EFFECT OF HEATED WATER ON THE TEMPERATURE AND EVAPORATION OF HYCO LAKE, NORTH CAROLINA, 1966-72

U S GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS 11-74

PREPARED IN COOPERATION WITH THE NORTH CAROLINA DEPARTMENT OF NATURAL AND ECONOMIC RESOURCES AND THE CAROLINA POWER AND LIGHT COMPANY

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.
4. Title and Subtitle The Effect of Heated Water on the Temperature and Evaporation of Hyco Lake, North Carolina, 1966-72			5. Report Date May 1974 6.
7. Author(s) W. L. Yonts and G. L. Giese			8. Performing Organization Rept. No. WRI 11-74
9. Performing Organization Name and Address U. S. Geological Survey Water Resources Division P. O. Box 2857 Raleigh, N. C. 27602			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Address U. S. Geological Survey Water Resources Division P. O. Box 2857 Raleigh, N. C. 27602			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes

Prepared in cooperation with the North Carolina Board of Water and Air Resources and the Carolina Power and Light Company

16. Abstracts Three levels of thermal loading of Hyco Lake by heat from two steam-electric generators has resulted in higher temperatures in the 3,750-acre lake and increased evaporation. Winter local temperature increases of as much as 19°C occurred at the lake surface. Summer surface temperature increases seldom exceeded 3.3°C.

Forced evaporation increased to a maximum of 586 millimeters for 1970, as compared to 1,412 millimeters of natural evaporation for that year. About 58 percent of the added heat was utilized in evaporation, 24 percent for back radiation, and 8 percent was conducted as sensible heat.

17. Key Words and Document Analysis. 17a. Descriptors

*Reservoir evaporation, *Water loss, *Thermal stress, *Energy budget, *Water temperature, Thermal powerplants, North Carolina.

17b. Identifiers/Open-Ended Terms

Hyco Lake, N coefficient, Mass-transfer water-budget technique

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restriction on distribution	UNCLASSIFIED	44
	20. Security Class (This Page) UNCLASSIFIED	22. Price

THE EFFECT OF HEATED WATER ON THE TEMPERATURE AND EVAPORATION OF HYCO LAKE, NORTH CAROLINA, 1966-72

By

W. L. Yonts and G. L. Giese

U. S. GEOLOGICAL SURVEY

Water-Resources Investigations 11-74

Prepared In Cooperation With The North Carolina

Department of Natural and Economic Resources

And The Carolina Power And Light Company

May 1974

CONTENTS

ILLUSTRATIONS

CONTENTS

TABLES

USE OF INTERNATIONAL SYSTEM UNITS

The U. S. Geological Survey has recently adopted a policy of including metric or International System (SI) units in all reports. In most instances, the SI equivalent follows the English unit in the text. For the convenience of the reader, the following table gives the factors used in converting from English to SI units:

Multiply English units	by	to obtain SI units
inches (in)	25.4	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square feet (ft^2)	.0929	square meters (m^2)
acres	.4047	square hectometers (hm^2)
square miles (mi^2)	2.59	square kilometers (km^2)
acre-feet (acre-ft)	1.233×10^{-3}	cubic hectometers (hm^3)
cubic feet per second (ft^3/s)	28.32	liters per second (l/s)
British thermal unit (Btu)	1,055	joules

The relation between Fahrenheit scale degrees (°F) and Celsius scale degrees (°C) is: (°F-32) 5/9 = °C.

THE EFFECT OF HEATED WATER ON THE TEMPERATURE AND EVAPORATION OF HYCO LAKE, NORTH CAROLINA, 1966-72

By W. L. Yonts and G. L. Giese

ABSTRACT

Three levels of thermal loading of Hyco Lake by heat from two steam-electric generators have resulted in higher temperatures and increased evaporation in the 3,750-acre (1,518 square hectometer) lake. During the winter, local temperature increases of 34°F (19°C) were sometimes observed at the surface as heated water spread out on top of the cooler, more-dense, lake water, affecting areas as large as 2,590 acres (1,048 square hectometers) with temperature increases averaging up to 12°F (6.7°C) higher than natural lake temperatures. In the summer average temperature increases at the surface seldom exceeded 6°F (3.3°C) and the maximum area affected was 2,570 acres (1,040 square hectometers).

Forced evaporation from the heated part of Hyco Lake increased in proportion to the added heat, reaching a maximum of 23.1 inches (586 millimeters) in 1970, as compared to 55.6 inches (1,412 millimeters) of natural evaporation for that year.

In 1969, over the heated area, 210,600 British thermal units per square foot per year or 2,407,510,000 joules per square meter per year of heat were added to the lake. Of this amount, about 58 percent of the heat was utilized for evaporation, 24 percent for back radiation, 8.0 percent was conducted as sensible heat from the lake, 1.0 percent was removed through outflow, and 0.04 percent was advected by the evaporated water. These percentages are fairly typical of the first three stages of thermal loading.

INTRODUCTION

Purpose and Scope

Electric energy demands have nearly doubled every decade since World War II and probably will continue to do so in the near future. Most of this energy is and will continue to be furnished by thermal power plants, utilizing either fossil or nuclear fuel. These thermal-electric power plants produce large amounts of excess heat. Tremendous quantities of cooling water are used to carry away this heat, which is usually dissipated in lakes and streams.

The discharge of heated water into a lake or stream produces two primary effects with respect to the receiving body. Water temperatures are increased, and greater evaporation occurs. In order to control degradation in water quality and excessive depletion of the available supply, it is desirable to monitor these effects and, if possible, be able to predict them before they occur. To do this requires precise knowledge of the mechanisms of heat dispersion in bodies of water. An opportunity to add to that knowledge presented itself when, in 1964, the U.S. Geological Survey, in cooperation with the Carolina Power and Light Company and the North Carolina Department of Natural and Economic Resources, Office of Water and Air Resources, undertook a study of the effects of cooling water on the evaporation and thermal conditions of Hyco Lake. In that year, construction of a dam on the Hyco River was completed by the Carolina Power and Light Company and the 3,750-acre (1,520 hm^2) Hyco Lake formed behind it. (See location map, fig. 1.) The lake was thermally loaded in successive stages by the rejected heat from two steam-electric power plants, which became operational in May 1966 and in March 1968, respectively.

The addition of heat to Hyco Lake in stages presented a unique opportunity to study the lake response over a wide range of conditions, both natural and induced, and hopefully to establish relations between the added heat and increased evaporation and water temperatures in the lake. This report summarizes the observed effects of thermal loading up to February 1972, at which time two generating units were in operation. A third generating unit began operation in mid-1973 along with a new system of discharge canals. An afterbay is also under construction below the dam. A future report will consider the effects of these and any other changes in thermal loading conditions that may take place.

Physical Setting

Hyco Lake (fig. 1) is an irregularly shaped impoundment of the Hyco River in Caswell and Person Counties in north-central North Carolina, near the Virginia border. The surrounding area is sparsely populated, with the largest incorporated community, Roxboro (pop. 10,000 in 1970), located 6 miles (9.6 km) southeast of the lake.

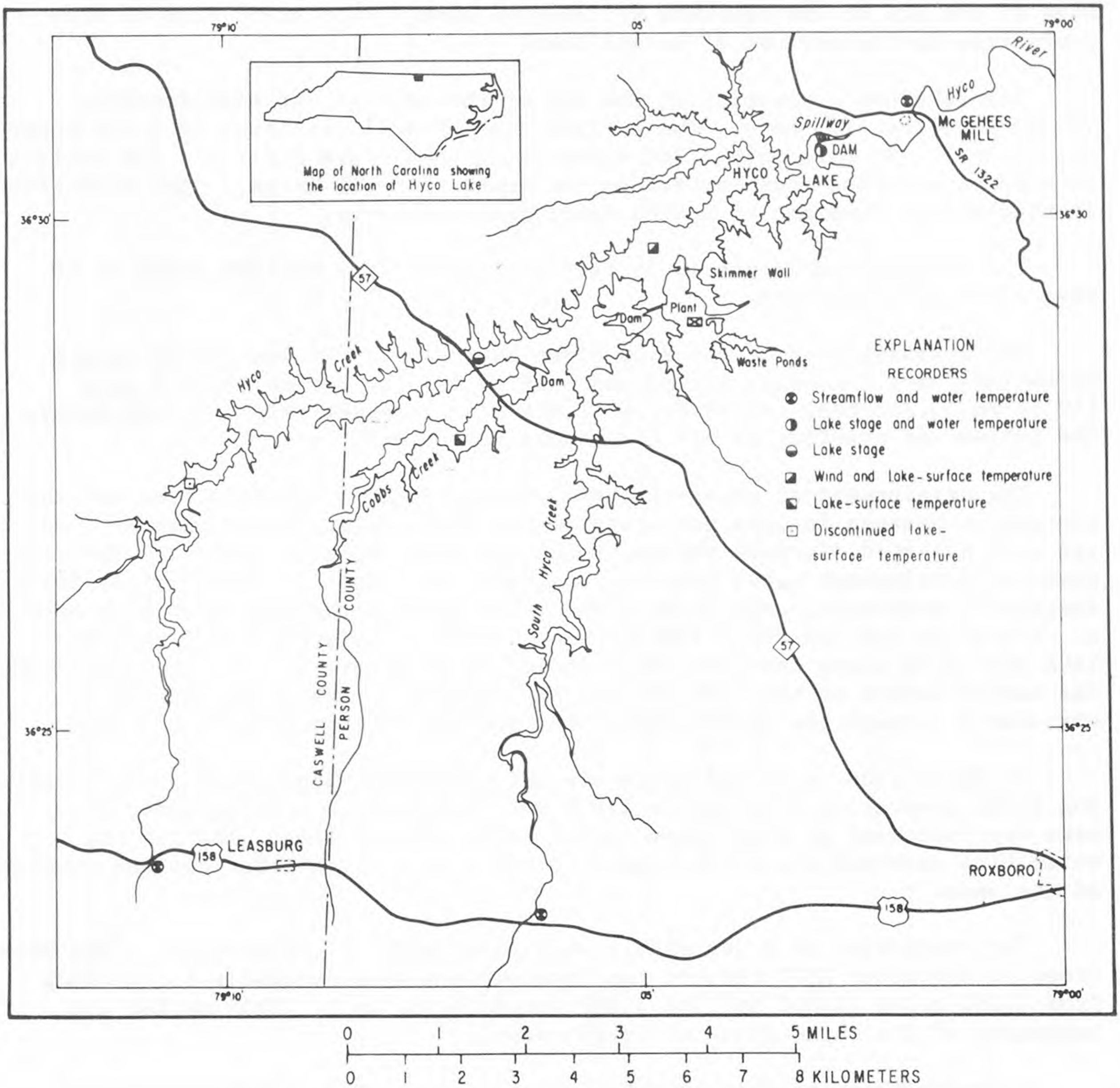

Figure 1.--Hyco Lake and location of recorders.

The dam forming the lake, which was completed in 1965, is a rolled earth structure approximately 1,600 feet (487 m) long and 70 feet (21 m) high. Overflow water cascades over a concrete spillway apron, which is 600 feet (182 m) wide and 1,000 feet (305 m) long. An emergency spillway near the southeast end of the dam is designed to handle flood flows above the capacity of the concrete spillway. An 18-inch (0.46 m) pipe was installed through the base of the dam at the concrete spillway to assure a constant flow of water downstream during periods of no spillage.

The lake has a capacity at the top of the spillway of approximately 75,500 acre-feet (93 hm^3). The surface area at spillway level is 3,750 acres (1,520 hm^2). Of this, only 3,360 acres (1,320 hm^2) were available for cooling because of a porous rock dam across the mouth of Cobbs Creek, which effectively blocked the movement of heated water into that area.

The average lake depth is 20 feet (6.1 m) and the maximum depth is 50 feet (15.2 m) at the dam.

The drainage area of the Hyco River basin above the dam is 189 square miles (489 km^2). Average inflow and outflow for the period 1966-70 were 117 ft^3/s (3,313 l/s) and 99 ft^3/s (2,804 l/s), respectively. Occasionally, the inflow was practically nil for months at a time.

The development of steam-electric power generation at Hyco Lake and the consequent changes in lake temperatures and evaporation due to thermal loading took place in discrete phases, which are summarized in table 1. The first phase of development dates from the beginning of operation of the first 385 mw (megawatt) generating unit in May 1966. The maximum cooling water flow rate at this stage was 365 ft^3/s (10,340 l/s), which circulated to and from the lake generally along the flow paths indicated in figure 2. Cooler water from the deeper layers of the lake entered an intake bay under a skimmer wall, circulated through the plant condensors, and was discharged into the lake.

In March 1968, a second steam-electric generator began operation, boosting total generating capacity to 1,055 mw. The maximum cooling water flow rate was increased at this phase to 862 ft^3/s (24,400 l/s). The cooling water flow path and the surface area of the lake available for cooling remained the same.

The completion of a dam with a small boat slip at the mouth of South Hyco Creek in September 1970 reduced the lake surface area available for cooling from 3,360 acres (1,360 hm^2) to 2,800 acres (1,130 hm^2). This marked the beginning of the third phase of development.

A fourth phase of development started in July 1973, ushering in major changes in thermal loading patterns. At that time, a third generating unit went into operation which increased total generating capacity to 1,775 mw and the maximum cooling water flow rate to 1,442 ft^3/s (40,800 l/s). Also, a new system of discharge canals went into operation at this time. This system

Table 1.--Phases of thermal loading of Hyco Lake[1]

Phase	Date	Generating units in operation	Total generating capacity in mw	Maximum cooling water flow rate in cfs	Surface area in acres of lake available for cooling
1	May 1966 through February 1968	Unit 1	385	365	3,360
2	March 1968 through August 1970	Units 1 and 2	1,055	862	3,360
3	September 1970 through June 1973	Units 1 and 2	1,055	862	2,800
4	July 1973	Units 1, 2, & 3	1,775	1,442	3,750

[1]See page preceding abstract for SI equivalents.

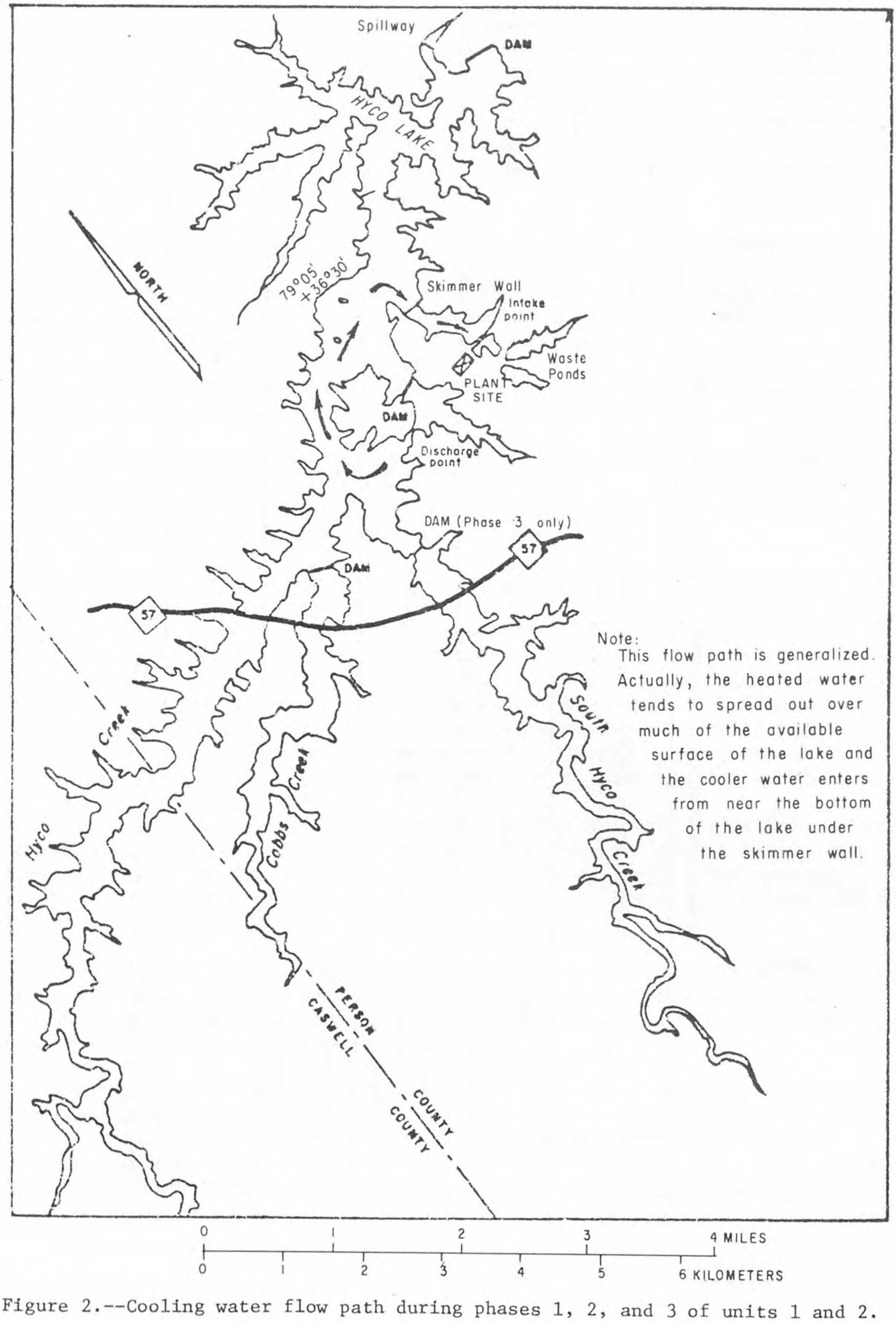

Figure 2.--Cooling water flow path during phases 1, 2, and 3 of units 1 and 2.

distributes the heat more evenly throughout the lake and increases the surface area available for cooling to 3,750 acres (1,520 hm^2), essentially the entire lake surface area. A generalized cooling water flow path at this stage is shown in figure 3. A later report will evaluate the effects of this fourth stage of development and any other changes which may take place.

Climate

The general climatic classification of the area is mild and humid. Warm temperatures prevail throughout the area from May through September with mild to freezing temperatures existing for the remainder of the year. The average annual temperature is 61°F (16°C) and varies from an average of 40°F (4.4°C) in January to an average of 77°F (25°C) in July. The average annual relative humidity is 71 percent.

Prevailing winds of the area are southwesterly. Wind velocity as observed 6.56 feet (2m) above the lake surface averaged 5.4 mph (miles per hour) or 8.7 km/hr (kilometers per hour) during the study period. Normal rainfall is 45 inches (1,143 mm) per year, and is about evenly distributed throughout the year, except for the summer months which receive 1 or 2 inches (25-51 mm) more than the other months.

Methodology

Beginning in March 1965, temperature surveys of Hyco Lake were made periodically in different seasons under natural conditions and, later, under various conditions of thermal loading. A total of 59 such field surveys were made between March 22, 1965, and February 29, 1972, the majority of them for the specific purpose of recording water temperatures at 76 points on the lake surface. During 15 of these surveys, vertical temperature profiles were taken to determine the extent of thermal stratification. In addition, thermographs on first one, then two rafts in different locations (see fig. 1) recorded lake-surface temperatures continuously throughout the study period. This information was used to determine the extent and degree of the heated lake water and the manner of its dispersion in the lake.

The relatively large number of surface-temperature observations were useful also as inputs for determining lake evaporation. Lake-surface temperature observations were used in conjunction with wind velocity and vapor pressures of the air at the lake surface and in the surrounding area to determine evaporation as given by the form of the mass-transfer equation suggested by Harbeck (1962, p. 101):

$$E = N\mu \, (e_o - e_a) \qquad (1)$$

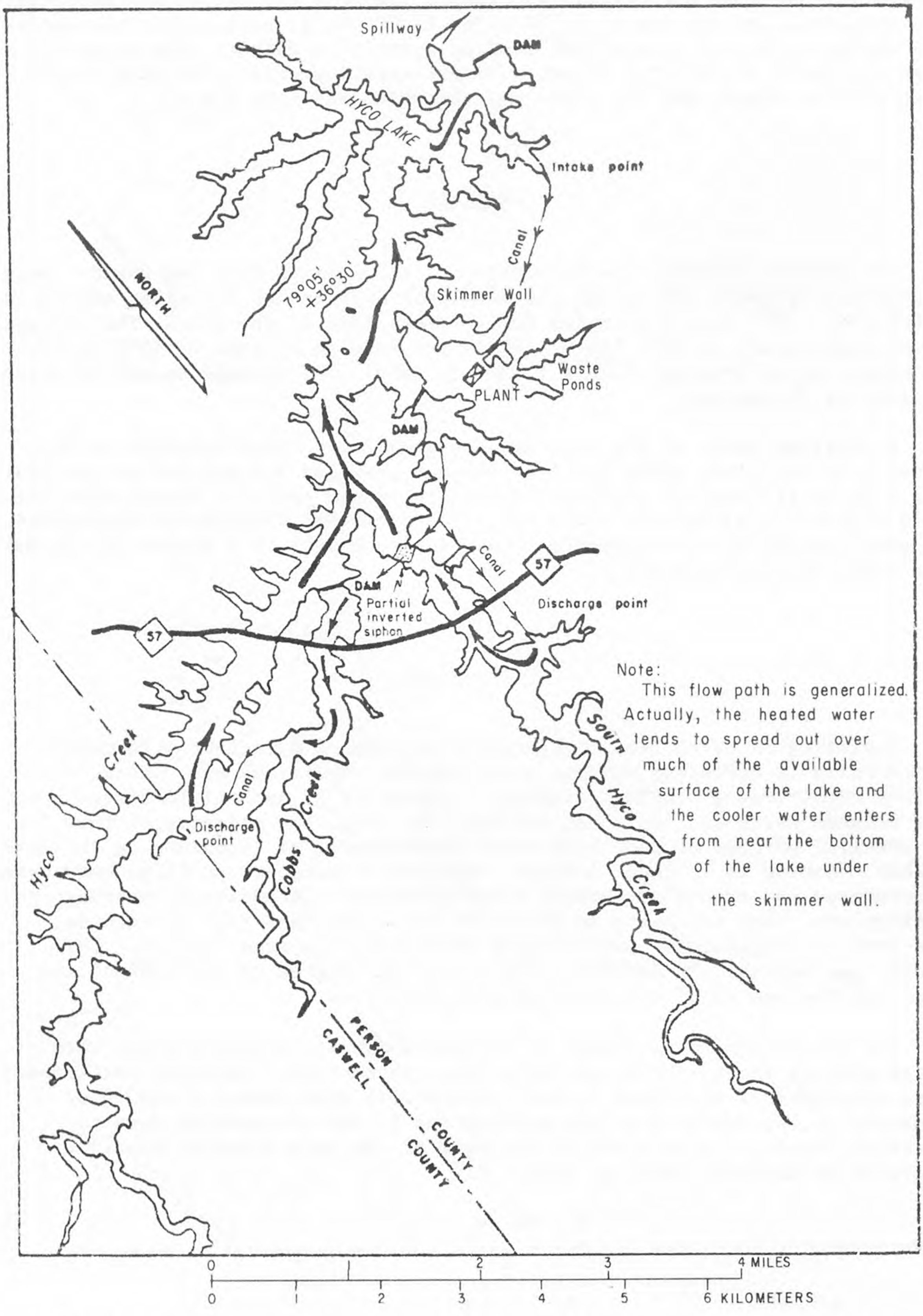

Figure 3.--Cooling water flow path during phase 4 of units 1, 2, and 3.

where N is a coefficient, unique for a given lake; μ is the wind speed as measured 6.56 feet (2.0 m) above the lake surface; e_o is the vapor pressure of saturated air at the temperature of the lake surface; e_a is the vapor pressure of the unaffected surrounding air; and E is the rate of evaporation per day.

The determination of the N coefficient for Hyco Lake was made through a calibration process equating evaporation to residuals from a water budget for the lake. This method is discussed further in the section on natural evaporation, but the equation simplifies to:

$$\Delta H_A = E \tag{2}$$

where ΔH_A is average change per unit time in water-surface elevation adjusted for inflow, outflow, and rainfall; and E is evaporation per unit time.

The simultaneous solution of equations 1 and 2 gives:

$$\Delta H_A = E = N\mu \, (e_o - e_a) \tag{3}$$

which is the equation used to determine N for Hyco Lake. The ΔH_A term was determined from measurements of inflow, outflow, lake stages, and rainfall for Hyco Lake. Figure 1 shows the location of the primary data-collection sites for these types of information.

The determinations of lake temperatures and evaporation rates for Hyco Lake made it possible to construct an energy budget accounting of the heat added to the lake by the generating units. The equation for the changes in energy processes may be given as:

$$\Delta Q_{bs} + \Delta Q_e + \Delta Q_h + \Delta Q_w + \Delta Q_{vo} = Q_c \tag{4}$$

in which ΔQ_{bs} is the change in long-wave radiation emitted by the body of water; ΔQ_e is change in energy utilized by evaporation; ΔQ_h is change in energy conducted from the body of water as sensible heat; ΔQ_w is change in energy advected by the evaporated water; ΔQ_{vo} is change in energy removed by volumes of water leaving the lake as outflow and Q_c is the heat added by the power plant.

The energy budget was computed for the years 1968 and 1969 when the heat load to the lake and cooling patterns in the lake were most nearly constant. The quantitative results of these and other analyses are presented in the following sections of this report.

EFFECTS OF ADDED HEAT ON TEMPERATURE

Variations of Surface Temperatures

The dispersal of the heated cooling water in Hyco Lake raises the lake temperature at many places in excess of what would naturally occur. Because the heated water is less dense than water already in the lake, it tends to float and spread out on the surface of the lake rather than mix thoroughly throughout the depths of the lake. Hence, the greatest increases in lake temperature over natural conditions are observed at the surface. For this reason, the surface temperatures were studied in particular detail during the 59 temperature surveys made during the study. From these data, a series of maps (figs. 4-9) showing lake-surface temperature was constructed, representing typical summer and winter conditions for the first three stages of lake development.

Figures 4 and 5 show typical summer (July and August) and winter (December through February) surface temperatures during the first stage of development, when only a 385 mw generating unit was in operation. Generally, the farther away from the discharge point along the cooling water flow path, the lower the rise in lake-surface temperature. The lines of equal temperature are perpendicular to the direction of flow of the heated water in the lake. As the heated water circulates through the lake, it mixes and diffuses with the cooler lake water. Some of this heat is stored in the lake, some is lost by outflow at the dam, and an insignificant amount may be conducted through the lake sides and bottom to the surrounding soil. At the lake surface, much heat is lost to the atmosphere through evaporation, conduction, convection, and back radiation.

All these processes have some resultant influence on the lake temperatures. The reverse of this statement is also true for many of these processes. Lake temperatures affect the rates of many of these energy processes. Consequently, there are seasonal variations in the manner and degree to which the heated cooling water affects lake temperatures.

The tendency of warm water to float on the cooler layers is more pronounced on Hyco Lake in winter. The difference in temperature between the "natural" lake water and the heated water discharged to the lake is greatest during the winter months and results in the greatest density differences of the year.

The amount of heat added to the lake and the cooling-water flow rate both have a large influence on the rate and manner of heat dispersion and the resulting temperatures at different locations in the lake. Figures 5 and 7 make for an interesting comparison in this respect. The beginning of phase 2 was marked by the start of operation of the second generating unit, having a capacity of 670 mw, which increased the heat added to the lake from an average of 1.2 trillion Btu's per month to 3.0 trillion Btu's per month. These amounts are equivalent in metric units to 1.3 quadrillion joules per month to 3.2

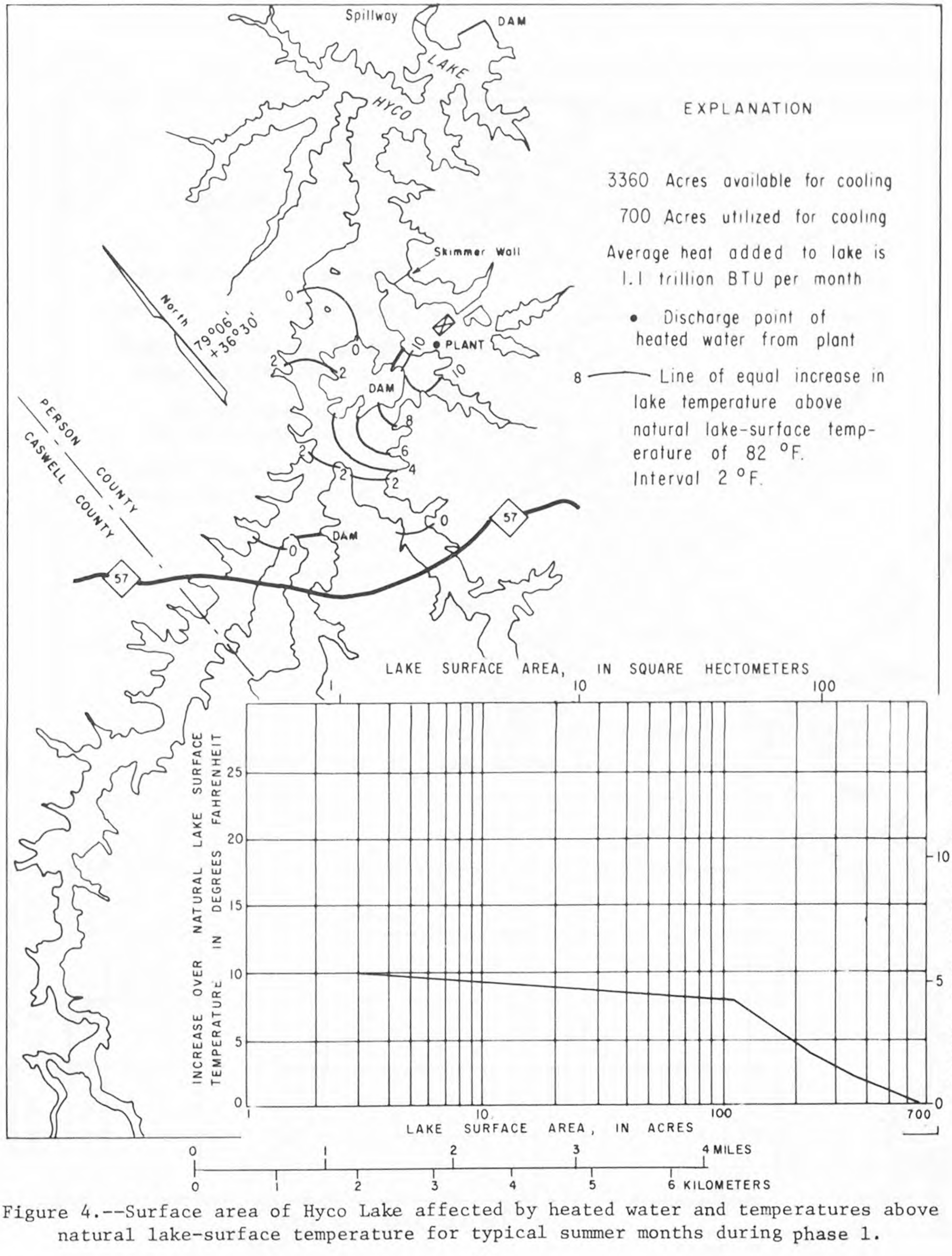

Figure 4.--Surface area of Hyco Lake affected by heated water and temperatures above natural lake-surface temperature for typical summer months during phase 1.

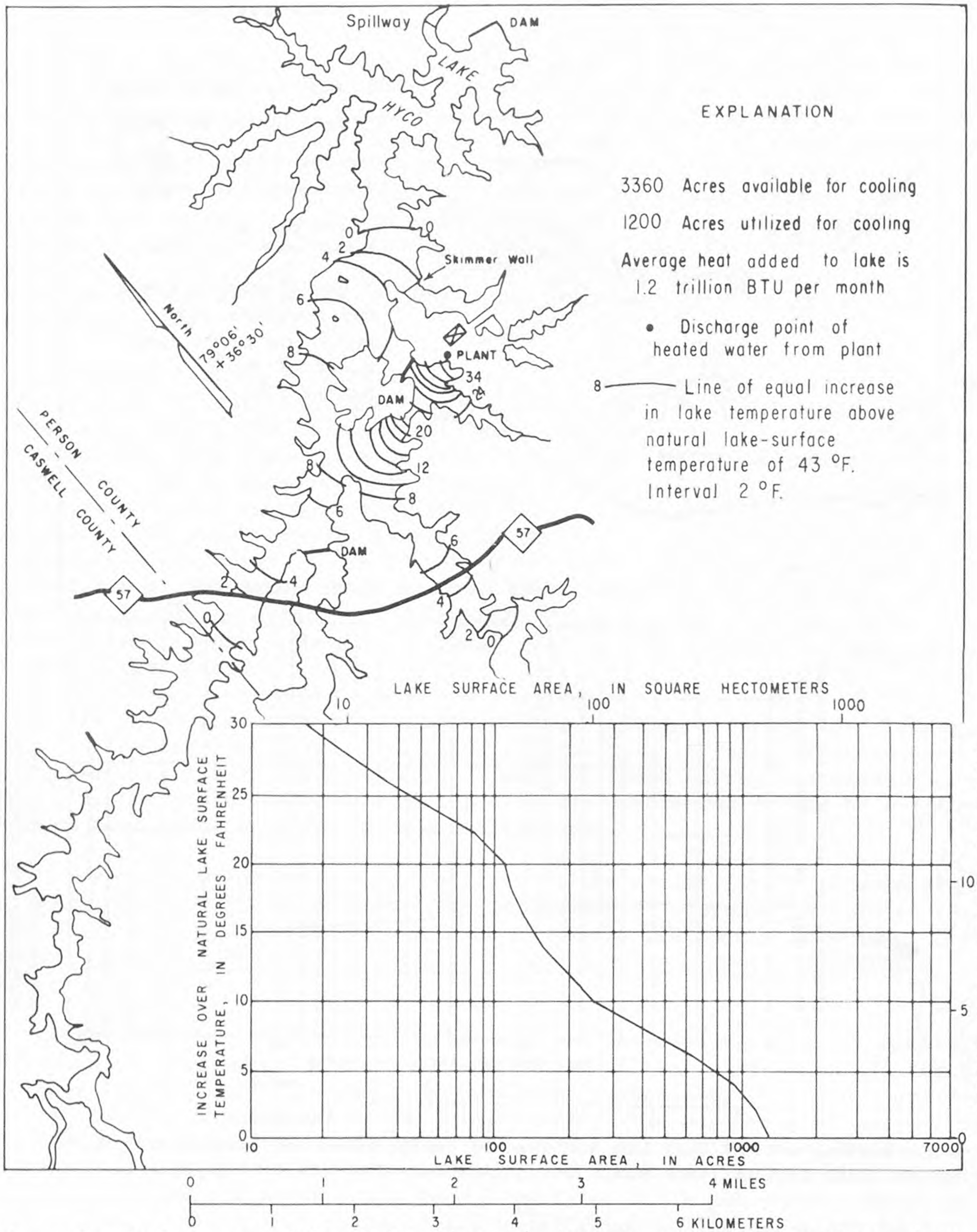

Figure 5.--Surface area of Hyco Lake affected by heated water and temperatures above natural lake-surface temperature for typical winter months during phase 1.

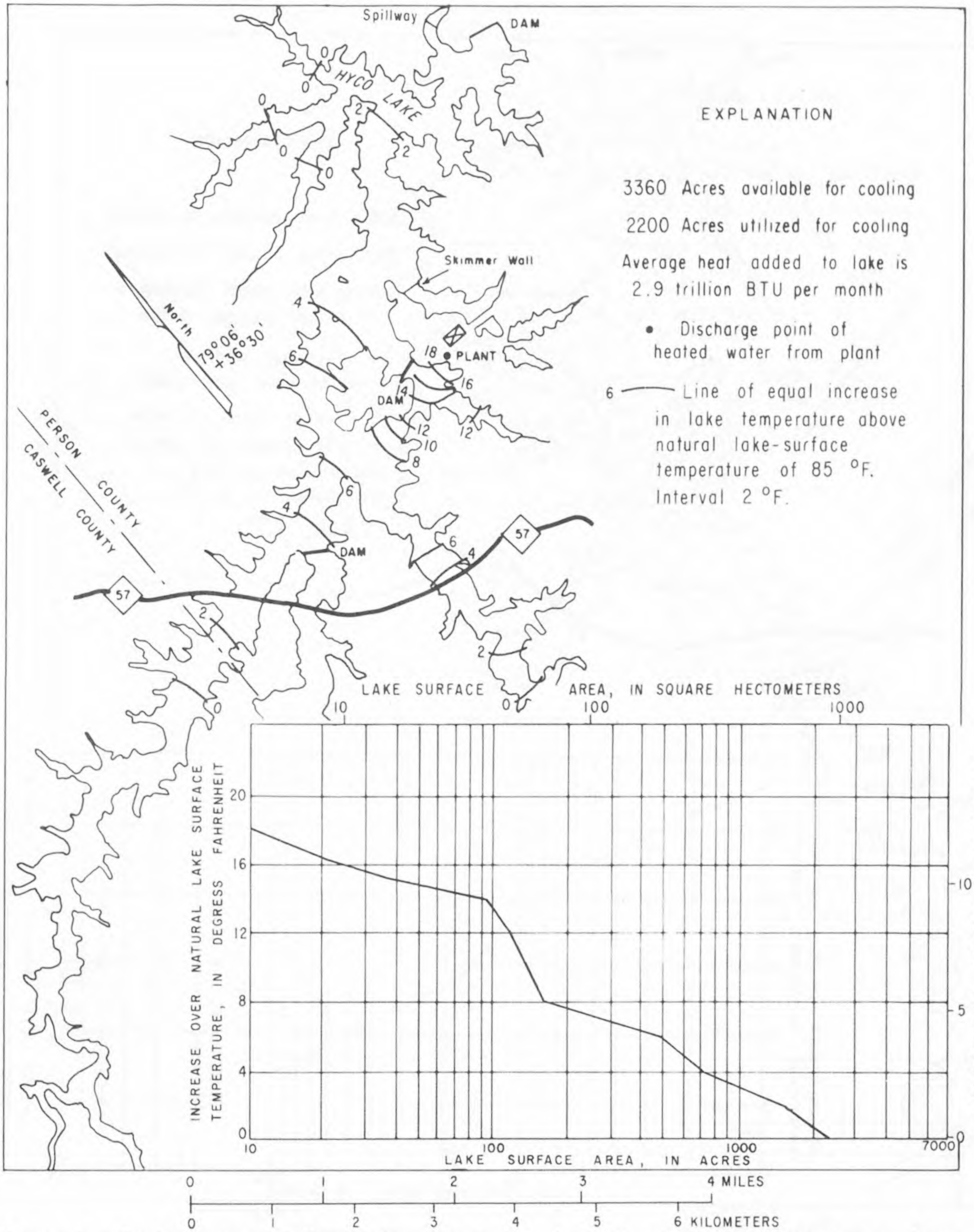

Figure 6.--Surface area of Hyco Lake affected by heated water and temperatures above natural lake-surface temperature for typical summer months during phase 2.

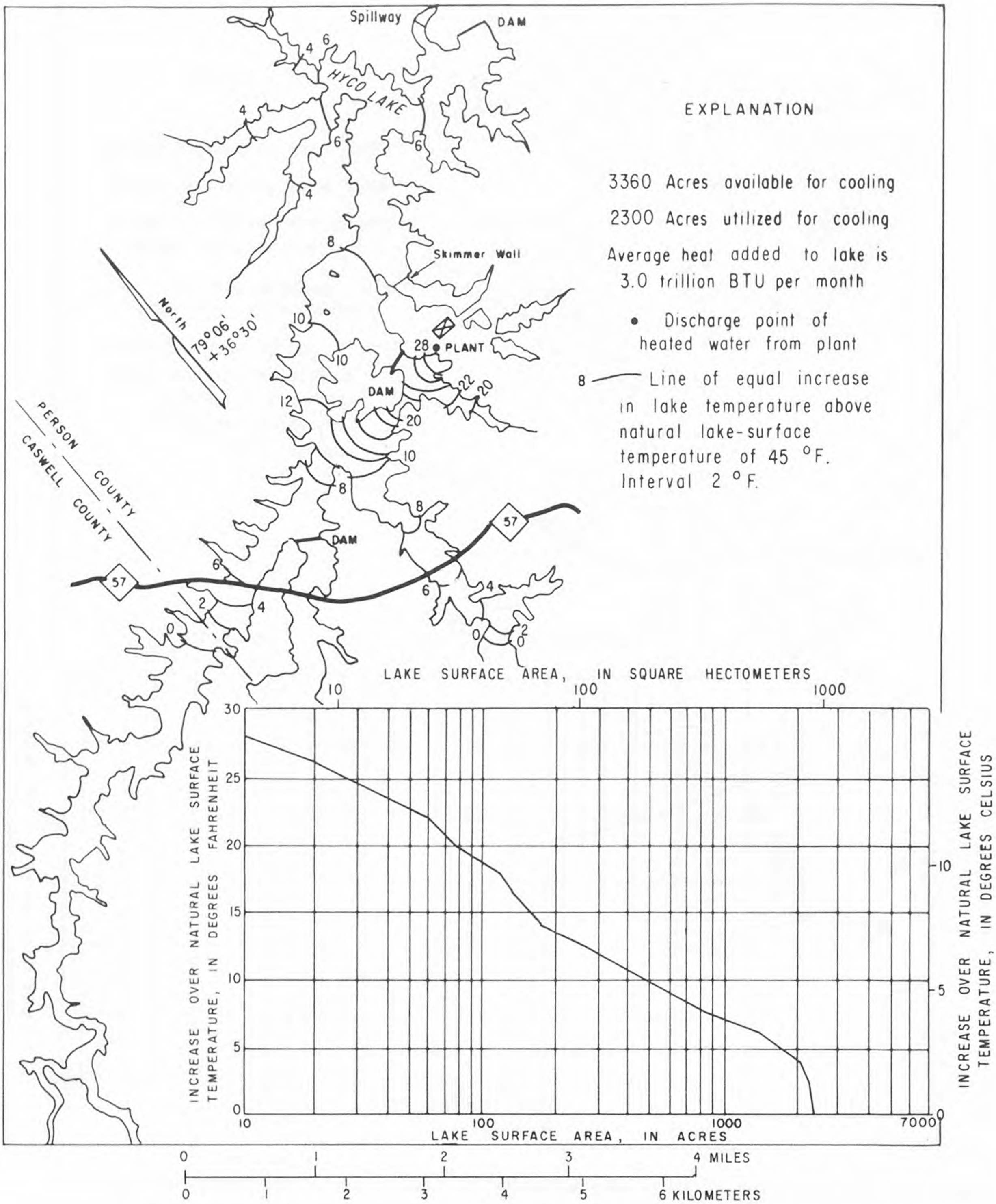

Figure 7.--Surface area of Hyco Lake affected by heated water and temperatures above natural lake-surface temperature for typical winter months during phase 2.

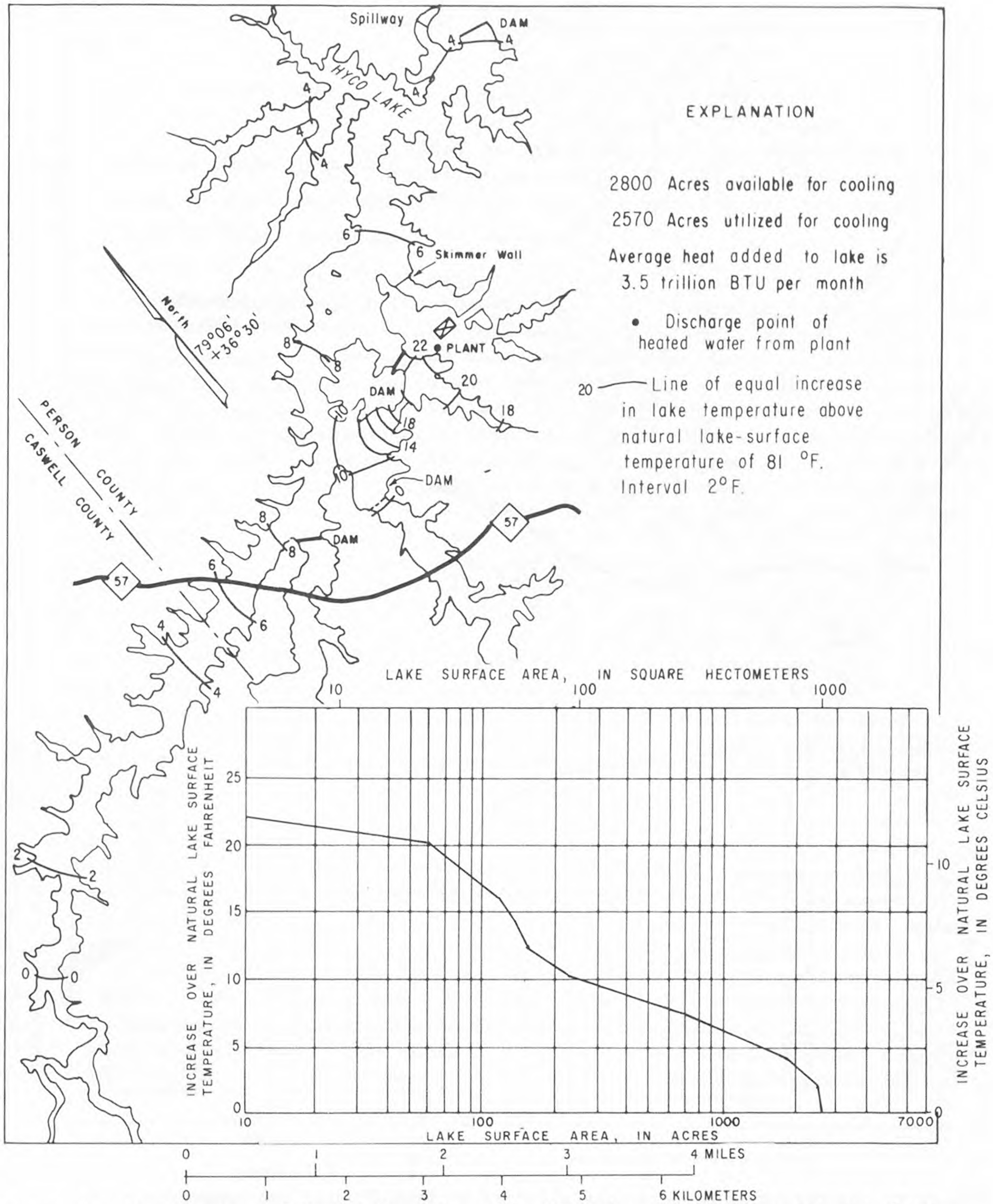

Figure 8.--Surface area of Hyco Lake affected by heated water and temperatures above natural lake-surface temperature for typical summer months during phase 3.

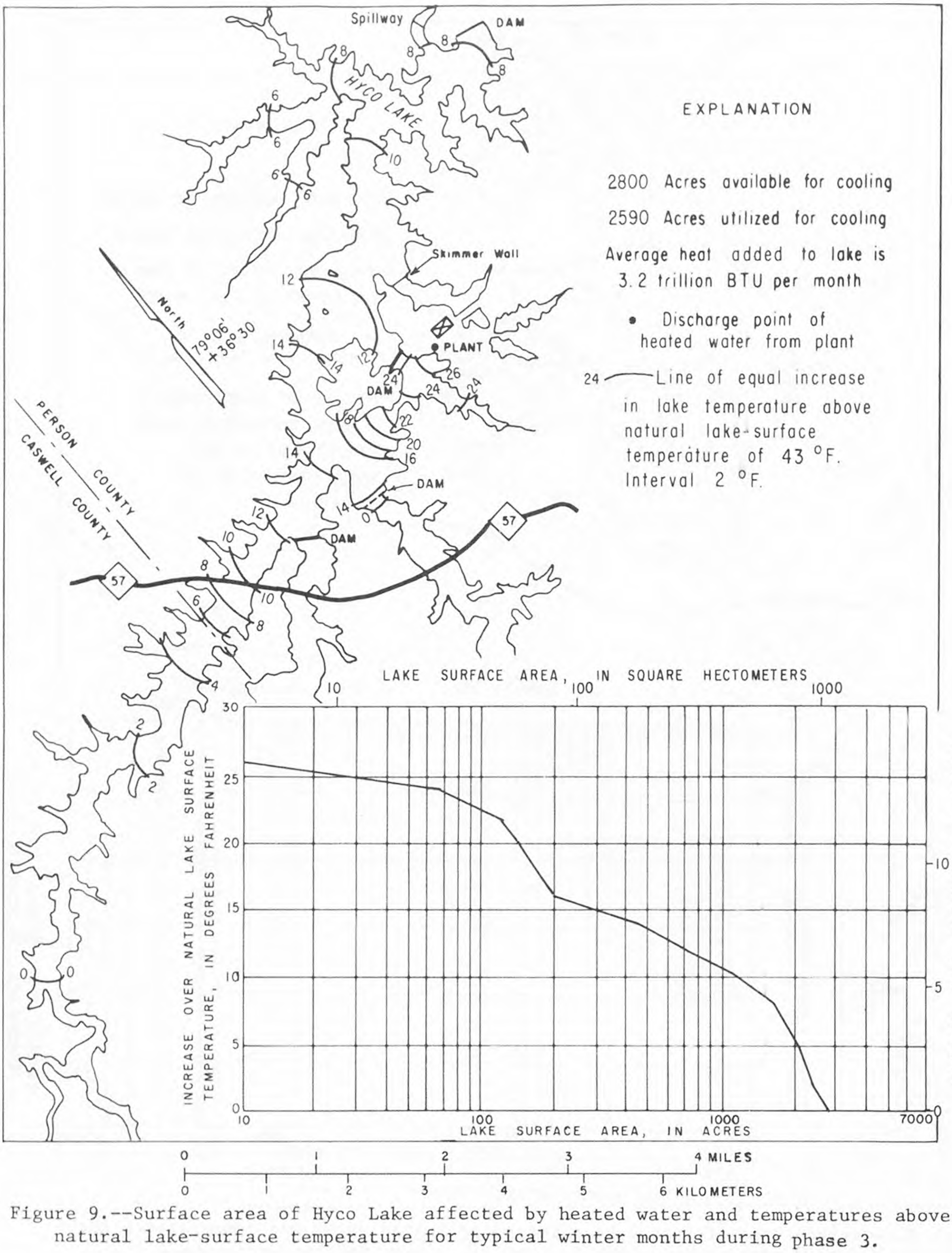

Figure 9.--Surface area of Hyco Lake affected by heated water and temperatures above natural lake-surface temperature for typical winter months during phase 3.

quadrillion joules per month, respectively. At the same time, the cooling water flow rate was increased from an average of 365 ft^3/s (10,340 l/s) to 862 ft^3/s (24,400 l/s). The amount of added heat to the lake per unit time is given by:

$$Qc = mC\Delta T \tag{5}$$

where Qc is the amount of heat added to the lake, m is the mass of the cooling water added, C is the specific heat of water, and ΔT is the temperature difference between water withdrawn from the lake for cooling and the water returned to the lake.

By increasing the amount of mass flow rate at the same time that the amount of heat was increased, the temperatures of the heated water at the discharge point were kept at about the same level as during phase 1. In fact, at times the temperatures were less than during phase 1, as shown on figure 7, where the temperature of the heated water near the discharge point was 73°F (23°C), as compared to 77°F (25°C) during the conditions shown for phase 1 on figure 5. Although the outlet temperatures were less during the phase 2 survey, the heat load and volume of heated water were greater and were dispersed over a larger area of the lake. As shown in figure 7, about 2,300 acres (930 hm^2) were affected by the heated water during the phase 2 winter survey, whereas only about 1,200 acres (486 hm^2) were affected during the phase 1 winter survey. Equation 5 and the lake-surface temperature data suggest that, for a constant heat rejection rate to the lake, increasing the cooling water mass flow rate will result in a decrease in water-surface temperatures in the vicinity of the outlet point and an increase in water-surface temperatures at points farther away from the discharge point along the cooling water flow path. Conversely, decreasing the cooling water flow rate for a constant heat rejection rate will result in higher water-surface temperatures near the discharge point and lower water-surface temperatures elsewhere. This relationship is of great practical importance in managing the thermal loading of Hyco or any other lake.

Table 2 summarizes variations in lake-surface temperatures by showing the average monthly temperature increase due to thermal loading of the affected surface area of Hyco Lake, from May 1966 to February 1972. As expected, the greatest increases occurred during the winter months in all three phases of development. The maximum monthly average temperature increase above natural conditions was 12°F (6.7°C) in December 1969 and the maximum annual average temperature increase was 6.0°F (3.3°C) for 1970. However, even the increased winter temperatures are still much less (27-36°F or 15-20°C) than summer water temperatures. The larger surface temperature increases after March 1968 are due to the increased heat load from the second generating unit.

Table 2.--Average increase in the surface temperature of Hyco Lake, in degrees Fahrenheit above natural temperature[1] [2]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
1966				-	0.9	1.1	0.3	0.5	0.4	[3] 0	3.9	2.9	
1967	2.4	2.5	0.2	[3] 0	[3] 0	[3] 0	1.3	2.0	2.4	4.1	5.6	4.5	2.1
1968	1.6	[3] 0	1.2	2.9	3.7	2.5	3.3	3.7	4.6	6.5	11.2	11.4	4.4
1969	10.3	9.2	6.7	0.5	2.4	4.0	0.6	6.0	6.2	6.0	7.7	12.0	5.5
1970	9.4	9.9	7.3	8.9	1.1	1.8	3.4	2.7	5.2	5.1	7.8	9.2	6.0
1971	9.7	6.7	1.0	2.0	2.3	3.9	5.3	4.9	5.6	6.6	7.9	4.5	5.0
1972	9.4	8.4											

[1]Monthly values through August 1970 represent the amount of surface temperature increase as averaged over the surface area available for cooling up to that time, 3,360 acres. Values from September 1970 are associated with an area of 2,800 acres. At that time, the completion of a dam with a small boat slip at the mouth of South Hyco Creek effectively reduced the surface area available for cooling.

[2]See page preceding abstract for SI equivalents.

[3]The addition of heat to the lake during these months did not result in measurable increase in surface temperatures above natural conditions. It is assumed that the heat added went into storage below the surface.

Variations of Temperatures With Depth

The winter natural temperature profile pattern in Hyco Lake is characteristically isothermal, as are all lakes in the southeastern United States. That is, lake temperatures are nearly uniform with depth. Beginning in the spring, the upper layers of the lake are heated sufficiently to create a density difference which prevents the warmer upper layers from mixing effectively with the cooler more dense waters below. This results in temperature stratification with depth. By summer the lake surface may be as much as 30°F (17°C) warmer than the lake bottom. This stratification normally persists until November or December when the winter isothermal pattern becomes reestablished.

The addition of heated water to Hyco Lake during the winter established some temperature stratification near the lake surface when none would have naturally existed. However, temperatures at and near the bottom remained unaffected. In the summer, the effect is mainly to increase temperatures at greater depths. Then, temperature increases over natural conditions are found to be greater at the lake bottom than at the surface at most locations. This is because, during the summer, when water temperatures are high, evaporation and back radiation are highest and transfer much heat from or near the surface of the lake to the atmosphere, which cools the surface. Also, the naturally established summer temperature gradient is more conducive to thorough mixing at depth than the isothermal winter profile.

Figure 10 shows typical summer and winter vertical temperature profiles at four locations in Hyco Lake under natural conditions and under each of the three phases of development discussed in this report.

Stations 1 and 2 of figure 10 were well within the heated part of the lake during all three phases. Stations 3 and 4 were just within the fringes of the heated part during phase 1. During phase 2, both of these stations were more affected by the heated water, as may be seen by the increased temperatures in the vertical profiles. During phase 3, station 3 was even more affected by heated water, whereas station 4 was totally unaffected because the construction of an inverted siphon on the South Hyco arm of the lake blocked off practically all the heated water from that part of the lake.

EFFECTS OF ADDED HEAT ON EVAPORATION

It was known from the beginning of the power development at Hyco Lake that the addition of the heated water used for cooling would have the general effect of increasing evaporation from the lake, but the magnitude of that increase could only be very roughly estimated. It was obvious that much more precise knowledge about evaporation was needed to ensure that the thermal

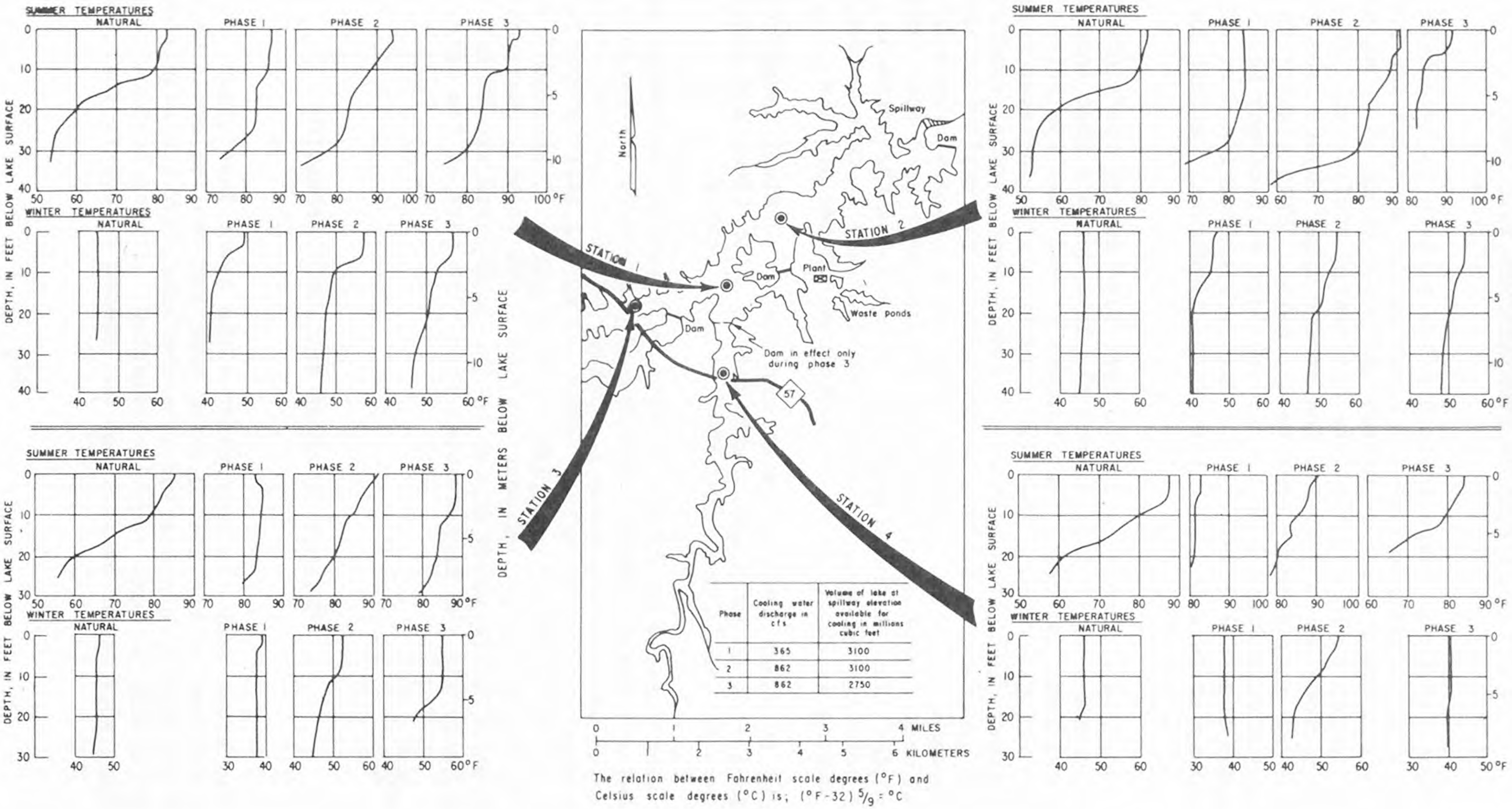

Figure 10.--Typical summer and winter temperature profiles for Hyco Lake during natural and heated conditions.

loading of the lake does not result in an evaporative loss greater than the water available for evaporation.

As a result of the thermal loading of Hyco Lake, the total evaporation from its surface may be said to have two components, natural and forced. Natural evaporation is that which would have occurred had there been no thermal loading. Forced evaporation is the evaporation due to thermal loading. The approach taken in this study was to first determine natural evaporation by the equation, previously discussed,

$$E = N\mu\ (e_o - e_a) \qquad (1)$$

where N is the mass-transfer coefficient; μ is wind speed as measured 6.56 feet (2.0 m) above the lake surface; e_o is the vapor pressure of the saturated air at the temperature of the lake surface; and e_a is the vapor pressure of the surrounding air.

Since heat was first added to the lake in May 1966, two instrument rafts have measured and recorded water-surface temperatures. One raft was located in the heated part of the lake opposite the plant, and the other raft has been in several locations but always where the water was unheated by the power plants. The data from these rafts were used to compute both the natural evaporation (that which would have occurred had no heat been added) and the total evaporation from the lake. Subtraction of natural evaporation from the total evaporation yields forced evaporation. Accordingly,

$$E_f = E' - E = N\mu\ (e'_o - e_a) - N\mu\ (e_o - e_a) = N\mu\ (e'_o - e_o) \qquad (6)$$

or

$$E_f = N\mu\ (e'_o - e_o)$$

where E' and e'_o refer to evaporation and saturation vapor pressure of the air at the water surface in the heated parts of the lake.

This description, in broad outline, is how the study of the effects of added heat on Hyco Lake evaporation was conducted. First, natural evaporation was determined. Then, the total evaporation of the lake from both the heated and unheated areas was determined. Finally, the forced evaporation due to thermal loading was isolated as the difference between the total observed evaporation and natural evaporation. The following sections enlarge on this procedure and present the quantitative results.

Natural Evaporation

Development of calibration curve

To compute evaporation as the product of $N\mu(e_o - e_a)$, the mass transfer coefficient, N, must first be determined. N may be defined as the slope of a straight line relating the mass-transfer product $\mu(e_o - e_a)$ to some independent measure of evaporation. In this study, evaporation was determined as the residual in the water budget developed to account for all the water entering and leaving the lake.

The water-budget equation for Hyco Lake may be expressed as

$$E - \Delta S + (O - I) - R = 0 \qquad (7)$$

where E is evaporation, ΔS is net change in storage, O is outflow, I is inflow, and R is precipitation. All of these quantities were directly measured or closely determined. The equation differs slightly from other water-budget equations in that it does not include a seepage term to account for underground inflow or outflow.

It is highly probable that any seepage outflow which occurs reappears in the Hyco River a short distance downstream from the dam at Hyco Lake and is included in the outflow term, O, in equation 7 which is measured at McGehees Mill, 1.7 miles (2.7 km) downstream from the dam. Seepage inflow is accounted for in the inflow term, I, which has been generated from inflow relations based on continuously gaged streams flowing into Hyco Lake. These relations encompass any seepage inflow to the lake. Thus, no separate accounting was required for seepage in this study.

Preliminary studies by Turner (written communication, 1969) indicated that there was a net seepage loss of 10 to 12 ft^3/s (283 to 340 l/s) from the lake, but intensive streamflow surveys later established that inflows were overestimated during the early investigation and unaccounted seepage losses did not, in fact, occur.

Figure 11 shows the calibration curve developed for Hyco Lake. The plotted points represent 56 computational periods of 3 to 16 consecutive days for which evaporation was determined by water-balance residuals and plotted against the concurrent values of the mass-transfer product $\mu(e_o - e_a)$. Seventeen of these computation periods represent data collected under natural conditions between May 25 and December 24, 1965, and the remainder of the points represent conditions during stages 1, 2, and 3 of thermal loading. The data reflecting natural conditions is apparently homogeneous with that reflecting heated conditions. Both sets of data scatter equally and unbiasedly around the line of figure 11. The relation defining N, the mass-transfer coefficient,

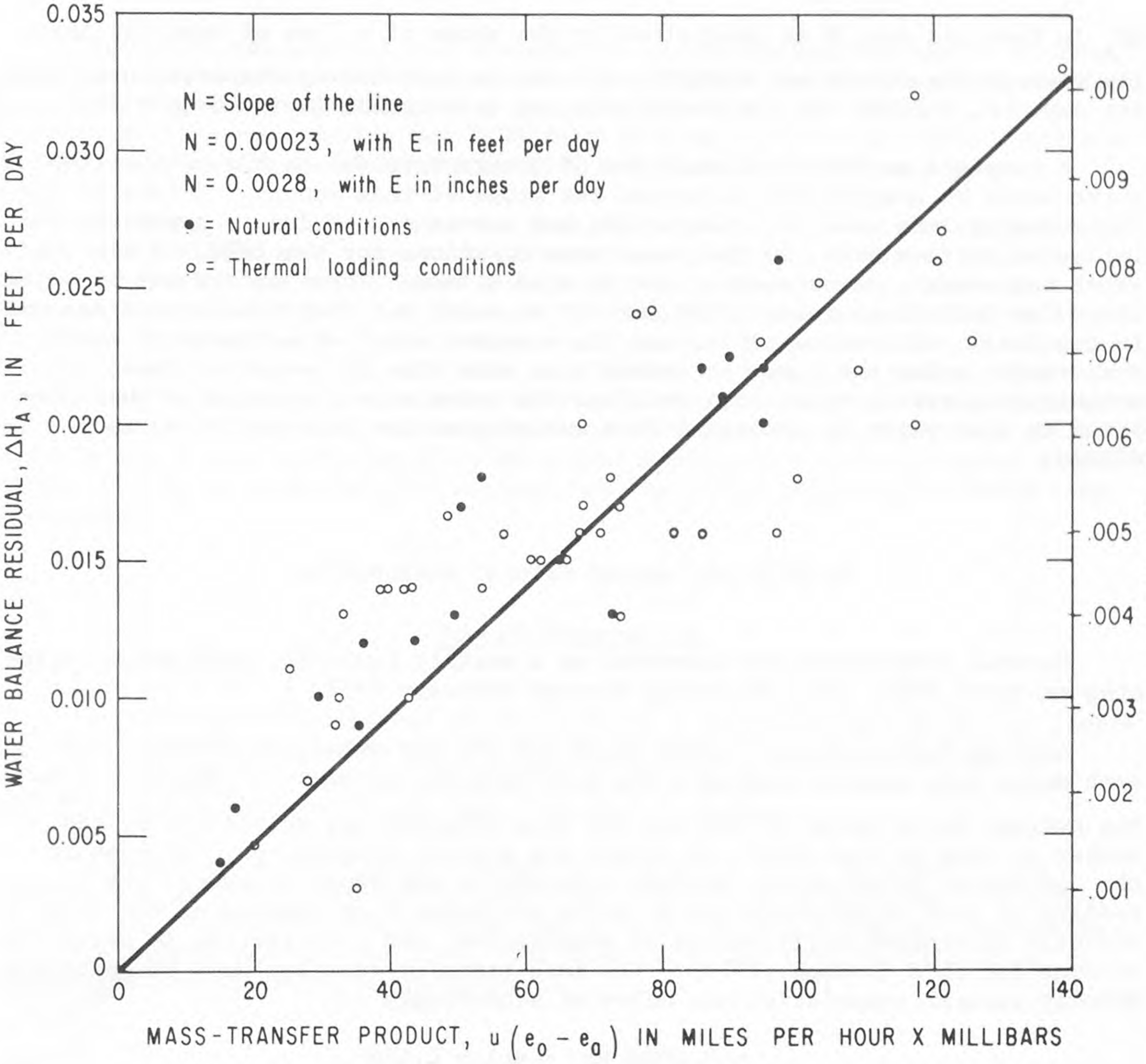

Figure 11.--Calibration curve showing relation of mass-transfer product and water-balance residual of Hyco Lake, N. C.

is dependent primarily on the manner of variation of wind with height above the lake surface, lake size and shape, and roughness of the water surface. None of these variables is affected in any significant way by thermal loading.

With the $\mu(e_o - e_a)$ term in units of miles per hour times millibars and ΔH_A in feet per day, N as determined by the slope of a line of best fit passing through the origin was 0.00023, for use in calculating evaporation in feet per day, or, 0.0028, for use in calculating evaporation in inches per day.

A complete mathematical analyses of errors involved in the calibration curve would be complex and is beyond the scope of this report. Errors in the individual points used in constructing the curves may be due to errors in the inflow or outflow term, in the stage-area relations for the lake, in air and water temperature measurements, and in wind speeds. These errors may be quite large for individual points (100 percent or more) but they tend to average out in the final calibration curve, and the standard error of estimate of monthly evaporation using the curve is probably no more than 10 percent. Thus, monthly evaporation rates computed from the curve appear reasonable when compared to what might be generated from pan evaporation data and other techniques.

Monthly and annual natural evaporation

Natural evaporation was computed on a monthly basis for each month beginning in March 1965, and continuing through February 1972.

Average daily values of wind speed and air and water temperatures for each month were used to evaluate the mass-transfer product $0.0028\mu(e_o - e_a)$. The average daily value of evaporation thus obtained was multiplied by the number of days in that month to obtain the monthly evaporation. Because of the non-linear relationship between temperature and vapor pressure, the results of this calculation are slightly different from summing of the individually determined daily values of evaporation, and a correction is needed to account for this (Jobson, 1972). The mass-transfer equation used to calculate monthly natural evaporation was adjusted accordingly to:

$$E = \frac{n\ 0.0028\mu(e_o - e_a) + 0.078}{1.023} \qquad (8)$$

where E is the corrected monthly evaporation in inches, n is the number of days in the month, and 0.078 and 1.023 are correction factors.

Table 3 shows monthly natural evaporation from Hyco Lake from March 1965 to February 1972. Monthly figures to April 1966 represent actual total evaporation from the lake. After that time, the lake was thermally loaded to varying degrees and the natural evaporation figures in the table represent only one component of total lake evaporation.

Typically, maximum natural evaporation occurs during the months of June, July, and August when water temperatures are highest, and minimum evaporation occurs during the winter months of December, January, and February. The minimum monthly evaporation was 0.38 inch (9.6 mm) in February 1966. Maximum monthly evaporation was 9.35 inches (237 mm) in July of the same year.

The average annual evaporation from Hyco Lake for the period 1966-71 was 47.6 inches (1,210 mm). This evaporation is significantly higher than the 37.9 inches (963 mm) of measured evaporation from Lake Michie, which is located 25 miles (40.2 km) to the south, during the 10-year period from 1961 to 1971. This difference bears some explanation. Inspection of raft-station data for the two lakes reveals that wind speeds at Hyco Lake ranged from approximately half again to three times as much as concurrent wind speeds at Lake Michie. The authors believe that the sheltered location of Lake Michie and its small size as compared to Hyco Lake account for the wind speed differences, which, in turn, largely account for the higher evaporation rates from Hyco Lake.

Forced Evaporation

Forced evaporation is one of the primary processes involved in the dissipation of the heat added to Hyco Lake and knowledge of the amount of this evaporation under various conditions of loading is important to the understanding and management of the lake for cooling purposes.

Forced evaporation was determined on a monthly basis by subtracting evaporation as determined for natural conditions from evaporation for heated conditions. The difference between the two values is the forced evaporation from the heated part of the lake. The basic equation used to calculate monthly values of forced evaporation is:

$$E_f = \frac{n\ N\ \mu(e_o' - e_o)}{1.023} \qquad (9)$$

where n is the number of days in the month, e_o' is the average saturated vapor pressure corresponding to the heated water surface, e_o is the average saturated vapor pressure of the unheated water surface, and 1.023 is the correction factor needed to adjust for using monthly average values of wind speed and air and water temperatures.

Table 3.--Monthly and annual natural evaporation, in inches, for Hyco Lake[1]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total for year
1965			1.68	2.18	4.89	5.74	6.29	5.99	5.56	4.65	2.64	2.02	45.14[2]
1966	2.17	0.38	2.20	2.57	3.99	8.20	9.35	6.29	5.18	3.22	1.84	2.08	47.47
1967	1.14	2.05	1.59	5.21	4.98	6.88	6.60	5.59	4.83	2.72	2.33	0.71	44.63
1968	1.32	2.26	2.74	4.01	5.17	6.12	7.68	8.41	5.24	4.41	1.75	0.90	50.01
1969	1.47	1.99	2.77	3.98	5.69	5.74	7.29	6.29	4.50	4.04	2.48	1.95	48.19
1970	2.50	2.30	2.38	2.74	5.92	8.49	7.19	6.96	6.79	4.53	3.07	2.72	55.59
1971	1.89	1.03	2.99	3.74	4.14	4.33	7.13	5.99	4.36	2.32	3.36	1.26	42.54
1972	1.29	2.21											
AVERAGE	1.68	1.74	2.34	3.49	4.97	6.50	7.36	6.50	5.21	3.70	2.50	1.66	47.65

[1]See page preceding abstract for SI equivalents.
[2]Includes data from 1972.

Table 4 shows monthly forced evaporation from Hyco Lake from May 1966 to February 1972. Values to February 1968 represent phase 1 thermal-loading conditions when only the first generating unit of 385 mw capacity was in operation. From March 1968 to August 1970, phase 2 loading conditions were in effect as the second generating unit of 670 mw was added. From September 1970 to February 1972 phase 3 loading conditions prevailed when the surface area of the lake available for cooling decreased from 3,360 to 2,800 acres (1,360 - 1,130 hm^2). It was expected that the reduction in surface area would result in increased evaporation from the heated area. However, no significant increase was observed at this time, probably because high lake outflows in 1971 carried away much of the heat that would otherwise have been utilized in evaporation.

Relation of added heat to forced evaporation

Actually, only a part of heat added to the lake is utilized by forced evaporation; the rest is dissipated by long-wave radiation, conduction, advection, or is removed from the lake in the outflow. The amount dissipated by evaporation is constantly varying, depending on wind speed, humidity, air and water temperatures, outflow, the manner of mixing of the heated water in the lake, and other factors. Although several of these factors vary seasonally, there is no corresponding seasonal variation clearly evident in forced evaporation. The maximum forced evaporation may occur during any month of the year. During the winter months on Hyco Lake the tendency of the heated water to spread out over the lake surface is much more marked than in summer, causing relatively larger water-surface temperature increases compared to those in summer. This factor considered by itself would indicate more forced evaporation in winter, except that, even with these larger increases in temperature, the actual surface temperatures are far less than in summer, and considerably less additional evaporation takes place per degree temperature rise at lower temperatures.

On an annual basis, the percentage of heat added which is utilized in evaporation has varied from a minimum of 39 percent in 1967 to 59 percent in 1968, as given in table 5. The average was 51 percent during the years 1967-71. Apparently, the percentage of heat added which is utilized in evaporation is relatively constant, regardless of the amount of heat added. Annual variations in the percentage of heat utilized for evaporation seem to be unrelated to the steadily increasing amount of heat added to Hyco Lake from 1967-71, but are due rather to variations in climatological and hydrological conditions. In 1971, for example, the outflows from the lake were above average for many months. This resulted in a larger-than-normal percentage of heat being carried away in the outflows. Consequently, the percentage of added heat utilized in evaporation dropped to 44 percent. Over a period of years, or in any average year, climatologically and hydrologically speaking, about 50 percent of any added heat can be expected to be utilized in evaporation from Hyco Lake.

Table 4.--Monthly and annual forced evaporation from Hyco Lake, in inches[1] [2]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total for year
1966					0.39	0.57	0.19	0.19	0.16	[3]0	0.69	0.58	2.77
1967	0.40	0.51	0.05	[3]0	[3]0	[3]0	0.65	0.94	0.95	1.08	1.24	0.72	6.54
1968	0.24	[3]0	0.35	0.87	1.73	1.21	1.98	2.33	1.86	2.64	3.35	2.82	19.38
1969	1.97	2.03	1.70	0.20	0.95	2.04	0.36	3.29	2.52	2.22	1.83	2.68	21.79
1970	2.11	2.07	1.84	3.14	0.41	0.93	1.85	1.45	2.82	1.96	2.16	2.33	23.07
1971	2.30	1.09	0.26	0.55	0.93	1.66	3.38	2.66	2.57	2.63	2.33	1.78	22.14
1972	2.12	1.96											

[1]Monthly values through August 1970 represent the amount of forced evaporation as averaged over the surface area available for cooling up to that time, 3,360 acres. Values from September 1970 are associated with an area of 2,800 acres. At that time, the completion of a dam with a small boat slip at the mouth of South Hyco Creek effectively reduced the surface area available for cooling.

[2]See page preceding abstract for SI equivalents.

[3]The addition of heat to the lake during these months did not result in measurable increase in forced evaporation above natural conditions. It is assumed that the heat added went into storage below the surface.

Table 5.--Comparison of the heat added to Hyco Lake that is utilized in evaporation with results estimated from Harbeck's (1964) technique

Year	Heat added in Btu/ft^2 per year	Percent of heat added to Hyco Lake that is utilized in evaporation		
		Estimated by Harbeck's technique		Actual
		Weather Service data	Hyco Lake data	
1967	96,543	49	50	39
1968	186,798	50	51	59
1969	210,592	48	50	58
1970	238,789	50	52	54
1971	282,739	50	51	44
	AVERAGE	49	51	51

An independent check of this figure by an empirical technique developed by Harbeck (1964), using wind speed and water surface temperatures, showed very close agreement. Harbeck's method was tried using two sets of data. One set utilized average annual wind speed measured 6.56 feet (2.0 m) above the water-surface and water-surface temperatures as measured at Hyco Lake. This is precisely the information upon which his relations are based. The other set used approximations of these parameters from readily available wind speed and water-surface temperatures from the National Weather Service station at the Raleigh-Durham Airport. The close agreement of the two sets of results indicates that Harbeck's technique has practical application in estimating forced evaporation from existing or proposed lakes where no data are available at the site in question.

It is possible, therefore, to develop a relation between the added heat and the resulting forced evaporation from Hyco Lake for "normal" hydrologic and climatologic conditions. This has been done and is shown in figure 12. The relation is approximately linear up to the limits of experience of thermal loading studied thus far, and theoretically will remain so at higher rates of thermal loading. Studies of forced evaporation under phase 4 thermal loading, when three generating units are in operation, may or may not confirm this relationship. It is not known at this time, for example, if the relocated intakes and the system of discharge canals will significantly alter the relations between the various processes of heat dissipation.

Comparisons between natural evaporation, total evaporation, and precipitation

Figure 13 is a comparison between natural evaporation, total evaporation, and precipitation on the lake for 1967-71. Before thermal loading began, the annual natural evaporation was nearly equal to precipitation on the lake. Thus, considering these two processes together, net evaporation was zero. With increased thermal loading, net evaporation increased to a maximum of 12.4 ft^3/s (351 l/s) in 1970. The average was 6.8 ft^3/s (193 l/s) for the entire period.

Even under natural conditions, drawdown of the lake occurs during some low-flow periods when losses from evaporation and outflow exceed gains from inflow and precipitation. For example, the maximum monthly drawdown of the lake between May 1966 and February 1972 was 8.97 inches (228 mm) in September 1968, when inflow was practically nil and precipitation was only 0.5 inch (12.7 mm). Natural evaporation for the month amounted to 5.24 inches (133 mm) and outflow amounted to 2.06 inches (52 mm). Forced evaporation accounted for only 1.67 inches (42.4 mm) of the total drawdown, a low amount for phase 2 in September. Only two generating units were in operation at that time and obviously this amount of forced evaporation would have been significantly more if three or more generating units had been in operation.

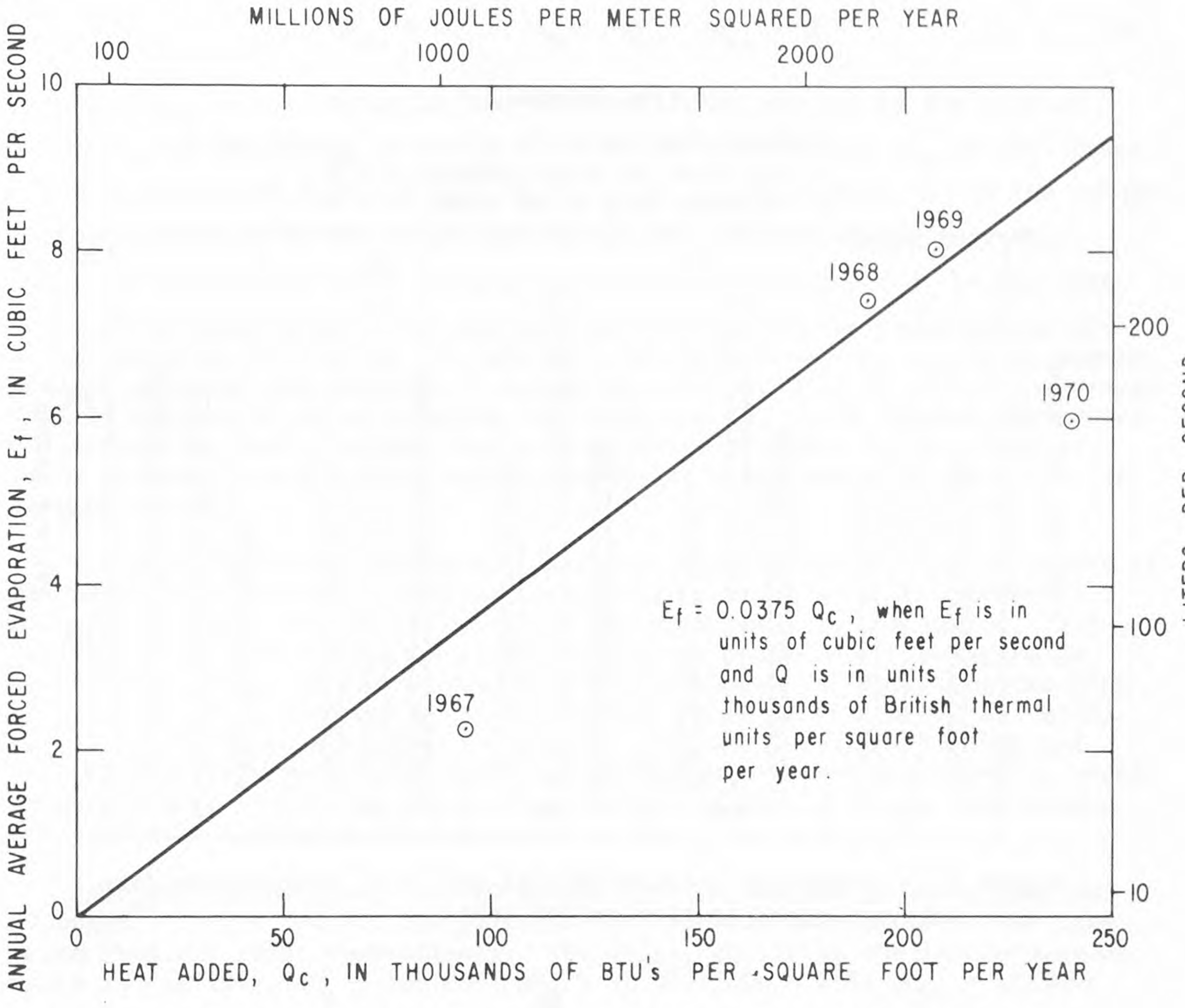

Figure 12.--Relation between the amount of heat added to Hyco Lake and the resulting forced evaporation.

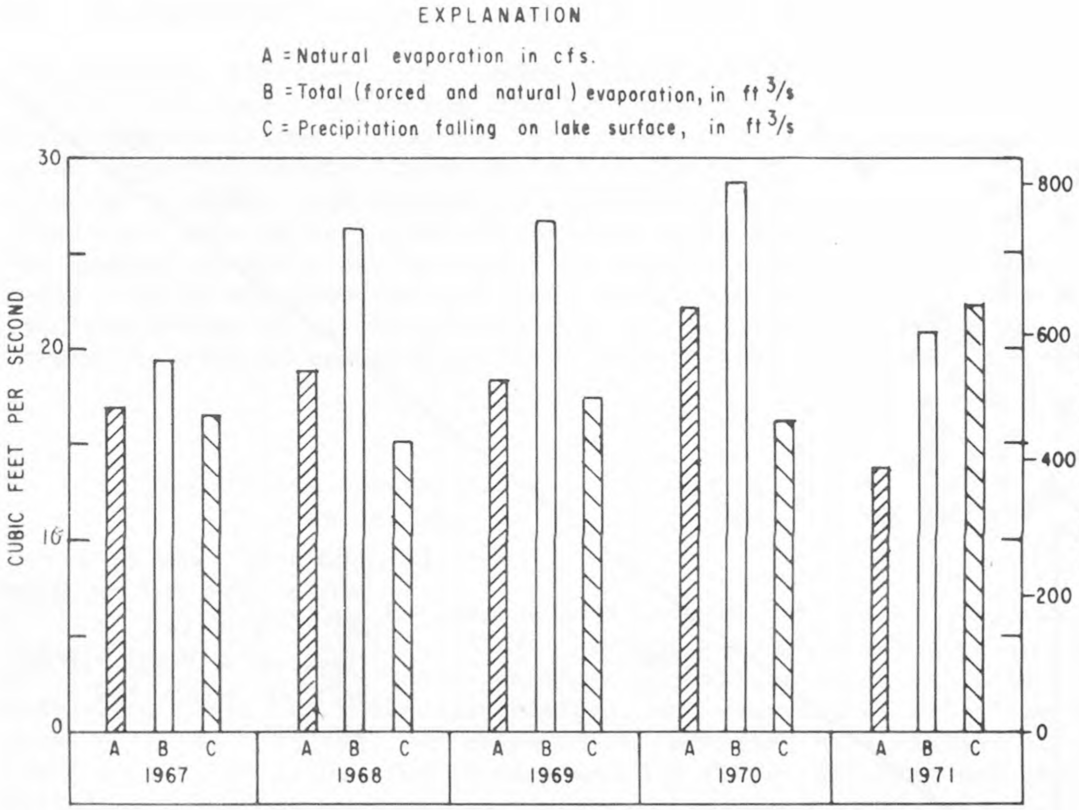

Figure 13.--Comparison between natural and total evaporation from Hyco Lake and precipitation on the lake.

ENERGY BUDGET

Annual Energy Budgets

To check the determinations of forced evaporation and temperature increases of Hyco Lake water, energy budget accountings were made for several years, according to equation 4:

$$\Delta Q_{bs} + \Delta Q_e + \Delta Q_h + \Delta Q_w + \Delta Q_{vo} = Q_c \quad (4)$$

in which ΔQ_{bs} is the change in long-wave radiation emitted by the body of water; ΔQ_e is the change in energy utilized by evaporation; ΔQ_h is the change in energy conducted from the body of water as sensible heat; ΔQ_w is the change in energy advected by the evaporated water; ΔQ_{vo} is the change in energy removed by volumes of water leaving the lake as outflow; and Q_c is the heat added by the power plant. The assumptions involved in the computations are (1) the addition of heat to the lake will not affect the net supply of energy received as solar and atmospheric radiation, (2) nor will it affect the energy added by volumes of water entering the lake, and (3) it is assumed that after equilibrium has been reached, over a long period of time, the increase in energy storage is negligible, except perhaps at times when the plant load is changing rapidly.

The years 1968 and 1969 were chosen for computation because the amount of heat added was relatively constant (both units 1 and 2 were in operation), thus satisfying the third assumption to the greatest possible extent. The results of the energy-budget studies for each year are shown in figure 14. The relative values of the various physical processes in dispersing the heat are expressed in percentage of the total heat added to the lake. All added heat to the lake was accounted for except 4.3 and 9.1 percent in 1968 and 1969, respectively, which is considered to be satisfactory and tends to verify the accuracy of the forced evaporation values and values of the temperature increases over natural conditions.

Over the heated area, 186,800 $Btu/ft^2/yr$ (18,300,000 $joules/m^2/yr$) and 210,600 $Btu/ft^2/yr$ (20,600,000 $joules/m^2/yr$) of heat were added to the lake during 1968 and 1969, respectively. Therefore, utilizing the percentages on figure 14 for 1968, ΔQ_e = 108,000; ΔQ_h = 30,000; ΔQ_w = 800; ΔQ_{bs} = 37,000; and ΔQ_{vo} = 1,500; (all in Btu ft^2/yr). For 1969 they are, ΔQ_e = 121,000; ΔQ_h = 16,400; ΔQ_w = 800; ΔQ_{bs} = 49,000; and ΔQ_{vo} = 2,100.

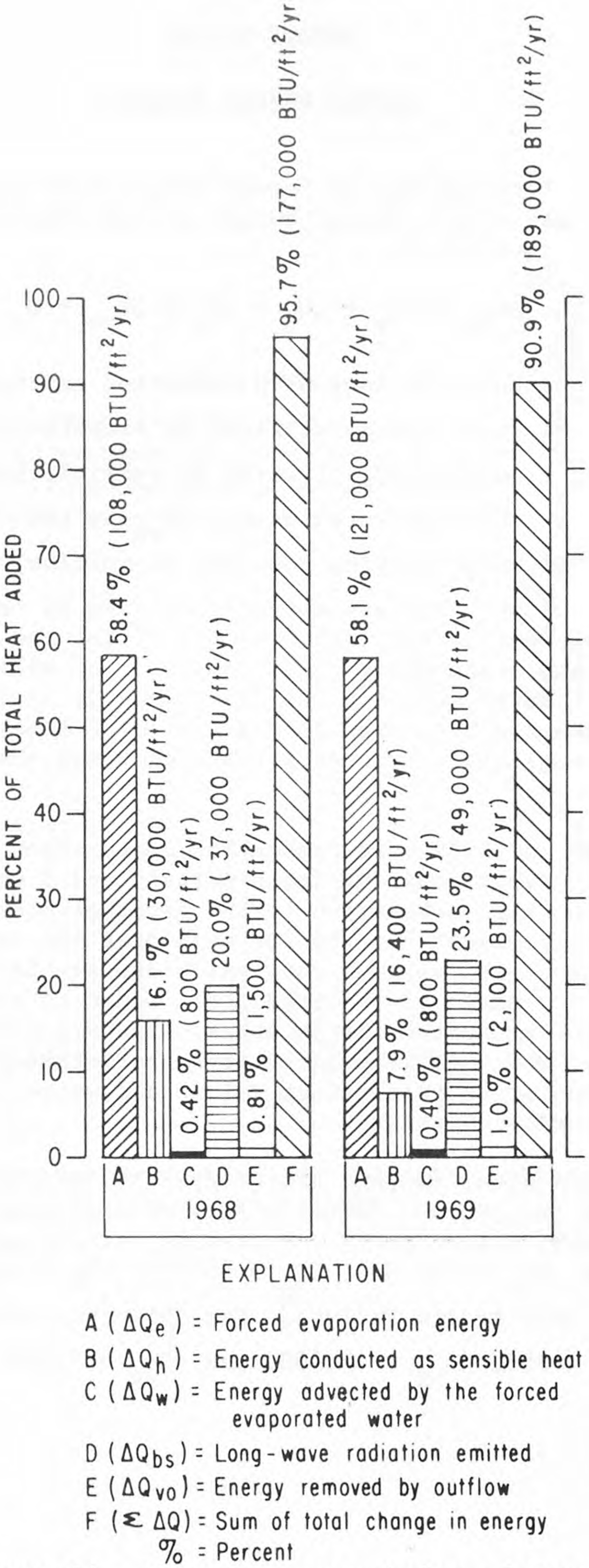

Figure 14.--Change in energy budget of Hyco Lake due to heat added.

Heat Storage

The assumption in equation 4 that over a long period of time the change in energy storage is negligible was not strictly met for Hyco Lake for many periods during the study due to step increases in heat loads, seasonal changes in air and water temperatures, and other less significant factors. To further investigate the changes in energy storage of the lake, we utilized vertical temperature data resulting from 10 surface to bottom surveys made at many locations on the lake during the study. From this data and topographic maps of the lake, we determined the average temperature change over natural conditions corresponding to the lake volumes at 10-foot (3-m) depth intervals for the heated area.

The additional energy due to the added heat was computed for the volume representing each station where the depth temperatures were taken. The increase in energy storage ΔQ_v can be expressed as follows (units: Btu per square foot):

$$\Delta Q_v = mc\Delta T \quad (10)$$

in which m is the mass of the volume, ΔT is the difference in natural lake temperature and temperature of the volume, and c is the specific heat of water. The subsections were summed to give the total heat in storage due to thermal loading for the lake.

The results of the energy storage analyses are summarized in table 6. Our analyses show that the maximum observed amount of energy stored due to thermal loading was 15,890 Btu/ft^2 (156,000 joules/m^2) which occurred on July 18, 1968. This amount was no doubt exceeded at other times for which no detailed surveys are available and certainly will be in the future when thermal loading is increased.

Table 6.--Energy storage due to thermal loading of Hyco Lake[1]

Date of survey	Heated area in millions of ft^2	Energy storage per unit of heated area in Btu/ft^2
10-11-66	144.8	7,060
1-30-68	146.1	3,560
7-18-68	158.9	15,890
12- 3-68	140.4	6,620
3-14-69	147.8	3,910
10-31-70	118.7	5,940
6- 1-71	123.8	9,650
11-17-71	122.8	10,300
2- 9-72	123.4	10,300
3-28-72	122.98	9,330

[1]See page preceding abstract for SI equivalents.

SUMMARY

The thermal loading of Hyco Lake in successive stages from May 1966 to February 1972 has resulted in successively increasing lake water temperatures and forced evaporation from the lake. With respect to increased water temperatures, during the winter months the maximum increases were observed at the lake surface because the tendency of the less dense heated water to "float" is greatest at that time. Near the discharge point of the heated water, the surface temperatures were sometimes 34°F (19°C) higher than natural surface temperatures and, in December 1969 the average monthly surface temperature of the area affected by the heated water was at a maximum of 12°F (6.7 C) over natural temperatures. In the summer, the maximum temperature increases occur at depth and may be 30°F (16.6 C) or more over natural conditions at places near the lake bottom. Apparently, the natural summer thermocline in the lake allows for more thorough vertical mixing of the heated water.

Forced evaporation from the heated part of the lake increased steadily as more heat was added, reaching a maximum of 23.1 inches (587 mm) in 1970, in addition to 55.6 inches (1,412 mm) of natural evaporation for that year. As heat is added in increasing amounts to the lake, forced evaporation will continue to increase. For Hyco Lake, about 50 percent of any added heat is utilized for evaporation, and the rest is dissipated by other processes, including back radiation and conduction of heat to the atmosphere, removal of heat through outflow from the lake, and heat advected by the evaporated water.

Energy budgets for the years 1968 and 1969 show that evaporation, back radiation, and conduction are the most significant of the processes of heat dissipation. In 1969, heat added to the lake amounted to 210,592 Btu/ft^2 (20,600,000 joules/m^2) over the affected lake area (about 3,360 acres or 1,360 hm^2) of which 58.1 percent was utilized in evaporation, 23.5 percent was radiated to the atmosphere, and 7.9 percent was lost through conduction as sensible heat. Only about one percent of the heat was removed in the outflow.

Since February 1972, the cutoff date for data analyzed for this report, there have been major changes in the amount and manner of thermal loading of Hyco Lake. A new 720 mw generating unit went on line in July 1973. At the same time, the maximum cooling water flow rate was increased from 862 ft^3/s to 1,442 ft^3/s (24,400 to 40,800 l/s) and a new system of discharge canals went into operation which will probably distribute the heat more evenly throughout the lake. Also, an afterbay to further cool water leaving Hyco Lake in the outflow is under construction below the dam. It is not precisely known at this time how these changes will affect the heat distribution in the lake and the resultant temperature patterns and forced evaporation. We propose to document these effects in a subsequent study of temperature and evaporation from Hyco Lake, utilizing data from March 1972 until early 1975. This will allow adequate time to assess the effects of the third generating unit and the revised cooling water flow system. At the end of that time a final report on the effects of thermal loading on Hyco Lake temperatures and evaporation will be prepared.

REFERENCES

Harbeck, G. E., 1962, A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory: U.S. Geol. Survey Prof. Paper 272-E, p. 101-105.

Harbeck, G. E., Jr., 1964, Estimating forced evaporation from cooling ponds: Jour. of the Power Division, Am. Soc. Civil Engineers Proc., v. 90, no. P03, October, p. 1-9.

Jobson, H. E., 1972, Effect of using averaged data on the computed evaporation: Am. Geophys. Union Trans., v. 8, no. 2, p. 513-518.

Marciano, J. J., and Harbeck, G. E., 1954, Mass-transfer studies in Water-loss investigations: Lake Hefner studies, technical report: U.S. Geol. Survey Prof. Paper 269, 158 p.

Yonts, W. L., Giese, G. L., and Hubbard, E. F., 1973, Evaporation from Lake Michie, North Carolina, 1961-71: U.S. Geol. Survey Water-Resources Inv. 38-73, 27 p.