BAY SPRINGS LAKE WATER-QUALITY STUDY

by

Steven C. Wilhelms[1]

PART I: INTRODUCTION

Project Overview

The Tennessee-Tombigbee Waterway will be a navigable waterway made up of natural rivers and streams and man-made canals and locks and dams. The waterway, located in Alabama, Mississippi, and Tennessee (Figure 1), will extend upstream from Demopolis, Alabama (on the existing Black Warrior-Tombigbee Waterway 217 miles above Mobile, Alabama), by way of the Tombigbee River to the east fork of the Tombigbee. The project then will extend up into Mackey's Creek, through a deep cut in the Tennessee Valley Divide, to Pickwick Lake by way of Yellow Creek. The waterway joins the Tennessee River System near the common boundary of Mississippi, Alabama, and Tennessee (Figure 2).

The "Tenn-Tom" is divided into three sections consisting of a river section, a canal section, and a divide section as shown in Figure 2. The river and canal sections extend from Demopolis, Alabama, to the Bay Springs Lock and Dam in Mackey's Creek. These two sections are 213 miles long and will have nine conventional locks to overcome a difference in elevation of 257 ft. The divide section consists of an 84-ft lift lock at the Bay Springs Dam and a 27-mile-long canal to be cut through the Tennessee Valley Divide into the Yellow Creek Embayment of Pickwick Lake.

The main justification of the Tennessee-Tombigbee Waterway is the lessened transportation costs for moving barges from the Gulf of Mexico to the Tennessee River system. Instead of navigating the Mississippi and Ohio Rivers to reach the Tennessee River system, tows can navigate directly from Mobile, Alabama. Although the largest part of the economic justification was the decreased transportation cost, recreational benefits, fish and wildlife enhancement, and area development were also included.

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[1] Steven C. Wilhelms, Research Hydraulic Engineer, Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station, CE, Miss.

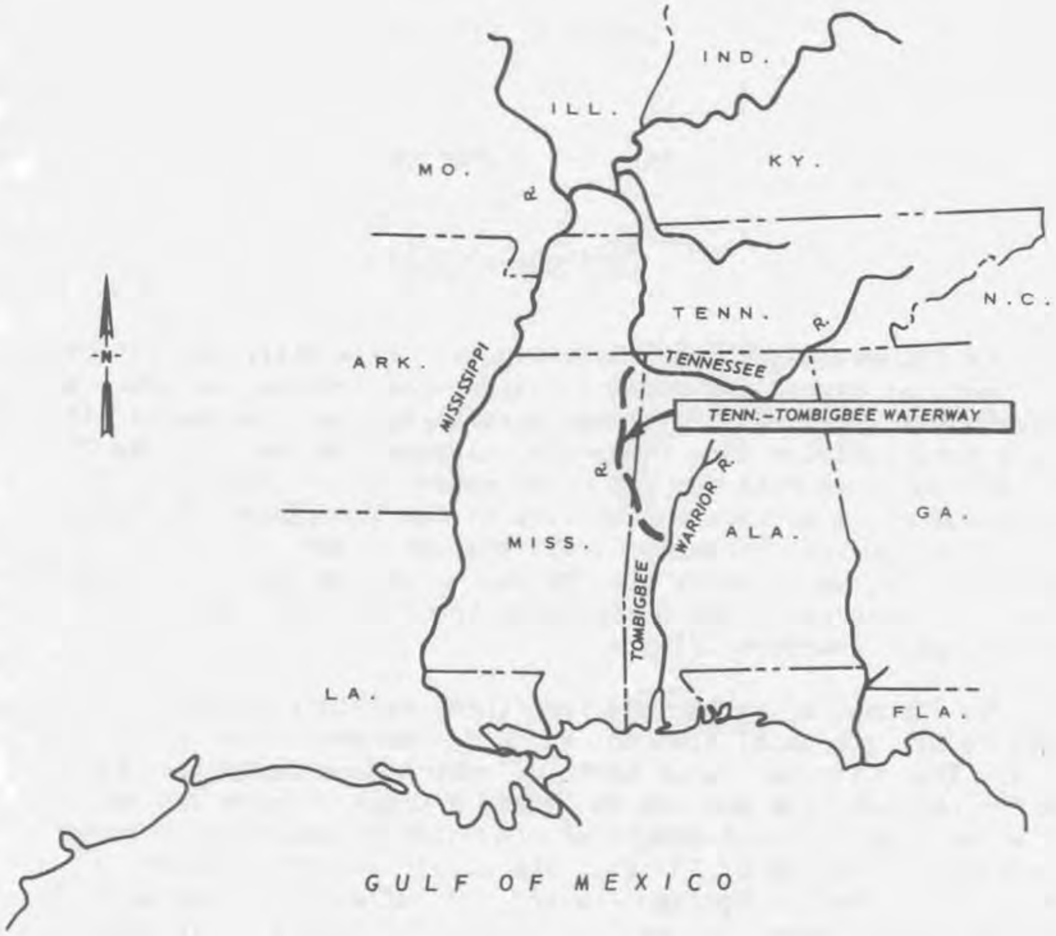

Figure 1. Location map, Tennessee-Tombigbee Waterway

Purpose and Scope of Study

The objective of the water-quality investigation was to predict the expected temperature and dissolved oxygen (DO) content of the water within and released from Bay Springs Lake. The location of the lock intakes was evaluated with respect to the ability to meet water-quality requirements established by state environmental and wildlife agencies.

Physical and mathematical models were used to assist in defining the hydrodynamics and simulate the temperature and DO regimes of the proposed Bay Springs Lake. The effects of lockage rates ranging from 5 to 24 per day for various study years were evaluated.

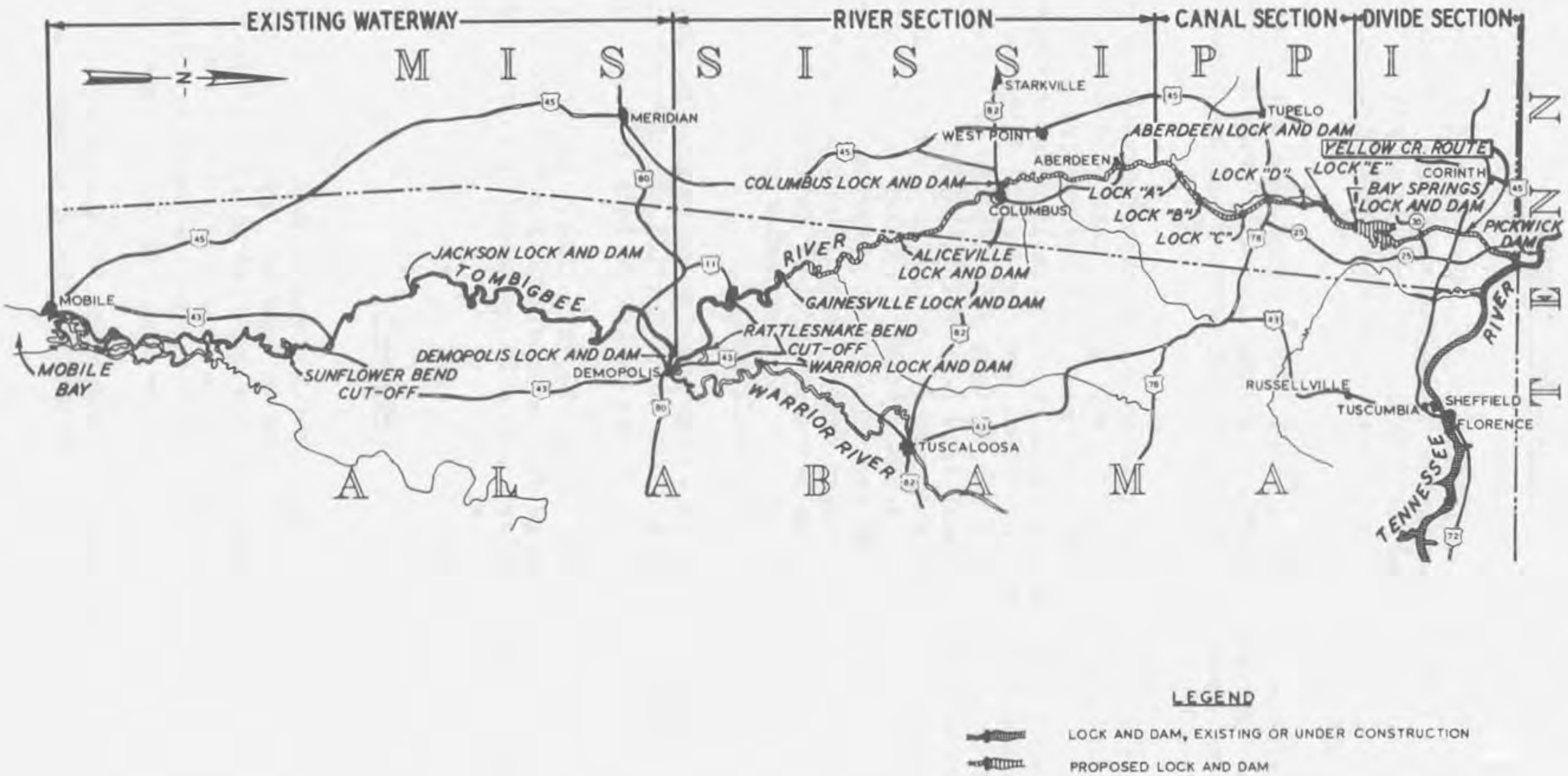

Figure 2. Vicinity map, Tennessee-Tombigbee Waterway

Project Description

The Bay Springs Lock and Dam project is proposed for construction in northeast Mississippi on the "Tenn-Tom" waterway. The dam site is located approximately one-half mile south of the crossing of Mississippi Highway 4 and Mackey's Creek, just west of Tishomingo, Mississippi (Figure 3).

The divide-cut canal connects Bay Springs Lake and Pickwick Lake. It will be approximately 27 miles long with an average bottom width of 300 ft. The canal will have a minimum depth of 13 ft, with the canal bottom being horizontal at el 395 ft.

With the exception of infrequent releases to sustain a minimum flow in Mackey's Creek, outflow from Bay Springs Lake will occur only during operation of the lock. Excess runoff into Bay Springs Lake will be passed down the divide-cut canal to Pickwick Lake and released through the Tennessee River System. Also, any rise in the Pickwick pool will be reflected by a rise in the Bay Springs pool because of uncontrolled flow through the divide-cut canal from Pickwick to Bay Springs. The lock will be located near the east end of the dam on a relatively flat, elevated plain. The lock intakes will be located on the inside of the upper approach walls in an excavation just upstream of the lock monolith. The forecast of lockage rates ranged from 5 lockages per day, the minimum use expected in the years immediately following project completion, to 24 lockages per day, the maximum number of lockages for barge traffic the facility can physically handle.

Under these lockage rates the average daily flow released from the lock will range from 355 to 1700 cfs. Outflow can also occur from Bay Springs Lake towards Pickwick Lake during periods of high local runoff.

Average daily inflows to Bay Springs Lake from local drainage areas are expected to range from approximately 10 to 1200 cfs. Additional inflow to Bay Springs Lake will be contributed from Pickwick Lake through the divide-cut canal.

Approach

The unique features and unusual conditions associated with the Bay Springs Lake project necessitated an improved approach to study the movement and quality of water to be expected within and downstream of the lake. Both physical and mathematical models were used to assist in defining the hydrodynamics and to simulate the temperature and DO regimes within and downstream of the proposed Bay Springs Lake.

Three models were used in conducting the investigation. Two physical models were used in conjunction with a mathematical model. An

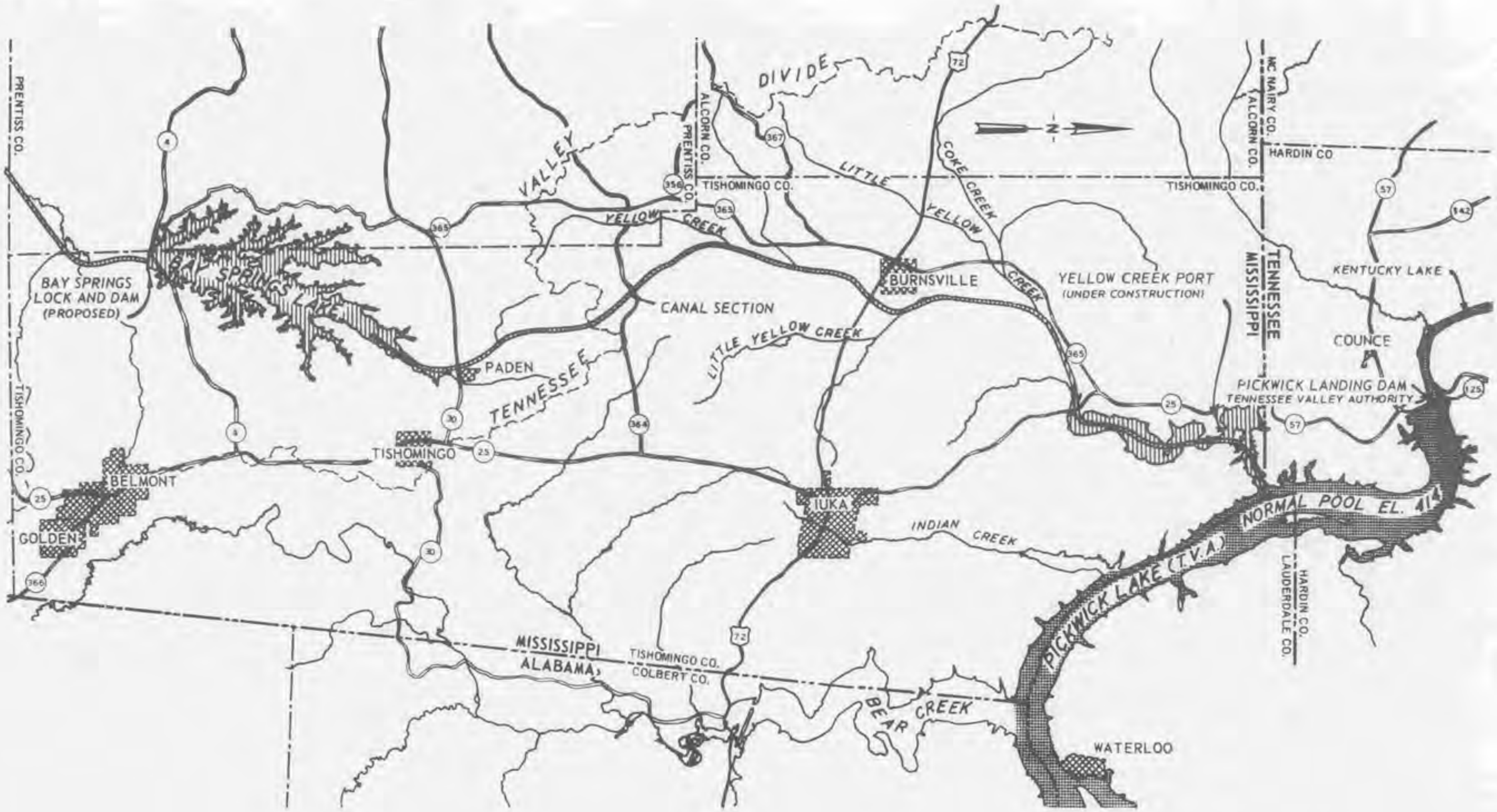

Figure 3. Location map of Bay Springs project

undistorted, 1:80-scale physical model was used to define the steady-state withdrawal characteristics of the Bay Springs Lock intakes and local topography. Because of size and cost limitations, a highly distorted-scale physical model (1:2400 horizontal, 1:80 vertical) was used to simulate Bay Springs Lake, the divide-cut canal, and the Yellow Creek embayment of Pickwick Lake. This model was used to determine the response of the proposed Bay Springs Lake to dynamic, unsteady state, density-stratified flow conditions. A mathematical model, entitled WESTEX, was used to simulate daily variations in the temperature and DO regimes within and released from the lake.

PART II: PHYSICAL MODELS

Lock Intakes Model

Purpose

The purpose of the undistorted, 1:80-scale physical model was to aid in determining the steady-state withdrawal characteristics of the lock intakes. This information was required to determine whether the withdrawal characteristics would be controlled by the geometry of the lock intakes or by the upstream approach topography. It was necessary to verify whether flow patterns resulting in the model could be predicted from the WES Generalized Selective Withdrawal Techniques[2] in order to evaluate the adequacy of the existing predictive technique. The withdrawal characteristics of the undistorted physical model were also needed to assess the adequacy of the highly distorted model to reproduce similar flow patterns when operated in a steady-state mode.

Scale relations

The accepted equations of hydraulic similitude based on Froudian criteria and the densimetric Froude number were used to express the mathematical relations between dimensions and hydraulic quantities of the model and prototype. The general relations for transfer of model data to prototype equivalents are as follows:

Dimension	Ratio	Scale Relation
Length	$L_r = L_m/L_p$	1:80
Velocity	$V_r = L_r^{1/2}$	1:8.94
Time	$T_r = L_r^{1/2}$	1:8.94
Discharge	$Q_r = L_r^{5/2}$	1:57,243
Density difference	$\Delta\rho_r = 1$	1:1

Measurements of flow and water-surface elevations can be transferred quantitatively from model to prototype dimensions with these relations.

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[2] Bohan, J. P. and Grace, J. L., Jr., "Selective Withdrawal from Man-Made Lakes; Hydraulic Laboratory Investigation," Technical Report H-73-4, Mar 1973, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Description

The undistorted, 1:80-scale physical model reproduced the lock intakes in the upstream guide walls and local topography of the upstream approach (Figure 4). The lock intakes and walls were constructed of transparent plastic to permit visual and photographic observation of the withdrawal patterns induced in the approach by steady-state releases. Flow through the simulated culverts was controlled with hand-operated slide gates. Topography just upstream of the lock was simulated with plywood surfaces.

Density stratification was created by placing fresh water over saline water by means of an overflow weir, the crest elevation of which could be varied. Density differences comparable with those anticipated in nature were reproduced in the model.

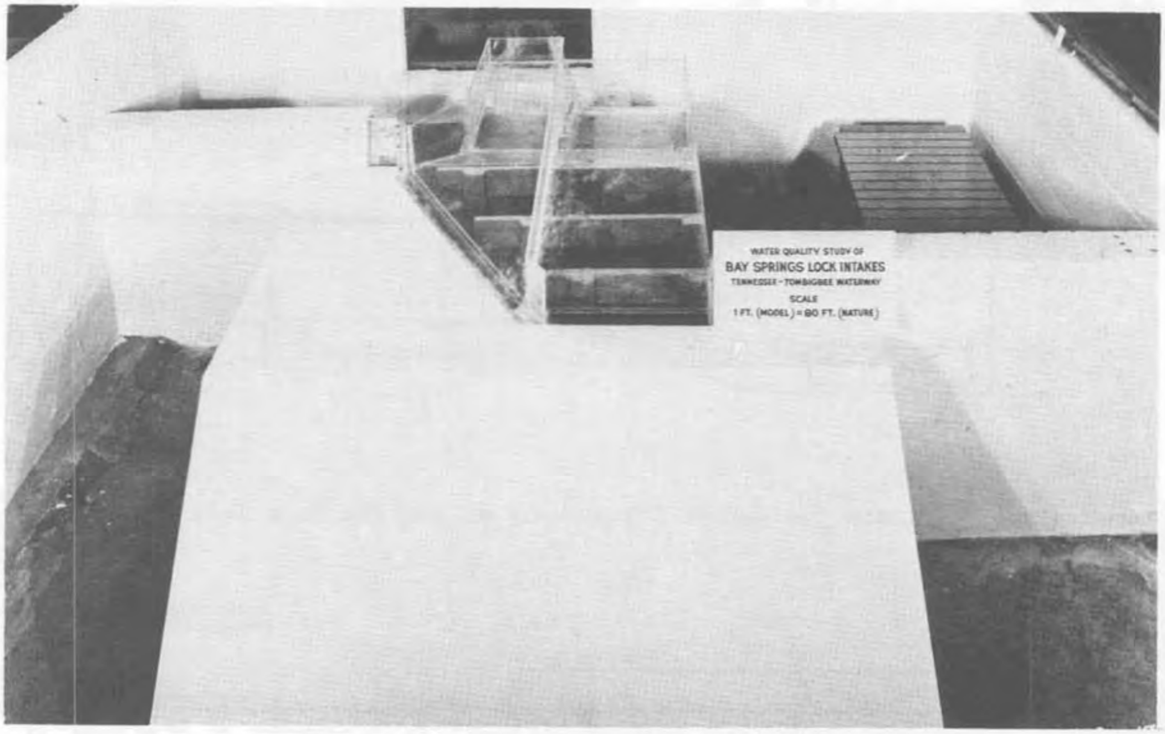
The density structure was determined from temperature and conductivity data obtained with probes that traversed the vertical direction. Photographic techniques and visual observations of dye streaks were used to record the withdrawal characteristics of the intakes.

Results

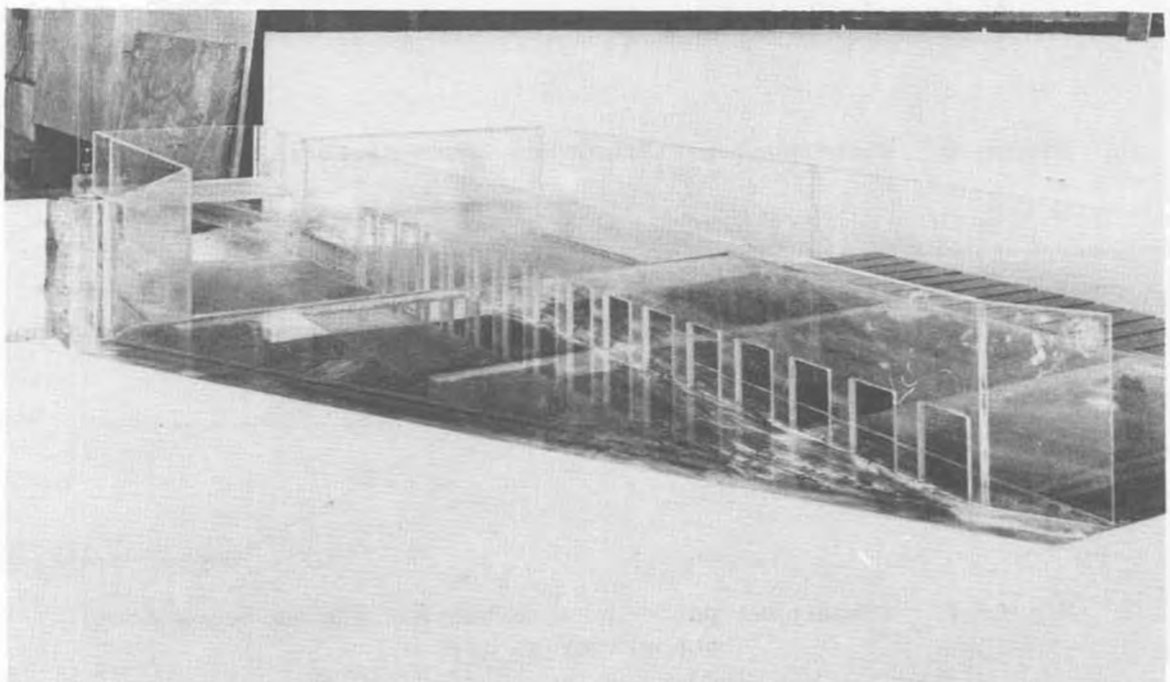
As previously stated, this model was used to define the withdrawal characteristics of the lock intakes including the approach topography. This was achieved by observing the withdrawal pattern in the model when flow was released through the lock in a steady state. Withdrawal patterns were determined for various flow rates up to approximately 16,000 cfs prototype. Each flow rate was tested under different stratification conditions with the thermocline located at various depths in the model.

It was determined that the withdrawal pattern was controlled by the elevated topography upstream of the lock intakes (Figure 5). The elevated topography acted as a submerged weir and controlled the vertical extent of the withdrawal zone. When the thermocline (simulated by the freshwater/saltwater interface) was located above the elevated topography, the lower limit of withdrawal extended to the lake bottom (Figure 6). When the interface was below the elevated topography, only epilimnial water was withdrawn (Figure 7). Two elevations of topography upstream of the lock intake were tested, 373 and 384 ft. Withdrawal characteristics were controlled by the elevated topography in both cases.

It was necessary to determine if the existing technique[2] for predicting withdrawal characteristics of intake structures would be applicable to this situation. Initial and final density profiles determined with conductivity and temperature probes and discharge rates were used for data input to the WES Generalized Selective Withdrawal Technique.[2] The vertical limits of withdrawal observed in the model were compared with those predicted by the WES technique for comparable conditions. It was determined that modifications to the technique were unnecessary since good agreement was obtained between the predicted and observed withdrawal patterns.



a. Approach topography



b. Lock intake in guide wall

Figure 4. 1:80-scale model of lock intake and approach topography

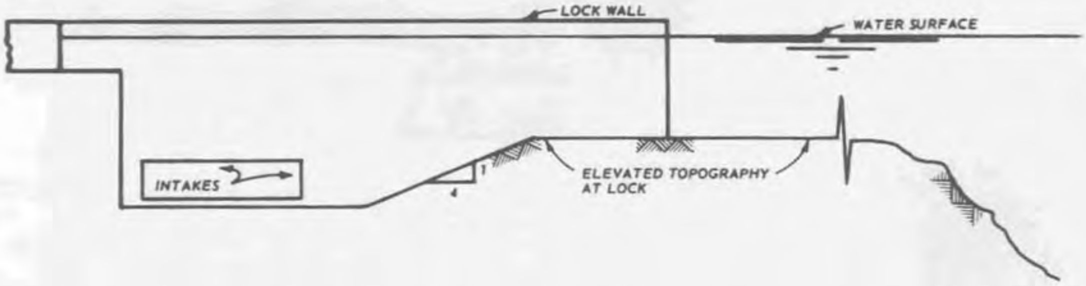


Figure 5. Local topography at Bay Springs lock

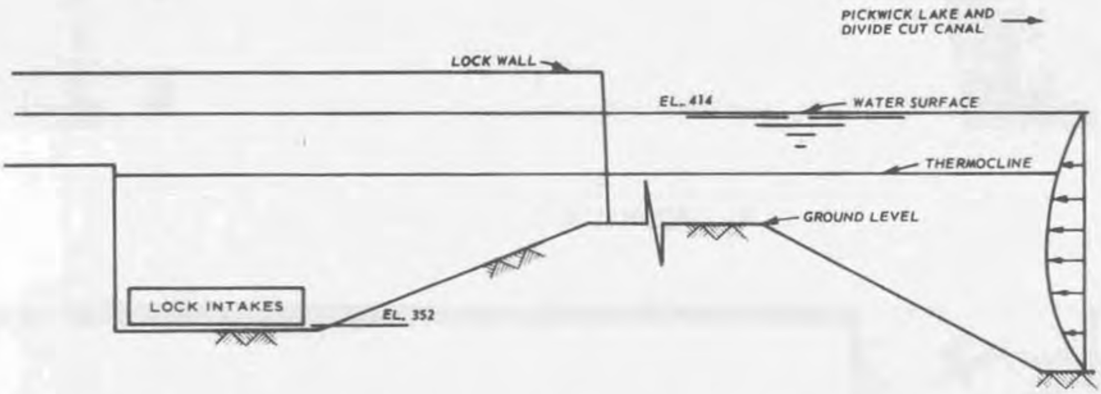


Figure 6. Withdrawal patterns when thermocline is high in pool

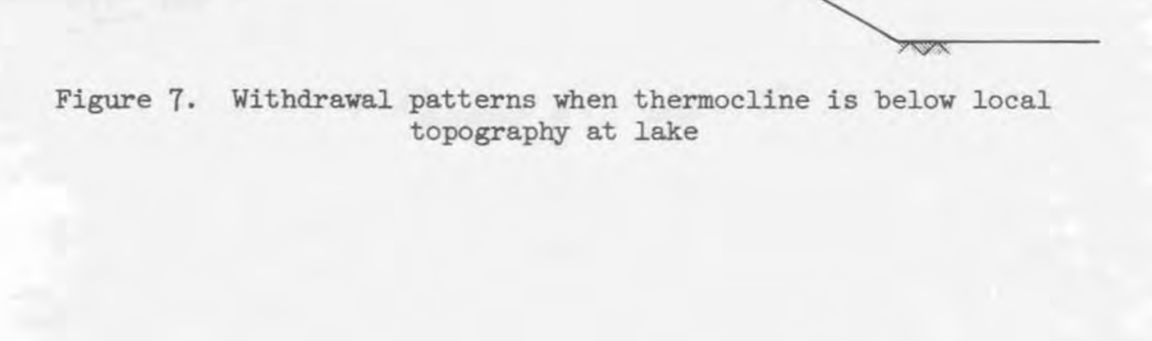


Figure 7. Withdrawal patterns when thermocline is below local topography at lake

Lake Hydrodynamic Model

Purpose

The purpose of the distorted scale model was to aid in defining the hydrodynamics of Bay Springs Lake resulting from unsteady and dynamic operating conditions representative of the prototype. The currents that developed in the model of Bay Springs Lake due to normal operation of the system were defined and used in subsequent numerical simulations. The hydrodynamic model was also used to determine the time required for water to travel from the point of inflow to the lake to the point of release downstream. The travel time is required to estimate the depletion in the DO content of the inflow as it passes through the lake.

Scale relations

The accepted equations of hydraulic similitude based on the Froudian criteria were also used to express the mathematical relations between dimensions and hydraulic quantities of the model and prototype. The general relations for transfer of distorted-scale model data to prototype equivalents are as follows:

Dimension	Ratio	Scale Relation
Length in vertical direction	$L_r = L_y$	1:80
Length in horizontal direction	$L_r = L_x$	1:2400
Area in a vertical plane	$A_r = L_x L_y$	1:192,000
Area in a horizontal plane	$A_r = L_x^2$	1:5,760,000
Time	$T_x = L_x / L_y^{1/2}$	1:268
Discharge	$Q_r = L_x L_y^{3/2}$	1:1,716,480
Density differences	$\Delta\rho_r = L$	1:1

Measurements of water-surface elevations, entrainment, and travel time can be transferred quantitatively from the model to the prototype by means of the scale relations above.

Description

The hydrodynamic model was a highly distorted scale (1:2400H, 1:80V) physical simulation of the Bay Springs Lake divide-cut canal including four major inflows along the canal, and the Yellow Creek embayment on Pickwick Lake. The entire model was constructed of transparent plastic to facilitate photography and visual observations of flow patterns (Figure 8).

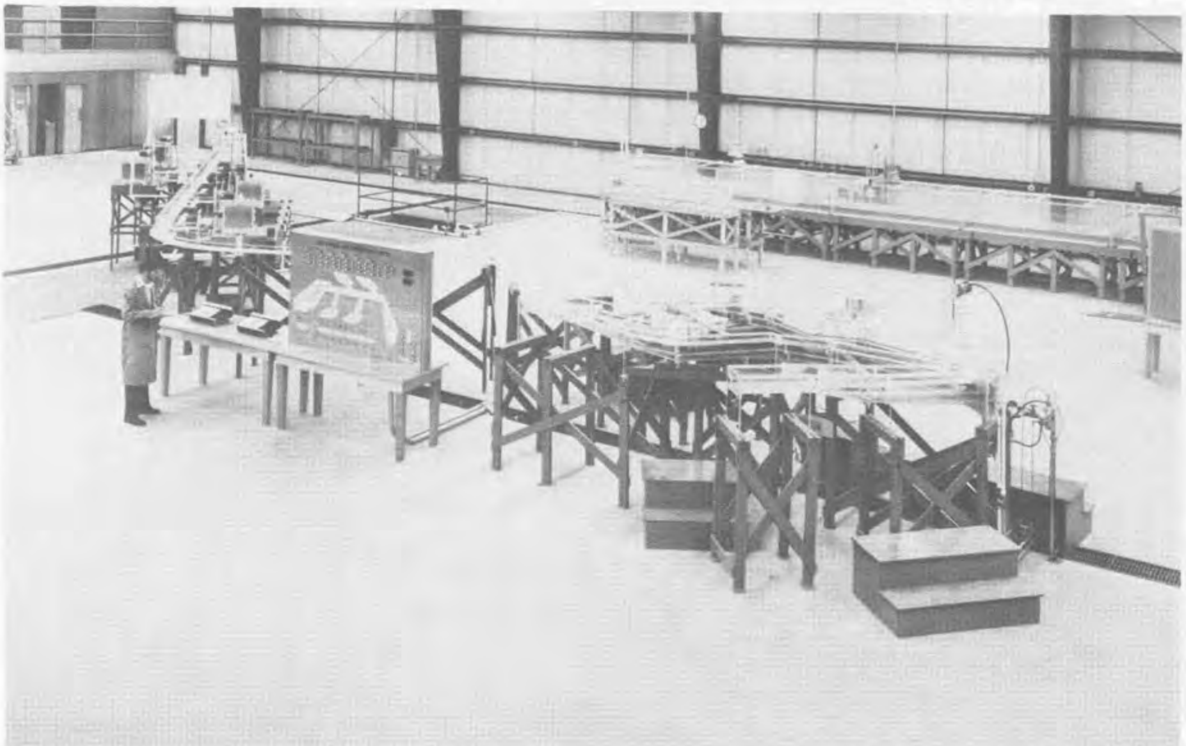


Figure 8. Bay Springs hydrodynamic model

The Bay Springs Lake portion of the model reproduced the geometry and the scaled elevation-storage relationship of the prototype lake. The anticipated density stratification was simulated using saline and fresh waters for the hypolimnion and epilimnion, respectively. The lock chamber was volumetrically simulated (Figure 9) and the lockage operation was reproduced by filling and emptying the lock chamber periodically to reproduce the expected lockage rates varying from 5 to 24 lockages per day.

The divide-cut canal was simulated along with four major creeks that flow into the canal.

A short portion of Pickwick Lake was simulated by reproducing the Yellow Creek embayment.

Figure 9. Simulated lock chamber

Results

Hydrodynamics

The steady-state withdrawal patterns occurring in the highly distorted scale hydrodynamic model were compared with those observed in the undistorted lock intakes model and those predicted by the WES Generalized Selective Withdrawal Technique,[2] "SELECT," and were found to be unsatisfactory. The geometry of the upstream lock approach in the hydrodynamic model was modified such that the steady-state withdrawal patterns matched those produced in the undistorted lock intakes model and those predicted by "SELECT."

The purpose of the hydrodynamic model was to determine the response of Bay Springs Lake to the expected normal dynamic operation of the prototype and mathematically describe the results for use in the numerical model WESTEX. Data from the study year 1969 and three forecasted lockage rates (5, 12, and 24 lockages per day) were used as input to the hydrodynamic model for daily operation. Under this dynamic mode, an upstream circulation current developed in the upper layers of the hypolimnion (Figure 10). This current was attributed

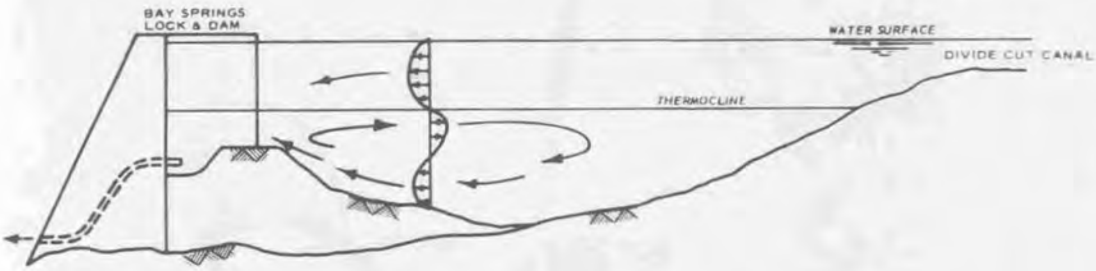


Figure 10. Upstream circulation current in upper layer of the hypolimnion

to water rebounding off the Bay Springs Dam at the completion of each lockage.

Travel time

Travel time was recorded from tests in the hydrodynamic model and subsequently related to inflow and outflow. It was determined that the time of travel for flow entering the lake any particular day was inversely proportional to the inflow and outflow conditions of approximately 10 succeeding days.

PART III: MATHEMATICAL MODEL

Description

As previously mentioned, the numerical simulation model WESTEX was used to predict the downstream release characteristics and the internal structures of temperature and DO for Bay Springs Lake. The computer model was developed at WES based upon results of Clay and Fruh,[3] Edinger and Geyer,[4] Dake and Harleman,[5] and others.

The previously discussed results from tests of the two physical models were incorporated into the WESTEX model to account for the unique features and unusual conditions in the Bay Springs project. A simplified flow chart of the WESTEX simulation procedure is shown in Figure 11.

Fundamental assumptions

The WESTEX model provides a procedure for examining the balance of thermal energy imposed on an impoundment. This energy balance and lake hydrodynamic phenomena are used to map vertical profiles of temperature and DO in the time domain. The model includes computational methods for simulating heat transfer at the air-water interface, advective heat due to inflow and outflow, and the internal dispersion 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 discrete layer is isotropic and physically homogeneous.
- c. Internal advection and heat transfer occur in the vertical direction only.

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[3] Clay, H. M., Jr., and Fruh, E. G., "Selective Withdrawal at Lake Livingston; and Impoundment Water Quality Emphasizing Selective Withdrawal," Progress Report EHE 70-18 (CRWR 66), Nov 1970, Environmental Health Engineering Research Laboratory, University of Texas, Austin, Texas.

[4] Edinger, J. E. and Geyer, J. C., "Heat Exchange in the Environment," Publication No. 65-902, Jun 1965, Edison Electric Institute, New York, N. Y.

[5] Dake, J. M. K. and Harleman, D. R. F., "An Analytical and Experimental Investigation of Thermal Stratification in Lakes and Ponds," Technical Report No. 99, Sep 1966, Massachusetts Institute of Technology Hydrodynamics Laboratory, Cambridge, Mass.

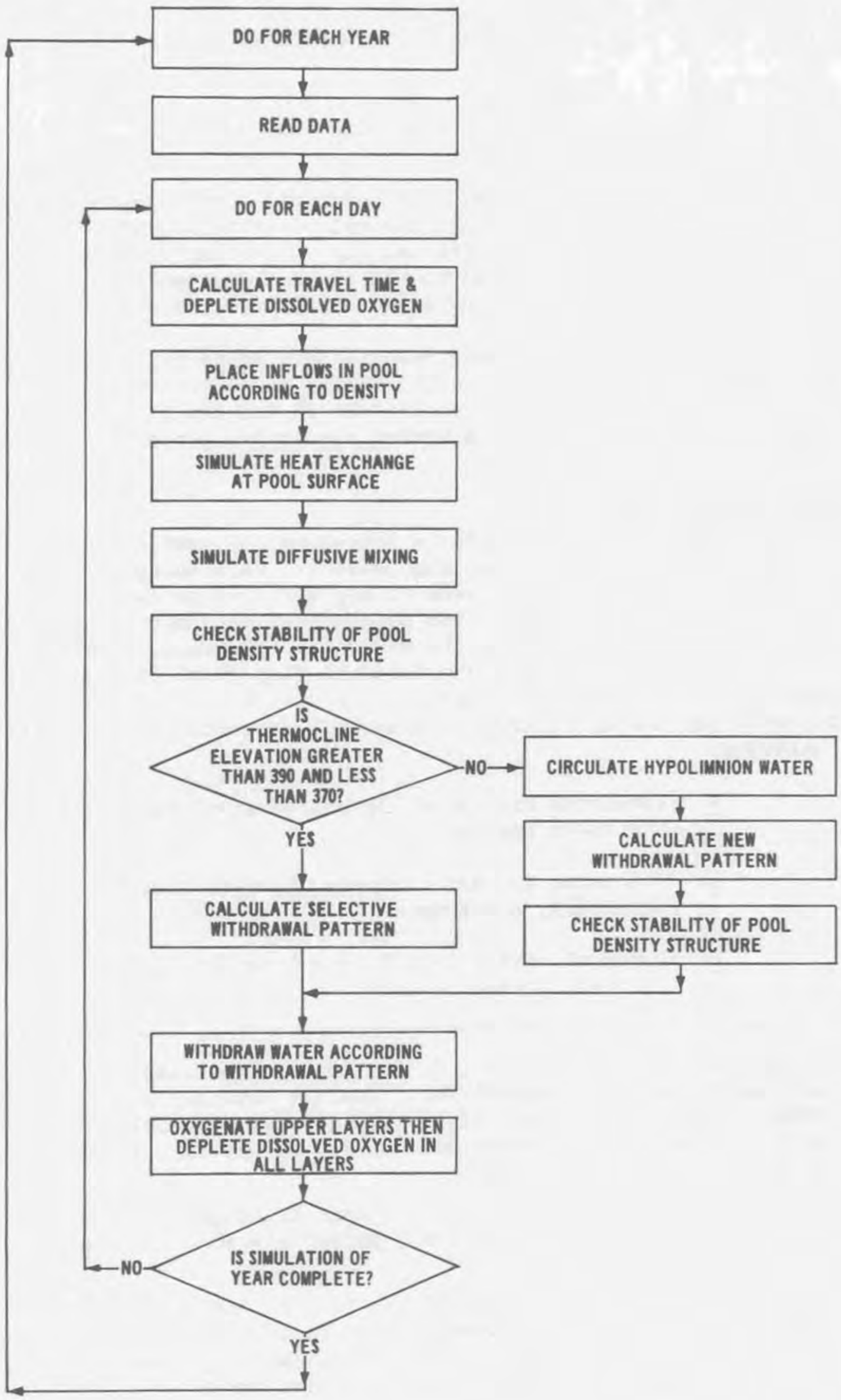


Figure 11. Schematic of WESTEX operation

d. External advection occurs as a uniform horizontal distribution within each layer.

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

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

Desired Release Temperature

A least-squares analysis was used to fit sine curves to each of the seven years of computed stream temperatures. The coefficients of the seven equations were arithmetically averaged resulting in an equation of the general form described by Equation 1.

$$\phi = A \sin (Bt + C) + D \tag{1}$$

where

ϕ = temperature on Julian day t, °F

A,B,C, and D = coefficients of the sine curve

t = Julian day

This equation defined the desired temperature of water to be released through the Bay Springs Lock.

Additionally, the seven years of computed local stream temperatures was scanned for the maximum temperature experienced for each day of the year. These 365 maximum temperatures were fitted with a sine curve of the same basic form as Equation 1. A similar curve was determined for the minimum temperatures expected each day of the year over the seven study years. These curves of maximum and minimum computed local stream temperatures indicate the natural stream temperatures variation from the smooth harmonic used as the desired release temperature. The maximum and minumum stream temperatures (sine curves discussed above) are plotted and labeled the "Objective Temperature Band".

PART IV: RESULTS

Implementing the modifications indicated by the physical models, WESTEX simulated the seven study years for two different local lock topography elevations and three lockage rates. As discussed earlier, the elevations examined were 373 and 384 ft. The lockage rates simulated were 5, 12, and 24 lockages per day.

Lock topography elevation 373 ft

The computed release temperature and DO for 1969 and the three lockage rates are shown in Plate 1. Under all three lockage rates, the release temperature is very close to or below the lower curve of the objective temperature band from the early spring up to midyear. The predicted release temperature then crosses the band and climbs to its peak above the upper curve in August-September. Then with the cooling of the fall months, the release temperature drops down into the desired range.

The computed release DO for 1969, which does not include any reaeration in the lock discharge outlet basin, stays above the required content of 5 mg/ℓ except in the July-August period under the conditions of 5 and 12 lockages per day. With 24 lockages per day, the release DO is always above the minimum desired level throughout the year.

Plates 2-4 show the expected seasonal variation of the temperature and DO structure within Bay Springs Lake. The temperature and DO profiles are essentially constant in the early spring at 9°C and 12 mg/ℓ, respectively. Under the influence of meteorological conditions and warm inflow, the temperature increases at the surface. The expected DO content, as affected by oxygen depletion, is slowly depleted in the lower layers of the lake. Under all the lockage rates simulated, the DO content is depleted to zero by the end of August in the lower levels of the lake. The DO in the lower levels begins to increase as the surface water cools and the lake becomes more isothermal.

Similar results were obtained for the remaining six study years.

Lock topography elevation 384 ft

The computed release temperature and DO for 1969 under the three lockage rates are shown in Plate 5. In each of the three conditions, the spring and early summer release temperatures are in the lower half of the objective temperature range. In late summer, the release temperature exceeds the upper curve of desired temperature band reaching a peak in the August-September period.

Without including reaeration in the outlet basin, the predicted release DO is always above the desired minimum of 5 mg/ℓ for all three lockage rates. Plates 6-8 show the temperature and DO structure of Bay Springs Lake on an end-of-month basis for the period of simulation in 1969. With the local lock topography at el 384, the DO is depleted to zero by late August in the lower layers of the lake.

Similar results for the remaining study years were obtained in the simulations.

PART V: DISCUSSION

In examining the predicted release temperatures for 1969 (Plate 1 or Plate 5), it can be seen that the release temperature curve is shifted upward as the lockage rate increases; the same is true for the predicted DO in releases. This trend can be attributed to the increased quantity of flow through the lake with the increased number of lockages. Similar results were obtained for all study years and conditions simulated.

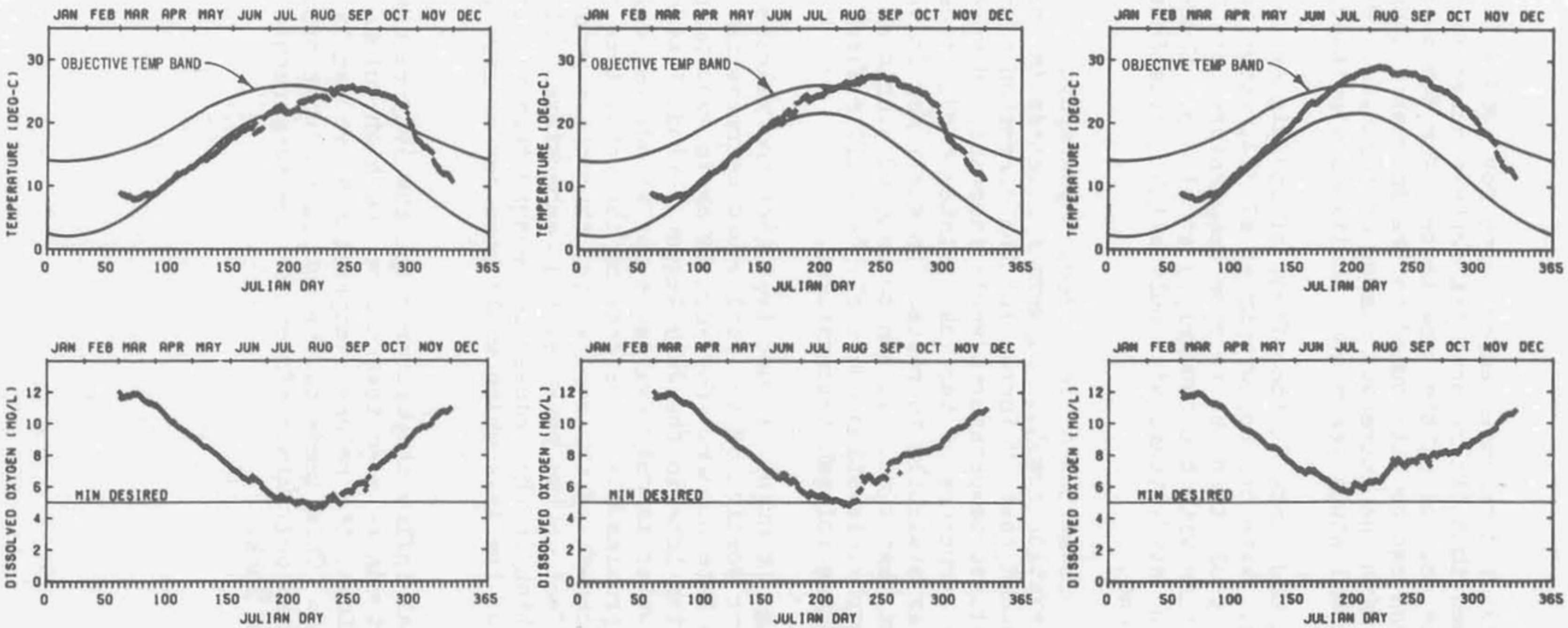
By comparing Plate 1 and Plate 5, the effect of the higher lock topography is discernible. With the topography at el 384, water is released from higher in the pool, thus the release temperatures are 1° to 2°C higher in the spring than with the topography at el 373. These trends are true for all the study years with only slight variations due to meteorological conditions.

By comparing the two elevations of local lock topography, it is observed that the higher elevation resulted in warmer releases in the spring. It could therefore be deduced that by increasing the elevation of the local lock topography, spring release temperatures would increase. However, by examining the temperature structure of the lake (Plates 6-8), it can be seen that the warmest water available to release in early May is very near the release temperature at that time. It can be concluded that an increase in the lock topography elevation above el 384 would reflect only minor increases in the spring release temperatures.

By the same reasoning, it might be conceived that the release of colder water from the lower portion of the pool would decrease the release temperatures in the late summer. However, by again examining the temperature structure of the lake in the July-August period (Plates 6-8), it can be seen that cool water is only available for withdrawal below el 375. There is only approximately 10 percent of the total lake volume, or approximately 23,000 acre-ft of the cool water, thus there would only be a short-term, minor effect on the peak release temperature. Also, there would be an adverse reduction in the release DO because this withdrawal is from the lower layers of the lake which would have low or zero DO content.

By comparing the canal inflow temperatures and the 1969 release temperatures (Plate 9), it can be seen that due to the high volume of flow through Bay Springs Lake, the release temperatures are nearly equal to the inflow temperatures. This leads to the conclusion that processes in the Bay Springs Lake have only minor effects on the temperature of water released through the lock.

PLATE 1



5 LOCKS PER DAY

12 LOCKS PER DAY

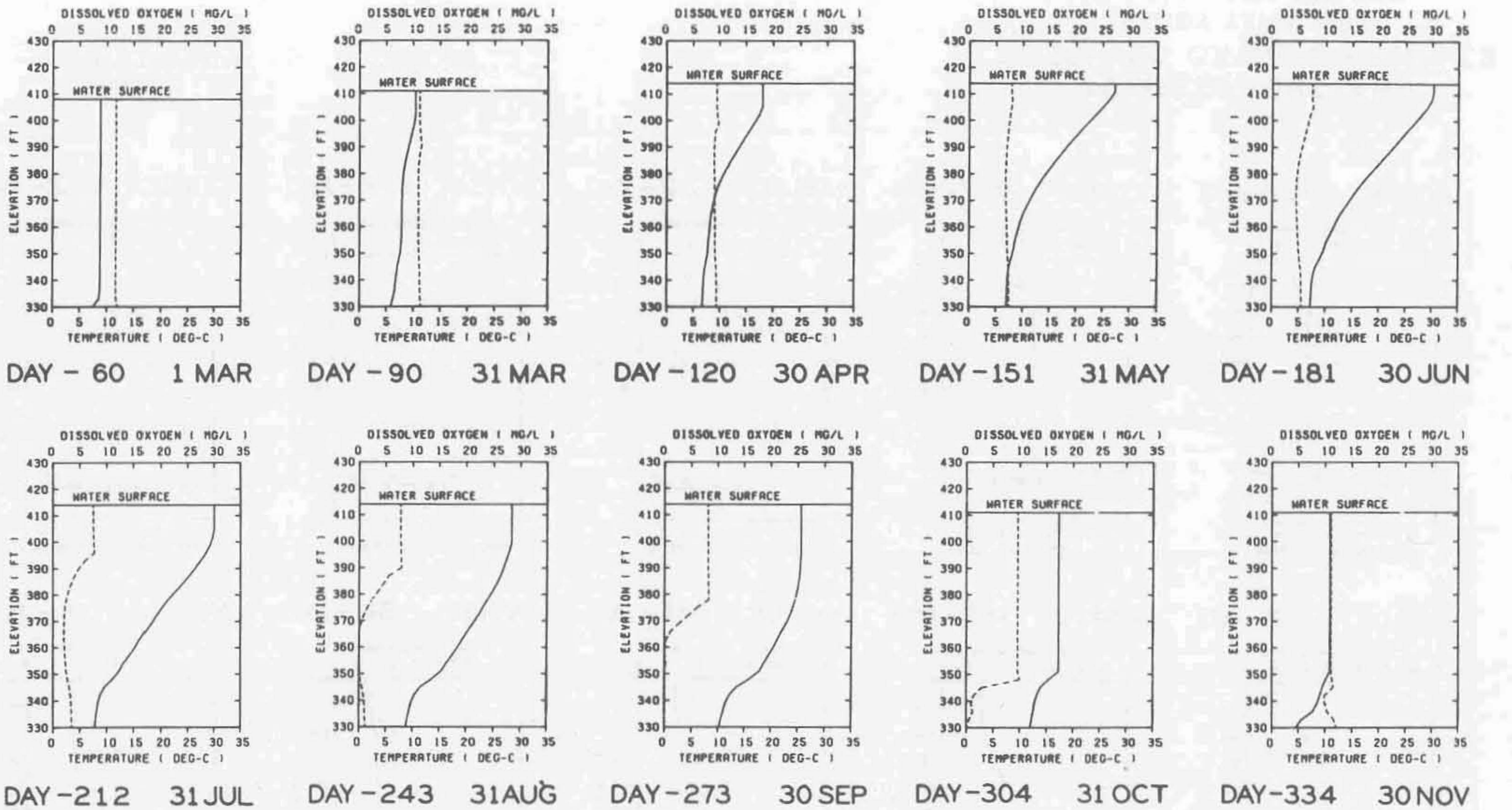
24 LOCKS PER DAY

BAY SPRINGS LAKE

COMPUTED RELEASE TEMPERATURE AND DISSOLVED OXYGEN

STUDY YEAR 1969

WIER EL 373.0 FT MSL



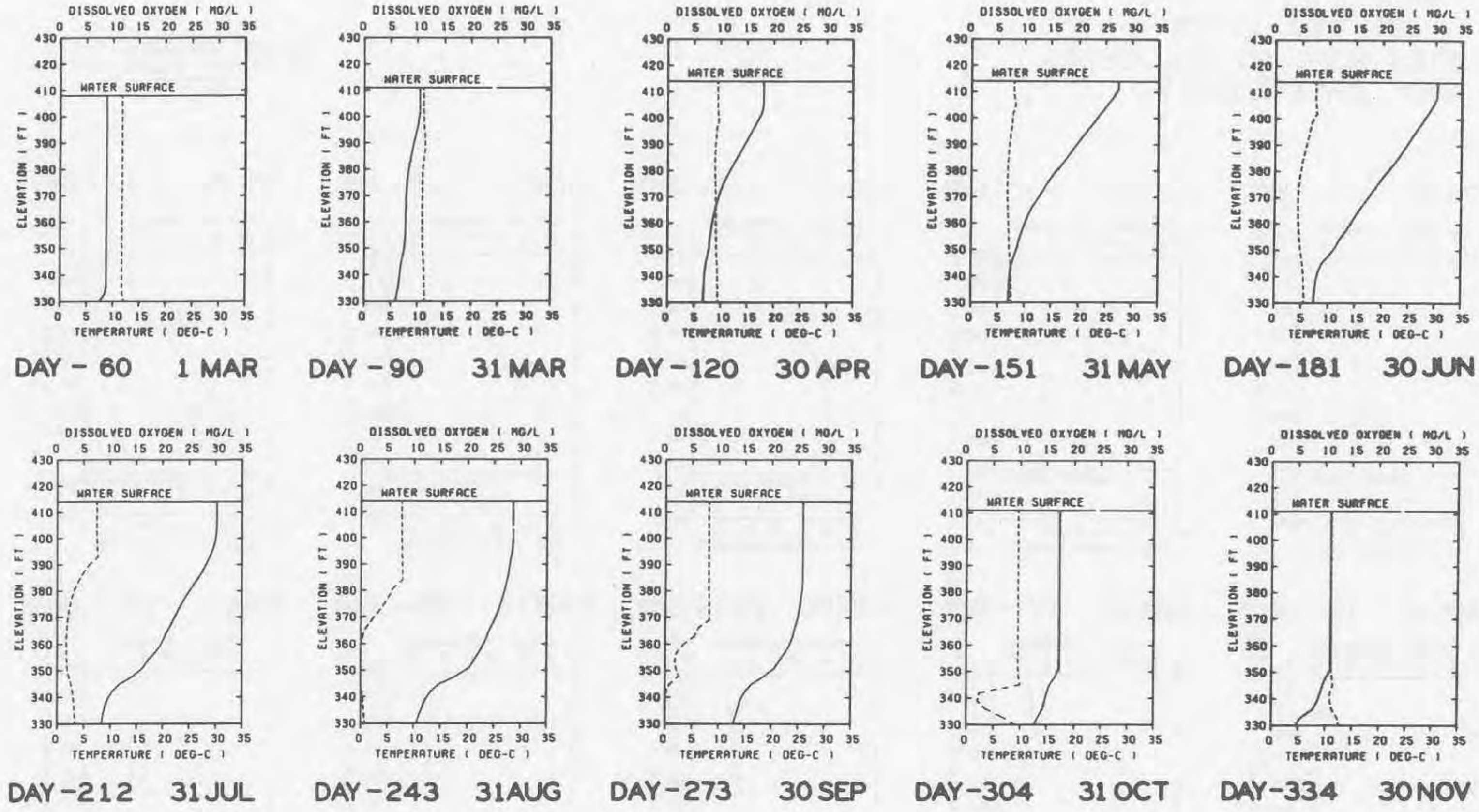
LEGEND

—— WATER TEMPRATURE
---- DISSOLVED OXYGEN

TEMPERATURE AND
DISSOLVED OXYGEN PROFILES
STUDY YEAR 1969
5 LOCKAGES PER DAY
WIER EL 373.0 FT MSL

PLATE 2

PLATE 3



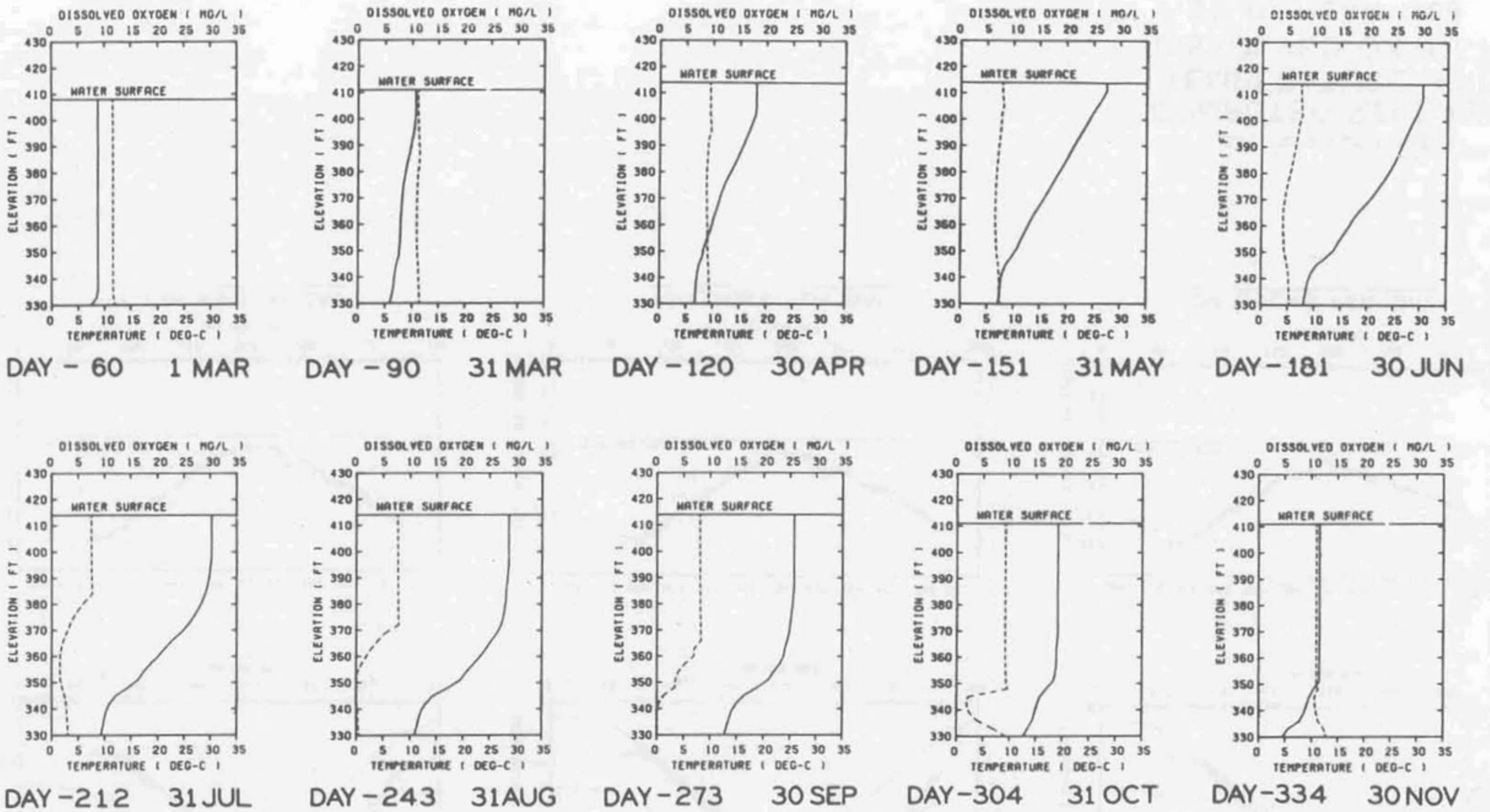
LEGEND

—— WATER TEMPRATURE

---- DISSOLVED OXYGEN

TEMPERATURE AND
DISSOLVED OXYGEN PROFILES
STUDY YEAR 1969
12 LOCKAGES PER DAY
WIER EL 373.0 FT MSL

PLATE 4



LEGEND

—— WATER TEMPRATURE

- - - - DISSOLVED OXYGEN

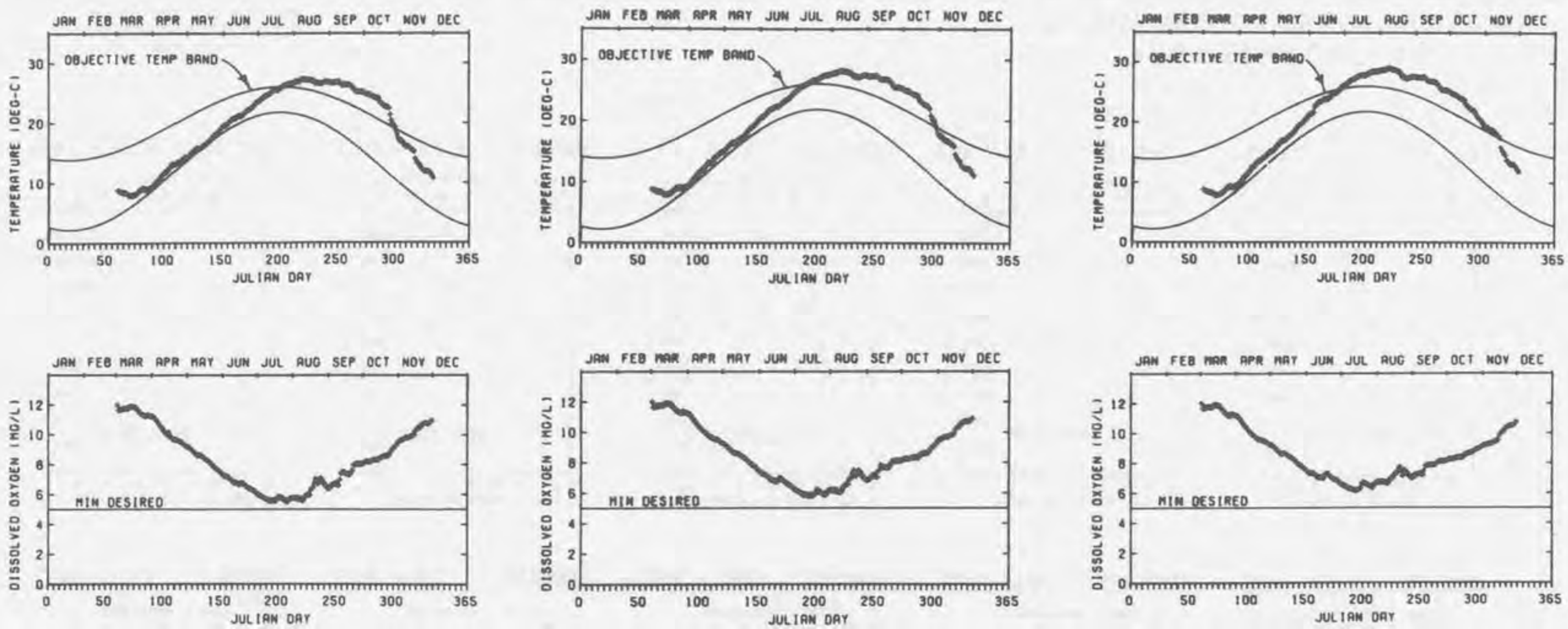
TEMPERATURE AND DISSOLVED OXYGEN PROFILES

STUDY YEAR 1969

24 LOCKAGES PER DAY

WIER EL 373.0 FT MSL

PLATE 5



5 LOCKS PER DAY | 12 LOCKS PER DAY | 24 LOCKS PER DAY

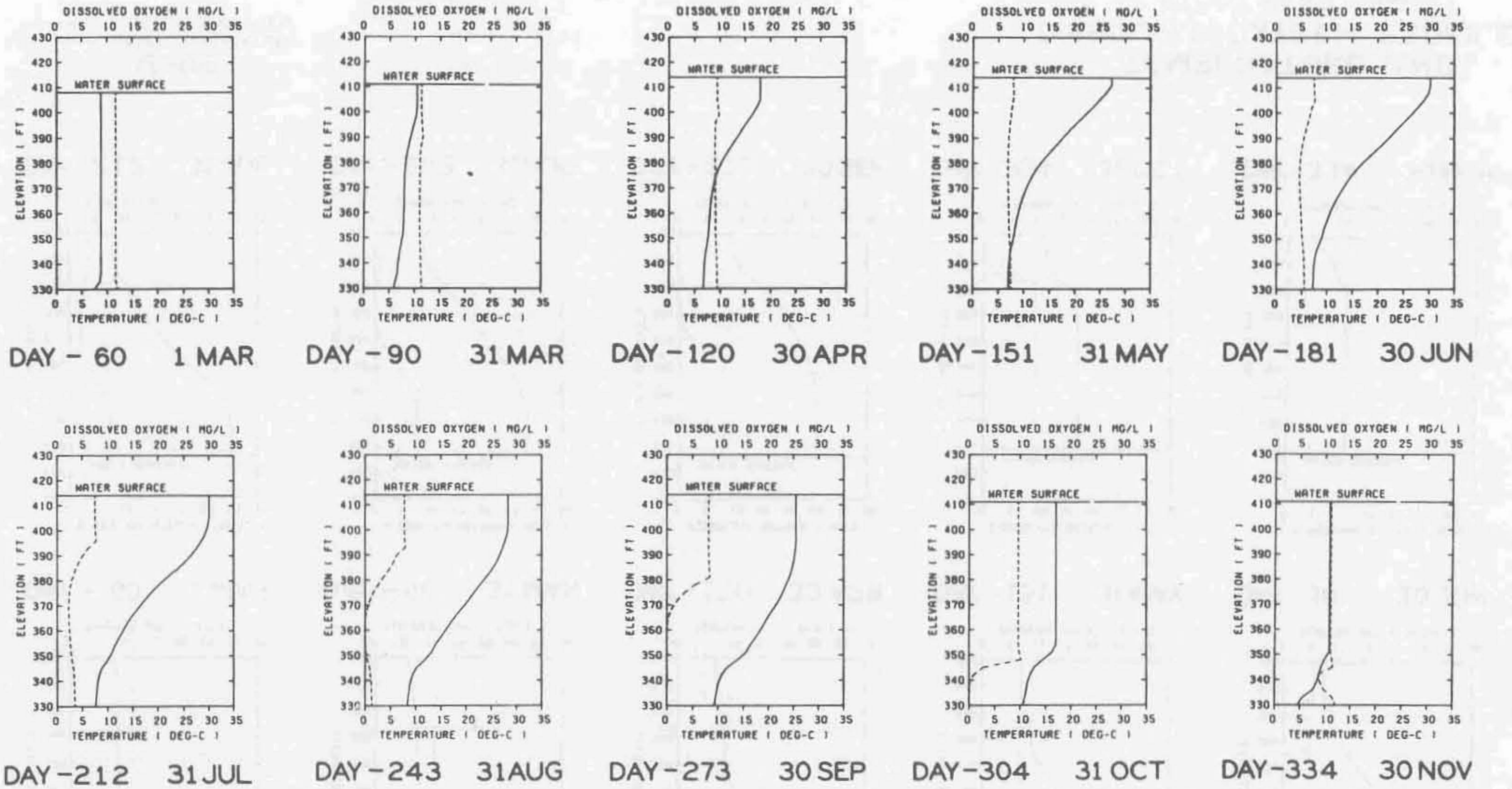
BAY SPRINGS LAKE

COMPUTED RELEASE TEMPERATURE AND DISSOLVED OXYGEN

STUDY YEAR 1969

WIER EL 384.0 FT MSL

PLATE 6

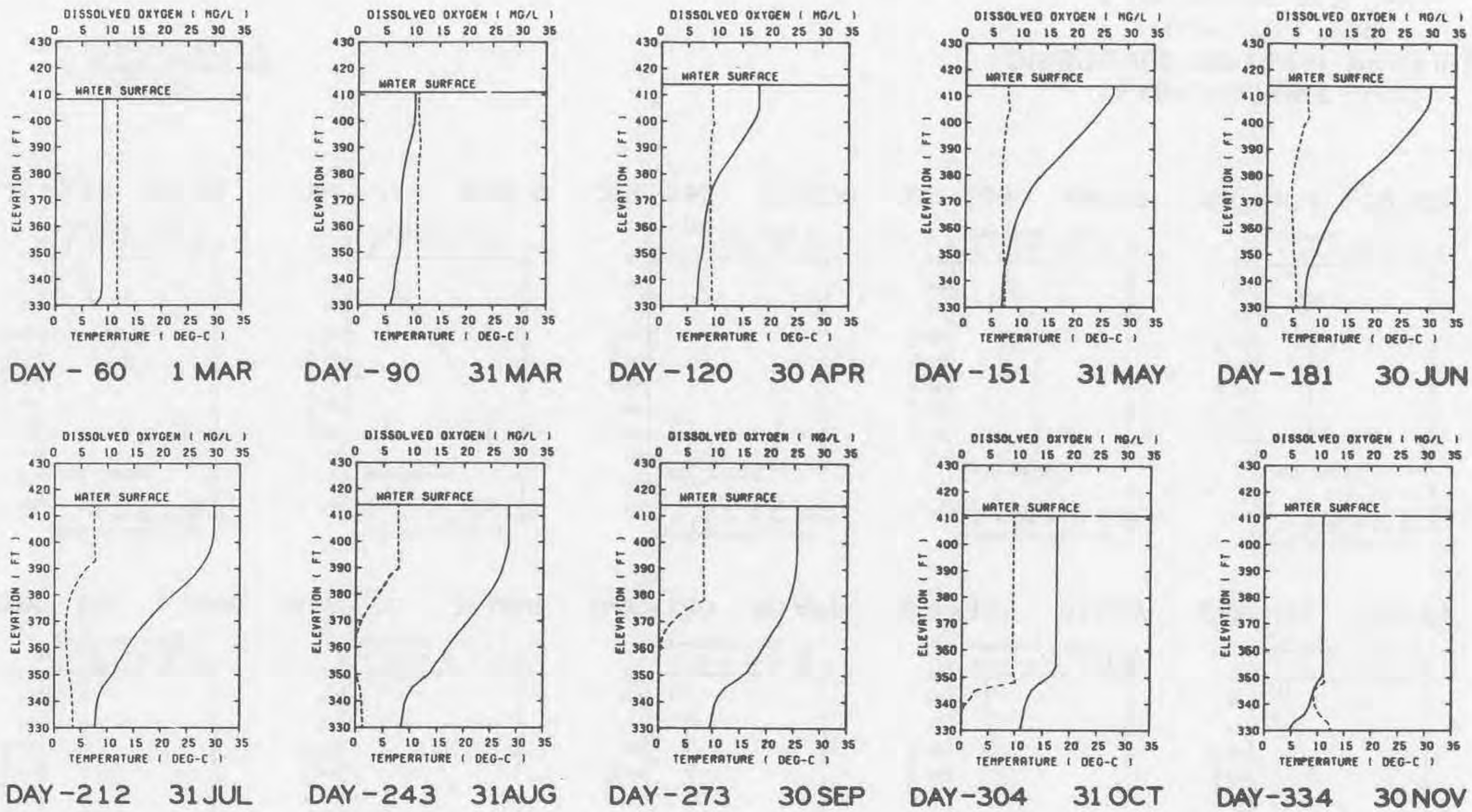


LEGEND

—— WATER TEMPRATURE
---- DISSOLVED OXYGEN

TEMPERATURE AND
DISSOLVED OXYGEN PROFILES
STUDY YEAR 1969
5 LOCKAGES PER DAY
WIER EL 384.0 FT MSL

PLATE 7



LEGEND

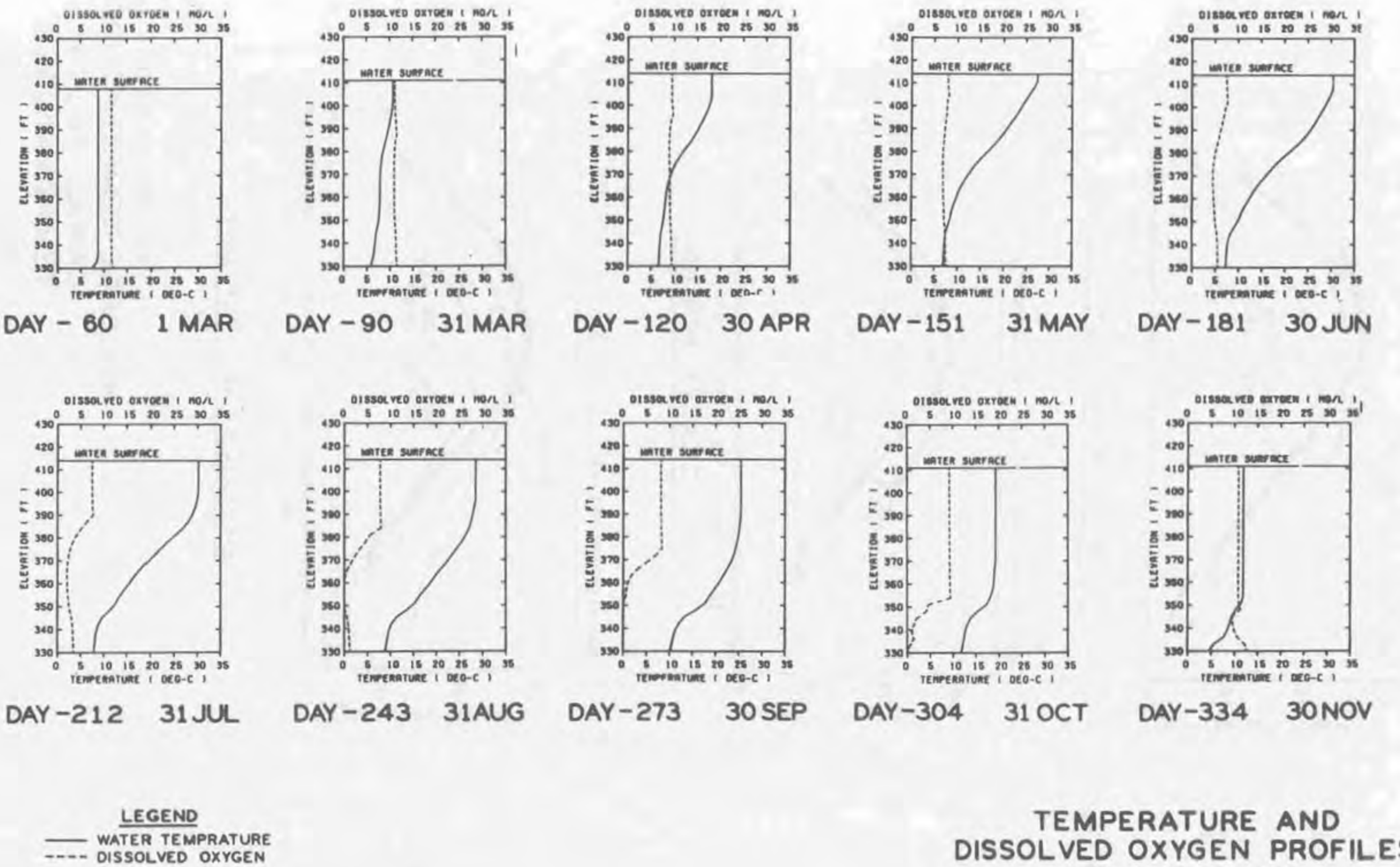
—— WATER TEMPRATURE
---- DISSOLVED OXYGEN

TEMPERATURE AND DISSOLVED OXYGEN PROFILES

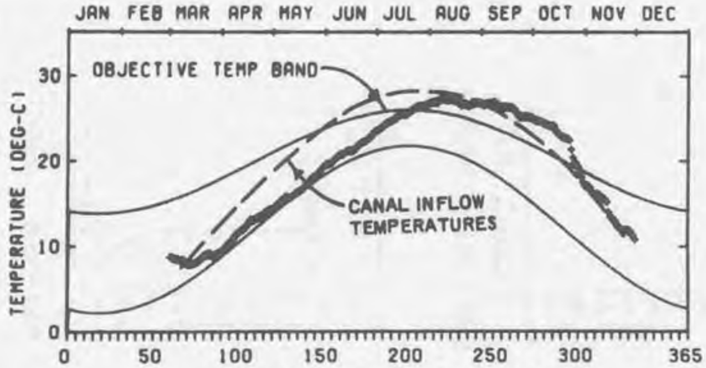
STUDY YEAR 1969

12 LOCKAGES PER DAY

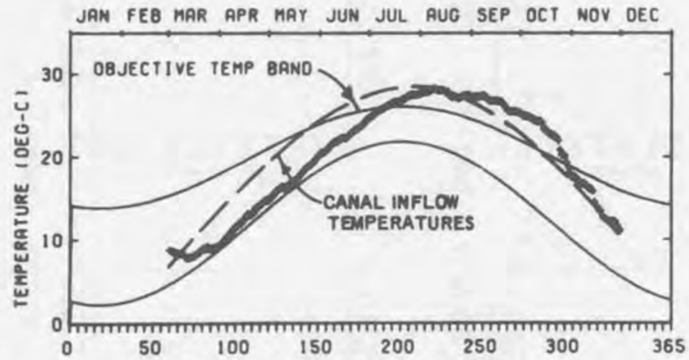
WIER EL 384.0 FT MSL



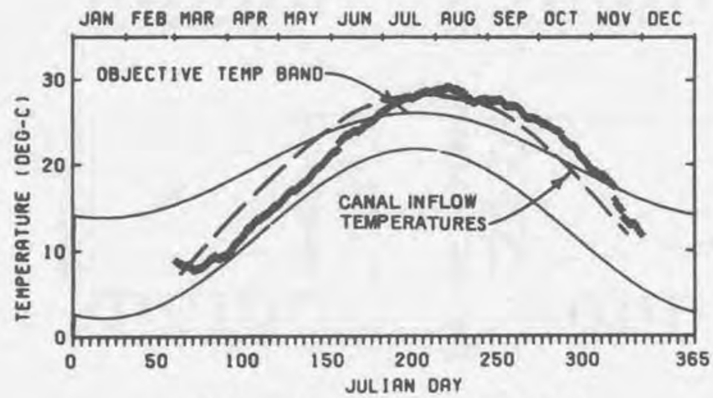
TEMPERATURE AND DISSOLVED OXYGEN PROFILES
STUDY YEAR 1969
24 LOCKAGES PER DAY
WIER EL 384.0 FT MSL



5-LOCKAGES PER DAY



12-LOCKAGES PER DAY



24-LOCKAGES PER DAY

BAY SPRINGS LAKE

RELEASE TEMPERATURES VS CANAL INFLOW TEMPERATURES

STUDY YEAR 1969

WIER EL 384.0 MSL