TEXAS WATER DEVELOPMENT BOARD

REPORT 24

EFFECT OF AN INCREASED HEAT LOAD ON THE THERMAL STRUCTURE AND EVAPORATION OF LAKE COLORADO CITY, TEXAS

By

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FOREWORD

On September 1, 1965 the Texas Water Commission (formerly, before February 1962, the State Board of Water Engineers) experienced a far-reaching realignment of functions and personnel, directed toward the increased emphasis needed for planning and developing Texas' water resources and for administering water rights.

Realigned and concentrated in the Texas Water Development Board were the investigative, planning, development, research, financing, and supporting functions, including the reports review and publication functions. The name Texas Water Commission was changed to Texas Water Rights Commission, and responsibility for functions relating to water-rights administration was vested therein.

For the reader's convenience, references in this report have been altered, where necessary, to reflect the current (post September 1, 1965) assignment of responsibility for the function mentioned. In other words credit for a function performed by the Texas Water Commission before the September 1, 1965 realignment generally will be given in this report either to the Water Development Board or to the Water Rights Commission, depending on which agency now has responsibility for that function.

This report was prepared in the Water Resources Division of the Geological Survey, United States Department of the Interior, by G. Earl Harbeck, Jr., Area Research Hydrologist, and J. Stuart Meyers of the Denver Area Office, and G. H. Hughes of the Austin District. Most of the fieldwork and data processing was performed by personnel of the Surface Water Branch, Austin District, under the supervision of Trigg Twichell, District Engineer. The study was conducted during 1959-60 in cooperation with the Texas Water Development Board.

The Texas Electric Service Company, Fort Worth, Texas, supported the studies culminating in the report and assisted with the installation of equipment and made routine daily observations.

The help of the U.S. Weather Bureau in installing a pan evaporation station is gratefully acknowledged.

A study of Lake Colorado City made in 1954-55 was reported in 1959 as U.S. Geological Survey Professional Paper 272-B, "The Effect of the Addition of Heat from a Powerplant on the Thermal Structure and Evaporation of Lake Colorado City, Texas" by G. Earl Harbeck, Jr., G. E. Koberg, and G. H. Hughes.

The second study made in 1959-60 covered by this report substantiated assumptions and conclusions made in the first study. Additional information helpful in the design of cooling ponds for powerplants and in the estimation of forced evaporation therefrom was developed and is presented herein through the 1964-65 cooperation of the Surface Water Cooperative Program and the Research Program of the Texas Water Development Board.

Texas Water Development Board

John J. Vandertulip

John J. Vandertulip
Chief Engineer

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

TABLES

ILLUSTRATIONS

Figures

TABLE OF CONTENTS (Cont'd.)

EFFECT OF AN INCREASED HEAT LOAD ON THE THERMAL STRUCTURE AND EVAPORATION OF LAKE COLORADO CITY, TEXAS

ABSTRACT

A thermal-electric powerplant of the Texas Electric Service Company in north-central Texas withdraws water from its reservoir, Lake Colorado City, uses it for cooling, and returns it to the lake practically undiminished in quantity, but at a higher temperature. A study was made in 1954-55 to determine the amount of forced evaporation resulting from the addition of heat by the plant, and the resultant rise in temperature of the lake. A formula was presented for use in computing the amount of forced evaporation that would occur if the plant heat load were increased.

Since the first study, the plant load has been increased. Champion Creek Reservoir was constructed as an auxiliary supply in time of drought. During 1959-60 a second and similar study was made.

Computed natural evaporation during a 12-month period in 1959-60 was 85 inches, exactly the same as for a like period in 1954-55. During a 10-month period evaporation from Champion Creek Reservoir, to which no heat was added, was 73 inches, which was almost exactly the same as the computed natural evaporation from Lake Colorado City for the same period. The amount of forced evaporation with an increased plant load during 1959-60, 1,108 acre-feet, agreed well with the amount computed from the formula in the report on the 1954-55 study.

The earlier report concluded that for a given surface area, the rise in water-surface temperature to be expected is almost directly proportional to the amount of heat added. This forecast was verified by the 1959-60 study; a temperature rise of 0.8°C resulted from a plant load of 1.3 billion kwhr per year in 1954-55, and a rise of 1.0°C resulted from a plant load of 1.64 billion kwhr per year in 1959-60.

An effort was made to forecast plant intake temperatures to be expected during critical periods in the summer. The results were inconclusive and the difficulty appeared to result from the fact that long-range weather forecasts are not yet sufficiently accurate and detailed.

EFFECT OF AN INCREASED HEAT LOAD ON THE THERMAL STRUCTURE AND EVAPORATION OF LAKE COLORADO CITY, TEXAS

INTRODUCTION

Water for cooling is essential for the operation of thermal-electric powerplants. Large amounts of heat must be absorbed by the cooling water at steam-electric stations, and carried away by streams or lakes or dissipated to the air in cooling towers. The temperature of the water is thereby raised and more water is evaporated. This report is concerned with the increased evaporation from Lake Colorado City, a reservoir constructed for the express purpose of providing cooling water for a large powerplant.

Evaporation from the same reservoir was the subject of an earlier investigation and report (Harbeck and others, 1959) which is supplemented by this study. Since the time of those observations, which were made in 1954-55, the capacity of the steam-electric powerplant at Lake Colorado City has been more than doubled, and the heat disposal to the reservoir has been considerably increased. This provided an opportunity to repeat the earlier observations for a higher level of added heat, and to extend, confirm, or correct the relationships developed therefrom. The results should be useful in the prediction of water temperatures and evaporation for a cooling pond, so that powerplants can be designed and operated with greater confidence. The mutual interest of the Texas Water Development Board and the U.S. Geological Survey in the subject led to a cooperative agreement for the 1959-60 investigations described herein. The active cooperation of the Texas Electric Service Company, owner of the Lake Colorado City plant, was a major factor in the study.

The recent series of observations and the present report generally parallel the previous observations and report for Lake Colorado City. This account, however, has been prepared as a complete and independent report rather than as a simple supplement. The recent results have generally agreed with the earlier results, so the observed data, derivations, and conclusions of Professional Paper 272-B (Harbeck and others, 1959) remain valid, subject to limitations to be discussed later. This report extends the range of observations and confirms the interpretations of the 1954-55 study.

DESCRIPTION OF RESERVOIRS AND DAMS

Lake Colorado City

Lake Colorado City is on Morgan Creek just above its junction with the Colorado River in north-central Texas (Figure 1), and is about 5 miles southwest of Colorado City, Mitchell County. The dam creating the lake was built in 1949 by the Texas Electric Service Company of Fort Worth to provide a supply of cooling water for its adjacent steam-electric powerplant that was constructed at the same time.

The dam is of rolled earth, approximately 4,800 feet long and 85 feet in height at the deepest section. Service and emergency spillways near the dam provide for the passage of flood discharges. The only spill from the reservoir since its construction occurred during the period May 10-June 20, 1957. The revised capacity of the reservoir at service spillway level is 31,000 acre-feet, and the corresponding water-surface area is 1,655 acres. During the 1959-60 observation period, however, the reservoir contents ranged from about 16,000 to 21,000 acre-feet, and the water-surface area ranged from about 1,000 to 1,200 acres. About 1,400 acre-feet of water per year was pumped from the reservoir to Colorado City for municipal use, but there were no other significant releases or withdrawals.

Water is taken from Lake Colorado City at the powerplant intake, pumped through the plant where it cools the condensers, and is returned to the lake through a canal. The canal discharges over a weir so that the water falls freely into the reservoir, at a point nearly a mile from the intake. Practically no water is consumed or permanently withdrawn in the cooling operation, but subsequent evaporation from the lake is somewhat increased because of the slightly warmer surface temperature. The upper portion of the lake is used extensively for recreation, but access to the lower part is restricted. No water is consumed or withdrawn as a result of the recreational use.

Lake Colorado City receives the natural runoff drained by Morgan Creek from the area of 322 square miles, of which 32 square miles is probably noncontributing. Upstream gaging stations on Morgan Creek and its tributary, Graze Creek, have measured the runoff from 250 (32 probably noncontributing) and 21 square miles, respectively. The channels of these ephemeral streams are often dry for periods that sometimes have continued for more than six consecutive months. Inflow to the reservoir averages several thousand acre-feet annually, but the totals for individual 12-month periods have ranged from about 500 to nearly 40,000 acre-feet of water. Nearly all this volume of flow comes down the stream channels in sharp peaks following the infrequent rainstorms. A storage reservoir was therefore necessary to obtain a continuous supply of cooling water from the highly variable natural flow.

Champion Creek Reservoir

The Texas Electric Service Company completed an enlargement of its powerplant at Lake Colorado City in June 1959 and also constructed an auxiliary reservoir to increase the dependable supply of cooling water. An earth dam 6,800 feet long and 114 feet high at the deepest section was built across Champion Creek near its mouth, at a site 7 miles south of the city of Colorado City and less than a mile from the Colorado River (Figure 1). A pumping station was

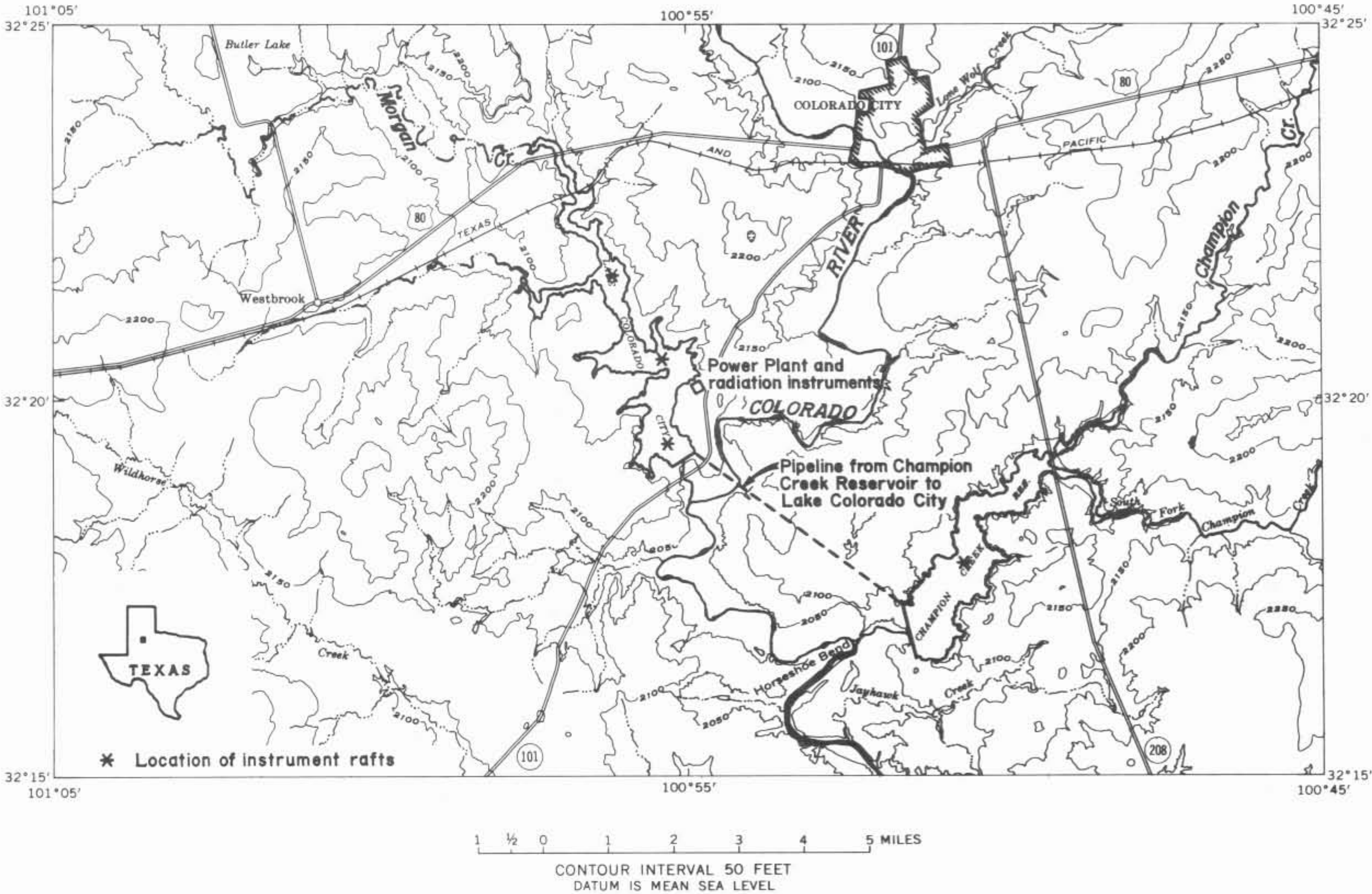


Figure 1

Map of Lake Colorado City and Champion Creek Reservoir

U.S. Geological Survey in cooperation with the Texas Water Development Board

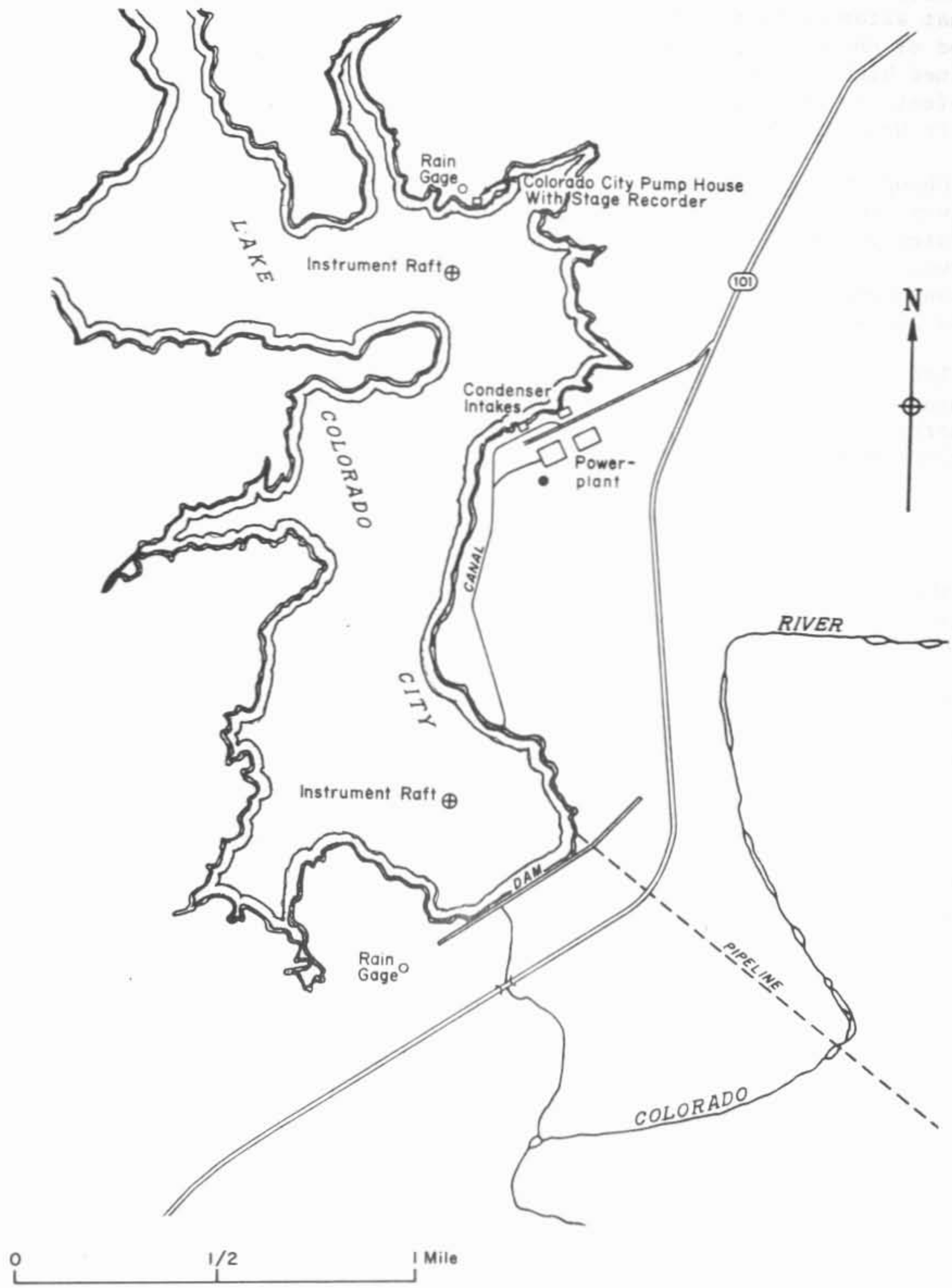


Figure 2

Location of Instruments and Plant Layout, Lake Colorado City

U.S. Geological Survey in cooperation with the Texas Water Development Board

installed at this dam with a discharge pipeline leading to Lake Colorado City so that water could be transferred to the latter reservoir. During the 1959-60 period of observations, however, the natural level of Lake Colorado City remained high enough for satisfactory powerplant operation, and only about 20 acre-feet of water was transferred from Champion Creek Reservoir during a pump test in March 1960.

Champion Creek Reservoir has a capacity of 42,500 acre-feet at service spillway level, and the corresponding surface area is 1,560 acres. The dam was completed in March 1959, although storage of water began in February 1959. Reservoir contents ranged from 2,700 to 4,000 acre-feet during the 1959-60 evaporation measurements, and the water-surface area in the same period ranged from 228 to 300 acres.

Inflow to the reservoir is the runoff from the area of 203 square miles draining to Champion Creek above the dam. Flow records for 12 years at a gage (formerly called Champlin Creek gage near Colorado City) 4 miles above the new dam show an average annual flow of 9,300 acre-feet from 194 square miles.

CLIMATOLOGY

The climate of the Colorado City area is semiarid, according to the classification proposed by Thornthwaite (1948). Average annual precipitation at Colorado City is about 21 inches, more than two-thirds of which is received during the 6-month summer period, April through September. The amount of precipitation at Colorado City during the observation period, August 1959 through September 1960, was 23.20 inches, which is 90 percent of the long-term average total of 25.92 inches for the same 14 months.

The average annual temperature at Colorado City is 64.8°F and at San Angelo, 73 miles south-southeast, 66.4°F. Figure 3 shows the normal[1] monthly temperatures and the 1959-60 values observed by the U.S. Weather Bureau at San Angelo. Also shown for comparison are air temperatures observed at Lake Colorado City during this investigation (see Figure 5), and water-surface temperatures at Lake Colorado City. The air temperatures at Colorado City during these observations averaged 67.7°F, about 1°F more than the long-term mean of 66.8°F for the corresponding 14-month period.

The nearest U.S. Weather Bureau stations for which wind and humidity data are available are those at Abilene (72 miles east of Lake Colorado City), at San Angelo (73 miles south-southeast), and at Midland (80 miles west-southwest). Average monthly wind speeds and vapor pressures at San Angelo are shown in Figure 4.

The 1959-60 weather conditions at Lake Colorado City were quite similar to those observed in 1954-55 and both periods were approximately normal.

[1] The word "normal" as herein used refers to the averages for the standard climatological period 1931-60.

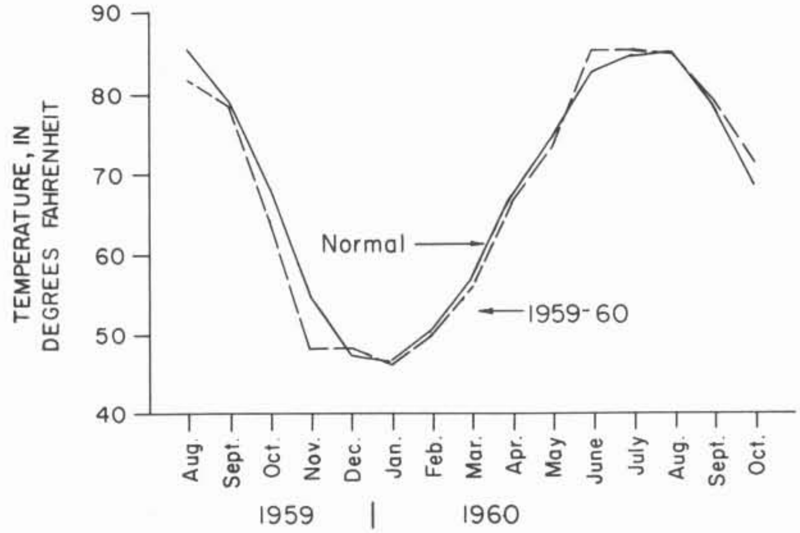


Figure 3

Monthly Average Air Temperature at San Angelo

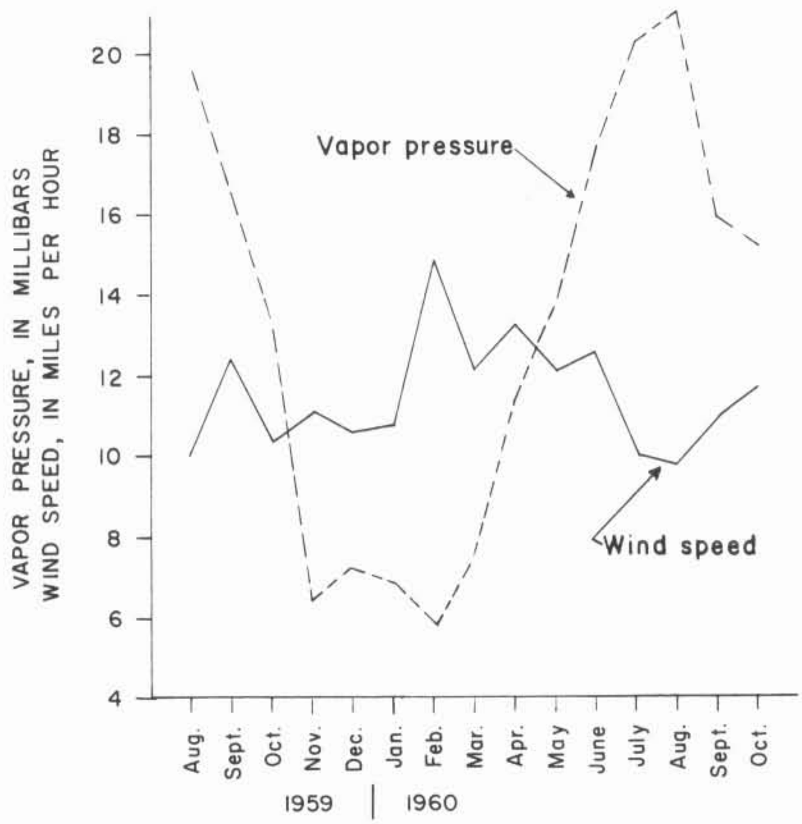
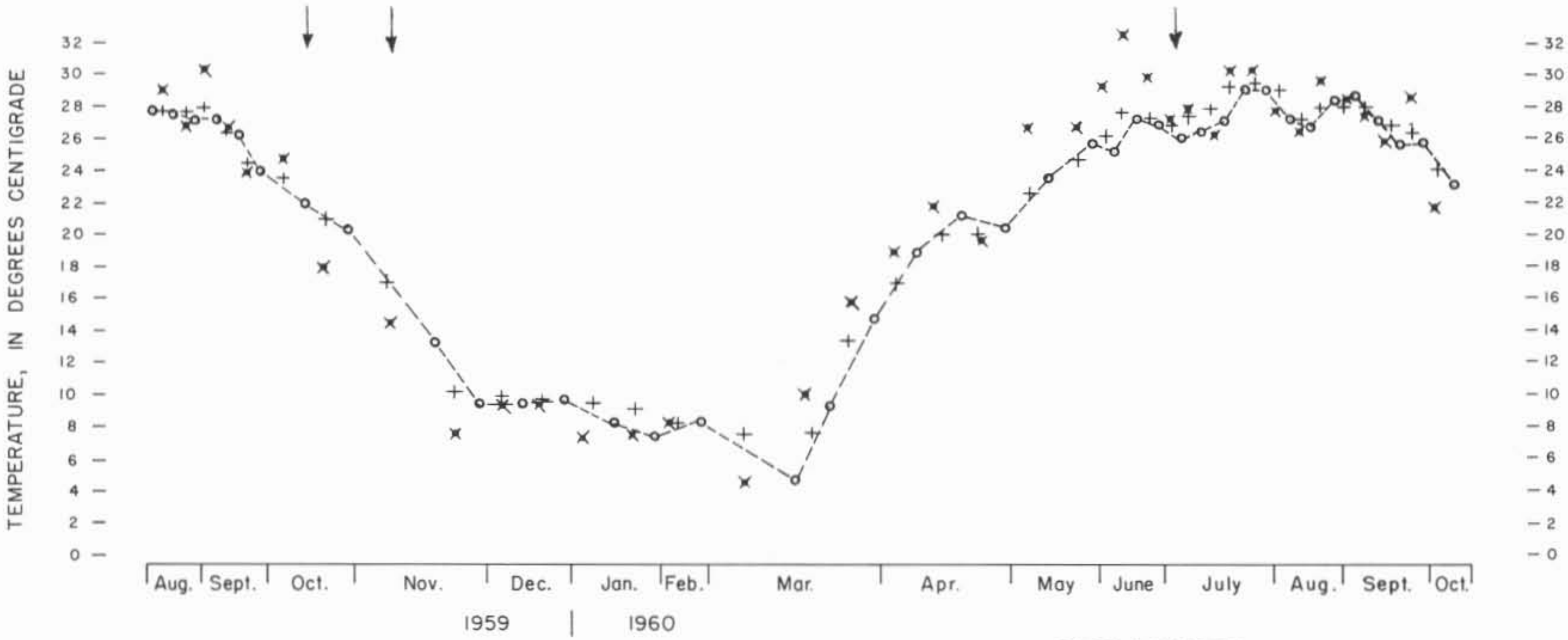


Figure 4

Monthly Average Wind Speed and Vapor Pressure at San Angelo

U.S. Geological Survey in cooperation with the Texas Water Development Board



EXPLANATION

- o Average temperature of all water in reservoir, from thermal survey
- + Average water-surface temperature (To) for time periods between surveys
- × Average air temperature (Ta) for time periods between surveys
- ↓ Principal periods of natural inflow

Figure 5

Temperatures at Lake Colorado City, 1959-60

U.S. Geological Survey in cooperation with the Texas Water Development Board

INSTRUMENTATION

Water-Budget Instrumentation

Evaporation from the Lake Colorado City and from Champion Creek Reservoir was computed by the energy-budget method for these analyses. In order to evaluate the advection and storage terms in the energy-budget equation, however, the inflows, outflows, and change in contents of a reservoir must be known. A water budget must be established for each reservoir where this procedure is applied. The necessary precision of measurement for different items in the water budget will depend on their magnitude and on their relative importance in the energy-budget evaluation. The methods of measurement and derivation of water-budget items are summarized in the following paragraphs.

Lake Colorado City

Inflow

Morgan Creek provides the surface inflow to Lake Colorado City. Gaging stations on Morgan Creek and its tributary, Graze Creek (discontinued September 30, 1959), measured the surface flow from 271 square miles (32 probably noncontributing), which is about 83 percent of the total area draining to the lake. As discovered during the earlier investigations (Harbeck and others, 1959, p. 19-21), however, at times there appears to be an unaccountable reduction in streamflow between the gaging stations and the lake. For both the 1954-55 and the 1959-60 investigations, therefore, inflow was computed from changes in lake stages and other data rather than being derived from streamflow measurements.

Precipitation

Precipitation is measured at Colorado City and at several points near Lake Colorado City and in the drainage basin of Morgan Creek. This evaporation investigation was concerned only with the amount of rainfall on the lake itself, so detailed analyses of rainfall rates and the variations in amounts measured at different locations were not needed. A simple average of the readings at the four gages around the lake was taken as the mean rainfall on the lake surface.

Transfer of Water From Champion Creek Reservoir

Another source of inflow to Lake Colorado City is the transfer of water by pumping from the new reservoir on Champion Creek. During the 1959-60 observation period, however, the pumps were operated on only one occasion for a few hours on March 10, 1960. The amount of water transferred was about 20 acre-feet, as computed by the manufacturer's rating for the pumps. No other measurement was attempted for this small quantity of inflow.

Outflow

Lake Colorado City has spilled only once, in May-June 1957. During the 1959-60 observation period the lake level ranged from about 7 to 11 feet below the spillway lip, and there was no surface outflow.

There is no evidence of surface seepage below the dam nor of deep seepage losses from the reservoir. Analyses made during the 1954-55 observations indicated that seepage, if any existed, was negligible. Even if seepage was large enough to be noticeable and measurable, the amount of heat energy thereby removed from the reservoir would be small in relation to other more important items in the energy budget. The possibility of seepage loss was, therefore, disregarded in making these evaporation computations, as it apparently could have no appreciable effect on the results.

Withdrawals for Municipal Use

Water was withdrawn from Lake Colorado City for domestic and municipal use by residents along the lakeshore by the powerplant and by the city of Colorado City, whose population was 6,457 in 1960. Of these, the diversion to Colorado City was the only one of significant size, and the other unmeasured minor diversions were not estimated for this evaporation study. Records of daily municipal withdrawals were computed from pumping records and meter readings furnished by the Colorado City Water Department. Withdrawals averaged about 1,400 acre-feet per year or 3.8 acre-feet per day and ranged from 0.6 to 8.9 acre-feet on individual days. The total diversion of 1,603 acre-feet during the 416-day period from August 14, 1959 to October 3, 1960, was about 14 percent of the computed evaporation for the same period.

Circulation of Water Through Powerplant

In the energy-budget equation for Lake Colorado City, the principal item of advected energy is that added by the water circulated through the powerplant. This flow of water was computed from the manufacturer's pump ratings, which were checked by current-meter measurements made at the weir in the discharge canal where water is returned to the lake. The rating curve developed from these measurements checked closely with the original pump ratings, the maximum difference being a reduction of 7 percent for one measurement and an increase of 5 percent for another. The average correction applied to the pump ratings was quite small, probably on the order of 1 percent.

Change in Reservoir Contents

For a reservoir like Lake Colorado City, where the amount of water ordinarily held in storage is much greater than the average annual inflow, changes in reservoir contents can constitute an important part of the water budget. A good record of water-surface elevations is therefore necessary, and also accurate information on the water-surface area and storage capacity for the range of lake levels experienced.

The area and capacity curves used to determine change of contents of Lake Colorado City were furnished by the Texas Electric Service Company. They are based on areas computed from four aerial photographs of the reservoir, taken with the lake surface at elevations of 2,047.3, 2,053.3, 2,061.2, and 2,068.2 feet above mean sea level. The scale of the photographs was determined from transmission alinement maps of the reservoir area. Available also was the area at the 2,070-foot contour, determined from deed records based on field surveys. The area and capacity curves used for these computations agree closely with curves furnished previously by the engineering firm that designed the dam and they are considered to be of satisfactory accuracy.

Lake levels were measured by a staff gage and a Stevens A-35 water-level recorder installed over a suitable stilling well on the outside of the Colorado City pumping station on the north shore of the lake, about 1.5 miles north of the dam (Figure 2). Lake elevations could be determined to one hundredth of a foot, which was sufficiently accurate for the evaporation determinations.

Strong winds can, of course, affect the level of even a comparatively small lake such as this, and a measurement at a single point does not always represent the average surface elevation. Surges produced by wind can generally be identified on the lake-elevation charts so that adjustments can be made if necessary. Such adjustments were not necessary at Lake Colorado City, however, where the only significant changes in reservoir contents were those for the periods between thermal surveys. As the thermal surveys could be made only when the wind was light, no interpretation of wind effects on lake levels was required.

Computation of Inflow

Inflow to Lake Colorado City from Morgan Creek occurs only for brief periods after occasional rainstorms and is zero for most of the time.

Inflow, including both direct rainfall and streamflow, was computed from the records of change in reservoir contents with allowances for diversion to Colorado City and for evaporation.

The estimated total inflow for the 14-month period, August 1, 1959 to October 3, 1960, was 6,935 acre-feet, which was received on 25 different occasions, totaling 48 days.

Champion Creek Reservoir

Inflow

As described in the earlier section entitled, "Description of Reservoirs and Dams," this reservoir is supplied by the surface flow of Champion Creek plus the small amount of rain falling directly on the reservoir surface.

The gage that formerly measured the flow of Champion Creek was drowned out by the rising water of the reservoir and the station was discontinued September 30, 1959. In the absence of usable streamflow data, inflow plus precipitation for Champion Creek Reservoir was computed from the change in reservoir contents and estimates of evaporation.

Outflow

There has been no surface outflow from Champion Creek Reservoir during the short time it has been in operation. There is no evidence of seepage from the dam. Aside from evaporation, the only water known to have left the reservoir since its formation is the 20 acre-feet that was pumped to Lake Colorado City on March 10, 1960, as previously mentioned.

Change in Reservoir Contents

A gage mounted on the outlet structure of the dam was established in April 1959 and has provided a continuous record of the reservoir water level since that time.

Area and capacity curves for Champion Creek Reservoir were computed from a U.S. Geological Survey topographic map published in 1950. The map scale of 1:24,000 and the contour interval of 10 feet are sufficiently detailed to provide accurate area and capacity data which were used to determine reservoir inflows.

Computed Inflow

For this study, inflow to Champion Creek Reservoir was computed from the change in reservoir contents with allowance for estimated evaporation. The procedure was the same as that used for Lake Colorado City except that for Champion Creek there were no municipal diversions. The estimated total inflow for the 12-month period, October 1, 1959 to October 3, 1960, was 4,165 acre-feet, which was received on 20 different occasions, totaling 34 days.

Energy-Budget Instrumentation

Application of the energy-budget method for determination of evaporation from a body of water requires the measurement of (1) solar and atmospheric radiation, (2) temperature and humidity of the air, (3) water-surface temperature, (4) change in energy stored in the reservoir, and (5) volumes and temperatures of inflow and outflow. In addition to these essentials, wind speed is measured to simplify interpretations and adjustments if some of the items of data are missing or questionable, and to permit the application of the alternative mass-transfer computation method.

The following paragraphs indicate the instruments used at Lake Colorado City for each of these classes of measurements. The pyrheliometer and the total hemispherical radiometer were the basic radiation instruments, instead of the Cummings Radiation Integrator that was used during the 1954-55 observations. The previous Lake Colorado City report (Harbeck and others, 1959, p. 12) cited the advantages of the Cummings Radiation Integrator and the reason for its selection as a simpler and less expensive substitute for more complete radiation equipment. Those advantages have largely disappeared since that time, however, because of improvements in techniques for the reading and processing of radiation and humidity data. When the 1959-60 observations were planned, it was considered preferable to use the pyrheliometer and radiometer.

The utilization of the different items of data in computing evaporation is discussed in a later section under the heading of "Energy-Budget Studies," after the instrumentation is described.

Radiation Instruments

Instruments for measuring radiation, air temperature, and humidity were installed near the intake structure of the Texas Electric Service Company powerplant. At this site, which is centrally located on the east shore of Lake Colorado City, power was available to operate an electrical recorder and plant personnel could care for the equipment.

Solar radiation was measured by a pyrheliometer, a standardized instrument that has been used for this purpose for many years. The pyrheliometer is a flat circular plate, about an inch in diameter, mounted horizontally inside a lime glass bulb. The plate is divided into a central white spot, a black ring, and an outer white ring. A 10-junction thermopile measures the temperature difference between the black and the white areas, which is proportional to the radiation flux penetrating the glass bulb.

Total incoming radiation was measured by a flat-plate radiometer (Dunkle and others, 1949) similar to the Gier and Dunkle instrument used successfully for the evaporation investigations at Lake Hefner (U.S. Geological Survey, 1954) and at Lake Mead (Harbeck and others, 1958). The sensing element of the radiometer is a $3\frac{1}{2}$-inch by $4\frac{1}{2}$-inch flat plate mounted horizontally in the air blast from a small blower. The plate is a sandwich with a blackened aluminum upper surface and a polished aluminum lower surface; between is a thermopile measuring the vertical temperature gradient across an insulating sheet forming the center layer of the sandwich. The thermopile voltage is thus proportional to the heat flow down through the plate, which in turn is proportional to the energy received at the blackened surface after deduction of the black-body radiation. To obtain the latter correction, a separate thermocouple is used to measure the temperature of the black surface. The function of the blower blast is to equalize convection losses from the upper and lower sides of the plate.

Psychrometric Equipment

Air temperatures and humidities were obtained from a thermocouple psychrometer (Bellaire and Anderson, 1951) mounted at the radiation station. The instrument was the same as that used successfully for the same purpose during the Lake Hefner and Lake Mead investigations.

Its principle is the same as that of the hand-operated sling psychrometer, but copper-constantan thermocouples replace the mercury thermometers, and the instrument is stationary. A dry thermocouple junction is used for ambient air temperature, while a second thermocouple is kept wet at all times and cooled by evaporation induced by natural air movement, which is concentrated by quide vanes. The voltages produced by the two thermocouples correspond to the wet- and dry-bulb temperatures of ordinary meteorological observations, and standard psychrometric tables or diagrams are used to determine vapor pressure and humidity of the air.

Recording Potentiometer

Thermocouple and thermopile voltages from the psychrometer and the radiometers were amplified and recorded on a multiple-channel recording potentiometer. The recorder has a strip type chart and a print wheel for printing the outputs from eight different circuits in sequence at 1-minute intervals. The printed record on the chart is accurate to about 0.01 mv (millivolt) and the instrument is sensitive to changes of about 0.004 mv. The value of 0.01 mv corresponds closely to 0.25°C for temperature and to 0.01 cal cm^{-2} day^{-1} (calories per square centimeter per day) for radiation, so no appreciable accuracy was lost in the recording process.

The printed points on the chart were arrayed in lines that clearly showed the daily regimen of radiation and of temperature, and indicated the nature of the weather for each day. Brief visual inspection of the potentiometer chart was usually enough to confirm satisfactory data or to spot any abnormality or malfunctioning of the instruments. Readings scaled from the potentiometer chart could be added or averaged to obtain hourly or daily values for radiation and for psychrometer temperatures. The scaling, adding, and averaging process can be done manually, but for the Lake Colorado City analyses most of it was done automatically.

Data Recording on Punched Tape

To provide a record on punched tape suitable for use in a high-speed computer, a digital encoder was added to the potentiometer and geared to the shaft that is positioned by the balancing motor. The angular rotation of the shaft corresponds to the electrical potential in mv of the circuit that is switched into the potentiometer. The purpose of the encoder was to convert the angular shaft position to the corresponding value in a digital code that could be accepted by an electrical computer. A punch and a programming unit were also provided to complete the instrumentation. Whenever the print wheel on the potentiometer was tripped to print a reading on the chart, the corresponding digital value was simultaneously punched on paper tape. After each 8-minute cycle of readings and at the end of each 2-hour and 24-hour period, additional information was punched for identification of the data. The resulting punched paper tape, after inspection and editing to insure its compatibility, was then run through a high-speed digital computer to obtain 2-hourly and daily values of solar radiation, atmospheric radiation, air temperature, wet-bulb temperature, and vapor pressure.

Water-Surface Temperature and Wind

Three instrument rafts constructed of oil drums were anchored near the upper and lower ends and near the center of Lake Colorado City (Figure 1), and a fourth raft was placed on Champion Creek Reservoir. A recording thermometer was mounted at the center of each raft so that its bulb was about half an inch under the water surface, and an anemometer was mounted at one corner with the rotating cups at a height of two meters above the water. The arrangement, although not used for the earlier Lake Hefner and Lake Mead studies where more detailed observations were made, has since been developed at other locations and and has proved very satisfactory.

The rafts were visited by boat at weekly intervals to check the instruments and to change the 7-day circular charts on the temperature recorders. An additional pen was mounted on each recorder and connected to the anemometer so that the passage of every 10 miles of wind was marked by a pip on the margin of the temperature chart.

Reservoir Temperature Profiles

For determining the average temperature of the reservoir contents, 26 well-distributed measurement points were located in Lake Colorado City, and 24 points in Champion Creek Reservoir. Thermal surveys of the reservoirs were made at intervals ranging from 1 week during periods of high evaporation in the summer to 1 month during the winter.

For each thermal survey, a temperature profile from the surface to the bottom of the reservoir was measured at each point with a Whitney underwater thermometer, which is a portable electrical instrument powered by a small battery. The sensing element is a small thermistor, which responds rapidly to changes in temperature, attached to the end of a long insulated cable. The underwater sensing element forms one arm of a Wheatstone bridge. Water temperature is indicated by a microammeter in a circuit adjusted so the meter reads directly in degrees Centigrade. The depth of water is measured by the length of line from the sensing element to the water surface. Calibration is easily checked by placing the sensing element just under water and comparing the Whitney reading with that of a mercury thermometer. Such checks have always agreed within 0.1°C, which is adequate for evaporation computations.

The Whitney thermometer, which was also used in the 1954-55 observations at Lake Colorado City, is not a recording instrument, but it is portable and convenient to use. For field use, it is considered an improvement over the temperature profile recorder (TPR) (Anderson and Burke, 1951) which was used for the Lake Hefner and the Lake Mead studies. The TPR can provide more detailed temperature information, but it is more elaborate and expensive. It requires a semipermanent installation in a boat, and more computation time to extract the desired energy storage data.

Temperatures of Circulating Water, Outflow, and Inflow

Water Circulated Through Powerplant

Recording thermometers were already installed in the powerplant at both the inlets and outlets of the three channels that were used for circulation of cooling water. The temperatures indicated by these instruments were checked with mercury thermometers at intervals of about 1 week, and adjustments were made when necessary. The total heat added by the powerplant was then computed by multiplying the temperature rise in each of the three channels by the flow in the corresponding channel.

Reservoir Outflow

The temperature of the water pumped to the city of Colorado City for municipal use was measured at the pumphouse as it was withdrawn from Lake Colorado City. Thermometers were also provided in the pumphouse at Champion Creek Dam to measure the temperature of water transferred from Champion Creek Reservoir to Lake Colorado City. During the 1959-60 observation period, however, this facility was used for only a few hours when the pumping installation was tested.

Reservoir Inflow

For both Lake Colorado City and Champion Creek Reservoir, the inflows were a combination of the rain falling directly on the water surface plus surface flow from the tributary creek channels, which occurred for only a few short periods. Rainfall temperatures were considered to be the same as the wet-bulb temperatures measured at the radiation station at the same time. Air temperatures at San Angelo were used as the basis for estimating the temperatures of surface inflow.

Mass-Transfer Instrumentation

No additional mass-transfer instrumentation was required at Lake Colorado City or at Champion Creek Reservoir. The instruments previously listed under the "energy-budget" heading also provided the information needed to apply the mass-transfer method.

Air temperature and humidity data for both reservoirs were taken from the radiation station at the powerplant. Water-surface temperature and wind data were obtained from the three instrument rafts on Lake Colorado City and the single raft on Champion Creek Reservoir.

Performance of Instruments

Design of Instrumentation

Previous experience at this and other sites was of great value in planning the instrumentation for the 1959-60 observations at Lake Colorado City. The instruments initially provided and installed were adequate for measuring and recording radiation, temperatures, wind, and water amounts and flows. No redesign or revision of the instrument setup was needed during the observation period.

New Features

There have been several developments in instrumentation since the 1954-55 evaporation measurements at Lake Colorado City (Harbeck and others, 1959), and the earlier observations at Lake Mead (Harbeck and others, 1958) and at Lake Hefner (U.S. Geological Survey, 1954). The same physical factors are still being measured, but changes in some details have reduced interruptions of records and have simplified both the field observations and the office processing of data. The principal improvements of this kind which were utilized during the 1959-60 observations at Lake Colorado City are indicated in the following paragraphs.

Wind and Water-Surface Temperatures

A standardized raft has been developed to carry instruments for measuring these factors. A recording thermometer with a 7-day circular chart provides a satisfactory record of water-surface temperatures. An extra marginal pen can be mounted on the thermometer and arranged so it is actuated by the anemometer. The same chart then provides a record of both water-surface temperature and wind movement, in a form convenient for taking off these data.

The instrument raft is a self-contained unit that can be anchored at the preferred mid-lake location, or readily moved to some more accessible site if desired. The recording feature provides more complete information, and obviates the need for daily visits to make manual readings of the instruments.

Centralized Recording of Radiation and Psychrometric Data

All radiation and psychrometric data were recorded on the same potentiometer chart, rather than on two or more recorders as in earlier practice. This had the advantage of not only reducing the number of instruments and of records to be handled, but also of facilitating both field inspections and data processing. Portrayal of all these items of data on the same chart permitted a better interpretation of the situation, so that adjustments or corrections could then be made more intelligently.

Elimination of Ice-Bath Reference

As used for these observations, a pair of thermocouples is needed to measure a single temperature. One thermocouple junction is placed at the point where temperature is to be determined, and the other is placed at a point where temperature is constant. The difference in the voltages generated by the two thermocouples is then a measure of the difference in their temperatures.

It has been customary to use an ice bath for the reference thermocouple to produce a temperature of 0°C. For satisfactory results, ice should frequently be added to the bath, even when it is kept in a vacuum flask, and corresponding amounts of water withdrawn to keep the thermocouple just submerged. This has not always been properly done under field conditions, and data have sometimes been lost as a result.

As an alternative, an electric circuit has been developed which eliminates the need for an ice-bath reference junction. This improvement, which was used during the 1959-60 observations at Lake Colorado City, eliminated a troublesome item of field maintenance and improved the overall accuracy and reliability of the system.

Data Processing

The punched tape and the corresponding potentiometer chart were sent to the U.S. Geological Survey's Denver office for inspection and comparison, and the tape fed through a digital computer for determination of the desired average daily values for each factor. This automatic computation process eliminated the need for manual transcription and averaging of the readings recorded on the potentiometer charts, and greatly reduced the possibilities for error.

Inspection and Maintenance

The radiation station was inspected almost every day by the powerplant operators, whose experience with other electrical equipment enabled them to understand the functioning of these instruments. They were successful in keeping the recording potentiometer in continuous operation, and were faithful in filling and occasionally replacing the psychrometer reservoir, cleaning the wet-bulb wick, and making minor adjustments when needed. They also made a complete weekly check of the readings of all the radiation station instruments, including the encoding and punching equipment, and reported the results to the Denver office.

The rafts on Lake Colorado City and on Champion Creek Reservoir were visited each week by U.S. Geological Survey personnel from a local office at San Angelo, who made check readings, changed charts, and cleaned and adjusted the instruments as necessary. On the same weekly trips they also inspected the instruments at the radiation station, checked the powerplant thermometers used for measuring inflow and outflow temperatures of the cooling water, and usually made thermal surveys of one or both reservoirs.

Usable Data

For a relatively complicated hydrologic investigation such as this, it is difficult to avoid occasional loss of records because of instrument malfunction and bad weather. At Lake Colorado City, however, there was essentially no such loss of data. There were interruptions when instruments were being cleaned, adjusted, or replaced, but readings for such brief periods could readily be estimated. There were periods when the wet-bulb psychrometer readings seemed questionable, but comparisons with other available weather data did not point to any definite errors. There were other times when strong winds prevented visiting the rafts on the scheduled dates, but the recording instruments continued to function and the data were preserved.

The encoding and punching equipment was the only part of the instrumentation whose functioning was not fully reliable. This was a new and complicated feature which had not been thoroughly tested under field conditions, and it broke down several times. The digital computer, however, was able to use the punched tape and to compute totals and averages for 312 of the 422 days when the radiation station was operated. For the other 110 days, or 26 percent of the total time, the punched tape was faulty or missing, and the corresponding values had to be read manually from the potentiometer chart.

This good record of instrument reliability at Lake Colorado City can be attributed to two principal factors: (a) the gradual improvement in instrumentation that has been made since earlier studies, and (b) better maintenance of the instruments in the field.

ENERGY-BUDGET STUDIES

Theory

The following brief description of energy-budget theory is taken from the earlier Lake Colorado City report (Harbeck, Koberg, and Hughes, 1959, p. 15):

"The energy budget per unit area of a reservoir per unit time may be expressed as follows:

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_\nu \qquad (1)$$

in which Q_s = solar radiation incident to the water surface
Q_r = reflected solar radiation
Q_a = incoming long-wave radiation from the atmosphere
Q_{ar} = reflected long-wave radiation
Q_{bs} = long-wave radiation emitted by the body of water
Q_v = net energy advected into the body of water other than that contained in evaporated water
Q_e = energy utilized by evaporation
Q_h = energy conducted from the body of water as sensible heat
Q_w = energy advected by the evaporated water
Q_ν = increase in energy stored in the body of water.

"Conduction of energy through the bottom, heating due to chemical and biological processes, and transformation of kinetic energy into thermal energy are neglected because of their small magnitude. For a thorough discussion of each term in equation 1, the reader is referred to the report by E. R. Anderson (1954, p. 74-110).

"For computational purposes, use is made of the following relations:

$$Q_e = \rho_e\ E\ L;\quad Q_h = R\ Q_e;\ \text{and}\ Q_w = \rho_e\ c\ E(T_e - T_b) \qquad (2,3,4)$$

in which E = volume of evaporated water
ρ_e = density of evaporated water
L = latent heat of vaporization
R = the Bowen ratio
c = specific heat of water
T_e = temperature of evaporated water
T_b = arbitrary base temperature.

"Substituting the above in equation 1 results in the following:

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_\nu + Q_v}{\rho e[L(1+R) + c(T_e - T_b)]} \qquad (5)$$

"The value of T_b, the base temperature, is immaterial provided that same base temperature is used in computing Q_ν and Q_v, and provided further that a balanced water budget is used in making the computations."

An explanation of the method used in determining each of the quantities in the energy-budget equation is not repeated herein. The principal difference between the 1954-55 and 1959-60 studies is that in the earlier study, the Cummings Radiation Integrator (CRI) was used to measure the sum of $Q_s - Q_r + Q_a - Q_{ar}$, whereas in the second study a pyrheliometer and total hemispherical radiometer were used to measure Q_s and Q_a, and Q_r and Q_{ar} were computed.

It was assumed that net incoming radiation received at Lake Colorado City was the same as that received at Champion Creek Reservoir a few miles away. Koberg (Harbeck and others, 1958, p. 26, 27) found no significant areal variation in radiation over much greater distances at Lake Mead. While this assumption may be untenable for short periods of time because of transient cloud effects, for periods of a week or more it appears reasonable.

Results

Computed evaporation from Lake Colorado City and from Champion Creek Reservoir is given in Tables 1 and 2.

Evaporation from both reservoirs on a calendar month basis was also computed. As no attempt was made to schedule thermal surveys at the end of each month, it was necessary to apportion evaporation for some energy-budget periods extending from one month into the following month. This was done on the basis of mass-transfer theory (which will be discussed later). It is assumed that evaporation is proportional to the product of the wind speed times the vapor pressure difference. Data are available to permit computation of this product on a daily basis, so that energy-budget evaporation for any period can be apportioned on a daily basis if desired. Calendar month evaporation from both reservoirs is shown in Figure 6, and in Table 3.

As might be expected, evaporation from Lake Colorado City is greater than from Champion Creek Reservoir, primarily because of the addition of heat from the powerplant. Using a technique to be described in a subsequent section, it can be shown that evaporation from Lake Colorado City for the period December 1, 1959 to September 30, 1960, would have been about 14 percent less if no heat had been added by the plant. Thus, the measured evaporation of 86.60 inches would have been reduced to 74.5 inches, which is in excellent agreement with the figure of 73.0 inches for the 10-month period for Champion Creek Reservoir, to which no heat was added.

Table 1.--Evaporation from Lake Colorado City as computed for energy-budget periods, August 14, 1959 to October 3, 1960

Period		Number of days in period	Evaporation	
From--	To--		Inches	Acre-feet
Aug. 14, 1959--	Aug. 21, 1959--	7	2.85	281
Aug. 21--------	Aug. 28--------	7	2.28	223
Aug. 28--------	Sept. 4--------	7	2.69	260
Sept. 4--------	Sept. 11--------	7	3.08	294
Sept. 11--------	Sept. 18--------	7	2.61	246
Sept. 18--------	Oct. 2--------	14	4.73	444
Oct. 2--------	Oct. 16--------	14	2.83	282
Oct. 16--------	Nov. 13--------	28	6.00	600
Nov. 13--------	Nov. 27--------	14	2.52	251
Nov. 27--------	Dec. 11--------	14	1.42	140
Dec. 11--------	Dec. 23--------	12	1.00	99
Dec. 23--------	Jan. 8, 1960--	16	1.63	161
Jan. 8, 1960--	Jan. 22--------	14	1.44	142
Jan. 22--------	Feb. 5--------	14	1.35	132
Feb. 5--------	Mar. 7--------	31	4.62	447
Mar. 7--------	Mar. 18--------	11	1.93	185
Mar. 18--------	Apr. 1--------	14	2.91	276
Apr. 1--------	Apr. 15--------	14	3.33	313
Apr. 15--------	Apr. 29--------	14	4.56	421
Apr. 29--------	May 13--------	14	5.27	480
May 13--------	May 27--------	14	5.27	473
May 27--------	June 10--------	14	5.30	470
June 10--------	June 17--------	7	3.51	308

(Continued on next page)

Table 1.--Evaporation from Lake Colorado City as computed for energy-budget periods, August 14, 1959 to October 3, 1960--Continued

Period		Number of days in period	Evaporation	
From--	To--		Inches	Acre-feet
June 17, 1960	June 24, 1960	7	3.38	293
June 24--------	July 1--------	7	3.86	332
July 1--------	July 8--------	7	2.94	255
July 8--------	July 15--------	7	2.46	223
July 15--------	July 22--------	7	2.39	216
July 22--------	July 29--------	7	2.43	218
July 29--------	Aug. 5--------	7	3.29	294
Aug. 5--------	Aug. 12--------	7	3.03	267
Aug. 12--------	Aug. 19--------	7	2.62	229
Aug. 19--------	Aug. 26--------	7	2.53	221
Aug. 26--------	Sept. 2--------	7	2.86	248
Sept. 2--------	Sept. 9--------	7	3.48	301
Sept. 9--------	Sept. 16--------	7	2.70	232
Sept. 16--------	Sept. 23--------	7	3.00	255
Sept. 23--------	Oct. 3--------	10	3.40	287

Table 2.--Evaporation from Champion Creek Reservoir as computed for energy-budget periods, November 16, 1959 to October 3, 1960

Period		Number of days in period	Evaporation	
From--	To--		Inches	Acre-feet
Nov. 16, 1959--	Dec. 14, 1959--	28	2.56	53
Dec. 14--------	Jan. 13, 1960--	30	1.55	32
Jan. 13, 1960--	Feb. 8--------	26	2.06	43
Feb. 8--------	Mar. 7--------	28	3.14	65
Mar. 7--------	Mar. 24--------	17	2.45	50
Mar. 24--------	Apr. 14--------	21	4.17	85
Apr. 14--------	May 4--------	20	5.55	111
May 4--------	May 25--------	21	7.23	141
May 25--------	June 15--------	21	7.85	166
June 15--------	July 11--------	26	10.91	245
July 11--------	Aug. 2--------	22	7.08	154
Aug. 2--------	Aug. 23--------	21	7.21	167
Aug. 23--------	Sept. 14--------	22	8.65	213
Sept. 14--------	Oct. 3--------	19	4.72	114

Table 3.--Monthly evaporation from Lake Colorado City, September 1, 1959 to September 30, 1960, and from Champion Creek Reservoir, December 1, 1959 to September 30, 1960

Month	Lake Colorado City		Champion Creek Reservoir	
	(inches)	(acre-feet)	(inches)	(acre-feet)
1959				
September------------------	11.61	1,101	--	--
October--------------------	6.90	686	--	--
November-------------------	5.10	509	--	--
December-------------------	2.85	283	2.05	42
1960				
January--------------------	3.19	314	2.02	42
February-------------------	4.59	445	3.37	70
March----------------------	5.01	478	3.98	80
April----------------------	8.73	812	7.56	152
May------------------------	11.14	1,005	10.63	212
June-----------------------	14.30	1,249	11.95	261
July-----------------------	11.81	1,052	10.73	237
August---------------------	12.42	1,090	10.73	251
September------------------	12.56	1,075	9.98	244
Total, last 10 months------	86.60	7,803	72.95	1,591
Total, water year 1959-60--	98.60	8,998	--	--
Total, 13-month period-----	110.21	10,099	--	--

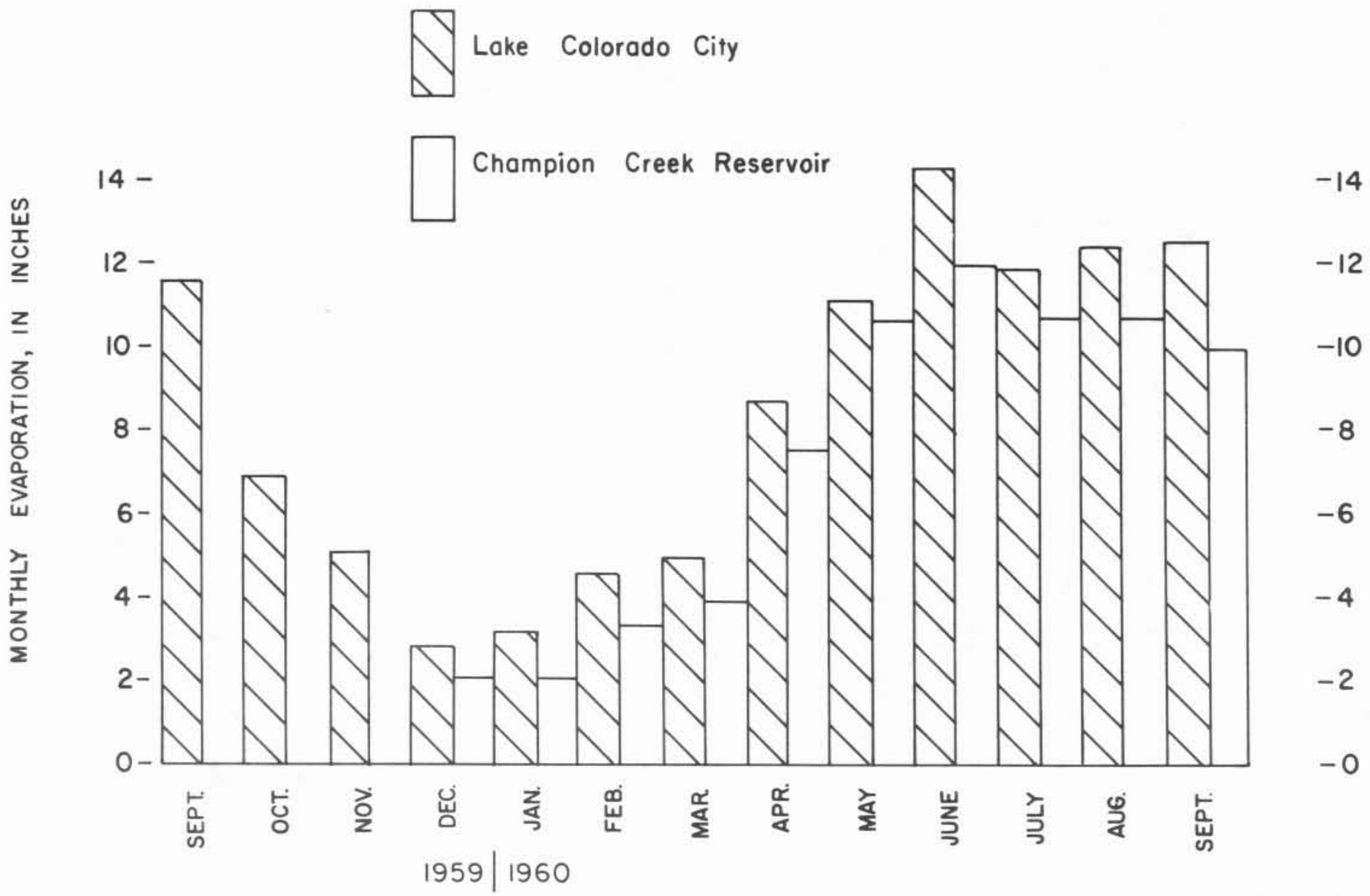


Figure 6

Monthly Evaporation from Lake Colorado City and Champion Creek Reservoir

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EFFECT ON EVAPORATION OF ADDING HEAT TO THE RESERVOIR

Theory

At many thermal-electric powerplants water is withdrawn from a stream or reservoir, used for cooling, and returned to the source practically undiminished in quantity, but at a higher temperature. Evaporation from the stream or reservoir is thereby increased. Where water supplies are ample, the increased evaporation is usually of little consequence, but it may be of considerable importance in arid and semiarid regions.

Evaporation is a surface phenomenon, and the rate of evaporation is dependent to a large extent upon the temperature of the water surface. A description of the theory utilized in computing the increase in evaporation and the temperature rise resulting from the addition of heat has been presented (Harbeck, Koberg, and Hughes, 1959, p. 24-26) and is not repeated here in detail. It is assumed that the addition of heat by the powerplant will have no effect on certain items in the energy budget for the reservoir (see p. 19), as follows: (1) The net supply of energy received as solar and atmospheric radiation, (2) the net energy being brought into the reservoir in natural inflow and outflow, and (3) the natural change in energy storage in the reservoir after the reservoir and powerplant are in equilibrium. It is also assumed that the addition of heat by the plant will not affect the wind speed over the lake nor the humidity of the air approaching the lake, which are two basic items in the mass-transfer theory of evaporation.

The addition of heat, therefore, causes an increase in evaporation and an increase in surface temperature, both of which are unknown but can be computed. The principle is simple, for there are two unknowns and two equations, one based upon energy-budget theory and one upon mass-transfer theory. The energy-budget equation is

$$\triangle Q_{bs} + \triangle Q_e + \triangle Q_h + \triangle Q_w = Q_c \qquad (6)$$

in which $\triangle$ = increment in an individual energy-budget item resulting from the addition of heat

Q_{bs} = long-wave radiation emitted by the body of water

Q_e = energy utilized by evaporation

Q_h = energy conducted from the body of water to the atmosphere as sensible heat

Q_w = energy carried away by the evaporated water

Q_c = heat added by the powerplant.

Details of computing each of the above items were given in the earlier Lake Colorado City report (Harbeck, Koberg, and Hughes, 1959, p. 25, 26). The mass-transfer equation is

$$\frac{E'}{E} = \frac{e_o' - e_a}{e_o - e_a} \qquad (7)$$

in which E = average daily evaporation in $g\ cm^{-2} day^{-1}$ ($\approx cm\ day^{-1}$)

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

e_a = vapor pressure of the air in mb, determined from wet and dry-bulb temperatures.

The unprimed symbols refer to the lake in its natural condition and the primed symbols to the lake after heat has been added.

A direct solution of the two equations is impractical because some of the mathematical relationships involved are complicated. However, solution by successive approximation is simple.

Results

Actual evaporation from Lake Colorado City during the 364-day period, August 14, 1959 to August 12, 1960, was 9,026 acre-feet (from Table 1). Using 364-day averages of the various parameters in equations 1-5, the ratio E'/E was found to be 1.140 and the increase in water-surface temperature was 1.0°C. Expressed in depth units, actual evaporation from Lake Colorado City was 96.9 inches; if no heat had been added by the plant, evaporation would have been 85.0 inches, which is exactly the same as the natural evaporation computed in 1954-55.[2] It should be noted, moreover, that instrumentation for measuring radiation was completely different for the two studies. In 1954-55, the Cummings Radiation Integrator (CRI) was used to measure net incoming radiation. In 1959-60, a pyrheliometer was used to measure solar radiation and a total hemispherical radiometer to measure atmospheric radiation.

In 1954-55, the heat added by the plant during a period of 1 year was 59 $cal\ cm^{-2} day^{-1}$ (equivalent to 1.30 billion kilowatthours per year). The heat added was disposed of as follows: 58 percent was utilized to increase evaporation from the reservoir, 25 percent was conducted to the air above the reservoir, 3 percent was carried away by the evaporated water, and 14 percent was radiated to the atmosphere. Average water surface temperature during the period was 18.8°C (65.8°F), and the computations showed that if no heat had been added by the plant, the water-surface temperature would have been 18.0°C (64.4°F).

During the 364-day period, August 14, 1959 to August 12, 1960, the heat added by the plant was 84 $cal\ cm^{-2} day^{-1}$ (equivalent to 1.64 billion kilowatthours per year). The heat added was disposed of as follows: 56 percent was utilized to increase evaporation from the reservoir, 29 percent was conducted to the air above the reservoir, 2 percent was carried away by the evaporated water, and 13 percent was radiated to the atmosphere. Thus it is evident that the relative amounts of heat disposed of by means of each of the above four processes was not greatly affected by a substantial increase in the plant load. It is not safe to assume, however, that these percentages will remain constant regardless of plant load, for the relationships involved are not linear.

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[2] Such close agreement is doubtless coincidental, but it should be remembered that year-to-year variations in evaporation are quite small in comparison with annual variation in other climatological factors such as rainfall and runoff.

In the earlier report (Harbeck, Koberg, and Hughes, 1959, fig. 21), it was postulated that within limits, forced evaporation from Lake Colorado City was directly proportional to the plant load, as follows:

$$E_f = 710\ Q_c \qquad (8)$$

in which E_f = forced evaporation, in acre-feet
Q_c = heat added by powerplant, in billions of kilowatthours per year.

The heat added by the plant during the 364-day period used previously was 1.64 billion kwhr. From equations 6 and 7, the forced evaporation should be 1,164 acre-feet. Measured evaporation was 9,026 acre-feet and the computed ratio E'/E was 1.140, so that forced evaporation, E_f, was therefore 1,108 acre-feet. Thus, the equation for forced evaporation published in the earlier report forecast the forced evaporation resulting from a greater plant load in 1959-60 within 5 percent.

FORECASTING INTAKE TEMPERATURES

Of particular interest to the powerplant engineer is the problem of estimating maximum intake water temperatures to be expected during critical periods in summer. Above-normal water temperatures may result from artificial or natural causes. The former may result from an increase in plant load, the latter from hot weather. Summer peak loads result from operation of air-conditioning equipment, and therefore come during periods of hottest weather, a time when reservoir temperatures are highest and plant efficiency is reduced.

It is possible to estimate with reasonable accuracy the rise in water-surface temperature resulting from an increase in plant load. (The relation between water-surface temperature and average lake temperature will be discussed later.) Computations of the rise in water-surface temperature resulting from the addition of heat by the plant were made for each period between thermal surveys, utilizing both the 1954-55 and 1959-60 data. Because of possible carryover effects from one period to another, it was considered preferable to choose for analysis one long hot-weather period in a summer rather than several short periods. Accordingly, a 43-day period, July 7 to August 19, 1955, and a 35-day period, July 8 to August 12, 1960, were selected for study.

The results are shown in Figure 7. For the two selected periods, it appears that the rise in water-surface temperature at Lake Colorado City is directly proportional to the amount of heat added. A rise of 1°C results from the addition of 5 million kilowatthours per day. Data are lacking to indicate the upper limit of safe extrapolation, but it appears that the probable error, even at a rate of say 10 million kilowatthours per day, would be 0.5°C or less. It must be emphasized that Figure 7 applies only to summer periods at Lake Colorado City, Texas, at times when reservoir contents are approximately the same as in 1954-55 and 1959-60.

It was found (Harbeck, Koberg, and Hughes, 1959, p. 30-32) that in summer, average water temperatures in the upper and lower basins of Lake Colorado City did not differ significantly. It was also found that intake temperature, or withdrawal temperature, differed from average lake temperature by less than 0.5°C. Although on an annual basis, water-surface temperatures and average

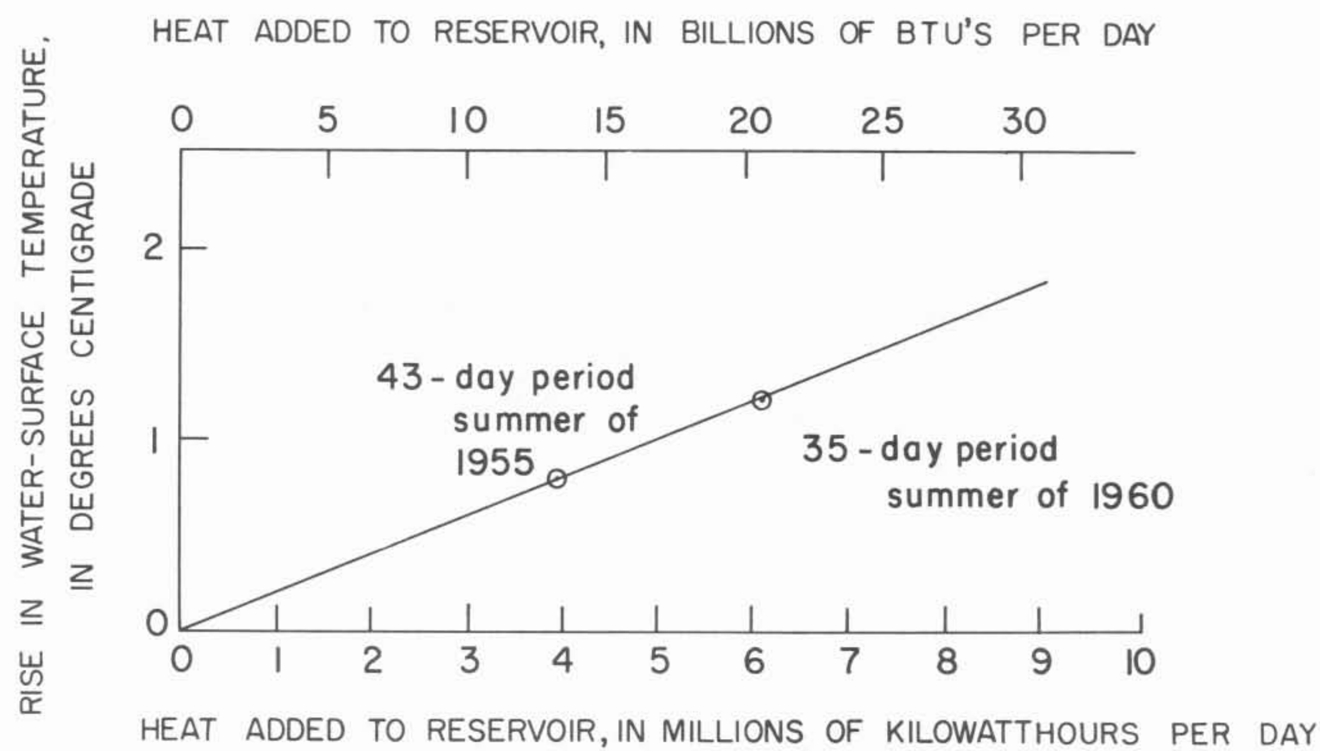

Figure 7

Relation Between Heat Added to Reservoir and Water-Surface Temperature Rise for Selected Summer Periods at Lake Colorado City

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water temperatures in Lake Colorado City were about the same, it does not follow that this is necessarily true at all seasons. Certainly it is not necessarily true of all reservoirs.

The relation between water-surface temperature and average water temperature for four water bodies of varying size is shown in Figure 8. The smallest is a Cummings Radiation Integrator (CRI), which is merely an insulated pan, 4 feet in diameter, containing water to a depth of 20 inches. The next largest is Lake Colorado City, which averaged about 17 feet in depth. Next in size is Lake Hefner, with an average depth of 27 feet. These three bodies of water are well mixed, and the change in temperature with depth is relatively small. The relation between water-surface temperature and average water temperature is well defined; few points depart more than a degree or two from the line through the mean, which shows that the average temperature is approximately 0.98 times the water-surface temperature.

The danger in assuming that this relation applies to a large stratified reservoir is illustrated by the data for Lake Mead, which are also plotted on Figure 8. Average water temperature lags markedly behind water-surface temperature as might be expected in a lake of this size. Thus the assumption that the reservoir is approximately isothermal in summer, and therefore that plant intake temperature will be approximately equal to water-surface temperature, may be reasonable for some reservoirs, but not for deep, stratified reservoirs.

For operational reasons, it would be exceedingly desirable to be able to forecast plant intake temperatures for various plant loads, particularly during hot-weather periods in summer. It is possible to adjust the observed plant intake temperature for the effect of heat added by the plant. The average plant intake temperature during say a 2-week period is correlated significantly with both air temperature during that same period and with the change in air temperature from a similar preceding period. The correlation between intake temperature (which is almost exactly the same as both surface temperature and average reservoir temperature at Lake Colorado City) and air temperature is not surprising, as air temperature is a good indicator of total incoming radiation. However, for a given air temperature, intake water temperature is generally higher than usual if the preceding period was warm and lower than usual if the preceding period was cool. The relation appears physically reasonable and the correlation is statistically significant. However, the relationship is so poorly defined that the possible errors in estimating intake temperatures to be expected are unduly large, and would not be useful in planning plant operations.

Basically the problem is one of weather forecasting. Long-range forecasts (i.e., for a week or two in advance) are not yet sufficiently accurate or specific. If reasonably accurate forecasts of wind speed and direction, humidity, and type and amount of cloud cover were available, it would be possible to utilize both mass-transfer and energy-budget theory to predict the proportion of any preselected heat load that would be disposed of by the processes of evaporation, conduction, and back radiation, and the proportion that would go into storage in the reservoir. The energy stored in a reservoir is, of course, directly proportional to the average temperature of the reservoir and thus to the temperature of the water taken into the plant, which is what the plant operator wants to know in advance, if possible.

Forecasting a week or two in advance the expected temperature of water to be withdrawn for cooling purposes from a lake or reservoir thus depends on

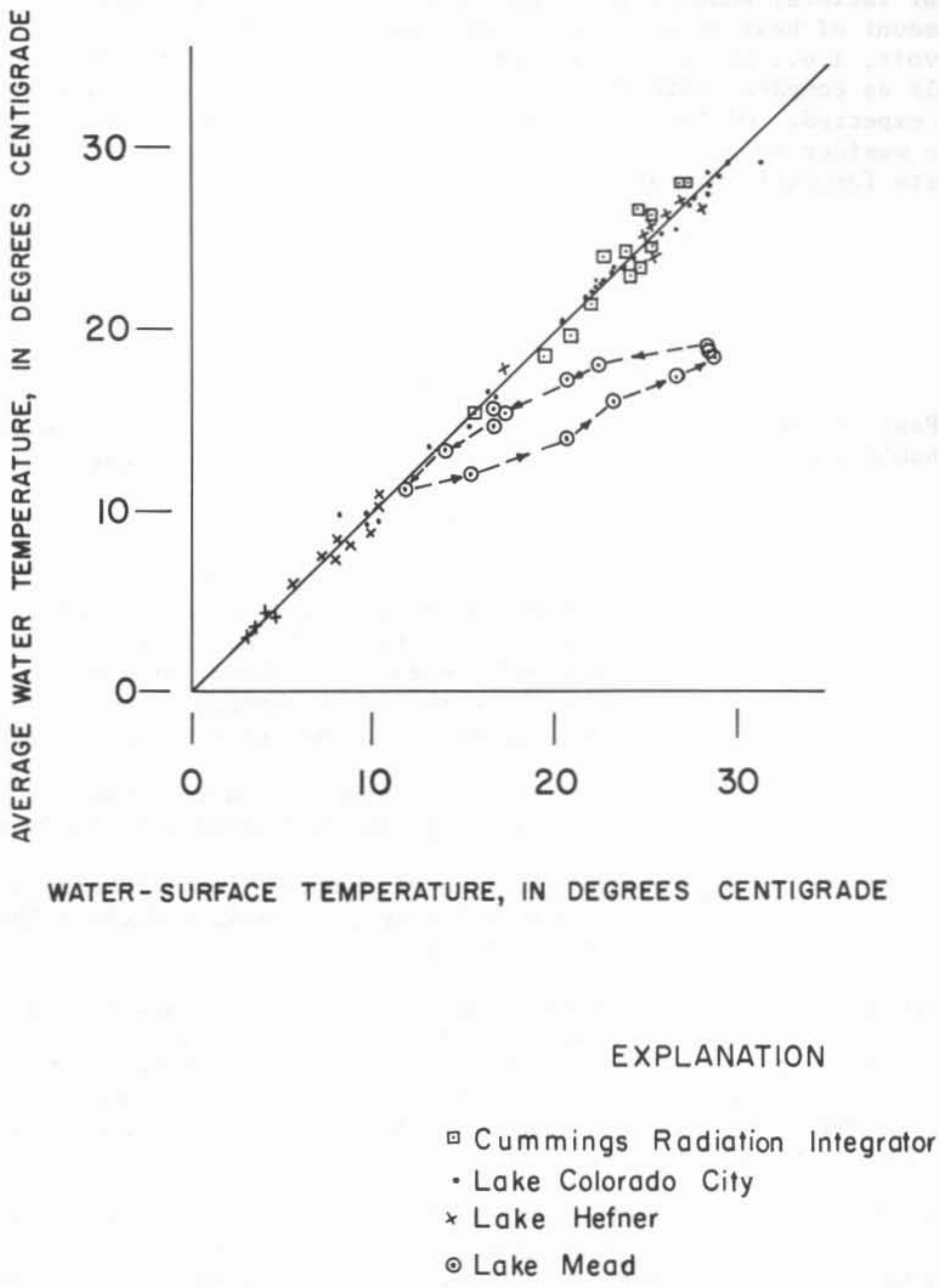

Figure 8

Relation Between Average Water Temperature at Time of Thermal Survey and Average Water-Surface Temperature on that Day

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several factors, some of which can be calculated or estimated, as follows: (1) The amount of heat to be added by the plant, (2) the thermal structure of the reservoir, i.e., whether stratified or not, (3) the volume and depth of withdrawals as compared with the volume of the reservoir, and (4) weather conditions to be expected. Of these, the most important and least known, unfortunately, is the weather to be expected, at least in the detail required for reasonably accurate forecasts of intake water temperatures.

MASS-TRANSFER STUDIES

Theory

Past studies have shown that reservoir evaporation can be estimated with reasonable accuracy on a daily basis using the following equation:

$$E = Nu(e_o - e_a) \qquad (9)$$

in which E = evaporation, in inches per day;
N = a coefficient of proportionality, hereafter called the mass-transfer coefficient;
u = wind speed, in miles per hour, at some height above the water surface; a numerical subscript, if used, indicates the height in meters;
e_o = saturation vapor pressure in millibars, corresponding to the temperature of the water surface;
e_a = vapor pressure of the air, in millibars; a numerical subscript, if used, indicates the height in meters.

The coefficient N for a reservoir can be determined in several ways. If evaporation can be determined volumetrically, in other words, by use of an inflow, outflow, and change-in-storage water budget, N can be computed by dividing the water-budget evaporation by the product $u(e_o - e_a)$ during a calibration period. The water budget can then be discontinued and evaporation computed thenceforth using the coefficient N previously determined.

Another way of determining N involves the separation of the measured change-in-stage into its two components of seepage and evaporation. A complete description of the technique is beyond the scope of this report, but has been given by Harbeck (1962). A basic requirement of this method is that for selected periods surface inflow and outflow must be negligible, or must be measured with sufficient accuracy so that the observed change in stage can be corrected for inflow and outflow with little error.

A third way of determining N, and the one used in this report, is to determine the relation for selected periods between energy-budget evaporation and the product $u_2(e_o - e_a)$. The slope of the line is, of course, the mass-transfer coefficient N.

Results

The results for Lake Colorado City and Champion Creek Reservoir are shown in Figure 9. The periods used were those between thermal surveys, and in each case the slope of the line was determined by dividing the average daily evaporation for the entire period of study by the average daily product $u_2(e_o - e_a)$.

"Least-squares" lines could have been fitted to the data shown in Figure 9. It is obvious, however, that the Y-intercept of any such lines would not be significantly different from zero. The best-fitting line was therefore put through the origin and the weighted mean of both variables.

As a check upon the reasonableness of the values of the coefficient N for the two reservoirs, they have been compared (see Figure 10) with values of N for other reservoirs ranging in size from 1 to 29,000 acres as given by Harbeck (1962, fig. 31). N for Champion Creek Reservoir plots very close to the general curve; N for Lake Colorado City is somewhat larger than for most reservoirs of its size. The latter is to be expected, because Lake Colorado City is essentially two basins separated by a constriction, and the wind speed measured in the center of either basin is less than would be observed over a single lake having the same surface area as the two basins together. Thus, if evaporation is to be the same, which is supported by energy-budget theory, N for a small lake would necessarily be greater than for a large lake.

The determination of N for both Lake Colorado City and Champion Creek Reservoir will permit evaporation to be computed on a continuing basis using equation 9. The data required (wind speed, water-surface temperature, and humidity) are not particularly difficult to obtain if it is considered desirable to continue obtaining records of evaporation.

SUMMARY AND CONCLUSIONS

Evaporation from Lake Colorado City was measured using the energy-budget method in 1959-60. For a 364-day period, evaporation was 96.9 inches; if no heat had been added by the plant, evaporation would have been 85.0 inches. Natural evaporation during a previous study in 1954-55 was also found to be 85.0 inches, but such close agreement is believed mostly coincidence.

Evaporation from Champion Creek Reservoir, to which no heat was added by the powerplant, was 73.0 inches for a 10-month period in 1959-60. Computed natural evaporation from Lake Colorado City for the same 10-month period was 74.5 inches, indicating that the technique of computing the amount of forced evaporation gives reliable results.

The report on the 1954-55 study gave a formula for computing forced evaporation from Lake Colorado City with an increased plant load. The results obtained using this formula were within 5 percent of the results given in the preceding paragraph.

The problem of forecasting intake temperatures during hot, summer periods was studied. The results were not satisfactory, primarily because more detailed and accurate long-term weather forecasts are needed than can be provided at this time.

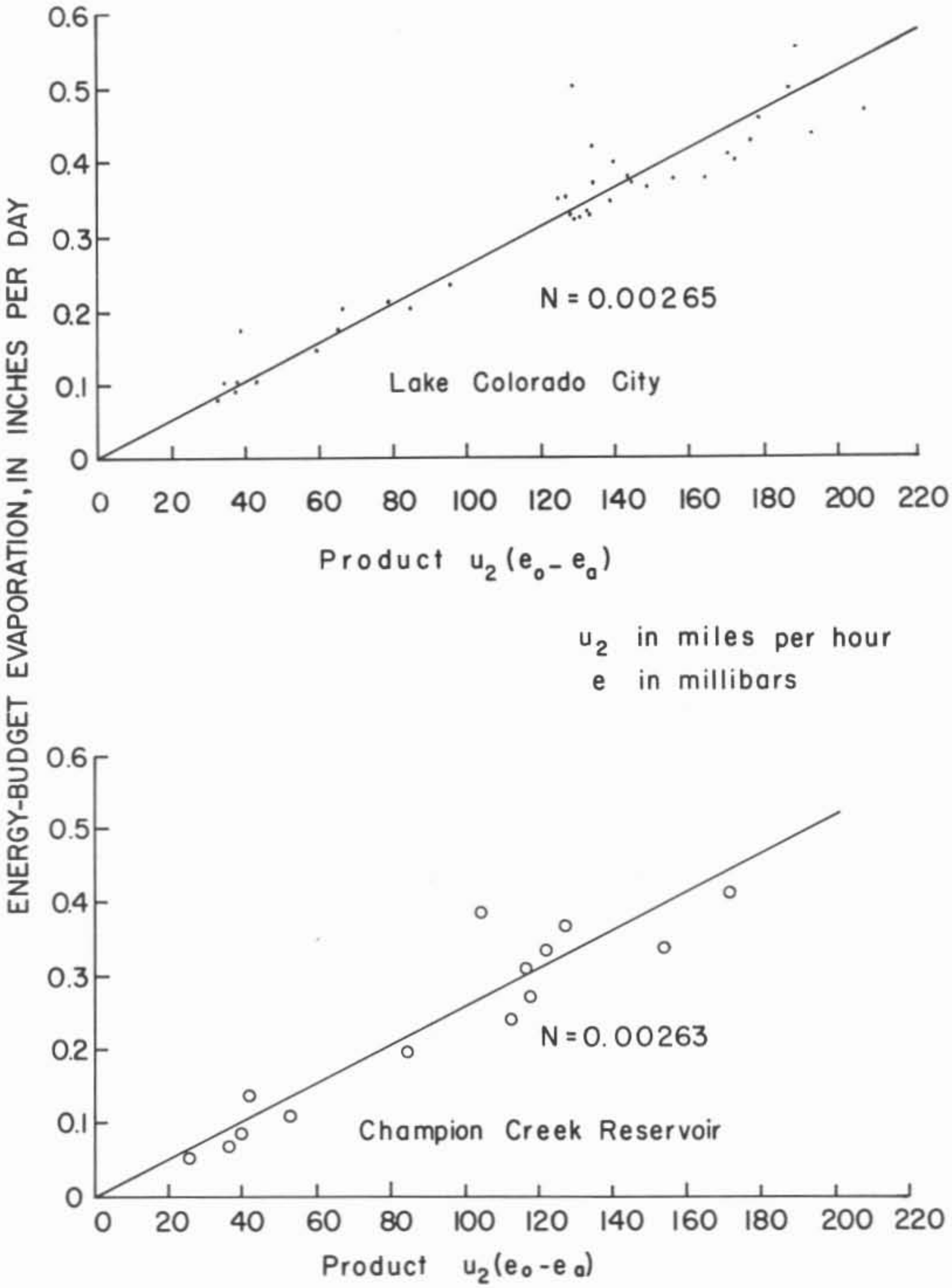

Figure 9

Relations Between Energy-Budget Evaporation and Product $u_2 (e_o - e_a)$

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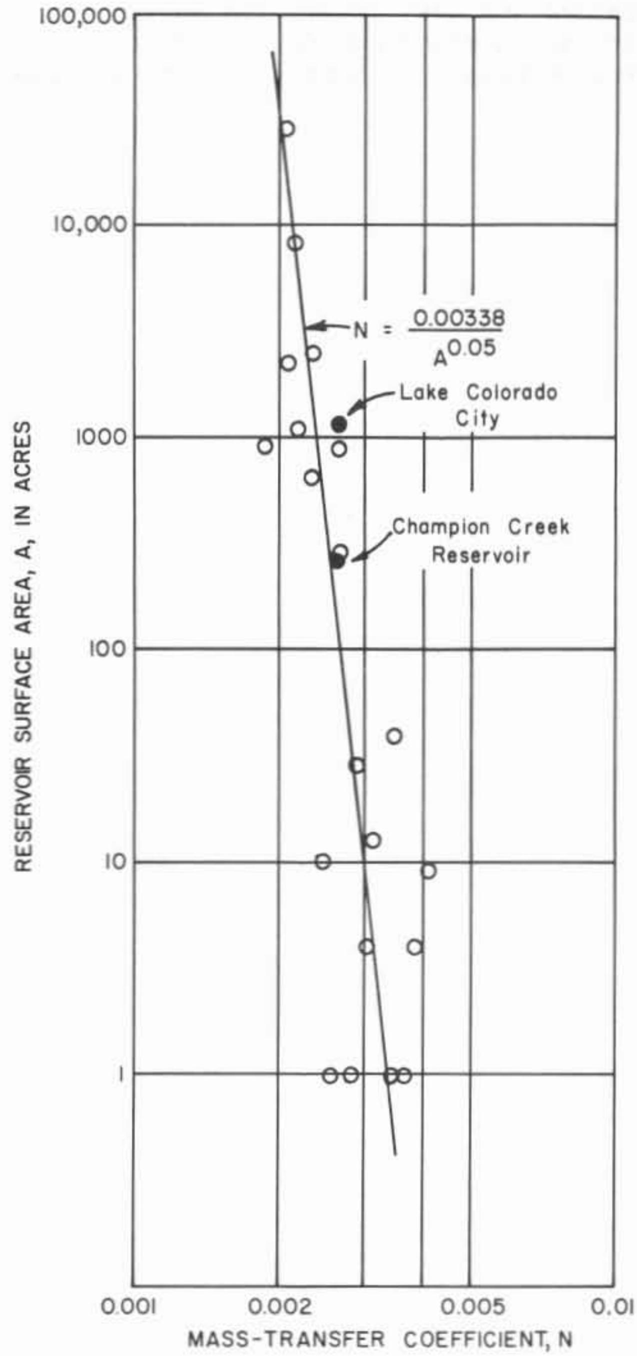

Figure 10

Relation Between Mass-Transfer Coefficient, N, and Reservoir Surface Area

(Adapted from Harbeck, 1962, fig. 31)

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"Mass-transfer coefficients" were calculated for both Champion Creek Reservoir and Lake Colorado City. The results were in good agreement with values of the coefficient determined for many reservoirs in the United States. If desired, the mass-transfer equation can be used to compute evaporation from both reservoirs on a continuing basis, without elaborate instrumentation.

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