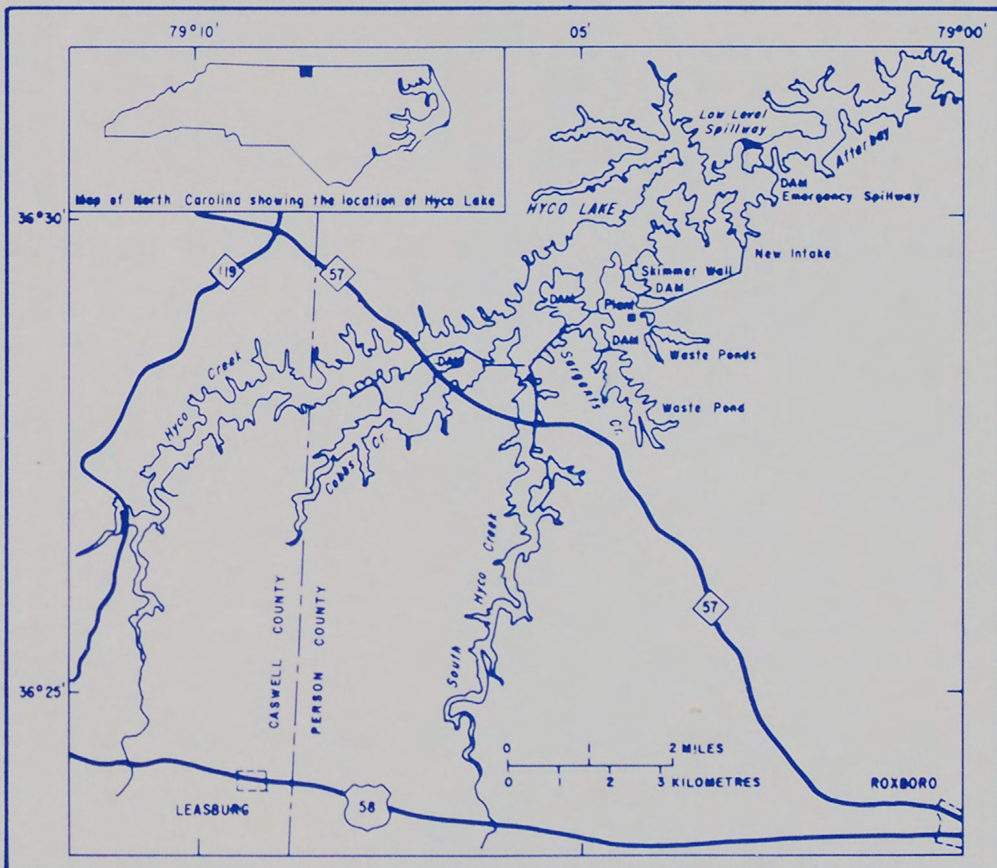
THERMAL LOADING OF HYCO LAKE, NORTH CAROLINA

The effect of heated water on temperature and evaporation, 1966-74



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WATER RESOURCES INVESTIGATIONS 76-48

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UNITED STATES DEPARTMENT OF THE INTERIOR

Thomas S. Kleppe, Secretary

GEOLOGICAL SURVEY

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May 1976

PREFACE

This is the final report on the effects of thermal loading on the temperature and evaporation of Hyco Lake. This report describes the effects of thermal loading through the years 1966-1974. A previous report (Yonts and Giese, 1974) described the effects of thermal loading through 1972. This earlier report contains much valuable information regarding the general mechanics of thermal loading; however, a large error in determination of the surface area of the lake invalidates the mass-transfer coefficient, the tables of natural and forced evaporation, and the tables of average increases in lake surface temperature; still valid are maps showing lines of equal surface temperature increase and temperature profiles. Recent determinations from U.S. Geological Survey 7.5-minute topographic maps show that the surface area of Hyco Lake is about 4,350 acres (1,760 hectares)--600 acres (240 hectares) larger than the 3,750 acres (1,520 hectares) used by Yonts and Giese.

In addition, the use of a computer enabled evaporation rates given in this report to be determined by a more accurate method involving daily values of wind speed and vapor pressures instead of adjusted monthly values.

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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	millimetres (mm)
feet (ft)	.3048	metres (m)
miles (mi)	1.609	kilometres (km)
square feet (ft^2)	.0929	square metres (m^2)
acres	.4047	hectares (ha)
square miles (mi^2)	2.59	square kilometres (km^2)
acre-feet (acre-ft)	1.233×10^{-3}	cubic hectometres (hm^3)
cubic feet per second (ft^3/s)	28.32	litres 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.

THERMAL LOADING OF HYCO LAKE, NORTH CAROLINA

The effect of heated water on temperature and evaporation, 1966-74

By G. L. Giese

ABSTRACT

Between May 1966 and December 1974, four phases of thermal loading from three steam-electric generators have resulted in higher temperatures and increased evaporation from Hyco Lake, a 4,350 acre (1,760 hectares) reservoir in north-central North Carolina. Average thermal loads during phases 1-4 were, respectively, 1.1, 2.6, 2.9, and 3.9 trillion British thermal units per month (1.2×10^{15}, 2.7×10^{15}, 3.1×10^{15}, and 4.1×10^{15} joules per month). Average monthly surface temperature increases during phases 1-4 were 2.4, 5.1, 5.0, and 5.8 degrees Fahrenheit (1.3, 2.8, 2.8, and 3.2 degrees Celsius), while average monthly forced evaporation was 2.9, 8.0, 8.4, and 9.9 cubic feet per second (84, 230, 240, and 280 litres per second), respectively. These values compare with an average annual natural lake surface temperature of 62.5 degrees Fahrenheit (16.9 degrees Celsius) and average annual natural evaporation of 37 inches (940 millimetres) or 18.4 cubic feet per second (521 litres per second).

Maximum forced evaporation tends to occur in the summer, although the maximum evaporation of any given year may occur in any month. The maximum monthly forced evaporation which occurred during the study was 3.7 inches (94 millimetres), or 21 cubic feet per second (590 litres per second), in March 1974, under phase 4 loading conditions.

Before July 1973, only parts of the lake were affected by heated water. At that time a six-mile-(10-kilometre) long canal system was completed, and it distributed heated water to several discharge points, causing the entire lake to be thermally loaded. Large quantities of heat, about 1.1 trillion British thermal units per month (1.2×10^{15} joules per month) are dissipated in the canal system itself before the heated water

reaches the lake. Consequently, average lake-surface temperatures are 2.2 to 4.2 degrees Fahrenheit (1.2 to 2.3 degrees Celsius) cooler than they would have been without the new canal system. Also, an average of about 4.1 cubic feet per second (116 litres per second) of water is evaporated from the canal system, which represents a permanent loss of water to the lake in addition to the 9.9 cubic feet per second (280 litres per second) of forced evaporation and the 18.4 cubic feet per second (535 litres per second) of natural evaporation from the lake itself.

Regarding future development of Hyco Lake for cooling purposes, it is possible that the planned utilization of cooling towers for disposing of excess heat may lead to excessive drawdowns of reservoir levels (greater than 5 feet) during some low-flow periods. Even without cooling towers, drawdown may be a problem when the fourth 720 mw generating unit is completed and becomes operational. Without cooling towers, the planned fourth 720 mw unit would increase the average surface temperature by 1-2 degrees Fahrenheit (0.6 - 1.1 degrees Celsius). However, with the planned cooling towers in operation, surface temperatures of the lake could be reduced by 5 degrees Fahrenheit (2.8 degrees Celsius) or more.

INTRODUCTION

Purpose and Scope

In 1964, the Carolina Power and Light Company (CP&L) completed construction of a dam on the Hyco River in Person County, North Carolina, thus creating the 4,350-acre (1,760 hectare) Hyco Lake. (See location map, fig. 1). The lake serves as a cooling pond for a series of coal-fired steam-electric generating units (known collectively as the Roxboro Plant). The several generating units have been built over a period of years and several schemes for thermal loading were used. First, the heated water was discharged into the lake through a single canal discharging at one location and, later, it was discharged through an extensive canal system releasing water at several points.

Even before completion of the dam in 1964, both CP&L and North Carolina State officials recognized the need to develop a better understanding of the effects of the thermal loading on the lake. Because of the complexity of the thermal loading, existing theoretical models could provide only a rough approximation of these effects. In 1964 the U.S. Geological Survey undertook a study in cooperation with the North Carolina Department of Water Resources (now (1975) a part of the Department of Natural and Economic Resources) to document and evaluate the effects of thermal loading on the temperature and evaporation of Hyco Lake.

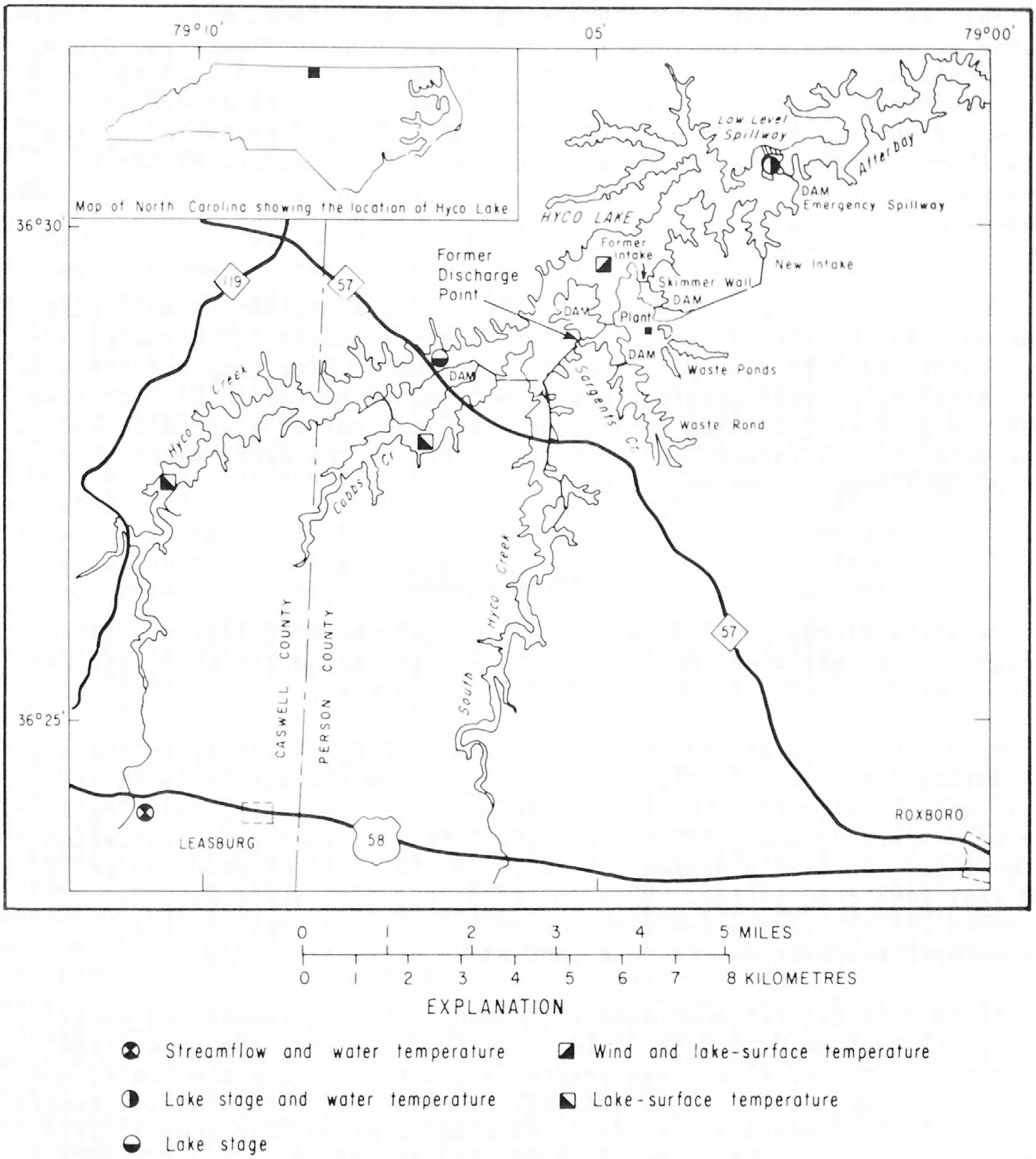


Figure 1.--Hyco Lake, location of recorders, and cooling system.

This report contains the final results of the study, based on observations of the lake during 1964-74. An earlier report (Yonts and Giese, 1974) contained preliminary data on the effects of thermal loading based on observations through February 1972, but that report is superseded because of revised methodology and a more accurate determination of the surface area of the lake. Determinations from U.S. Geological Survey 7.5-minute topographic maps (1968) show that the surface area of Hyco Lake is about 4,350 acres (1,760 ha). The previously published figure of 3,750 acres (1,520 ha) should not be applied.

This report describes the temperature and evaporation of Hyco Lake under natural conditions and under four distinct phases of thermal loading. Information is also provided about how much water temperatures have been raised by thermal loading, how much forced evaporation has occurred under the different loading conditions, how much forced evaporation could be expected in the future, and what the effect of the canal system has been on lake evaporation and temperature.

General Hydrology

Detailed discussions of various aspects of the hydrology are given throughout the text where pertinent. To set the stage for these discussions a brief summary of the hydrology is given here.

Precipitation averaged about 41 inches (1,040 mm) yearly in the study area during 1964-73, slightly below the long-term average of 45 inches (1,140 mm). Inflow from the 189 square-mile (490 km^2) area draining into Hyco Lake averaged about 175 ft^3/s (4,960 l/s), including precipitation on the lake. Outflow averaged 145 ft^3/s (4,110 l/s), or about 30 ft^3/s (850 l/s) less than inflow. This 30 ft^3/s (850 l/s) difference is accounted for by evaporation from the surface of the lake--including both natural evaporation and that induced by thermal loading.

Flows vary greatly according to season. In late summer and early fall, outflows from Hyco Lake of 10 ft^3/s (280 l/s) or less were often recorded. At times, inflow was practically zero. During the winter and spring, flows were often above average. The largest daily outflow recorded during 1964-74 was 8,570 ft^3/s (2.43×10^5 l/s) on September 7, 1974. This flow was the result of nearly 3 inches (76 mm) of rain which fell during the preceding week. This rain included 1.2 inches (30 mm) on September 6.

History of Thermal Loading, 1964-73

The addition of heated water to Hyco Lake in discrete phases presented a unique opportunity to study the lake response over a wide range of thermal conditions, both natural and induced, and to develop relations between the added heat and the increased evaporation and temperature of the lake.

The completion of the dam on the Hyco River in 1964 in north-central North Carolina near Roxboro created Hyco Lake. The dam is a rolled-earth structure approximately 1,600 feet (488 m) long and 70 feet (21 m) high. Excess water cascades over a concrete low-level spillway apron 600 feet (183 m) wide and 1,000 feet (305 m) long. Hyco Lake has an irregular shape, is 10 miles (16 km) long, and lies in sparsely populated areas of Person and Caswell Counties. At elevation 409.76 feet (124.89 m), the top of the low level spillway, the lake capacity is about 80,000 acre-feet (100 hm^3) and the surface area is 4,350 acres (1,760 ha). The average lake depth is 20 feet (6.1 m) and the maximum depth is 50 feet (15 m) at the dam. An emergency spillway near the southeast end of the dam is designed to function during floods greater than the 50-year flood. A controlled release channel (elevation 400.00 feet (121.92 m) MSL) with sluice gates to regulate releases is at the southeast end of the dam. This channel is normally used only when the lake level falls below 409.76 feet (124.89 m) MSL and required releases are no longer met by water falling over the concrete spillway apron.

Hyco Lake first filled to spillway level in March 1965. The addition of heated water began in May 1966 when the first 385 megawatt (mw) generating unit went into operation, marking the first phase of thermal loading. (See table 1.) At that time, as much as 365 ft^3/s (10,340 l/s) of water was drawn from the lake under a skimmer wall (See figure 1.) located just northeast of the plant. This water was circulated through the plant condensers where it picked up excess heat and was then discharged just west of the plant through a man-made bay and then into the lake at a point labelled "former discharge point" on figure 1. From there, heated water circulated and spread out over much of the available surface of the lake. At that time only 3,900 acres (1,578 ha) of the lake surface were available for cooling because a porous dam constructed at the mouth of Cobbs Creek blocked the movement of heated water into that area. Part of the excess heat went into storage in the lake, part was removed by outflow, part by long-wave radiation to the atmosphere, part by direct conduction, part by advection--but the largest part (fifty percent) was utilized in the process of evaporation. This general pattern of thermal loading continued from May 1966 through February 1968.

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 ft^3/s	Surface area of lake available for cooling, in acres
1	May 1966 through February 1968	Unit 1	385	365	3,900
2	March 1968 through August 1970	Units 1 and 2	1,055	862	3,900
3	September 1970 through mid-July 1973	Units 1 and 2	1,055	862	3,330
4	mid-July 1973-	Units 1, 2, & 3	1,775	1,442	4,230

[1]See page preceding abstract for SI equivalents.

In March 1968, a second generating unit of 670 mw capacity began operation. Added pumping capacity increased the maximum cooling water flow rate to 862 ft^3/s (24,410 l/s). This marked a second phase of increased thermal loading which continued through August 1970.

In September 1970, the third phase began when the completion of a dam with a small boat slip at the mouth of South Hyco Creek inhibited the movement of heated water into that area. This reduced the effective lake area available for cooling to 3,330 acres (1,350 ha), resulting in local increases in temperature and evaporation above those observed under similar thermal loads during the second phase of development.

Present Pattern of Thermal Loading, 1973-76

The third phase of development continued until mid-July, 1973, when a number of changes took place, ushering in the fourth phase of development. At that time, a third generating unit of 720 mw capacity, began operation. Simultaneously, a network of canals (fig. 1) totalling about six miles in length was utilized to distribute the heat more evenly throughout the lake. This increased the effective lake surface area available for cooling to 4,230 acres (1,710 hm^2), virtually the entire lake surface. The maximum cooling-water flow rate was increased at this time to 1,442 ft^3/s (40,830 l/s). Also, the cooling water intake was relocated to a point one and one-half miles (2.4 km) northeast of its former location. (See fig. 1.) This relocation had the effect of lengthening the flow path of the recirculating cooling water and allowing it more time to cool before being reused. These changes define the loading conditions during the fourth phase of development.

Figure 2 shows the direction of flow of the cooling water through the canal system and the lake during the fourth phase of development. Actually, much of the canal system is composed of dikes and levees built across numerous small inlets. Some of the isolated inlets are shown in figure 2 along the east side of South Hyco Creek just north of State Highway 57. As a result, the original lake area of 4,350 acres (1,760 hm^2) was reduced by about 120 acres (49 hm^2).

Heated water leaving the plant moves through the canal system to a point at the mouth of South Hyco Creek. About two-thirds of the heated water is diverted through an inverted siphon under the mouth of South Hyco Creek and into a canal which discharges into the Cobbs Creek arm of the lake. Because of the dam at the mouth of Cobbs Creek, the heated water is prevented from moving directly out of this arm of the lake. Instead, it moves midway up the arm and then enters another canal connecting Cobbs Creek to Hyco Creek. Meanwhile, the remaining one-third of the heated water travels along the right bank of South Hyco Creek, finally discharging into this arm about one and one-half miles from its mouth. The

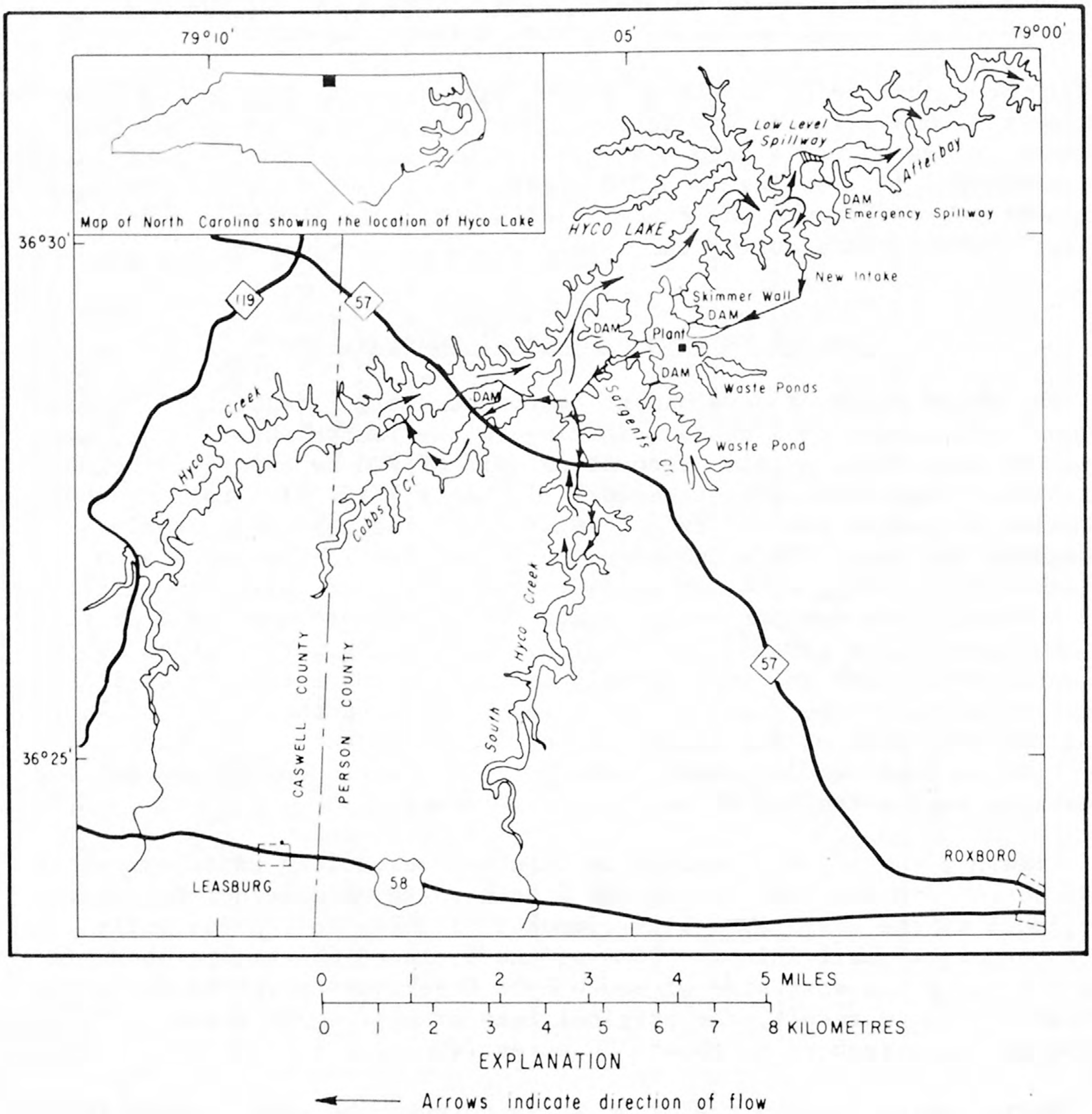


Figure 2.--Generalized cooling-water flow path during phase 4 of thermal loading.

heated water travels towards the mouth of South Hyco, through a narrow boat slip over the inverted siphon, and joins with heated water from the Hyco Creek arm of the lake. The heated water then moves through the main body of the lake towards the dam. Most of this water is drawn in by the plant intake near the dam and recirculated through the plant. On the average, only about 10 percent of the circulating water flows over or through the dam. During its journey through the lake, the heated water may be cooled by as much as 30°F (17°C) or more by evaporation, conduction, back radiation, advection, and mixing with natural lake water.

A 650-acre (260 ha) afterbay reservoir below the dam, completed in May 1974, provides additional storage (about 12,000 acre-feet or 1.5×10^7 hm^3) to further cool the water released downstream and to maintain the State-required low-flow releases of 11 ft^3/s (311 l/s) during the summer and fall. This eliminates the need to draw down the main lake during low-flow periods, thus preserving more lake water for cooling purposes.

Future Plans for Development, 1976-81

CP&L plans to construct a series of cooling towers at the Roxboro Plant; a cooling tower for the third generating unit is scheduled for completion in 1976. A fourth generating unit at the Roxboro Plant is planned for completion and to be in service by March, 1980. This unit, which will be 720 mw, will come in service with cooling towers and will boost the total generating capacity to 2,495 mw. CP&L has no other plans at present for further additions to the Roxboro Plant. In general, the future of coal-fired generating plants seems secure. The United States has sufficient resources of recoverable coal to meet energy demands for centuries (U.S. Bureau of Mines, Bull. 650, 1970, p. 24). As other energy sources are depleted or become relatively expensive, coal will continue to be used, and the possibility of adding a fifth unit at the Roxboro Plant to meet future demands may seem attractive.

Analysis

Data used

Figure 1 shows the location of continuous recorders where data on streamflow, water temperature, lake stage, and wind speed were collected by the U.S. Geological Survey during 1964-74. These data were used to determine lake temperatures and the natural and forced evaporation from Hyco Lake. In addition, 65 comprehensive one-day field surveys were made to define the spatial distribution of lake temperatures. During these field surveys, temperature observations were made at 76 points on the lake surface, and a number of vertical temperature profiles were made to determine the extent of thermal stratification.

In addition to data collected by the Geological Survey, heat loads and temperatures of the condenser water were supplied by CP&L on a monthly basis. Daily climatological data on precipitation, relative humidity, and air temperatures were taken from the records of the National Weather Service Station at the Raleigh-Durham Airport.

Methodology

Surface temperatures measured during the comprehensive thermal surveys were related to surface temperatures at continuous recorders located at the dam, mid-lake, and in Cobbs Creek, in order to generate average daily lake surface temperatures for heated and unheated conditions of Hyco Lake. These temperature data were also used to define the distribution of lake-surface temperatures during the four phases of thermal loading. Until July 1973, Cobbs Creek was practically unaffected by heated water and temperatures at the raft station located there reflected natural lake surface temperatures. The data at Cobbs Creek were used to develop a relation between natural temperatures in nearby Lake Michie and natural temperatures in Hyco Lake. Lake Michie is a 480-acre (190 ha) lake, located about 20 miles (33 km) south of Hyco Lake, at which the Survey conducted studies of evaporation and temperature during 1961-71 (Yonts and others, 1973). After the canal system began distributing heated water into Cobbs Creek, natural lake temperatures were estimated from daily observed values of surface temperatures in Lake Michie and the relation $T_H = T_M - 1.6$, where T_H is Hyco Lake natural temperature and T_M is Lake Michie natural temperature, both in degrees Fahrenheit. The standard error of this relation was found to be no more than $\pm$ (1.1°C).

Natural and forced evaporation were determined by application of the mass-transfer equation suggested by Harbeck (1962, p. 101):

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

where N, called the mass-transfer coefficient, is unique for a given lake; μ is 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.

The mass-transfer coefficient, N, was determined by a calibration process utilizing residuals from a water budget for Hyco Lake. The process is described in detail by Turner (1966, p. 141), but the equations simplify to:

$$\Delta H_A = E \pm \delta, \text{ or, } \Delta H_A = N\mu\ (e_o - e_a) \pm \delta \qquad (2)$$

where ΔH_A is the average rate of change of the water-surface elevation adjusted for inflow, outflow, and precipitation; δ is net ground-water seepage (positive when the lake is losing water to the ground and negative when the lake is gaining from the ground); N, μ, e_o, and e_a are as defined under equation 1. The derivation of N is discussed later in the section on evaporation, but was determined to be 0.00228, for use in computing evaporation in inches per day when ΔH_A is in feet per day, μ is in miles per hour, and e_o and e_a are in millibars.

A computer program was written in Fortran IV by F. E. Arteaga of the U.S. Geological Survey to compute daily and monthly values of natural and forced evaporation from daily values of wind speed, lake temperatures, air temperatures, and relative humidity. The results, based on all four phases of development, are presented in the following sections of this report.

EFFECTS OF ADDED HEAT ON TEMPERATURE

The average natural surface temperature of Hyco Lake varies from about 85°F (29°C) in July to about 42°F (5.6°C) in January. The average annual natural lake-surface temperature is about 63°F (17°C). Table 2 at the end of the report gives monthly values of average natural lake-surface temperatures from May 1966 to December 1974. In 1965 and 1966, before thermal loading, the natural variation in temperatures over the surface of the lake was only about 5°F (2.8°C) in the summer--the upper reaches of the lake fingers being several degrees warmer than the middle areas of the lake. In winter, the natural variation was even less, typically only one or two degrees Fahrenheit (0.6 - 1.1°C). Again, the upper reaches of the lake fingers were slightly warmer.

During the summer a vertical temperature gradient becomes established as the upper layers of the lake are heated more than the deeper layers. The vertical variations are greatest in the deeper parts of the lake, near the dam, where the surface temperature may be 85°F (29°C) while the bottom temperature may be 50°F (10°C). In the winter, when the lake surface is cooled to temperatures below those existing at greater depths, density differences cause the layers to become thoroughly mixed because the cooler, more dense surface water sinks and displaces the warmer water below. Thus, temperatures become nearly uniform from top to bottom. In the spring, the surface temperature begins to increase and a vertical temperature gradient is established again.

Typical temperatures under both natural and thermally loaded conditions are shown in figure 3, which compares typical summer and winter temperature profiles. The situations portrayed here apply generally to all four phases of thermal loading. During the winter, some thermal stratification is created where none would have existed under natural conditions, because the heated water tends to float on the cooler more-dense unheated lake water. Hence, the greatest water temperature increases over natural conditions occur at the surface and become progressively less at depth. During the summer, the heated water mixes more thoroughly with the lake water and in fact, the greatest summer temperature increases over natural conditions occur at depth. With this knowledge of natural temperature conditions in the lake and the general effects of thermal loading on them, it is appropriate to discuss in more detail the actual changes that have occurred in the lake, particularly during the most recent phases of development.

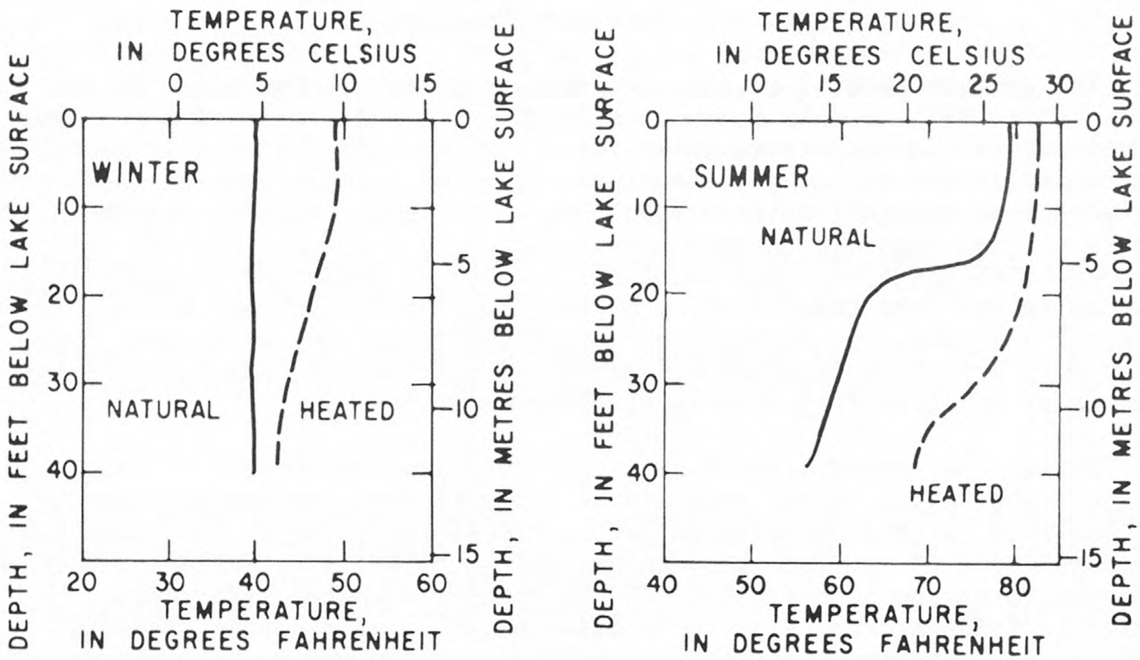


Figure 3.--Comparison of typical summer and winter lake temperature profiles under natural and heated conditions.

Surface Temperatures

Figure 4 compares the heat added to Hyco Lake with the resultant increases in lake-surface temperature during 1966-74. Tables 3 and 7 summarize this information in tabular form. The obvious step increases in heat load in March 1968 and again in July 1973 reflect the beginning of operation of the second (670 mw) and the third (720 mw) generating units. Other month to month variations in heat load are caused by the rise and fall of monthly power generation at the Roxboro Plant, which in turn is influenced by both customer demand and the pattern of operation of other generating plants within the CP&L system. There is no clear repetitive pattern in these monthly variations except for a rather steep drop in heat load every spring which is related to a combination of low power demand and planned outages for maintenance (Bert Tandy, CP&L official, oral commun., 1975).

By comparison, lake surface temperature increases show a marked cycle of maximum increases in winter and minimum increases in summer. For example, during calendar year 1974, the increase over natural temperature of the lake surface averaged 8.7°F (4.8°C) during the colder months of January through April and November and December. During the warmer months of May through October of 1974, increases averaged 5.5°F (3.1°C). This cycle is caused partly by the aforementioned tendency of the heated water to float in the winter and to mix more thoroughly at depth in the summer. It is also due to the fact that at lower winter temperatures the processes of heat dissipation are less efficient and a larger temperature differential is required to dissipate a given amount of heat.

Surface temperatures generally increase with increased heat load, although this may not be easily discerned from figure 4. Figure 5 shows this much more clearly. It is a plot of average heat load and average increase of lake-surface temperature for each phase of thermal loading. The average increase in lake-surface temperatures rose from about 2.4°F (1.3°C) when only the first generating unit was in operation (phase 1), to about 5.1°F (2.8°C) after the second unit became operational (phase 2). Then a curious thing happened. Even though the average heat load during phase 3 was higher than during phase 2, the average increase in surface temperature over natural conditions was slightly less than during phase 2. The most likely cause of this unexpected drop in average lake-surface temperature is related to the reduction in lake surface area available for cooling from 3,900 acres (1,580 hm^2) to 3,330 acres (1,350 hm^2) by the completion of a dam with a small boat slip at the mouth of the South Hyco arm of the lake. The heated water, being restricted to a smaller area of the lake, is at a higher temperature than it would be if it were able to spread out. All processes of heat dissipation, but particularly evaporation, are more efficient at high temperatures than at low temperatures. Therefore, more rapid heat loss occurs to the atmosphere from the 3,300 acres (1,350 hm^2) than if the same amount of heated water were allowed to

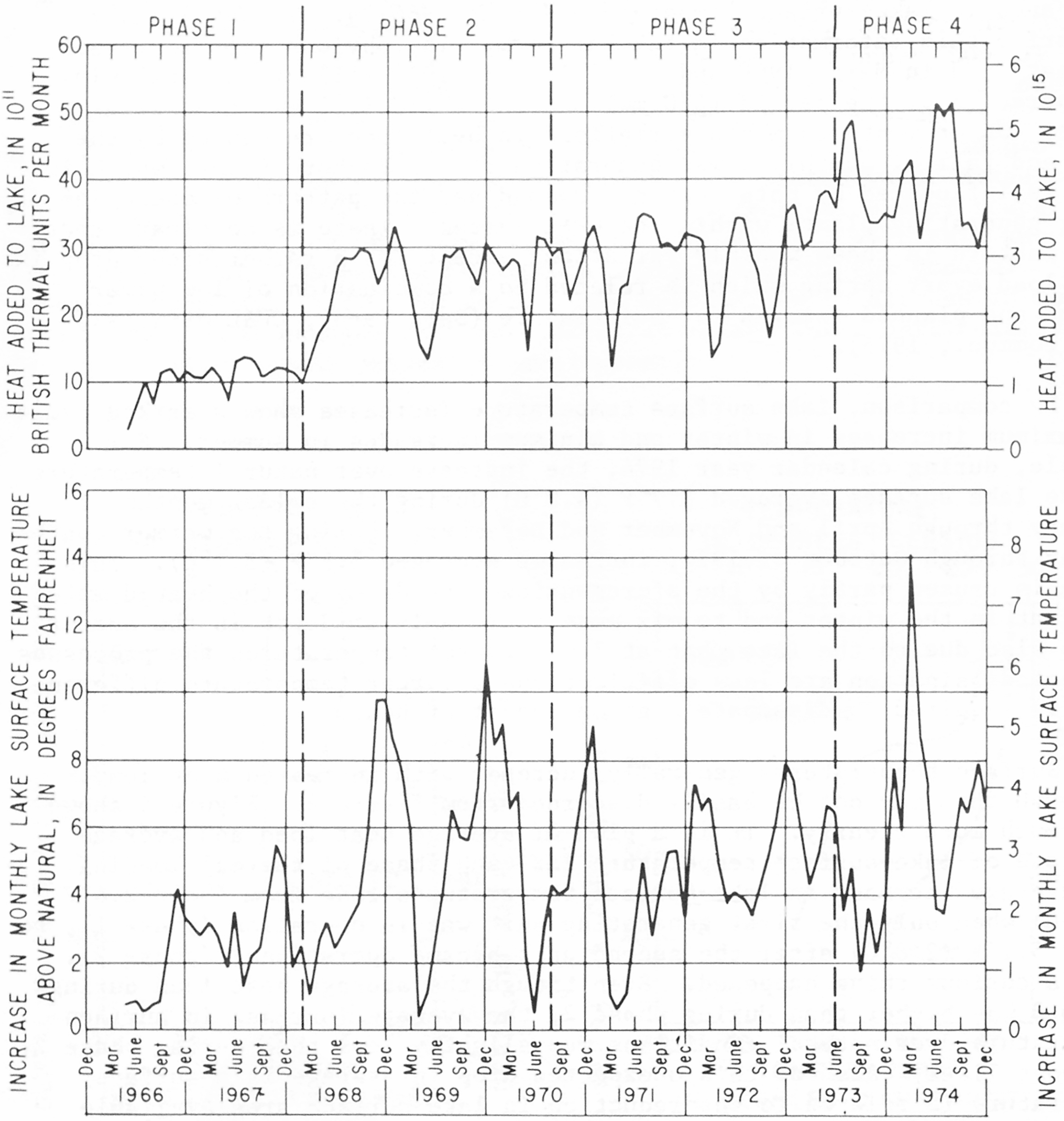


Figure 4.--Average monthly heat load and surface temperature increase above natural conditions, 1966-74.

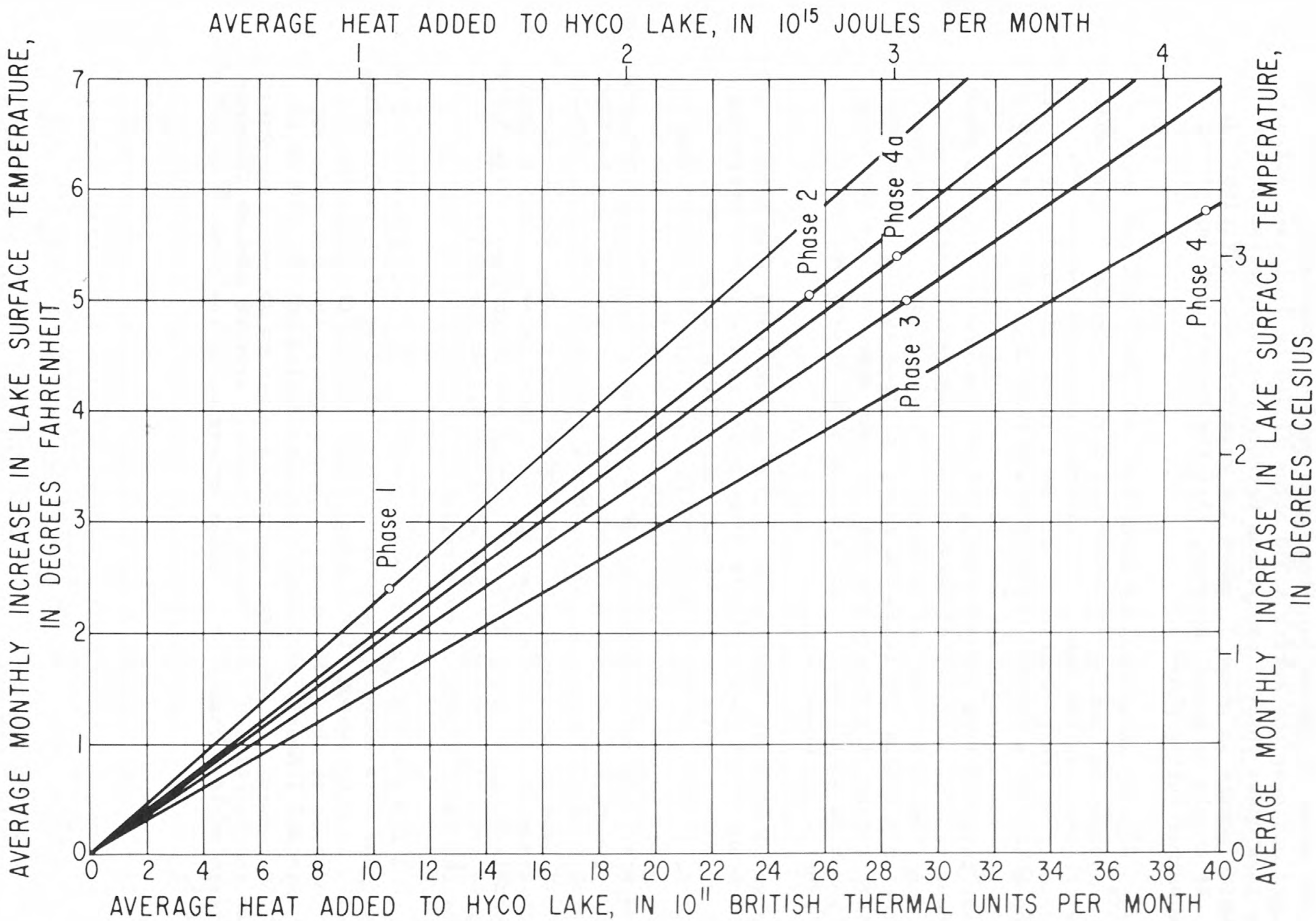


Figure 5.--Relation of added heat to average increases in lake-surface temperature for phases 1, 2, 3, and 4 of thermal loading.

occupy 3,900 acres (1,580 hm^2). Thus, when surface temperature increases are averaged out over the entire 4,350 acres (1,760 hm^2) of lake surface, they were less under phase 3 conditions because the restriction on the mixing, which occurs in phase 3, makes the reservoir more efficient for cooling. It should be added, however, that the heated portions of the lake were warmer during phase 3.

During phase 4, an average of about 1.1 trillion Btu's per month (1.2 x 10^{15} joules per month) of added heat were dissipated in the canal system before reaching the lake. This is equivalent to the increase in heat rejected from the generating plants as a result of adding the fourth generating unit. As a result, the heat loads reaching the lake proper were about the same during phase 4 as they were during phase 3, even though heat rejected from the generating plants was more. Figure 5 shows a much lower rate of increase of lake-surface temperature per unit of heat added during phase 4 as compared to phase 3. However, because the heat lost in the canals does not reach the lake, the true rate of increase of surface temperature of the lake per unit of heat added to the lake is as shown by phase 4a on figure 5. This rate is about midway between the rates of phase 2 and phase 3.

The heat lost in the canal distribution system results in temperature drops of 5.4 and 7.2°F (3 to 4°C) from the plant to the points where the heated water enters South Hyco Creek and Cobbs Creek, respectively. In addition, the temperature drops another 1.8°F (1°C) in the short canal from Cobbs Creek to North Hyco Creek. The total heat losses in the canal system, as previously mentioned, average about 1.1 trillion Btu's per month (1.2 x 10^{15} joules per month). This amounts to 28 percent of the average phase 4 heat load of about 3.9 trillion Btu's per month (4.1 x 10^{15} joules per month). Were it not for these heat losses in the canal system, the average increase in lake surface temperatures under phase 4 loading conditions probably would be about 7 to 9°F (3.9 to 5.0°C) instead of the 5.8°F (3.2°C) rise actually observed. (See also the discussion about the effects of the canal system on evaporation.)

Figure 6 shows monthly gross power generation plotted against monthly heat load. The data appears homogeneous from one phase of thermal loading to another. In other words, the thermal efficiency of the plant has remained constant at about 34 percent. This suggests that the relation could be extended linearly when the fourth generating unit of 720 mw is added in the future. If the canal distribution system is still in operation, then the relation of heat added to monthly average surface temperature increase would probably be a linear extension of the phase 4 relation of figure 5.

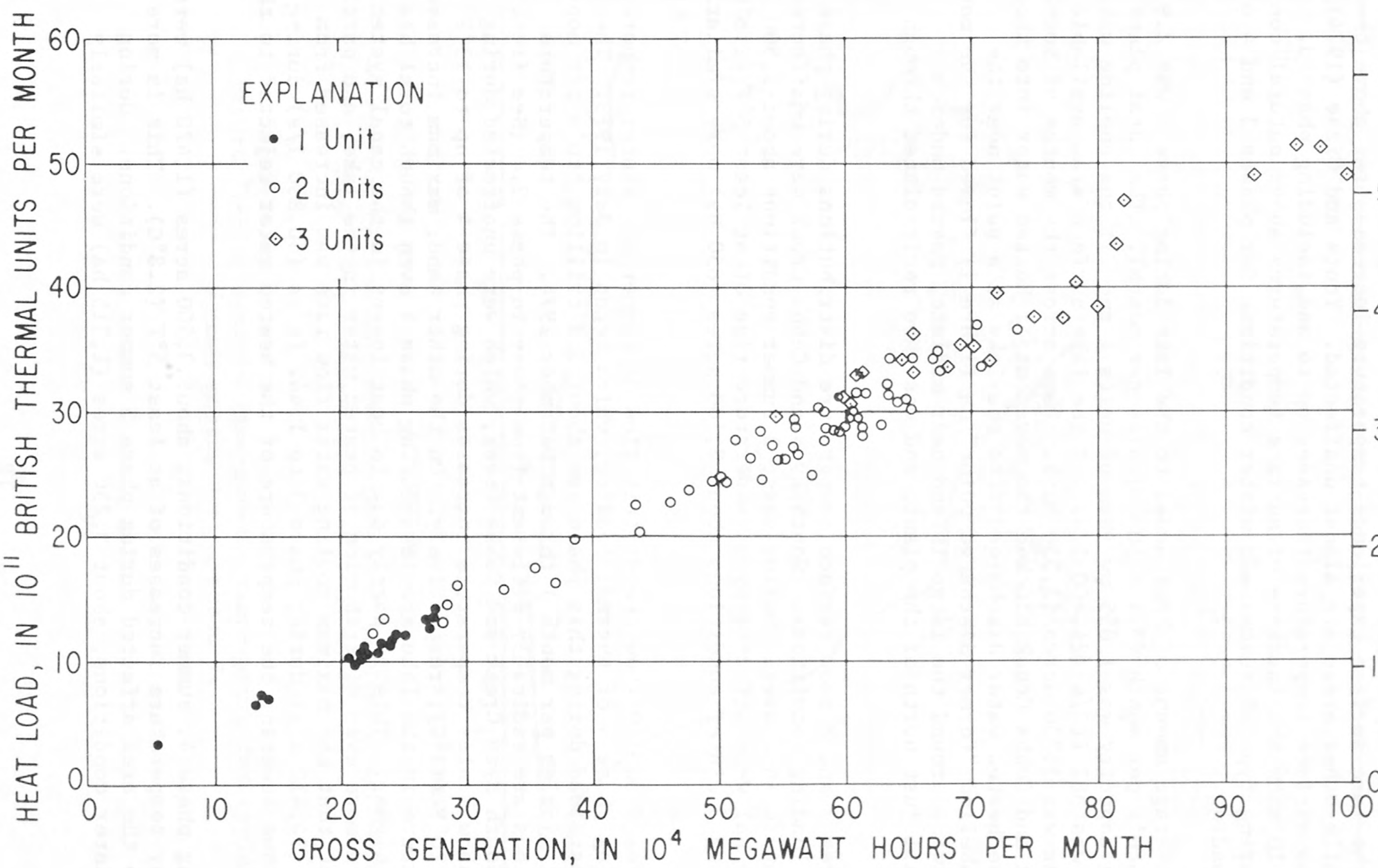


Figure 6.--Relation of gross power generation to heat load.

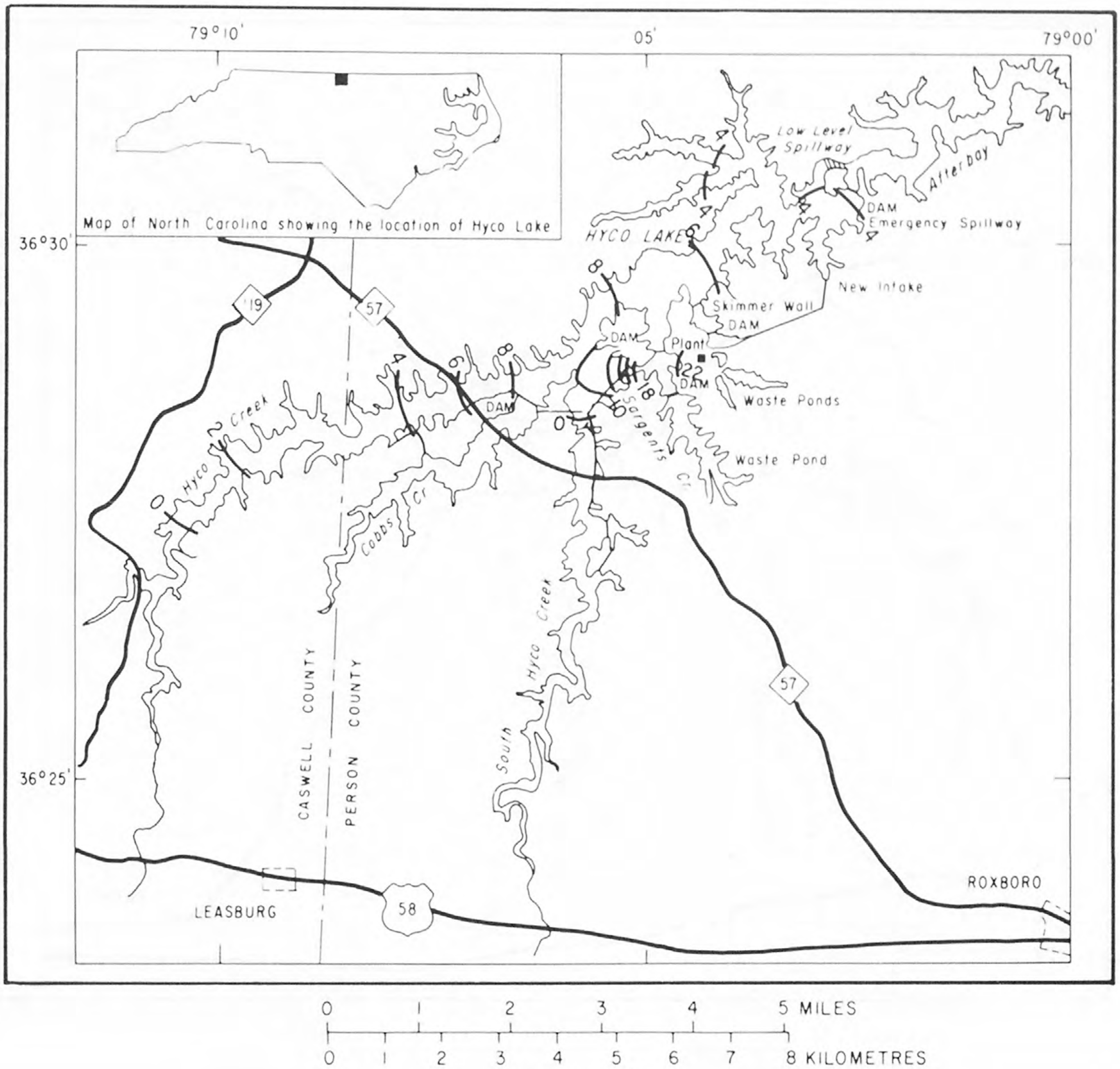
Of greater interest, perhaps, than average increases in lake temperature, are the surface-temperature distributions throughout the lake. Some areas of the lake surface experience temperature increases far above the average while other areas are almost unaffected. Yonts and Giese (1974) reported on surface temperature increases up to and including phase 3. Figures 7-10 show the increase of surface temperatures above natural conditions during typical summer and winter conditions for phases 3 and 4 of thermal loading.

The average amount of heat added to the lake during phase 3 was 2.9 trillion Btu's per month (3.1×10^{15} joules per month). The total plant generating capacity was 1,055 mw (sum of units 1 and 2), the cooling water flow rate was 862 ft^3/s (24,400 l/s) and the lake surface area available for cooling was 3,330 acres (1,350 hm^2). Dams across the mouths of South Hyco Creek and Cobbs Creek blocked the movement of heated water into those areas. The heated water discharged into the lake at a point near the plant, (labelled "former discharge point" on figure 1) flowed for the most part clockwise around the large island near midlake, passed under a skimmer wall just north of the plant, and was then recirculated through the plant.

Figures 7 and 8 show surface temperature distributions during phase 3 thermal loading conditions. South Hyco and Cobbs Creek were unaffected by temperature increases. During phase 3 summer conditions about 1,500 acres (600 ha) were affected by a temperature rise of at least 5°F (2.8°C); during phase 3 winter conditions about 2,100 acres (850 ha) were similarly affected.

Figures 9 and 10 show the distribution of summer and winter temperatures during phase 4 of thermal loading, which began in July 1973. The average heat load during this phase was about 3.9 trillion Btu's per month (4.1×10^{15} joules per month) through December 1974. The temperature distributions are radically different from those in phase 3. (See figs. 7 and 8.) South Hyco Creek and Cobbs Creek, which were unaffected during phase 3, show winter temperature increases during phase 4 of up to 13°F (7°C) and 20°F (11°C), respectively. On the other hand, maximum increases in temperature in the lake are less during phase 4 even though total heat loads are higher. This is partly due to heat losses in the canal system, partly to a more even distribution of heated water in the lake, and partly to the fact that the maximum cooling water flow rate was increased from 862 ft^3/s (24,410 l/s) during phase 3 to 1,442 ft^3/s (40,830 l/s) during phase 4, thus lowering the temperature of the heated water rejected to the lake.

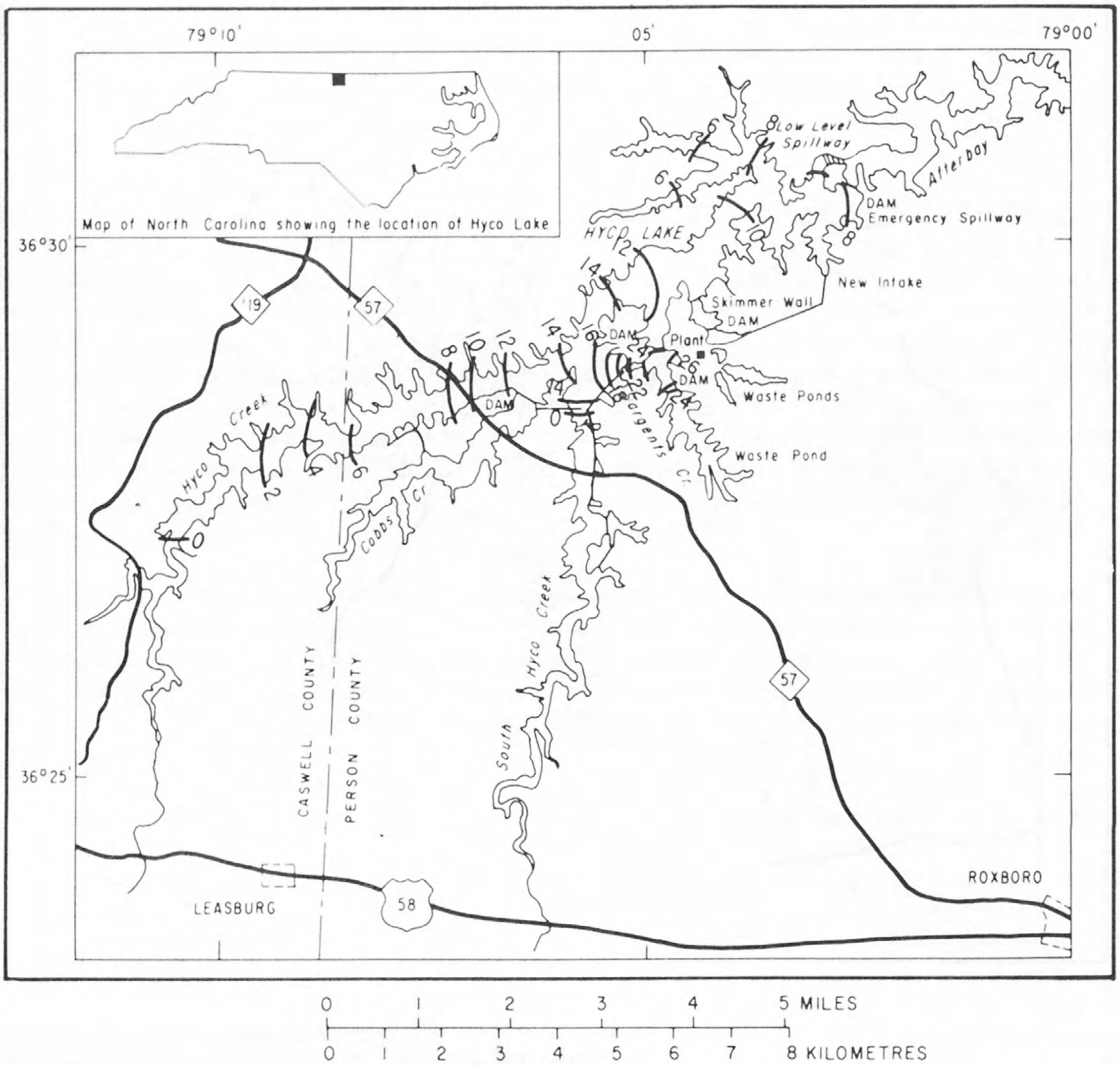
During phase 4, summer conditions, about 3,500 acres (1,420 ha) were affected by temperature increases of at least 5°F (2.8°C). This is more than twice the area affected during phase 3 summer conditions. During phase 4 winter conditions, about 3,250 acres (1,315 ha) were similarly affected.



EXPLANATION

—4— LINE OF EQUAL LAKE SURFACE TEMPERATURE, IN DEGREES FAHRENHEIT
Contour interval variable. Datum is 81°F (27°C)

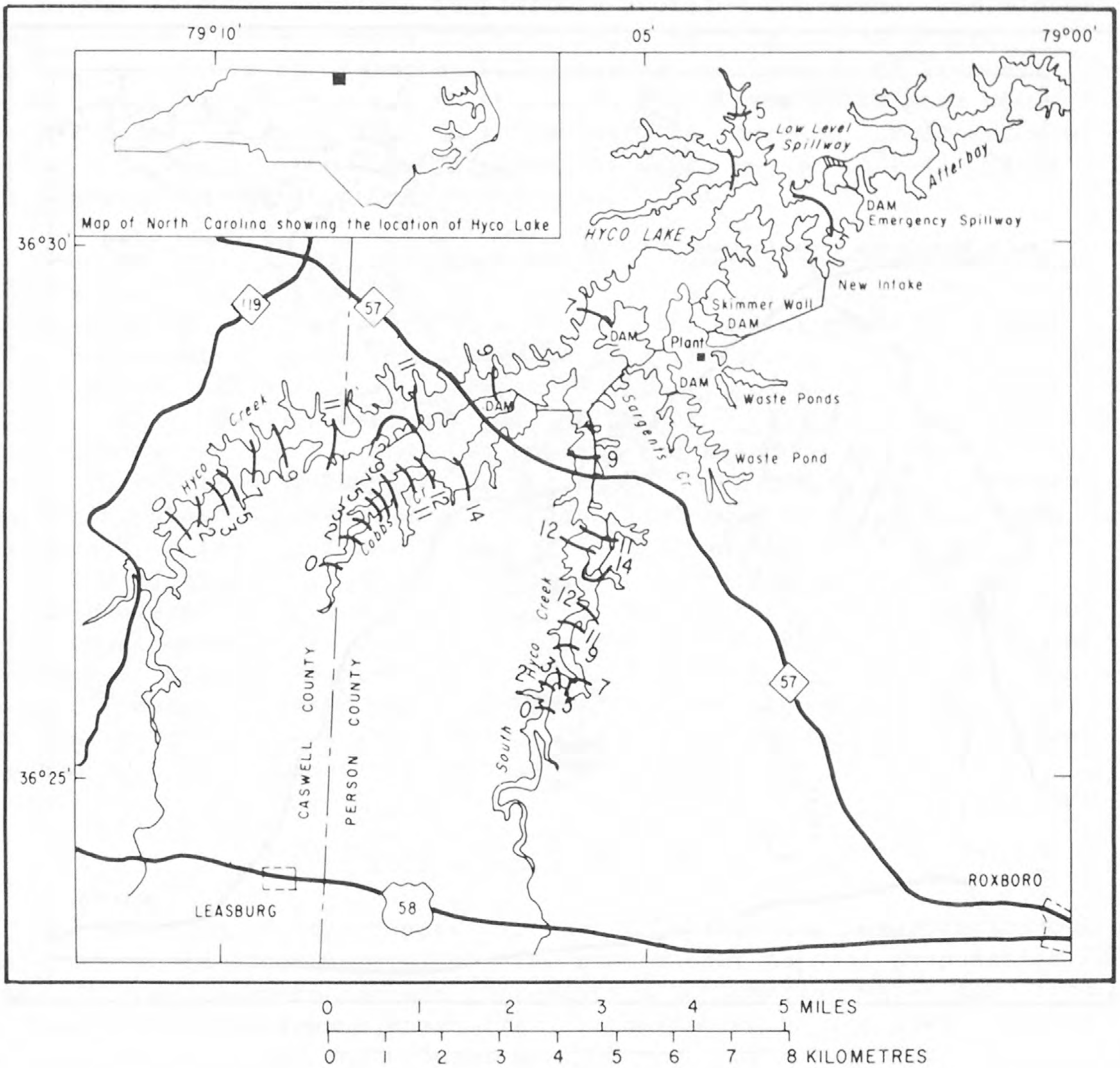
Figure 7.--Increase in lake-surface temperature for typical summer months during phase 3.



EXPLANATION

— 8 — LINE OF EQUAL LAKE SURFACE TEMPERATURE, IN DEGREES FAHRENHEIT
Contour interval variable. Datum is 43°F (6°C)

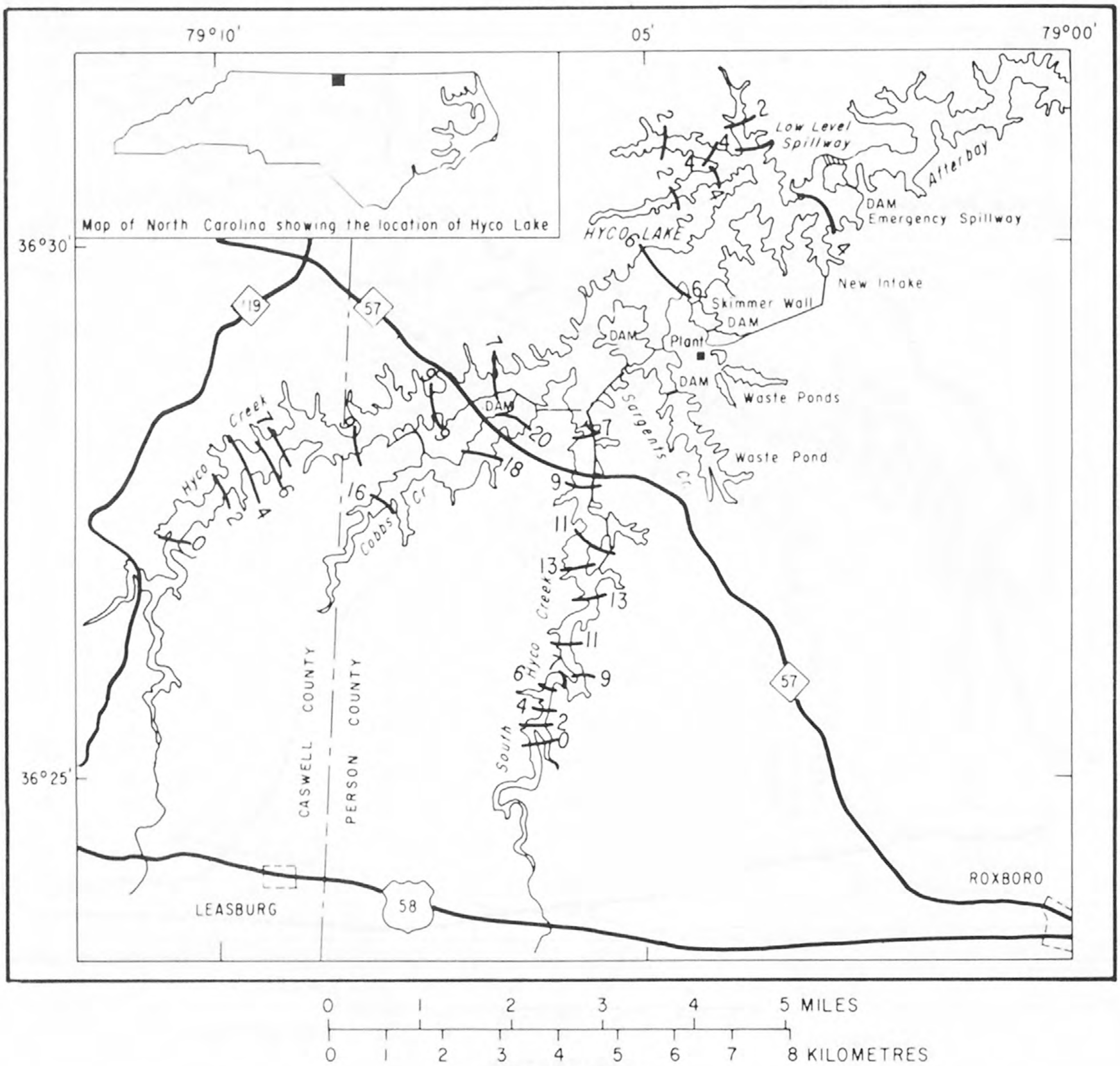
Figure 8.--Increase in lake-surface temperature for typical winter months during phase 3.



EXPLANATION

—9— LINE OF EQUAL LAKE SURFACE TEMPERATURE, IN DEGREES FAHRENHEIT
Contour interval variable. Datum is 79°F (26°C)

Figure 9.--Increase in lake-surface temperature for typical summer months during phase 4.



EXPLANATION

—— 4 —— LINE OF EQUAL LAKE SURFACE TEMPERATURE, IN DEGREES FAHRENHEIT
Contour interval variable. Datum is 48°F (9°C)

Figure 10.--Increase in lake-surface temperature for typical winter months during phase 4.

Temperatures at Depth

Figure 11 shows vertical temperature profiles for summer and winter conditions for phases 3 and 4 for four selected points. As stated earlier, one effect of adding heated water to the lake is to create a temperature gradient from top to bottom in the winter where none would have previously existed, and, in the summer, to increase temperatures at depth. In some locations, temperatures at depth may be 25°F (14°C) or more higher than under natural conditions.

Station 4 on Cobbs Creek under phase 3 loading conditions nearly typifies lake temperature profiles under natural conditions. The natural summer stratification is evident; likewise, the winter profile is typically isothermal. During phase 4, some stratification occurs during the winter, while in the summer, temperatures are increased more at depth. Station 3 on North Hyco Creek shows similar marked changes between phases 3 and 4, while stations 1 and 2 at midlake and near the dam show little change. Water leaving the lake during phase 4 was only slightly warmer than during phase 3, even though the heat load from the plant had been increased by a factor of one-third, or 1 trillion Btu's per month (1.1×10^{15} joules per month). The maximum monthly temperatures at the dam averaged 0.7°F (0.4°C) higher during the first year of operation of the canal system than during the preceding year under phase 3 loading conditions. Heat dissipated in the canal system and in South Hyco, Cobbs, and Hyco Creeks accounted for the disposition of most of the additional heat load during phase 4, so water temperatures from midlake to the dam were modified only slightly from phase 3.

EFFECT OF ADDED HEAT ON EVAPORATION

The addition of heated water to Hyco Lake increases evaporation over that which would occur naturally. The excess over natural evaporation is termed "forced" evaporation and represents a consumptive water loss from the lake. Although it was known from the beginning of the power development at Hyco Lake that such losses would occur, their magnitude could only be roughly approximated. Because of minimum release requirements and temperature criteria, it was important for management purposes to determine more precisely the amount of water lost from evaporation.

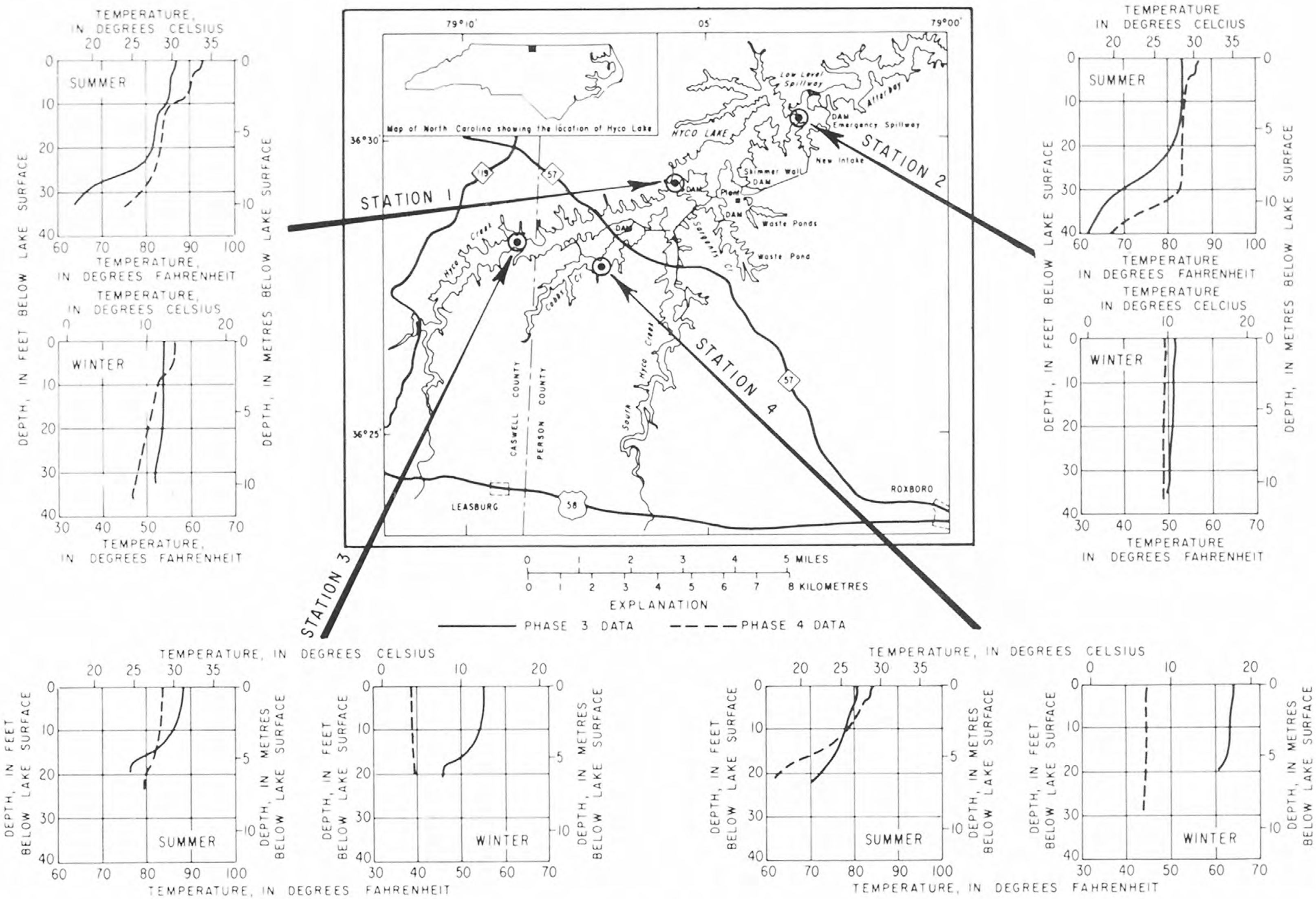


Figure 11.--Typical summer and winter temperature profiles during phases 3 and 4 of thermal loading.

Analytical Technique

The mass-transfer equation

The basic equation used to compute evaporation was the mass-transfer equation suggested by Harbeck (1962, p. 101):

$$E = N\mu\ (e_o - e_a) \tag{1}$$

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; e_a is the vapor pressure of the surrounding air; and E is evaporation.

Equation 1 applies to both natural and heated conditions; however, E' and e_o' will be used to designate heated conditions. Subtraction of natural evaporation from total evaporation yielded forced evaporation (E_f).

Accordingly:

$$E_f = E' - E = N\mu\ (e_o' - e_a) - N\mu\ (e_o - e_a) = N\mu\ (e_o' - e_o) \tag{3}$$

or

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

The variables e_o' and e_o were determined from lake surface temperatures measured at rafts in heated and unheated parts of the lake (See fig. 1.); e_a was determined from data of the National Oceanic and Atmospheric Administration station located at the Raleigh-Durham Airport; μ, wind speed, was determined from anemometers located on the lake rafts; and N was determined by a calibration process (explained in detail in the following section) equating residuals from a water-budget accounting to evaporation as determined by the mass-transfer equation.

The calibration process

The mass-transfer coefficient, N, may be defined as the slope of a straight line relating the mass-transfer product $\mu (e_o - e_a)$ to an independent measure of evaporation. In this study, water budgets were developed to provide the independent measure of evaporation according to the equation:

$$E = I - O + R + \Delta S \pm \delta \qquad (4)$$

where E is evaporation, I is inflow, O is outflow, R is precipitation, ΔS is net change in storage, and δ is ground-water seepage into or out of the lake.

All the terms in the water budget, except E and δ, were either measured directly or calculated. Equation 4 then reduced to:

$$\Delta H_a = E \pm \delta \qquad (2)$$

where ΔH_a is the average change in water surface elevation (storage) per unit time adjusted for inflow, outflow, and precipitation. The term $N\mu (e_o - e_a)$ was then substituted for E in equation 2, yielding:

$$\Delta H_a = N\mu (e_o - e_a) \pm \delta \qquad (2)$$

All terms in equation 2 could be accounted for during each calibration period except N and δ; ΔH_a was determined for 54 different consecutive-day periods varying in length from 3 to 16 days and plotted against the concurrent values of the mass-transfer-product $\mu (e_o - e_a)$, as shown on figure 12. Some of the calibration periods were under natural lake conditions and others were under heated conditions. With respect to their use in determining the coefficient, N, they can be considered as if they are homogeneous data. A straight line of best fit was drawn through the points such that the sum of the squares of the deviations from it were a minimum. The slope of the line, N, was determined to be 0.00019, for use in calculating evaporation in feet per day, or, 0.00228, for use in calculating evaporation in inches per day. The seepage term (δ), as determined by the intercept on the ΔH_a axis of figure 12, is +0.004 feet per day (0.001 m/day) or 8.8 ft^3/s (2.50 l/s) out of the lake. For reasons discussed in the following section of this report, it is doubtful that this or any significant amount of seepage actually occurs.[1/]

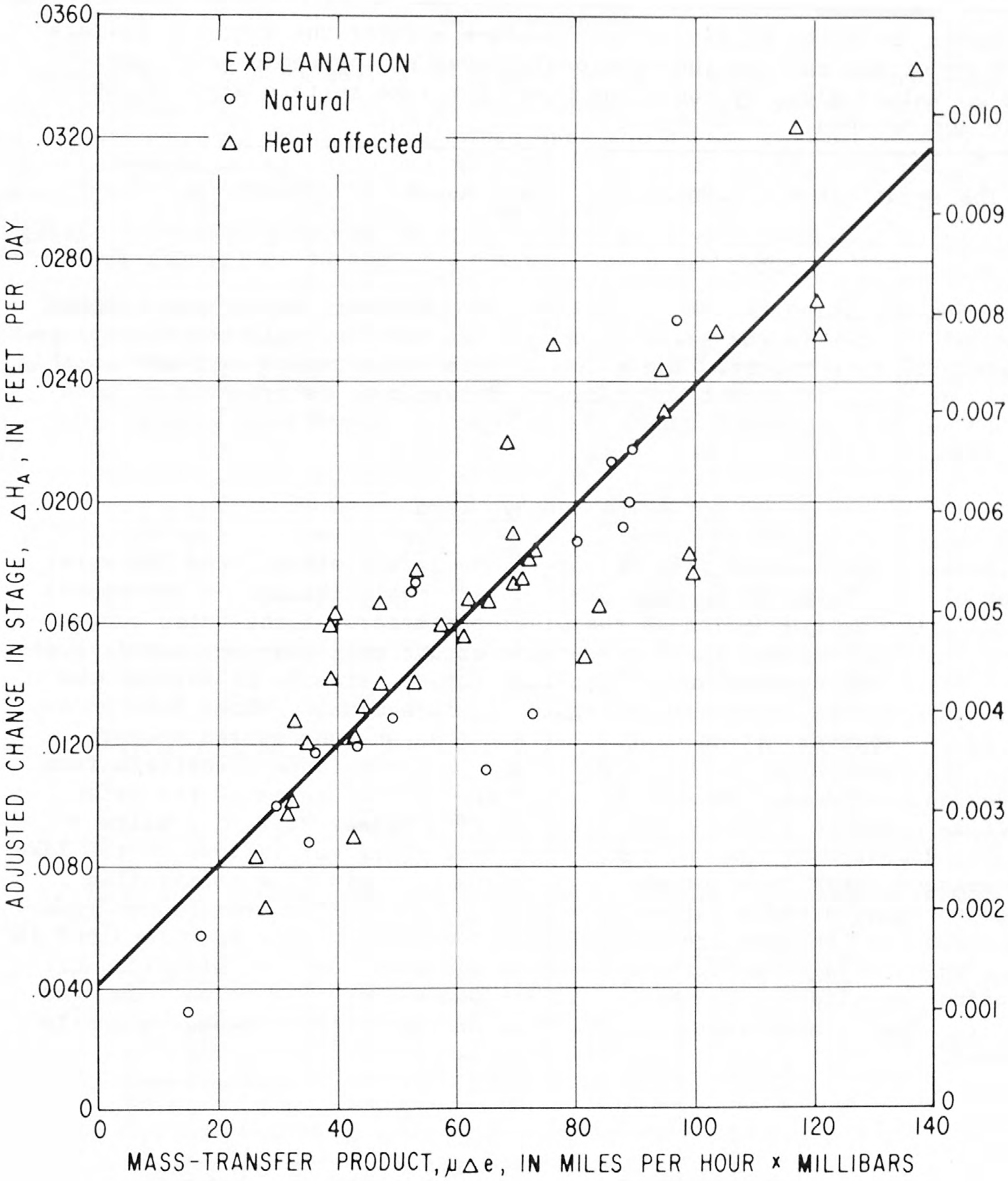


Figure 12.--Relation of mass-transfer product to water-balance residual for Hyco Lake.

[1/] Revision of the values for the surface area of the lake necessitated reworking of the calibration previously developed by Yonts and Giese (1974). Values given by Yonts and Giese for lake surface area, N, and δ should not be used.

The equations $E = 0.00228\mu\ (e_o - e_a)$ and $E_f = 0.00228\mu\ (e_o' - e_o)$ were used to compute daily values of natural and forced evaporation during 1966-74; with μ in miles per hour, and e_o, e_o', and e_a in millibars, the units of evaporation are in inches per day. However, because of a large amount of scatter in the daily values of evaporation, only monthly values are given in this report. The standard error of estimate of these monthly values, although it cannot be precisely determined, is probably no more than 10 percent.

The Seepage Term

Because the seepage term is determined as a residual from the water budget of Hyco Lake, it is sensitive to systematic (biased or one-sided) errors in the determination of the other parameters of the water budget and may in fact reflect these systematic errors more than any actual seepage. Unmeasured seepage out of the lake (under, around, or through the dam), based on the intercept in figure 12, is nominally about 8.8 ft^3/s (249 l/s). However, it is nearly certain that any unmeasured seepage would have reappeared in the Hyco River a short distance downstream from the dam and would have been included in the outflow terms of the water budget as measured at the gaging station at McGehees Mill, 1.7 miles (2.7 km) downstream from the dam. More likely, either inflows to the lake from ungaged areas were somewhat overestimated during the calibration process or some other possible systematic error in the water budget equation appears in the seepage term of equation 4. This may have resulted in an upward shift of the calibration curve without, however, significantly affecting the slope or the N coefficient and evaporation values computed from it. Thus, the writer believes that no significant seepage actually occurred.

Natural Evaporation

Figure 13 shows the average monthly natural evaporation for Hyco Lake during 1966-74. The maximum evaporation usually occurs in July, and averaged 5.8 inches (147 mm) for that month over the 9-year period. Minimum evaporation usually occurs in December or January and averaged 1.2 and 1.1 inches (30 mm and 28 mm) for those months, respectively. Natural evaporation depends primarily on solar radiation, but it is influenced by wind speed, water and air temperatures, and relative humidity.

Tables 8 and 9 show the natural evaporation for each month of the study period and also give annual summaries. The average annual natural evaporation for the 9-year period was 37 inches (940 mm), which compares closely to the 37.9 inches (963 mm) of annual average natural evaporation measured at nearby Lake Michie during 1961-71 (Yonts, Giese, and Hubbard, 1973).

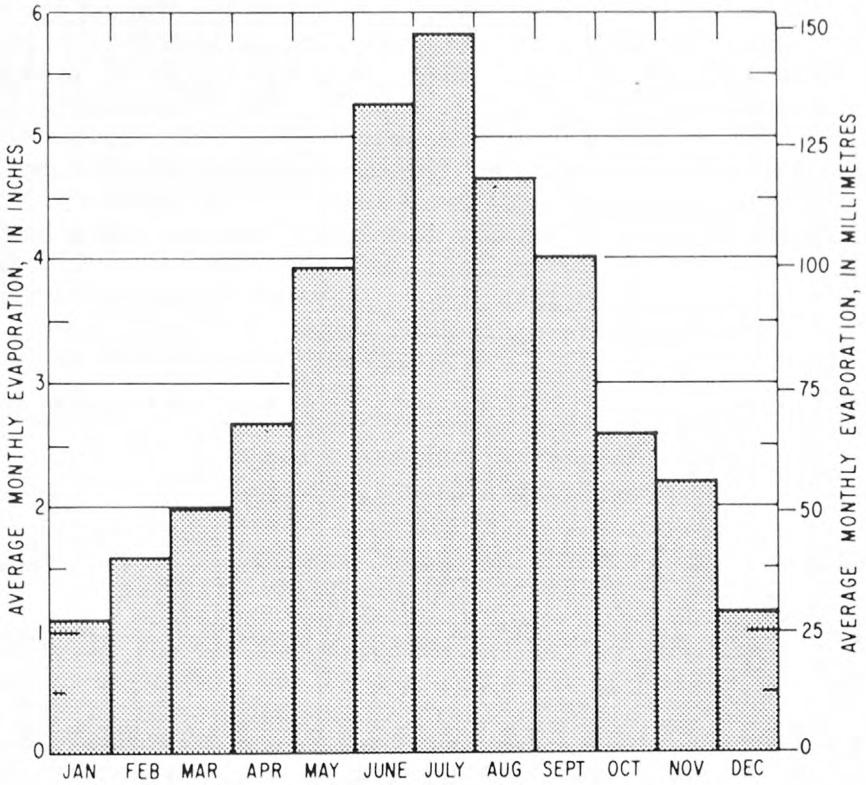


Figure 13.--Average monthly natural evaporation for Hyco Lake, 1966-74.

Forced Evaporation

Natural monthly evaporation and monthly heat load and forced evaporation for each month between May 1966 and December 1974 are plotted on figure 14. The annual cycle of natural evaporation is clearly evident, with maximums occurring in the summer and minimums in the winter. The maximums in forced evaporation tend to occur in summer, but this tendency is not substantial, and the maximum forced evaporation may occur during any month of the year. (Tables 10 and 11 show monthly forced evaporation in tabular form.) The low amounts of forced evaporation during many of the spring months reflects lower heat loads due to a combination of low power demand and scheduled outages for maintenance purposes.

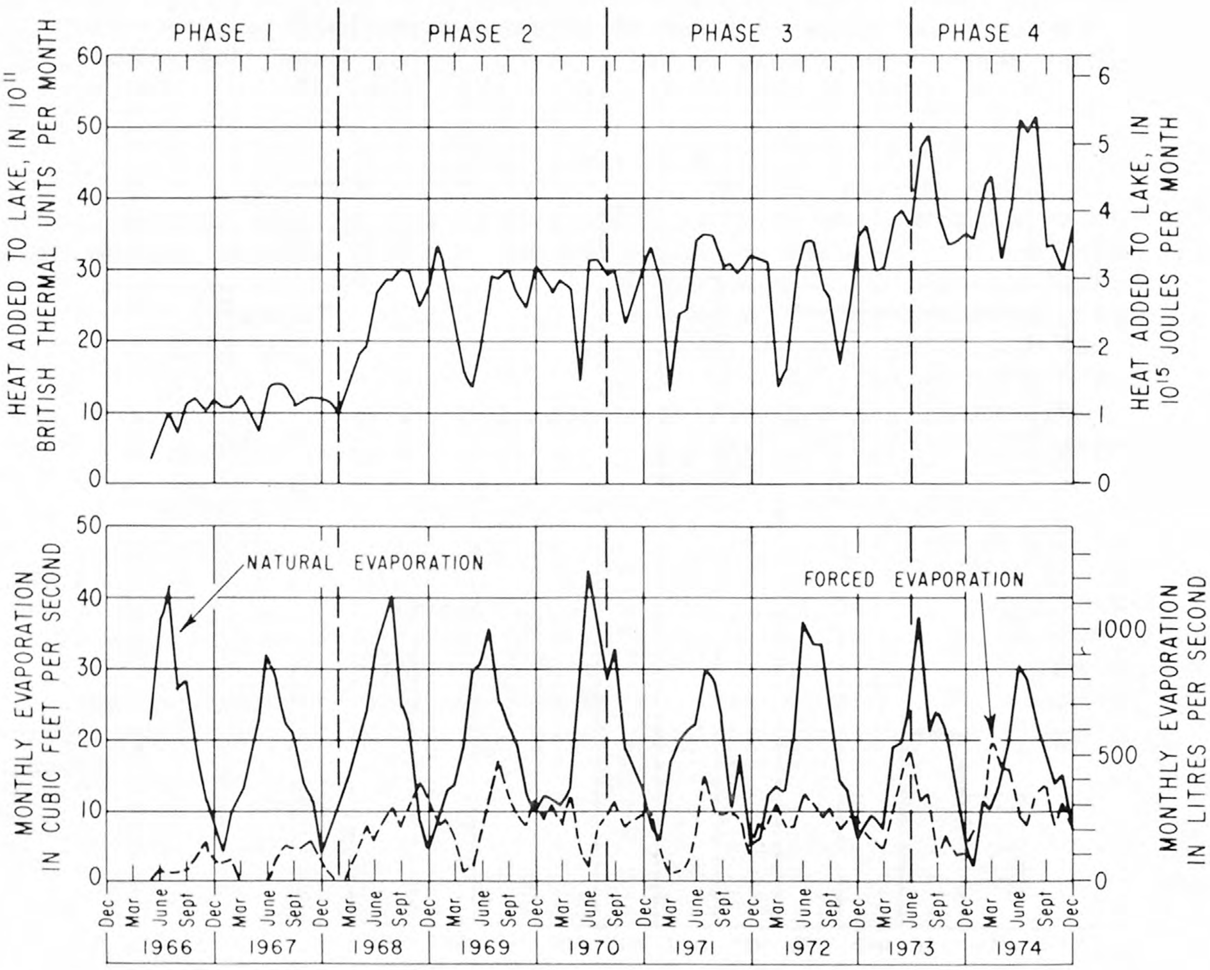


Figure 14.--Heat added, natural evaporation, and forced evaporation for Hyco Lake, 1966-74. Canal evaporation is not included in evaporation values given here.

Forced evaporation increases with increased thermal loading. Figure 15 shows this relation clearly. It is a plot of average monthly heat load and average monthly forced evaporation for phases 1 through 4. As shown by the slopes of the lines passing through the plotted points, the amount of forced evaporation per unit heat added increases from phase 1 to phase 2, then becomes progressively less with each succeeding phase. These changes almost parallel the changes in average lake-surface temperature shown previously in figure 5. The relatively large drop in forced evaporation per unit of heat added during phase 4 was due primarily to the heat lost through forced evaporation in the canal system. The canal evaporation is not included in the data presented in tables 10 and 11 and figure 14. If only the amount of heat actually reaching the lake is considered, the forced evaporation per unit of heat added is somewhat larger than during the previous three phases. This relation is designated as phase 4a on figure 15.

With respect to lake management, the water lost through natural and forced evaporation in the canal system represents a permanent loss of water to the lake. As mentioned previously, about 1.1 trillion Btu's per month (12. x 10^{15} joules per month) of added heat were dissipated in the canal system. From work done by Yonts and Giese (1974) utilizing Harbeck's 1964 techniques, about half of this heat was assumed to be lost to the atmosphere through evaporation, or about 0.55 trillion Btu's per month (0.58 x 10^{15} joules per month). This amount of heat would be sufficient to evaporate from the canal about 3.25 ft^3/s (92.0 l/s) of water in addition to the 0.85 ft^3/s (24 l/s) of natural evaporation from the canal. These amounts are in addition to natural and forced evaporation from the lake itself. Table 12 shows total monthly evaporation from Hyco Lake and the canal system, including natural and forced evaporation from the lake and canal, in ft^3/s.

IMPLICATIONS OF THE FINDINGS OF THIS STUDY FOR FUTURE DEVELOPMENT

The Roxboro Plant and Hyco Lake are designed for a maximum drawdown of 5 feet (1.5 m) to elevation 405.00 feet (123.44 m) MSL. The maximum drawdown during the study period was to elevation 407.2 feet (124.1 m) MSL in December 1967. This drawdown was the culmination of a six-month decline in water levels due to unusually low streamflows during July-November 1967. The recurrence interval of flows of this low magnitude for a five-consecutive-month period is estimated to be about 50 years. During 1967 only the first generating unit was in operation. If the second and third units and the canal system had been operational at that time, the reservoir could have dropped another 1.1 feet (0.3 m) to 406.1 feet (123.8 m) MSL. If we assume that the afterbay was in operation at that time, however, it is possible that the maximum lake drawdown could have been held to 1.1 feet (0.3 m) to elevation 408.9 feet (124.6 m) MSL.

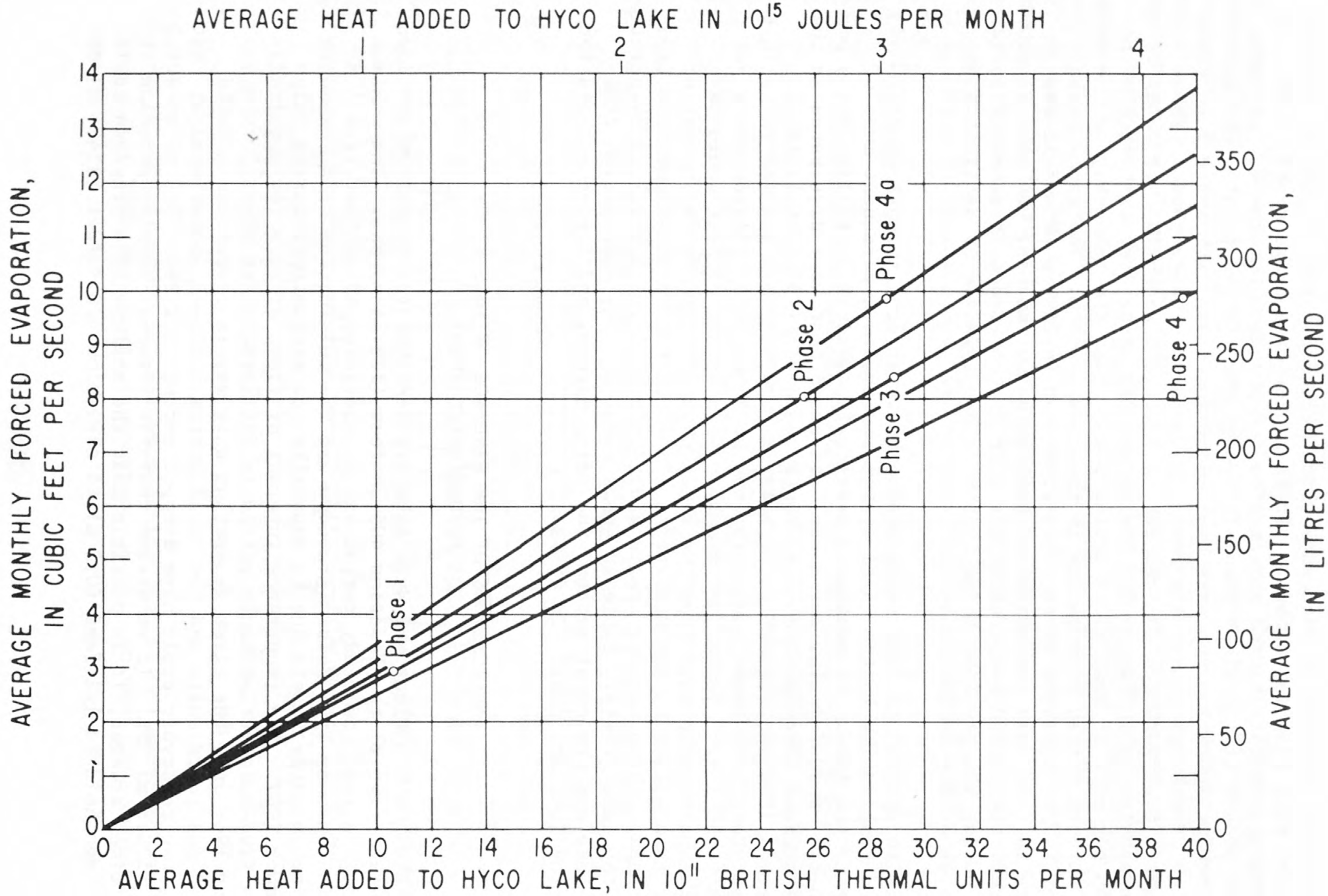


Figure 15.--Relation of added heat to forced evaporation for phases 1, 2, 3, and 4 of thermal loading.

However, the analysis here assumes no afterbay or that storage depleted from the afterbay would have to be immediately made up from the lake. The drawdown probably would have exceeded the 5-foot (1.5 m) design limit if cooling towers were in operation with three generating units, and it may have done so without towers but with the fourth generating unit in operation. If cooling towers become operational (which would increase forced evaporation considerably) there may be recurring problems with excessive drawdown even during less extreme low-flow periods than occurred in 1967. This possibility should be studied further.

The effect of the planned fourth 720-mw generating unit on average surface temperatures of the lake would be to increase them by 1 - 2°F (0.6 - 1.1°C). However, with the planned cooling towers in operation, surface temperatures of the lake would be greatly reduced.

SUMMARY

Thermal loading of Hyco Lake in successive operational stages by a series of steam-electric generating units from May 1966 to December 1974 has resulted in increasing lake temperatures and increasing forced evaporation from the lake. Average thermal loads during phases 1-4 were 1.1, 2.6, 2.9, and 3.9 trillion Btu's per month, respectively (1.2×10^{15}, 2.7×10^{15}, 3.1×10^{15}, and 4.1×10^{15} joules per month). Average monthly increases in surface temperatures during phases 1 - 4 were 2.4, 5.1, 5.0, and 5.8°F (1.3, 2.8, 2.8, and 3.2°C). The average annual natural temperature of the lake surface is 62.5°F (16.9°C). The greatest increases in the temperature of the lake surface occur in winter. For example, during calendar year 1974, the increase in temperature of the lake surface averaged 8.7°F (4.8°C) during the colder months of January through April and November and December. During the warmer months of May through October of 1974, increases averaged 5.5°F (3.1°C). The greatest temperature increases at depth occur in the summer months, when increases at some locations may be 25°F (14°C) higher than under natural conditions.

Average monthly forced evaporation during phases 1-4 of thermal loading (excluding the canal system) was 2.9, 8.0, 8.4, and 9.9 ft^3/s (84, 230, 240, and 280 l/s), respectively, compared to an average annual natural evaporation of 18.4 ft^3/s (521 l/s). Maximum forced evaporation tends to occur during the summer months because power generation and, hence, thermal loading tend to be greatest during those months. However, the maximum forced evaporation may occur in any month; the maximum forced evaporation to occur during the May 1966 - December 1974 study period was 21 ft^3/s (590 l/s) during March 1974.

The canal system, which began operation in July 1973, has had the expected effect of distributing the heated water more evenly throughout the lake. More importantly, it has had the not-so-expected effect of dissipating large quantities of heat, about 1.1 trillion Btu's per month on the average (1.2×10^{15} joules per month). About half of this heat is dissipated by forced evaporation, which averaged about 3.25 ft^3/s (92.0 l/s) during phase 4. Natural evaporation from the canal system averaged about 0.85 ft^3/s (24 l/s). This canal evaporation represents a consumptive loss of water to Hyco Lake in addition to the forced and natural evaporation from the surface of the lake itself.

Regarding future development of Hyco Lake for cooling purposes, it is possible that the planned utilization of cooling towers for disposing of excess heat may lead to excessive drawdowns of reservoir levels (greater than 5 feet) during some low-flow periods. Even without cooling towers, this may be a problem when the fourth 720 mw generating unit is completed and becomes operational. Without cooling towers, the effect of the planned fourth 720 mw generating unit on average surface temperatures would be to raise them by 1 - 2°F (0.6 - 1.0°C). However, with the planned cooling towers in operation, surface temperatures of the lake would be greatly reduced.

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Table 2.--Monthly and annual average natural surface temperature of Hyco Lake in degrees Fahrenheit

[These are estimates of lake temperatures that would have occurred without thermal loading]

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					75.1	80.5	87.0	84.2	76.6	64.6	54.0	46.5	
1967	42.2	41.4	50.0	64.1	67.3	80.0	82.1	80.9	73.6	64.3	50.0	44.1	61.7
1968	38.7	41.2	50.2	64.0	69.9	81.5	86.4	87.4	78.0	68.8	51.8	42.1	63.3
1969	40.8	42.5	47.0	63.0	74.7	82.1	85.9	80.3	76.3	66.4	51.5	41.0	62.6
1970	41.5	43.3	49.7	57.8	73.3	83.2	85.2	83.0	81.0	68.6	56.6	47.4	64.2
1971	38.5	40.1	46.8	58.0	68.9	80.3	82.4	83.0	77.8	66.3	57.4	47.4	62.2
1972	44.5	42.3	49.6	56.5	68.5	76.9	84.1	82.9	76.5	62.2	53.5	44.5	61.8
1973	41.6	41.8	51.5	59.1	67.9	80.2	85.5	82.6	81.6	69.3	56.5	45.7	60.6
1974	48.4	47.7	52.7	59.7	70.3	78.6	82.5	81.6	74.8	64.1	56.5	46.1	63.6
Monthly and average annual	42.0	42.5	49.7	60.3	70.7	80.4	84.6	82.9	77.4	66.1	54.2	45.0	62.5

Table 3.--Monthly average heat load to Hyco Lake, in British thermal units × 10^{11} [1]

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					3.28	6.65	10.13	6.87	11.58	12.04	9.98	11.85	[2] 9.05
1967	10.88	10.72	12.61	10.33	7.07	13.47	14.10	13.50	10.73	11.62	12.10	11.89	11.58
1968	11.38	9.96	13.69	17.50	19.86	26.21	28.41	28.37	30.12	29.40	24.54	27.73	22.26
1969	33.66	28.98	22.86	15.72	13.21	20.05	28.96	28.69	30.14	26.63	24.30	30.94	25.34
1970	28.93	26.20	28.61	27.38	14.63	31.55	31.37	28.79	29.93	22.23	26.09	30.93	27.22
1971	33.28	27.21	12.22	23.89	24.65	34.07	34.98	34.40	30.15	30.49	29.33	32.19	28.90
1972	31.64	31.11	37.01	16.04	28.45	34.16	34.27	27.90	23.70	16.40	24.51	33.83	28.25
1973	36.35	29.57	30.76	37.49	38.55	35.60	47.07	49.09	37.83	33.36	33.53	35.23	37.04
1974	34.12	40.62	43.50	31.15	39.71	51.30	49.06	51.53	33.16	33.43	29.74	36.43	39.48

[1] These figures are actually heat rejected from the plant.

[2] Average for May to December.

Table 4.--Monthly and annual average lake surface temperature of Hyco Lake, in degrees Fahrenheit

[These temperatures reflect the increases due to thermal loading]

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					63.4	81.4	87.5	84.9	77.4	66.9	58.2	49.8	
1967	45.2	44.2	49.7	63.5	65.9	79.5	83.4	83.1	76.1	68.2	55.6	48.8	63.6
1968	40.5	40.9	51.3	66.6	73.2	83.9	89.3	90.7	82.0	74.6	61.6	51.9	66.2
1969	49.3	50.1	53.0	63.4	75.8	84.8	90.2	86.8	82.0	72.0	58.4	51.8	66.4
1970	49.9	52.4	56.2	64.9	75.5	83.7	88.0	87.3	85.0	72.8	62.6	55.1	68.0
1971	47.5	45.2	47.8	58.6	70.0	83.3	87.3	86.8	82.0	71.5	62.7	50.8	66.1
1972	51.9	48.8	56.5	61.4	72.3	81.0	88.0	86.3	80.9	67.4	59.9	52.5	67.2
1973	48.9	47.5	55.8	64.4	74.6	86.6	89.0	87.5	83.3	73.0	58.8	49.7	68.3
1974	56.1	54.6	66.8	68.5	77.6	82.2	86.0	86.7	81.8	70.5	64.5	52.7	70.7

Table 5.--Monthly and annual average surface temperature of the heated part of Hyco Lake, in degrees fahrenheit

[During May 1966-August 1970, the heated area was 3,900 acres (1,580 ha). From September 1970-June 1973, it was 3,330 acres (1,350 ha). From July 1974-December 1974, it was 4,230 acres (1711 ha)]

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					69.9	81.5	87.6	85.0	77.5	67.2	58.7	50.2	
1967	45.6	44.5	49.7	63.5	65.7	79.4	83.6	83.4	76.4	68.7	56.2	49.3	63.8
1968	40.8	40.9	51.4	66.9	73.6	84.2	89.7	91.1	82.5	75.3	62.7	53.0	67.7
1969	50.3	51.0	53.7	63.5	75.9	85.1	90.7	87.6	82.6	72.7	59.2	53.0	68.8
1970	50.9	53.4	57.0	65.8	75.8	83.8	88.3	87.3	86.2	74.1	64.5	57.5	70.4
1971	50.3	46.7	48.1	58.8	70.3	84.2	88.8	88.0	83.3	73.1	64.3	51.9	67.3
1972	54.2	50.8	58.6	62.9	73.4	82.3	89.2	87.4	82.3	69.0	61.8	54.9	68.9
1973	51.1	49.2	57.1	66.0	76.6	88.6	90.1	87.5	83.3	73.0	58.8	49.7	69.2
1974	56.1	54.6	66.8	68.5	77.6	82.2	86.0	86.7	81.8	70.5	64.5	52.7	70.7

Table 6.--Average increase in the surface temperature of the heated part of Hyco Lake, in degrees fahrenheit above natural temperature

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average increase
1966					1/ 0.8	1.0	0.5	0.8	0.9	2.6	4.7	3.7	2/ 1.8
1967	3.4	3.1	1/ 3.2	1/ 2.7	1/ 1.8	1/ 3.5	1.5	2.4	2.8	4.4	6.3	5.2	3.4
1968	2.1	1/ 2.6	1.2	2.9	3.7	2.6	3.3	3.7	4.5	6.5	10.9	11.0	4.6
1969	9.5	8.5	6.7	0.5	1.2	3.0	4.7	7.3	6.2	6.3	7.8	12.0	6.1
1970	9.4	10.1	7.3	8.0	2.5	0.6	3.1	4.3	5.2	5.5	7.8	10.1	6.2
1971	11.8	6.6	1.3	0.9	1.4	3.9	6.3	5.0	5.5	6.7	7.0	4.5	5.1
1972	9.7	8.6	8.9	6.4	4.9	5.4	5.1	4.5	5.8	6.8	8.3	10.4	7.1
1973	9.5	7.4	5.6	7.0	8.7	8.4	4.6	4.9	1.6	3.7	2.3	4.1	5.6
1974	7.7	6.9	14.1	8.8	7.3	3.6	3.5	5.2	7.0	6.5	8.0	6.6	7.1

1/ Values for these months were estimated.

2/ Average for eight months only.

Table 7.--Monthly and annual difference between average actual and average natural lake surface temperatures of Hyco Lake, in degrees Fahrenheit

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					1/ 0.8	0.9	0.5	0.7	0.8	2.3	4.2	3.3	2/ 2.9
1967	3.0	2.8	1/ 2.9	1/ 2.4	1/ 1.6	1/ 3.1	1.3	2.2	2.5	3.9	5.6	4.7	3.0
1968	1.8	1/ 2.3	1.1	2.6	3.3	2.4	2.9	3.3	4.0	5.8	9.8	9.8	4.1
1969	8.5	7.6	6.0	0.4	1.1	2.7	4.3	6.5	5.7	5.6	6.9	10.8	5.5
1970	8.4	9.1	6.5	7.1	2.2	0.5	2.8	4.3	4.0	4.2	6.0	7.7	5.2
1971	9.0	5.1	1.0	0.6	1.1	3.0	4.9	3.8	4.2	5.2	5.3	3.4	3.9
1972	7.4	6.5	6.9	4.9	3.8	4.1	3.9	3.4	4.4	5.2	6.4	8.0	5.4
1973	7.3	5.7	4.3	5.3	6.7	6.4	3.5	4.9	1.7	3.7	2.3	4.0	4.7
1974	7.7	6.9	14.1	8.8	7.3	3.6	3.5	5.1	7.0	6.4	8.0	6.6	7.1

1/ Temperature increases for these months were estimated.

2/ Average for eight months only.

Table 8.--Monthly and annual natural evaporation from Hyco Lake, in inches

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1966					[1/] 3.9	6.0	7.2	4.6	4.8	3.3	2.0	1.5	[2/] 35.2
1967	0.7	1.6	[1/] 2.0	[1/] 2.7	[1/] 3.9	[1/] 5.3	5.0	3.9	3.5	2.4	1.9	0.6	33.7
1968	1.1	[1/] 1.6	2.4	3.1	4.0	5.3	6.2	7.0	4.2	3.6	1.5	0.7	41.2
1969	1.3	1.8	2.3	3.1	5.0	5.0	6.2	4.3	3.6	3.4	2.1	1.6	39.8
1970	2.0	1.8	1.8	2.1	4.4	7.2	6.0	4.7	5.5	3.3	2.6	2.2	43.6
1971	1.3	0.8	2.6	3.1	3.5	3.6	5.1	4.8	3.5	1.7	3.0	0.8	33.8
1972	1.0	1.8	2.2	2.0	3.5	5.9	5.6	5.6	4.1	2.4	2.0	1.0	37.2
1973	1.2	1.4	1.2	3.0	3.4	4.3	6.5	3.6	4.0	3.6	2.4	1.0	35.7
1974	0.3	1.8	1.7	2.2	3.3	5.0	4.8	3.7	3.0	2.2	2.5	1.0	31.5
Monthly and average annual	1.1	1.6	2.0	2.7	3.9	5.3	5.8	4.7	4.0	2.6	2.2	1.2	37.0

[1/] Evaporation values were estimated for these months.

[2/] Average for eight months. This value not included in calculation of average annual evaporation.

Table 9.--Monthly and annual natural evaporation from Hyco Lake, in cubic feet per second

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					1/ 23.0	36.7	42.0	26.5	28.6	19.4	12.3	8.6	2/ 24.6
1967	4.0	10.2	1/ 12.1	1/ 16.4	1/ 23.0	1/ 32.2	28.9	22.4	21.0	13.8	11.1	3.5	16.6
1968	6.5	1/ 10.2	14.4	18.8	23.8	32.1	36.0	40.6	24.7	20.5	8.8	3.9	20.0
1969	7.4	12.2	13.7	18.7	29.5	30.7	36.1	25.1	21.4	19.4	12.4	9.3	19.7
1970	11.9	11.6	10.6	13.2	26.4	43.7	35.2	28.1	33.2	18.9	15.9	12.9	21.8
1971	7.8	5.4	15.3	19.2	21.0	22.0	30.1	28.2	21.7	10.3	18.5	4.7	17.0
1972	5.8	11.4	13.4	12.7	21.1	36.6	33.6	33.3	24.6	14.1	12.4	5.8	18.7
1973	7.2	9.1	7.1	18.8	19.6	25.7	37.7	20.9	24.0	20.6	13.8	5.9	17.5
1974	1.9	11.6	10.1	13.6	19.7	30.4	28.4	22.0	18.2	13.2	15.0	6.2	15.9
Monthly and average annual	6.6	10.2	12.1	16.4	23.0	32.2	34.2	27.5	24.2	16.7	13.4	6.8	18.4

1/ Evaporation values were estimated for these months.

2/ Average for eight months. Not included in calculation of average annual value.

Table 10.--Monthly and annual forced evaporation from Hyco Lake, in inches

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total annual
1966					1/ 0.2	0.3	0.2	0.2	0.3	0.7	1.0	0.6	2/ 3.5
1967	0.5	0.5	1/ 0.7	1/ 0.6	1/ 0.4	1/ 0.7	0.6	0.9	0.8	0.9	1.1	0.7	8.4
1968	0.2	1/ 0.5	0.2	0.7	1.4	1.1	1.6	1.9	1.5	2.1	2.7	2.2	16.1
1969	1.5	1.5	1.2	0.2	0.4	1.3	2.4	3.2	2.0	1.8	1.5	2.1	19.1
1970	1.6	1.7	1.5	2.1	0.8	0.3	1.4	1.7	2.4	1.7	1.8	2.1	19.0
1971	2.0	0.8	0.2	0.2	0.5	1.3	3.2	2.2	2.0	2.1	1.8	0.8	17.2
1972	1.8	1.6	2.3	1.6	1.7	2.6	2.4	2.1	2.2	1.6	1.9	2.0	23.7
1973	1.5	1.1	1.0	2.0	3.5	4.0	2.3	2.1	0.6	1.1	0.7	0.7	20.5
1974	1.2	1.3	3.7	2.7	2.7	1.5	1.3	2.2	2.2	1.4	1.9	1.3	23.4

1/ Evaporation values were estimated for these months.

2/ Total for eight months only.

Table 11.--Monthly and annual forced evaporation from Hyco Lake, in cubic feet per second

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					1/ 1.0	1.8	1.1	1.1	1.6	3.8	5.5	2.9	2/ 2.5
1967	2.4	3.1	1/ 3.7	1/ 3.0	1/ 2.1	1/ 3.9	3.4	4.9	4.5	4.7	5.8	3.5	4.0
1968	1.2	1/ 2.9	0.9	3.7	7.7	5.8	8.1	10.1	7.8	10.7	14.0	11.2	7.4
1969	7.8	8.6	6.6	1.1	1.9	6.9	12.4	16.8	10.7	9.3	7.7	10.9	8.4
1970	8.4	10.2	7.9	11.8	4.5	1.5	7.2	9.0	10.9	7.5	8.3	9.4	8.0
1971	9.2	4.2	1.0	1.1	2.1	6.3	14.5	9.8	9.4	9.7	8.3	3.7	6.6
1972	8.0	7.6	10.5	7.6	7.8	12.2	10.9	9.3	10.2	7.5	9.0	9.0	9.1
1973	6.8	5.5	4.7	9.2	15.6	18.2	11.2	12.1	3.2	6.3	3.7	3.9	8.4
1974	7.3	8.4	21.0	16.1	15.6	9.1	7.5	12.5	13.5	7.8	11.0	7.5	11.4

1/ Evaporation values were estimated for these months. These values were not used in calculations of annual averages.

2/ Average for eight months.

Table 12.--Total monthly evaporation from Hyco Lake, in cubic feet per second

[Values are the total of natural and forced evaporation from the lake and the canal system]

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1966					1/ 24.0	38.5	43.1	27.6	30.2	23.2	17.8	11.5	2/ 27.0
1967	6.4	13.3	1/ 15.8	1/ 19.4	1/ 25.1	1/ 36.1	32.3	27.3	25.5	18.5	16.9	7.0	20.3
1968	7.7	1/ 13.1	15.3	22.5	31.5	37.9	44.1	50.7	32.5	31.2	22.8	15.1	27.0
1969	15.2	20.8	20.3	19.8	31.4	37.6	48.5	41.9	32.1	28.7	20.1	20.2	28.1
1970	20.3	21.8	18.5	25.0	30.9	45.2	42.4	37.1	44.1	26.4	24.2	22.3	29.9
1971	17.0	9.6	16.3	20.3	23.1	28.3	44.6	38.0	31.1	20.0	26.8	8.4	23.6
1972	13.8	19.0	23.9	20.3	28.9	48.8	44.5	42.6	34.8	21.6	11.4	14.8	27.0
1973	14.0	14.6	11.8	28.0	35.2	23.9	54.0	37.7	31.1	30.3	20.7	12.9	26.2
1974	12.1	23.7	35.0	32.7	39.2	44.7	40.9	39.5	35.0	24.2	28.9	16.9	31.1

1/ Evaporation values partly estimated for these months.

2/ Average for eight months only.

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