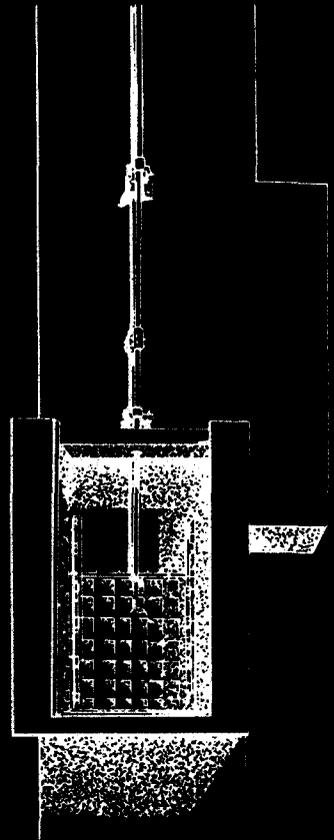


Evaluation of Effect of Impoundment on Water Quality in Cheney Reservoir



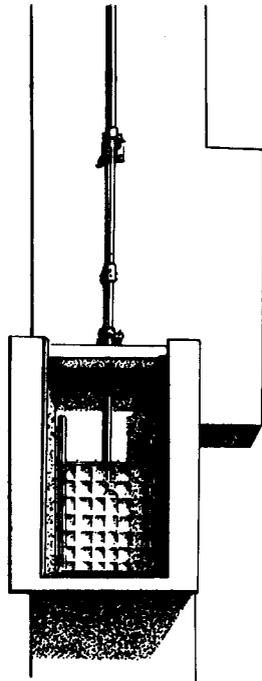
A Water Resources
Technical Publication

RESEARCH REPORT NO. 25

United States Department of the

INTERIOR

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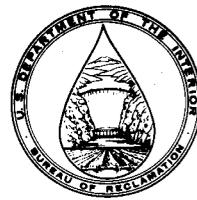
Evaluation of Effect of Impoundment on Water Quality in Cheney Reservoir

A Study Performed for
The Bureau of Reclamation
By J. C. Ward and S. Karaki
Colorado State University,
Fort Collins, Colo.



UNITED STATES DEPARTMENT OF THE INTERIOR
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BUREAU OF RECLAMATION
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FOREWORD

The Bureau of Reclamation is studying the quality of waters impounded and released from reservoirs, and the factors which influence important quality parameters. This report is an evaluation of the physical, chemical, and biological data collected from Cheney Reservoir from 1965 to 1967. This study was undertaken to measure the changes in water quality in a new plains-type reservoir, to compute the salt balance of this type reservoir, and to evaluate the usefulness of multiple outlets in controlling the quality of released water.

The field investigations were jointly developed by Bureau representatives from its Engineering and Research Center in Denver, its Regional Office, Region 5, Amarillo, Tex., together with representatives from the Water Department, Wichita, Kans. The field data were collected, under contract with the Bureau of Reclamation, by the city of Wichita. A subsequent contract was made with J. C. Ward and S. Karaki, Colorado State University, Fort Collins, Colo., for analysis and interpretation of these data. Their report is reproduced in its entirety herein. The data were also processed for submittal to the National Water Quality Storage and Retrieval System (STORET) in Washington, D.C.

Cheney Dam and Reservoir are on the North Fork of the Ninnescah River, a tributary of the Arkansas River, approximately 25 miles northwest of Wichita. Cheney Reservoir was designed to provide an urgently needed supplemental water supply for municipal and industrial uses in the city of Wichita, by furnishing approximately 42,900 acre-feet of additional water annually for municipal and industrial uses to supplement existing ground-water supplies. The operation of the reservoir is integrated with the present water supply, which consists of 35 wells located some 12 to 26 miles northwest of the city. The city is now operating and maintaining the facility and will repay the municipal water repayment obligation with interest to the Federal Government over a period of 40 years. Through the regulation and storage of flows of the North Fork of the Ninnescah River, the system will provide fish and wildlife enhancement, recreational opportunities, and substantial flood control benefits.

We believe this to be an excellent report and that it well satisfies the purposes stated above. Specific background information is furnished to help broaden and enhance understanding of the report, which has been reviewed by Reclamation offices and the city of Wichita. Two specific items deserve further comment on the basis of these reviews. One concerns the proposal for a bypass of low flows to achieve a decrease in the dissolved solids concentration, and the other the effectiveness of multilevel outlets in controlling the quality of water released to the city.

Reference is made relative to the dissolved salt concentration on page 46, which states "* * * bypassing a relatively small quantity of water will effect a large reduction in dissolved solids concentration. However, a bypass channel or conduit was not constructed for Cheney Reservoir." The implication is that the Bureau was remiss for not constructing a channel for the removal of some of the concentrated salts. Bureau studies showed that the total yield of the reservoir would be required, and at this time the city is already looking for an additional surface supply. Examination of flow data in Table 2-1 and conductivity readings at Station K-17 in Table 4-1 does not indicate that a significant reduction in the salt concentration would be achieved by a bypass channel. Low flow concentrations are higher, however, but not to the degree implied.

Reference is also made to the statement that "* * * the multiple level outlet structure was neither necessary nor effective in controlling the quality of water pumped to the city of Wichita during the period of study." This statement is recognized as a valid conclusion of the study underlying the report. At the time Cheney Dam was designed, careful consideration was given to the utilization of engineering features that would optimize the quality of waters released. This was reinforced by a request from the city of Wichita's consultants, Black and Veatch, for inclusion of the multiple outlets in the dam. At the time of design, neither the consultants nor the Bureau had the benefit of present knowledge and information from which to appraise the probable behavior of the reservoir from a stratification standpoint. Additional time and operational experience may be necessary to fully evaluate the effectiveness of the multiple outlets at Cheney Dam.

These statements with respect to dissolved salt concentration, and to the multiple outlet structure will, we hope, bring into proper perspective more of the factors involved in the design, construction, and operation of Cheney Dam and Reservoir. Photographs have been added to render more vivid the physical features of the structures mentioned in the report.

We acknowledge the assistance of personnel from the Denver and Regional Office of the Bureau of Reclamation, and the Water Department of the city of Wichita, in development of the program. In addition, the Bureau of Reclamation expresses appreciation to the authors for their excellent evaluation and comments expressed in this report. Their data and ideas will be invaluable for future studies.

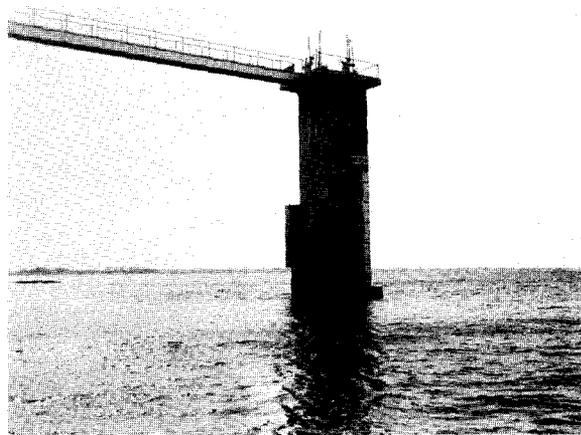
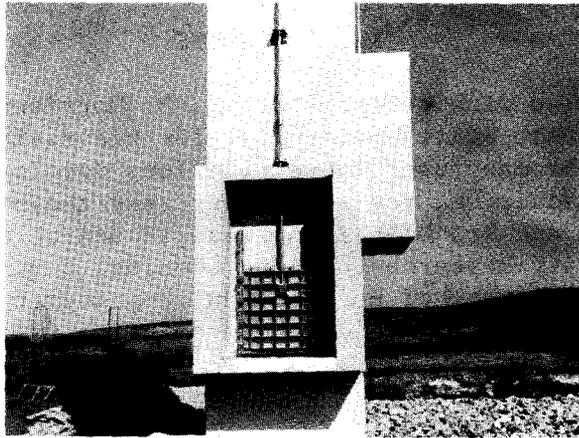
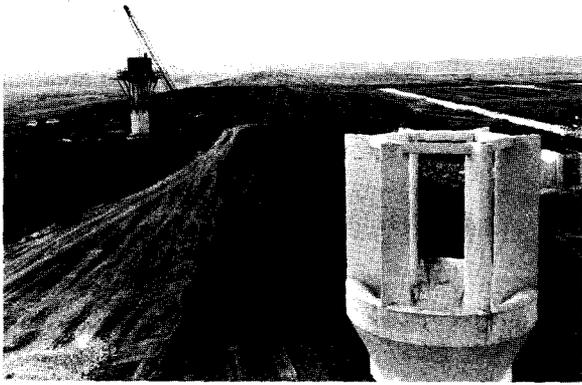
Included in this publication is an informative abstract and list of descriptors, or key words, and "identifiers." The abstract was prepared as part of the Bureau of Reclamation's program of indexing and retrieving the literature of water resources development. The descriptors were selected from the Thesaurus of Descriptors, which is the Bureau's standard for listing of key words.

Other recently published Water Resources Technical Publications are listed on the inside back cover of this report.

P. R. Tramutt
Chemistry and Water Quality
Research Section
Division of Research
Bureau of Reclamation

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The authors also wish to thank Dr. S. M. Morrison, Professor of Microbiology at Colorado State University, for his review of the entire manuscript and for the many useful contributions developed in the course of that review. In addition, the authors express their appreciation to P. R. Tramutt, Head, and Dr. Dale A. Hoffman, Research Scientist, Chemistry and Water Quality Research Section, Chemical Engineering Branch, Division of Research, Bureau of Reclamation, Engineering and Research Center in Denver, for their excellent comprehensive review and evaluation of the rough drafts.



Construction, details, and operation of multiple level outlets at
Cheney Reservoir.

EVALUATION OF THE EFFECT OF IMPOUNDMENT ON
WATER QUALITY IN CHENEY RESERVOIR

by

J. C. Ward and S. Karaki
Department of Civil Engineering
Colorado State University
Fort Collins, Colo.

This study was performed under Contract No. 14-06-D-6578 with the U.S. Bureau of Reclamation, Denver, Colo., and is here reprinted in its original form in the interest of expediting publication.

September 1969

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EVALUATION OF THE EFFECT OF IMPOUNDMENT
ON WATER QUALITY IN CHENEY RESERVOIR

J. C. Ward and S. Karaki

1. INTRODUCTION

Purpose of the Study

The principal purpose of this study was to determine the effect of impoundment on water quality in Cheney Reservoir. To this end, physical, chemical, and biological data collected from Cheney Reservoir by the City of Wichita, Kansas, Water Department during a period from November 8, 1964, to September 30, 1967, were evaluated. The results of the evaluation are presented in this report.

General Background

A brief background concerning Cheney Reservoir and a discussion of the pertinent data collected from the reservoir will be useful before presenting the analysis of the data.

Cheney Reservoir - Cheney Dam was constructed on the North Fork of the Ninnescah River approximately 25 miles west of Wichita, Kansas. The dam is an earth-fill structure, 86 feet high with crest elevation at 1,454.0 feet and a length of 24,500 feet.

The reservoir created by the dam is approximately 10 miles long. At maximum water surface level of 1447.8 feet, the volume in the reservoir is 566,280 acre-feet. The active capacity of the reservoir is 246,950 acre-feet, of which 151,780 acre-feet is for municipal and industrial uses, and 14,310 acre-feet is for fish and wildlife. The spillway at Cheney Dam is a morning-glory type with a maximum discharge capacity of 3,000 cfs. The reservoir river outlet works consists of an 11-foot diameter conduit through the dam which has a maximum discharge capability of 4,580 cfs.

The pumping station at Cheney Reservoir delivers raw water to the existing water treatment plant of the City of Wichita. With normal rainfall, the reservoir is expected to supply 60 mgd. In periods of drought this supply might reduce to 35 mgd. In addition to the pumping station, there are facilities for pretreatment consisting of chemical feed equipment and storage facilities. The primary purpose of pretreatment is taste and odor control. Chlorine, chlorine dioxide, potassium permanganate, and activated carbon are the chemicals used, where chlorine dioxide is generated by combining chlorine and sodium chlorite. Provision has been made for future installation of microstraining equipment which would be in addition to the present basket strainers.

The intake tower in the reservoir provides for withdrawal from four 6' x 6' slide gates, each 10 feet apart in elevation. The sill of the lowest port

is at elevation 1,379.0. There is a 96-inch diameter conduit connected to the intake tower which extends through the dam. This line connects to a 72-inch influent line to the pump station.

Data collection - Collection of data used in this study was accomplished by the City of Wichita under contract with the U. S. Bureau of Reclamation.

The reservoir outlet gates were closed on November 8, 1964, and water was pumped from the reservoir for the first time on May 25, 1965. Initial chemical data for water in the reservoir was collected on May 3, 1965, and the data analyzed in this report is for the period from May 3, 1965, through September 30, 1967.

Sampling stations were established at Cheney Reservoir at various locations as indicated in figure 1-1. A sampling and gaging station was established at the bridge of Highway 17 across the Ninnescah River upstream of the reservoir. This station is labelled K-17 on the figure. The intake tower of the municipal outlet was also used as a sampling station. Another sampling and gaging station was established at the outlet channel from the reservoir outlet works although this station was not used during the data collection period.

Water was pumped from the east port (elevation 1389.0 ft) of the intake tower up to July 1, 1965. On July 1, 1965, this port was closed, and the west port (elevation 1399.0) was opened on the intake tower. This was done to reduce the turbidity of the pumped water. As reported by Mr. F. R. Williams, Water Treatment Supervisor, the reduction in turbidity in Jackson turbidity units was from 100 to 38. On August 6, 1965, the west port was closed and the east port was again used. Water was pumped from this port until December 27, 1965. From this date until September 30, 1967, the west port was used exclusively.

A combination temperature and dissolved oxygen (D.O.) probe made by Pro-Tech was used to obtain data for most of the period. After November, 1965, this instrument was calibrated against a Delta Scientific dropping mercury dissolved oxygen analyzer. In the reservoir, temperature and D.O. readings were taken at the middle of every ten-foot vertical interval at the sampling stations where depth permitted.

Determinations of pH were made in the laboratory until October, 1965, using a Beckman Model H-2 pH meter. This was changed thereafter to direct field determinations using a Beckman Model G pH meter with extended leads. Beginning in August, 1965, field conductivity readings were made weekly with a portable conductivity meter. Continuous recordings were made at K-17 beginning in June, 1966, with daily readings



Figure 1-1. Cheney Reservoir vicinity map and location of sampling stations.

at 9:00 a.m. reported in the data. Readings at the pump station were made during the week; exclusive of Saturdays, Sundays, and holidays beginning in April 1966.

Sampling procedures were standardized beginning May 24, 1966. At all stations, D.O., temperature, conductivity, pH, and turbidity were measured at 5-ft intervals. Complete chemical analyses were taken at 10-ft intervals at Stations A1, R1-3, R3-1, R5-3, R7-1 and R9-2, and only at mid-depth at the other stations in the reservoir. Sampling was discontinued from the first week in September to the first week in November and again in December 1966, except that D.O. and temperature readings were taken during this period with the Delta Scientific instrument and thermometer respectively.

Biological samples were collected with a Clarke-Bumpus plankton sampler with sampling beginning in November 1965. Prior to this time qualitative information was provided in monthly letter summaries, in which such indications as locations of algal blooms, schools of minnows and residing flocks of birds were noted. Full scale biological sampling began on May 24, 1966. Algal samples were collected at prescribed stations in a 3.1-liter Kemmerer water sampler with the top of the sampler just under the water surface. Two hundred and fifty ml. of each sample was concentrated to 20 ml. by means of a Sedgwick-Rafter sand filter. One ml. of the concentrate was placed in a Sedgwick-Rafter counting cell and 10 fields were counted at 150x magnification. The numbers of each organism were multiplied by a factor of 32 in order to determine the number of organisms per ml.

The plankton analysis was modified in October 1966. The strip clump count was used in place of the field clump count. Quoting Mr. Puzig, Water Chemist, City of Wichita;

". . . The strip count is essentially the enumeration of a selected group of organisms as they occur within an area represented by the full length of a Sedgwick-Rafter cell (50 mm) and the width of the microscopic field (0.5 mm). In the actual count, enumeration is begun at one end of the cell and all organisms which are to be recorded are counted as the slide is moved past the objective by the mechanical stage." ". . . A clump count consists of counting an organism as one, whether it consists of one or more cells."

During July and August, 1965, taste and odor were described as a musty, woody, earthy taste with a threshold odor number of eight. In September however, there was no detectable odor along the shores of the reservoir. The intake water, however, still contained a musty odor with threshold number decreasing to three by the end of October and continued through November and December. The first half year in 1966 had musty, grassy, sweetish, and fishy odors with threshold numbers between 3 and 4 for the intake waters although septic odors were noticed by July, 1966, in areas of the reservoir where high concentrations of vegetation were decomposing. By August, 1966, the threshold odor number increased to 6 and diminished slightly to 5 by December, 1966. No treatment problem was noted. The threshold odor number remained constant at 5 through the first 9 months in 1967 although a fishy odor that prevailed in June and July, apparently diminished in August and September as the lake level rose appreciably.

2. WATER BUDGET

The water budget for Cheney Reservoir is a volumetric accounting of all water inflow and outflow including evaporation and seepage. An illustration of these items is shown on figure 2-1. Daily values of reservoir level, river inflow, local precipitation, reservoir outflow, and pumped outflow for the study period are shown graphically on figure 2-2. The equation for the water balance is

$$\begin{aligned}
 (\text{Increase in Storage}) &= (\text{River Inflow}) + (\text{Local Rainfall}) \\
 &\quad - (\text{Reservoir Outflow}) - (\text{Pumped Outflow}) \\
 &\quad - (\text{Evaporation}) - (\text{Seepage})
 \end{aligned}
 \tag{2-1}$$

or notationally,

$$\Delta V_r = V_i + V_p - V_o - V_{pu} - V_e - V_s, \tag{2-2}$$

where the symbols in equation 2-2 represent the terms in equation 2-1.

In the equation above, volumes of evaporation, V_e , and seepage, V_s , were unknown. Therefore in

reality, the water budget was used to determine the unknown combined quantities of evaporation and seepage. The balance was made for each day of the study period with monthly summaries to average the fluctuations of the daily quantities. Determination of each volumetric quantity is discussed below.

Change in storage - The water surface level of Cheney Reservoir was recorded daily to the nearest one hundredth of a foot and reported by the U. S. Geological Survey (23). The total volume in the reservoir corresponding to this level was then determined from a stage-volume calculation of the reservoir prepared by the U. S. Bureau of Reclamation. The stage-volume calculations were evidently made from maps with one-foot contour intervals. A straight line interpolation was then used to calculate the volumes for reservoir surfaces between the one-foot levels. The reservoir level varied from 1410.21 feet to 1417.05 feet during the study period, with the volume changing from 80,231 acre-feet to 127,247 acre-feet. Maximum daily increase in volume amounted to 2,033 acre-feet on June 28, 1967, and maximum decrease in volume was 529 acre-feet on October 6, 1966.

Stream inflow - The daily stream flow readings at K-17 reported by the U. S. Geological Survey were

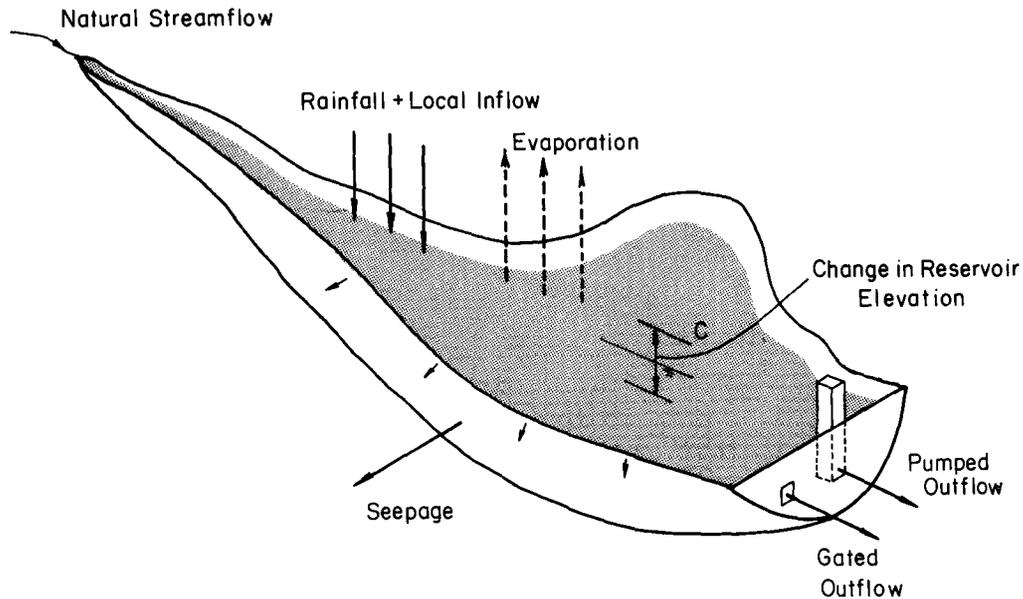


Figure 2-1. Schematic representation of items included in the water budget.

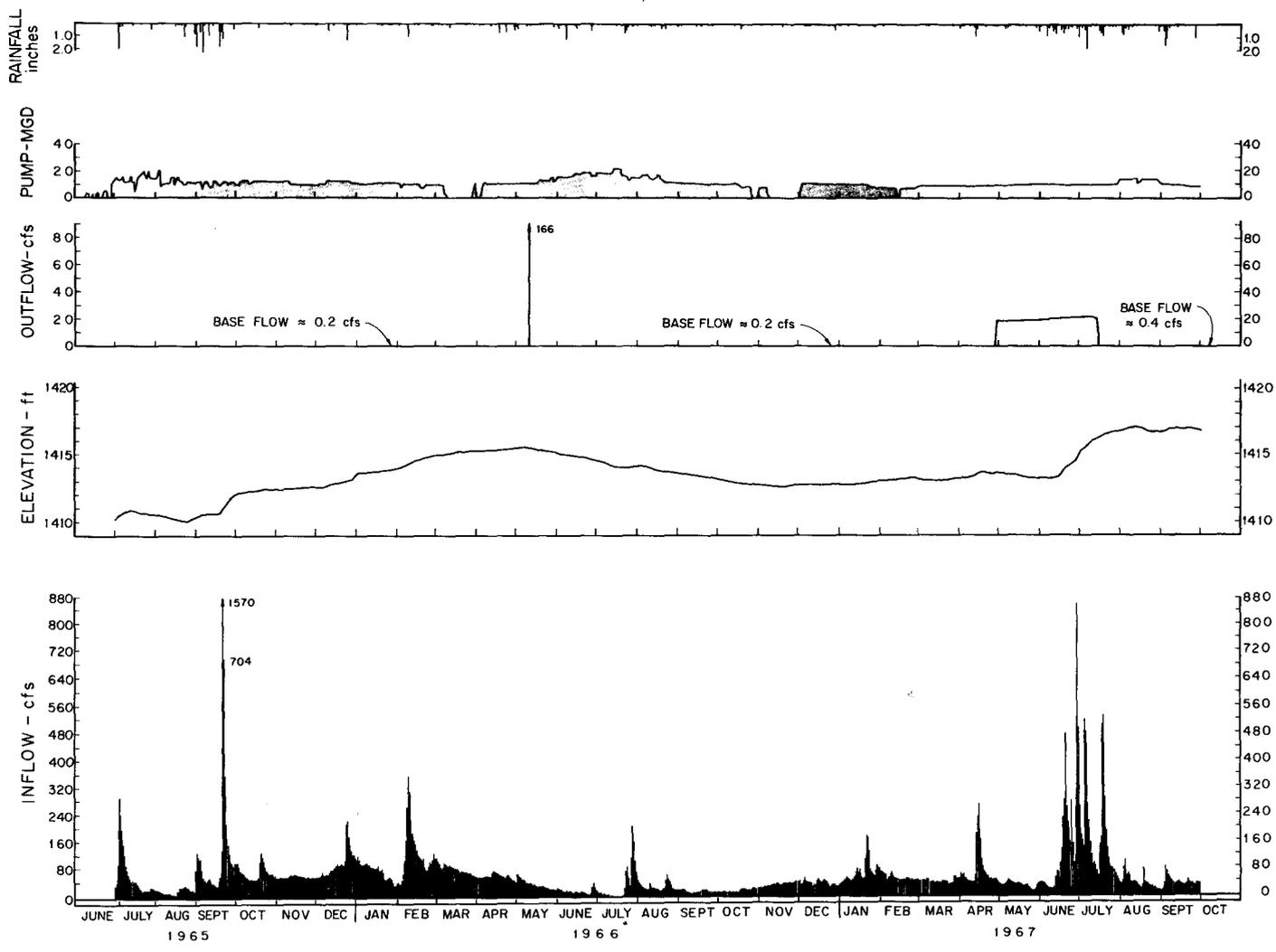


Figure 2-2. Daily records of inflow and outflow - Cheney Reservoir.

assumed to be for mid-day. The quantity of inflow was then calculated using the mid-day readings even though it was recognized that some diurnal fluctuations probably existed, particularly during times of snow cover on the watershed upstream. According to the U. S. Geological Survey records, the total area of the watershed upstream of K-17 is 787 square miles of which 550 square miles is probably contributing.

Precipitation inflow - In addition to stream inflow recorded at K-17, the watershed area draining directly into the reservoir totals approximately 114 square miles (including the reservoir surface area). The rainfall on this portion of the watershed can therefore amount to an appreciable quantity in relation to the stream flow at K-17. This 114 square miles is over 17 percent of the total contributing watershed area.

Rainfall at the reservoir site was not recorded, or at least it was not available for this study. It was necessary therefore, to use the U. S. Weather Bureau rainfall data at Wichita and assume that the rainy days applied to the reservoir area, and in addition assume that the rainfall there was in proportion to the rainfall at Wichita. These being assumed, it was necessary to establish a coefficient for runoff, which included not only the runoff characteristics of the watershed, but also the coefficient of proportional rainfall at the site in relation to the rainfall at Wichita. The value of the coefficient used in the standard rational formula was 0.126. This value was determined by a number of trials, which was facilitated by computer analyses. The trials indicated mainly that higher runoff coefficients resulted in large amounts of evaporation, which were unrealistic when compared to the average annual evaporation for the South-Central Kansas area. In any event, it is possible to conclude that the minimum coefficient would be 0.094, which is the ratio of reservoir surface area to watershed area.

Although evaporation loss is discussed below, let us examine the resulting evaporation by assuming various values for the runoff coefficients:

Assumed Coefficient of Runoff	Resulting Annual Evaporation ft/year
0.055	3.35
0.25	6.90
0.65	14.2

As evaporation is generally about 4.7 ft per year, a runoff coefficient of 0.126 would seem to be reasonable. This is because, in the above table, a plot of runoff coefficient versus annual evaporation is a straight line, and this line, when intersected at 4.7 feet per year, gives a runoff coefficient of 0.126.

Outflow - Water releases through the reservoir outlet works took place only for one period from April 27, 1967, to July 14, 1967. The maximum flow was 23.0 cfs with an average of around 20.0 cfs for the period. Aside from this period there was one day on May 10, 1966, when a discharge of 166.0 cfs was released. These data were also obtained from the U. S. Geological Survey records. There was a base flow at the gaging station downstream from Cheney Dam which amounted to a trickle of about 0.2 cfs, but which nevertheless was included in the water balance.

Pumpage - Water pumped to the City of Wichita was recorded by the flow meter at the pump station in million gallons per day (mgd). There were three periods when pumping was stopped, March 8 to March 28, 1966, October 27 to October 30, 1966, and November 8 to December 4, 1966. Pumping was otherwise continuous through the study period.

Evaporation and Seepage - The calculated monthly totals in acre-ft are tabulated in Table 2-1 which are converted to inches in Table 2-2. The conversion was made by using the average monthly surface area of the reservoir. Calculated monthly evaporation values are plotted on figure 2-3 along with comparative evaporation values calculated from the heat balance (discussed in Section 3) shown for the year 1966.

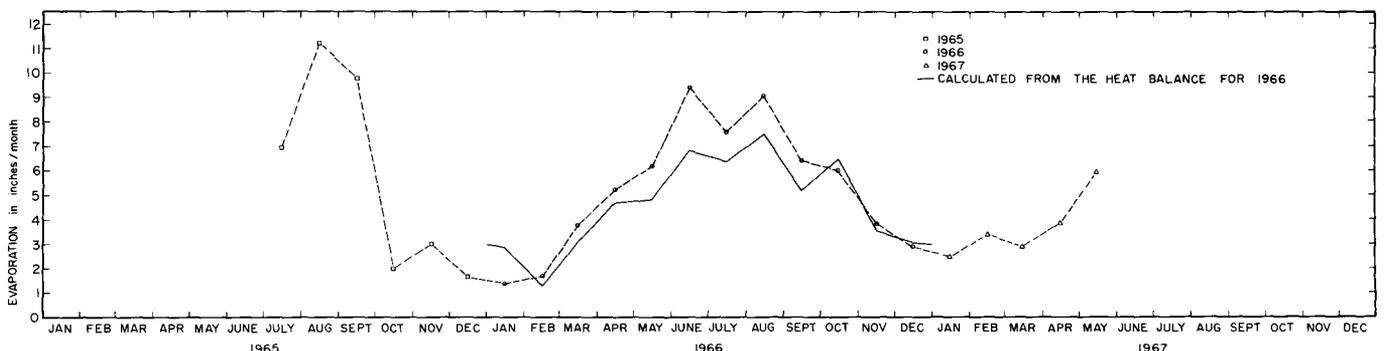


Figure 2-3. Evaporation from Cheney Reservoir

TABLE 2-1. WATER BUDGET
Monthly Totals in Acre-Feet

Month	Year	Change in Reservoir Storage	River Inflow	Local Rainfall	Reservoir Outflow	Pumped Outflow	Evaporation and Seepage
July	1965	2193.4	4292.2	2773.2	11.3	1345.1	3515.5
August		-1422.7	1434.0	3761.5	14.3	1197.2	5406.7
September		10,294.3	9820.2	6465.7	15.3	1036.9	4939.4
October		2703.3	4665.1	245.1	12.7	1127.6	1066.7
November		1172.5	3748.8	84.3	9.3	985.1	1666.1
December		5853.8	6218.2	1685.4	13.5	1120.2	916.2
January	1966	3172.2	4838.6	176.2	10.9	1007.3	829.4
February		6553.2	7346.8	1103.2	16.5	841.0	1039.3
March		2759.1	5131.2	199.2	12.1	251.6	2307.6
April		1267.5	3627.8	1693.0	11.9	842.0	3199.3
May		-2385.9	2243.3	582.2	336.8	1114.9	3759.3
June		-4245.0	983.0	2045.4	6.1	1544.2	5723.1
July		-2640.0	2067.4	1363.6	7.1	1656.6	4407.2
August		-3935.5	1844.6	835.0	9.7	1318.9	5286.6
September		-3104.0	893.8	551.6	8.7	978.7	3561.9
October		-2676.7	1096.9	360.1	11.7	773.7	3348.2
November		-97.7	2140.2	68.9	11.1	158.1	2137.7
December		228.0	2429.8	329.4	12.3	915.6	1603.3
January	1967	2341.7	4421.2	214.5	12.3	886.5	1395.1
February		614.0	3038.7	68.9	10.3	580.2	1903.1
March		682.2	2751.1	436.7	9.0	865.9	1630.6
April		2285.4	4536.2	995.9	130.1	858.5	2258.1
May		-2319.5	1995.4	1087.8	1182.1	926.6	3293.9
June		13,202.5	9697.2	4305.4	1253.6	916.3	-1369.8
July		12,099.4	11,065.8	3271.2	580.3	989.2	668.0
August		-467.0	2390.1	1463.2	20.9	1286.3	2079.1
September		1050.8	2334.5	3056.7	26.0	858.5	3455.8
Totals		45,101	107,056	39,222	3,754	26,383	71,040

Excepting for two months, June and July, 1967, the losses due to evaporation and seepage seem reasonable. As expected, the evaporation and seepage losses are greatest in the summer months and smallest during winter. In the months of June and July, 1967, there was heavy rainfall in the area. The negative value for evaporation and seepage could only result from an erroneous accounting of rainfall at the reservoir, as it seems unreasonable to assume heavy groundwater inflow during the month of June. The low evaporation in July also results from the same error source.

As a consequence of the approximations used in this water balance to account for evaporation and

seepage, it was desirable to make an estimate of evaporation from an independent approach. A heat budget was therefore used.

Figure A-1 (in the Appendix) indicates that seepage losses are negligible when compared to evaporation losses. While the water budget calculations give the total of evaporation and seepage, the heat budget calculations and the evaporation pan data give only the evaporation losses. However, the evaporation losses given by all three methods are essentially the same, and therefore seepage losses must be negligible in comparison.

TABLE 2-2. WATER BUDGET
 Monthly Totals in Inches Based on Average Surface Area During the Month

Month	Year	Change in Reservoir Storage	River Inflow	Local Rainfall	Reservoir Outflow	Pumped Outflow	Evaporation and Seepage	Precipitation at Wichita Kansas
July	1965	4.34	8.49	5.47	0.02'	2.67	6.97	3.62
August		-2.95	2.97	7.78	0.03	2.48	11.22	4.91
September		20.35	19.41	12.78	0.03	2.05	9.76	8.44
October		5.10	8.80	0.46	0.03	2.13	2.01	0.32
November		2.11	6.75	0.15	0.02	1.77	3.00	0.11
December		10.54	11.19	3.03	0.02	2.02	1.65	2.25
January	1966	5.46	8.33	0.30	0.02	1.73	1.43	0.23
February		10.78	12.09	1.81	0.03	1.38	1.71	1.44
March		4.54	8.44	0.33	0.02	0.41	3.80	0.26
April		2.09	5.97	2.79	0.02	1.39	5.26	2.21
May		-3.93	3.69	0.96	0.55	1.83	6.19	0.76
June		-6.98	1.62	3.36	0.01	2.54	9.43	2.67
July		-4.54	3.56	2.35	0.01	2.85	7.58	1.78
August		-6.77	3.17	1.44	0.02	2.39	9.09	1.09
September		-5.59	1.61	0.99	0.02	1.16	6.41	0.72
October		-4.82	1.97	0.65	0.02	1.39	6.03	0.47
November		-0.18	3.85	0.12	0.02	0.28	3.85	0.09
December		0.41	4.37	0.59	0.02	1.65	2.89	0.43
January	1967	4.22	7.96	0.39	0.02	1.60	2.51	0.28
February		1.11	5.47	0.12	0.02	1.04	3.43	0.09
March		1.23	4.95	0.79	0.02	1.56	2.94	0.57
April		3.93	7.80	1.71	0.22	1.48	3.88	1.30
May		-4.17	3.59	1.96	2.13	1.67	5.93	1.42
June		22.71	12.00	7.40	2.16	1.58	-2.36	5.62
Total		58.99	158.05	57.73	5.47	41.65	114.60	41.08

3. HEAT BUDGET

The rate at which the heat content of a surface water body decreases, q , in Btu/(hr)(ft²), is

$$q = q_c + q_r + q_e - q_s \quad (3-1)$$

where:

q_c = rate of heat loss by convection, Btu/(hr)(ft²)

q_r = rate of heat loss by radiation, Btu/(hr)(ft²)

q_e = rate of heat loss by evaporation, Btu/(hr)(ft²)

q_s = rate of heat gain by solar radiation, Btu/(hr)(ft²).

The first three terms on the right can be evaluated as follows:

$$q_c = h_G(T - T_a), \quad (3-2)$$

$$q_r = \sigma(\epsilon T_A^4 - \alpha T_{Aa}^4), \quad (3-3)$$

$$q_e = k_Y \tau_T \left(\frac{M_V}{M_a} \right) \left(\frac{\bar{p} - \bar{p}_a}{p} \right), \quad (3-4)$$

where:

h_G = heat transfer coefficient, Btu/(hr)(ft²)(°F)

T = water temperature, °F

T_a = air temperature, °F

σ = Stefan-Boltzman constant = 1.730×10^{-9} Btu/(ft²)(hr)(°R⁴)

ϵ = emissivity of water surface

T_A = absolute temperature of the water = $460^\circ\text{F} + T$, °R

α = absorptivity of atmosphere

T_{Aa} = absolute temperature of air = $460^\circ\text{F} + T_a$, °R

k_Y = mass transfer coefficient, lb/(hr)(ft²)

τ_T = latent heat of vaporization of water at temperature T , Btu/lb

M_V = molecular weight of water = 18.0

M_a = molecular weight of air = 29

\bar{p} = vapor pressure of water at temperature T , atm.

\bar{p}_a = partial pressure of the water vapor in the air, atm.

p = atmospheric pressure, atm.

As long as the air flow conditions are turbulent, the ratio $h_G/k_Y \approx c$ is independent of the air velocity. For air-water systems under a total pressure, p ,

of 1 atm, the value of c is approximately equal to 0.24 Btu/(°F)(lb). [1]*

It can be shown that the value of q in equation (3-1) is

$$q = -c_p \rho D \frac{dT}{dt}, \quad (3-5)$$

where:

c_p = specific heat of water at constant pressure \approx 1 Btu/(lb)(°F) when $p = 1$ atm, and $32 \leq T \leq 212^\circ\text{F}$

ρ = density of water \approx 62.4 lb/ft³ when $p = 1$ atm, and $32 \leq T \leq 212^\circ\text{F}$

D = effective depth of the reservoir, ft

dT/dt = rate of change of water temperature, °F/hr.

$$D \equiv V/A = A_c/w, \quad (3-6)$$

where:

V = volume of water underlying the horizontal surface area, A , of the reservoir, ft³

A = horizontal surface area of the volume, V , ft²

A_c = cross-sectional area of the reservoir, ft²

w = width of the surface of the reservoir from bank to bank, ft.

For reservoirs, D is 1/3 of the maximum depth (see equation 3-16).

The following equation closely fits the annual variation of water temperature at a given point on a stream or at a given depth in a reservoir [2-7]:

$$T = a[\sin(bx + c_T)] + \bar{T}, \quad (3-7)$$

where:

a = amplitude, °F

b = 0.987 degrees/day = 0.0172 radians/day

x = number of days since October 1 ($x = 1$ for October 1), days

c_T = phase coefficient, degrees or radians

\bar{T} = average value of T , °F.

$$\frac{dT}{dx} = a[\cos(bx + c_T)] b = 0.0172a[\cos(bx + c_T)] . \quad (3-8)$$

If monthly values are used,

$$\frac{dT}{dt} = \frac{dT/dx}{24} = \frac{0.0172a}{24}[\cos(bx + c_T)] . \quad (3-9)$$

Numbers in brackets refer to reference list (bibliography).

Evaluation of Mass Transfer Coefficient, k_Y - The

mass transfer coefficient, k_Y , is usually related to the wind velocity, W , in miles per hour, by the following empirical relationship:

$$k_Y = c_W W \quad (3-10)$$

where c_W = a constant for a given location, lb/(ft²)^W (mile). The relationship between k_Y and W may be more complex than indicated by equation (3-10) above. On the other hand, values of c_W for lakes may be roughly similar from lake to lake on a given basis. Finally, it is possible that other variables may be of significance in the relation between k_Y and W . As indicated below, values currently used for c_W vary by a factor of over 2 for convection and by a factor of over 3 for evaporation.

Several (but not all) values of k_Y implied in equations of various authors are listed in Table 3-1. The average value of c_W appears to be about 0.68. The value of c_W for Cheney Reservoir was determined by using an average annual evaporation figure of 56 inches per year [14]. The value of c_W calculated for Cheney is 0.61, which is the same for Lake Hefner and the open ocean [9]. This same technique (using an annual average evaporation figure) was also applied

to the Arkansas River at Little Rock, Arkansas, giving a value of c_W of 0.635. However, this technique cannot be applied to bodies of water that are thermally stratified. For example, if the technique is applied to Lake Mead, the resulting value of c_W (0.370) is too low. In summary, the value of c_W reported for Cheney Reservoir appears to agree with those reported in the literature as well as the value calculated for a river in Arkansas.

Effective Depth of Cheney Reservoir, D - The volume determined from the area and capacity tables for Cheney Reservoir can be expressed by an equation of the form

$$V = n H^m, \quad (3-11)$$

where:

n and m are constants (the indicated magnitude of m is about 3),

H = depth of water at the deepest part of the reservoir, feet.

Using E to represent lake surface elevation in feet, and E_0 to represent the elevation of the deepest part of the reservoir, in feet, then

TABLE 3-1. VALUES OF k_Y IMPLIED IN EQUATIONS OF VARIOUS AUTHORS

Author	Evaporation	Convection	Assumptions for compatibility between Evaporation and Convection
Albertson and others [8]	$1,630 \frac{pW}{\lambda_T}$	$1.01W$	$p = 1 \text{ atm}; \lambda_T = 1,613 \text{ BTU/lb}^*$
Bromley [9]	$0.61 W$	$0.55W$	$c = 0.216 \text{ Btu}/(^{\circ}\text{F})(\text{lb})$ [The value used in this report is $c = 0.24 \text{ Btu}/(^{\circ}\text{F})(\text{lb})$].
Davidson and Bradshaw [10]	$562.0 \frac{pW}{\lambda_T}$	$0.58W$	$p = 1 \text{ atm}; \lambda_T = 969 \text{ BTU/lb}^{**}$
Raphael [11]	$502.3 \frac{pW}{\lambda_T}$	$0.44Wp$	$\lambda_T = 1,140 \text{ BTU/lb}^*$
Velz and Gannon [12]	$0.35Cp(1 + 0.1W)$ $10 \leq C \leq 15$	$3.33 + 0.67W$	$p = 1 \text{ atm}; 9.52 \leq C \leq 19.14$ for $0 \leq W \leq \infty$
Hatheway [13]	$0.882W$	$0.882W$	None
Average of [8], [10] and [11]	$898 \frac{pW}{\lambda_T}$	$0.68W$	$p = 1 \text{ atm}; \lambda_T = 1,305 \text{ BTU/lb}^*$

* Maximum value at 32°F is 1,075.8 BTU/lb

** Minimum value at 212°F is 970.3 BTU/lb

$$H = E - E_0 \quad (3-12)$$

It should be noted that equation (3-11) was not used in calculating the water budget because it was not sufficiently accurate for this purpose.

The derivative of equation (3-11) gives the surface area of the reservoir:

$$\frac{dV}{dH} = A = n m H^{m-1} \quad (3-13)$$

For Cheney Reservoir, $E_0 = 1,367.7$ feet. The volume of Cheney Reservoir, in acre-feet is

$$\text{volume (acre-feet)} = \frac{V}{43,560} = 0.619H^{3.13} \quad (3-14)$$

and the area in acres is

$$\text{area (acres)} = \frac{A}{43,560} = 2.30H^{2.09} \quad (3-15)$$

Substituting equations (3-11) and (3-13) into equation (3-6) gives

$$D = \frac{H}{m} = \frac{H}{3} \quad (3-16)$$

Evaluation of the Radiation Term, q_r - The value

of ϵ in equation (3-3) appears to be 0.97. [11] [15] According to Raphael, [11] [16] the value of α in equation (3-3) is 0.9708, where β is expressed by one of two types of empirical equations, namely

$$\beta = \beta_0 + \left(\frac{\Delta\beta}{\Delta p_a} \right) \bar{p}_a \quad (3-17)$$

or

$$\beta = \beta_0 + \left(\frac{\Delta\beta}{\Delta \sqrt{p_a}} \right) \sqrt{p_a} \quad (3-18)$$

The maximum possible value of β is 1. Values assigned to β_0 , $\Delta\beta/\Delta p_a$, and $\Delta\beta/\Delta \sqrt{p_a}$ by various authors are listed in Table 3-2.

An annual average value of β appears to be in the vicinity of 0.85 [13]. Sometimes a constant value of about 0.87 is used [17]. In any event, there is little to support the validity of either equation (3-17) or (3-18). For this reason, the equation developed by Anderson and Baker [20] was used in this report. Based on comparisons of estimated and observed incident long-wave radiation at 10 locations varying in elevation from 30 to 7,170 feet, the following conclusions can be stated: (1) Their equation gives results comparable within a few percent on a long-term basis (6 months or longer); (2) For any specific atmospheric condition, there is no tendency for the equation to over or under compute or to give increased

scatter; and (3) When data for periods of 6 months or more were analyzed, correlation coefficients of approximately 0.90 were obtained between computed and observed daily radiation values. It should be noted that radiometers currently available will not provide atmospheric radiation data of accuracy within 5 percent. The equation given by Anderson and Baker is

$$\beta = 1 - \frac{[35.0 + 54.5 (\sqrt{p_s} - \sqrt{p_a}) - S] \left(\frac{Q_s}{Q_{sc}} \right)^2}{\sigma T_{Aa}^4} \quad (3-19)$$

where:

\bar{p}_s = vapor pressure of water at temperature T_a , atm.,

S = station adjustment term, Btu/(ft²)(hr),

$Q_{sc} = Q_s$ when $C_t = 0$.

Values of Q_{sc} are maximum values [21]. Equation (3-19) gives Q_{sc} the clear sky value of β when $S = 0$ and $Q_s = Q_{sc}$.

The values of β calculated by equation (3-19) for Cheney Reservoir are:

Month 1966	β
January	0.767
February	0.805
March	0.803
April	0.806
May	0.839
June	0.832
July	0.839
August	0.831
September	0.820
October	0.810
November	0.803
December	0.797
Annual Average	0.816

Water Temperature, T - Cheney Reservoir is essentially homogeneous, from a water temperature standpoint, as will be shown later. Therefore, the daily temperatures reported in the Cheney pumping station monthly water reports were used. Usually, water temperatures were recorded daily, except for weekends and holidays. A regression analysis indicated that, for Cheney Reservoir, equation (3-7) is

$$T = -20.9[\sin(0.987x - 24.6)] + 57.4 \quad (3-20)$$

The coefficient of correlation was 0.992. Equation (3-20) is plotted in figure 3-1 along with average monthly water temperatures for 1966.

TABLE 3-2. VALUES OF β_0 ASSIGNED BY VARIOUS AUTHORS

Reference	β_0	Equation	$\frac{\Delta\beta}{\Delta\bar{p}_a}$ or $\frac{\Delta\beta}{\Delta\sqrt{\bar{p}_a}}$	Value of \bar{p}_a for which $\beta = 1$	Remarks
11, 16	$0.74 \leq \beta_0 \leq 0.86$ for 0 to 100% cloud cover respectively	3-17	$(\Delta\beta/\Delta\bar{p}_a)$ decreases as cloud cover increases (reference 13). (Raphael)	0.057	0 cloud cover
				0.049	Complete cloud cover
17	1.08 B, B is determined from T_a and the ratio Q_s/Q_{sc} . B can be evaluated only when $24 \leq T_a \leq 96$ °F and when $0.5 \leq Q_s/Q_{sc} \leq 0.95$	3-18	$(\Delta\beta/\Delta\sqrt{\bar{p}_a}) = 0.925$ (Brunt)	0.048 when B = 0.74 (0.74 is maximum value of B)	Q_s = incoming solar radiation and Q_{sc} = clear sky solar radiation, BTU/(hr)(ft ²). Calculated value of β is within 10 to 20% of measured values.
18	0.68	3-18	$(\Delta\beta/\Delta\sqrt{\bar{p}_a}) = 1.14$	0.078	FOR CLEAR SKIES ONLY
18	$\beta_0 = 0.740 + 0.025 C_t \exp(-5.86 \times 10^{-5}H)$	3-17	$(\Delta\beta/\Delta\bar{p}_a) = 4.96 - 0.574 C_t \exp(-6.01 \times 10^{-5}H)$ (Anderson)	depends on C_t and H	C_t = cloudiness in tenths = 10 for complete cloud cover. H = cloud height in feet. When H < 1,639 feet, H is assumed to be 1,639 feet.
18	0.740	3-17	$(\Delta\beta/\Delta\bar{p}_a) = 4.96$	0.052	if $C_t = 0$ or if H = ∞
18	$0.740 + 0.0227C_t$	3-17	$(\Delta\beta/\Delta\bar{p}_a) = 4.96 - 0.504C_t$	depends on C_t	if H \leq 1,639 feet
18	0.967	3-17	$(\Delta\beta/\Delta\bar{p}_a) = -0.008$	negative value indicates numerical discrepancy	if H \leq 1,639 feet <u>and</u> if $C_t = 10$
19	0.567	3-18	$(\Delta\beta/\Delta\sqrt{\bar{p}_a}) = 1.87$	0.053	FOR CLEAR SKIES ONLY (Parmalee and Aubele)
	0.66 AVERAGE FOR CLEAR SKIES ONLY		$(\Delta\beta/\Delta\sqrt{\bar{p}_a}) = 1.31$ AVERAGE $[(\Delta\beta/\Delta\bar{p}_a) = 1.5$ average for clear skies]	0.056 AVERAGE (0.06 is average for clear skies)	Opinion appears to be equally divided between equations (3-17) and (3-18). This is true even in the special case of clear skies.

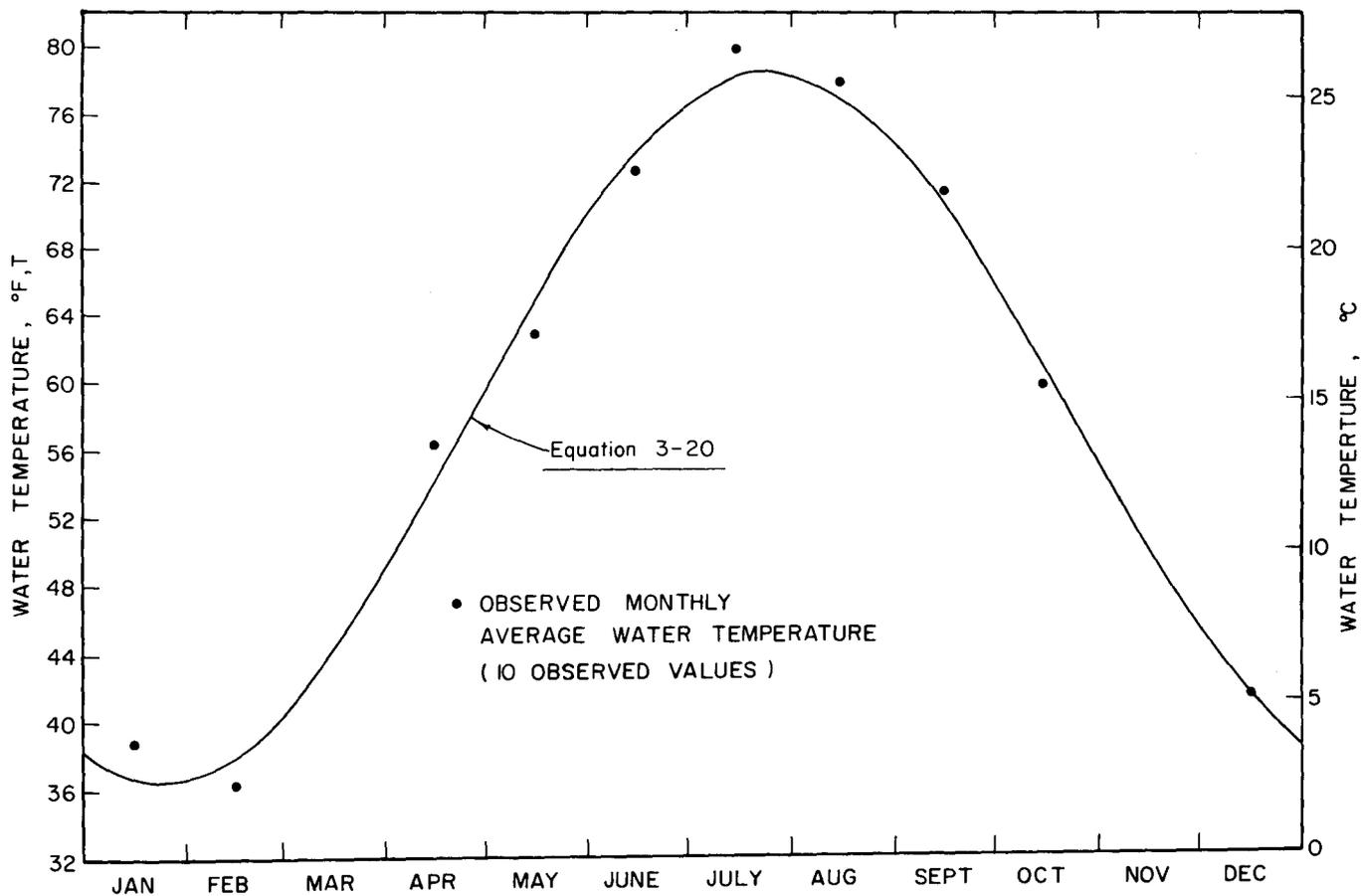


Figure 3-1. Average monthly reservoir temperature (1966).

Atmospheric Pressure, p - Atmospheric pressure at Cheney Reservoir averages 0.953 atmospheres, and the monthly variations are small as indicated below:

Atmospheric Vapor Pressure, \bar{p}_a - The following equation is accurate within ± 20 percent for the Cheney Reservoir area:

$$\bar{p}_a = 0.004 e^{0.0362(T_a - 32)} \quad (3-21)$$

for $T_a \geq 32^\circ\text{F}$. Actual atmospheric vapor pressures for 1966 were:

Month, 1966	Atmospheric Pressure p , Atmospheres
January	0.960
February	0.958
March	0.955
April	0.954
May	0.955
June	0.954
July	0.953
August	0.956
September	0.956
October	0.957
November	0.958
December	0.957
Annual Average	0.953

Month, 1966	Atmospheric Vapor Pressure, \bar{p}_a , Atmospheres
January	0.00362
February	0.00477
March	0.00618
April	0.00881
May	0.0127
June	0.0181
July	0.0247
August	0.0199
September	0.0160
October	0.00861
November	0.00673
December	0.00395

Solar Radiation - The value of the solar constant is 425 Btu/(hr)(ft²) and varies ±2 percent. In the absence of observed data, the value of solar radiation can be estimated from maximum and minimum values given for each month of the year by correcting for cloudiness and elevation:

$$q_s = q_{so}(1 + 0.0185 \times 10^{-3} E), \quad (3-22)$$

where q_{so} = intensity of solar radiation at sea level, Btu/(hr)(ft²).

The nearest solar observations were at Dodge City, Kansas. Because Dodge City is at a latitude of 37° 46'N, which is practically the same as Cheney Reservoir, these observations were corrected for elevation (Dodge City elevation is 2,590 feet; Cheney Reservoir normal pool elevation is 1,422 feet) using equation (3-22). Dodge City is approximately 116 miles west of Cheney Reservoir. The variation in visible solar radiation with elevation is also given by equation (3-22) if the coefficient 0.0185 is replaced by 0.00925.

Figure 3-2 is a plot of total and visible solar radiation at Cheney Reservoir. The intensity is in

terms of gram calories per square centimeter day which can be converted to the units used in this report, Btu/(hr)(ft²), by multiplying by 0.1535. The reason for including visible solar radiation is because algae respond to visible solar radiation as follows:

$$w_a = eSA/h \quad (3-23)$$

where:

h = unit heat of combustion, cal/gram

w_a = net weight of algae synthesized daily, grams per day

e = efficiency of energy conversion

S = visible solar radiation intensity in Langleys, calories/(cm²)(day)

A = surface area of Cheney Reservoir, cm².

The surface area of Cheney Reservoir varied from 5,790 acres to 7,300 acres and averaged 6,760 acres during the period July, 1965, through June, 1967.

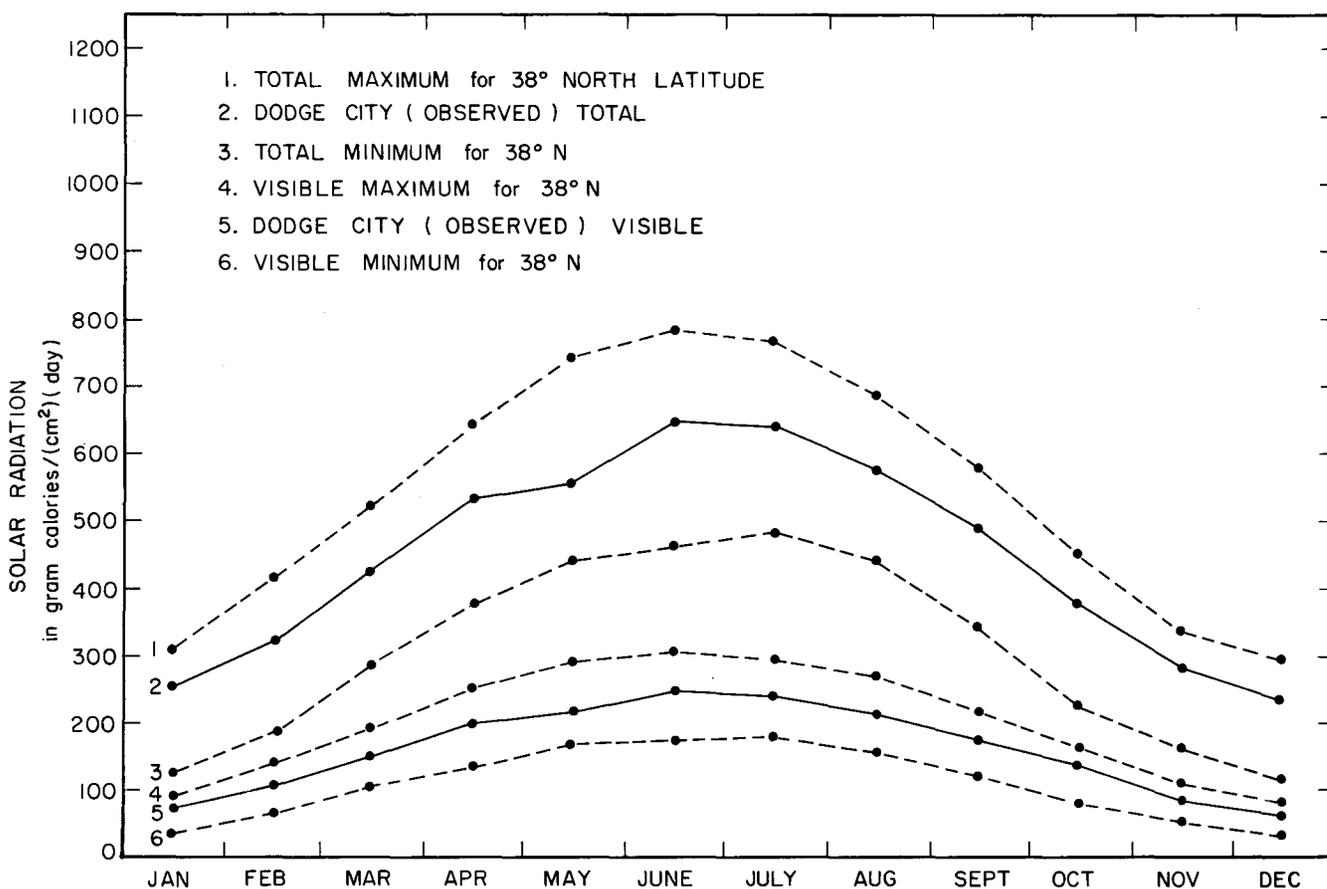


Figure 3-2. Total and visible solar radiation at Cheney Reservoir.

Oxygen production is related to the weight of algae synthesized daily by the oxygenation factor, p :

$$p = \frac{w_{O_2}}{w_a} \quad (3-23a)$$

where:

w_{O_2} = net weight of oxygen produced daily, gm/day.

Algae grown on sewage have an h value of about 6,000 cal/gm on an ash-free basis. Usually, $1.25 \leq p \leq 1.75$, and $p = 1.64$ for oxidation pond algae (cellular material) of composition $C_{6.14} H_{10.3} O_{2.24} N$. When growth is limited by nutritional deficiencies and adverse environmental conditions, the value of e is very small (even in oxidation ponds, e averages only about 0.04). Combining equations (3-23) and (3-23a), and substituting the appropriate values for Cheney Reservoir, one obtains:

$$w_{O_2} = 7.4 \times 10^7 eS \quad (3-23b)$$

Other Meteorological Variables - The remaining meteorological variables are given in the Table below. All meteorological data, unless otherwise mentioned, were obtained from Weather Bureau records at Wichita, Kansas.

Month 1966	Air Temperature, T_a , °F	Wind Velocity, W , miles per hour
January	28.3	11.9
February	33.6	11.1
March	49.1	15.5
April	53.5	13.6
May	65.7	12.7
June	76.2	13.4
July	84.9	11.5
August	76.1	10.7
September	68.6	9.9
October	58.0	12.9
November	48.3	12.0
December	32.7	11.7
Average	56.2	12.2

Heat Balance - Equation (3-1) can be rewritten:

$$0 = q_c + q_r + q_e - q_s - q = \Delta q \quad (3-24)$$

where Δq = heat imbalance, Btu/(hr)(ft²). Theoretically, Δq should be zero, but practically it is very difficult

to achieve. Therefore, a more realistic statement of equation (3-24) is the following:

$$q_c + q_r + q_e = q_s + q + \Delta q \quad (3-25)$$

where the left side of equation (3-25) may be considered to be the heat depletion of the reservoir, and the right side, the heat input. The quantities calculated for all the terms in equation (3-25) are listed in Table 3-3. If the depth had remained constant, one would have expected that the Σq on an annual basis would be zero. Actually the depth varied during 1966 as shown in the following table:

Month 1966	Effective Depth, D , in Feet (1/3 of total depth H)
January	14.50
February	14.25
March	15.18
April	15.58
May	15.76
June	15.42
July	15.50
August	15.08
September	15.24
October	14.74
November	14.32
December	14.32
Average	15.00

As expected, the largest heat inflow was due to solar radiation, q_s . It should be noted that 94 percent of the incoming solar radiation was assumed to be absorbed by the water. The largest quantity of heat outflow, as expected, was due to evaporation, q_e , followed by radiation, q_r , and convection, q_c , in that order.

On an annual basis, the heat balance shown in Table 3-3 is within ± 4 percent. One quantity not accounted for in the heat balance is the amount of heat conducted to and from the soil at the bottom of the reservoir. This can be estimated from

$$Q = \frac{kA_B}{x} (T_s - T) , \quad (3-26)$$

where:

Q = flow of heat per unit time, Btu/hr

k = thermal conductivity of wet soil, (Btu)(ft)/(hr)(ft²)(°F)

A_B = area of bottom of Cheney Reservoir, ft²

x = effective thickness of conducting soil layer, ft

T_s = soil temperature, °F.

TABLE 3-3. HEAT BALANCE
Btu/(Hr) (Ft²)

Month 1966	Heat Outflow =			Heat Inflow		Heat Imbalance Δq
	Convection q_c	Radiation q_r	Evaporation q_e	Solar Radiation q_s	Heat Storage Change q	
January	18.32	31.62	21.88	36.67	2.52	32.63
February	4.39	21.42	10.92	46.20	-5.08	-4.39
March	-11.34 *	17.51	22.87	61.07	-11.32	-20.71
April	5.77	24.71	36.06	76.38	-14.59	4.75
May	-5.39 *	17.86	35.73	79.70	-13.88	-17.62
June	-6.86 *	20.39	51.88	93.13	-9.43	-18.29
July	-8.59 *	18.89	47.17	91.97	-2.41	-32.09
August	2.66	29.41	55.24	82.44	4.90	-0.03
September	4.06	25.69	39.56	69.74	9.10	-9.53
October	3.21	24.98	47.93	53.71	13.70	8.71
November	3.16	24.11	27.30	39.56	13.07	1.94
December	14.74	26.88	23.13	32.77	8.99	22.99
Total	24.13	283.47	419.67	763.34	-4.43	-31.64
Annual Net Heat Outflow = 727.27			Annual Net Heat Inflow = 727.27			

* Air temperature was greater than the water temperature.

In addition,

$$\Delta q = Q/A = \frac{k}{x} \left(\frac{A_B}{A} \right) (T_s - T) \quad (3-27)$$

A reasonable value for T_s appears to be 57.4° F, the average water temperature of Cheney Reservoir. A plot of Δq versus $T_s - T$ gave the following:

$$\frac{k}{x} \left(\frac{A_B}{A} \right) = 1.57 \quad (3-28)$$

If one considers Cheney Reservoir to be a cone, then

$$V = \frac{A}{3} H \quad (3-29)$$

and

$$A_B = \frac{1}{2} (\text{perimeter of base})(\text{slant height}) \quad (3-30)$$

and

$$A = \pi R^2 \quad (3-31)$$

where R = radius, ft, of a circle of area A . Therefore, the perimeter of the base is $2\pi R$ and the slant height is $\sqrt{R^2 + H^2}$. Dividing equation (3-30) by equation (3-31) gives:

$$\frac{A_B}{A} = \frac{\sqrt{R^2 + H^2}}{R} \quad (3-32)$$

Equation (3-29) can be restated

$$V = \frac{\pi R^2 H}{3} \quad (3-33)$$

Comparison of equations (3-33) and (3-11) gives

$$R^2 = \frac{3nH^2}{\pi} \quad (3-34)$$

and therefore equation (3-32) becomes

$$\frac{A_B}{A} = \frac{\sqrt{\frac{3nH^2}{\pi} + H^2}}{\sqrt{\frac{3n}{\pi}} H} = \sqrt{1 + \frac{\pi}{3n}} \quad (3-35)$$

so that the bottom area A_B bears a constant relationship to the surface area A . From equations (3-11) and (3-14), it is apparent that the value of n is 27,000, which is large in comparison to π , so that $A_B \approx A$. In other words, the area of the bottom of this lake is only slightly greater than its surface area A because it is shallow compared to its areal extent. Therefore, in order to evaluate x from equation (3-28), one only needs the appropriate value of k . The value of k for water seems to be appropriate and is approximately 0.328 (Btu)(ft)/(hr)(ft²)(°F) at 57.4°F. This means that the effective thickness of conduction is 0.209 feet (2.51 inches), which is a reasonable value.

Evaporation - The quantity of water evaporated can be calculated from the values given for q_e in Table 3-3. The quantity of water evaporated, in feet per hour, is $q_e/(\tau_T)(\rho)$. In order to convert to inches per month, $q_e/(\tau_T)(\rho)$ must be multiplied by 24 hours per day \times number of days per month \times 12 inches per foot. In

other words, $q_e/(\tau_T)(\rho)$ times 288 times the number of days in that particular month is the evaporation in inches per month. For comparison, the evaporation calculated from the heat balance is compared with that calculated from the volume balance and that observed in evaporation pans at Cheney Reservoir in the following table:

Month, 1966	Evaporation, inches per month		
	Calculated from heat balance	Calculated from volume balance	Evaporation pan (observed)
January	2.92	1.43	
February	1.31	1.71	
March	3.07	3.80	
April	4.72	5.26	4.90
May	4.83	6.19	6.52
June	6.83	9.42	7.85
July	6.43	7.58	8.29
August	7.53	9.09	6.45
September	5.21	6.41	5.17
October	6.47	6.03	4.78
November	3.55	3.85	
December	3.09	2.89	
Total (inches per year)	56.00	63.66	58.0*

*The total evaporation (in inches) and the percent of the annual evaporation observed during the months of April through October, 1966, were as follows:

	Evaporation during the months of April through October, 1966, (inches)	Percent of annual evaporation
Calculated from heat balance	42.02	75.0
Evaporation pan	43.96	(75.9)
Calculated from volume balance	49.98	78.5

The percent figure for the evaporation pan (75.9%) was determined by interpolation. Therefore, the annual evaporation pan evaporation is $(43.96/0.759 =)$ 58.0 inches. All evaporation pan data was adjusted by a factor of 0.7 .

On an annual basis, the quantities of evaporation calculated are within ± 12 percent of each other. However, if one uses the evaporation figures from the volume balance for the period July, 1965, through June, 1967, the average annual evaporation is 57.3 inches per year, which is within ± 2.3 percent of the figure calculated from the heat balance and is within ± 1.2 percent of the observed evaporation pan data.

Water Temperature in the Absence of Evaporation - As will be shown later, the excess of evaporation over precipitation is the most important single quantity which affects water quality in impoundments. For this reason, and because of the desire to conserve water, various methods of evaporation reduction have been attempted in the past. It is believed worthwhile then, to attempt to calculate the resulting water temperature either in the absence of evaporation or for a partial reduction in evaporation.

In the event of evaporation reduction or elimination, water temperature, T , will be increased. This increase will, in turn, increase the quantities of heat lost by convection, radiation, and conduction. The value of q , because it depends on the rate of change of temperature, would probably not be affected significantly even with a very slight increase in effective depth, D . Of course, q_s , would be exactly the same.

Equation (3-3) may be rewritten as

$$q_r = \sigma \epsilon (T_A^4 - \frac{\alpha}{\epsilon} T_{Aa}^4) \quad (3-36)$$

A rough approximation of equation (3-36) would be

$$q_r \approx 4\sigma \epsilon^{1/4} \alpha^{3/4} T_{Aa}^3 (T - T_a) \quad (3-37)$$

The quantity $4\sigma \epsilon^{1/4} \alpha^{3/4} T_{Aa}^3$, for a given month would not be changed by an increase in water temperature T . Therefore, substituting equations (3-2), (3-37), and (3-27) into equation (3-25), and solving for the elevated water temperature, T' , one obtains:

$$T' = \frac{q_s + q - q_e' + \frac{k}{x} \frac{A_B}{A} T_s + (h_G + 4\sigma \epsilon^{1/4} \alpha^{3/4} T_{Aa}^3) T_a}{(h_G + 4\sigma \epsilon^{1/4} \alpha^{3/4} T_{Aa}^3 + \frac{k}{x} \frac{A_B}{A})} \quad (3-38)$$

where

T' = elevated water temperature due to evaporation control, °F

q_e' = reduced quantity of heat lost by evaporation, Btu/(hr) (ft²).

For Cheney Reservoir, equation (3-38) becomes

$$T' = \frac{q_s + q + 90.1 + (h_G + 4\sigma \epsilon^{1/4} \alpha^{3/4} T_{Aa}^3) T_a}{(h_G + 4\sigma \epsilon^{1/4} \alpha^{3/4} T_{Aa}^3 + 1.57)} \quad (3-38A)$$

if it is assumed that evaporation control is 100 percent effective (that is $q_e' = 0$). If the evaporation had been reduced, say only 40 percent, then the value of q_e' would have been $0.6q_e$.

The calculations using equation (3-38A) are illustrated in Table 3-4. In Table 3-4, h_G was calculated using equation (3-10) and the relation $h_G = ck\bar{v}$. These equations combine to give $h_G = cc_w W = (0.24)(0.61)W = 0.1464W$. The quantity $4\sigma \epsilon^{1/4} \alpha^{3/4} T_{Aa}^3$ simplifies to $(4)(1.730 \times 10^{-9})(0.97) \beta^{3/4} T_{Aa}^3 = 6.72 \times 10^{-9} \beta^{3/4} T_{Aa}^3$. The values of β previously given were used along with the values of $T_{Aa}^3 = (T_a + 460)^3$. Water temperatures with evaporation, T , were taken from figure 3-1. The values of T_a used are the same as those previously given. Values of $q_s + q$ were taken from Table 3-3.

As is observable in Table 3-4, water temperatures would be increased from 12 to 19° F (average, 15° F) if evaporation was completely eliminated. During some portions of the year, the increased water temperatures would not matter much. However, a temperature of 96.6° F, predicted for July, would be intolerable. Therefore, water temperature is a limiting factor when evaporation reduction is considered. Water temperatures would be excessive at the same time that evaporation reduction would be most effective. In addition, increased water temperatures would mean reduced dissolved oxygen concentrations.

It should be noted that, in making the heat balance in Table 3-3, that the actual water temperatures were used rather than the water temperatures read from the sine curve in figure 3-1 which are listed in Table 3-4. Also, it should be noted that equation (3-38) takes into account heat losses by convection, radiation, evaporation, as well as heat gains by solar radiation, change in heat storage, and heat exchange by conduction.

TABLE 3-4. CHENEY RESERVOIR WATER TEMPERATURES, T' , IN THE EVENT OF EVAPORATION ELIMINATION

Month 1966	T , Water Temperature °F with no Evaporation Reduction	T_a , Air Temperature °F	$q_s + q$, Btu (hr) (ft ²) (from Table 3-3)	h_G , Heat Transfer Coefficient Btu per (hr) (ft ²) (°F)	$4\sigma \epsilon^{1/4} \alpha^{3/4}$ times T_{Aa}^3 Btu per (hr) (ft ²) (°F)	T' , Water Temperature °F with no Evaporation	$\Delta T = T' - T$ Water Temperature Increase °F
January	36.8	28.3	39.19	1.74	0.639	50.4	13.6
February	37.8	33.6	41.12	1.62	0.691	54.4	16.6
March	44.1	49.1	49.75	2.27	0.752	63.4	19.3
April	53.9	53.5	61.79	1.99	0.778	69.8	15.9
May	64.7	65.7	65.82	1.86	0.860	78.6	13.9
June	73.5	76.2	83.70	1.96	0.901	89.1	15.6
July	78.0	84.9	89.56	1.68	0.955	96.6	18.6
August	77.0	76.1	87.34	1.56	0.900	91.1	14.1
September	70.7	68.6	78.84	1.45	0.857	85.0	14.3
October	60.9	58.0	67.41	1.89	0.798	74.2	13.3
November	50.1	48.3	52.63	1.75	0.747	65.4	15.3
December	41.3	32.7	41.76	1.71	0.681	53.6	12.3
Total			758.91				
Average	57.4	56.2				72.6	15.2

4. SALT BUDGET

Most of the inorganic salts exist as ions in water solutions and exhibit the ability to conduct an electric current. The magnitude of the conductance is dependent upon the nature and concentrations of the ions present. Conductivity is defined as the reciprocal of specific resistance of the solution and is approximately proportional to the concentration of ions present in dilute solutions such as Cheney Reservoir. Because total conductivity is equal to the sum of the conductivities of individual ions of the salts present, measurements of conductivity may be used to obtain a measure of the total dissolved salts in the water. The precision is about 5 percent for water of relatively constant composition.

Mass balances of salt for Cheney Reservoir can be made by properly accounting for inflow, outflow and storage of salt. The equation for mass salt balance is simply

$$(\text{Mass in reservoir}) = \left(\begin{array}{l} \text{Mass in reservoir} \\ \text{at beginning} \end{array} \right) + \left(\begin{array}{l} \text{Mass inflow} \\ \text{by stream} \end{array} \right) + \left(\begin{array}{l} \text{Mass inflow} \\ \text{from watershed} \end{array} \right) - (\text{Mass outflow}) \quad (4-1)$$

The mass of salt can be determined by concentration and volume. Conductivity readings were used for the concentrations because, as is shown later (see equations 6-1 and 6-2), conductivity and concentration are directly proportional for Cheney Reservoir water.

Field conductivity readings were first taken on August 3, 1965, and weekly conductivity measurements were made in the reservoir thereafter except that some data were unavailable during periods of ice cover and high winds. The conductivity data are presented in Table 4-1.

In preparation for the salt budget, the longitudinal, lateral and vertical distributions of conductivity were studied. Data were available until January, 1966, from one station on each range line with readings at the middle of every 10-ft vertical interval. These stations were A-1, R1-1, R3-2, R5-2, R7-1 and R9-2. Of course, where depths were shallow, only one or two readings were available. These vertical readings indicated uniformity of conductivity in the vertical direction. Although the values vary a slight amount with depth, they were all within the accuracy expected. The variations were random and no evidence of stratification could be detected. Thus, in the table a single value is given for each station, which is an average of all readings in the vertical direction. The longitudinal variations were significantly different however.

Conductivity readings were also made laterally across the reservoir at other stations on the range lines, beginning in January 1966, in addition to those stations mentioned in the preceding paragraph. At these stations, only one mid-depth reading was generally taken. In view of the vertical uniformity exhibited at the selected stations, single readings probably were sufficient. The lateral measurements indicated that variations in conductivity across any range line was only about 10 percent with some exceptional cases when variations were as large as 30 percent. For the most part however, the salt distributions vertically and laterally were found to be substantially uniform.

The averaged values are tabulated in Table 4-1 for the dates after January 1966. In the latter part of 1966 and most of 1967, the longitudinal variations of concentration were less pronounced than in the earlier "life" of the reservoir.

Let equation (4-1) be re-expressed in notational form. Thus:

$$(C_R V_R)_2 = (C_R V_R)_1 + C_I V_I + (C_P V_P) - (C_O V_O), \quad (4-2)$$

where C is the conductivity provided in the data and V is water volume in acre-feet.

The products formed in equation (4-2) are not total mass because the dimensions for conductivity and volume are micromhos per cm at 25°C and acre-feet, respectively. However, we can use these products to represent mass in equation (4-1) if we adhere to consistent dimensions, as the entire equation may be multiplied by or divided by a constant. In any event, it is the third term on the right of the equal sign in equation (4-2) which is unknown, and in particular it is C_P which can be determined in the equation. Thus, by rearrangement we get that

$$C_P = \frac{1}{V_P} [(C_R V_R)_2 - (C_R V_R)_1 - C_I V_I + C_O V_O]. \quad (4-3)$$

The implication is that, for sufficiently accurate determinations of the terms on the right, equation (4-3) should lead to concentration of salt inflow from the watershed surrounding the reservoir. It should be noted that the outflow is a combination of pumpage and gated outflow, where the trickle of water recorded at the stream gaging station downstream from the dam is attributed to leakage through the gates. Since the inflow from the watershed surrounding the reservoir was small (about 10 percent) in relation to stream inflow at K-17 (see Table 2-2), salt inflow from this watershed should also be a small quantity. Equation (4-3) was then solved for each weekly period or for such intervals of time permissible by the data intervals. In making these calculations, the average concentration in the reservoir on specific dates were determined by a volume-weighted concentration of the values at specific range lines in relation to the volumes of water between midpoints to the range lines. For instance, the concentration at R3 (see Table 4-1) was weighted with a volume in the reservoir contained between a line midway between R3 and R5 and a line midway between R3 and R1. Similarly, where data were available average concentrations (actually average mass) were calculated with daily inflow or outflow values.

A summary of the calculations for C_P from the surrounding watershed is presented in Table 4-2. As is readily evident, the computations are very sensitive to determination of C_R , for the volume of water in the reservoir at any time, V_R , is very much larger than the combined volumes of inflow and outflow. In most instances this ratio is about 25:1 or larger. It was concluded, therefore, that the data was not adequate to justify this calculation of salt budget for Cheney Reservoir.

TABLE 4-1. CONDUCTIVITY AT CHENEY RESERVOIR IN MICROMHOS PER CENTIMETER AT 25°C
(vertical average)

Date		Stations								Pump Intake Tower	Date		Stations								Pump Intake Tower
1965	K-17	R-11	R-9	R-7	R-5	R-3	R-1	A		1966	K-17	R-11	R-9	R-7	R-5	R-3	R-1	A			
Aug	3		890	705	670	670	677	690		May	25									750	
	10	995	900	675	700	695	695	700	680		26									740	
	17		835	710	705	675	680	675			27									740	
	19	790									31									730	
	25	700	750	675	660	660	640	625	675	June	1	1090								740	
Sept	1	500	410	685	680	680	673	672	680		2	1050								730	
	8	850	800	690	675	680	676	625			3*	1050						900		730	
	10								675		4	1000								730	
	15	830							650		5	1080									
	22	380	210	660	660	660	660	660	700		6	1190								730	
	27										7	1100								730	
	28		790	600	625	700	690	675			8*	1160								925	
	29	975									10	1100								750	
Oct	1								700		11	1110									
	6	950	830	668	660	660	648	662	680		12	1120									
	8										13									740	
	12	975	890	610	605	590	605	650			14	1100								750	
	20	1020	900	690	680	650	602	607			15									750	
	27		1010	630	700	695	697	697			16		1100	945	930	925	925	925	925	740	
Nov	1								700		17									750	
	3	1050	985	790	700	725	710	710			20									750	
	10	1030	995	800	735	740	718	718	730		21									750	
	17		1010	750	730	715	710	707			22									800	
	20								700		23									790	
	24								720		24					945	945	945		760	
	30		1000	810	780	770	745	737			25										
Dec	1	1200									26										
	9	1180	1020	840	815	800	780	767			27									790	
	20								720		28									800	
	21		1100	725	652	705	705	715			29									790	
	22	1200									30									780	
	23								700		July	1	1200	1250	950	940	945	945	945	945	790
	28						700	665	702		2	1280									
	29	1150									3	1110									
	30								750		4	1090									
1966											5	1060								760	
Jan	1	1000									6	1050								790	
	7						740	720	713		7	1070								800	
	10								750		8	1010	1100	955	950	950	950	950	950	770	
	12	1100									9	990									
	14								780		10	1000									
	18			855	820	830	810	805			11	1000								790	
	19	1100									12	1000								800	
	21								880		13	1030								790	
	25								800		14									790	
	26	1100									15		1130	975	950	950	950	950	950	790	
Feb	2	1100									18									760	
	4										19									760	
	16	1000									20	625								790	
	18								690		21	480								790	
	19										22	950	1100	955	950	950	950	950	953	790	
	23	900					735	730	700		23	950									
	28								690		24	1100									
March	2	1100									25	1160								750	
	5								705		26	925								760	
	10	990									27	800								760	
	14		910	790	710	700	700	705			28	750								760	
	16	900									29	850								760	
	23	975									30	1050								760	
	28		880	825	767	700	750	700	710		Aug	1	1080							750	
	29								710		2	1200								760	
	30	900							700		3	1150								760	
	31								675		4	1120	1075	925	910	910	920	920	920	760	
April	4								710		5	1100								760	
	5								710		6	1140									
	6	920							715		7	900									
	7								725		8	650								760	
	8								730		9	555								770	
	11								725		10	490								780	
	12		730	640	600	600	630	630	750		11	750								780	
	13								750		12	850	945	925	925	925	925	925	925	780	
	14								730		13	950									
	15	940							720		14	975									
	18								730		15									750	
	19		910	805	720	720	790	770	790		16	1050								750	
	20								740		17									760	
	21								730		18		1100	970	935	930	930	930	930	750	
	22								750		19									750	
	25								730		22									760	
	26								730		23									750	
	27	800							730		24	1200								760	
	28								730		25		1200	955	925	925	925	925	925	760	
	29		705	600	600	600	600	600	730		26									780	
May	2								750		29									720	
	3								740		30									780	
	4								730		31	675								780	
	5	900							740		Sept	1		1080	945	945	945	945	945	77	

TABLE 4-1. CONDUCTIVITY AT CHENEY RESERVOIR IN MICROMHOS PER CENTIMETER AT 25°C - continued

Date	Stations										Date	Stations									
1966	K-17	R-11	R-9	R-7	R-5	R-3	R-1	A	Pump Intake Tower		1967	K-17	R-11	R-9	R-7	R-5	R-3	R-1	A	Pump Intake Tower	
Sept 18	920										Jan 1	1150									
19	950								760		2	1200									
20	1000								770		3	1250								800	
21	1030								770		4	1380								800	
22	810								770		5	1380								800	
23	780	675	575	575	580	550	575	575	770		6	1380								800	
24	720										7	1390									
25	750										8 [†]	1390									
26	1240								770		9	1400								800	
27	1350								770		10	1480								830	
28	1310								770		11	1470								1050	
29		600	600	575	575	575	550	560	770		12	1320								1060	
30									770		13	1230								1080	
Oct 1	1150										14	1180									
2	1180										15	1290									
3	1080								760		16	1360								1060	
4	1160								760		17	1310						820		1050	
5	1150	650	560	580	590	580	590	560	790		18	1400								1030	
6	1150								780		19	1450								1010	
7	1150								790		20	1400								1010	
8	1150										21	1200									
9	1150										22	1060									
10	1140								800		23	990								1000	
11	1130								770		24	1250								950	
12	1120								760		25	1050		900	900	900	875	870	850	950	
13	1100	650	600	560	590	600	600	570	780		26	530								950	
14	1100								740		27	600								950	
15	1100										28	690									
16	1100										29	360									
17	1150								760		30	620								950	
18	1440								760		31	1300								950	
19	1100								770		Feb 1	1275		950				870	867	950	
20	1120								760		2	1100								900	
21	1200								790		3	1175								1100	
22	1280										4	1050									
23	1300										5	1100									
24	1290								800		6	1325								1000	
25	1280								800		7	1250								1000	
26	1300								790		8	1210		950	950	950	950	900	900	950	
27	1300	680	600	580	575	575	575	560			9	1200								1000	
28	1280										10	1200								980	
29	1250										11	1200									
30	1250										12	1150									
31	1250										13	1100								950	
Nov 1	1320								800		14	900								950	
2	1220	1250	1060	1060	1070	1080	1090	1110	810		15	1200								940	
3	1280								800		16	1150								950	
4	1290								800		17	1150		950	950	950	950	900	900	900	
5	1300										18	1125									
6	1300										19	1175									
7	1280								820		20	1200								1000	
8	1280										21	1140								990	
9	1280										22	1100									
10	1280		1050	1000	1000	1000	1000	1000			23	1080								1000	
11	1250										24	1120								1000	
12	1250										25	1120									
13	1245										26	1080									
14	1245										27	1140								1000	
15	1245										28	1125		900	950	950	950	950	920	980	
16	1250										March 1	1130								980	
17	1290										2	1120								990	
18	1320										3	1120								960	
19	1310										4	1150									
20	1290										5	1140									
21	1290										6	1100								940	
22	1290										7	1100								960	
23	1250		1090	1015	1015	1015	1015	1010			8	1272								930	
24	1250										9	1190								930	
25	1250										10	1190								950	
29		1050	1010	1010	1010	1010	1012	1013			11	1170									
30	1010										12	1050									
Dec 1	1300										13	1040								920	
2	1390										14	1040								1050	
3	1420										15	1100								1000	
4	1310										16	1100		925	900	900	900	900	892	1000	
5	1150								800		17	1050								1000	
6	1175								800		18	1100									
7	1210		1050	1010	1010	1010	1010	1010	810		19	1090									
8	1280								800		20	1080								1010	
9	1300								820		21	1070		900	875	875	875	875	875	1000	
10	1310										22	1100								1000	
11	1350										23	1000								1000	
12	1370								800		24	1000								1010	
13	1280								800		25	1050									
14	1250		875	875	875	875	875	875	810		26	1200									
15	1150								800		27	1120								990	
16	1200								810		28	1310								990	
17	1210								875		29	1200				875	875	875		1000	
18	1250										30									1000	
19	1250								800		31									1000	
20	1250		900	850	830	830	830	850	810		April 3									1000	
21	1250								810		4									1000	
22	1200								800		5	1300								1000	
23	1210								800		6			1025	1025	1025	1025	1025	1025	1000	
24	1180										7									1000	
25	1150										10									1000	
26	1150										11									1000	
27	1100								800		12	1400								1000	
28	1100								800		13									1000	
29	1100								810		14									1000	
30	1100								800		17									1000	
31	1100										18									990	

[†]Note: Conductivity meter recalibrated this date and was found to be low.

TABLE 4-1. CONDUCTIVITY AT CHENEY RESERVOIR IN MICROMHOS PER CENTIMETER AT 25°C - continued

1967										1967									
Date	Stations									Date	Stations								
1967	K-17	R-11	R-9	R-7	R-5	R-3	R-1	A	Pump Intake Tower	1967	K-17	R-11	R-9	R-7	R-5	R-3	R-1	A	Pump Intake Tower
April 19	1150								990	Aug 1									950
20									990	2									950
21			1050	1050	1050	1030	1030		1030	3	1020	1000	920	900	900	912	885	890	950
24									1050	4									940
25									1000	7	1070								930
26	1150								1000	8	1100								930
27			1100	1050	1043	1030	1030		1000	9	1100								930
28									1000	10	1100	925	925	925	925	925	925	925	930
May 1	1400								1000	11	1090								930
2	1125								990	12	1050								930
3	825		1100	1050	1050	1050	1050		990	13	1100								930
4	900								980	14	1100								930
5	860								980	15	1100								930
6	800									16	1100								930
7	850									17	1100	1005	900	900	900	900	890	843	930
8	750								970	18	1075								930
9	800		1100	1050	1050	1050	1050		970	19	700								930
10	800								970	20	1000								920
11									950	21	1050								920
12									940	22	1100								920
15									1050	23	1075	950	950	950	950	950	950	950	920
16									1010	24	1075								920
17					1050	1050	1050	1050	1010	25	1050								920
18									1010	26	1050								920
19	1200								1010	27	1050								920
20	1075									28	1050								920
21	1050									29	1080	1040	1030	1025	1025	1030	1020		940
22	1075								1000	30	1025								940
23	1125								1000	31	1025								940
24	1200								1000	Sept 1	1050								940
25	1225								1000	2	1010								
26	1225								1050	3	950								
27	1240									4	600								
28	1125									5	750								940
29	1025								1000	6	1050								940
30	1050		1200	1050	1050	1050	1050	1050	1000	7		800	900	950	950	950	950	950	930
31	1100								1000	8									930
June 1									1000	11									930
2									1000	12	1100								930
5									1000	13	1100								930
6									1000	14	1110	1000	950	950	950	1000	950	950	930
7	1150						1025	1025	1000	15	1110								930
8									1000	16	1100								
9									1000	17	1110								
12									950	18	1120								930
13									1050	19	1120								930
14	1050								1000	20	1100								930
15									980	21	975								930
16		1100	1025	1025	1025	1025	1025	1025	1000	22	1000	950	950	950	950	950	950	950	930
19									1000	23	1110								
20				967	1025	1050	1050	1050	1000	24	1180								
21									1000	25	1200								930
22									1000	26	550								920
23									1000	27	600								920
26									1000	28		950	950	950	950	950	950	950	930
27									1000	29									930
28			850	950	1000	1025	1025	1025	1000										
29									1000										
30									1000										
July 1	200																		
2	240																		
3	260								950										
4	260																		
5	200								950										
6	420			825	925	1000	1000	1000	950										
7	820								950										
8	920																		
9	600																		
10	560								950										
11	340								950										
12	320								950										
13	310								920										
14	275								950										
15	260																		
16	210																		
17	245								950										
18	120								950										
19	200								950										
20	890								930										
21	1050								930										
22	1100																		
23	1100																		
24	1100								920										
25	1100								930										
26	1000								920										
27		980	935	900	900	920	900	955	920										
28	900								920										
31									950										

TABLE 4-2. CONCENTRATIONS OF SALT FROM THE WATERSHED SURROUNDING CHENEY RESERVOIR

Date	C _P	C _R	C _I	C _O	Date	C _P	C _R	C _I	C _O
<u>1965</u>					<u>1966</u>				
Aug 3	--	684	--	--	Sept 1	9371	945	760	945
10	32360	699	615	700	16	-255211	469	770	470
17	-5062	689	612	675	23	37127	576	770	570
25	-2170	652	675	625	29	-28073	561	760	550
Sept 1	1148	676	675	672	Oct 5	0	581	790	550
8	-292	672	667	625	13	6092	591	790	575
15	-670	668	675	672	27	-9381	591	800	560
22	-215	661	675	660	Nov 2	0	1080	820	1100
29	1040	669	690	675	10	0	1001	820	1000
Oct 6	0	661	690	662	23	16142	1018	820	1010
12	0	616	700	650	29	0	1013	820	1015
20	9244	644	650	607	Dec 7	-102719	1011	800	1010
27	0	696	675	697	14	0	875	810	875
Nov 3	0	726	715	710	20	0	825	800	850
10	0	741	715	718	<u>1967</u>				
17	-25038	725	750	707	Jan 25	7383	878	950	850
30	0	768	810	737	Feb 1	4085	891	950	867
Dec 9	28401	800	760	767	8	0	927	950	900
21	-16609	707	700	715	17	0	927	1000	900
28	-336	706	750	702	28	0	934	980	900
<u>1966</u>					Mar 16	-361826	892	1000	890
Jan 7	0	740	770	715	21	-21293	875	1000	875
18	0	817	800	800	Apr 6	45771	875	1000	1025
Feb 19	-9031	744	715	730	21	-382	1033	1030	1030
Mar 14	-14957	704	740	705	27	-124114	1033	1000	1030
28	0	736	760	700	May 3	0	1051	1000	1050
Apr 12	-129790	621	780	630	9	-983	1051	975	1050
19	31947	768	760	800	17	0	1051	1025	1050
27	-40431	600	730	600	30	-1033	1053	1000	1050
May 6	15341	702	675	700	June 7	-4109	1025	1000	1025
20	-50229	650	650	650	16	1459	1025	1000	1025
24	0	870	740	875	20	3798	1036	1000	1050
June 2	-62711	640	630	640	28	2511	1003	1000	1025
8	1721	660	935	660	July 6	-296	952	940	1000
16	94969	926	910	925	27	-2496	924	950	930
24	0	945	850	945	Aug 2	-7786	900	930	895
July 1	-124	945	850	945	10	--	--	930	925
8	0	950	800	950	17	--	--	920	875
15	-55473	950	785	950	23	0	950	920	950
22	-285	951	850	955	29	26150	1023	940	1000
28	-19125	895	910	920	Sept 7	-3502	949	930	950
Aug 4	0	917	875	920	14	10052	961	930	950
12	-5293	925	850	925	22	-56969	950	930	950
18	782	932	750	930	28	-656	950	930	950
25	-5189	926	780	925					

Although it is not explicitly stated in the data, it should be recognized that probably three separate instruments were used to acquire conductivity data. One at K-17, a permanent installation at the gaging station, a portable unit for measuring conductivity in the reservoir and still another at the pump station. In the data there were notable discrepancies in values from the three instruments on several occasions. Regardless of this, however, it is recognized that acquisition of field data is difficult and the amount of data needed to calculate an accurate mass of salt in the reservoir at any time would be large and the cost may well be unjustified.

Instead of quantitative salt balances for Cheney Reservoir, let us turn our attention to the conductivity values and trends which they provided during the period of study. The conductivities as shown in Table 4-2, which are the volume-weighted conductivities for the

reservoir, stream inflow, and pumped outflow are plotted in figure 4-1. The curve for reservoir concentration of salt increases with time as might readily be expected because of the excess of evaporation over precipitation. There is no definitive lag in time between the changes in reservoir salts and that at the pump station. Nor is there any significant difference in the magnitudes of the conductivities between the pump station and the reservoir.

Note that between September, 1966, and January 1967, there seem to be inconsistencies in the conductivity data. It was mentioned earlier in the introduction that sampling was discontinued during this period except for temperature and D.O. How the conductivity data were taken during this period was not apparent on the data sheets nor in the summary letters transmitting the data.

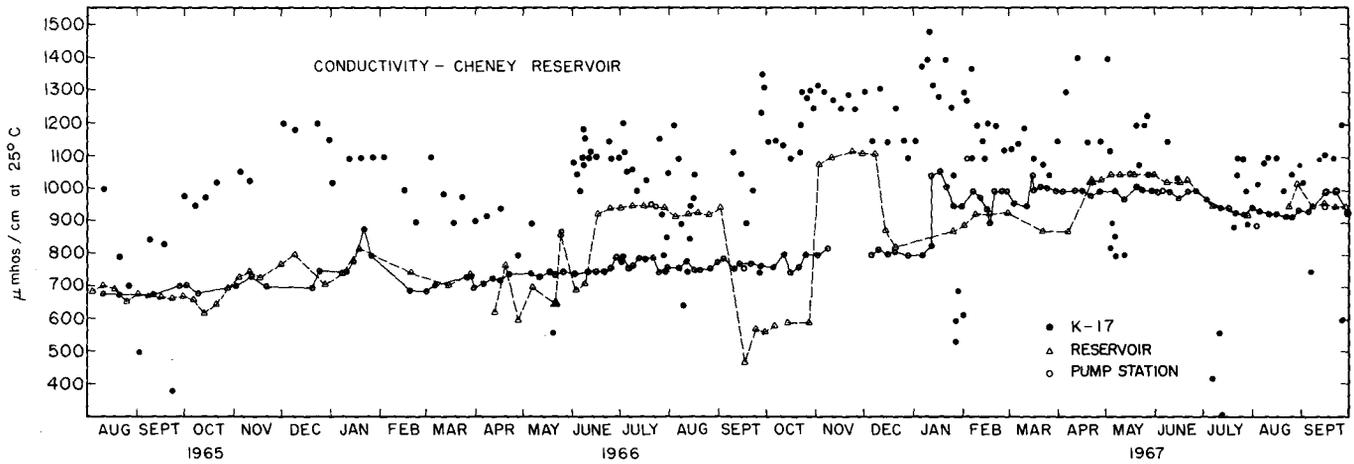


Figure 4-1. Volume-weighted conductivity

The effect of evaporation from the surface of Cheney Reservoir is, of course, to increase the concentration of the dissolved solids and can be calculated by knowing the evaporation volume. During the last five months of 1965, the total evaporation was about 14,000 a.f. with a reservoir volume of about 95,000 a.f. During the same period the data indicated an increase in concentration of about 25 percent. The quantitative calculation of the salt budget was unfortunately not sufficiently accurate to verify the foregoing.

Evaporation in 1966 was about 37,200 a.f. for a reservoir volume of about 100,000 a.f. The increase in concentration due to evaporation was approximately 25 percent. Up to October 1967, evaporation is estimated to have amounted to about 25,000 a.f. with an average reservoir volume of about 120,000 a.f.

As the reservoir fills and reaches an anticipated average volume of about 150,000 a.f., there should be an average of 35,000 a.f. of evaporation each year.

Evaporation at Cheney Reservoir caused the conductivity to increase by a factor of about 1.7. Average conductivity during the early period of the reservoir is estimated to have been about 630 micromhos/cm. at 25°C. At the end of September 1967, conductivity had increased to about 1,090 micromhos/cm at 25°C.

5. TURBIDITY

Turbidity in natural waters is caused by the presence of suspended matter such as clay, silt, finely divided organic matter, plankton, and other microscopic organisms. Turbidity is an expression of the optical property of a sample that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. Attempts to correlate turbidity with the mass concentration of suspended matter are impractical, as the size, shape, and refractive indices of the particulate materials are of most importance optically, but bear little direct relationship to the concentration and specific gravity of the suspended matter. Accuracy of turbidity readings are generally in accordance with the following:

Turbidity Range Units	Recorded to Nearest	Percent Error Range
0.0 - 1.0	0.1	10 and greater
1 - 10	1	10 to 100
10 - 100	5	5 to 50
100 - 400	10	10 to 2.5
400 - 700	50	12.5 to 7.1
700 or more	100	14 or less

Vertical turbidity profiles were studied at various stations for Cheney Reservoir. They were substantially uniform, except that during the month of May, 1966, turbidity was greater near the bottom of the reservoir than at the surface by a factor of about 2, with the largest variation occurring upstream of range line R5. By June, however, the distribution was uniform, and

remained that way, for all other months of the study period. The event seems unrelated to large stream inflow, as it did not occur for the months of June and July, 1967, for instance, when inflow was large. Therefore, the turbidity variations during the one month of May, 1966, was treated as an isolated event and average turbidity in the vertical were calculated for all stations. These averages are tabulated in Table 5-1. There were some lateral variations of turbidity in 1965 and the first six months of 1966, but during the balance of 1966 and through September, 1967, these variations were not significant. The longitudinal variations, however, were large as is noted in the table. A study of the values shows that turbidity at the shallow end of the reservoir was greater than at the deeper end. This can be more readily visualized in figure 5-1 where turbidity for R9-2, R3-1, and the pump station are shown as a function of time. The turbidity at the pump station during 1967 seems to vary only slightly with changes at the upstream end of the reservoir while in the early period of the reservoir, changes of turbidity at say R9-2 seems to reflect its effect at the pump station. In the absence of stratification, this is reasonable as greater reservoir volume would reduce turbidity fluctuations.

The longitudinal variation of turbidity can be quantitatively expressed by the ratio of the turbidity at a given station (say at 5 foot depth) to the average turbidity at all stations (5 foot depth). The computed average values of turbidity at 5 foot depth are plotted in figure 5-2. The following table gives the average value of this ratio as a function of miles from the municipal outlet at Cheney Reservoir dam. The stations listed approximated a straight line from the municipal outlet to K-17.

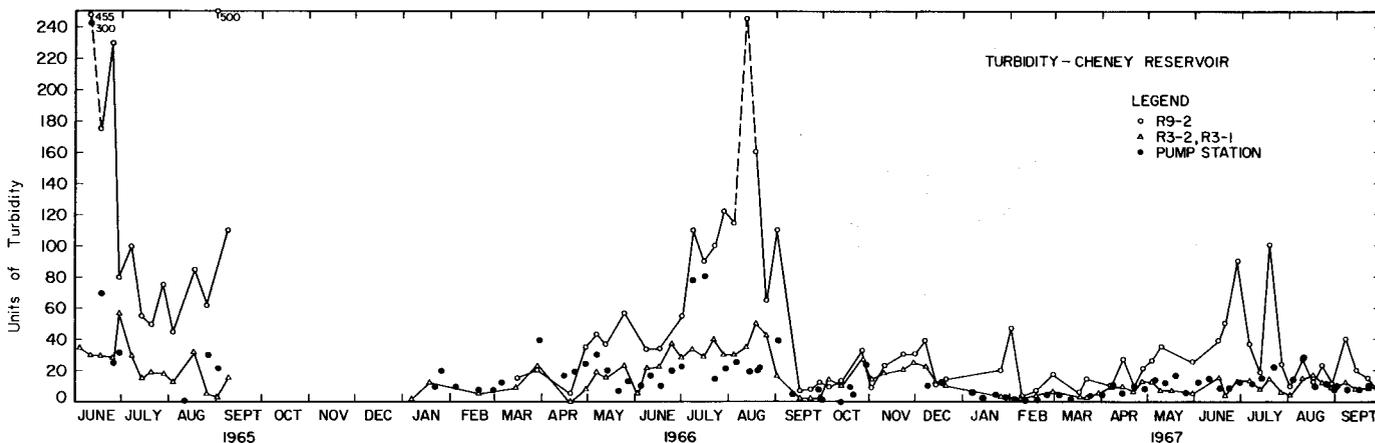


Figure 5-1 Turbidity at selected sampling stations.

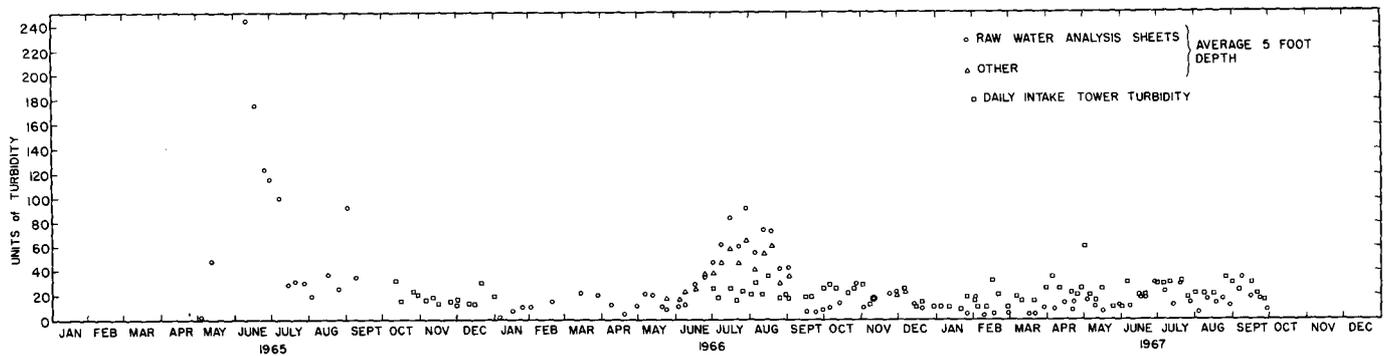


Figure 5-2 Average turbidity.

Station	Miles above Municipal Outlet	Ratio of Turbidity at That Station to the Average at All Stations
Municipal Outlet	0	0.47
A-3	0.407	0.60
R1-3	0.862	0.73
R3-3	2.01	0.98
R5-3	3.77	0.98
R7-2	5.25	1.33
R9-2	6.87	2.33
R11-1	8.14	3.82
K-17	13.07	

It is apparent from this table that turbidity decreases by a factor of 8.1 (3.82/0.47), as the water moves toward the municipal outlet from R11-1, a distance of about 8.1 miles.

It was noted in a letter of transmittal that change in level of the intake port caused reduction of turbidity at the pump station. The last change was made in December, 1965. As the curve for pump station turbidity in figure 5-1 shows, need for changing port levels because of turbidity did not arise thereafter. With the view that neither stratification nor density currents will exist in Cheney Reservoir, it is unlikely

that the multiple level intake tower will be particularly useful for control of turbidity in the pumped output.

In figure 5-2, points labeled "raw water analysis sheets" were taken at the 5 foot depth out in Cheney Reservoir as well as points labeled "other", so that for the same date, the points should be reasonably close. However, in both cases, each point is an average for all stations observed for that date, and many more stations were canvassed for the points labeled "other" and therefore they should be more representative.

The candle turbidimeter was used for all turbidity determinations, but has a lower limit of 25 units. Many of the turbidity determinations for Cheney Reservoir were less than 25 units, and most of the turbidity determinations for the last year of observation are less than 25 units. Therefore, turbidity observations or 25 units or less should be regarded with caution as to accuracy. In any event, a better method of determining turbidity is by measuring light scattered 90° with a photomultiplier tube. This latter method is more objective and is applicable to turbidity ranges from 0 to 1,000 JTU (Jackson Turbidity Units) which would have been adequate for the observations for Cheney Reservoir. Another method applicable for a range of 0 to 5,000 JTU, is to measure light scattered approximately 90° by the surface of a turbid sample (this is a continuous flow technique) with a photocell assembly. For very high turbidity (0 - 40,000 JTU), a photocell can be used to measure the direct absorption of a light beam.

TABLE 5-1. TURBIDITY AT SELECTED STATIONS - continued
Vertical Averages in units

Date		Stations									Date		Stations								
1967	K-17	R-11	R9-2	R7-1	R5-3	R3-1	R1-3	A-1	Pump Intake Tower	1967	K-17	R-11	R9-2	R7-1	R5-3	R3-1	R1-3	A-1	Pump Intake Tower		
Aug 16	7									Sept 7		150	40	23	13	12	12	13			
17		11	12	13	8	17	13	18		8									7		
18									9	13	13										
23		26	23	11	11	12	13	15		14	65	20	15	8	8	8	9				
25	5								10	15									8		
29		32	11	7	7	8	7	8		22	8	63	15	12	10	9	8	8	10		
30									7	27	3										
Sept 1									9	28			8	5	5	9	7	7			
6	65									29									5		

6. CHEMICAL WATER QUALITY

It is desirable to discuss briefly each chemical water quality characteristic before discussing the analysis of the chemical water quality data. This is done in the next 13 sections.

Silica (SiO_2)- Silicon (Si) ranks next to oxygen

in abundance and is a common constituent of igneous rocks, quartz, and sand. Many natural waters contain less than 10 mg/l silica, although some may approach 60 mg/l. According to the measurements made in Cheney Reservoir shown in figure 6-1, Cheney Reservoir ordinarily contains less than 10 mg/l silica.

Silica is present in natural waters in soluble and colloidal forms. Also, a silica cycle occurs in many bodies of water containing organisms, such as diatoms, that utilize silica in their skeletal structure. The silica removed from the water may be slowly returned by re-solution of the dead organisms. Cheney Reservoir, of course, has diatoms, which could account for the fact that the SiO_2 concentration is consistently less than the 11.5 mg/l predicted from stream records (with evaporation included this would be a predicted SiO_2 concentration of 19.8 mg/l as will be shown later).

Dissolved Solids - The standard temperature for drying residues or solids is 103°C. Many residues or solids are organic in nature and release water of composition in significant amounts at higher temperatures. Drying at 103°C insures the removal of all free water if the drying period is long enough, and minimizes the loss of other water.

The temperature at which the residue is dried is important, because weight losses due to volatilization of organic matter, mechanically occluded (absorbed) water, water of crystallization, and gases from heat-induced chemical decomposition, as well as weight gains due to oxidation, are a function of both temperature and heating period. Residues dried at 103° - 105°C may be expected to retain water of crystallization and some mechanically occluded water. Loss of carbon dioxide will result in the conversion of bicarbonate to carbonate. Loss of organic matter by volatilization will be very slight at this temperature. Because the expulsion of occluded water is marginal at 105°C, attainment of constant weight is very slow.

Residues dried at 179 - 181°C will lose almost all the mechanically occluded water, but some water of

crystallization may remain, especially if sulfates are present as they are in Cheney Reservoir. Organic matter is reduced by volatilization, but is not completely destroyed. Bicarbonate is converted to carbonate, and carbonate may be partially decomposed to oxide or basic salts. Some chloride and nitrate salts may be lost. Usually evaporating and drying water samples at 179 - 181°C yields values for total residue which conform more closely to those obtained by summation of individually determined mineral salts if the conversion of bicarbonate to carbonate is taken into account. This is done by converting reported bicarbonate to carbonate (multiply mg/l HCO_3^- by 0.492) and adding all determined dissolved solid material reported in the analytical statement. For example, from Table 6-2, the average volume weighted dissolved solids concentration (residue at 180°C) for the stream feeding Cheney Reservoir is 358 mg/l, and the calculated value is 430 mg/l. However, the true value is $358 + (162.5 \text{ mg/l } \text{HCO}_3^-)(0.508) = 441 \text{ mg/l}$ compared with a calculated value of 430 mg/l. Therefore, it is clear that the U. S. Geological Survey analyses (for the stream) represent 98 percent of the dissolved ions present.

Waters that are low in organic matter and total mineral content may be examined at either 104°C or 180°C (U. S. Geological Survey temperature). Waters containing considerable organic matter or those with pH over 9 should be dried at 180°C.

Ignitions are at 600°C to ensure the destruction of all organic matter by oxidation to carbon dioxide and water while minimizing the loss of inorganic salts by volatilization or decomposition. Calcium carbonate is a major component of many residues and is stable at 600°C. The residue remaining after ignition for one hour at 600°C does not distinguish precisely between organic and inorganic residue because the loss on ignition is not confined to organic matter, but includes losses due to decomposition or volatilization of certain mineral salts.

Values of dissolved solids for Cheney Reservoir are plotted in figure 6-2. The values were determined using the 180°C temperature. The values in figure 6-2 generally exceed the 358 mg/l (predicted from stream flow records without taking evaporation into account) expected initially, and seem to fluctuate about the predicted equilibrium value of 616 mg/l calculated in Table 6-2.

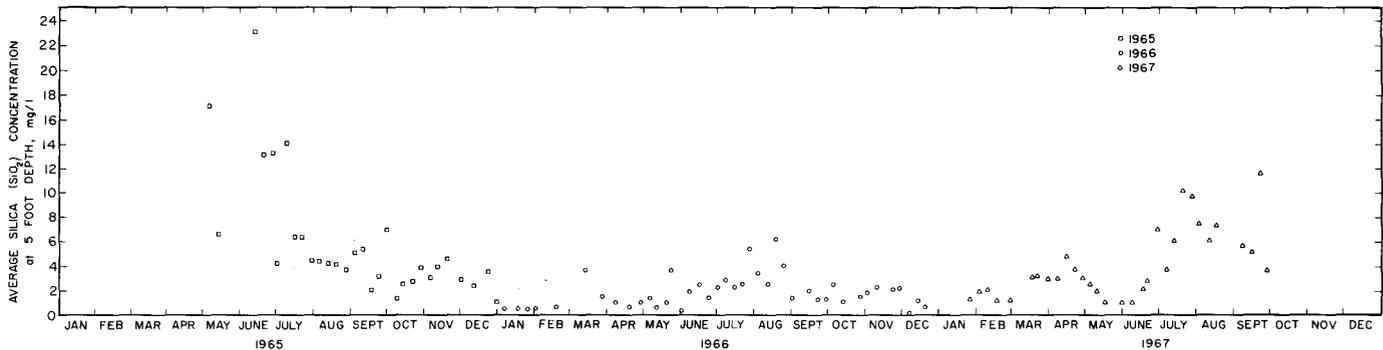


Figure 6-1. Average silica concentration (5-foot depth).

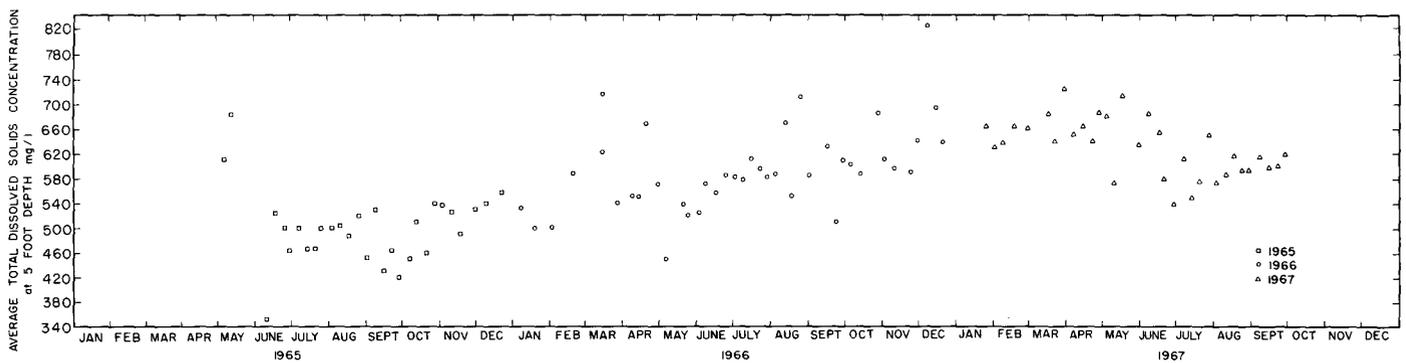


Figure 6-2. Average dissolved solids concentration (5-foot depth).

Conductivity - Specific conductance, K , is usually reported as $\mu\text{mhos/cm}$ at 25°C . Empirically, for the stream serving Cheney Reservoir,

$$\text{Dissolved Solids} = 0.55K \quad (6-1)$$

for $260 \leq K \leq 1,770 \mu\text{mhos/cm}$ at 25°C . Also,

$$\text{True dissolved solids} = 0.67K \quad (6-2)$$

so that the dissolved solids determined would be expected to be 82 percent (0.55/0.67) of the true dissolved solids which checks with 81 percent (358/441) calculated for the stream into Cheney Reservoir. Also, the proportionality constants given in equations (6-1) and (6-2) check with those given in the literature where the values of the proportionality constant in equations (6-1) and (6-2) vary from 0.55 to 0.7 (Standard Methods) and 0.65 ± 0.05 (U. S. Geological Survey). Additional empirical relations include

$$\frac{K}{100} = \frac{\text{total me/l}}{2} \quad (6-3)$$

for $K \leq 9,000 \mu\text{mhos/cm}$ at 25°C , and

$$\mu = 10^{-5} K^{1.036} \quad (6-17)$$

for $K \leq 7,000 \mu\text{mhos/cm}$ at 25°C where

μ = ionic strength.

The equivalent conductance, Λ , is:

$$\Lambda = \frac{10^3 \kappa}{N} \quad (6-4)$$

where
$$\Lambda = \frac{\text{mho} \cdot \text{cm}^2}{\text{equivalent}} = \frac{\mu\text{mhos/cm}}{\text{me/l}}$$

$$\kappa = \text{mhos/cm}, \kappa \times 10^6 = K$$

N = normality, equivalents per liter.

The equivalent conductance at infinite dilution, Λ_0 , is

$$\Lambda_0 = \tau_0^+ + \tau_0^- \quad (6-5)$$

where
$$\Lambda_0 = \frac{\mu\text{mhos/cm}}{\text{me/l}}$$

τ_0^+ = equivalent ionic conductance of a given cation at infinite dilution, $\frac{\mu\text{mhos/cm}}{\text{me/l}}$

τ_0^- = equivalent ionic conductance of a given anion at infinite dilution, $\frac{\mu\text{mhos/cm}}{\text{me/l}}$.

Values of τ_0^+ and τ_0^- are given in Table 6-1 for various cations and anions.

From Table 6-1 it can be seen that even pure water will have some conductivity due to H^+ and OH^- ions. This conductivity contribution at various pH values is as follows:

pH	K in $\mu\text{mhos/cm}$ at 25°C
0	352,000
5	3.52
6	0.354
7	0.0539
8	0.191
9	1.87
14	187,000

However, it is clear that for pH values between 5 and 9, the conductance due to H^+ and OH^- ions is negligible compared to the conductance of Cheney Reservoir water.

It is also clear from Tables 6-1a and 6-1b that both τ_0^+ and τ_0^- decrease with increasing concentration. This decrease is given by the theoretically derived Onsager equation:

$$\Lambda = \Lambda_0 - (\theta \Lambda_0 + \sigma) \sqrt{C} \quad (6-6)$$

or

$$\tau = \tau_0 - (\theta \tau_0 + \frac{1}{2} \sigma) \sqrt{C} \quad (6-7)$$

TABLE 6-1a. CONDUCTANCE FACTORS OF IONS COMMONLY FOUND IN WATER

Cation	Micromhos per cm per mg/l at 25°C	τ_0^+ in Micromhos per cm per me/l at 25°C	Anion	Micromhos per cm per mg/l at 25°C	τ_0^- in Micromhos per cm per me/l at 25°C
Ca ⁺⁺	2.97	59.5	HCO ₃ ⁻	0.730	44.5
H ⁺	347	350.0	CO ₃ ⁼	2.31	69.4
Fe ⁺⁺	1.91	53.4	Cl ⁻	2.15	76.7
Fe ⁺⁺⁺	3.65	68.0	F ⁻	2.91	55.4
Mg ⁺⁺	4.36	53.1	OH ⁻	11.6	197.5
K ⁺	1.88	73.5	NO ₃ ⁻	1.15	71.5
Na ⁺	2.18	50.1	SO ₄ ⁼	1.66	79.8
NH ₄ ⁺		73.4	CH ₃ COO ⁻		40.9

TABLE 6-1b. CONDUCTANCE FACTORS AT 90 to 120 MICROMHOS PER CM AT 25°C

Cation	Micromhos per cm per mg/l at 25°C	τ_0^+ in Micromhos per cm per me/l at 25°C	Anion	Micromhos per cm per mg/l at 25°C	τ_0^- in Micromhos per cm per me/l at 25°C
Ca ⁺⁺	2.50	52.0	HCO ₃ ⁻	0.715	43.6
Mg ⁺⁺	3.82	46.6	Cl ⁻	2.14	75.9
K ⁺	1.84	72.0	NO ₃ ⁻	1.15	71.0
Na ⁺	2.13	48.9	SO ₄ ⁼	1.54	73.9

where

$\theta \cong 0.241$ times the absolute value of ion valence

$\sigma \cong 57.1$ times the absolute value of ion valence

c = equivalents per liter of either cations or anions (not cations + anions) because equivalents per liter cations

= equivalents per liter anions

τ = equivalent ionic conductance of a given ion at concentration c , $\frac{\mu\text{mhos/cm}}{\text{me/l}}$

The three most common cations in natural waters are Ca⁺⁺, Mg⁺⁺, and Na⁺ which have an average τ_0^+ value of $54.3 \frac{\mu\text{mhos/cm}}{\text{me/l}}$ and the most common anion is

HCO₃⁻ with a τ_0^- of $44.5 \frac{\mu\text{mhos/cm}}{\text{me/l}}$, so that the value of Λ_0 is about $99 \frac{\mu\text{mhos/cm}}{\text{me/l}}$ which justifies the value of $100 \frac{\mu\text{mhos/cm}}{\text{me/l}}$ indicated by equation (6-3). In addition, equations (6-1) and (6-2) indicate values of 1.82 and $1.49 \frac{\mu\text{mhos/cm}}{\text{mg/l}}$ respectively which are within the range indicated by Table 6-1a.

The volume weighted average conductivity calculated from U. S. Geological Survey records for the stream that feeds Cheney Reservoir is 633 $\mu\text{mhos/cm}$ at 25°C which, from equations (6-1) and (6-2) gives a dissolved solids value of 348 mg/l (compared with 358 mg/l) and a true dissolved solids value of 424 mg/l (compared with 441 mg/l).

Based on stream records, one would expect the initial conductance of Cheney Reservoir to increase

from 633 $\mu\text{mhos/cm}$ at 25°C to an equilibrium conductance of about 1,090 $\mu\text{mhos/cm}$ at 25°C because of evaporation. It is shown in figure 6-3 that this is approximately

what was observed. There are some errors apparent in the conductivity measurements. For example, the daily conductivity values recorded at the pump station

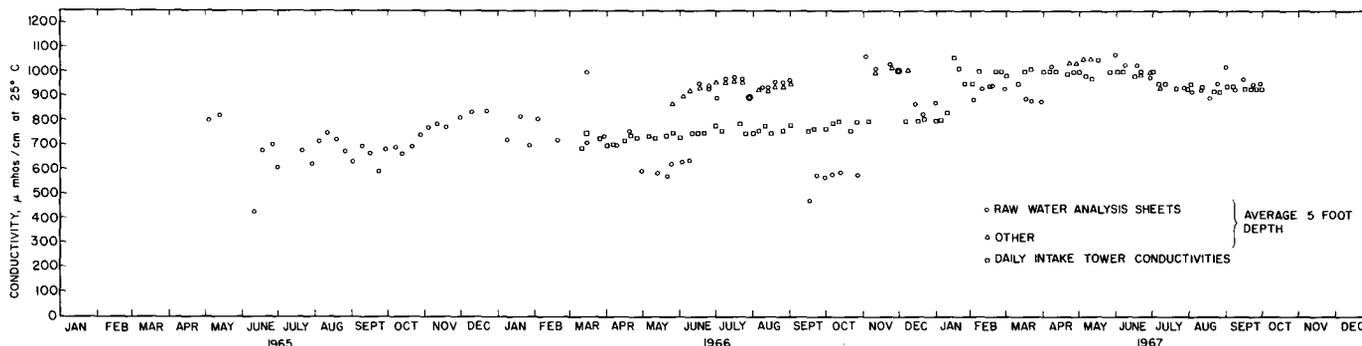


Figure 6-3. Average conductivity in Cheney Reservoir.

increased gradually from about 700 $\mu\text{mhos/cm}$ at 25°C to 830 $\mu\text{mhos/cm}$ at 25°C in the period from March, 1966, to January 10, 1967. On January 11, the reading was 1,050 $\mu\text{mhos/cm}$ at 25°C and decreased to about 920 $\mu\text{mhos/cm}$ at 25°C by September 1967. According to the data, the conductivity readings increased 27 percent in one day. There was a notation in the records that on January 8, 1967, "the conductivity meter was calibrated and was found low." Therefore, the daily conductivities recorded at the pump station prior to January 11, 1967, are not directly comparable to later readings except to possibly indicate general trends. Only the value observed every fifth day was plotted in figure 6-3 in order to make the graph legible.

It will be noticed also that the average conductivity taken at the 5 foot depth from the raw water analysis sheets showed extreme fluctuations, especially when compared to other conductivity readings made at the same time and depth. For example, these readings (circles on the graph) drop suddenly from about 760 to 595 $\mu\text{mhos/cm}$ at 25°C in the last ten days of April, 1966. After continuing at this level for a little over a month, an increase is suddenly noted from 640 to 955 $\mu\text{mhos/cm}$ at 25°C in about one week in June, 1966. This is again followed by a drop from 970 to 475 $\mu\text{mhos/cm}$ at 25°C in the first half of September, 1966. After about one and one-half months at this level, there is another increase from 580 to 1,065 $\mu\text{mhos/cm}$ at 25°C in the last week of October, 1966. The readings obtained independently for the same dates increased slowly from about 870 to about 1,010 $\mu\text{mhos/cm}$ at 25°C in the last seven months of 1966 (indicated by the triangles in figure 6-3).

As noted earlier, it was impossible to compute a salt balance for the reservoir because neither the conductivity in the reservoir nor the conductivity of the water pumped out of the reservoir could be accurately determined from the observed data. As nearly as can be determined, the conductivity data reported approximately weekly during the last eight months of 1965 and the first nine months of 1967 are correct. It is also presumed that about four months of conductivity data

in 1966 are correct (see the triangular points on figure 6-3). Subjectively, these are in logical sequence of events joining 1965 to 1967 data.

Figure 6-4 shows the calculated volume weighted average conductivities observed at K-17 (based on daily observations of conductivity and flow rate) compared with previous observations made by the U. S. Geological Survey.

The conductivity at infinite dilution was calculated from the chemical analyses for the 5 foot depth at station A-1 using the values given in Table 6-1a. The result was that the reported conductivities associated with the chemical analyses were approximately 65.5 percent of the calculated conductivity at infinite dilution. This ratio varied from 57 percent to 73 percent in the 21 samples analyzed. Therefore, the ratio is roughly 66 ± 8 percent.

A comparison of equations (6-1) and (6-2) shows that for the stream serving Cheney Reservoir, the reported dissolved solids was about 82 percent of the true dissolved solids. Using the aforementioned 21 samples, this ratio averaged 83 percent and the ratio of the sum of the dissolved constituents to the true dissolved solids averaged 91 percent. Variations in these two ratios were from 80 percent to 86 percent and from 75 percent to 121 percent respectively. Therefore, it is probably more accurate to say that the dissolved solids test recovered 83 ± 3 percent of the total dissolved solids present. The second ratio indicates that most of the significant cations and anions were reported, but that the analyses may not have been too accurate at times, especially in view of the fact that the recovered anions and cations were in excess of the maximum possible about 30 percent of the time. On the other hand, the analyses were within ± 10 percent at least half the time.

In addition to poor calibration, one additional possible explanation for such poor conductivity determinations could have been the failure to correct to 25°C (77°F). As figure 6-5 shows, this could have

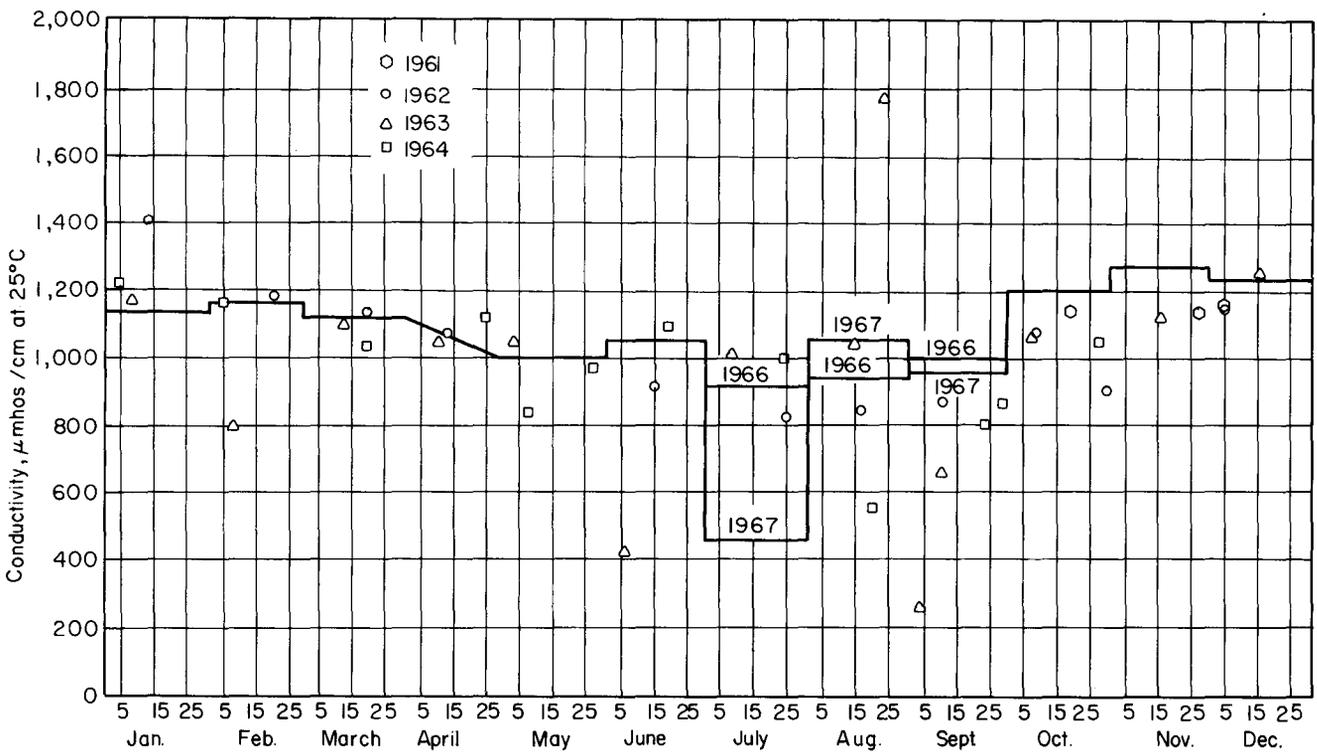


Figure 6-4. Volume-weighted average conductivity at K-17 compared with previous stream records. The horizontal lines are the volume-weighted average conductivity at K-17, and the plotted points are the previous stream records.

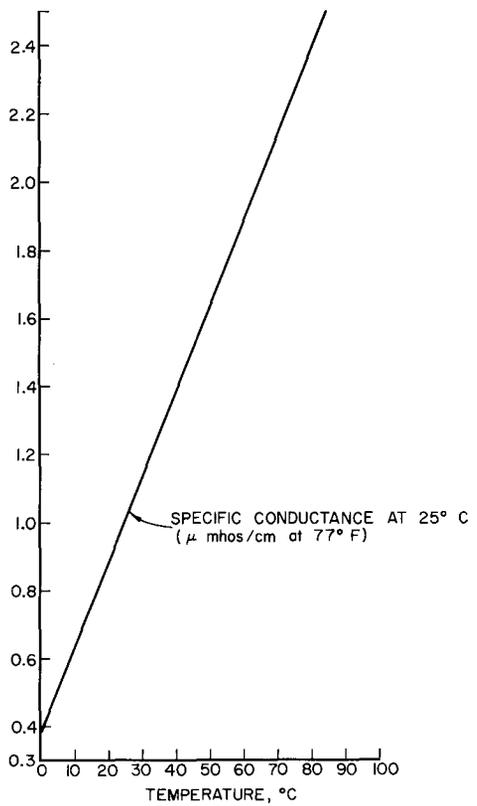


Figure 6-5. Temperature dependence of conductivity.

caused errors as great as 60 percent low because the water temperature in the reservoir exceeded 77°F only about one month per year (July 6 to August 15) and then the maximum water temperature was only about 78°F. The best way to avoid this problem is to make conductivity determinations at 25°C, but this is not possible unless samples are taken (as opposed to determining conductivity in place). The next best way is to correct to 25°C using a graph similar to figure 6-5 based on the actual water being tested. It should be kept in mind that figure 6-5 is only an average correction curve and does not apply to all waters. However, if serious errors in conductivity had been made due to inaccurate temperature corrections, then one would expect to see

a variation of conductivity similar to water temperature. The periodic variation which would result because of periodic variation of water temperature was not observed.

pH and Alkalinity - Figure 6-6 shows the pH values observed. In the years before Cheney Reservoir was constructed, the north fork of the Ninescah had pH values ranging from 7.2 to 8.3 and averaged 7.8. It should be noted that almost all of the pH observations in Cheney Reservoir exceed 7.8. However, it appears that the pH of Cheney Reservoir has stabilized at about 8.3 ± 0.1 . Apparently the pH has been increased from about 7.8 to about 8.3.

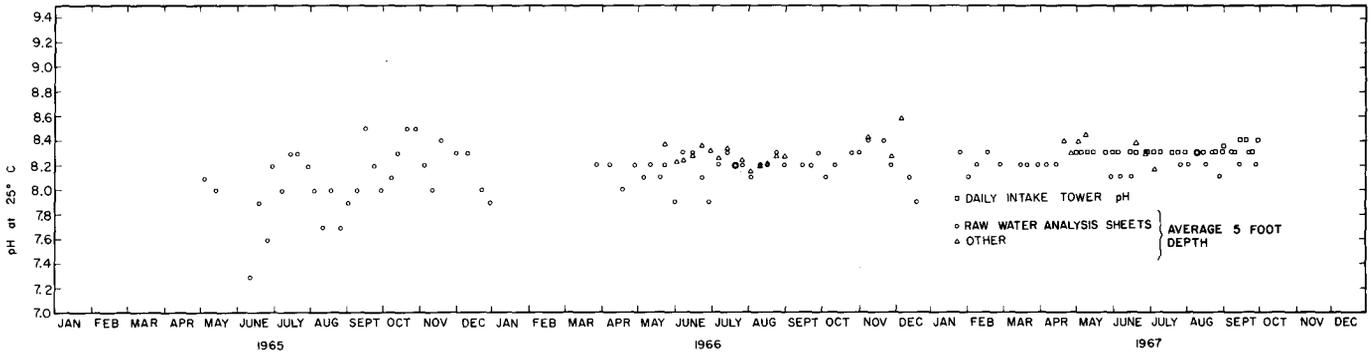


Figure 6-6. pH of Cheney Reservoir.

Temperature has a two-fold effect on experimental determinations of pH. One of these two effects is illustrated in figure 6-7. Actual water solutions exhibit similar effects. This temperature effect is ordinarily not taken into account, and for this reason

pH determinations are best run at 25°C. The other effect is due to the fact that the output voltage of the glass electrode increases linearly with the absolute temperature, but this can be easily accounted for electronically.

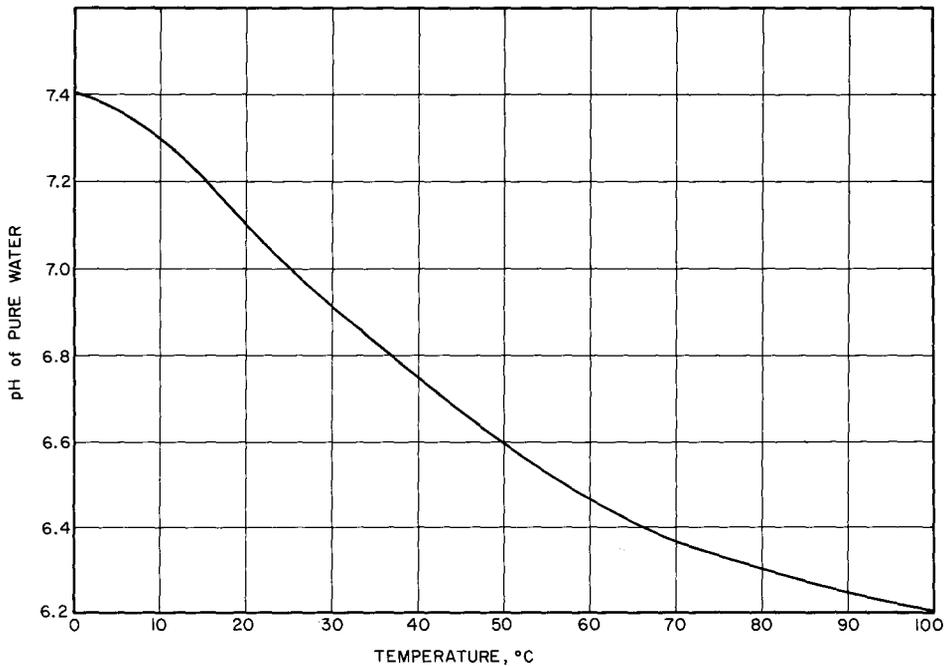


Figure 6-7. Temperature dependence of pH.

Very low or high values of pH have a pronounced effect on conductivity as shown in figure 6-8. This figure shows only the contribution to the total con-

ductivity from pH. The figure is approximate in that it does not account for the fact that the equivalent ionic conductancies of H^+ and OH^- decrease with increasing concentration.

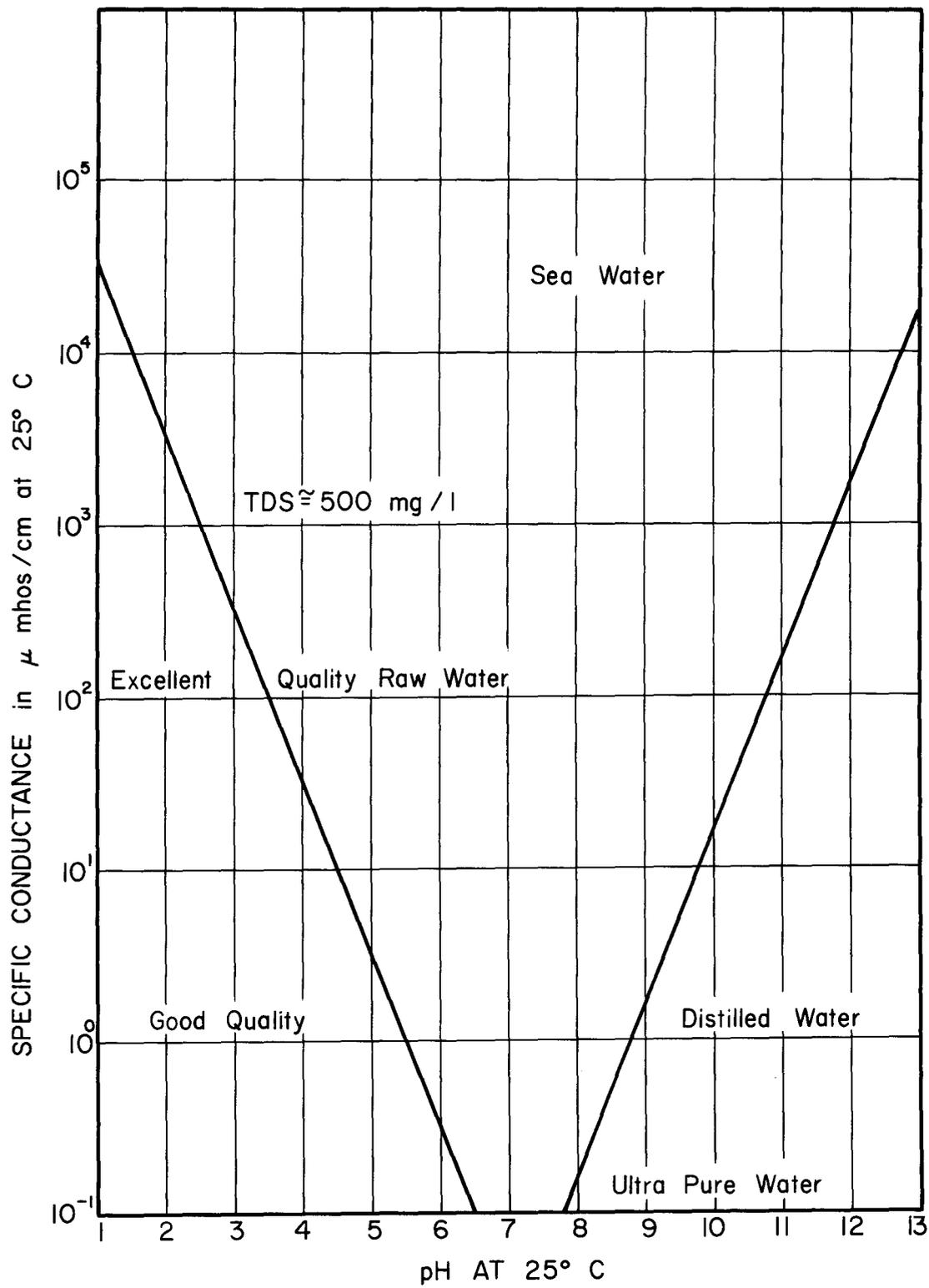


Figure 6-8. Conductance due to pH.

The lowest and highest average pH observations of Cheney Reservoir water were 7.3 and 8.58, respectively. It is clear from figure 6-8 that for $7 \leq \text{pH} \leq 9$, the effect of pH on conductivity is negligible for Cheney Reservoir water.

Figure 6-9 shows the average alkalinity (as CaCO_3 in mg/l) for Cheney Reservoir. Alkalinity as CaCO_3 in mg/l can be converted to me/l by dividing by 50. The concentration of HCO_3^- in mg/l can be converted to me/l by multiplying by 0.0164 and the concentration of CO_3^{2-} in mg/l can be converted to me/l by multiplying by 0.0333.

If the concentrations of $[\text{HCO}_3^-]$, $[\text{CO}_3^{2-}]$, and $[\text{OH}^-]$ are expressed in milliequivalents per liter, and if the total alkalinity [A] is expressed as milliequivalents per liter of titratable alkalinity, the equations for alkalinity, bicarbonate, carbonate, hydroxyl, and carbon dioxide are:

$$[A] = [\text{HCO}_3^-] + [\text{CO}_3^{2-}] + [\text{OH}^-] - 10^{3-\text{pH}} \quad (6-8)$$

$$[\text{HCO}_3^-] = \frac{[A] + 10^{3-\text{pH}} - K'_w 10^{\text{pH}+3}}{1 + 2K'_2 10^{\text{pH}}} \quad (6-9)$$

$$[\text{CO}_3^{2-}] = 2K'_2 10^{\text{pH}} [\text{HCO}_3^-] \quad (6-10)$$

$$[\text{OH}^-] = K'_w 10^{\text{pH}+3} \quad (6-11)$$

$$[\text{CO}_2] = \frac{2 \times 10^{-\text{pH}}}{K'_1} [\text{HCO}_3^-] \quad (6-12)$$

where

$$K'_w = K_w 10^x \quad (6-13)$$

$$K'_1 = K_1 10^x \quad (6-14)$$

$$K'_2 = K_2 10^{2x} \quad (6-15)$$

$$x = \frac{\sqrt{\mu}}{1 + \sqrt{\mu}}, \text{ for } \mu \leq 0.1, \text{ and} \quad (6-16)$$

$$\mu = 10^{-5} (\text{conductivity at } 25^\circ \text{C, in micromhos/cm})^{1.036} \quad (6-17)$$

If concentrations are expressed in me/l, the relationship of ionic strength μ to concentration c_i and charge z_i is

$$\mu = 5 \times 10^{-4} \sum_1^i c_i z_i^2 \quad (6-18)$$

where z_i is taken as positive for both cations and anions. For a total dissolved-solids content S_d of less than 500 mg/l,

$$\mu = 2.5 \times 10^{-5} S_d, \quad (6-19)$$

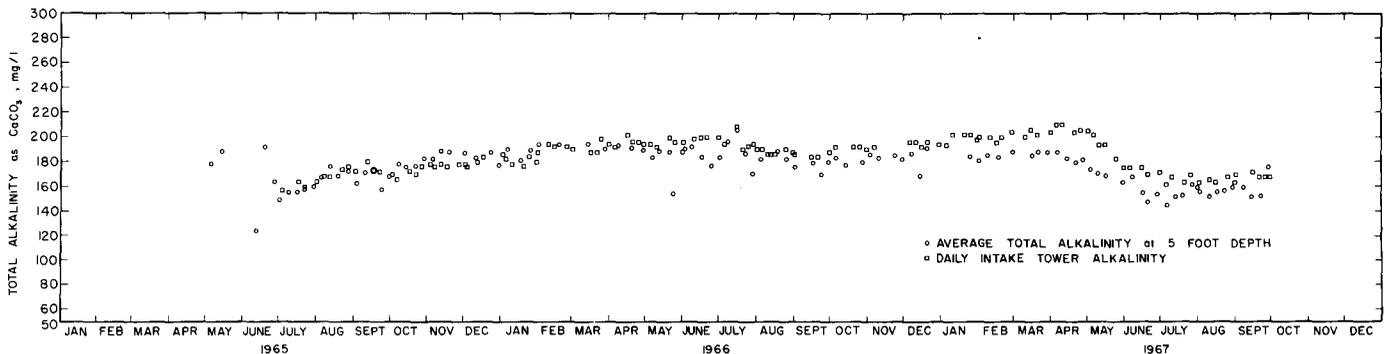


Figure 6-9. Average alkalinity of Cheney Reservoir.

At 25°C, $K_w = 1.01 \times 10^{-14}$, $K_1 = 4.45 \times 10^{-7}$, and $K_2 = 4.69 \times 10^{-11}$.

Rewriting equation (6-8a), the hydroxyl fraction of the total alkalinity is:

$$\frac{[\text{OH}^-]}{[\text{A}]} \approx 1 - \frac{[\text{HCO}_3^-]}{[\text{A}]} - \frac{[\text{CO}_3^{2-}]}{[\text{A}]} \quad (6-8b)$$

Therefore, the distribution of alkalinity among HCO_3^- , CO_3^{2-} , and OH^- appears to be primarily a function of pH for Cheney Reservoir. This is probably true for other reservoirs as well. The concentration of OH^- appears to be primarily a function of pH also for Cheney Reservoir. From equations (6-12a) and (6-9b) one obtains:

$$\frac{[\text{CO}_2]}{[\text{A}]} \approx \frac{(3.57 \times 10^{6-\text{pH}})}{1 + 1.49 \times 10^{\text{pH}-10}} \quad (6-12b)$$

The relationship between carbon dioxide and alkalinity is primarily a function of pH for Cheney Reservoir.

If one uses equations (6-9c), (6-10b), (6-8b), (6-12b), and (6-11a), then one obtains for Cheney Reservoir the following values:

pH	$\frac{[\text{HCO}_3^-]}{[\text{A}]}$	$\frac{[\text{CO}_3^{2-}]}{[\text{A}]}$	$\frac{[\text{OH}^-]}{[\text{A}]}$	$\frac{[\text{CO}_2]}{[\text{A}]}$	$\frac{[\text{OH}^-]}{\text{me/l}}$
7	1	0	0	0.357	0.000127
8	0.985	0.015	0	0.0357	0.00127
9	0.870	0.130	0	0.00311	0.0127

Therefore, for Cheney Reservoir, essentially none of the alkalinity is due to OH^- and equation (6-8a) can be simplified further to

$$[\text{A}] \approx [\text{HCO}_3^-] + [\text{CO}_3^{2-}] \quad (6-8c)$$

Equations (6-9c) and (6-10b) are plotted in figure 6-10 along with some observed values from Cheney Reservoir.

Observations on the stream serving Cheney Reservoir for the period before operation of the Reservoir gave a volume weighted average concentration for the bicarbonate ion of 163 mg/l. Essentially all the alkalinity was bicarbonate. This concentration of bicarbonate ion is equivalent to 134 mg/l as CaCO_3 (163×0.820). Because of evaporation, this would be expected to increase to 231 mg/l as CaCO_3 (134×1.723). All of the alkalinity observations in Cheney Reservoir (see figure 6-9) lie between these two values of 134 and 231 mg/l.

Chlorides - Chlorides in natural waters come from mineral soils and rocks and from organic decomposition. Chloride is one of the major anions in water and sewage. Some waters containing 250 mg/l chloride (the maximum concentration observed in Cheney Reservoir) may evidence a detectable salty taste with sodium ions.

The chloride concentrations observed in Cheney Reservoir for a period of about three years are plotted in figure 6-11. It is apparent that the chloride

T_{OC}	$\frac{K_w(T)}{K_w(25^\circ)}$	$\frac{K_1(T)}{K_1(25^\circ\text{C})}$	$\frac{K_2(T)}{K_2(25^\circ)}$
0	0.13	0.60	0.50
5	0.20	0.71	0.60
10	0.30	0.79	0.70
15	0.44	0.87	0.80
20	0.67	0.94	0.90
25	1.00	1.00	1.00
30	1.46	1.05	1.10
35	2.00	1.10	1.20
40	2.80	1.14	1.30
45	3.90	1.17	1.40
50	5.40	1.20	1.50

For the pH ranges observed in Cheney Reservoir, equation (6-8) can be approximated as

$$[\text{A}] \approx [\text{HCO}_3^-] + [\text{CO}_3^{2-}] + [\text{OH}^-] \quad (6-8a)$$

and equation (6-9) can be approximated as

$$[\text{HCO}_3^-] \approx [\text{A}] / (1 + 2K_2' \cdot 10^{\text{pH}}) \quad (6-9a)$$

For a conductivity of 1,000 $\mu\text{mhos/cm}$ at 25°C, $\mu \approx 10^{-2}$, and $x = 0.1$. Therefore, 10^x and 10^{2x} are roughly 1.26 and 1.59 respectively. Hence, at 25°C, $K_w' \approx 1.27 \times 10^{-14}$, $K_1' \approx 5.61 \times 10^{-7}$, and $K_2' = 7.46 \times 10^{-11}$. Substituting these three values into equations (6-9a), (6-10), (6-11), and (6-12), gives, for Cheney Reservoir,

$$[\text{HCO}_3^-] \approx [\text{A}] / (1 + 1.49 \times 10^{\text{pH}-10}) \quad (6-9b)$$

$$[\text{CO}_3^{2-}] \approx (1.49 \times 10^{\text{pH}-10}) [\text{HCO}_3^-] \quad (6-10a)$$

$$[\text{OH}^-] \approx 1.27 \times 10^{\text{pH}-11} \quad (6-11a)$$

$$[\text{CO}_2] \approx (3.57 \times 10^{6-\text{pH}}) [\text{HCO}_3^-] \quad (6-12a)$$

Rewriting equation (6-9b), the bicarbonate fraction of the total alkalinity is:

$$\frac{[\text{HCO}_3^-]}{[\text{A}]} \approx \frac{1}{1 + 1.49 \times 10^{\text{pH}-10}} \quad (6-9c)$$

Using equation (6-9c), the carbonate fraction of the total alkalinity is:

$$\frac{[\text{CO}_3^{2-}]}{[\text{A}]} \approx \frac{1}{1 + (1.49 \times 10^{\text{pH}-10})^{-1}} \quad (6-10b)$$

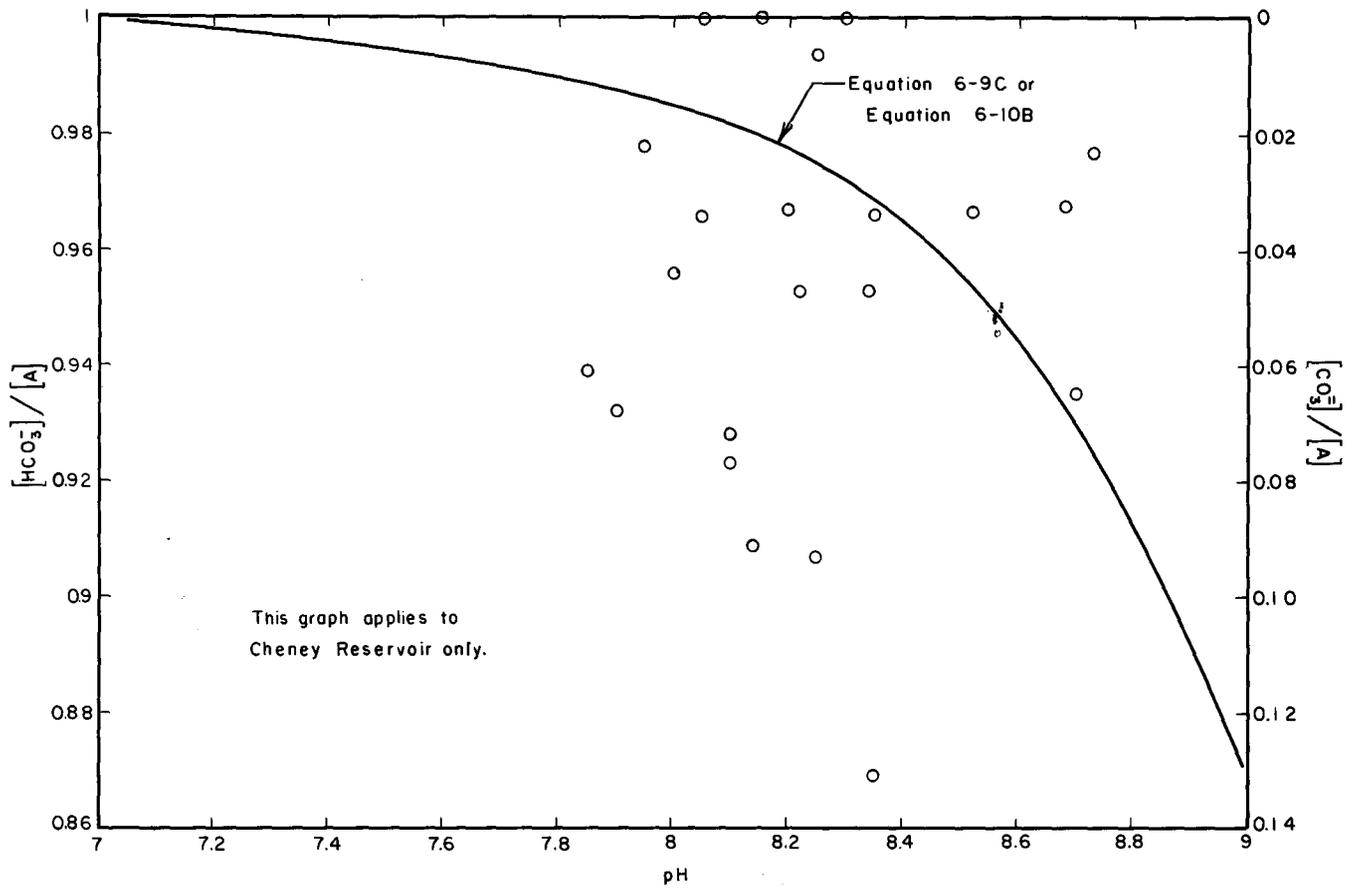


Figure 6-10. Carbonate and bicarbonate alkalinity fractions.

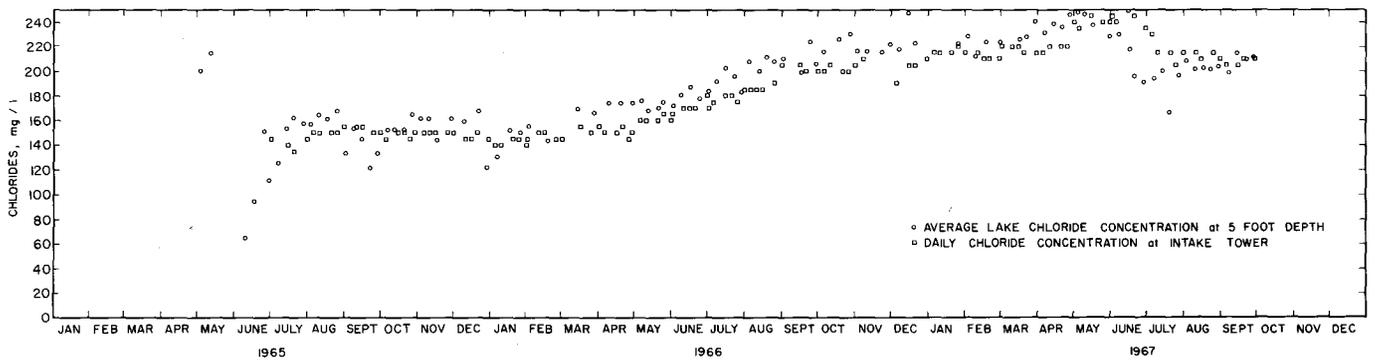


Figure 6-11. Chlorides in Cheney Reservoir.

concentration at the intake tower increased from about 150 mg/l to about 250 mg/l in about two years. Evaporation would have caused a concentration increase to 258 mg/l (150 x 1.723). Therefore, it is clear that the increase in chloride concentration can be accounted for entirely by evaporation. It is believed that the chloride data represents some of the best analytical work done on Cheney Reservoir. It should be noted that only every fifth observation at the intake tower was plotted.

Sodium - Sodium, like chloride, comes from mineral soils and rocks and from organic decomposition. Because sodium ranks sixth among the elements in order of abundance, it is present in most natural waters. Alka-

line samples of water containing sodium should be stored in polyethylene bottles in order to eliminate leaching of the glass container. Alkaline solutions attack glass, and sodium, which is present in glass, is re-leased into solution.

The sodium observations are plotted in figure 6-12. Again, the increase in sodium concentration is explained by evaporation. The initial concentration appears to be roughly 120 mg/l (July 1965) and the concentration two years later appears to be roughly 230 mg/l. From evaporation one would have expected an increase to about 210 mg/l (120 x 1.732), which is within ten percent of the observed value.

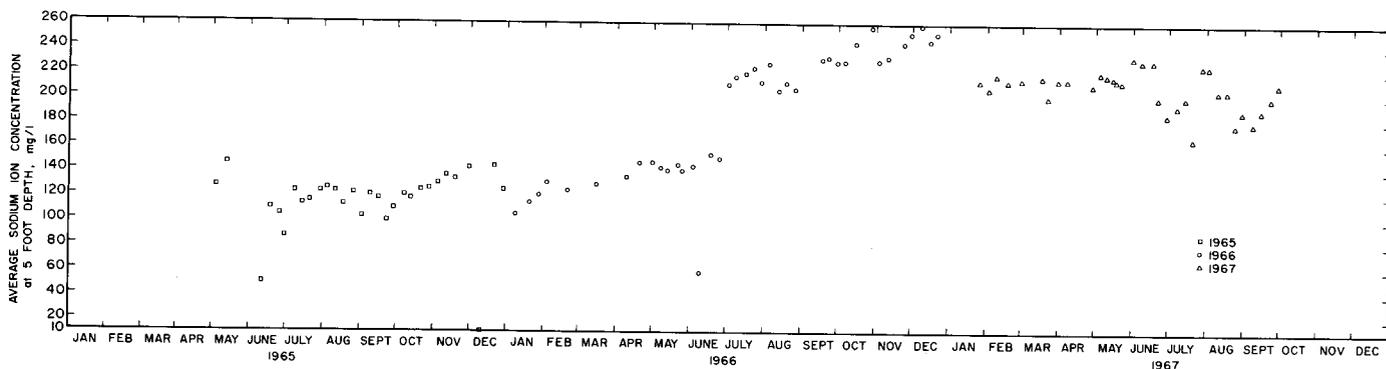


Figure 6-12. Average sodium concentration (5-foot depth).

Magnesium - Magnesium ranks eighth among the elements in order of abundance and is a common constituent of natural waters. Magnesium comes from mineral soils and rocks. The magnesium determinations in Cheney Reservoir are plotted in figure 6-13. The volume weighted average concentration of magnesium in

the stream serving Cheney Reservoir before operation of the reservoir was 10.7 mg/l. The concentration of magnesium in Cheney Reservoir on July 1, 1965, was 10.9 mg/l. Therefore, one would expect an increase in two years (because of evaporation) to 18.4 mg/l (10.7 x 1.723). The observed concentration in June, 1967, was roughly 18 mg/l.

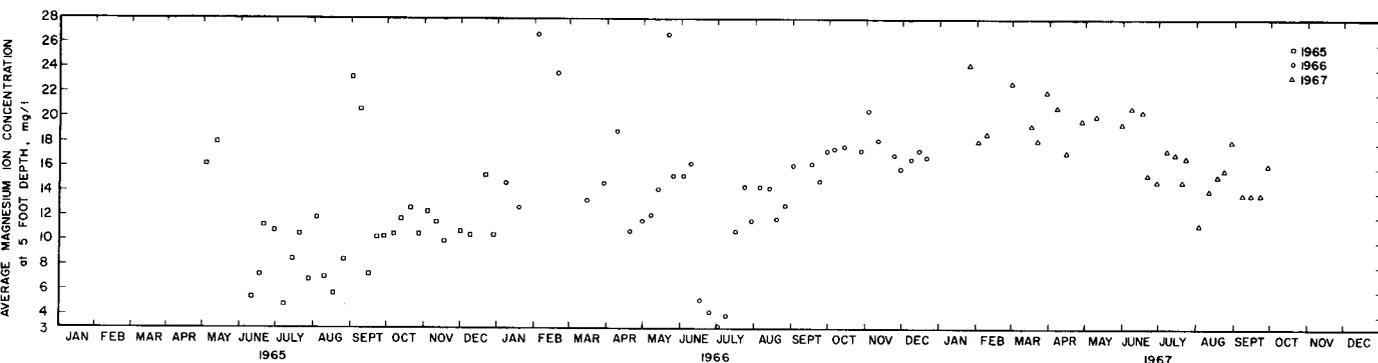


Figure 6-13. Average magnesium ion concentration (5-foot depth).

Calcium - Calcium, like magnesium, comes from mineral soils and rocks. The presence of calcium (fifth among the elements in order of abundance) in natural waters results from passage through or over deposits of limestone, dolomite, gypsum, and gypsiferous shale.

The saturation pH is (at 25°C):

$$pH_s = 8.313 - \log[Ca^{++}] - \log[A] + 2x \quad (6-20)$$

where $[Ca^{++}]$ = calcium ion concentration in me/l and x is given by equation (6-16). The value of $2x$ used previously was 0.2. Therefore, for Cheney Reservoir, equation (6-20) simplifies to

$$pH_s = 8.513 - \log[Ca^{++}] - \log[A]. \quad (6-20a)$$

If the observed pH is greater than pH_s , then the water is oversaturated with $CaCO_3$ (or lacking in excess CO_2) and will tend to deposit $CaCO_3$. Equation (6-20a) may be rewritten

$$pH_s = 8.513 - \log\{[Ca^{++}][A]\}. \quad (6-20b)$$

This equation is plotted in figure 6-14 along with Cheney Reservoir water samples and all samples taken from the stream that serves Cheney Reservoir before the initiation of operation of Cheney Reservoir. While some of the stream samples have pH values less than pH_s , all of the Cheney Reservoir samples have pH values in excess of pH_s . Therefore, the Cheney Reservoir water is oversaturated with $CaCO_3$ (and has no excess CO_2) and hence will tend to deposit $CaCO_3$.

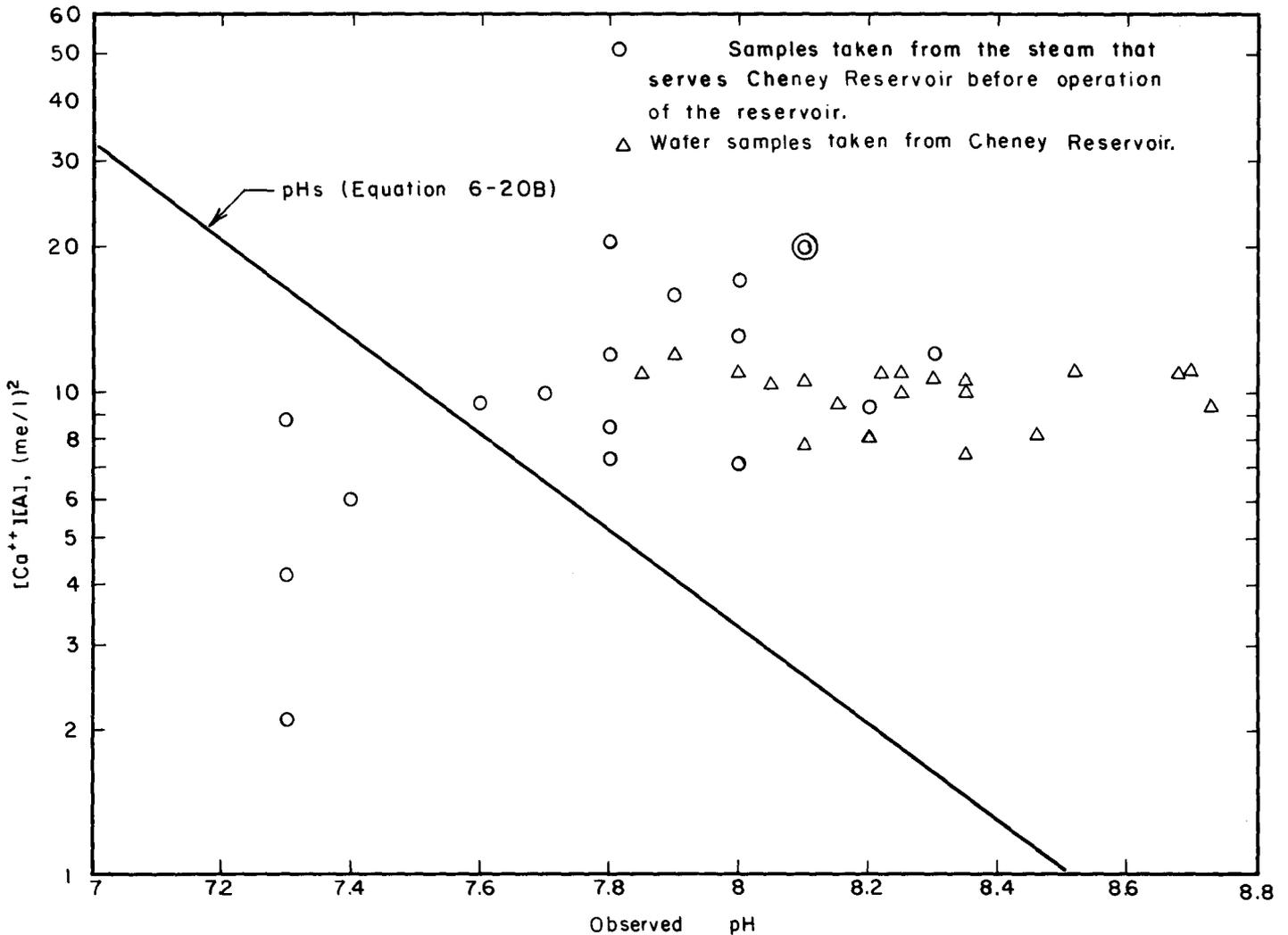


Figure 6-14. Saturation pH versus the calcium-alkalinity product.

Precipitation of some of the calcium appears to be verified by the observations plotted in figure 6-15. Using the observations made on the stream serving Cheney Reservoir before the operation of Cheney Reservoir, the volume weighted average calcium concentration was 40.2 mg/l, which would have been expected to increase to 69.4 mg/l (40.2×1.723) because of evaporation. Inspection of figure 6-15 indicates that the initial concentration of calcium was, if anything, greater than the final concentration. Apparently the increase in pH from about 7.8 to about 8.3 increased the fraction

of alkalinity due to carbonate from 1 percent to 2.8 percent. From figure 6-9, the alkalinity appears to have increased from roughly 160 mg/l as CaCO_3 to roughly 210 mg/l as CaCO_3 . Therefore, the increase in carbonate concentration was from about 1.6 mg/l as CaCO_3 to 5.9 mg/l as CaCO_3 . From figure 6-14, an increase of pH from 7.8 to 8.3 would decrease the $[\text{Ca}^{++}][\text{A}]$ product from 5.2 (me/l)² to 1.6 (me/l)². Even if the alkalinity had remained the same, figure 6-14 shows a clear tendency for the calcium concentration to decrease because of an increase in pH.

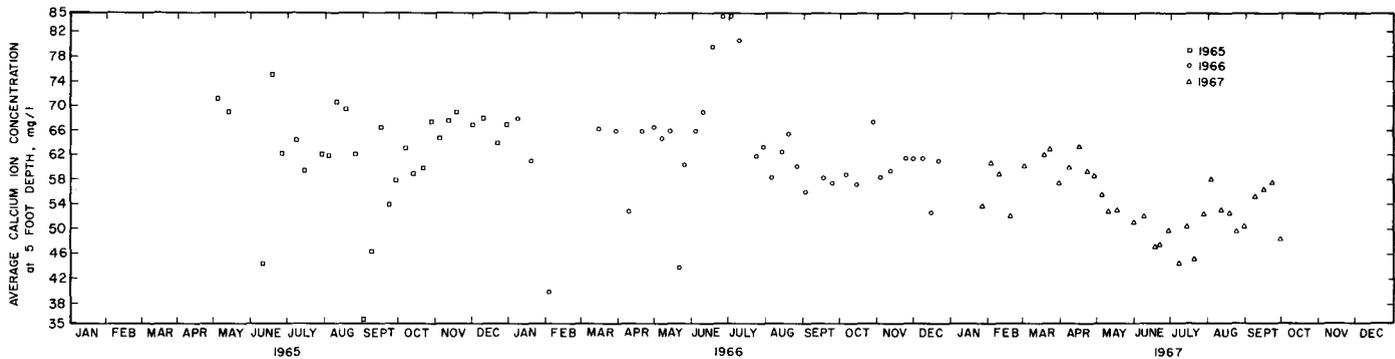


Figure 6-15. Average calcium ion concentration (5-foot depth).

Fluoride - The source of fluoride in natural waters is mineral soils and rocks. A fluoride concentration of approximately 1 mg/l may be an effective preventative of dental cavities. Some fluorosis may occur when the fluoride level exceeds the recommended limits. In rare instances, the fluoride concentration naturally occurring may approach 10 mg/l.

The volume weighted average concentration of fluoride in the stream serving Cheney Reservoir is 0.40

mg/l and the resulting concentration because of evaporation would be expected to be 0.69 mg/l (1.723×0.4).

Figure 6-16 shows the observed fluoride concentrations in Cheney Reservoir. According to these observations, the fluoride concentration dropped from 0.3 mg/l in 1965 to 0 mg/l in 1966 (there were no observations in 1967). The reason for this apparent decrease is unknown.

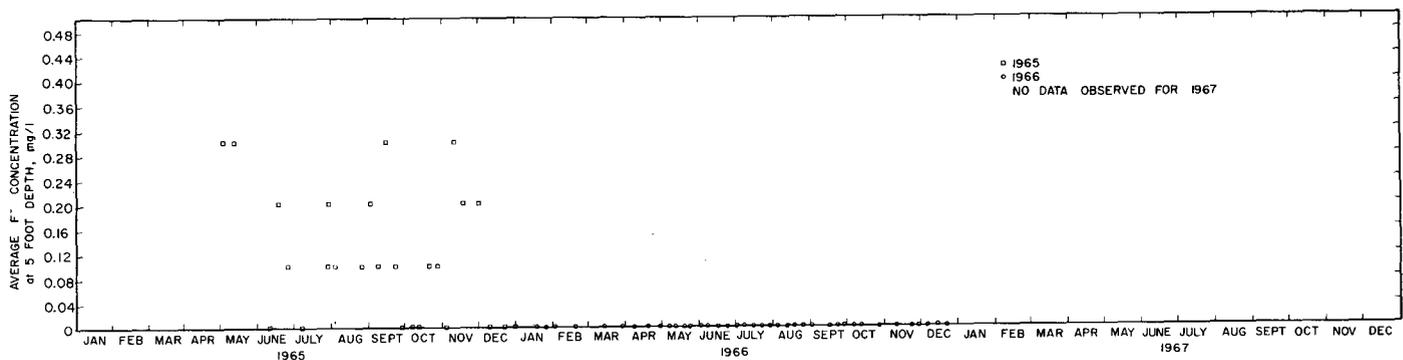
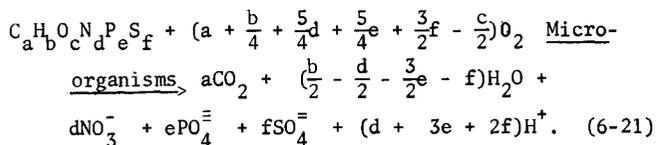


Figure 6-16. Average fluoride concentration (5-foot depth).

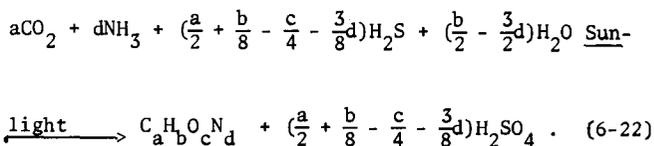
Sulfate - Sulfate is widely distributed in nature and may be present in natural waters in concentrations ranging from a few to several thousand mg/l. The recommended sulfate concentration in potable supplies is limited to 250 mg/l which is far greater than the maximum observed in Cheney Reservoir (88 mg/l). The source of sulfate in natural waters is from mineral soils and rocks, from the atmosphere, and from organic sulfur.

Release of sulfate from organic matter can be empirically represented as follows:



Sulfite may be oxidized to sulfate by dissolved oxygen above pH 8. On the other hand, in the presence of organic matter, certain bacteria may reduce sulfate to

sulfide. Sulfate may be precipitated from solution by microbial mass that settles to the bottom of the reservoir (precipitation of sulfate by bacterial protein). One possible additional source of sulfate would be photosynthesis by bacteria:



The volume weighted average sulfate concentration in the stream serving Cheney Reservoir was 32.9 mg/l and the expected concentration in Cheney Reservoir would be expected to increase to 56.7 mg/l (1.732 x 32.9) because of evaporation. The results plotted in figure 6-17 indicate that these two values are approximately correct. Production of much sulfate (compared to the total concentration of sulfate) by the mechanisms in either equation (6-21) or equation (6-22) appear to be unlikely in Cheney Reservoir.

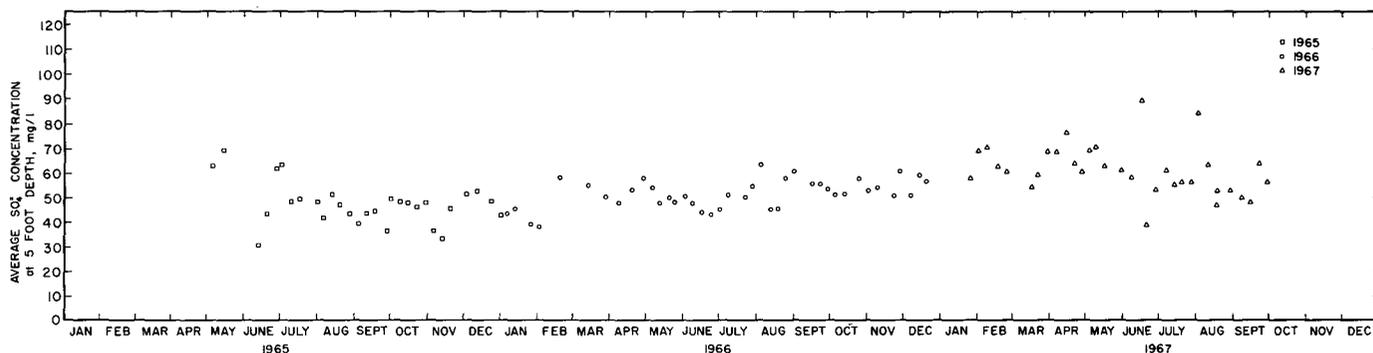


Figure 6-17. Average sulfate concentration (f-foot depth).

Phosphate - Phosphate occurs in traces in most natural waters, and often in appreciable amounts during periods of low biologic productivity. Some phosphate is contributed by certain geologic formations. Phosphate increases the tendency of troublesome algae to grow in reservoirs. Waters receiving raw or treated sewage, agricultural drainage, and certain industrial wastewaters normally contain significant concentrations of phosphate. Trace amounts of phosphate may also be com-

binated with organic matter (seldom more than a few tenths of a mg/l). It is possible that phosphate may be precipitated, adsorbed, or desorbed during sampling and storage. Materials, such as asbestos, can adsorb phosphate from solution. Natural conversion of organic phosphorus (see equation (6-21)) and polyphosphate to orthophosphate (PO_4^{3-}) is possible by microbiologic activity. Algae utilize PO_4^{3-} for their protoplasmic synthesis.

The volume weighted average concentration of PO_4^{\equiv} in the stream serving Cheney Reservoir was 0.6 mg/l which would be expected to increase to about 1 mg/l

(1.723×0.6) because of evaporation. The PO_4^{\equiv} concentrations in Cheney Reservoir plotted in figure 6-18 are generally lower than either of these figures indicating some utilization by organisms.

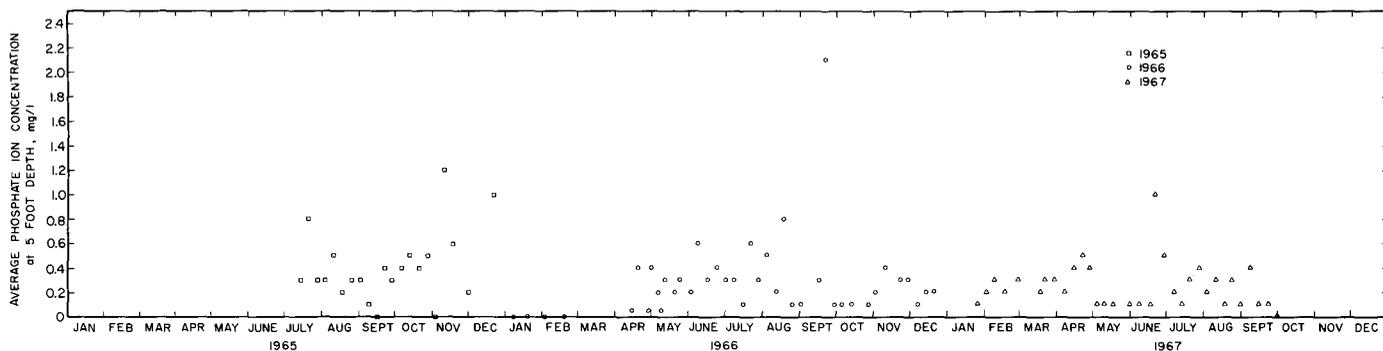


Figure 6-18. Average phosphate (PO_4^{\equiv}) concentration (5-foot depth).

Nitrate - The source of nitrate in natural waters is from mineral soils and rocks and from organic decomposition (equation (6-21)). Nitrate represents the most highly oxidized phase in the nitrogen cycle and usually reaches important concentrations in the final stages of biologic oxidation. Nitrate usually occurs in trace quantities in surface water supplies, but may attain high levels in some ground waters. The nitrate concentration of most natural waters is less than 10 mg/l (the maximum observed in Cheney Reservoir is 4.7 mg/l).

Endogenous metabolism is the reverse of the above equation. In equation (6-23), for algae, the source of nitrogen could be nitrite and/or nitrate instead of, or in addition to, NH_3 . For nitrate, the reverse of equation (6-21) with $e = f = 0$ would be correct.

If $\text{C}_a\text{H}_b\text{O}_c\text{N}_d$ is used to represent the empirical composition of algae cells, then for algae synthesis (photosynthesis),

The volume weighted average concentration of nitrate in the stream serving Cheney Reservoir was 3.3 mg/l which would be expected to increase to 5.7 mg/l (1.723×3.3) because of evaporation. The observed values of nitrate in figure 6-19 are all less than 4.7 mg/l and most are less than 3.3 mg/l. In fact, all of the 1967 observations are less than 2.4 mg/l. This indicates an uptake of as much as 3.3 mg/l ($5.7 - 2.4$) by the algae.

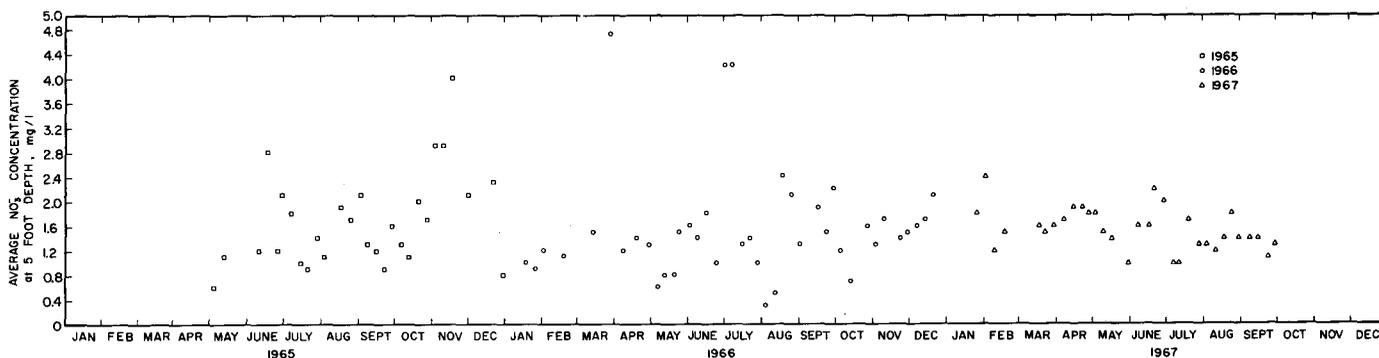
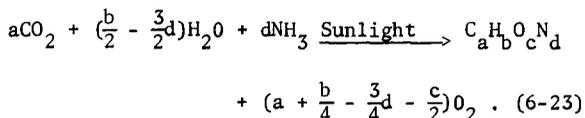


Figure 6-19. Average nitrate concentration (5-foot depth).

Dissolved Oxygen - The dissolved oxygen data is plotted in figure 6-20. Supersaturation could be caused by algae (see equation (6-23)). The average percent saturation at each depth is shown in figure 6-21. Each point in the figure represents the average of 25 observations with the exception of the following:

Depth, Feet	Number of Observations
0	0
30	19
35	10
40	1
45	0

For the depths with the same number of observations (5 through 25 feet), the average percent saturation is about the same (81 to 87%).

The saturation dissolved oxygen concentration in Cheney Reservoir is 95.3 percent of that at sea level because the average atmospheric pressure at Cheney Reservoir is 0.953 atmospheres. For the water temperature range observed in Cheney Reservoir, the saturation dissolved oxygen concentration (at 1 atmosphere pressure) is

$$c = 14.62 - 0.387T + 0.005335T^2 \quad (6-24)$$

where

c = saturation dissolved oxygen concentration (at sea level) in mg/l

T = water temperature, °C.

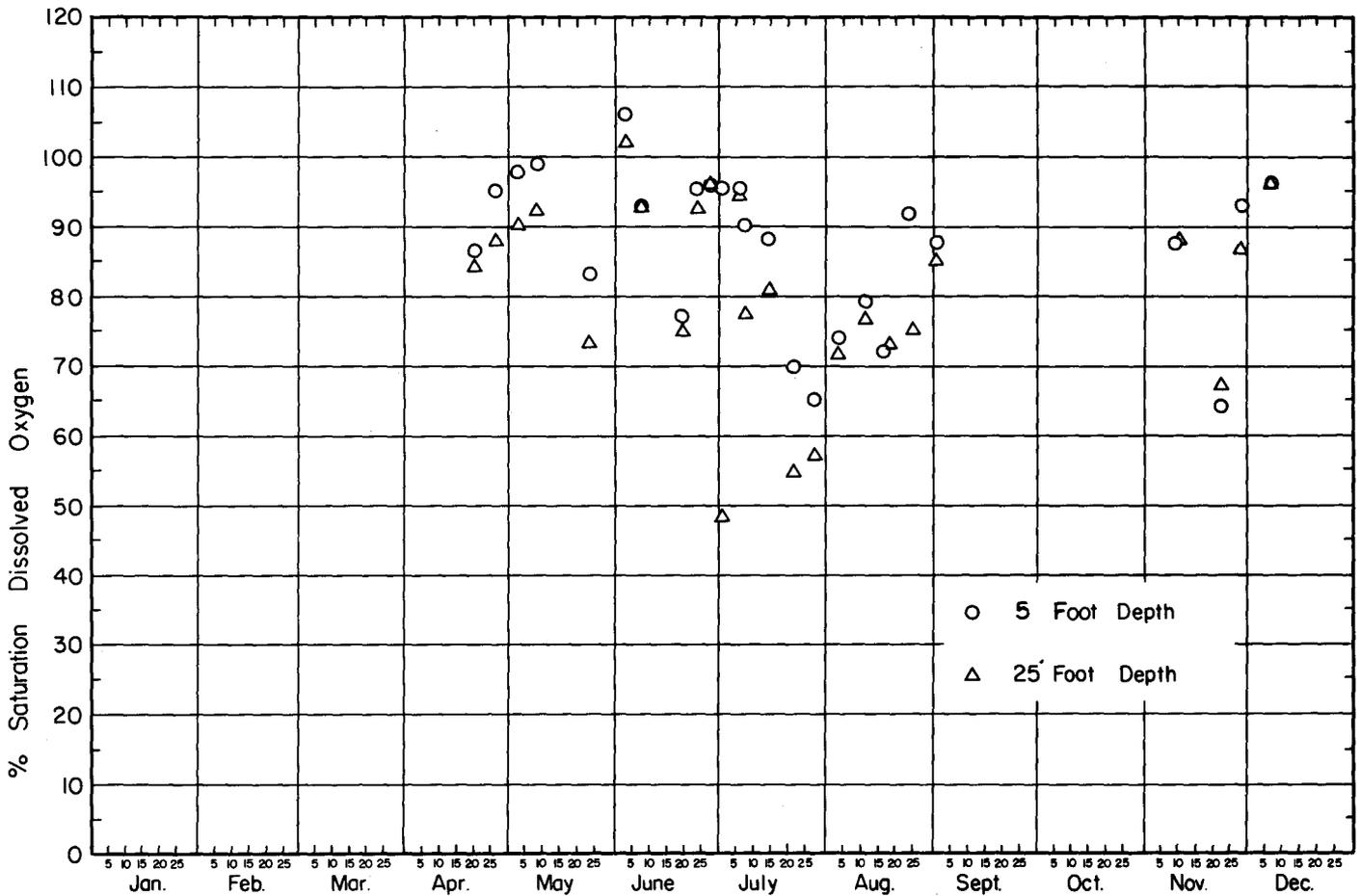


Figure 6-20. Dissolved oxygen percent saturation for Cheney Reservoir.

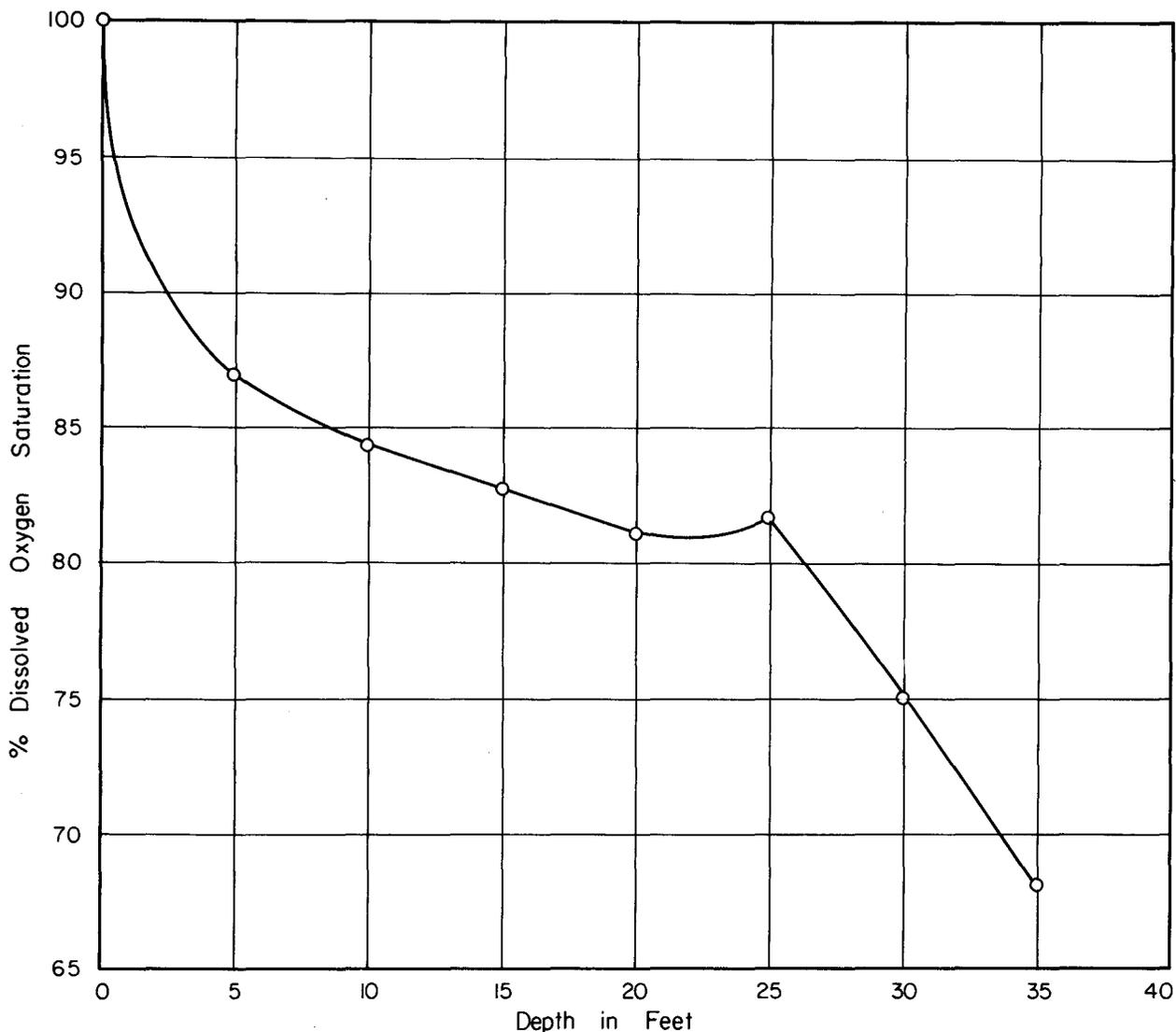


Figure 6-21. Average dissolved oxygen percent saturation versus depth.

Increase in Dissolved Solids Concentration Due to Evaporation - The best way to demonstrate that the increase in dissolved solids concentration is due to evaporation is by means of a salt balance, but, as was explained in Chapter 4, a salt balance for Cheney Reservoir was impossible because of inadequate and inaccurate data. However, this can still be demonstrated by using the data presented in Table 2-2 of Chapter 2. For the two-year period beginning July 1, 1965, and ending June 30, 1967, the total evaporation was 114.60 inches. During this same period, the precipitation was 41.08 inches, so that the net evaporation was 73.52 in. The stream inflow was 158.05 inches and the runoff from the drainage area around the reservoir was 16.65 inches, so that the total inflow was 174.70 inches. Subtracting the net evaporation, the difference (inflow) was 101.18 inches. In other words, 42 percent of the total inflow was evaporated. Clearly, this will cause a substantial increase in dissolved solids concentration. This increase can be easily calculated by realizing that all the dissolved solids originally present in the total inflow of 174.70 inches are now present in only 101.18 inches, so that the increase in dissolved solids concentration can be obtained by multiplying the volume weighted average dissolved

solids concentration in the stream serving Cheney Reservoir by 1.723 (174.70/101.18) as has been done throughout this chapter.

Table 6-2 shows the predicted and actual concentrations of dissolved solids in Cheney Reservoir. In column 3, the pH value listed is simply the arithmetic mean pH. Computing the volume weighted average pH is useless when pH is only read to two significant figures. Column 4 is column 3 x 1.723. Columns 5 and 6 were computed from column 3. The dissolved solids data in columns 7 and 8 were computed. Column 9 is column 8 divided by column 7 except for HCO_3^- where the value listed in column 9 is column 10 divided by column 11. Columns 10 and 11 were taken from figures 6-1 through 6-19. Column 12 is column 8 minus column 7. Fish may be responsible for the temporary depletion of some ionic species.

Column 9 clearly shows that the predicted increase in concentration (172.3 percent) because of evaporation is very close to the actual average value (170 percent). The unusually high increase in sodium concentration (214 percent) is apparently due to possible analytical errors.

For most of the chemical parameters, columns 3 and 7 would be expected to have similar values as would columns 4 and 8. The values listed in column 11 would be expected to be greater than the low values listed in column 2.

The increase in pH was predicted using equation (6-11a) as follows:

$$[\text{OH}]_1 \cong 1.27 \times 10^{\text{pH}_1 - 11} \quad (6-11b)$$

and

$$[\text{OH}]_2 \cong 1.27 \times 10^{\text{pH}_2 - 11} \quad (6-11c)$$

so that

$$\frac{[\text{OH}]_2}{[\text{OH}]_1} \cong 10^{\text{pH}_2 - \text{pH}_1} \quad (6-25)$$

and

$$\log \left\{ \frac{[\text{OH}]_2}{[\text{OH}]_1} \right\} \cong \text{pH}_2 - \text{pH}_1 \quad (6-25a)$$

Because $[\text{OH}]_2/[\text{OH}]_1 = 1.723$, $\text{pH}_2 - \text{pH}_1 = 0.237$; therefore, the pH would be expected to increase by about 0.24 units.

The decrease in calcium concentration could be predicted as follows. From columns 5 and 6, the value of $[\text{Ca}^{++}] [\text{A}]$ was $5.39 (\text{me}/\ell)^2$. From figure 6-14, this corresponds to a pH_s of 7.78, which, by coincidence, is the same as the stream pH. Now, if the pH is increased by 0.24 units, the new pH would be 8.02 corresponding to a $[\text{Ca}^{++}] [\text{A}]$ value of $3.1 (\text{me}/\ell)^2$. Therefore, one would expect that some of the calcium and carbonate would precipitate out. Because of imprecise pH readings, it would not be possible to predict how much precipitation would take place.

The summation (Σ) line is the sum of all values with the exception of dissolved solids, conductivity, and pH. In column 9, the summation is column 8 divided by column 7.

Reducing the Increase in Dissolved Solids Concentration - One method is to reduce evaporation, but, as was shown in Chapter 3, this leads to intolerable water temperature increases. However, one can reduce the dissolved solids concentration by bypassing the stream flows containing the most dissolved solids around the reservoir. Because the lowest stream flows usually have the greatest dissolved solids concentrations, bypassing a relatively small quantity of water will affect a large reduction in dissolved solids concentration. However, a bypass channel or conduit was not constructed for Cheney Reservoir.

For the rest of this discussion, the following definitions will be helpful: t_i is the number of days during which the stream discharge was Q_i cubic feet per second (cfs) with a concentration C_i milligrams per liter (mg/l). The time-weighted average stream discharge is \bar{Q}_t cfs, and the annual time-weighted average stream discharge is Q_t cfs. Similarly, the time-weighted average concentration is \bar{C}_t mg/l and the annual time-weighted average concentration is C_t mg/l. Finally, the volume-weighted average concentration is \bar{C}_v mg/l and the annual volume-weighted average concentration is C_v mg/l.

The following three equations define the relationships between these variables.

$$\bar{Q}_t \cong \frac{\sum_{i=1}^{i=k} t_i Q_i}{\sum_{i=1}^{i=k} t_i} \quad (6-26)$$

where k represents the order number of arrangement. Obviously \bar{Q}_t approaches Q_t as k approaches n , where n is the number of pairs of observed values of t_i and Q_i in a given water year for a given stream station.

TABLE 6-2. CONCENTRATION OF DISSOLVED SOLIDS BEFORE AND AFTER EVAPORATION

Chemical Parameter	Stream Serving Cheney Reservoir					Cheney Reservoir					
	Prior to 1965	Average	Predicted Conc.	cation me/l	anion me/l	July 1, 1965	June 30, 1967	Conc. Factor	Max. Conc.	Min. Conc.	Decrease
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
SiO ₂	4 - 18	11.5	19.8			4.2	7	1.67	23	0.02	
Diss. Solids	165 - 967	358	616			404	665	1.64	822	352	
Conductivity	260 - 1770	633	1090			605	1000	1.66	1075	425	
pH	7.2 - 8.3	7.8	8			8.2	8.3		8.58	7.3	
HCO ₃ ⁻	98 - 288	163	280		2.67	188	204	1.70	256	151	
CO ₃ ⁼	0 - 17	0.38	0.65		0.01						
Cl ⁻	23 - 402	96.1	166		2.71	145	235	1.62	250	65	
Na ⁺	16 - 265	66.1	114	2.87		87	186	2.14	259	10	
Mg ⁺⁺	4.6 - 22	10.7	18.4	0.88		10.9	18.3	1.68	26.7	3.1	
Ca ⁺⁺	26 - 85	40.2	69.4	2.01		62.2	49.6		84.6	35.6	12.6
F ⁻	0.3 - 0.5	0.40	0.69			0.1	0		0.3	0	0.1
SO ₄ ⁼	11 - 85	32.9	56.7		0.68		53		89	30	
PO ₄ ⁼	0.1 - 0.8	0.6	1.0			0.8	0.5		2.1	0	0.3
NO ₃ ⁻	0.4 - 10	3.3	5.7		0.05	2.1	2.0		4.7	0.3	0.1
K ⁺	1.6 - 8	5.4	9.3								
Fe ⁺⁺	0.04 - 0.30	0.10	0.17	0.00							
Mn ⁺⁺	0.00 - 0.11	0.003	0.005								
B	0.07 - 0.32	0.10	0.17								
Σ		430	742	5.76	6.12	500	756	1.51			13.1
Average								1.70			

Column 2 = Range observed in stream serving Cheney Reservoir prior to beginning of operation of the reservoir
 Column 3 = Volume weighted average
 Column 4 = Predicted maximum Cheney concentration, Column 3 x 1.723
 Column 5 = Cation volume weighted average, me/l
 Column 6 = anion volume weighted average, me/l
 Column 7 = July 1, 1965
 Column 8 = June 30, 1967
 Column 9 = Increase in concentration factor due to evaporation
 Column 10 = Maximum concentration observed in Cheney Reservoir
 Column 11 = Minimum concentration observed in Cheney Reservoir
 Column 12 = Decrease in concentration

Also,

$$\bar{C}_t \equiv \frac{\sum_{i=1}^{i=k} t_i C_i}{\sum_{i=1}^{i=k} t_i} \quad (6-27)$$

and again \bar{C}_t approaches C_t as k approaches n .

Finally,

$$\bar{C}_v \equiv \frac{\sum_{i=1}^{i=k} t_i Q_i C_i}{\sum_{i=1}^{i=k} t_i Q_i} \quad (6-28)$$

and once again \bar{C}_v approaches C_v as k approaches n .

Throughout this discussion it is assumed that the corresponding values of t_i , Q_i , and C_i will be ordered from the lowest observed value of C_i to the highest value of C_i , and that the summations will be made in this same order.

Often the values of Q_t , C_t , and C_v are given on an annual basis. In general, C_v is approximately the concentration that would be found in a reservoir if it were constructed at that stream station if there was no evaporation. On the other hand, C_t would be approximately the average concentration that would be obtained if a constant volume per unit time of water was withdrawn from a stream directly and on a continuous basis and at a rate less than or equal to the lowest value of Q_i . The effect of constructing a reservoir at a stream station is to reduce the value of C_t to approximately the value of C_v . The value of C_t is ordinarily greater than or equal to the value of C_v because the concentration in general usually decreases as the stream discharge increases. For example, for 12 stream stations for which values of Q_t , C_t , and C_v were given, the ratio of C_v/C_t varied from 0.38 to 1.

Both C_t and C_v should be studied quantitatively to ascertain ordinary variations from year to year as well as variations in their relationship from year to year. For streams with increasing reservoir development, C_t would be expected to decrease with time while C_v might increase somewhat with increasing population on the watershed. For streams with a great deal of irrigation, both the time-weighted average concentration and the volume-weighted average concentration would probably be greater during the irrigation season than during the rest of the year.

For each stream station studied, and on an annual basis, the ratio of \bar{C}_v/C_v should be determined as a function of the ratio \bar{V}_t/V_t where

$$\bar{V}_t = \sum_{i=1}^{i=k} t_i Q_i \quad (6-29)$$

and

$$V_t = \sum_{i=1}^{i=n} t_i Q_i \quad (6-30)$$

It is clear that as the ratio \bar{V}_t/V_t approaches 1, the ratio \bar{C}_v/C_v also approaches 1. It should be noted that the actual annual volume of flow is approximately

$$V = 365 Q_t \quad (6-31)$$

where V has the units of cfs-days per year. One cfs-day is 646,000 gallons. The resulting graphs of \bar{C}_v/C_v versus \bar{V}_t/V_t for each year of record should be compared to determine annual variations, if any. It is possible that for all streams having a given C_v/C_t ratio, that the graph of \bar{C}_v/C_v versus \bar{V}_t/V_t would be very similar. For example, if $C_v/C_t = 1$, it would be expected that the value of \bar{C}_v/C_v would be approximately 1 for all values of \bar{V}_t/V_t .

The above results, if at all possible, should be expressed analytically if sufficient accuracy can be preserved. In other words, the ratio \bar{C}_v/C_v should be expressed as a function of $(C_v/C_t, \bar{V}_t/V_t)$. If possible, this functional relationship should be derived on a purely theoretical basis.

As an example, consider a stream station for which values of Q_t , C_t , and C_v are given. Assume that a desired maximum value of C_v of 500 mg/l is desired. Knowing the ratios \bar{C}_v/C_t and \bar{C}_v/C_v the ratio \bar{V}_t/V_t is determined from the expression relating the ratios \bar{C}_v/C_v , C_v/C_t , and \bar{V}_t/V_t . This ratio times V gives the total volume that can be obtained from this stream station that will have a dissolved solids concentration of 500 mg/l.

A possible deterministic model relating Q_i and C_i can be developed as follows.

$$Q_i = \sum_{i=1}^{i=j} q_i \quad (6-32)$$

The case for $j=1$ is not meaningful. It is more likely that $j=3$. For $j=3$, q_1 could represent surface runoff, q_2 could represent groundwater discharge (q_2 might be negative if q_1 is sufficiently great), and q_3 could represent interflow.

Also,

$$Q_i C_i = \sum_{i=1}^{i=j} q_i c_i \quad (6-33)$$

Again, the case for $j=1$ is trivial. For $j=3$, c_1 could represent the surface runoff concentration, c_2 could represent the groundwater concentration (c_2 might have about the same value as c_1 if q_2 is negative), and c_3 could represent the interflow concentration.

Perhaps the best method of determining the value of j is by studying the composition of the water. For this purpose, triangular coordinate graph paper (such as Keuffel and Esser, Number 46 4490) can be used. Whenever the sum of three fractions is always equal to 1, one point on triangular co-ordinate graph paper specifies all three fractions simultaneously.

Probably the three most predominant cations in most natural waters are calcium, magnesium, and sodium. Also, the most predominant anions in most natural waters are likely to be alkalinity, sulfate, and chloride. Therefore, two triangular co-ordinate graphs could be prepared for each stream station (one for cations and one for anions). If all the points fall in one location, $j=1$. If all the points fall on a straight line, $j=2$. If all the points fall within a triangle, $j=3$. If all the points fall within a circle, $j=\infty$.

An example of one case where j might be 2 is for the stream stations where most of the base stream flow is from sewage treatment plant effluents, supplemented primarily by surface runoff. Another possibility is where most of the base stream flow is irrigation return flow supplemented mainly by surface runoff. This latter case may be considerably more complex, however, because the stream characteristics may be quite different during the irrigation season than at other times of the year.

The value of j may not be indicated correctly by a triangular coordinate graph paper plot if all or most components have about the same composition which can be the case. Another possibility is that the concentration of one of the components is so great that the composition is not altered very much on mixing.

Perhaps it is worthwhile to examine the case for $j=2$. For $j=2$, q_1 and c_1 could be the same as for the case when $j=3$, and q_2 and c_2 could be the combined quantities for groundwater and interflow.

Therefore, for $j=2$, from equations (6-32) and (6-33),

$$C_i = c_1 + \frac{q_2(c_2 - c_1)}{Q_i} \quad (6-34)$$

because as Q_i becomes very large, one would expect C_i to approach c_1 . Also, as Q_i approaches q_2 , one would expect C_i to approach c_2 . Even if q_2 is negative, c_2 approaches c_1 and therefore C_i also approaches c_1 . The normal range for C_i is between c_1 and c_2 because $Q_i \approx q_2$.

If one assumes that c_1 is approximately constant and that the product $q_2(c_2 - c_1)$ is approximately constant, the implied relationship between c_2 and q_2 is

$$c_2 = c_1 + \frac{\text{constant}}{q_2} \quad (6-35)$$

which has the same general form as equation (6-34).

If the above assumptions are valid,

$$\sum_{i=1}^{i=k} t_i Q_i C_i = c_1 \quad \sum_{i=1}^{i=k} t_i Q_i + q_2(c_2 - c_1) \quad \sum_{i=1}^{i=k} t_i \quad (6-36)$$

and from equations (6-26), (6-28), and (6-36),

$$\bar{C}_v = c_1 + \frac{q_2(c_2 - c_1)}{\bar{Q}_t} \quad (6-37)$$

and therefore,

$$\frac{\bar{C}_v}{C_v} = \frac{c_1}{C_v} + \frac{q_2}{\bar{Q}_t} \frac{(c_2 - c_1)}{C_v} \quad (6-38)$$

From equations (6-26), (6-29), and (6-30),

$$\frac{\bar{V}_t}{V_t} = \frac{\bar{Q}_t \bar{t}}{Q_t t} \quad (6-39)$$

where

$$\bar{t} = \sum_{i=1}^{i=k} t_i, \quad \text{and} \quad t = \sum_{i=1}^{i=n} t_i \quad (6-40)$$

t has a maximum value of 365 days (or 366 days during leap year).

Combining equations (6-38) and (6-39), one obtains

$$\frac{\bar{C}_v}{C_v} = \frac{c_1}{C_v} + \frac{q_2(c_2 - c_1)}{C_v Q_t} \left(\frac{\bar{t}}{t} \right) \quad (6-41)$$

For a given stream, if the above assumptions are valid, the ratio c_1/C_v might be constant, and for several streams it may be a function of C_v/C_t . The ratio \bar{t}/t would vary with i for a given stream, but this variation would be expected to be about the same from stream to stream. For the special case where all t_i values are the same,

$$\frac{\bar{t}}{t} = \frac{i t_i}{t} \quad (6-42)$$

When $\bar{V}_t/V_t = 1$, equation (6-41) becomes

$$1 = \frac{c_1}{C_v} + \frac{q_2(c_2 - c_1)}{C_v Q_t} \quad (6-43)$$

which is the same as equation (6-37) when $\bar{C}_V/C_V = 1$. Substituting equation (6-43) into equation (6-41) gives

$$\frac{\bar{C}_V}{C_V} = \frac{c_1}{C_V} + \left(1 - \frac{c_1}{C_V}\right) \left(\frac{\bar{t}}{t}\right) \left(\frac{\bar{V}_t}{V_t}\right)^{-1} \quad (6-44)$$

At this point a set of example calculations should help clarify the preceding. The example calculations are for sodium for the 1963 water year for the stream serving Cheney Reservoir and are shown in Table 6-3 and plotted in figure 6-22. From figure 6-22, it is clear that, for example, if ten percent of the stream flow containing the largest concentration could be bypassed around Cheney Reservoir, then the dissolved solids could be reduced by 30 percent. In other words, the dissolved solids concentration in Cheney Reservoir would be 431 mg/l instead of 616 mg/l, a reduction of 185 mg/l.

The effect of Cheney Reservoir on the stream below Cheney Dam is to greatly reduce the variation in dissolved solids concentration as is shown in figure 6-22.

It should be realized that bypassing 10 percent of the flow around Cheney Reservoir does not seriously affect the water quality below Cheney Reservoir. In other words, the volume weighted average dissolved solids concentration in the stream below Cheney Reservoir would be 616 mg/l with no bypassing. With 10 percent bypassing, the concentration would be about 710 mg/l in the stream below Cheney Reservoir, an increase of only 11.5 percent. In fact, if 20 percent of the total stream flow was bypassed around Cheney Reservoir, the downstream concentration of dissolved solids would only be about 610 mg/l, or somewhat less than with no bypassing, and the dissolved solids concentration in Cheney Reservoir would be 48 percent less, a decrease of 300 mg/l.

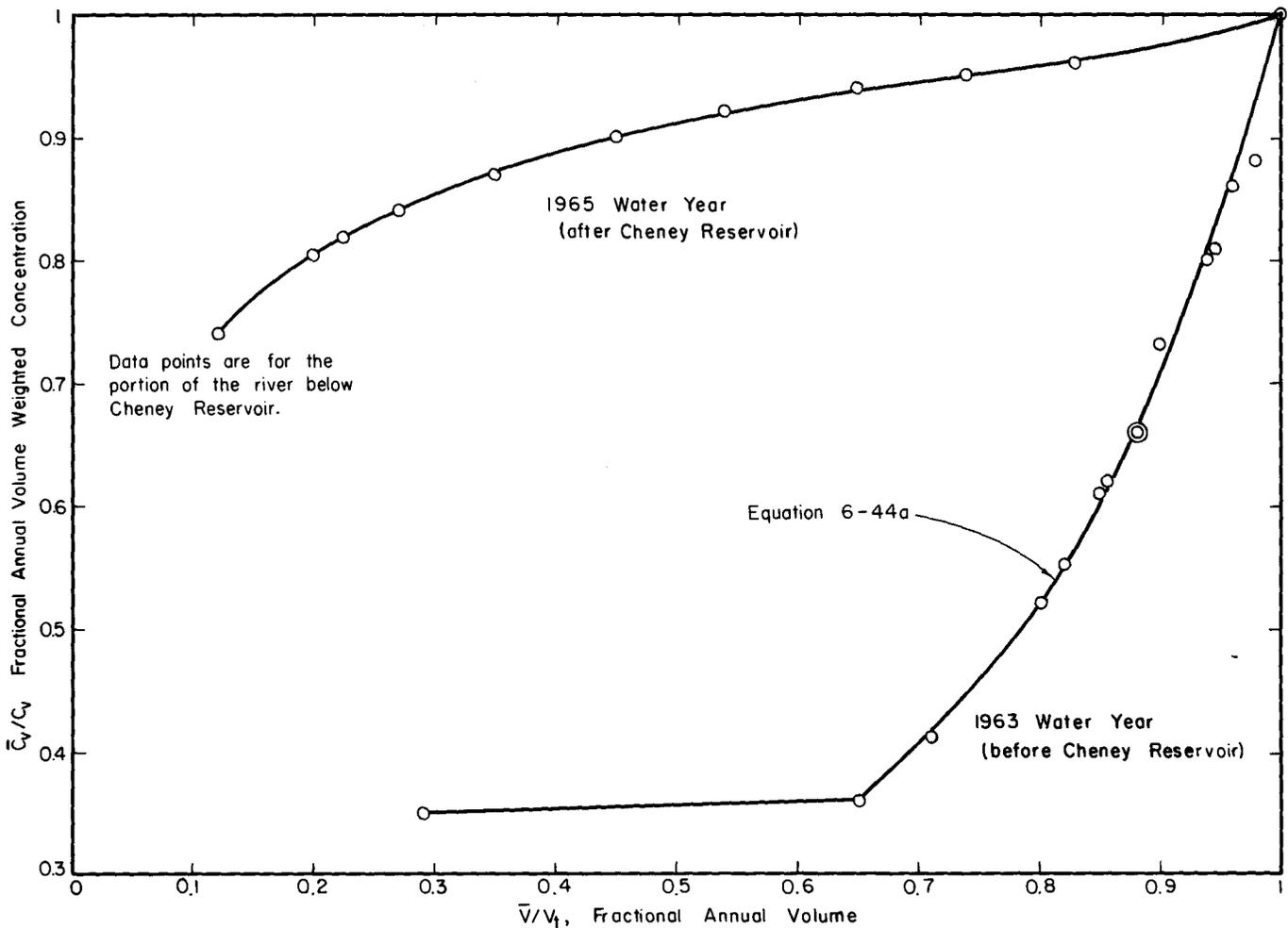


Figure 6-22. Sample calculation for North Fork Ninescah River.

TABLE 6-3. EXAMPLE CALCULATIONS FOR THE STREAM SERVING CHENEY RESERVOIR

Given:				Calculated:												Given:		
i	C _i	Q _i	t _i	Σt _i	t _i Q _i	Σt _i Q _i	\bar{Q}_t	t _i C _i	Σt _i C _i	\bar{C}_t	t _i Q _i C _i	Σt _i Q _i C _i	\bar{C}_v	\bar{V}_t/V_t	\bar{C}_v/C_v	Month	Day	Year
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)
1	16	1790	1	1	1790	1790	1790	16	16	16	28,700	28,700	16	0.292	0.349	Sept.	4	1963
2	17	2200	1	2	2200	3990	1995	17	33	16.5	37,400	66,100	16.55	0.652	0.361	Sept.	3	1963
3	40	384	1	3	384	4374	1458	40	73	24.3	15,350	81,450	18.65	0.713	0.407	June	5	1963
4	68	508	1	4	508	4882	1220	68	141	35.2	34,600	116,050	23.75	0.798	0.518	Sept.	10	1963
5	89	122	1	5	122	5004	1000	89	230	45.1	10,850	126,900	25.40	0.816	0.554	Oct.	29	1962
6	89	229	1	6	229	5233	872	89	319	53.2	20,350	147,250	28.10	0.853	0.613	Feb.	7	1963
7	112	13	1	7	13	5246	750	112	431	61.5	1,456	148,706	28.40	0.855	0.620	July	8	1963
8	115	125	1	8	125	5371	671	115	546	68.2	14,370	163,076	30.40	0.876	0.663	Oct.	9	1962
9	123	7.8	1	9	7.8	5379	598	123	669	74.4	960	164,036	30.50	0.878	0.665	Aug.	14	1963
10	126	168	1	10	168	5547	555	126	795	79.5	21,200	185,236	33.50	0.904	0.730	Dec.	4	1962
11	128	190	1	11	190	5737	522	128	923	83.8	24,300	209,536	36.50	0.936	0.797	March	12	1963
12	128	48	1	12	48	5787	483	128	1051	87.6	6,150	215,686	37.30	0.945	0.813	May	3	1963
13	131	125	1	13	125	5910	453	131	1182	91.0	16,400	232,086	39.30	0.963	0.857	Jan.	7	1963
14	135	76	1	14	76	5986	428	135	1317	94.3	10,250	242,336	40.50	0.977	0.883	April	9	1963
15	265	145	1	15	145	6131	408	265	1582	105.4	38,430	280,766	45.80	1	1	Aug.	23	1963

Chemical Compositon - Figure 6-23 shows the predicted and average composition of Cheney Reservoir as well as variations in composition from ten different Cheney water samples. The predicted and average compositions are roughly the same, and the variation in composition of Cheney Reservoir is small (anion composition variation is less than cation composition variation).

Figure 6-24 shows the variation in composition of the stream serving Cheney Reservoir. It is clear that $j=3$ would be sufficient to account for all variations in stream composition, and that a rough approximation could be made for $j=2$ (solid line).

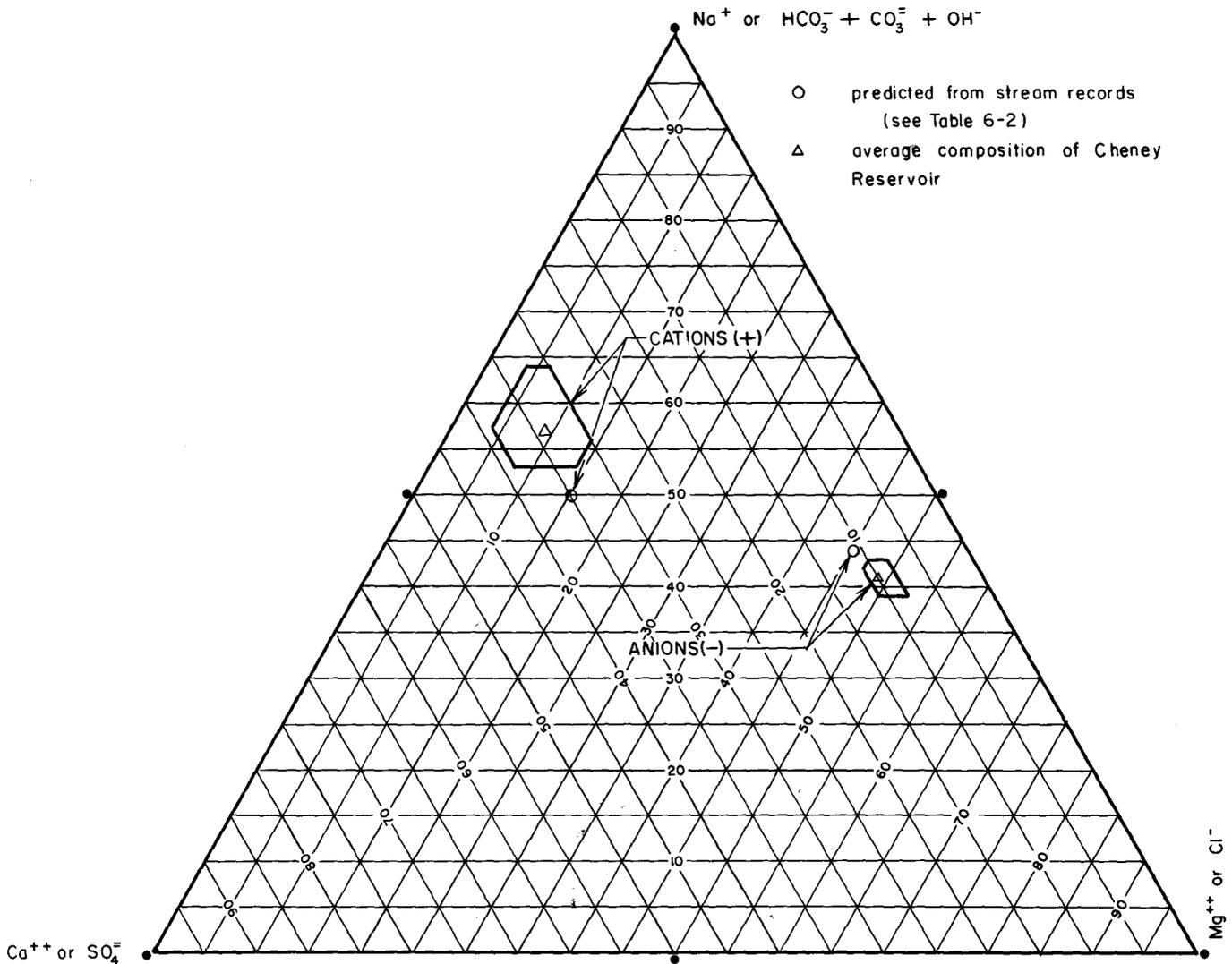


Figure 6-23. Average, predicted, and variation in composition of Cheney Reservoir.

The Cheney Reservoir Chemical Continuous Flow Model - Complete mixing with intermixing identifies the flow model in which increments of the influent intermix immediately with the contents of a vessel and, thereby, lose their identity in every respect. The fluid in the vessel is completely mixed so that its properties are uniform and identical with those of the effluent. The complete mixing model is approximated by Cheney Reservoir for turbidity, conductivity, pH, alkalinity, chlorides, and other water quality parameters of a similar nature. Figures 5-2, 6-3(1967), 6-6 (1967), 6-9 (1965 and 1966), and 6-11 show that the effluent concentrations are the same as the concentrations in Cheney Reservoir for these water quality parameters.

The rate of response of effluent properties to abrupt changes in influent properties can be determined by setting up a hypothetical situation in which a chemical ion not initially present in the influent is suddenly increased to a finite constant concentration, C_0 . Then the effluent concentration, C , would be

$$\frac{C}{C_0} = 1 - e^{-t/t_0} \quad (6-45)$$

where t = time and t_0 is the retention time of Cheney Reservoir, which is the volume of the reservoir divided by the outflow rate. For Cheney Reservoir, t_0 is approximately 3.3 years. Therefore, if the influent concentration continued to be C_0 for an entire year, the effluent concentration would only rise to 26 percent of C_0 .

In order to show that the chemical properties of Cheney Reservoir are uniform throughout, a statistical analysis was made of all the chemical data from all of the horizontal and vertical locations in Cheney Reservoir. Vertical properties were measured at depth intervals of five feet from the surface to the bottom. The coordinates of the horizontal stations are given in Table 6-4 in miles. The origin of the coordinate system is at the intersection of Highway 17 and 21st

Street of Wichita, Kansas. All A, R-1, R-3, R-5, R-7, and R-9 stations are on the same straight line (six different straight lines). All distances are measured east and north of the coordinate system origin. It should be noted that the average coordinate is on a straight line drawn between K-17 and the municipal outlet at Cheney Dam. This average coordinate is 2.9 miles from the municipal outlet at Cheney Dam and 8.5 miles from K-17 (K-17 and the municipal outlet are 11.4 miles apart).

The following statistical parameters were calculated: average = $M = \sum X/n$, where X is the magnitude of each observation and n is the number of observations involved; arithmetic standard deviation = $\sigma = \sqrt{\sum X^2/(n-1)}$, where $x = X-M$; coefficient of variation = $c_v = \sigma/M$; standard deviation of mean = $\sigma_M = \sigma/\sqrt{n}$; and uniformity coefficient = $\sigma_M/M = \sigma/(M\sqrt{n})$. Although all of these parameters should be independent of the number of observations, this was not the case. The following parameters are independent of the magnitude of the observation: c_v and uniformity coefficient. The meaning of the uniformity coefficient is that if it had a value of say ± 0.01 , or ± 1 percent, then the mean of that set of observations would be within ± 1 percent of the true mean about two-thirds of the time.

In general, the Raw Water Analysis Sheets did not have as many observations as the data recorded on the "other" sheets (see figures 6-3, etc.). As a result, the uniformity coefficients were not the same for the same parameter. For example, for the "other" sheets, the overall average horizontal value of the uniformity coefficient for conductivity was ± 0.0035 , but was ± 0.0172 for the Raw Water Analysis Sheets. Because this indicated that the uniformity coefficients would, in general, be more than five times as great merely because of less data, the uniformity coefficients given for temperature, dissolved oxygen, conductivity, pH, and turbidity are for the data recorded on these "other" sheets, and the remainder is for the data on the Raw Water Analysis Sheets.

TABLE 6-4. COORDINATES OF HORIZONTAL SAMPLING STATIONS ON CHENEY RESERVOIR

Station	East	North									
A-1	7.2	0.6	R-3-1	6.0	1.5	R-5-1	4.7	2.7	R-11-1	2.4	6.7
A-2	7.4	0.7	R-3-2	6.2	1.8	R-5-2	4.9	3.0	average	5.8	2.6
A-3	7.5	0.8	R-3-3	6.5	2.1	R-5-3	5.2	3.3	K-17	0	8.7
A-4	7.7	1.0	R-3-4	6.7	2.4	R-7-1	3.5	3.9	outlet	7.8	0.5
R-1-1	6.7	0.7	R-3-5	7.0	2.7	R-7-2	3.8	4.1			
R-1-2	6.9	0.9	R-3-6	7.2	3.0	R-7-3	4.1	4.3			
R-1-3	7.8	1.2	R-3-7	7.4	3.2	R-9-1	2.8	5.3			
R-1-4	7.5	1.5				R-9-2	3.1	5.6			

For each date and depth, the values of all five of the statistical parameters were determined. Also, for each date and station, all five of the statistical parameters were calculated. The uniformity coefficients are plotted in figure 6-25. With the exception of calcium and bicarbonate, all of the chemical and physical parameters are more uniform vertically than horizontally. This is to be expected, because the variations in stream concentrations coming into Cheney Reservoir are reflected in the horizontal determinations. The parameters of conductivity, pH, and temperature show that the properties of Cheney Reservoir are uniform chemically and physically. It is believed that the uniformity coefficients plotted for bicarbonate are in error because these should be the same as for alkalinity.

Recommendations for Additional Research - With the exception of dissolved oxygen, all of the chemical properties of Cheney Reservoir can be determined adequately by analysis of samples taken at the intake tower. Turbidity determinations should be done either using a photomultiplier tube to measure light scattered 90° or by using a photocell assembly to measure surface scattered light. Dissolved solids determinations should be made by drying residues at 180°C. Conductivity should be determined to three significant figures (such as 983 μmhos/cm at 25°C) measured at 25°C. Errors in conductivity greater than ±1 percent are avoidable by using reasonable analytical care. In fact, with the proper equipment, laboratory determinations of conductivity are possible where errors greater than + 0.1% are avoidable.

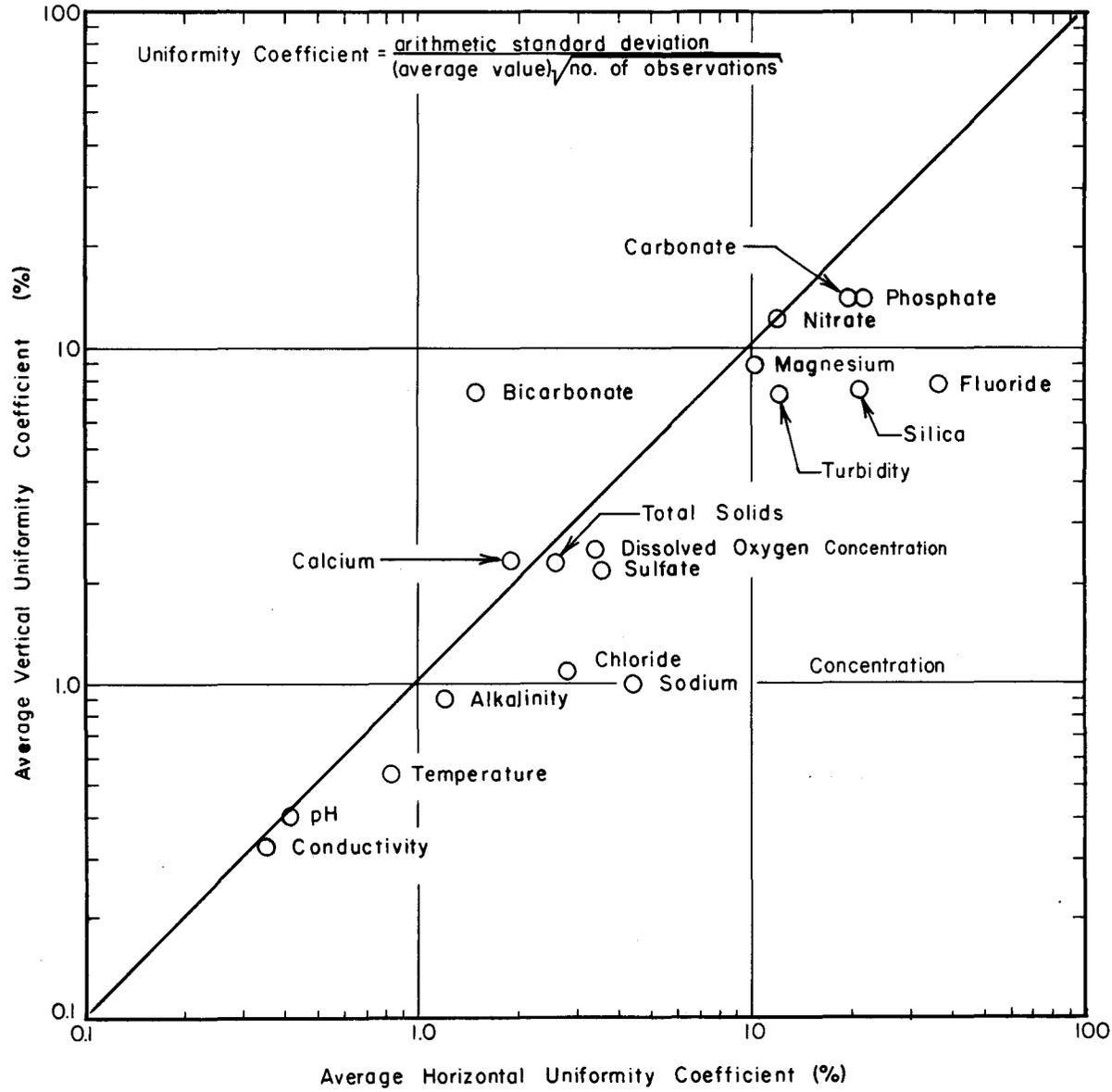


Figure 6-25. Average uniformity coefficients for Cheney Reservoir.

In the laboratory, pH should be determined to four significant figures (such as pH = 7.843) at 25°C using a thermocompensator. In the field, pH should be determined to three significant figures (such as pH = 7.84) and corrected to 25°C. Bicarbonate, carbonate, and hydroxide alkalinity as well as carbon dioxide should be calculated from pH, alkalinity, and conductivity using equations (6-8) through (6-16) and either equation (6-17), (6-18), or (6-19).

Dissolved oxygen should be measured in place. Analyses should be checked by cation-anion balance, true dissolved solids, and conductivity at infinite dilution (see equations 6-4, 6-5, and 6-6 as well as Table 6-1a).

A salt balance should be made using daily conductivities at the intake tower and daily volume weighted conductivities at K-17. A salt balance is necessary to adequately demonstrate the phenomenal increase in conductivity due to evaporation.

A study, like this one on Cheney Reservoir, should be made with one person in complete charge from start to finish. Less and much more accurate data should be thoroughly analyzed as soon as it has been obtained. The length of future studies of this nature should be at least several years in order to offset yearly variations. Complete meteorological and hydraulic data taken at the reservoir are absolutely needed. In fact, as much information as possible, preferably over a period of several years, should be obtained before construction of a new reservoir. In order to have a reliable estimate of stream quality, daily observations are necessary, even though some daily observations may be composited according to stream flow rate and/or conductivity.

In reservoirs, unlike Cheney Reservoir, that are stratified at least part of every year, observations at various consistent depth intervals should be made. Horizontal observations have far less significance than vertical measurements. Where more than one vertical profile is to be taken, the horizontal position should be established only after thorough studies of the hydraulics of the reservoir. The number of horizontal stations and consistent depth intervals should be kept as small as possible so that observations can be made at every depth at every horizontal station whenever measurements are made. Measurements should be made at equal intervals throughout the year, regardless of ice cover. Consistency throughout a given project is of paramount importance for realistic data interpretation. Continuous data analysis will, however, indicate observations that can be reduced as well as additional observations that are necessary for adequate representation. The most important chemical parameters, in general, are: temperature, conductivity, pH, alkalinity, chlorides, sodium, magnesium, calcium, sulfate, and dissolved oxygen. Additional parameters would depend on the characteristics of a given location. It is better to have very few precise observations than to have many

inaccurate observations. Where possible, three significant figures or better should be used for all experimental determinations, except for pH laboratory measurements, which must be to four significant figures.

The most important result of this study is the tremendous increase in dissolved solids concentration due to evaporation that is possible for some reservoirs. The most important development given in this report is the section in this chapter entitled, "Reducing the Increase in Dissolved Solids Concentration" (equations (6-26) through (6-33), (6-39), and (6-40)).

When equation (6-44) is applied to the stream serving Cheney Reservoir (1963 water year), the value of c_1/C_V is approximately 0.16. Also,

$$\frac{\bar{t}}{t} = \left(\frac{\bar{v}_t}{v_t} \right)^{4.7} \quad (6-46)$$

Therefore, for Cheney Reservoir, equation (6-44) simplifies to

$$\frac{\bar{c}_v}{c_v} = 0.16 + 0.84 \left(\frac{\bar{v}_t}{v_t} \right)^{3.7}, \quad (6-44a)$$

and a plot of \bar{c}_v/c_v versus $(\bar{v}_t/v_t)^{3.7}$ is a straight line with intercept 0.16 and slope 0.84. A plot of equation (6-44a) in figure 6-22 gives the curve drawn through the experimental points. Therefore, it is clear that, for the stream serving Cheney Reservoir, $j \approx 2$, and equations (6-34) through (6-38) and equations (6-41) through (6-44) are applicable.

The importance of the section in this chapter entitled, "Reducing the Increase in Dissolved Solids Concentration," is that the concepts developed show not only how to reduce the dissolved solids concentrations in reservoirs, but also how to reduce the dissolved solids concentrations in the streams below these reservoirs at the same time. For this reason, an experimental program should be initiated at the earliest possible time to further develop these concepts and to verify experimentally the theoretically predicted results.

7. ODOR, BACTERIA, AND ALGAE

Odor - According to physiologists, there are only four true taste sensations: sour, sweet, salty, and bitter. All other sensations commonly ascribed to the sense of taste are actually odors, even though the sensation is not noticed until the material is taken into the mouth. Odors occur in water because of the presence of foreign substances, usually organic. Some inorganic compounds, such as hydrogen sulfide, also cause odor. The contaminating materials may be of natural origin, may come from domestic or industrial waste discharges, may be a result of biochemical reactions, or may be due to a combination of these. Because odorous materials are often detectable when present in only a few micrograms per liter and are often complex, it is usually impractical and often impossible to isolate and identify the odor-producing chemical.

The threshold odor number is

$$\text{Threshold Odor Number} = \frac{200\text{ml}}{\text{Sample Volume (in ml)} \text{ Diluted to } 200 \text{ ml}} \quad (7-1)$$

One classification of odor characteristics is given in Table 7-1. The only odor characteristics observed in Cheney Reservoir were Bs, Df, G, and M. Figure 7-1 shows the times when these four odors were observed. It should be noted that the odor characteristics were not consistent from one year to the next. Also plotted in figure 7-1 are the threshold odor numbers. The threshold odor number apparently has stabilized at a value of five, because it has had that value for over one year. The threshold odor numbers and odor characteristic were determined daily, and the daily values are plotted in figure 7-1. The most

prevalent odor characteristic is musty, followed by fishy. The grassy and sweetish odors were only observed for a total period of less than one month. Odors in the future will probably be either musty or fishy since this has been the case for almost two years, although short periods of other odors may occur due to seasonal changes in organisms or surface drainage from grasslands.

Bacteria - The coliform group density was estimated using the "most probable number" (MPN). The only values possible for MPN are 40 integer values ranging from two to 1,609 per 100 ml. The 95 percent confidence limits range from 1 to 17 for a MPN of 7 up to 640 to 5,800 for a MPN of 1,609 per 100 milliliters. All the MPN determinations are plotted in figure 7-2. The solid line was computed using the dimensionless ranking numbers for each month of the year and using all observed values. This solid line best represents the most likely values to be observed at a given time of year based on all the observations and indicates a very low coliform level and consequently no continuous input of human or other higher animal waste. However, in late spring of 1967, there is some indication of a period of relative increase in coliforms.

Algae - The simplest definition of algae is that it includes all microscopic plants carrying out true photosynthesis. Photosynthesis is greatest at the water surface and decreases with depth (the lower limit of photosynthesis occurs at a depth of about 15 feet). Algae, however, may distribute themselves throughout the reservoir. Equation (6-23) describes the photosynthetic reaction. The composition of algae and some other organic materials is shown in Table 7-2. Analyses of various algae are shown in Table 7-3.

TABLE 7-1. QUALITATIVE DESCRIPTIONS OF ODORS

Code	Nature of Odor	Description (Such as Odors of:)
A	Aromatic (spicy)	camphor, cloves, lavender, lemon
Ac	cucumber	<u>Synura</u>
B	Balsamic (flowery)	geranium, violet, vanilla
Bg	geranium	<u>Asterionella</u>
Bn	nasturtium	<u>Aphanisomenon</u>
Bs	sweetish	<u>Coelosphaerium</u>
Bv	violet	<u>Mallomonas</u>
C	Chemical	industrial wastes or treatment chemicals
Cc	chlorinous	free chlorine
Ch	hydrocarbon	oil refinery wastes
Cm	medicinal	phenol and iodoform
Cs	sulfuretted	hydrogen sulfide
D	Disagreeable	(pronounced, unpleasant)
Df	fishy	<u>Uroglenopsis</u> , <u>Dinobryon</u>
Dp	pigpen	<u>Anabaena</u>
Ds	septic	stale sewage
E	Earthy	damp earth
Ep	peaty	peat
G	Grassy	crushed grass
M	Musty	decomposing straw
Mm	moldy	damp cellar
V	Vegetable	root vegetables

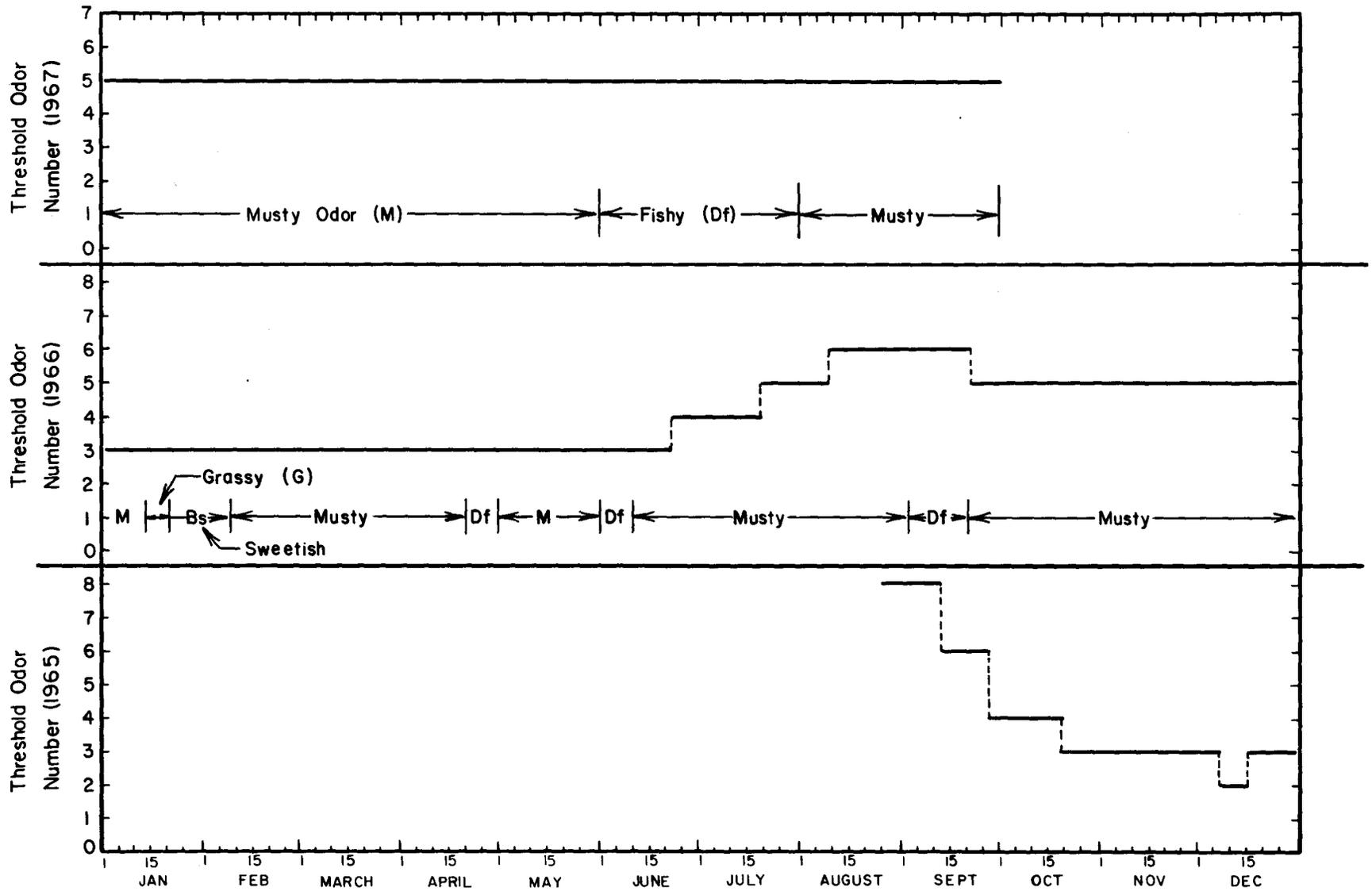


Figure 7-1. Threshold odor numbers and odor descriptions.

TABLE 7-2. COMPOSITION OF SOME ORGANIC MATERIALS, $C_a H_b O_c N_d P_e S_f$

Organic Material	a	b	c	d	e	f
Composition of activated sludge (for industrial wastewaters). Composition of trickling filter slimes is similar	118	170	51	17	1	
Organic material in human wastewater	11	29	7	1		
Human urine (urea)	1	4	1	2		
Human feces	12	22	5	2		
Cattle manure	186	548	168	11	1	2
Bacteria organic fraction	5	7	2	1		
Fungi organic fraction	10	17	6	1		
Protozoa protoplasm	7	14	3	1		
Algae protoplasm	5	8	2	1		
Oswald's algae formula	7.6	8.06	2.53	1		
Oxidation pond algae (cellular material)	6.14	10.3	2.24	1		
Chlorella protoplasm (algae)						
Burlew	5	8	2	1		
Fogg	5.7	9.8	2.3	1		
Aerobic composting						
Before	31	50	26	1		
After	11	14	4	1		
Proteins	142	225	44	38	1	1

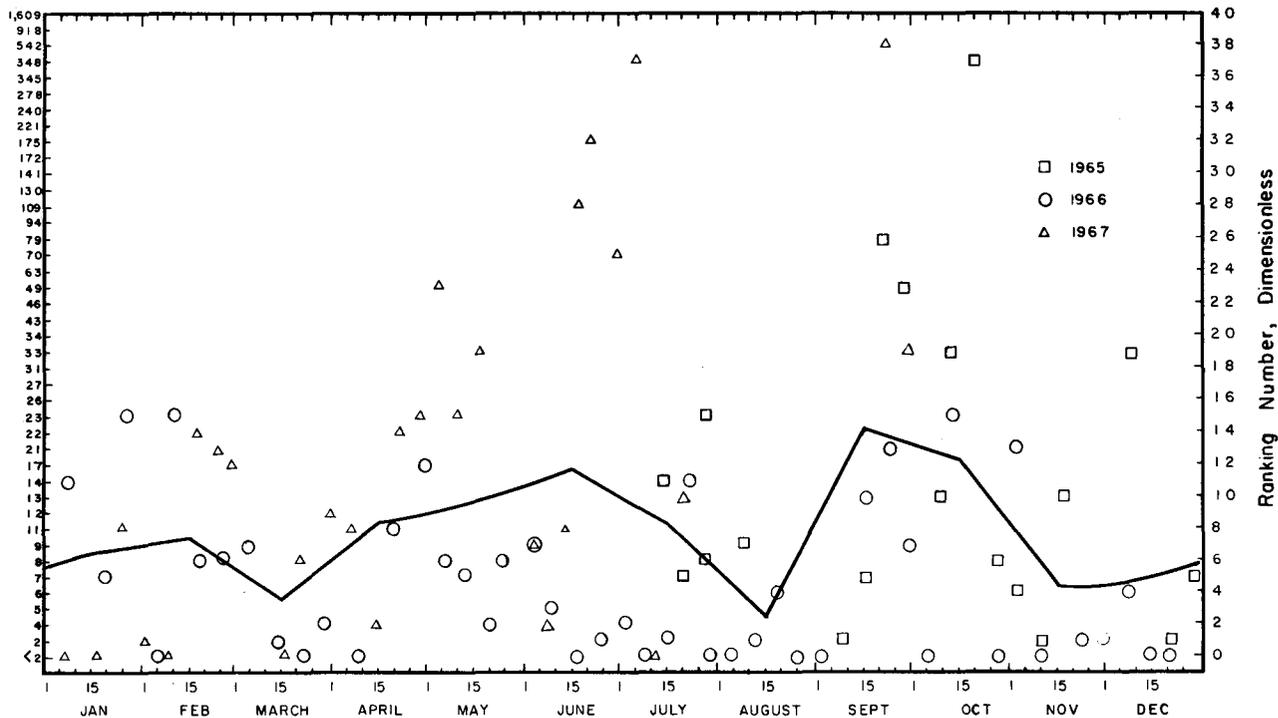


Figure 7-2. Coliform group density.

TABLE 7-3. ANALYSES OF VARIOUS ALGAE, PERCENT

Organism	N	P	Ca	Mg	Si	R ₂ O ₃ *
Blue-green: (cyanophyta) (5)						
Microcystis	8.35**	0.52	0.66	0.38	0.06	0.84
Anabaena	8.27	0.51	1.02	0.42	0.44	1.27
Anabaena and Coelosphaerium	8.35		0.58	0.38	0.13	
Volvox	7.61	1.09	0.78	0.56	0.11	0.80
Aphanizomenon	9.30					
Average	8.38	0.71	0.76	0.44	0.19	0.97
Green: (chlorophyta) (1)						
Spirogyra	3.47					
Cladophora	2.77	0.14	2.32	0.97	3.30	1.80
Overall Average	6.89	0.45	0.89	0.45	0.67	0.94

* Al₂O₃ + Fe₂O₃ combined, no differentiation

**Values on specimens from three different lakes

Endogenous metabolism is the reverse of equation (6-23), so the demand by algae for oxygen in the absence of sunlight is of great importance in depleting DO. Therefore, unless algae are prevented from multiplying promiscuously, they could become a problem in the depletion of DO.

Algae are particularly troublesome from two viewpoints. Many species give rise to taste and odor problems while others interfere seriously with filtration practice. Nitrogen and phosphorous are major mineral nutrients required by all algae. The requirement of blue-green algae (5) for these elements is somewhat higher than that of the green algae (1 and 2) because of the higher protein content of the former.

It has been stated that by placing a given lake or reservoir under survey for one calendar year and employing modern methods of analysis for all conceivable critical nutrients, it should be possible to ascertain which nutrients are actually critical in the body of water under consideration. However, there are two qualifications that must be recognized for successful application of this method of determining critical nutrients. One is that all forms of inorganic nitrogen (ammonia, nitrate, and nitrite) must be considered, not just nitrate. Only nitrate was determined in Cheney Reservoir, but probably very small quantities of either ammonia or nitrite are present. The second is related to phosphorus. In many lakes or reservoirs receiving domestic wastewater, the phosphorus available may be so great with regard to the phosphorus requirement that a decrease in concentration may not be observable during the growing season. This condition is known to exist when phosphorus concentrations are in the range of 0.5 mg/l. Phosphate concentrations in Cheney Reservoir were generally less than 0.5 mg/l.

The five divisions of fresh-water algae are:

1. Chlorophyta (grass-green algae)
2. Euglenophyta (motile green)

3. Crysophyta (diatoms et al.) - yellow-green to golden brown
4. Pyrrophyta (motile greenish tan to golden brown)
5. Cyanophyta (blue-green algae)

Euglenophyta (2) grow best in a rich NH₃ medium. Cyanophyta (5) prefer high pH and/or high soluble inorganic ion concentrations.

Algae are autotrophic organisms in that they are able to utilize inorganic compounds for their synthesis. The mineral requirements for algae protoplasm are similar to that of bacteria protoplasm (see Table 7-2). Carbon often comes from CO₂ as it does for the autotrophic bacteria. Available phosphorous is always in the orthophosphate (PO₄³⁻) state, while S is usually as the SO₄²⁻. The normal trace elements of Na, K, Ca, Mg, iron, cobalt, molybdenum etc., are all required. Some algae prefer low pH or soft water.

For Cheney Reservoir, the non-critical nutrients appear to be Ca⁺⁺, Mg⁺⁺, SO₄²⁻, and Na⁺. Because no analyses were made for potassium, iron, cobalt, and molybdenum, no statement can be made with regard to whether they are critical nutrients or not. For Cheney Reservoir, the critical nutrients appear to be nitrogen, phosphorus, and SiO₂ because apparent reductions in concentration were observed.

For purposes of classifying algae with respect to water temperature, the following grouping is used (from lowest to highest water temperature: diatoms (3), green (1 and 2), blue-green (5), and pyrrophyta (4). No pyrrophyta (4) were observed in Cheney Reservoir which was expected because they usually grow best when water temperatures exceed 104°F.

Table 7-4 was constructed from the observations made on Cheney Reservoir. The maximum concentration of algae was observed at a water temperature of 59°F. This was also the point at which the diatom percentage

TABLE 7-4. CONCENTRATION AND COMPOSITION OF ALGAE AS A FUNCTION OF WATER TEMPERATURE FOR CHENEY RESERVOIR

Water Temperature °F	Number of Algae per mL	Percent Composition		
		Blue-green (5)	Diatoms (3)	Green (1+2)
36	245	0	67	33
37	285	0	61	39
38	330	0	55	45
39	380	0	48	52
40	435	0	44	56
41	500	0	40	60
42	580	0	37	63
43	670	0	35	65
44	770	0	33	67
45	900	0	31	69
46	1,000	0	29	71
47	1,200	0	27	73
48	1,350	0	26	75
49	1,600	0	25	76
50	1,850	0	23	77
51	2,100	0	22	78
52	2,400	0	21	79
53	2,800	0	20	80
54	3,200	0	19	81
55	3,750	0	18	82
56	4,300	0	17	83
57	5,000	0	17	83
58	5,700	0	16	84
59	6,600	0	15	85
60	6,000	0	16	84
61	5,250	0	17	83
62	4,800	0	17	83
63	4,300	0	18	82
64	3,900	0	19	81
65	3,500	1	20	79
66	3,200	1	21	78
67	2,800	1	22	77
68	2,600	1	22	77
69	2,300	2	24	74
70	2,100	2	25	73
71	1,900	2	26	72
72	1,700	3	27	70
73	1,550	3	28	69
74	1,400	4	29	67
75	1,250	4	30	66
76	1,100	5	32	63
77	1,000	6	33	61
78	900	7	35	58
79	820	8	36	56
80	740	10	38	52
81	660	12	39	49

It must be emphasized that Table 7-4 is a very rough approximation but appears to be the best that can be done with the observed data. However, Table 7-4 should give a fair qualitative idea of the effect of water temperature on algae composition and concentration.

According to equation (3-23b), the net weight of oxygen produced daily would be directly proportional to the intensity of visible solar radiation if the efficiency of energy conversion is constant. Assuming one percent efficiency, the daily increase in dissolved oxygen concentration would be expected to be ≈ 1.47 (mg/l)/day. The actual efficiency is likely to be substantially less than one percent, because values as low as two percent have been reported for oxidation ponds. Using 15 feet as the lower limit of photosynthesis, the top 15 feet encompasses about seventy-two percent of the total volume of Cheney Reservoir.

was a minimum (15 percent) and the green percentage was a maximum (85 percent). From figure 3-1, the water temperature is 59°F at the end of April and about the middle of October. Algae numbers reflect also the visible sunlight available for photosynthesis. At temperatures about 60°F, bacterial competition for nutrients probably have some effect on algae numbers. The effect of fish on algae numbers could not be determined because there was no fish data available.

8. CONCLUSIONS

The water budget for Cheney Reservoir was made with estimated precipitation using Wichita rainfall data. After analysis had been made and evaporation was estimated, and after this report had been substantially written, meteorological data from the station at Cheney Dam was received. The evaporation data included with this latter set was then evaluated and compared to the calculated values. The results are shown in the figure in the Appendix. Inasmuch as there was substantial agreement between measured and calculated evaporation, the original data was not reanalyzed, and Chapter 2 was not rewritten, for the important outcome of the calculation (evaporation) was not affected. The evaporation from Cheney Reservoir averages about 56 inches annually.

The calculation for the heat balance in the reservoir also indicated fair agreement with the water budget in the amount of evaporation from the reservoir.

The salt budget calculations were based on conductivity measurements. Mass balances could not be made because of inadequacy and inaccuracy of the data. Nevertheless, increases in salt concentrations were inferred from concentration measurements and calculations. The conductivity in Cheney Reservoir increased from about 630 micromhos/cm at 25°C for 1965 to 1,090 micromhos/cm at 25°C by the end of September 1967. The increase was related directly to evaporation.

Based on temperature, conductivity, and turbidity measurements, it is concluded that Cheney Reservoir is not stratified. It is essentially a wide shallow reservoir and the flow from the North Fork of the Ninnescah River is effectively diffused through the reservoir. As a consequence, the multiple level outlet structure was neither necessary nor effective in controlling the quality of water pumped to the City of Wichita during the period of study.

The results of the analysis of the chemical concentrations in Cheney Reservoir water are tabulated in Table 6-2. The predominant cations (calcium, magnesium, and sodium) were traced with time. It was concluded that saturation of calcium existed, for the slight decrease in concentration from 1965 to 1967 is related directly to the increase in pH of the water. Precipitation of CaCO_3 must be occurring in the reservoir. Magnesium and sodium on the other hand increased predictably with time from 11 to 18 mg/l and from 120 to 230 mg/l respectively due to evaporation. The increase in concentration of the prominent anions (bicarbonate, sulfate, and chloride) was related directly to evaporation. All increased with time from 1965 to 1967. It was shown that the alkalinity of Cheney water was due primarily to bicarbonate ions.

The interplay of critical nutrients with biological activity in Cheney Reservoir were manifest in phosphate, nitrate, and silica variations within the reservoir. Biological activity in Cheney Reservoir is not of material concern at the present time even though locally strong odors were detected at various times along the shores of the reservoir due to decay of organic matter. Within the third year of the reservoir, very little objectionable odor was evident.

It is suggested that some thought be given to control of the dissolved solids concentration in Cheney Reservoir. This could take effect in the form of reduction of evaporation and by a system to bypass some of the river water around the reservoir. Reduction in evaporation will not by itself be a satisfactory solution, for the increase in reservoir temperature will invite additional biological activity which in turn will deteriorate water quality. More serious study should be made on the effect of the bypass before it can be effectively implemented, but without some control, the dissolved solids concentration will remain relatively high.

9. DATA STORAGE AND RETRIEVAL

The data used in the various analyses of this report have been adapted to the STORET system and filed in Washington, D. C. with the Federal Water Pollution Control Administration (FWPCA) of the U. S. Department of the Interior. STORET is an acronym used for reference to the Water Quality Data Storage and Retrieval System developed by the Division of Water Supply and Pollution Control, U. S. Public Health Service, to facilitate the voluminous quantities of data collected on the nation's rivers, lakes, and estuaries. Detailed descriptions concerning the overall system can be found in other publications so that this chapter will describe only the manner of storage of Cheney Reservoir data and how the data may be retrieved.

Data Storage - The original form of the data collected at Cheney Reservoir was generally arranged chronologically in the order that data were taken at all stations and heterogeneous in manner. The preferred storage arrangement in STORET, however, is chronological order of various data (parameters) for each station. Thus, some group rearrangement of the original data was necessary. It should also be noted here that not all parameters are included in the data storage, primarily because parameter coding has not been completed by FWPCA at the time of this writing, especially for biological data and also because some of the parameters were not considered sufficiently important for inclusion. The latter refers especially to the many sub-species of the biological groups.

The location coding relative to the Southwest Lower Mississippi River basin was established with the assistance of Mr. Robert L. King of the FWPCA, Denver, Colorado, in coordination with the national office. While the current location coding for the sampling stations is somewhat arbitrary in that river mileage of the Arkansas River from the Mississippi is referenced to an arbitrary junction mileage, it nevertheless provides a unique six digit number for each sampling station. The assigned coding for each station is tabulated below:

Parameter Coding - Standard Parameter Codes were used in accordance with "Parameter Code List for the STORET System, 3rd Ed., July 1966, FWPCA, U. S. Department of Interior." There are many more codes provided in this manual than were used; thus to avoid confusion the parameters included in the file of Cheney Reservoir data are listed below:

Parameter Code List

Code	Parameter
00075	Turbidity, Hellige (ppm as SiO ₂)
00095	Conductivity (Micromhos at 25°C)
00515	Total Solids (Residue)
01055	Manganese (µg/l as Mn)
00410	Alkalinity, Total (mg/l as CaCO ₃)
00430	P-Alkalinity
74021	Excess Alkalinity
00902	Hardness, Non Carbonate (mg/l as CaCO ₃)
00900	Hardness, Total (mg/l as CaCO ₃)
00400	pH (Standard Units) at 25°C
00011	Temperature, Water (°F)
00010	Temperature, Water (°C)
00300	Dissolved Oxygen (mg/l)
00910	Calcium (mg/l as CaCO ₃)
00920	Magnesium (mg/l as CaCO ₃)
01045	Iron (µg/l as Fe)
00930	Sodium (mg/l as Na)
00955	Silica (mg/l as SiO ₂)
00653	Phosphate, Total Soluble (mg/l)
00445	Carbonate Ion (mg/l as CO ₃)
00440	Bicarbonate Ion (mg/l as HCO ₃)
00945	Sulfate (mg/l as SO ₄)
00940	Chloride (mg/l as Cl)
00620	Nitrate (mg/l as N)
00950	Fluoride (mg/l as F)
00060	Stream Flow (cfs)
74020	Pumped Flow (gpm)
31507	Coliform, MPN Completed
31505	Coliform, MPN Confirmed
00035	Wind Velocity (mph)
00036	Wind Direction
00020	Temperature, Air (°C)

Station Location Codes

STORET Number	Cheney Reservoir Station	STORET Number	Cheney Reservoir Station	STORET Number	Cheney Reservoir Station
190200	Intake Tower	190208	R1-4	190216	R7-1
190201	A-1	190209	R3-1	190217	R7-2
190202	A-2	190210	R3-2	190218	R7-3
190203	A-3	190211	R3-3	190219	R9-1
190204	A-4	190212	R3-4	190220	R9-2
190205	R1-1	190213	R5-1	190221	R11-1
190206	R1-2	190214	R5-2	190222	K-17
190207	R1-3	190215	R5-3	190223	Pump Sta.
				190224	Gaging Sta. d/s from dam

No code was available for the other parameters for which data were taken at Cheney Reservoir.

Data Retrieval - To retrieve any part of the data stored, it is necessary to identify the station, the parameters desired and the pertinent dates for which data are desired. The programmer (in Washington, D.C.)

will then prepare the proper retrieval codes. In preparation of these codes, however, the programmer will require additionally the agency and locking codes. The codes applicable to the Cheney Reservoir data may be obtained by writing to Paul R. Tramutt, Chemical Engineering Branch, Bureau of Reclamation, Denver Federal Center, Denver, Colorado 80225.

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APPENDIX

Table A-1 gives the recorded evaporation at Cheney Reservoir. Figure A-1 is a comparison of calculated (by heat balance and by volume balance) and the measured evaporation values listed in Table A-1.

Figure A-2 shows the average annual evaporation excess for most of the United States. The evaporation excess is defined as lake evaporation minus precipitation. The importance of the evaporation excess is that it indicates the probable type of water quality problem that is likely to be of paramount importance in a given area. In other words, if the evaporation excess is positive, then dissolved solids concentration is likely to be the major water quality problem. Furthermore, the magnitude of the evaporation excess indicates the intensity of the dissolved solids concentration problem. For example, the evaporation excess at Cheney Reservoir (Wichita, Kansas) is (56 - 32) = 24 inches per year, and this excess was sufficient to

cause an increase in dissolved solids concentration in one reservoir of 170 percent.

On the other hand, where the evaporation excess is negative, the major water quality problems are likely to be something other than dissolved solids concentration. In fact, the mere construction of a reservoir in a negative evaporation excess area, reduces the dissolved solids concentration.

Because most of the U. S. population is currently (1969) in a negative evaporation excess area, the water quality problems receiving the most attention have been other than dissolved solids concentration. However, Figure A-2 clearly shows that most of the area of the United States has a positive evaporation excess, and therefore the major water quality problem for most of the United States would appear to be dissolved solids concentration.

TABLE A-1. RECORDED EVAPORATION AT CHENEY RESERVOIR SITE
(Adjusted Evaporation Pan Data by Factor of 0.7)

Month	Year	Inches		
		1965	1966	1967
January			--	--
February			--	--
March			--	--
April			4.90	5.34
May			6.52	6.68
June			7.85	5.36
July			8.29	5.37
August			6.45	7.10
September	3.21		5.17	4.15
October	3.62		4.78	4.09
November	1.56		1.03*	--
December	0.65*		--	--
Totals		9.04	44.99	38.09

* Partial month only because of freezing.

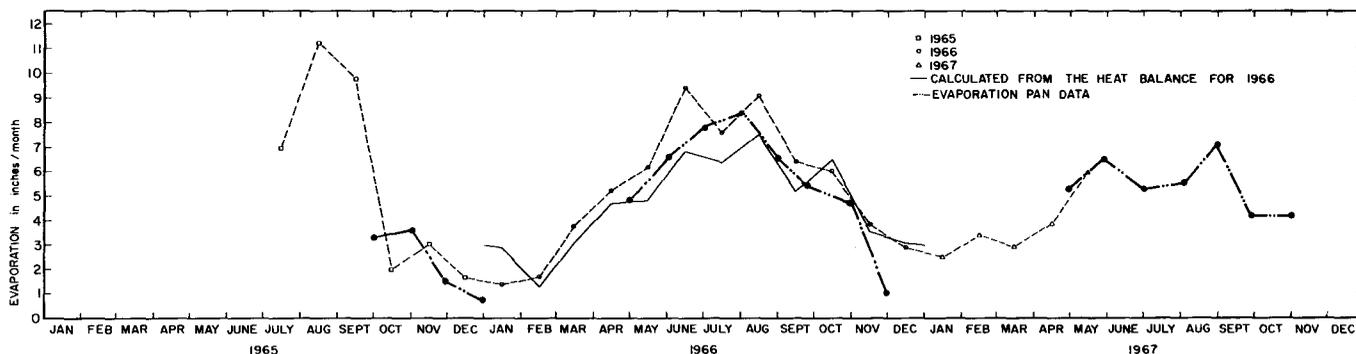
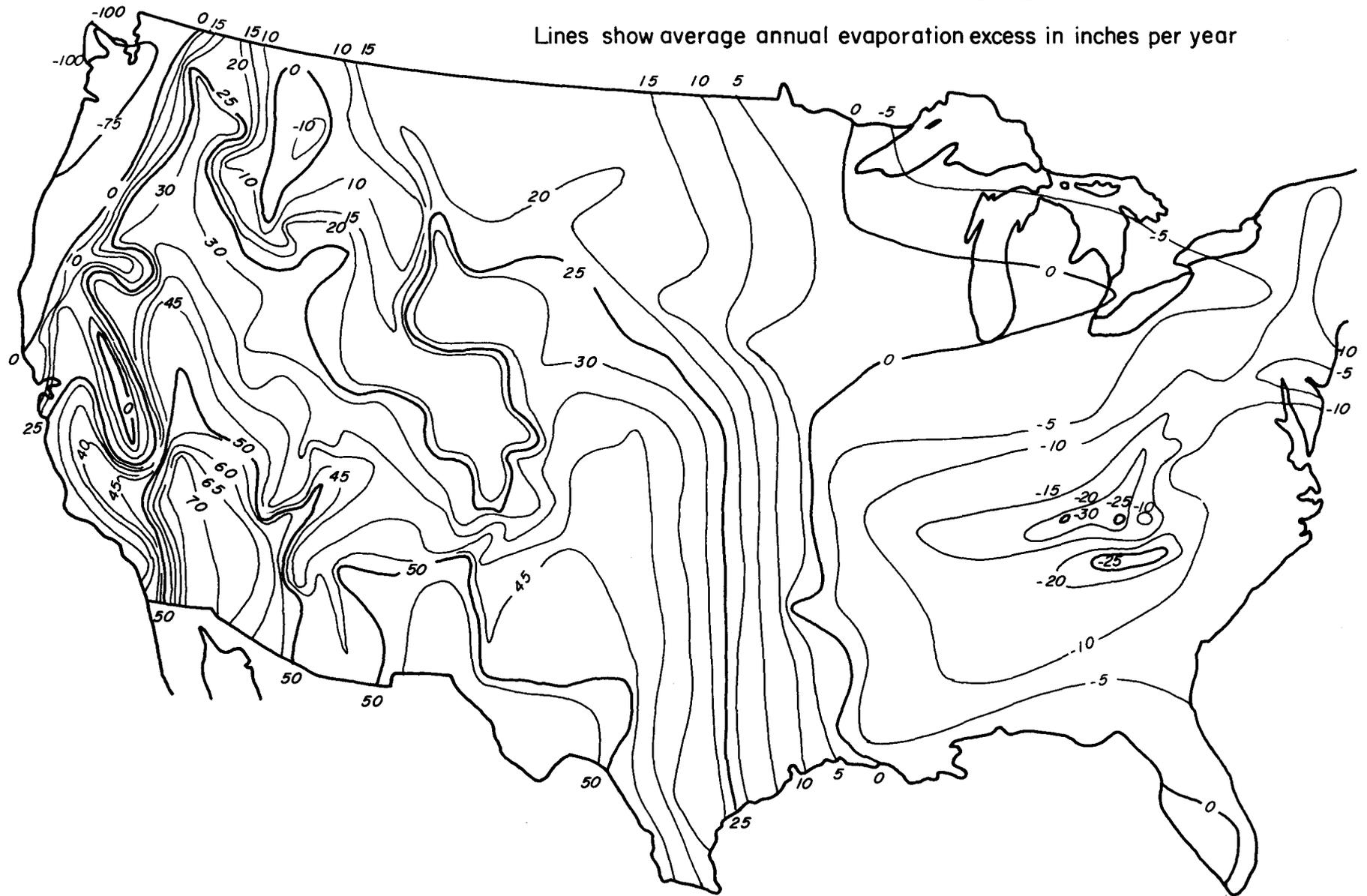


Figure A-1. Comparisons of calculated and measured evaporation.

AVERAGE ANNUAL EVAPORATION EXCESS

Lines show average annual evaporation excess in inches per year

67



Evaporation Excess = Lake (Free - water) Evaporation minus precipitation

Figure A-2.



ABSTRACT

A study was conducted to determine the effect of impoundment on the quality of water in Cheney Reservoir near Wichita, Kans. The reservoir did not stratify during the period of data collection. The increase in the dissolved solids concentration was directly related to evaporation. On an annual basis, 42 percent of the total inflow was evaporated from the reservoir. Suggestions are presented for controlling the dissolved solids concentration. Evaporation control is indicated, but the increase in reservoir temperature (12° to 19° F) may present an undesirable condition. Bypassing the poorest quality waters of the stream serving the reservoir is suggested to reduce the dissolved solids concentration in the reservoir and in the stream below the reservoir. The biological activity within this reservoir did not seem to affect the water quality materially. Odor appears to have stabilized at a threshold odor number of about 5. The effect of the interaction between the microorganisms and nutrients was characterized in the analysis of phosphates, nitrates, and silica concentrations in the reservoir. The dissolved oxygen percent saturation decreased from 100 percent at the water surface to 82 percent at a 25-foot depth.

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Colorado State University Sanitary Engineering Paper No. 4, Fort Collins,
Colo. September 1969.

DESCRIPTORS - *dissolved solids/ evaporation control/ water chemistry/
water temperature/ *reservoir evaporation/ water balance/ heat budget/
*water quality/ *impounded waters/ bypasses/ salinity/ bibliographies/
reservoir design.

IDENTIFIERS - *Cheney Dam, Kans./ USBR Research Contracts.

