UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

HYDROLOGY OF HORSESHOE LAKE, ARKANSAS

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Prepared by the U.S. Geological Survey in cooperation with the
Arkansas Geological Commission

Open-File Report 71-177
Little Rock, Arkansas
1971

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ABSTRACT

During the summer and fall, seepage and evaporation losses from Horseshoe Lake, an oxbow or an "old river" lake adjacent to the Mississippi River, exceed inflow to the lake, and seasonal declines of 2.5-3.0 feet in the lake level are common. In exceptionally dry years, the minimum lake level has been as much as 4 feet below the normal seasonal low. These low levels severely affect the recreational uses of the lake.

Seepage and evaporation rates at Horseshoe Lake were determined from hydrologic and meteorologic data. Analysis of these data indicates that the direction of seepage is out of the lake except for a period of about 2 months in the spring, when the stage of the Mississippi River is high.

The lake can be maintained at a constant level by supplementing the inflow to the lake with surface or ground water. Contributions to the lake from local drainage can be increased, but this water contains undesirable amounts of pesticides, herbicides, and plant nutrients, and the flow is insufficient

to eliminate seasonal declines in the lake level. Water from the Mississippi River can be used to maintain a given lake level, but the bacteriological quality of water from the river makes this an undesirable source of supplemental water. Water from the Quaternary alluvium contains troublesome amounts of iron, but it probably is free of pesticides, herbicides, and coliform bacteria which are commonly found in surface water.

An electric-analog model was used to determine the rate at which inflow to the lake must be supplemented to maintain various lake levels. During this investigation, the lake could have been maintained very near the normal spring level by supplementing the inflow at a maximum rate of 10,600 gallons per minute. The analog model was also used to determine the effects of pumping wells on seepage. With the exception of wells near the southeast end of the lake, wells located within one-half mile of the lake would obtain more than 50 percent of their yield from the lake after pumping for 90 days.

INTRODUCTION

This report describes the hydrologic system in the area of Horseshoe Lake, a popular recreational lake in south Crittenden County, Ark. Seasonal declines in the water level of the lake average between 2.5 and 3.0 feet. The low lake levels resulting from these declines, particularly from declines greater than 3 feet, expose fish spawning grounds and aid the growth of aquatic vegetation, both of which severely limit the recreational uses of the lake. Concern among residents and recreational interests led to a study to determine the cause of the changes in the lake level and to evaluate several methods of controlling the level. The study described in this report began in July 1969, and was conducted by the U.S. Geological Survey in cooperation with the Arkansas Geological Commission. The report presents observations and conclusions based on the analyses of hydrologic and meteorologic data, a large part of which was collected between July 1969 and January 1971. The methods used to analyze these data are discussed briefly in this report. A more detailed treatment of the methods of analysis is given in the references.

ACKNOWLEDGMENTS

The author acknowledges, with thanks, the help received from the many people who contributed to this investigation. Many residents of the area allowed access to their property for water-level measurements, the collection of water samples, and the installation of observation wells and test holes. Pat Bonds and Fred New assisted as lake-stage observers. A. H. Shoemaker permitted the installation of water-stage and rainfall recorders on his pier on Horseshoe Lake. Louis Bonds permitted the installation of meteorological equipment at Kamp Kare Free R. B. Snowden permitted the installation of four observation wells on his property and the use of his irrigation well for a pumping test. Permission was also given to conduct pumping tests on two irrigation wells on the H. M. Brinkley Estate.

The author also acknowledges the help received from other agencies and individuals concerned with the problem at Horseshoe Lake. William J. Gilbreath, former District Fishery Biologist with the Arkansas Game and Fish Commission, furnished information and data collected during his preliminary investigations of the problem. Gilbert Strammel, of the Arkansas Soil and Water Conservation Commission, furnished background information and copies of correspondence with other individuals and agencies concerning Horseshoe Lake. Irby Seay, consulting engineer to the Horseshoe Lake Improvement Association, furnished information collected in his investigation of the problem in 1966. The U.S. Army Corps of Engineers, Memphis District, furnished stage records of the Mississippi River, well logs, and the results of permeability analyses of soil samples collected near the Mississippi River levee. The U.S. Soil Conservation Service furnished information on drainage improvements made in the area of Horseshoe Lake and on proposed projects that will affect the lake.

DESCRIPTION OF THE AREA

The area of this report includes 72 square miles in Crittenden, St. Francis, and Lee Counties, Ark. Horseshoe Lake is an oxbow lake, about 6¼ miles long and three-eighths to 1 mile wide, in Crittenden County about 16 miles southwest of West Memphis, Ark., and about 6 miles east of Hughes, Ark. It is the largest of five lakes that occupy an old meander loop of the Mississippi River (fig. 1). The five lakes and their approximate surface areas are: Horseshoe Lake, 2,300 acres; Porter Lake, 460 acres; Goose Lake, 110 acres; Brushy Lake, 64 acres; and a small lake between Brushy and Porter Lakes that has a surface area of about 4 acres.

Horseshoe Lake, the deepest of the five lakes, has a maximum depth of about 30 feet. Porter Lake has a maximum depth of about 9 feet. The smaller lakes are shallow and have maximum depths of 6 feet or less.

These oxbow or "old river" lakes have a combined drainage area of about 19,150 acres. The approximate drainage areas of the larger lakes are: Horseshoe Lake, 15,000 acres; Porter Lake, 1,920 acres; Goose Lake, 1,600 acres; and Brushy Lake, 615 acres. Prior to the completion of the Mississippi River levee, these lakes received floodwaters from the river during periods of high river stage and drained excess water into the river during periods of high lake stage. When the levee was

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completed, in about 1917, the surface connection between the Mississippi River and the lakes was blocked. The system of lakes now (1971) has no drainage outlet except during periods of high lake stage, when the lakes drain into the St. Francis River basin by way of Fish Bayou, Fifteen Mile Bayou, and Blackfish Bayou.

The area of this report is on the alluvial plain of the Mississippi River. This alluvium, of Quaternary age, consists of sand and gravel, and varying amounts of silt and clay at the surface. These deposits average about 150 feet in thickness in the vicinity of Horseshoe Lake, and the gravel and coarse sand at the base of the alluvium yield large quantities of water to wells. The alluvium is underlain by deposits of Tertiary age, which yield water to the deep wells in the area. Land surface in the area is relatively flat, with elevations ranging from 195 to 206 feet above mean sea level. Because of the flat terrain, streams in the area are sluggish. Average annual rainfall is about 49 inches. Average annual air temperature is 16.7°C (62.0°F), and mean monthly temperatures range from 5.8°C (42.4°F) in January to 27.2°C (81.0°F) in July. The economy is predominantly agricultural, with cotton, soybeans, wheat, and alfalfa the most important crops.

CONTROLS ON LAKE STAGE

Lake-stage fluctuations in the five lakes are the result of variation in rainfall, runoff to and from the lakes, evaporation, pumpage from the lakes, and underground seepage into and out of the lakes. At present pumpage from the lakes is small and changes in lake levels are primarily the result of natural conditions. In summer and fall, the amount of water lost due to evaporation and seepage exceeds that contributed to the lakes by rainfall and runoff, and lake levels decline. Hydrographs of Horseshoe and Porter Lakes are shown in figure 2.

In 1969 the minimum observed lake-level elevations of Horseshoe and Porter Lakes were 190.06 and 190.88 feet, very near the normal minimum lake levels. (In this report all elevations are referred to mean sea level.) During extremely dry years, the lakes have declined to levels several feet below the normal seasonal minimum. In 1954 Horseshoe Lake is reported to have declined to an elevation of about 186 feet (4 feet below the normal minimum level).

The maximum elevation to which the lake level can rise depends on the elevation of the control that regulates flow out of the lakes. The outlet control for Horseshoe Lake is the highest point of the flow line in Beck Bayou that connects Horseshoe Lake and Fish Bayou. Normally, the highest point in the flow line of Beck Bayou is a section of filled-in channel that has a crest elevation of 192.7 feet, but the channel occasionally is obstructed

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by debris, vegetation, and beaver dams. Interpretation of the hydrograph in figure 2 indicates that in 1969 Horseshoe Lake reached an elevation of 192.7 feet (the normal spring lake level) in April. Inflow to the lake in the latter part of April and the early part of May 1969 was lost to Fish Bayou by way of Beck Bayou. In 1970 a beaver dam on Beck Bayou made it possible for the lake to contain the heavy spring rainfall and runoff, and the lake level rose to an elevation of 193.5 feet. Elevation of the control regulating flow between Horseshoe and Porter Lakes in 1970 was about 193.3 feet, as interpreted from hydrographs (fig. 2) and rainfall records. In the latter part of April 1970, Porter Lake contributed water to Horseshoe Lake and the two lakes were probably connected until late May or early June.

The controls which regulate flow out of these lakes also serve to regulate the flow into the lakes. When the elevation of the water level in Fish Bayou is greater than that of the control in Beck Bayou, water flows from Fish Bayou into Horseshoe Lake. The average amount of water contributed annually to Horseshoe Lake by Fish Bayou is relatively small, but occasionally flooding on Fish Bayou causes floods on Horseshoe and Porter Lakes. In the spring of 1962, backwater from floods in St. Francis River caused severe flooding in Fish Bayou and in the lakes. The water-level elevation in Horseshoe Lake that year is reported to have been 195 feet (more than 2 feet above the normal maximum).

PUMPAGE FROM THE LAKES

Pumpage from the lakes has never been great. During dry years water has been pumped for supplemental irrigation of cotton and soybeans for periods of about 1 week, two or three times during the growing season. The total withdrawal for irrigation during any one year probably did not exceed 500 acre-feet on Horseshoe Lake and 100 acre-feet on Porter Lake. These withdrawals are small and represent a volume of water equivalent to a depth of about 2½ inches over the surfaces of the lakes. Local concern about low lake levels has caused most landowners to stop irrigating with water from the lakes and little if any water is presently pumped from the lakes.

EVAPORATION

Evaporation is a significant factor in the water budget of the lakes. U.S. Weather Bureau evaporation maps (Kohler, Nordenson, and Baker, 1959, pl. 2) show that the average annual lake evaporation from Horseshoe Lake is about 41 inches, which is equivalent to an annual loss of about 7,860 acre-feet of water. Kohler, Nordenson, and Baker (1959, pl. 4) indicate that about 72 percent of the annual evaporation occurs during the period May through October. During this period, lake evaporation averages about 30 inches, or 5,750 acre-feet, and is equivalent to an average daily decline of 0.014 foot in the stage of the lake. Evaporation rates at nearby Weather Bureau stations for the period May through October 1969 were among the highest of record. Evaporation from Horseshoe Lake during this period may have been as much as 37 inches, which would result in an average daily decline of 0.017 foot, or 0.20 inch in the stage of the lake.

Although lake evaporation cannot be measured directly, several methods have been used to compute lake evaporation in studies by the Geological Survey (Harbeck and others, 1958; Shjeflo, 1968). These studies confirmed the long-held belief that evaporation is proportional to the product of wind speed, in miles per hour, and the difference between the vapor pressure corresponding to the temperature of the water surface, in millibars, and the vapor pressure of the air, in millibars. This method of determining evaporation from lakes, known as the mass-transfer method, has been applied to the study of Horseshoe Lake. A detailed explanation of the theory, method of analysis, and instrumentation required are not contained in this report but are given elsewhere (Marciano and Harbeck, 1954; Harbeck and others, 1958; and Shjeflo, 1968).

The mass-transfer equation for determining evaporation, as used in this study, can be expressed as

$$E=Nu(e_o-e_a),$$

in which E is evaporation, in inches per day; N is the coefficient of proportionality, hereafter called the mass-transfer coefficient; u is wind speed, in miles per hour, at a height of 2 meters above the water surface; e_o is saturation vapor pressure, in millibars, corresponding to the temperature of the water surface; and e_a is vapor pressure of the air, in millibars, which is equal to the product of the saturation vapor pressure corresponding to the air temperature and the relative humidity.

The factors affecting evaporation were measured with recording instruments located as shown in figure 1. Wind speed and water-surface temperature were measured with a recording anemometer and a water-temperature recorder, mounted on a raft anchored in the middle of the lake. Air temperature and relative humidity were measured with a recording hygrothermograph at Kamp Kare Free.

The mass-transfer coefficient N was determined graphically in the following manner. The decline in lake stage, ΔH, in feet per day, was plotted against $u\Delta e$, the average daily value of the product $u(e_o - e_a)$, for periods ranging from 2 to 5 days in length during which there was little or no surface inflow or outflow. The slope of the least-squares line, drawn through these plotted points, is the mass-transfer coefficient, N. The mass-transfer coefficient for Horseshoe Lake was determined from nine periods in November and December 1969, when the Mississippi River was at a low stage, and also from seven periods in March, April, and

May 1970, when the river was at a high stage. Data for these periods are given in table 1. No significant difference was found between the slopes or mass-transfer coefficients for the two sets of data, and an average slope of 0.000232 was used for both sets (fig. 3). Interpretation of figure 3 indicates that the value of the mass-transfer coefficient N for Horseshoe Lake probably remains constant throughout the year. This is in agreement with the results of other mass-transfer studies (Harbeck and others, 1961). Although the degree of accuracy with which changes in lake stage were measured was less than that commonly used in more detailed mass-transfer studies, the mass-transfer coefficient determined for Horseshoe Lake (0.000232) is in excellent agreement with those determined for other lakes of about the same surface area (Harbeck, 1962). Evaporation from Horseshoe Lake for the period July 1969 through December 1970, as computed from the mass-transfer equation, is given in table 2.

SEEPAGE

The net seepage between the lake and the alluvial aquifer depends on the permeability of the lakebed material and the difference in hydraulic head forcing water to move through this material. Much of Horseshoe Lake is underlain by mud and clay of low permeability, but parts of the lake are underlain by

Table 1.—*Hydrologic and meteorologic data at Horseshoe Lake for selected periods in 1969 and 1970*

Computation period	Length of period, in days	Average wind velocity (u), in miles per hour	Average daily value of saturation vapor pressure (e_o), in millibars, corresponding to water-surface temperature	Average daily value of vapor pressure of the air (e_a), in millibars	Δe, average daily e_o-e_a, in millibars	Product, $u\Delta e$	Decline in lake stage (ΔH), in feet per day[1]
			1969				
Nov. 1-4-------	4	4.65	16.35	7.95	8.40	39.1	[2]0.0160
Nov. 5-7-------	3	3.62	15.90	10.77	5.13	18.6	.0100
Nov. 8-10------	3	2.13	16.50	10.83	5.67	12.1	.0100
Nov. 26-30-----	5	5.60	11.50	6.18	5.32	29.8	[3].0122
Dec. 1-3-------	3	5.04	11.13	6.23	4.90	24.7	.0100
Dec. 4-5-------	2	7.14	10.80	4.40	6.40	45.7	.0150
Dec. 10-14-----	5	5.34	10.12	7.20	2.92	15.6	.0080
Dec. 15-16-----	2	5.42	10.20	5.85	4.35	23.6	.0100
Dec. 17-20-----	4	3.96	10.20	6.65	3.55	14.1	.0075
			1970				
Mar. 13-16-----	4	7.56	10.60	4.70	5.90	44.6	0.0100
Mar. 29-31-----	3	7.08	11.93	8.43	3.50	24.8	[3].0069
Apr. 7-9-------	3	7.71	15.90	9.57	6.33	48.8	.0100
Apr. 10-11-----	2	3.83	18.00	11.50	6.50	24.9	.0050
Apr. 14-15-----	2	6.00	17.70	10.15	7.55	45.3	.0100
May 5-7--------	3	5.24	25.30	16.07	9.23	48.4	.0100
May 11-15------	5	9.22	27.76	20.74	7.02	64.7	.0160

[1]Average daily decline in stage computed from total decline for the computation period, measured to the nearest 0.01 foot.
[2]Adjusted for 0.05 inch of rainfall on the lake.
[3]Adjusted for 0.01 inch of rainfall on the lake.

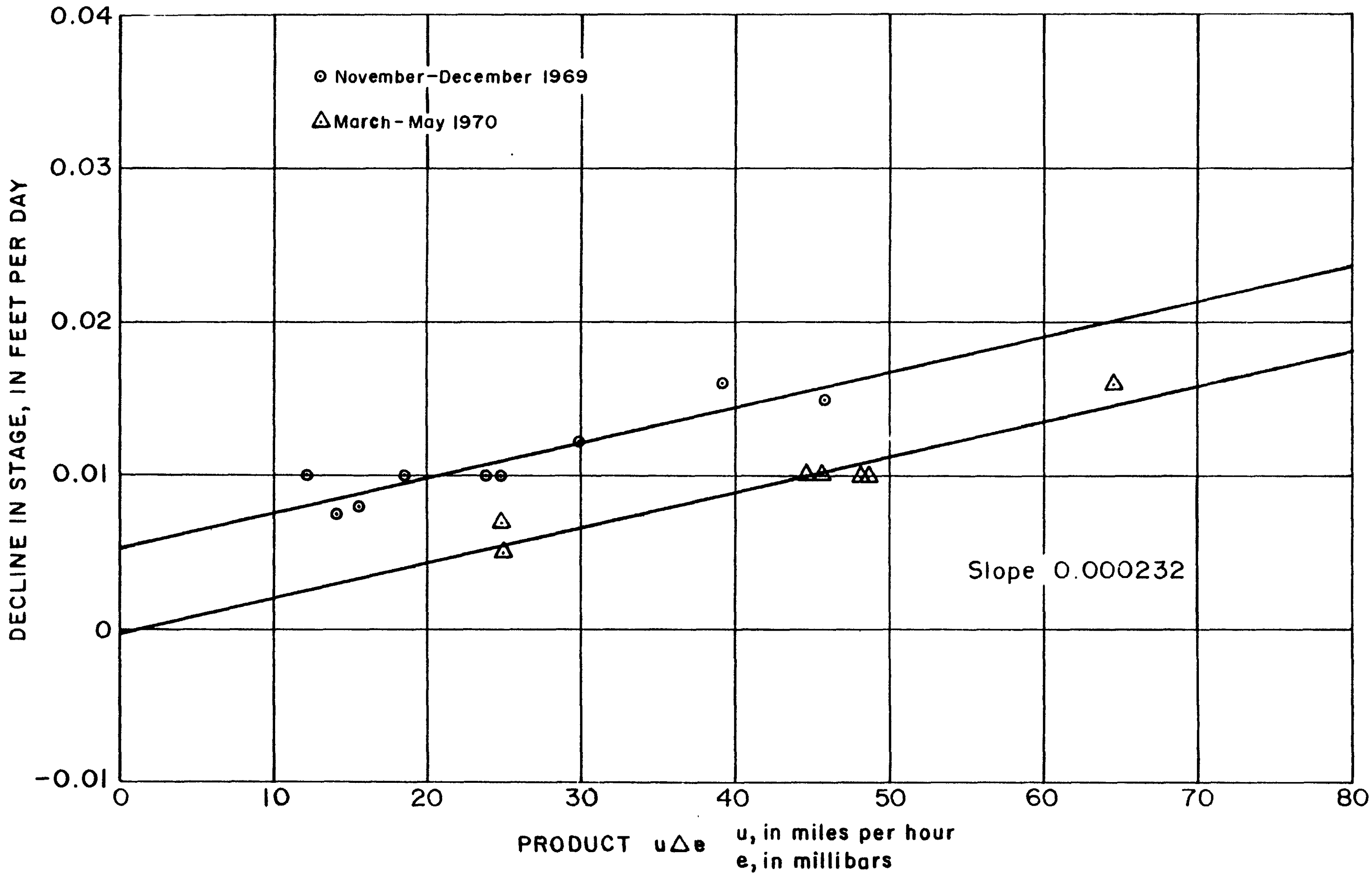

Figure 3.—Relation between decline in stage of Horseshoe Lake and the product $u\Delta e$ for spring and fall periods.

Table 2.—*Evaporation from Horseshoe Lake, Ark.*

[Based on the mass-transfer equation with a mass-transfer coefficient of 0.000232]

Month	Average wind speed (miles per hour)	Average water temperature		Average air temperature		Average relative humidity (percent)	Evaporation	
		°C	°F	°C	°F		Feet	Inches
1969								
July-------	[1]5.26	[1]31.1	[1]88	[1]28.9	[1]84	[1]75	[2]0.526	[2]6.31
August-----	4.75	28.9	84	25.6	78	76	.512	6.14
September--	4.35	26.1	79	22.2	72	79	.381	4.57
October----	6.14	20.0	68	16.1	61	69	.477	5.72
November---	5.83	11.9	53	9.4	49	68	.231	2.77
December---	6.15	6.7	44	4.4	40	74	.158	1.90
1970								
January----	6.76	2.8	37	1.7	35	67	0.140	1.68
February---	6.28	4.4	40	5.0	41	70	.095	1.14
March------	7.41	8.3	47	8.9	48	70	.161	1.93
April------	8.44	16.1	61	17.8	64	64	.312	3.74
May--------	6.75	23.3	74	22.8	73	65	.521	6.25
June-------	6.68	25.6	78	24.4	76	71	.510	6.12
July-------	4.75	27.8	82	25.6	78	76	.428	5.14
August-----	4.19	27.8	82	25.0	77	81	.350	4.20
September--	5.58	27.8	82	23.9	75	78	.552	6.62
October----	5.26	18.9	66	16.7	61	73	.316	3.79
November---	7.78	12.2	54	10.0	50	69	.309	3.71
December---	6.67	10.0	50	8.3	47	73	.205	2.46

[1]Average is for the period July 4-31, 1969.
[2]Adjusted to a full month.

46.78

medium-grained sand of relatively high permeability. Permeability tests were made on 45 samples of lakebed material, and 82 percent of these samples had permeabilities of less than 1 gpd per sq ft (gallon per day per square foot) at 15.6°C (60.0°F). However, the permeabilities of two samples, collected near the north shoreline a few hundred yards west of Kamp Kare Free, were 165 and 231 gpd per sq ft at 15.6°C (60.0°F). These permeabilities indicate a high degree of connection between the lake and the alluvial aquifer near the north shore.

Seepage as Determined From Mass-Transfer Analysis

The technique used in measuring the net seepage into and out of Horseshoe Lake was first developed by Langbein and others (1951, p. 13-15). It involves the measurement of evaporation by the use of the mass-transfer method and assumes that, during periods of no surface inflow or outflow, changes in lake stage are the result of evaporation and seepage.

Seepage at Horseshoe Lake was determined for 47 periods, ranging from 2 to 13 days in length, during which there was very little or no surface inflow or outflow (table 3). Seepage rates for each of these periods were determined by taking the difference between the rate of change in lake stage and the evaporation rates computed by using the mass-transfer equation described earlier in

Table 3.—*Seepage computation sheet for selected periods for Horseshoe Lake, Ark.*

[Decline in lake stage: Average daily decline in stage computed from total decline for the computation period, measured to the nearest 0.01 foot]

Computation period	Length of period, in days	Decline in lake stage (ΔH), in feet per day	Average wind velocity (u), in miles per hour	Average daily value of saturation vapor pressure (e_o), in millibars, corresponding to water-surface temperature	Average daily value of vapor pressure of the air (e_a), in millibars	Δe, average daily e_o-e_a, in millibars	Evaporation ($0.000232 X u X \Delta e$), in feet per day	Seepage into (+) or out of (-) lake (evaporation minus ΔH), in feet per day
1969								
July 4-10-------	7	0.0243	5.79	47.34	31.70	15.64	0.0210	-0.0033
July 14-17------	4	.0275	5.72	48.97	29.15	19.82	.0263	-.0012
July 29-Aug. 8--	11	.0227	3.66	40.27	23.55	16.72	.0142	-.0085
Aug. 11-15------	5	.0260	5.22	40.86	22.76	18.10	.0219	-.0041
Aug. 24-31------	8	[1].0201	3.65	39.81	24.85	14.96	.0127	-.0074
Sept. 7-19------	13	.0223	4.71	34.91	20.48	14.43	.0158	-.0065
Sept. 25-30-----	6	.0167	2.98	30.78	17.75	13.03	.0090	-.0077
Oct. 10-12------	3	.0167	9.51	28.03	22.66	5.37	.0118	-.0049
Oct. 15-25------	11	.0191	5.12	21.11	9.78	11.33	.0134	-.0057
Oct. 27-29------	3	.0233	5.88	18.53	7.10	11.43	.0156	-.0077
Nov. 1-4--------	4	[2].0160	4.65	16.35	7.95	8.40	.0091	-.0069
Nov. 5-7--------	3	.0100	3.62	15.90	10.77	5.13	.0043	-.0057
Nov. 8-10-------	3	.0100	2.13	16.50	10.83	5.67	.0028	-.0072
Nov. 26-30------	5	[1].0122	5.07	11.50	6.18	5.32	.0063	-.0059
Dec. 1-3--------	3	.0100	5.04	11.13	6.23	4.90	.0057	-.0043
Dec. 4-5--------	2	.0150	7.14	10.80	4.40	6.40	.0106	-.0044
Dec. 10-14------	5	.0080	5.34	10.12	7.20	2.92	.0036	-.0044
Dec. 15-16------	2	.0100	5.42	10.20	5.85	4.35	.0055	-.0045
Dec. 17-20------	4	.0075	3.96	10.20	6.65	3.55	.0032	-.0043
1970								
Jan. 16-22------	7	0.0057	6.15	6.73	4.72	2.01	0.0029	-0.0028
Jan. 27-31------	5	[3].0043	9.54	8.88	7.36	1.52	.0034	-.0009
Feb. 9-13-------	5	.0060	5.88	8.16	5.50	2.66	.0036	-.0024
Feb. 18-22------	5	[4].0045	6.77	8.60	6.06	2.54	.0040	-.0005
Mar. 13-16------	4	.0100	7.56	10.60	4.70	5.90	.0103	+.0003
Mar. 29-31------	3	.0069	[1]7.08	11.96	8.43	3.53	.0058	-.0011
Apr. 7-9--------	3	.0100	7.71	15.90	9.57	6.33	.0113	+.0013
Apr. 10-11------	2	.0050	3.83	18.00	11.50	6.50	.0058	+.0008
Apr. 14-15------	2	.0100	6.00	17.70	10.15	7.55	.0105	+.0005
May 5-7---------	3	.0100	5.24	25.30	16.07	9.23	.0112	+.0012
May 11-15-------	5	.0160	9.22	27.76	20.74	7.02	.0150	-.0010
May 18-24-------	7	.0143	3.85	32.37	19.27	13.10	.0117	-.0026
June 6-13-------	8	[3].0177	7.06	31.22	21.06	10.16	.0166	-.0011
June 14-20------	7	[1].0187	7.07	35.64	25.83	9.81	.0161	-.0026

Table 3.—*Seepage computation sheet for selected periods for Horseshoe Lake, Ark.*--Continued

Computation period	Length of period, in days	Decline in lake stage (ΔH), in feet per day	Average wind velocity (u), in miles per hour	Average daily value of saturation vapor pressure (e_o), in millibars, corresponding to water-surface temperature	Average daily value of vapor pressure of the air (e_a), in millibars	Δe, average daily $e_o - e_a$, in millibars	Evaporation ($0.000232 X u X \Delta e$), in feet per day	Seepage into (+) or out of (-) lake (evaporation minus ΔH), in feet per day
1970--Continued								
June 26-July 7---	12	0.0250	4.91	38.36	22.18	16.18	0.0184	-0.0066
July 12-14------	3	.0167	4.21	38.93	26.03	12.90	.0126	-.0041
July 17-21------	5	[1].0222	6.33	35.02	23.22	11.80	.0173	-.0049
July 28-Aug. 5--	9	.0211	4.38	41.16	29.92	11.24	.0114	-.0097
Aug. 11-24------	11	.0191	3.90	37.82	26.25	11.57	.0105	-.0086
Aug. 24-Sept. 2-	10	.0210	4.51	36.37	23.90	12.47	.0130	-.0080
Sept. 6-9-------	4	.0200	5.26	40.80	28.68	12.12	.0148	-.0052
Sept. 11-17-----	7	.0214	4.50	40.00	24.76	15.24	.0159	-.0055
Sept. 28-Oct. 6-	9	.0222	4.37	28.58	13.86	14.72	.0149	-.0073
Oct. 14-18------	5	.0220	6.06	20.68	10.94	9.74	.0137	-.0083
Oct. 21-23------	3	[1].0136	3.60	19.00	12.17	6.83	.0057	-.0079
Oct. 30-Nov. 8---	10	[5].0157	5.80	17.05	10.34	6.71	.0090	-.0067
Dec. 6-10-------	5	.0120	6.57	13.20	8.24	4.96	.0076	-.0044
Dec. 11-14------	4	[6].0096	5.32	12.50	7.40	5.10	.0063	-.0033

[1] Adjusted for 0.01 inches of rainfall on the lake.
[2] Adjusted for 0.05 inches of rainfall on the lake.
[3] Adjusted for 0.02 inches of rainfall on the lake.
[4] Adjusted for 0.03 inches of rainfall on the lake.
[5] Adjusted for 0.08 inches of rainfall on the lake.
[6] Adjusted for 0.10 inches of rainfall on the lake.

this report. Seepage was not determined for periods of heavy rainfall because runoff to the lake could not be measured. However, seepage was determined for several periods during which small amounts of rain fell on the lake. For these periods, the change in stage was adjusted to include that rainfall, and runoff to the lake was assumed to be zero.

Seepage rates computed for consecutive periods were not always in good agreement due to a changing rate of seepage, undetected runoff, and errors inherent in meteorologic and hydrologic measurements. The seepage rates for the 47 periods were plotted on a seepage hydrograph and a smooth curve was drawn through the data for these periods (fig. 4). Average monthly seepage rates for July 1969 through December 1970 were taken from this smooth curve on the seepage hydrograph and used to compute the total monthly seepage given in table 4 (p. 22). Figure 4 indicates that the net seepage is out of the lake about 10 months out of the year and the maximum rate of seepage normally occurs in late summer and fall. In August and September 1970, the decline in lake stage resulting from seepage averaged about 0.0083 foot per day, equivalent to a loss of about 4,320 gpm (gallons per minute). In the latter part of March and April and the early part of May 1970, the net seepage was into Horseshoe Lake at an average rate of about 0.0004 foot per day (208 gpm).

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Seepage as Affected by Ground-Water Levels

Water levels in the Quaternary alluvium in the vicinity of Horseshoe Lake were measured at 5-week intervals from July 1969 through December 1971. The measurements were made in five irrigation wells, 43 shallow domestic wells, and eight observation wells installed by the Geological Survey. These measurements indicate that water levels are highest near the Mississippi River levee, about 3½ miles north of Horseshoe Lake. This ground-water high indicates that the Quaternary alluvium near the lake is receiving recharge from an area to the north. Water-level measurements indicate that, during the period when seepage was out of the lake, a ridge of high-water levels extended from this ground-water high to the north shore of the lake. Ground-water movement during this period was toward the Mississippi River east of this ridge and westward on the west side of the ridge.

Water-level measurements in wells near Horseshoe Lake indicate that the direction of ground-water movement was away from the lake during the periods July 1969 through February 1970 and July through December 1970. In the latter part of March, the last of April, and in the early part of June, water-level measurements indicate that the direction of ground-water movement was toward the lake along part of the north and northeast shoreline and away from the lake along the south and west shoreline.

Seepage gains and losses during these months were the net result of seepage into the lake along part of the north shoreline and seepage out of the lake along the rest of the shoreline.

Water-level contour maps, based on water-level measurements made in December 1969, April-May, 1970, and December 1970, are shown in figures 5, 6, and 7. The configuration of the water-level contour lines in December 1969 and December 1970, when the stage of the Mississippi River was low (figs. 5 and 7), indicates that most of the seepage out of the lake was occurring along the north shoreline and that seepage out of Porter Lake was less than that out of Horseshoe Lake. This is supported also by the results of permeability tests on samples of lakebed material. Much of the south shoreline of Horseshoe Lake is underlain by clay and fine-grained material of low permeability, as is Porter Lake.

Seepage as Affected by the Stage of the Mississippi River

The stage of Horseshoe Lake is affected by changes in the stage of the Mississippi River in that changes in river stage are reflected in the ground-water levels which govern the rate and direction of seepage into or out of the lake. The response of ground-water levels to changes in river stage is shown in

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figure 8 for wells[1] 4N-7E-12aac and 4N-8E-19add, which are located one-half mile and 1 mile, respectively, from the Mississippi River. Ground-water levels in wells near the river respond more rapidly and have greater fluctuations than water levels in wells farther from the river (fig. 8). In wells more than a few miles from the river, ground-water fluctuations resulting from changes in river stage generally are small and may occur several weeks after the change in river stage. During the period July 1969 through December 1970, water-level fluctuations in wells ranged from more than 20 feet in wells near the river to less than 2 feet in wells more than 6 miles from the river.

Seepage rates into and out of Horseshoe Lake undergo a gradual seasonal change in response to river-induced changes in the water table in the vicinity of the lake. Although evapotranspiration and recharge from rainfall affect the water table, the seasonal changes in the water table near the lake are primarily the result of seasonal variation in the average elevation of the Mississippi River. The correlation between average monthly seepage

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[1] Well numbers refer to the location of the well and are composed of the township number, the range number, the section number, and three lowercase letters that indicate, respectively, the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section. The lowercase letters are assigned in counter-clockwise order, beginning with "a" in the northeast quarter.

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rates and the average monthly elevation of the river is shown in figure 9 for the period July 1969 through December 1970. If this correlation between river stage and seepage rate is applied to average annual stage and seepage rates, the average annual seepage loss from Horseshoe Lake is greater today than it was 20 years ago. The average annual elevation of the Mississippi River at the U.S. Army Corps of Engineers low-water gage 255.0 at Star Landing, Miss., is shown in figure 10. The elevation of the river averaged 186.5 feet for the period 1931 through 1951 and 183.4 feet for the period 1952 through 1970. The lower average annual elevation of the river during the past 19 years has resulted in a small decline in the average elevation of the ground-water table and a corresponding increase in the net seepage loss from the lake. The correlation between seepage and the elevation of the river (fig. 9) indicates that the average annual seepage loss from the lake during the period 1952-70 was about 30 percent greater than the average annual seepage loss for the period 1931-51.

RAINFALL AND RUNOFF

Rainfall on Horseshoe Lake averages about 49 inches a year. In addition to rainfall on the lake, Horseshoe Lake receives rainfall runoff from a drainage area of about 12,700 acres, a large part of which is noncontributing except during periods of

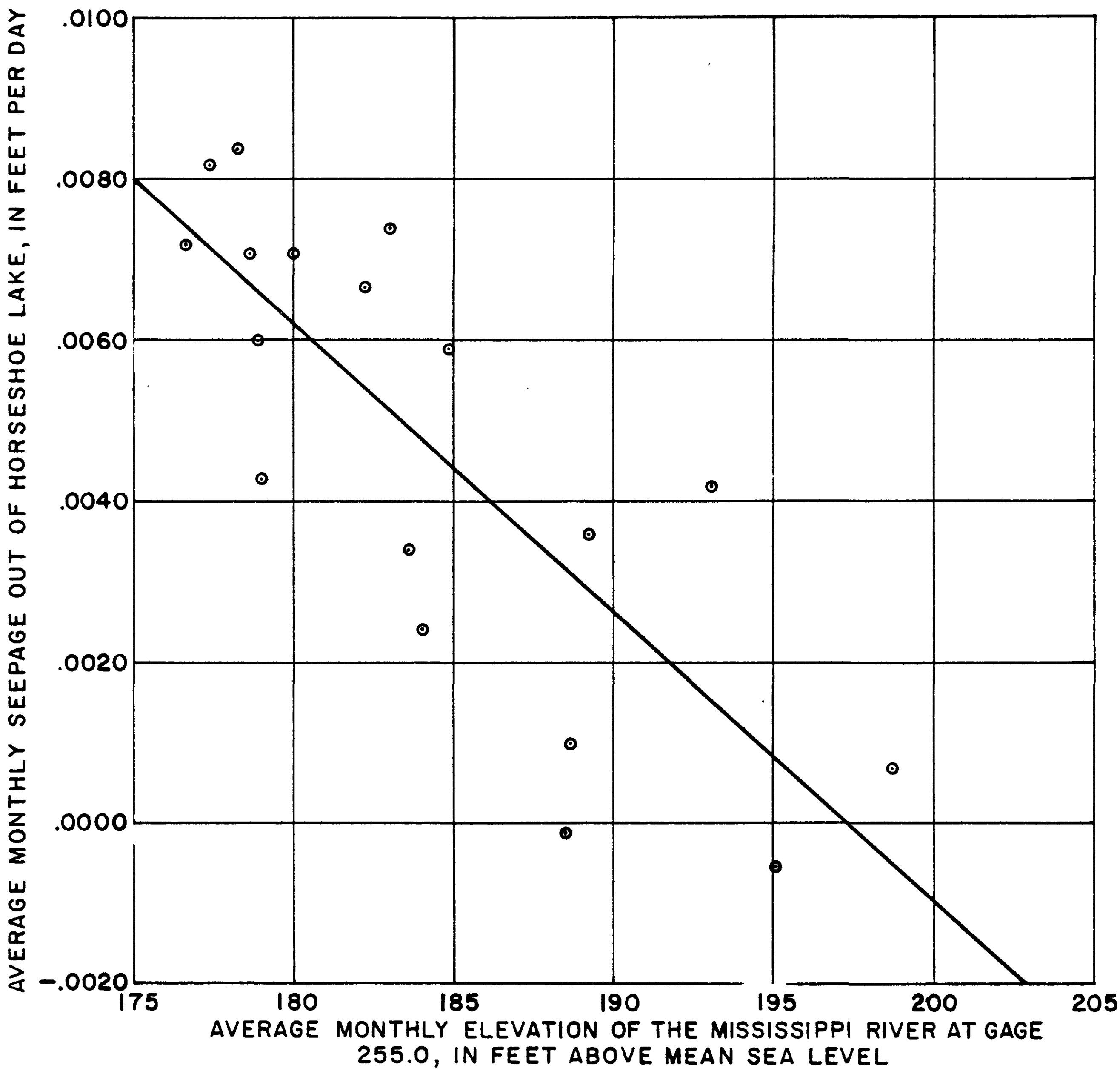

Figure 9.-Relation between elevation of the Mississippi River and seepage at Horseshoe Lake.

excessive rainfall. Rainfall, measured at Horseshoe Lake, and runoff to the lake, calculated from changes in lake contents by using seepage and evaporation data calculated earlier in this report, are shown in table 4. The information contained in this table indicates that the average amount of water contributed annually to the lake by rainfall and runoff from the drainage area is equivalent to a depth of about 7½ feet over the surface of the lake and generally exceeds the amount of water lost due to evaporation and seepage.

Large deviations from normal rainfall and runoff rates result in uncommonly high or low lake levels. The average annual rainfall at Marianna, Ark., about 25 miles southwest of Horseshoe Lake, is shown in figure 10. This figure indicates that in 1954 and 1966, when the level of Horseshoe Lake was reported to be uncommonly low, rainfall was deficient and seepage out of the lake was probably high as a result of the uncommonly low average annual elevation of the Mississippi River. Although deficient rainfall and runoff frequently result in large seasonal declines in lake levels, extremely low lake levels are probably the result of a combination of large seasonal declines and poor recovery from previous declines. Uncommonly high lake levels in the spring help to maintain lake levels at or above the normal seasonal minimum level, even during years when the seasonal declines are large. Horseshoe Lake probably would have declined to a level well below

Table 4.—*Water budget for Horseshoe Lake, Ark.*

[Net = (Rainfall+runoff) - (seepage+evaporation)]

Month	Net increase (+) or decrease (-) in lake stage (feet)	Rainfall		Runoff from drainage area		Seepage into (+) or out of (-) lake (feet)	Evaporation (feet)
		Inches	Feet	Increase in lake stage (feet)	Acre-feet		
1969							
July[1]	-0.42	1.38	0.115	0.109	251	-0.118	0.526
August	-.17	3.85	.321	.229	527	-.208	.512
September	-.37	2.03	.169	.058	133	-.216	.381
October	-.48	.81	.068	.149	343	-.220	.477
November	+.15	4.15	.346	.215	494	-.180	.231
December	+.97	7.51	.626	.635	1,460	-.133	.158
1970							
January	+0.01	0.70	0.058	0.166	382	-0.074	0.140
February	+.35	3.60	.300	.173	398	-.028	.095
March	+.50	4.07	.339	.319	734	+.003	.161
April	+1.22	6.91	.576	[2].941	[2]2,164	+.015	.312
May	-.18	1.93	.161	.202	465	-.022	.521
June	-.33	2.02	.168	.120	276	-.108	.510
July	-.30	3.91	.326	.022	51	-.220	.428
August	-.42	1.60	.133	.057	131	-.260	.350
September	-.50	1.99	.166	.132	304	-.246	.552
October	+.10	5.73	.478	.167	384	-.229	.316
November	-.15	2.01	.168	.168	386	-.177	.309
December	+.15	3.41	.284	.176	405	-.105	.205

[1] Data are for the period July 4-31.
[2] Includes water contributed by Fish Bayou and Porter Lake.

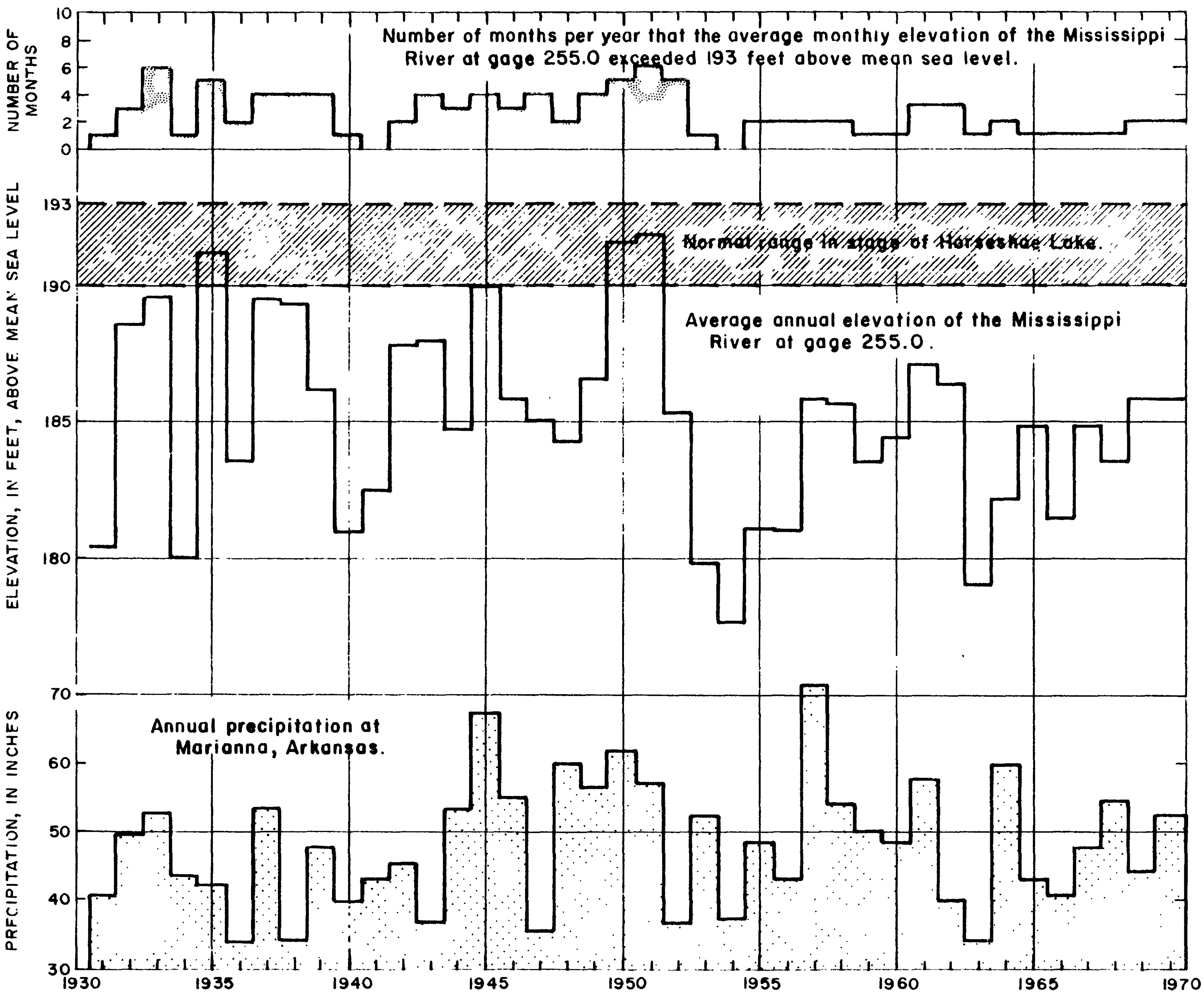

Figure 10.–Average annual elevation of the Mississippi River at gage 255.0 and the annual precipitation at Marianna, Ark.

the normal seasonal minimum (190 feet above msl) in 1963, when rainfall was deficient and the average annual elevation of the river was low, but lake levels in the spring of that year were reported to have been higher than normal.

The elevation to which the lake levels rise is dependent not only upon rainfall and runoff rates but also upon the elevation of the control which regulates the flow out of the lakes. When the elevation of the level of Horseshoe Lake is greater than that of Fish Bayou and greater than the highest point in the flow line of Beck Bayou, water flows from the lake into Fish Bayou. Beck Bayou is a relatively narrow ditch, which was originally dug to drain floodwater from Horseshoe Lake into Fish Bayou. Two floodgates were installed on this bayou to prevent backwater from Fish Bayou from flooding Horseshoe Lake, but these floodgates have not been used in recent years. When these floodgates are left open and this ditch is free of other obstructions, Horseshoe Lake cannot permanently exceed the elevation of a section of filled-in channel located between these floodgates. The elevation of the highest point in the channel floor is about 192.7 feet. This is the elevation of the highest lake level observed in 1969 and is reported to be very near the elevation of the average spring lake level. Interpretation of the hydrograph of Horseshoe Lake in figure 2 and rainfall records indicate that the amount of water draining from the lake into Fish Bayou in April and May of

1969 may have been equivalent to a depth of one-half foot or more over the surface of the lake.

Although the floodgates on Beck Bayou are seldom closed, this ditch is occasionally obstructed by vegetation, debris, or beaver dams and the water level in Horseshoe Lake rises to levels well above the average spring lake level (192.7 feet above msl). In 1970 a beaver dam on Beck Bayou made it possible for the lake to contain the heavy spring rainfall and runoff, and the lake level reached an elevation of 193.5 feet (0.8 feet above the average spring lake level). Because of this additional 0.8 foot of water in the lake and because of above average rainfall in the month of October 1970, the lowest lake level elevation in 1970 was 191.4 feet, well above the normal seasonal low.

In addition to runoff from the drainage area, Horseshoe Lake receives some surface water from Fish Bayou. When the elevation of the water level in Fish Bayou exceeds the elevation of the control in Beck Bayou and the elevation of the water level in Horseshoe Lake, water flows from Fish Bayou into the lake. During periods of extremely high stage on Fish Bayou, water sometimes flows from Fish Bayou into Horseshoe Lake through Zanone Bayou. The amount of water that Fish Bayou contributes to the lake depends largely upon the elevation of the water surface in Fish Bayou and upon the elevations of the controls in Beck and

Zanone Bayous. In 1970, when the elevations of the controls in Beck and Zanone Bayous were 193.5 and 196.6 feet, respectively, the amount of water contributed to the lake by Fish Bayou was probably equivalent to a depth of no more than 2 or 3 inches over the surface of the lake. If the elevation of the control in Beck Bayou had been 192.7 feet, as it normally is, Fish Bayou would have contributed much more water to the lake. This contribution would serve only to reduce the amount of time required for the lake levels to recover from seasonal declines, because the lake level could not permanently exceed this elevation unless a floodgate or some other control was used to hold the water in the lake. In the summer and fall, when lake levels are declining, the elevation of the water surface in Fish Bayou is seldom high enough for Fish Bayou to contribute water to the lake.

Horseshoe Lake probably receives small amounts of water from Porter Lake in the spring, when lake levels are high. Because Porter Lake generally does not decline as much as Horseshoe Lake and the recovery rate is about the same for both lakes, the level of Porter Lake generally is higher than that of Horseshoe Lake in the early spring. Hydrographs of these lakes (fig. 2) indicate that in the spring of 1970, Porter and Horseshoe Lakes were filling at about the same rate until in late April, when Porter Lake began contributing water to Horseshoe Lake. These hydrographs indicate that the elevation of the control which regulates flow between the two lakes was about 193.4 feet in the spring of 1970. By the end of April 1970, Porter Lake had contributed the equivalent of about 1 inch of water over the surface of Horseshoe Lake and the two lakes were at the same level. The two lakes were probably connected throughout most of May 1970 when the two lakes were at the same level.

ARTIFICIAL CONTROL OF LAKE STAGE

FLOOD STAGE

Extremely high lake levels are generally the result of floodwaters in Fish Bayou flowing into Horseshoe Lake by way of Beck and Zanone Bayous. In recent years, however, the frequency and magnitude of floods in the vicinity of Horseshoe Lake have been greatly reduced by the construction of the St. Francis River-Marianna cutoff and drainage improvements along Blackfish, Fifteen Mile, and Fish Bayous. Although some flooding occurs periodically in Horseshoe Lake, it is seldom a serious problem at present, and the floodgates, which were constructed to prevent floodwaters from Fish Bayou from causing floods in the lakes, have been abandoned or are seldom, if ever, closed. In the early part of 1962, heavy rains on the drainage area and backwater from Fish Bayou caused the water level in Horseshoe Lake to reach an elevation of about 195 feet, and resulted in some property damage to private piers and boathouses on the lake. Although flooding in Horseshoe

Lake is not a frequent problem, it could be largely controlled by the use of properly maintained floodgates on Beck and Zanone Bayous and by drainage improvements along Fish Bayou. Any drainage changes made along Fish Bayou must take into consideration the effect of reducing or increasing the amount of water that flows from Fish Bayou into Horseshoe Lake. Any drainage changes that would significantly reduce the amount of water that the lake receives from Fish Bayou might contribute to the problem of low lake levels in the fall and early winter, particularly if rainfall is deficient.

LOW STAGE

Low lake levels are primarily the result of a combination of deficient inflow, seepage out of the lake, and evaporation. Because of the difficulty and expense involved in reducing seepage and evaporation, the only practical method of combating low lake levels is to supplement the natural flow of water into the lake. To maintain the lake at a particular level during a period of no rainfall, it would be necessary to pump or divert water into the lake at a rate equal to or greater than the rate of seepage and evaporation losses. Seepage and evaporation rates for the period July 1969 through December 1970 are shown in table 4. Although evaporation rates are relatively independent of lake stage, seepage out of the lake would increase as a result of supplementing the inflow to the lake. If wells were used to supplement the inflow to the lake, an additional increase in seepage out of the lake might result from the lower ground-water table in the vicinity of the wells. Any effort to control the level of the lake must take into consideration these additional seepage losses. The economic and hydrologic feasibility of controlling the lake stage by diverting water from a particular stream or by pumping water from a particular aquifer would depend largely upon the desired lake level, the degree to which the seasonal declines are to be reduced, and the availability of a dependable source of surface or ground water.

Opinions differ as to the most desirable lake level. William Gilbreath, former district biologist with the Arkansas Game and Fish Commission, recommended in 1967 that all lakes in the complex be connected and the lake levels raised to an elevation of 195 feet. This would undoubtedly reduce the vegetation problems and would benefit the fish and waterfowl in these lakes, but it would require considerable dredging and the construction of several control structures and levees. A lake level elevation of 195 feet would be about 2.3 feet higher than the normal seasonal high and would inundate several private piers. It is hydrologically possible to maintain the lake level at or near an elevation of 195 feet, but the seeage out of the lake would be greatly increased and a large amount of water would be required to maintain this level.

Horseshoe Lake normally reaches a maximum elevation of about 192.7 feet in the spring. At this elevation, there is about 3 feet of water over the shallow mudflats that provides cover for fish and waterfowl. If the lake level were maintained at or near this elevation, aquatic vegetation would be less of a problem and fish and waterfowl could use the shallow areas that are presently exposed during late summer and fall. A minimum lake level elevation of 192.7 feet would be more beneficial to the lake than would lower minimum levels, but it would be more expensive to maintain. A minimum lake-level elevation of 192.0 or 191.0 feet would cause more inconvenience to property owners along the shoreline, but fish and waterfowl would not be severely affected by these lake levels.

The amount of supplemental water needed to maintain a particular minimum lake level could be reduced by raising the lake to an elevation of about 193.5 feet in the spring. The lake level could be raised to this elevation, 0.8 foot above the normal spring lake level, by a control structure in Beck Bayou. The natural inflow to Horseshoe Lake, including the contribution from Fish Bayou and Porter Lake, probably would be sufficient to fill the lake to an elevation of 193.5 feet during most years. During the period November 1969 through April 1970, when rainfall on the lake was about normal, Horseshoe Lake recovered from a low of 190.1 feet to a level of 193.5 feet. Interpretation of the hydrograph in figure 2 indicates that if the lake were filled to an elevation of 193.5 feet in the spring, the amount of time that the lake level would be below the desired minimum level might be reduced by as much as 2 months.

Sources of Water for Supplementing Inflow to the Lake

Fish Bayou

The amount of water contributed to Horseshoe Lake by Fish Bayou could be substantially increased. Fish Bayou does not flow throughout the year, but when the stage is high it does contribute water to the lake by way of Beck Bayou and Zanone Bayou. In 1970 when the elevation of the control in Beck Bayou was approximately 193.5 feet, the amount of water contributed to the lake by Fish Bayou was probably equivalent to a depth of no more than 2 or 3 inches over the surface of the lake. If Beck Bayou were cleared out, the elevation of the control would be about 192.7 feet, and Fish Bayou would contribute much more water to the lake. However, a floodgate or some other adjustable control structure would be required on Beck Bayou in order for the level of the lake to exceed that elevation.

The average annual flow of Fish Bayou is about 5,800 acre-feet at the confluence of Zanone Bayou and about 10,600 acre-feet at the confluence of Beck Bayou. A large part of this average annual flow could be diverted into Horseshoe Lake if a dam were constructed on this bayou. However, most of the average annual flow occurs in the winter and spring, when the lake level is recovering from seasonal declines. Increasing the inflow from Fish Bayou would reduce the time required for the lake to recover from seasonal declines and help the lake to recover when winter and spring rainfall is deficient. However, diversion of water from Fish Bayou would not greatly reduce the magnitude of seasonal declines on the lake because there is no flow in Fish Bayou during much of the summer and fall, when lake levels are normally declining.

Mississippi River

The Mississippi River is, of course, the largest and most dependable source of surface water with which the inflow to Horseshoe Lake can be supplemented. The quantity of water available from the Mississippi River is more than sufficient to maintain the level of Horseshoe Lake at any desired level, but a large pump would be needed to get the water from the river, over the levee, and into the lake.

It would be necessary to pump water from the Mississippi River over the levee except during periods of high stage on the river. During periods when the elevation of the river exceeds the elevation of the lake, it would be possible to siphon water from the river. The elevation of the water surface in the river frequently exceeds the elevation of the lake level in the months of March, April, and May. The number of months during the period 1931-69 when the average elevations of the water surface in the Mississippi River east of Horseshoe Lake exceeded an elevation of 193.0 feet is shown in figure 10. This figure indicates that in most years the lake could be raised to the desired level in the spring by siphoning water from the river. However, to eliminate or reduce the seasonal declines that normally occur in the summer and fall, it would be necessary to pump river water over the levee and into the lake because the elevation of the river seldom exceeds that of the lake during this period.

If water were pumped over the levee northeast of the lake, it would be possible to channel the water into Zanone Bayou and from there into the lake, a distance of several miles. If river water were pumped over the levee into Porter Lake, it would be necessary to clean out the stream channel connecting Porter and Horseshoe Lakes. If river water were pumped into Goose Lake, it would be necessary to connect the north end of this lake with Horseshoe Lake and to open the dikes built across the lake, or install large culverts in the dikes. Mississippi River water could also be pumped over the levee and into the southeast end of Horseshoe Lake by way of an abandoned stream channel that runs from Horseshoe Lake to the levee. This stream channel would require little dredging, but it would be necessary to pump the water almost three-fourths of a mile to the levee.

Part of the cost of pumping water from the Mississippi River into Horseshoe Lake would involve the construction of ditches or pipelines to move water from the river to the levee and from the levee to the lake. Northeast of the lake, the Mississippi River is less than one-half mile from the levee, but the levee is several miles from the lake. Southeast of the lake, the levee is less than one-half mile from Horseshoe, Porter, and Goose Lakes, but the Mississippi River is three-fourths of a mile from the levee. The amount and the cost of pumping required would depend upon the pumping rate and the difference in head between the river and the discharge outlet into the lake. The difference in head between the lake and the river varies throughout the year, but seldom exceeds 25 feet.

Wells

Seasonal declines in the level of Horseshoe Lake may be reduced by pumping water into the lake from wells tapping one of the major aquifers in the area. Two aquifers, the alluvium of Quaternary age and the deeper sands of Tertiary age, yield relatively large quantities of water to wells near the lake.

The Quaternary alluvium is the most productive aquifer in the vicinity of the lake. This aquifer averages about 150 feet in thickness and generally grades from a clay or silt at the surface to coarse sand and gravel at the base. Many shallow domestic wells and several large irrigation wells are screened in the alluvium. Irrigation wells screened in the coarse sand and gravel at the base of the alluvium generally are 8-12 inches in diameter and yield from 1,500 to 3,000 gpm. A series of these large wells could be used to maintain the lake at a particular level, but if the wells were located too near the lake, the drawdown in the ground-water table in the vicinity of the pumping wells would result in an increase in the seepage out of the lake.

The effects of pumping wells near the lake were demonstrated on November 24 and 25, 1969, when a pumping test was conducted on a small irrigation well owned by R. B. Snowden. This well, 4N-7E-22bcc, was pumped at a rate of 80 gpm for a period of about 24 hours. Water-level measurements were made at frequent intervals in four observation wells installed by the Geological Survey. Analysis of the water-level declines or drawdowns in these wells indicated that the alluvium in the vicinity of the pumped well has a coefficient of transmissivity of 258,000 gpd per ft (gallons per day per foot) and a storage coefficient of about 0.001. Additional analysis of the pumping-test data indicated that the lake, which is about 500 feet south of the well, was recharging the alluvium as the well was pumped. It was also determined that if this well was pumped for a period of 3 months, seepage from the lake would be increased by more than 95 percent of the well yield. If the aquifer characteristics and the degree of connection between the lake and the aquifer in the vicinity of this well are representative of conditions along the lake in section 22 and the western part of section 23, wells as much as one-half mile north of the lake in this area would increase seepage from the lake by more than 65 percent of the well yield after pumping for 3 months. Pumping water into the lake from wells north of the lake, in the area where much of the seepage out of the lake is occurring, would not raise lake levels significantly unless the wells were several miles from the lake. Pumping water from wells near the ends of the lake, or near the south shoreline, would also tend to increase seepage out of the lake but to a lesser extent, because of the lower degree of connection between the lake and the alluvium. Because the cost of supplementing inflow to the lake with ground water is dependent upon the seepage from the lake, wells should be located as far from the lake as possible and in areas where the degree of connection between the lake and the alluvium is low.

Pumping water into the lake from the Tertiary aquifers, which lie below the Quaternary alluvium, would affect seepage from the lake less than pumping from wells in the alluvium, because of the apparent lack of connection between the lake and the Tertiary aquifers. The major water-bearing sand in Tertiary deposits is at a depth of about 1,300 feet below land surface in the vicinity of Horseshoe Lake. This aquifer is artesian. Prior to about 1950 wells tapping this formation flowed, but the water levels have declined in recent years and presently stand about 13 feet below land surface. Several domestic and public-supply wells in the vicinity of Horseshoe Lake pump water from this Tertiary aquifer. These wells average more than 1,600 feet in depth and reportedly yield less than 300 gpm. Well yields from this aquifer range from 500 to 2,000 gpm in the Memphis area, and it is probable that wells yielding as much as 1,000 gpm could be developed in the vicinity of Horseshoe Lake. However, the cost of installing these deep wells and the number of wells that would be needed to maintain desirable lake levels make this aquifer a less suitable source of water for supplementing inflow to the lake. Water may also be obtained from sands of Tertiary age at depths of 200-800 feet below land surface, but wells in these sands would probably yield less than 150 gpm and would be unsuitable for supplementing inflow to the lake.

Quantity of Water Required to Supplement Inflow to the Lake

The quantity of water required to maintain Horseshoe Lake at a particular level is dependent upon rainfall and runoff contributed to the lake and water lost due to evaporation and seepage. Rainfall, runoff, and evaporation are relatively independent of lake stage, but seepage out of the lake increases when the difference between lake level and the ground-water level is increased. It is necessary to know the increase in seepage resulting from maintaining a constant lake level in order to calculate the supplemental water requirements.

The effect of raising the level of the lake on seepage was analyzed on an electric analog model, in which the flow of electricity in a resistance-capacitance circuit is analogous to the flow of water in a porous and permeable medium. This model was constructed so that the electrical properties were representative of hydrologic properties of the aquifer and lakebed. Verification of the model was accomplished by simulating lake stage and fluctuations in the stage of the Mississippi River and duplicating the water-level response of the aquifer on the analog model.

The effects of increased head in the lake are shown in the graph of figure 11 that relates increase in lake stage to the percentage of increase in seepage. This graph indicates that, for a given river stage and ground-water table, the seepage out of the lake would increase about 22 percent for each foot that the lake level is raised. This graph was used to calculate the increase in seepage which was, in turn, used to calculate the rates at which it would have been necessary to supplement inflow to Horseshoe Lake in 1969 and 1970 to maintain lake levels of 192.5, 192.0, and 191.0 feet above mean sea level. These rates are given in table 5. The data in this table are based only on

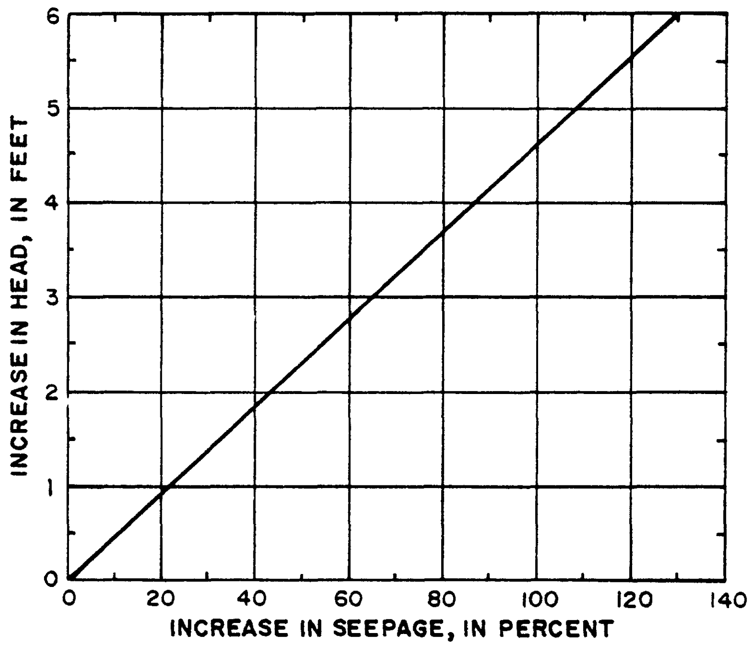

Figure 11.—Relation between increased head and seepage out of Horseshoe Lake.

Table 5.—*Supplemental water requirements for Horseshoe Lake, Ark.*

Month	ΔH, decline in lake stage (feet)	Average monthly lake stage (feet, msl)	Average monthly seepage out of lake (feet)	ΔS, increase in seepage (feet) at indicated lake stage (feet, msl)			$\Delta H+\Delta S$ (feet)			Supplemental water required (gpm) to maintain indicated stage (feet, msl)		
				191.0	192.0	192.5	191.0	192.0	192.5	191.0	192.0	192.5
1969												
June	0.50	192.0	[1]0.108	------	------	0.01	------	------	0.51	0	0	8,850
July	.60	191.4	[2].131	------	0.01	.03	------	0.61	.63	0	10,230	10,570
August	.17	191.0	.208	------	.05	.07	------	.22	.24	0	3,690	4,030
September	.37	190.9	.216	0.00	.05	.07	0.37	.42	.44	6,430	7,290	7,630
October	.48	190.4	.220	.03	.08	.10	.51	.56	.58	8,550	9,390	9,730
1970												
August	0.42	192.4	0.260	------	------	0.00	------	------	0.42	0	0	7,060
September	.50	191.9	.246	------	0.00	.03	------	0.50	.53	0	8,670	9,190
October	-.10	191.7	.229	------	.01	.04	------	-.09	-.06	0	0	0
November	.15	191.7	.177	------	.01	.03	------	.07	.12	0	1,220	2,080

[1]Estimated, seepage assumed to be the same as that in June 1970.

[2]Adjusted to a full month.

hydrologic conditions that existed in 1969 and 1970, but the seasonal decline in 1969 was reported to be near the normal seasonal decline. The lake level could probably be maintained at an elevation of 192.5 feet in most years by supplementing the inflow to the lake at a maximum rate of 10,600 gpm. However, during periods of extreme meteorologic and hydrologic conditions, the maximum rate of decline would exceed this rate. During the month of September 1970, when seepage and evaporation were relatively high, the lake would have declined 0.8 foot if there had been no rainfall, and it would have been necessary to supplement the lake at a rate of 14,400 gpm that month to maintain the level at 192.5 feet.

The reported minimum lake levels were 6 feet below normal mininum in 1954 and 4 feet below normal minimum in 1966. However, analysis of rainfall records and estimates of seepage, evaporation, and runoff indicate that these low levels were the result of incomplete recovery from previous declines and relatively high seasonal declines of about 3.8 feet. The average rate of decline during the months of May through December in 1954 and 1966 was probably less than 0.02 foot per day (10,400 gpm). However, the rate of decline probably exceeded 0.03 foot per day (15,600 gpm) during some months in 1954 and 1966.

The supplemental water requirements given in table 5 are applicable only if the supplemental water is obtained from surface-water sources or from wells located far enough from the lake so that ground-water drawdowns in the vicinity of the wells would not affect the seepage out of the lake. If wells located near the lake were used to supplement the inflow, part of the well yield would be derived from increased seepage out of the lake or decreased seepage into the lake and the net contribution to the lake would be less than the total yield of the wells.

The loss of water from Horseshoe Lake that would result from pumping wells at different locations in the vicinity of the lake after periods of 30, 60, and 90 days was determined from the analog model. If the lake were to be maintained at a high stage, it might be necessary to pump for as many as 150 days. However, the increase in seepage due to pumping would be only slightly higher after 150 days of pumping than it would be after 90 days' pumping. The loss of water from Horseshoe Lake, espressed as a percentage of the yield after 30, 60, and 90 days of pumping a well at any location within the area of this report, may be determined from figures 12, 13, and 14. If the inflow to the lake were to be supplemented at a rate of 10,000 gpm for a period of about 90 days from wells located on the 25-percent line a well yield of about 13,300 gpm would be required. Figure 14 indicates that, except for the southeastern end of the lake, wells located within one-half

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mile of the lake would increase seepage from the lake by more than 50 percent of the well yield after pumping for 90 days. If wells are to be used to supplement the lake, they should be located so that little or no loss of water results from pumping these wells.

Effects of Supplementing Inflow on the Chemical Quality, Bacteriological Quality, and Ecology of the Lake

The feasibility of supplementing the inflow to Horseshoe Lake depends also on the effects of this additional inflow on the quality of the water in the lake. The results of chemical analyses of samples collected from Horseshoe, Porter, Goose, and Brushy Lakes, the Mississippi River, Beck Bayou, and from several wells near Horseshoe Lake, are given in table 6. These analyses indicate that water from the lakes, the Mississippi River, Beck Bayou, and from wells in the Quaternary alluvium, is a calcium magnesium bicarbonate type; whereas, water from the Tertiary aquifer is a sodium bicarbonate type. The chemical analyses in this table indicate that, although the dissolved-solids content of water from the Quaternary alluvium and the Mississippi River generally is higher than that of water from the Tertiary aquifer, the lakes, and smaller streams, water from the Quaternary alluvium and the Mississippi River is suitable for fish and wildlife. However,

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the concentrations of nitrogen and phosphorus in the surface waters and the concentrations of iron in water from the Quaternary alluvium are high enough to be troublesome.

Nitrogen and phosphorus are plant nutrients. High concentrations of these nutrients in lakes and streams often result in dense growths of aquatic vegetation which interfere with the recreational uses of the stream or lake. Although undesirable algal blooms may occur at lesser concentrations, the suggested limit for total phosphorus in lakes and streams entering lakes is 50 micrograms per liter, or 0.05 milligram per liter (Federal Water Pollution Control Adm., 1968, p. 34). The concentration of total phosphorus in surface waters in the vicinity of Horseshoe Lake frequently exceeds this suggested limit (table 6). The green turbid appearance of Horseshoe Lake, and Porter Lake in particular, is due to algal blooms that result from the high concentrations of plant nutrients. Under certain conditions, the algae may die and their decomposition lowers and sometimes depletes the dissolved oxygen in the lakes. The addition of water containing high concentrations of plant nutrients to these lakes would only add to the aquatic-vegetation problems.

The chemical analyses of water from the Quaternary alluvium indicate that water from this aquifer is high in iron content. If water were pumped from this formation into the lake, the iron would precipitate in the form of iron oxide (a reddish-brown precipitate, only slightly soluble in water). This precipitate, if not allowed to settle before entering the lake, would make the lake turbid and rust colored in the area where the ground water is introduced. This condition has been observed on Brushy and Goose Lakes, which are often supplemented with water from large wells in the Quaternary alluvium. The rusty appearance of the water is unsightly, but this condition has no apparent effect on the fish and wildlife in these lakes. Most of this iron oxide precipitate could be removed from the ground water by aerating the water when it is pumped to the surface and by channeling this water through smaller lakes or settling ponds to allow the precipitate to settle.

The major chemical constituents of ground water and surface water in the vicinity of Horseshoe Lake are given in table 6, but the suitability of these waters to support fish and wildlife is adversely affected by very low concentrations of certain chemicals and minor elements. The most toxic of these chemicals and minor elements are pesticides, herbicides, and certain heavy metals.

Minor-element analyses of surface waters in the vicinity of Horseshoe Lake are given in table 7. Although trace amounts of some of these minor elements occur in the natural environment and are essential in the growth of some organisms, they have been shown to be highly toxic at quite small concentrations. The

Table 7.—*Minor-element analyses of surface waters in the vicinity of Horseshoe Lake, Ark.*

[Concentrations in micrograms per liter]

Source	Location	Date	Cadmium (Cd)	Chromium (Cr)	Cobalt (Co)	Copper (Co)	Lead (Pb)	Mercury, total (Hg)	Nickel (Ni)	Silver (Ag)	Zinc (Zn)
Horseshoe Lake-----	Near mouth of Zanone Bayou.	10-14-71	0	4	2	13	5	<0.5	18	0	20
Porter Lake--------	Near mouth of drainage ditch.	10-14-71	0	5	0	16	4	<0.5	19	0	10
Beck Bayou---------	At floodgate on county road.	10-14-71	0	4	3	22	6	3.4	19	0	20

<Less than.

toxic effects of these minor elements on fish and wildlife has not been thoroughly investigated, but many of these heavy metals are accumulated in animals. Exposure to sublethal concentrations of some of these metals during a long period of time may injure the growth or metabolism of the animals. Another characteristic of many heavy metals that makes them troublesome is their persistence in the environment. Permissible concentrations in surface water to be used for public water supplies that have been suggested by the Federal Water Pollution Control Administration (1968) are: cadmium, 10 micrograms per liter; chromium, 50 micrograms per liter; copper, 1,000 micrograms per liter; lead, 50 micrograms per liter; mercury, 5 micrograms per liter; silver, 50 micrograms per liter; and zinc, 5,000 micrograms per liter. The concentrations of heavy metals in surface water in the vicinity of the lakes are less than the recommended limits for public water supplies but higher than normal environmental concentrations. Their presence indicates that surface waters in the area probably receive pesticides and herbidides that frequently contain these heavy metals.

Pesticides and herbicides are similar to heavy metals in that they are often toxic to fish and wildlife in extremely low concentrations and are accumulated in various organisms. Many of the pesticides, particularly the chlorinated hydrocarbon insecticides, are very persistent and may remain in the environment many years after their initial application. Fortunately, much of the pesticides and herbicides adheres to soil particles and does not remain in solution in the aquatic environment. Ground water generally is free of these chemicals, but surface water adjacent to farmland probably contains significant amounts of these toxic materials at various times throughout the year.

The content of pesticides and herbicides in streams and lakes in the vicinity of Horseshoe Lake varies with the flow and with the seasonal application of these chemicals to farmland. The toxicity of many of the pesticides is so high that they could not be applied directly to or near surface water without endangering aquatic organisms. Concentrations of commonly used pesticides and herbicides in surface waters and bottom sediments in the vicinity of Horseshoe Lake are given in table 8.

The compounds classified as insecticides in table 8 are acutely toxic at concentrations of 5 micrograms per liter and less. The herbicides generally are not acutely toxic at concentrations of 1,000 micrograms per liter. The data in this table indicate that concentration of insecticides in bottom sediments is much greater than that in the water. Bottom-feeding fish, wildlife, and other organisms in the area where the samples were collected probably ingest sufficient quantities of these pesticides to cause damage. Although concentrations of pesticides and herbicides in surface water are much lower than the concentrations in bottom sediments, water samples from Porter Lake,

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Beck Bayou, and the Mississippi River contained chlorinated hydrocarbon pesticides in excess of the environmental limit of 0.05 micrograms per liter recommended by the Federal Water Pollution Control Administration (1968). Two of the pesticides found in the vicinity of Horseshoe Lake were DDT and toxaphene. Studies have shown that when bass were exposed to a concentration of 2.1 micrograms per liter of DDT, for a period of 48 hours, 50 percent of these fish died. Similar studies with rainbow trout and toxaphene show that 50 percent of the trout, exposed for 48 hours to a concentration of 2.8 micrograms per liter of toxaphene, died (Federal Water Pollution Control Adm., 1968, table III-5A). The concentrations of pesticides and herbicides in water samples collected during this investigation may not be representative of the entire body of water, but the presence of these compounds indicates a need for pollution surveillance. Water containing concentrations of insecticides and herbicides in excess of the environmental limits of 0.05 microgram per liter and 10 migrograms per liter, respectively, recommended by the Federal Water Pollution Control Administration (1968) should not be used to supplement inflow to Horseshoe Lake.

The temperature of any supplemental inflow to the lake will affect the ecology of the lake. Because the temperature of shallow ground water remains relatively constant at about 16.7°C (62.0°F) throughout the year, the temperature of the ground water would differ at times from that of the lake by as much as 15°C (27°F). The addition of water to the lake that is cooler or warmer than the lake would probably result in some changes in feeding habits and movement of fish in the area, but this has caused no apparent damage to the fish and wildlife in Goose and Brushy Lakes, which are periodically supplemented with ground water. The temperature of the water from the Mississippi River or other streams in the area would be very close to that of the lake throughout the year, and the addition of surface water into the lake would not seriously affect the temperature of the lake.

The introduction of surface water into the lake might lead to problems with sediment. Runoff in most streams in the area contains sizable sediment loads, particularly during periods of high stage. This sediment, if not allowed to settle before being channeled into the lake, would increase the turbidity. The effects of supplementing the inflow to the lake with surface water would depend upon the concentration of sediment in the surface water and the amount of surface water introduced into the lake. If care were taken to introduce this surface water into the lake only during periods when the sediment content is relatively low, the turbidity and appearance of the lake probably would not be seriously affected. Runoff from streams draining into Horseshoe Lake presently contains sediment and the lake becomes slightly turbid after periods of high runoff into the lake. This turbidity does detract from the beauty of the lake, but the sediment soon settles and the lake clears. A slight turbidity in the lake water would help combat algae and vegetation, but care must be taken not to introduce sediment loads high enough to keep the lake highly turbid or muddy, as this is harmful to fish and wildlife. The periodic introduction of surface water from the Mississippi River or from Fish Bayou into Horseshoe Lake would result in temporary increases in the turbidity but probably would not permanently affect the turbidity of the lake. The inflow to the lake should be supplemented only when needed, as any attempt to direct the entire flow of Fish Bayou through the lake would lead to problems with turbidity and siltation.

One other aspect of water quality that must be considered is the bacteriological quality of the lake and of the alternate sources of water for supplementing inflow to the lake. Water from wells that are protected from surface contamination is normally free of coliform bacteria, but surface water generally contains some of these bacteria. The coliform-bacteria content of lakes and streams would vary with flow and with drainage from barnyards, septic tanks, and privies. During a sanitary survey of Horseshoe Lake, performed on October 15, 1965, by the Arkansas Water Pollution Control Commission, 15 samples were collected and analyzed for coliform bacteria. Ten of the 15 samples contained less than 500 coliform bacteria per 100 milliliters of water, but some samples collected in shallow water near the mouth of Beck Bayou and Zanone Bayou contained as many as 2,300 coliform bacteria per 100 milliliters. Bacteriological analyses of surface waters made during the course of this investigation are given in table 9. The number of samples analyzed for coliform bacteria was insufficient to determine accurately the suitability of these waters for recreational uses, but these analyses indicate that water in ditches and bayous flowing into the lakes frequently contains high concentrations of these bacteria.

Water containing more than 1,000 coliform bacteria per 100 millimeters generally is considered unfit for water-contact sports such as swimming. A better indicator organism for evaluating the microbiological suitability of recreational waters is fecal coliform. The Federal Water Pollution Control Administration (1968) recommended that fecal-coliform content of primary contact recreation waters, as determined from not less than five samples for a 30-day period of the recreation season, not exceed a log mean of 200 per 100 milliliters, nor should more than 10 percent of the samples exceed 400 per 100 milliliters. The analyses in table 9 indicate that Horseshoe and Porter Lakes are normally suitable for primary contact recreational uses, but the Mississippi River and streams such as Beck Bayou which carry local runoff to the lakes are often unsuitable for these uses. Analyses of lake

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samples collected near tributaries contributing runoff to the lakes show that fecal-coliform concentrations in these areas are high. During periods when local runoff is entering the lake, the areas near the inflow would be unsuitable for water-contact sports. The introduction of large quantities of water from local streams or from the Mississippi River into Horseshoe Lake would temporarily increase the coliform-bacteria content and would make the lake less suitable for recreational uses.

CONCLUSIONS

Horseshoe Lake, a popular recreational lake, receives runoff from a small drainage area and has no surface outflow during most of the year. Rainfall on the lake averages about 49 inches a year and together with inflow from runoff normally exceeds losses from seepage and evaporation. However, evaporation and seepage losses during the summer and fall exceed rainfall and inflow from runoff. Seasonal declines of 2.5-3.0 feet in the lake level are common. In exceptionally dry years, when the lake does not recover completely from previous declines and when losses due to seepage and evaporation are high, the minimum lake level has been as much as 4 feet below the normal seasonal minimum. These low lake levels severely affect the recreational use of the lake.

The frequency with which exceptionally low lake levels occur has increased in the last 15 or 20 years. This increase is due to the fact that the lake now receives less floodwater from Fish Bayou because of drainage improvements made in the St. Francis River basin and because of an increase in the net seepage out of the lake as a result of a lower average annual stage in the Mississippi River.

Seasonal declines in lake levels can be reduced and the lake can be maintained at a constant level by supplementing inflow to the lake during the summer and fall. However, it would be necessary to supplement the inflow at a rate greater than the present rate of decline, because seepage would increase as the result of raising the lake level. Seepage is out of the lake except for a brief period in the spring. In 1970 the net seepage loss was equivalent to a decline of 1.45 feet in the lake level. Analysis of the effects of maintaining the lake level above the normal level indicates that seepage out of the lake, which reached a maximum rate of 0.260 foot per month during the period July 1969 through 1970, would increase by 22 percent for each additional foot of water in the lake.

During the period July 1969 through December 1970, the maximum monthly supplemental inflow required to maintain the lake at a level of 192.5 feet above mean sea level was about 10,600 gpm, but in extremely dry years this rate would be insufficient. During the month of September 1970, a supplemental rate of about 14,400 gpm would have been necessary to maintain this level if it had not rained. Less water would be required to maintain the lake at a lower level because of the shorter period of time that it would be necessary to supplement the inflow. However, data collected in 1969 and 1970 indicate that it would be necessary to supplement the inflow at a rate of 8,600 gpm or more during some months to maintain the level of Horseshoe Lake at or above an elevation of 191.0 feet.

The inflow to Horseshoe Lake could be supplemented with water from the Mississippi River, Fish Bayou, and wells in the Quaternary alluvium and in the deeper Tertiary aquifer.

Water from the Mississippi River could be pumped over the levee with a large pump and channeled into the lake, but water from the river contains sediment, pesticides, herbicides, and coliform bacteria. The addition of sediment, pesticides, herbicides, and coliforms to the lake would be undesirable; but if water could be pumped from the river only when the concentration of these constituents is low, their effects on the quality of the lake water would be minimum. However, all four of these parameters do not have high or low concentrations at the same time. At the time when river water would be needed most to raise lake levels, sediment concentrations fortunately would be low. However, coliforms would be high enough in the river to make it unfit for public bathing. Pesticides and herbicides are lower in concentration in the river than in the natural drainage to the lake. If the river were pumped into the lake, these pesticides and herbicides would tend to add to the accumulation already in the lake. The introduction of water from the river probably would make the lake unsuitable for water-contact sports. However, as the river now supports fish and wildlife, the introduction of river water into Horseshoe Lake probably would not seriously affect fish and wildlife in the lake.

Water from a series of large wells in the quaternary alluvium could be used to supplement inflow to the lake, but wells would be less efficient than pumping water from the river. Pumping wells in the vicinity of the lake would result in an increase in seepage out of the lake. The effects of pumping wells on the seepage were analyzed on an electric-analog model. This analysis indicated that, with the exception of the southeastern end of the lake, after 90 days' pumping from wells located within one-half mile of the lake, the seepage would be increased by more than 50 percent of the yield from these wells. This increase in seepage could be minimized by locating the wells as far from the lake and as near the river as possible and in areas where the degree of hydraulic connection between the lake and the alluvium is low.

Water pumped from the Quaternary alluvium would be better suited for supplementing inflow to the lake than would water from the Mississippi River. Water from wells in this aquifer would be relatively free of sediment, pesticides, herbicides, and coliform bacteria. However, the temperature of water from these wells at times would differ from that of the lake, and the water would probably contain enough iron to cause a rust-colored precipitate when the water comes in contact with air. The effects of introducing ground water into the lake on the quality of Horseshoe Lake could be minimized by locating the wells some distance from the lake and channeling the water into the lake. During the time the water is flowing through this channel or ditch, the temperature difference between the ground water and the lake would be reduced and much of the iron oxide precipitation would settle.

Water from the deeper Tertiary aquifers could be used to supplement inflow to the lake. Water from these aquifers, which occur at a depth of about 1,300 feet below land surface, would be free of pesticides, herbicides, coliform bacteria, and sediment, but the water is not the same chemical type as the water in Horseshoe Lake. Wells in the Tertiary aquifers yield smaller quantities of water than do wells in the Quaternary alluvium. The number of wells that would be required and the cost of installing these wells would make the Tertiary aquifers an impractical source of water for supplementing inflow to the lake.

Seasonal declines in lake levels cannot be eliminated by diverting water from Fish Bayou because of insufficient flow during the summer and fall, but diversions into the lake in most years could fill the lake during the winter and spring. The construction and maintenance of a dam on Fish Bayou and floodgates or other control structures on Beck and Zanone Bayous would allow water to be diverted from Fish Bayou when it is available. However, water from Fish Bayou frequently contains suspended sediment, pesticides, herbicides, and coliform bacteria, as does the natural drainage into the lake.

During the summer and fall, the concentrations of pesticides and herbicides in water from Fish Bayou probably are high enough to make the water unsuitable for supplementing the inflow to the lake. The concentrations of pesticides and herbicides in Fish Bayou would probably be lowest in the spring, because the concentrations of these chemicals in surface waters vary with flow and with seasonal application. Flow from Fish Bayou might be diverted into the lake in the spring in order to fill the lake without contributing harmful quantities of these toxic substances to the lake, but the diversion of water from Fish Bayou into the lake during the rest of the year would probably be harmful to fish and wildlife.

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