MISCELLANEOUS PAPER H-76-6

# FALLS LAKE WATER-QUALITY STUDY

## Hydraulic Laboratory Investigation

by


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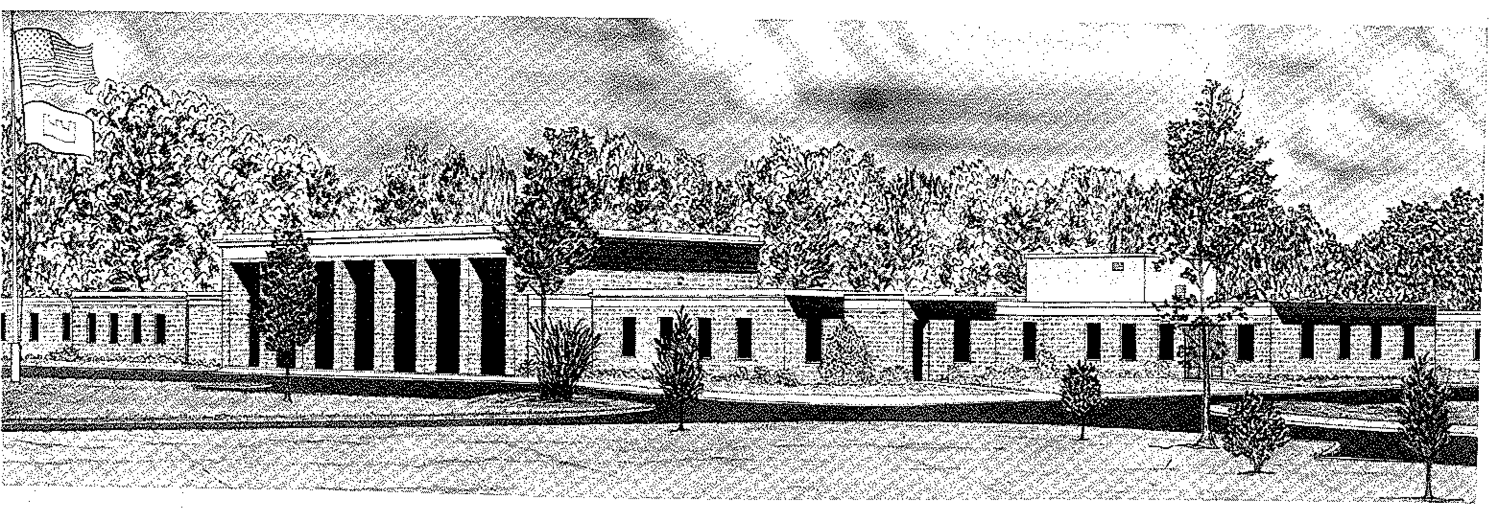
April 1976

Final Report





Prepared for U. S. Army Engineer District, Savannah
Savannah, Georgia 31402

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

| | | |
|---|---|---|
| 1. REPORT NUMBER<br>Miscellaneous Paper H-76-6 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (*and Subtitle*)<br>FALLS LAKE WATER-QUALITY STUDY; Hydraulic Laboratory Investigation | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final report<br>6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Bruce Loftis<br>Darrell G. Fontane | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>U. S. Army Engineer Waterways Experiment Station<br>Hydraulics Laboratory<br>P. O. Box 631, Vicksburg, Mississippi 39180 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>U. S. Army Engineer District, Savannah<br>P. O. Box 889<br>Savannah, Georgia 31402 | | 12. REPORT DATE<br>April 1976<br>13. NUMBER OF PAGES<br>76 |
| 14. MONITORING AGENCY NAME & ADDRESS(*If different from Controlling Office*) | | 15. SECURITY CLASS. (*of this report*)<br>Unclassified<br>15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Dissolved oxygen
Falls Lake
Intake structures
Water quality
Water temperature

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

A mathematical model was used to simulate the thermal and dissolved oxygen (D.O.) content of the proposed Falls Lake project and to evaluate the adequacy of the proposed multilevel intake structure for satisfying downstream temperature and D.O. objectives. The study indicated that proper operation of the proposed impoundment would result in satisfying the temperature objective. Low D.O. content values are predicted, reflecting the quality of water available for release through the intake

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20. ABSTRACT (Continued)

structure and outlet works. However, reaeration of flow released through the multilevel outlet works should be sufficient to increase the D.O. content of the downstream release up to or above the desired minimum level of 5 mg/ℓ.

# PREFACE

The study reported herein was conducted by personnel of the Hydraulics Laboratory (HL), U. S. Army Engineer Waterways Experiment Station (WES), during the period March-July 1974, under the direction of Mr. H. B. Simmons, Chief of HL, and Mr. J. L. Grace, Jr., Chief of the Structures Division. The investigation was sponsored by the U. S. Army Engineer District, Savannah.

The numerical simulations were conducted by Messrs. B. Loftis and D. G. Fontane, under the direct supervision of Mr. J. P. Bohan, Chief of the Spillways and Channels Branch. The report was prepared by Messrs. Loftis and Fontane, with assistance from Mr. P. E. Saunders.

Director of WES during this study and the preparation and publication of this report was COL G. H. Hilt, 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 |
|---|---|---|
| inches | 2.54 | centimetres |
| feet | 0.3048 | metres |
| miles (U. S. statute) | 1.609344 | kilometres |
| square feet | 0.09290304 | square metres |
| square miles (U. S. statute) | 2.589988 | square kilometres |
| acre-feet | 1233.482 | cubic metres |
| cubic feet per second | 0.02831685 | cubic metres per second |
| Btu (International Table) | 1055.056 | joules |
| Fahrenheit degrees | 5/9 | Celsius degrees or Kelvins* |

* 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: $K = (5/9)(F - 32) + 273.15$.

# FALLS LAKE WATER-QUALITY STUDY

## PART I: INTRODUCTION

### Purpose

1. This study was conducted to predict the thermal and dissolved oxygen (D.O.)* structures of the proposed impoundment and to determine the adequacy of the proposed multilevel intake structure to satisfy downstream temperature and D.O. objectives. The downstream temperature objective is the natural stream temperature before impoundment; the downstream D.O. objective is a minimum release of 5 mg/ℓ.

### Project Description

2. The proposed Falls Lake project will be located on the Neuse River approximately 17 miles** east-southeast of Durham, North Carolina, and 10 miles north of Raleigh, North Carolina, just northwest of the village of Falls, North Carolina. The damsite is in the upper part of the Neuse River Basin, 226 miles above the mouth. The drainage area at the site is 760 square miles and represents approximately 13 percent of the total Neuse River Basin. A 2000-ft-long earthfill dam will impound water for flood control, municipal and industrial water supply, general recreation, and fish and wildlife conservation.

3. The lake will have a flood-control capacity of 243,000 acre-feet, a conservation storage capacity of 115,000 acre-feet, and sedimentation storage capacity of 30,000 acre-feet. The maximum pool depth at the top of conservation pool will be 50.1 ft. A multilevel intake tower will be located in the upstream face of the dam to provide quality control and release of low flows.

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* Unusual abbreviations and symbols used in this report are listed and defined in the Notation (Appendix A).

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

4. The outlet works will include an intake structure with provisions for multilevel releases up to 750 cfs and flood releases up to 8000 cfs. An uncontrolled emergency spillway will pass larger flood flows. Multilevel releases will pass through two wet wells in the intake structure. Each wet well will have two 8- by 8-ft intakes with inverts at el 231 and 241.* Two flood-control passages having inverts at el 200 with 8.5- by 19.5-ft slide gates will be provided to control flood flows.

## Simulation Technique

5. The thermal and D.O. structures of the proposed Falls Lake project were predicted by using a mathematical simulation model. The model used in conjunction with this study was developed originally at the University of Texas by Clay and Fruh.[1] Development of this model (WESTEX) has been continued by the U. S. Army Engineer Waterways Experiment Station (WES).

6. The WESTEX model provides a procedure for examining the balance of thermal energy imposed on an impoundment and the effect of this energy balance on the temperature and D.O. regimes. The model includes computational methods for simulating heat transfer at the air-water interface, advective heat due to inflow and outflow, and the internal distribution of thermal energy. The model is conceptually based on the division of the impoundment into discrete horizontal layers. Fundamental assumptions include the following:

- a. Isotherms are laterally and longitudinally parallel to the water surface.
- b. The water in each layer is isotropic and physically homogeneous.
- c. Internal advection and heat transfer occur only in the vertical direction.
- d. External advection occurs as a uniform horizontal distribution within the elements.

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* All elevations (el) cited herein are in feet referred to mean sea level.

e. Internal distribution of thermal energy is accomplished by a diffusion mechanism which combines the effects of molecular diffusion, turbulent diffusion, and thermal convection.

7. The surface heat exchange, internal diffusion, inflow, and outflow processes are simulated separately, and their effects are introduced sequentially at daily intervals.

8. The WESTEX model employs an approach to the evaluation of net heat transfer at the air-water interface that was developed by Edinger and Geyer.[2] Their method formulates equilibrium temperatures and coefficients of surface heat exchange. 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 at which the heat transfer process will occur. The equation describing this relationship is

$$H = K(E - T_s) \qquad (1)$$

where

$H$ = net rate of heat transfer, Btu/ft$^2$/day

$K$ = coefficient of surface heat exchange, Btu/ft$^2$/day/°F

$E$ = equilibrium temperature, °F

$T_s$ = surface temperature, °F

The computation of equilibrium temperature and surface heat exchange coefficient is based solely on meteorological data as outlined by Edinger, Duttweiler, and Geyer.[3]

9. The inflow process into a lake is simulated in WESTEX by the placement of the inflow quantity and quality at that layer where the density of the lake corresponds most nearly to the density of the inflow. This displaces upward a volume equal to the inflow quantity. The upward displacement is reflected numerically by an increase in the water surface. A corresponding decrease in the water surface occurs as a result of the outflow simulation.

10. The outflow component of the model incorporates the selective-withdrawal technique developed at WES.[4] Transcendental equations

defining the upper and lower limits of the withdrawal zone are solved with a half-interval search method. After the withdrawal limits have been determined, the velocity profile can be evaluated. The flow in each layer is the product of the velocity in the layer, the width of the layer, and the thickness of the layer. A flow-weighted average is applied to temperature and D.O. profiles to determine the value of the release of each parameter for each time step.

11. The reservoir regulation algorithm in WESTEX has been formulated at WES to realistically simulate operation of a selective-withdrawal system. Minimum and maximum flows from each port and from the flood gate are specified. Also, the maximum flow for the selective-withdrawal system is specified. The algorithm will attempt to withdraw water at or near the objective temperature from one port level, two adjacent port levels, or the flood gate, depending on the objective temperature, the temperature profiles, and the quantity of flow to be released.

## PART II: PROCEDURE

### General Approach

12. This study involved the selection of several study years and simulation of reservoir operation for each of these years. Study years selected had combinations of streamflow quantities and air temperatures that could create extreme conditions of thermal stratification. The data required to conduct the simulations were reservoir inflows and outflows, inflow stream temperatures, meteorological data for each of the study years, geometry of the lake, and geometry of the intake structure.

13. The heat transfer into and out of the lake was evaluated, and the heat was distributed within the lake. A heat budget for each horizontal layer was maintained throughout the simulation period. An objective temperature was specified for each simulation day, and an operating scheme was determined. The operation for any day was the combination of open ports which minimized the difference between the objective downstream temperature and the predicted release temperature. The output from the simulation included a comparison of objective and release temperatures in graphical form through the simulation period, as well as tabular summaries for each day and plotted profiles of temperature and D.O. within the reservoir at specified times of the year.

14. Observed temperature profiles in nearby John Kerr Lake used for model calibration purposes indicated that thermal stratification consistently begins to build after 1 April. For the Falls Lake study, simulation was initiated on 1 April for each study year.

### Selection of Study Years

15. A statistical analysis of the monthly runoffs and mean monthly dry bulb temperatures was conducted using the period of record, 1933-1972. Monthly means and standard deviations for January through December and the deviations from the means for runoff and dry bulb

temperature are presented in Tables 1 and 2, respectively. These tables, along with plots of mean monthly dry bulb temperatures and mass curves of runoff shown in Plate 1, were used to select study years.

16. The selection of study years was limited to the period after 1948 due to the lack of adequate meteorological data prior to 1948. The following years were selected for study:

1949: Runoff was normal throughout the year; air temperatures were warm during isothermal months but were normal during the stratification period.

1951: Runoff was consistently less than average throughout the year; air temperatures were average until the end of stratification.

1957: Runoff was normal; air temperatures were slightly colder than average.

1960: Runoff was well above normal for the period February-June; subsequent runoff was normal; air temperatures were considerably below average throughout the year.

1967: Runoff was well below normal for the entire year; air temperatures were considerably colder than average during the stratification period and were somewhat warmer than average the rest of the year.

## Data Requirements

17. The daily average reservoir inflow and outflow quantities from the study years are shown in Plates 2 and 3. Hydrologic routings, using two different operation schedules based on water-quality considerations, were conducted by the Savannah District (SAS) to arrive at these flows.

18. Meteorological data from the Raleigh Weather Station, which is approximately 10 miles from the damsite, were used for the study. The required data consisted of dry bulb temperature, dew point temperature, cloud cover, and wind speed. These data were obtained from the National Climatic Center in Asheville, North Carolina. Eight meteorological observations were furnished for each day. Daily average values were computed and used to determine the daily net solar radiations, equilibrium temperatures, and coefficients of surface heat exchange for each study year.

19. The reservoir inflow temperatures for each of the five study years were not available. Observed values of temperature for the Neuse River at Falls, North Carolina, were available for the period November 1960 through September 1967. A regression equation relating equilibrium temperature and flow quantity to water temperature was developed using the observed Neuse River temperature at Falls.

$$\Theta = \alpha + \beta_1 Q_t + \beta_2 E_t + \beta_3 E_{t+1} + \beta_4 E_{t+2} \tag{2}$$

where

$\Theta$ = stream temperature, °F

$Q$ = mean daily streamflow, cfs

$t$ = time, Julian days

$E$ = equilibrium temperature, °F

and $\alpha$ and $\beta$ are regression coefficients as follows:

$\alpha$ = 12.2623

$\beta_1$ = -0.0004

$\beta_2$ = 0.2467

$\beta_3$ = 0.1398

$\beta_4$ = 0.3670

The regression equation was used to generate inflow temperatures for each of the five study years. Predicted inflow temperatures are shown in Plate 4.

20. A least squares analysis was used to fit a harmonic curve to the predicted stream temperatures for each of the five study years. The harmonic curve represents the average natural stream temperature variation during a year. An average annual variation was derived by arithmetically averaging the coefficients for the five harmonic equations. The average annual variation is expressed as

$$\Theta'_t = a \sin (bt + c) + d \tag{3}$$

where

$\Theta'$ = average stream temperature, °F

$t$ = time, Julian days

The coefficient $b$ is a unit conversion from days to radians. The coefficients $a$ , $c$ , and $d$ were determined by solving Equation 3 and were computed to be the following:

$a = 18.19°F$

$b = 1.721 \times 10^{-2} \text{ day}^{-1}$

$c = 1.281$

$d = 59.2°F$

Equation 3 was used to define the temperature objective below the dam.

## Model Verification

21. The mathematical model used for the simulation requires the determination of coefficients for (a) distribution of heat transferred at the air-water interface and (b) diffusion of internal heat. These coefficients were determined by simulating the Falls Lake impoundment and adjusting the coefficients until the predicted profiles of temperature and D.O. corresponded in shape and range to observed profiles in an existing impoundment in the same area. The observed temperature and D.O. profiles in the John Kerr Reservoir located about 40 miles north of the Falls Lake damsite were used for this purpose. Falls Lake was operated in a manner similar to that for the John Kerr Reservoir for the verification simulation. Plate 5 contains examples of the temperature and D.O. profiles observed in John Kerr Reservoir.

## PART III: RESULTS

### Operation Objectives

22. Daily streamflow routings were conducted by SAS for two sets of operational criteria. The following criteria were considered to be the essential features of the plans operation.

Period 1975-1985

a. Average daily water supply diversions from the lake for the City of Raleigh will be 59 cfs with a return flow of 47 cfs downstream of the dam.

b. Releases from Falls Lake will be made to maintain minimum flows at Smithfield, North Carolina, varying from 184 to 404 cfs throughout the year when combined with local inflows between the dam and Smithfield.

c. The required minimum release from Falls Lake to the Neuse River will be 27 cfs.

d. The maximum controlled flood release from the lake will be 8000 cfs.

e. Annual average evaporation losses from the lake amount to 33.84 in.

Period 1985-2020

a. Raleigh water supply withdrawal from the lake will be 155 cfs.

b. The required minimum release to the Neuse River will be 90 cfs.

c. The maximum controlled flood release from the lake will be 8000 cfs.

d. The temperature and D.O. content of water released from the dam during low flow periods are to conform with state water-quality standards that existed at the time of initiation of the study. These standards require a daily D.O. average of 5 mg/ℓ and stream temperatures not to exceed 5°F above the natural water temperature, and in no case above 90°F.

### Original Design

23. The initial simulations of Falls Lake were conducted with the selective-withdrawal structure as originally designed. This design

includes withdrawal levels at 9.5 ft (flood control gates) and 31.0 and 41.0 ft (selective-withdrawal ports) above the bottom of the lake. Maximum and minimum flow quantities were established for each selective-withdrawal port, for the selective-withdrawal system, and for the floodgates. These flow ranges were used for all of the simulations. Selective-withdrawal ports were assumed capable of passing 10 to 500 cfs. The selective-withdrawal system maximum capacity was originally set at 750 cfs. The minimum floodgate release was assumed to be 90 cfs. The original design will be referred to as four-port operation.

24. The results of simulation of the five study years with the original design are shown in Plate 6 for the 1975-1985 routings and in Plate 7 for the 1985-2020 routings. The sinusoidal curve on each plot represents the average annual stream temperature variation for all of the study years. This average is used as the objective temperature of the release. The computed release temperature for every day of simulation is plotted in comparison with the objective. Also, on each plot is contained a description of the ports operated to achieve the computed release temperature. Port level 1 corresponds to the selective-withdrawal ports to be located 41 ft above the bottom. Port level 2 is to be located 31 ft from the bottom and port level 3 is the floodgate to be located 9.5 ft above the bottom. Plates 8 and 9 show isotherms as computed by the WESTEX model for the two routings.

25. It can be seen from Plates 2 and 3 that inflow and outflow hydrographs are essentially the same for the two routings. The 1985-2020 period requires a minimum release of 90 cfs for any given day. Simulation during this period allows operation of the floodgate when there exists the condition of minimum flow release and cold objective temperature. For the period 1975-1985, the minimum release required is 27 cfs. This minimum flow cannot be passed through the floodgate but must be passed through the selective-withdrawal system, resulting in release temperatures which are warmer than the objective temperature. Because the 1975-1985 routing is the worst-case condition, subsequent analysis will be directed toward this period.

26. It must be noted that the objective temperature is not the

natural stream temperature for any simulation day, but simply a point on a statistically produced curve. The curve reflects an average of stream temperatures for all study years. Natural stream temperatures deviate from the objective temperature curve as do the computed release temperatures. The standard deviation of natural stream temperature from the objective for the study years considered is 2°C. Natural maximum deviations are as much as 5 to 6°C. Natural stream temperatures do not generally demonstrate significant change from day to day; therefore, a good operation scheme for the proposed lake will not produce large daily temperature fluctuations.

27. The computed release temperature (Plates 6 and 7) is within 2°C of the objective temperature for most days of each of the five study years. There can be significant deviation from the objective for either of two operation conditions. First, during the beginning of a year, the lake is subject to the process of warming, and the desired operational scheme required to achieve objective temperatures is usually to release flow from the top ports. A large flow release on a particular day requires opening of the floodgates and subsequent release of cold water. Secondly, during the latter part of a year, the lake is in the process of losing heat to the atmosphere. The operational scheme for meeting the objective temperature as well as possible during this period is usually to release cold water through the floodgates. The flow requirement for a day in this period, which is less than the assigned minimum capacity of a floodgate, is released from the selective-withdrawal ports. The result is a release temperature which is warmer than the objective temperature.

28. The warm year of 1949 had low flows in October, which is the end of the stratification period, and releases were computed to be from selective-withdrawal ports. Thus, for the month of October, the computed release temperature was 6°C warmer than the objective temperature. The maximum temperature change over a one-day period was 3°C. This occurred three different days as a result of peaks in the outflow hydrograph. Both 1951 and 1967 were years of less than average flows. For this condition, the primary mechanism for heating the lake is the penetration

of shortwave radiation. The heat exchange due to advective inflows and outflows is negligible. For a relatively shallow impoundment like the proposed Falls Lake, the heat transfer through the air-water interface penetrates to the bottom of the pool. Thus, the lake is characteristically warmer during a low-flow year than in a high-flow year. In the latter part of the stratification period of a dry year, the outflow is replaced by warmer water from above and the cold water is depleted. Thus, for dry years such as 1951 and 1967, the computed release temperatures during the latter part of the stratification period will be warmer than the objective temperature. For years similar to these two years and 1957 there will be no extreme one-day release temperature gradients. Normal runoff and slightly colder than average stream temperatures were observed in 1957. Computed release temperatures for these conditions were within 3°C of the objective curve during the stratification period. For the wet year of 1960, the computed release temperatures were within 3°C of the objective except for a two-day period in October when the flow requirements were small and the resultant release temperature was 5°C warmer than the objective. The flows for 1960 and similar years were such that the procedure for operating the structure to minimize the deviation between release and objective temperatures was erratic and unreasonable. During October, nine operational changes in the flood control gates alone were required. This would also result in release temperatures which would not be consistent from day to day.

## Increased Selective-Withdrawal Capacity

29. The original design outlet works provided a selective-withdrawal capacity of 750 cfs. As discussed previously, a small selective-withdrawal capacity coupled with the demand for a large-release flow condition will produce cold release temperatures because of the necessity to operate the floodgates. The capacity of the selective-withdrawal system was varied in the model and the effect on the release temperature was assessed. Capacities of 1000 cfs and 1500 cfs were used, and the improvement was marginal. The outflow duration curve (Plate 10)

shows that a selective-withdrawal system with a capacity of 750 cfs can pass 91 percent of all flows without the need for releasing through the flood control gates. Increasing capacity to 1000 and 1500 cfs allows the selective-withdrawal system to pass 93 and 96 percent of all flows, respectively. Doubling the selective-withdrawal capacity only accommodates an additional 5 percent of flows. It is not thought that this is an effective means of providing increased water-quality control.

## Additional Low-Level Selective-Withdrawal Ports

30. Simulations were conducted with the original 750-cfs selective-withdrawal structure and an additional low-level, small-capacity selective-withdrawal intake. The additional intake level could take the form of piggyback gates within the service gates. The centerline elevation of the additional low-level intake for selective withdrawal was assumed to be at the same elevation as that of the flood control gates. Blending between the original two-level selective-withdrawal system and the additional low-level intakes was allowed for all flows. This configuration was designated as six-port operation. The results (Plates 11 and 12) indicate some advantage is to be expected during the late summer and early fall. It is possible to release from the low-level ports when cold water is needed to meet the objective and a small flow release is required. The greatest improvement occurs in the normal flow years similar to 1949 and 1957. Computed release temperatures for these years are within 3°C of the objective temperature for all of the periods of simulation. The deviation of release temperature from the objective for the dry years similar to 1951 and 1967 is improved only slightly with the six-port operation. The notable improvement for wet years, such as 1960, is the smoothing of floodgate operation. The extreme daily variations of release temperature produced with four-port operation are eliminated with six-port operation. In fact, the inclusion of low-level selective-withdrawal intakes provides for smoother operation of the flood control facilities in each of the five study years. Isotherms for the simulations with six-port operation are shown in Plates 8 and 9.

## Dissolved Oxygen Prediction

31. The procedure used to predict the D.O. content of Falls Lake was based on the work done at WES for the Richard B. Russell water-quality study.[5] For the Richard B. Russell water-quality study, an algorithm to predict the D.O. regime of a lake was developed based on the work of Bella[6] and Carroll and Fruh.[7] The D.O. was accounted for in the lake model in a manner similar to that used for other water-quality parameters, such as temperature. The D.O. content of the inflow and outflow was accounted for and used to adjust the lake D.O. structure. The surface layers of the lake were assumed saturated with D.O. The saturated D.O. condition was extended below the surface to a depth at which a 1°C difference from the temperature of the water surface was predicted. Prototype measurements of temperature and D.O. profiles at the John H. Kerr Reservoir were used to determine that the 1°C value approximated the depth of saturated D.O. conditions. After saturation of the surface layers, D.O. was vertically diffused through the vertical extent of the lake in a manner analogous to thermal diffusion. A D.O. depletion term based on the work of Markofsky and Harleman[8] was then applied to each layer in the lake for each computation step. This depletion term had the form

$$D = K_D(T)L \qquad (4)$$

where

$D$ = D.O. depletion, mg/ℓ/day

$K_D(T)$ = temperature-dependent deoxygenation coefficient, $day^{-1}$

$L$ = biochemical oxygen demand (B.O.D.), mg/ℓ

The temperature-dependent deoxygenation coefficient $K_D(T)$ was computed from

$$K_D(T) = K_D(20°C) \times 1.047^{(T-20)} \qquad (5)$$

where

$K_D(20°C)$ = deoxygenation coefficient at 20°C, $day^{-1}$

$T$ = temperature of the layer, °C

For the Richard B. Russell water-quality study, the B.O.D. (L) in all layers was considered equal and constant throughout the year, i.e. independent of time and depth.

32. For the Falls Lake study, B.O.D. was considered time dependent. The B.O.D. was handled in the WESTEX model in the same manner as D.O. It was budgeted in the inflow and outflow processes and vertically diffused in a manner analogous to thermal diffusion. During every time step, the following B.O.D. depletion term was applied to each layer in the lake:

$$B = K_B L \tag{6}$$

where

$B$ = B.O.D. depletion, mg/ℓ/day

$K_B$ = decay coefficient

$L$ = B.O.D., mg/ℓ

Values of the D.O. and five-day B.O.D. content of the inflow were obtained from observed preimpoundment data[9] at the Falls Lake site. Linear interpolation was used to develop a record of daily inflow B.O.D. from the existing data. This one-year record of daily inflow B.O.D. loadings was used for each of the five study years. For the development of daily inflow D.O. data, a linear relationship was determined between observed D.O. values and the value of saturated D.O. As shown in References 6 and 7, the resulting expression for saturated D.O. as a function of inflow temperature is

$$D.O._{sat} = \frac{1}{(p + q\phi)} \tag{7}$$

where

$D.O._{sat}$ = saturated D.O. content, mg/ℓ

$p = 6.77 \times 10^{-2}$

$q = 2.08 \times 10^{-3}$

$\phi$ = stream temperature, °C

The relationship between observed D.O. content of the inflow and saturated D.O. was

$$D.O._{in} = \sigma D.O._{sat} + \varepsilon \qquad (8)$$

where

$D.O._{in}$ = computed D.O. content of inflow, mg/ℓ

$\sigma = 1.7115$

$\varepsilon = -9.6791$ mg/ℓ

At each time step the value of saturated D.O. was computed and used to determine an inflow D.O. value from the above relationship. Because of the lack of sufficient data or a physical model to establish flow-through times, no attempt was made to deplete the D.O. and B.O.D. content of the inflow for travel time from the headwaters to the dam.

33. Initially, the deoxygenation coefficient $K_D(T)$ and the decay coefficient $K_B$ (Equations 4 and 6, respectively) were assumed equal and set to values between 0.1 and 0.13. While these values are perhaps reasonable in a stream environment, Markofsky and Harleman[8] suggest they may be inappropriate for use in a lake. A five-day B.O.D. value will not be a good estimate of the ultimate B.O.D. in a lake, and the decay process may proceed at a slower rate than in a stream. Markofsky and Harleman suggest using a B.O.D. decay coefficient on the order of 0.01 and increasing the B.O.D. values to represent a larger ultimate demand. However, accurate estimation of ultimate B.O.D. in the proposed Falls Lake is not possible with existing data.

34. It has been observed by Markofsky and Harleman as well as by Carroll and Fruh[7] that the overall oxygen depletion in a relatively unpolluted lake is on the order of 0.1 mg/ℓ/day. This value of oxygen depletion was used for the Richard B. Russell water-quality study.

Based on the predicted Falls Lake B.O.D. loading, a deoxygenation coefficient $K_D(T)$ and decay coefficient $K_B$ of 0.06 was chosen to give oxygen depletion rates ranging from 0.1 to 0.5 mg/ℓ/day. The results of that simulation, in terms of predicted release D.O. content, fall along the upper portion of the band shown in Plate 13. The results of the simulations with a deoxygenation coefficient $K_D(T)$ and decay coefficient $K_B$ of 0.13 fall along the lower portion of the band in Plate 13. A deoxygenation coefficient and decay coefficient of 0.13 gives an average oxygen depletion ranging from 0.2 to 1.0 mg/ℓ/day. The predicted D.O. profiles from the simulation with the deoxygenation coefficient and decay coefficient of 0.13 most closely represented the D.O. profiles observed at John Kerr Reservoir.

35. To evaluate the sensitivity of the D.O. prediction routine and to provide a means to evaluate the effect of the inflow B.O.D. loadings on the D.O. prediction, a range of values for the deoxygenation and decay coefficients were evaluated. For example, the decay coefficient for B.O.D. was set to 0.01, while the deoxygenation coefficient was set at 0.1. While it is not a realistic condition for D.O. to be depleted faster than B.O.D., it has the mathematical effect of maintaining levels of B.O.D. in the reservoir longer than if the decay coefficient was 0.1. This procedure is representative of increasing the inflow B.O.D. Since the depth of saturated D.O. conditions is a variable dependent on many factors, the saturated D.O. condition was extended below the surface to depths at which 1.5°C and 2°C differences from the temperature at the water surface were present. This had the effect of extending the saturation condition deeper in the pool.

36. Eight combinations of decay coefficients (0.01 to 0.1), deoxygenation coefficients (0.01 to 0.13), and temperature differences to determine saturation (1°C to 2°C) were evaluated. The results of the simulations in terms of predicted D.O. content of flow entering the intake structure are represented by the band in Plate 13. The results show the predicted D.O. content entering the intake structure at Falls Lake to be less than 5 mg/ℓ for at least three months during the year.

## PART IV: CONCLUSIONS

37. An attempt was made in this study to satisfy a single objective temperature curve for each of the years investigated. The downstream temperature objective was computed as the mean of natural stream temperatures for the five study years. Evaluation of model results indicates that there should be no significant problems in satisfying the natural stream temperature objective. The simulations show that, because the lake accumulates heat during the summer months, the lake will be warmer in the fall than the natural stream for most years. Although the lake cools in the late summer and fall in response to heat transfer with the atmosphere, the cooling of a lake is a slower process than the cooling of a stream. Therefore, excess heat energy remains in the lake at the end of the stratification period. For most years, the release temperatures will be somewhat warmer in this period than the corresponding natural stream temperatures.

38. Investigations were made with increased selective-withdrawal capacity to assess possible improvement in deviations of computed release temperatures from objective temperatures. Model results indicate that the original design of 750 cfs for the selective-withdrawal system capacity is adequate. Increasing the capacity does not significantly diminish the deviation of release temperatures from objective temperatures.

39. Model results indicated the advantage of including low-level ports in the selective-withdrawal system. These ports could take the form of piggyback gates located in the floodgates and would provide more control over the cold-water releases. Thus, objective temperatures could be more nearly achieved in the summer and fall. The provision of the low-level ports also results in smoother operation of the flood control facilities than occurs without the low-level ports. Additionally, it is thought that piggyback gates have significant capability for aeration of release flows.

40. The D.O. content of the lake and of the flow into the intake structure was simulated in the same manner as temperature. However,

considerably more data were available for describing temperature than were available for describing D.O. content and B.O.D. By the use of interpolation, a one-year record of oxygen inflow data was developed from existing data. This one-year record of inflow D.O. and B.O.D. values was used as input for each of the five study years. A range of deoxygenation and decay coefficients was applied in the simulations to produce the effect of a range of inflow D.O. and B.O.D. values. It was felt that a range of possible output, such as that shown in Plate 13, was the most appropriate way to present the results of the D.O. simulations.

41. The predicted low D.O. content values reflect the quality of water entering the intake structure. The gate-within-a-gate or piggyback concept will allow reaeration on all sides of the water issuing from the low-level control gate. Free surface flow through the conduit will allow further reaeration. A stilling basin designed to induce turbulence with a free hydraulic jump will also allow further reaeration. Methods for predicting the amount of reaeration are not available. However, based on experience and observed prototype data,[10] it is believed that sufficient reaeration will occur to maintain D.O. contents equal to or greater than 5 mg/ℓ in the releases from the multilevel outlet works.

42. It is recommended by WES that the proposed Falls Lake be operated for a downstream temperature objective and that low-level selective-withdrawal ports be included in the intake configuration. It is felt that this configuration and operation will provide the downstream temperature and D.O. objectives.

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Table 1

Runoff Data for Years 1928-1970, Falls Lake, North Carolina

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Monthly Mean of Runoff (Inches) | | | | | | | |
| | 1.8 | 3.4 | 5.0 | 6.1 | 6.6 | 7.1 | 7.6 | 8.2 | 8.8 | 9.4 | 10.0 | 11.1 |
| | | | | | Standard Deviation from Mean (Inches) | | | | | | | |
| | 1.0 | 1.6 | 2.0 | 2.3 | 2.4 | 2.4 | 2.6 | 2.8 | 3.1 | 3.3 | 3.5 | 4.0 |
| | | | | | Departure of Runoff from Mean (Inches) | | | | | | | |
| 1928 | (-1.5) | (-1.9) | (-2.4) | -1.7 | -0.9 | -0.2 | -1.1 | -1.3 | 2.3 | 2.0 | 1.4 | 0.3 |
| 1929 | (-1.8) | (-2.1) | 1.3 | 1.5 | 2.1 | (2.9) | (4.1) | (4.3) | (3.7) | (8.0) | (9.1) | (9.1) |
| 1930 | -0.6 | -0.9 | (-2.1) | (-2.8) | (-3.2) | (-3.3) | (-3.4) | (-4.0) | (-4.5) | (-5.0) | (-5.6) | (-6.3) |
| 1931 | (-1.4) | (-2.9) | (-4.2) | (-3.6) | (-2.6) | (-2.9) | (-3.1) | -1.1 | -1.7 | -2.3 | -2.8 | -3.9 |
| 1932 | -0.0 | -0.7 | -0.1 | -0.6 | -1.1 | -1.5 | -2.1 | -2.7 | (-3.3) | (-3.4) | -3.0 | -1.5 |
| 1933 | -0.3 | -0.6 | -1.7 | -1.4 | -1.8 | -2.2 | (-2.7) | (-3.0) | (-3.6) | (-4.2) | (-4.7) | (-5.9) |
| 1934 | (-1.8) | (-3.2) | (-3.2) | -1.3 | -0.9 | -0.0 | -0.3 | -0.3 | 0.8 | 0.3 | 0.4 | 2.3 |
| 1935 | -0.2 | -1.0 | -0.8 | 1.3 | 1.4 | 0.9 | 0.6 | 0.0 | 0.2 | -0.3 | -0.5 | -0.9 |
| 1936 | (3.6) | (5.8) | (7.4) | (10.2) | (9.9) | (9.8) | (9.7) | (9.9) | (9.5) | (9.4) | (8.9) | (9.5) |
| 1937 | (3.2) | (3.7) | (3.3) | (4.9) | (5.1) | (5.0) | (4.6) | (6.7) | (7.3) | (7.1) | (6.8) | (5.9) |
| 1938 | -0.9 | (-1.7) | (-2.4) | (-2.7) | (-3.0) | -1.2 | 2.0 | 2.5 | 2.0 | 1.4 | 1.3 | 1.1 |
| 1939 | -0.8 | (1.7) | (2.9) | (3.3) | (3.9) | (3.8) | (4.3) | (7.5) | (8.1) | (7.7) | (7.2) | (6.3) |
| 1940 | (-1.2) | -0.7 | -1.1 | -0.8 | -0.3 | -0.2 | -0.7 | 0.3 | -0.3 | -0.8 | -0.3 | -1.0 |
| 1941 | (-1.2) | (-2.5) | (-2.9) | (-2.8) | (-3.3) | (-3.6) | (-3.5) | (-4.1) | (-4.7) | (-5.3) | (-5.8) | (-6.9) |
| 1942 | (-1.3) | (-2.9) | (-3.5) | (-4.4) | (-3.9) | (-4.4) | (-4.8) | (-4.4) | (-4.6) | (-3.8) | (-3.6) | -3.1 |
| 1943 | 0.9 | 0.9 | 1.2 | 1.3 | 1.0 | 0.7 | 0.5 | -0.1 | -0.7 | -1.3 | -1.8 | -2.9 |
| 1944 | -0.2 | -0.5 | 0.9 | 2.3 | 2.1 | 1.7 | 1.6 | 1.4 | 2.1 | (4.4) | (4.7) | (5.4) |
| 1945 | -0.6 | 0.3 | -0.1 | -0.8 | -1.1 | -1.5 | 0.8 | 1.4 | (7.8) | (7.7) | (7.4) | (8.9) |

(Continued)

Note: Values in parentheses have departures greater than one standard deviation for the month.

Table 1 (Concluded)

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Departure of Runoff from Mean (Inches) (Continued) | | | | | | | | |
| 1946 | (1.2) | (3.0) | (2.2) | 1.7 | 2.3 | 2.3 | (2.8) | 2.3 | 1.9 | 1.8 | 1.5 | 2.9 |
| 1947 | (-1.2) | -1.6 | (-2.3) | (3.2) | (-3.7) | (-4.1) | (-4.5) | (-4.9) | (-4.9) | -2.6 | -2.5 | -2.5 |
| 1948 | (2.2) | (2.6) | (3.1) | 2.3 | (2.5) | 2.3 | 2.3 | 1.7 | 1.9 | 2.7 | (6.1) | (7.4) |
| 1949* | 0.2 | -0.7 | -1.3 | -1.2 | -1.6 | -1.3 | -1.5 | -1.1 | -1.7 | -0.8 | -3.0 | -1.6 |
| 1950 | (-1.2) | (-2.6) | (-3.7) | (-3.8) | (-3.8) | -1.9 | -2.2 | -2.6 | (-3.2) | (-3.7) | (-3.8) | (-4.8) |
| 1951* | (-1.2) | (-2.4) | (-2.2) | (-2.9) | (-3.3) | (-3.4) | (-3.8) | (-4.4) | (-4.9) | (-5.5) | (-5.8) | (-6.1) |
| 1952 | 0.4 | (2.5) | (2.5) | (2.4) | 2.0 | 1.7 | 2.2 | (3.4) | 2.9 | 3.3 | (3.9) | (4.8) |
| 1953 | (1.4) | (1.8) | (2.8) | 2.1 | (2.5) | 2.3 | 1.8 | 1.2 | 0.7 | 0.1 | 0.1 | 0.6 |
| 1954 | 0.2 | 0.4 | 0.1 | -0.3 | -0.6 | -1.1 | -1.6 | -2.2 | -2.6 | -3.1 | -3.1 | (-4.1) |
| 1955 | -0.0 | -0.2 | -0.9 | -1.7 | -2.1 | -2.2 | -0.7 | -0.6 | -0.5 | -1.0 | -1.4 | -2.5 |
| 1956 | 0.0 | 0.2 | 0.3 | 0.3 | 0.2 | -0.2 | -0.5 | -1.0 | -1.3 | -1.2 | -1.1 | -1.6 |
| 1957* | (1.5) | (1.9) | 1.3 | 0.8 | 0.8 | 0.3 | -0.3 | -0.3 | -0.5 | -0.9 | 1.2 | 1.8 |
| 1958 | 0.5 | 0.6 | (2.1) | (4.4) | (4.4) | (4.5) | (4.4) | (4.1) | (3.6) | 3.1 | 2.6 | 3.4 |
| 1959 | -0.2 | -0.9 | 0.2 | -0.3 | -0.1 | 0.5 | 0.7 | 0.8 | 1.7 | 2.4 | (3.8) | (4.2) |
| 1960* | (3.2) | (3.9) | (5.7) | (5.5) | (5.5) | (5.2) | (5.2) | (5.7) | (5.5) | (5.0) | (4.6) | (4.5) |
| 1961 | 0.5 | 0.6 | 1.7 | 2.3 | 2.3 | (2.7) | (2.8) | (3.1) | 2.5 | 2.0 | 2.1 | 4.0 |
| 1962 | 0.4 | 1.3 | (3.0) | 2.3 | 2.1 | 2.3 | 2.0 | 1.6 | 1.1 | 2.6 | 2.5 | 3.2 |
| 1963 | -0.4 | 1.0 | -0.0 | -0.9 | -1.3 | -1.8 | -2.2 | -2.8 | (-3.3) | -3.3 | -3.3 | -2.7 |
| 1964 | 0.7 | 0.2 | 0.6 | -0.2 | -0.7 | -1.2 | -1.6 | -1.7 | -0.9 | -1.3 | -1.4 | -1.6 |
| 1965 | 0.4 | 0.6 | -0.0 | -0.5 | 0.4 | 2.0 | 2.4 | 1.9 | 1.4 | 0.8 | 0.2 | -0.7 |
| 1966 | 0.2 | 1.5 | 0.2 | 0.8 | 0.8 | 0.3 | -0.2 | -0.7 | -1.3 | -1.9 | -2.4 | -3.0 |
| 1967* | -0.6 | (-1.9) | (-3.4) | (-4.3) | (-3.9) | (-4.0) | (-4.5) | (-4.8) | (-5.3) | (-5.9) | (-6.2) | (-5.0) |
| 1968 | (-1.4) | (-2.0) | (-3.2) | (-4.2) | (-4.1) | (4.4) | (-5.0) | (-5.6) | (-6.1) | (-6.5) | (-7.0) | (-7.5) |
| 1969 | -0.2 | 0.1 | -0.5 | -1.5 | -1.6 | -2.1 | -2.2 | -2.7 | -3.1 | (-3.6) | (-4.1) | (-4.8) |
| 1970 | 0.1 | -1.1 | -0.8 | -1.6 | -2.1 | -2.0 | -2.6 | (-3.2) | (-3.7) | (-4.0) | (-4.5) | (-4.8) |

* Indicates study year.

Table 2

Monthly Means and Standard Deviations of Dry Bulb Temperature for 1933-1972,

Falls Lake, North Carolina

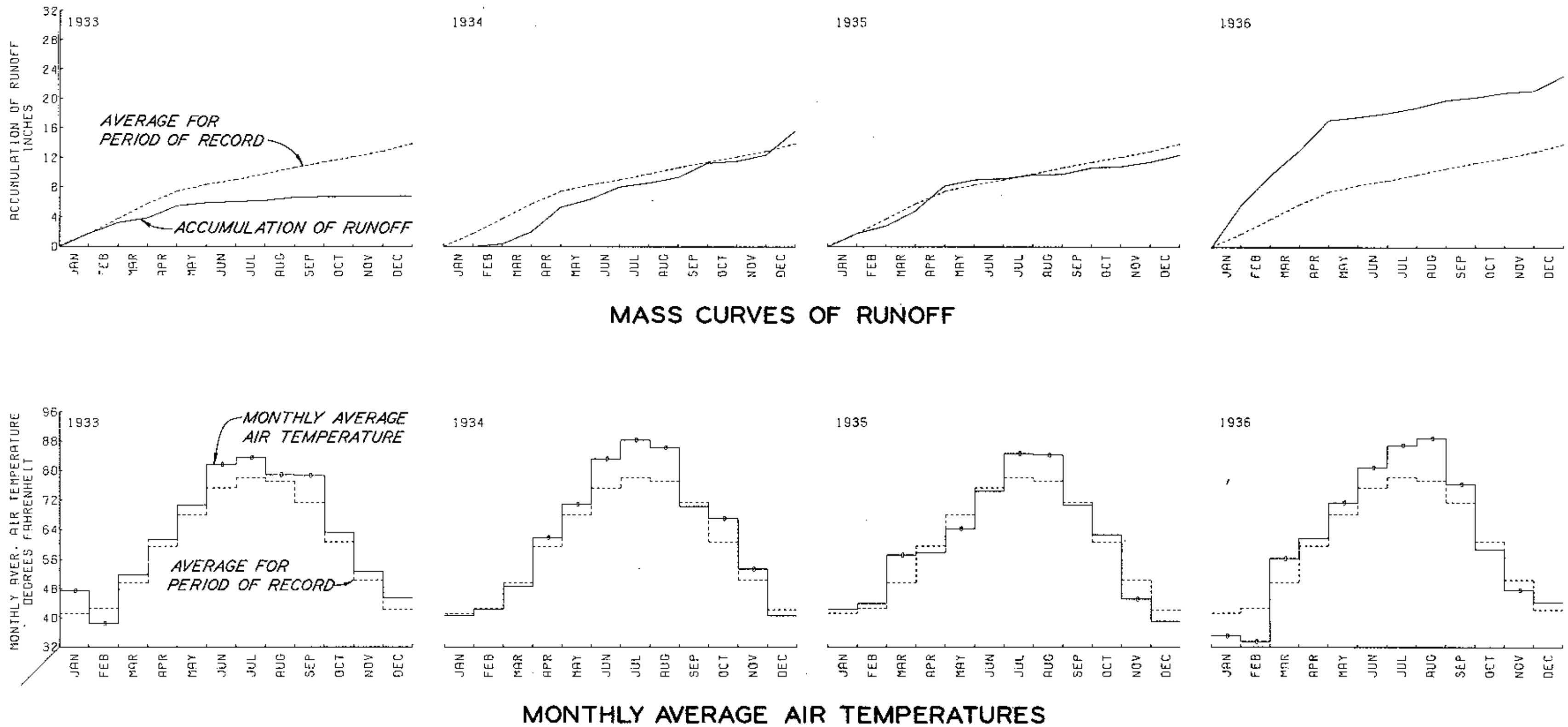
| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Monthly Mean (°F) | | | | | | |
| | 41.3 | 42.6 | 49.7 | 59.6 | 69.0 | 75.3 | 78.1 | 77.1 | 71.3 | 60.8 | 50.5 | 42.3 |
| | | | | | | Standard Deviation from Mean (°F) | | | | | | |
| | 4.8 | 3.9 | 4.4 | 2.2 | 2.8 | 2.4 | 1.6 | 1.5 | 2.3 | 2.7 | 2.4 | 4.0 |
| | | | | | | Departure of Temperature from Mean (°F) | | | | | | |
| 1933 | (8.7) | 2.7 | 1.8 | 0.4 | (5.3) | (2.6) | -0.2 | 0.1 | (6.2) | 1.6 | 0.2 | (6.1) |
| 1934 | (4.9) | (-7.8) | -1.5 | 0.8 | -0.3 | (3.5) | (2.7) | 1.0 | (2.5) | -0.2 | (3.3) | 0.3 |
| 1935 | -0.3 | 1.3 | (6.8) | (-2.6) | -1.5 | 2.2 | 0.1 | 0.8 | -0.2 | 1.4 | (3.5) | (-6.1) |
| 1936 | -3.1 | -2.9 | (5.5) | (-2.4) | (3.4) | 0.1 | (1.8) | (2.3) | (2.7) | (2.8) | -0.3 | 2.9 |
| 1937 | (9.5) | 0.5 | -0.3 | 0.4 | 1.2 | (2.7) | 0.5 | (1.5) | -1.8 | -1.6 | -0.9 | 0.3 |
| 1938 | 0.7 | (6.5) | (7.5) | (2.4) | 1.3 | -1.3 | -0.5 | (3.6) | 0.3 | 0.5 | (4.1) | 1.7 |
| 1939 | 4.7 | (8.4) | (5.2) | 0.4 | 0.6 | (3.9) | -0.5 | 0.8 | (3.5) | (2.8) | -0.9 | 2.4 |
| 1940 | (-9.7) | 1.8 | -1.3 | -1.6 | 0.0 | (3.1) | 0.4 | 0.3 | -1.3 | 0.1 | 1.8 | (4.9) |
| 1941 | -0.7 | (-3.9) | (-4.9) | (4.0) | 2.2 | 0.3 | (2.1) | (1.6) | (3.8) | (7.4) | (2.9) | 3.9 |
| 1942 | -0.7 | -3.4 | 3.1 | (2.6) | 2.2 | (2.5) | (3.2) | 0.5 | (2.3) | 1.7 | (2.5) | -1.3 |
| 1943 | 2.1 | 2.8 | 0.2 | -1.6 | (3.0) | (5.1) | 1.1 | (2.0) | -2.1 | -0.7 | -1.0 | -0.7 |
| 1944 | 0.1 | 2.3 | -0.3 | -0.4 | (5.4) | 2.3 | -0.8 | -1.4 | 1.1 | -1.3 | -1.5 | (-4.8) |
| 1945 | -2.3 | 0.9 | (10.5) | (2.7) | (-3.1) | 1.3 | -0.2 | (-1.6) | (3.3) | -1.3 | 1.4 | (-5.5) |
| 1946 | 0.0 | 2.0 | -3.3 | -0.4 | -1.7 | -1.0 | (-2.0) | (-3.2) | -0.5 | 0.6 | (4.2) | 3.3 |
| 1947 | (5.1) | (-7.0) | (-7.7) | 1.5 | 0.4 | -1.0 | (-2.9) | 1.0 | 0.0 | (3.8) | (-3.7) | -1.6 |
| 1948 | (-6.8) | -0.8 | 4.1 | 1.9 | -0.4 | 0.6 | (1.8) | -0.7 | -1.2 | (-3.7) | (4.3) | 2.6 |
| 1949* | (7.9) | (6.0) | 1.7 | -2.0 | 0.0 | 1.1 | (3.0) | 0.5 | (-2.3) | (3.4) | -1.0 | 1.9 |
| 1950 | (10.9) | 2.2 | -2.1 | -1.8 | 0.6 | -0.1 | -1.0 | -1.1 | -1.2 | 2.6 | (-2.5) | (-4.7) |

(Continued)

NOTE: Values in parentheses have departures greater than one standard deviation for the month.
* Indicates study year.

Table 2 (Concluded)

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Departure of Temperature from Mean (°F) (Continued) | | | | | | | | | | | |
| 1951* | 1.8 | 1.6 | -0.3 | -1.2 | -1.8 | 0.9 | 1.2 | 1.0 | 0.2 | (2.8) | (-4.4) | 3.1 |
| 1952 | (5.5) | 2.0 | -0.7 | -0.3 | 0.2 | (4.7) | (2.4) | -0.3 | -1.0 | (-5.0) | 0.2 | 1.1 |
| 1953 | (5.4) | 3.1 | 1.6 | -0.2 | (5.5) | -0.5 | 1.5 | 0.7 | 0.0 | 1.1 | -0.2 | 1.1 |
| 1954 | 0.3 | (4.6) | -0.6 | (4.0) | (-4.7) | 0.1 | 0.7 | 0.3 | (3.6) | 1.9 | (-3.4) | -2.3 |
| 1955 | -2.4 | 1.1 | 3.8 | (3.5) | 1.7 | (-4.3) | (2.1) | 1.3 | 0.6 | -1.4 | -2.1 | (-5.0) |
| 1956 | -2.4 | 3.3 | -0.9 | (-2.4) | -0.5 | -0.4 | -0.3 | 0.1 | -2.2 | 1.1 | -1.7 | (8.7) |
| 1957* | -0.6 | (4.5) | -1.0 | (3.4) | 0.1 | 0.3 | -0.2 | (-1.7) | 1.1 | (-5.3) | 1.2 | 2.5 |
| 1958 | (-5.4) | (-7.1) | (-5.1) | -0.5 | -0.7 | -2.4 | 1.3 | -0.3 | -2.3 | -2.5 | (2.8) | (-5.4) |
| 1959 | -1.7 | 1.1 | -1.1 | 1.1 | 2.1 | -1.0 | -0.6 | 1.5 | -0.3 | 0.9 | -1.4 | 1.0 |
| 1960* | 0.3 | -2.1 | (-12.1) | (2.5) | -1.9 | -0.3 | (-2.0) | 0.5 | -0.5 | -0.3 | 0.3 | (-5.7) |
| 1961 | -4.8 | 2.3 | 3.0 | (-6.0) | (-3.8) | (-2.5) | -0.5 | -0.5 | 1.9 | -1.7 | 1.9 | -1.0 |
| 1962 | -2.5 | 1.3 | -4.2 | -2.2 | (4.0) | -1.8 | (-2.4) | -1.3 | (-3.1) | 1.0 | (-2.8) | (-4.3) |
| 1963 | -4.6 | (-6.5) | 3.7 | 0.9 | -2.6 | (-2.6) | (-2.1) | -0.8 | (-4.2) | -0.3 | 0.5 | (-7.6) |
| 1964 | -0.1 | -3.2 | 0.9 | 0.0 | 0.1 | 0.3 | (-1.7) | (-2.2) | -2.0 | (-5.6) | 2.2 | 1.0 |
| 1965 | -0.8 | 0.3 | (-5.1) | -1.3 | (3.9) | (-3.4) | (-1.9) | 0.1 | 1.4 | -2.0 | 0.4 | 1.5 |
| 1966 | (-5.5) | -0.3 | 0.0 | (-2.6) | -1.5 | -1.9 | 1.0 | 0.6 | -0.3 | -2.2 | 0.3 | -0.4 |
| 1967* | 3.5 | -3.7 | 4.0 | (2.9) | (-4.1) | (-3.3) | -1.2 | -0.8 | (-3.8) | -1.4 | (-3.7) | 4.0 |
| 1968 | -4.2 | (-6.2) | 2.9 | -1.5 | (-4.1) | -1.7 | -1.2 | (2.1) | -0.4 | 1.2 | 1.2 | -3.5 |
| 1969 | -3.9 | -1.7 | (-6.3) | -0.9 | -1.8 | -0.6 | -0.1 | (-3.3) | (-3.8) | -2.2 | (-4.4) | (-4.6) |
| 1970 | (-8.4) | -3.7 | -3.5 | -0.2 | -2.0 | (-2.6) | (-2.0) | (-1.8) | 2.0 | 0.2 | -1.1 | 0.4 |
| 1971 | -4.3 | -0.5 | (-4.6) | (-3.2) | (-3.6) | 0.1 | -1.5 | (-1.8) | 0.7 | (4.0) | -1.8 | (8.0) |
| 1972 | 3.4 | -2.6 | -0.2 | -1.6 | (-3.7) | (-5.4) | -1.0 | -1.5 | -0.9 | (-3.4) | -2.4 | 3.9 |




**LEGEND**

o EXCEEDS ONE STANDARD DEVIATION FROM THE AVERAGE.

## RUNOFF AND AIR TEMPERATURES 1933 – 1936

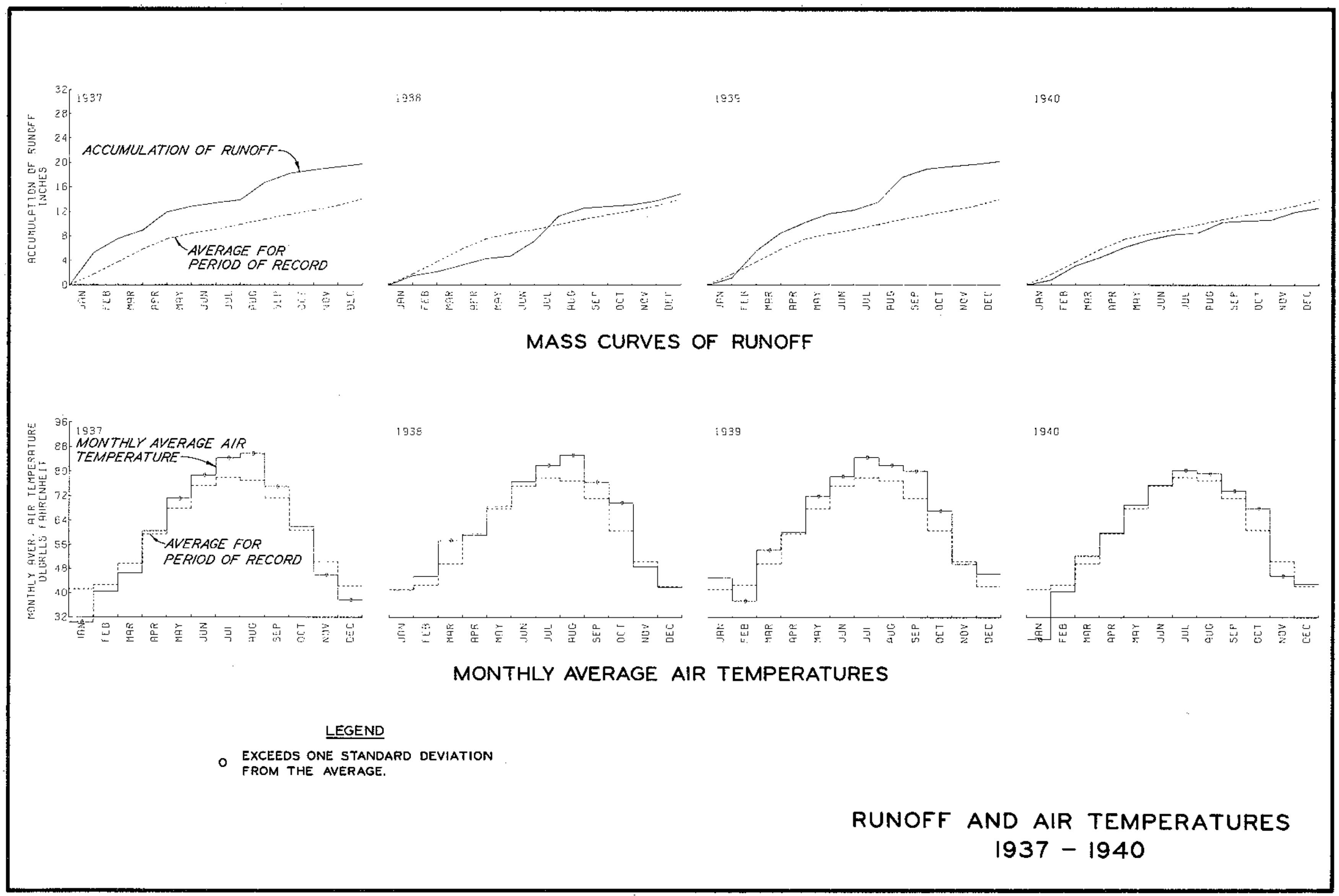



PLATE 1
(Sheet 2 of 10)

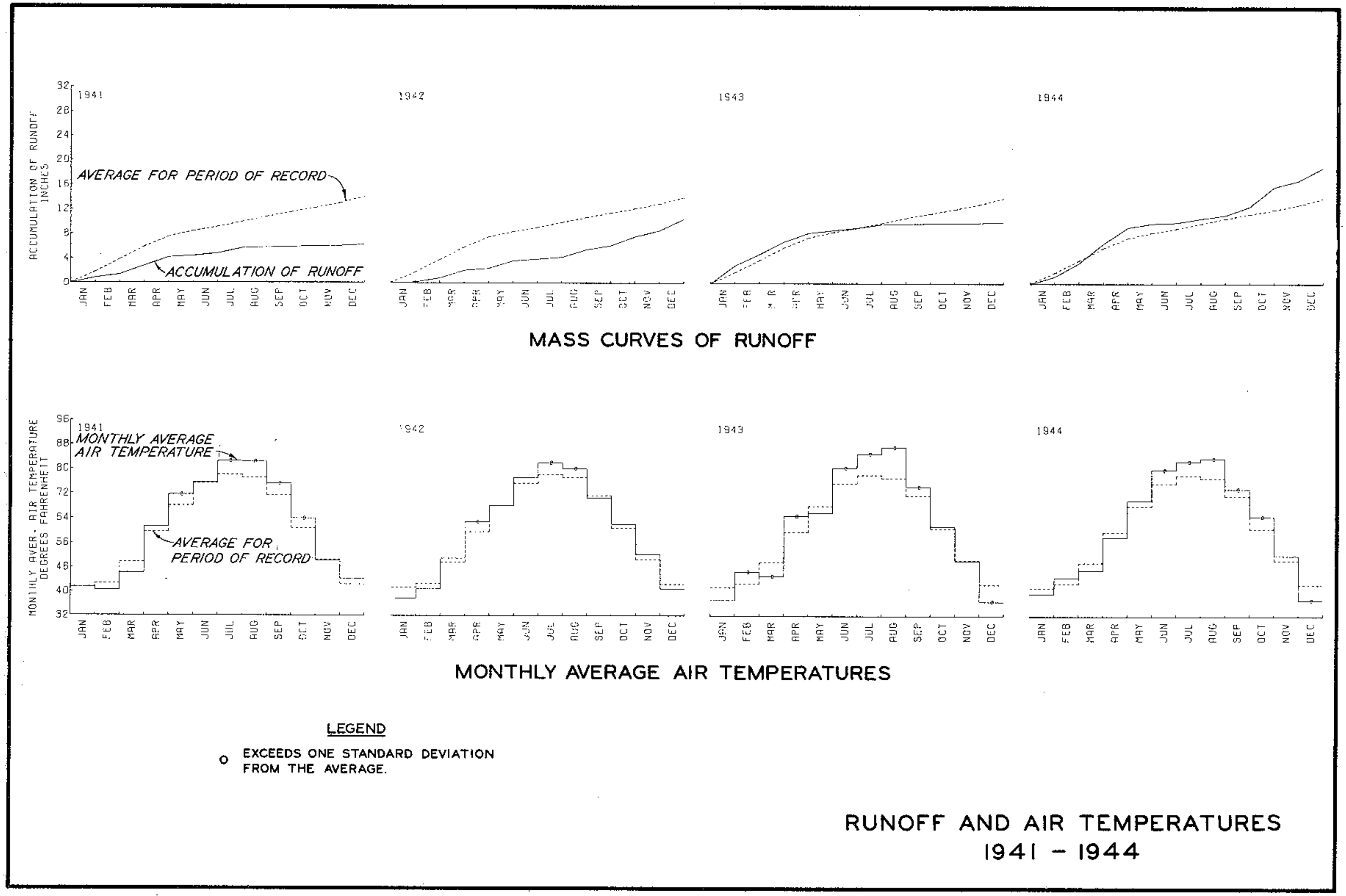
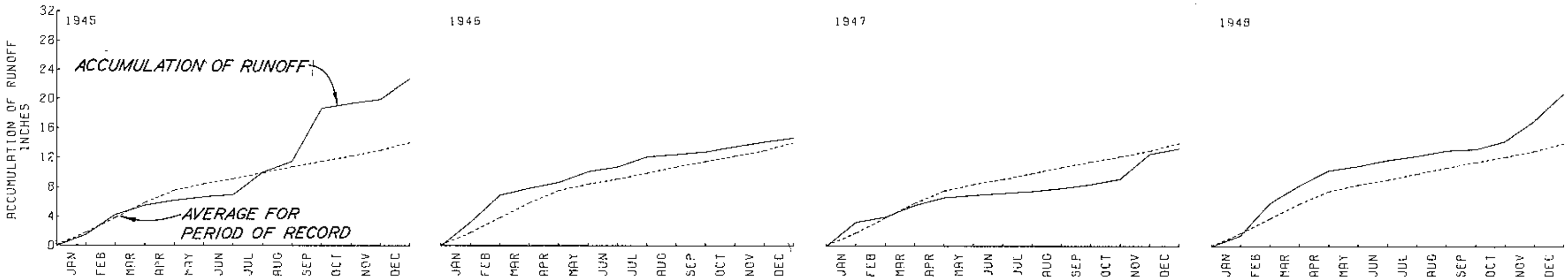
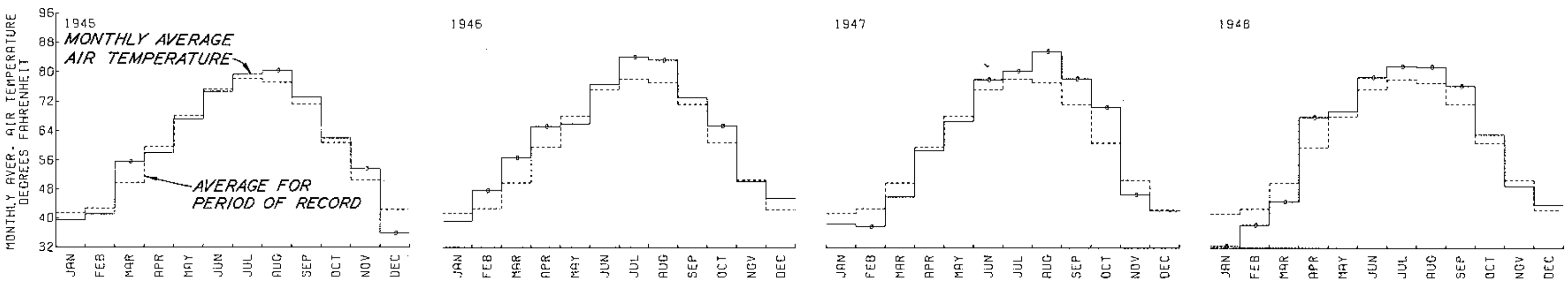



PLATE 1
(Sheet 3 of 10)




MASS CURVES OF RUNOFF



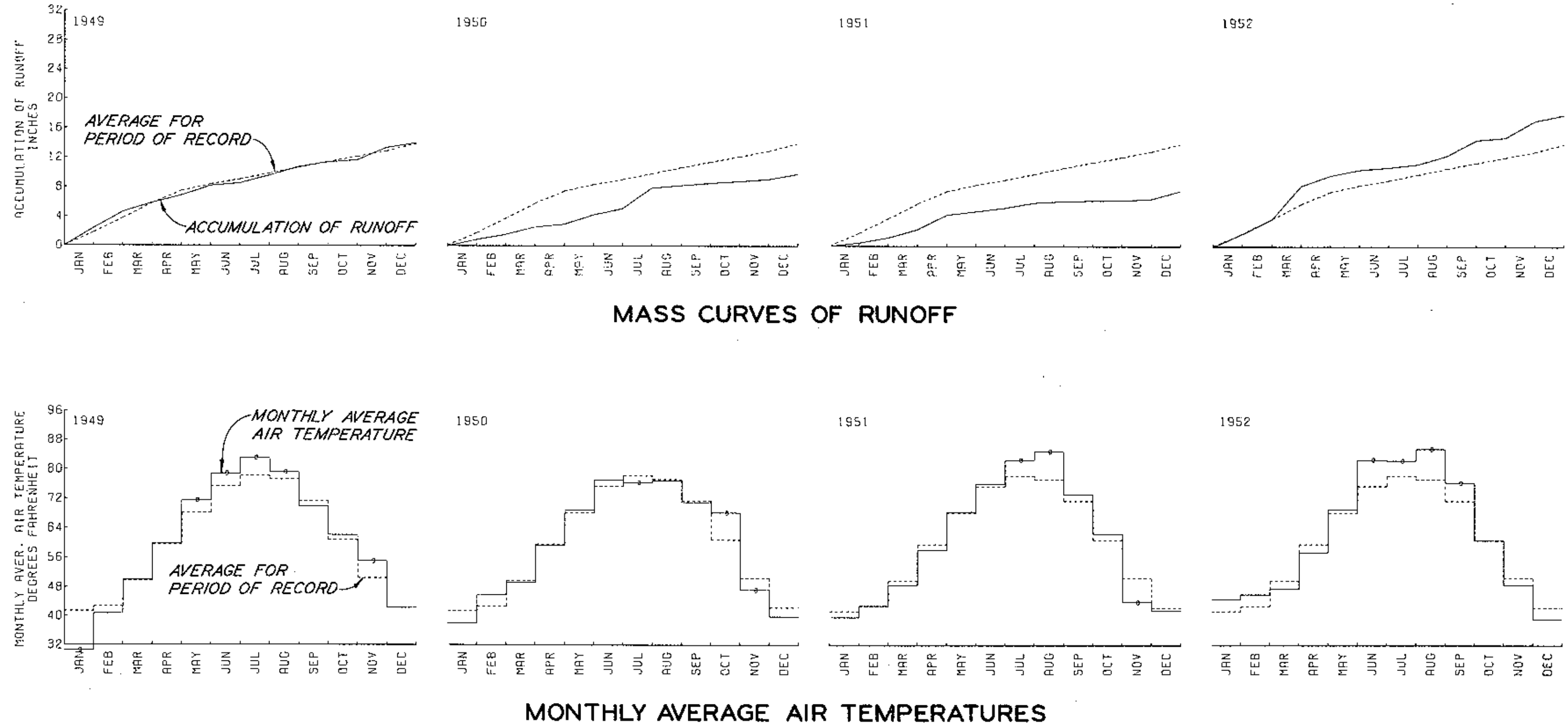

MONTHLY AVERAGE AIR TEMPERATURES

LEGEND

o EXCEEDS ONE STANDARD DEVIATION FROM THE AVERAGE.

RUNOFF AND AIR TEMPERATURES
1945 – 1948

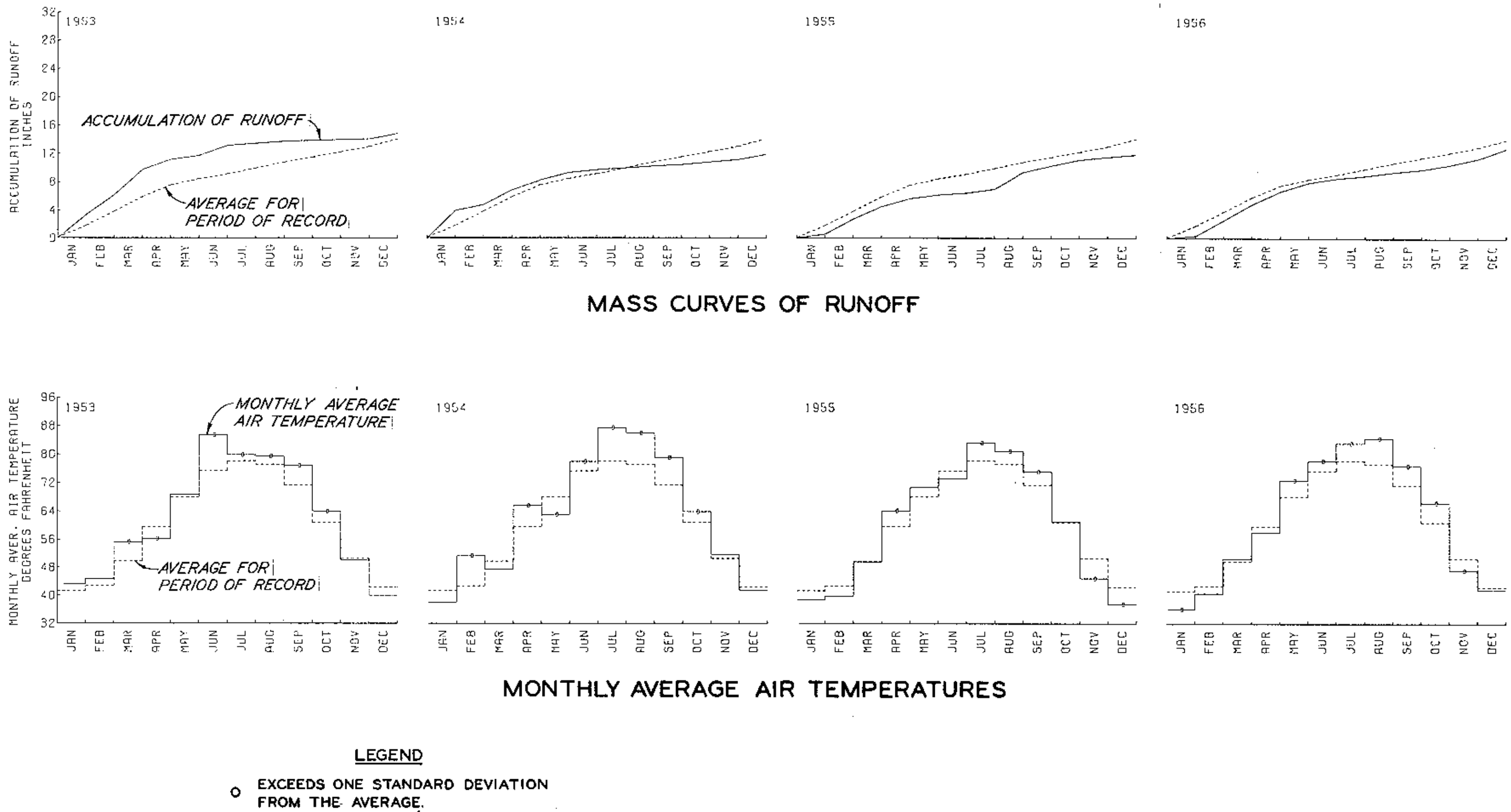
PLATE 1
(Sheet 4 of 10)




**LEGEND**

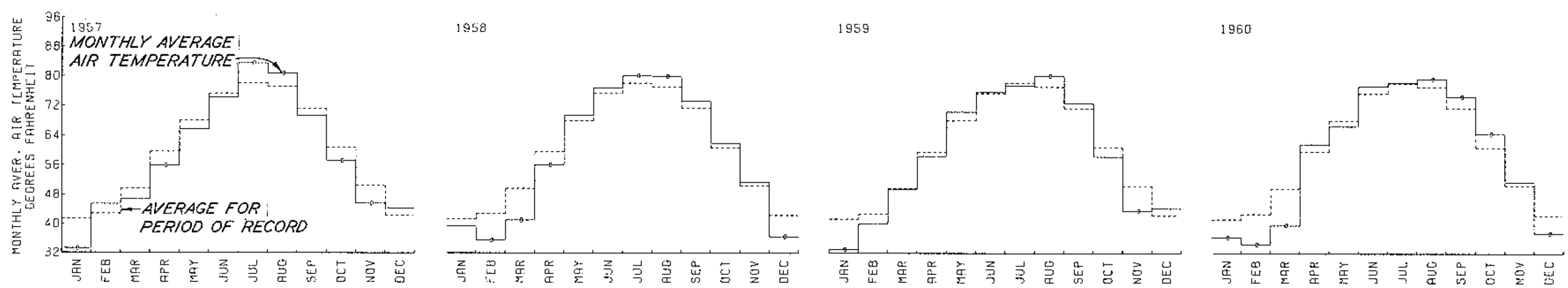
o EXCEEDS ONE STANDARD DEVIATION FROM THE AVERAGE.

## RUNOFF AND AIR TEMPERATURES 1949 - 1952




RUNOFF AND AIR TEMPERATURES
1953 - 1956


MASS CURVES OF RUNOFF




MONTHLY AVERAGE AIR TEMPERATURES

LEGEND

o EXCEEDS ONE STANDARD DEVIATION FROM THE AVERAGE.

RUNOFF AND AIR TEMPERATURES
1957 - 1960

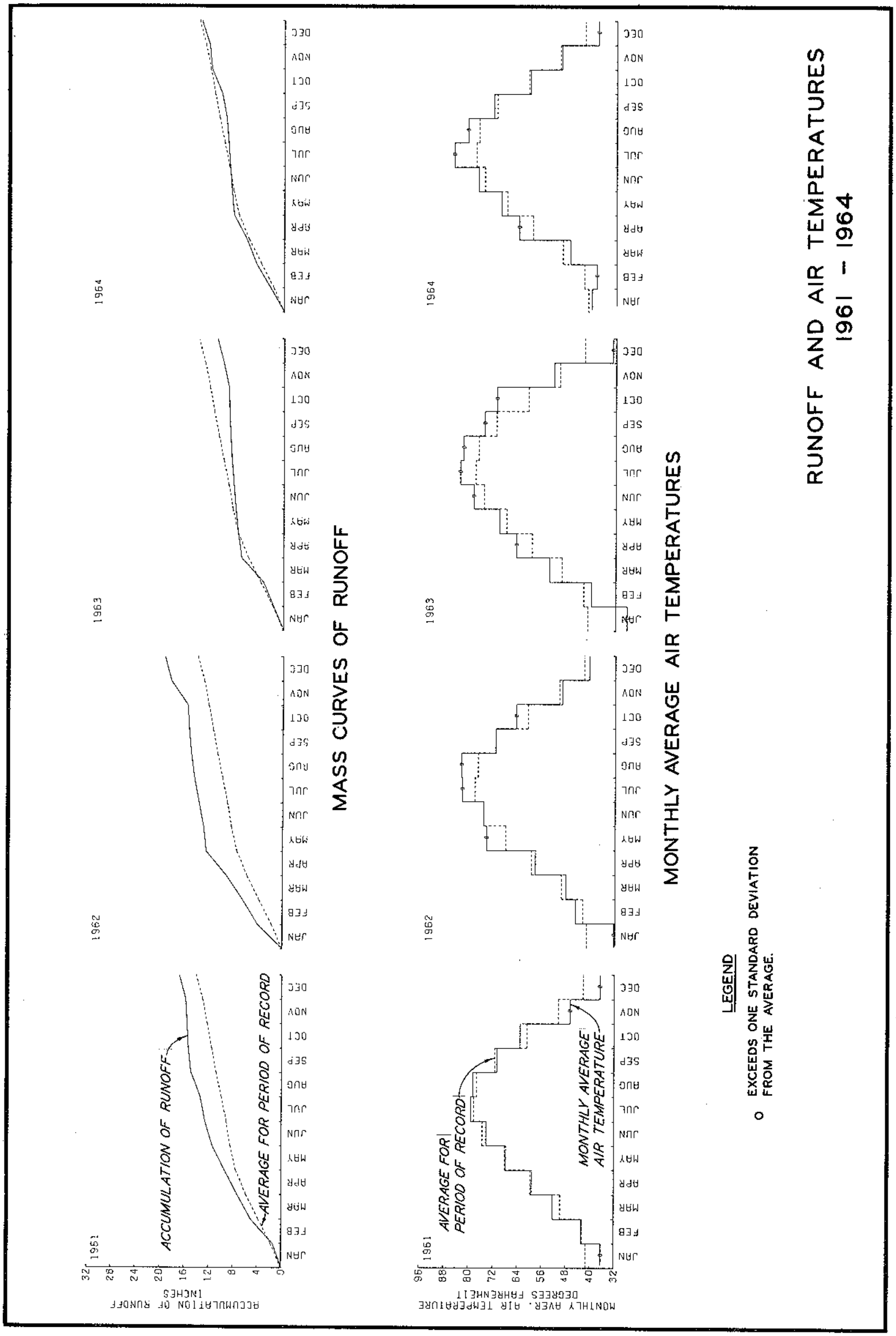
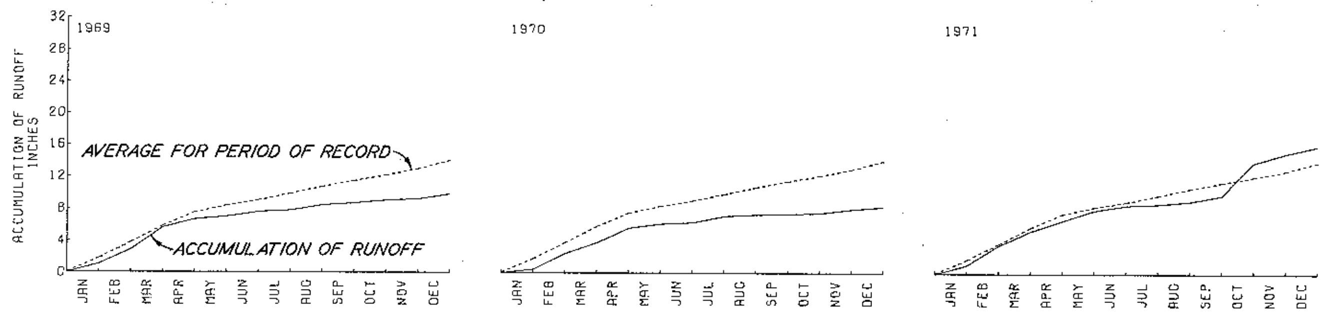
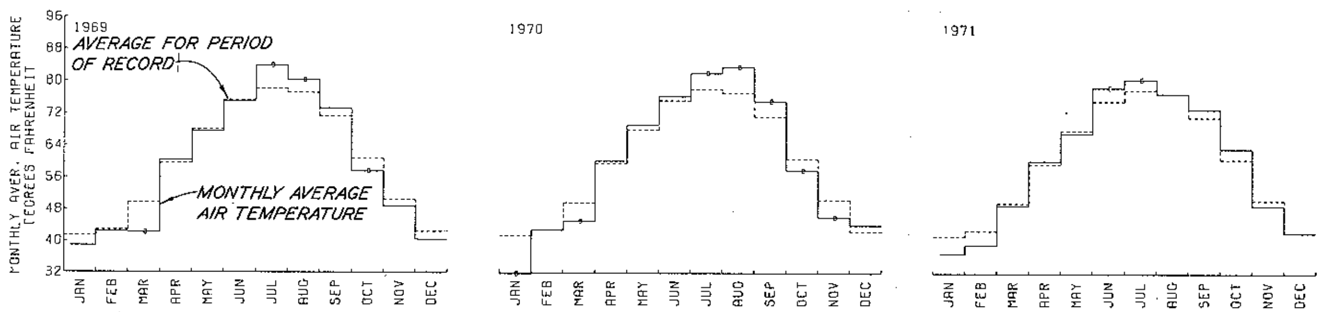



PLATE 1
(Sheet 8 of 10)




## MASS CURVES OF RUNOFF




## MONTHLY AVERAGE AIR TEMPERATURES

**LEGEND**

o EXCEEDS ONE STANDARD DEVIATION FROM THE AVERAGE.

# RUNOFF AND AIR TEMPERATURES 1969 – 1971

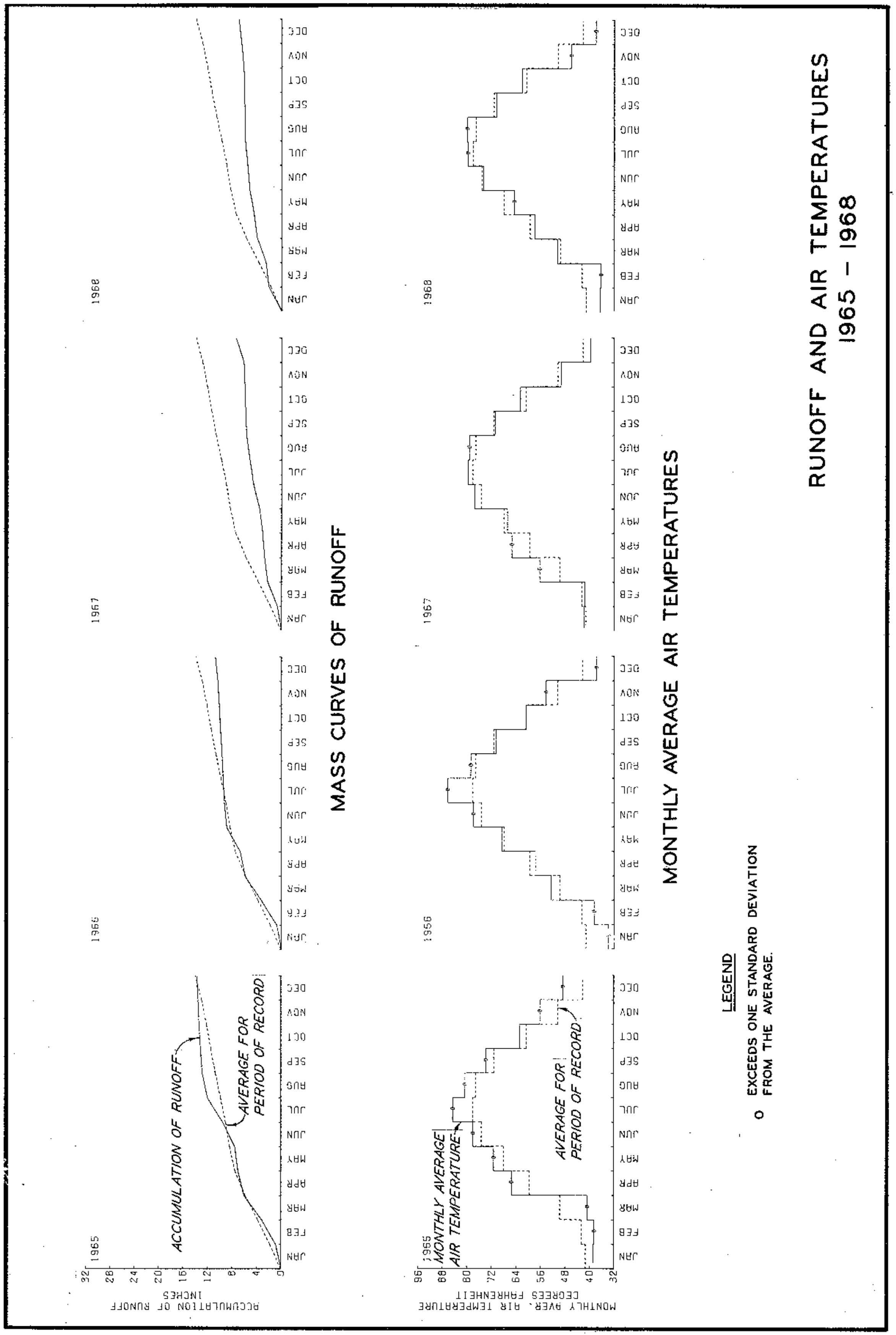
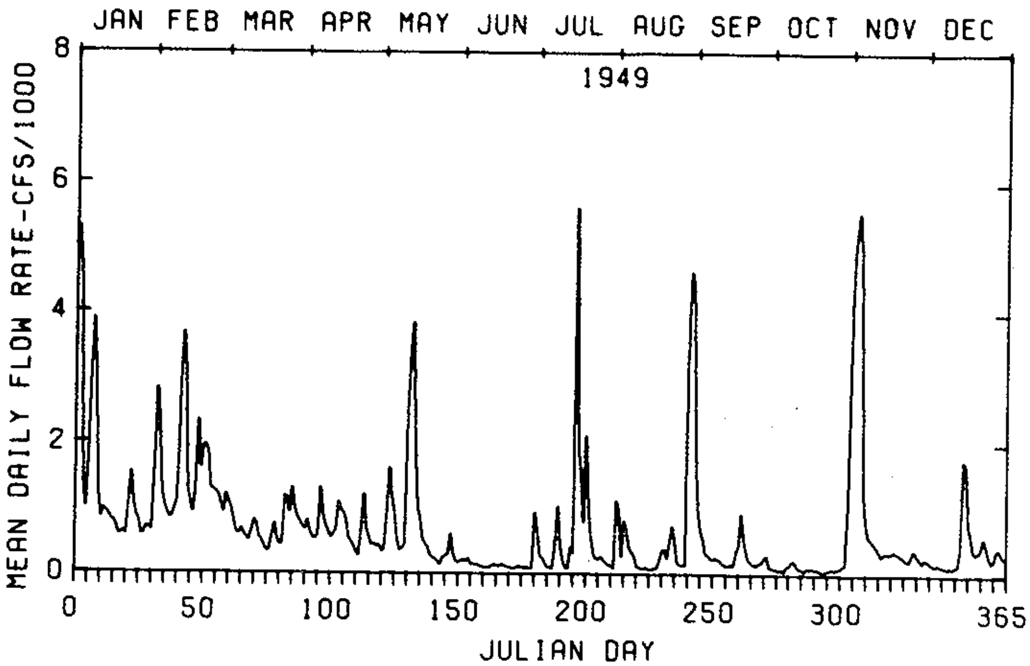
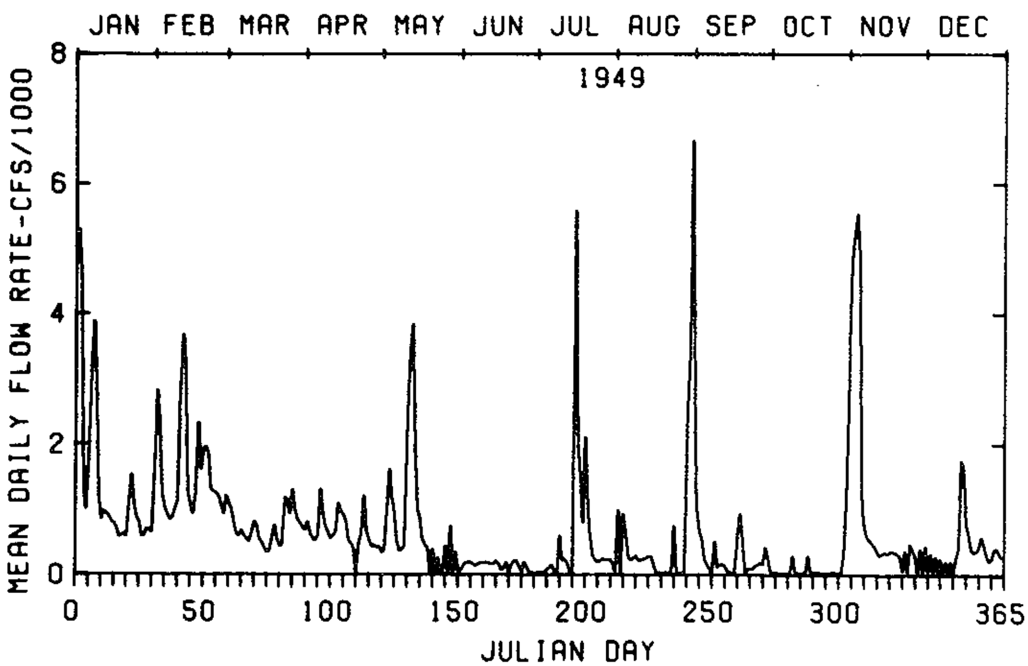



PLATE 1
(Sheet 10 of 10)

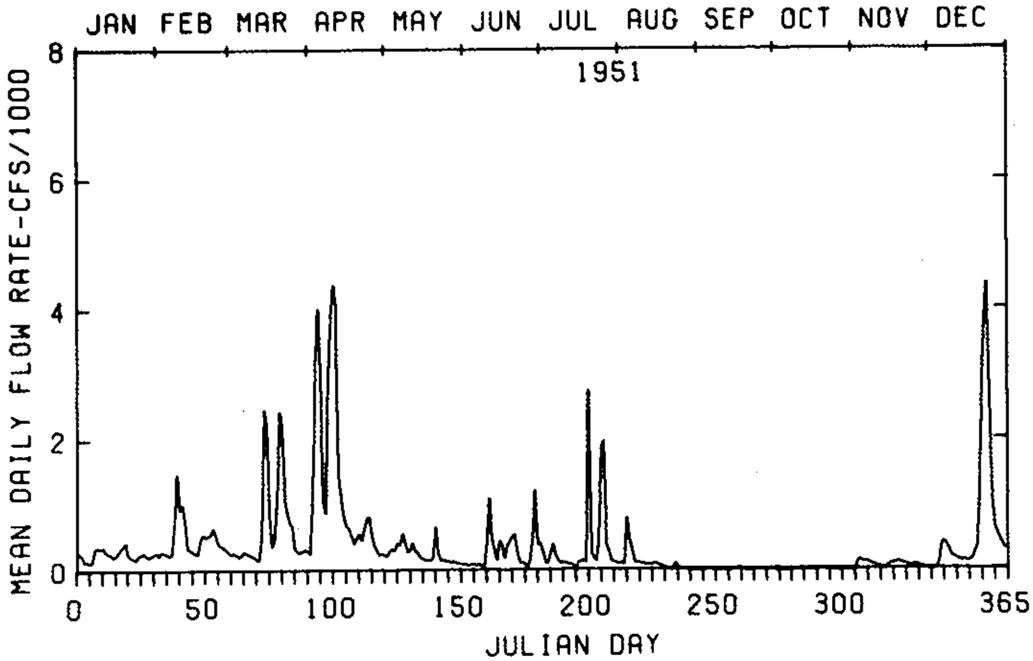



INFLOW

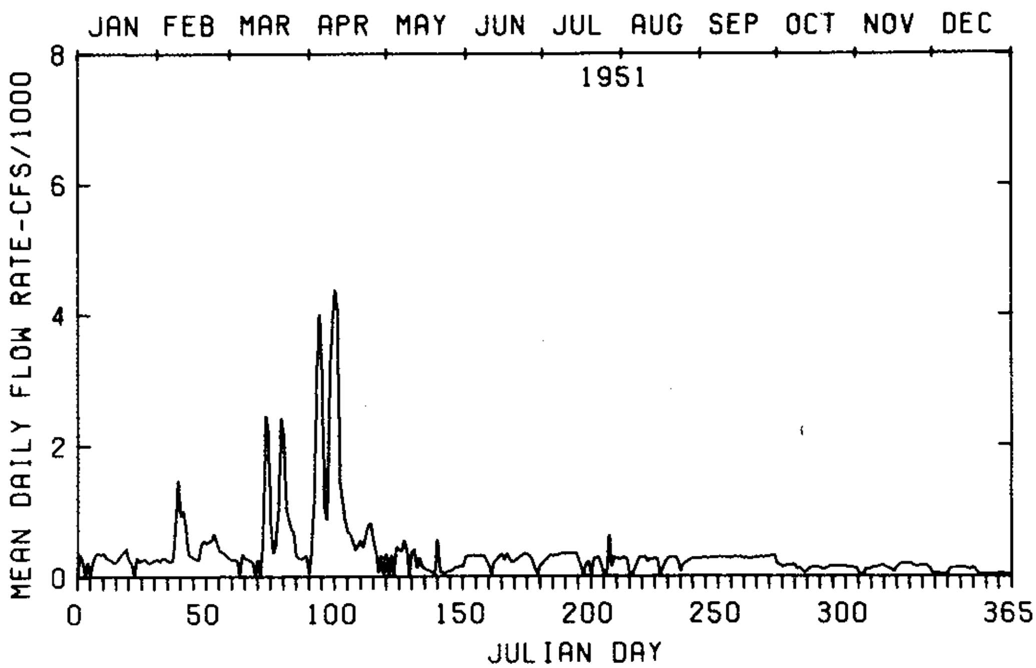



OUTFLOW

FLOW HYDROGRAPHS
1975 - 1985 ROUTINGS
1949



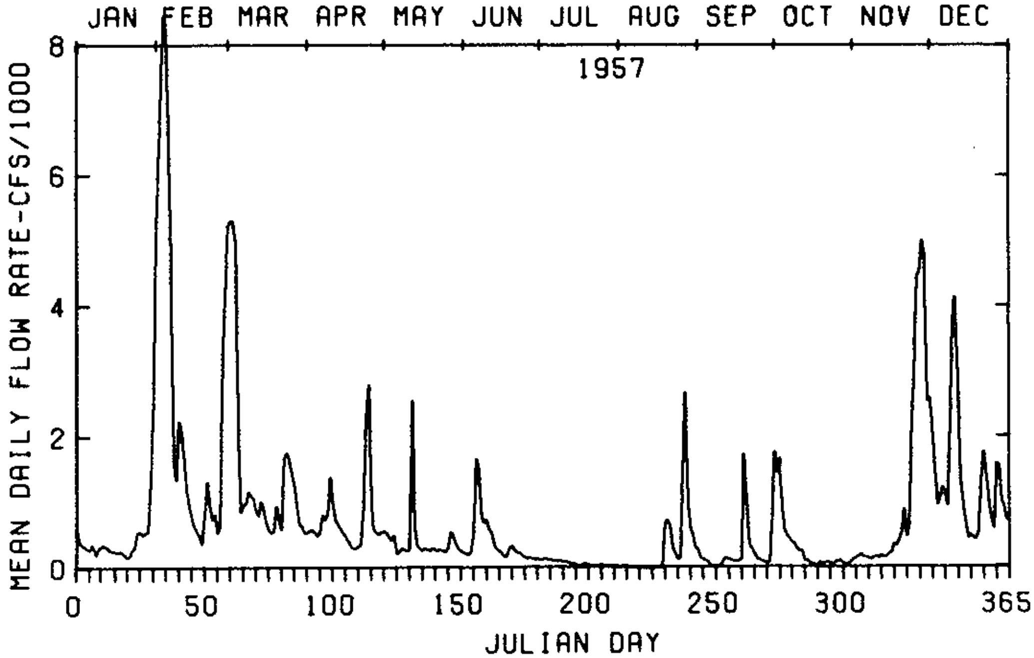

INFLOW



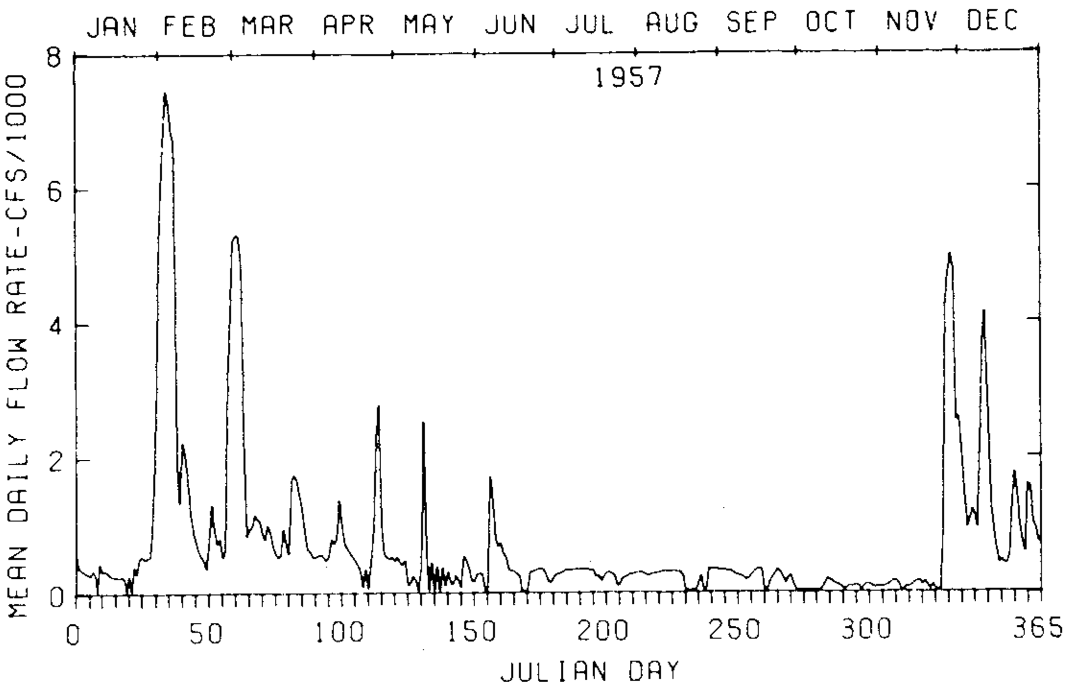

OUTFLOW

FLOW HYDROGRAPHS
1975 - 1985 ROUTINGS
1951

PLATE 2
(Sheet 2 of 5)

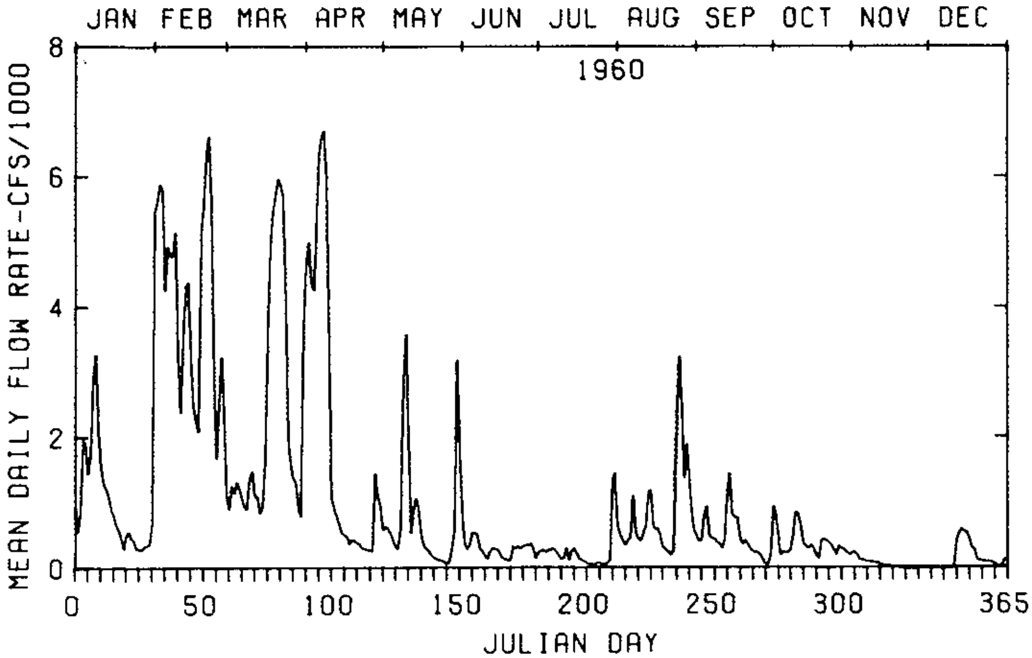



INFLOW

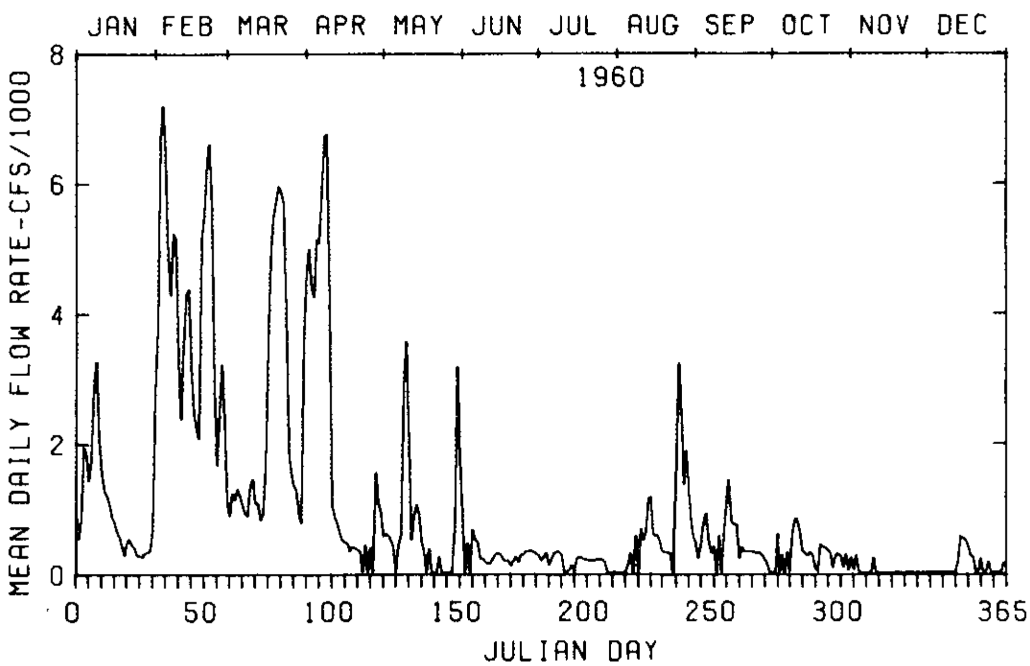



OUTFLOW

FLOW HYDROGRAPHS
1975 - 1985 ROUTINGS
1957

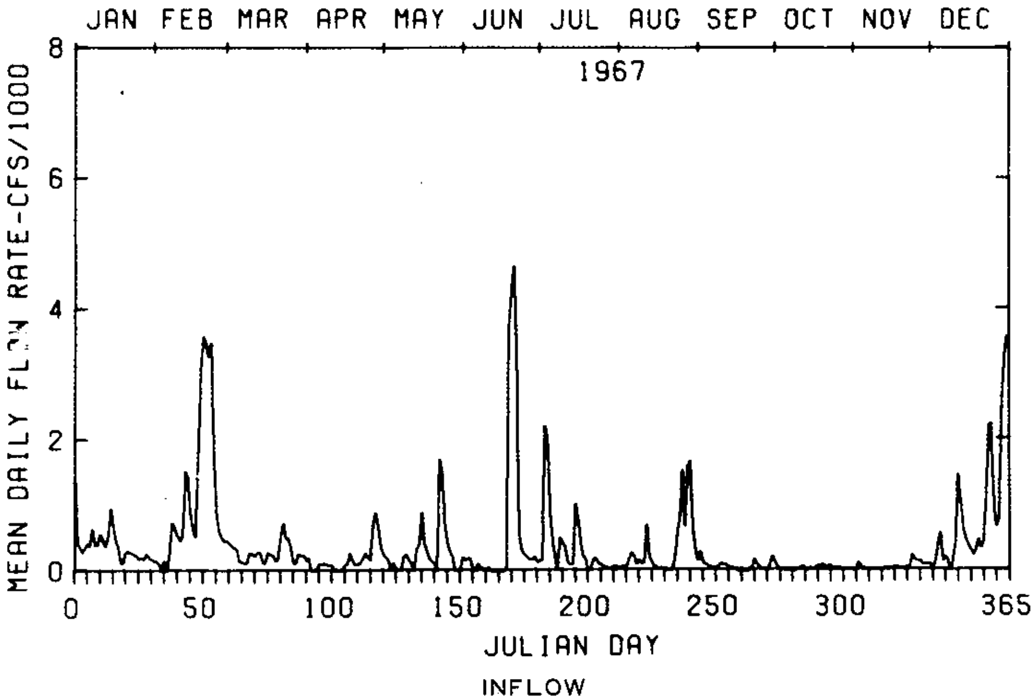


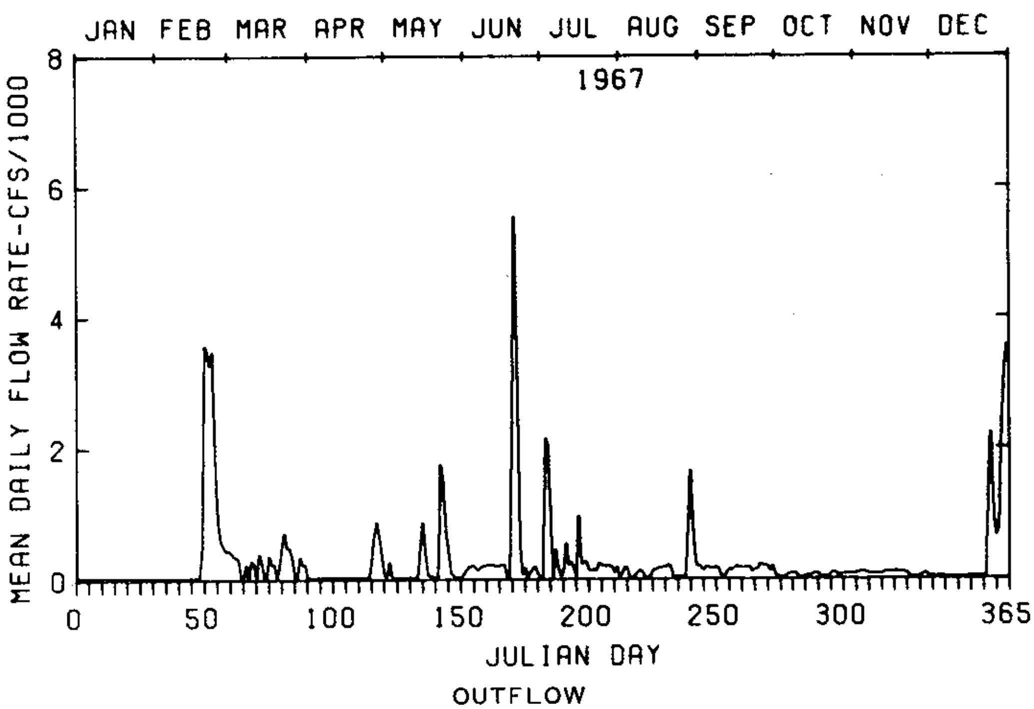

INFLOW




OUTFLOW

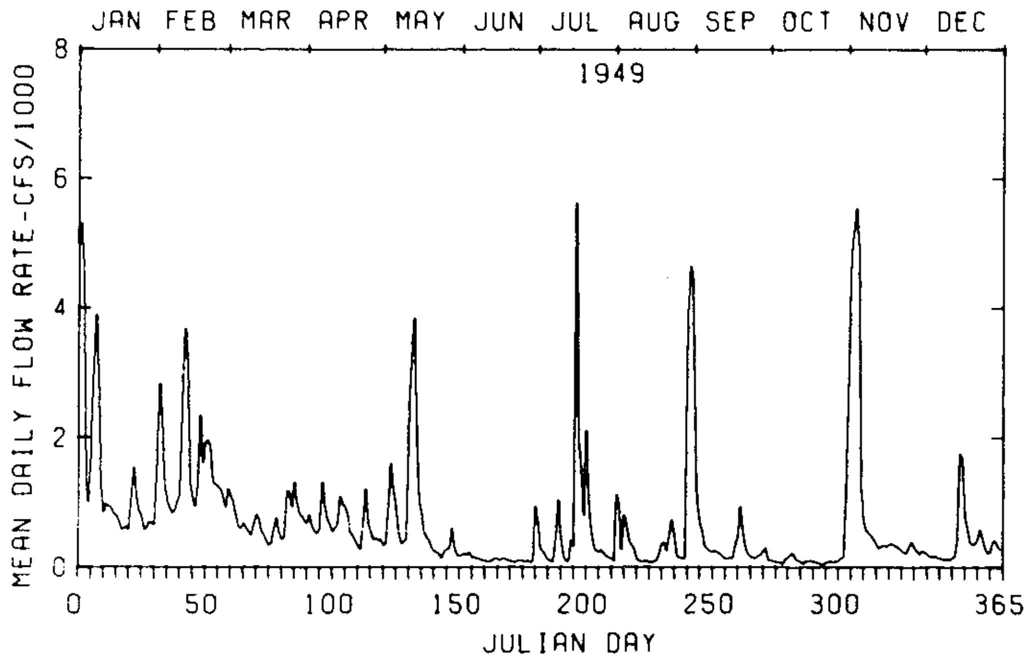
FLOW HYDROGRAPHS
1975 – 1985 ROUTINGS
1960



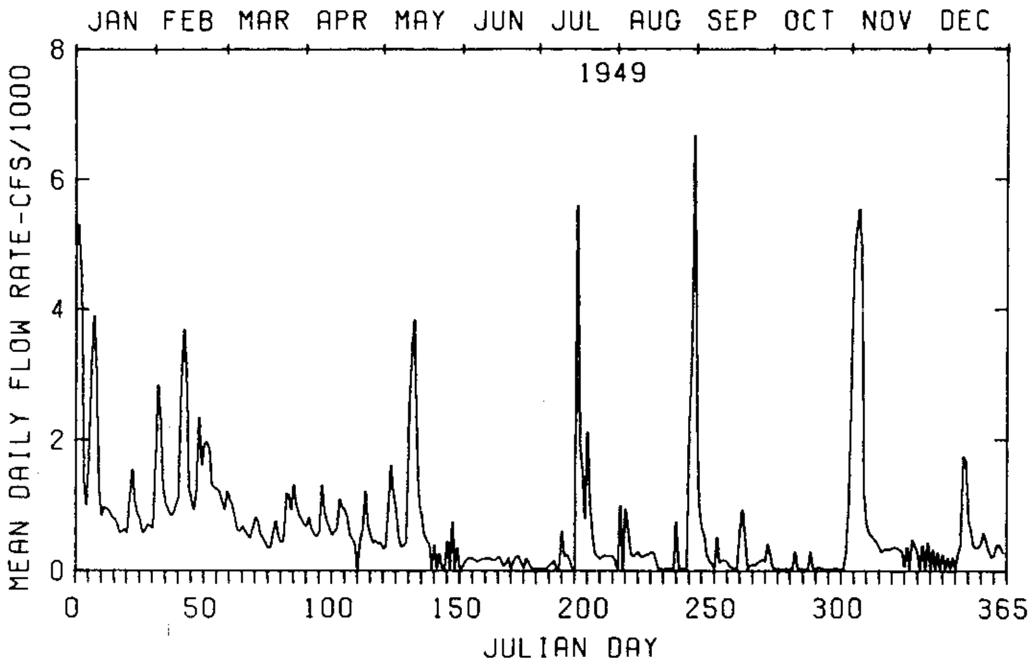




FLOW HYDROGRAPHS
1975 - 1985 ROUTINGS
1967

PLATE 2
(Sheet 5 of 5)



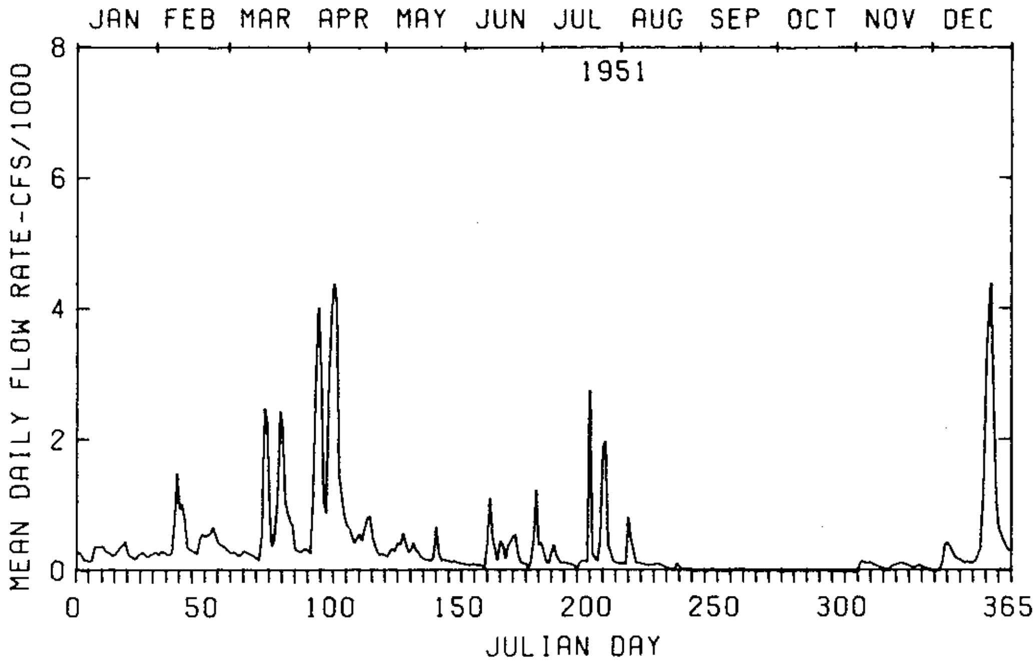

**INFLOW**



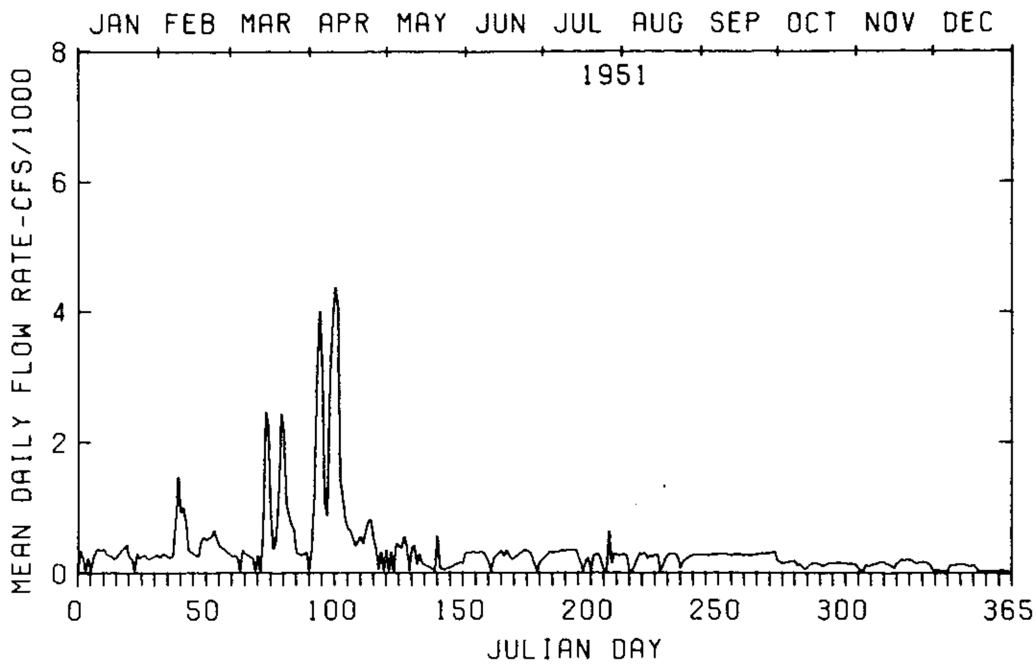

**OUTFLOW**

FLOW HYDROGRAPHS
1985 - 2020 ROUTINGS
1949

PLATE 3
(Sheet 1 of 5)

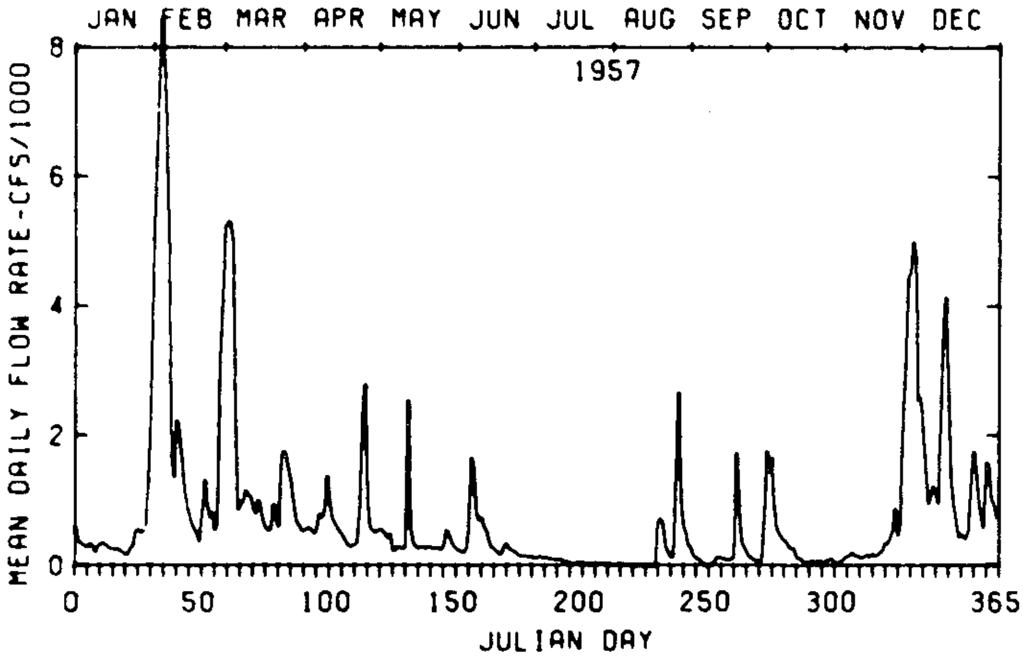



INFLOW

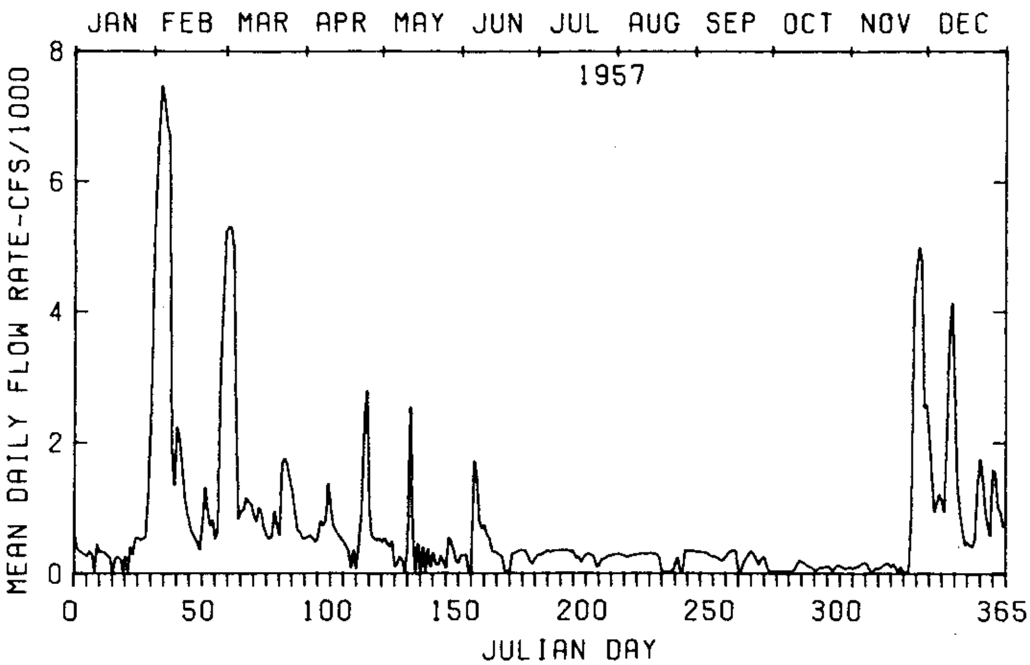



OUTFLOW

**FLOW HYDROGRAPHS**
**1985 – 2020 ROUTINGS**
**1951**



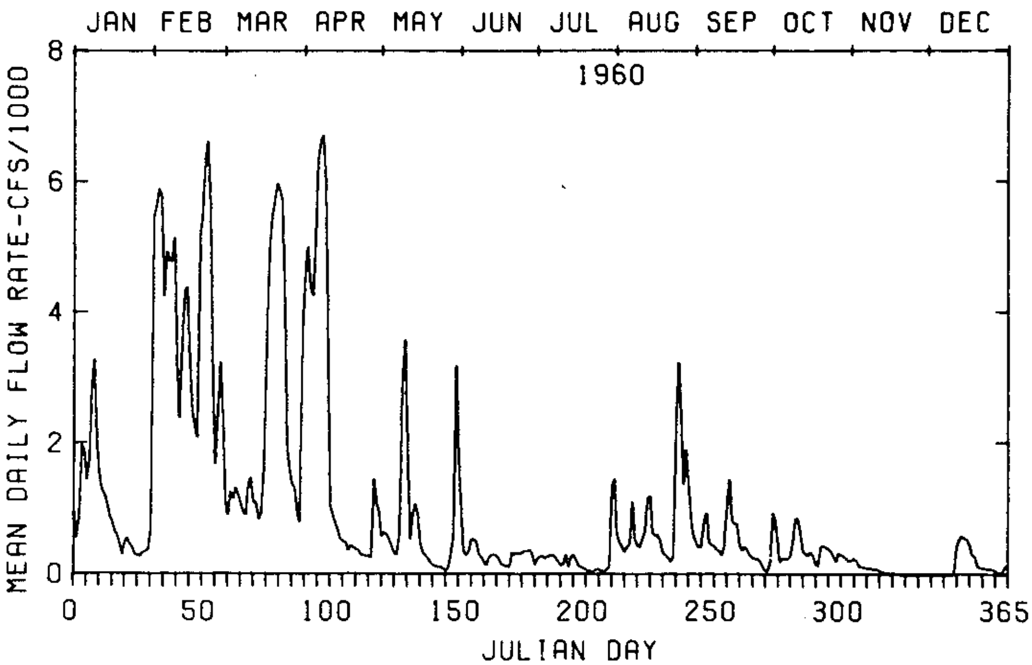

INFLOW



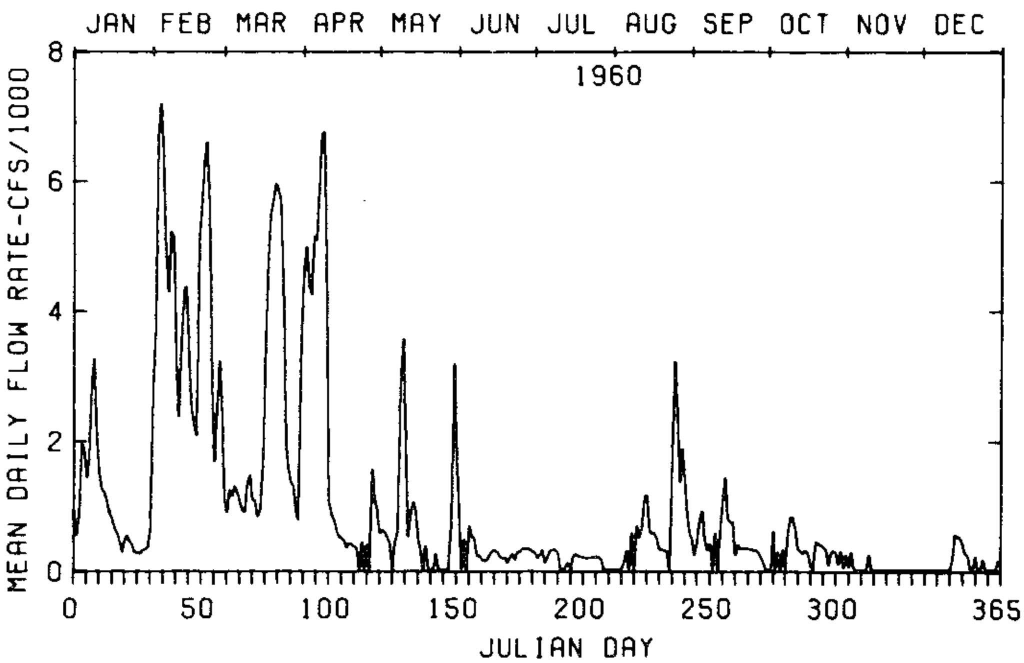

OUTFLOW

FLOW HYDROGRAPHS
1985 - 2020 ROUTINGS
1957

PLATE 3
(Sheet 3 of 5)

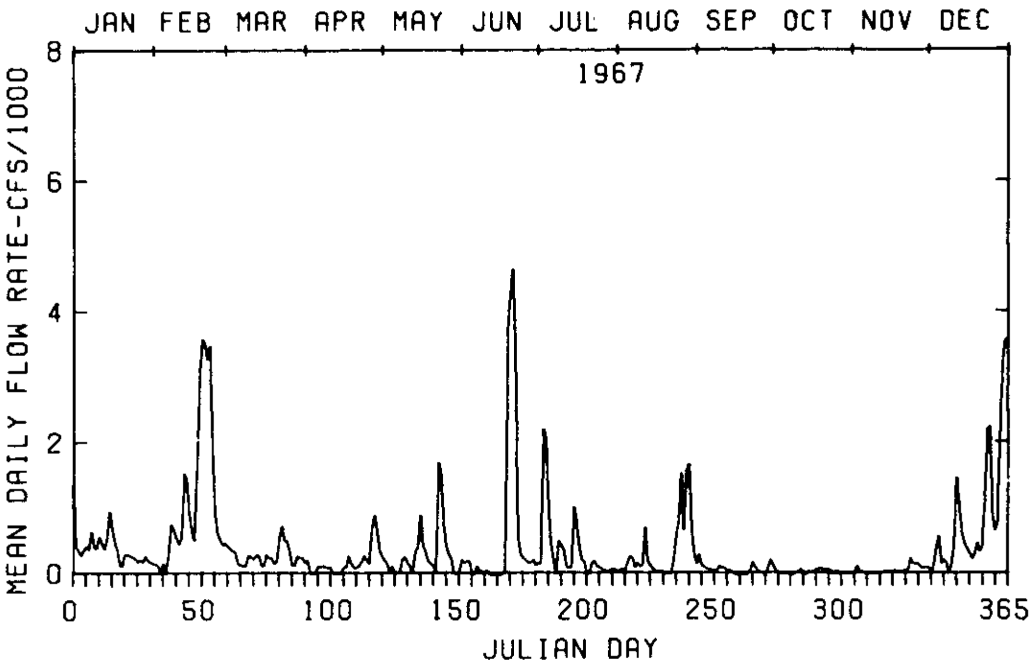



INFLOW

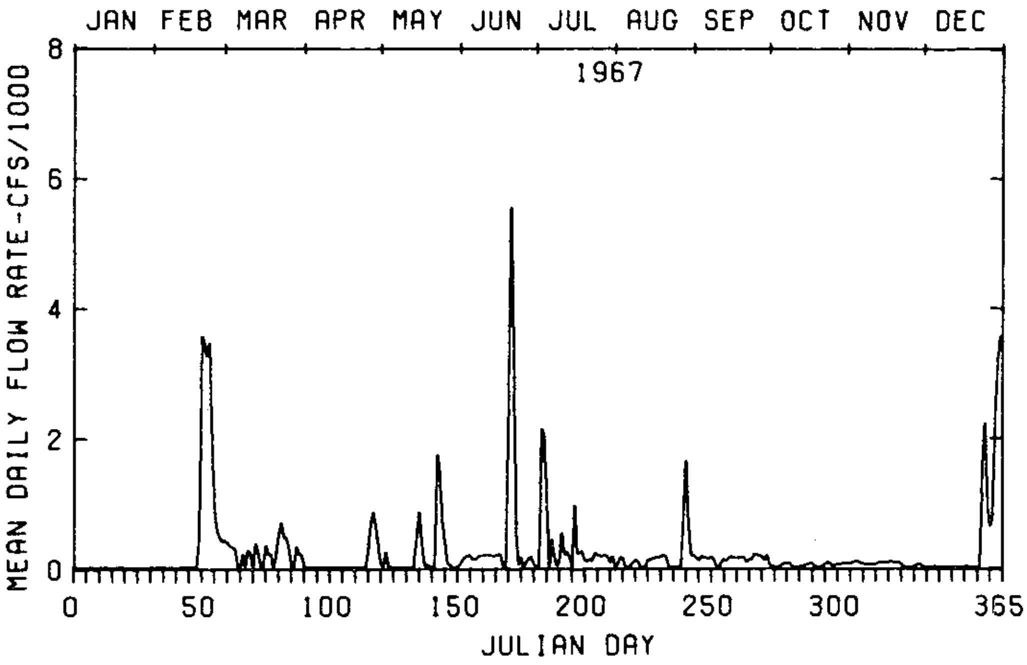



OUTFLOW

FLOW HYDROGRAPHS
1985 - 2020 ROUTINGS
1960



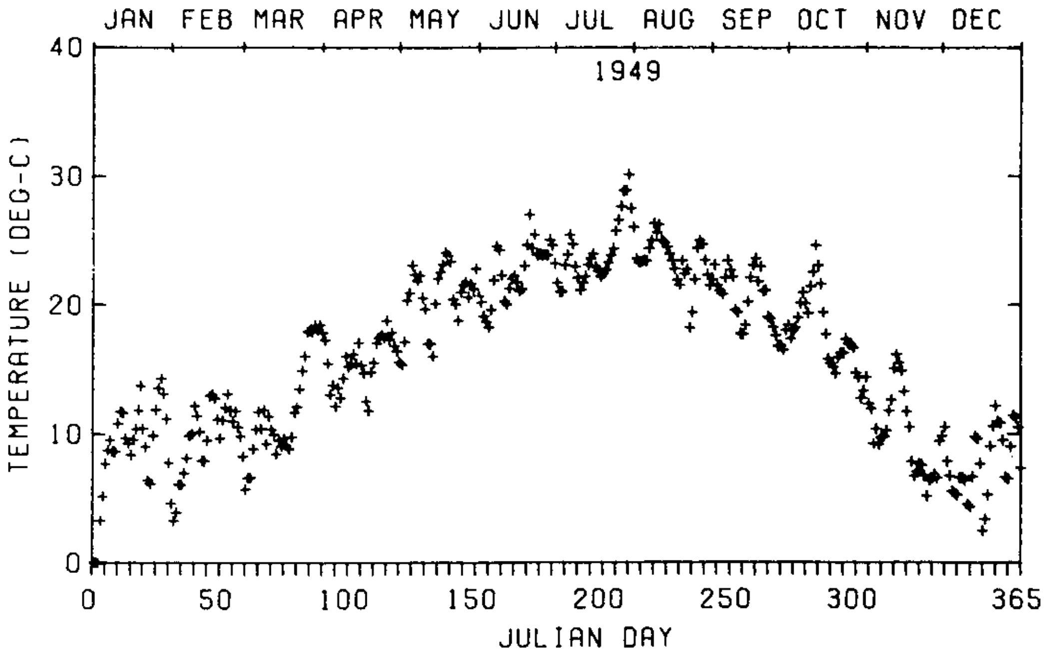

INFLOW

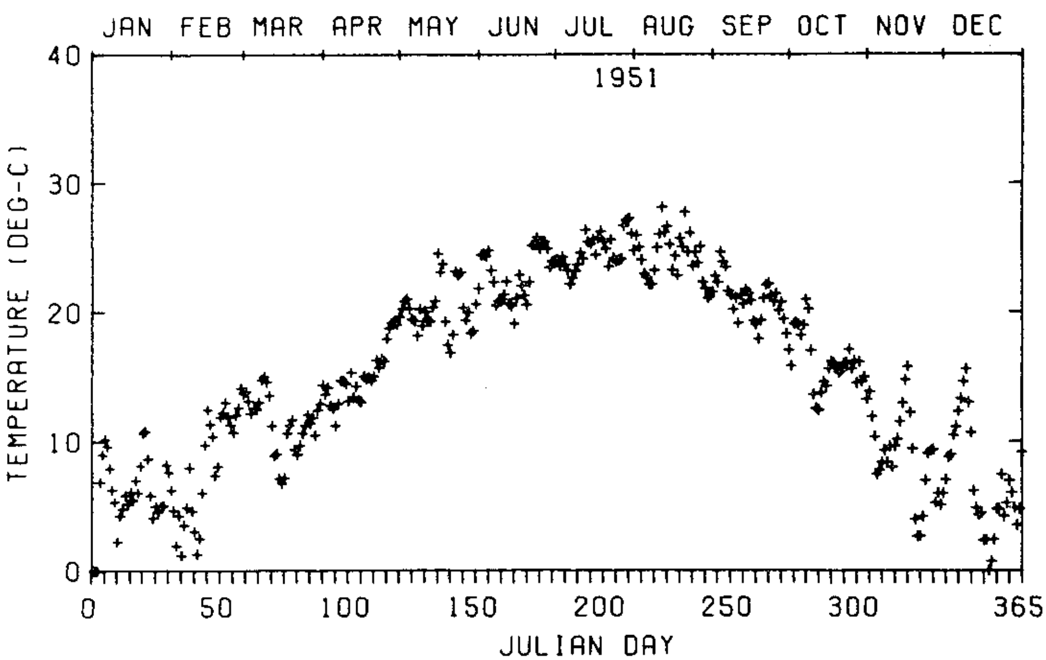



OUTFLOW

FLOW HYDROGRAPHS
1985 – 2020 ROUTINGS
1967

PLATE 3
(Sheet 5 of 5)

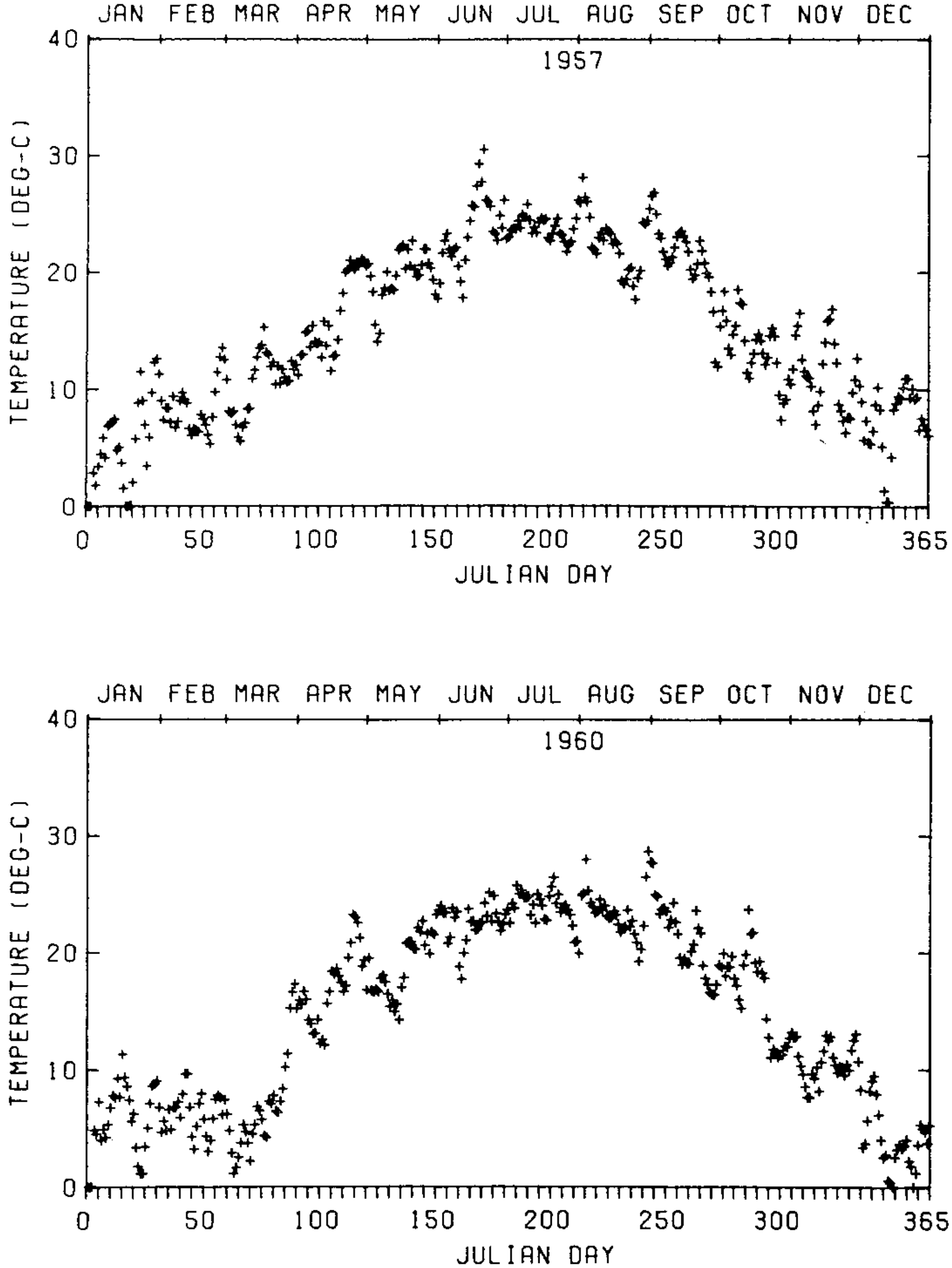



COMPUTED STREAM TEMPERATURE

**1949 AND 1951**

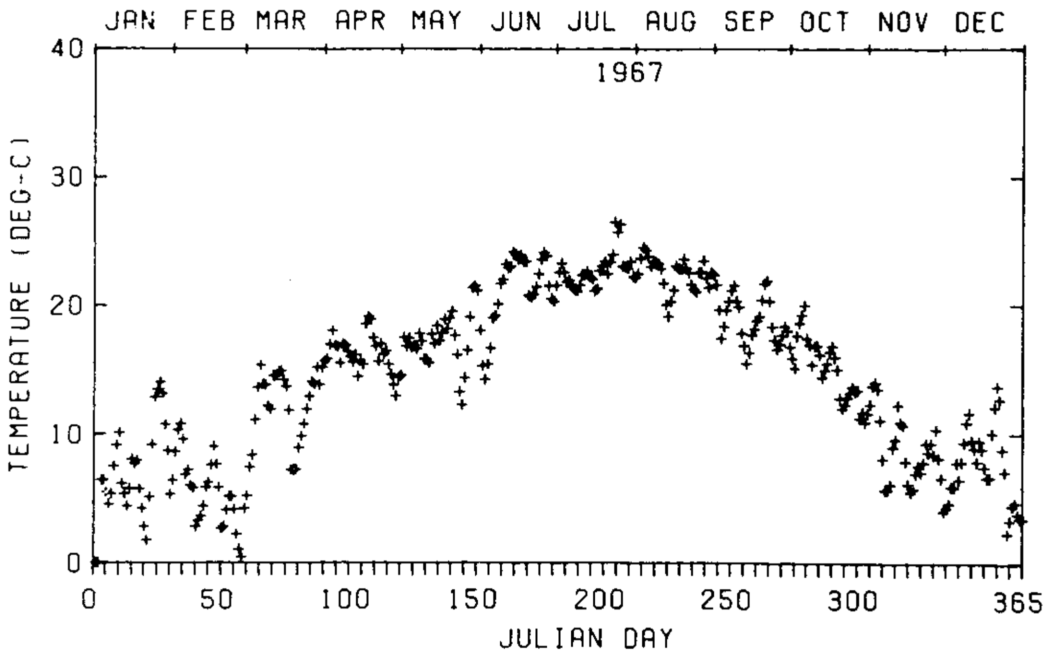
PLATE 4
(Sheet 1 of 3)




COMPUTED STREAM TEMPERATURE

1957 AND 1960

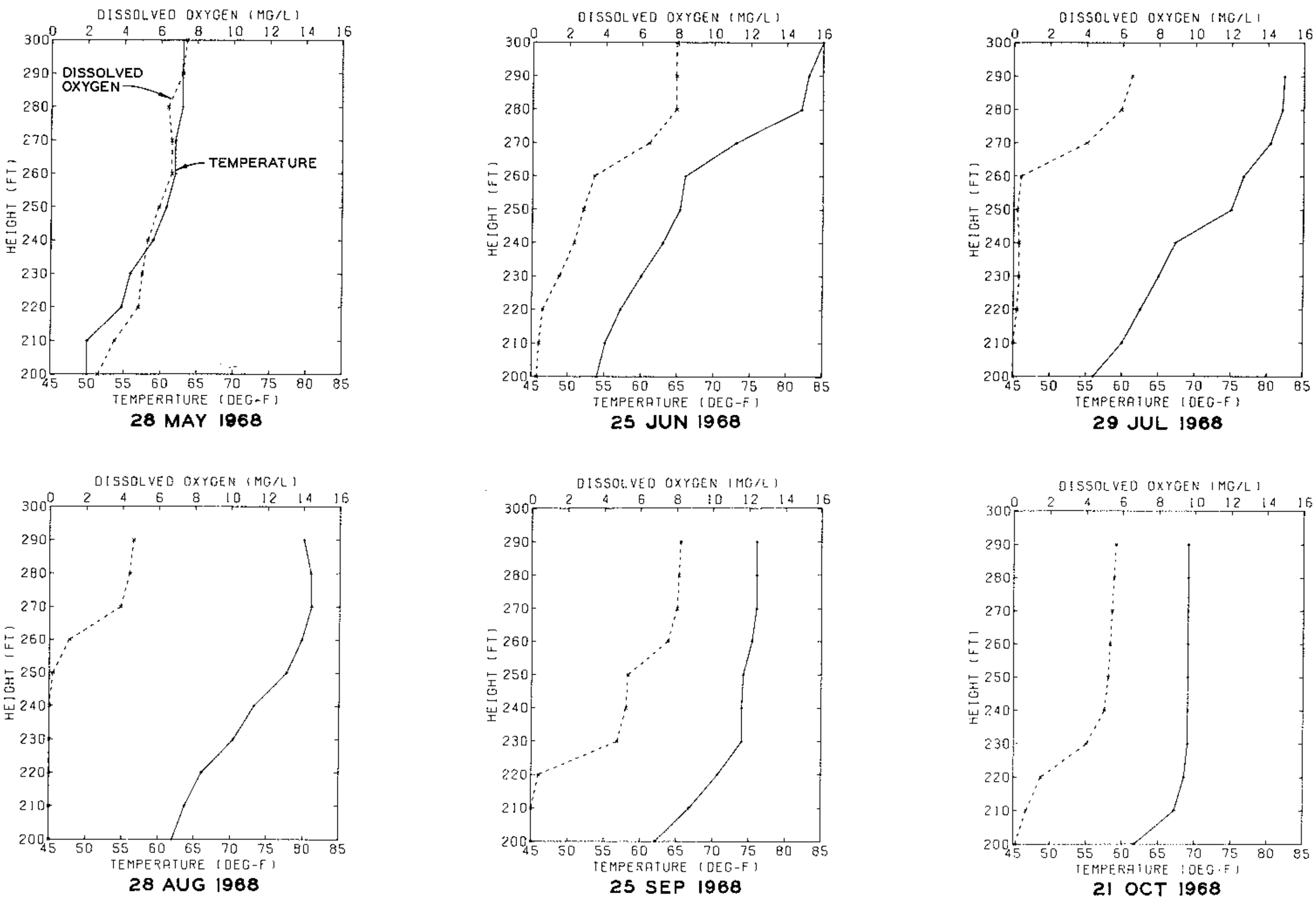
PLATE 4
(Sheet 2 of 3)




COMPUTED STREAM TEMPERATURE

1967

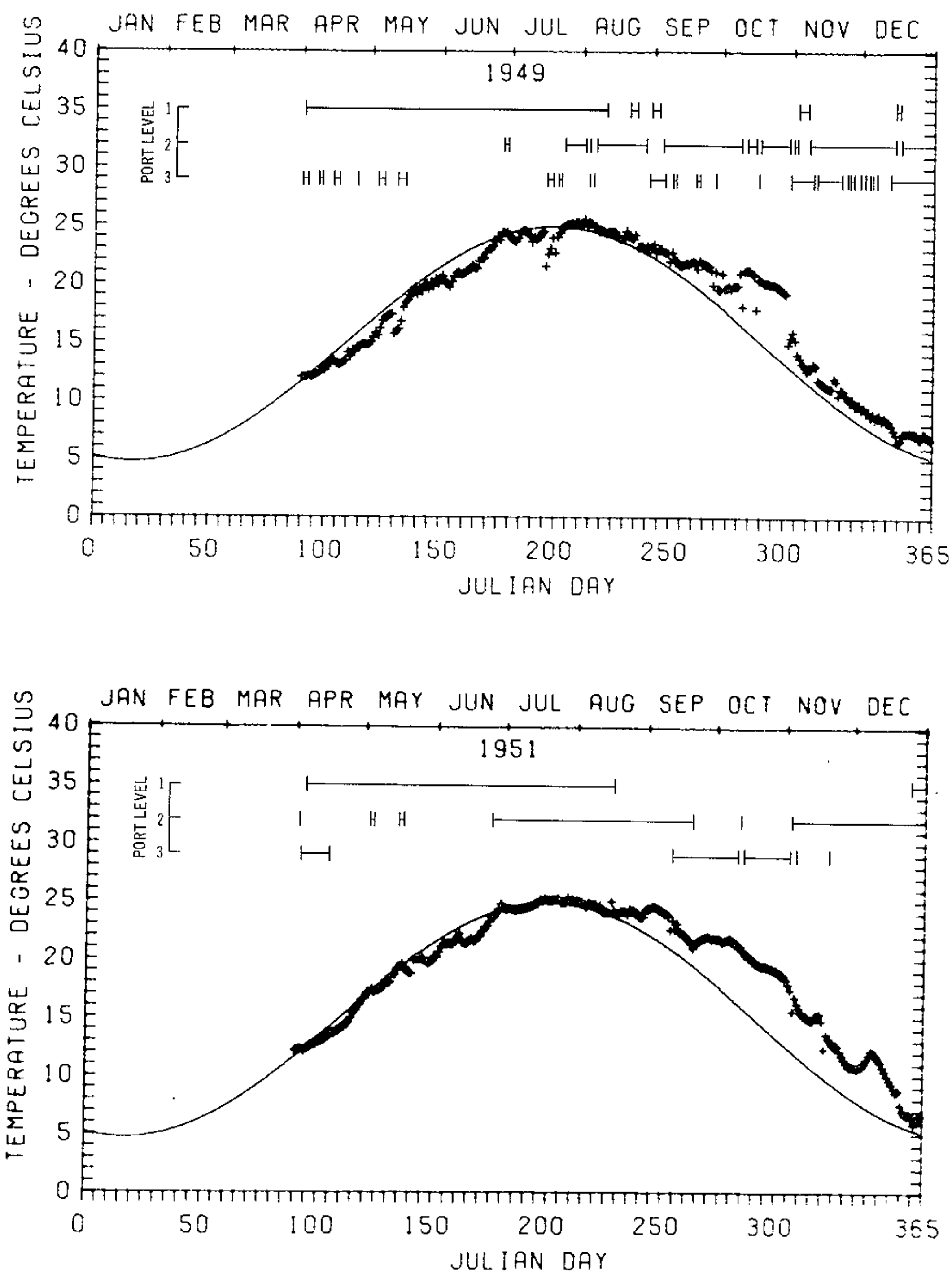
PLATE 4
(Sheet 3 of 3)




## JOHN H KERR LAKE PROFILES

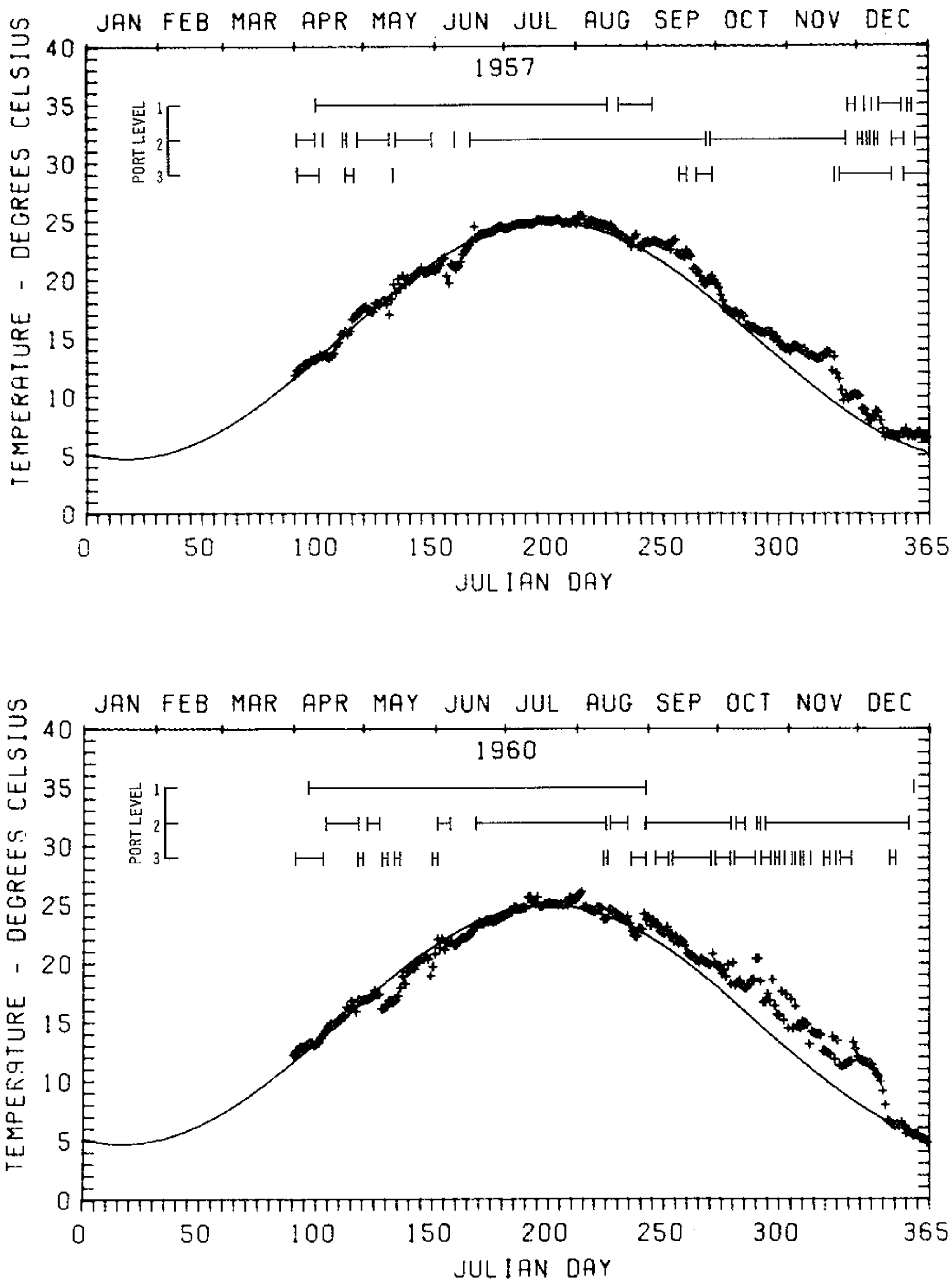
28 MAY 1968 – 21 OCT 1968

PLATE 5




**1975 - 1985 ROUTINGS**
**4-PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**

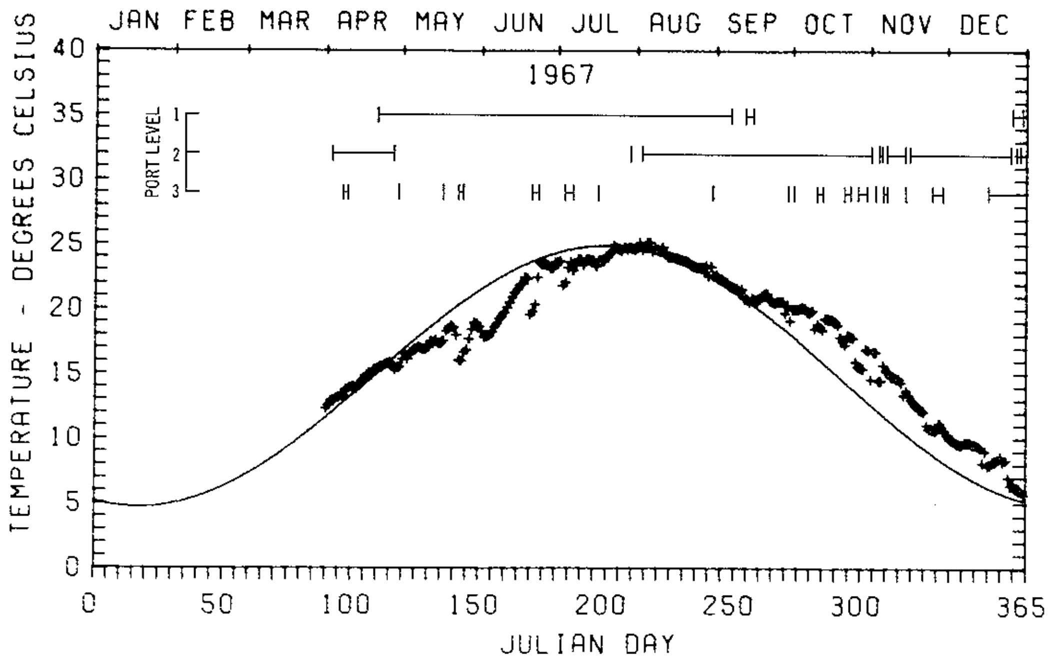
**1949 AND 1951**




**1975-1985 ROUTINGS**
**4-PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**

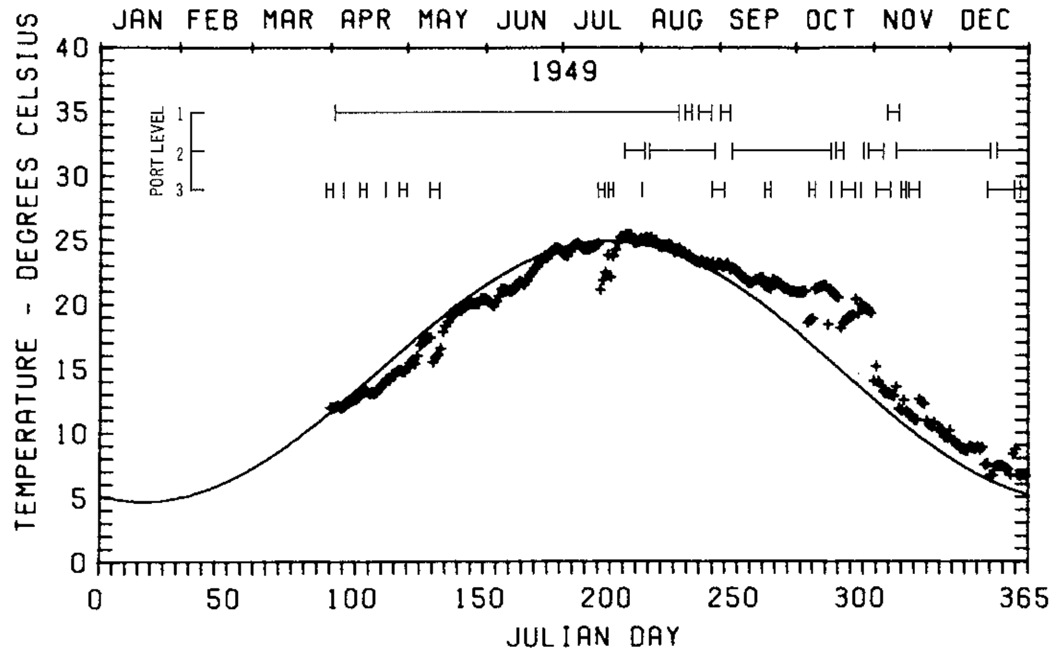
**1957 AND 1960**

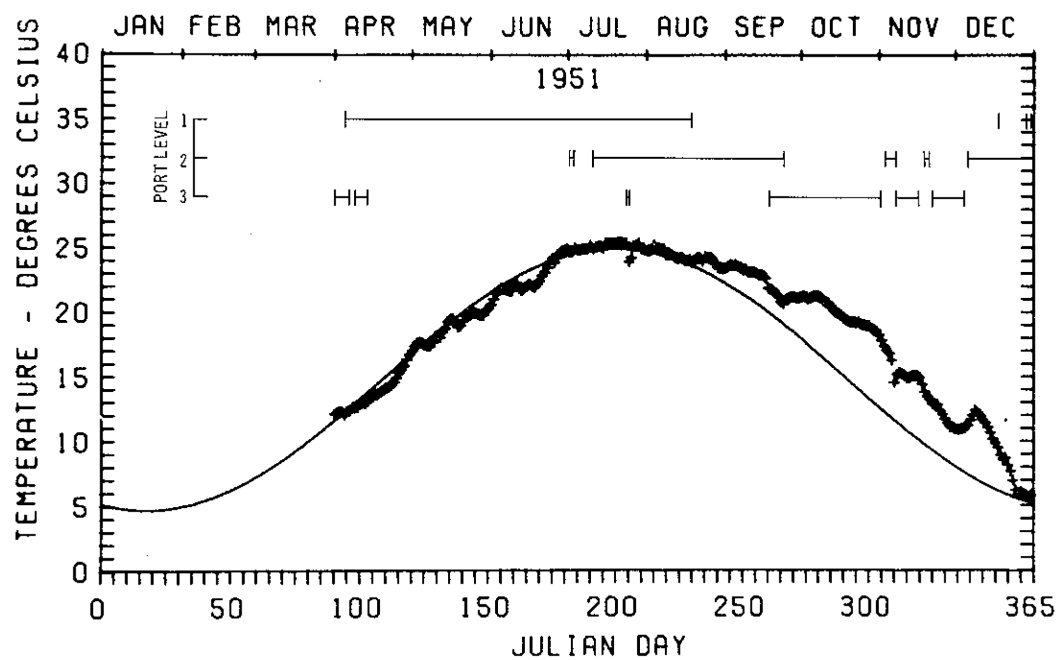
PLATE 6
(Sheet 2 of 3)




**1975 - 1985 ROUTINGS**
**4-PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**
**1967**

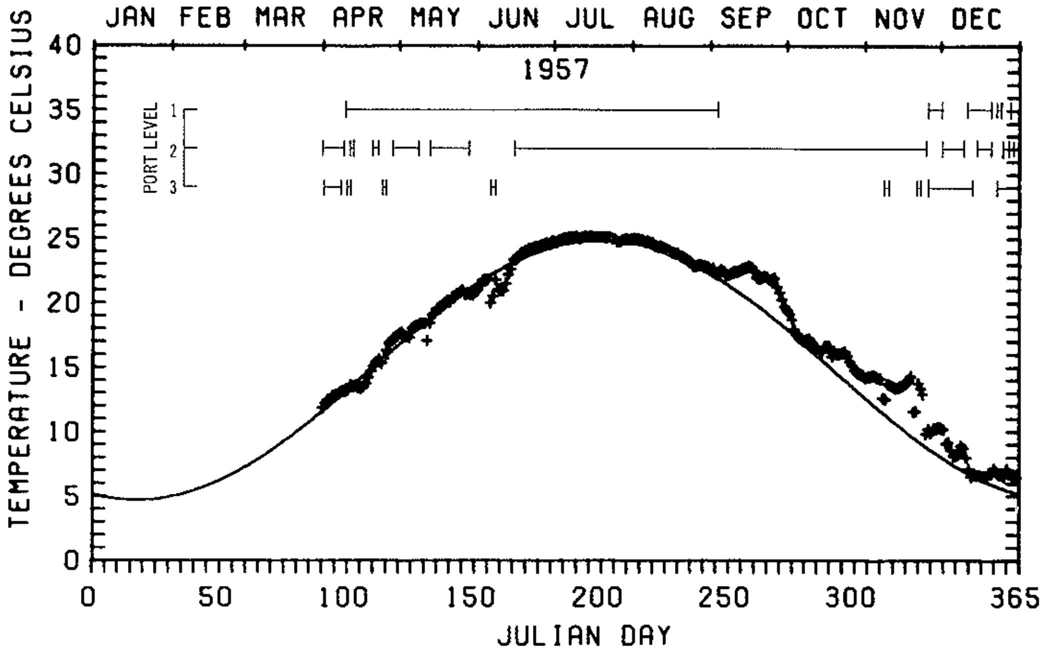
PLATE 6
(Sheet 3 of 3)

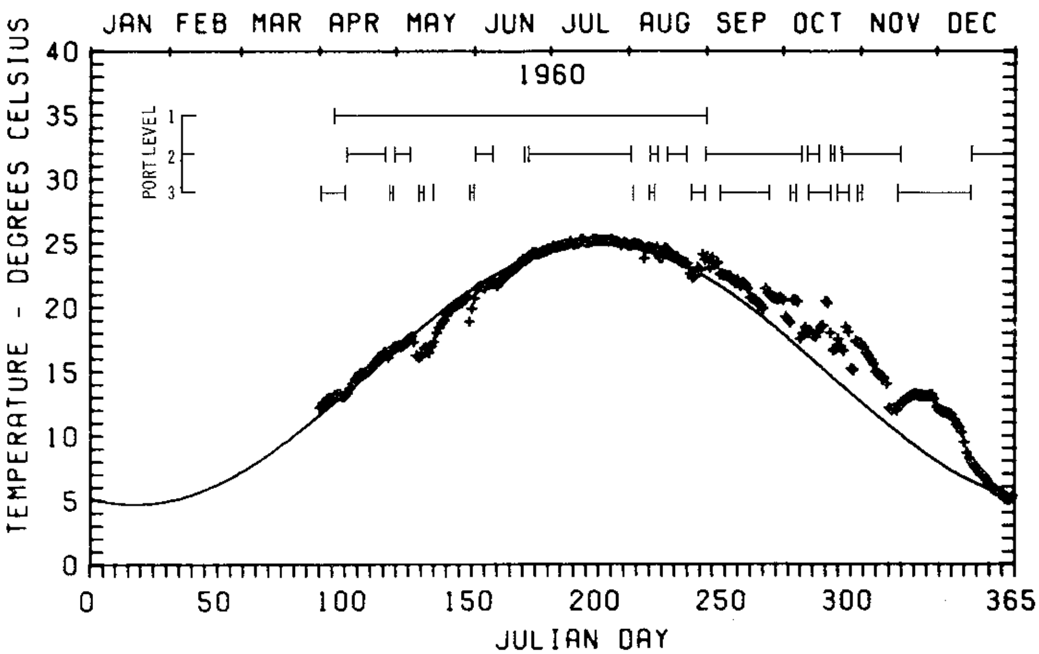



1985-2020 ROUTINGS
4-PORT OPERATION
COMPUTED RELEASE TEMPERATURE

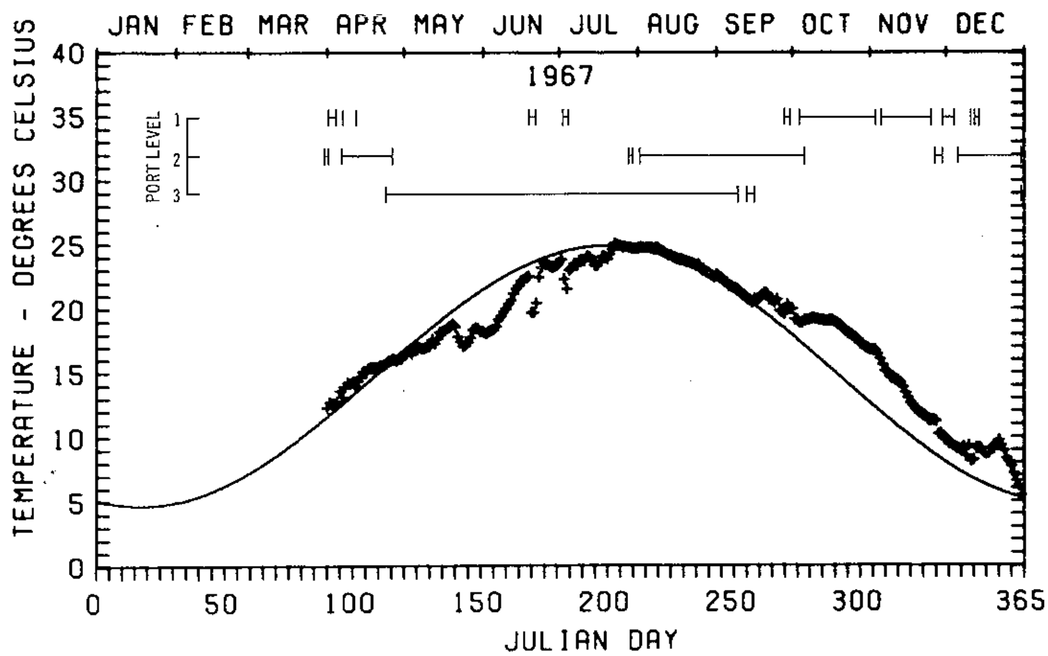
**1949 AND 1951**



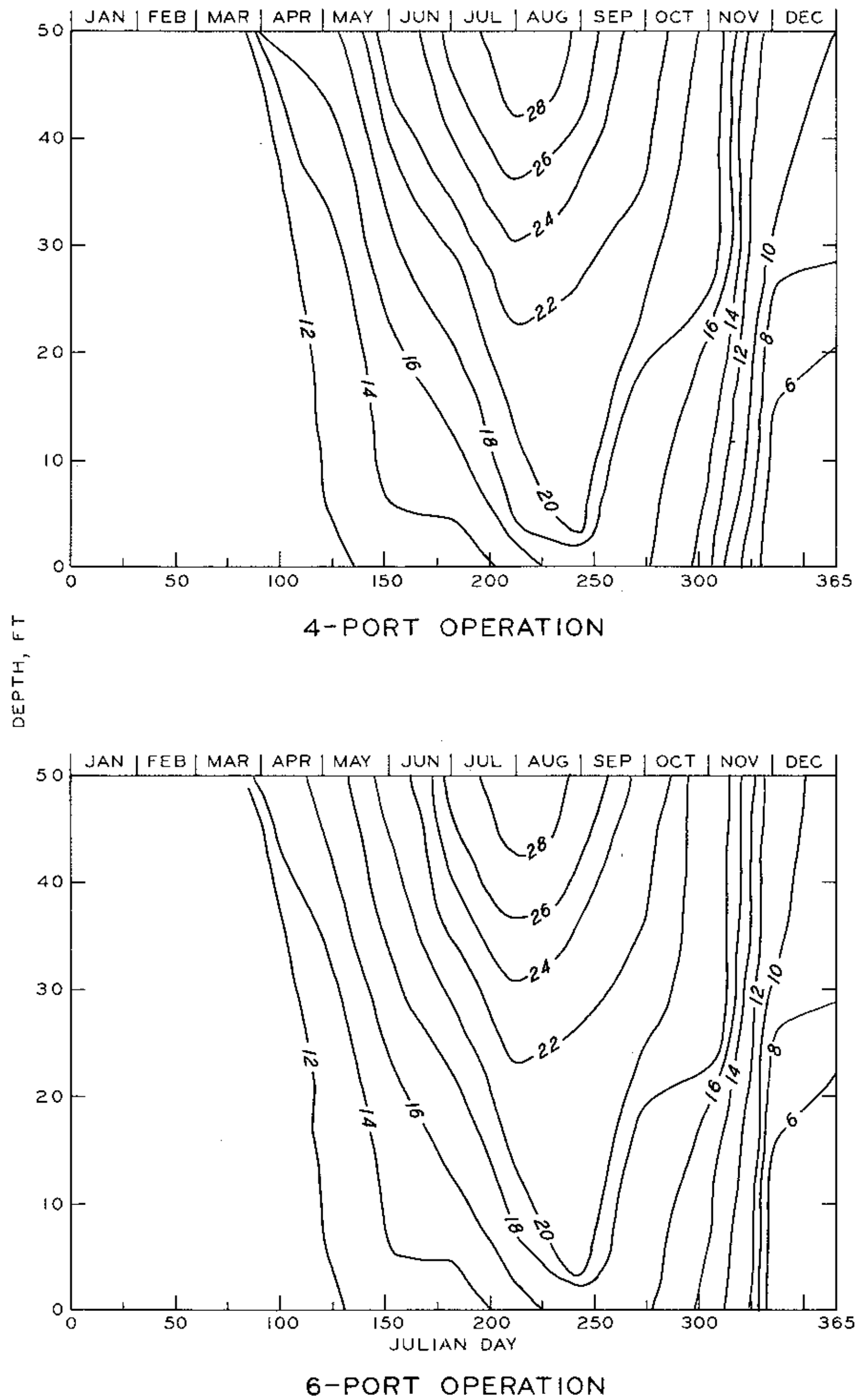

1985-2020 ROUTINGS
4-PORT OPERATION
COMPUTED RELEASE TEMPERATURE

1957 AND 1960




**1985-2020 ROUTINGS**
**4-PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**
**1967**

PLATE 7
(Sheet 3 of 3)

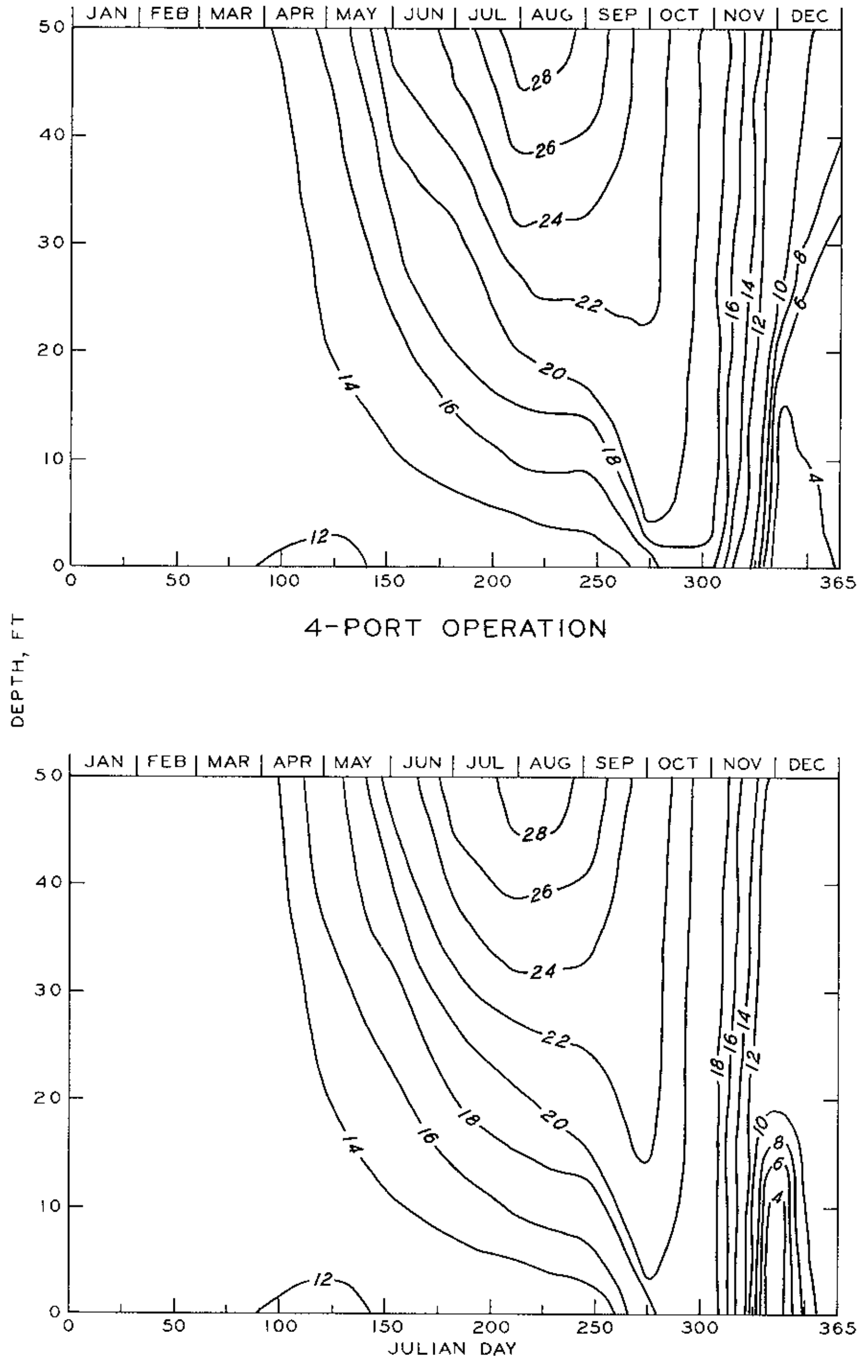



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

## 4-PORT AND 6-PORT OPERATIONS

1975-1985 ROUTING

1949 ISOTHERMS

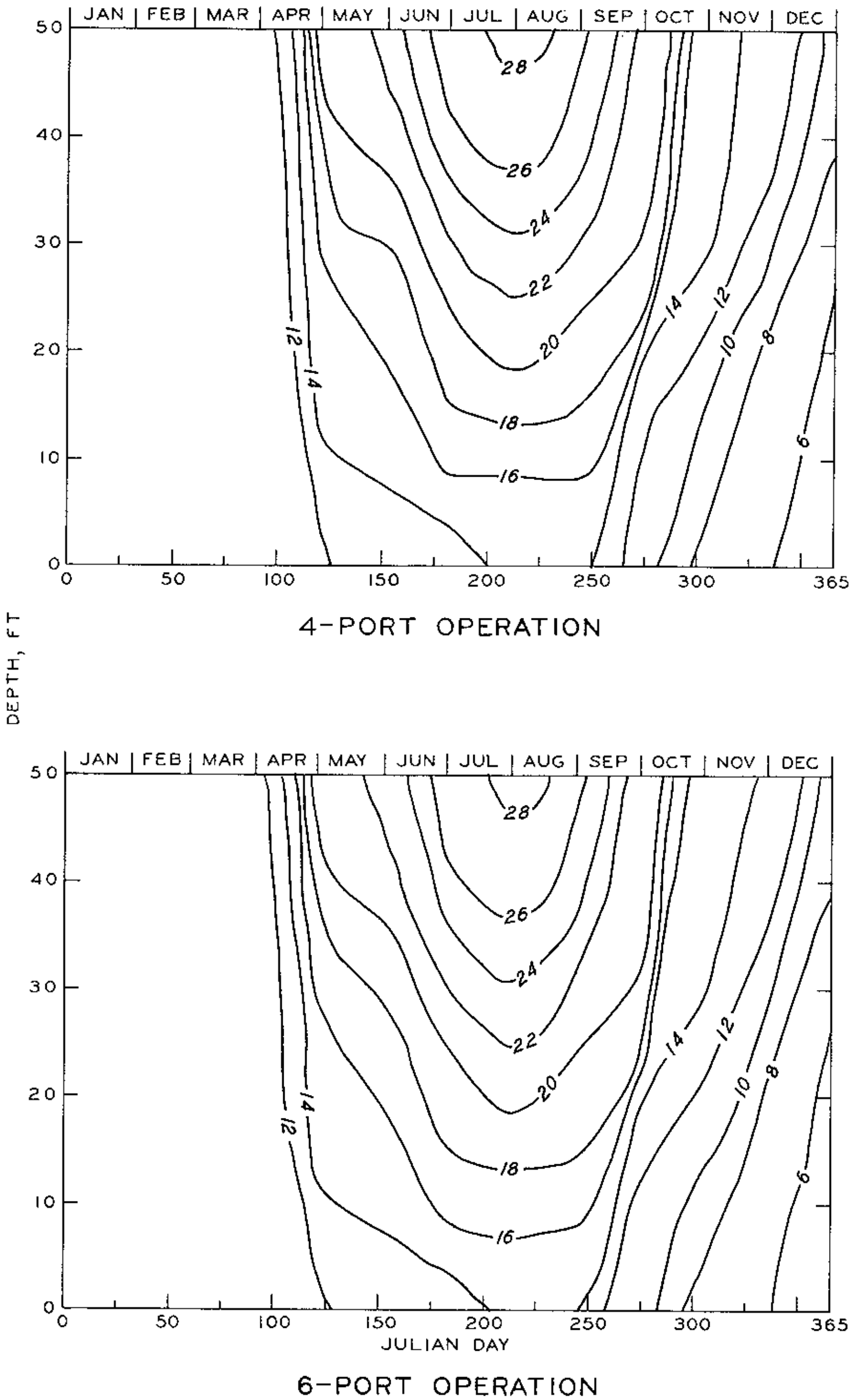



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

# 4-PORT AND 6-PORT OPERATIONS

## 1975-1985 ROUTING

## 1951 ISOTHERMS

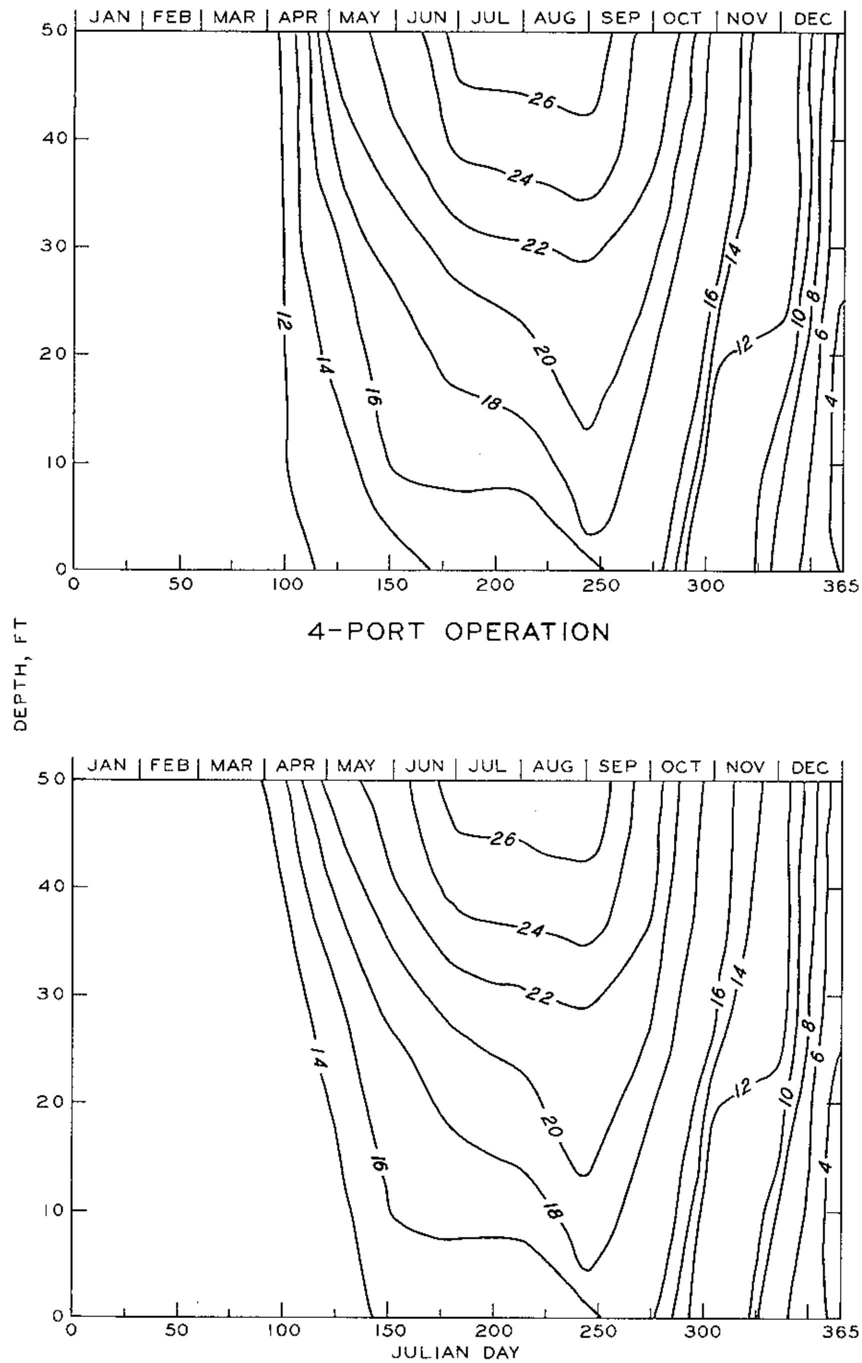



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

**4-PORT AND 6-PORT OPERATIONS**

**1975-1985 ROUTING**

**1957 ISOTHERMS**



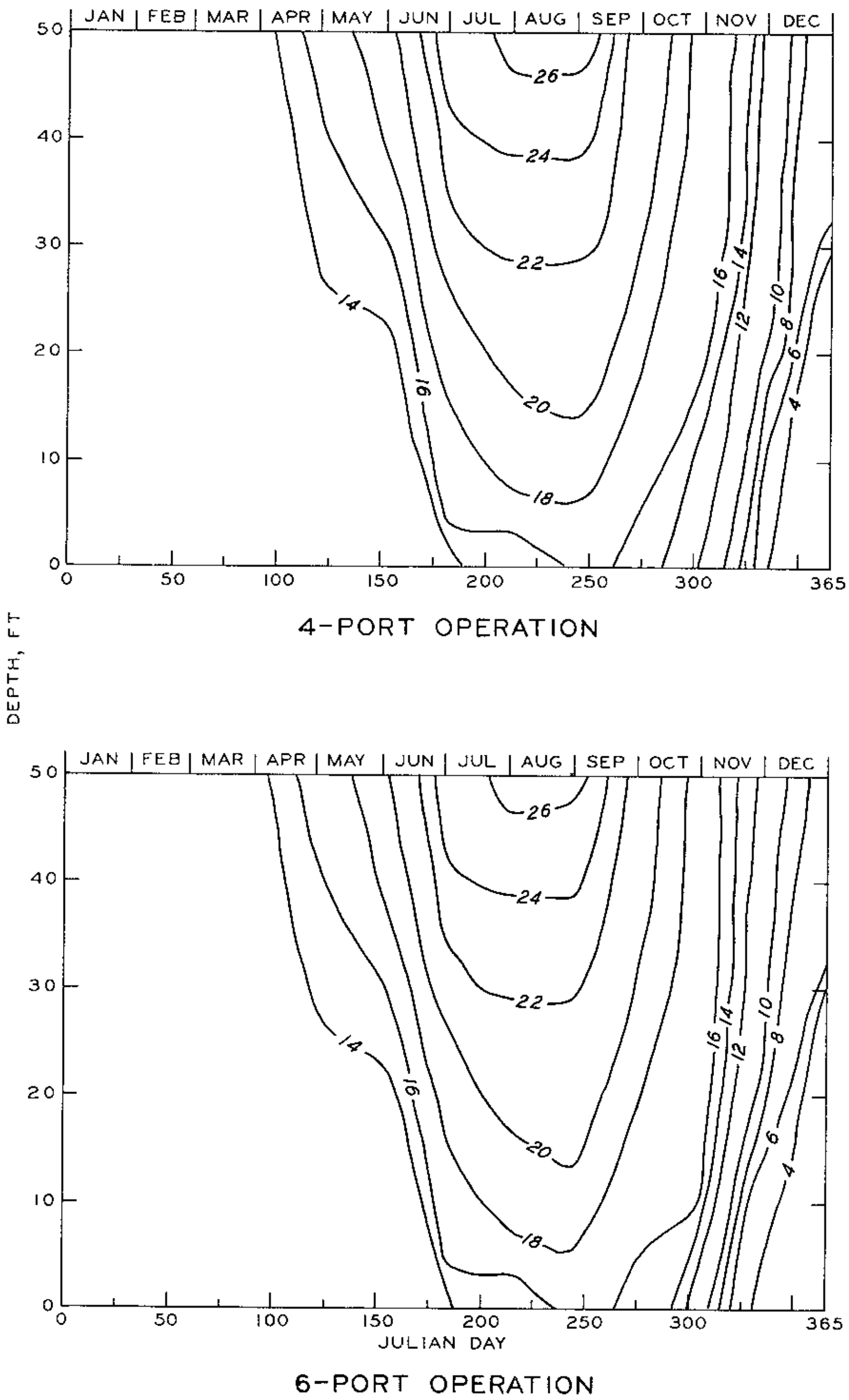

6-PORT OPERATION

NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

**4-PORT AND 6-PORT OPERATIONS**

1975-1985 ROUTING

1960 ISOTHERMS

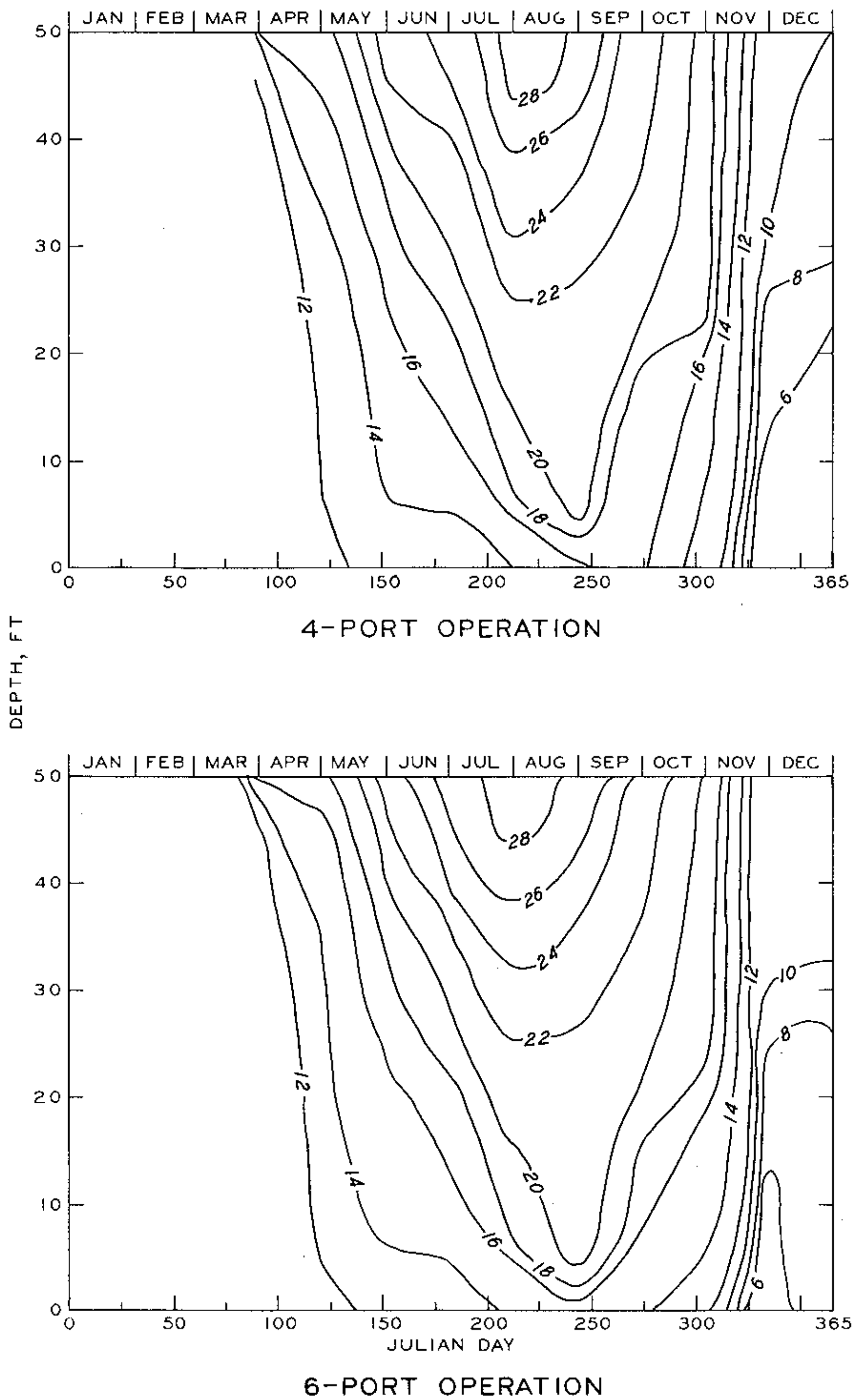



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS

# 4-PORT AND 6-PORT OPERATIONS

## 1975-1985 ROUTING

## 1967 ISOTHERMS

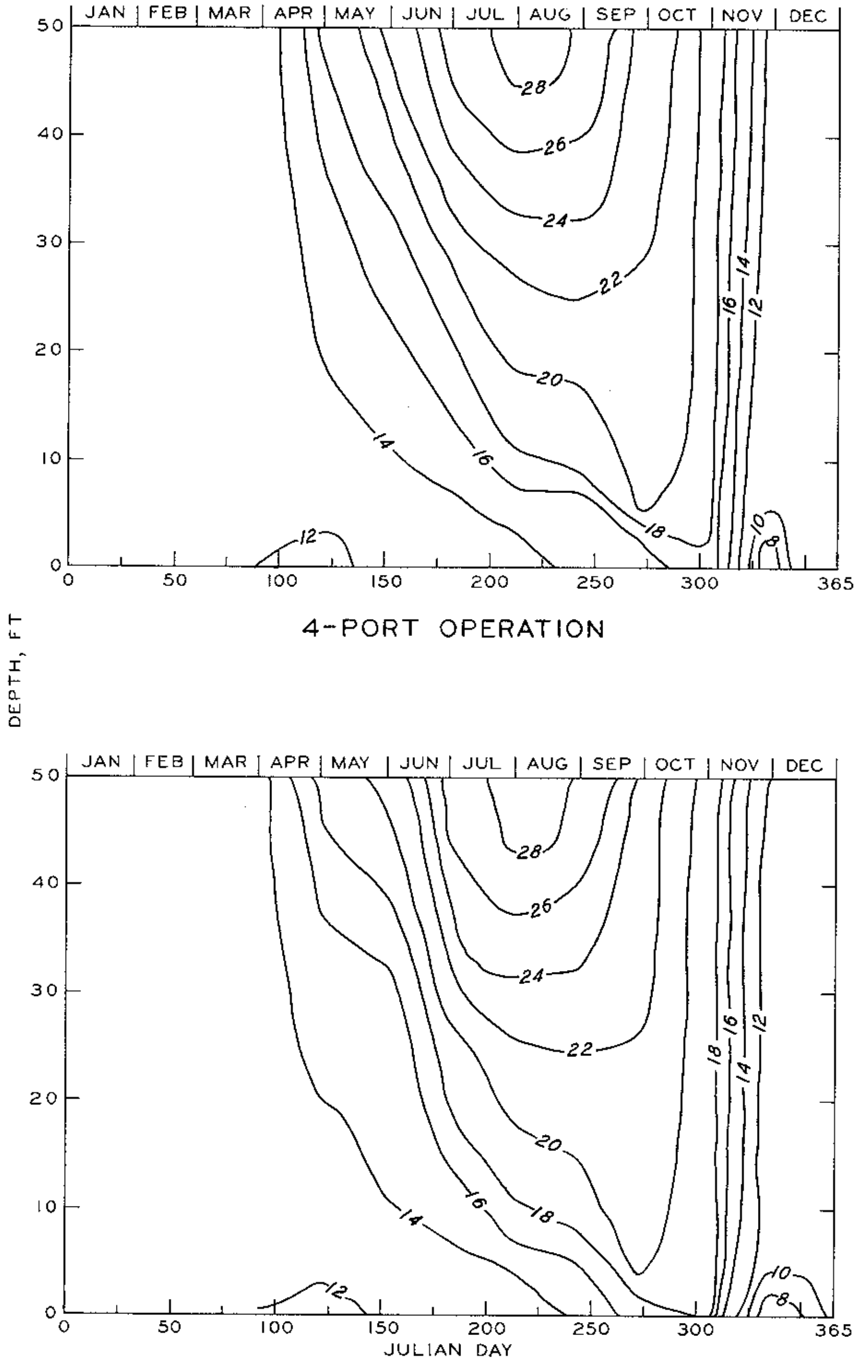



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

**4-PORT AND 6-PORT OPERATIONS**

1985–2020 ROUTING

1949 ISOTHERMS

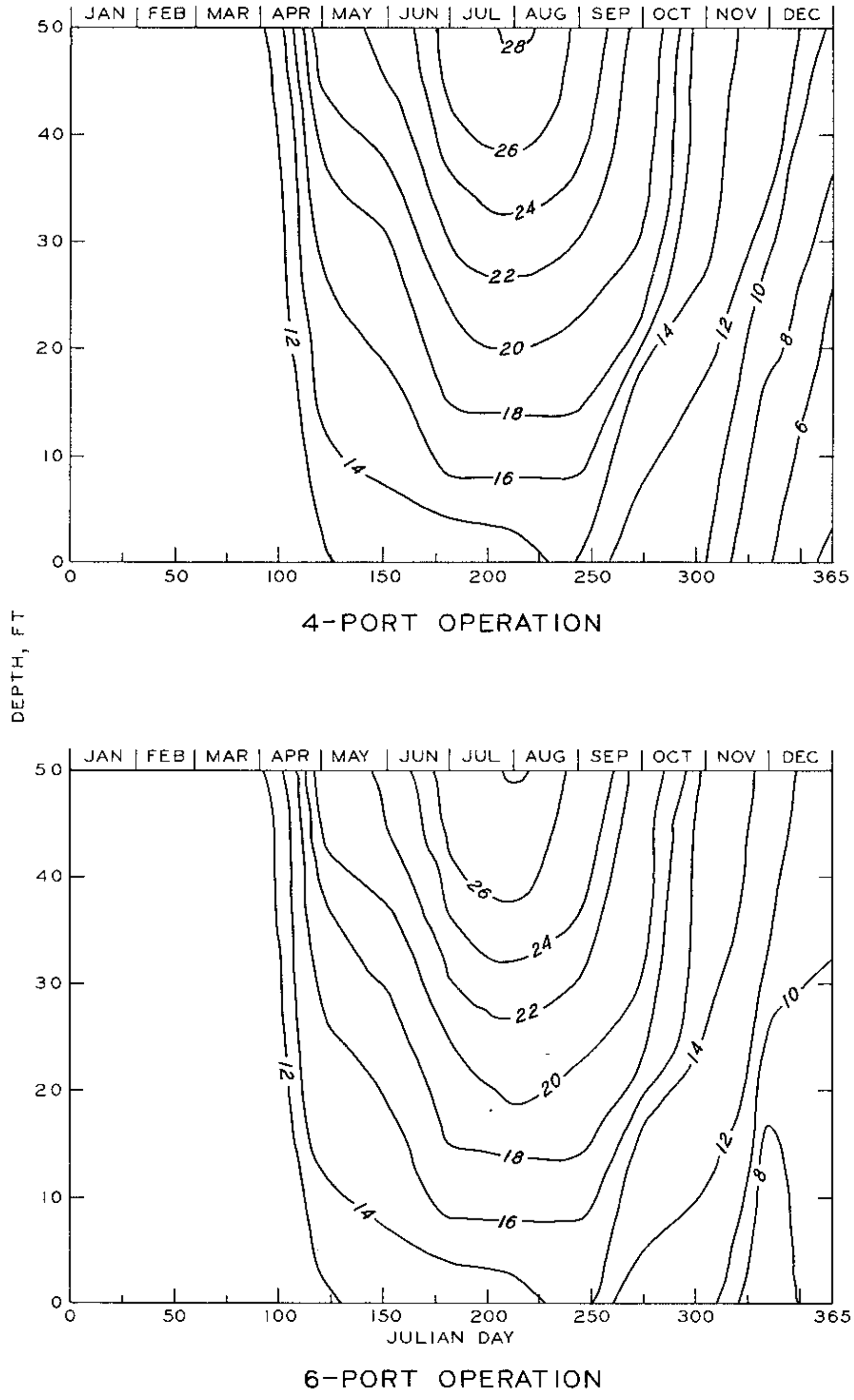



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

**4-PORT AND 6-PORT OPERATIONS**

1985-2020 ROUTING

1951 ISOTHERMS



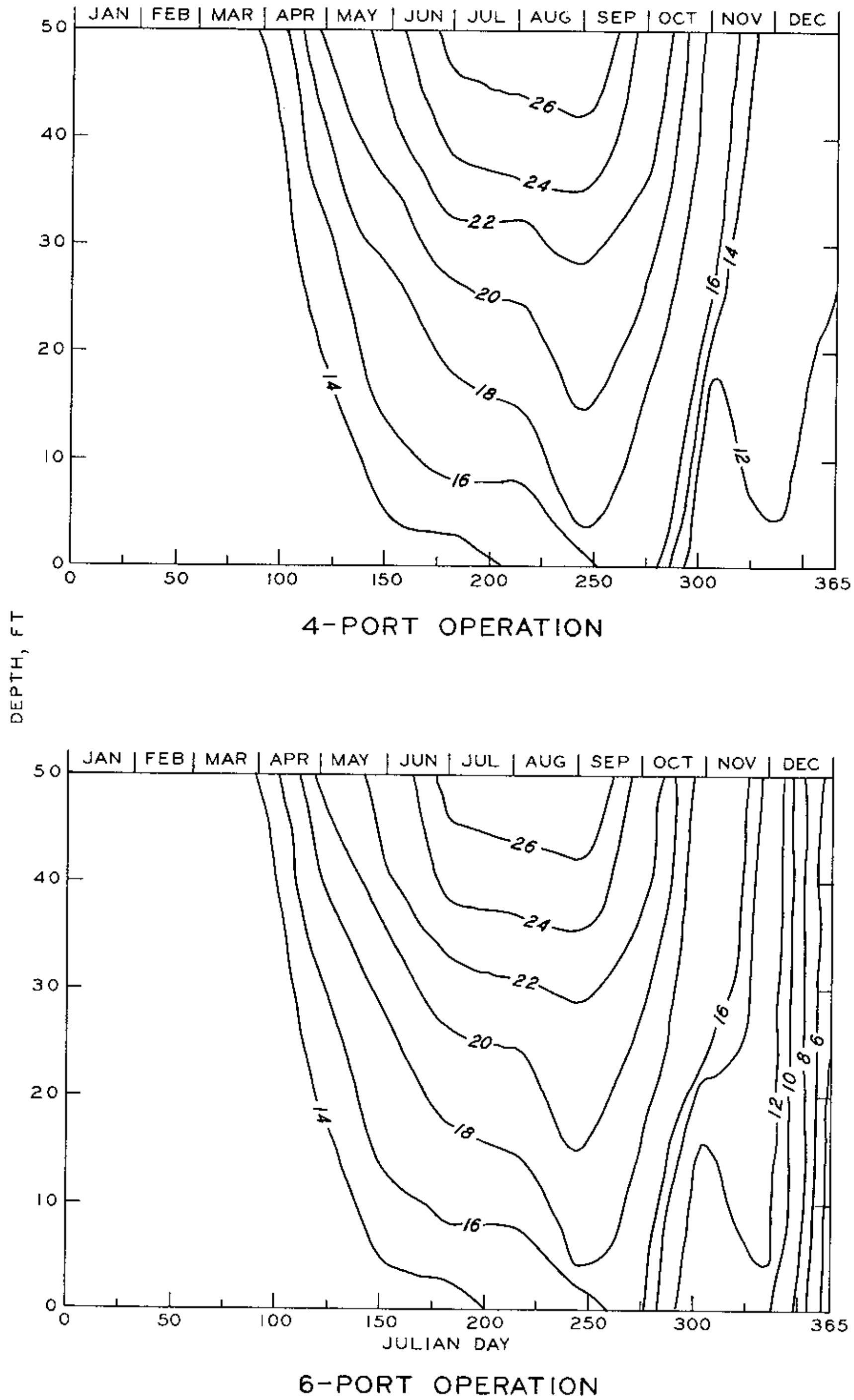

NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

## 4-PORT AND 6-PORT OPERATIONS

1985-2020 ROUTING

1957 ISOTHERMS

PLATE 9
(Sheet 3 of 5)

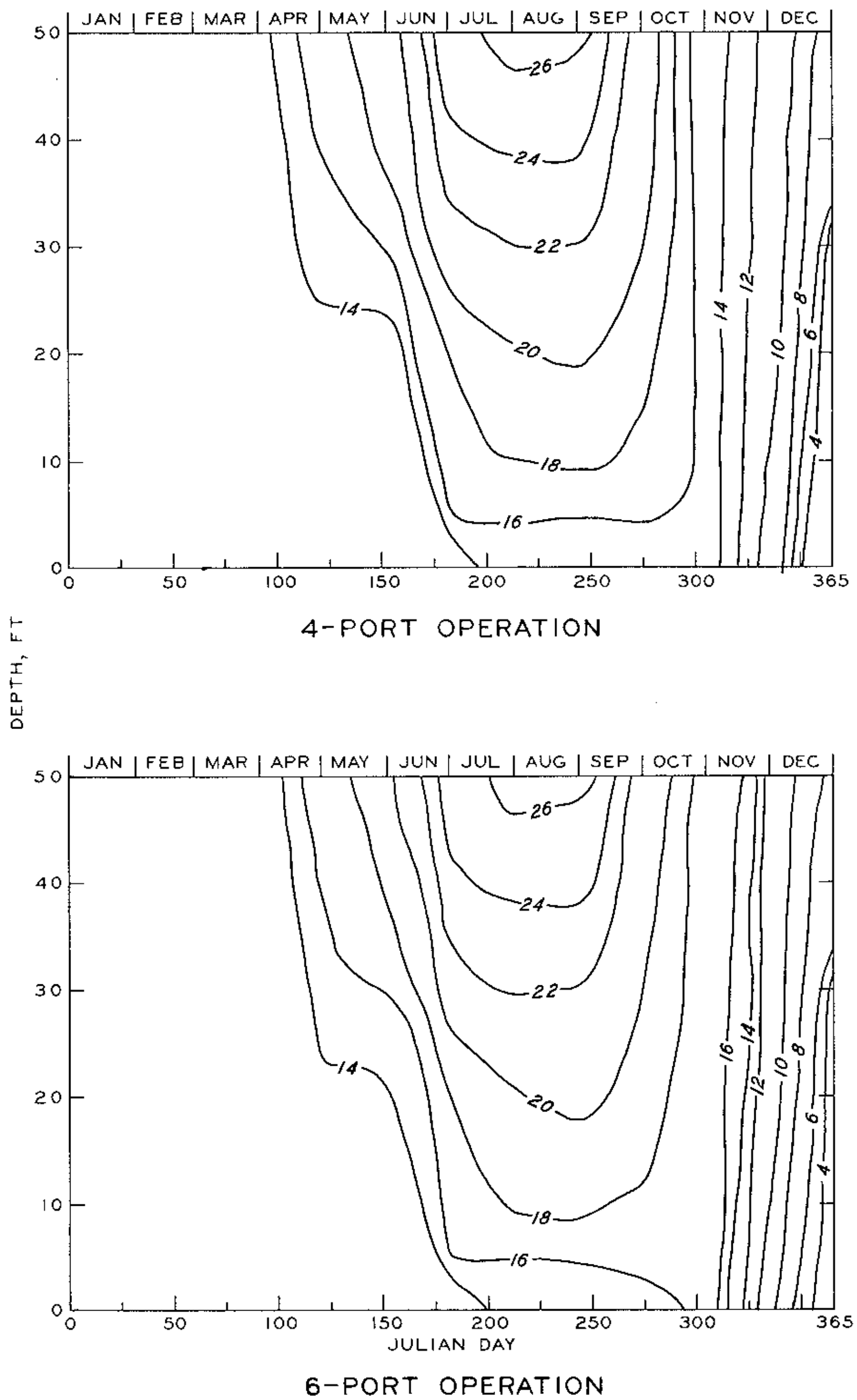



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

# 4-PORT AND 6-PORT OPERATIONS

1985-2020 ROUTING

1960 ISOTHERMS

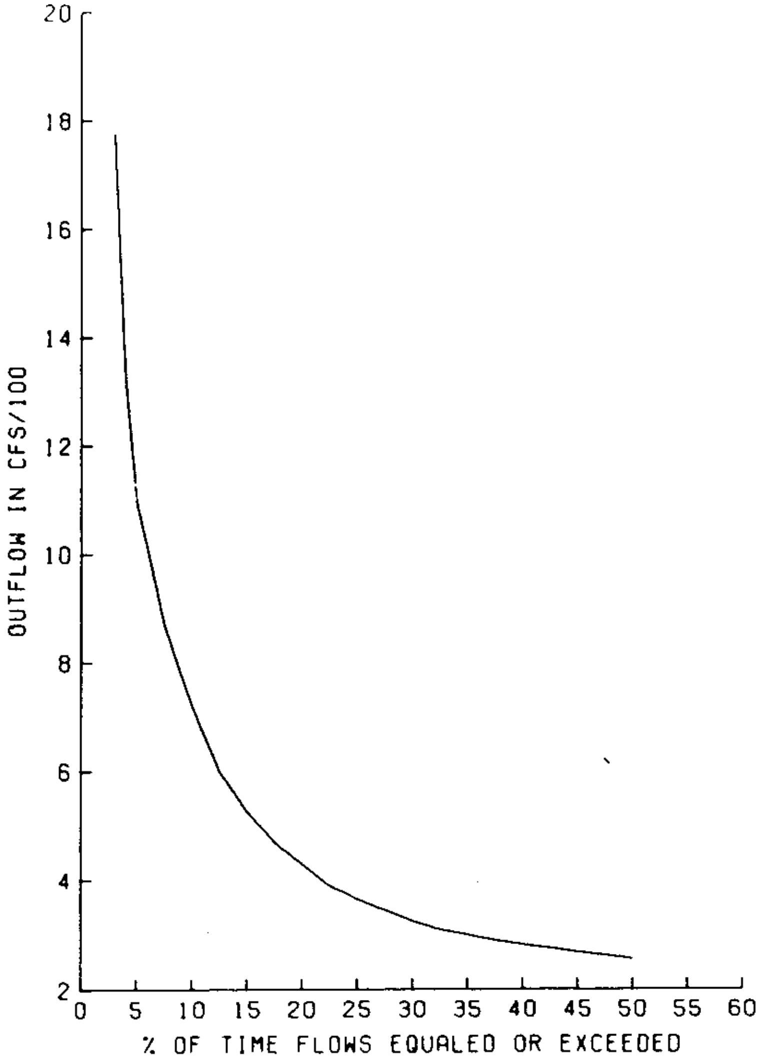



NOTE: CONTOURS SHOWN ARE TEMPERATURES IN DEGREES CELSIUS.

# 4-PORT AND 6-PORT OPERATIONS

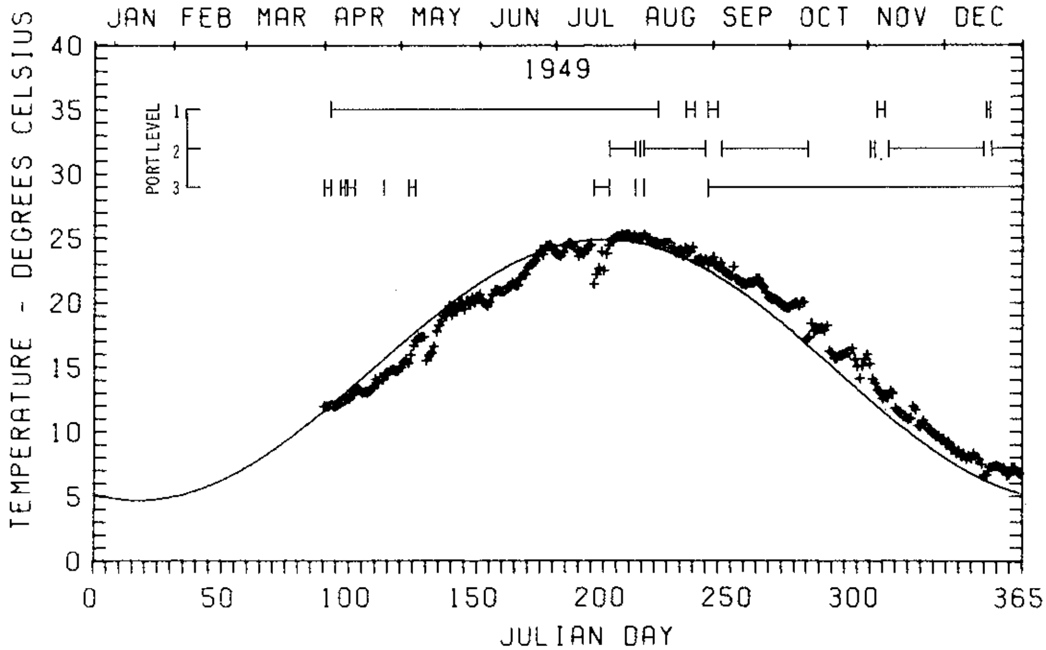
## 1985–2020 ROUTING

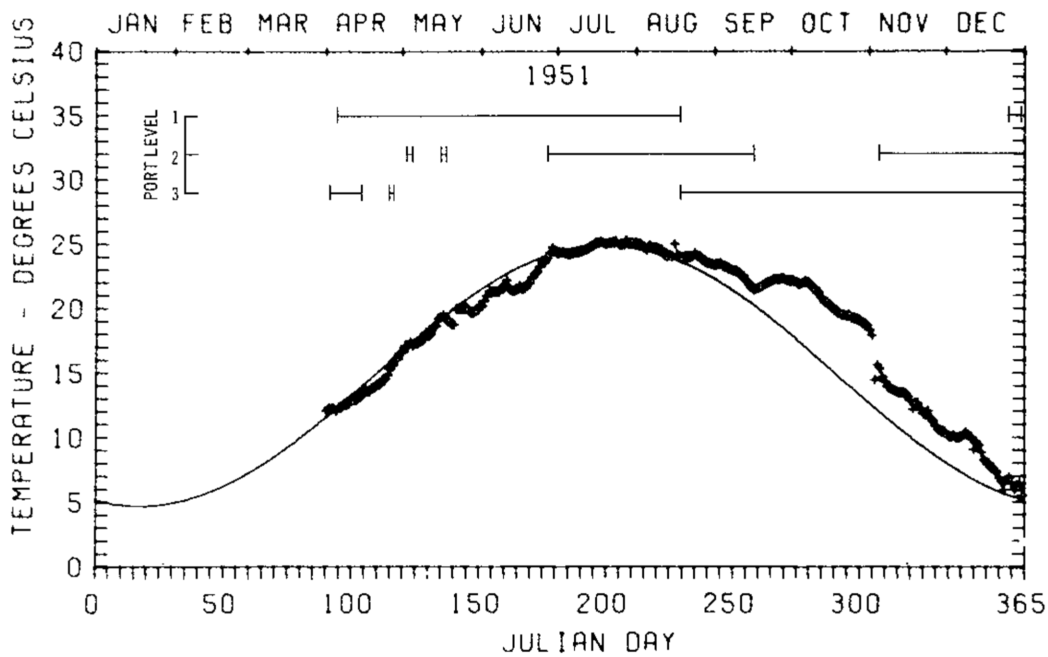
## 1967 ISOTHERMS




OUTFLOW DURATION

15 APR – 30 SEP

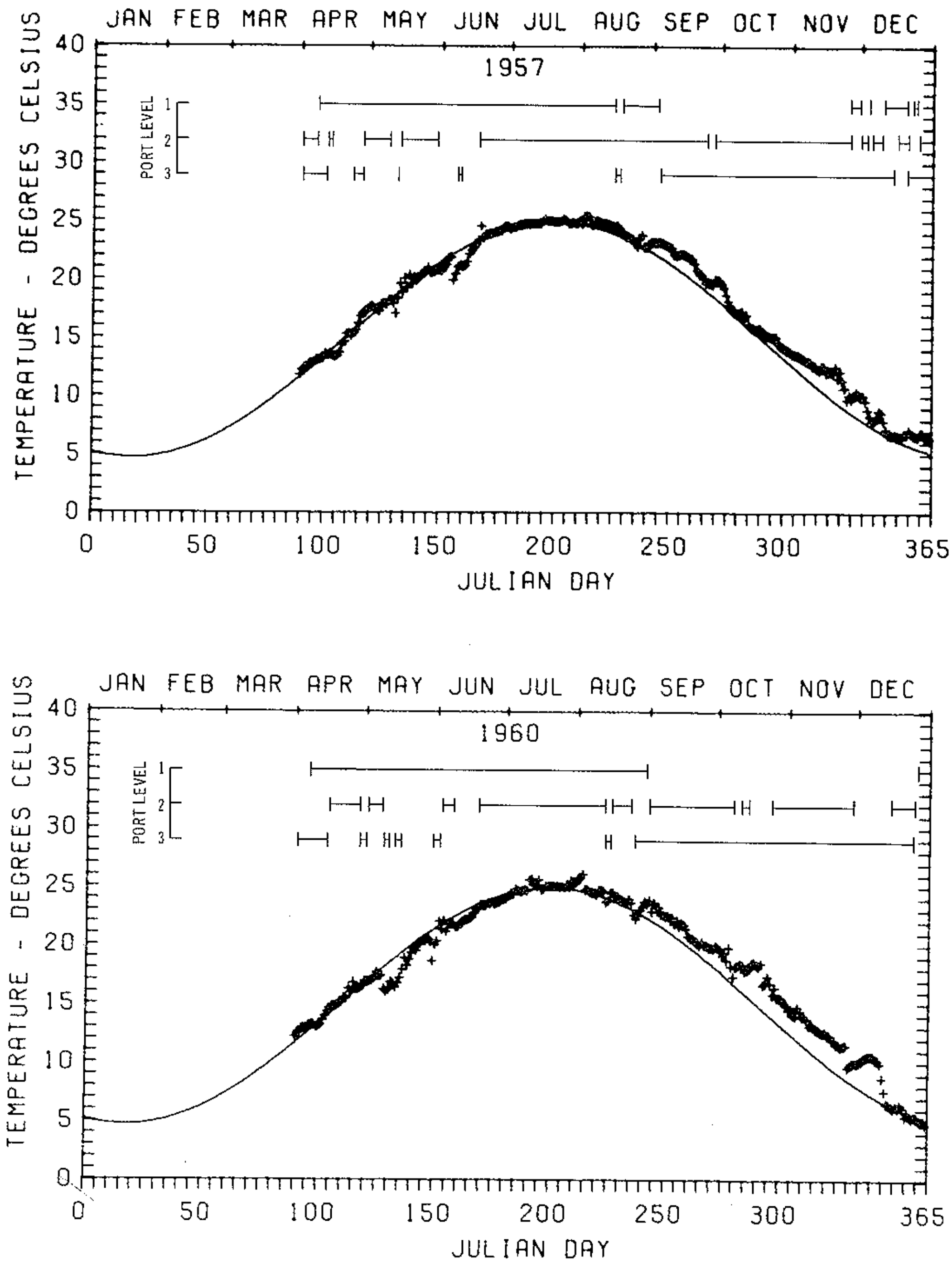



**1975 - 1985 ROUTINGS**
**6 - PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**

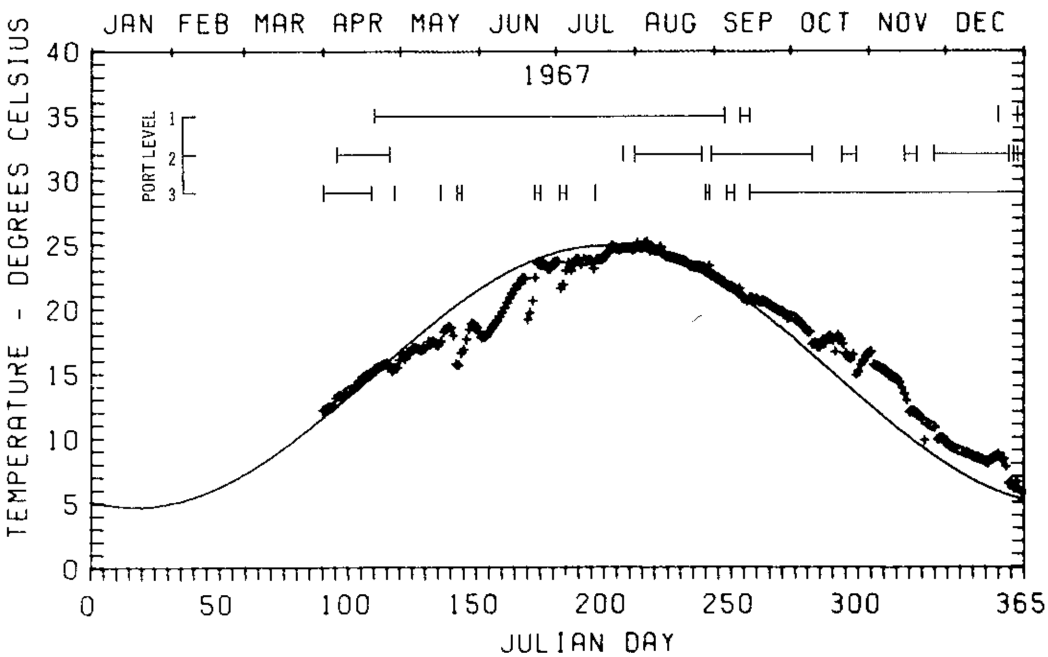
**1949 AND 1951**

PLATE 11
(Sheet 1 of 3)



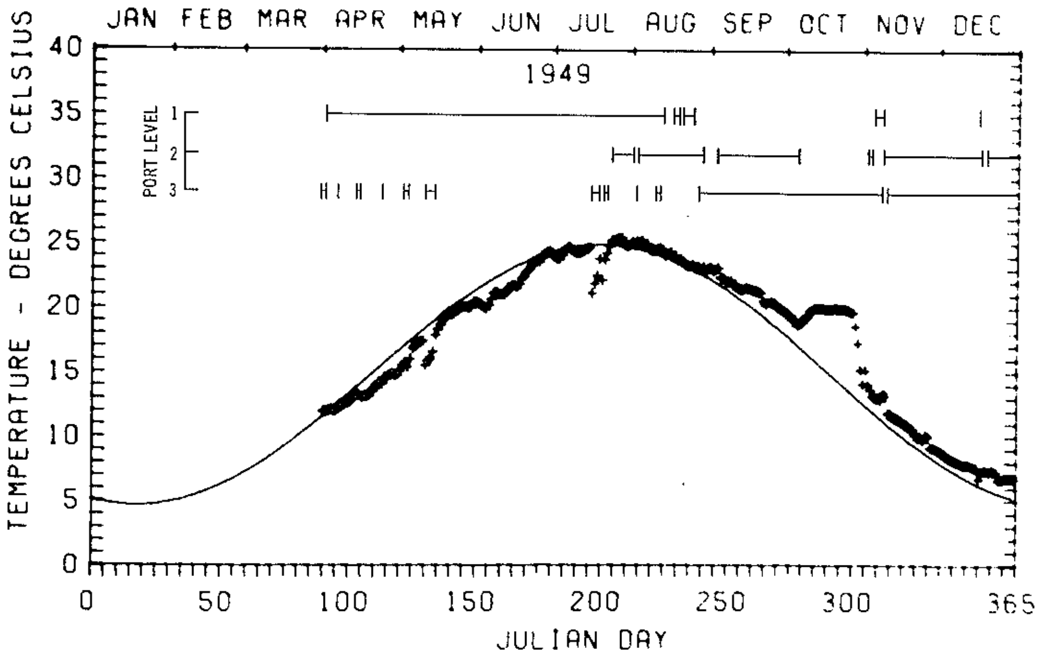

**1975 - 1985 ROUTINGS**
**6 - PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**

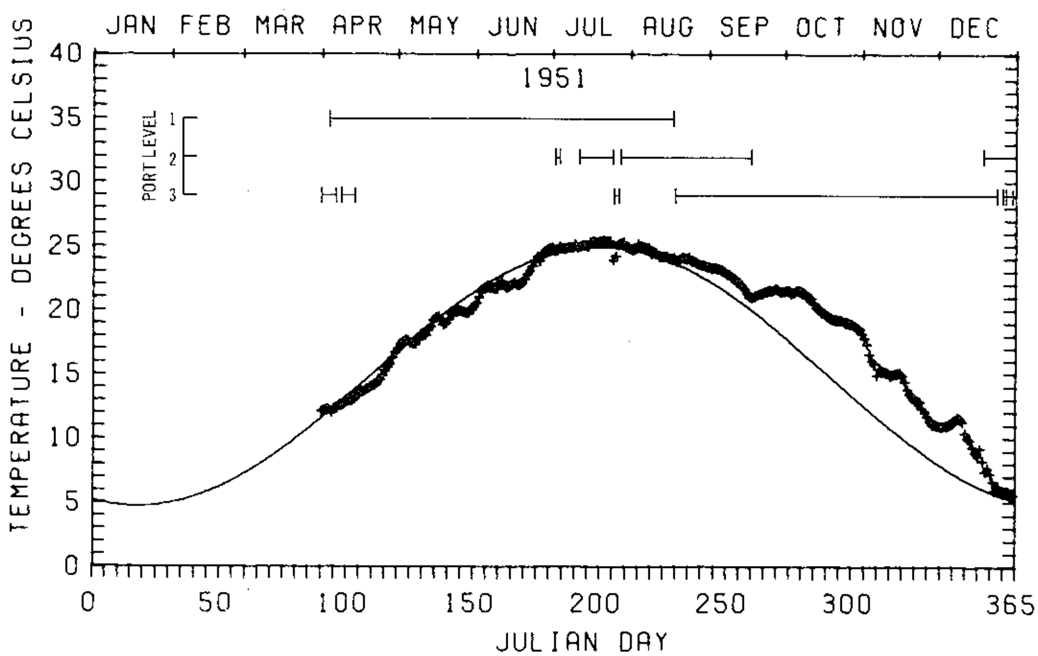
**1957 AND 1960**




1975 -1985 ROUTINGS
6-PORT OPERATION
COMPUTED RELEASE TEMPERATURE
1967

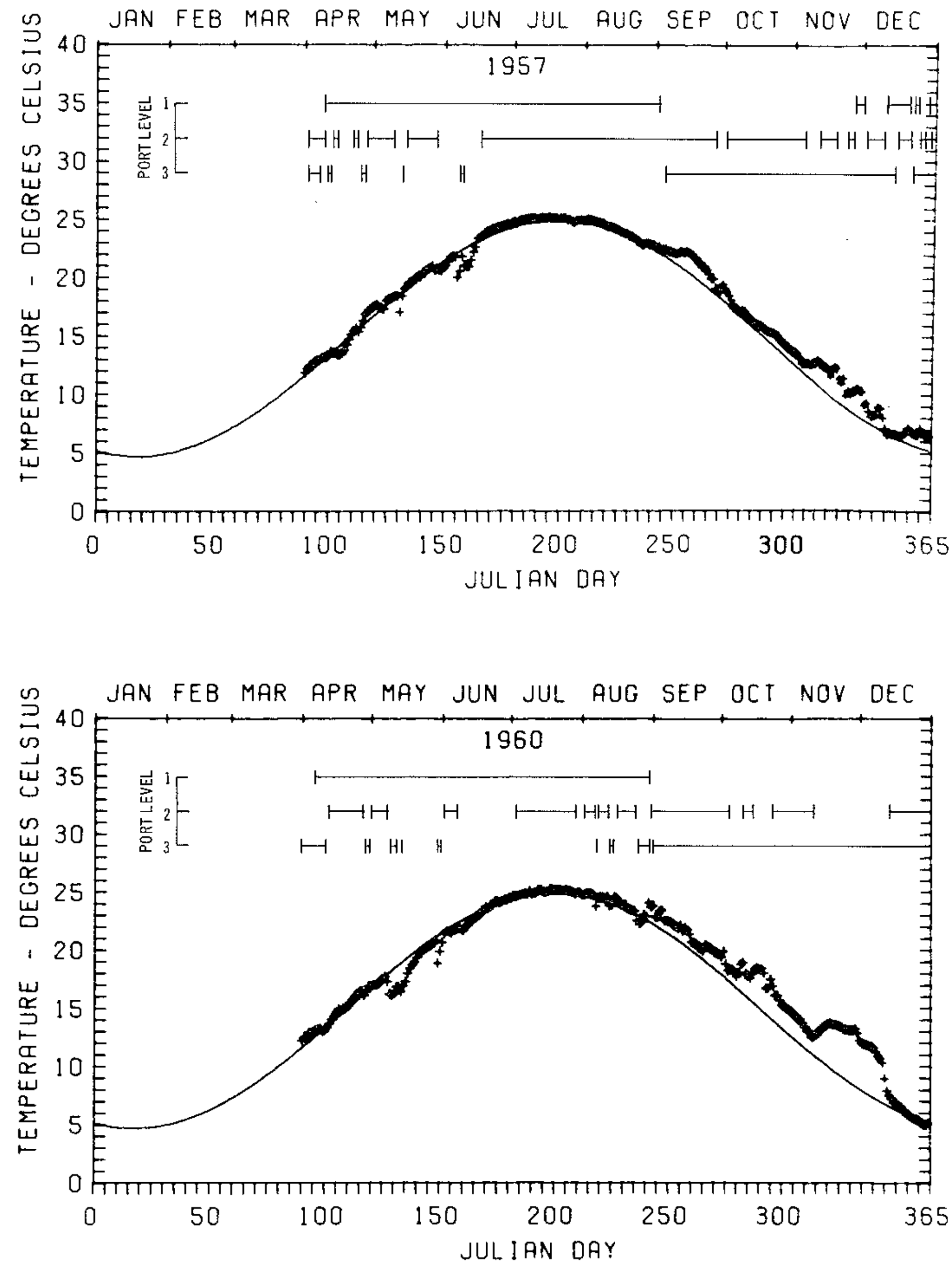
PLATE 11
(Sheet 3 of 3)



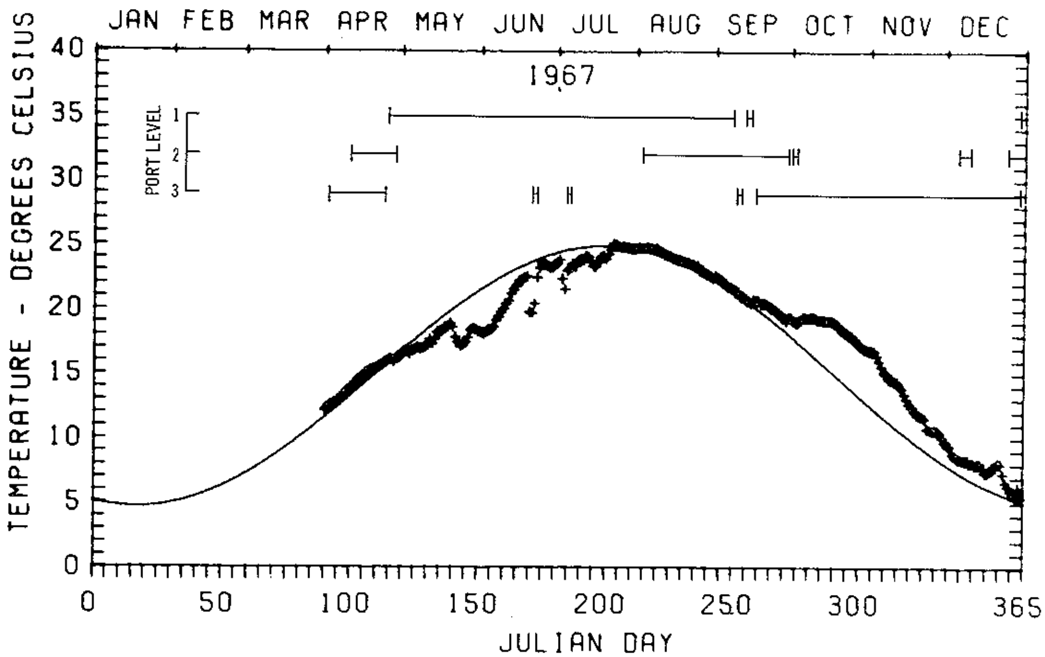

**1985-2020 ROUTINGS**
**6-PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**

**1949 AND 1951**



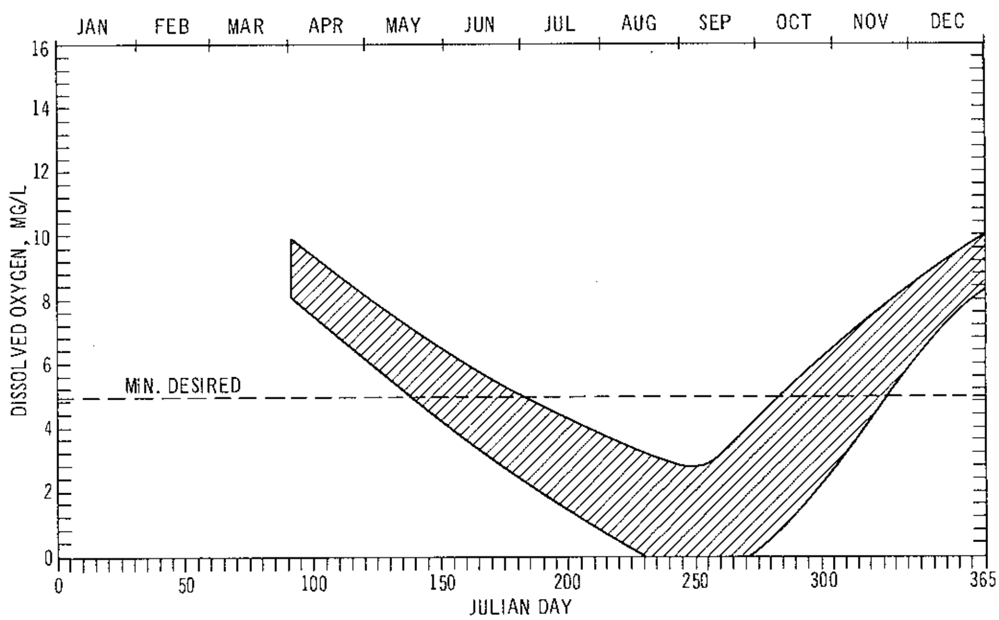

**1985-2020 ROUTINGS**
**6-PORT OPERATION**
**COMPUTED RELEASE TEMPERATURE**

**1957 AND 1960**




1985 - 2020 ROUTINGS
6 - PORT OPERATION
COMPUTED RELEASE TEMPERATURE

1967




COMPUTED DISSOLVED OXYGEN
CONTENT OF FLOW ENTERING
THE INTAKE STRUCTURE

**BAND OF ALL SIMULATION RESULTS**

# APPENDIX A: NOTATION

| | |
|---|---|
| $a$ | Coefficient (18.19°F) |
| $b$ | Coefficient ($1.721 \times 10^{-2}$ day$^{-1}$) |
| $B$ | B.O.D. depletion, mg/ℓ/day |
| B.O.D. | Biochemical oxygen demand, mg/ℓ |
| $c$ | Coefficient (1.281) |
| $d$ | Coefficient (59.2°F) |
| $D$ | D.O. depletion, mg/ℓ/day |
| D.O. | Dissolved oxygen |
| $D.O._{in}$ | Computed D.O. content of inflow, mg/ℓ |
| $D.O._{sat}$ | Saturated D.O. content, mg/ℓ |
| $E$ | Equilibrium temperature, °F |
| $H$ | Net rate of heat transfer, Btu/ft$^2$/day |
| $K$ | Coefficient of surface heat exchange, Btu/ft$^2$/day/°F |
| $K_B$ | Decay coefficient |
| $K_D(T)$ | Temperature-dependent deoxygenation coefficient, day$^{-1}$ |
| $K_D(20°C)$ | Deoxygenation coefficient at 20°C, day$^{-1}$ |
| $L$ | B.O.D., mg/ℓ |
| $p$ | $6.77 \times 10^{-2}$ |
| $q$ | $2.08 \times 10^{-3}$ |
| $Q$ | Mean daily streamflow, cfs |
| $t$ | Time, Julian days |
| $T$ | Temperature of the layer, °C |
| $T_s$ | Surface temperature, °F |
| $\alpha$ | Regression coefficient |
| $\beta$ | Regression coefficient |
| $\varepsilon$ | Coefficient (−9.6791 mg/ℓ) |
| $\Theta$ | Stream temperature, °F |
| $\Theta'$ | Average stream temperature, °F |
| $\sigma$ | Coefficient (1.7115) |
| $\phi$ | Stream temperature, °C |

**In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.**

Loftis, Bruce
Falls Lake water-quality study; hydraulic laboratory investigation, by Bruce Loftis and Darrell G. Fontane. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Miscellaneous paper H-76-6)
Prepared for U. S. Army Engineer District, Savannah, Savannah, Georgia.
Includes bibliography.

1. Dissolved oxygen. 2. Falls Lake. 3. Intake structures. 4. Water quality. 5. Water temperature. I. Fontane, Darrell G., joint author. II. U. S. Army Engineer District, Savannah. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper H-76-6)
TA7.W34m no.H-76-6