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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

FACTORS ALTERING THE MICROCLIMATE IN CARLSBAD CAVERNS, NEW MEXICO

By

J. S. McLean

Open-file report 76-171

Prepared in cooperation with the Office of
Natural Sciences, Southwest Region, National Park Service
under NPS Research Project CACA-N-1a

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Contents

Illustrations

Illustrations - Concluded

Page

Tables

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Abstract

In 1972 the U.S. Geological Survey, in cooperation with the National Park Service, extended a study (National Park Service Research Project CACA-N-1a) of the microclimate in Carlsbad Caverns to evaluate the effect on evaporation in the cave of reducing the airflow up the elevator shaft. The existing monitoring program included data on temperature, humidity, and carbon dioxide content of the air in the cave, evaporation, water levels in pools, and the rate of inflow of water at several locations. This program was expanded by the addition of measurements of pool levels, evaporation, and relative humidity at several new locations.

Revolving doors installed during the summer of 1972 at the bottom of the elevator shaft reduced airflow up the elevator shaft which in turn reduced the net evaporation in the cave at least 10 percent. Evaporation pans near the elevator shaft showed a 34 percent average decrease in the annual evaporation rate. Annual evaporation at most locations remote from the elevator shaft increased an average of 23 percent. It is assumed that the increase in evaporation in remote areas of the cave is caused by the heat output resulting from energy consumption for lighting the cave due to increased traffic and the change from guided to self-guided tours. An analysis using least-squares equations indicated that part of the evaporation at four of the nine evaporation pans can be correlated with energy consumption and may represent an average of 23 percent of total evaporation at these locations.

It is suggested that continued efforts be made to reduce energy consumption by increasing the efficiency of the lighting system and maintaining a basic-data collection program to warn of additional changes in the cave microclimate.

Introduction

In 1968, the U.S. Geological Survey began a cooperative program with the National Park Service to study the microclimate in Carlsbad Caverns, to determine ways of reducing excess evaporation from the cave pools and restoring the cave microclimate to more nearly natural conditions. It was concluded that airflow up the elevator shaft should be restricted by installing revolving doors in the lower lobby, the lighting system should be improved to give off less heat, and the scenic pools should be refilled to former levels.

In 1972, the project was extended to include an evaluation of the effect on the cave microclimate of installing the revolving doors. The additional data obtained during the extension would also aid in improving the description of the cave microclimate and evaluating the effect of the heat produced by the lighting system.

In this report figures are given both in metric units and in English units (with the exception of tables, which contain metric units only). The following list contains selected conversion factors of the dual system of the metric "International System of Units (SI)" and English units:

Metric		Multiplied by	English	
Unit	Abbreviation		Unit	Abbreviation
Millimetre	mm	0.0394	Inch	in
Square millimetre	mm^2	1.55×10^{-3}	Square inch	in^2
Metre	m	3.28	Foot	ft
Kilometre	km	0.622	Mile	mi
Hectare	ha	2.47	Acre	acre

Temperature in degrees Celsius (°C) is converted to temperature in degrees Fahrenheit (°F) by the following equation: $F = \frac{9}{5} C + 32$

Study area

Carlsbad Caverns are in the mountains of south-central New Mexico (fig. 1). More than 24 kilometres (15 miles) of passages have been mapped beneath an area of less than 120 hectares (300 acres). The large Natural Entrance to the cave is at an altitude of 1,325 metres (4,348 ft). The top of the elevator shaft is at an altitude of 1,343 m (4,406 ft). Major levels in the cave include Bat Cave at an altitude of 1,270 m (4,167 ft), the Big Room at an altitude of 1,112 m (3,650 ft), and Lower Cave at about 1,090 m (3,580 ft). The lowest point reached in the cave is Lake of the Clouds at an altitude of 1,009 m (3,311 ft).

The climate at the surface above Carlsbad Caverns is semiarid. The rainfall is irregularly distributed throughout the year, and there are large variations in rainfall from year to year (fig. 2). The mean-annual rainfall is 370 millimetres (14.4 in).

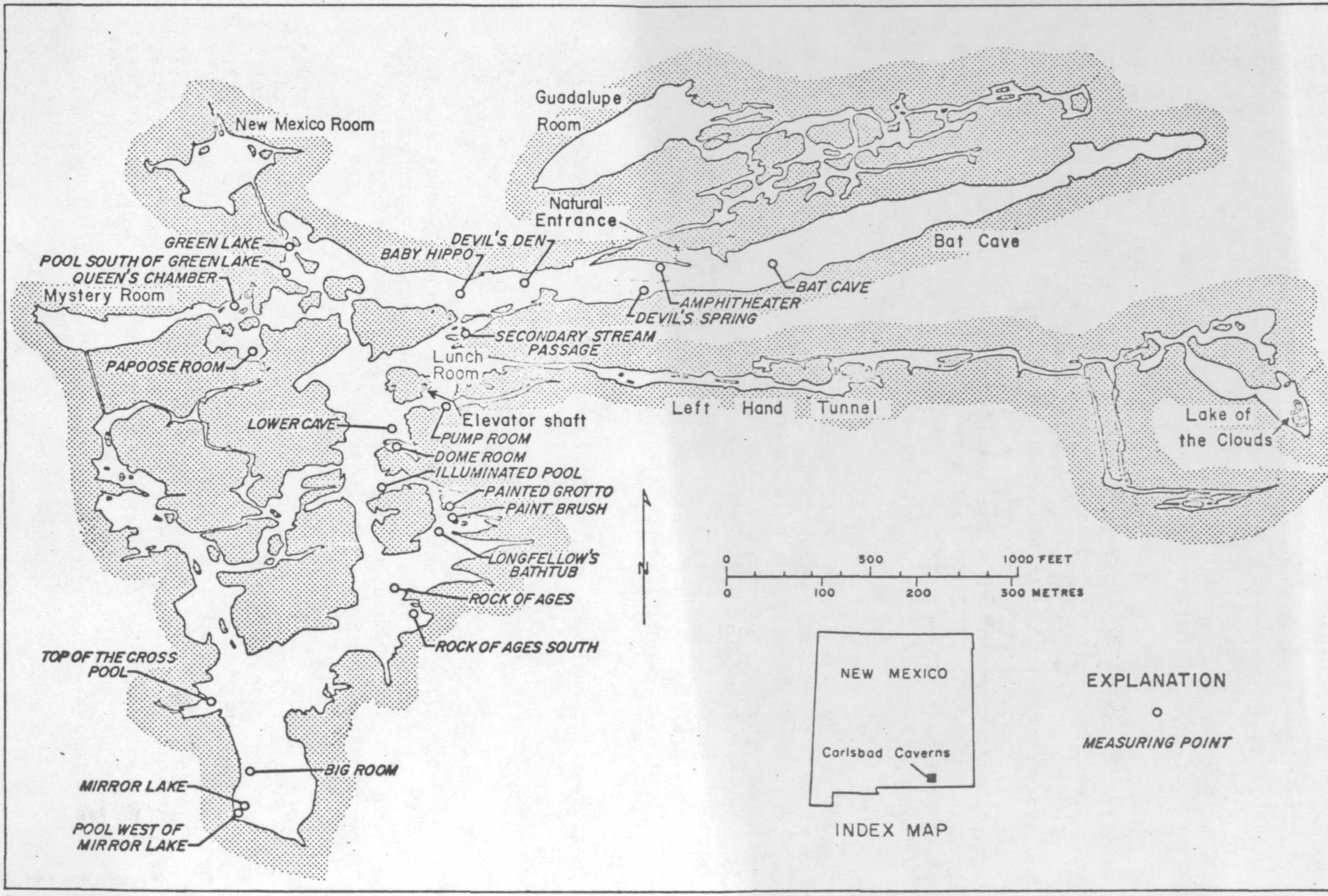
Previous studies

Lange (1954a; 1954b) used equations of heat flow in an isotropic medium to describe the temperatures in caves.

Quitt (1965) noted that monthly evaporation in caves in the Moravian karst reached a maximum in Februray. He related this to the wind velocity in the caves, which he in turn related to cold air moving into the caves. Conn (1966) measured wind velocities in Wind Cave, S. Dak., and showed a quantitative relationship to barometric pressure fluctuations outside the cave. Wigley (1967) analyzed the response of caves to barometric pressure changes as a function of the permeability of the limestone comprising the cave walls.

The microclimate of the entrance area of Bower Cave, Calif., was described by Graham (1969). Cropley (1965) described the temperatures in two West Virginia caves which contain streams. He presented an equation describing temperatures in the cave as a function of the time of year and distance from the cave entrance. Bamburg (1973) collected data on air movement, temperature, carbon dioxide content, and water chemistry in Lehman Caves, Nev. He found that with a decrease in external temperatures air circulation in the cave increased, carbon dioxide content of the air decreased, and the air temperature in the cave decreased.

A previous report on Carlsbad Caverns (McLean, 1971) indicated that the flow rate, humidity, temperature, and carbon dioxide content of the air, the evaporation rate, and the water levels in pools all varied as the result of functions of the air temperatue outside the cave.



Base modified from Moore, 1960

Compiled by J.S. McLean, 1974

Figure 1.--Map of Carlsbad Caverns showinq location of measuring points.

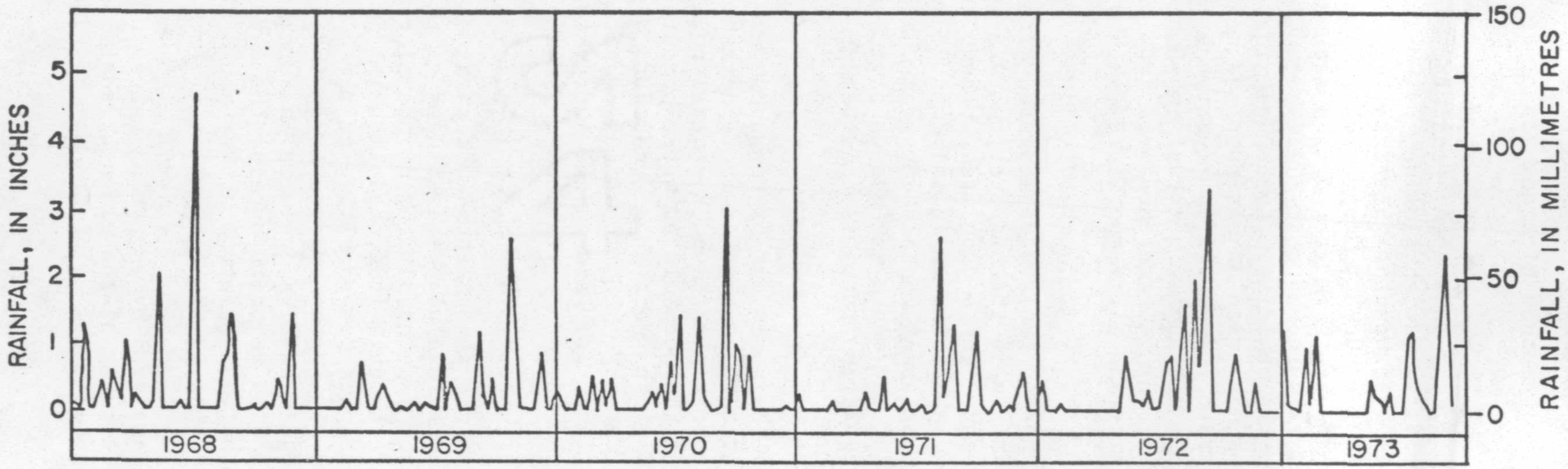


Figure 2.--Weekly rainfall at Carlsbad Caverns.

Method of study

The instrumentation for this study consisted of units which measured temperature, humidity, carbon dioxide, evaporation, and water-level changes in pools. Although sample intervals for many parameters were irregular, all were reduced to mean-weekly values for comparison. Temperature was measured by thermistor probes accurate to ±0.1°C, relative humidity was measured by gold-electrode units accurate to about ±2 percent relative humidity. Carbon dioxide was sampled at three locations in the cave with an air pump and measured with an infrared analyzer, accurate to about 5 ppm (parts per million). These data were recorded on a 24-channel recorder in which each channel is sampled five times per hour. These data were supplemented with spot measurements of humidity and air temperature taken with a sling psychrometer.

Water-level changes in pools were measured with rulers graduated in millimeters. Variation in the evaporation rate was measured with nonstandard plastic pans. These pans are rectangular, 79,400 mm^2 (123 in^2) in area, and about 150 mm (6 in) deep. One liter of water was placed in the pan at about monthly intervals, and the water remaining at the end of the month was measured with a graduated cylinder. The average evaporation rate was then computed in millimeters per week.

Data from several hair-element hygrographs were averaged to give a qualitative estimate of changes in temperature and humidity in the cave. Buckets were placed under several points of dripping water in the cave, and the accumulated water measured at approximately monthly intervals. The data were then reduced to a value of inflow in cubic millimetres per day. The locations of data collection points are shown in figure 1. Data on the energy consumed by the lighting system and the number of visitors were supplied by the National Park Service.

Data which showed the most response to changes in the cave microclimate were used to evaluate the effects of the increased use of electrical power and the closing of the elevator shaft. An initial inspection of the data indicated that the evaporation measured with nonstandard pans was sensitive to these changes. Relative humidity measurements, by hygrothermographs or individual sling psychrometer, were less sensitive, as were measurements of the cave air temperature. The wind velocity outside the cave, as measured by an anemometer at the weather station, was not a significant control on the evaporation in the cave.

These data were analyzed by comparing values of evaporation before and after the closing of the elevator shaft as mean values, as graphical relationships, and as equations constructed by the least-squares method.

Acknowledgments

Data from 1971 through 1973 have been collected by Charlie Peterson of the National Park Service. The work was funded by the National Park Service through the Office of Natural Sciences of the Southwest Region.

Cave microclimate

Description

Variation in the microclimate in Carlsbad Caverns is due primarily to variation in the air temperature outside the cave. High evaporation rates in the cave occur during the winter months when cold air flows into the cave through the Natural Entrance. Mean weekly minimum temperatures at the weather station above the cave are shown in figure 3. This cold air inflow results in much of the cave being cooler than the mean-annual surface temperature of 17° Celsius (63°F). During the summer the cool air inside the cave is more stable than the warm air outside and the cave microclimate is characterized by high humidity, low evaporation, and rising air temperature, increasing carbon dioxide content of the air (fig. 4), and rising pool levels (figs. 5-14). The first cool days of fall induce cold airflow in the upper main corridor, producing a seasonal drying of the trails and many formations. Dense fogs sometimes occur in the cave at this season as warm, moist air from deeper in the cave is displaced upward, and cooled adiabatically and by radiation to the cooler walls of the upper main corridor. As the winter progresses, cold, dry air moves throughout most of the cave, reducing the relative humidity, increasing evaporation, and lowering the water levels in the pools. The increased rate of air circulation during the winter lowers the carbon dioxide content of the air (fig. 4).

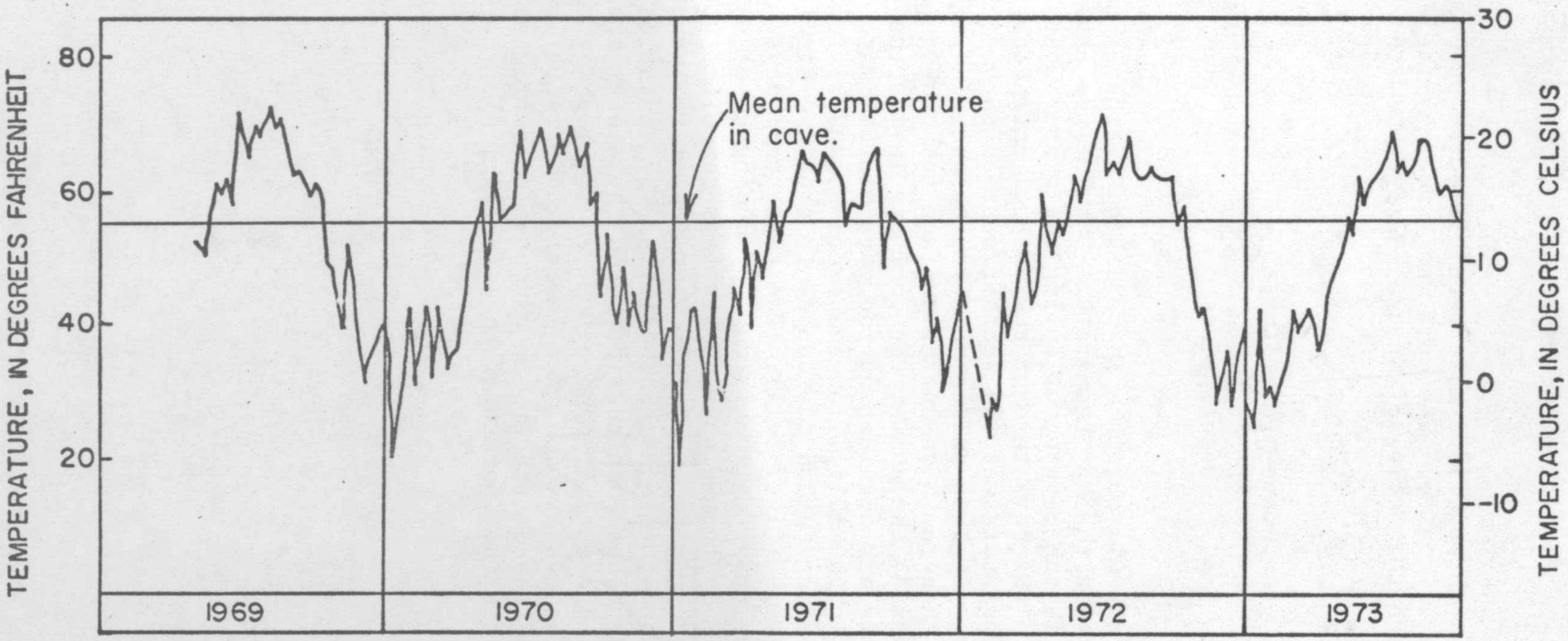


Figure 3.--Mean-weekly minimum temperatures at the weather station, Carlsbad Caverns.

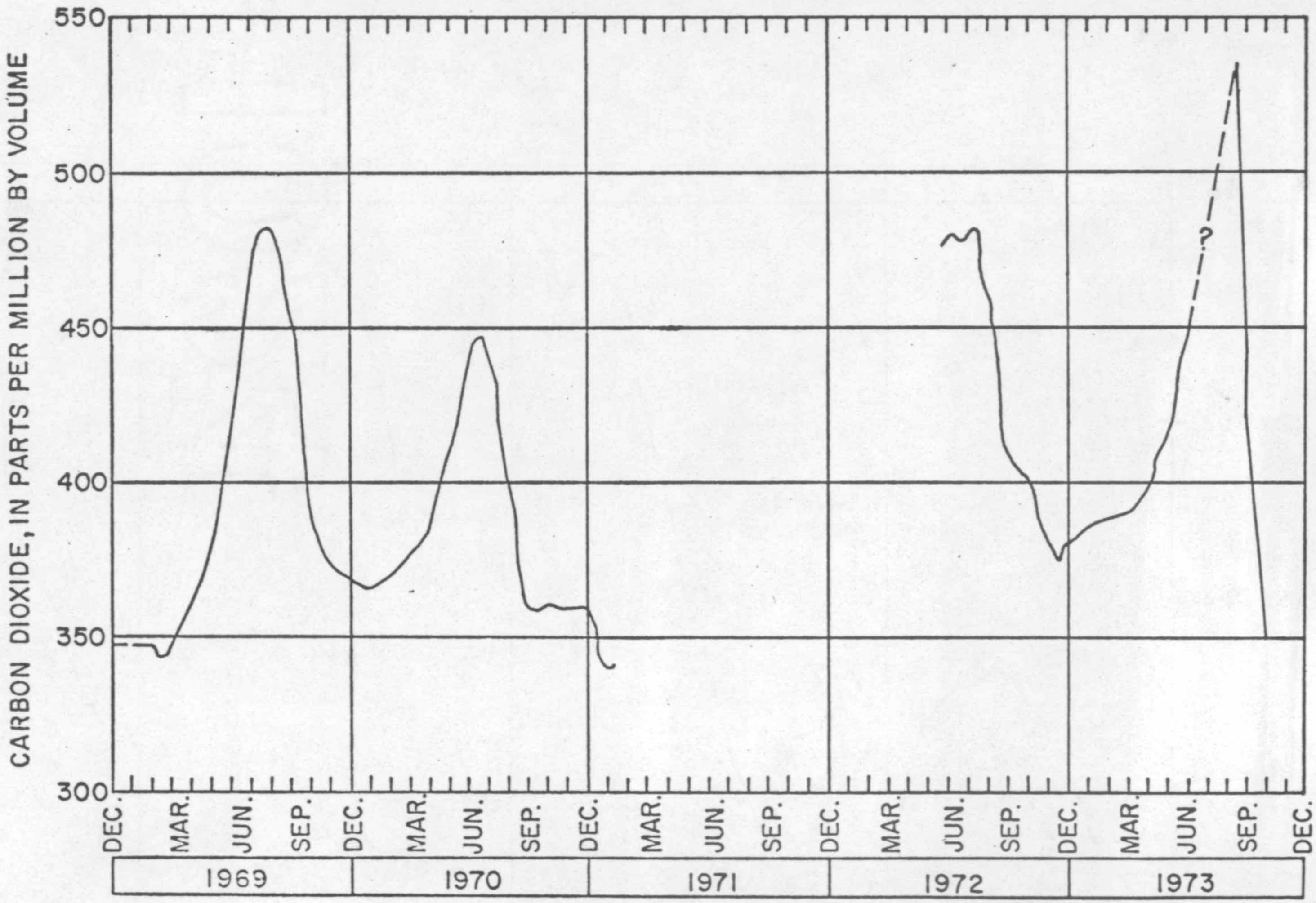


Figure 4.--Carbon dioxide content of the air in the Lunch Room (near base of elevator shaft).

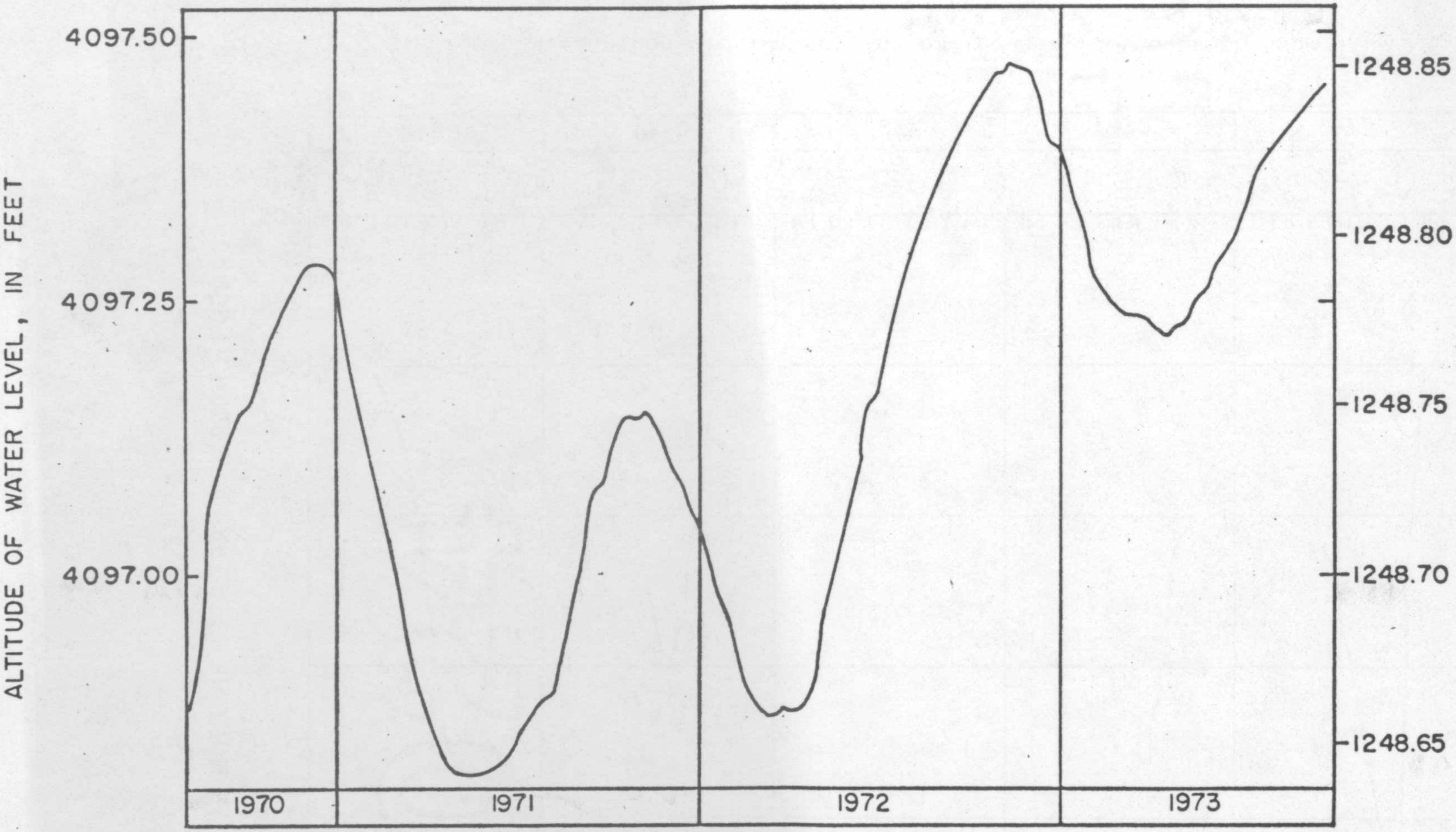


Figure 5.--Hydrograph of pool level at Devil's Spring.

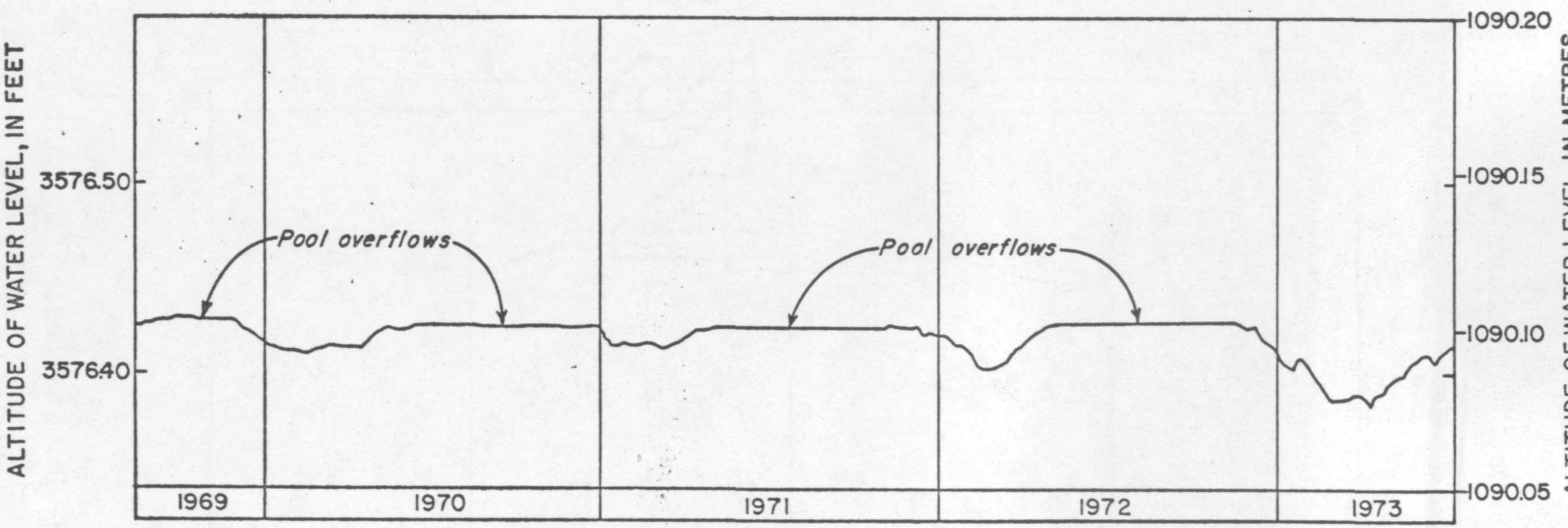


Figure 6.--Hydrograph of Green Lake.

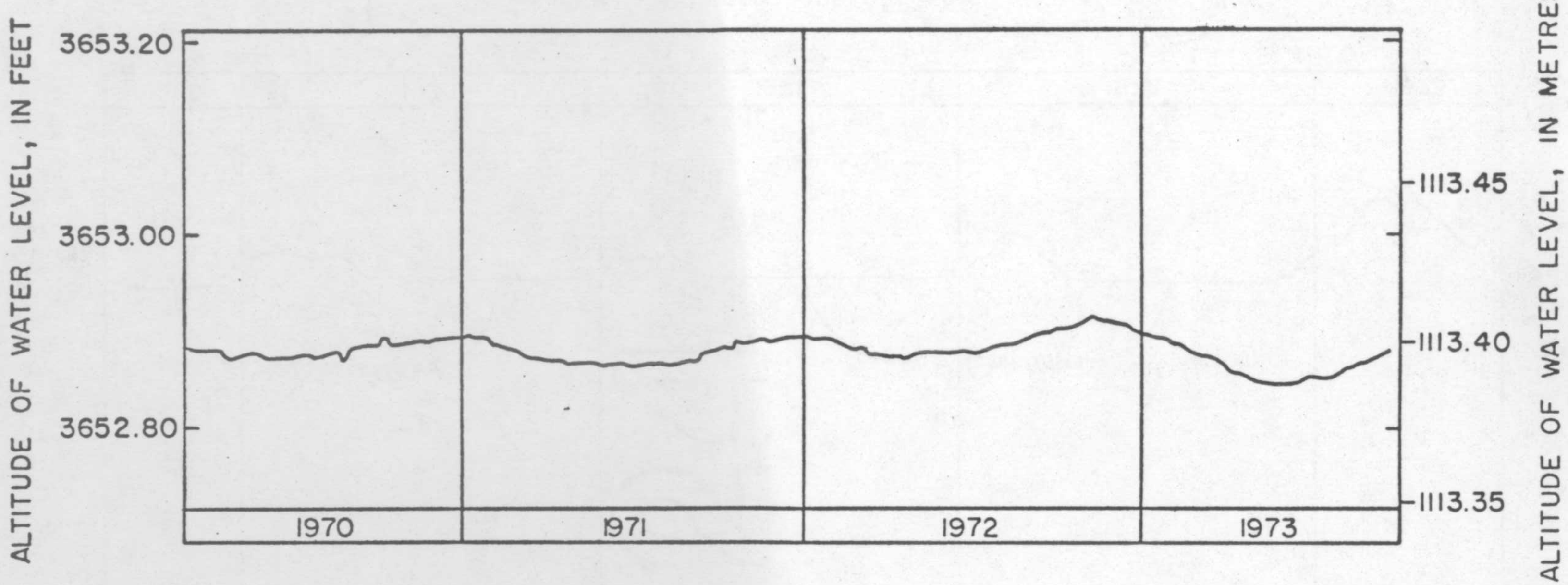


Figure 7.--Hydrograph of the pool west of Mirror Lake.

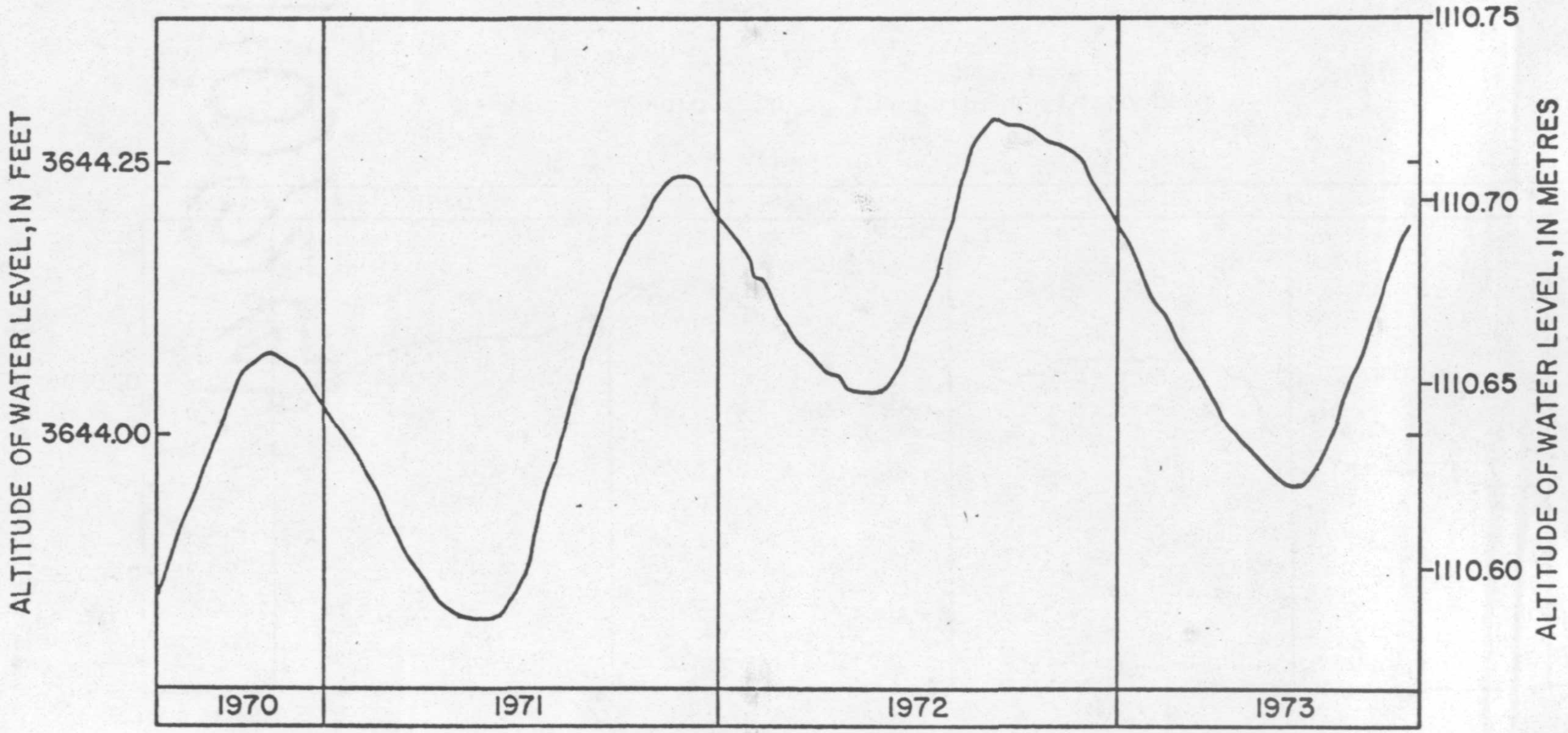


Figure 8.--Hydrograph of the Dome Room pool.

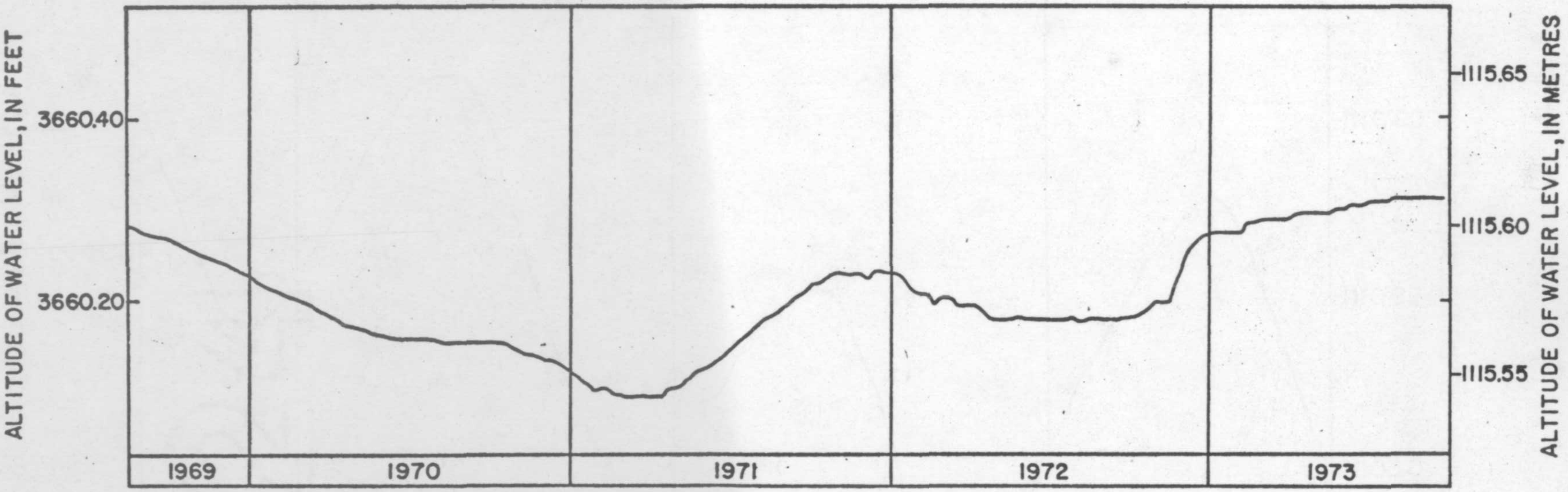


Figure 9.--Hydrograph of the Painted Grotto pool.

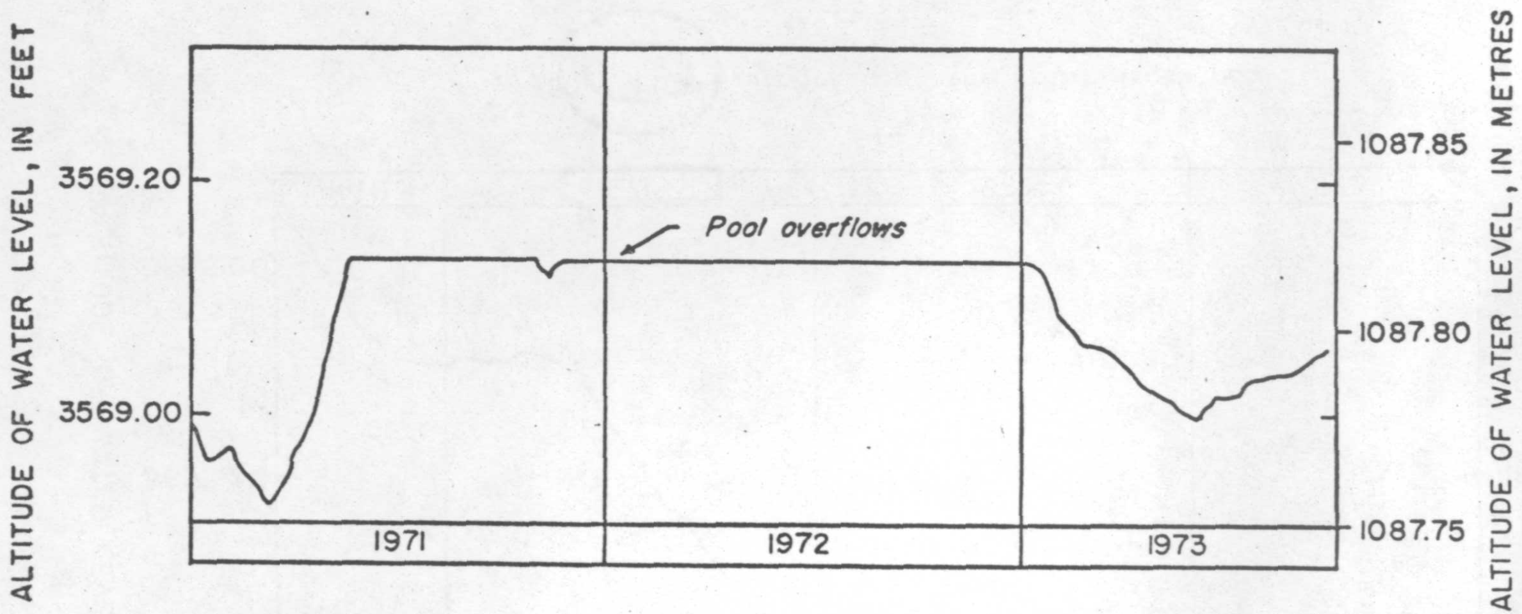


Figure 10.--Hydrograph of the Papoose Room pool.

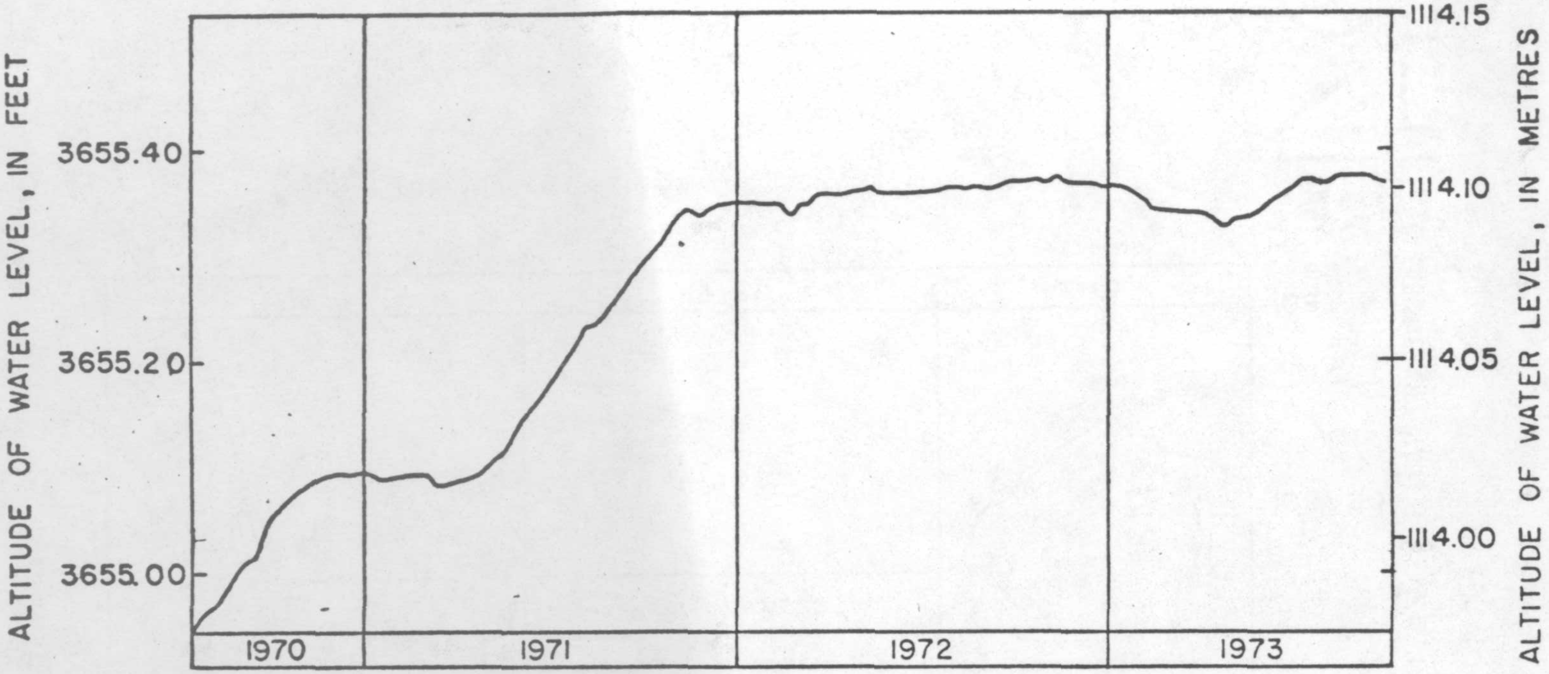


Figure 11.--Hydrograph of the Paint Brush pool.

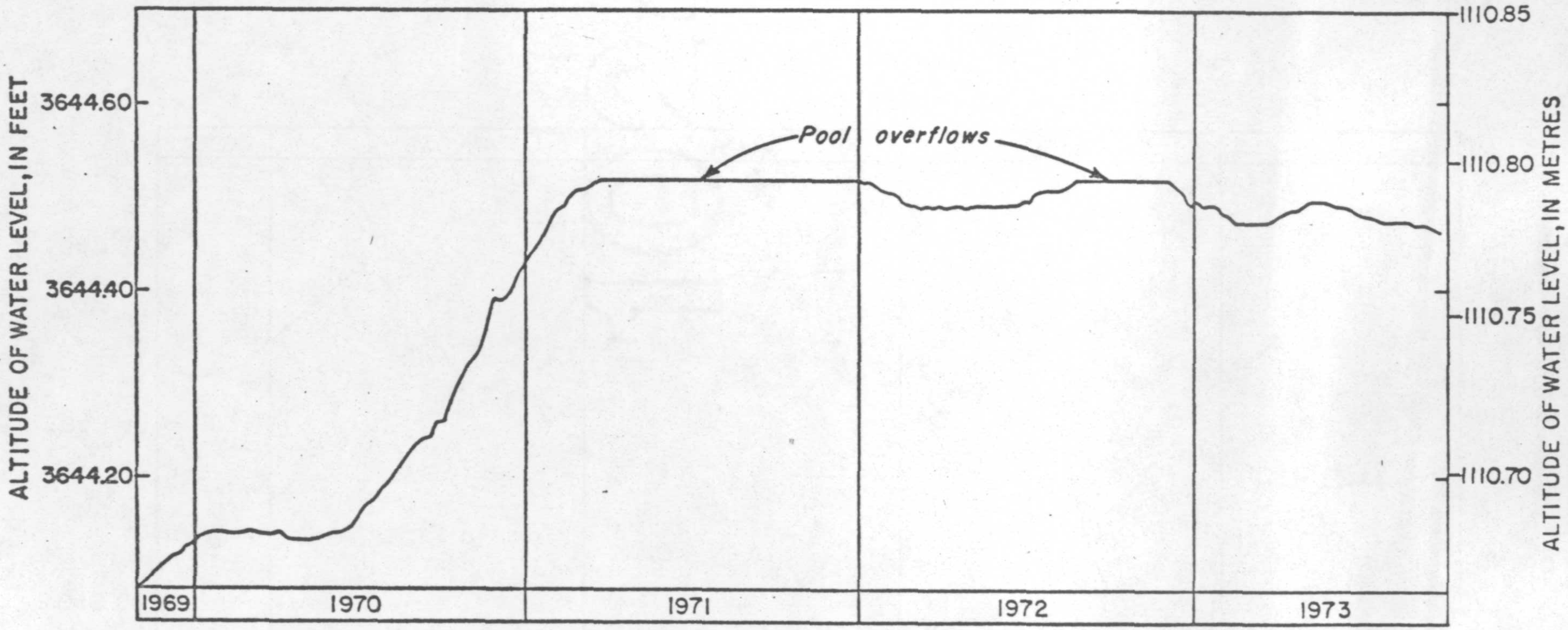


Figure 12.--Hydrograph of the Top of the Cross pool.

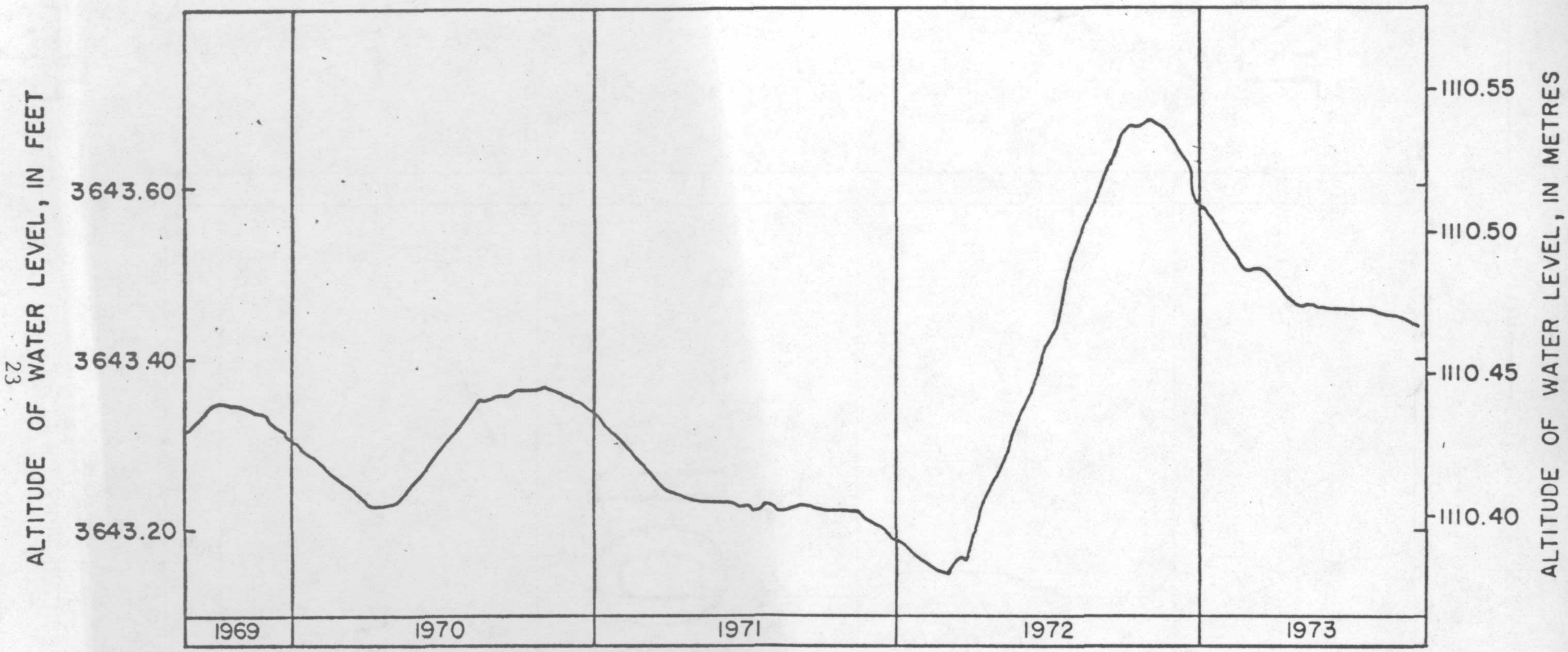


Figure 13.--Hydrograph of the Illuminated pool.

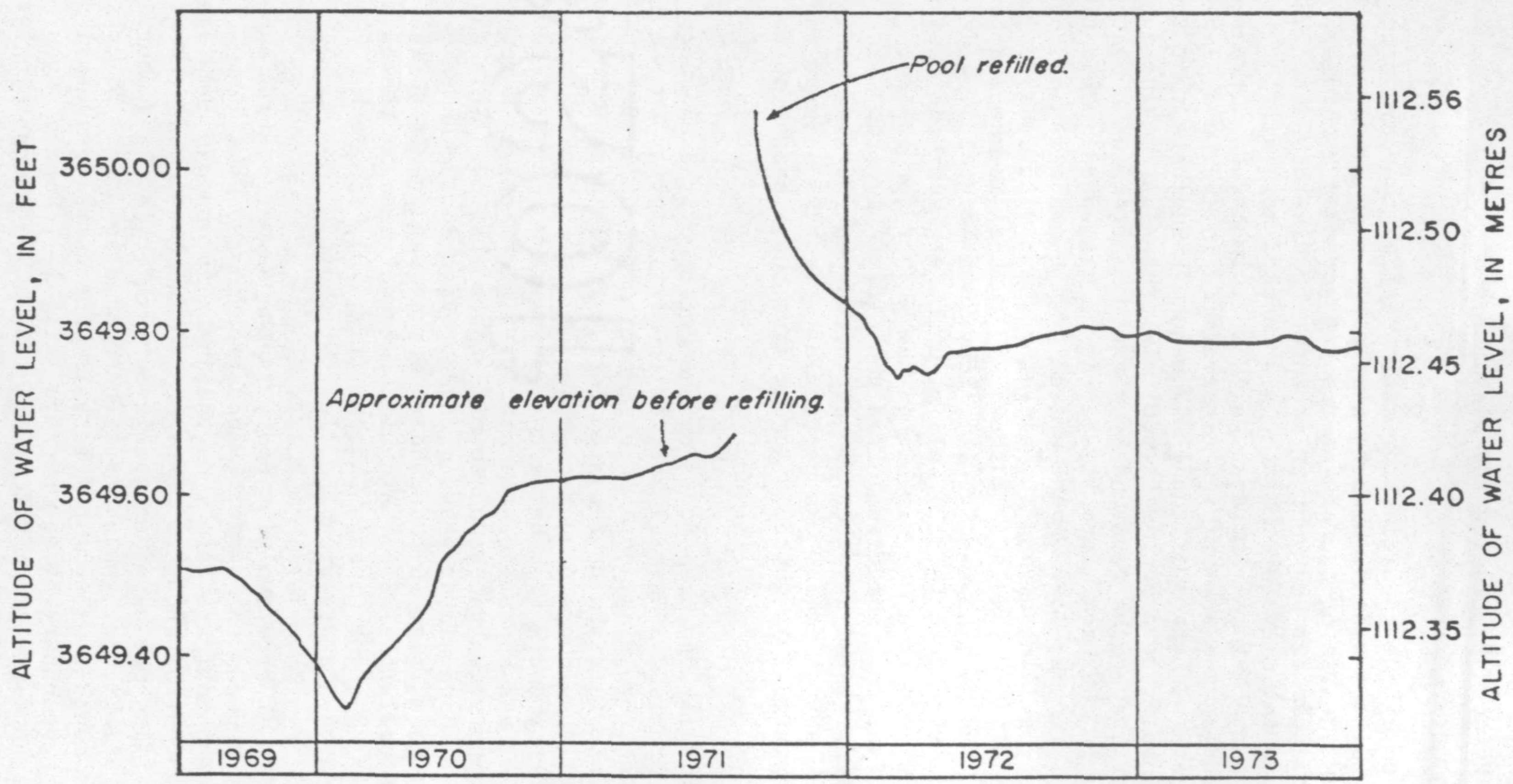


Figure 14.--Hydrograph of Mirror Lake.

Changes in the cave microclimate

Effects of closing the elevator shaft

The presence of the open elevator shaft altered the cave microclimate by providing a second, higher point for air exchange with the surface. During the winter the elevator shaft acted as a chimney, warming the cool cave air and venting it into the Visitor Center on the surface above the elevator shaft. This induced more airflow into the cave through the Natural Entrance which in turn caused increased evaporation. During the summer high temperatures in the Lunch Room in the caverns at the bottom of the elevator shaft indicate that the flow was occasionally reversed, with cool air presumably moving out the Natural Entrance, to be replaced by warmer air from the elevator shaft. Changes in the cave microclimate can be evaluated qualitatively by inspection of figures 15-23. The effect of air conditioning the visitor center by pulling air up the elevator shaft with fans during July and August of 1969 and 1970 is shown as 'spikes' in the evaporation curves for the Dome Room (fig. 15), Pump Room (fig. 16), and Secondary Stream Passage (fig. 17), all of which are near the elevator shaft. Although no spikes are visible on the graphs for the Rock of Ages South (fig. 18), and Illuminated pool (fig. 21), the mean summer evaporation was higher when air was withdrawn for air conditioning than in later summers. No particular effect is seen at the Queen's Chamber (fig. 20), which is remote from the elevator shaft (fig. 1).

The electrically operated doors on the bottom of the elevator shaft may have provided a partial barrier to airflow prior to the installation of the revolving doors late in the summer of 1972. The force of the winter airflow up the elevator shaft was often sufficient to hold all the doors open two inches or more. Metal stops which prevented the doors from being opened inward were installed in the fall of 1971, and appear to have been partly effective in reducing the high evaporation rates due to mid-winter airflow. This can be seen in the reduced winter peaks of evaporation in the Dome Room (fig. 15), Pump Room (fig. 16), Secondary Stream passage (fig. 17), and Illuminated pool (fig. 21). Mid-winter evaporation increased at Green Lake (fig. 22), the Queen's Chamber (fig. 20), and Rock of Ages (fig. 19), all areas remote from the elevator shaft.

Installation of the revolving doors in the summer of 1972 appears to have greatly reduced the summer evaporation in the Dome Room (fig. 15). The approximate date when the installation was complete is shown in figures 15 through 23. Figure 15 indicates that the reduction in airflow may have been achieved earlier in the summer, during the installation of the doors. There is also a lack of definition due to the month-long sample interval. The summer evaporation decreased at the Secondary Stream passage (fig. 17), Rock of Ages South (fig. 18), and the Illuminated Pool (fig. 21). Surprisingly, the summer evaporation increased in the Pump Room (fig. 16), but the winter evaporation decreased substantially.

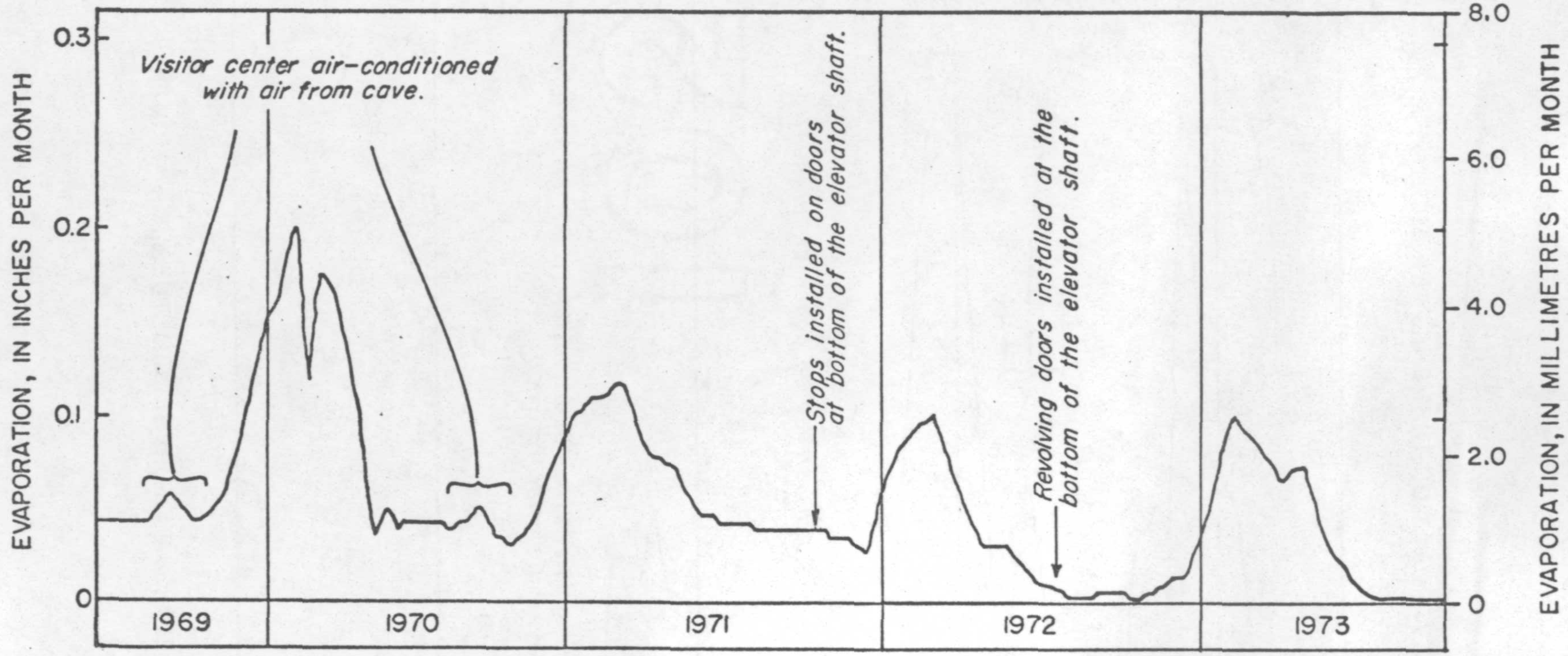


Figure 15.--Evaporation in the Dome Room.

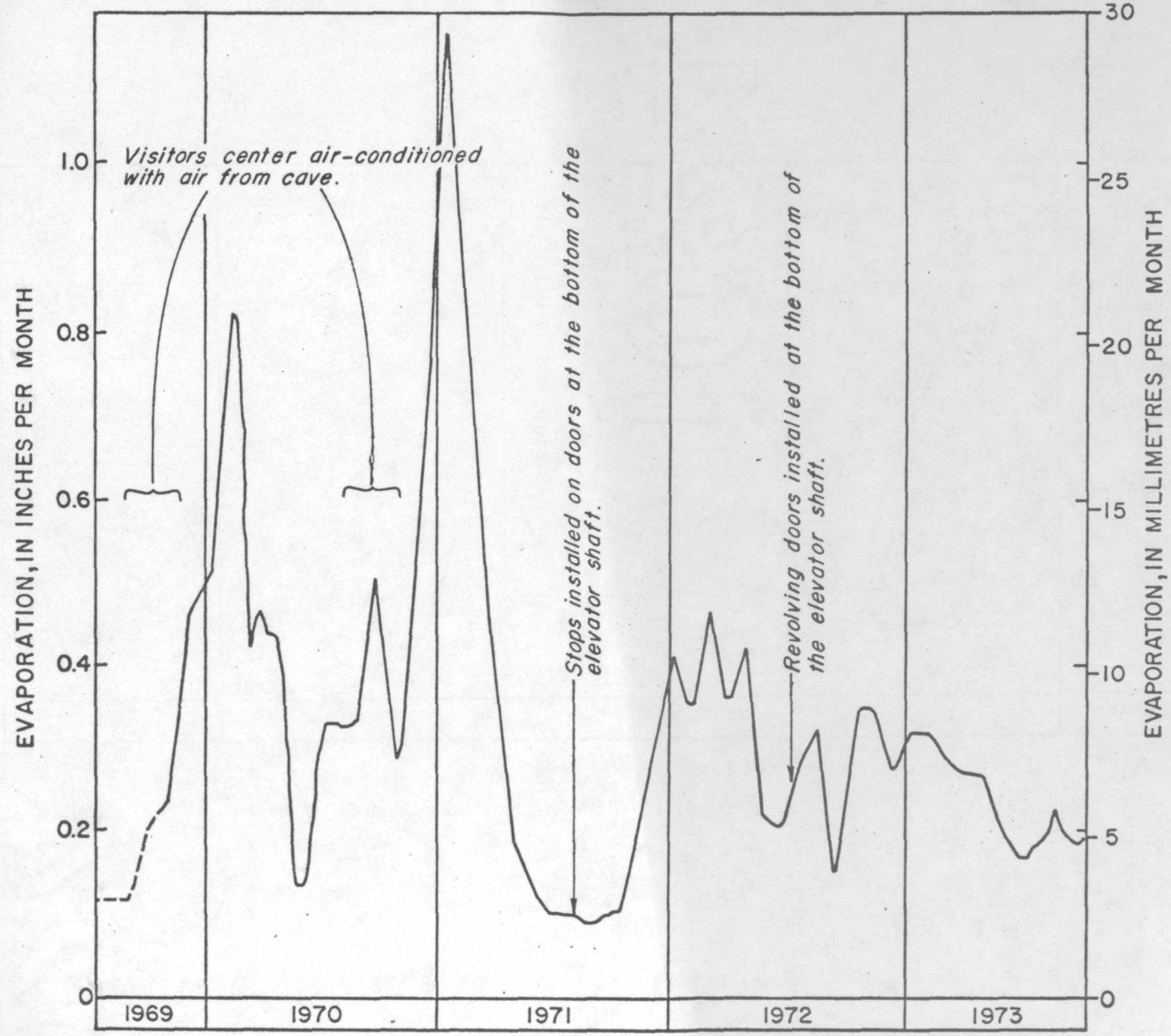


Figure 16.--Evaporation in the Pump Room.

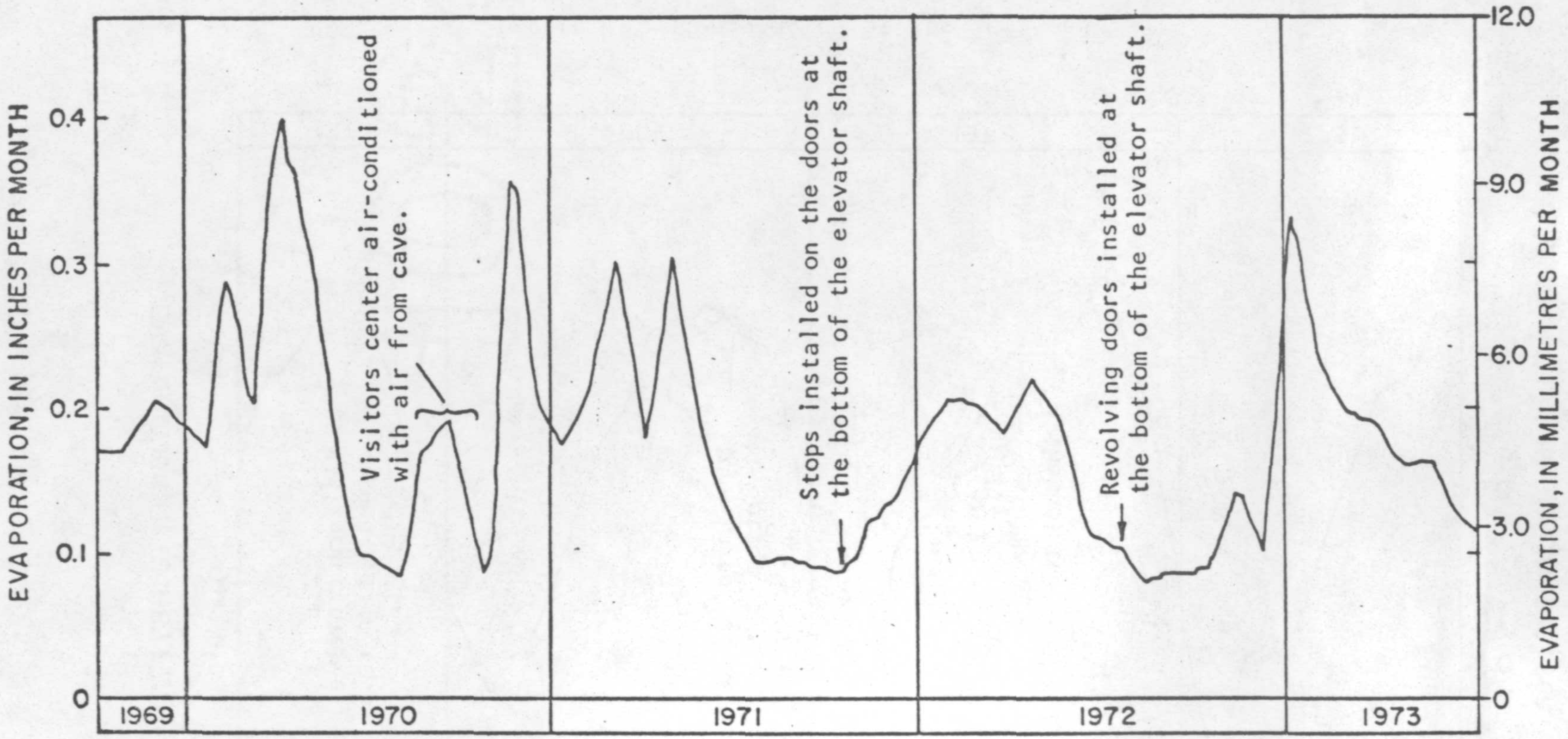


Figure 17.--Evaporation in the Secondary Stream passage.

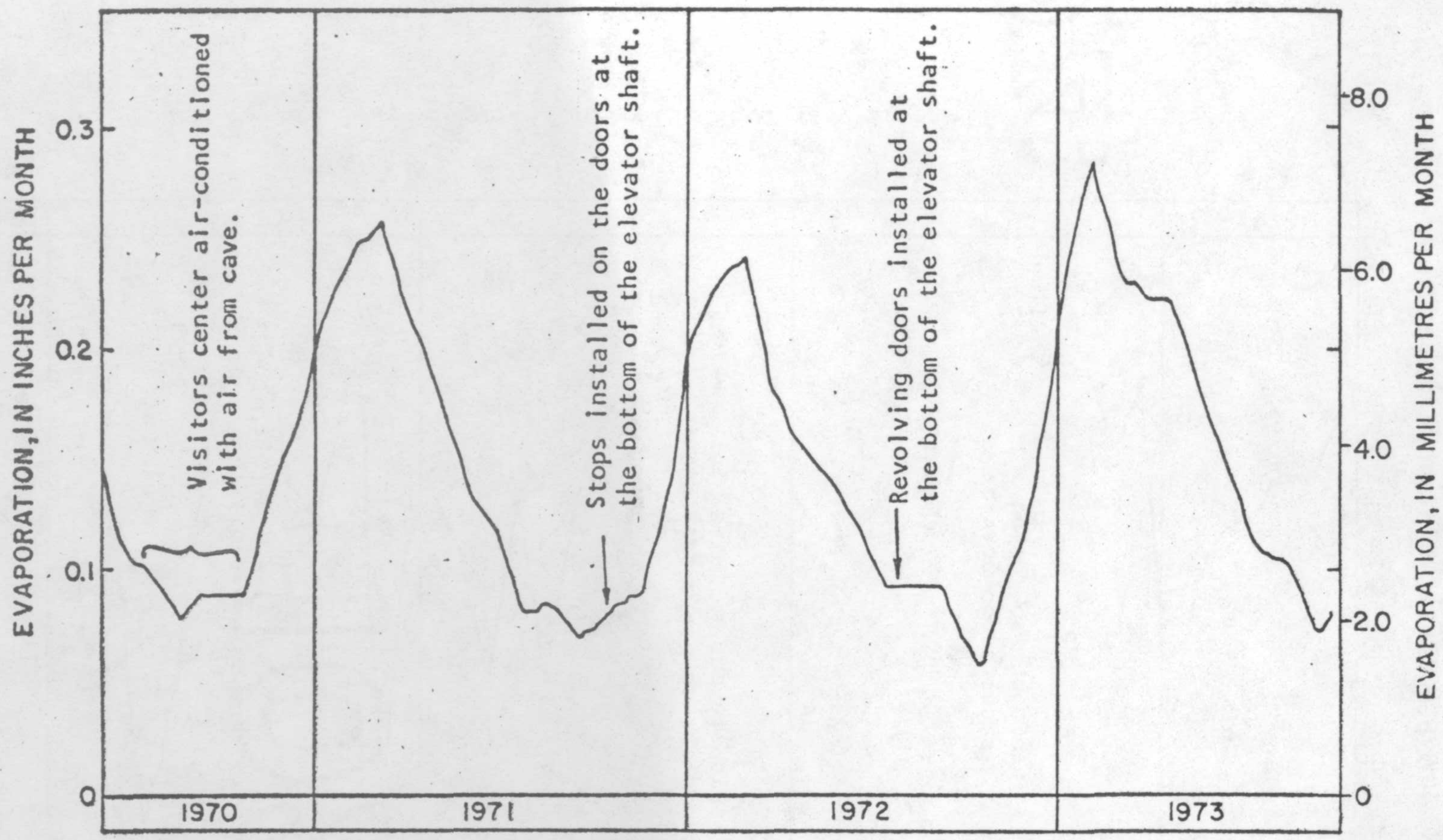


Figure 18.--Evaporation at Rock of Ages South.

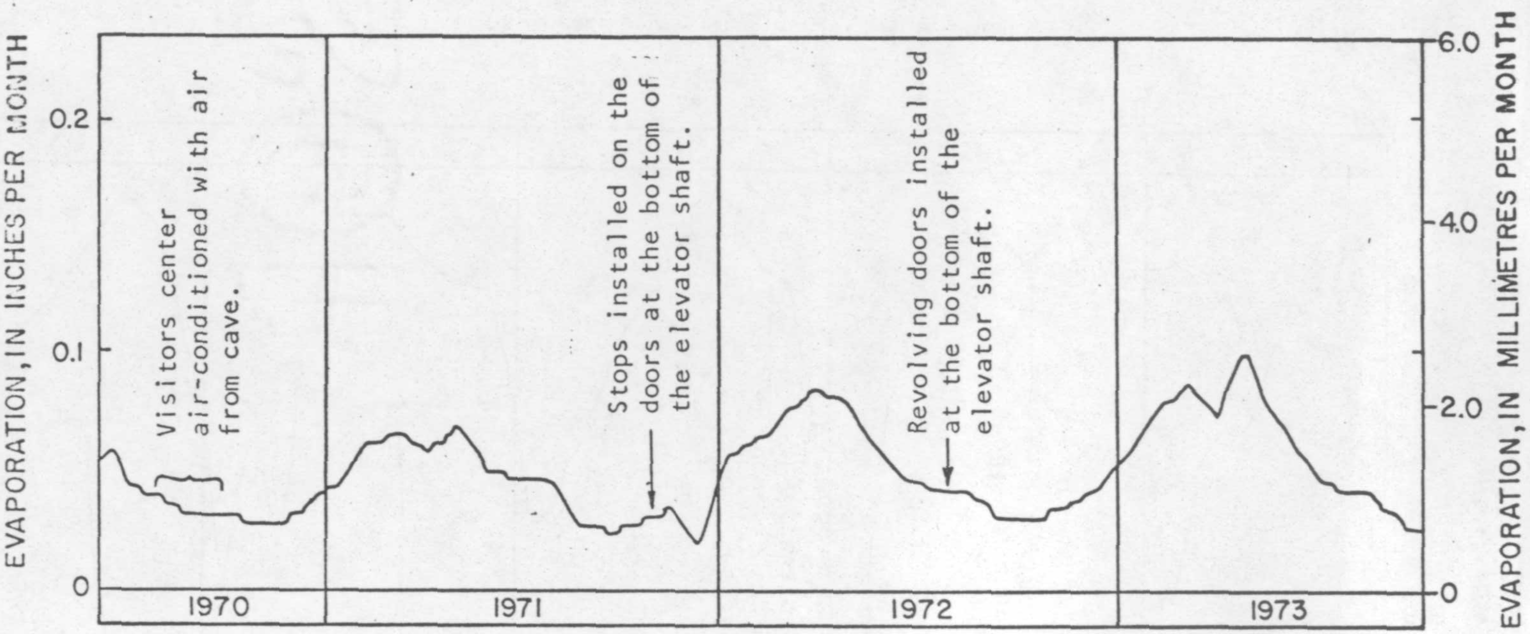


Figure 19.--Evaporation at Rock of Ages.

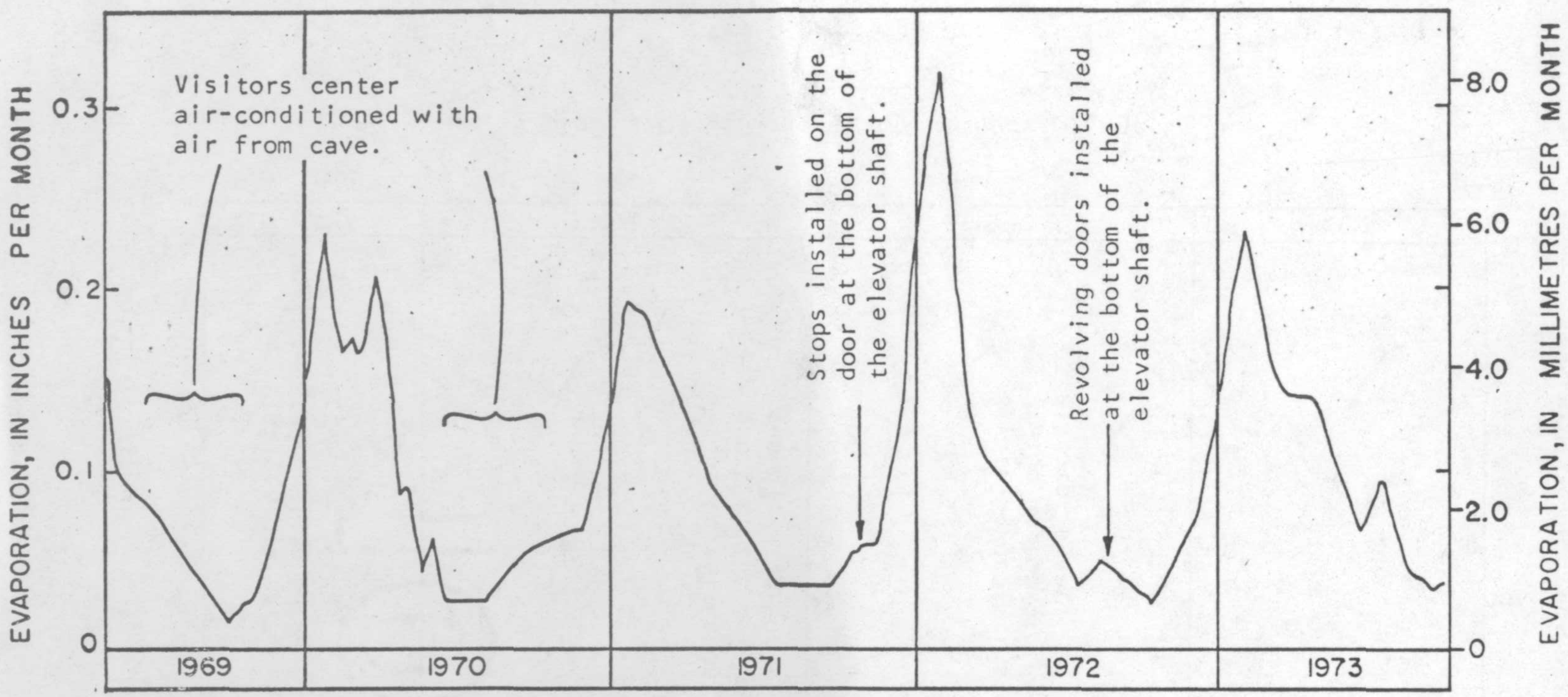


Figure 20.--Evaporation in the Queen's Chamber.

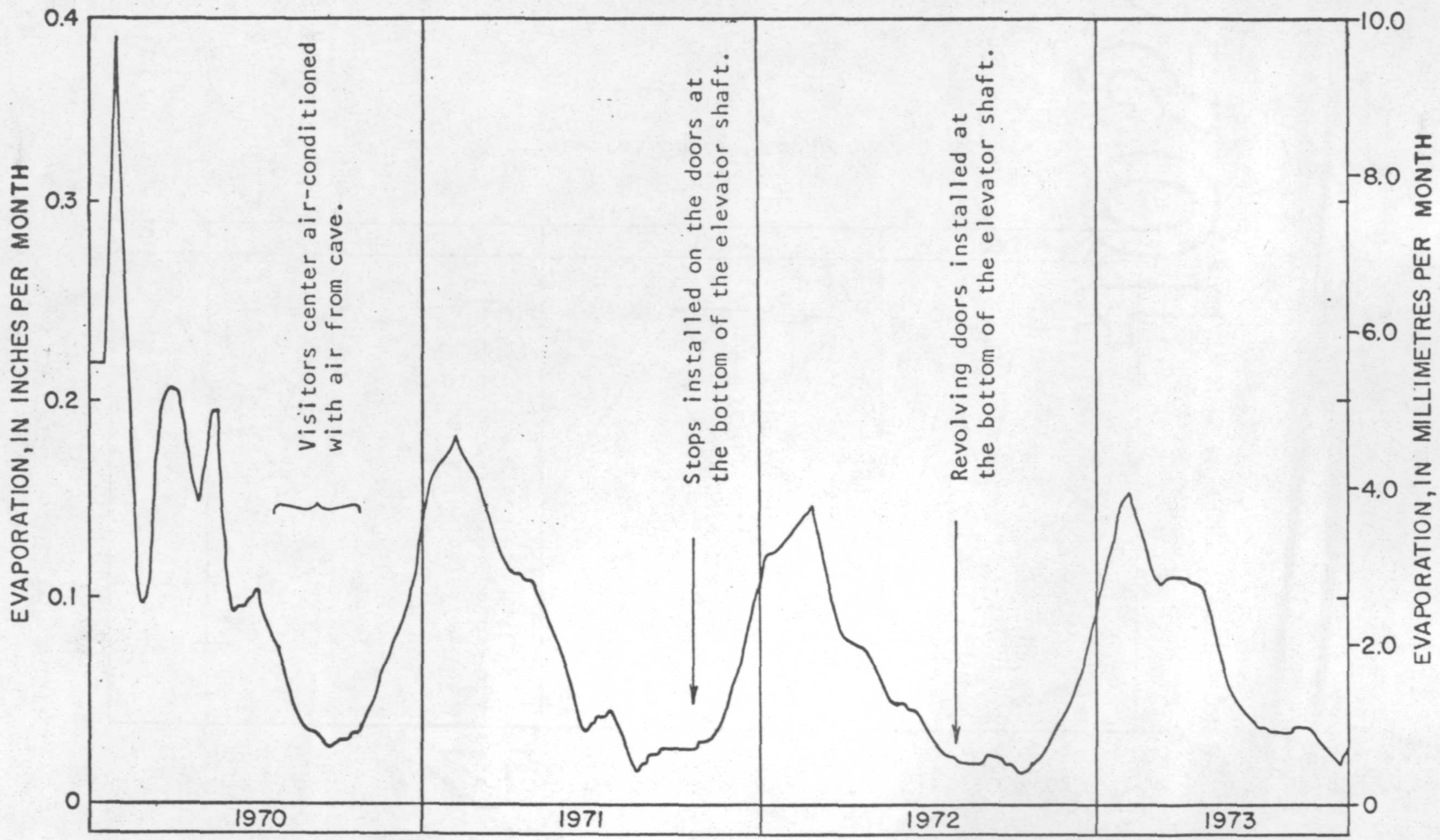


Figure 21.--Evaporation at the Illuminated pool.

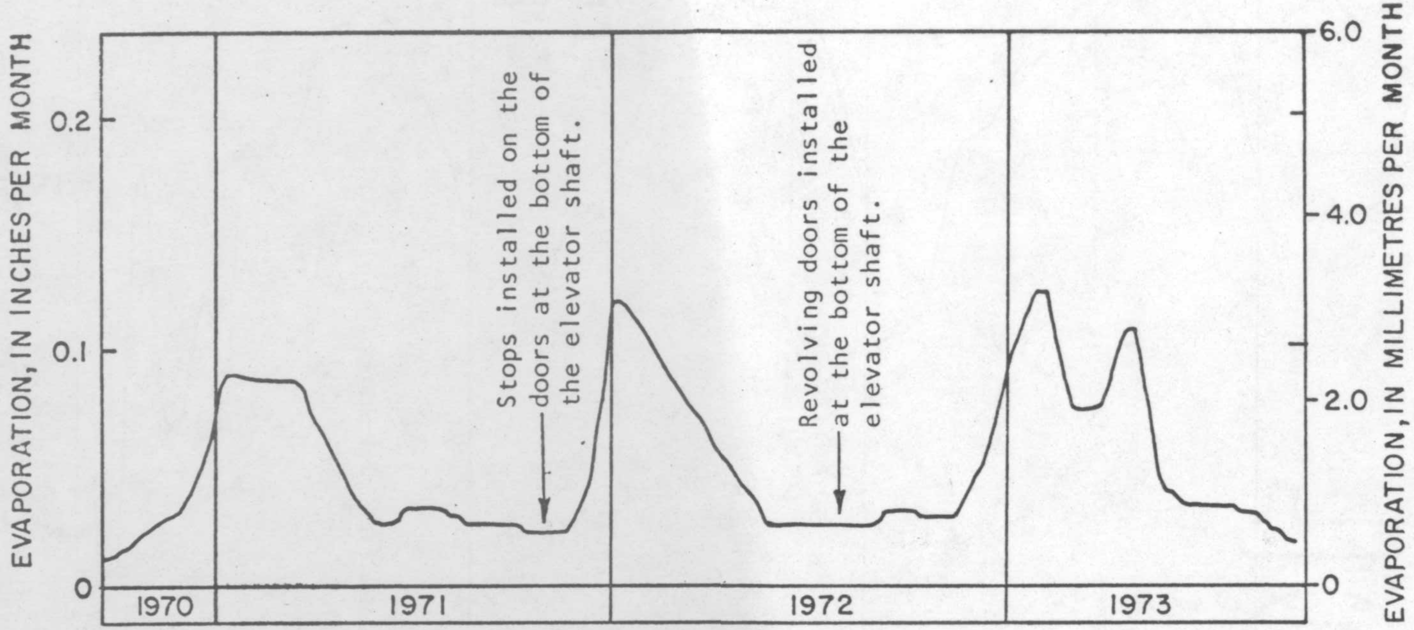


Figure 22.--Evaporation at Green Lake.

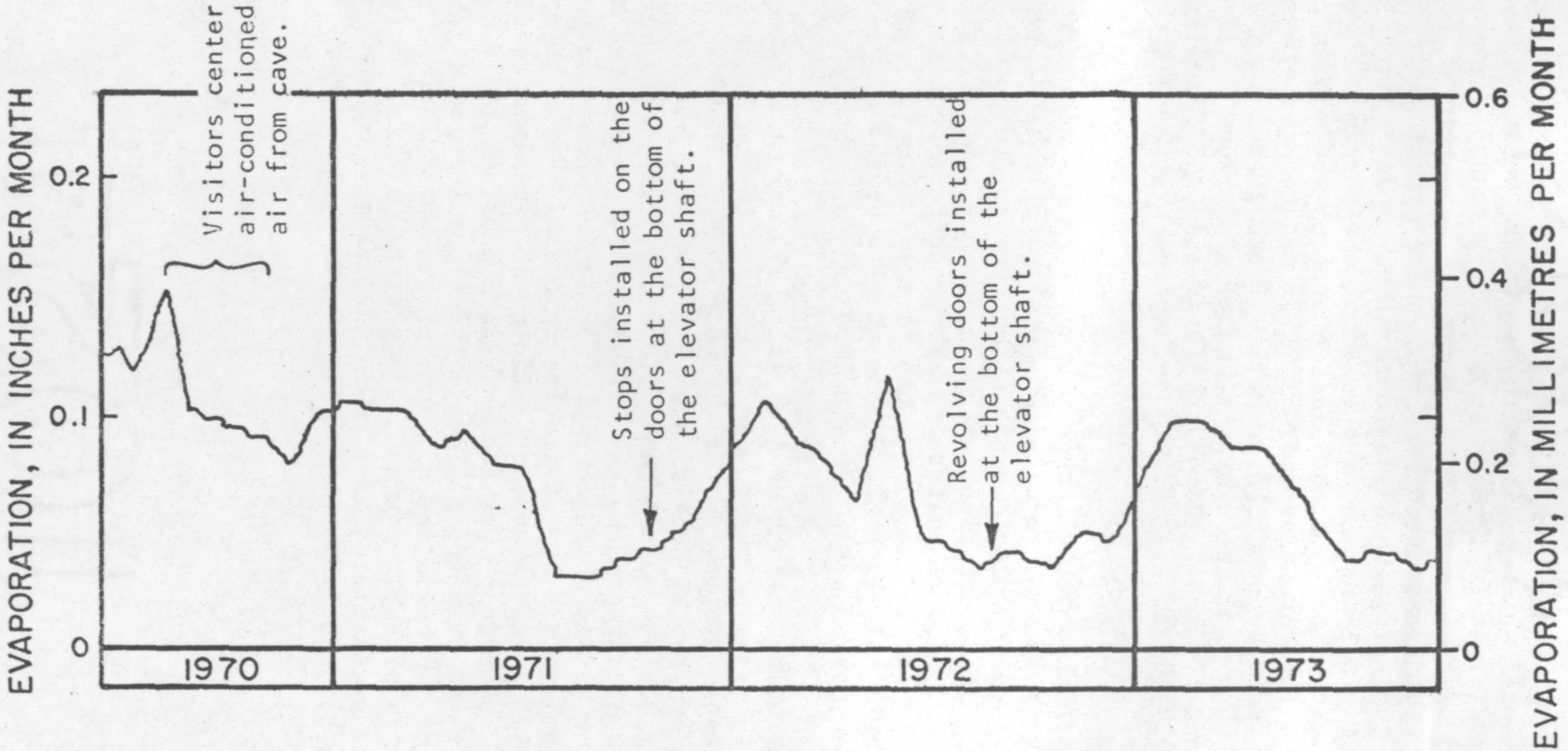


Figure 23.--Evaporation at Mirror Lake

One hypothesis which explains these effects would be that pulling air up the elevator shaft during the summer increased evaporation for a short period of time in the late summer and that this effect is most noticeable at evaporation pans near the elevator shaft, but that the effect is indistinguishable at more distant pans; that placing stops in the original doors at the elevator shaft reduced the high winter evaporation rates, but had less effect on the summer rates; and that installing the revolving doors further reduced the winter evaporation and the summer evaporation as well. These effects are most easily seen at those pans near the elevator shaft,--Pump Room (fig. 16), Illuminated Pool (fig. 21), Dome Room (fig. 15), and Secondary Stream passage (fig. 17),--and are reduced and spread over a longer timespan at more distant pans.

The Mirror Lake pan, although distant from the elevator shaft, appears to have responded to closing the elevator shaft (fig. 23). This response is difficult to explain, but may be due to air currents circulating out along the floor of the Big Room. An intriguing alternate explanation might be that there is a restricted entrance for air in the Big Room, say at the top of the dome above Bottomless Pit. Air might be drawn in this entrance due to airflow up the elevator shaft, and increase evaporation at Mirror Lake.

The evaporation at Rock of Ages (fig. 19) may be more sensitive to increased energy consumption due to changes in the lighting system than to changes in airflow up the elevator shaft. The Rock of ages pan is located on top of Rock of Ages Hill, about 8 m (26 ft) above the level of the floor of the Big Room. Therfore, evaporation at this pan is believed to be affected by the air which has been heated by the lighting system and is moving out of the Big Room near the ceiling level. The temperature stratification in the Big Room was measured on June 15, 1973, using a weather balloon and a maximum reading thermometer. The temperature was found to be a constant 14.7° C (58° F) from 1 m (3 ft) to 29 m (96 ft) above the floor. At a height of 36 m (120 ft) inside a dome in the ceiling, the temperature rose to 15.7°C (60°F). This is probably due to the restricted airflow in the dome as opposed to the unrestricted airflow in most of the Big Room. Evaporation is summarized in table 1.

Table 1.--Evaporation in Carlsbad Caverns

[Mean evaporation, in millimetres per month]

Location	August 1970 to August 1971	August 1971 to August 1972	August 1972 to August 1973
Near elevator shaft:			
Pump Room	11.20	6.79	6.60
Secondary Stream passage	5.52	4.16	4.38
Dome Room	1.69	1.15	.95
Illuminated Pool	2.28	1.68	1.75
Distant from elevator shaft:			
Green Lake	1.12*	1.05	1.38
Queen's Chamber	2.40	2.67	2.62
Rock of Ages South	3.98	3.56	4.16
Mirror Lake	2.30	1.69	1.62
Outflowing air(?):			
Rock of Ages	1.19	1.28	1.50

*11-months average only

Evaporation at most of the pans near the elevator shaft decreased sharply after the stops were installed in the elevator shaft doors, and either increased or decreased a small amount the following year when revolving doors were installed. This is due in part to the fact that the winter of 1972 was colder (average 8.98°C (48.2°F) minimum temperature at the weather station) than the winter of 1971 which had a 10.03°C (50.05°F) minimum temperature. Thus the decrease in evaporation due to the stops and revolving doors was much more noticeable in the period August 1971 to August 1972 than it was the next winter. The sum of the evaporation from all pans from the fall of 1970 to the fall of 1972 (first and third columns, table 1) was reduced 21 percent. Some early values for the Pump Room are suspect. The sum of the evaporation for all pans except the Pump Room decreased 10 percent. The four evaporation pans near the elevator shaft,--Pump Room, Secondary Stream passage, Dome Room, and Illuminated Pool,--showed a net decrease in evaporation of 34 percent. Pans distant from the elevator shaft, excluding Mirror Lake, showed an average increase in evaporation of about 10 percent. Rock of Ages, which may represent outflowing air from the Big Room, showed an increase of 26 percent.

Since evaporation in the cave occurs through cold-air inflow during the winter, it should be possible to estimate these effects by a plot of outside minimum temperatures against evaporation. Unfortunately, as shown in figure 24, no simple relation exists. The response of evaporation to temperature varies seasonally, with less evaporation in the fall than in the spring at corresponding temperatures. This is probably due to the moisture which has accumulated and is available for evaporation from wet trails and formations in the fall. The evaporation rates are suppressed by the larger quantity of moisture available until the cave becomes drier in mid-winter.

An approximation of the change in the response of evaporation to temperature before and after closing the elevator shaft can be made by fitting the data to straight lines. In spite of the scatter in the data, the change in the slope of the line should indicate the change in the response of evaporation to cold air flowing in from outside the cave, and thus indicate changes in the degree of air circulation. These least-squares equations are shown in table 2. The period August 1970 to August 1972 represents the period before the closing of the elevator shaft, and the period August 1972 to August 1973 the first year after closing the elevator shaft.

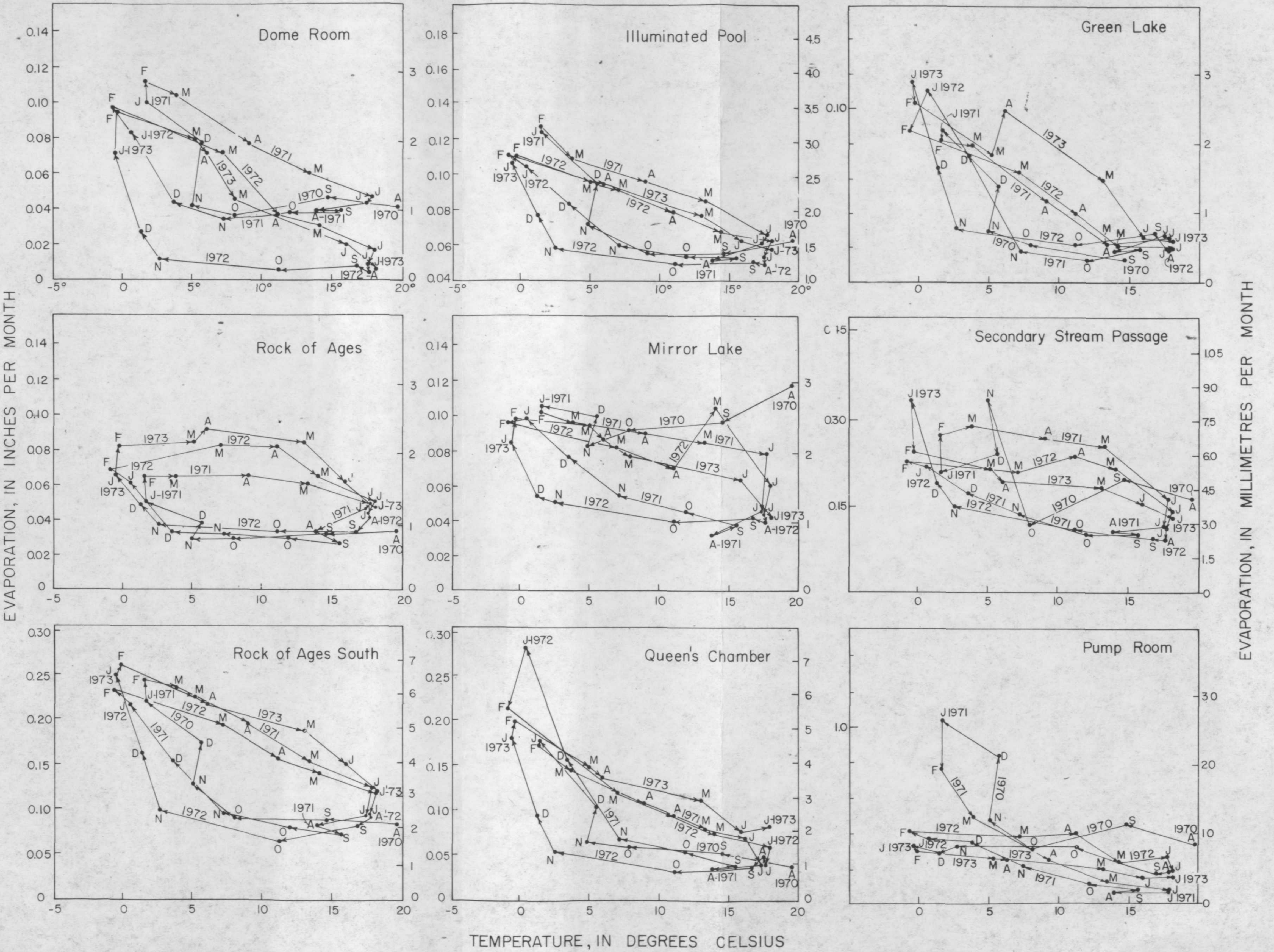


Figure 24.--Seasonal variation in evaporation and temperature, August 1970 to July 1973.

Table 2.--Evaporation as a function of temperature

$$E = \overline{E} + K(\overline{T}-T) \quad (1)$$

where: E = Evaporation rate, in mm per month.

$\overline{E}$ = Evaporation constant, in mm per month.

K = Temperature regression coefficient, in mm per month per degree Celsius.

T = Mean-monthly minimum temperature at the weather station, in degrees Celsius.

$\overline{T}$ = Mean-annual minimum temperature at the weather station, in degrees Celsius (9.61°C).

Location	August 1970 to August 1972		August 1972 to August 1973	
	$\overline{E}$	K	$\overline{E}$	K
Dome Room	1.45	8.77×10^{-2}	0.90	8.09×10^{-2}
Illuminated Pool	2.03	1.52×10^{-1}	1.67	1.20×10^{-1}
Rock of Ages	1.24	1.98×10^{-2}	1.48	2.90×10^{-2}
Rock of Ages South	3.83	1.85×10^{-1}	4.05	1.60×10^{-1}
Mirror Lake	2.01	4.32×10^{-2}	1.55	3.71×10^{-2}
Queen's Chamber	2.61	2.23×10^{-1}	2.54	1.36×10^{-1}
Green Lake	1.09	9.85×10^{-2}	1.32	9.35×10^{-2}
Secondary Stream passage	4.88	1.49×10^{-1}	4.27	1.85×10^{-1}
Pump Room	8.78	5.02×10^{-1}	6.51	1.35×10^{-1}

The slope of the temperature-evaporation curve, shown as 'K' in table 2, decreased for all evaporation pans except Rock of Ages and the Secondary Stream passage. The increased temperature response in the Secondary Stream passage is probably a result of the elimination of the high summer rate of evaporation caused by air conditioning the visitor center with air from the cave during 1970.

Computing evaporation from a straight-line relationship between temperature and evaporation produces a lag between the calculated and measured values of evaporation, as shown in figure 25. This lag is a function of the amount of moisture available along the airflow path, thus the evaporation pans and lakes which are most distant from the entrance lag most behind the time of minimum temperature (fig. 26). Note that the Rock of Ages pan has a lag time equivalent to a much greater distance from the entrance, suggesting that it is responding to outflowing air with a longer flow path than the inflowing air affecting Rock of Ages South.

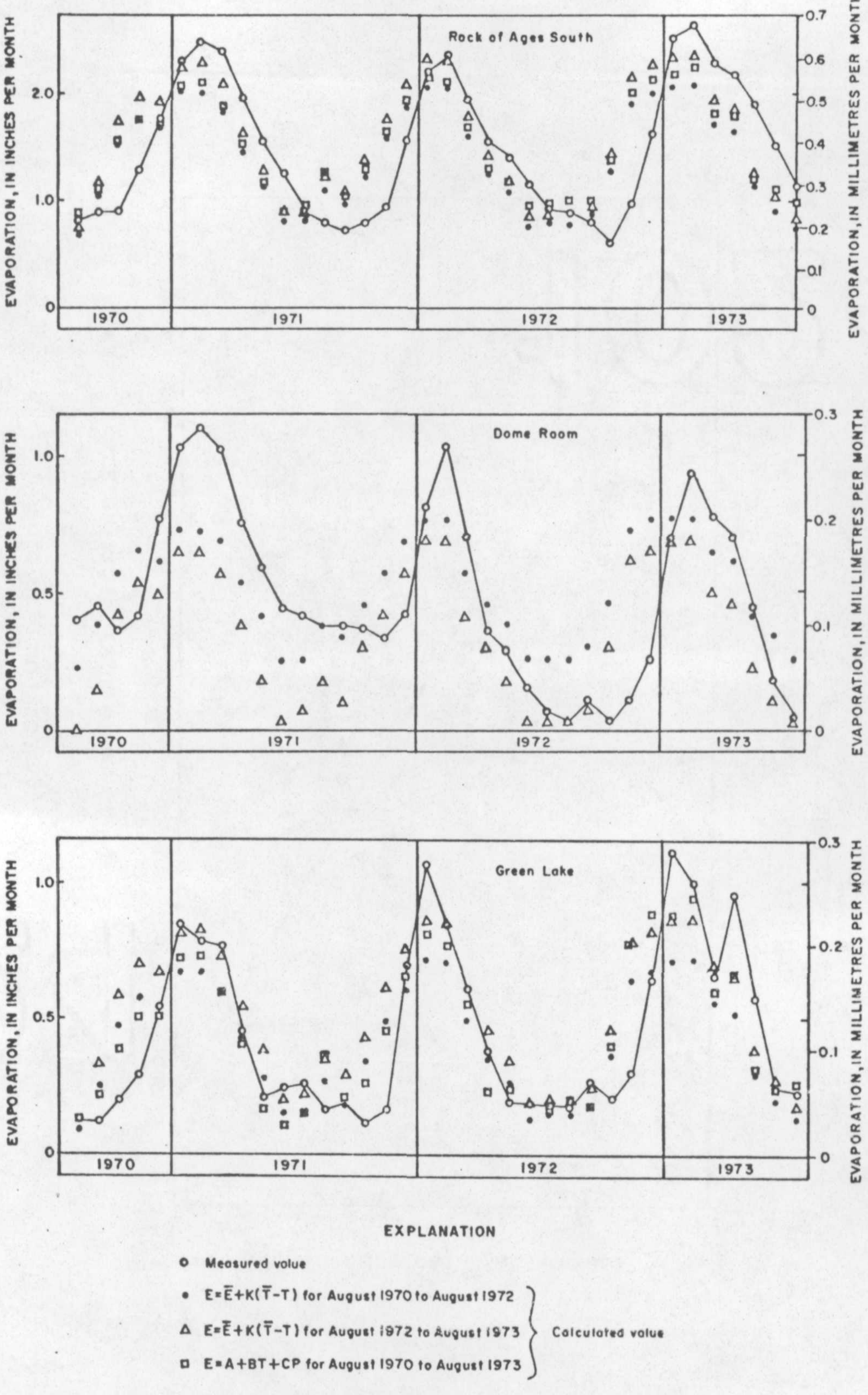


Figure 25.--Measured and calculated monthly evaporation at Rock of Ages South, Dome Room, and Green Lake.

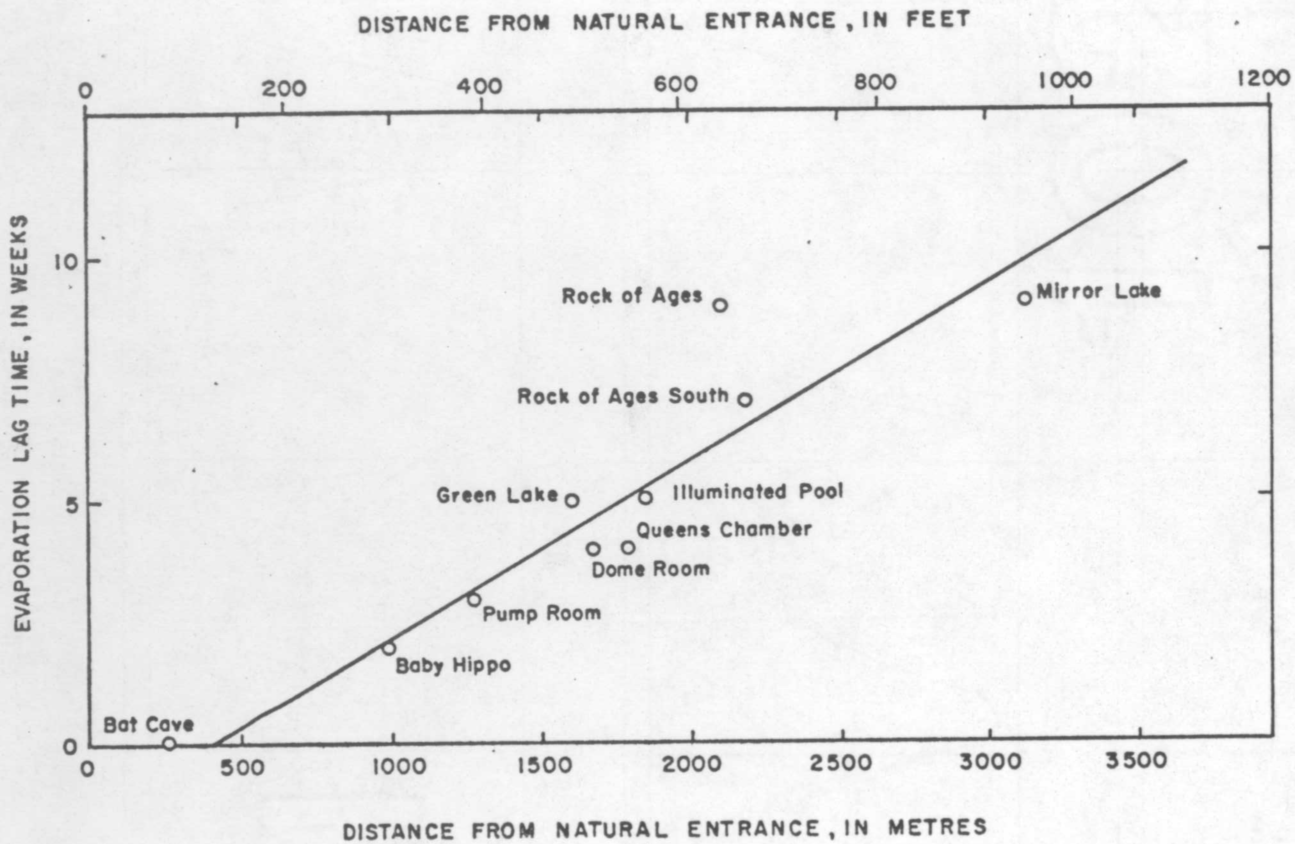


Figure 26.--Evaporation lag times.

Effects of increased energy consuumption

It is impossible to separate the effects of heat added by the lighting system from the effects of the heat added by the visitors. Since tour length and hours of operation are dependent on the number of visitors to the Caverns, the two are highly correlated (fig.27). Although the energy contributed to the cave by the lighting system is only slightly greater than that contributed by the visitors' metabolism, the effect of the visitors is somewhat mitigated by the contribution of exhaled water vapor to the cave microlimate. The number of visitors was deleted and the effects were assumed to be combined with the energy consumption in the equations in table 3. The effects of the air conditioning and airflow up the elevator shaft appear to be greatest at those pans near the elevator shaft, so to evaluate the effect of increased heat from the lighting system, pans distant from the elevator shaft were used: Green Lake, Queen's Chamber, Rock of Ages South, and Rock of Ages. The Mirror Lake pan was not used because of its apparent reaction to the closing of the elevator shaft (fig. 23).

Energy consumption by the cave lighting system ranged from a minimum of 15,000 KWH (kilowatt-hours) per month during November 1970 to a maximum of 65,000 KWH during July 1973. The energy consumed increased 20 percent from 354,100 KWH in the period August 1970 to August 1971 to 423,800 KWH during the period August 1971 to August 1972, and an additional 24 percent to 527,200 KWH during the period August 1972 to August 1973. The constants and coefficients shown in table 3 were generated by a least-squares analysis of evaporation as a linear function of temperature and energy consumed by the lighting system. If average values of energy consumption and temperature are inserted in these equations, an estimate of the importance of these parameters in causing evaporation can be made. The average energy consumed by the lighting system during the period August 1970 to August 1973 was 36,253 KWH per month. The energy consumption term (CP) in equation (2) is therefore $36,253 \times 5.93 \times 10^{-7} = 0.215$ mm/month at Rock of Ages. Since the average evaporation for Rock of Ages from table 1 is 1.32 mm/month the energy consumption term accounts for 16 percent of the total evaporation. Likewise, the energy term accounts for 12 percent of the total evaporation at Rock of Ages South, 26 percent in the Queen's Chamber, and 61 percent at Green Lake. The effect at Green Lake is surprisingly high, possibly because the total evaporation is low (table 1) and the pan is in a small, well-lit alcove. The sum of the CP terms for all four pans is 2.04 mm/month, or 23 percent of the total evaporation at these pans.

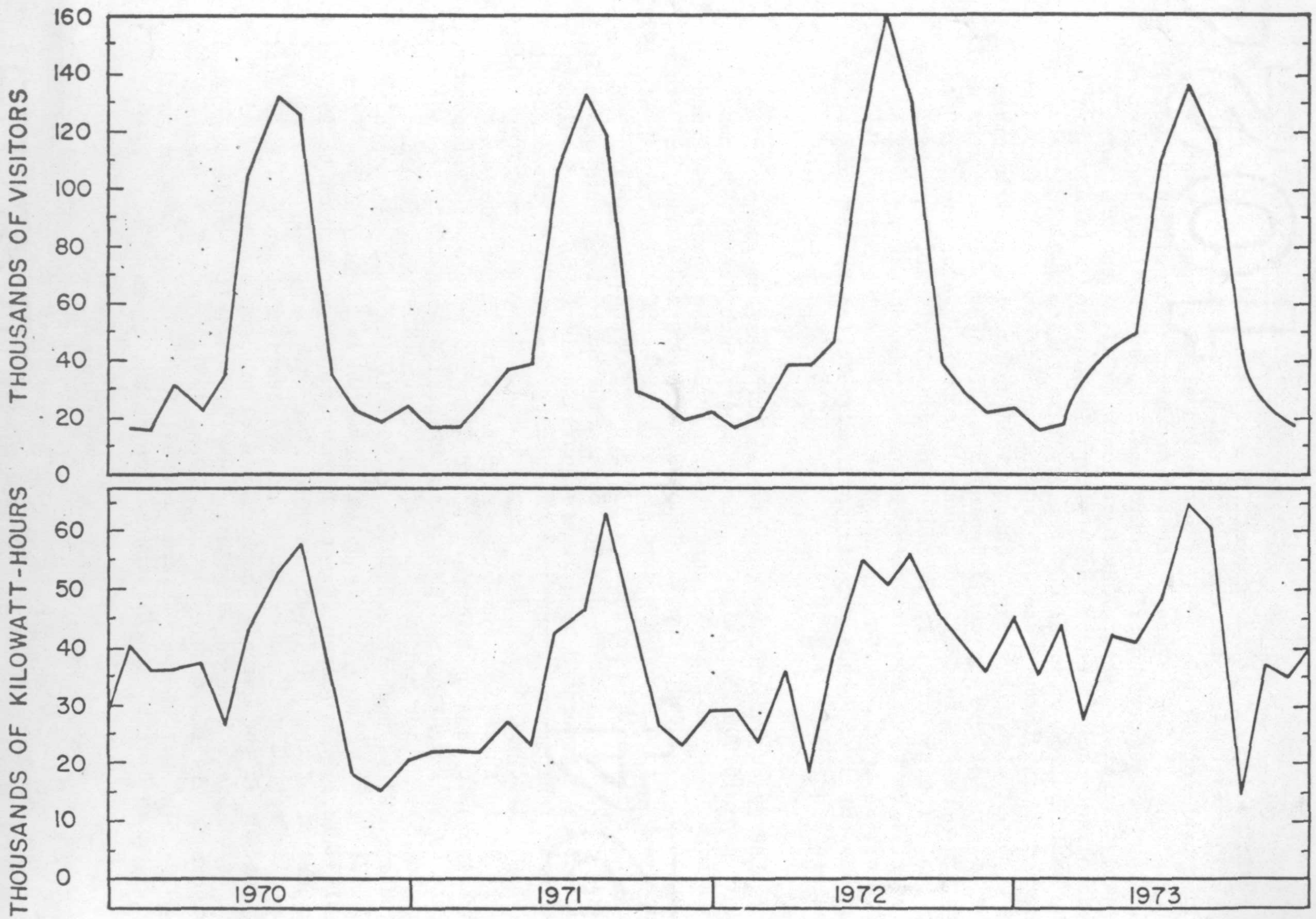


Figure 27.--Number of visitors to Carlsbad Caverns and energy consumed by the cave lighting system.

Table 3.--Evaporation as a function of temperature and energy consumption

$$E = A + B(\overline{T} - T) + CP \qquad (2)$$

where: E = Mean-monthly evaporation, in mm per month.

A = Evaporation constant, in mm per month.

B = Temperature coefficient, in mm per month per degree Celsius.

T = Mean-monthly minimum temperature at the weather station, in degrees Celsius.

$\overline{T}$ = Mean-annual minimum temperature at the weather station, in degrees Celsius (9.61°C).

C = Energy consumption coefficient, in mm per month per kilowatt-hour.

P = Total monthly energy consumption in the cave, in kilowatt-hours.

Location	A	B	C
Rock of Ages	1.11	3.19×10^{-2}	5.93×10^{-6}
Rock of Ages South	3.43	1.92×10^{-1}	1.29×10^{-5}
Queen's Chamber	1.89	2.11×10^{-1}	1.87×10^{-5}
Green Lake	.45	1.22×10^{-1}	1.99×10^{-5}

The above analysis assumes that evaporation can be approximated as a linear function of both temperature and energy consumption. This is not strictly true, but is believed to be adequate to allow an approximate comparison of effects. Another way of looking at the same data is to compare the almost 50 percent increase in lighting energy during the study period with the 10 percent increase in evaporation at the four pans discussed above, indicating that energy input to the lighting system accounts for about 20 percent of the evaporation at these stations as compared to 23 percent above. This is a minimum value, since we can assume that some decrease in evaporation however small, would have occurred at all the pans as a result of closing the elevator shaft.

Water levels

In order to better understand the cave microclimate, infiltration has been measured as weekly accumulations of water under specific dripping points through the cave (figs. 28-33). It was hoped that an analysis of the infiltration combined with the evaporation would allow simulation of water-level fluctuations in the cave pools.

The values of monthly infiltration were correlated with monthly rainfall. The monthly infiltration was then correlated with the preceding month's rainfall, the rainfall of the second month previous, and so on. This serial correlation indicated that the lag time between rainfall and the resulting increased drip rate in the cave was not a simple function of quantity of rainfall or time since the storm. After about 4-5 months the effects of the monthly rainfall cannot be separated from the background. While a fit to the data could probably be obtained using polynomial fitting techniques, the data are not adequate to justify such treatment. Inspection of the data indicated that a linear response could be assumed as a rough approximation.

The formula $I_v = 0.333\ R_0 + 0.267\ R_1 + 0.200\ R_2 + 0.133\ R_3 + 0.067\ R_4$, in which I_v is that part of the infiltration which varies as a function of rainfall, R is monthly rainfall, and the subscripts refer to the lag time of the rainfall, in months, was used to simulate infiltration. Infiltration due to rainfall which occurred more than 4 months ago is assumed to be constant. The period of data collection is not sufficient to identify any long-term trends in the infiltration.

Since evaporation had been shown to be highly correlated with temperature outside the cave, the mean monthly minimum temperature was used to simulate evaporation.

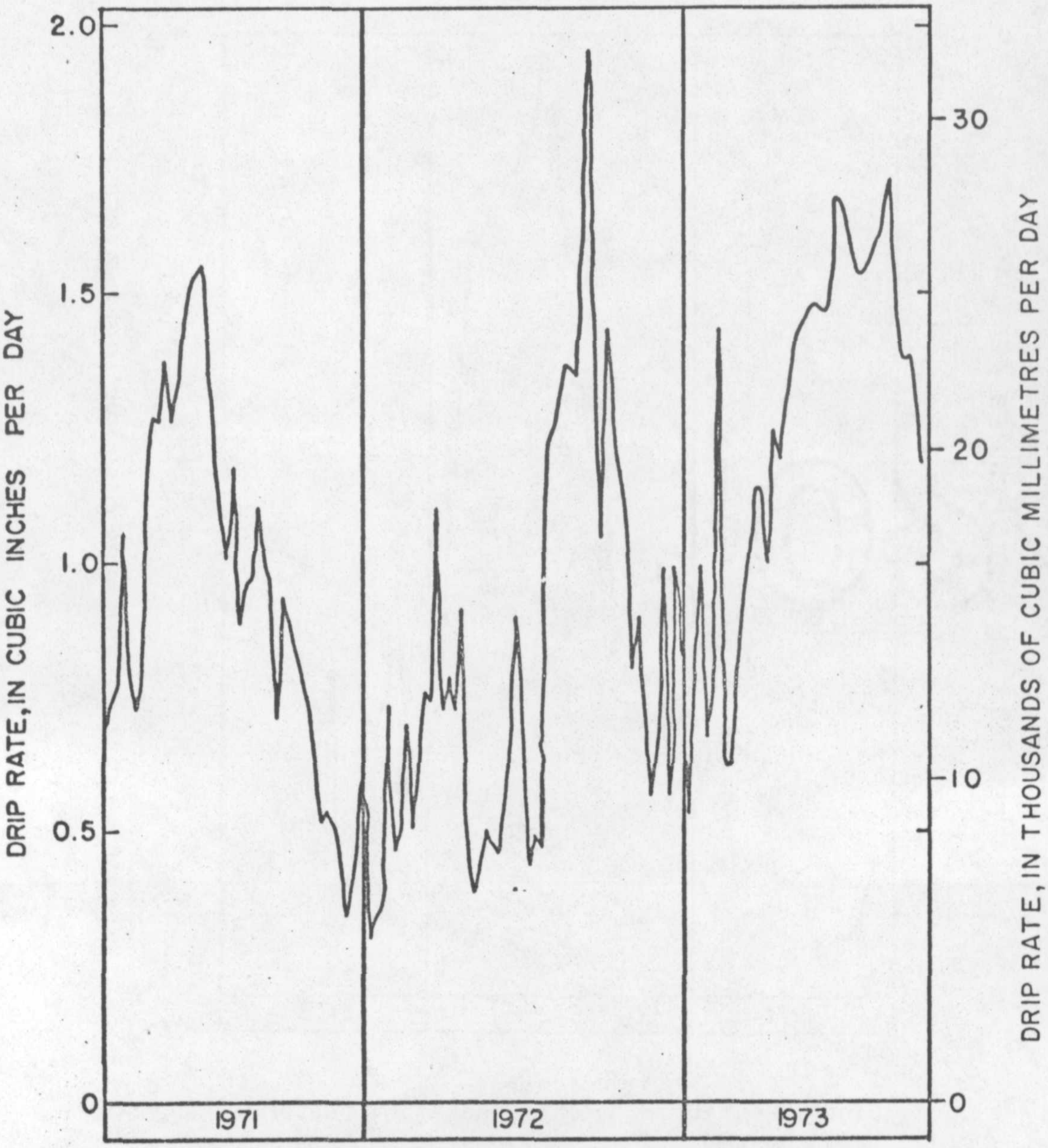


Figure 28.--Drip rate in Bat Cave.

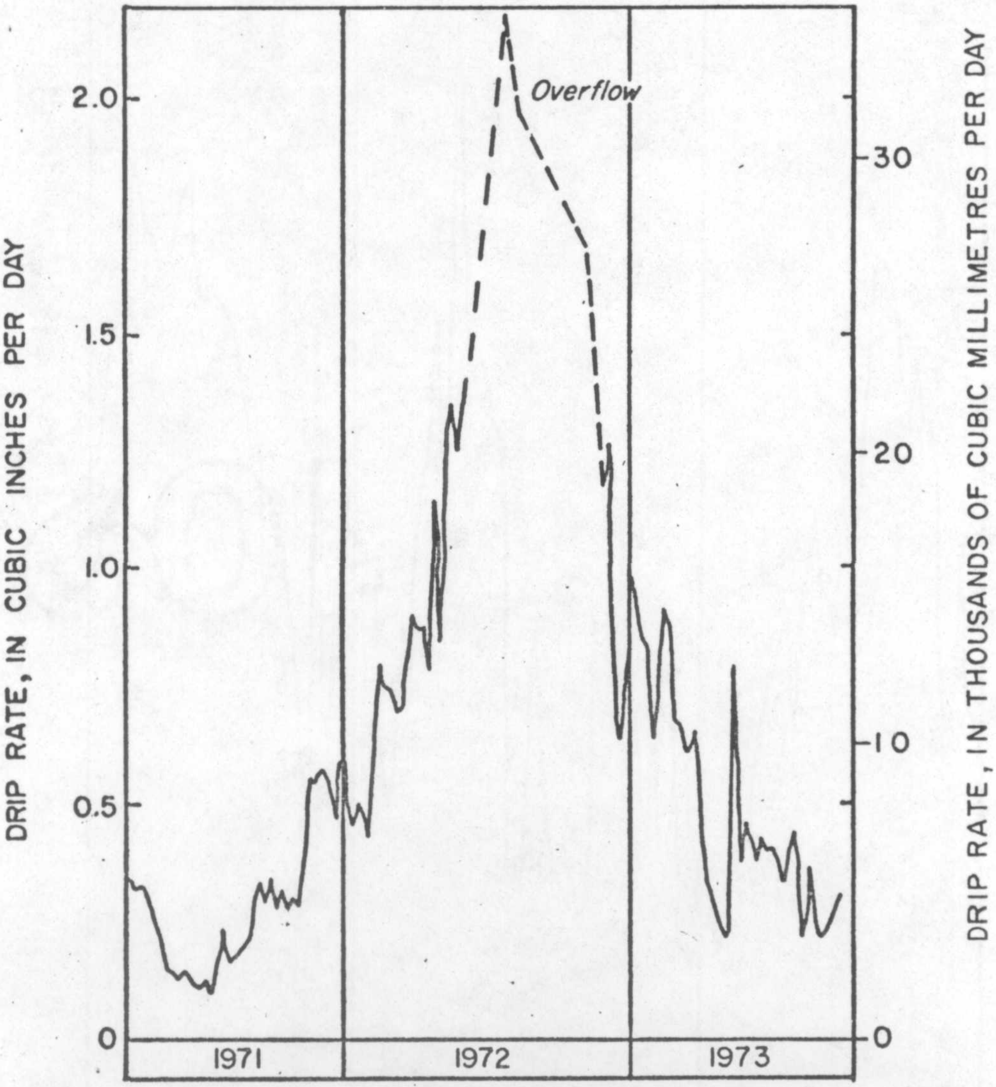


Figure 29.--Drip rate in the Amphitheater.

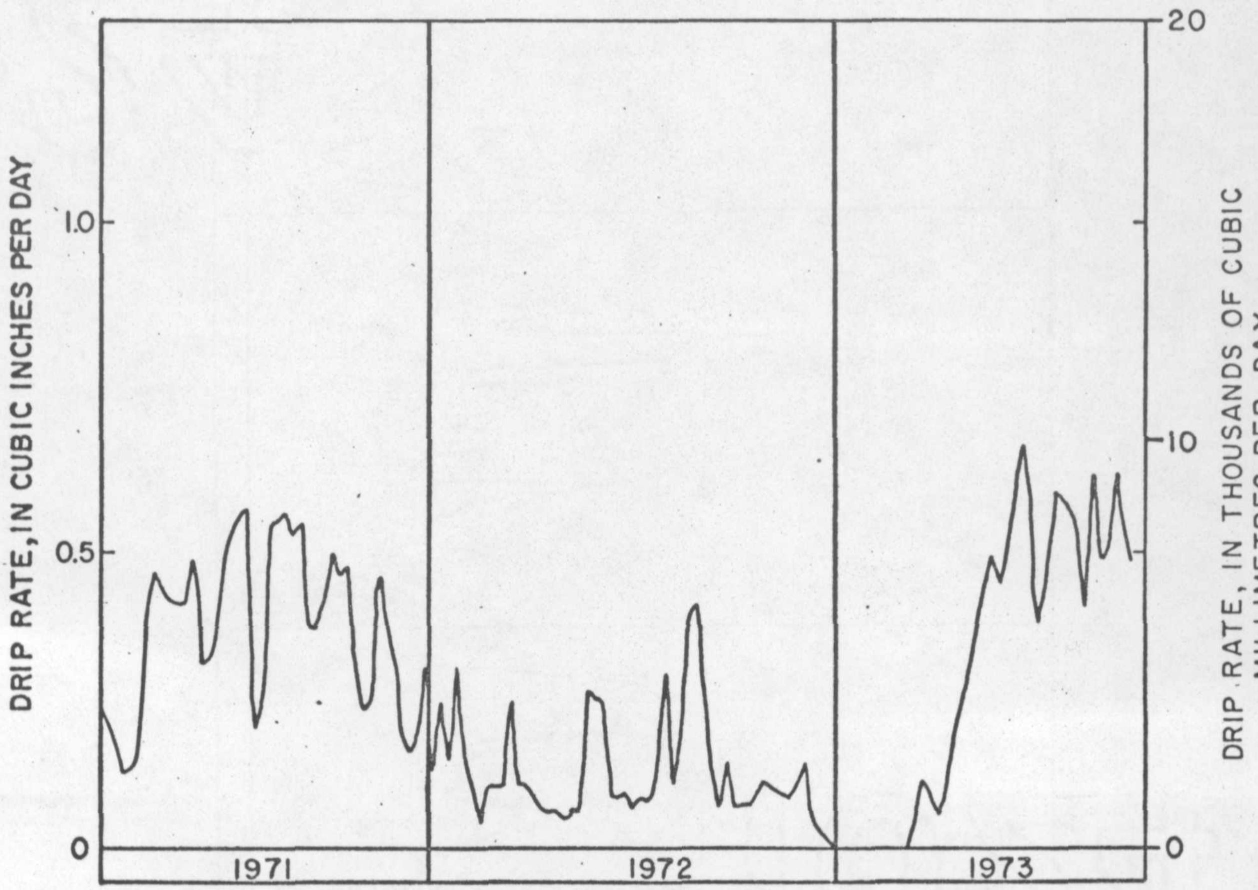


Figure 30.--Drip rate at the Baby Hippo.

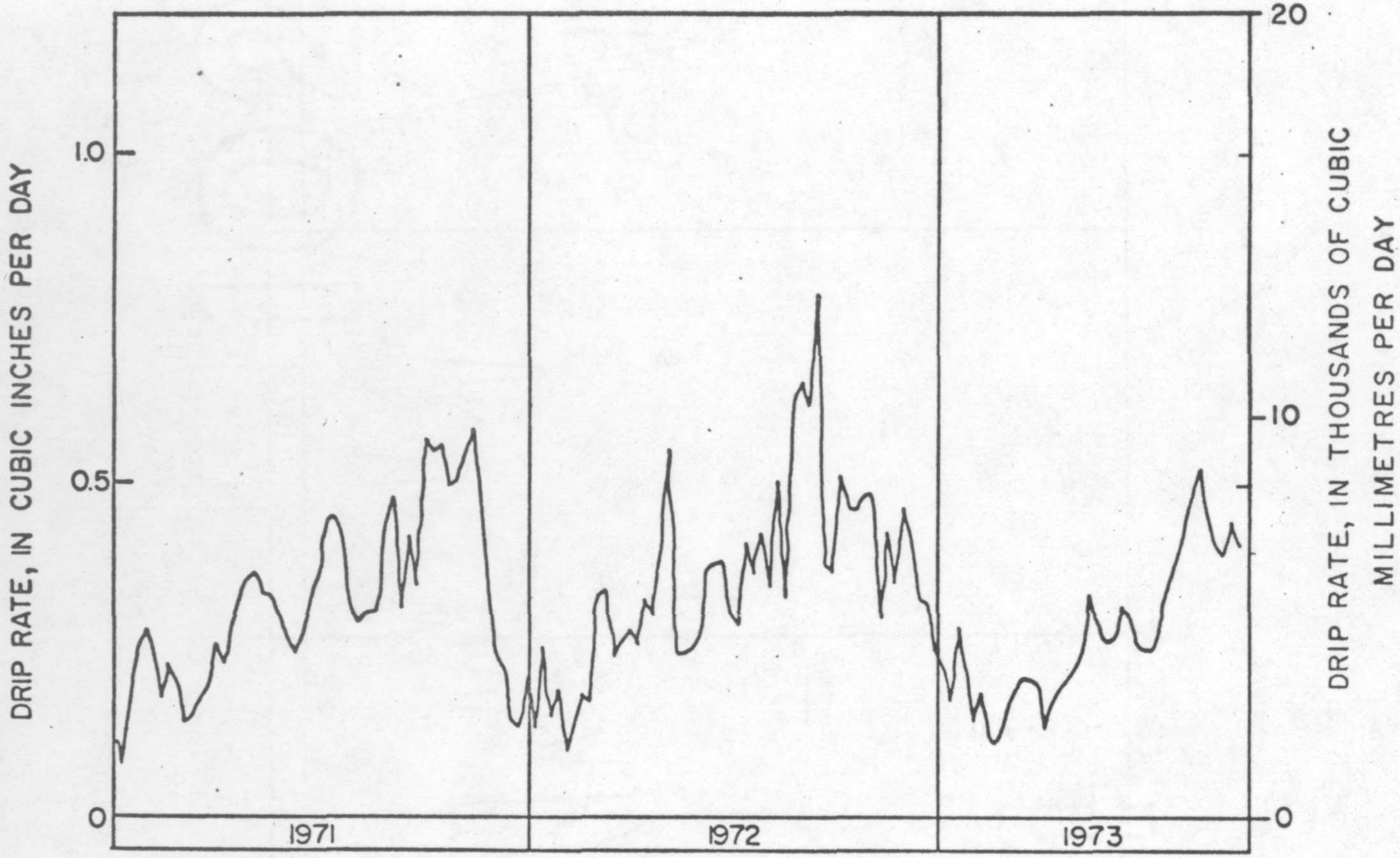


Figure 31.--Drip rate at Green Lake.

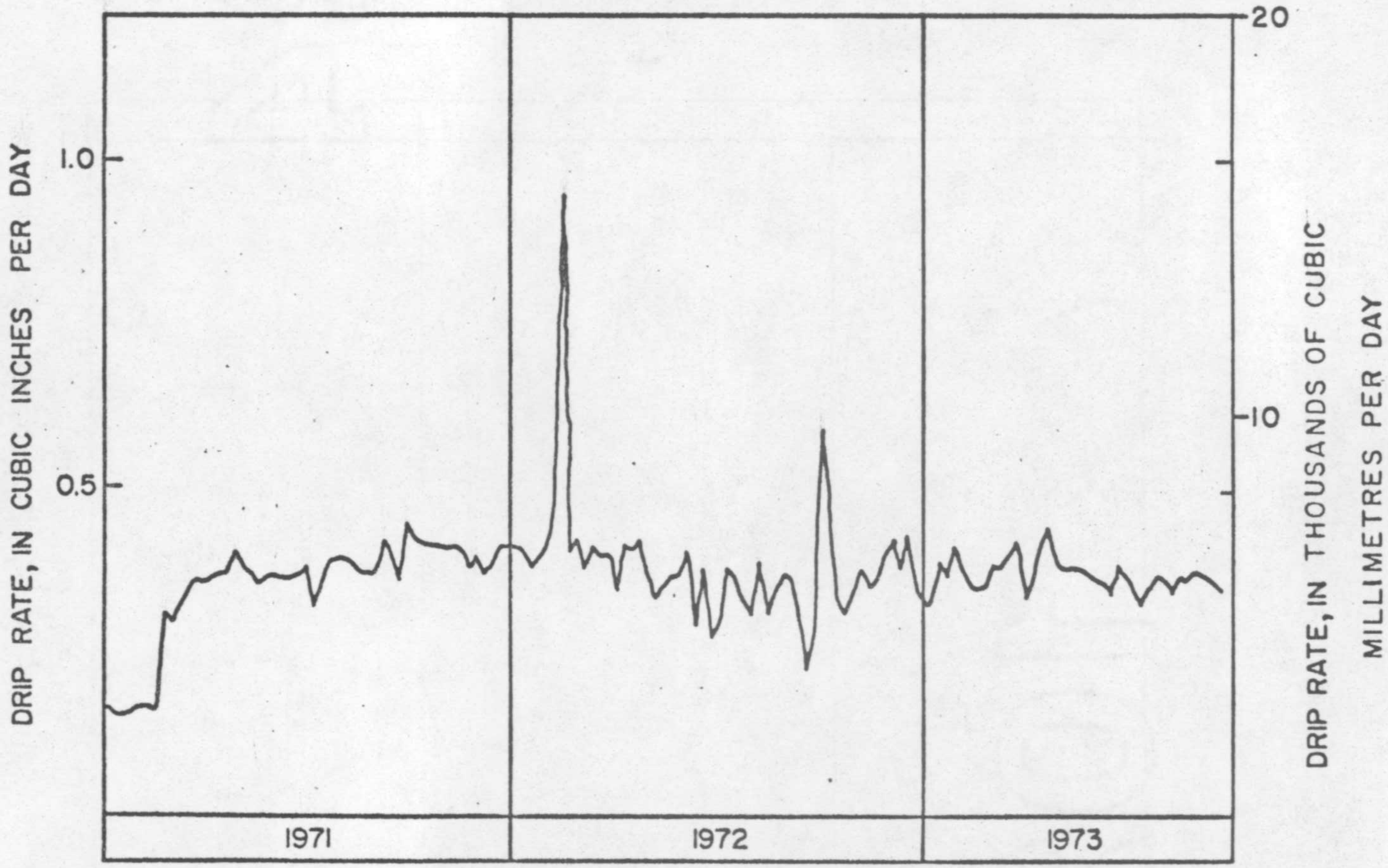


Figure 32.--Drip rate in the Big Room.

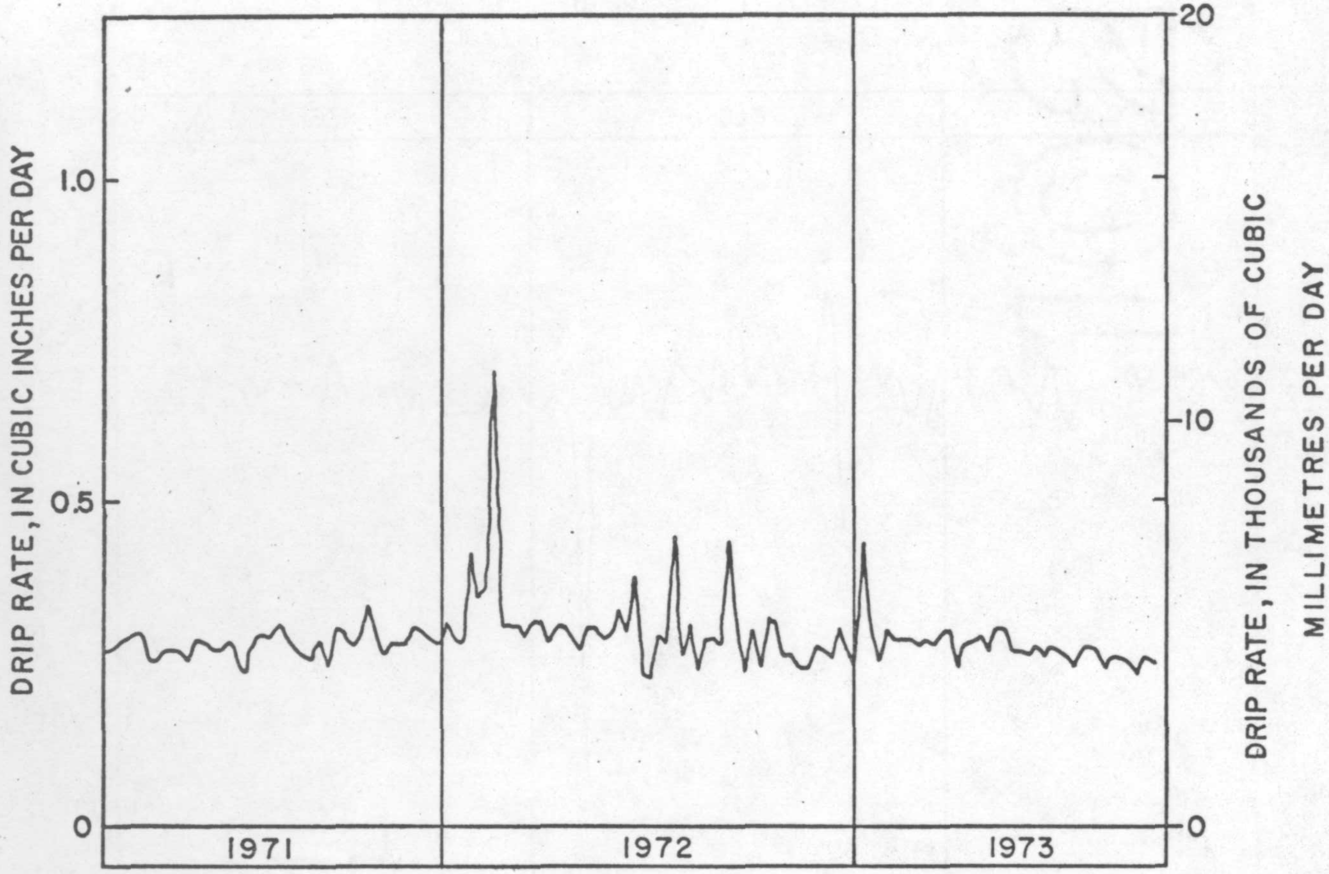


Figure 33.--Drip rate in the Dome Room.

The mass balance for a cave pool is simply:

$$\Delta V = I - E$$

Where: ΔV is the change in storage in the pool

I is infiltration

E is evaporation

for pools with no seepage from the bottom. For large pools with straight sides the evaporation from the capillary fringe becomes negligible, and the change in volume with water level is constant, so that $\Delta V = \Delta WL$, where ΔWL is the change in water level in the pool.

A series of equations was prepared for the cave pools using minimum temperature and the infiltration equation. These equations yielded a single regression constant for the combined infiltration and evaporation constants (K).

The validity of the equations in table 4 was checked by comparing measured and calculated values for water-level changes in the cave pools for the period August 1973 to June 1974. The agreement was only fair-to-poor for most pools, indicating that the equations give only a very rough estimate of the water-level changes. This may be due to the short period of record since the closing of the elevator shaft, and the lack of a reliable estimate of either evaporation or infiltration.

Table 4. Water-level change as a function of rainfall, temperature, and energy consumption

$$\Delta WL = K + AI_v - BT + CP \quad (3)$$

where: ΔWL = change in water level, in mm per month.

K = infiltration and evaporation constant, in mm per month.

A = infiltration regression coefficient, dimensionless.

$I_v = 0.33\ R_0 + 0.267\ R_1 + 0.200\ R_2 + 0.133\ R_3 + 0.067\ R_4$

R = rainfall at the weather station, in mm per month. Subscripts refer to lag time in months.

B = temperature regression coefficient, in mm per degree Celsius.

T = mean monthly minimum temperature at the weather station, in degrees Celsius.

C = energy regression coefficient, in mm per kilowatt-hour.

P = monthly energy consumption in the cave, in kilowatt-hours.

Pool location	K	A	B	C
Devil's Spring	34.28	2.92	3.12	-
Pool west Mirror Lake	1.57	.562	.275	8.00×10^{-5}
Dome Room	21.75	1.75	1.86	-
Painted Grotto	.88	.292	.108	-
Paint Brush	- 2.60	-	.696	1.62×10^{-4}
Illuminated Pool	8.21	.404	1.38	1.45×10^{-4}
Mirror Lake	- 2.71	.381	.396	1.59×10^{-4}
Pool west of Green Lake	1.66	.050	.354	5.46×10^{-5}

Conclusions

Revolving doors installed at the lower lobby of the elevator shaft in the underground lunchroom have reduced the flow of air up the elevator shaft. Some leakage of air past the seals is unavoidable. Reducing the airflow has reduced evaporation in the cave. This conclusion is based on the following evidence: (1) The greatest reduction in evaporation (34 percent) occurred at the pans nearest the elevator shaft. (2) The response of evaporation to cold-air inflow was reduced at all except two of the evaporation pans. (3) The sum of the evaporation from all pans was reduced 21 percent, or 10 percent from all except the Pump Room pan. These probably represent minimum values. It is also concluded that evaporation in the cave increased due to increased energy consumption by the cave lighting system and increased visitor use. Visitor use and lighting are highly correlated and were not separated for this study. An analysis using least-squares equations indicates that evaporation coefficients for combined visitor use and lighting energy account for an average of 23 percent of the evaporation at four pans distant from the elevator shaft.

The present efforts to increase the efficiency of the cave lighting system should be continued to minimize the effect on evaporation. The goal of this effort should be to reduce the total electrical energy consumed in the cave. Overlighting of local areas in the cave, as more efficient light sources are installed, should be avoided.

Data collection should be continued on a reduced basis to provide a warning of additional changes in the microclimate. A long-term record of evaporation, water-level changes, and infiltration would also be valuable for future studies in the cave. A program of monthly measurements of water levels in Devil's Spring, Mirror Lake, and the pool west of Mirror Lake, the Illuminated Pool, and the pool west of Green Lake, combined with evaporation readings at the Pump Room, Rock of Ages, Rock of Ages South, the Illuminated Pool, the Queen's Chamber, and Green Lake would provide a useful data base.

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