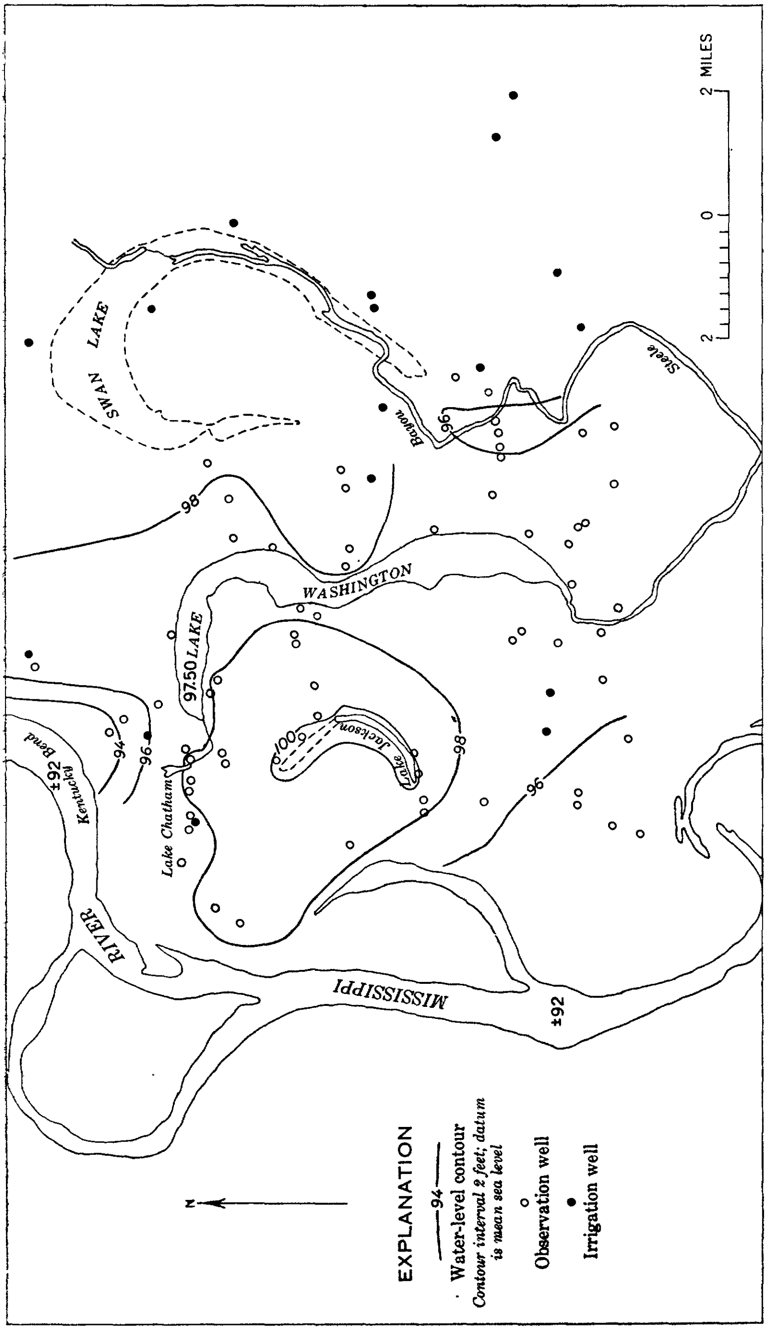

FIGURE 41.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium in June 1955.

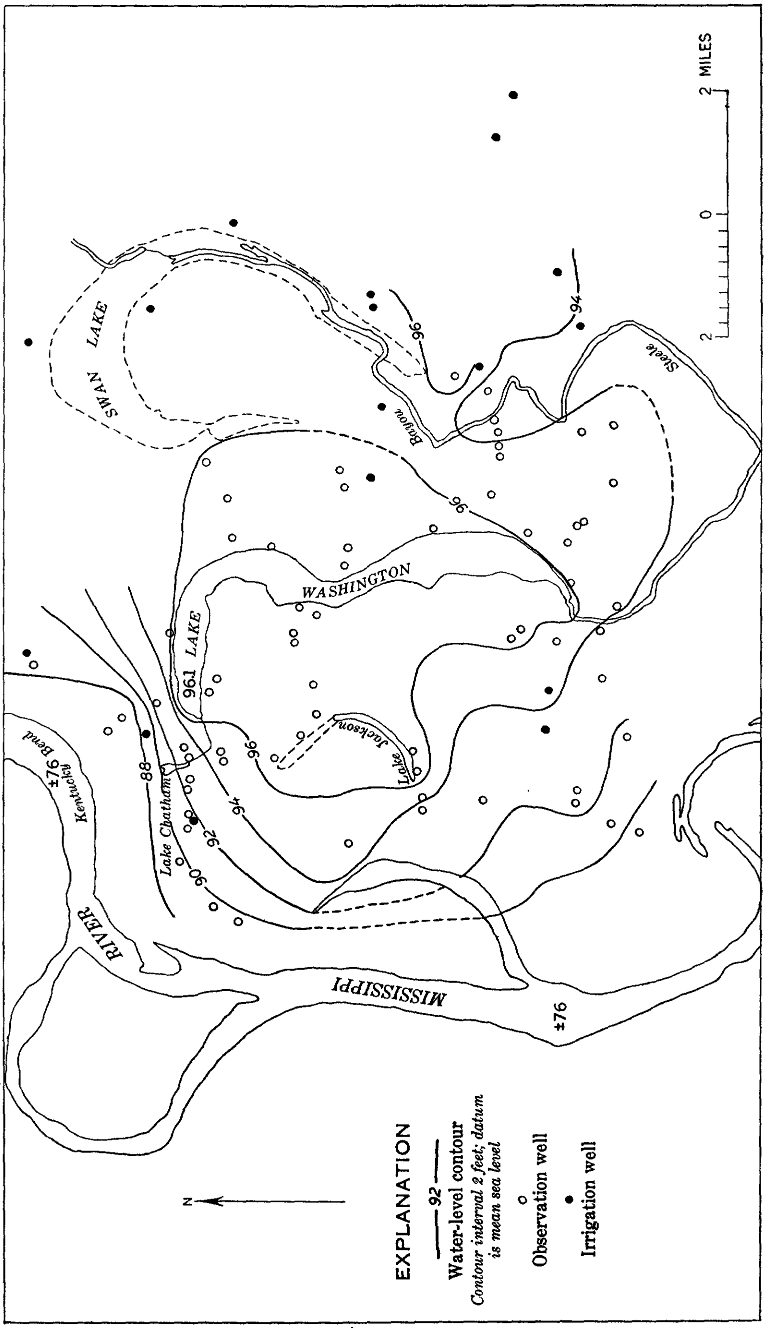

FIGURE 42.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium on January 20, 1956

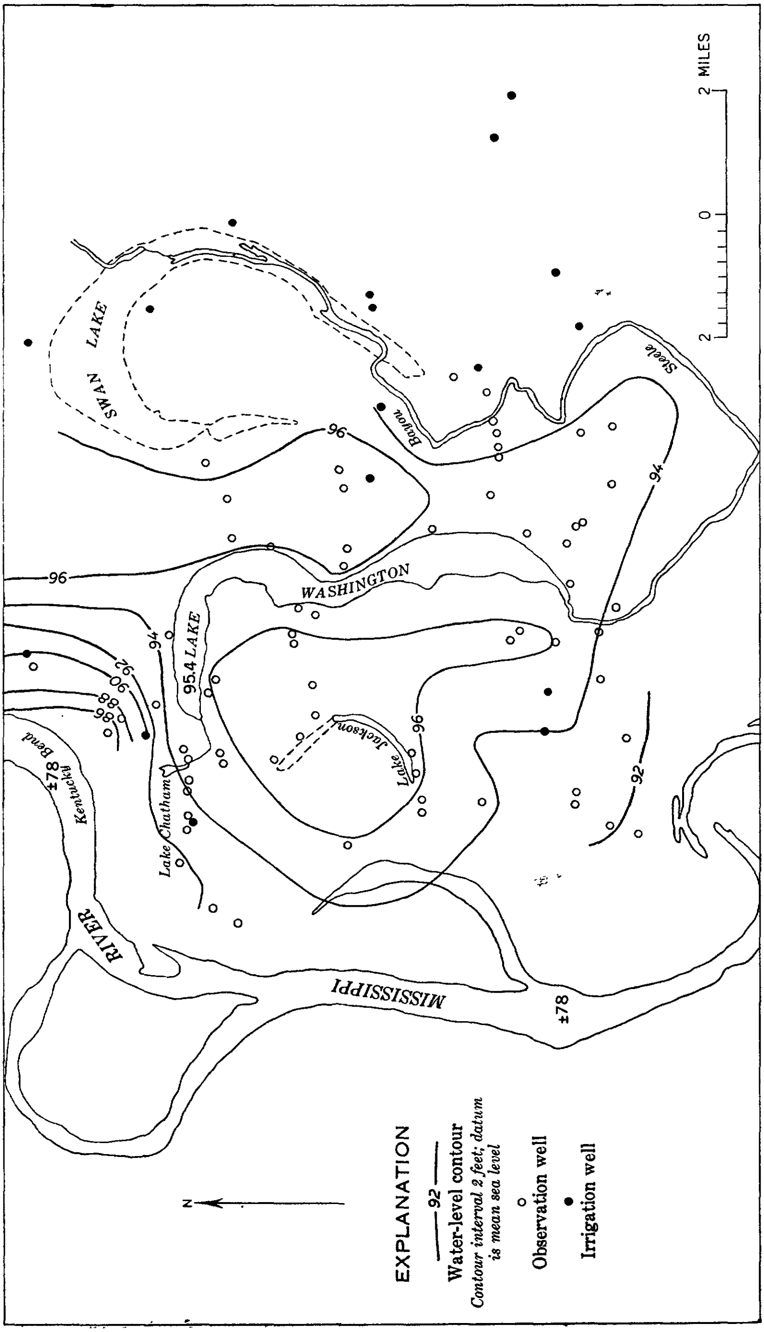

FIGURE 43.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium on October 4–9, 1956.

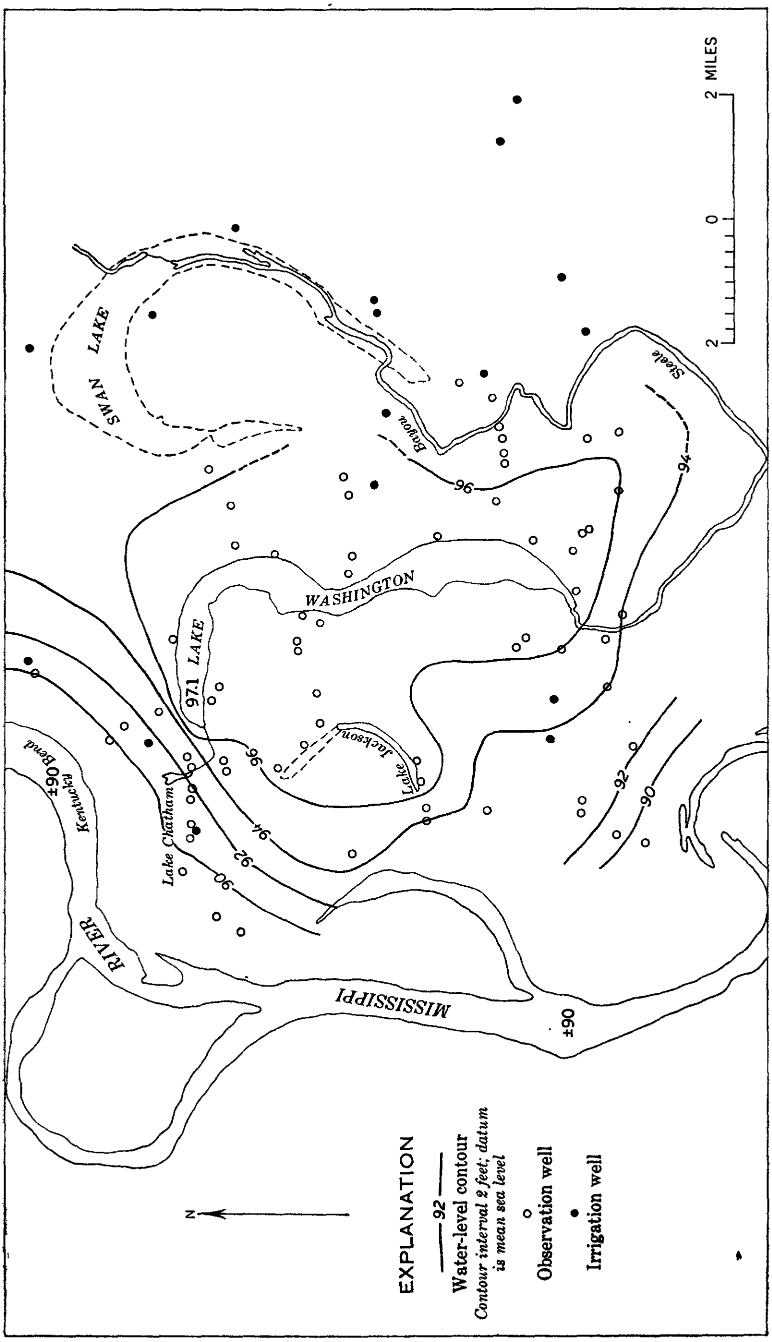

FIGURE 44.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium on December 27, 28, 1956.

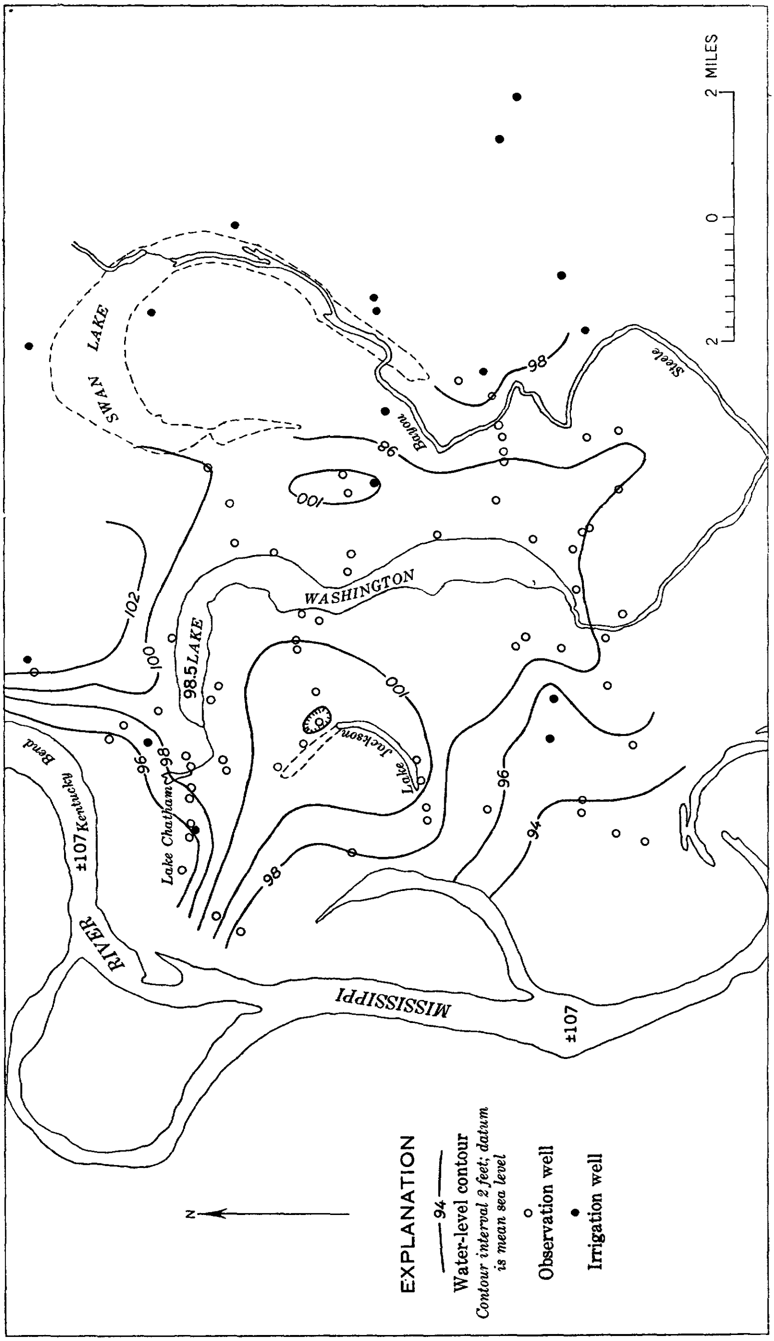

FIGURE 45.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium on April 18, 1957.

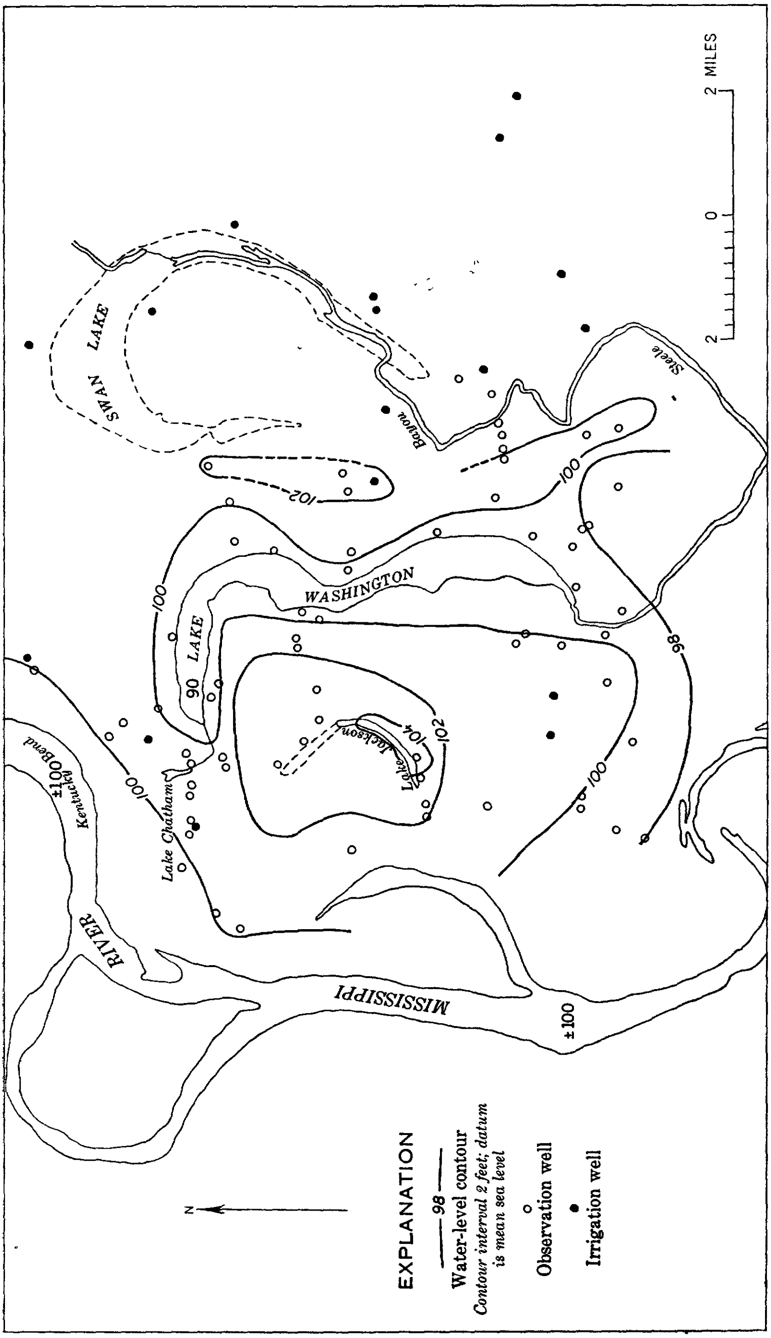

FIGURE 46.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium in March 1958.

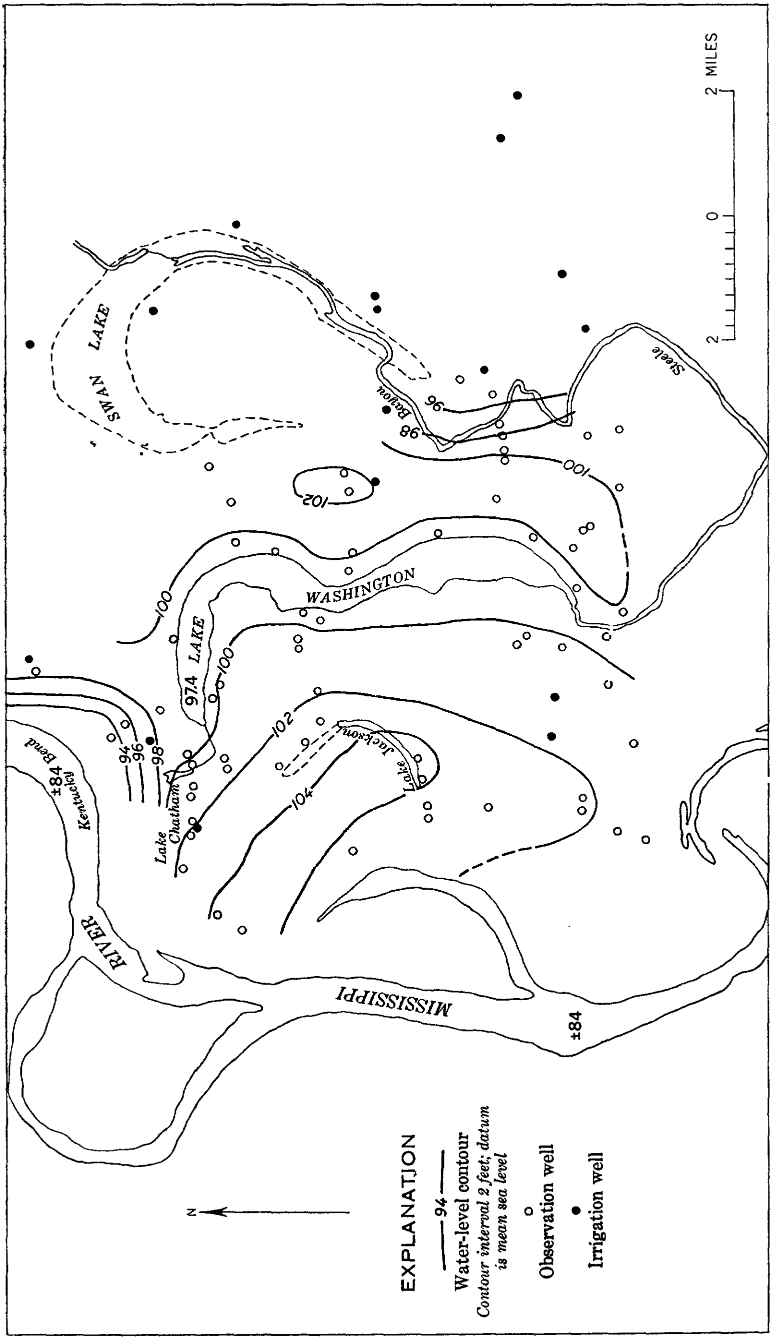

FIGURE 47.—Water-level contour map of Lake Washington area showing the elevation of the water surface in the alluvium on September 9, 1958.

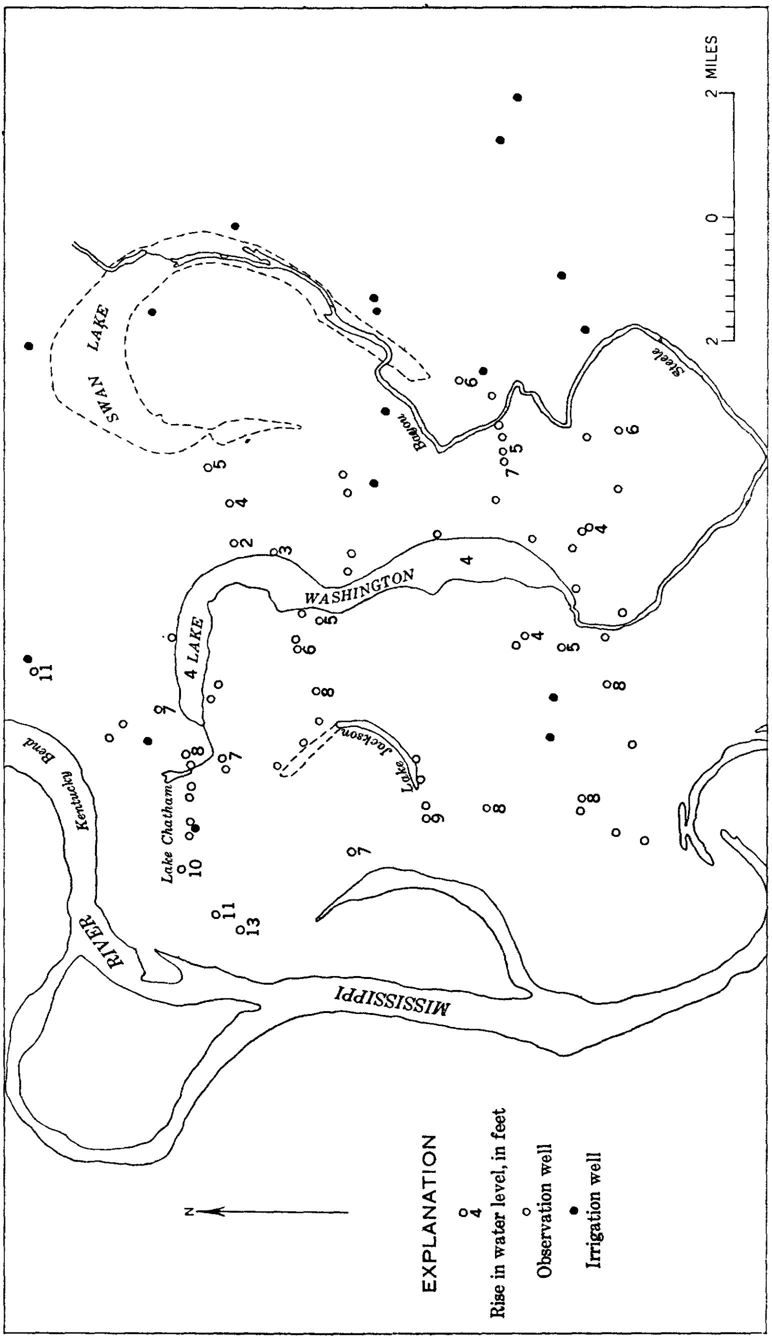

FIGURE 48.—Rise in water levels from November 1954 to March 1958.

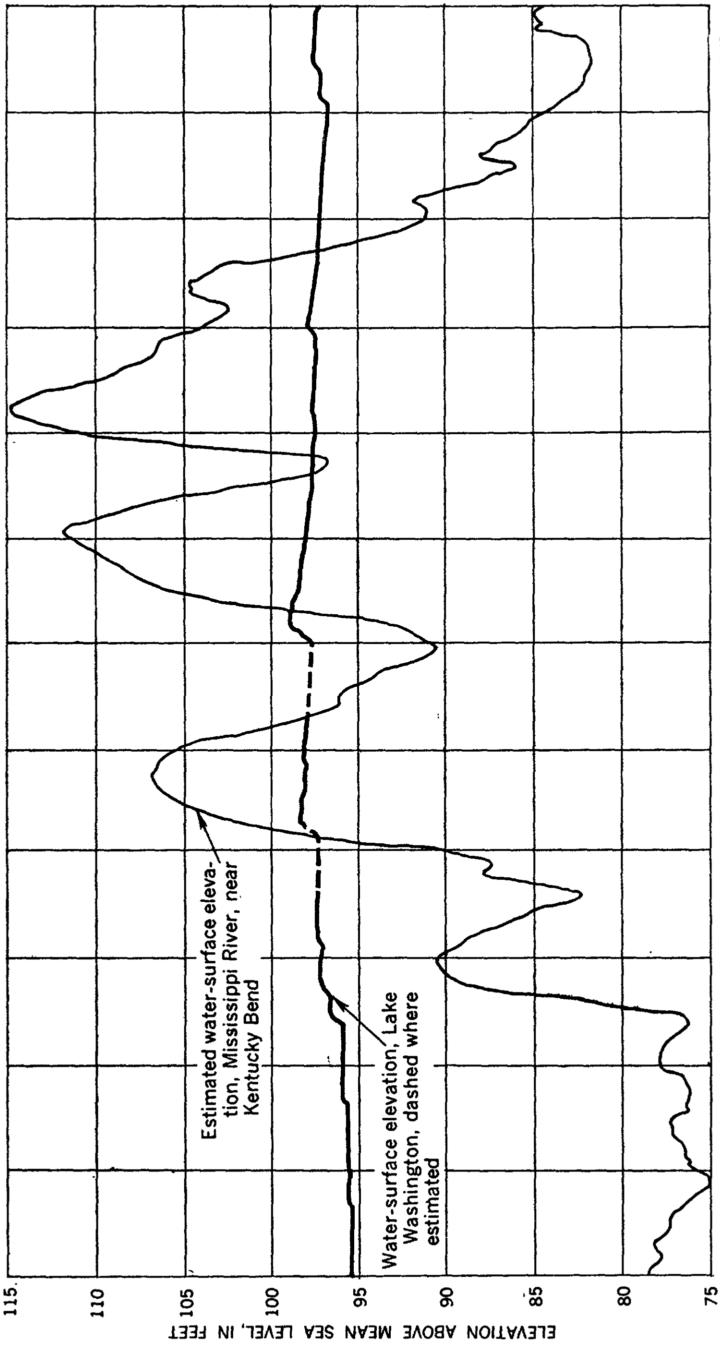

FIGURE 49.—Water-surface elevations of Lake Washington and Mississippi River near Kentucky Bend during the year ending September 30, 1957.

ing May and June 1957, was 0.0061 foot per day. If spring inseepage results from the winter rise in ground-water levels, the computed storage coefficient is 0.18.

The above values of storage coefficient, 0.10 and 0.18, are only approximate, and are given only to show that in general, water-table conditions prevail in the Lake Washington area. The aquifer is heterogeneous, however and the coefficient varies widely throughout the area. A more dependable value of the average for the alluvial deposits would aid in determining the probable increase in seepage caused by steepened hydraulic gradient in the lake area as a result of increased irrigation withdrawals.

CONCLUSIONS

The basic question is the possible effect of increased irrigation withdrawals on the level of Lake Washington. Normal annual precipitation in this area is 52 inches, which over a surface area of 3,300 acres is about 14,000 acre-feet. Evaporation from Lake Washington is somewhat less than the rainfall, so that in normal years, the lake would spill even if it received no surface inflow. Irrigation withdrawals in 1957 were small in comparison with both rainfall on the lake and discharge of ground water into the lake. If irrigation withdrawals ever became large enough to lower the lake level appreciably, the hydraulic gradient toward the lake would be steeper, thus increasing the seepage into the lake during periods when the Mississippi River stage is high or when the water table is high. Also, the relation between lake stage and outflow is such that if the volume of water pumped for irrigation were increased by a specific amount, the lake will not be lowered by an equivalent amount.

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