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NORFORK LAKE, ARKANSAS, TEMPERATURE ANALYSIS

Mathematical Model Investigation

by

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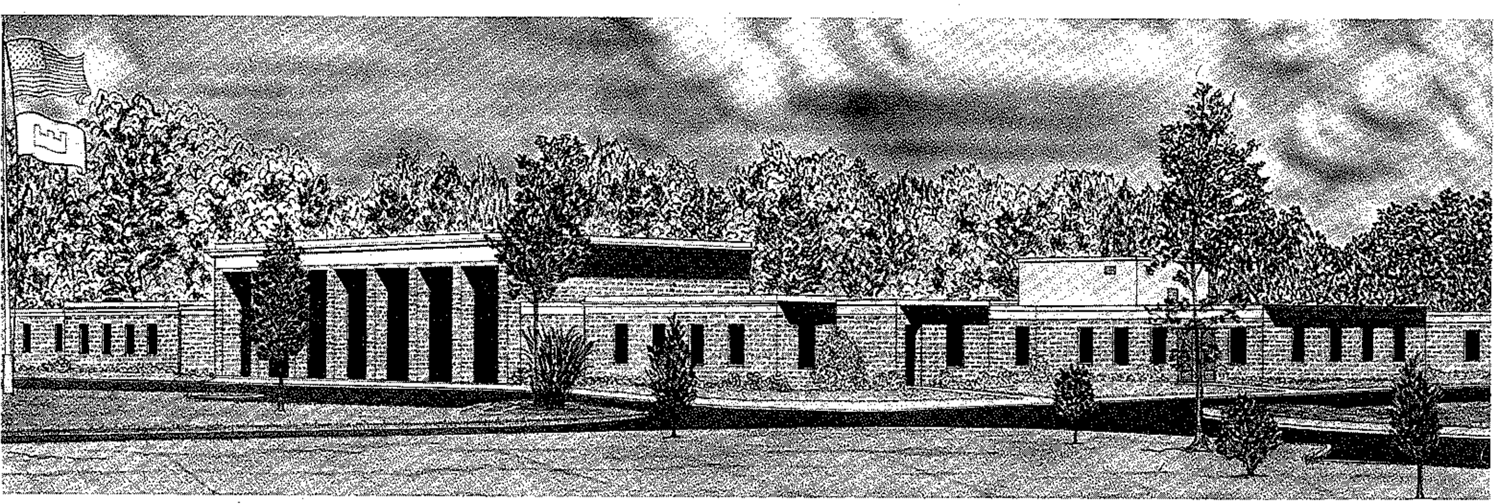
Final Report



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The impact of a proposed hydropower modification upon the thermal structure of the Norfork Lake and upon the releases from the proposed reregulation structure was investigated with a one-dimensional numerical model. The numerical simulation model was adapted from previous analyses of pumped-storage projects (Marysville and Dickey-Lincoln School Lakes hydrothermal studies). The approach involved the selection of three study years (1974, 1975, and 1976) and

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simulation of lake operation for each year both with and without pumped-storage hydropower. The simulations without pumped-storage operations were compared with the existing data bases for the respective years to verify the accuracy of the simulations. Subsequently, the simulations with pumped-storage operations were compared with the simulations with conventional hydropower operations to determine the relative thermal changes both in the reservoir and the release that would have occurred with pumped-storage operations in the respective or similar years.

PREFACE

The study reported herein was authorized by the Office, Chief of Engineers (OCE), U. S. Army, at the request of the U. S. Army Engineer District, Little Rock.

The investigation reported herein was conducted during the period January 1981 to June 1981 in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, J. L. Grace, Jr., Chief of the Hydraulic Structures Division, and Dr. D. R. Smith, Chief of the Reservoir Water Quality Branch (Physical). The study was conducted by Messrs. J. P. Holland and M. S. Dortch. The report was prepared by Messrs. Holland, Dortch, and Dr. Smith and was reviewed by Mr. Grace and Dr. Smith.

Commanders and Directors of WES during the conduct of this study and the preparation and publication of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.856	square metres
acre-feet	1233.482	cubic metres
Btu (International Table)	1055.056	joules
cubic feet	0.02831685	cubic metres
cubic feet per second	0.02831685	cubic metres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

Figure 1. Vicinity map

NORFORK LAKE, ARKANSAS, TEMPERATURE ANALYSIS

Mathematical Model Investigation

PART I: INTRODUCTION

Purpose and Scope of Study

1. The Norfork Lake project was authorized by Congress in the flood Control Act of 28 June 1938 (Public Law 75-761) and modified to include hydroelectric power generation in the Flood Control Act of 18 August 1941 (Public Law 77-228). In addition to flood control and hydroelectric power, Norfork Lake provides recreation and fishery enhancement. The existing project operates with two conventional turbines. The U. S. Army Engineer District, Little Rock (SWL), is presently evaluating a proposed hydropower modification to the project involving the addition of a reregulation pool below the dam and two reversible turbines capable of pumped-storage operations. This study was conducted to investigate the temperature characteristics of the existing Norfork Lake project and to assess changes in these characteristics resulting from the proposed hydropower modification.

Project Description

2. Norfork Dam is located on the Norfork River 4.8 miles* upstream from its confluence with the White River in Baxter County, Arkansas, as shown in Figure 1. The dam reaches a maximum height (el 590**) of 216 ft above the streambed. The length of the dam is 2624 ft; the crest of the spillway, which is 568 ft in length, is at el 552.

3. The top of the conservation pool is at el 550 and el 554 from

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

** All elevations (el) cited herein are in feet referred to National Geodetic Vertical Datum (NGVD).

September to April and April to September, respectively. The lake impounds 1,295,700 acre-ft and covers 22,620 acres at the latter elevation. With the elevation of the lake at the top of the flood-control pool, el 580, the lake impounds 1,983,000 acre-ft, covers 30,700 acres, and has 510 miles of shoreline.

4. Construction of Norfork Dam included the installation of two 35,000-kw generating units and penstocks for future installation of two additional units. The intake center line of the penstocks is at el 447.4 (Figure 2). Should the proposed hydropower modification be

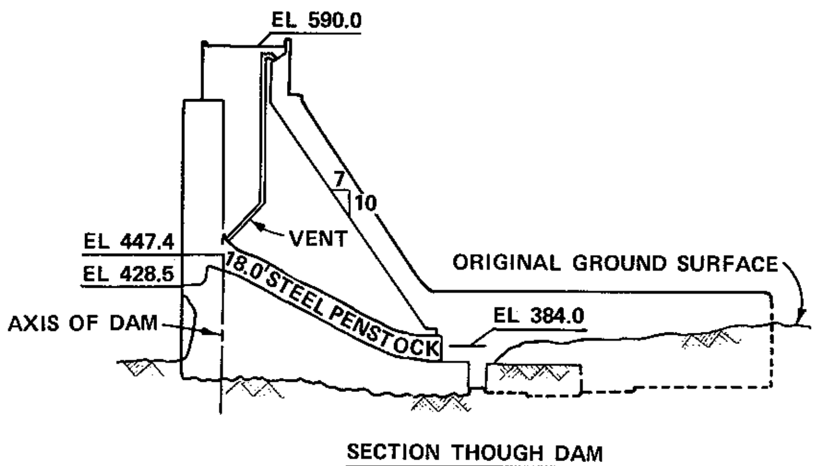

Figure 2. Configuration of penstocks

instituted, two reversible turbines would be added to the project. The proposed hydropower modification would also result in construction of an afterbay just downstream of the dam. The proposed afterbay (at the initiation of this study) would have a volume of 12,600 acre-ft and cover an area of 470 acres at maximum pool el 405. The volume and surface area are 2100 acre-ft and 150 acres, respectively, at minimum pool el 373.

Approach

5. This study was accomplished with the use of a numerical reservoir thermal simulation model adapted from previous analyses of pumped-storage projects (Fontane and Bohan 1974, Dortch et al. 1976, and

Fontane et al. 1977). The approach involved selection of three study years and simulation of lake operation for each year. In order to evaluate the effects of the proposed hydropower modification, simulation was divided into two phases. In the first phase, simulation results from three years of historical data were used to verify the accuracy of the numerical technique and to evaluate the thermal characteristics of the existing project without pumped-storage operations.

6. In the second phase, operating schedules that reflected proposed pumped-storage operations (provided by SWL) replaced their historical counterparts. Simulation results with pumped-storage operations were compared with their Phase 1 counterparts to assess the impact of the proposed hydropower modification upon the thermal characteristics of the project. Output from the simulations for each study year included prediction of in-lake temperature profiles and release temperatures from the dam for both the historical and proposed conditions. In addition, the output also included predicted release temperatures from the afterbay (Phase 2) and predicted stream temperature at the site of the proposed reregulation structure (Phase 1). A one-dimensional steady-state description (described in Appendix A) was used to estimate the change in temperature of releases from the existing Norfork Dam as the flow travels downstream to the site of the proposed reregulation structure. Computing the temperature of the historical releases at the site of the proposed afterbay dam allowed the addition of a more valid assessment of the changes in downstream release temperature resulting from pumped-storage operations.

PART II: NUMERICAL MODEL INPUT REQUIREMENTS

7. The downstream release characteristics and in-lake temperature structures for both the existing and modified versions of Norfork Lake were predicted with a numerical simulation model. An overview of the numerical model and the input data required appears below.

Thermal Model Description

8. The thermal model, hereinafter identified as WESTEX, was developed at the U. S. Army Engineer Waterways Experiment Station (WES) based on the results of Clay and Fruh (1970), Edinger and Geyer (1965), Dake and Harleman (1966), Bohan and Grace (1973), Fontane et al. (1977), Dortch et al. (1976), Bloss and Harleman (1979), and Ford (1976).

9. The WESTEX model provides for the solution of the unsteady one-dimensional (vertical) thermal energy equation for an impoundment and results in the prediction of vertical temperature profiles and release temperatures in the time domain. The model includes computational methods for simulating heat transfer at the air-water interface, advective heat due to inflow, outflow, and pumpback processes, and the internal dispersion of thermal energy. These computational components require various hydrological and meteorological data which are explained in the following paragraphs. The model further requires determination of surface heat exchange coefficients. This determination procedure is explained at the close of this section. A more complete discussion of the WESTEX model appears in Appendix A.

Development of Thermal Model Inputs

10. As stated in the previous paragraph, the WESTEX thermal model requires data for lake inflow and outflow rates, inflow stream temperature, operation schedules, and various meteorological data. Three study years, 1974, 1975, and 1976, were selected due to the availability of historical hydrology and observed temperature profiles. Although it is

customary to select historical study years that display a range of hydrological and meteorological conditions for analysis, the availability of observed temperatures from the U. S. Geological Survey for these years was felt to provide a better reference to the existing project than study years without observed profiles. An overview of the components of input data for the simulation model appears below.

Lake geometry

11. The area-elevation and volume-elevation curves and data describing the location and design of the intake structure were furnished by SWL.

Meteorology

12. Daily averaged values for equilibrium temperature, surface heat exchange coefficient, and net shortwave solar radiation are used within the simulation model to account for the effects of surface heat exchange and short-wave penetration (see Appendix A). Daily averaged values of these parameters are computed (for the study site) from observations of dry bulb temperature, dew-point temperature, wind speed, and cloud cover taken every three hours. These and other meteorological data are collected at weather stations throughout the United States and can be obtained from the National Climatic Center in Asheville, North Carolina.

13. The weather stations nearest the Norfork project which were operative during the study years were at Little Rock, Arkansas, and Springfield, Missouri. The Springfield and Little Rock stations are 80 miles northwest and 100 miles south, respectively, of the Norfork project. Neither of the two stations, as is the case with the project, is located in the Ozark Mountains. As a result, meteorological data considered representative of the conditions at the project were not available. Simulations were executed with the respective data sets to determine if either could be used to approximate meteorological conditions at Norfork. Simulation with the Little Rock meteorological data resulted in predicted thermal profiles at Norfork that were too warm when compared with the observed data. Similar comparison of predicted profiles

obtained using Springfield meteorological data resulted in thermal profiles that were too cold.

14. To circumvent this problem, a regression technique was used to predict representative meteorological conditions at the Norfork project. These predictions were predicted on the correlation of meteorological data from Springfield, Missouri, and Little Rock, Arkansas, with meteorological data from Harrison, Arkansas. A weather station was operative through 1968 at Harrison, Arkansas, which is about 45 miles southwest of the project site. The meteorological data from Harrison, the nearest weather station to the site with any available data and also located in the Ozark Mountains, was considered to be the most representative of the conditions at Norfork Lake. At the time these regressions were performed, meteorological data were available for the entire period of record for Little Rock and Springfield; however, only the period 1967-1968 was readily available for Harrison. With the time constraints of the study, there was not adequate time to order meteorological data for previous years at Harrison. Therefore, observed data for 1967 were used to perform the regression analysis and observed 1968 data were used to evaluate the regressions.

15. Regressions were developed for the dew-point temperature, dry-bulb (or air) temperature, wind speed, and cloud cover. A stepwise, multiple linear regression program obtained from the International and Mathematical Statistical Library (IMSL) was used to perform the regressions and tests for significance. The general form of the regression sought was:

$$\hat{X} = a + b_1 X_{LR} + b_2 X_S + b_3 X_{LR}^2 + b_4 X_S^2 + b_5 X_{LR} X_S$$

where

$\hat{X}$ = the estimate from the regression of the meteorological parameter at Harrison

X_{LR}, X_S = the observed values of the meteorological parameter at Little Rock and Springfield, respectively

a, b_i = values of the coefficients of the regression

A level of 0.05 was used to test the significance of each term of the regression. During the stepwise procedure, insignificant terms are dropped and the regression is repeated. The following regression equations were found for the four meteorological parameters correlated:

$$\hat{T}_d = 0.551 + 0.831\ T_{d_{LR}} + 0.002\ T^2_{d_S}$$

$$\hat{T}_a = 0.05 + 0.721\ T_{a_{LR}} + 0.240\ T_{a_S}$$

$$\hat{W} = 5.492 + 0.047\ W_{LR}\ W_S$$

$$\hat{C} = 1.205 + 0.782\ C_{LR}$$

where

$\hat{}$ = designator for predicted Harrison value of the given parameter
T_d = dew-point temperature, °F
T_a = dry-bulb or air temperature, °F
W = wind speed, miles per hour
C = cloud cover, tenths

The standard deviation of the residuals and the percentage of variation explained are indicated below for each of the four regressions:

Parameter	Standard Deviation of the Residuals	Percentage of Variation Explained
T_d	3.61	95
T_a	4.13	93
W	2.22	52
C	1.83	65

As indicated from the percentage of variations explained, the wind speed and cloud cover at Harrison did not correlate strongly with those observed at Little Rock and Springfield. However, dew-point and air temperatures from Harrison correlated well with Little Rock and Springfield data.

16. Meteorological data from Little Rock and Springfield for 1974-1976 were used in conjunction with the above regressions to predict meteorological conditions at Harrison for the same period. These synthetic Harrison data were used to predict the thermal distribution of Norfork Lake for the study period. Comparison of Norfork Lake temperature profiles predicted from synthetic Harrison data with observed profiles demonstrated poor seasonal correlation. The weak correlation of Harrison wind speed and cloud cover (as discussed in the previous paragraph) with the Little Rock and Springfield conditions suggested that observed values of wind speed and cloud cover at Little Rock could be considered at least as meaningful as the synthetic values predicted for Harrison. Therefore, simulations were again conducted using Little Rock wind speed and cloud cover data and synthetic Harrison dry-bulb and dew-point temperatures for the heat exchange data. This produced computed in-lake temperatures that were in reasonable agreement with observed temperature profiles. Thus, input data resulting from the combination of historical and synthetic meteorological data were used for the study.

Stream temperature

17. Stream temperature records for the three study years were not available. A multiple linear regression equation was provided by SWL based on some observations during 1967 from the nearby Buffalo River. The regression equation relates stream temperature and equilibrium temperature on various preceding days as follows:

$$\Theta(t) = 0.42T_E(t - 2) + 0.31T_E(t - 5) + 19.8$$

where

$\Theta(t)$ = stream temperature of day t, °F

$T_E(t - 2)$ = equilibrium temperature 2 days prior to day t, °F

$T_E(t - 5)$ = equilibrium temperature 5 days prior to day t, °F

The equilibrium temperatures used in the development of the regression equation were computed from 1967 observed Harrison meteorological data.

Flow quantity was included in the preliminary regression and was determined to be statistically insignificant. The equilibrium temperatures used to generate the stream temperatures in this study consisted of those computed with the regression analysis for Harrison as described in paragraphs 12 through 16.

Hydrology

18. Mean daily inflow and outflow rates for the historical routings and the inflow and afterbay release rates supplied by SWL for the proposed project are shown in Plates 1 and 2. Proposed pumpback and generation routings are shown in Plate 3. Because the Norfork Lake power plant is a peaking operation, it is necessary to consider flow rates for short time intervals as well as the total release volume in a day. The total release volume or average flow rate is required to maintain the water balance in the lake during the computations. The actual flow rates are important for defining the selective withdrawal characteristics of the release, especially the upper and lower limits of withdrawal. The historical operation schedule summaries did not provide flow rates, but rather the average hourly power production in megawatts and the total daily discharge were recorded. Although the model can accommodate hourly generation and pumpback periods, this degree of precision was found not to be necessary. Some simplifying assumptions were made relative to the number of daily operation cycles to conserve computer time while maintaining sufficient accuracy to describe the operation schedules for both phases.

19. Historical. The historical hourly power production typically ranged from 10 to 75 Mw. Power generation is functionally dependent on head and flow rate; but, in general, one Norfork turbine operating at full capacity generates about 35 Mw and two turbines generating at full capacity generate about 70 Mw. The operation schedule for the model was determined by identifying the number of hours with the approximate effect of one turbine operating and the number of hours with the approximate effect of two turbines operating. The range of hourly power production from 10 to 52 Mw was assumed to be equivalent to be the effect of one turbine generating. The range from 53 to 75 Mw was assumed to be

equivalent to the effect of both turbines operating. The operation was modeled in Phase 1 as no more than two generation periods per day with the flow duration(s) corresponding to the number of hours in the previously described power ranges. The actual flow rates were determined by assuming that the release from two turbines is twice the flow rate of one turbine. By knowing the total daily average release as provided by SWL and the number of hours of one-turbine release and two-turbine release, the flow rates can be determined from the following:

$$F_1 = \frac{24Q}{(H_1 + 2H_2)}$$

$$F_2 = 2F_1$$

where

F_1 = flow rate for one turbine, cfs
F_2 = flow rate for two turbines, cfs
Q = daily average discharge, cfs
H_1 = number of hours of one-turbine release
H_2 = number of hours of two-turbine release

Conservation of volume is maintained because

$$H_1F_1 + H_2F_2 = 24Q$$

20. Proposed. Operation schedules and routings were provided by SWL for the modified hydropower design. These data included the monthly average value for each of the following items:

a. Daily release rate from the dam.

b. Daily inflow rate into the reservoir.

c. Number of days per week for generation.

d. Number of days per week for pumpback.

e. Number of hours per day that each unit operates for generation.

f. Number of hours per day that each unit operates for pumpback.

g. Flow rate for each unit for generation.

h. Flow rate for each unit for pumpback.

At the request of SWL a constant daily discharge of 100 cfs was added to the release from Norfork Lake to account for leakage and other sources of water loss.

21. The generation cycle simulated by the model was the following:

a. One unit operating for 2 hr at 3,250 cfs.

b. Two units operating for 2 hr at 6,500 cfs.

c. Three units operating for 2 hr at 9,750 cfs.

d. Four units operating for a specified number of hours at 13,000 cfs.

The daily schedule was modeled as one or two generation cycles. For simulation with one generation cycle per day the release flow rate is computed as

$$R = \frac{2(3,250) + 2(6,500) + 2(9,750) + x(13,000)}{6 + x}$$

where

R = release flow rate, cfs

x = number of hours with four units operating

The duration of this flow rate is (6 + x) hours.

22. For simulation with two generation cycles per day, one flow rate was computed as the average rate of one, two, and three units operating.

$$R_1 = \frac{2(3,250) + 2(6,500) + 2(9,750)}{6}$$

$$R_1 = 6,500 \text{ cfs}$$

The duration (D_1) of this flow rate was 6 hr. The second generation cycle represented the flow rate and duration for four units operating.

$$R_2 = 13,000 \text{ cfs for x hr}$$

Thus, simulation of the daily operation schedule as two generation cycles uses the following generation flow rates and durations:

$$R_1 = 6{,}500 \text{ cfs}$$

$$D_1 = 6 \text{ hr}$$

$$R_2 = 13{,}000 \text{ cfs}$$

$$D_2 = x \text{ hr}$$

23. The pumpback schedule was created in a similar manner. Pumpback was modeled as one cycle per day in the following manner:

$$R_p = \frac{H_1 R_{p_1} + H_2 R_{p_2}}{H_1 + H_2}$$

$$D_p = H_1 + H_2$$

where

R_p = pumpback rate, cfs
D_p = duration of pumpback, hr
H_1 = number of hours with one pumpback unit operating
R_{p_1} = flow rate for one pumpback unit (2,650 cfs)
H_2 = number of hours with two pumpback units operating
R_{p_2} = flow rate for two pumpback units (5,300 cfs)

24. Data provided by SWL indicated either 5 or 7 days per week of generation. During weekends with no generation, the 100-cfs leakage was the only quantity released from the lake. In months that pumpback operation were specified, a maximum of 5 days per week of pumpback were used since the schedules provided by SWL indicated no weekend pumped-storage operations.

25. Release flow rates from the Norfork afterbay were computed by WES to satisfy a minimum downstream release of 800 cfs for May-September and 100 cfs for October-April. The afterbay volume, and thus the depth of the afterbay pool, was allowed to fluctuate during the week. However, at the end of each week the afterbay returned to the specified initial volume of 2,100 acre-ft. During weeks with no generation on the weekend, a sufficient volume was retained in the afterbay during the prior weekdays to meet the minimum release requirement on the weekend. The constant 100-cfs leakage was assumed to be available for release from the afterbay. It was determined that in September of each of the study years it was not possible to maintain the 800-cfs minimum release for each day. Thus, for September, the minimum release was maintained for each weekend and for as many days as possible. For the remaining days the afterbay releases were adjusted below the minimum release of 800 cfs so that the pool would return to the specified volume (2,100 acre-ft) at the end of the week.

26. For three holidays in each year (Memorial Day, Independence Day, and Labor Day), no hydropower operations were simulated during the 3-day holiday period. However, the minimum downstream release, which was 800 cfs for each day of the holiday period, was to be maintained. Therefore, the Norfork afterbay volume, and subsequently the afterbay depth, was allowed to increase during the week previous to each 3-day holiday period in the amount required to meet the minimum release for each day of the holiday period. Following release on the third day of the holiday period, the afterbay volume and depth returned to the values specified upon initiation of simulation (2,100 acre-ft and water-surface el 373, respectively).

Determination of Coefficients of Surface Heat Exchange

27. The WESTEX model requires determination of two surface head exchange coefficients. The first, β , is the percentage of incoming solar radiation absorbed in the top 2.0 ft of the water body. The second, λ , is a light extinction coefficient. Calibration of these

coefficients was not required in this study since Secchi disk data existed for Norfork Lake. From data furnished by SWL, the average Secchi disk depth was computed to be 10.1 ft. From this value the light extinction coefficient, λ , was estimated (Williams et al. 1980) to be about 0.20 ft^{-1}. The fraction of light absorbed in the top 2.0 ft, β , corresponding to this value of λ was 0.50. These values were used for this study.

PART III: DISCUSSION OF SIMULATION RESULTS

28. As stated previously, simulation of operations at the Norfork project were divided into two distinct phases. Phase 1 simulated the operation of the existing project with historical data. Phase 2 simulated operation of the project with the proposed addition of pumped-storage facilities. This discussion section will examine the results of simulation of each of these phases individually. A discussion of the sensitivity of the Phase 2 results to the pumpback coefficients used in this study is given next. Using Phase 1 and 2 results, an assessment of the impacts of the proposed pumped-storage addition follows.

Phase 1: Historical Operations

29. Simulation of historical conditions constituted the Phase 1 portion of this study. The initial purpose of the Phase 1 simulations was to validate the numerical model by comparing predicted temperature profiles with observed temperature data. Following validation, Phase 1 (historical) simulations were then required for comparison with those from Phase 2 (proposed) in order to assess the impact of the proposed hydropower modification.

30. Predicted and observed (for the same date) in-lake temperature profiles for Phase 1 (historical) are plotted in Plates 4-6 for all three study years. The predicted temperatures agree reasonably well with the observed. The discrepancies that occurred during the spring are probably due to departures of the meteorological data used for simulation from conditions actually experienced at the project. The exception to the above comparison between the predicted and observed profiles is 15 May 1974. On this date, the predicted and observed profile do not compare favorably quantitatively or qualitatively. This discrepancy is believed to be due to instrument failure. Several observations support this conclusion. The observed profile for 15 May 1974 does not appear correct when compared with the observed profiles for April or July 1974. The observed profile for 15 May 1974 suggests

more heat in the hypolimnion in May than that observed in July 1974. Additionally, the May profile appears atypical when compared with the general trends of the profile for all of 1974, 1975, and 1976. With this exception, the comparison between predicted and observed profiles was adequate and validation was considered to be demonstrated.

31. To provide a meaningful comparison of release temperatures from the proposed (Phase 2) reregulation pool (afterbay) with Phase 1 (historical) release temperatures, it was necessary to predict the expected temperature of the release after it is routed to the site of the afterbay dam (see Appendix A). The Phase 1 predicted average Norfork Dam release temperatures are plotted versus time in Plate 7. The predicted daily average temperature of the release from Norfork Dam which has been routed downstream to the proposed afterbay damsite is also plotted in Plate 7 and tabulated in Tables 1-3. The maximum predicted release temperature from Norfork Dam in the study years simulated was 18.5°C on 19 October 1974. The maximum predicted temperature of water released from Norfork Dam and routed downstream to the site of the proposed reregulation dam was 18.8°C on 26 October 1974. Plate 7 shows that because of the short time of travel from Norfork Dam to the proposed reregulation damsite, there is little opportunity for significant change in the temperature of the release in most instances. The maximum temperature difference between the release temperatures at Norfork Dam and the routed downstream temperature at the proposed reregulation damsite was 7.9°C on 7 April 1976. This warming, and most other periods of significant warming for the years simulated, occurred during a period of both very low releases (as low as 120 cfs) from Norfork Dam and warm meteorological conditions. The predominant flow rates for the study years were well above the very low releases associated with larger temperature increases. Therefore, warming of the routed releases was generally small as shown in Plate 7.

32. From comparison of predicted 1974 release temperatures with those of 1975 and 1976, it was noticed that 1974 releases are warmer than 1975 and 1976. This was attributed to the larger advection (inflow and outflow) that occurred during the spring of 1974 (see Plate 1

routings). The larger advection moved more heat deeper into the reservoir earlier in the simulation period in 1974 than in either 1975 or 1976.

Phase 2: Proposed Pumped-Storage Operations

33. The Phase 2 simulations were conducted to evalute the impact of the proposed pumped-storage operations and the reregulation pool on the thermal characteristics of the project.

34. Predicted in-lake temperature profiles for Phases 1 and 2 are plotted together for comparison in Plates 8-10. From this comparison it is obvious that the proposed pumped-storage operations result in increased summer warming of the hypolimnion of up to 5°C above that observed without pumped-storage operations. Additionally, this increased rate of warming of the hypolimnion would cause fall overturn to occur earlier as shown in Plates 8-10. The thermal characteristics of the epilimnion are changed very little from that predicted for the Phase 1 simulations. This is due to the tendency of the epilimnion to rapidly seek an equilibrium condition through surface heat exchange.

35. Most of the changes in the temperature profiles can be attributed to the advective characteristics of pumped-storage operation and mixing due to the pumpback jet. The Norfork Lake intake is located deep in the hypolimnion and cold water is withdrawn from the hypolimnion during the generation cycle. The withdrawal volume is replaced by warmer water from a higher level in the pool. This warming occurs with or without pumped-storage operations. The water released downstream into the afterbay is exposed to ambient meteorological conditions and subsequently some of it is pumped back into Norfork Lake. The pumpback volume enters the lake as a jet, entrains water from the hypolimnion, and the mixed jet seeks a level of neutral buoyancy. All of the pumpback processes combine to effect a warming of the hypolimnion.

36. Some differences in the Phase 1 and 2 profiles do exist, however, which are due to differences in the proposed and historical generation schedules rather than the pumpback mixing. For example,

differences in the profiles prior to August 1974 are due to different generation patterns between the two phases since pumpback did not commence until August of that year. Although these profile differences in 1974 were prior to the commencement of actual pumpback operations, they are attributable to variations in project operations due to pumped-storage capability. With pumped-storage operations, more generation can occur prior to or on a given day than with conventional hydropower operations since the power pool, which is lowered by generation, is later resupplied by the quantity of water pumped back. This is particularly evident during the 1974 study year. With the proposed operations, more generation occurred prior to August than with historical operations. This is reflected in the July profiles by a lower water elevation and warmer hypolimnion region with proposed operations than with historical operations. Thus, pumped-storage capability often affects the water and thermal budgets of the reservoir prior to pumpback because the generation pattern reflects anticipation of pumpback.

37. The Phase 2 predicted average release temperatures from both the Norfork Dam and reregulation dam are plotted versus time in Plate 11. Additionally, the predicted daily release temperatures from the reregulation dam are tabulated in Tables 4-6. The maximum release temperature from Norfork Dam was computed to be 19.6°C on 5 October 1974; the predicted afterbay maximum was 20.3°C on 25 August 1974. Retention in the afterbay of the releases from Norfork Dam allows some natural warming to occur prior to release from the afterbay. The magnitude of warming (or cooling) in the reregulation pool depends upon a coupling of meteorological conditions and operational strategy. As net flow rate through the afterbay increases, the temperature change within the afterbay is reduced. Increased flow through the afterbay results in decreased detention of Norfork Dam releases in the afterbay. Subsequently, the warming (or cooling) of these releases is lessened. The warming effect (during spring and summer) of the afterbay for the operating conditions simulated is indicated in Plate 11. The release temperature from the afterbay was greater than 20°C only twice in the three study years; both times were in 1974.

Sensitivity of Release Temperature Predictions to Pumpback Coefficients

38. As stated in Appendix A, the amount of pumpback entrainment is an input into the model which is specified by the value of the entrainment coefficient E . The amount of entrainment is related to structure and reservoir geometry, momentum and buoyancy flux, boundary proximity, and ambient stratification. General descriptions of entrainment for these relationships are not complete. Research is being conducted at WES to develop relationships for estimating E for various source and ambient conditions. Physical models have been used in previous studies (Dortch et al. 1976, Fontane et al. 1977, Smith et al. 1981) and are often necessary to evaluate both withdrawal characteristics and E accurately for site-specific conditions. Due to the time and funding constraints of this study, the construction of a physical model and an experimental determination of the entrainment were not conducted. However, the use of this hybrid coupling of both physical and numerical model simulations may be a future consideration.

39. Estimates of E were made (Roberts 1981*) for a range of flow and stratification conditions. These estimated values of E varied from about 1.9 for a 1,000-cfs pumped flow per unit into a strong density stratification to approximately 5.0 for a 2,650-cfs pumped flow per unit into a mild stratification. A value of 2.5 was used for E in the Phase 2 simulations as shown in Plates 8-11. To assess the effect on release temperatures for greater entrainment rates, simulations were made with E = 5.0 . The computed Norfork Dam and afterbay release temperatures for this condition are presented in Plate 12. As expected, the larger value for E resulted in increased warming of the hypolimnion and higher release temperatures. These results represent an approximate upper bound with respect to the effects of entrainment. To better compare the effect of higher entrainment on the project release temperatures,

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* Personal communication, Apr 1981, from Philip J. W. Roberts, Department of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga.

the differences between predicted afterbay release temperatures for E = 5.0 and E = 2.5 are plotted in Plate 13 for 1975. This year was more sensitive to a change in E than the other two study years. The higher value of E increased the afterbay release temperature a maximum of 2°C during the fall. A temperature increase of at least 1.0°C was noted with the higher E between August and early November.

40. Another coefficient required by the model, PBCOF, represents the fraction of generation water released earlier in the day that is contained in the pumpback flow (see Appendix A). The remaining portion of pumped flow is composed of afterbay water already in residence in the afterbay prior to the given day's generation. This coefficient is important because it ultimately affects the average temperature of both the pumpback flow and the generation inflow into the afterbay. The generation water that is not pumped back is mixed with the remaining afterbay volume. The value of PBCOF used for the initial Phase 2 simulations was 0.5. Additional simulations were made for the extreme conditions of PBCOF = 0 and 1.0 . Of primary interest was the increased warming of afterbay releases with these latter two values of PBCOF when compared with the base condition (PBCOF = 0.5). A 0.0 value of PBCOF simulates no pumpback of water released by the prior generation cycle. Conversely, a 1.0 value of PBCOF simulates a pumpback flow consisting totally of water released earlier in that day. Both of these pumpback scenarios are unrealistic due to mixing of afterbay waters and water released at the time of generation which would preclude both scenarios. However, these values for PBCOF were chosen in order to obtain bounds on the changes in afterbay release temperature resulting from these extreme values. Plots of predicted Norfork Dam and afterbay release temperatures for PBCOF equal to 0.0 and 1.0 are shown in Plates 14 and 15. These plates indicate that in general, slightly warmer afterbay releases occurred with PBCOF = 1.0 than with PBCOF = 0.0 . Thus, afterbay release temperatures with PBCOF = 1.0 were compared with those predicted for PBCOF = 0.5 in Plate 16 for the most sensitive study year, 1975. From this plot, it is recognized that the maximum possible value of PBCOF (1.0) increased the afterbay release temperature about 2°C during

July 1975 over the base condition of PBCOF = 0.5 . The remaining discussions comparing proposed and historical simulations are for Phase 2 results obtained with E = 2.5 and PBCOF = 0.5 .

Phase 2 Versus Phase 1 Downstream Temperatures

41. The predicted daily average temperatures of the afterbay release for Phase 2 (proposed) are plotted in Plate 17 with the Phase 1 (historical) release temperatures routed to the afterbay damsite. Although only every second day is plotted for Phase 2, these plots allow a visual evaluation of the impact of the proposed project modifications on the stream temperature immediately downstream of the proposed reregulation dam. It is readily apparent that pumped-storage and reregulation operations will warm the releases as compared with historical operations. Two pumped-storage operational effects contribute to these warmer releases at the reregulation dam. First, pumpback flows warm the lake hypolimnion (Plates 8-10), which results in warmer releases from the Norfork Dam. Secondly, the increased residence time in the reregulation pool will result in additional warming during much of the year. The magnitude of the latter effect is directly coupled with the operation characteristics of both the hydropower facilities and the releases from the reregulation structure. Results presented in Plate 17 reflect both of these effects. The apparent scatter in the predicted afterbay release temperatures is primarily due to the operational strategy simulated.

42. The effect of the operational strategy simulated for Norfork pumped-storage operations upon release thermal characteristics, and its severity, may be evaluated in two steps. First, a typical 2-week operation schedule (18 August-1 September 1975) is given in Table 7 and shown graphically in Figure 3. Table 7 shows that pumped-storage operations resulted in a 2.5-3.0°C increase in the temperatures of releases from Norfork Dam when compared with the temperatures of Norfork Dam releases for historical operations. Further examination of the table shows that detention of Phase 2 Norfork Dam releases in the afterbay during weekdays

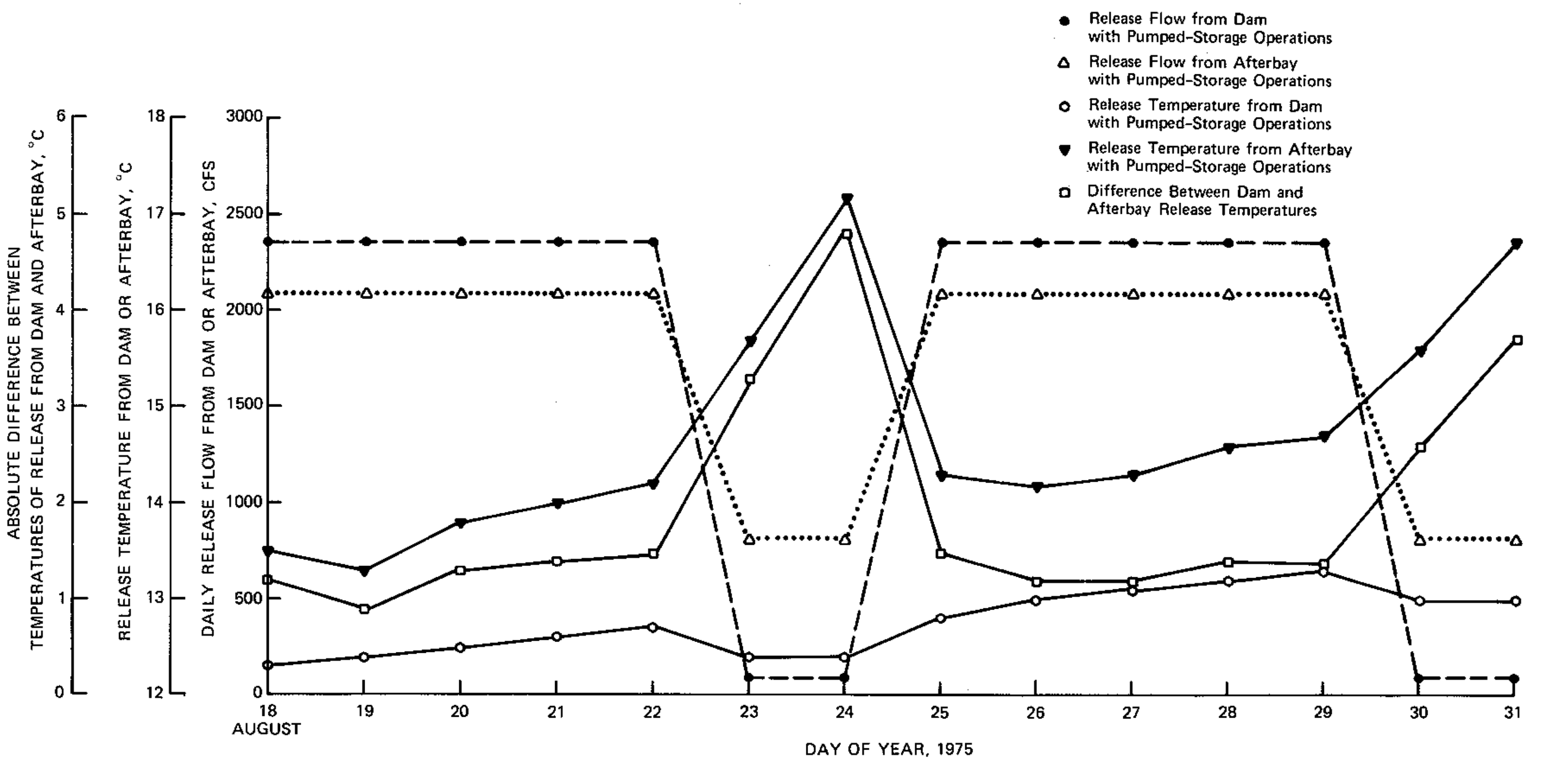

Figure 3. Effects of proposed hydropower operations on typical summer 2-week period upon release temperature

(e.g., 18-22 August) resulted in an additional 1.0-1.5°C warming of these releases. During this period, both generation and pumpback operations occurred. However, on weekends (e.g., 23-24 August) no hydropower operations occurred; only 100-cfs leakage from Norfork Dam flowed into the afterbay. Thus, waters warmed by afterbay residence remained warm on weekends due to the lack of cooler generation flow from Norfork Dam. However, the minimum downstream release, 800 cfs, was still required. To meet this minimum on weekends, these waters warmed by increased afterbay residence times must be released. The effect of this operation is shown vividly both in Table 7 and Figure 3. The difference between the temperature of release from the dam and the release from the afterbay increased from 1.5°C on 22 August to 3.3°C on 23 August. This difference increased further to 4.8°C on 24 August (Sunday). Resumption of generation on Monday, 25 August, reduced the predicted "afterbay-dam" temperature difference back to 1.5°C.

43. The severity of "no weekend generation" is further enhanced when a 3-day holiday weekend occurs which experiences warm meteorological conditions. Three such holidays (Memorial Day, Independence Day, and Labor Day) were simulated with no hydropower operations during any part of each 3-day holiday period. The effect of this operation upon predicted afterbay release temperatures is seen in Table 7 for Labor Day, 1975. Afterbay release temperatures increased approximately 1.1°C for each day of the holiday period. Further, the difference in the afterbay release temperature and the routed release temperature from Phase 1 increased from 4.0°C on 29 August to a maximum simulated difference of 7.0°C on 1 September. Thus, approximately a 3.0°C increase in afterbay release temperature is directly attributable to the operational strategy employed for this holiday period. Table 8 shows very similar results for the majority of the holiday periods simulated. Further, from the above analysis, it is apparent that most regular weekend periods with no hydropower operations and warm meteorological conditions will experience an analogous warming of generally lesser severity. When historic releases from Norfork Dam are small and warm meteorological conditions occur, the routed release temperatures will increase as

explained in paragraph 31. When this occurs on a weekend (i.e. 23-24 August 1974) the difference between the routed and afterbay release temperatures may be less than expected. This smaller difference should not be viewed as an overall lessening of warming due to pumped-storage operations for the period, but rather as a period in which, for the conditions simulated, significant warming would have occurred with or without pumped-storage operations.

44. The maximum afterbay release temperature predicted for the 3 years simulated was 20.3°C on 25 August 1974. Only two times in the years studied did the afterbay release temperature exceed 20.0°C. Both occasions were Sundays with no weekend hydropower operations. By comparison, a maximum routed (Phase 1) release temperature of 18.8°C was predicted on 26 October 1976.

PART IV: SUMMARY

46. Effects of proposed pumped-storage operations on Norfork Lake thermal characteristics were predicted for three study years. Numerical simulation indicated that the hypolimnion of Norfork Lake may be up to 5.0°C warmer in the summer and will overturn faster with pumped-storage operation than with the existing conventional hydropower operation. This warming is due both to pumpback jet mixing and differences in generation quantity between the proposed and historical phases. The epilimnion, however, will remain relatively unchanged with either type of hydropower operation. As a result of this hypolimnion warming, releases from Norfork Lake will be warmer with pumped-storage operation than with the existing hydropower operation.

47. The predicted maximum temperature of release from the Norfork afterbay was 20.3°C; further, only two times in the 3 years simulated was an afterbay temperature predicted greater than 20.0°C. Both occasions were on weekends with no hydropower releases. Considerable warming can occur in the afterbay during periods of warm meteorological conditions and little or no release from Norfork Dam. The afterbay release temperature warmed approximately 1°C each day of several 2-day weekends that had no hydropower operations. The severity of this temperature increase was exacerbated for three simulated holiday periods (Memorial Day, Independence Day, and Labor Day) during which no hydropower operations occurred for a 3-day period. A maximum predicted increase of 7.0°C in the afterbay release temperature (Phase 2) over the expected temperature of releases routed downstream from Norfork Dam to the site of the proposed reregulation dam (Phase 1) occurred on 1 September 1975 (Labor Day). At least 3.0°C of this difference was found to be directly attributable to the lack of hydropower operations for the 3-day period. For the three holiday periods simulated, the temperature of release from the Norfork afterbay was generally 1.0 to 3.5°C warmer on the third day of the holiday period than on the first.

48. The confidence with which these temperature predictions are asserted must be weighed against the assumptions made in the numerical

model. As explained in paragraphs 38-40, a coefficient representing the total entrainment volume of the pumpback jet (E) was assumed to be 2.5. Sensitivity analysis indicated that the choice of E = 5.0 warmed the afterbay temperatures 1 to 2°C from August to early November for 1975. A second pumpback coefficient relating the percent of generation flow returned to the lake in the pumpback flow, PBCOF, was assumed to be 0.5 for the study. Analysis showed that simulation with PBCOF = 1.0 warmed the afterbay releases up to 2.0°C in July 1975 above the afterbay release temperatures predicted for PBCOF = 0.5 . Further variability of prediction could be introduced due to the difficulty with which representative meteorological data (described in paragraphs 12-16) were obtained. Two sources of variability remain. The descriptions of selective withdrawal and pumpback used in this study were assumed from previous studies (Bohan and Grace 1973, Fontane et al. 1977, and Dortch et al. 1976) without aid of a physical model study. Finally, the proposed routing scheme with pumped-storage operations supplied by SWL contained monthly average hydropower operations since the study was conducted early in the planning phase. These routings may not accurately represent the daily operations which will be implemented.

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Table 1

Average Temperature of Historical Releases from Norfork Dam Routed Downstream to Proposed Reregulation Structure, 1974

Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C
1	9.2	51	7.6	101	8.2	151	9.8	201	12.1	251	16.8	301	16.7	351	10.8
2	9.0	52	7.7	102	8.3	152	9.9	202	12.2	252	16.5	302	18.0	352	10.6
3	8.5	53	7.7	103	13.8	153	10.1	203	12.4	253	16.6	303	17.8	353	10.6
4	8.5	54	7.8	104	10.6	154	9.9	204	12.6	254	16.8	304	17.5	354	10.3
5	8.3	55	7.5	105	8.1	155	9.9	205	12.5	255	16.8	305	18.5	355	10.3
6	8.1	56	7.6	106	8.2	156	10.0	206	12.6	256	16.6	306	18.6	356	10.5
7	7.9	57	7.6	107	8.2	157	10.3	207	12.8	257	17.0	307	17.9	357	10.6
8	7.9	58	7.7	108	8.3	158	10.9	208	13.0	258	17.2	308	17.4	358	10.4
9	7.4	59	7.7	109	8.4	159	11.4	209	12.9	259	16.8	309	17.6	359	10.0
10	7.4	60	7.8	110	12.1	160	11.5	210	13.0	260	16.9	310	17.6	360	9.9
11	7.0	61	7.9	111	8.5	161	10.8	211	12.9	261	17.1	311	17.3	361	9.9
12	6.9	62	8.0	112	8.5	162	11.1	212	13.1	262	17.1	312	17.3	362	9.6
13	6.9	63	7.9	113	8.4	163	10.6	213	13.7	263	17.2	313	17.2	363	9.9
14	6.8	64	7.7	114	8.4	164	11.1	214	13.4	264	17.4	314	16.4	364	9.8
15	7.0	65	8.0	115	8.4	165	11.5	215	13.9	265	16.8	315	15.9	365	9.8
16	7.0	66	7.9	116	8.5	166	11.2	216	14.0	266	16.2	316	15.7		
17	7.1	67	7.9	117	8.7	167	11.0	217	13.5	267	17.0	317	15.8		
18	7.0	68	8.0	118	8.9	168	11.1	218	13.5	268	17.1	318	15.6		
19	7.1	69	7.8	119	8.9	169	11.8	219	13.8	269	17.2	319	15.3		
20	7.0	70	7.9	120	8.9	170	11.7	220	14.4	270	17.3	320	15.2		
21	7.1	71	7.7	121	8.7	171	12.5	221	14.6	271	17.0	321	15.2		
22	7.1	72	7.7	122	8.8	172	11.8	222	14.8	272	17.7	322	15.1		
23	7.0	73	7.7	123	8.6	173	12.3	223	14.4	273	17.3	323	15.2		
24	7.0	74	7.8	124	8.5	174	11.4	224	14.0	274	17.3	324	14.9		
25	7.0	75	7.7	125	8.5	175	10.7	225	14.7	275	17.2	325	15.0		
26	7.1	76	7.7	126	8.6	176	10.6	226	14.8	276	17.4	326	14.8		
27	7.1	77	7.9	127	8.8	177	10.6	227	14.8	277	17.4	327	14.8		
28	7.1	78	7.7	128	8.9	178	10.6	228	15.0	278	18.0	328	14.5		
29	7.2	79	7.7	129	8.8	179	10.7	229	15.3	279	18.1	329	14.6		
30	7.2	80	7.7	130	8.7	180	11.2	230	15.5	280	17.4	330	14.5		
31	7.2	81	7.7	131	8.9	181	11.2	231	15.0	281	17.6	331	14.3		
32	7.3	82	7.4	132	9.0	182	11.3	232	15.3	282	17.7	332	14.1		
33	7.3	83	7.5	133	9.4	183	11.3	233	15.4	283	17.8	333	13.7		
34	7.3	84	7.7	134	9.1	184	11.4	234	15.4	284	17.8	334	13.0		
35	7.2	85	7.8	135	9.2	185	11.5	235	15.5	285	18.2	335	12.7		
36	7.3	86	7.9	136	9.3	186	11.3	236	15.7	286	18.3	336	12.9		
37	7.2	87	7.9	137	9.6	187	11.3	237	16.0	287	17.6	337	12.9		
38	7.2	88	7.9	138	9.5	188	11.7	238	15.7	288	17.4	338	12.8		
39	7.3	89	7.8	139	9.5	189	11.5	239	15.9	289	17.9	339	12.6		
40	7.3	90	8.2	140	9.5	190	11.6	240	16.0	290	17.9	340	12.6		
41	7.4	91	11.7	141	9.3	191	11.9	241	15.8	291	18.0	341	12.2		
42	7.4	92	8.0	142	9.5	192	12.1	242	15.9	292	18.5	342	12.0		
43	7.5	93	8.0	143	9.4	193	11.6	243	16.1	293	16.7	343	11.7		
44	7.5	94	7.8	144	9.4	194	11.6	244	16.6	294	17.6	344	11.7		
45	7.4	95	7.8	145	9.3	195	11.8	245	16.0	295	17.9	345	11.5		
46	7.4	96	7.9	146	9.3	196	12.1	246	16.0	296	17.8	346	11.5		
47	7.5	97	8.1	147	9.5	197	12.0	247	16.0	297	17.7	347	11.4		
48	7.5	98	7.9	148	9.9	198	11.8	248	16.1	298	17.7	348	11.3		
49	7.5	99	7.9	149	10.1	199	12.2	249	16.3	299	18.8	349	11.2		
50	7.6	100	8.0	150	10.1	200	12.3	250	16.4	300	17.9	350	10.8		

Table 2

Average Temperature of Historical Releases from Norfork Dam Routed Downstream to Proposed Reregulation Structure, 1975

Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C
1	9.7	51	7.5	101	7.9	151	14.6	201	12.6	251	11.8	301	12.7	351	10.2
2	9.6	52	7.6	102	8.0	152	14.3	202	10.1	252	11.4	302	13.1	352	10.2
3	9.4	53	7.6	103	7.9	153	9.6	203	10.4	253	11.5	303	17.7	353	10.0
4	9.3	54	6.9	104	8.2	154	9.8	204	10.2	254	14.0	304	12.6	354	9.9
5	9.0	55	7.2	105	8.3	155	9.9	205	10.1	255	12.2	305	14.8	355	9.9
6	9.2	56	7.4	106	8.4	156	9.6	206	10.4	256	12.4	306	14.6	356	9.6
7	9.3	57	7.2	107	8.4	157	9.8	207	10.8	257	12.4	307	12.9	357	9.5
8	9.2	58	7.3	108	8.5	158	9.8	208	10.1	258	11.1	308	13.7	358	9.1
9	9.4	59	7.3	109	8.4	159	10.8	209	10.3	259	13.6	309	13.8	359	8.0
10	8.9	60	7.3	110	8.5	160	15.1	210	10.4	260	15.1	310	13.3	360	8.9
11	8.9	61	7.2	111	8.5	161	9.7	211	10.8	261	16.4	311	14.3	361	7.6
12	8.7	62	7.2	112	8.6	162	10.9	212	10.9	262	12.2	312	15.0	362	8.5
13	8.5	63	7.3	113	8.8	163	10.0	213	10.6	263	13.7	313	14.2	363	8.1
14	8.5	64	7.3	114	9.0	164	10.6	214	11.4	264	11.8	314	13.6	364	7.4
15	8.4	65	7.4	115	8.8	165	12.4	215	12.1	265	12.4	315	13.7	365	7.0
16	8.1	66	7.4	116	8.9	166	12.1	216	12.1	266	11.8	316	13.5		
17	8.1	67	7.3	117	9.0	167	10.4	217	10.9	267	11.5	317	13.5		
18	8.1	68	7.3	118	8.8	168	10.0	218	12.4	268	11.5	318	13.6		
19	8.0	69	7.3	119	8.8	169	10.1	219	12.7	269	11.8	319	12.8		
20	7.9	70	7.3	120	8.7	170	10.0	220	10.5	270	13.3	320	13.3		
21	7.9	71	7.1	121	8.8	171	9.9	221	12.6	271	11.7	321	13.6		
22	7.8	72	6.9	122	8.8	172	11.7	222	12.1	272	11.6	322	13.7		
23	7.8	73	7.1	123	8.9	173	11.8	223	11.7	273	11.6	323	13.8		
24	7.8	74	6.9	124	8.9	174	9.7	224	10.9	274	12.4	324	13.9		
25	7.8	75	7.1	125	9.1	175	9.8	225	10.7	275	11.8	325	13.7		
26	7.8	76	7.0	126	9.0	176	9.9	226	10.6	276	11.6	326	13.3		
27	7.9	77	7.3	127	9.0	177	9.9	227	12.5	277	12.6	327	13.2		
28	8.0	78	7.3	128	9.0	178	9.8	228	12.9	278	12.7	328	13.0		
29	7.8	79	7.3	129	9.1	179	10.2	229	12.7	279	11.7	329	12.6		
30	7.9	80	7.3	130	9.0	180	10.3	230	11.3	280	11.8	330	12.2		
31	7.8	81	7.2	131	9.1	181	10.0	231	10.7	281	11.9	331	12.1		
32	7.8	82	7.3	132	9.3	182	10.0	232	10.6	282	12.2	332	12.0		
33	7.7	83	7.1	133	9.3	183	10.1	233	10.6	283	12.1	333	13.1		
34	7.8	84	7.1	134	9.2	184	10.1	234	10.6	284	13.0	334	11.7		
35	7.9	85	7.1	135	9.3	185	12.7	235	13.6	285	13.0	335	11.7		
36	7.6	86	7.2	136	9.3	186	13.1	236	13.3	286	12.0	336	11.3		
37	7.3	87	7.1	137	14.2	187	13.5	237	10.7	287	12.3	337	11.3		
38	7.4	88	6.9	138	15.2	188	9.8	238	10.9	288	12.0	338	11.7		
39	7.4	89	7.2	139	9.8	189	10.2	239	10.6	289	12.0	339	12.0		
40	7.2	90	7.2	140	9.5	190	11.6	240	10.7	290	11.9	340	9.4		
41	7.1	91	7.3	141	9.7	191	10.7	241	10.7	291	12.1	341	10.3		
42	7.1	92	7.2	142	9.8	192	10.5	242	10.7	292	12.1	342	10.8		
43	7.1	93	7.4	143	9.8	193	12.6	243	10.7	293	12.0	343	10.8		
44	7.1	94	7.5	144	10.4	194	12.1	244	10.8	294	12.4	344	10.9		
45	7.2	95	7.5	145	10.4	195	10.2	245	10.9	295	12.0	345	10.9		
46	7.2	96	7.6	146	9.6	196	10.0	246	11.0	296	12.5	346	11.1		
47	7.3	97	7.6	147	9.4	197	10.2	247	11.1	297	15.1	347	12.9		
48	7.3	98	7.7	148	9.3	198	10.3	248	11.0	298	10.5	348	13.2		
49	7.3	99	7.8	149	9.3	199	10.0	249	12.9	299	12.8	349	10.7		
50	7.4	100	7.8	150	9.5	200	12.4	250	14.8	300	12.2	350	10.5		

Table 3

Average Temperature of Historical Releases from Norfork Dam Routed Downstream to Proposed Reregulation Structure, 1976

Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C
1	10.0	51	7.1	101	7.1	151	11.2	201	9.5	251	12.1	301	14.3	351	7.4
2	9.0	52	5.8	102	7.2	152	8.4	202	9.6	252	12.6	302	14.3	352	7.4
3	5.4	53	6.5	103	7.1	153	7.8	203	9.4	253	14.0	303	10.6	353	7.7
4	6.3	54	6.4	104	7.2	154	8.4	204	9.6	254	13.1	304	11.2	354	7.6
5	8.8	55	6.5	105	7.5	155	8.5	205	9.6	255	13.3	305	13.9	355	6.9
6	8.8	56	6.7	106	7.7	156	9.9	206	12.2	256	12.1	306	13.9	356	6.7
7	8.0	57	6.6	107	7.6	157	9.3	207	9.5	257	12.2	307	13.9	357	6.7
8	7.9	58	6.7	108	14.4	158	8.3	208	9.9	258	12.3	308	13.8	358	6.5
9	7.5	59	6.8	109	8.0	159	8.5	209	9.9	259	12.4	309	13.3	359	5.6
10	7.0	60	6.8	110	7.3	160	8.2	210	10.2	260	12.5	310	11.3	360	5.2
11	7.2	61	7.4	111	7.7	161	8.2	211	9.6	261	14.2	311	13.7	361	6.3
12	7.3	62	7.3	112	7.5	162	8.4	212	10.1	262	14.4	312	12.9	362	6.6
13	7.2	63	7.3	113	9.5	163	8.8	213	10.6	263	13.5	313	12.3	363	6.2
14	7.2	64	8.3	114	12.5	164	8.5	214	11.9	264	13.6	314	13.1	364	6.1
15	7.0	65	5.5	115	11.3	165	8.6	215	12.3	265	14.0	315	13.0	365	5.4
16	6.8	66	6.8	116	7.2	166	8.6	216	11.4	266	13.6	316	12.4		
17	6.5	67	6.6	117	7.4	167	8.8	217	12.4	267	13.6	317	8.3		
18	6.2	68	6.6	118	7.4	168	8.3	218	11.1	268	14.7	318	7.6		
19	6.6	69	7.0	119	8.3	169	9.0	219	10.4	269	14.9	319	11.0		
20	6.5	70	7.3	120	8.1	170	9.8	220	11.2	270	13.8	320	11.4		
21	6.6	71	7.4	121	9.0	171	11.1	221	10.1	271	14.3	321	11.4		
22	6.7	72	7.1	122	11.0	172	8.3	222	9.9	272	13.6	322	11.2		
23	7.0	73	6.3	123	9.8	173	8.4	223	10.1	273	13.6	323	11.4		
24	8.1	74	7.0	124	9.7	174	8.5	224	10.4	274	13.7	324	11.6		
25	6.4	75	7.0	125	7.8	175	8.8	225	10.4	275	14.0	325	10.9		
26	6.4	76	6.7	126	11.2	176	8.7	226	10.6	276	14.3	326	10.9		
27	6.5	77	7.1	127	12.2	177	8.5	227	15.3	277	13.0	327	10.8		
28	6.5	78	8.6	128	8.5	178	8.8	228	10.4	278	14.0	328	10.7		
29	6.6	79	12.2	129	10.6	179	9.1	229	10.8	279	13.7	329	10.4		
30	6.6	80	9.9	130	8.2	180	8.9	230	10.7	280	13.4	330	11.0		
31	6.5	81	7.0	131	9.2	181	9.2	231	10.8	281	12.4	331	12.3		
32	6.5	82	7.3	132	13.3	182	9.4	232	10.8	282	12.5	332	8.7		
33	6.5	83	7.5	133	9.2	183	10.7	233	10.6	283	13.6	333	9.9		
34	6.4	84	7.0	134	9.7	184	12.6	234	10.8	284	13.7	334	9.7		
35	6.6	85	7.4	135	12.2	185	13.5	235	10.9	285	13.7	335	9.5		
36	6.3	86	6.9	136	8.6	186	10.9	236	11.0	286	13.9	336	9.3		
37	6.0	87	7.0	137	11.3	187	8.8	237	11.0	287	14.0	337	9.2		
38	5.0	88	6.8	138	7.8	188	9.5	238	11.2	288	15.1	338	8.7		
39	6.6	89	7.0	139	7.7	189	8.9	239	11.6	289	14.7	339	7.7		
40	6.6	90	6.7	140	8.1	190	8.7	240	11.5	290	13.5	340	8.9		
41	7.1	91	6.9	141	7.8	191	8.8	241	14.1	291	13.9	341	8.5		
42	6.4	92	6.9	142	8.3	192	8.8	242	11.9	292	14.0	342	8.2		
43	6.5	93	7.9	143	9.2	193	9.1	243	12.6	293	14.0	343	7.9		
44	6.5	94	8.6	144	7.9	194	9.2	244	12.3	294	14.0	344	8.1		
45	8.6	95	7.0	145	8.0	195	9.1	245	12.2	295	14.0	345	8.1		
46	10.4	96	7.0	146	7.9	196	10.0	246	12.3	296	14.0	346	7.5		
47	7.1	97	7.1	147	8.2	197	10.2	247	12.9	297	14.9	347	7.8		
48	6.6	98	7.1	148	7.7	198	12.5	248	12.9	298	14.1	348	7.1		
49	6.5	99	7.0	149	8.8	199	11.5	249	13.0	299	14.0	349	7.3		
50	6.5	100	6.9	150	11.2	200	9.5	250	11.7	300	14.2	350	7.4		

Table 4

Average Daily Release Temperatures from Norfork Afterbay,* 1974

Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C
1	6.6	51	7.6	101	8.8	151	11.6	201	15.9	251	19.1	301	18.2	351	10.6
2	7.9	52	7.7	102	9.3	152	11.6	202	15.6	252	19.3	302	19.0	352	10.3
3	7.8	53	7.8	103	9.5	153	11.7	203	16.4	253	19.4	303	19.0	353	10.5
4	8.0	54	7.9	104	8.9	154	11.7	204	16.3	254	19.8	304	18.5	354	10.2
5	7.9	55	7.2	105	8.9	155	11.7	205	16.1	255	19.5	305	18.7	355	9.9
6	7.8	56	7.5	106	8.8	156	11.7	206	16.2	256	18.8	306	18.8	356	10.1
7	7.5	57	7.6	107	8.9	157	12.2	207	16.3	257	19.0	307	18.7	357	10.6
8	7.5	58	7.8	108	9.1	158	11.9	208	16.5	258	19.3	308	17.5	358	10.1
9	7.0	59	8.1	109	9.5	159	13.4	209	16.4	259	19.0	309	17.8	359	9.6
10	7.0	60	8.2	110	9.4	160	12.7	210	16.4	260	19.3	310	17.9	360	9.6
11	6.5	61	9.4	111	9.1	161	12.4	211	16.1	261	19.6	311	17.5	361	9.8
12	6.4	62	10.9	112	9.4	162	12.3	212	16.6	262	19.7	312	17.6	362	9.5
13	6.6	63	8.9	113	9.4	163	12.4	213	16.8	263	19.7	313	17.3	363	9.2
14	6.6	64	8.1	114	9.1	164	12.6	214	17.0	264	19.8	314	16.9	364	10.2
15	6.9	65	8.9	115	9.3	165	13.3	215	17.4	265	19.4	315	16.4	365	9.8
16	7.0	66	8.7	116	9.5	166	13.1	216	18.0	266	18.8	316	16.1		
17	7.4	67	8.8	117	10.1	167	12.8	217	16.6	267	19.1	317	15.8		
18	7.3	68	9.9	118	10.2	168	12.9	218	16.7	268	19.2	318	15.4		
19	7.2	69	10.2	119	10.0	169	13.6	219	17.1	269	19.2	319	15.3		
20	7.0	70	8.9	120	9.7	170	13.7	220	17.1	270	19.5	320	14.6		
21	7.1	71	8.2	121	9.5	171	14.2	221	17.9	271	19.0	321	14.2		
22	7.2	72	8.0	122	10.1	172	14.4	222	18.6	272	19.1	322	14.5		
23	6.8	73	8.0	123	10.1	173	14.3	223	19.3	273	19.4	323	14.7		
24	6.9	74	8.1	124	9.6	174	13.5	224	17.5	274	19.3	324	14.2		
25	6.9	75	8.3	125	9.6	175	13.3	225	17.4	275	18.8	325	14.4		
26	7.1	76	8.7	126	9.8	176	13.3	226	17.7	276	19.4	326	14.3		
27	7.2	77	8.6	127	10.1	177	13.4	227	17.8	277	19.1	327	14.6		
28	7.1	78	7.7	128	10.6	178	13.6	228	18.0	278	19.0	328	13.7		
29	7.2	79	7.6	129	10.8	179	13.7	229	19.2	279	19.3	329	13.9		
30	7.2	80	7.7	130	10.5	180	14.3	230	20.0	280	19.3	330	13.8		
31	7.3	81	7.7	131	10.5	181	14.5	231	17.9	281	19.3	331	13.7		
32	7.7	82	6.3	132	10.4	182	15.0	232	18.5	282	19.5	332	13.5		
33	7.9	83	5.6	133	11.1	183	15.1	233	18.5	283	19.6	333	13.0		
34	8.0	84	7.7	134	10.7	184	15.3	234	18.6	284	19.7	334	11.3		
35	7.3	85	8.2	135	10.8	185	16.5	235	18.8	285	19.9	335	10.2		
36	7.3	86	8.4	136	11.1	186	15.1	236	19.5	286	20.0	336	11.9		
37	6.9	87	8.5	137	11.5	187	14.7	237	20.3	287	18.5	337	12.0		
38	6.6	88	8.8	138	11.5	188	14.9	238	18.5	288	18.7	338	12.0		
39	6.7	89	9.5	139	11.6	189	15.2	239	18.9	289	19.2	339	11.9		
40	6.5	90	11.6	140	11.2	190	15.6	240	19.1	290	19.3	340	11.9		
41	6.6	91	9.3	141	11.1	191	15.7	241	18.8	291	19.4	341	11.1		
42	7.0	92	8.9	142	11.5	192	15.5	242	18.9	292	19.3	342	10.5		
43	7.5	93	8.8	143	11.4	193	15.2	243	19.1	293	18.7	343	11.0		
44	7.6	94	8.3	144	11.8	194	15.0	244	19.4	294	18.7	344	11.3		
45	7.3	95	8.2	145	12.5	195	14.9	245	19.3	295	19.0	345	10.9		
46	7.0	96	8.3	146	13.0	196	15.0	246	18.7	296	19.1	346	11.1		
47	7.3	97	8.9	147	14.0	197	15.3	247	18.6	297	18.9	347	11.1		
48	7.4	98	8.4	148	12.3	198	15.5	248	18.6	298	18.8	348	10.9		
49	7.4	99	8.4	149	12.7	199	16.0	249	19.0	299	18.9	349	10.5		
50	7.5	100	8.4	150	12.6	200	16.1	250	19.1	300	18.9	350	10.3		

* With pumped-storage operations.

Table 5

Average Daily Release Temperatures from Norfork Afterbay,* 1975

Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C
1	7.8	51	7.6	101	9.0	151	10.6	201	15.2	251	14.8	301	15.9	351	10.1
2	9.1	52	7.8	102	9.1	152	11.6	202	11.7	252	14.7	302	15.6	352	10.1
3	9.2	53	8.1	103	8.7	153	10.4	203	12.5	253	14.8	303	15.5	353	10.0
4	8.8	54	6.8	104	9.1	154	11.1	204	12.3	254	15.6	304	15.5	354	9.2
5	8.5	55	7.0	105	9.4	155	11.4	205	12.2	255	14.6	305	15.7	355	9.1
6	9.0	56	7.4	106	9.7	156	11.0	206	12.2	256	14.6	306	15.9	356	9.4
7	9.3	57	7.2	107	9.8	157	11.4	207	13.3	257	14.7	307	15.9	357	9.2
8	9.1	58	7.4	108	10.0	158	12.4	208	14.0	258	14.2	308	16.0	358	8.8
9	9.5	59	7.6	109	9.5	159	13.2	209	12.5	259	14.5	309	16.0	359	8.4
10	8.6	60	7.6	110	9.5	160	10.7	210	12.6	260	15.0	310	16.0	360	8.6
11	8.1	61	7.2	111	9.4	161	10.5	211	13.1	261	15.3	311	16.2	361	8.2
12	7.5	62	7.1	112	9.6	162	11.1	212	12.8	262	15.0	312	16.3	362	8.2
13	7.8	63	7.4	113	10.2	163	11.0	213	12.7	263	15.4	313	16.4	363	8.2
14	8.1	64	7.7	114	10.5	164	11.8	214	13.8	264	15.1	314	15.7	364	8.0
15	8.2	65	8.0	115	10.1	165	13.2	215	14.7	265	14.7	315	15.8	365	8.1
16	7.7	66	7.6	116	10.3	166	14.2	216	12.4	266	14.4	316	15.0		
17	7.8	67	7.4	117	10.5	167	12.2	217	12.8	267	14.5	317	15.0		
18	8.0	68	7.1	118	10.0	168	11.9	218	13.0	268	14.7	318	15.3		
19	7.4	69	7.2	119	10.1	169	12.2	219	13.0	269	14.8	319	14.6		
20	7.4	70	7.3	120	9.7	170	12.1	220	13.0	270	15.1	320	14.4		
21	7.6	71	7.1	121	9.8	171	11.8	221	14.1	271	15.4	321	15.1		
22	7.5	72	6.7	122	9.7	172	13.0	222	15.1	272	15.2	322	15.3		
23	7.7	73	7.3	123	10.0	173	14.4	223	13.4	273	15.3	323	15.1		
24	7.6	74	7.1	124	10.0	174	11.1	224	13.6	274	14.8	324	14.0		
25	7.6	75	7.4	125	10.4	175	11.2	225	14.1	275	14.6	325	13.5		
26	7.7	76	7.3	126	10.3	176	11.4	226	13.4	276	14.8	326	12.2		
27	8.2	77	7.6	127	10.4	177	11.6	227	14.0	277	15.1	327	11.7		
28	8.7	78	7.8	128	10.1	178	11.5	228	15.1	278	15.4	328	12.3		
29	8.0	79	8.1	129	10.3	179	13.0	229	16.1	279	15.3	329	12.0		
30	8.0	80	8.5	130	10.1	180	14.2	230	13.5	280	15.4	330	11.5		
31	7.7	81	8.2	131	10.1	181	11.8	231	13.3	281	15.4	331	11.6		
32	7.3	82	8.5	132	10.1	182	11.7	232	13.8	282	15.8	332	11.9		
33	7.0	83	7.8	133	10.2	183	12.0	233	14.0	283	16.1	333	13.1		
34	7.5	84	7.6	134	10.0	184	12.0	234	14.2	284	16.8	334	11.9		
35	7.8	85	7.3	135	10.2	185	13.7	235	15.7	285	17.2	335	11.8		
36	7.3	86	7.7	136	10.1	186	15.6	236	17.2	286	15.9	336	11.5		
37	6.9	87	7.4	137	10.2	187	17.2	237	14.3	287	15.9	337	11.6		
38	7.2	88	6.9	138	10.4	188	11.1	238	14.2	288	15.8	338	11.7		
39	7.2	89	7.4	139	10.9	189	12.1	239	14.3	289	15.0	339	11.9		
40	6.6	90	7.7	140	10.6	190	11.9	240	14.6	290	15.0	340	11.2		
41	6.9	91	8.2	141	11.0	191	11.8	241	14.7	291	14.9	341	10.9		
42	7.3	92	7.9	142	11.3	192	12.1	242	15.6	292	14.7	342	11.3		
43	7.2	93	8.6	143	11.6	193	13.1	243	16.7	293	15.3	343	11.2		
44	7.0	94	8.8	144	12.4	194	14.0	244	17.8	294	15.6	344	11.2		
45	7.2	95	8.9	145	13.6	195	11.4	245	14.9	295	15.7	345	11.3		
46	7.5	96	8.8	146	14.1	196	11.6	246	15.1	296	16.0	346	11.3		
47	7.3	97	8.7	147	11.4	197	11.9	247	15.2	297	15.9	347	11.8		
48	7.2	98	8.8	148	10.5	198	12.1	248	14.8	298	14.9	348	12.3		
49	7.3	99	9.0	149	10.3	199	12.3	249	15.3	299	14.9	349	11.1		
50	7.5	100	8.9	150	10.7	200	14.1	250	15.9	300	15.4	350	10.8		

* With pumped-storage operations.

Table 6

Average Daily Release Temperatures from Norfork Afterbay,* 1976

Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C	Julian Day	Temp °C
1	8.2	51	7.4	101	8.9	151	11.8	201	12.1	251	15.5	301	14.8	351	7.8
2	8.8	52	6.8	102	10.2	152	13.4	202	12.7	252	15.5	302	14.7	352	7.9
3	7.7	53	6.8	103	8.8	153	9.7	203	12.5	253	15.1	303	13.8	353	8.1
4	7.1	54	7.0	104	8.2	154	9.9	204	12.6	254	15.0	304	12.9	354	8.5
5	8.3	55	7.1	105	8.7	155	10.0	205	12.5	255	15.3	305	12.9	355	6.5
6	8.5	56	7.4	106	9.3	156	9.7	206	14.1	256	15.8	306	14.6	356	6.7
7	7.5	57	7.1	107	9.1	157	10.2	207	15.5	257	15.5	307	14.3	357	6.8
8	7.3	58	7.3	108	11.2	158	11.2	208	13.1	258	15.4	308	13.7	358	6.8
9	7.1	59	8.0	109	11.7	159	9.8	209	13.8	259	15.6	309	13.1	359	6.7
10	7.0	60	8.9	110	9.3	160	9.7	210	13.9	260	15.6	310	13.2	360	6.3
11	6.9	61	8.6	111	9.0	161	9.7	211	13.0	261	15.6	311	13.3	361	6.2
12	7.2	62	8.7	112	8.6	162	10.2	212	13.3	262	16.2	312	12.6	362	6.9
13	7.2	63	8.2	113	8.8	163	10.4	213	14.9	263	16.7	313	12.8	363	6.4
14	7.1	64	8.6	114	8.9	164	11.9	214	16.0	264	15.7	314	13.4	364	6.3
15	7.0	65	7.1	115	10.0	165	13.6	215	12.6	265	15.5	315	13.3	365	4.9
16	6.6	66	7.2	116	9.6	166	11.3	216	12.7	266	15.5	316	11.9		
17	6.1	67	7.2	117	8.6	167	11.4	217	13.0	267	15.7	317	11.6		
18	5.6	68	6.9	118	8.4	168	10.5	218	13.5	268	15.9	318	10.3		
19	6.5	69	7.2	119	8.0	169	11.0	219	13.8	269	16.4	319	9.6		
20	6.6	70	7.4	120	7.9	170	10.3	220	14.9	270	16.6	320	11.7		
21	6.8	71	7.4	121	8.0	171	11.4	221	15.7	271	15.5	321	11.6		
22	6.9	72	7.2	122	8.8	172	12.4	222	13.0	272	15.4	322	11.6		
23	7.2	73	7.1	123	10.0	173	10.4	223	13.4	273	15.6	323	11.6		
24	7.5	74	7.6	124	8.7	174	10.4	224	13.9	274	15.7	324	11.7		
25	7.1	75	7.3	125	8.7	175	10.9	225	14.0	275	16.0	325	11.5		
26	6.4	76	7.2	126	8.7	176	10.8	226	14.2	276	16.5	326	10.7		
27	6.5	77	7.3	127	8.9	177	10.4	227	15.7	277	17.0	327	10.9		
28	6.5	78	7.6	128	8.5	178	11.7	228	16.6	278	16.0	328	10.7		
29	6.7	79	8.4	129	9.1	179	13.0	229	14.2	279	15.1	329	11.0		
30	6.8	80	9.1	130	9.7	180	11.2	230	14.4	280	15.3	330	11.4		
31	6.6	81	9.4	131	9.0	181	11.6	231	14.0	281	15.2	331	11.6		
32	6.5	82	8.0	132	9.2	182	11.1	232	14.3	282	15.1	332	9.7		
33	6.5	83	7.7	133	9.2	183	10.7	233	14.3	283	15.1	333	8.4		
34	6.5	84	7.4	134	8.8	184	11.3	234	15.2	284	15.4	334	9.1		
35	6.8	85	8.1	135	9.1	185	12.9	235	16.0	285	16.1	335	9.2		
36	6.3	86	8.3	136	9.6	186	13.7	236	14.1	286	16.1	336	9.3		
37	5.7	87	8.9	137	10.9	187	14.7	237	14.4	287	16.2	337	9.4		
38	5.3	88	9.0	138	9.3	188	10.6	238	14.5	288	16.2	338	9.2		
39	5.6	89	8.5	139	9.1	189	11.3	239	14.9	289	16.0	339	8.7		
40	6.8	90	7.6	140	9.1	190	11.3	240	14.8	290	15.3	340	8.5		
41	7.6	91	7.7	141	9.3	191	11.5	241	15.6	291	14.8	341	8.6		
42	6.8	92	7.8	142	9.0	192	12.9	242	16.3	292	15.8	342	8.2		
43	7.3	93	8.1	143	10.1	193	14.3	243	14.5	293	15.2	343	8.0		
44	7.2	94	9.1	144	11.0	194	11.7	244	14.4	294	15.7	344	8.3		
45	7.7	95	9.7	145	9.5	195	11.6	245	14.7	295	15.6	345	8.3		
46	8.7	96	8.4	146	9.1	196	11.5	246	14.9	296	15.7	346	7.6		
47	8.1	97	8.1	147	9.0	197	12.0	247	15.1	297	15.6	347	7.4		
48	7.3	98	8.0	148	9.0	198	12.1	248	16.0	298	15.5	348	7.5		
49	7.0	99	7.9	149	9.4	199	13.1	249	16.7	299	15.1	349	7.7		
50	7.0	100	7.9	150	10.6	200	14.3	250	17.1	300	15.0	350	7.8		

* With pumped-storage operations.

Table 7

Effect of Pumped-Storage on Release Temperatures of Norfork Project

18 August to 1 September 1975

Day 1975	Phase 2: Proposed Pumped-Storage Operations: Release Flow from Dam* cfs	Afterbay Release Flow cfs	Release Temperature from Dam °C	Release Temperature from Afterbay °C	Temperature Difference Between Afterbay and Dam Releases °C	Phase 1: Historical Operations: Release Flow from Dam* cfs	Release Temperature from Dam °C	Routed Release Temperature °C	Temperature Difference Between Routed and Dam Releases °C	Temperature Difference Between Releases from Norfork Dam** °C	Temperature Difference Between Afterbay and Routed Releases† °C
Aug 18	2360	2080	12.3	13.5	1.2	800	9.8	11.3	1.5	2.5	2.2
19	2360	2080	12.4	13.3	0.9	1130	9.9	10.7	0.8	2.5	2.6
20	2360	2080	12.5	13.8	1.3	1700	9.9	10.6	0.7	2.6	3.2
21	2360	2080	12.6	14.0	1.4	1990	9.9	10.6	0.7	2.7	3.4
22	2360	2080	12.7	14.2	1.5	2380	9.9	10.6	0.7	2.8	3.6
23	100	800	12.4	15.7	3.3	380	10.0	13.6	3.6	2.4	2.1
24	100	800	12.4	17.2	4.8	450	10.0	13.3	3.3	2.4	3.9
25	2360	1940	12.8	14.3	1.5	2570	10.0	10.7	0.7	2.8	3.6
26	2360	1940	13.0	14.2	1.2	1470	10.0	10.9	0.9	3.0	3.3
27	2360	1940	13.1	14.3	1.2	2910	10.1	10.6	0.5	3.0	3.7
28	2360	1940	13.2	14.6	1.4	2620	10.1	10.7	0.6	3.1	3.9
29	2360	1940	13.3	14.7	1.4	2790	10.2	10.7	0.5	3.1	4.0
30	100	800	13.0	15.6	2.6	2320	10.2	10.7	0.5	2.8	4.9
31	100	800	13.0	16.7	3.7	4150	10.3	10.7	0.4	2.7	6.0
Sep 1††	100	800	13.0	17.8	4.8	3490	10.4	10.8	0.4	2.6	7.0

* Rate represents total average daily generation flow from Norfork Lake.
** With pumped-storage operations and the same with historical operations.
† Temperature difference between afterbay releases with pumped-storage operations and routed releases from historical operations.
†† Labor Day, 1975.

Table 8

Release Temperatures (°C) from Norfork Dam and Afterbay for Selected Holidays

	Memorial Day					Independence Day					Labor Day			
	Phase 1: Historical		Phase 2: Proposed			Phase 1: Historical		Phase 2: Proposed			Phase 1: Historical		Phase 2: Proposed	
Date	Dam	Routed	Dam	Afterbay	Date	Dam	Routed	Dam	Afterbay	Date	Dam	Routed	Dam	Afterbay
1974					1974					1974				
May 25	9.0	9.3	9.6	12.5	July 4*	10.8	11.5	13.1	16.5	Aug 31	15.8	16.1	18.4	19.1
26	9.1	9.3	9.6	13.0		--	--	--	--	Sep 1	15.6	16.6	18.4	19.4
27	9.2	9.5	9.6	14.0		--	--	--	--	2	15.6	16.0	18.4	19.3
1975					1975					1975				
May 24	9.0	10.4	8.8	12.4	July 4	9.2	12.7	9.6	13.7	Aug 30	10.2	10.7	13.0	15.6
25	8.9	10.4	8.8	13.6	5	9.2	13.1	9.6	15.6	31	10.3	10.8	13.0	16.7
26	9.0	9.6	8.8	14.1	6	9.2	13.5	9.6	17.2	Sep 1	10.4	10.8	13.0	17.8
1976					1976					1976				
May 29	7.2	11.2	7.7	10.6	July 3	8.0	13.5	9.1	12.9	Sep 4	12.0	12.9	13.9	16.0
30	7.3	11.2	7.7	11.8	4	8.0	10.9	9.1	13.7	5	12.2	13.0	13.9	16.7
31	7.5	8.4	7.7	13.4	5	8.1	8.8	9.1	14.7	6	11.4	11.7	13.9	17.1

* Independence Day for 1974 was on Thursday; therefore, no 3- or 4-day weekend was assumed.

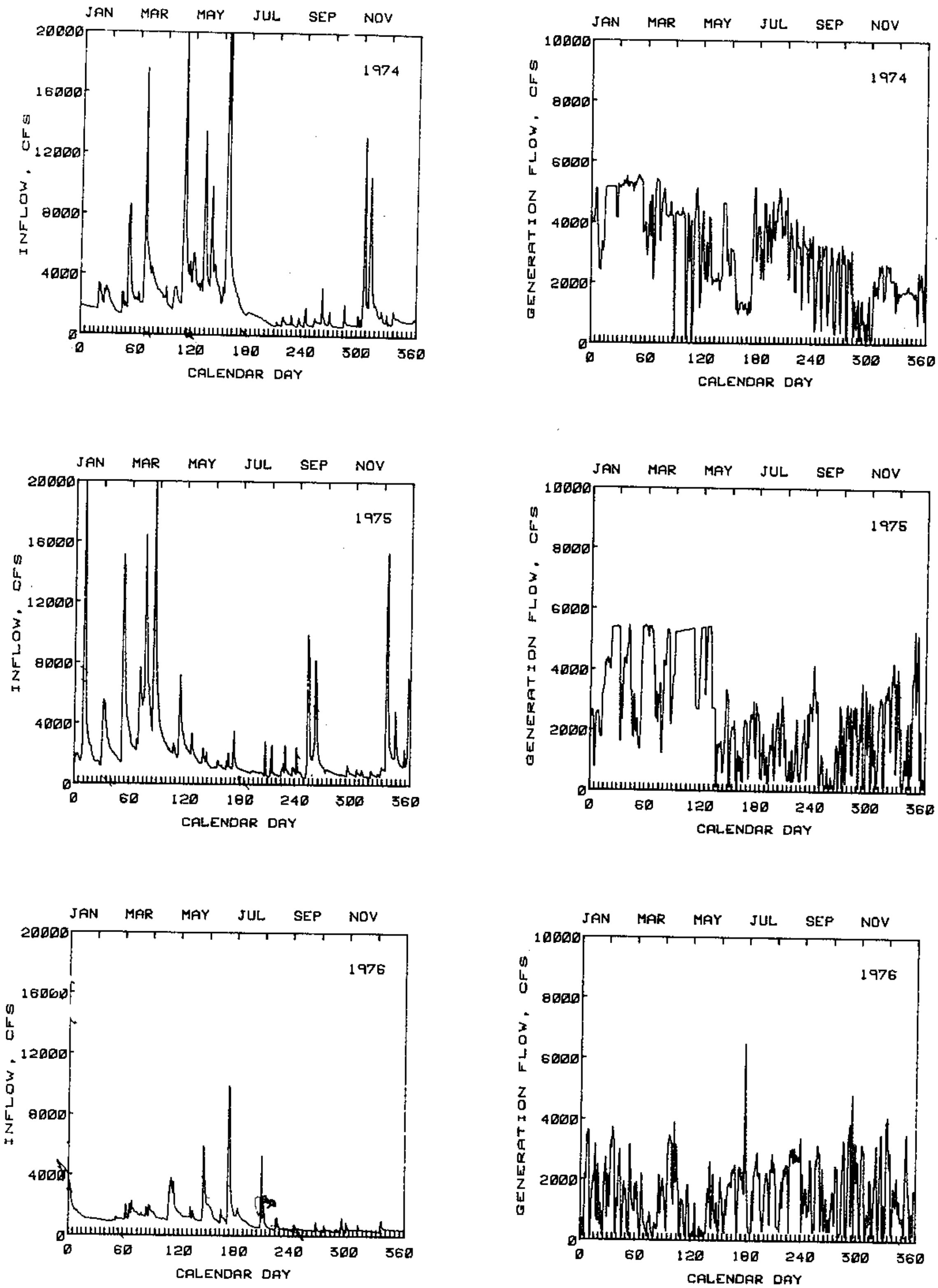


Plate 1. Inflow and generation rates for historical routings without pumped-storage operations

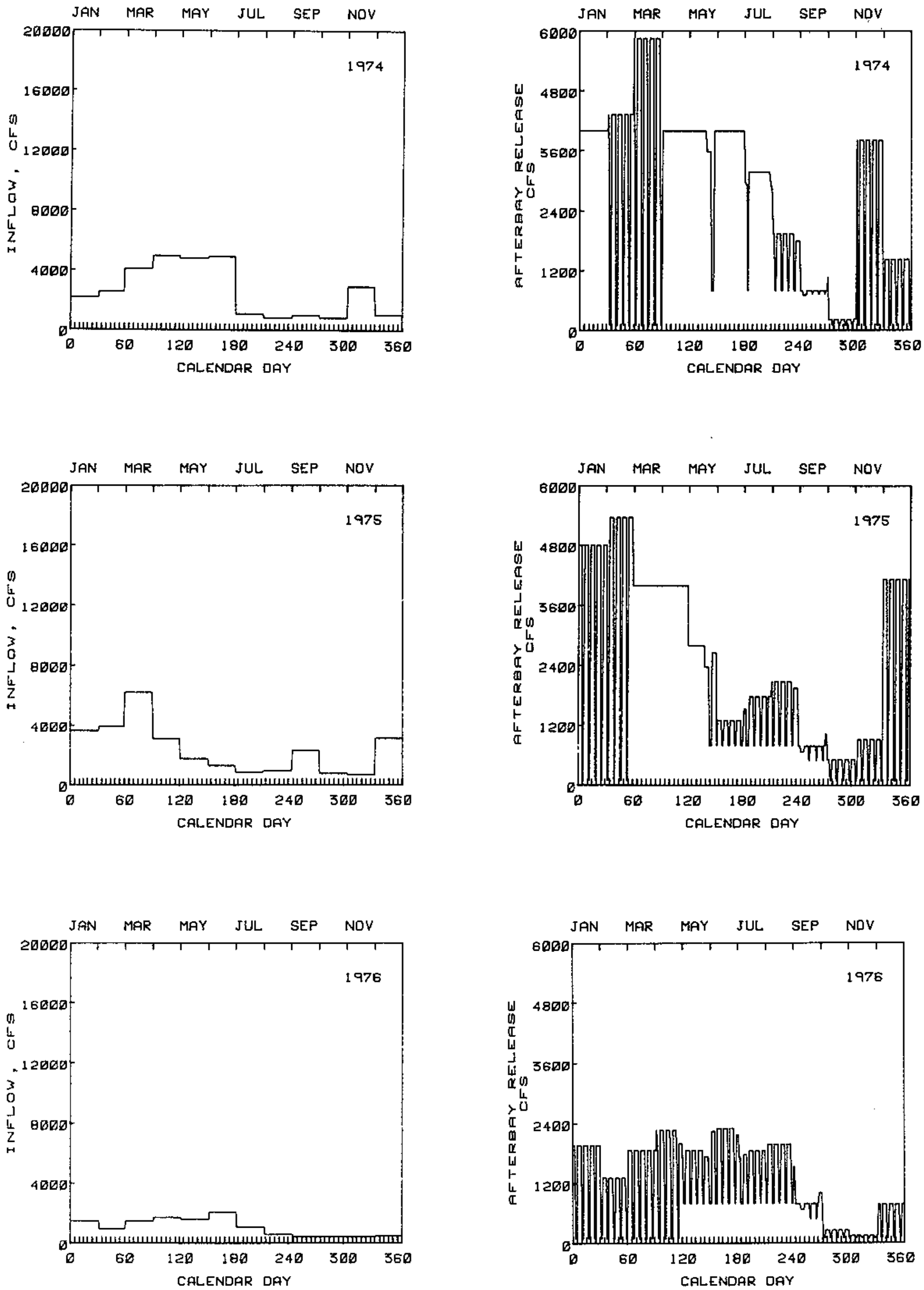


Plate 2. Inflow and afterbay release rates for proposed pumped-storage operations

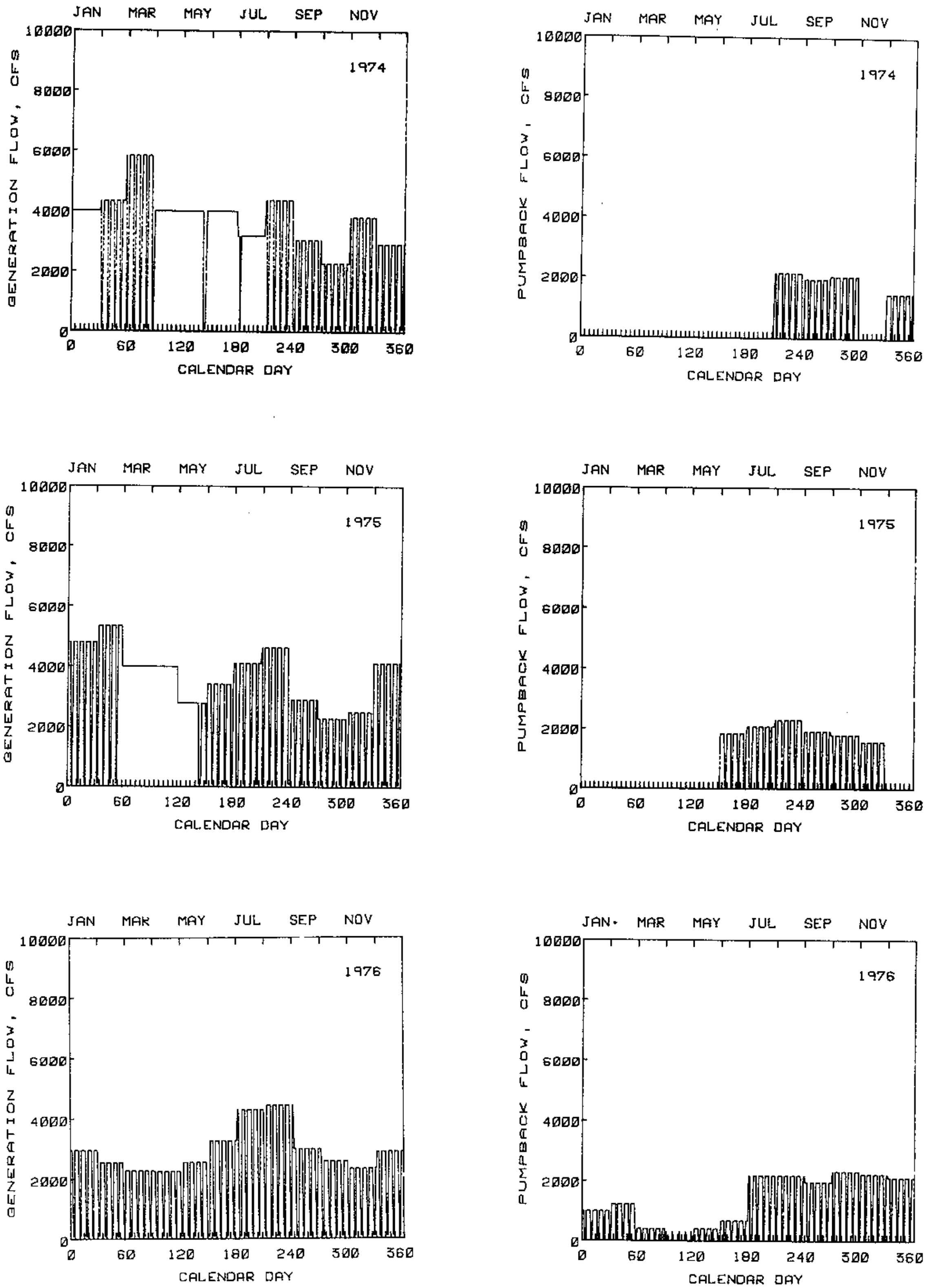


Plate 3. Generation and pumpback rates for proposed pumped-storage operation

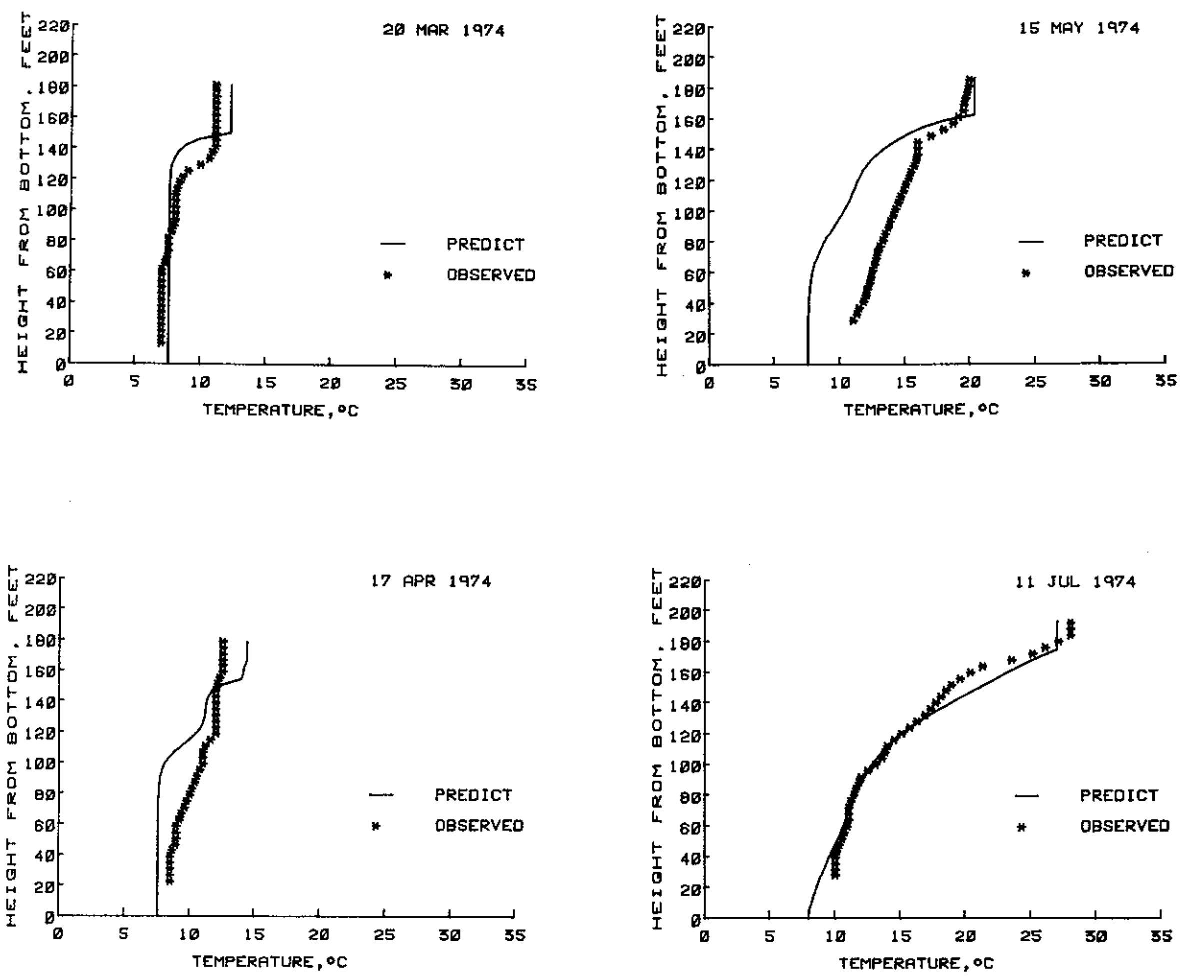


Plate 4A. Predicted and observed in-lake temperature profiles for historical routings without pumped-storage operations (Phase 1), Mar-Jul 1974

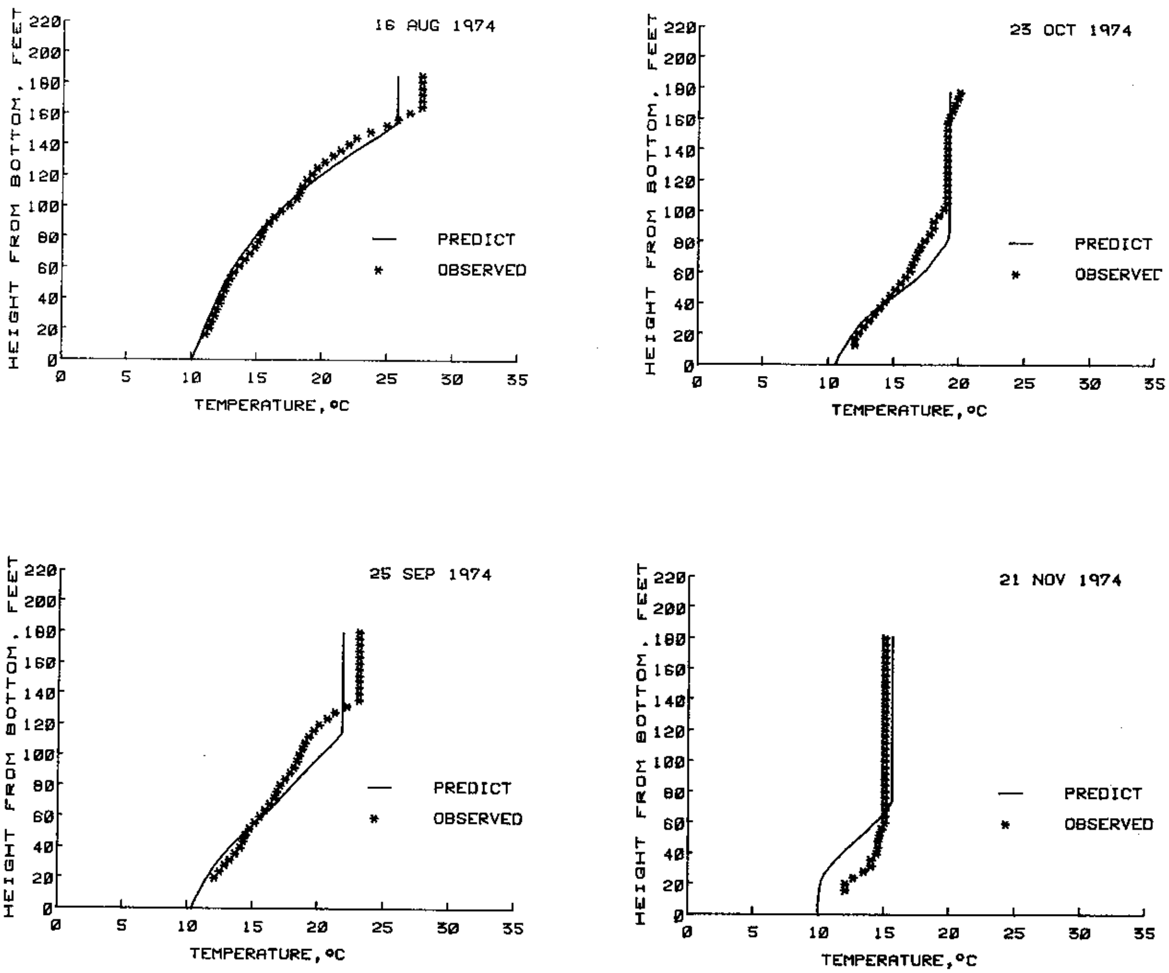


Plate 4B. Predicted and observed in-lake temperature profiles for historical routings without pumped-storage operations, Aug-Nov 1974

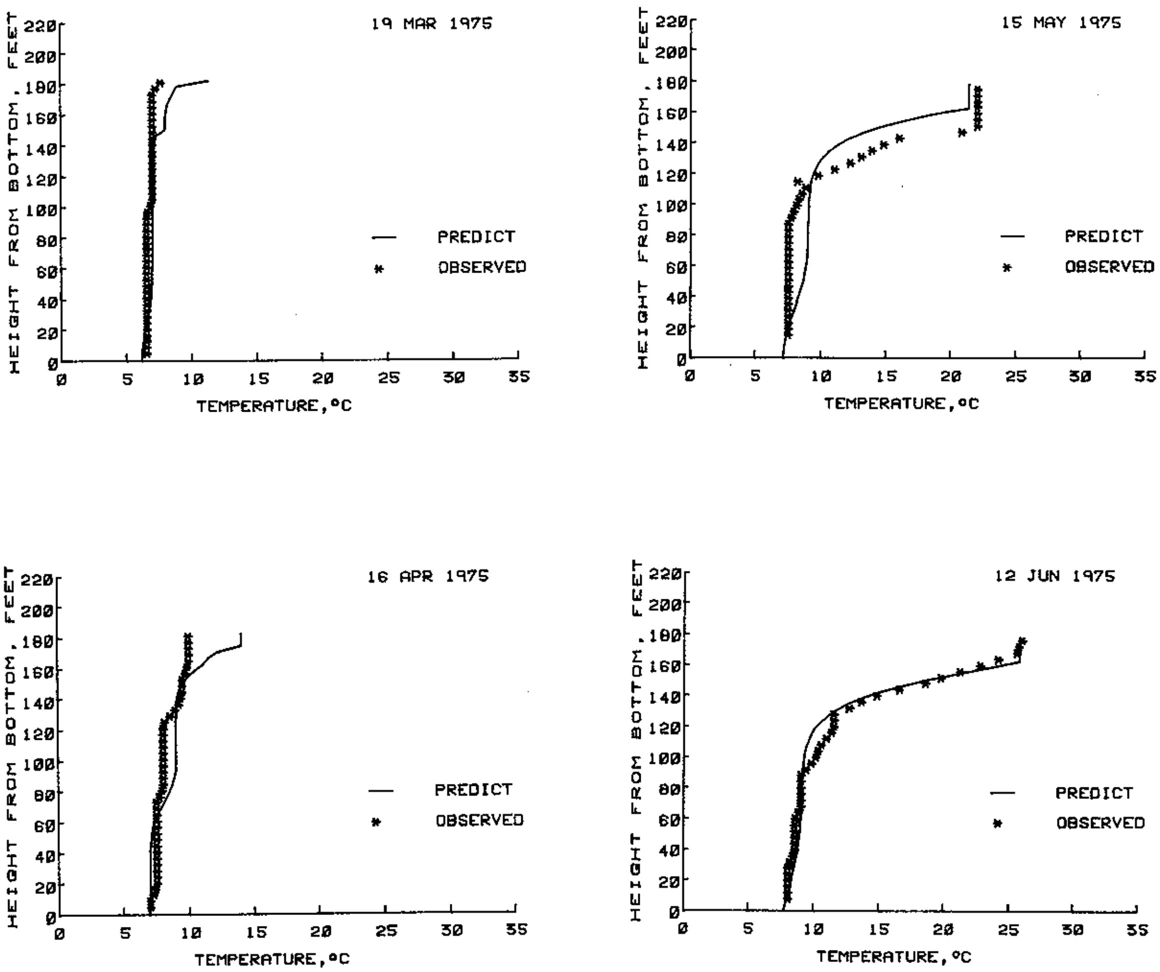


Plate 5A. Predicted and observed in-lake temperature profiles for historical routings without pumped-storage operations, Mar–Jun 1975

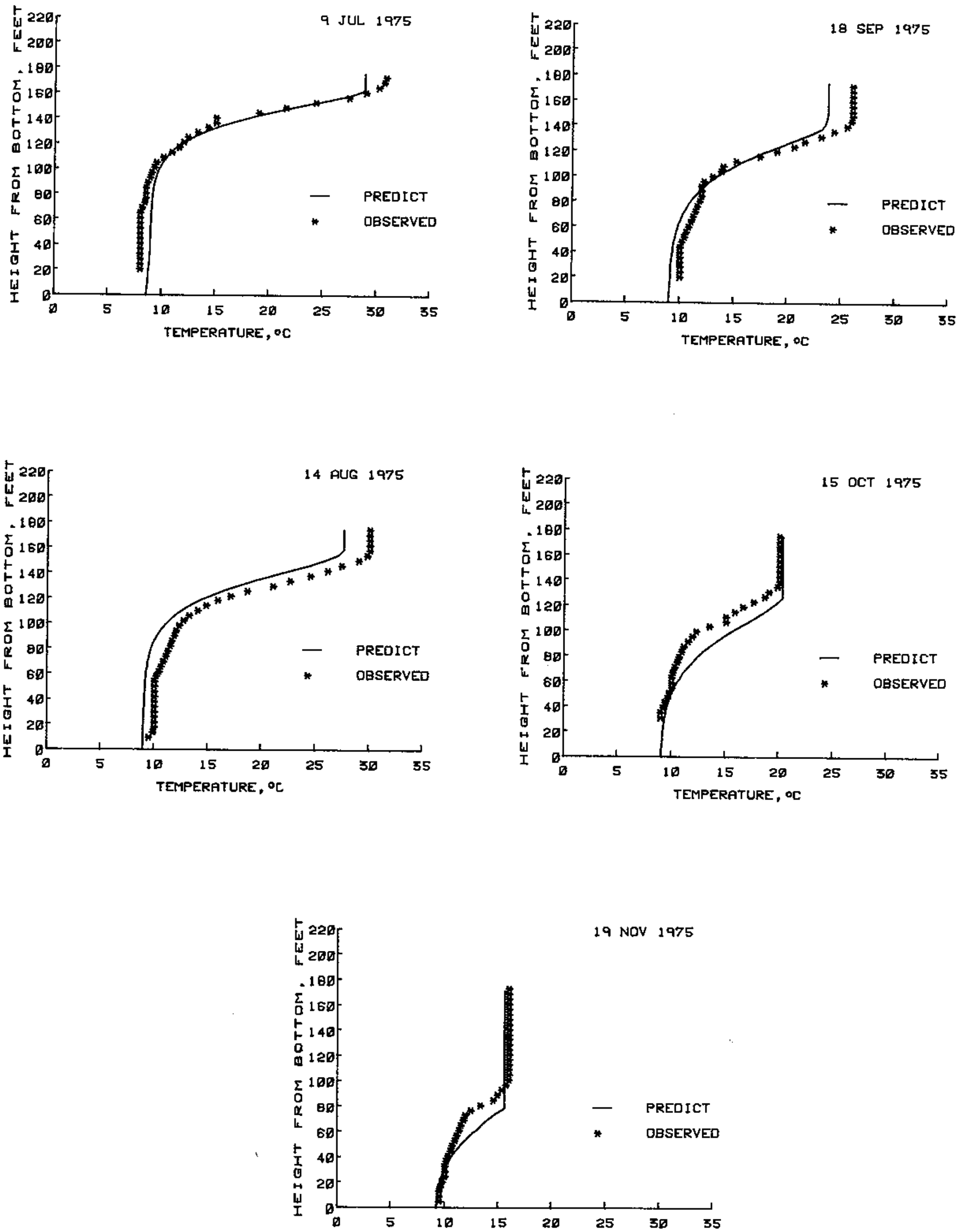


Plate 5B. Predicted and observed in-lake temperature profiles for historical routings without pumped-storage operations, Jul-Nov 1975

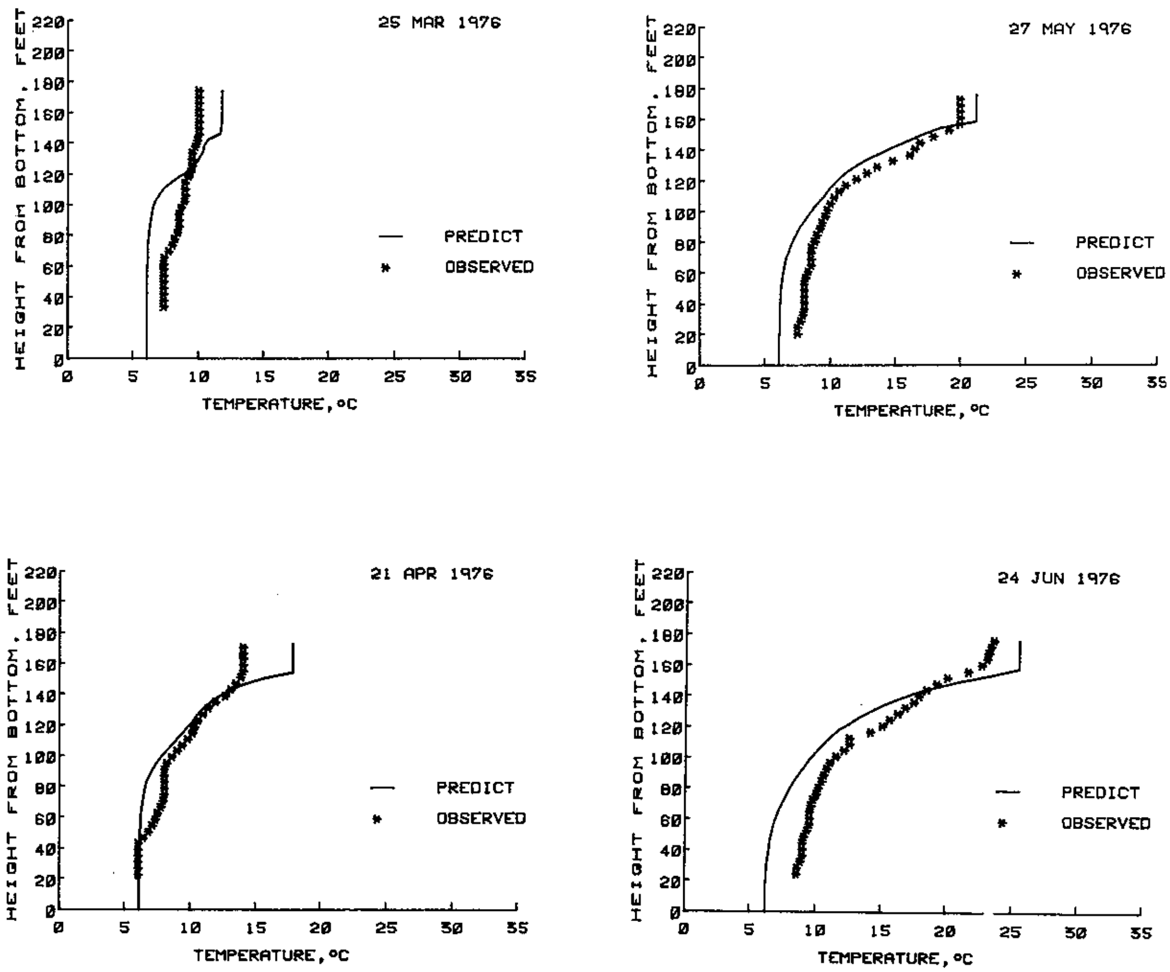


Plate 6A. Predicted and observed in-lake temperature profiles for historical routings without pumped-storage operations, Mar-Jun 1976

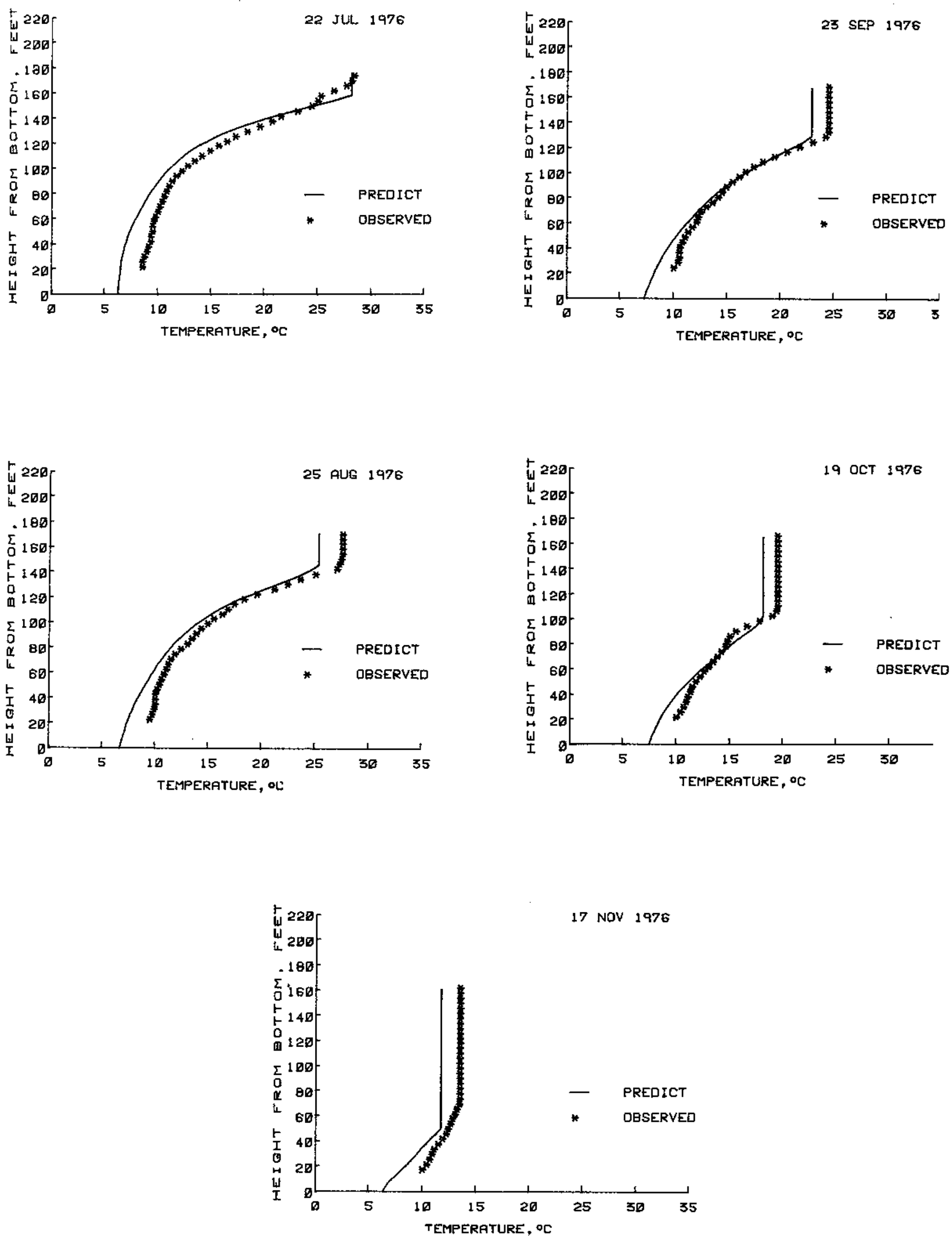
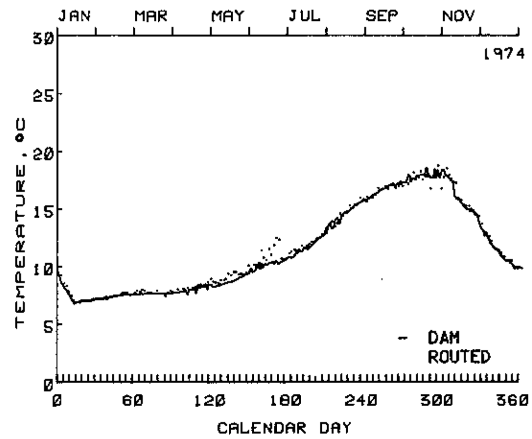
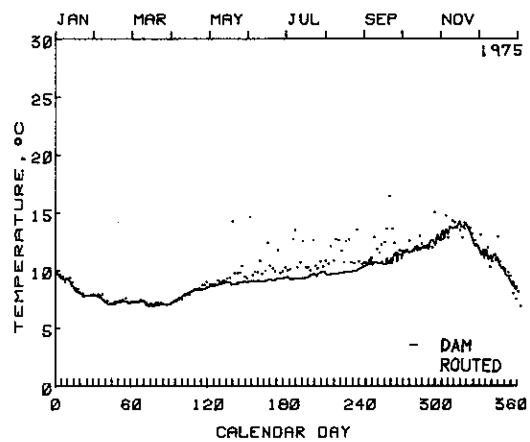


Plate 6B. Predicted and observed in-lake temperature profiles for historical routings without pumped-storage operations, Jul-Nov 1976





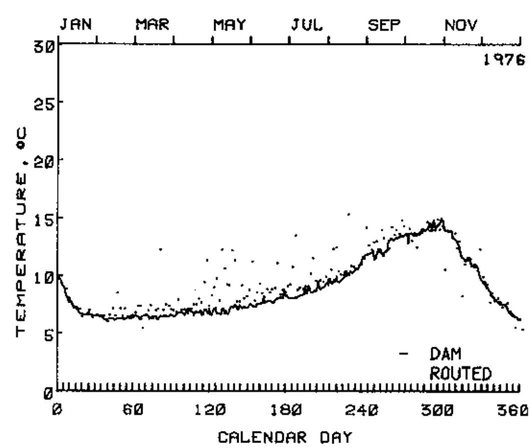


Plate 7. Predicted daily average release temperatures from Norfork Dam without pumped-storage operations and the temperature of those releases routed downstream to the site of the proposed reregulation dam

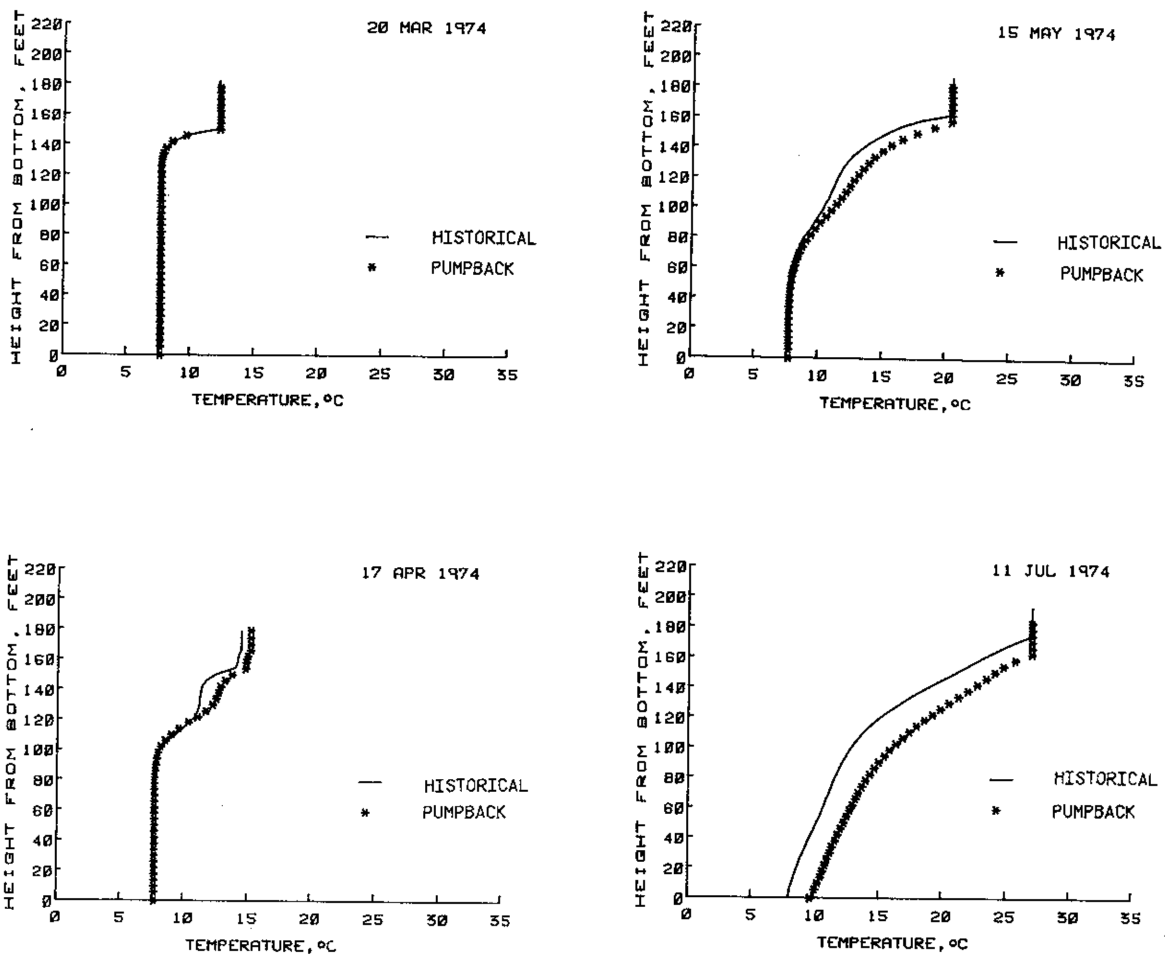


Plate 8A. Predicted in-lake temperature profiles for historical and proposed pumped-storage operations, Mar-Jul 1974

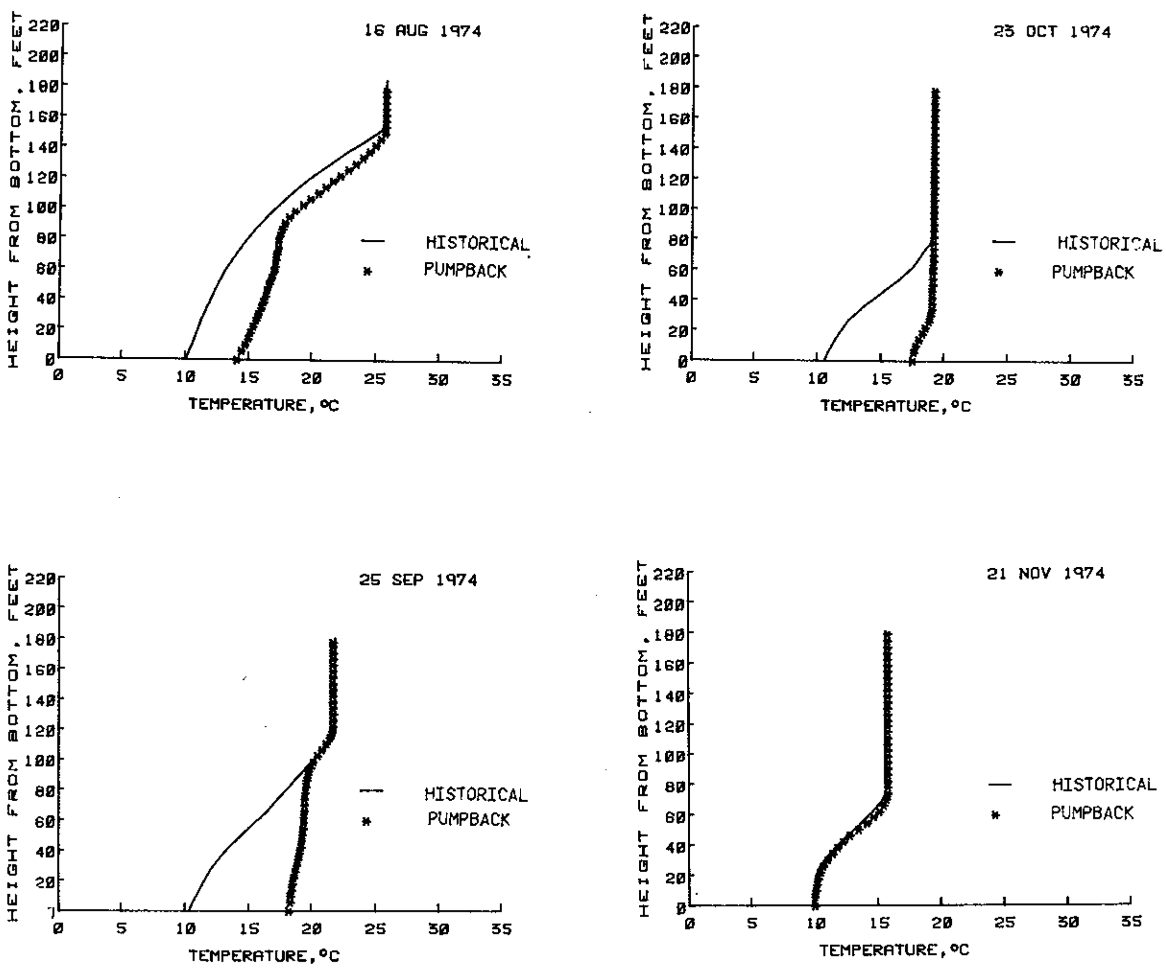


Plate 8B. Predicted in-lake temperature profiles for historical and proposed pumped-storage operations, Aug-Nov 1974

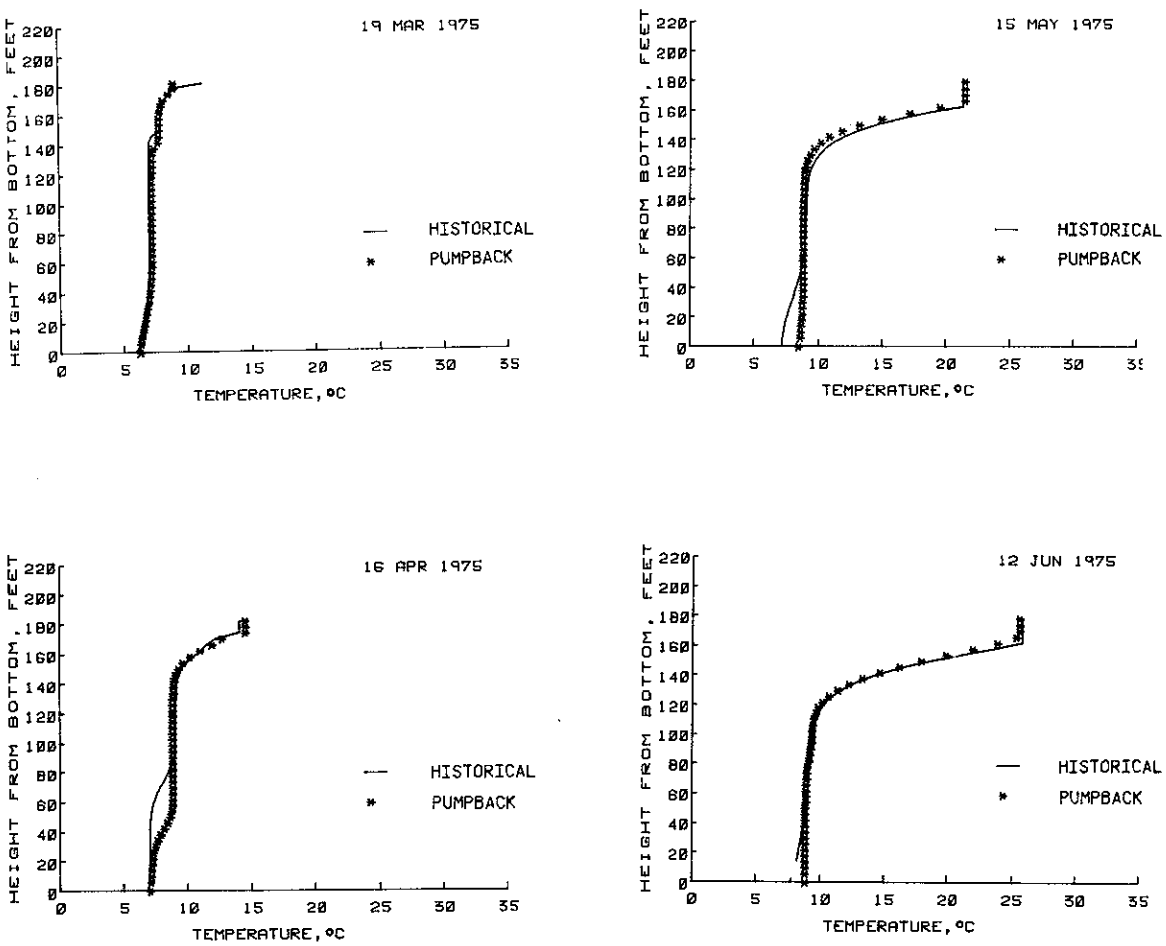


Plate 9A. Predicted in-lake temperature profiles for historical and proposed pumped-storage operations, Mar-Jun 1975

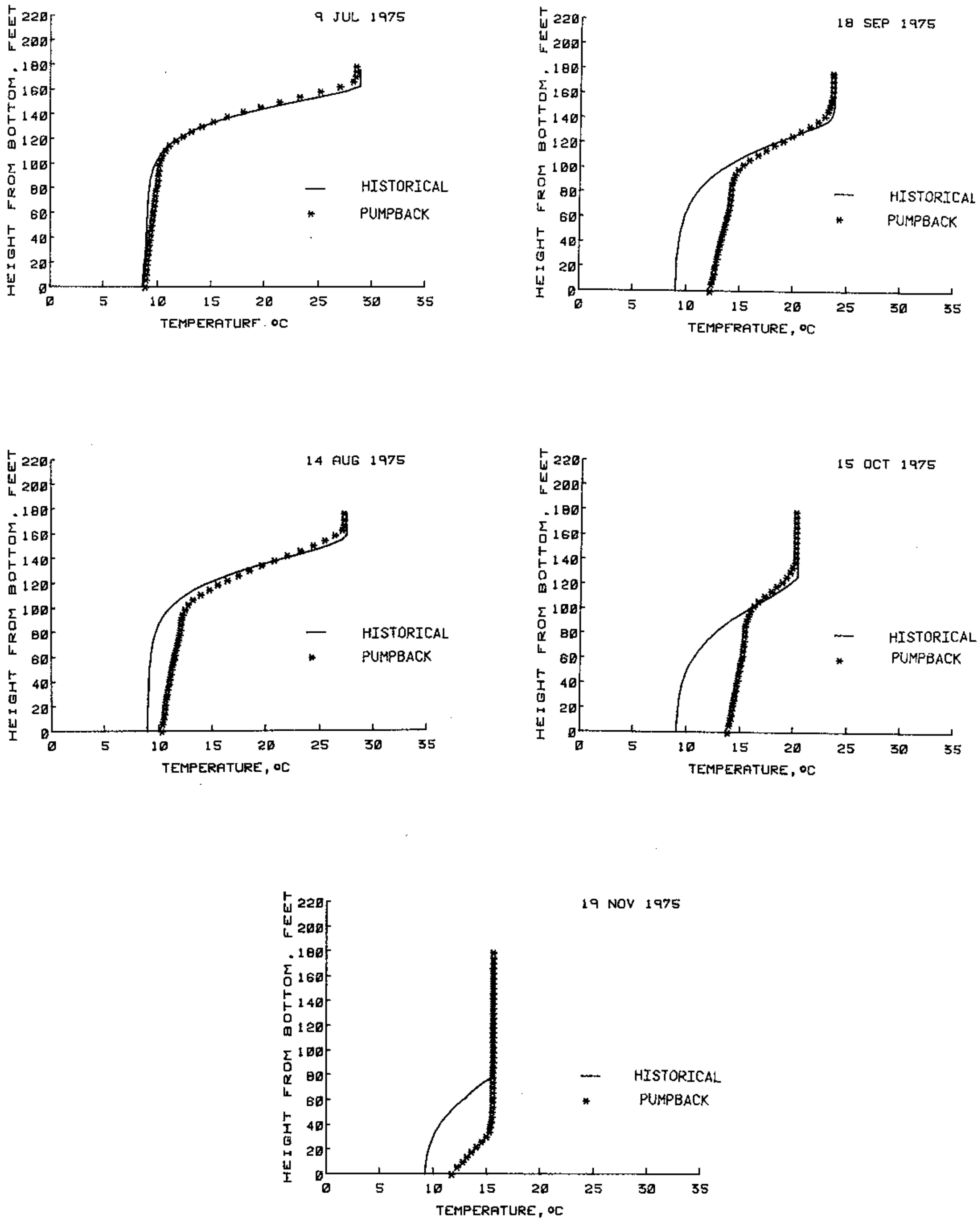


Plate 9B. Predicted in-lake temperature profiles for historical and proposed pumped-storage operations, Jul-Nov 1975

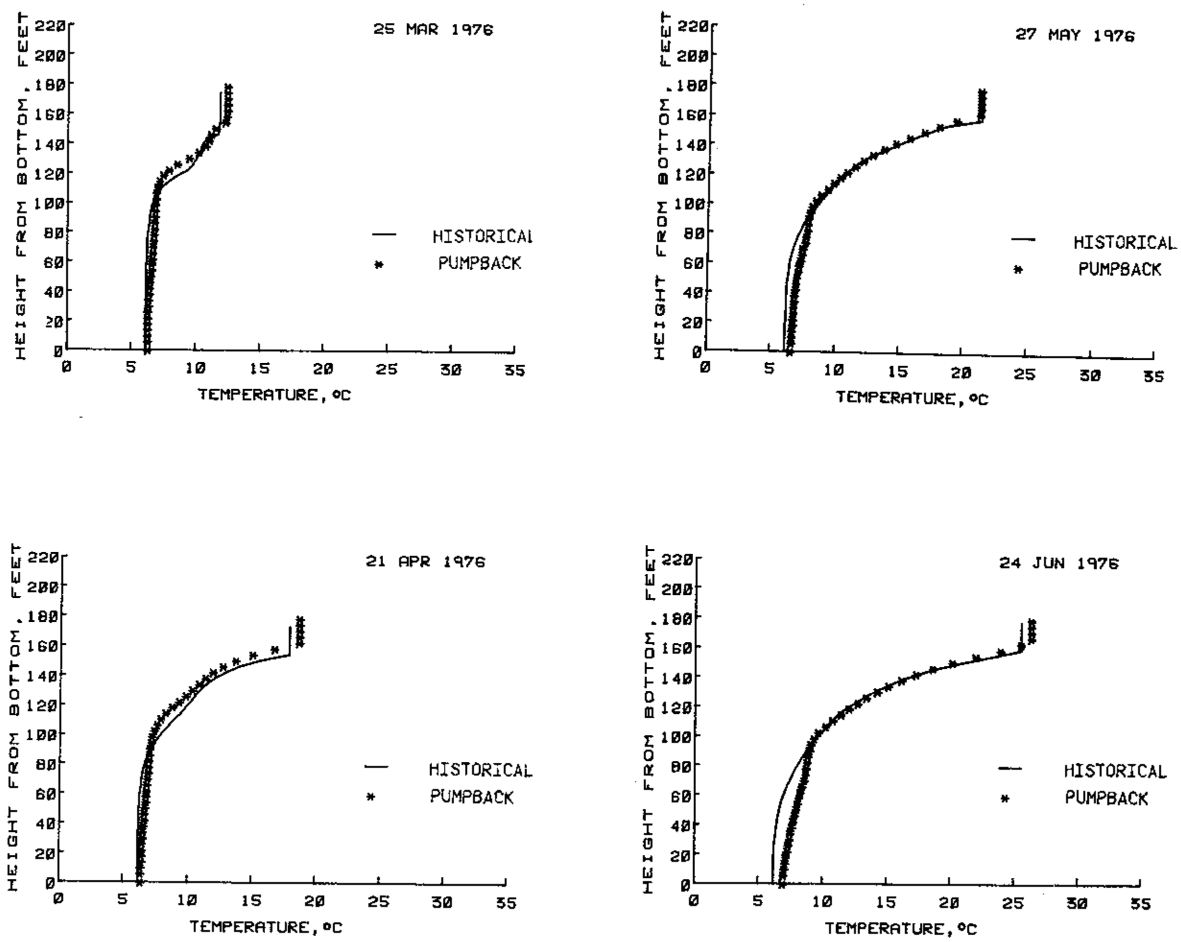


Plate 10A. Predicted in-lake temperature profiles for historical and proposed pumped-storage operations, Mar-Jun 1976

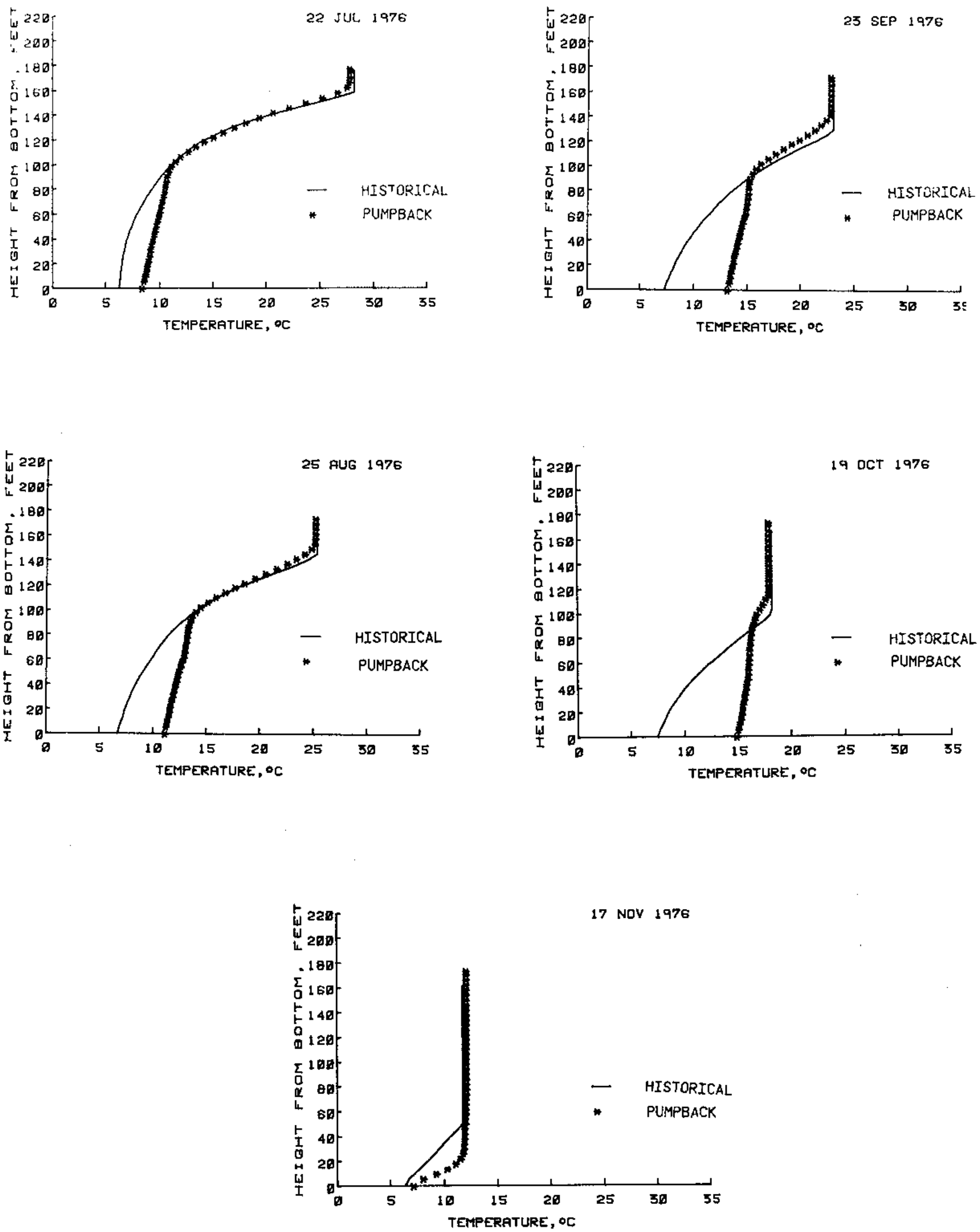


Plate 10B. Predicted in-lake temperature profiles for historical and proposed pumped-storage operations, Jul-Nov 1976

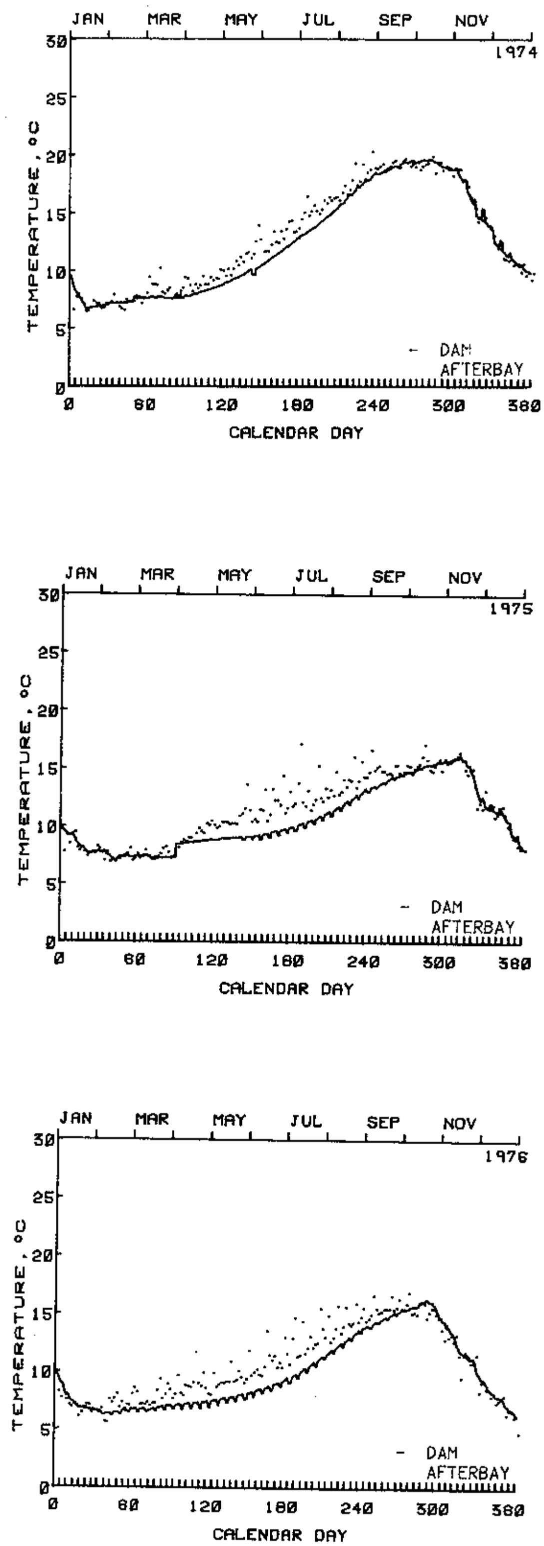


Plate 11. Predicted release temperatures from Norfork Dam and afterbay with proposed pumped-storage operations for E = 2.5

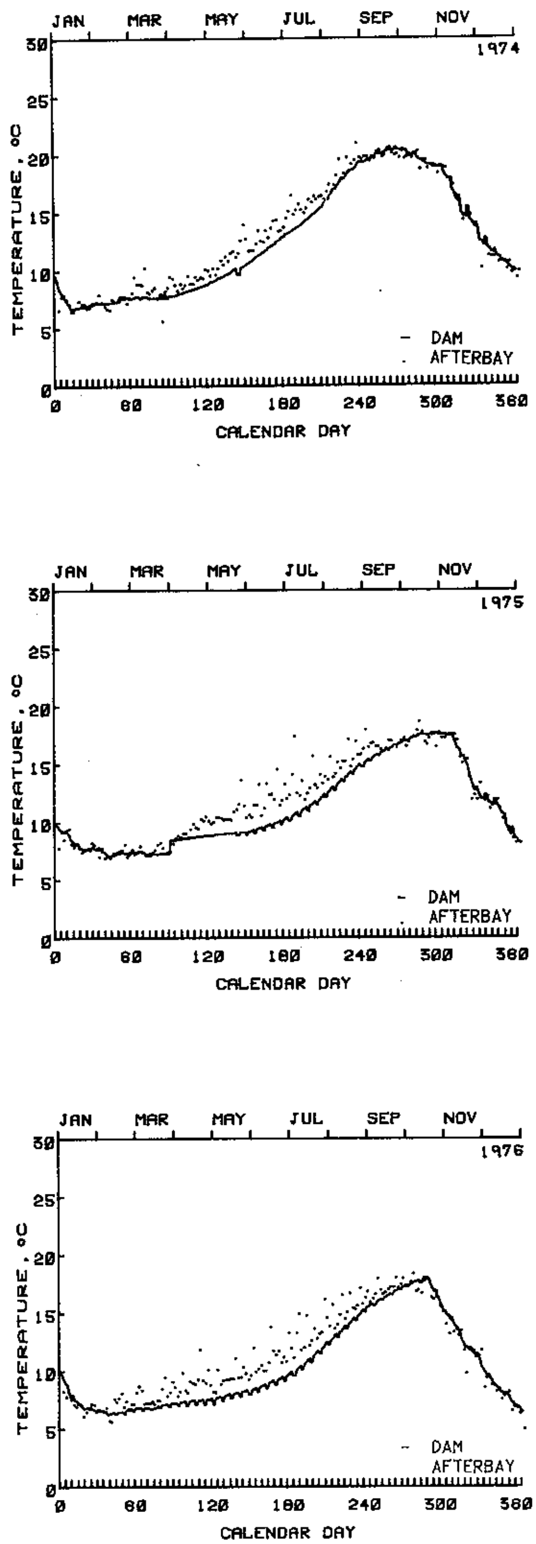


Plate 12. Predicted release temperatures from Norfork Dam and afterbay with proposed pumped-storage operations for E = 5.0

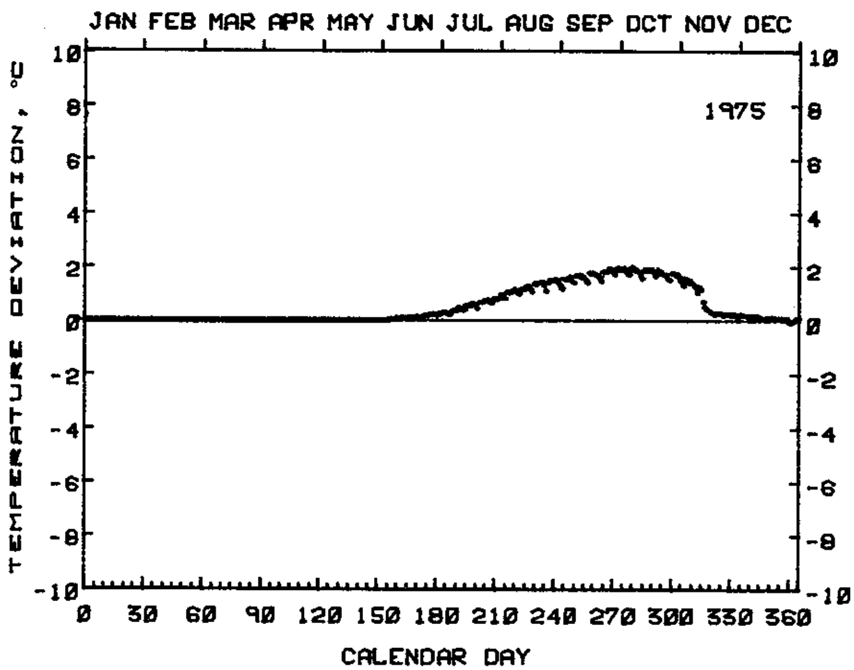


Plate 13. Norfork afterbay release temperatures for E = 5.0 minus Norfork afterbay release temperatures for E = 2.5

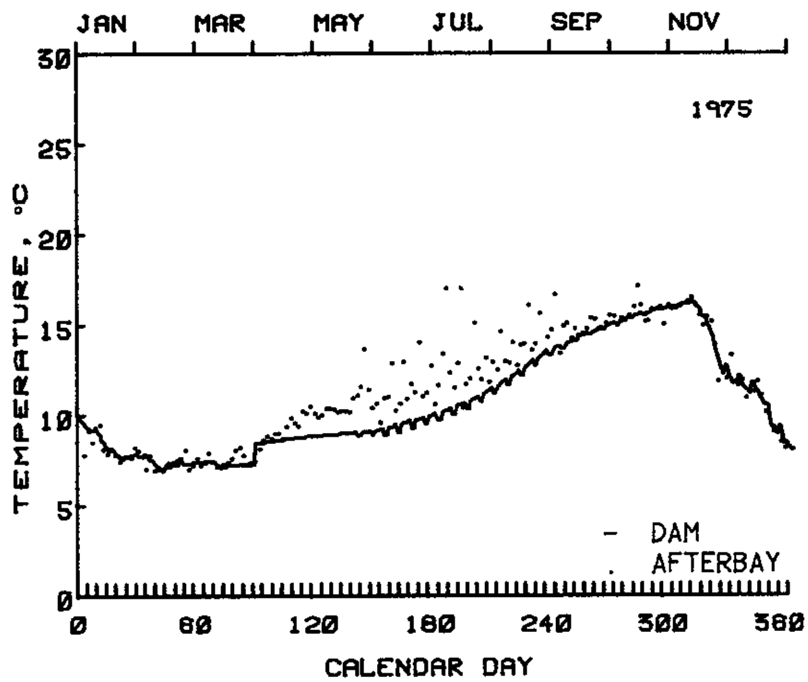


Plate 14. Predicted release temperatures from Norfork Dam and afterbay with pumped-storage operations, 1975, for E = 2.5, PBCOF = 0.0

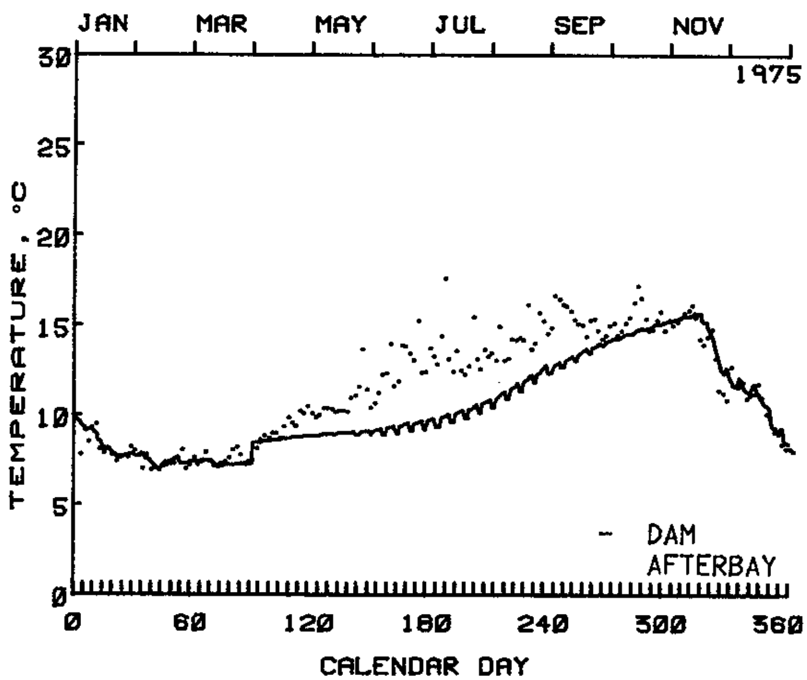


Plate 15. Predicted release temperatures from Norfork Dam and afterbay with pumped-storage operations, 1975, for E = 2.5, PBCOF = 1.0

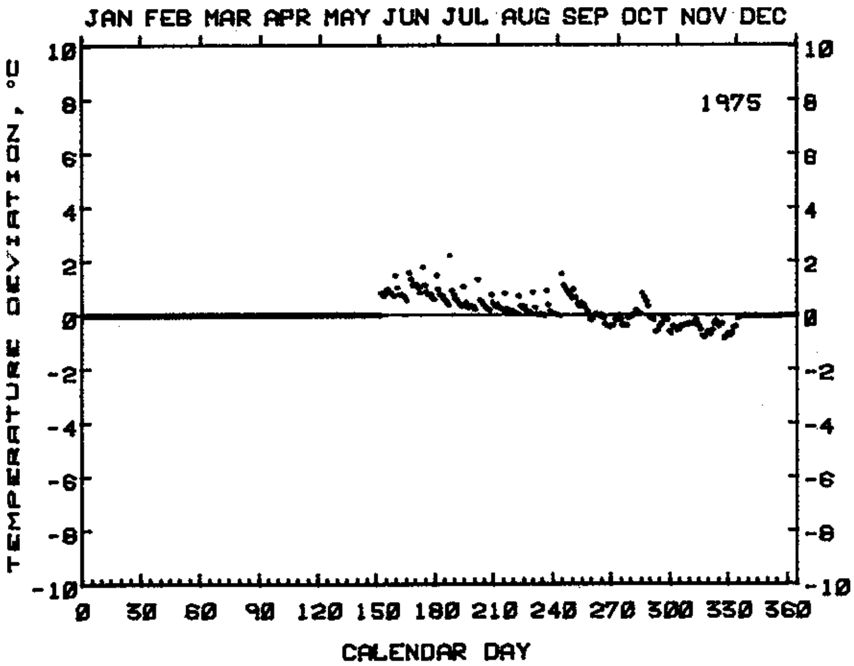


Plate 16. Predicted Norfork afterbay release temperature, PBCOF = 1.0, minus predicted Norfork afterbay release temperature, PBCOF = 0.5

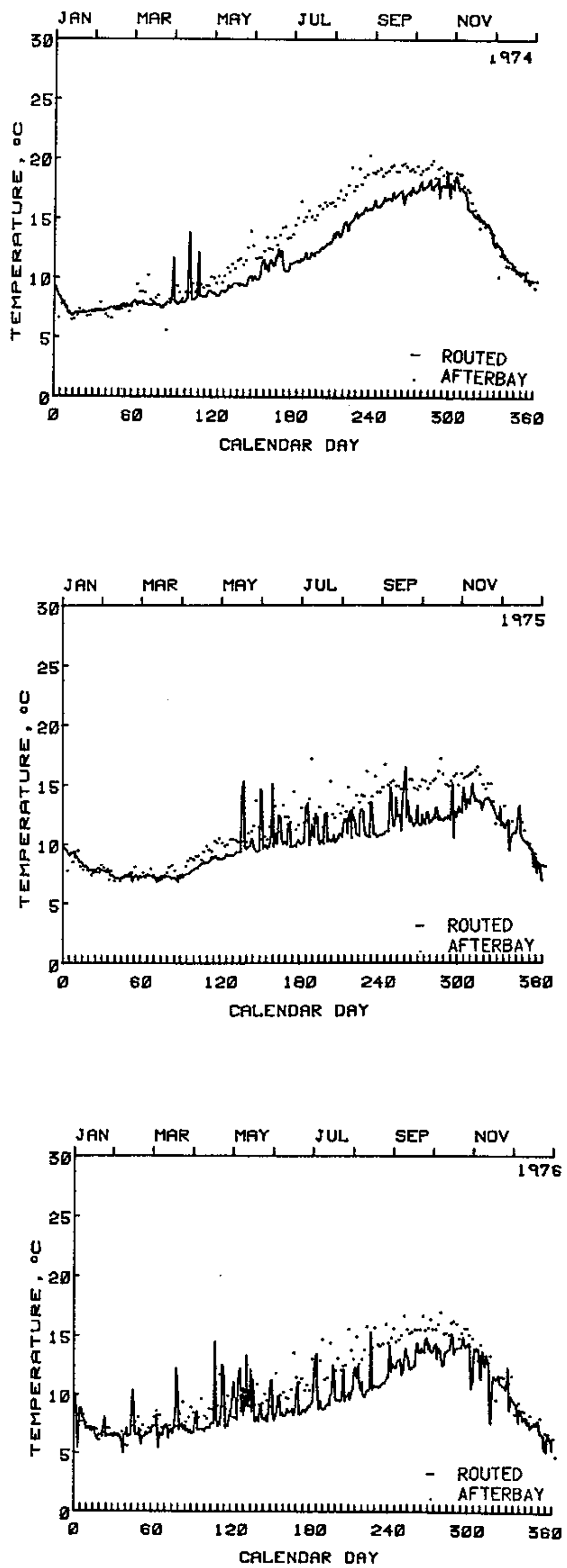


Plate 17. Predicted historical release temperature routed downstream to the site of the proposed afterbay and the predicted afterbay release temperature with pumped-storage operations

APPENDIX A: DESCRIPTION OF WESTEX THERMAL MODEL

Simulation Model Description

1. Downstream release characteristics and internal structure of temperature within a reservoir are predicted with a numerical simulation model. The model, hereinafter identified as WESTEX,* was developed by the U. S. Army Engineer Waterways Experiment Station (WES) based on results of Clay and Fruh (1970)**, Edinger and Geyer (1965), Dake and Harleman (1966), Bohan and Grace (1973), and Dortch el al. (1976).

Introduction

2. The reservoir is conceptualized as a number of homogeneous horizontal layers stacked vertically, and the heat sources and sinks to a general layer are represented as shown in Figure A1. The temperature history of a general layer is obtained by solving conservation of mass and energy equations. The governing energy equation is:

$$\frac{\Theta_L}{\partial t} = \frac{\Theta_i \; Q_i}{A \Delta Z} - \frac{\Theta_o \; Q_o}{A \Delta Z} + \frac{1}{A} \frac{\partial}{\partial Z}\left(kA \frac{\Theta_L}{\partial Z}\right) - \frac{1}{A} \frac{\partial (Q_v \Theta_L)}{\partial Z} + \frac{1}{\rho C_p \; A} \frac{\partial H}{\partial Z} \qquad \text{(A1)}$$

where

Θ_L = temperature of layer, °F
t = time, days
Θ_i = inflow temperature, °F
Q_i = flow rate into layer, ft^3/day
A = horizontal cross-sectional area, ft^2
ΔZ = layer thickness, ft
Θ_o = outflow temperature, °F
Q_o = outflow rate, ft^3/day
Z = elevation, ft

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* Bruce Loftis, "WESTEX, A Reservoir Heat Budget Model" (first draft), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.
** See REFERENCES at end of main text.

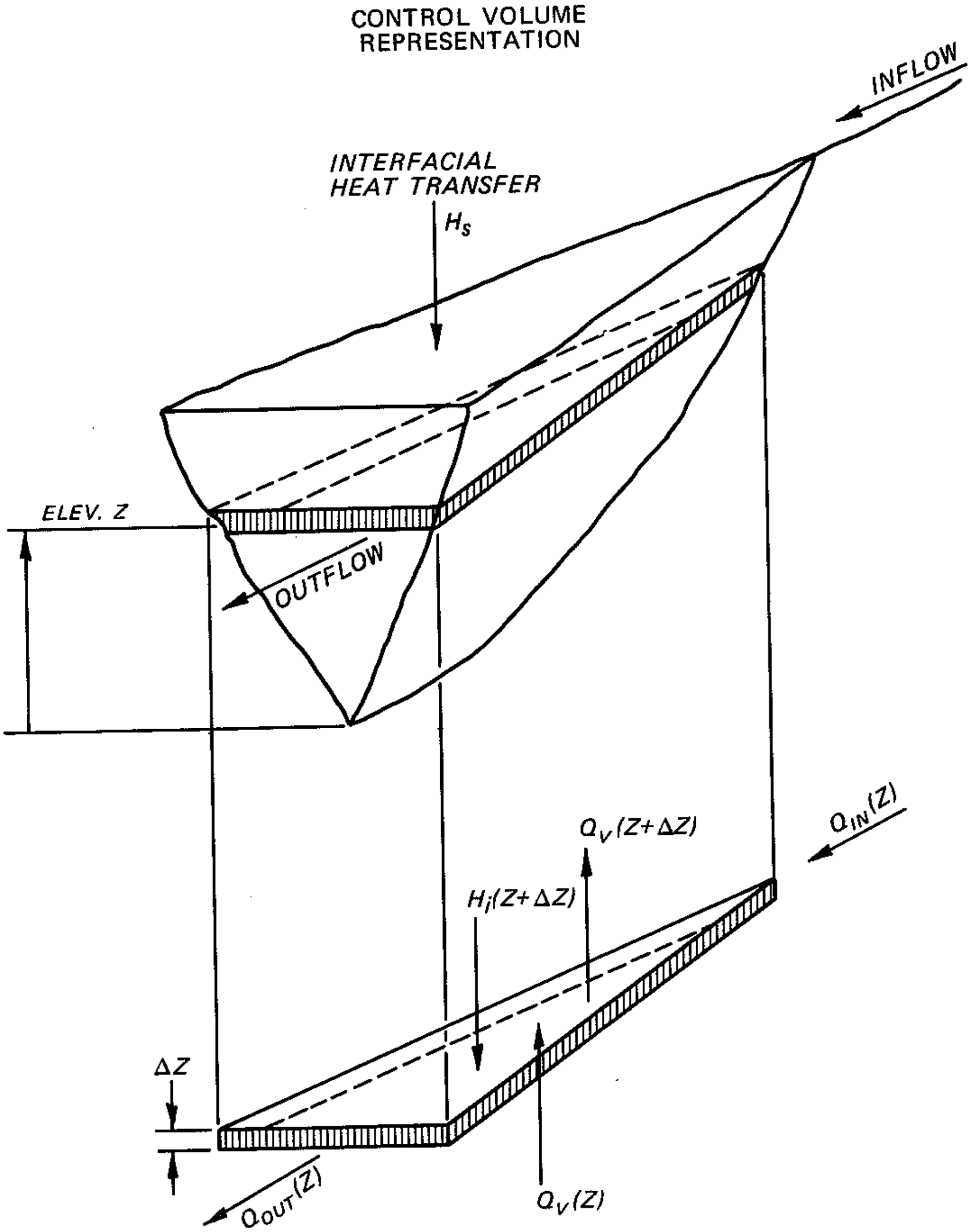

Figure A1. Typical layer in one-dimensional description

k = vertical diffusion coefficient, ft^2/day

Q_v = net vertical flow into or out of layer, ft^3/day

ρ = density of water, lb/ft^3

C_p = specific heat of water, Btu/lb/°F

H = external heat source, $Btu/ft^2/day$

Appropriate boundary conditions must be supplied for inflow and outflow rates, inflow temperatures and for surface heat exchange at the air-water interface. Solution of Equation A1 for each layer through time yields the dynamic vertical temperature distribution of the reservoir. Fundamental assumptions and the various processes employed to solve this equation will be discussed in the following section.

Fundamental Assumptions

3. Reservoir hydrodynamic phenomena and a thermal energy balance are used to predict temperature profiles and release temperatures in the time domain. The model includes computational methods for simulating heat transfer at the air-water interface; advective heat due to inflow, outflow, and pumpback processes; and the internal diffusion of thermal energy. The model is conceptually one-dimensional based on the division of the impoundment into discrete horizontal layers of uniform thickness. Assumptions include the following:

   a. Isotherms are parallel to the water surface both laterally and longitudinally.

   b. The water in each discrete layer is physically homogeneous.

   c. Internal advection and heat transfer occur only in the vertical direction.

   d. External advection (inflow and outflow) occurs as a uniform distribution within each layer.

   e. Internal dispersion (between layers) of thermal energy is accomplished by a diffusion mechanism that combines the effects of molecular diffusion and turbulent diffusion.

4. The surface heat exchange, internal mixing, and advection processes are explicitly computed and their effects are sequentially introduced during each time-step. A simplified flow chart of the

mathematical simulation procedure is presented in Figure A2. Each of these processes will be discussed.

Surface Heat Exchange

5. The net heat exchange at the surface is composed of seven heat exchange processes:

- a. Shortwave solar radiation.
- b. Reflected shortwave radiation.
- c. Long-wave atmospheric radiation.
- d. Reflected long-wave radiation.
- e. Heat transfer due to conduction.
- f. Back radiation from the water surface.
- g. Heat loss due to evaporation.

6. The surface heat transfer process is solved in the WESTEX model by an approach developed by Edinger and Geyer (1965). The thermal equation quantifying the net surface heat exchange (after some linearization) is:

$$H_S = K\,(E - \Theta_S) \tag{A2}$$

where

H_S = net rate of surface heat transfer, Btu/ft^2/day
K = coefficient of surface heat exchange, Btu/ft^2/day/°F
E = equilibrium temperature, °F
Θ_S = surface temperature, °F

Equilibrium temperature is defined as that temperature at which the net rate of heat exchange between the water surface and the atmosphere is zero. The coefficient of surface heat exchange is the rate of heat transfer at the air-water interface. The computation of equilibrium temperature and heat exchange coefficient is based solely on meteorological data as outlined by Edinger, Duttweiler, and Geyer (1968).

7. The components of surface heat exchange, with the exception of shortwave radiation, are immediately absorbed at the surface or in the top

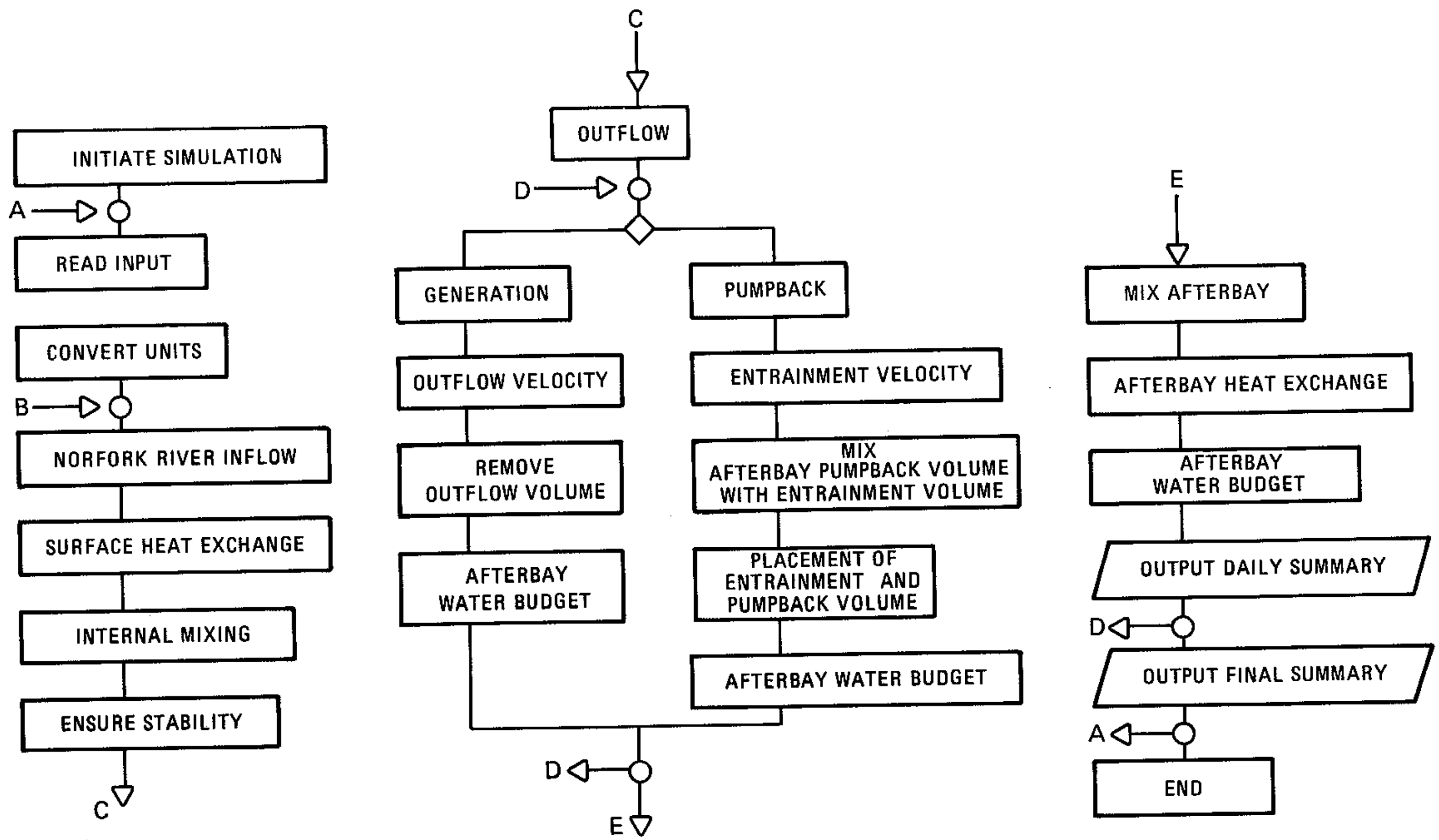

Figure A2. Flow chart

few feet of the lake. Depending upon the color and clarity of the water, shortwave radiation penetrates and increases the temperature at greater depths. Based on laboratory investigations, Dake and Harleman (1966) have proposed an exponential decay with depth for describing the heat flux due to shortwave penetration. This approach is used in WESTEX.

8. The surface heat exchanges are implemented in the model by the placement of varying percentages of the incoming shortwave radiation in each layer of the lake and by the placement of all other sources of surface heat exchange into the surface layer. The shortwave radiation is distributed exponentially, so that most is absorbed in the top layers and relatively little is absorbed in the lower layers. The procedure can be expressed mathematically by the following two equations:

$$H_s = K\,(E - \Theta) - (1 - \beta)\,\psi \tag{A3}$$

$$H_i = (1 - \beta)\,\psi e^{-\lambda z_i} \tag{A4}$$

where

H_s = heat transfer rate into or out of the surface layer, btu/ft^2/day

H_i = rate of heat absorption in layer i, Btu/ft^2/day

β = percentage of incoming solar radiation absorbed in surface layer

ψ = total incoming shortwave radiation rate, Btu/ft^2/day

λ = light extinction coefficient, ft^{-1}

z_i = depth below surface of layer i, ft

Both β and ψ are numerical model inputs which are generally determined by calibration or through correlation with Secchi disk measurements (Williams et al. 1980).

9. Equations A3 and A4 are applied once during each 1-day time-step. The net heat exchange rate into each layer is computed and converted into a temperature change. The temperature changes are used to determine an updated temperature profile for the lake.

Inflow

10. The inflow process is simulated numerically in three basic steps. The point of neutral buoyancy of the inflow is found, water in the lake is displaced by and mixed with the inflow, and a new water-surface elevation is computed.

11. The point of neutral buoyancy is found by a linear interpolation or extrapolation upon the density profile of the lake. The inflow volume is allocated to the layer of neutral buoyancy. The contents of the layer of neutral buoyancy are then fully mixed with the inflow quantity, thereby producing a volume-weighted average temperature for this layer. If the inflow volume into the neutrally buoyant layer (layer i) causes the physical capacity of that layer to be exceeded, the excess is displaced upward at the mixed temperature of the inflow layer. This displacement either flows into the next higher layer (i+1) or forms a new surface layer (described in the next paragraph). If the layer of neutral buoyancy is below the surface layer, the excess is fully mixed with layer i+1 and a new volume-weighted temperature for that layer is produced. This process continues in this sequential fashion until the introduction of the excess volume from one layer into the next highest layer does not exceed the physical capacity of the upper layer. In this manner increments of inflow, whose magnitude decreases with increasing distance from the inflow layer, are distributed from the inflow layer to the surface.

12. If the inflow current is found to be an overflow (the inflow density is less than that of the surface layer), the inflow quantity is mixed with volume of the surface layer. If the inflow quantity exceeds the volume of the surface layer, the excess forms a new surface layer at the mixed temperature of the inflow layer. The addition of the inflow quantity in any manner results in an increase in the surface elevation. A corresponding decrease in the surface elevation occurs as a result of the outflow simulation process.

Internal Mixing

13. The internal mixing process is represented by a mixing scheme based on an integral energy model (Ford 1976). The model assumes the lake to be composed of a well-mixed upper region (epilimnion) overlying a stable lower region (hypolimnion). The depth of this well-mixed upper region is determined by comparing the available kinetic energy influx from wind shear to the work required to lift an incremental volume (a layer) of water from the stable lower region to the center of mass of the well-mixed region. If the available kinetic energy influx is greater than the computed work required for mixing, the two volumes are mixed. The available kinetic energy influx is then reduced by the required work plus dissipation due to viscosity and internal wave effects. This dissipation term is computed from the Richardson number formulation developed by Bloss and Harleman (1979). Conversely, if the work required to mix the volume with the well-mixed region is greater than the available kinetic energy influx, no mixing occurs and the depth of the well-mixed region is established as its present depth.

14. Mixing in the hypolimnion is approximated by an eddy diffusion approach. A diffusivity coefficient of approximately 10 times the molecular diffusivity coefficient was used in this approach which accounted for the effects of molecular diffusion, turbulent diffusion, and additional internal processes not explicitly addressed. This value has been investigated in a number of studies including Bloss and Harleman (1979).

Outflow

15. The outflow component of the model incorporates the selective withdrawal techniques for orifice flow developed at WES by Bohan and Grace (1973). Transcendental equations defining the location of the zero-velocity limits are solved iteratively. The zero-velocity limits are functionally dependent on the release flow rate and the intake density structure. After determination of the withdrawal limits, the

outflow withdrawal profile and the flow-weighted release temperature are computed. The change in the internal heat budget is then computed to account for the vertical advection resulting from the specified outflow. If multilevel ports are open, then a flow-weighted relative velocity profile is computed independently for each port, and the velocity profiles are superimposed on the basis of a controlled shift of the withdrawal limits in the zone of overlap to achieve a total relative velocity profile.

Operation Schedules

16. Generation and pumpback flows change markedly in a single simulation day. Since the rate of these flows affects withdrawal and pumpback characteristics, it was not adequate to use daily averaged flows at Norfork Lake to accurately simulate generation and pumpback operations. Daily average flow routings usually are quite adequate for less dynamic reservoirs. For this model, the generation and pumpback schedule was approximated by the weighting procedures discussed in paragraphs 21 through 23 of the main text. The model can handle several different flow conditions within a day. The day number, modes of operation (generation or pumpback), flow rates, and durations of flow are input for each day that a change in the operation schedule occurs.

Afterbay

17. The afterbay is modeled numerically by maintaining heat and water budgets. The afterbay is assumed to not be vertically stratified. This assumption is supported by previous physical model investigations (Fontane et al. 1977, Dortch et al. 1976). Each of the pumped-storage projects studied previously has an afterbay deeper and larger than the proposed Norfork afterbay. It can be assumed that if the larger afterbays do not stratify vertically then the smaller Norfork afterbay will not. However, even though vertical temperature gradients may be insignificant, longitudinal temperature gradients may exist which could

affect the afterbay release temperature. Two extreme conditions may be assumed for the quantification of these longitudinal temperature gradients: (a) plug flow (maximum longitudinal temperature gradients due to no longitudinal mixing); and (b) fully mixed (no longitudinal temperature gradients with complete longitudinal mixing). Plug flow was assumed because: (a) it resulted in a worst case condition (maximum warming) for afterbay release temperatures; and (b) it provided estimates for afterbay release temperature considered more accurate for the long, narrow configuration of the Norfork afterbay. A sequential solution was used to approximate plug flow. Initially, it is assumed that the afterbay is continuous and homogeneous. Once during each day of simulation the volume of water in the afterbay is adjusted to account for (a) Norfork Lake generation volume that is not pumped back, (b) pregeneration afterbay volume that is pumped back, and (c) afterbay volume that is released downstream. The net contributions of the generation volumes from Norfork Lake at their respective temperatures are added to the postpumpback afterbay volume and a volume-weighted average temperature for the afterbay is computed. The daily surface heat exchange is then introduced by applying Equation A2 to the afterbay surface area and a new afterbay temperature is computed. This temperature in the afterbay is assumed to be the downstream release temperature for that day of simulation. This order of individual computations can be shown to approach the analytical solution for plug flow for the Norfork afterbay.

Pumpback Temperature and Entrainment

18. For the numerical simulations it is necessary to define the temperature of the volume pumped from the afterbay to the lake. If generation does not occur on the same day that there is pumpback, then the temperature of the pumpback volume is defined to be the temperature of the afterbay. However, if generation occurs prior to pumpback on a particular day, then the temperature of the pumped volume is determined by mixing a selected volume of pregeneration afterbay water and water released during prior generation. The pumpback temperature is computed

as a volume-weighted average of the two temperatures. A weighting factor, designated PBCOF in the model, is used to express the percentage of total pumpback volume that is contributed by the generation process.

19. The pumpback process within the reservoir is represented in the model with three components--entrainment, mixing, and placement. Entrainment is expressed as a percentage (designated E) of the pumpback volume. The entrained water is withdrawn from the lake according to a specified vertical distribution and numerically mixed with the pumpback volume at its temperature. This total volume of water at its weighted-average temperature is placed in the lake at an elevation corresponding to neutral buoyancy. The percentage of entrainment is required as input data for the model. Roberts* has suggested that a normalized entrainment distribution (as shown in Figure A3) could be used to characterize the entrained flow. In the absence of a physical model to delineate the appropriate description, the normalized entrainment distribution of Figure A3 was used in this analysis. The temperature

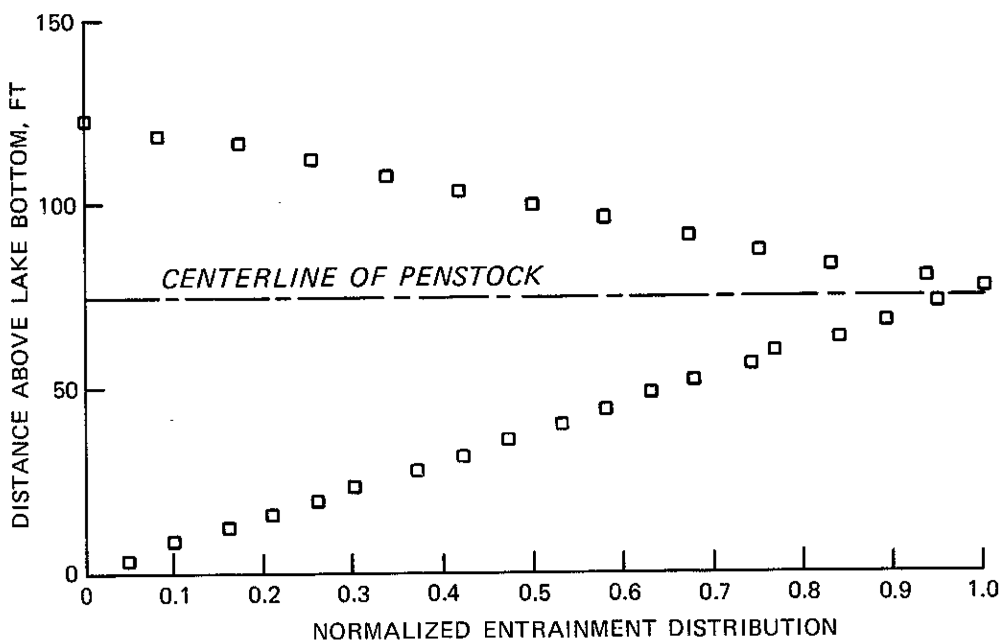

Figure A3. Normalized entrainment distribution of pumpback jet for Norfork Lake (as suggested by Roberts)

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* P. J. W. Roberts, personal communication, Apr 1981.

of the entrainment volume is computed from a weighting of the entrainment distribution and the in-lake temperatures.

Routed Release Temperature

20. In order to more realistically evaluate the warming of releases from the afterbay for proposed pumped-storage operations (Phase 2) at the Norfork project, predicted afterbay release temperatures were compared with predicted temperatures of historical releases from the existing conventional hydropower operations (Phase 1) which were routed from Norfork Dam to the site of the proposed reregulation dam. These historical releases were routed to this point, which is the point of release from the proposed afterbay for Phase 2, to show the expected natural warming of releases from Norfork Dam that could be expected without addition of an afterbay.

21. For the historical conditions, temperatures within the reach between the Norfork Dam and the proposed reregulation structure were assumed to be governed by the one-dimensional (longitudinal), energy equation

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = E_L \frac{\partial^2 T}{\partial x^2} - \frac{KA\ (T - E)}{\gamma\ C_p\ V} \tag{A9}$$

where

T = cross-sectionally averaged temperature

t = time

U = cross-sectionally averaged velocity

x = longitudinal distance

E_L = longitudinal dispersion coefficient

K = surface heat exchange coefficient

A = surface area

E = equilibrium temperature

γ = specific weight of water

C_p = specific heat of water

V = volume of reach

22. For an advection-dominated system with steady-state conditions, Equation A9 becomes

$$U \frac{\partial T}{\partial x} = - \frac{KA\ (T - E)}{\gamma\ C_p\ V} \qquad \text{(A10)}$$

Defining $\Theta = E - T$, and applying the following boundary conditions at Norfork Dam ($x = 0$) and at the reregulation structure ($x = L$)

$$\text{at} \quad x = 0 \qquad T = To$$

$$\Theta_o = E - To$$

and

$$\text{at} \quad x = L \qquad T = T_1$$

$$\Theta_L = E - T_L$$

the solution of Equation A10 becomes

$$T_L = (To - E)\ e^{-\frac{K\ A}{\gamma C_p Q}} + E \qquad \text{(A11)}$$

where

To = temperature of release water at Norfolk Dam

T_L = temperature of water routed to the reregulation structure

Q = daily average release flow rate

and all other variables are defined by Equation A9. Equation All was used to predict the temperature of releases at the site of the proposed reregulation structure.

Density Stability

23. Cooling of the lake surface causes a density instability and

results in convective mixing within the water column. Stability is checked by searching adjacent layers from bottom to top, comparing densities. If a density instability is identified, the two unstable layers are mixed, and the mixed density is compared with the density of the layer above the mixed region. If an instability still remains, the layer above the mixed region is included in the mixed region, and the process continues until stability is achieved or the surface is reached. By mixing layers above an instability, it is possible to create an instability below the mixed region. If such an instability is detected, then mixing proceeds downward until stability is achieved or the bottom is reached.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Holland, Jeffery P.
Norfork Lake, Arkansas, temperature analysis : mathematical model investigation / by Jeffery P. Holland, Mark S. Dortch, Dennis R. Smith (Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1982.
53 p., 23 p. of plates ; ill. ; 27 cm. -- (Technical report ; HL-82-12)
Cover title.
"April 1982."
Final report.
"Prepared for U.S. Army Engineer District, Little Rock."
Bibliography: p. 31.

1. Lakes--Temperature. 2. Mathematical models. 3. Norfork Lake (Ark.)--Temperature. 4. Numerical analysis. 5. Temperature. I. Dortch, Mark S. II. Smith, Dennis R. III. United States. Army. Corps of Engineers.

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