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UTILITY OF SELECTED WESTERN LAKES AND RESERVOIRS FOR WATER-LOSS STUDIES

By

G. Earl Harbeck, Jr., and others

INTERIM REPORT
ON
LAKE HEFNER WATER-LOSS INVESTIGATIONS

UNITED STATES DEPARTMENT OF THE INTERIOR
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GEOLOGICAL SURVEY
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PREFACE

This report on selected lakes and reservoirs was prepared in the Water Resources Division of the U. S. Geological Survey, C. G. Paulsen, Chief Hydraulic Engineer, under the administrative supervision of R. W. Davenport, Chief, Technical Coordination Branch.

Many of the data included in this report were furnished by the district engineers and geologists of the Water Resources Division, U. S. Geological Survey, and by the regional directors of the U. S. Bureau of Reclamation. The wealth of personal knowledge of the particular areas contributed by field representatives of the Geological Survey and Bureau of Reclamation often more than compensated for the lack of published information concerning many lakes and reservoirs.

The City Water Department of Oklahoma City, M. B. Cunningham, superintendent and engineer, cooperated to the fullest extent in providing information concerning Lake Hefner. The field inspection was guided by Mr. Cunningham and S. K. Bean, civil engineer for the city water department. F. S. Taylor, in charge of the filter plant, provided many data on operating details. Frank Herrmann, office engineer, furnished maps of the reservoir area and operational data from his files. The part of this report describing the geology and ground-water conditions in the Lake Hefner area was written by E. W. Reed. Many climatological data were furnished by W. E. Maughan, U. S. Weather Bureau, Oklahoma City, Okla. The part of this report describing meteorological conditions at Lake Hefner was prepared by members of the staff of R. D. Russell, U. S. Navy Electronics Laboratory, San Diego, Calif.

The discussion of meteorological conditions at Pyramid Lake was prepared by E. R. Anderson, U. S. Navy Electronics Laboratory, San Diego, Calif. Much of the information on ground-water conditions at Pyramid and Walker Lakes was supplied by T. W. Robinson. Data on surface inflow were furnished by L. R. Sawyer.

General information on the hydrology of the Bynum Reservoir and Lake Frances area in northern Montana was furnished by H. W. Genger of the Bureau of Reclamation, Great Falls, Mont. J. A. Tidyman of The Valier Company, Valier, Mont., guided the inspecting party on its visit to Lake Frances and provided general climatological information and many operational data for the reservoir. The part of this report describing the geology and ground-water conditions at Bynum Reservoir and Lake Frances was prepared by A. F. Bateman, Jr.

R. A. Work, Irrigation Division, Soil Conservation Service, Medford, Oreg., furnished many data on reservoirs and lakes in that area. Because of his many acquaintances among hydraulic engineers and watermasters he was able to provide much essential information.

The geology and ground-water conditions at Big Sage Reservoir in northern California were described by J. F. Poland. T. R. Simpson and I. M. Ingerson of the State of California Division of Water Resources, Sacramento, Calif., provided invaluable data on construction of the dam and operation of the reservoir. Victor Scammon of the State of California Division of Water Resources, Alturas, Calif., guided the inspecting party on its trip to the reservoir and furnished many operational data. S. B. Kelley, president of the Hot Springs Valley Irrigation District, Alturas, Calif., contributed much historical information on conditions in the reservoir area before and after construction of the dam.

That part of the report describing the geology and ground-water conditions at Lake Mathews and at Elsinore Lake in California was prepared by J. E. Upson. Many hydraulic data for Lake Mathews were furnished by R. B. Diemer and C. C. Elder of the Metropolitan Water District of Southern California. V. P. Pentegoff of the Corps of Engineers, Los Angeles, was consulted on the geology and ground-water conditions at Lake Mathews. Current data on depths of Elsinore Lake were furnished by William Breyette of Elsinore. D. R. Crane, civil engineer, Elsinore, was the source of information on ground-water levels and well logs in the Elsinore Lake area.

B. A. Weiss and A. J. Boles of the Imperial Irrigation District, Imperial, Calif., supplied much information on Salton Sea (including data on inflow) taken from the files of the irrigation district. The discussion of meteorological conditions at Salton Sea was prepared by members of the staff of R. D. Russell, U. S. Navy Electronics Laboratory, San Diego, Calif.

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INTRODUCTION

Spurred by ever-increasing demands, a growing national awareness of the importance of water has arisen. Because the natural distribution of water supplies with respect to both time and place does not necessarily coincide with the demand, storage and transmission of water have long been relied upon to bridge the gap. In addition to the obvious and calculable construction and operation costs of a water-supply project, the cost or economic value of water lost in storage or transmission must be considered. Such losses are unavoidable but can be minimized to a limited extent by proper design and operational procedure.

Evaporation from the water surface and transpiration from vegetation in the reservoir area and along transmission canals are nonrecoverable losses. Practically speaking, evaporation losses from bodies of surface water cannot as yet be prevented, and a knowledge of their magnitude is essential to reservoir design in order that a proper balance may be reached between costs of construction and costs of water loss by evaporation. It must be realized, of course, that evaporation costs are but one of many factors to be considered in reservoir design.

Evaporation from reservoirs in the 17 Western States is roughly estimated to be 15,000,000 acre-feet per year. This does not include evaporation from the water surfaces of natural streams--such evaporation is not properly attributable to reservoir construction.

The amount of water consumed by phreatophytes is probably greater than is generally realized. In the 17 Western States, the use of water by phreatophytes, which is almost entirely nonbeneficial, may be 20 to 25 million acre-feet per year, according to unpublished preliminary figures compiled by T. W. Robinson of the Geological Survey. This is about twice the annual flow of the Colorado River. Most phreatophytes are found on stream bottoms and valley floors of the intermontane valleys. Although the amount of water consumed by phreatophytes in some reservoir areas is substantial, by far the larger part of the total must be ascribed to other factors. Removal of phreatophytes has been undertaken on an experimental scale in some reservoir areas.

In contrast to losses by evaporation and transpiration, seepage losses are not true losses in the sense that the water is permanently unavailable for use. Seepage losses may reduce the amount of water available for withdrawal from a reservoir, but the water apparently lost may reappear elsewhere to augment stream flow or may be available for withdrawal from wells.

Records of evaporation from pans have long been relied upon and have proved quite useful as indicators of reservoir evaporation in the absence of more precise information; but their limitations are well known. In addition, many crude equations for the estimation of reservoir evaporation have been proposed, and some have been widely used.

Reservoir losses may be computed as the difference between inflow and outflow (both surface and subsurface), allowing for changes in storage. Proved techniques have been developed for the direct measurement of the last three items. Reservoir losses thus computed are a residual, and may be subject to large error if inflow, outflow, and changes in storage are large compared with evapotranspiration. A field-proved method of measuring reservoir evaporation directly is needed. This report describes the utility of several reservoirs and lakes for the comprehensive studies required to test a number of proposed methods for the direct measurement of evaporation.

THE PROBLEM

The primary objective of this investigation was to select a reservoir or lake suitable for a comprehensive study of the exchange of energy between the atmosphere and a water surface. Because of their common interest in the basic theory, representatives of the Department of Interior and the Navy Department met in December 1948 to discuss the problem. An agreement was reached by the Bureau of Reclamation and the Geological Survey of the Department of Interior and the Navy Electronics Laboratory of the Navy Department to undertake a joint study of water losses from a pilot lake or reservoir. The ultimate objective was to determine the evaporation from Lake Mead and other western reservoirs and to predict evaporation losses at projected reservoirs from available climatological data.

The contemplated study of water losses, and more particularly evaporation, is described fully by Anderson, Anderson, and Marciano (1950) in a separate report. Three methods are proposed to determine evaporation from the lake or reservoir: (1) water budget, (2) energy budget, and (3) mass transfer. In the water-budget method evaporation is determined by measurements of inflow, outflow, and changes in storage. The energy- or heat-budget method involves the determination of the difference between incoming and outgoing energy. The mass-transfer method requires the measurement of certain parameters related to the factors affecting the transport of water vapor by turbulent diffusion.

The second and third methods have not been tested adequately in the field. In this study the first, or water-budget, method will be used to determine the actual evaporation, thus providing a control for evaluating certain parameters and physical constants needed in the determination of evaporation by the second and third methods.

The need for an accurate water budget is therefore a prime consideration. At first thought it might seem that many lakes and reservoirs exist for which accurate water budgets can be obtained. In a sense this is true because inflow and outflow from many reservoirs can be measured by ordinary methods to within, say, 5 percent. For this study, however, it is necessary to determine accurately the difference between inflow and outflow. If the inflow and outflow are large compared with evaporation, small errors in their measurement may be large compared with evaporation. A comprehensive evaluation of many lakes and reservoirs was therefore necessary before a site for the water-loss studies could be chosen.

THE SEARCH FOR A PILOT LAKE

In December 1948, representatives of the Geological Survey, Bureau of Reclamation, and Navy Department discussed specifications for a lake or reservoir to be used for the water-loss studies. In January 1949 the regional directors of the Bureau of Reclamation were asked to submit names of suggested reservoirs or lakes and information concerning them. The suggestions of these regional directors were studied, and inquiries also were made of certain field offices of the Geological Survey.

At that time it was contemplated that the studies would be made only during the summer months when evaporation rates are high. In California rainfall and runoff are generally low in summer, thus improving the prospects of determining the water budget accurately. The reservoirs first investigated were therefore in California. The results of these investigations were presented to representatives of the three agencies at a meeting in Boulder City, Nev., on July 21-22, 1949. It was concluded that none of the lakes and reservoirs previously investigated could be used for the study. The requirements were revised and listed in detail at that meeting. In order of importance they are as follows:

1. Water budget.
   a. The error in the monthly difference between total inflow and outflow, including both surface and subsurface, allowing for changes in storage (including bank storage), must be less than 5 percent of the best present estimates of the mean monthly-evaporation loss. It is desirable that inflow and outflow be as small as possible during the period of high evaporation.

b. Infrequent short periods of storm inflow, during which the water budget cannot be determined with the accuracy required under 1a, can be tolerated.
c. Subsurface inflow and outflow must be negligible compared with evaporation, unless it is known that they can be measured accurately.
d. Substantial bank storage is undesirable.
e. Transpiration losses must be small.
f. An accurate area-capacity curve is needed, but if not available a hydrographic survey can be made.

2. Size.
a. The minimum desirable size is 3 miles in width and 5 miles in length or an area of 10 square miles if the water body is nearly circular or if the longer dimension is in the direction of the prevailing summer winds.
b. The maximum desirable size is 50 square miles if the lake is nearly circular, otherwise 30 square miles. Larger lakes (50 to 200 square miles) may be considered if other requirements are met, but more equipment will be required and cost therefore increased.

3. Shape.
a. A circular shape is ideal. A very irregular shore line is unsatisfactory; an irregular shore line downwind is not as objectionable as one upwind. A long, narrow lake is not satisfactory.
b. An unobstructed expanse of water (few or no islands) extending 5 miles in the direction of the prevailing summer winds is desirable.

4. Depth.
a. Not more than 20 percent of the lake should be less than 5 feet deep (and preferably not less than 10 feet). A deep lake is desirable.
b. Playa lakes should be considered if they meet all requirements except depth.

5. Topographic setting.
a. Low relief is preferable; lakes in canyons are not satisfactory.
b. The drainage area preferably should be small.

6. Location and climate.
a. An arid region is preferable.
b. There should be fairly long periods of no rainfall during the season of high evaporation, but infrequent storms are are not objectionable.
c. It is preferable, but not essential, that the lake does not freeze in the winter.

A list of lakes was prepared for which more information was required. Many of these were selected because on the maps available they were seen to approach the desired shape and size. This list of lakes and a copy of the specifications was sent to the district offices of the Water Resources Division of the Geological Survey in the Western States. It was requested that information be submitted for each of the lakes listed and for any others that appeared to meet the specifications in most respects. Lakes in the humid region were not considered because of the improbability that the water budget could be determined with the required accuracy.

The replies were reviewed by the three agencies, and at a meeting in San Diego September 12-13, 1949, a number of lakes were selected as needing further investigation. Lake Hefner, near Oklahoma City, Okla., was recommended strongly by local Geological Survey engineers and geologists for further investigation. For some of the suggested lakes, available data on which to base a decision were lacking; for some of the others the information indicated that these lakes were worthy of field investigation.

September 14-15, 1949, a reconnaissance was made by Navy plane over western Nevada, southern Oregon, and northern California. The party included R. D. Russell, U. S. Navy Electronics Laboratory, San Diego, Calif.; W. O. Smith and G. E. Harbeck, Jr., U. S. Geological Survey, Washington, D. C.; and W. U. Garstka, U. S. Bureau of Reclamation, Denver, Colo. Modern maps of much of the region do not exist, but on the basis of observations from the plane it was possible to eliminate most of the suggested lakes and reservoirs in this area because of unsatisfactory shape, size, or surrounding terrain.

September 16-17, 1949, representatives of the three agencies visited the Salton Sea area. The remaining lakes considered worthy of field investigation were then visited during September 19-30, 1949, by a group that included W. U. Garstka, W. O. Smith and G. E. Harbeck, Jr., mentioned above, and E. R. Anderson, U. S. Navy Electronics Laboratory, San Diego, Calif. This group was accompanied by representatives of the various district offices of the Geological Survey.

Preliminary reports were prepared to summarize the results of the field investigations. These reports were studied at a meeting held at Boulder City, Nev., October 17-19, 1949. At that meeting Lake Hefner, at Oklahoma City, Okla., was selected as the site for the water-loss studies.

The following reports on lakes and reservoirs in the Western States were prepared to make clear the reason for the choice of Lake Hefner and to make the data collected available to those engaged in studies of evaporation or general limnology.

LAKE HEFNER, OKLAHOMA

General description

Lake Hefner is a reservoir completed in 1944 by Oklahoma City for its municipal water supply. It is in the southeastern part of T. 13 N., R. 4 W., about 8 miles northwest of the center of the city. According to area-capacity tables furnished by the city water department, its capacity at full pool (elevation 1,199) is 75,681 acre-feet and its surface area 2,595 acres. The lake, fairly regular in shape, is formed by a long horseshoe-shaped dam on Bluff Creek. (See fig. 1.) The dam, about 3½ miles long with a maximum height of 105 feet (from thalweg to road on top of dam), is of rolled-earth fill with a clay core and a seepage collection system.

The lake is supplied principally by a canal from the North Canadian River, although it lies in the Cimarron River Basin. In the Oklahoma City area the North Canadian River is at an elevation several hundred feet higher than the Cimarron River, and only a short diversion canal was needed to permit gravity flow of selected water from the North Canadian

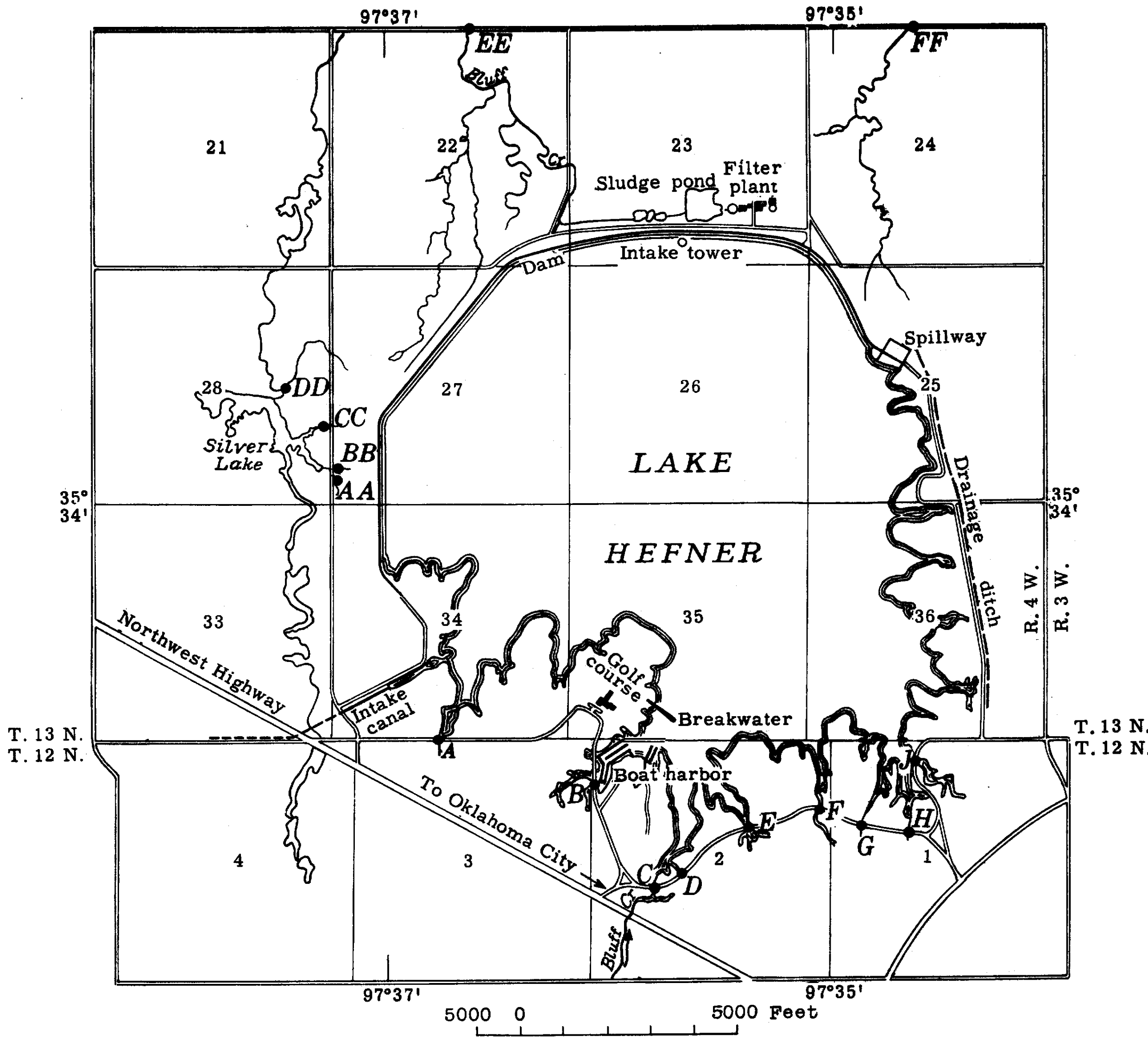

Figure 1.-- Map of Lake Hefner, Okla.

River into Lake Hefner. The natural drainage area of Bluff Creek and other contributing streams above the dam is 3,156 acres, excluding the area of the lake surface. In addition, runoff from an area of about 200 acres discharges into the intake canal and thence into Lake Hefner. The drainage area above the lake is only about 30 percent greater than the area of the lake at full pool.

Geology

Except where covered by alluvium, the Hennessey shale of Permian age is the surface formation of the Lake Hefner area. It is primarily red shale containing a few thin, lenticular sandstone beds. The formation crops out in a north-south band covering the western third of Oklahoma County and dips westward at a rate of about 40 feet per mile. The thickness of the Hennessey shale in Oklahoma County ranges from a feather edge along the surface contact with the underlying Garber sandstone in the central part of the county to about 650 feet at the western edge of the county. As Lake Hefner is near the middle of the outcrop of the Hennessey shale, it is underlain by more than 250 feet of the shale.

Bluff Creek and its tributaries have cut back into a high terrace of the North Canadian River about a mile south of Lake Hefner. This terrace consists of unconsolidated sand, gravel, and clay deposited by the North Canadian River in some past period when the river was at a much higher elevation and probably had a much greater flow than at present. The terrace, now equivalent in area to a single township, was at one time a wide flood plain. The terrace is now being actively dissected by tributaries of both the North Canadian and the Cimarron Rivers, and the divide between the two systems is now on the terrace. The deposits underlying the terrace contain relatively large amounts of water, and many wells, including those supplying the city of Bethany, have been drilled into it.

The Hennessey shale underlying the reservoir weathers to a dark soil that is readily eroded and shows relatively little relief. The thin soil layer is grass-covered. Trees, mostly cottonwoods and willows, are found only along the watercourses where the soil is thicker and capable of storing water.

Seepage

The Hennessey shale is practically impermeable, and any recoverable water in the shale is believed to be contained in joints and fractures. Most of the wells tapping the Hennessey shale are farm wells, and the few towns that use water from this formation have wells of low yield. No pumping tests to determine permeability have been made on any well in the Hennessey shale, but from the yields of these wells it is evident that the permeability of the sandstones in the Hennessey shale is less than that of the underlying Garber sandstone. Tests on sandstone of the Garber show its permeability to be about 40 gallons per day through an aquifer 1 foot in thickness and 1 mile in width under a hydraulic gradient of 100 percent (Meinzer's units). No faults are known to be in the Hennessey shale, and the possibility of seepage of any important quantity of water into or out of the lake through the Hennessey shale seems remote.

Because the regional dip of the strata in this area is westward, a cross section was selected along the western side of Lake Hefner for use in computing approximately the possible magnitude of deep seepage. The length of the cross section from the northern end of the lake to the southern end of the dike is approximately 10,000 feet. Its thickness was assumed to be 100 feet. The hydraulic gradient is assumed to conform to the regional dip of 40 feet per mile. The field coefficient of permeability was assumed to be 40 gallons per day (Meinzer's units). This is an average figure for the Garber sandstone; the permeability of the Hennessey shale is believed to be much less. From these data, the maximum deep-seepage loss is computed to be 300,000 gallons per day, or 0.9 acre-foot per day. As will be demonstrated later, this figure is of little practical significance when compared with other items included in the water budget. The so-called "wet-weather springs" in the Hennessey shale are caused by rainfall percolating down through the thin soil mantle and along the contact with the shale or sandstone until it reaches the outlet. Very little of the precipitation on the outcrop actually enters the Hennessey shale.

Construction of a series of fish-rearing ponds in the area west of the sludge pond was under way during early 1950. Construction of a canal, a part of the seepage-collection system, necessitated excavation into the previously undisturbed shale to a depth of 3 or 4 feet. The newly exposed shale was dry when inspected in January 1950.

There are, however, small but measurable shallow seepage losses from the reservoir. Because seepage from the reservoir is a function of reservoir stage only, it is essential that measurements of seepage be made during dry periods when there is no surface runoff from the area below the dam. The possibility of defining the relation of seepage to reservoir stage does not appear probable, because the range in reservoir stage is relatively small. However, a series of seepage measurements at weekly or biweekly intervals during dry periods should provide adequate data on collected seepage.

Any seepage that occurs beneath or through the dike along the northern and western sides of the lake is collected by a series of drains. Along the northern side of the dam, between the west line of sec. 24 and the center of sec. 28, seepage collects and drains into the old Bluff Creek channel below the dam.

Operation of the sludge pond west of the filter plant (see fig. 1) at times complicates the determination of seepage in this area. When filters are washed, the wash water is discharged into the sludge pond, usually causing it to overflow through the morning-glory spillway and temporarily to increase the flow of Bluff Creek below the dam. From time to time small quantities of water are recovered from the sludge pond by pumping. This water does not, however, pass through the raw-water venturi meter. Under normal conditions, filter wash water is not being discharged into the sludge pond and the recovery pump is not in operation, so that, neglecting evaporation from the pond, the amount of water leaving the sludge pond by spillway overflow and gate leakage is equal to seepage into the sludge pond. A recording gage below the sludge pond is essential to determine when seepage measurements can be made without the complicating effect of sludge-pond operation. Seepage from the dam will be relied upon to furnish sufficient water to keep the fish-rearing ponds full. It may prove necessary to adjust the measured quantities of seepage for the loss by evaporation from the fish-rearing ponds and from the sludge pond.

Most of the seepage from the west side of the reservoir is collected in a ditch paralleling the dam. It flows northeast along the dike to a point near the north quarter corner of sec. 27 and thence in a northerly direction. A small pond in the NW¼ sec. 27 also drains northeast, paralleling the main drainage ditch. The two seepage channels join near the center of sec. 22 (see fig. 1) and reach the Bluff Creek channel at a point approximately 1,000 feet south of the north line of sec. 22. Several small seepage areas were noted in the SW¼ sec. 22. At one of these, a spring issues from a small depression in an open field and flows into the westernmost of the two seepage channels previously described. There are several uncontrolled farm ponds--perhaps an acre in extent--in the S½ sec. 22. They are kept filled by seepage and overflow continuously. The flow of Bluff Creek where it crosses the highway along the north line of sec. 22 (location EE on fig. 1) includes the seepage from the area along the northern side of the reservoir, west of the filter plant. The seepage flow measured at EE on April 7, 1950, was 0.89 cubic foot per second, or 1.8 acre-feet per day.

Along the west side of the reservoir a number of small seepage areas discharge into a tributary, that joins Bluff Creek about 2 miles below the dam. Seepage can be measured at locations AA, BB, and CC (see fig. 1) at culverts under the highway. A fourth seep, DD, has its origin in marshy areas on both sides of the highway, and can be measured just above its confluence with Silver Lake outflow. The total flow of the four seeps, AA-DD, inclusive, on April 7, 1950, was 0.07 cubic foot per second, or 0.1 acre-foot per day.

In the area east of the filter plant several seepage areas discharge into a small stream channel. During a period of dry weather it was noted that small tributaries from the west or reservoir side of the stream continued to flow, but tributaries from the east side were dry. It was therefore concluded that the observed flow was seepage from the reservoir. There are several small marshy areas below the spillway in the NW¼ sec. 25. Discharge from these marshy areas flows under Hefner Road near the south quarter corner of sec. 24. The flow from a small seep in the SW¼ sec. 24 joins the seepage from the spillway area just below Hefner Road. Other minor seepage areas in sec. 24 contribute minor amounts, and the total seepage can be measured at point FF on the north line of sec. 24. (See fig. 1.) The measured seepage flow at FF on January 25, 1950, was 0.17 cubic foot per second, or 0.3 acre-foot per day.

Withdrawals

Water is released from Lake Hefner through a 48-inch raw-water main. Outflow rates are measured with a venturi meter. The recording device is actuated by a mercurial manometer, and the difference in head, converted to equivalent rate of flow in million gallons per day, is recorded on a circular chart in the filter plant. A cam-actuated totalizing device registers total flow. Although the manufacturer's rating for the venturi meter is quite adequate for the needs of the city water department, it is essential that, for the purposes of this study, the venturi meter be calibrated in order that reservoir withdrawals may be measured as accurately as possible. It is estimated that, after calibration, the error in measuring withdrawals will not exceed 3 percent and may be substantially less.

Reservoir withdrawals are the major item in total outflow from Lake Hefner. Combined capacity of the three pumps is 24 million gallons per day (73.7 acre-feet per day), but filter capacity limits the maximum possible withdrawal to a peak rate of approximately 22 million gallons per day. During daytime hours in the summer months the ordinary peak rate of flow usually is 18-20 million gallons per day, with a total of 15 million gallons for the entire 24-hour period. During nonsummer months pumpage is somewhat less, averaging perhaps 6 million gallons per day.

Inflow

The major source of inflow to Lake Hefner is the canal from North Canadian River. (See fig. 1.) During the 3-year period ending September 30, 1949, substantial volumes of inflow occurred during 11 periods totaling 64 days, or an average of 21 days per year. Average inflow on those days was approximately 1,000 acre-feet. Because of the relatively large volumes of water concerned, it is not certain that the water-budget accuracy requirement can be met on days when canal inflow is of this magnitude. A 5-percent error in measuring inflow would amount to 50 acre-feet, which is approximately equal to the average daily evaporation. With frequent discharge measurements during the infrequent periods of high inflow it may be possible to compute weekly reservoir losses with sufficient accuracy.

A small amount of natural flow also reaches the reservoir through the intake canal. The canal cuts across the previously described Bethany terrace and intercepts part of the surface- and ground-water flow that formerly reached the stream that enters Bluff Creek as a tributary from the west several miles below the dam. Part of the canal is paved, and drain tile has been installed beneath the paved section to prevent "floating." The water thus drained is discharged into the afore-mentioned Bluff Creek tributary, which bypasses the lake. A small amount of ground water drains into the canal and is conveyed into Lake Hefner. Storm runoff from an area of approximately 200 acres also drains into the canal. A recording gage and an artificial control are required to measure this flow. The best site appears to be at the point of emergence of the siphon, about one-half mile above the lake, where a wide broad-crested concrete weir has been provided. As normal ground-water discharge is about 0.5 cubic foot per second, or 1 acre-foot per day, the existing concrete weir is too insensitive, and a small rectangular weir is needed for precise determination of low flows.

Excluding the intake canal, the natural drainage area above full pool elevation of 1,199 feet is 3,156 acres, based on a transit-stadia determination by S. K. Bean, civil engineer of the Oklahoma City Water Department. Of the total area, 2,484 acres lies above the road that encircles the southern end of the lake. The size of the area lying between the road and the lake varies with reservoir stage but is 672 acres when the lake stage is 1,199 feet.

The major stream that flows into the reservoir is Bluff Creek, which has a drainage area of 1,037 acres above the encircling road. The headwater tributaries of Bluff Creek drain part of the Bethany terrace, and the perennial flow of Bluff Creek is derived from ground water in that area. A recording gage and artificial control at the road bridge (location C on fig. 1) are required to measure Bluff Creek flow.

The remainder of the storm runoff is carried under the encircling road by concrete culverts, thus limiting the number of points at which inflow must be measured. Records of flow are required at 8 points (locations A, B, D, E, F, G, H, J on fig. 1). These may be obtained with sufficient accuracy if a weir is installed at the entrance to each culvert. A crest-stage gage is required at each location to record the peak stage reached during storm runoff. One or more points on the recession hydrograph can be obtained by direct observation. Based on continuous records of Bluff Creek flow and rainfall in the reservoir area, the discharge hydrograph at each inflow point may be estimated with sufficient accuracy.

According to S. K. Bean, inverts of all culverts have been set at elevation 1,199, the maximum reservoir stage. This has resulted in the formation of small pond areas on the upstream side of several culverts. Flow through the culverts takes place only when the pond levels have risen to the culvert invert elevation. During many storms runoff is insufficient to raise the ponds to the overflow point, and inflow to the lake does not occur.

The possible error in measuring storm inflow to Lake Hefner is small compared to the possible error in measuring rainfall on the lake surface. Discharge of Bluff Creek and the intake canal can be measured with sufficient accuracy except possibly for a few short periods of high flow each year. Estimates of flow through the culverts and from the ungaged area are subject to fairly large percentage errors, but the actual magnitude of those errors is small. During minor floods, runoff is seldom greater than one-third to one-half of the flood-producing rainfall. On an annual basis the difference between rainfall and runoff is even more striking. Rainfall at Oklahoma City, from U. S. Weather Bureau records, averages 31.76 inches annually. Average annual runoff in this area is between 2.5 and 5.0 inches, according to Langbein (1949, pl. 1). The total drainage area above full-pool elevation is 3,156 acres, compared with a lake-surface area of 2,595 acres, as taken from the area-capacity table of the city water department. As the area of the lake surface is nearly as great as that of the tributary drainage basin, rainfall on the lake surface is a much larger item in the water budget than is runoff from the area above the lake. Therefore, possible additional refinements in measuring inflow do not appear justified.

Rainfall on the lake is a large item in the water budget, and a dense network of rain gages will be required. It is proposed to place recording rain gages at each of the meteorological stations and 18 nonrecording gages spaced as uniformly as possible around the lake. It is planned to install a recording rain gage on the barge in the middle of the lake on which meteorological equipment will be placed. A municipal golf course is under construction on the south side of Lake Hefner. It is proposed to irrigate the new greens and fairways with water pumped directly from the lake. The maximum pumpage contemplated is 250,000 gallons, or 0.8 acre-foot, per day. The metered withdrawals from the lake present no problem, but the possibility of return flow from irrigation cannot be ignored. Records of water-level elevations at several test wells in the area between the golf course and the lake will be necessary to determine whether return flow is reaching the lake and, if so, to estimate the quantity. It appears improbable that the quantity will be sufficiently large to warrant inclusion in the water-budget calculations.

Water budget

An approximate average monthly water budget has been estimated in order to illustrate the relative magnitude of the quantities involved, when there are no diversions from North Canadian River. Estimates of the probable upper limit of measurement errors have been shown. The reservoir is assumed to be full at the beginning of the month (contents 75,681 acre-feet, surface area 2,595 acres, from city water department area-capacity table.) (See fig. 2.) Annual reservoir evaporation at Oklahoma City is estimated to be about 66 inches; January evaporation is estimated to be 1.5 inches and July evaporation to be 10.2 inches, according to the American Society of Civil Engineers (1949, p. 127, table 15). At these rates monthly evaporation from Lake Hefner averages 324 acre-feet during January and 2,210 acre-feet during July.

Item	Quantity	Measurement error	
	(acre-feet per month)	(percent)	(acre-feet per month)
Inflow:			
Natural runoff	43	±5	±2.2
Rainfall on lake	572	±5	±28.6
Irrigation return flow	1	±100	±1.0
Total	616	-	
Outflow:			
Seepage	69	±10	±6.9
To filter plant	737	±3	±22.1
Golf-course irrigation	12	±5	±0.6
Total	818	-	
Loss in storage	1,392	-	±25.6
Evaporation	1,190	-	

The loss in storage was computed by subtracting inflow from the sum of outflow plus evaporation. The error was computed by assuming that the error in the measured change in stage will not exceed 0.01 foot.

It is required that the error in the difference between inflow and outflow shall not exceed 5 percent of the mean monthly evaporation. The error in measuring change in contents must, of course, be included. For short periods of time, change in contents becomes the controlling factor. During periods of high winds, it is doubtful that changes in stage can be measured closer than 0.01 foot. On this basis daily evaporation as computed from the water budget is subject to a possible error of 65 percent, and weekly evaporation an error of 9 percent. A week, therefore, appears to be the shortest interval for which dependable evaporation figures can be obtained, except during periods when nocturnal winds are light, so that midnight stages can be accurately determined.

The errors shown in the table are believed to represent the maximum error to be expected. For average months the errors in monthly values in any item may be expected to follow the normal law of error. The variance of the sum of a number of items is the sum of the variances of the individual items. If the errors in the individual items be conservatively considered to represent two standard deviations (i.e., it is expected that they may be exceeded once in 20 times), it is also to be expected that the error in their sum will exceed 44.9 acre-feet only once in 20 times, on the average. The maximum allowable error in the sum is 59.5 acre-feet, which is 5 percent of the evaporation. The probability is 8 in 1,000 or a little less than 1 in 100 that this figure will be exceeded. The probability that the maximum error in all items will occur simultaneously is 3 in 10,000, or about 1 in 3,300.

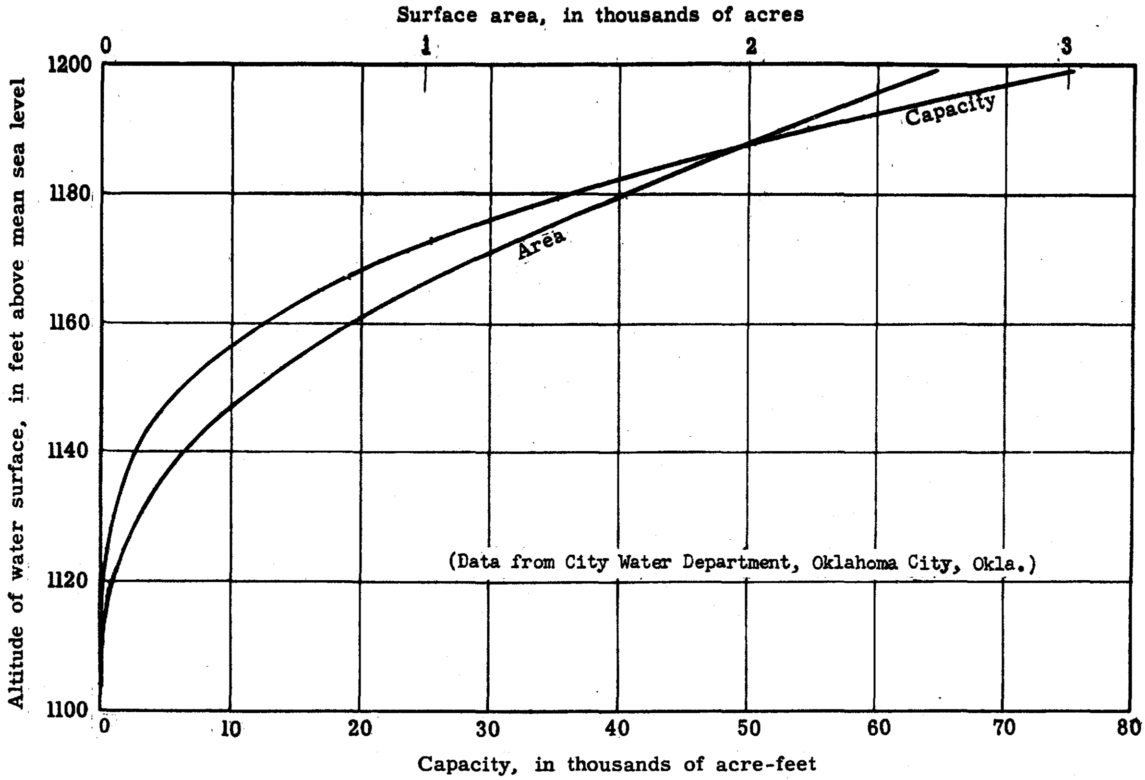

Figure 2.-- Graph showing area and capacity curves for Lake Hefner, Okla.

It is anticipated that during major storms it will be impracticable to obtain sufficiently accurate records of rainfall and runoff. Average daily evaporation is approximately 40 acre-feet. An inch of rainfall on the lake surface amounts to 216 acre-feet at full pool. A 5-percent error in the determination of average rainfall amounts to 10.8 acre-feet, or more than 25 percent of the daily evaporation. The error in measuring total storm runoff from the gaged and ungaged areas is probably greater than 5 percent, but runoff is small in comparison with rainfall. The accuracy of the water budget during major storms is limited primarily by the accuracy of the determination of rainfall on the lake. A study of the areal variability in rainfall as measured by the network of rain gages will indicate the magnitude of the possible error in the determination of precipitation on the reservoir surface.

The frequency of storm rainfall has been investigated. For the 10-year period 1939-48, the frequency of daily precipitation is as follows:

Daily precipitation in inches	Average number of occurrences per year
0.50 - 0.99	13
1.00 and greater	10

The number of days which had rainfall of 1 inch or greater was significantly greater for the months of April, May, and June. A succession of several days of heavy rainfall was not uncommon. Therefore, although on the average it may be expected that daily precipitation will be 1 inch or more on 10 days each year, the number of storm periods would be somewhat less.

The area-capacity table for Lake Hefner used by the city water department was prepared on the basis of a topographic survey made prior to the construction of the dam. Although the existing table is entirely adequate for operational purposes, a complete hydrographic survey of the lake will be required to determine the amount of deposition of sediment, if any, since the reservoir was filled, and the amount of overburden removed for construction of the embankment. The resurvey should be particularly precise in the area covered by the top few feet of water in order that the changes in volume and area resulting from small changes in stage may be accurately determined.

Meteorological conditions

Meteorological conditions at Lake Hefner are favorable for water-loss studies. Because the surrounding topography is gently sloping, the wind structure is not distorted by mechanically induced turbulence except in the area near the dike. Northerly and southerly winds predominate, as shown in figure 3. The following table (Weather Bureau, Oklahoma City) shows the average monthly wind speeds at the U. S. Weather Bureau station in the residential section of Oklahoma City.

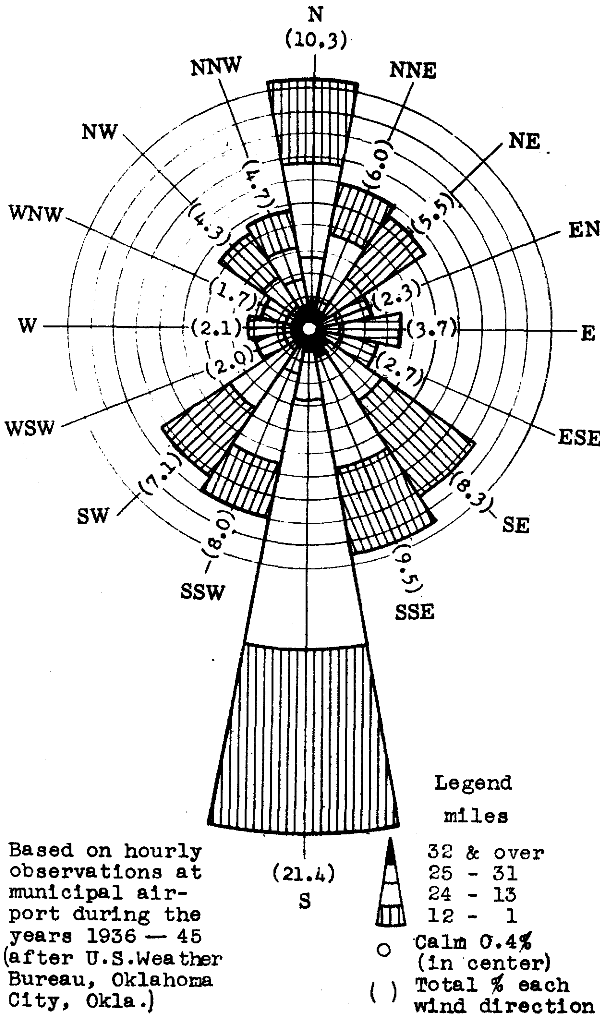

Figure 3.—Wind rose for Oklahoma City, Okla.

Month	Average wind speed (miles per hour)	Month	Average wind speed (miles per hour)
Jan.	11.2	July	9.3
Feb.	12.2	Aug.	9.0
Mar.	13.3	Sept.	10.3
Apr.	13.1	Oct.	11.1
May	11.6	Nov.	11.1
June	10.7	Dec.	11.1
		Yearly avg.	11.1

The winds at Lake Hefner are expected to have a speed of approximately 5 miles per hour greater than those observed at the city station. The maximum 5-minute average speed at Lake Hefner may approach 60 miles per hour.

The humidity at Oklahoma City is shown in the following table (Weather Bureau, Oklahoma City). Prior to July 1939 observations were made at the city office, but since 1939 the data have been obtained at Will Rogers Field, approximately 7 miles southwest of the city office.

Month	Relative humidity in percent at indicated time 3:00 a.m.	6:30 a.m.	12:30 p.m.	6:30 p.m.
Jan.	77	80	62	65
Feb.	74	79	57	60
Mar.	71	76	50	53
Apr.	73	77	51	52
May	77	82	57	59
June	79	82	55	57
July	73	79	48	51
Aug.	71	79	47	51
Sept.	69	81	51	55
Oct.	72	79	53	57
Nov.	72	78	56	61
Dec.	76	80	61	66
Year	74	79	54	57
Years of record	9	58	31	58

Two series of humidity measurements were made at Lake Hefner on September 30, 1949, using a sling psychrometer. Between 10:00-10:15 a.m. at the upwind shore the wind was from south-southeast and its speed was estimated at 20 to 25 miles per hour. At the downwind shore the wind was also from south-southeast; its speed was 30 to 35 miles per hour and it was very gusty. Average wave heights on the lake were 1.5 feet, with a maximum of 4 feet. The wave length was estimated to be 15 feet. Wave data were estimated from the downwind shore. Measurements of humidity at this time showed a vapor-pressure difference (downwind minus upwind) of 2.9 millibars. Relative humidity at the upwind location was 42 percent; at the downwind location, 53 percent.

The second set of measurements was made in the afternoon, from 2:15 to 2:30 p.m. The wind was south-southeast at 15 miles per hour. Wave heights were approximately 0.5 foot. The vapor-pressure difference was 2.0 millibars. Relative humidity at the upwind location was 32 percent; at the downwind location, 43 percent. The water temperature at this time was 69° F., indicating a vapor-pressure difference of 19.7 millibars between the vapor pressure of saturated air at the temperature of the water and the actual vapor pressure of the air at psychrometer level. The grass on the south side of the lake averages about 12 inches in height, indicating a roughness parameter of approximately 6-7 centimeters for light winds, and 3-4 centimeters for strong winds that flatten the grass and thus create a smoother surface.

A third series of humidity measurements were made on October 3, 1949. The wind was south-southwest, 5 to 10 miles per hour at the upwind (south) shore, 0 to 3 miles per hour at the downwind shore. The average of 8 readings at the upwind location indicated the relative humidity was 77 percent; the average of 13 readings at the downwind location indicated the relative humidity was 82 percent. The vapor-pressure difference (downwind minus upwind) was 1.4 millibars.

The humidity measurements, and particularly the last set, which were made under conditions of light winds and high humidities, indicate that the vapor-pressure difference is easily measurable. The humidity equipment to be used will measure a difference of 0.2 millibar.

Conclusions

Lake Hefner is believed to meet more of the requirements for the water-loss studies than any other of the reservoirs investigated. A somewhat larger lake would be desirable, but Lake Hefner is reasonably regular in shape, and preliminary meteorological observations indicate that humidity differences across the lake are measurable. The general wind structure is uncomplicated by orographic effects. More detailed investigations are required of certain factors affecting the water budget, such as a more precise determination of possible deep-seepage losses and a test of the venturi meter rating. A careful study of the relative magnitudes of the quantities involved in the water budget and of the errors of measurement leads to the conclusion that the evaporation from Lake Hefner can be determined by the water-budget method with acceptable accuracy for a large part of the time. It was on the basis of these facts, therefore, that the representatives of the Geological Survey, Bureau of Reclamation, and Navy Department agreed that the water-loss studies should be conducted at Lake Hefner.

PYRAMID LAKE, NEVADA

Pyramid Lake lies in a closed basin in Washoe County, Nev., approximately 40 miles northeast of Reno. It is supplied by inflow from Truckee River, but since shortly after the turn of the century, much of the natural flow of Truckee River has been diverted for irrigation, thus accelerating the decline in lake levels that has continued since about 1870. The lake is now approximately 8 miles wide and 22 miles long.

Pyramid Lake is sheltered by mountain ranges--the Virginia Range rising on the west to more than 4,000 feet and the Lake Range on the east side to more than 2,000 feet. (See fig. 4.) Russell (1885, pl. 3) noted, on each side of the long axis of the lake, the existence of a major fault marked by the edges of upheaved blocks of basalt. The lake occupies part of the bed of the Pleistocene Lake Lahontan, which was first described in detail by Russell (1885) who visited the region in 1881-83. According to Jones (1925, p. 3), "only the valleys in the western portion of Nevada were occupied by Lake Lahontan. The great peninsulas and islands formed by the mountain ranges impressed an exceedingly irregular shore line upon the lake. At the time of the greatest expansion of the water surface it covered an area of about 8,500 square miles, and as the surface of the lake fell and uncovered the different divides, it separated into a number of independent smaller bodies of water. At present these subsidiary basins are all in a state of dessication. Some retain permanent bodies of water, such as Pyramid, Winnemucca, and Walker Lakes; others may go entirely dry in exceptionally dry years, as Carson, Honey, and Humboldt Lakes; still more are playas, covered with water for only brief periods of the year, as the Black Rock and Smoke Creek Deserts." Winnemucca Lake, however, has been dry since 1939.

The lacustrine sediments deposited during the life of Lake Lahontan were classified by Russell (1885, p. 125) into three divisions: upper lacustral clays, medial gravels, and lower lacustral clays. The lacustral marly clays are fine and evenly laminated. Near the mouth of Truckee River only the upper clays are exposed. On the basis of a field examination, these beds are considered relatively impermeable. Probably the present lake bed is composed of essentially similar deposits.

The surface-water supply of Pyramid Lake is derived from Truckee River. The average daily discharge of Truckee River into the lake is estimated to be approximately 50 cubic feet per second, or 36,000 acre-feet per year. During the flood of December 1937, peak discharge of Truckee River at Reno was approximately 13,000 cubic feet per second, indicating that much larger volumes of inflow may occur, but flows of this magnitude are infrequent and of short duration.

Also flowing into Pyramid Lake are a number of small, ephemeral streams that drain an area of approximately 315 square miles. Average annual runoff in this region is 0.25 inch or less, according to Langbein (1949, pl. 1). Using the figure of 0.25 inch, average annual inflow from this source is 4,000 acre-feet.

There is little information available on the volume of ground-water flow into Pyramid Lake. Two small springs were observed near the water's edge on the southwest side of the lake. A distinct odor of hydrogen sulfide was noted. Total discharge from the two springs was estimated to be about 0.5 cubic foot per second, or 400 acre-feet per year. The proprietor of an inn at Sutcliffe, on the west shore of the lake, reported that domestic water supplies are obtained from springs in the mountains and from wells in the alluvial fans. The Southern Pacific Lines have a well near Sutcliffe for feed-water supply and another at Big Canyon.

The eastern side of the lake is inaccessible by road and was not inspected. The aerial reconnaissance on September 14, 1949, revealed no perennial streams flowing into the lake, but ground-water conditions could not be determined.

There are evidences of ancient hot springs near the south and north ends of the lake. It is reported that there are hot springs in the lake on the north side of Pyramid Island; steam is reported to rise from this area on cold days. Russell (1885, p. 60) noted several hot springs rising from the bottom of the lake and along the base of the tufa crags on the north side of the peninsula at The Needles near the north end of Pyramid Lake. No such springs were observed on September 19, 1949.

There is believed to be no movement of underground water from Warm Springs and Winnemucca Valleys to Pyramid Lake, according to D. A. Phoenix, who has studied the area and states that the pass from Warm Springs Valley to Pyramid Lake contains fine-grained lake sediments.

Areas of phreatophytes along the southern, western, and northern shores of Pyramid Lake are relatively minor. On the west shore opposite Anaho Island a patch of salt cedar covers approximately 1 acre. Approximately 2 miles north of Sutcliffe, on the west shore, a verdant area of not more than 5 acres is evidence of a small ground-water supply. An irrigated

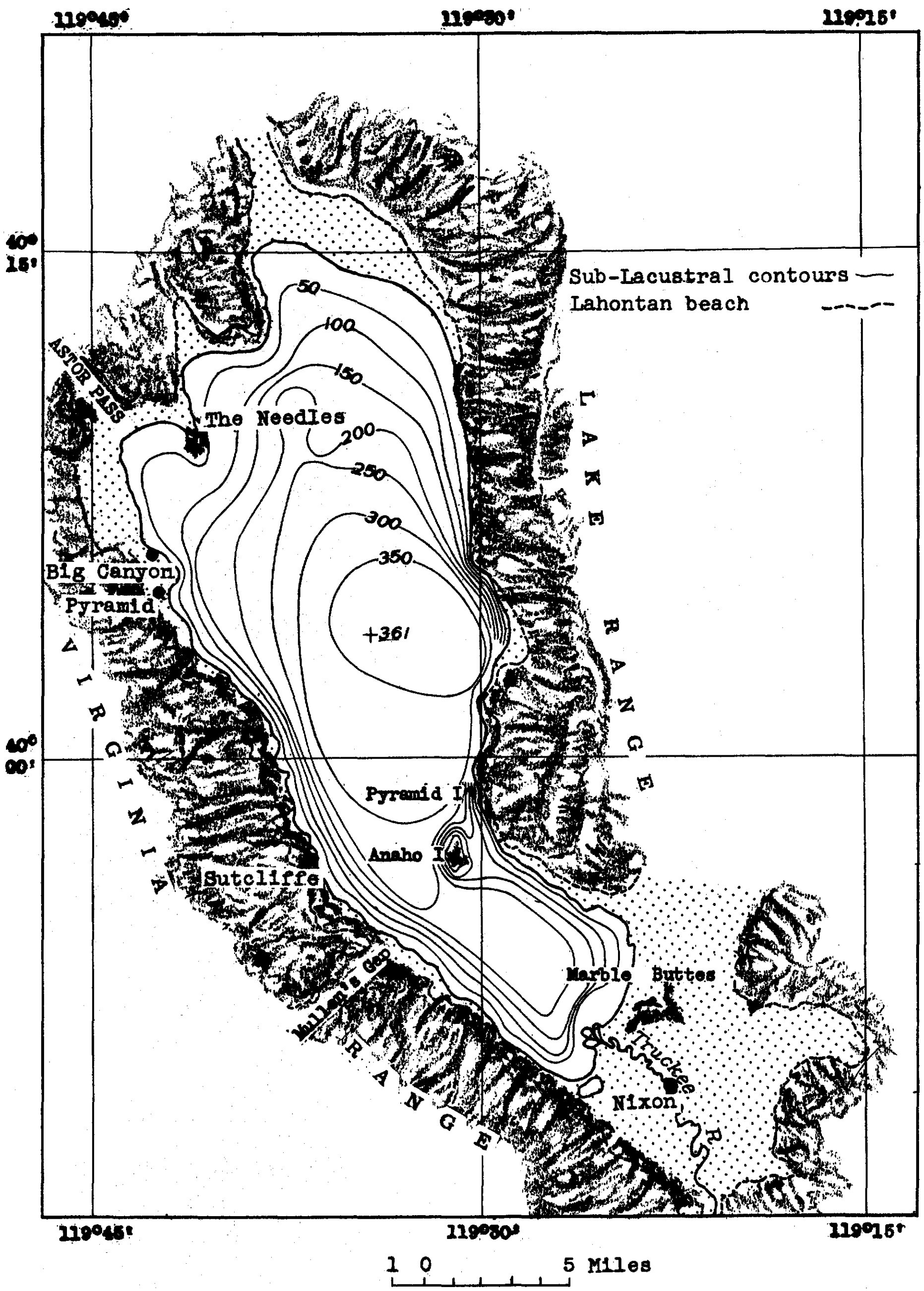

Figure 4. -- Map of Pyramid Lake, Nev. (after Russell, I. C. 1885).

ranch near the town of Pyramid produces a small amount of hay. Along the northwest shore of the lake is a narrow band of vegetation averaging perhaps 100 feet wide and about 1 mile long. At the north end of the lake, east of The Needles, a larger area of about 2 square miles is rather sparsely covered with phreatophytes. At an estimated consumptive-use rate of 1.0 acre-foot of water per acre, the total water consumed probably does not exceed 1,300 acre-feet per year. As previously mentioned, the east shore could not be inspected, but the aerial reconnaissance revealed that there is very little marginal vegetation along the east shore or in the draws leading up into the mountains.

The volume of ground-water inflow cannot be precisely evaluated, but it is believed small. Movement of ground water through the fine-grained Lake Lahontan beds is undoubtedly small, but the possibility of substantial ground-water flow in the Truckee River channel should be investigated. Pumping tests to determine the permeability of these deposits would be required. Based on this information and on observations of hydraulic gradient in test wells, the volume of ground-water flow in the Truckee River channel could be computed with acceptable accuracy. The field coefficient of permeability, as defined by Meinzer (1949, p. 454), is conservatively estimated to be 5,000 gallons per day. The hydraulic gradient is assumed to parallel the stream bed, which has a gradient of about 8 feet per mile. From a topographic map the average width of the channel is estimated to be 1 mile. The thickness is assumed to be 100 feet on the basis of a rather common thickness of this magnitude in many western areas. Based on these data, flow through the aquifer is computed as 4,400 acre-feet per year.

An approximate water budget for Pyramid Lake can be calculated. Evaporation is estimated by Harding (1935, p. 508) to be about 4 feet per year. The surface area of the lake is approximately 120,000 acres, so that annual evaporation is 480,000 acre-feet. There is no surface outflow from the lake and no evidence of deep-seepage losses. Annual surface inflow from Truckee River averages 36,000 acre-feet per year and from the remainder of the Pyramid Lake Basin about 4,000 acre-feet. Rainfall on the lake averages about 7 inches per year, or 70,000 acre-feet. Total surface inflow is approximately 110,000 acre-feet per year. If it is assumed that infrequent short periods of storm runoff may be excluded from the computations, it is estimated that surface inflow can be measured within 10 percent, or 11,000 acre-feet, which is 2.3 percent of the annual evaporation. If the allowable error in measuring the difference between inflow and outflow (outflow from Pyramid Lake is zero) is to be not more than 5 percent of the evaporation, the maximum permissible error in measuring inflow to Pyramid Lake must not exceed 24,000 acre-feet. To meet this requirement, it is necessary that the error in measuring ground-water inflow not exceed 13,000 acre-feet. Meeting this requirement appears practicable in view of the magnitudes of the quantities involved.

The meteorological conditions at Pyramid Lake are complicated by its large size and by the surrounding terrain. It is evident that surface winds are affected by the topography. When the lake was visited on September 19, 1949, several residents of Nixon at the south end of the lake agreed that westerly winds prevailed throughout the year; and the wind was observed to be westerly on this day. A resident of Sutcliffe, on the west side of the lake, stated that the wind blew in the direction of the long axis of the lake (northwest-southeast) during the entire year, which is in agreement with the wind direction observed at this point on the day of the inspection trip. At the north end of Pyramid Lake near The Needles, gusts up to 20 miles per hour were observed several times, indicating the possibility of local thermal winds.

It appears reasonable to assume that local land and sea breezes develop during the night and day around a lake as large as Pyramid Lake. This would occur even if the surrounding terrain were flat. Drainage tongues from the adjacent mountains reinforce the land breeze. Local valley winds during the day reinforce the lake breeze, moving inshore and up the valleys. The wind structure over the lake, both day and night, therefore, consists of a series of tongues around the shore superimposed upon and confusing the general flow.

For the contemplated studies, it is required that the stream-line pattern of wind flow over the lake surface be known, and for Pyramid Lake this information is lacking. A study of the local wind structure is needed; this would require the operation of a network of at least 8 or 10 anemometer stations for at least a year. Without such a study, the proper choice of sites for the meteorological installations could not be made. Moreover, the size of the lake and the probable complexity of its wind structure make it likely that a larger number of meteorological installations will be needed than is now planned for the pilot lake.

Direct evidence is lacking as to the maximum height of waves to be expected. According to Sverdrup (1945, p. 1055), the maximum probable wave height, in feet, in the ocean for very strong winds is $1.5 \sqrt{F}$, when F is the fetch in nautical miles. For a fetch of 18 nautical miles, the maximum height of waves to be expected is $6\frac{1}{2}$ feet. Based on his observations in 1882, Russell (1885, p. 62) wrote "Even in summer the gales rise suddenly, without warning, and sweep down upon the lake with the fury of a tempest. Sometimes within a few moments the lake is changed from a placid mirror to a sea of frothing billows that break on the shore in long lines of foam. The suddenness with which the wind changes, and the bleak, inhospitable character of the shores, make the navigation of this lake somewhat dangerous, even to experienced boatmen."

A detailed hydrographic survey of Pyramid Lake would be required. The only hydrographic map available is that prepared by Russell (1885, pl. 9) on the basis of soundings made in 1882. The maximum depth of water found at that time was 361 feet at a point approximately 8 miles northwest of Anaho Island. Based on area-capacity curves prepared from Russell's data, Pyramid Lake now contains approximately 20,000,000 acre-feet of water; its surface area is approximately 120,000 acres (187 square miles); and its average depth 167 feet.

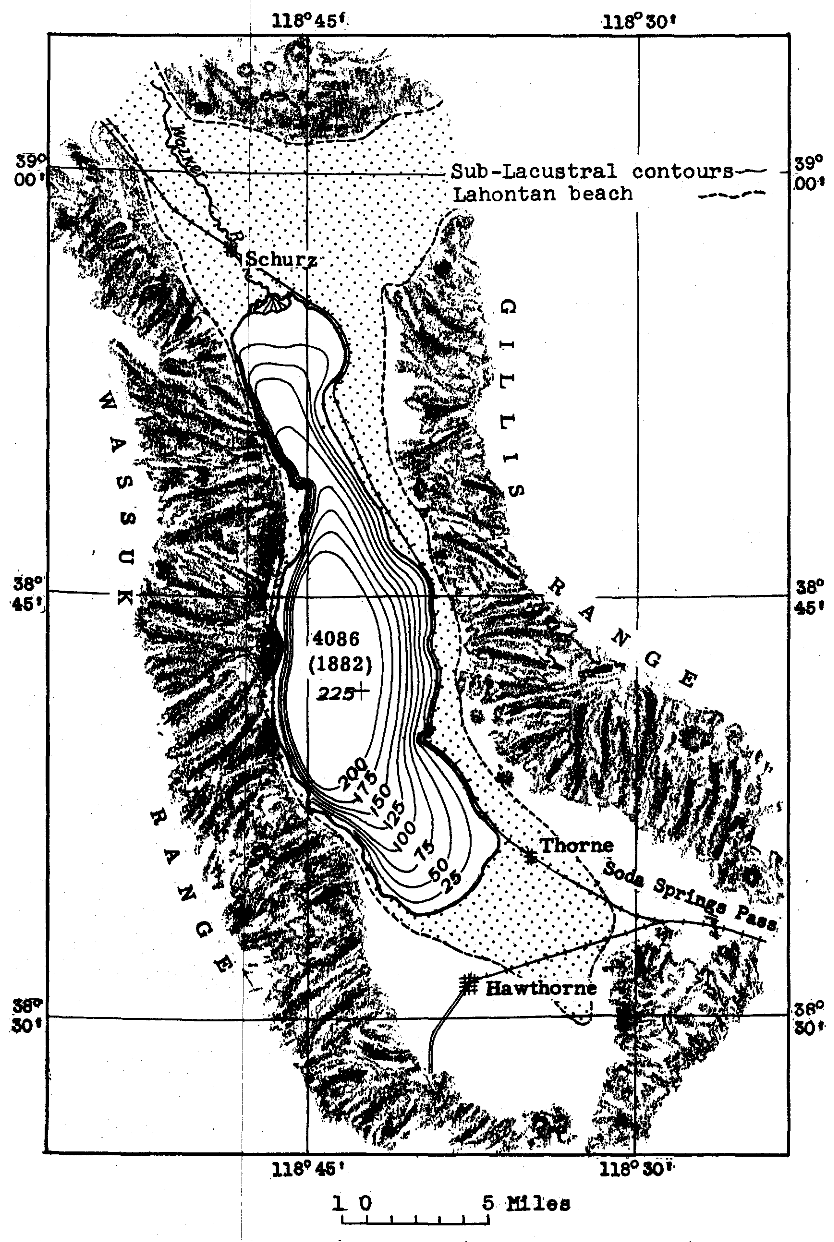

Figure 5.—Map of Walker Lake, Nev. (after Russell, I. C., 1885).

As a pilot lake for the water-loss studies, Pyramid Lake has both its advantages and disadvantages. Its greatest advantage is that the water budget can presumably be determined with the required degree of accuracy. The complexity of the wind structure would require further investigation; but probably the most serious disadvantage is the large size of the lake. Size, by itself, if above the required minimum, cannot be considered a disadvantage on theoretical grounds. From a practical viewpoint, however, the large size of Pyramid Lake poses many problems, of which one of the more important is the increased instrumentation required. The hydrographic survey would not be a simple task; the inaccessibility of the eastern shore complicates the transportation problem. These apparent objections are not insurmountable, however, and Pyramid Lake has much to recommend it for a study of this nature.

WALKER LAKE, NEVADA

Walker Lake is located in Mineral County in western Nevada. It lies in one of the several closed basins that are remnants of Lake Lahontan, a Pleistocene lake of the Great Basin. Walker Lake was approximately 23 miles long and varied from 1½ to 7 miles in width when surveyed in 1909. The lake is now about 75 feet lower than in 1909, and the area has decreased considerably, particularly at the north end where the slope is flat. (See fig. 5, p. 13.)

Area-capacity curves for Walker Lake have been prepared (see fig. 6) based on Russell's hydrographic survey (1885, pl. 15) of the lake in 1882. The surface area in September 1949 was approximately 44,000 acres and the contents 4,000,000 acre-feet. Maximum depth at this time was approximately 140 feet.

The accompanying graph (fig. 7) shows how lake levels have declined in recent years. The data prior to 1927 are from a compilation by Antevs (1938, p. 40). Following a sharp rise in the 1860s, the lake level declined only 14 feet between 1868 and 1919. Increasing use of water for irrigation during the last 30 years has greatly diminished the inflow from Walker River, and the decline in lake level has been greatly accelerated. Only in 1938 did a substantial rise occur. The elevation of the water surface on September 30, 1949, was 4,002.8 feet.

Walker Lake lies between the Wassuk Range which rises more than 11,000 feet on the west and southwest and the Gillis Range which rises 7,500 feet on the east. Slopes on the west side of the lake are much steeper than those on the east.

The surface supply of Walker Lake is derived principally from Walker River. A number of ephemeral streams drain directly into Walker Lake, mostly on the east slope of the Wassuk Range.

An aerial reconnaissance of the lake on September 14, 1949, revealed with great clarity the areas in which ground water is available for plant growth. Only a few green patches were seen along the eastern shore and very little green vegetation in the many small draws extending into the Gillis Range to the

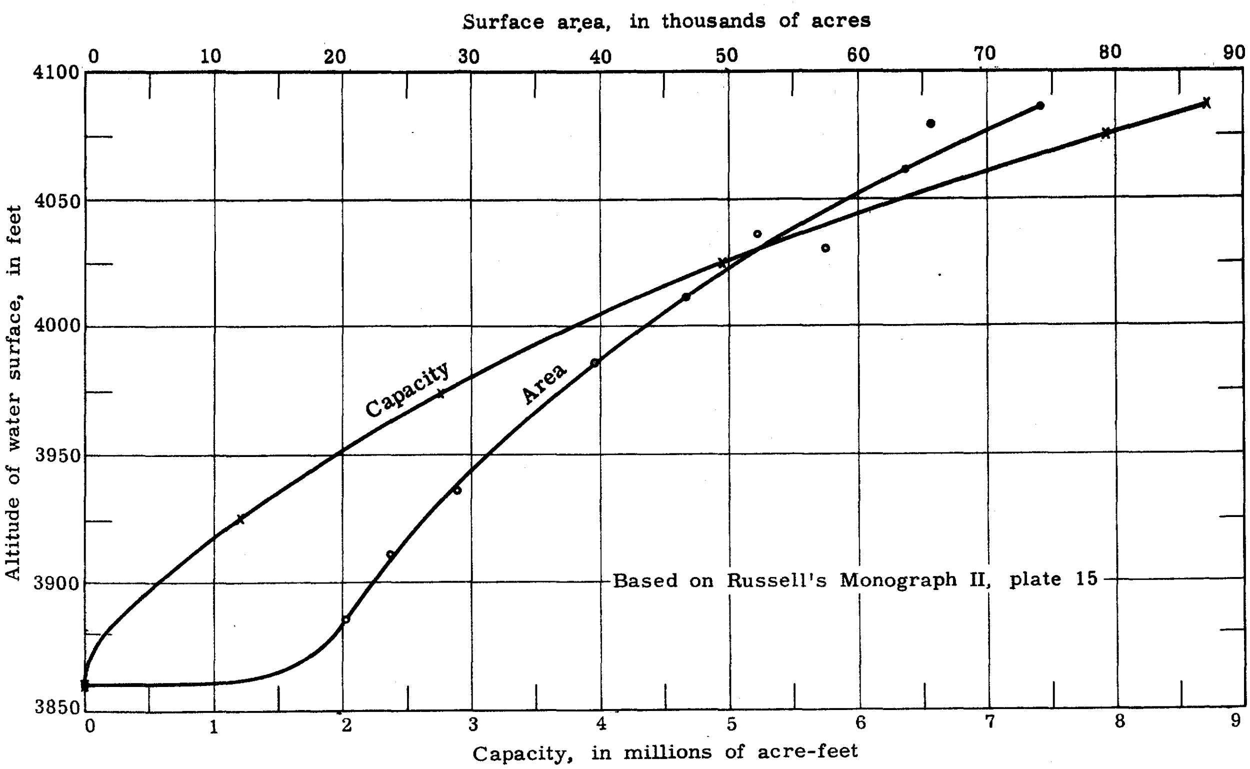

Figure 6.-- Graph showing area and capacity curves for Walker Lake, Nev.

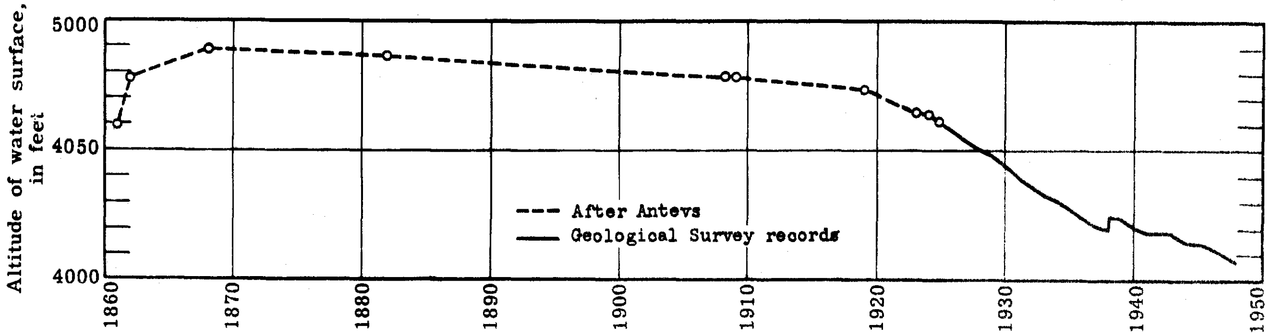

Figure 7. -- Graph showing stages of Walker Lake, Nev.

east. Fairly extensive areas of plant growth border the south end of the lake. The draws on the west side of the lake extending up into the Wassuk Range have green vegetation in their upper reaches. At the north end of the lake the Walker River delta is marked by extensive areas of phreatophytes, presumably supplied from underflow of Walker River and from subsurface return flow from irrigation.

An approximate annual water budget for Walker Lake has been prepared. Based on the hydrograph of lake levels (see fig. 7) and the area-capacity curves (see fig. 6) based on Russell's survey, the average annual change in contents for October 1, 1923, to September 30, 1949, was 133,000 acre-feet. This may be in error, for the area-capacity curves based on Russell's survey are questionable. When the Hawthorne quadrangle was mapped by the Geological Survey, the water surface elevation of Walker Lake was found to be 4,078 feet (adjustment of 1912). The surface area of the lake as planimetered from this map is 66,000 acres. Based on Russell's hydrographic survey, the surface area at an elevation of 4,078 feet is 72,000 acres. Harding (1935, p. 508) used a figure of about 90 square miles, or 57,600 acres, at a stage of 4,030 feet. The area from Russell's curve corresponding to an elevation of 4,030 feet is 52,000 acres. If Walker Lake is to be used for water-loss studies, a hydrographic survey will be required, but for the purposes of this report, the area-capacity curves based on Russell's survey are assumed to be correct.

Average annual runoff of Walker River at Schurz for the water years 1924-33 (after storage in Topaz and Bridgeport Reservoirs began) was 24,300 acre-feet. This is believed to be of the approximate general order of magnitude for present-day conditions, although possibly less than during the period 1934-49. Flow of West Walker River near Coleville, Calif., which is believed to be reasonably representative of natural runoff in this region, during the water years 1924-33 averaged about 70 percent of flow during the years 1934-49. It is difficult to estimate discharge of Walker River into Walker Lake after 1933, because records of flow at Schurz are lacking. The capacity of Topaz Reservoir was increased in 1937 and the area of irrigated land has been increased since the 1924-33 period, thus further complicating the situation. In the absence of accurate discharge data for Walker River for the entire 1924-49 period, however, average inflow is assumed to be 24,300 acre-feet, on the basis of records at Schurz for the water years 1924-33.

Other inflow items in the water budget include the flow of ephemeral streams, precipitation on the lake surface, and ground-water inflow. A number of ephemeral streams discharge directly into Walker Lake, mostly on the east slope of the Wassuk Range; their total contribution to Walker Lake is small, probably averaging less than 8,000 acre-feet per year, based on estimated runoff of 0.25 inch or less from an area of approximately 600 square miles. Average annual rainfall on the lake, taken as the mean of the Weather Bureau records at Schurz and Thorne, is 4.4 inches. The average surface area of the lake during the period 1924-49 was 55,000 acres; therefore, average rainfall on the lake surface was 20,000 acre-feet. The ground-water inflow to the lake can be approximated within reasonable limits. Most ground-water inflow is supplied by Walker River. The Walker River flood plain below Schurz is 1 to 4 miles wide. Assuming a width of 4 miles, a hydraulic gradient of 8 feet per mile, a thickness of 100 feet, and a permeability of 1,000 gallons per day (Meinzer's units), ground-water inflow is 3,600 acre-feet per year. The assumed permeability of 1,000 gallons per day is believed to be a conservative upper limit for the Lake Lahontan and Walker River fine sediments.

To summarize, an approximate annual water budget is as follows:

	Quantity (acre-feet)
Walker River inflow	24,300
Runoff of ephemeral streams	8,000
Precipitation on lake surface	20,000
Ground-water inflow	3,600
Decrease in contents of Walker Lake	133,000
Total	188,900

On this basis average annual evaporation is computed to be 3.4 feet, which appears to be somewhat low. The estimates are admittedly only approximate, and have been prepared only to illustrate the relative magnitudes of the quantities involved. The annual decrease in contents is by far the largest item, and can be measured with sufficient precision. Of the other items, ground-water inflow is probably the most difficult to determine accurately; but an error of a hundred percent in measuring this item would be almost insignificant compared with evaporation. It therefore appears that the water budget for Walker Lake can be determined with the required accuracy.

Meteorological conditions at Walker Lake were not investigated. The mountain ranges on each side of the lake undoubtedly complicate the wind-flow pattern. Data on prevailing surface winds at Walker Lake are not available, but because of the mountain ranges on each side the general flow is probably parallel to the long axis of the lake except where locally modified by valley breezes on summer days and air drainage at night. The effect on the general wind flow of turbulence induced by the mountain ranges on each side of the lake is not known.

It appears that a satisfactory water budget can be obtained at Walker Lake. The decision to reject it as a site for the water-loss studies was based primarily on its undesirable shape and its complicated wind structure resulting from the nearby mountain ranges. No field investigation was made to provide an estimate of the cost of either the stream-gaging stations required or the necessary ground-water studies. Although unsuitable for the present study, Walker Lake may prove satisfactory for studies to which its elongated shape and complicated wind structure are of no consequence.

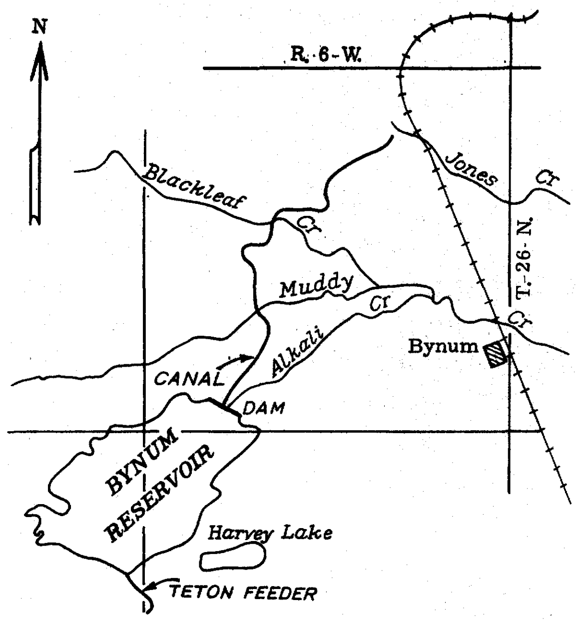

Figure 8. -- Map of Bynum Reservoir, Mont.

BYNUM RESERVOIR, MONTANA

Bynum Reservoir in north-central Montana is an irrigation reservoir supplied from Teton River and formed by a dam on Alkali Creek in T. 26 N., R. 6 W., 4 miles west of the town of Bynum, in Teton County. (See fig. 8.) It is owned by the Teton Cooperative Reservoir Co. The reservoir is roughly circular in shape. Its surface area as measured on the best available map is 4,120 acres (Congress, 1932, map 12) and its average depth at full pool is approximately 20 feet. It holds 85,000 acre-feet of water at full pool elevation of 4,175 feet and 500 acre-feet at 4,130 feet. The reservoir stage on September 24, 1949, was estimated to be 10 feet lower than normal high water as shown by well-defined marks on the intake tower. Annual diversions to Bynum Reservoir average 25,000 acre-feet.

Built in 1910 and enlarged in 1926, the earth-fill dam, including the dike, is approximately 1 mile long, and its maximum height is 60 feet. The westernmost quarter mile of the dike is faced with concrete on the upstream side. The concrete outlet tunnel discharges into the distribution canal which is lined with concrete for a distance of 150 feet below the dam. A gated wasteway from the canal discharges into a small natural channel below the dam.

Both the dam and the reservoir are underlain by the lower part of the Two Medicine formation, which consists of coarse-bedded gray, greenish-gray, red, and yellowish-brown jointed shale interbedded with many irregular and extremely lenticular sandstone beds. A few siltstone beds and one 6-inch bed of sandy, orange-brown bentonite were observed. In this locality the shales break down into tough, highly plastic clays upon remoulding. The sandstones are brownish-gray in color and have calcareous cement. Most of them are thinly and irregularly bedded, but a few are massive. Cross bedding is common. Thickness and composition vary greatly. Some beds are made up of coarse uniform grains, others of grains well-graded from coarse to fine, and still others of grains so fine as to be barely discernible with the naked eye. The variations in texture indicate that permeability probably varies greatly with the individual bed.

The regional dip of the Two Medicine formation is about 120 feet per mile southwestward with a strike of about N. 38° W. (Dobbin and Erdmann, 1946). In the field, a local dip of 4° SW. was measured about 100 feet below the downstream toe of the dam, 0.23 mile from its north end. Strike of these beds was N. 67° W. On the south shore of the lake about 0.25 mile from the dam, exposed sandstones dip 5° SW. and strike N. 40° W.

Three joint systems are present in the sandstone beds. One set is parallel to the bedding. A second system, very regularly developed at intervals of 0.5 to 3.0 feet, dips 85° N. with strikes ranging from N. 78° E. to N. 85° E. A third set, roughly perpendicular to the second, is poorly developed and many joints deviate from the average a few degrees to 30 degrees. All the joints are open on the surface from 1/16 inch to a maximum of 1/2 inch. The dip is vertical.

No faults have been recognized in the immediate vicinity of the reservoir.

Swamp grass and efflorescent salts along the downstream toe indicate that water seeps under the dam almost its entire length. There are a number of small flowing seeps, and most of the ground in the area below the dam is soggy. The discharge of one seep was estimated to be 0.04 second-foot on September 24, 1949, and the leakage through the dam around the outlet tunnel was estimated to be 0.5 second-foot.

Nearly all of the seepage is collected in the wasteway, and at a point 300 feet below the dam, the flow was estimated to be from 1 to 2 second-feet.

Figure 9 is a sketch showing seepage areas below the dam and a cross section through the dam. Although water seeping from the reservoir along the bedding planes in the sandstone must travel up dip, the static head is sufficiently high to produce substantial outflow below the dam.

Seepage when the reservoir is full is undoubtedly greater than that observed on September 24, 1949, when the reservoir was only partly full due to irrigation withdrawals. At full pool the water seeping below the dam is under greater head, and the cross-sectional area is also increased. It does not appear unreasonable to suppose that seepage may then amount to 5 second-feet.

The possibility of deep seepage, or leakage through the bottom of the reservoir that might not reach the ground surface for a considerable distance below the dam, is considered remote because of the regional southwesterly dip of the Two Medicine formation and the relatively impervious character of the sediments at the bottom of the reservoir. Samples of the sediments that were deposited when the reservoir was at a higher stage and that are exposed along the shores were found to be composed predominantly of clay and silt.

Bynum Reservoir is supplied partly from Teton River. Water is conveyed by canal from Teton River to a point in the Alkali Creek basin, from whence it flows down a natural stream channel to the reservoir. A gravel delta approximately 600 feet wide and 2,000 feet long has been formed where the stream debouches from the hills and flows into the reservoir. There was no evidence of surface flow at the delta at the time of the reconnaissance. A few small pools of standing water were observed near the edges of the delta. The bottoms of some of the pools were silted.

At a point approximately 2,000 feet upstream from the shore of the lake the stream channel narrows to 200 feet in width. Here a small stream with a flow of from 1 to 2 second-feet disappeared into the gravel of the main channel and was not observed to reappear on the surface anywhere in the delta.

The stream was followed for a mile upstream from this point. Many side gullies were observed, and the sparsely covered hillsides show evidence of heavy overland flow and erosion. The nearest point to the lake at which it would be practicable to obtain a record of flow in the channel is approximately a mile above the mouth, where the stream has been cut down to the underlying sandstone. Although heavy rains are infrequent, unmeasured inflow

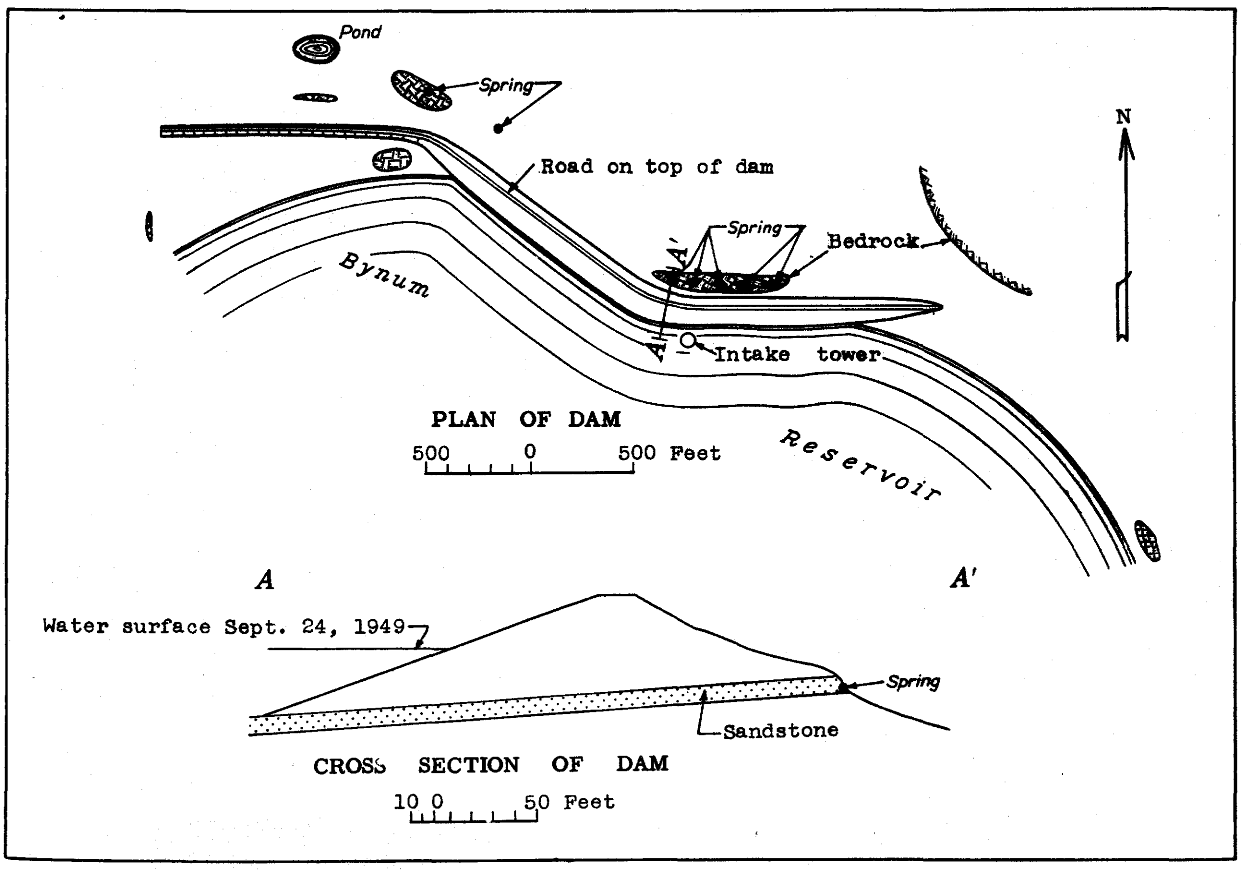

Figure 9. -- Sketch showing seepage springs below Bynum Dam, Mont.

between this point and the reservoir might be of considerable magnitude.

Harvey Lake is a small irrigation reservoir located southeast of Bynum Reservoir (see fig. 8) and is supplied from the Teton River. Its capacity is about 3,000 acre-feet (Congress, 1932, p. 90). At its nearest point Harvey Lake is approximately 1,000 feet from Bynum Reservoir. Its water-surface elevation was estimated to be 20 to 30 feet higher than that of Bynum Reservoir. A dike has been constructed at the west end of Harvey Lake to prevent outflow to Bynum Reservoir. Alkali and swamp grass were observed in the 300-foot-wide connecting valley, indicating that there is subsurface flow from Harvey Lake to Bynum Reservoir.

On the northwest side of Bynum Reservoir well-defined drainage channels are lacking. There is evidence that, in this area, during heavy rains there may be substantial overland flow which would be difficult, if not impossible, to measure accurately. No attempt has been made to evaluate the volume or frequency of such flows.

Annual evaporation from Bynum Reservoir is approximately 33 inches, on the basis of an analysis of available records of evaporation from pans. Of this amount about 9 inches evaporates during the months from April to June, the period of maximum inflow, and about 12 inches during the months of July and August, the period of maximum outflow.

The annual water budget cannot be accurately determined because of incomplete information on surface-water inflow and outflow and because of the total lack of data on magnitude of ground-water flow. Neglecting ground-water flow, the annual water budget may be approximated as follows:

	Quantity (acre-feet)
Inflow:	
Diversions into Bynum Reservoir	25,000
Surface inflow from Alkali Creek basin	2,000
Rainfall on reservoir surface	5,600
	32,600
Outflow:	
Evaporation	11,000
Reservoir releases (by difference)	21,600

It must again be emphasized that ground-water inflow, which may be an item of considerable magnitude, has not been included. Ground-water outflow of necessity has been included in the amount shown for reservoir releases. This figure was obtained by subtracting the evaporation, which is the only loss that could be estimated, from the total of the estimated inflow items. If the inflow items and the reservoir releases could be measured within 5 percent, which could be attained only at considerable expense for stream-gaging installations and operations, the error in the difference, on an annual basis, would be 18 percent of the evaporation. This figure would be substantially increased if errors in measuring ground-water flow should be included, which is necessary for a complete determination of the difference between inflow and outflow. It is probable that, with an extensive collecting system below the dam, most of the seepage through the dam could be collected and measured. The volumes of ground-water inflow entering the reservoir in the areas adjacent to the supply canals and in the Harvey Lake area are unknown.

Bynum Reservoir was considered unsuitable for the water-loss studies primarily because of the uncertainties involved in measuring surface- and ground-water inflow and outflow. The rather short season of high evaporation is an undesirable but not disqualifying feature. In many other respects, however, such as size, shape, and freedom from undesirable orographic effects, Bynum Reservoir meets the desired standards.

LAKE FRANCES, MONTANA

Lake Frances is an irrigation reservoir on a small tributary of Dry Fork Marias River in north-central Montana, in T. 29 N., R. 5 W., in Pondera County. The town of Valier is on its north shore. The oval-shaped lake is approximately 4 miles long and $2\frac{1}{2}$ miles wide. At full pool the water-surface elevation is 3,816 feet (mean sea level), the surface area is 5,536 acres, and contents are 112,000 acre-feet, according to J. A. Tidyman of The Valier Company, Valier, Mont., which owns the reservoir.

The reservoir is supplied by a canal known as the C-3 Canal (see fig. 10) which conveys water diverted from Birch and Dupuyer Creeks. Inflow is greatest during the months of May and June. Tidyman estimates that 50,000 acre-feet passes through the reservoir annually. Storm runoff from the natural drainage basin of approximately 25 square miles occurs infrequently.

The main dam at the southeast end of the lake is constructed of earth, has a concrete core wall (Congress, 1932, p. 82), and is 700 feet long and 50 feet high. Dike No. 1, on the northwest side of the lake, is 6,260 feet long and 20 feet high. Dike No. 2 on the northeast side of the lake is 725 feet long and 4 feet high.

The extreme southeast end of the reservoir and the dam site are underlain by the Virgelle sandstone member of the Eagle sandstone, which consists of buff to grayish-buff, highly cross-bedded sandstone. It is thinly laminated, fine-grained, soft, and friable, with some calcareous cement. The remainder of the reservoir is underlain by the Two Medicine formation. Contact between the two formations is hidden by surficial deposits. The Two Medicine formation consists of poorly bedded, gray, greenish-gray, red, and yellow clay shales interbedded with irregular amounts of lenticular gray-to-buff sandstones and an occasional siltstone. It is not exposed in the immediate vicinity of the lake but can be seen in the valley of Dupuyer Creek.

In the vicinity of Lake Frances these beds dip gently northwestward at 75 to 80 feet per mile (Dobbin and Erdmann, 1946). The strike of the beds varies from N. 41° E. to N. 33° E. along the northern and eastern shores of the lake but changes gradually to nearly north on the south side of the lake. No faults have been recognized in this immediate vicinity.

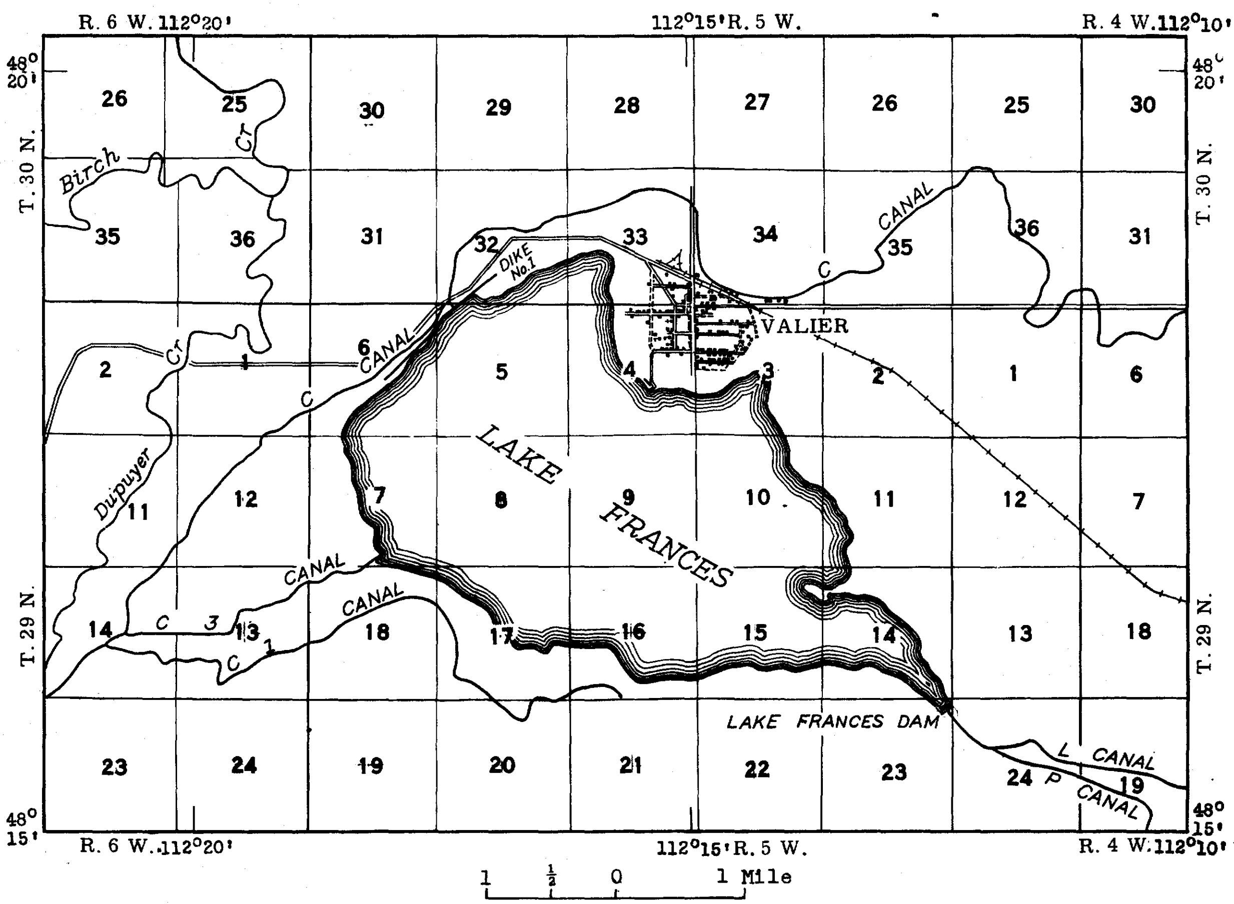

Figure 10. -- Map of Lake Frances, Mont.

Except for the previously mentioned small area at the lake outlet, bedrock is covered by an unknown thickness of glacial debris and alluvium throughout the lake basin and adjacent areas. Little is known of the character of these surficial deposits because the land is farmed and no good exposures were found.

Most of the inflow to Lake Frances is conveyed by the C-3 Canal which was inspected at the road crossing approximately half a mile above the lake. Its design capacity is 900 cubic feet per second, but on September 24, 1949, the flow was estimated to be 70 cubic feet per second. The canal banks at this point are of soil underlain by a comparatively impermeable gravel-clay mixture. Along a 300-foot reach the canal had cut through this material, exposing from 0.5 to 3.0 feet of clean coarse highly permeable sandy gravels of fluvial origin. Water entering these gravels may be discharged into the lake. A precise determination of the amount of water reaching the lake as canal underflow would be difficult.

Annual inflow from the natural drainage basin of approximately 25 square miles is between 0.5 and 1.0 inch, according to Langbein (1949, pl. 1). Using the higher figure, annual inflow is approximately 1,300 acre-feet. Some storm runoff would be included in the measured flow of C-3 Canal, but the determination of inflow from the area immediately adjacent to the lake might prove difficult.

It is probable that some return flow from irrigation may enter the reservoir along the southwest shore. According to Tidyman, an area of about 300 acres is irrigated from the C-1 Canal, usually only once each year. A total of 200 acre-feet of water is applied. The return flow probably does not exceed 100 acre-feet.

Annual precipitation at Valier, according to U. S. Weather Bureau records (Commerce, 1948, p. 254), averages 12.65 inches, which amounts to 5,800 acre-feet at full-reservoir level. Precipitation during May and June, the two wettest months, averages 1.83 and 3.00 inches, respectively.

Surface outflow from the lake is discharged through the dam into a canal. Because of a diversion structure half a mile below the dam, precise measurements of outflow might prove difficult. It is also possible to release water from Lake Frances into the C Canal at a point near the northeast end of dike No. 1. The floor of the outlet structure is at 3,800 feet elevation, or 16 feet below full-pool elevation.

Subsurface outflow from the reservoir is apparently restricted to the area near the main dam and to the area near dike No. 1. A collecting gallery intercepts part of the seepage through the dam. This flow, about 0.5 cubic foot per second, is pumped to the Conrad municipal water-supply system. Near the dam, Virgelle sandstone is exposed along the shore on both sides of the lake for a distance of about 2,000 feet above the dam. It is also exposed along the Dry Fork Marias River tributary below the dam in sec. 24, T. 29 N., R. 5 W. The beds dip in a northwesterly direction at low angles. The following determinations were made:

No.	Location	Strike	Dip
1	Lake shore, SW¼SW¼ sec. 14, T. 25 N., R. 5 W.	N. 44° W.	6° SW.
2	Dry Fork Marias River tributary, SE¼NW¼ sec. 24, T. 29 N., R. 5 W.	N. 58° E.	5° NW.
3	Dry Fork Marias River tributary, SE¼NW¼ sec. 24, T. 29 N., R. 5 W.	N. 75° E.	3° NW.
4	Road cut, E¼ corner sec. 23, T. 29 N., R. 5 W.	N. 30° W.	7° SW.

Determinations 1 and 4 are probably on cross laminations, but determinations 2 and 3 agree roughly with the regional dip and are believed to represent true bedding of the sandstone. Permeability normal to the bedding of the sandstone is probably comparatively low, but permeability along the bedding and cross-bedding surfaces is fairly high. This is demonstrated by a series of seeps that discharge along the north wall of the valley (called the P Canal) and that are supplied from the L Canal. The seepage water is under a head of about 14 feet and travels along paths varying from 25 to 200 feet in length. Discharge is entirely along the bedding and cross-bedding surfaces. The seepage in this area on September 24, 1949, was estimated to be about 3 gallons per minute. Without doubt seepage is also taking place through these sandstones around both abutments of the dam. A well into rock at the farmhouse near the northwest corner of sec. 24, T. 29 N., R. 5 W., intercepts part of this flow. The water level in this well is reported to fluctuate with the stage of the reservoir. The quantity of seepage water may not be large, but it would be difficult to measure accurately.

There is considerable seepage along dike No. 1. This seepage water, together with seepage from the C Canal, collects in a pond at the S¼ corner sec. 31, T. 30 N., R. 5 W. Seepage appears to be confined to the contact between the dike and its foundation and to the lower part of the dike. It might be possible to separate the amount of seepage through the dam from amount of the seepage through the canal banks by measurements of the seepage when the canal flow is zero.

The remainder of the lake basin appears to be comparatively watertight despite the fact that it is floored by strata of the Two Medicine formation that contain many permeable sandstone members. Seepage is prevented by a blanket of surficial deposits, no doubt assisted to some extent by silting of the reservoir. The impermeability of the soil and underlying surficial deposits is demonstrated by the fact that on September 24, 1949, water was standing in a pond about a quarter of a mile east of the lake, in the SW¼ sec. 13, T. 29 N., R. 5 W., at an elevation approximately 35 feet higher than maximum lake level. This pond was formed in June 1948 by surface runoff following unusually heavy rains. Subsequent loss of water has been at a sufficiently low rate to be accounted for by evaporation, indicating that seepage losses have been negligible.

Annual evaporation from Lake Frances as based on an analysis of available records of evaporation from pans is about 33 inches. At full pool, annual evaporation is 15,200 acre-feet.

An approximate annual water budget, assuming Tidyman's estimate of 50,000 acre-feet passing through the reservoir to be outflow, is as follows:

	Quantity (acre-feet)
Outflow:	
Reservoir releases	50,000
Evaporation	15,200
Seepage	1,000
Total outflow	66,200
Inflow:	
Rainfall on lake	5,800
Return flow from irrigation	100
C-3 Canal (by difference)	60,300
Total inflow	66,200

The figure for seepage loss is admittedly only a rough estimate and has been included only to indicate its approximate relative magnitude. The water budget indicates that inflow and outflow are approximately four times as great as evaporation. If the measurement errors are considered to be normally distributed, and both inflow and outflow can be measured within 5 percent, the error in the difference between the two quantities is about 4,000 acre-feet, or more than 25 percent of the annual evaporation.

The water budget is further complicated by the configuration of the lake, which makes accurate determinations of mean stage somewhat difficult. The lower end of Lake Frances terminates in a rather narrow neck. The amplitudes of seiches caused by the prevailing westerly winds are probably magnified very much in the area near the dam. The assumption of a plane water surface cannot be made, and a network of precise stage gages would be required.

Meteorological conditions at Lake Frances appear to be favorable. The terrain is fairly flat except along the south shore where hills rise to a height of 100 to 200 feet above the lake at a distance of a mile or so away. The wind structure apparently is not complicated by orographic effects. The prevailing winds are westerly. Summer humidity is low.

According to Tidyman, the lake is frozen from approximately December 5 to April 15 each year. Average January temperature is 16.6° F. and average July temperature is 65.4° F., according to Weather Bureau records (Agriculture, 1941, p. 917). Year-round observations of evaporation appear impractical.

Lake Frances was rejected as a possible site for the water-loss studies because of the difficulty in obtaining a water budget of the required degree of accuracy. In many other respects, such as shape, size, depth, and freedom from orographic effects, the lake meets the requirements. The long period of ice cover in the winter is an undesirable but not disqualifying feature.

LAKE ABERT, OREGON

Lake Abert, oval-shaped and approximately 10 miles long and 3 miles wide, is in a closed basin about 30 miles north of the town of Lakeview in south-central Oregon. Waring (1908, p. 38) made a geologic and hydrologic reconnaissance of the area in 1906 and determined the surface area of Lake Abert to be 60 square miles at that time. It has less than half that area at present and is much shallower than it used to be. No soundings were made on the day the reconnaissance was made, September 20, 1949, but the depth at the present time is reported by R. A. Work (in a personal communication relaying information from Philip Smith) to be about 3 feet. The lake is shallower now than it has been for several years, although it was lower in 1931 and 1934. Antevs (1938, p. 18) reported that it was dry in August 1924 except for a few small pools fed by springs and a small area on the east side supplied by Poison Creek. According to Waring (1908, p. 38), "The northern end of the Abert Lake basin is so nearly level that it is said that a strong south wind often forces the water back nearly 2 miles over the alkaline flat * * *."

Lake Abert lies upon a huge block of Miocene basalt that dips to the east. It is confined on its eastern side by the Abert Rim, a fault scarp that towers more than 2,000 feet above the lake and is said to be one of the highest in the United States. Russell (1884, p. 447) described the Lake Abert fault as follows: "The grand cliffs that present an impassable barrier along the eastern shore of Abert Lake expose the broken edges of the strata on the heaved side of a fault; while the thrown side underlies the lake basin and forms the gently sloping western shore." A geologic section in an approximately east-west direction through Lake Abert is shown in figure 11.

According to Waring (1908), "The basalt is a dark gray, fine-grained, rather vesicular rock, approximately parallel partings, usually at intervals of only a few feet, mark the division between successive flows, but in some places much thicker beds are exposed. Fissures nearly perpendicular to the parting planes break the basalt into blocks, which by transverse fracturing are reduced to smaller and smaller fragments, forming the characteristic talus slopes of the cliffs."

Chewaucan River enters the south end of Lake Abert, after flowing through the Chewaucan Marsh, and constitutes almost the entire surface-water inflow into the lake. The average annual flow of Chewaucan River above Conn ditch, near Paisley, Oreg., is approximately 95,000 acre-feet. However, not all the flow reaches Lake Abert as water is diverted from the Chewaucan River for irrigation in the Paisley area; and although the return flow from irrigation eventually finds its way through the Narrows to Lake Abert, the consumptive use may amount to more than half of the flow in some years. On the average, surface inflow to Lake Abert is roughly estimated to be 60,000 acre-feet, which is less than the evaporation from the lake. Flow of Chewaucan River into Lake Abert is not now measured and it is by no means certain that it can be measured within 5 percent, for the slope in the water surface in the reach below the dam and falls is small, and may be affected by strong winds or changes in lake levels. Runoff from spring rains in the area directly tributary to the lake would be difficult to measure accurately. No studies have been made of the frequency of these storms, but the total volume of runoff is small compared with the flow of Chewaucan River.

Many small fresh-water springs were seen on the east side of Lake Abert between the highway and the lake. The flow of some springs was so small as to produce only a marshy area having small pools of standing water. Many springs were discharging water directly to the lake. The volume of flow was small; discharge of most springs was estimated to be less than 0.05 cubic foot per second. The temperature of the water in the seeps along the eastern shore was from 78° to 79° F. on September 20, 1949. The temperature of both the air and the water in the lake was 65° F. at that time. The temperature of the water in a seep near the northeastern corner of the lake was also 65° F.

At the north end of the lake are fairly extensive areas of marshland on which hay is grown. Irrigation water is supplied from numerous seeps. There is no simple way to measure the return flow from the irrigated areas. Waring (1908, p. 51) mentions a strong spring at the ranch house, but this spring was not looked for on the reconnaissance September 20, 1949.

Along the western shore the seepage area was estimated to be at least three times as great in extent as that along the eastern shore. The flow of several springs was estimated to be 0.5 cubic foot per second or more.

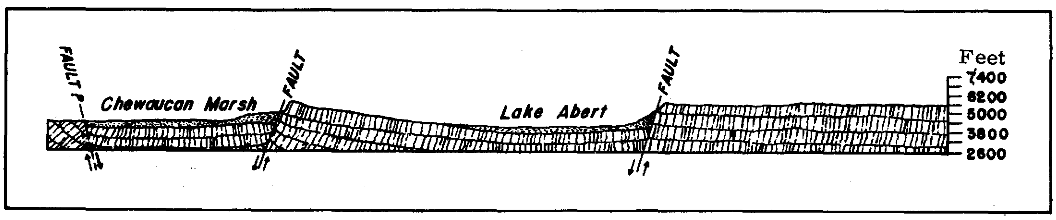

Figure 11.-- Cross section through Chewaucan Marsh and Lake Abert, Oreg. (after Waring, 1908, plate 10).

The seeps and springs along the western shore according to Waring (1908, p. 51), are evidently fed by waters that accumulate on the slopes between Lake Abert and Chewaucan Marsh, seep down the dip of the basalt, and reach the surface at the lake shore. (See fig. 11.) He did not mention the springs or seeps along the eastern shore, but it seems likely that they are supplied from the same source. As the water travels down dip under the lake it may be prevented from discharging into the lake bottom by the relatively impervious sediments that have been deposited over the lake bed and can find its way to the surface only after it reaches the fault zone on the eastern side of the lake.

Annual evaporation from Lake Abert is estimated to be approximately 4 feet, based on an analysis of available records of evaporation from pans. Of the 4-foot total, approximately 2.3 feet occurs during the 4-month period June to September.

An annual water budget for Lake Abert is difficult to estimate because of the lack of data but may be approximated as follows:

	Quantity (acre-feet)
Evaporation	77,000
Inflow:	
Surface water	60,000
Ground water (by difference)	17,000

Outflow is considered to be zero. Ground-water inflow was assumed to be that amount which, when added to the surface inflow, is required to maintain the lake at its present level. Both surface- and ground-water inflow are known to vary widely from year to year. The lake is now much smaller than in times past, indicating that inflow has generally been less than evaporation during recent years. On an annual basis, 5 percent of the estimated evaporation is 3,850 acre-feet--possible error in measuring ground-water inflow alone exceeds this amount. The possible error in measuring surface-water inflow may also exceed 5 percent of the evaporation. The slope of the water surface of Chewaucan River in the reach upstream from the lake is flat and may be affected by the level of Lake Abert.

The volume of ground-water inflow during summer months, when flow of Chewaucan River is depleted by irrigation, may amount to a substantial portion of the total inflow. Obtaining continuous records of the flow of the many springs would be an expensive undertaking. The possibility of springs in the lake bed, although remote, cannot be ignored. The measurement of total inflow to Lake Abert within the allowable limits of accuracy was deemed impracticable.

Annual precipitation at Valley Falls, at the southern end of Lake Abert, averages 11.10 inches. Rainfall during July, August, and September is light, but the remainder is well-distributed throughout the year. Humidity is normally low in central Oregon during the summer, and westerly winds predominate. Average temperature at Valley Falls is 30.4° F. in January and 66.7° F. in July (Agriculture, 1941, p. 1075).

The effect of topography upon meteorological conditions at Lake Abert was not studied in detail. The great fault scarp on the eastern side of the lake unquestionably affects the wind structure over the lake. Westerly winds predominate in the large scale circulation, but southerly surface winds prevail at the southern end of the lake at Valley Falls, as might be expected.

Because of the impracticability of determining the water budget with the required degree of accuracy, Lake Abert was considered unsuitable as a pilot lake for the water-loss study. Meteorological conditions are not favorable, and the lake is shallower than is desirable, but the decision to reject Lake Abert was based upon the lack of an accurate water budget.

BIG SAGE RESERVOIR, CALIFORNIA

Big Sage Reservoir is an irrigation reservoir in northeastern California, 10 miles northwest of Alturas in Modoc County. (See fig. 12.) The reservoir is irregularly shaped, and when full covers an area of 5,570 acres and stores 77,000 acre-feet of water. It was constructed in 1921 by damming Rattlesnake Creek, a Pit River tributary that drains a broad, nearly flat, upland plateau about 5,000 feet above sea level. The drainage area is 107 square miles, according to Ingerson (1932).

The plateau on which Big Sage Reservoir lies is known as the Gardens (Russell, 1928, p. 400) or the Devils Gardens (Zander, 1933, pp. 24-27). According to Russell, the Gardens plateau is about 2,000 square miles in area, and has a cap of smooth lava which he named the Warner basalt. The basalt is a vesicular volcanic flow of surprising extent and uniformity. It is approximately 30 feet thick at the south rim of the Gardens as exposed in the bluff north of the Alturas-Canby road (U. S. Highway 299). Near the south end of Goose Lake, at the east edge of the Gardens, it is at least 225 feet thick.

Russell's Warner basalt is underlain by his Cedarville series, a group of andesitic rocks about 7,500 feet thick. They are composed of tuff beds, agglomerate, and lava, all andesitic in character, with about 5 percent of interbedded sedimentary rocks of nonvolcanic origin. Where observed in the bluffs north of Highway 299 near the dirt road leading to Big Sage Reservoir, the Warner basalt is underlain by a dense, white tuff bed which had the appearance of a "chalk rock". This tuff bed is very extensive, according to Russell.

Big Sage Dam was built in Rattlesnake Creek canyon, which has been eroded 40 to 50 feet below the surface of the Warner basalt. It is not known whether the stream had cut through the basalt into the tuffaceous beds beneath. Photographs made during the excavation for the dam suggest that the white tuff beds are exposed in the cut. T. R. Simpson of the California State Division of Water Resources, Sacramento, Calif., who was present when the excavation was made, states that the white tuff bed was exposed. The cut-off trench, which was excavated to a depth of 10 feet below the base of the dam, is therefore believed to penetrate the fine-grained white tuff.

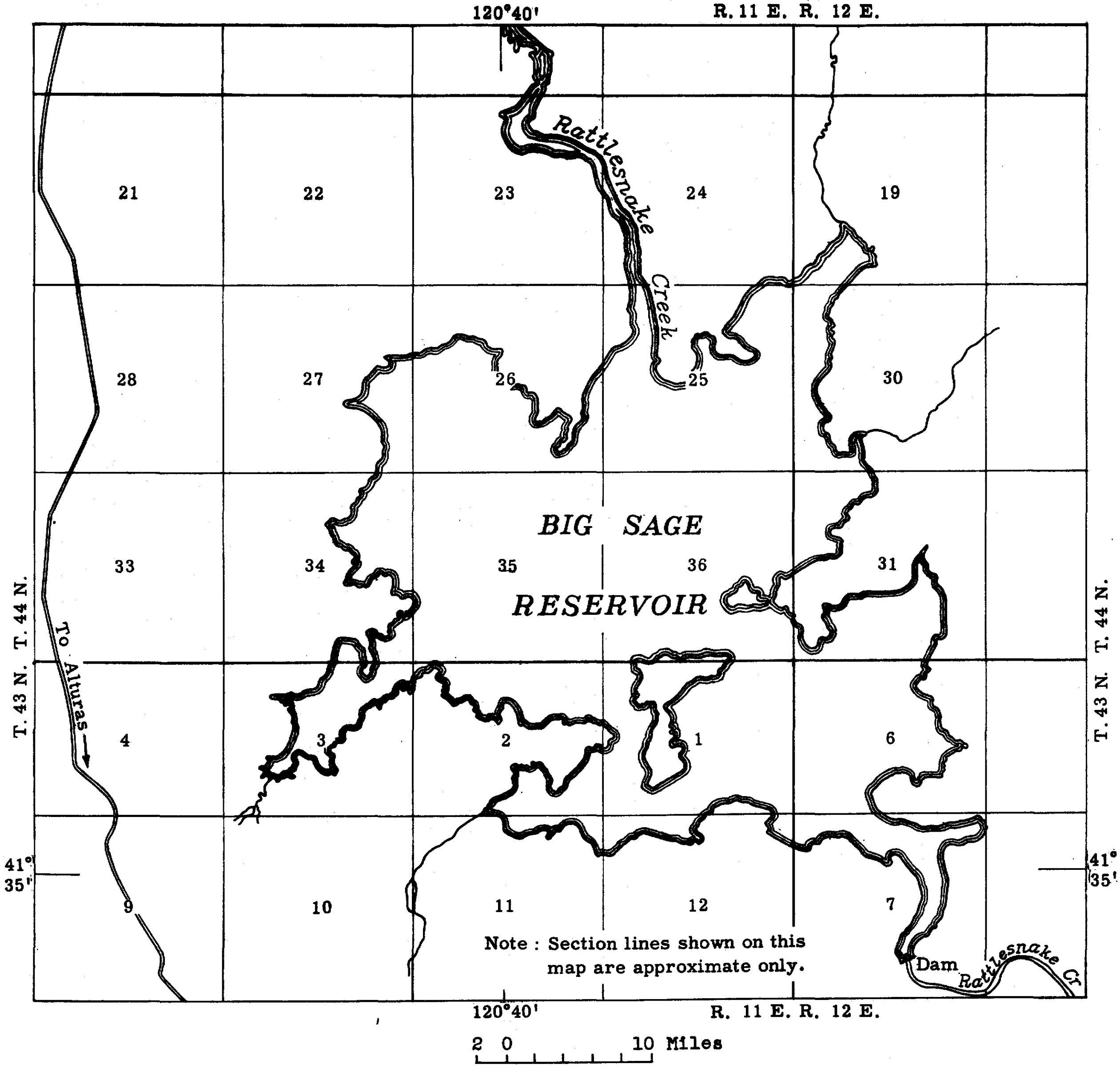

Figure 12.-- Map of Big Sage Reservoir, Calif.

Russell's Warner basalt has a coarse columnar jointing and is vesicular. The vesicles are commonly not interconnected and do not cause the rock to be permeable, but the columnar jointing may. Ingerson (1932, p. 4) states that the basin is relatively impervious because of a surface accumulation of cementing ash and adobe soils. No ash was observed in the area visited on June 12, 1949, but it is believed that the underlying tuffaceous beds are relatively impermeable and provide an essentially watertight foundation. According to Ingerson, Supervising Hydraulic Engineer, California State Division of Water Resources, Sacramento, Calif., colloidal material remains in suspension in the reservoir indefinitely, regardless of whether the water is disturbed or quiescent, and the reservoir bed has been virtually sealed.

If the basalt were sufficiently permeable to absorb and yield large quantities of water, springs should appear where the base of the basalt is exposed. No springs were seen along the bluffs north of the Alturas-Canby highway. According to Silas B. Kelley, President, Hot Springs Valley Irrigation District, Alturas, Calif., prior to the construction of the dam in 1921 Rattlesnake Creek ceased to flow in July or August, and no springs were known for several miles downstream from the dam site. However, the Alturas reconnaissance sheet (1892), which was based in part on information obtained by the Wheeler Survey, shows several springs about 3 miles downstream from the dam site. They are apparently at a somewhat higher elevation than the reservoir, although elevations shown on the Alturas reconnaissance sheet are admittedly not precise. Simpson reports that a spring in the reservoir site supplied the Woods ranch with sufficient water to irrigate 40 to 50 acres of meadow during the summer. It is presumed that this spring discharged water stored in the fractured basalt. Reports suggest that its flow was not greater than approximately 1 cubic foot per second. Ingerson estimates that the flow of small springs in the reservoir area totaled possibly 4 or 5 cubic feet per second.

There appears to be little seepage through and around the dam. A small seepage area marked by green grass and standing water was noted on the left bank 200 feet below the dam and 20 to 25 feet above the stream. There was no visible discharge. An inspection trip was made on foot for a distance of about 3,500 feet downstream from the dam. A small amount of side seepage is evident. A strip of green grass about 2,000 feet long and 40 feet in average width borders each bank of Rattlesnake Creek. Up to a height of 3 to 5 feet above the stream bed, cattle hoofprints stand full of water, but no running water was observed. If the grassy strips, whose total area is approximately 4 acres, are supplied by seepage through or around the dam, as is likely, the volume of water thus consumed is probably about 10 acre-feet per year. However, seepage losses are apparently very small for, according to Ingerson, when the outlet valve in the dam is closed, the creek is dry below the dam.

About 2,000 feet downstream from the dam a grove of poplars lines the right bank of the creek for a quarter of a mile. These trees antedate the construction of the dam, and presumably are supplied from water stored in the basalt and resting on the tighter tuffs beneath.

The reservoir was inspected by boat. The surrounding terrain is quite flat, and the point at which Rattlesnake Creek enters the reservoir could not be located readily, so that ground-water conditions along the creek were not investigated. Seepage along the shoreline was noted at only one point, where three springs seeping from an amphitheatre-like area were discharging into the reservoir at a rate estimated to be 0.05 cubic foot per second.

Total ground-water discharge from the reservoir is believed negligible. Ground-water inflow cannot be measured precisely, but is certainly small. The surrounding terrain is quite flat, and storage of water in the reservoir has substantially decreased the hydraulic gradient causing the flow of the spring or springs known to have existed in the reservoir area. Although the quantities involved are quite small in comparison with evaporation during the summer, further investigation to determine the approximate spring discharge is warranted.

Flow of Rattlesnake Creek, according to Ingerson, averages not more than 2 cubic feet per second during May and June, and is practically zero during July, August, and September. Records of contents in and outflow from the reservoir have been made available by V. R. Scammon, Watermaster, California State Division of Water Resources, Alturas, Calif.

Based on records for the years 1940-48, an approximate water budget for April-September has been calculated.

	Quantity (acre-feet)
Inflow:	
Rattlesnake Creek	240
Rainfall on reservoir surface	1,200
Estimated ground-water inflow	300
Total	1,740
Outflow:	
Reservoir releases	8,350

The average decrease in reservoir contents during April-September for the years 1940-48 was 16,100 acre-feet. Average evaporation was (1,740 - 8,350 + 16,100), or 9,490 acre-feet. The reservoir surface area averaged 4,100 acre-feet. Estimated average evaporation for this 5-month period was therefore 28 inches over the reservoir surface.

The three major items in the water budget are the rainfall on the reservoir surface, change in reservoir contents, and reservoir releases. Rainfall on the reservoir surface doubtlessly can be measured with sufficient precision. Although existing area-capacity tables are quite adequate for the needs of the irrigation district, a hydrographic resurvey of the reservoir would be required, so that changes in reservoir contents could be measured with the degree of accuracy necessary for the water-loss studies. Reservoir releases are at present measured by means of an outlet-valve rating. A continuous record of outflow can be obtained below the dam, but the construction of an artificial control, possibly a Parshall flume, would be required. It is believed that the requirement that the error in the volumetric determination of evaporation shall not exceed 5 percent can be met.

The wind structure over Big Sage Reservoir is not complicated by orographic effects. The reservoir is on a high plateau, and the slopes are gentle. Average January temperature at Alturas is 27.3° F. and average July temperature is 67.3° F. Rainfall averages 12.60 inches annually (Agriculture, 1941, p. 785).

Water temperature in the reservoir, measured on June 12, 1949, near the intake tower at a depth of approximately 6 inches, was 79° F. The temperature of the water measured at the discharge end of the outflow pipe was 61° F. A water sample was taken, and the results of the analysis made by the Geological Survey are as follows:

Ion	Parts per million
Iron (Fe)	0.03
Calcium (Ca)	17
Magnesium (Mg)	9.5
Sodium (Na), potassium (K)	13
Carbonate (CO_3)	16
Bicarbonate (HCO_3)	88
Sulfate (SO_4)	8
Chloride (Cl)	2
Nitrate (NO_3)	.1
Borate (BO_3)	.1
Dissolved solids	109
pH	8.5

There are no recent maps of the reservoir area. Older maps show the reservoir to be quite regular in shape. Aerial photographs made September 20, 1948, when the reservoir stage was approximately 10 feet below full pool, show the reservoir outline to be quite irregular at that stage, as illustrated in figure 12, which was prepared from an aerial photograph.

When the reservoir was inspected by boat on June 12, 1949, the stage was approximately 1 foot higher than on September 20, 1948, when the aerial photographs were made. Rocky shoals were noted by the inspecting party. Many long reaches of shore slope so gently that extensive areas may be quite shallow. At 4,100 acres, the average surface area during the period 1940-48, a change in stage of 1 foot results in a change in surface area of nearly 5 percent. Because the reservoir area was not cleared of trees when the dam was built, many trunks are still standing.

Big Sage Reservoir was rejected as a possible site for the water-loss studies chiefly because of its irregular shape. A fairly regular shape is essential for a test of certain theoretically derived equations relating evaporation to observed meteorological elements. It appears, however, that a water budget of the required accuracy can be obtained.

ELSINORE LAKE, CALIFORNIA

Elsinore Lake, a natural lake in southern California, lies about 20 miles south of Riverside, Calif., in Riverside County. It is supplied infrequently by San Jacinto River, and only during or after years of exceptionally heavy rainfall has it overflowed into Temescal Creek, its natural outlet. Schanck (1919, p. 71) has prepared an excellent account of the early history of Elsinore Lake. There has been no outflow since 1917 (Water-Supply Paper 1091).

The lake is quite regular in shape and is about 5 miles long and 1½ miles wide. According to Harding (1922), the elevation of the Temescal Creek outlet is 1,260 feet, and at this stage the surface area is about 6,000 acres and the contents 123,000 acre-feet. The stage is now much lower. On June 7, 1949, the elevation of the lake surface was 1,232.7 feet. It was reported by William Breyette, a local resident, that the maximum depth of water in the lake is approximately 9 feet. Much of the lake is less than 5 feet deep. According to Harding (1927, p. 328) the lake has gone dry in periods of deficient rainfall.

The geology and ground-water conditions in this area have been described by Waring (1919, pp. 69-79). The basin in the vicinity of Elsinore Lake is underlain by Recent and Pleistocene alluvial deposits and Tertiary sedimentary rocks. The alluvial deposits contain ground water, and probably at least some of the Tertiary rocks are sufficiently permeable to contain ground water. The thickness of these deposits is not known accurately, but Waring (1919, p. 76) gives the log of an artesian well near the northwest end of Lake Elsinore that penetrated at least 254 feet of material that was probably unconsolidated. A well of the South Elsinore Mutual Water Co. near the southwest end of the lake penetrates 497 feet of apparently unconsolidated deposits. Wells in the alluvial deposits flowed in earlier years, and Waring mentions the existence of hot sulfureted springs in the town of Elsinore on the northeast lake shore. D. R. Crane, civil engineer in Elsinore, reports that in January 1947 the water level in several irrigation wells near the northwest end of the lake was 20 to 50 feet below the lake level at that time. It is not known whether the hot springs now flow or whether the flow is decreasing. Apparently no wells in the vicinity flow at the present time, the head presumably having been reduced by pumping for irrigation.

Although the water level in relatively deep wells may be below lake level, it seems possible that shallow water may stand above and drain toward the lake even at present. Discharge of hot springs may also enter the lake.

A sample of water was taken just below the lake surface on June 7, 1949, near the pier at the Aloha Beach Club at Elsinore. The water temperature close to the surface was 90° F. in the afternoon of this day. The sample was analyzed by the Geological Survey and the results are as follows:

Ion	Parts per million
Iron (Fe)	0.01
Calcium (Ca)	7.3
Magnesium (Mg)	52
Sodium (Na), potassium (K)	3,370
Carbonate (CO_3)	782
Bicarbonate (HCO_3)	1,400
Sulfate (SO_4)	496
Chloride (Cl)	3,250
Borate (BO_3)	24
Dissolved solids	8,880
pH	9.4

The chemist making the analysis also reported the presence of hydrogen sulfide in the sample.

The ground-water conditions around Lake Elsinore are complicated and would have to be studied carefully before any accurate determination could be made as to whether or not there is substantial seepage of ground water into or away from the lake, and before an estimate could be made of the quantities involved. It would be difficult to determine accurately the amounts of seepage loss or gain to or from ground water in the basin. There might also be a discharge of warm ground water from suballuvial springs whose presence might not be detected at all.

Elsinore Lake has been used for many studies of evaporation. It has generally been assumed that there is no ground-water inflow or outflow. Harding (1927, p. 328) states, "The lake bed appears to be impervious. It is stated that no inflow from adjacent ground water was apparent when the lake was dry. There is no indication of seepage from the lake, adjacent wells with water below lake level showing no indication of mixture with the salty water of the lake." One wonders, however, if at those times when the lake was reported dry there may not have been marshy areas where ground-water inflow evaporated as it reached the surface. Schanck (1919, p. 71) mentions that the original Mexican name for the lake was "Laguna Grande", and that a traveler in 1810 noted that it was but little more than a swamp about a mile long. It is entirely possible that ground-water inflow is negligible compared with evaporation since magnitude of the evaporation indicated by records at Elsinore Lake appears to be consistent with that at other places.

The determination of the amounts of ground-water inflow and outflow, if any, would require an exhaustive study of the entire ground-water situation. Such a study might prove to be a monumental task because conditions are admittedly quite complex, and there is no positive assurance that results of the required degree of accuracy could be obtained at a reasonable cost. Because of the uncertainty in measuring ground-water flow, and because the lake is very shallow, Elsinore Lake was given no further consideration.

LAKE MATHEWS, CALIFORNIA

Lake Mathews, formed by Cajalco Dam, is located about 10 miles southwest of Riverside, in Riverside County, Calif. The dam was completed in 1938 by the Metropolitan Water District of Southern California as a unit in the distribution of water from the Colorado River. The capacity of Lake Mathews is 107,000 acre-feet, and its surface area at spillway level is 2,020 acres.

It is supplied principally from the Los Angeles aqueduct through the Val Verde tunnel. Present operating practice is to maintain contents at approximately 85,000 to 100,000 acre-feet. According to C. C. Elder, hydrographic engineer, Metropolitan Water District of Southern California, Los Angeles, Calif., annual inflow and outflow may total 100,000 acre-feet. In the dry months, monthly inflow and outflow may amount to 20,000 acre-feet and 15,000 acre-feet, respectively. Evaporation is estimated from pan records at about 6,000 acre-feet per year, with a maximum of 1,100 to 1,200 acre-feet per month. Thus errors of 1 percent in measuring monthly inflow and outflow may amount to about one-third of the evaporation during summer months. Although inflow and outflow are now measured with a precision quite adequate for operational purposes, it appears impracticable to measure the difference between inflow and outflow with the accuracy required for the water-loss study. In order to meet the requirement that the error in the difference between monthly inflow and outflow shall not exceed 5 percent of the monthly evaporation during the summer months it would be necessary that the error in measuring inflow and outflow not exceed about 0.2 percent, which appears impracticable.

The reservoir area is underlain by igneous rocks ranging from granite through granodiorite and gabbro, and a small body of tonalite. Seepage losses from the reservoir are not large and can be accurately measured. A detailed study of ground-water conditions would be required to demonstrate conclusively the possible magnitude of ground-water inflow from the Gavilan hills to the south.

Meteorological conditions at Lake Mathews are generally favorable. The surrounding terrain slopes gently, and the wind structure is believed to be uncomplicated by mechanically induced turbulence. Annual rainfall averages about 10 inches.

Lake Mathews was rejected as a site for the water-loss studies because of the impracticability of measuring inflow and outflow volumes with the required accuracy. In many other respects Lake Mathews is quite suitable, but the volumes of inflow and outflow are so large that the possible error in the difference between these two quantities is greatly magnified.

SALTON SEA, CALIFORNIA

Salton Sea lies in a closed basin in southeastern California. In middle Tertiary time the Gulf of California extended much farther north than at present and included what is now the Salton Sea, according to Blake (1914, pp. 2-3). Later, as the continental land surface rose, the increased silt load of the Colorado River formed an immense delta. The head of the Gulf became an inland salt sea, fed at intervals by flood waters of the Colorado. Eventually, however, desiccation took place. Prior to 1905, large quantities of water reached Salton Sea only infrequently, according to Cory (1913, p. 1228). Its recent history has been described in detail by Mendenhall (1909, pp. 21-24), Brown (1923, pp. 3-12), and many others, with special reference to the Colorado River floods of 1905-06. During this period the floodwaters of Colorado River poured into the Salton Sea, transforming it from an old dry lake, or playa, to the present large inland sea.

The elevation of the water surface of Salton Sea in 1949 was approximately 240 feet below sea level. (See fig. 13.) The stage has varied little since 1944. At elevation -240, the surface area of Salton Sea is 210,000 acres and its contents 4,033,000 acre-feet.

The major source of surface-water supply of Salton Sea is drainage from irrigated areas in the Imperial Valley in the United States and Mexico. The drainage enters Salton Sea in the channels of New and Alamo Rivers. Records of the Imperial Irrigation District show that for the 5-year period 1944-48 the average annual discharge into Salton Sea was 1,079,000 acre-feet. Whitewater River and San Felipe Creek flow directly into Salton Sea, but contribute substantial volumes of runoff only after infrequent storms. Peak discharge of Whitewater River at Point Happy, near Indio, during the January 1916 flood was 10,160 cubic feet per second, according to Tait (1917, p. 9).

The volume of ground-water inflow in the Coachella Valley area is difficult, if not impossible, to estimate. According to Mendenhall (1909, p. 37), "there is a continuous slow movement of these subterranean waters beneath the Indio region toward the southeast, but the water does not escape to the gulf. Much the greater part of the subsurface percolation probably reaches the surface eventually in the vicinity of the Salton Sea, and before the inflow of the Colorado it escaped into the air by evaporation." The saturated sands average more than 1,000 feet in thickness in an area of at least 400 square miles, Mendenhall estimated. Since the time of Mendenhall's report (1909), the ground-water resources of the Coachella Valley have been extensively developed, and much of the water formerly reaching the Salton Sea area is now used for irrigation.

Ground-water inflow is not limited to the Coachella Valley area. According to Brown (1923, p. 66), "Nearly every permanent or intermittent

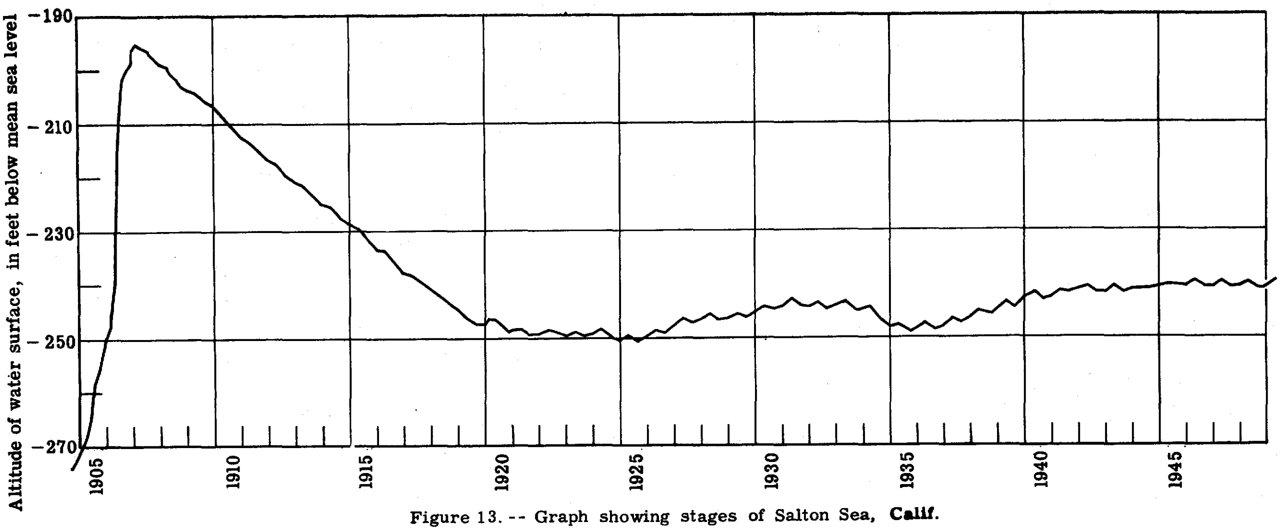

Figure 13.-- Graph showing stages of Salton Sea, Calif.

stream becomes interrupted in its lower portion as it nears the desert, because of gradual changes in the character of its bed and the increasing amount of porous gravel along its course. Without exception, all the streams either sink completely into the desert soil or flow only in certain stretches before reaching their ultimate destination in the Salton Basin or other desert basins."

Estimates of evaporation from Salton Sea vary within rather wide limits. Annual evaporation from three screened pans in the vicinity of Salton Sea averaged 93.7 to 114.9 inches over a 2-year period, according to A. C. Bowen of the U. S. Soil Conservation Service, who states that a coefficient of 0.98 is applicable to this type of pan. Other evaporation-pan records obtained in this area indicate annual evaporation to be approximately 90 inches. LaRue (1916, p. 142) estimated annual evaporation from Salton Sea to be 5.8 feet, but his estimate appears low, for he did not take ground-water inflow into account. Normal evaporation from a Class-A pan, as taken from the map prepared by Horton (1943, p. 750, fig. 2), is about 115 inches per year. Using a coefficient of 0.7, equivalent reservoir evaporation is 80 inches. Mean annual evaporation in the Salton Sea area, as taken from the map prepared by Meyer (1942, map 4), is approximately 85 inches per year.

For the purpose of estimating the possible magnitude of unmeasured surface- and ground-water inflow into Salton Sea, annual evaporation is taken as 80 inches. During 1944-48, the surface area of Salton Sea remained fairly constant at about 200,000 acres. Average annual evaporation is therefore estimated to be 1,330,000 acre-feet. Measured inflow during this period averaged 1,079,000 acre-feet per year. Since the contents of the sea did not change substantially during this period, unmeasured inflow apparently averaged 250,000 acre-feet per year. However, a computation of this nature is subject to gross errors, for an error of 6 inches in the estimated evaporation would result in an error of 100,000 acre-feet in the estimate of unmeasured inflow.

The fact remains, however, that since the stage of Salton Sea has remained relatively constant during the last few years, evaporation must approximately equal inflow. For the purposes of this study it is required that the maximum allowable error in measuring evaporation by volumetric means must not exceed 5 percent of the actual evaporation. It appears that a measurement of this accuracy for Salton Sea is impracticable. Most of the surface inflow is now measured by the Imperial Irrigation District. Even if the infrequent periods of storm runoff are excluded from the accounting, an extensive network of stream gaging stations would be required merely to demonstrate conclusively the occurrence or nonoccurrence of storm runoff. Although each gaging station could be of extremely simple construction, many would be required, and the total cost would be high.

The problem of measuring ground-water inflow is immensely more difficult. Considerable field study would be required to select proper sites for a network of observation wells. Pumping tests would be necessary for permeability determinations. Continuous records of water-level elevations would be required. Admittedly a costly undertaking, it has the more serious drawback that there is no positive assurance that results would be of the necessary high degree of accuracy.

The large size of Salton Sea poses some problems in connection with the meteorological observations to be made as a part of the water-loss study. The number of meteorological observation stations deemed adequate for a lake of say 10 square miles surface area is inadequate for a water surface as large as Salton Sea. Preliminary field studies of the areal variations in meteorological elements might be needed before a decision could be reached as to the number and location of observation stations. A hydrographic survey of Salton Sea would be required. With modern equipment the task would be essentially routine in nature, despite its magnitude. Another problem complicated by the size of Salton Sea is the precise determination of stage. Seiche amplitudes may be fairly high. In addition to a number of gages along the shores, it would appear essential that some method be devised for the precise measurement of stages at points on the lake in order to obtain a true picture of the surface, whether flat or tilted, or warped by wind action.

The decision to eliminate Salton Sea from further consideration as a site for the water-loss investigations was, therefore, based primarily on the belief that it would be impracticable to determine the water budget with the required degree of accuracy. The problems arising from the great size of Salton Sea are not considered unsurmountable.

OTHER RESERVOIRS

Many other reservoirs and lakes were suggested for consideration as possible sites for the water-loss study. They were rejected because of failure to meet the specifications in one or more respects. Brief comments on many of the suggested lakes have been prepared to indicate the principal reason for eliminating them from further consideration. Many of these reservoirs and lakes may also fail to meet the specifications in respects other than those mentioned, but detailed studies were not made if preliminary investigations indicated that the lake was unsuitable because of size, shape, or the impracticability of determining an accurate water budget.

Arizona

Green Reservoir.--Abandoned.
Mormon Lake.--Dry in 1947; little water in 1949. Very shallow, saucer-shaped basin; small changes in stage result in large changes in surface area.
Roosevelt Reservoir.--Long, narrow; prevailing winds at right angles to long axis; large fluctuation in stage.

California

Buena Vista Lake.--Dry in 1949 and will not contain water again until a fairly large flood occurs in Kern River.
Butte Lake.--Formerly a shallow reservoir but now abandoned.
Calaveras Reservoir.--Small; surface area slightly more than 2 square miles; inflow and outflow are large compared with evaporation.
Clear Lake (Cache Creek).--Ground-water movement into or out of Quaternary deposits may be substantial and would be difficult to measure accurately; irregular shape; mountains on three sides.
Clear Lake (Lost River).--Irregular shape; islands and shoals divide lake into two basins; adjacent swamp is larger than lake.
Copper Basin Reservoir.--Small; surface area less than 1 square mile.
Crystal Spring Reservoir.--Small; surface area slightly more than 2 square miles; inflow and outflow large compared with evaporation.
Eagle Lake.--Very irregular shape; large ground-water outflow.
East Park Reservoir.--Small; surface area less than 3 square miles at full pool; large irrigation withdrawals.
Hayfield Reservoir.--Contains no water other than infrequent waste from Colorado River Aqueduct.
Honey Lake.--Irregular shape; dry in September 1949.
Horse Lake.--Dry in 1949; very irregular shape.
Kern Lake.--Generally dry or nearly so.
Lake Almanor.--Mountain reservoir; extremely irregular shape.
Lake Arrowhead.--Small; surface area slightly more than 1 square mile.
Lake Henshaw.--Subsurface inflow during late summer months may amount to 25 percent of the evaporation.
Lake Levitt.--Small; large irrigation withdrawals.
Lake Pillsbury.--Irregular shape; inflow and outflow large in comparison with evaporation.
Lake Tahoe.--Large; surface area 193 square miles. Inflow and outflow large compared with evaporation; inflow difficult to measure.
Mesquite Lake.--Dry in 1949.
Mono Lake.--Many springs in lake bottom.
Morris Reservoir.--Canyon reservoir.
Mountain Meadows Reservoir.--Shallow; average depth about 4 feet when reservoir is full.
Owens Lake.--Shallow; average depth less than 10 feet; mountain ranges rise 6,000-7,000 feet above lake on east and west.
Prado Reservoir.--Flood-control reservoir; normally empty.
Salinas Reservoir.--Canyon reservoir.
Shasta Reservoir.--Very irregular shape; canyon reservoir; probable errors in measuring inflow and outflow large compared with evaporation.
Stony Gorge Reservoir.--Canyon reservoir.
Tinnemaha Reservoir.--Small; inflow and outflow large in comparison with evaporation.

Colorado

Green Mountain Lake.--Inflow and outflow very large compared with evaporation.
John Martin Reservoir.--Irrigation withdrawals occasionally reduce contents to zero.

Idaho

Bear Lake.--Impracticable to determine surface- and ground-water inflow and outflow with required accuracy; large shallow areas with water-using vegetation.
Blackfoot Marsh Reservoir.--Irregular shape; subsurface losses difficult to determine.
Coeur d'Alene Lake.--Extremely irregular shape.
Crane Creek Reservoir.--Long, narrow; inflow and outflow large compared with evaporation.
Deer Flat Reservoir.--Large and variable subsurface losses.
Grays Lake.--Large shallow areas; considerable portion of lake area covered with tules.
Hayden Lake.--Reported to have large subsurface losses, particularly at high stages; surrounding terrain mountainous.
Henrys Lake.--Ground-water inflow and outflow difficult to determine accurately.
Island Park Reservoir.--Large changes in bank storage.
Magic Reservoir.--About 8 miles long and up to 2 miles wide with long axis approximately at right angles to prevailing winds; shore line irregular.
Mud Lake.--Substantial ground-water inflow, difficult to measure.

Missouri

Wappapello Reservoir.--Long, narrow; very irregular shore line; humid climate; inflow-outflow difference cannot be measured with sufficient accuracy.

Montana

Deadmans Basin.--Small; surface area less than 3 square miles.
Hebgen Reservoir.--Irregular shape; mountain reservoir.
Pishkun Reservoir.--Small; surface area less than 3 square miles.
Ruby Reservoir.--Small; surface area less than 1 square mile.
Swan Lake.--Long, narrow; mountain lake.
Tongue River Reservoir.--Long, narrow; irregular shore line.
Willow Creek Reservoir (Sun River).--Small; less than 3 square miles.

Nebraska

Johnson Reservoir.--Inflow and outflow very large in comparison with evaporation.
McConaughy Lake.--Considerable bank storage; long, narrow; irregular shore line; prevailing summer winds across long axis.
Sutherland Reservoir.--Substantial subsurface losses.

Nevada

Carson Lake.--Large subsurface return flow from irrigation; large area of water-using vegetation.
Lahontan Reservoir.--Long, narrow; irregular shape.
Lake Tahoe.--See list of California lakes and reservoirs.
Rye Patch Reservoir.--Long, narrow; irregular shore line.
Snow Water Lake.--Supplied mainly by subsurface flow; dry much of the time.
Washoe Lake.--Large subsurface inflow; very shallow; large areas of water-using vegetation.

New Mexico

Alamogordo Reservoir.--Long, narrow; irregular shore line; prevailing summer winds normal to long axis of lake.
Blue Water Lake.--Irregular shore line; broken terrain; subsurface losses reported to be of considerable magnitude.
Caballo Reservoir.--Long, narrow; rugged terrain; irregular shore line; subsurface inflow from Black Range on west.
Conchas Reservoir.--Two arms nearly at right angles; shore line very irregular.
El Vado Reservoir.--Long, narrow; irregular shore line.
Elephant Butte Reservoir.--Long, narrow; mountains on east side; subsurface inflow from Black Range on west; transpiration losses large.
Hondo Reservoir.--Seldom contains water.
Lake McMillan.--Used for temporary detention only.

North Dakota

Devils Lake.--Magnitude of surface- and ground-water inflow and outflow uncertain and difficult to measure; irregular shore line with large bays and arms, which may be separated from main body of water during dry years.

Oklahoma

Great Salt Plains Reservoir.--Inflow and outflow very large compared with evaporation and cannot be measured accurately.

Oregon

Agency Lake.--Large swampy areas bordering lake.
Agency Valley Reservoir.--Small; surface area at full pool less than 3 square miles; large withdrawals for irrigation during summer months.
Antelope Reservoir.--Large irrigation withdrawals during summer months; reported dry in late summer of 1949.
Cottage Grove Reservoir.--Small; surface area less than 2 square miles.
Crater Lake.--Substantial portion of inflow believed lost by seepage; surrounded by escarpment from 500 to 2,000 feet high.
Drew Reservoir.--Long, narrow; very shallow on west side; apparently considerable ground-water inflow.
Fern Ridge Reservoir.--Very shallow; considerable marginal vegetation; large drawdown in winter; may be considerable bank storage in terrace gravels along east shore.
Gerber Reservoir.--Very irregular shape; too small in September 1949 because of large irrigation withdrawals.
Malheur Lake.--Very shallow, if not dry; occasional outflow to Harney Lake difficult to measure accurately.
Owyhee Reservoir.--Long, narrow; canyon reservoir.
Summer Lake.--Practically dry in September 1949.
Upper Klamath Lake.--Considerable marginal vegetation; shallow; irregular shape.
Warmsprings Reservoir.--Large irrigation withdrawals in late summer; contents only about 7,000 acre-feet in August 1949.
Wickiup Reservoir.--Substantial subsurface inflow and outflow.

Texas

Barker Reservoir.--Detention reservoir with no provision for permanent storage.
Bridgeport Reservoir.--Very irregular shape.
Brownwood Reservoir.--Irregular shape; inflow and outflow large compared with evaporation.
Buchanan Reservoir.--Irregular shape; inflow and outflow large compared with evaporation.
Buffalo Lake.--Small; surface area about 3 square miles when reservoir contents are 18,150 acre-feet, but contents usually much less than this.
Eagle Mountain Reservoir.--Long, narrow; irregular shore line.
Fort Phantom Hill Reservoir.--Irregular shape; small; surface area less than 4 square miles on September 30, 1949.
Lake Abilene.--Small; surface area less than 1 square mile.
Lake Dallas.--Inflow and outflow large compared with evaporation.
Lake Kemp.--Extremely irregular shape.
Lake Kickapoo.--Long, narrow; inflow occasionally very large in comparison with evaporation.
Lake Kirby.--Small; surface area less than 1 square mile.
Lake Travis.--Very irregular shape.
Possum Kingdom Reservoir.--Very irregular shape.
Red Bluff Reservoir.--Monthly changes in contents very large in comparison with evaporation.
San Angelo Reservoir.--Not yet completed in spring 1950.

Utah

Bear Lake.--See Idaho list of lakes and reservoirs.
Deer Creek Reservoir.--Canyon reservoir.
Hyrum Reservoir.--Small; surface area less than 1 square mile.
Midview Reservoir.--Small; surface area less than 1 square mile.
Salt Lake.--Usually dry.
Sevier Bridge Reservoir.--Long, narrow; has been dry at times.
Sevier Lake.--Usually contains little, if any, water.
Strawberry Reservoir.--Inflow and outflow large compared with evaporation, which is reported to be low; elevation 7,500 feet.
Utah Lake.--Shallow; average depth less than 10 feet. Subsurface inflow difficult to determine.

Washington

Blue, Lenore, and Soap Lakes.--A chain of elongate lakes in the lower and south half of the Grand Coulee; shape and topographic setting unsatisfactory.
Moses Lake.--Irregular shape.

Wyoming

Jackson Lake.--Irregular shape; many tributary streams.
Lake Hattie.--Seldom contains any large quantity of water.
Wyoming Development No. 2.--Long, narrow reservoir; inflow and outflow large compared with evaporation.
Wyoming Development No. 3.--Irregular shape; inflow and outflow large compared with evaporation.

REFERENCES CITED

American Society of Civil Engineers, 1949, Hydrology Handbook, ASCE Manual of Engineering Practice No. 28.

Anderson, E. R., Anderson, L. J., and Marciano, J. J., 1950, A review of evaporation theory and development of instrumentation: U. S. Navy Electronics Lab. Rept. No. 159 (free on application to U. S. Geol. Survey, Washington 25, D. C.).

Antevs, E. V., 1938, Rainfall and tree growth in the Great Basin: Carnegie Inst. Washington Pub. No. 469.

Blake, W. P., 1914, The Cahuilla Basin and Desert of the Colorado, in MacDougal, D. T., The Salton Sea: Carnegie Inst. Washington Pub. No. 193.

Brown, J. S., 1923, The Salton Sea region, Calif.: U. S. Geol. Survey Water-Supply Paper 497.

Congressional documents: 72d Congress, 1st sess., H. Doc. 191, 1932.

Cory, H. T., 1913, Irrigation and river control in the Colorado River delta: Am. Soc. Civ. Eng. Trans., vol. 76.

Dobbin, C. E., and Erdmann, C. E., 1946, Structure contour map of the Montana plains, U. S. Geol. Survey geophysical investigations map.

Erdmann, C. E., Davis, N. A., Beer, Wm., and Nordquist, J. W., 1946, Preliminary structure contour map of the Cut Bank--West Kevin border districts, U. S. Geol. Survey geophysical investigations map.

Harding, S. T., 1922, Report on San Jacinto River Hydrographic Investigation: California Div. of Water Rights.

Harding, S. T., 1927, Evaporation on Reclamation projects (discussion): Am. Soc. Civ. Eng. Trans., vol. 90.

Harding, S. T., 1935, Evaporation from large water surfaces based on records in California and Nevada: Am. Geophys. Union Trans., pt. 2.

Horton, R. E., 1943, Evaporation maps of the United States: Am. Geophys. Union Trans., pt. 2.

Ingerson, I. M., 1932, Report on supervision of diversions from Pit River and Rattlesnake Creek in Hot Springs Valley, Modoc County, Calif., 1931 season: State of California Div. of Water Resources Rept. (mimeographed).

Jones, J. C., 1925, Quaternary climates: Geologic history of Lake Lahontan, Carnegie Inst. Washington Pub. No. 352.

Langbein, W. B., 1949, Annual runoff in the United States: U. S. Geol. Survey Circ. 52.

LaRue, E. C., 1916, Colorado River and its utilization: U. S. Geol. Survey Water-Supply Paper 395.

Meinzer, O. E., Ground water, in Physics of the Earth, Nat. Research Council, McGraw-Hill, 1942, reprinted by Dover Publications, Inc., 1949.

Mendenhall, W. C., 1909, Ground waters of the Indio region, Calif.: U. S. Geol. Survey Water-Supply Paper 225.

Meyer, A. F., 1942, Evaporation from lakes and reservoirs: Minnesota Resources Comm.

Russell, I. C., 1884, A geological reconnaissance in southern Oregon: U. S. Geol. Survey 4th Ann. Rept.

Russell, I. C., 1885, Geological history of Lake Lahontan: U. S. Geol. Survey Mon. 11.

Russell, R. J., 1928, Basin range structure and stratigraphy of the Warner Range, northeastern California: California Univ., Dept. Geol. Sci., Bull. vol. 17.

Schanck, F. R., 1919, in Waring, G. A., Ground water in the San Jacinto and Temecula Basins, Calif.: U. S. Geol. Survey Water-Supply Paper 429.

Sverdrup, H. U., 1945, Oceanography, in Handbook for Meteorologists, 1st ed., McGraw-Hill.

Tait, C. E., 1917, Preliminary report on conservation and control of flood water in Coachella Valley, Calif.: 5th Bienn. Rept., California Dept. Eng., Appendix D.

U. S. Dept. Agr., 1941, Climate and Man: 1941 Yearbook of Agriculture.

U. S. Dept. Commerce, Weather Bur., 1948, Climatological data, vol. 35, No. 13.

U. S. Geol. Survey, 1949, Surface-water supply of the United States, 1947, Water-Supply Paper 1091.

Waring, G. A., 1908, Geology and water resources of a portion of south-central Oregon: U. S. Geol. Survey Water-Supply Paper 220.

Waring, G. A., 1919, Ground water in the San Jacinto and Temecula Basins, Calif.: U. S. Geol. Survey Water-Supply Paper 429.

Zander, Gordon, 1933, Pit River investigation: State of California Div. of Water Resources, Bull. 41.