282

GEOLOGICAL SURVEY CIRCULAR 282

THE USE OF RESERVOIRS AND LAKES FOR THE DISSIPATION OF HEAT

UNITED STATES DEPARTMENT OF THE INTERIOR
Douglas McKay, Secretary

GEOLOGICAL SURVEY
W. E. Wrather, Director

GEOLOGICAL SURVEY CIRCULAR 282

THE USE OF RESERVOIRS AND LAKES FOR THE DISSIPATION OF HEAT

By G. Earl Harbeck, Jr.

Washington, D. C., 1953

Free on application to the Geological Survey, Washington 25, D. C.

PREFACE

This report on the use of reservoirs for the dissipation of excess heat 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, and under the technical direction of W. B. Langbein, Hydraulic Engineer.

The study was originally suggested by J. D. Doherty, Synthetic Liquid Fuels Branch, U. S. Bureau of Mines, who also furnished useful information concerning approximate quantities of heat to be disposed of as a result of certain industrial processes.

The advice and helpful suggestions of E. R. Anderson and J. F. T. Saur of the U. S. Navy Electronics Laboratory, San Diego, Calif., are gratefully acknowledged.

THE USE OF RESERVOIRS AND LAKES FOR THE DISSIPATION OF HEAT

By G. Earl Harbeck, Jr.

CONTENTS

ILLUSTRATIONS

TABLES

ABSTRACT

A method is presented for estimating the possible saving in water resulting from the use of lakes or existing reservoirs instead of cooling towers for the dissipation of excess heat. For the two reservoirs studied, annual savings were found to be 45 to 50 percent.

INTRODUCTION

Cooling by evaporation has long been used for the dissipation of unwanted heat in certain industrial processes. Where water supplies are plentiful, the consumptive use of water in cooling towers presents no problem, but where supplies are scarce and relatively expensive, other methods of cooling warrant consideration.

An alternative method, which has long been used, is to withdraw water from a reservoir or lake, let it absorb heat, and then return it to the reservoir or lake in such a manner as to prevent immediate reuse. It is obvious that evaporation from the lake will be increased thereby. If consumption of water is the only criterion, the practicability of the method depends on whether the amount of water lost by increased evaporation is less than that which would have been used by a cooling tower in dissipating the same amount of heat. Some theoretical aspects of the problem have been studied by other investigators, including Lima (1936) and Throne (1951). Although the general principles were understood, this is the first opportunity to explore the problem using field data and to apply the results of the Lake Hefner experience and refinements in theory to this problem.

THEORY

The energy budget for a lake or reservoir may be expressed as follows:

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} - Q_e - Q_h + Q_{vi} - Q_{vo} - Q_w = Q_\theta. \qquad (1)$$

In the equation above:

- 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_e = energy utilized by evaporation.
- Q_h = energy conducted from the body of water as sensible heat.
- Q_{vi} = energy advected into the body of water.
- Q_{vo} = energy advected out of the body of water.

Q_w = energy advected by the evaporated water.
Q_ϑ = increase in energy stored in the body of water.

In order to illustrate the approximate magnitude of the various items in the energy budget, data obtained at Lake Hefner, Okla., during the interagency water-loss investigations (1952) have been used. For the 12-month period Sept. 1, 1950, to Aug. 31, 1951, average daily values of certain of the items in equation (1) in calories per square centimeter per day were approximately as follows:

Q_{bs} =	781	Q_{vo} =	6
Q_e =	222	Q_w =	6
Q_h =	8	Q_ϑ =	-2
Q_{vi} =	8		

Inserting the figures given for these items in equation (1), we find that $Q_s - Q_r + Q_a - Q_{ar}$ = 1,018 calories per square centimeter per day. The data presented in table 7 and figures 65 and 66 of the interagency report (1952) and the relation $Q_{ar} = 0.03\ Q_a$ (as found by Gier and Dunkle and given in the same report) were used as a guide in apportioning the total of 1,013 calories per square centimeter per day among the four items approximately as follows:

Q_s = 432
Q_r = 26
Q_a = 622
Q_{ar} = 19

Among the various energy-budget items, Q_{bs} (the long-wave radiation emitted by the body of water), Q_a (the incoming long-wave radiation from the atmosphere), and Q_s (the incoming solar radiation) are the largest. Measurements of water-surface temperatures are all that is needed to determine Q_{bs} at any reservoir; few measurements of surface temperatures have been made, however. Eppley pyrheliometers have long been used to measure Q_s at certain Weather Bureau stations, and many such records are available. Except for the data obtained at Lake Hefner, there have been extremely few measurements of Q_a, and many additional data are needed to determine the areal variation in this important item.

In studies of annual evaporation, it is customarily assumed that the change in energy storage in the body of water is negligible for a period of a year. The figure of -2 calories per square centimeter per day for Q_ϑ given above substantiates this assumption; of course, this figure is invalid for shorter periods of time.

Consider a natural lake or a reservoir that is to be utilized for the purpose of dissipating excess heat. The addition of heat to the lake will not affect the following items in the energy budget: Q_s, Q_r, Q_a, Q_{ar}, Q_{vi}, and Q_ϑ, where Q_ϑ is considered to be the increase in energy stored in the body of water resulting from natural processes only. Of these, Q_s, Q_r, Q_a, and Q_{vi} obviously are not affected by the water-surface temperature of the lake. Q_{ar}, the reflected long-wave radiation, is also independent of water-surface temperature, depending only on Q_a. Thus from equation (1) it follows that when heat is added to a lake

$$(Q'_{bs} - Q_{bs}) + (Q'_e - Q_e) + (Q'_h - Q_h) + (Q'_{vo} - Q_{vo}) + (Q'_w - Q_w) = Q_c \quad (2)$$

(in which the unprimed symbols refer to the lake in its natural condition, the primed symbols to the lake after heat has been added, and Q_c to the amount of heat added). Or, rewriting in a more simple form,

$$\Delta Q_{bs} + \Delta Q_e + \Delta Q_h + \Delta Q_{vo} + \Delta Q_w = Q_c. \quad (3)$$

A direct solution for each of the terms on the left side of equation (3) for a given value of Q_c is not possible. Each term, however, varies directly with the temperature rise, and for various temperature rises it is possible to solve equation (3) for corresponding values of Q_c.

It should be emphasized that all the terms on the left-hand side of equation (3), with the possible exception of ΔQ_{vo}, are surface phenomena. They depend only on water-surface temperatures and characteristics of the ambient air but are independent of the thermal structure of the reservoir. Consider the case where water is withdrawn from a reservoir at some depth, used for cooling, and then the heated water is returned to the surface of the reservoir. Assuming complete lateral mixing over the surface, some of the heat added inevitably must be utilized in increasing heat storage in the lake. The rate at which this occurs will depend to a large extent on the amount of wind-induced mechanical turbulence. The following computations are based on the premise that equilibrium has been reached and that all heat added to a lake is dissipated to the atmosphere and is not used to increase energy storage in the lake, or in other words, over a long period of time $\Delta Q_\vartheta = 0$. Until equilibrium is reached, the amount of heat dissipated from the surface, including that utilized to increase reservoir evaporation, will be less than the computed value. The addition of heat at the surface of the lake may tend to cause stratification, and equilibrium may be attained quickly if little mechanical mixing occurs.

If all reservoir outflow occurs at the surface level, as in the case of an overflow dam, there is little or no error introduced by assuming the outflow temperature to be the same as the water-surface temperature. If outflow occurs at considerable depth, some error may be introduced by this assumption, but in most storage reservoirs the amount of heat removed in this manner is quite small compared with other items in the energy budget. For a run-of-the-river reservoir, inflow and outflow volumes are large relative to its capacity, and the resultant mixing reduces or eliminates vertical temperature gradients in the reservoir.

BASIC DATA

Selected data from the Lake Hefner investigations were used to compute Q_c for arbitrarily chosen values of ΔT (temperature rise), as given in table 1.

In order to obtain some idea of the possible effect of reservoir size, inflow, outflow, and other hydrologic and climatologic factors, a hypothetical reservoir was selected for study, and the assumed conditions are given in table 2.

Although no specific location was selected, the assumed climatic and hydrologic conditions are reasonably representative of southeastern Colorado. In comparison, the surface area of the hypothetical lake is 22 percent, and the capacity is 8 percent, of that of Lake Hefner.

Table 1.—Selected hydrologic and meteorological data for Lake Hefner, Okla.

	October 1950	January 1951	April 1951	July 1951	September 1, 1950, to August 31, 1951
Water-surface temperature..........°C..	19.28	3.48	11.29	26.73	14.96
Air temperature, 8-meter level..........°C..	19.02	2.52	12.85	26.45	14.57
Wet-bulb temperature, 8-meter level..........°C..	13.72	-0.27	8.43	21.89	10.68
Evaporation..........acre-feet..	1271	459	496	1385	10,293
Outflow..........acre-feet..	832	860	890	1346	11,724
Reservoir surface area..........acres..	2342	2232	2182	2316	2275

Table 2.—Assumed hydrologic and meteorological data for hypothetical lake

Drainage area above reservoir..........square miles..	100
Reservoir capacity..........acre-feet..	5,000
Surface area..........acres..	500
Annual inflow including rainfall on lake surface..........acre-feet..	3,300
Annual reservoir evaporation under natural conditions..........acre-feet..	2,200
Annual outflow (by difference)..........acre-feet..	1,100
Average annual air temperature..........°C..	10
Average annual water-surface temperature under natural conditions..........°C..	10
Average relative humidity..........percent..	50

COMPUTATION METHODS

The various terms in equation (3) were computed as follows (units: calories per organic centimeter per day):

$$\Delta Q_{bs} = 0.970\sigma[(T_o' + 273)^4 - (T_o + 273)^4] \qquad (4)$$

in which σ = Stefan-Boltzman constant for black-body radiation (= 1.71×10^{-7} calories per square centimeter per (degree)^4 per day).

$$\Delta Q_e = \rho E'L' - \rho EL \qquad (5)$$

in which ρ = average density of evaporated water ($\approx$ 1 gram per cubic centimeter)

E = average daily evaporation in grams per square centimeter per day ($\approx$ centimeter per day)

L = latent heat of vaporization in calories per gram at T_o (= $595.9 - 0.545\,T_o$, very closely).

But from mass-transfer theory, assuming no change in wind speed and that the possible effect of changes in atmospheric stability resulting from an increase in water temperature is negligible,

$$\frac{E'}{E} = \frac{e_o' - e_8}{e_o - e_8} \qquad (5a)$$

in which e_0 = saturation vapor pressure at T_o in *mb*

e_8 = vapor pressure of the air at the 8-meter level in *mb*, determined from T_8 and W_8.

$$\Delta Q_h = R'Q_e' - RQ_e = R'\rho E'L' - R\rho EL \qquad (6)$$

in which R = the Bowen ratio $\frac{Q_h}{Q_e} = \frac{0.61\,P\,(T_0 - T_8)}{1000\,(e_0 - e_8)}$

P = atmospheric pressure in *mb*.

$$\Delta Q_{vo} = c\rho(T_o' - T_o)V_o \qquad (7)$$

in which c = specific heat of water ($\approx$ 1 calorie per gram per degree)

V_o = outflow volume in grams per square centimeter per day ($\approx$ centimeter per day).

$$\Delta Q_w = c\rho\,(E'T_o' - ET_o). \qquad (8)$$

Using the Lake Hefner data, values of Q_c for various assumed temperature rises (ΔT) were computed using equation (3) with the individual terms being computed using equations (4) to (8). Similar computations were made for the hypothetical reservoir under the conditions listed in table 2 and also for assumed relative humidities of 30 and 70 percent.

After the values of Q_c had been computed, the next step was to compare, for each value of Q_c, the increase in evaporation ($E' - E$) with the amount of water that would be evaporated in a conventional cooling tower during disposition of the same quantity of heat. For the purposes of this study, the amount of water evaporated from a cooling tower, E_t, was computed by dividing the amount of heat to be dissipated, Q_c, by the latent heat of vaporization of water at the original temperature, T_o. Admittedly, this is only an approximation, because both the heat removed by convection as sensible heat and the heat carried away by the evaporated water have been ignored. The heat removed by convection is small as compared with the heat removed by evaporation. At least partly counterbalancing this omission is the fact that no allowance has been made for drift or spray losses.

It should be pointed out that the above method of computation probably results in smaller values of E_t than would be observed in an actual cooling tower, because of the decrease in latent heat of vaporization, L, with temperature. If the evaporating water is at 10°C, as was assumed for the hypothetical reservoir, the disposal of 1×10^{13} calories per day (3.97×10^{10} Btu per day) by evaporation only would use 1.69×10^{10} grams per day (4.47 mgd). If the evaporating water is at 70°C, however, disposal of the same quantity of heat would use approximately 6 percent more water. Thus the values of E_t, as computed, are probably conservative, despite the fact that certain small items in the energy budget for the cooling tower have been ignored.

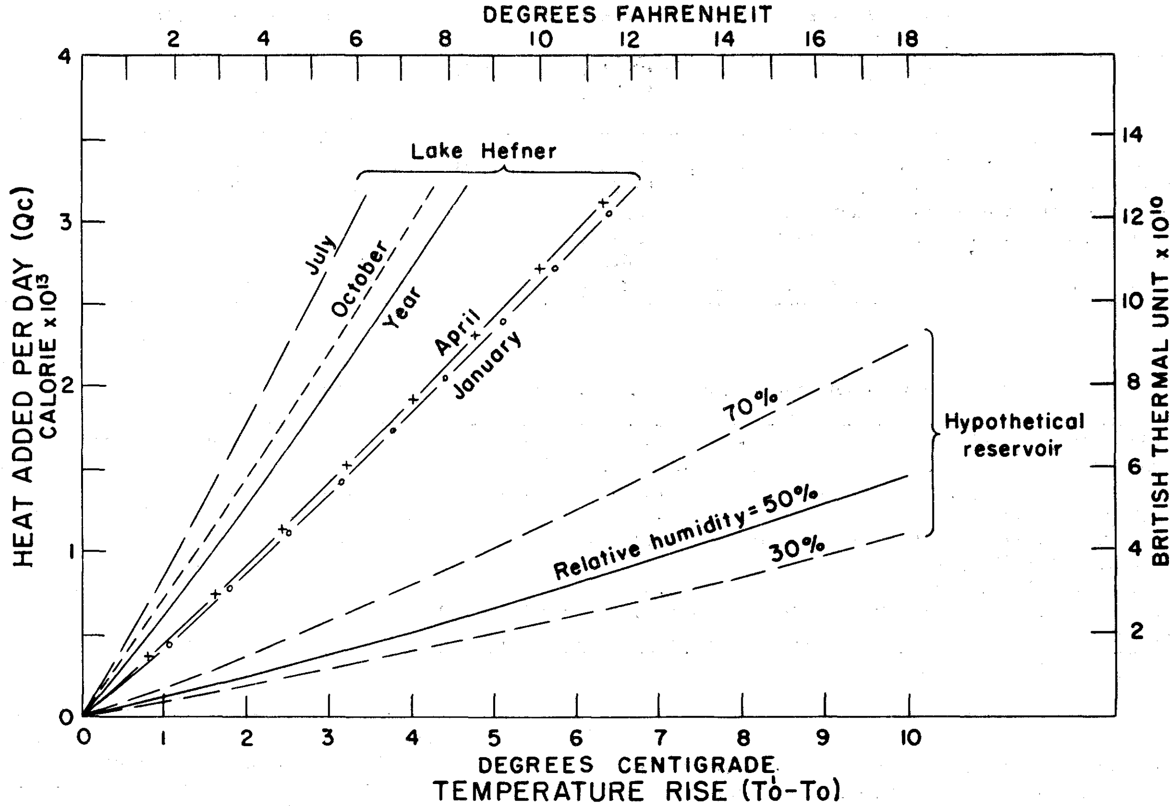

Figure 1.—Reservoir temperature rise resulting from the addition of heat.

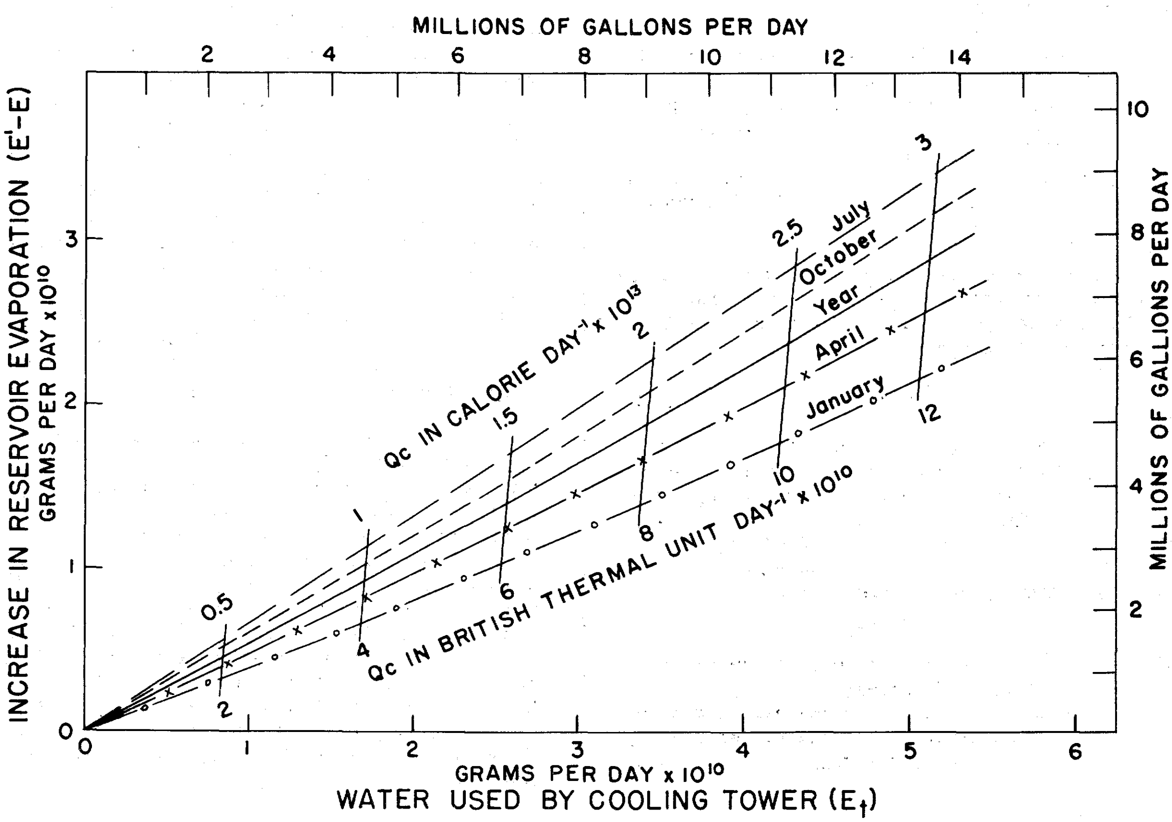

Figure 2.—Comparison between cooling-tower water use and increase in evaporation from Lake Hefner.

Table 3.—Percent of total heat added that is dissipated by each of the various processes and percent of water saved

[For Q_c = 1 x 10^{13} calories per day = 4 x 10^{10} Btu per day]

Period	Relative humidity (percent)	ΔQ_{vo}	ΔQ_{bs}	ΔQ_e	ΔQ_h	ΔQ_w	Percent saving in water
Lake Hefner							
October	56.3	1	15	59	24	1	40
January	58.1	1	19	40	39	1	60
April	55.8	1	20	47	31	1	52
July	67.3	1	14	64	18	3	35
Year	62.9	1	15	54	28	2	46
Hypothetical Lake							
Year	30	1	20	49	27	3	50
Do	50	1	15	52	30	2	48
Do	70	1	10	54	34	1	45

RESULTS

Figure 1 indicates that Q_c, the heat added to the reservoir, is almost directly proportional to ΔT, the temperature rise, over the range investigated. For a value of Q_c of 1 x 10^{13} calories per day (3.97 x 10^{10} Btu per day), the temperature rise in Lake Hefner for the 4 selected months would range from 1.1°C in July to 2.0°C in January, with an average of 1.6°C for the year. Temperature rises are approximately inversely proportional to water-surface temperatures. For the hypothetical lake, the temperature rise is much greater of course, because its surface area is much smaller. On a unit-area basis, the Lake Hefner results agree reasonably well with the hypothetical lake results. However, the computed values of Q_c as shown in figure 1, purposely were not presented on a unit-area basis in order to avoid any inference that generalization is possible. For a run-of-the-river reservoir, for example, annual outflow may be many times greater than the capacity of the reservoir, and the amount of heat used to increase reservoir evaporation may be negligible as compared to the amount of heat carried away by the outflow.

Table 3 shows the relative magnitudes of amounts of heat disposed of by the various processes, and it shows a comparison between the amount of water used by increased reservoir evaporation and that used in a conventional cooling tower.

Figure 2 indicates that for Lake Hefner the present water saving in percent does not vary appreciably with Q_c within the limits shown. All of the curves are slightly concave upward, as might be expected, because if Q_c were allowed to increase without bound, the increase in evaporation, $E' - E$, would approach the cooling-tower use, E_t.

The Lake Hefner results illustrate the seasonal change in amounts of heat disposed of by the various processes. Seasonal changes in ΔQ_{vo}, ΔQ_{bs}, and ΔQ_w are small compared with the changes in ΔQ_e and ΔQ_h. In January, for example, only 40 percent of the total heat is disposed of by increased evaporation, and 39 percent is carried away as sensible heat, but in July the percentages are 64 and 18, respectively. The greater amount of heat dissipated by convection in January results from the fact that the Bowen ratio is larger; dissipation of heat by convection is directly proportional to the temperature gradient and inversely proportional to vapor-pressure gradient. Temperature gradients are usually large in winter and vapor-pressure gradients are small. The percentages for the hypothetical lake are of the same order of magnitude as for Lake Hefner.

It will be noted that each figure in the column headed ΔQ_e is almost exactly equal to the figure in the last column subtracted from 100. If L, the latent heat of vaporization, did not vary with temperature, they would agree exactly, because

$$\frac{\Delta Q_e}{Q_c} = \frac{E'L' - EL}{Q_c} \times 100 \text{ in percent}$$

and percent saving in water =

$$100\left[1 - \frac{E' - E}{E_t}\right] = 100\left[1 - \frac{E'L - EL}{Q_c}\right].$$

The saving in water that would result from the use of Lake Hefner for cooling, as shown in the last column of table 3, is 46 percent for the year and ranges from 40 to 60 percent for the selected months. For the hypothetical reservoir, the saving is approximately the same. It should not be expected that these figures apply to all lakes or reservoirs (particularly to reservoirs in an extremely arid or extremely humid region or to run-of-the-river reservoirs).

As has been previously discussed, the computed water savings are based on the assumption that the reservoir has reached thermal equilibrium. Until this condition has been attained (the time required may range from hours for a small pond to years for a large, deep reservoir), the computed increase in reservoir evaporation will be greater than that which actually occurs, and the saving in water will be correspondingly greater.

CONCLUSIONS

The results of the study indicate that, for the dissipation of excess heat resulting from certain industrial processes, substantial savings in water often can be realized, as compared with conventional cooling-tower methods, if it is practicable to withdraw water from a reservoir or natural lake, to let it absorb heat, and then to return it to the reservoir.

It should not be assumed that a water saving will result if a reservoir is constructed solely for the purpose of dissipating excess heat. In that case, the increase in evaporation resulting from the construction of the reservoir must be added to the increase in evaporation resulting from the addition of heat, and their sum will in all probability be greater than the amount of water used by a cooling tower.

There are many interrelated factors involved, and it would be unwise to assume that the figures of possible water savings shown for the two reservoirs studied will apply to all lakes or reservoirs. The theory presented is completely general, however, and may be applied to any body of water, if the necessary hydrologic and climatologic data are available.

REFERENCES

Lima, D. O., 1936, Pond cooling by surface evaporation; Power, v. 80, no. 3, p. 142-4.

Throne, R. F., 1951, How to predict lake cooling action; Power, v. 95, no. 9, p. 86-89.

U. S. Geol. Survey, 1952, Water-loss investigations; volume 1–Lake Hefner studies, technical report: U. S. Geol. Survey Circ. 229. Also published as U. S. Navy Electronics Laboratory report 327.

INT.-DUP. SEC., WASH., D.C63077