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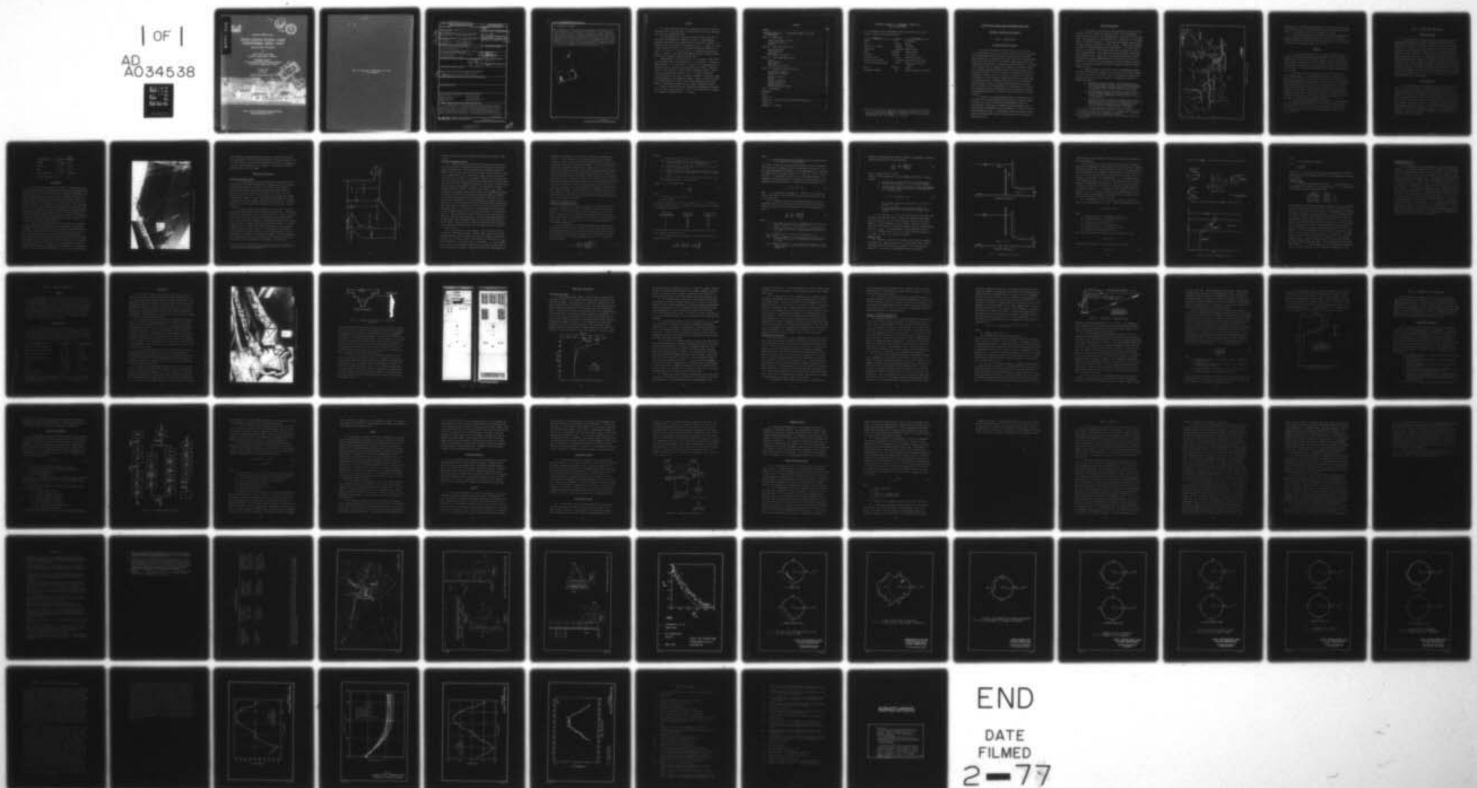

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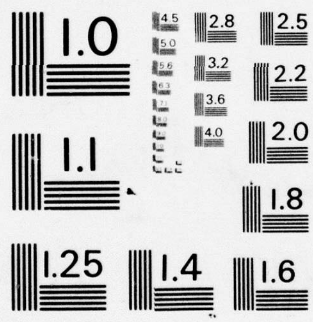

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DICKEY-LINCOLN SCHOOL LAKES HYDROTHERMAL MODEL STUDY

Hydraulic Laboratory Investigation

by

Mark S. Dortch, Bruce Loftis
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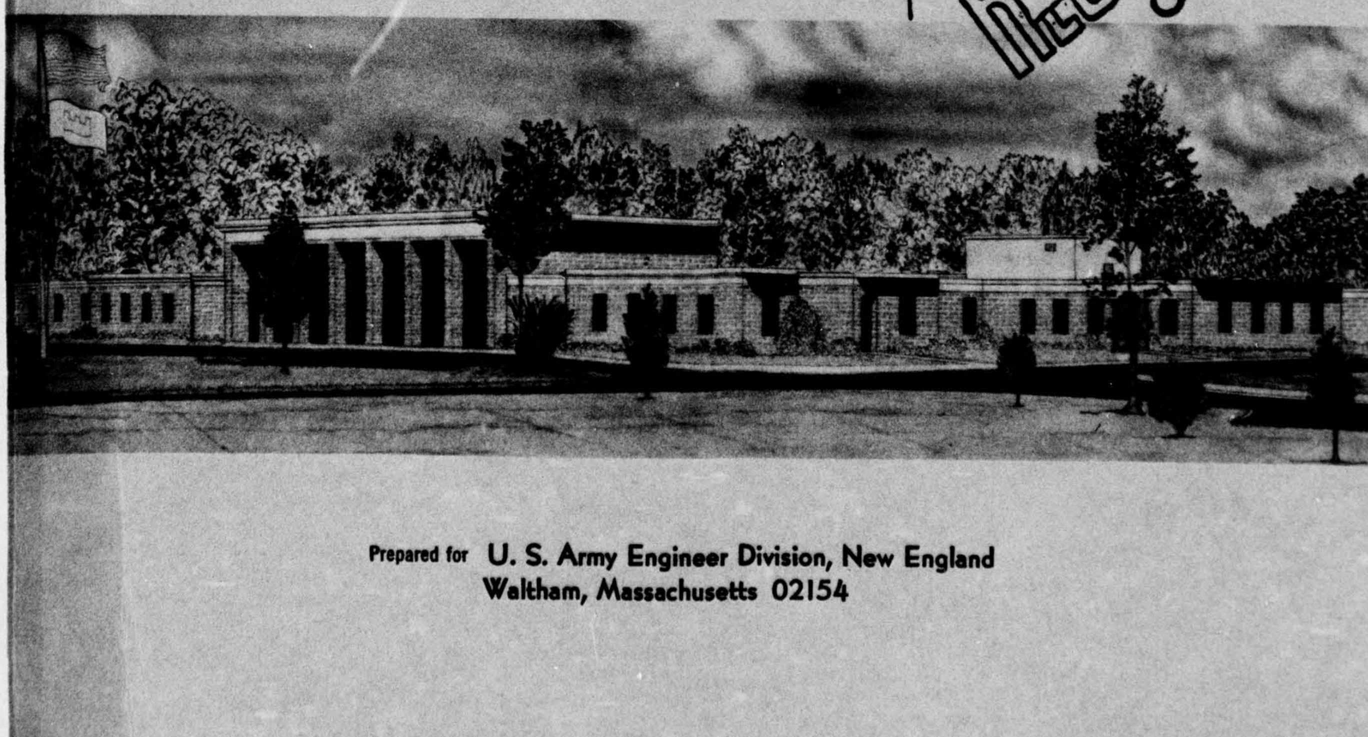
Final Report



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

A one-dimensional, vertically stratified, thermal simulation model was developed for prediction of temperature within and downstream from Dickey-Lincoln School Lakes. Two physical hydraulic models were used to obtain an improved understanding and description of the hydrodynamic response of the lakes to pumped-storage hydropower. An undistorted, 1:200-scale model of the Dickey Lake intake structures and local topography was used to determine

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20. ABSTRACT (Continued).

the steady-state selective withdrawal and pumpback flow characteristics for various conditions. A highly distorted-scale model (1:3600 horizontal, 1:180 vertical) was used to simulate the entire dual reservoir system and to determine the response to dynamic, unsteady-state, density stratified flow. Information from the two physical models was used to modify existing algorithms and to develop new algorithms for the mathematical model. The mathematical model allows simulation of the hydrodynamic and heat exchange characteristics so that the thermal regimes within and downstream from the two lakes can be determined for various hydrologic and meteorologic conditions and various pumped-storage hydropower operations.

PREFACE

The study reported herein was authorized by the Office, Chief of Engineers (OCE), on 22 May 1975, at the request of the U. S. Army Engineer Division, New England (NED).

The investigation was conducted during the period July 1975 to June 1976 in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and J. L. Grace, Jr., Chief of the Structures Division. The study was conducted by Messrs. M. S. Dortch, B. Loftis, D. G. Fontane, and S. C. Wilhelms with assistance from J. H. Riley. This report was prepared by Messrs. Dortch, Fontane, Loftis, and Wilhelms and reviewed by Mr. Grace.

Representatives of WES met with Mr. R. J. DiBuono of NED at WES during November 1975 and with Messrs. D. P. Buelow and R. J. DiBuono of NED and Messrs. E. E. Eiker and S. B. Powell of OCE during May 1976 to discuss the scope, objectives, and approach of the study. During the course of this study, Mr. Charles Wener of NED was detailed to WES to assist in physical model testing. Mr. D. P. Buelow of NED also visited WES during June 1976 to review the progress to date and to gain an understanding of the mathematical model. Messrs. Fontane and Loftis visited NED during July 1976 to deliver the mathematical model and assist in preparing the model for use in NED's computer facilities.

Directors of WES during this study and the preparation and publication of this report were COL G. H. Hilt, CE, and COL John L. Cannon, 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	25.4	millimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square feet	0.09290304	square metres
acres	4046.856	square metres
acre-feet	1233.482	cubic metres
feet per second	0.3048	metres per second
cubic feet per second	0.02831685	cubic metres per second
feet per second per second	0.3048	metres per second per second
Btu's	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: $K = (5/9)(F - 32) + 273.15$.

DICKEY-LINCOLN SCHOOL LAKES HYDROTHERMAL MODEL STUDY

Hydraulic Laboratory Investigation

PART I: INTRODUCTION

Purpose and Scope of Study

1. The overall objective of this study was to provide the U. S. Army Engineer Division, New England (NED), with an understanding of the hydrothermal processes unique to the Dickey-Lincoln School Lakes project and to incorporate these processes into a numerical simulation model that NED could use to predict temperatures within and downstream from the lakes for planning and design purposes. Initially, it was planned that the capability to simulate the dissolved oxygen (D.O.) regimes within and downstream from the lakes by means used in previous studies[1-4] would be included in the numerical simulation technique. However, because of the lack of adequate data relative to estimates of the total daily oxygen depletion rate in large lakes in this locality that is needed for application of the referenced technique and the lack of an adequate methodology for estimating the D.O. uptake in the reregulating pool, NED decided to use existing limnological analysis techniques and the limited data available for estimating far-field D.O. profiles required relative to fishery interests.

2. Because of the highly dynamic nature of operational characteristics of the proposed pumped-storage project, physical hydraulic models were used to determine the hydrodynamic response to various modes of operating the pumped-storage hydropower project. Physical model hydrodynamic input was necessary to develop a descriptive mathematical model. The mathematical model provided the capability for assessing the effect of historical data on the lakes for yearlong periods.

Project Description

3. The proposed Dickey-Lincoln School hydropower project would be located on the St. John River in northern Maine. The two damsites, Dickey and Lincoln School, are approximately 30 miles* west of Fort Kent, Maine. Dickey damsite is just upstream of the confluence of the Allagash and St. John Rivers (Figure 1). Dickey Lake would extend upstream about 45 miles, reaching into Quebec Province, Canada. Lincoln School damsite is about 11 miles downstream of the Dickey damsite. The lake would extend to the tailwater of the Dickey Dam and for a distance of 2 miles up the Allagash River. Both lakes would provide hydropower during peak power demand periods. Pumped flow from Lincoln School Lake to Dickey Lake during low energy demand periods is proposed for the project to maintain the Dickey pool, thus increasing the power production capabilities. The proposed pumpback would pass through the multiple penstock intake structure.

4. Dickey Dam would include two earth-fill embankments, termed the North and South Dams, separated by a rock hill on the right abutment of the St. John River. The outlet works and hydroelectric power plant would be located in this hill (Plate 1). The hydraulic features of Dickey Dam consist of:

a. Multipurpose intake structure, with selector gates to provide water-quality control, which discharges through a 30-ft-diam bifurcated conduit connected to one turbine in the powerhouse and to the flood control outlet works.

b. Multiple penstock intake structure, with selector gates, which discharges through three (authorized) to five (proposed) 27-ft-diam penstocks each connected to one unit in the powerhouse.

c. Powerhouse with four conventional (authorized) or three conventional and one reversible (proposed initial development) turbines with provisions for two additional reversible turbines (proposed ultimate development).

d. A converging chute spillway with crest el 910.**

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

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

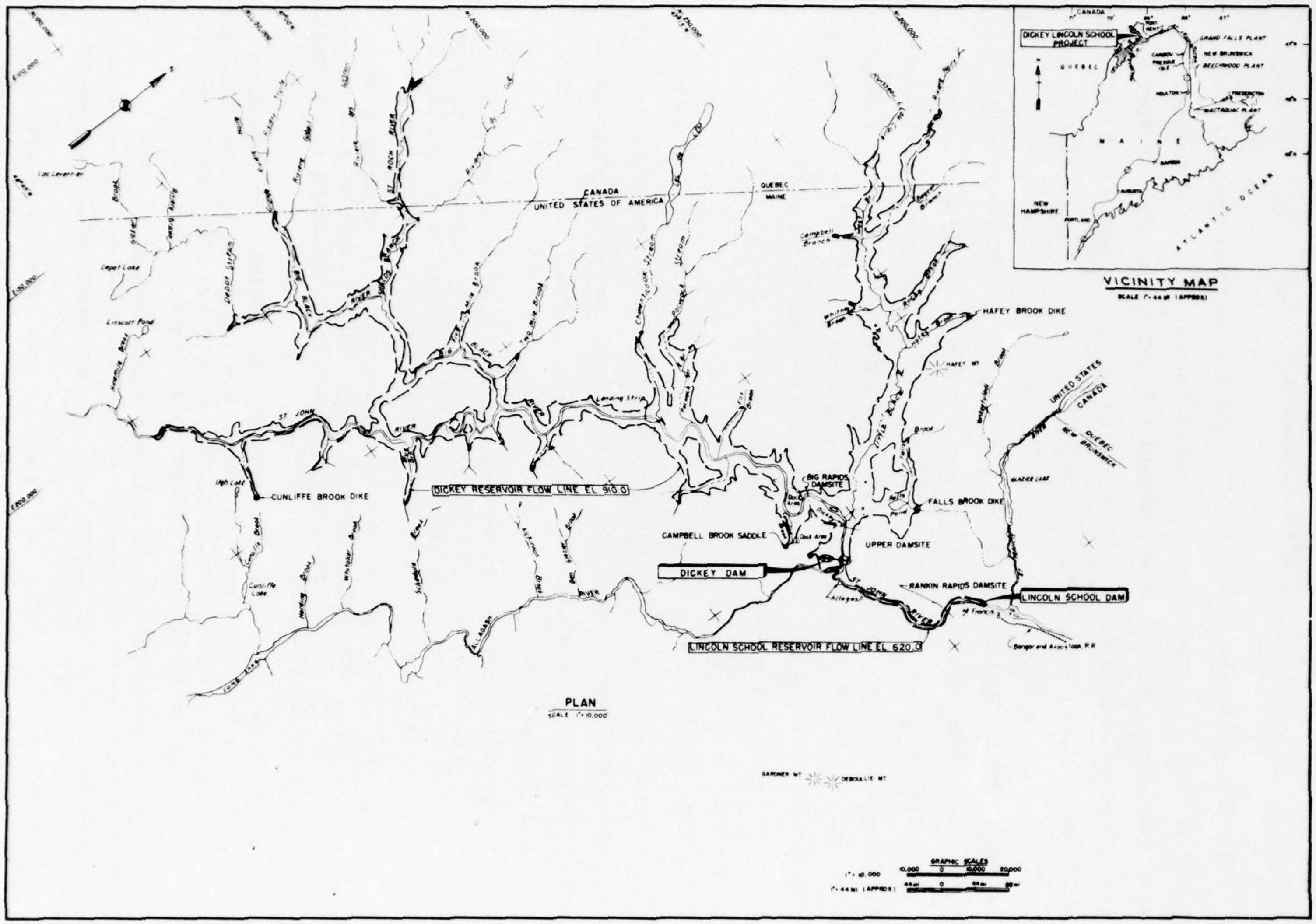

Figure 1. Location map

With the pool at the maximum operating level (el 910), the total storage of Dickey Lake would be 7,700,000 acre-feet and the surface area 86,000 acres. The streambed elevation at the damsite is el 580.

5. Lincoln School Dam would consist of an earth-fill embankment, a gated spillway, and powerhouse with three turbines. The Lincoln School reregulation reservoir would have a total storage of about 85,000 acre-feet at a maximum operating level of el 620.

Approach

6. The thermal characteristics of lakes are affected by flow processes such as inflow mixing and displacement, outflow withdrawal distribution, diffusion, and internal currents. With a lake having the highly dynamic flow conditions and flow magnitudes associated with the Dickey-Lincoln School project, an understanding of these flow processes is necessary if a reasonable description of the thermal characteristics is to be made.

7. Two physical hydraulic models were used to provide an improved understanding of the hydrodynamics unique to the project. An undistorted, 1:200-scale model of the Dickey Lake intake structures and local topography was used to determine the steady-state selective withdrawal and pumpback characteristics for various conditions. A highly distorted-scale model (1:3600 horizontal, 1:180 vertical) was used to simulate the entire dual reservoir system and determine the response to dynamic, unsteady-state, density-stratified flow. Information from the two physical models was used to modify existing and develop new algorithms for a one-dimensional mathematical model.

8. The mathematical model allowed simulation of the hydrodynamic and heat exchange characteristics so that the thermal regimes within and downstream of the two lakes could be evaluated for various hydrologic and meteorologic conditions and various pumped-storage hydropower operations.

PART II: DICKEY LAKE INTAKE MODEL

Purpose and Scope

9. The undistorted, 1:200-scale physical model was required to determine the steady-state selective withdrawal and pumpback mixing characteristics unique to the intake structures and local topography of Dickey Lake. Because of the high discharge rates (40,000-60,000 cfs) and unusual local topography, a physical model was needed to determine whether or not the vertical flow distribution and outflow temperature could be predicted from the U. S. Army Engineer Waterways Experiment Station (WES) Generalized Selective Withdrawal Technique[5] and to provide information with which to modify the predictive technique if discrepancies were found. The generalized technique was used to route outflow in the numerical model. The undistorted model was also needed to determine the gross entrainment, mixing, and dilution characteristics of the pumpback jet for various modes of operation. This information was required for mathematical model improvements.

Scale Relations

10. The predominant forces affecting density-stratified flows in lakes are inertia and gravity as modified by density differences. In such cases, hydraulic similarity between a model and prototype system requires that the ratio of inertial to gravitational forces, defined as the Froude number of flow, be the same in both the model and the prototype. With the density differences in the model set equal to those in the prototype, the accepted equations of hydraulic similitude, based on the Froudian relations, were used to express the mathematical relations between the dimensional and hydraulic quantities of the model and the prototype. The general relations for transfer of model data to prototype equivalents are as follows:

Dimension	Ratio	Scale Relation
Length	$L_r = L_m/L_p$	1:200
Velocity	$V_r = L_r^{1/2}$	1:14.14
Time	$T_r = L_r^{1/2}$	1:14.14
Volume flow rate	$Q_r = L_r^{5/2}$	1:565,685
Density difference	$\Delta\rho_r = 1$	1:1

Description

11. The Dickey Lake intake model (Figure 2) reproduced the preliminary details of the multiple penstock and multipurpose intake structures (Plates 2 and 3) and 4000 by 4000 ft of approach topography. The structural members, piers, wet well, and bell-mouthed intakes of the Dickey intake structures were constructed of transparent plastic. The selector gates, which were made of sheet metal, could be raised and lowered manually. The trashracks were simulated with 1/8-in. wire mesh. The model of the multiple penstock intake structure included five penstocks so the authorized (three 27-ft-diam penstocks) and proposed (five 27-ft-diam penstocks) plans could be tested. Urethane foam was contoured to simulate topography surrounding the structures. The model was contained in a 20- by 20-ft transparent plastic flume so vertical velocity profiles could be easily observed.

12. Saline and fresh waters were used to reproduce the density variations that are anticipated[6] in the prototype due to temperature differences. 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 to achieve the desired density distribution. Density profiles were determined from temperature and conductivity data obtained with sensors that traversed the vertical direction. Generation and pumpback flow rates were regulated with hand-operated valves and measured with rotameters. Pumpback water was pumped from a supply tank in which a brine solution was prepared. Vertical velocity distributions

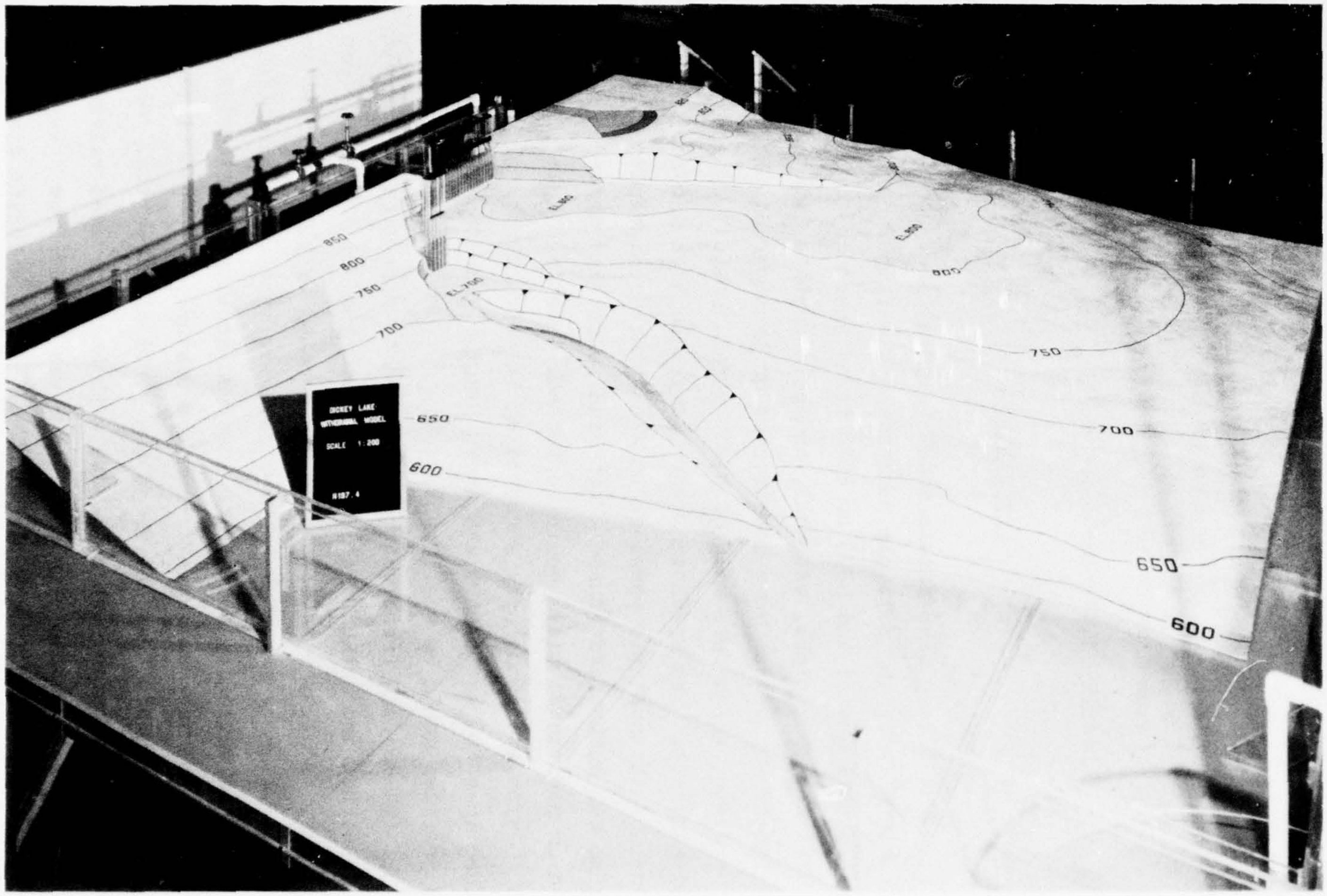

Figure 2. Dickey Lake intake model

were obtained by dropping dye particles into the flume and recording the displacement of the resulting dye streaks with video equipment. This is a very reliable technique for determining velocities with magnitudes as low as those occurring in lake currents. Water-surface elevations were measured with a staff gage.

Model Tests and Results

Selective withdrawal tests

13. The anticipated selective withdrawal plan during periods of stratification consisted of maintaining a submerged-weir flow condition by withdrawing water over the top of the selector gates (Figure 3). This mode of operation was tested with both intake structures for various stratification conditions and heads on the weirs H_w * that ranged from 23 ft to 43 ft. A 23-ft head was the minimum head allowed by the project design. Control valves allowed the operation of single or multiple units of the multiple penstock intake structure. Discharges were set at 10,000 cfs per unit; releases from all six units totaled 60,000 cfs.

14. Density profiles were obtained before each test. Velocity profiles and outflow density were recorded during the test. By providing the density stratification, weir crest elevation, weir length, discharge rate, and pool elevation, selective withdrawal predictions were made with the WES generalized technique. The generalized predictive technique has been coded for computer application and entitled SELECT. A version of SELECT is also included as an outflow subroutine to the numerical simulation model described in Part IV. Each prediction was compared with the observed velocity distribution and outflow density to verify the accuracy or determine the inaccuracy of SELECT. Where discrepancies existed between physical model and generalized results, physical model results were used to modify portions of SELECT to provide a more

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

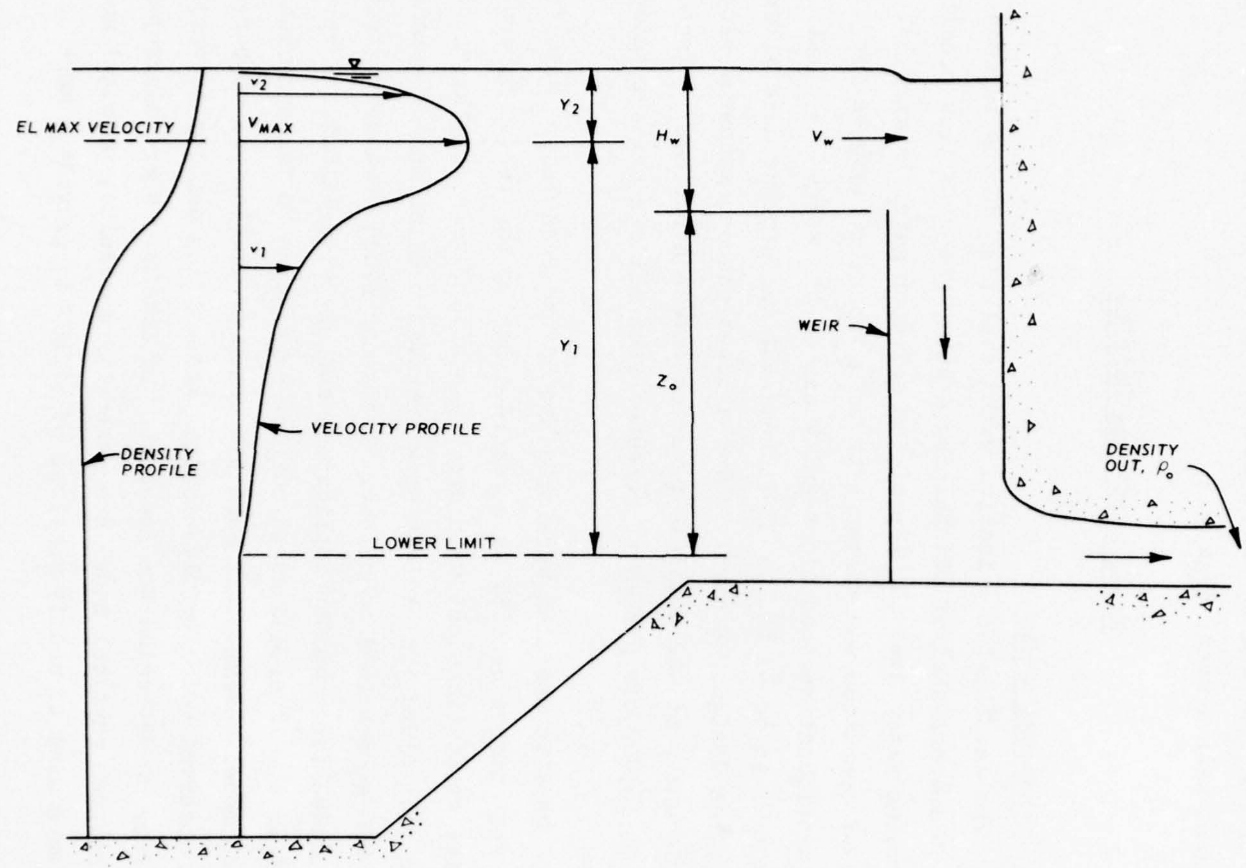


Figure 3. Definition sketch of selective withdrawal

accurate description of the withdrawal characteristics unique to this project.

Selective withdrawal results

15. Releases from the multipurpose intake structure and any one unit of the multiple penstock intake structure produced similar withdrawal characteristics. These characteristics correlated well with SELECT predictions for conditions of mild stratification (spring or fall) or H_w greater than 40 ft. However, for summer stratification conditions and H_w less than 40 ft, a greater contribution of flow from the lower portion of the velocity profile and a larger outflow density (about 3°F colder for a 30°F temperature difference from surface to bottom) were observed than that predicted by SELECT. The increased contribution of flow from below the location of the maximum velocity, V_{max}, was attributed to a slightly superelevated thermocline immediately upstream of the weirs resulting from a hydrostatic pressure gradient reduction near the weir crest caused by local acceleration. With the weir for each wet well segmented into four individual gates separated by piers, contraction of the flow around the piers could cause local accelerations. Also, high rates of discharge (10,000 cfs per penstock) over the weirs, relatively small H_w with respect to the discharge, and the position of the thermocline near the weir crest could contribute to these accelerations. These accelerations would certainly be more pronounced for small H_w and strong stratification. This is a reasonable explanation for the fairly small discrepancy between the model and generalized results[5] (SELECT) considering that the generalized results were obtained for a uniform, continuous, single weir that extended the full width of a 1-ft-wide flume.

16. A distribution of flow similar to that discussed above was observed for simultaneous releases through three or more units of the multiple penstock intake structure for the entire range of stratification and H_w conditions tested. Additionally, the elevation of V_{max} and the elevation of the lower limit of withdrawal, Z_o, were observed to be lower than the predicted elevations for releases through three or more of these five penstocks. These deviations in the anticipated flow

phenomena were believed to be created by topographical approach conditions. It was concluded that the approach geometry and elevated topography (knoll) combined with high discharges created a restricted (converging) flow field upstream of the weirs. This flow restriction influenced the withdrawal characteristics farther out in the lake. Although the approach topography of the multiple penstock intake structure did not completely control the withdrawal characteristics, it did have an increasing influence as the number of units operating was increased from three to five. With all five units of the multiple penstock intake structure operating, the maximum variation in observed temperatures (projected from densities) of outflow from predicted values was about 6°F colder or 20 percent of the total temperature difference expected in the pool during the summer. The influence of the topography was negligible when operating a single unit of the multiple penstock structure, and as stated previously, the withdrawal characteristics compared closely with those of the multipurpose intake.

Selective withdrawal modifications for mathematical model

17. Three basic revisions were made to the mathematical model to improve the accuracy of withdrawal predictions. These revisions consisted of: (a) reduction of the actual weir length to force a lower limit of withdrawal, (b) lowering of the maximum velocity elevations, and (c) modification of the equation that predicts the velocity distribution below V_{max} . The specifics of each revision are discussed in the following paragraphs.

18. To account for the deepened withdrawal zone created by the topographical flow restriction upstream of the multiple penstock structure during multiunit operation, modifications were made to the mathematical model to reduce the weir length, thus decreasing the elevation of the lower limit. The lower withdrawal limit, Z_o , is calculated from the equation

$$V_w = 0.32\left(\frac{Z_o + H_w}{H_w}\right)\sqrt{\left(\frac{\Delta\rho_w}{\rho_w}\right) gZ_o} \qquad (1)$$

where

V_w = average velocity over the weir, fps

Z_o = vertical distance from the elevation of the weir crest to the lower limit of the zone of withdrawal, ft

H_w = head on the weir for free flow or depth of flow over the weir for submerged flow, ft

$\Delta\rho_w$ = density difference of fluid between the elevations of the weir crest and the lower limit of the zone of withdrawal, g/cc

ρ_w = density of fluid at the elevation of the weir crest, g/cc

g = acceleration due to gravity, ft/sec^2

Because V_w is calculated from

$$V_w = \frac{Q}{bH_w} \tag{2}$$

where

Q = discharge over the weir, cfs

b = weir length

a reduction in weir length causes an increase in Z_o. The effective weir length corresponding to the number of units operating is provided in the following tabulation:

Number of Units Operating	Actual Weir Length, ft	Effective Weir Length, ft
1	80	80
2	160	160
3	240	230
4	320	290
5	400	340
6	480	380

For the majority of the tests conducted, the elevation of the lower limit ranged from el 700 to 800.

19. The equation used in SELECT to calculate the height of the maximum velocity is

$$\frac{Y_1}{H_w + Z_o} = \left[\sin\left(1.57 \frac{Z_o}{H_w + Z_o}\right)\right]^2 \tag{3}$$

where

Y_1 = vertical distance from the elevation of the maximum velocity to the lower limit of withdrawal, ft

With three or more units of the multiple intake structure in operation, the location of the maximum velocity was observed to be lower in the pool than was predicted by Equation 3. This phenomenon was not observed for higher heads (H_w greater than 33 ft). With H_w of 23 ft, the location of Y_1 was found to be about 10 ft lower than predicted. The mathematical model was modified to calculate a revised location of the maximum velocity with respect to the lower limit of withdrawal from

$$Y_1' = Y_1 - (33 - H_w) \tag{4}$$

where Y_1 is calculated from Equation 3. Equation 4 is only used if three or more units of the multiunit structure are operating and H_w is less than 33 ft.

20. The equation obtained from the WES generalized selective withdrawal results[5] for describing the dimensionless velocity distribution for the portion below the maximum velocity with submerged weir flow is

$$\frac{v_1}{V_{max}} = \left(1 - \frac{y_1 \Delta\rho_1}{Y_1 \Delta\rho_{1m}}\right)^3 \tag{5}$$

where

v_1 = local velocity in the zone of withdrawal at a distance y_1 below the elevation of the maximum velocity V_{max}, fps

y_1 = vertical distance from the elevation of the maximum velocity V_{max} to that of the corresponding local velocity v_1, ft

V_{max} = maximum velocity in the zone of withdrawal, fps

$\Delta\rho_1$ = density difference of fluid between the elevations of the maximum velocity and the corresponding local velocity v_1, g/cc

$\Delta\rho_{1m}$ = density difference of fluid between the elevations of the maximum velocity and the lower limit of the zone of withdrawal, g/cc

Equation 5 was modified as follows to account for situations in which a larger contribution of flow was realized:

$$\frac{v_1}{V_{max}} = \left(1 - \frac{y_1 \Delta\rho_1}{Y_1 \Delta\rho_{1m}}\right)^p \qquad (6)$$

where p varied from 1.8 to 3.0.

Equation 6 was incorporated into the mathematical model to be used as follows:

a. Whenever three or more units of the multiple intake structure are operating, $p = 1.8$ for all conditions.

b. For fewer than three of the multiple intakes discharging, during summer stratification, and H_w less than 40 ft, p is calculated from

$$p = 1.8 + 0.0706(H_w - 23.0) \qquad (7)$$

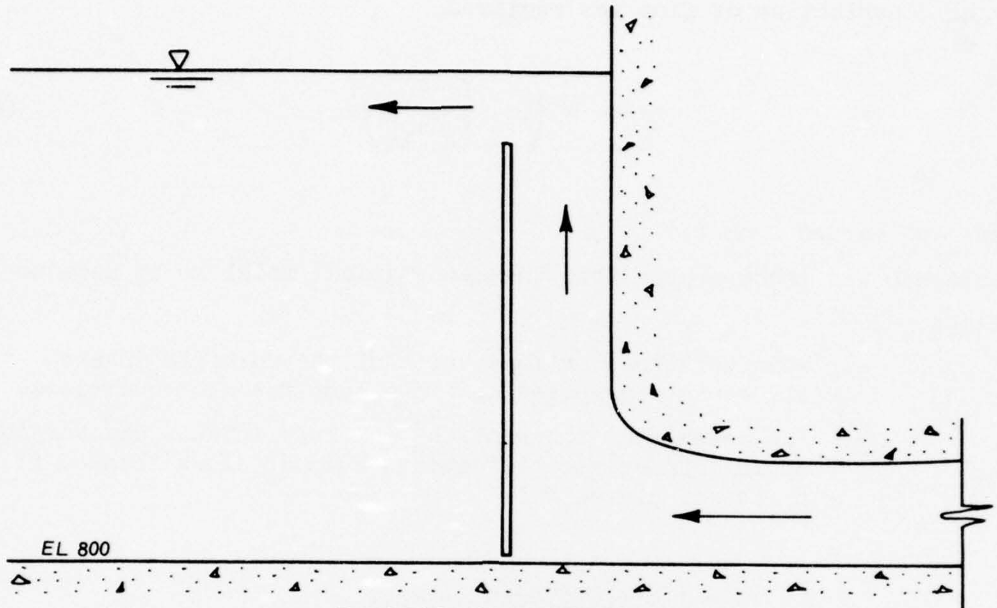
For the same conditions, except with H_w of 40 ft or greater, $p = 3.0$.

c. For fewer than three of the multiple intakes discharging during mild stratification (spring or fall), $p = 3.0$.

21. The exponent, p , of 1.8 was obtained by fitting model data (obtained from test conditions of single unit operation with summer stratification and $H_w = 23$ ft and condition a above) to the form of Equation 6, using the method of least squares. The data fit gave a correlation coefficient of 0.95 and a standard error of 0.08 for predictions of v_1/V_{max} . These model data, the least-squares curve fit ($p = 1.8$), and Equation 6 with $p = 3.0$ (WES generalized results) are all plotted in Plate 4 for comparison purposes.

Pumpback tests

22. Basically, two modes of operation were tested for pumpback characteristics: pumping over the top of the selector gates (weirs) and pumping under the gates with the gates in the raised position (Figure 4). Variations in the pumpback density, the density



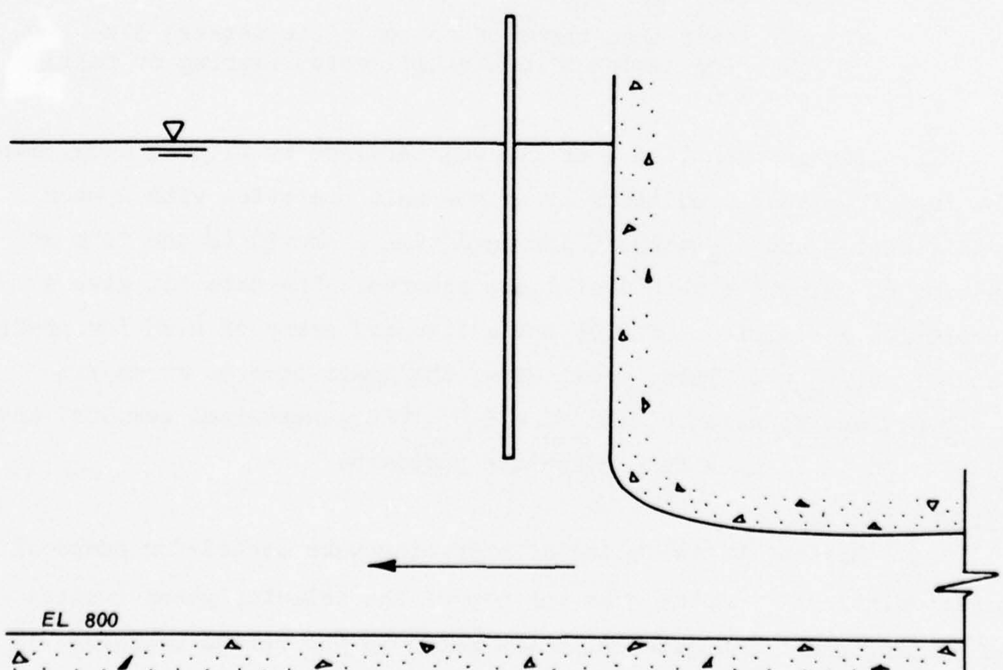


Figure 4. Pumpback configurations

stratification, and the number of units operating were investigated for both configurations.

23. The layers of the lake that contributed to the entrainment process were determined by visual observation, and the amount of entrainment was determined from density measurements and dilution calculations. A definition sketch of the pumpback characteristics is provided in Figure 5. For each test condition, an initial density profile (prior to pumpback), the density of the pumped water, ρ_o , the average density of the pumpback current, ρ_c , and the final density profile (after termination of pumped flow) were measured. The initial and final density profiles were plotted to determine the approximate average density of the pumpback current, ρ_c . An example of this technique is shown in Figure 6. The ρ_c value was compared with measurements taken in the density current during pumpback to substantiate the procedure. These two densities usually correlated very well.

24. Conservation of mass and volume was used to determine the amount of gross entrainment as follows. From the conservation of mass

$$\rho_c Q_c = \rho_o Q_o + \rho_e Q_e \tag{8}$$

where

ρ_c = average density of the pumpback current, g/cc
Q_c = volume flow rate of the pumpback current, cfs
ρ_o = density of the pumped water, g/cc
Q_o = volume flow rate of water pumped, cfs
ρ_e = average density of the entrained flow, g/cc
Q_e = volume rate of entrained flow, cfs

Also, from the continuity of volume for an incompressible fluid

$$Q_c = Q_o + Q_e \tag{9}$$

Substitution of Equation 9 into Equation 8 for Q_c yields

$$Q_e = \varepsilon Q_o \tag{10}$$

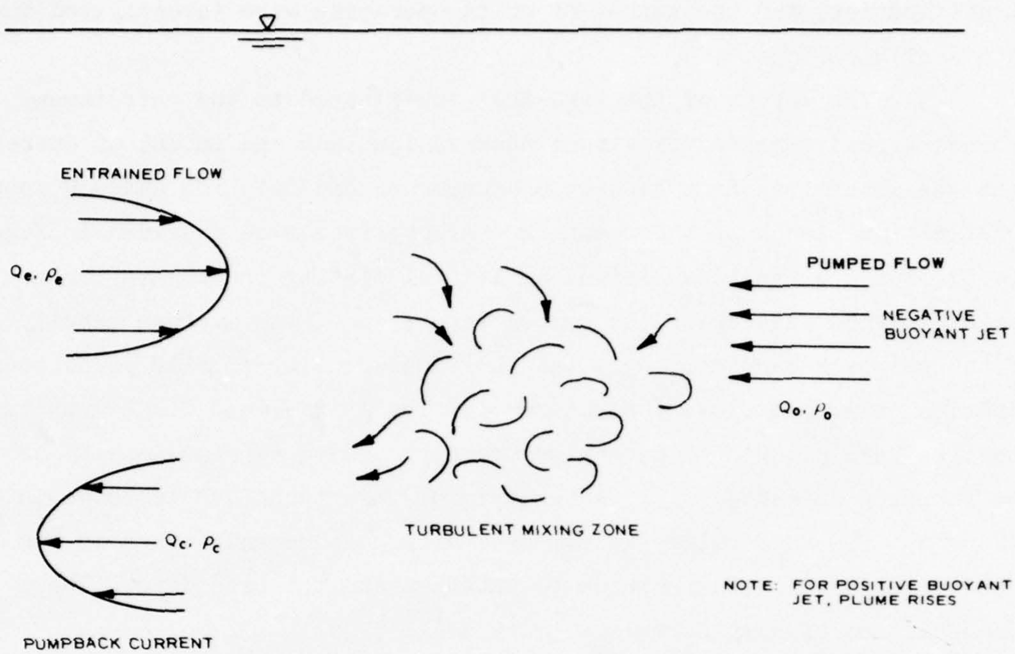


Figure 5. Definition sketch of pumpback characteristics

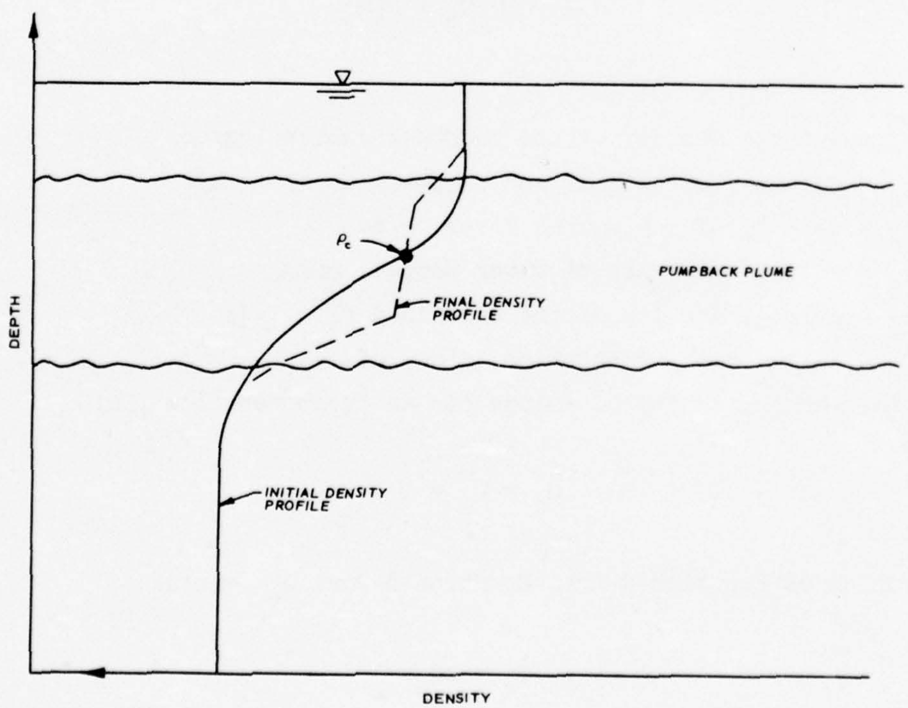


Figure 6. Effect of pumpback on density

where

ε = the entrainment coefficient

and

$$\varepsilon = \frac{\rho_o - \rho_c}{\rho_c - \rho_e}$$

The value of ρ_e was taken from the initial density profile from the elevation at which the maximum contribution of entrainment was observed in the model.

Pumpback results

25. The gross entrainment coefficient, ε , was determined for each pumpback test condition. The average values of ε for the various configurations tested are tabulated below.

Pumping Configuration	Buoyancy of Jet	ε
Over the gates	Negative	0.3
Over the gates	Positive	0.3
Under the gates	Positive	0.6

With pumpback over the gates and negative buoyancy, water was entrained into the jet primarily from the layers of the pool in the vicinity of and above the elevation of the weir crest. With pumpback over the gates and positive buoyancy, water was entrained into the jet primarily from the layers of the pool existing below the weir crest down to el 800. The maximum contribution was observed to be about 20 ft below the weir crest. With pumpback under the gates (buoyancy in this case was always positive because of the depth of the penstock center line, el 823.5), water was primarily entrained from layers between el 800 and 850. The higher ε for this configuration was attributed to the greater velocity of the jet exiting from the bell mouth of the penstock. For pumpback over the weir, the flow was able to spread out to the full weir length, causing a smaller average velocity of the jet and a smaller ε . The model indicated that the number of units pumping back had a negligible effect on ε , probably because the unit discharge and average velocity of the jet were the same for three units pumping as for one.

Pumpback algorithm
for mathematical model

26. The mathematical model was modified to include the pumpback results. To facilitate the description of entrainment in the mathematical model, entrainment was assumed to occur from only one layer of the pool. The location of this layer is dependent on the pumping configuration and buoyancy of the pumpback jet. For pumpback over the gates with a negative buoyancy (ρ_o greater than density existing in the pool at the elevation of the weir crest, ρ_w), ρ_w and the layer that includes ρ_w are used for entrainment. For pumpback over the gates with a positive buoyancy ($\rho_o < \rho_w$), water is entrained from the layer 20 ft below the elevation of the weir crest. For pumpback under the gates, water is entrained from the layer that includes el 823, which is about the center line of the penstock. Water from the entrainment layer is mixed with the pumped discharge in the amount of $\varepsilon Q_o \Delta t$, where Δt is the pumping period. The density of this mixture, ρ_c, is determined and the pumpback mixture is placed into the lake at the elevation that ρ_c exists in the density profile. Further descriptions of budgeting and mixing related to pumpback are discussed in the hydrodynamic and mathematical model sections (Parts III and IV, respectively).

PART III: LAKE HYDRODYNAMICS MODEL

Purpose

27. The purpose of the distorted-scale model was to aid in defining the hydrodynamics of Dickey-Lincoln School Lakes resulting from the expected operating conditions of the proposed prototype. The model was needed to determine the effects of unsteady generation and pumpback on the density stratification of Dickey and Lincoln School Lakes during any particular stratification period and to help identify, validate, and quantify any modifications to be made to the mathematical model to improve the reliability of the predictions.

Scale Relations

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

Dimension	Ratio	Scale Relation
Length in vertical direction	$L_r = L_y$	1:180
Length in horizontal direction	$L_r = L_x$	1:3600
Area in a vertical plane	$A_r = L_x L_y$	1:648,000
Area in a horizontal plane	$A_r = L_x^2$	1:12,960,000
Velocity	$V_r = L_y^{1/2}$	1:13.42
Time	$T_r = L_x/L_y^{1/2}$	1:268
Flow	$Q_r = L_x L_y^{3/2}$	1:8,693,832
Density difference	$\Delta\rho_r = 1$	1:1

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

Description

29. The model (Figure 7) was constructed to highly distorted length scale ratios of 1:180 vertically and 1:3600 horizontally. With the vertically distorted model, turbulent flow was preserved while simulating the entire dual reservoir system in order to maintain the same fundamental character of flow as in the prototype. Use of an undistorted model of the entire system would require a model of such large dimensions and discharge capacity that the cost would be impractical. By horizontal scale compression, the total size of the model was reduced and hydraulic similitude was preserved.

30. The model lakes were constructed of transparent and opaque plastic to facilitate photography and visual observations of currents in the vertical and longitudinal directions. The model approximated the geometry and reproduced the scaled elevation-storage relationships of the prototype lakes. The sides of the model flume were stepped vertically (Figure 8) to satisfy the above requirements without visual distortion through the side. Urethane foam was contoured to simulate the knoll where the intake structures are to be located, the topography at the confluence of the Allagash and St. John Rivers, the configuration of the tailrace of Dickey Dam, and a large island located in the Little Black arm of Dickey Lake.

31. As in the undistorted model, the anticipated density stratification was generated with saline and fresh waters, and density measurements were performed with conductivity and temperature sensors. Velocity distributions were again determined from video recordings of dye streak displacement. Various dyes were used to follow the movement of water of particular interest.

32. Because of the compressed horizontal scale, it was not practical to reproduce the 24 gates and 6 intakes of the intake structures in the scaled horizontal dimension of 0.13 ft. Therefore, the selector gates were combined into a single gate that was vertically controlled by an electromechanical actuator and the six intakes were combined into two. Provisions for two intakes and wet wells were necessary to maintain

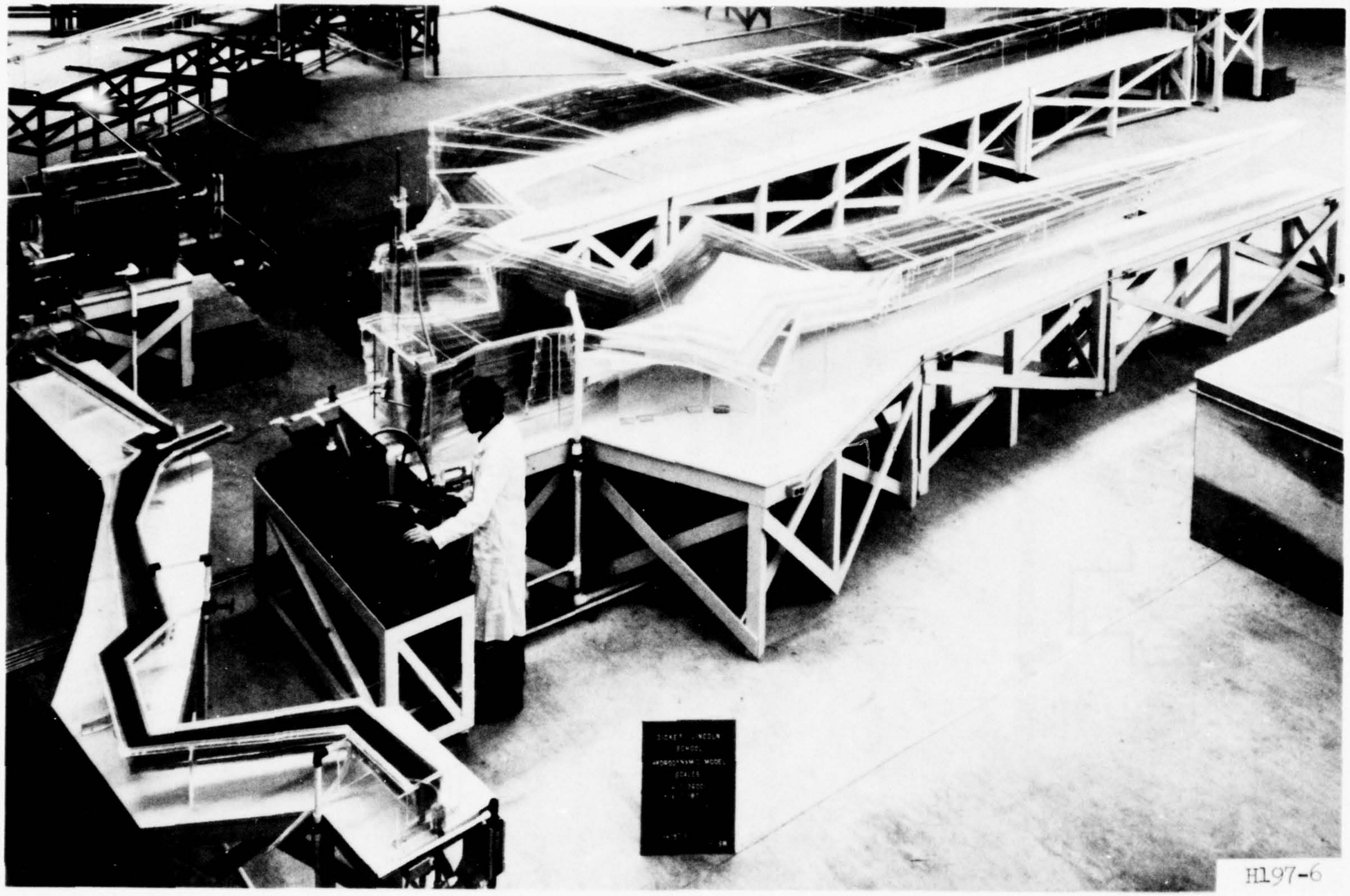


Figure 7. Dickey-Lincoln School Lakes hydrodynamic model

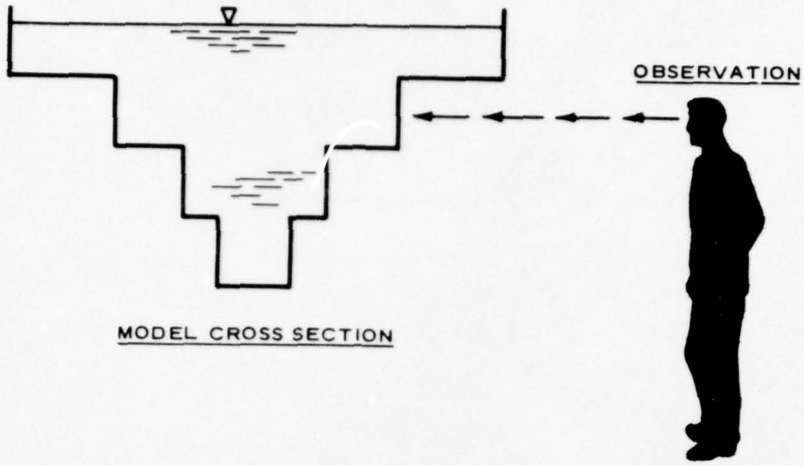


Figure 8. Example of model design for convenient observation

the proper (scaled) inlet-outlet dimensions used during the two different flow processes of generation and pumpback. Generation and pumpback hydrographs of Dickey Lake were simulated by means of a programmable, reversible flow, rotary pump. Allagash River inflow was provided and regulated by a programmable rotary pump. Inflow to Dickey Lake was supplied by a head tank and regulated with a rotameter and hand valve. Generation periods at Lincoln School Dam were simulated by means of an automatically activated solenoid valve which allowed water to be released from Lincoln School Lake through a gate valve, which was preset with a rotameter to give the desired discharge.

33. Model control devices could be operated manually or automatically from the control panels (Figure 9). Automatic control was achieved through analog signals generated by magnetic card readers that tracked input data. Automatic control allowed unsteady operation to proceed for extended simulation periods (4 to 6 weeks prototype time). Since the physical model did not have the capability to reproduce surface heat exchange, realistic prototype simulations exceeding 6 weeks were not attempted because the meteorological effects could exceed the hydrodynamic effects.

Figure 9. Model control panels

Model Tests and Results

Description of tests

34. Anticipated spring, summer, and fall thermal stratification conditions[6] (Figure 10) of Dickey Lake, without power operations, were tested in the model. The spring and fall conditions represented a 54°F water temperature in the epilimnion and 40°F in the hypolimnion, and the summer condition represented a 70°F epilimnion and a 40°F hypolimnion. With the Dickey pool at el 907, the thermocline was set at approximately el 900 and 890 for the spring and summer conditions, respectively. For the fall condition, the pool was set at el 903 and the thermocline at about el 860. Because the physical hydrodynamic model did not reproduce surface heat exchange, the period of time simulated by the model was relatively short so that the hydrodynamic effects would have a much greater influence on stratification changes than would the surface heat exchange. Time simulated by the model was limited to 2 prototype weeks

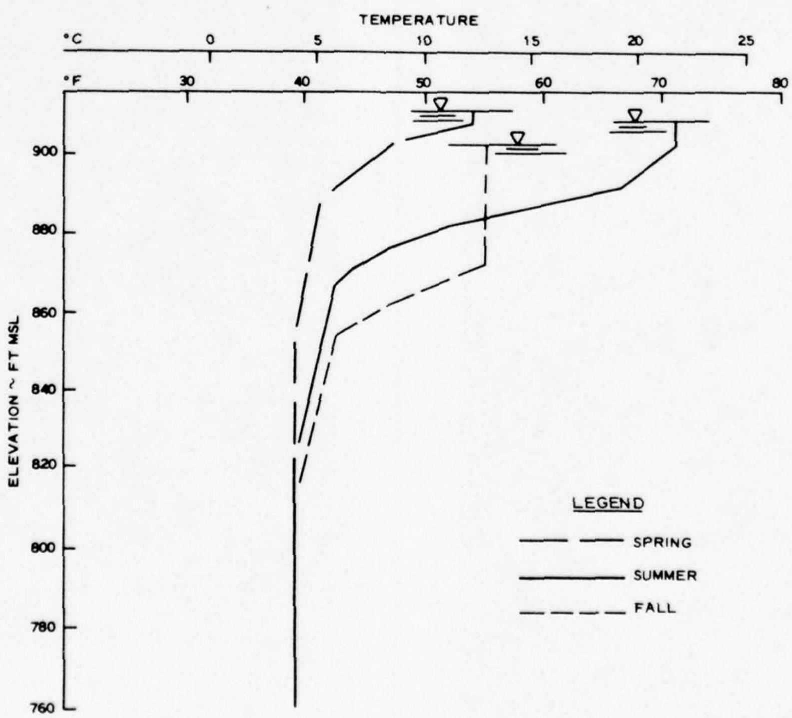


Figure 10. Stratification conditions simulated

for spring and fall stratification and 4 to 6 weeks for summer stratification. The longer simulation period of the summer conditions was permissible because the rate of change in density stratification due to surface heat transfer is less in the summer than in the spring or fall.

35. The Lincoln School Lake model was stratified with fresh and saline water to simulate a summer condition of 75°F water for the epilimnion and 65°F for the hypolimnion. This was determined through mathematical simulations[6] to be the strongest thermal stratification that could be expected to exist in Lincoln School Lake with the normal St. John and Allagash River flows. Tests were conducted to determine if the Lincoln School water would become fully mixed for the expected power releases.

36. The model was tested, under all stratifications, on a steady-state flow basis to evaluate the selective withdrawal and pumpback characteristics of the intakes. Similarity of these flow characteristics to the undistorted model results was necessary to assure valid simulations. Release densities, withdrawal velocity profiles, and entrainment coefficients were determined for comparison with results from the undistorted model and SELECT.

37. The effects of unsteady operation on Dickey Lake stratification were investigated by operating the hydrodynamic model on the anticipated prototype schedules. Generation and pumpback densities were monitored to evaluate transient effects on release density resulting from the unsteady operation. Changes in the stratification of Dickey Lake were evaluated by comparing vertical density profiles taken at the end of each prototype week of simulation. The two proposed operation plans tested are summarized in Table 1. Both plans include pumpback. The authorized plan (no pumpback) was not tested because the complexity of the water mixing and transport characteristics of the project were greatly reduced, and description of the advection processes in the mathematical model did not require these additional tests.

38. During summer stratification, steady-state inflow tests were conducted to estimate the time of travel for St. John River flows entering Dickey Lake. Flow was introduced into Dickey headwater at an

average rate of 3200 cfs. The time required for the flow to reach Dickey Dam and be released was observed to be 90 days with the 3200-cfs steady-state flow.

39. A unique feature of the reregulation pool, besides the high generation and pumpback flow rates, was the contribution of flow from the Allagash River. Because the confluence of the Allagash and the reregulation pool is in the vicinity of the Dickey tailrace, the Allagash River was considered to have a high potential for contributing to the quality of the pumpback flow from Lincoln School Lake. Therefore, tests were conducted to determine what proportion of the pumpback water was Allagash water. Fluorescent dye, sulpha Rhodamine B, was used to trace the Allagash water. With the model simulating the unsteady generation-pumpback modes, samples of pumpback, generation, and Allagash water were collected and analyzed for fluorescent dye concentration. The contribution of the Allagash to the pumpback was determined from the dye concentrations (paragraph 44). Allagash flows of 1570 and 4710 cfs and unsteady operations described in Table 1 were used for these tests.

Steady-state test results

40. The steady-state selective withdrawal characteristics of the distorted-scale lake model compared closely with the generalized selective withdrawal results[5] but differed from the undistorted-scale model results. With the 6 intakes and 24 weirs combined into 2 intakes and a single weir in the distorted-scale model, the selective withdrawal characteristics of the distorted- and undistorted-scale models could be expected to differ some. Also, because of the distortion, the effect that the approach topography had on selective withdrawal in the undistorted model did not exist in the distorted model. For the simplified representation of the intake structures and topography modeled in the distorted model, the distorted model results were expected to agree with SELECT predictions. Because the selective withdrawal characteristics of the distorted- and undistorted-scale models were in reasonable agreement, results from the hydrodynamic model were considered to be reliable for understanding the dynamic response of the lakes.

41. Entrainment coefficients obtained from the distorted-scale

model during steady-state pumpback tests compared closely with those obtained from the undistorted-scale model, and adjustment of distorted model results was not necessary.

42. With the St. John River inflow into Dickey Lake equal to a constant outflow of 3200 cfs at Dickey Dam (paragraph 38), the dyed inflow was observed to travel to the dam in about 90 prototype days. This long travel time demonstrated that the effect of inflow on temperature stratification in the vicinity of the dam was insignificant relative to meteorological effects in this large lake.

Results of unsteady operation and
mathematical model implementation

43. Releases from both of the proposed hydropower operation modes (4 and 6 units) almost totally destroyed the stratification setup in Lincoln School Lake (paragraph 35) within one week of prototype operation. Only the top 2 ft of pool at the dam were not well mixed after one week of prototype operation. After two weeks of prototype simulation, the reregulation pool was totally mixed. It is reasonable to believe that stratification will not develop in Lincoln School Lake with power operation. Therefore, Lincoln School Lake was considered fully mixed for mathematical model application. Power releases from Dickey Lake were observed to travel from the Dickey tailrace to the Lincoln School Dam in a period of approximately a day. This meant that net flows into Lincoln School Lake could be mixed with water remaining in the lake from the previous day for the mathematical simulations.

44. Water from the Allagash River made a considerable contribution to pumpback flow from Lincoln School Lake to Dickey Lake. The amount of Allagash water pumped back was found to be a function of the pumpback flow rate and the Allagash River inflow rate. With the proposed plan of three reversible turbines (pumpback flow of 20,000 cfs for 6 hr), the pumped discharge consisted of about 20 and 55 percent Allagash River water for Allagash River inflows of 1570 and 4710 cfs, respectively. With the alternate plan of one reversible turbine pumping 7000 cfs for 6 hr, the Allagash River water composed about 54 and 90 percent of the water pumped from Lincoln School Lake for the same

respective Allagash inflow rates. This operational mode provided a higher percentage of Allagash water than did the 3-unit pumpback mode, probably because the generation flow of 40,000 cfs prior to pumpback with one unit did not create as high a backwater stage (backing the Allagash flow upstream) as did the generation flow of 60,000 cfs. Also, the ratio of the rate of Allagash River flow with respect to the total pumpback flow rate was higher for the single pumpback mode, thus increasing the influence of the Allagash River on pumpback. An equation was developed to compute the amount of Allagash water pumped back as a percentage of the total pumped flow occurring in a pumpback period. This percentage of Allagash water to the total pumped flow, σ , is a function of the Allagash River inflow and pumpback flow rate and is calculated from

$$\sigma = (42.0 - 0.00179Q_o)Q_A^{(0.25 + 3.76 \times 10^{-5}Q_o)} \qquad (11)$$

where

Q_o = pumpback flow rate, cfs

Q_A = Allagash River inflow, 1000 acre-ft/day

Because only two pumpback rates were tested, the application of Equation 11 should be limited to those conditions. The Allagash water with corresponding temperature is mixed with either Lincoln School Lake water or water released from Dickey Lake during the previous generation period (if generation occurred on that day) to obtain the temperature of water pumped back. To conserve mass and energy, there is a limit to the maximum amount of Allagash water that can be pumped back; that is, pumpback water should not exceed the total volume of Allagash flow that enters Lincoln School Lake in a day.

45. With the distorted-scale model, the pumpback characteristics in Dickey Lake were observed for an unsteady operation plan over an extended time period (2 to 6 prototype weeks). The flow conditions in Dickey Lake resulting from pumpback with a submerged turbulent jet consisted basically of two parts: a turbulent mixing zone in the vicinity of the dam and gravity-driven density currents in the far field (Figure 11). The turbulent mixing zone extended from the dam to a distance

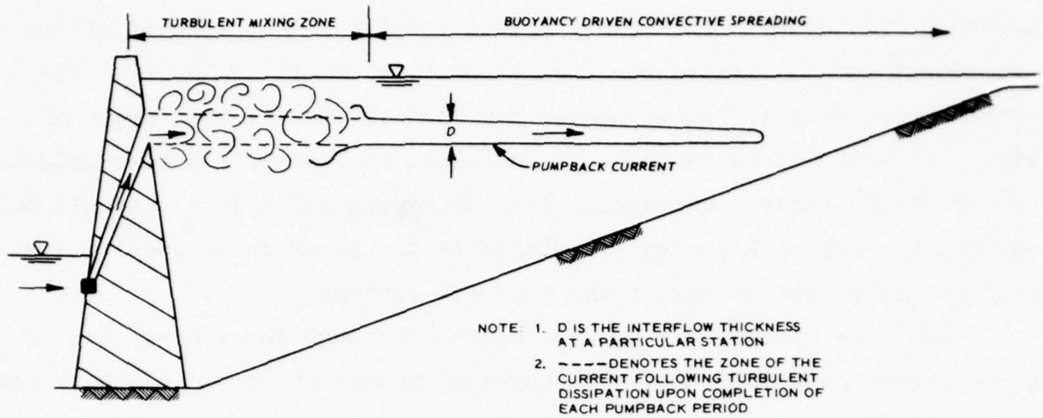


Figure 11. Description of pumpback current

upstream of the dam ranging from 0.5 to 1.5 miles. Upon completion of each pumpback period, the turbulent zone would practically dissipate before initiation of generation and form a mixed layer similar to the convective current farther out in the lake.

46. The model demonstrated the pumpback current to be a two-dimensional flow phenomenon, which would be expected for a long, narrow reservoir. The current was thickest at the dam and gradually diminished in thickness from the dam to the front of the current, which progressed up the lake. The existence of a strong two-dimensional effect was demonstrated by the long time required for the current to progress up the lake. For summer conditions and with three reversible units pumping back over the weirs, the current traveled about half the total distance up the Little Black arm and a third of the total length of the Saint John arm during a one-month simulation. This produced a longitudinal variation in the temperature (density) profile within the zone of interflow of the convective current. The most significant aspect of this longitudinal variation is that the density profile near the dam, which affects the outflow quality of Dickey Lake, endured more mixing than that farther out in the lake.

47. After completion of the pumpback period and dissipation of turbulence, the thickness and density variations within the pumpback current were fairly uniform from the dam to a distance of about 3 miles

upstream of the dam. From the physical model results, special mixing procedures were developed for the mathematical model to describe the temperature changes created by the pumpback current in this reach of reservoir adjacent to the dam. To maintain the energy and mass budget, the advection process throughout the lake was handled in a conventional manner; the pumpback current is placed in the layer whose density most nearly equals the density of the pumpback current.

48. The special mixing procedures discussed above consisted of three parts: prediction of the pumpback current thickness in the vicinity of the dam, determination of mixing coefficients, and partial mixing of layers within the zone of the current. For any particular stratification condition and operational mode, there was a corresponding thickness of the pumpback current (zone of interflow) near the dam. The thickness of this zone was known to be dependent upon the unit discharge rate and density differences due to stratification and was therefore considered to be a function of the densimetric Froude number. A form of the densimetric Froude number used by the Water Resources Engineers[7] (developed from Debler's criteria) was modified and used to predict a zone thickness that correlated well with thicknesses observed in the model. The interflow thickness, D (ft), can be evaluated as

$$D = 4.1\left(\frac{Q_c}{W\sqrt{\frac{\Delta\rho}{\rho_c}\,g}}\right)^{2/3} \qquad (12)$$

where

Q_c = volumetric flow rate of the pumpback current (includes entrainment), cfs

W = average reservoir width at the elevation of the current in the vicinity of the dam, ft

$\Delta\rho$ = density difference of the epilimnion and hypolimnion, g/cc

ρ_c = average density of the pumpback current, g/cc

Even with unsteady operation, the thickness of the pumpback current remained constant in the vicinity of the dam for a particular stratification, pumpback rate, and proposed operational mode.

49. Density profiles taken at the end of each week of prototype simulation revealed that the amount of mixing which occurred within the zone of interflow was proportional to time. This phenomenon is demonstrated by the temperature profiles shown in Figure 12 which are typical of the data obtained from the model. Model data of this type were used to develop the mixing procedure and mixing coefficients that were used in the mathematical model. A complete description of the mixing technique is provided in the mathematical model description (Part IV).

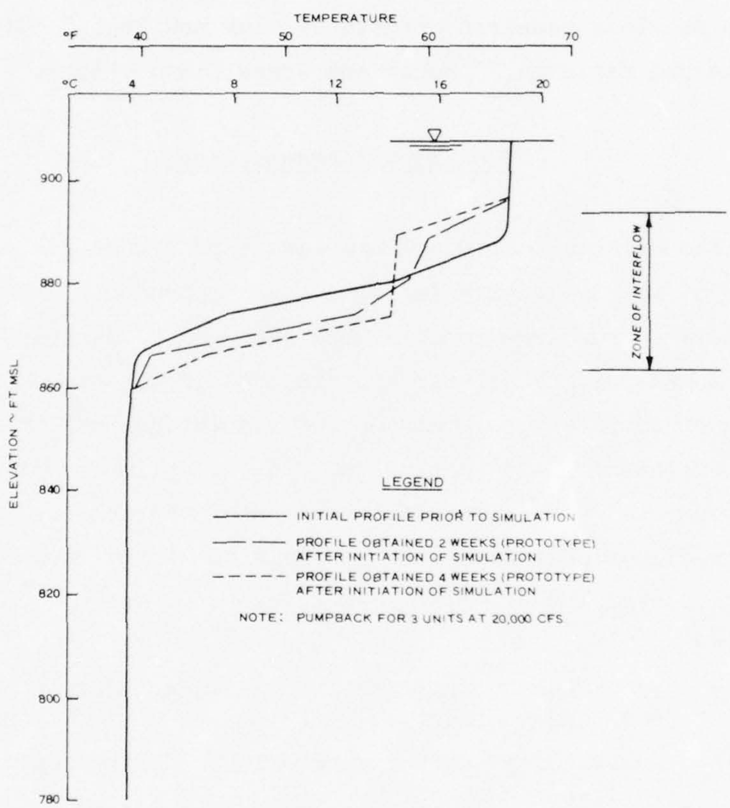


Figure 12. Time-dependent effect of unsteady operation on stratification

PART IV: MATHEMATICAL MODEL DESCRIPTION

50. The internal heat budget in Dickey Lake and the release temperatures downstream of Lincoln School Lake were predicted using a numerical simulation model. The model used in conjunction with this investigation was developed at WES to uniquely describe the thermal characteristics and hydrodynamic patterns of the Dickey-Lincoln School Lakes project. During the development of the model, considerable insight was gained from previous research efforts of Clay and Fruh,[8] Edinger and Geyer,[9] Dake and Harleman,[10] Bohan and Grace,[5] and others.

Fundamental Assumptions

51. The mathematical 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 release temperatures in the time domain. The model includes computational methods for simulating heat transfer at the air-water interface; advective heat due to inflow, outflow, and pumpback processes; and the internal dispersion of thermal energy. The model is one-dimensional based on the division of the impoundment into discrete horizontal layers of uniform thickness. Assumptions include the following:

- a. Isotherms are parallel to the water surface both laterally and longitudinally.
- b. The water in each discrete layer is isotropic and physically homogeneous.
- c. Internal advection and heat transfer occur only in the vertical direction.
- d. External advection (inflow, outflow, and pumpback) occurs as a uniform distribution within each layer.
- e. Internal dispersion (between layers) of thermal energy is accomplished by a diffusion mechanism which combines the effects of molecular diffusion, turbulent diffusion, and thermal convection.

52. The surface heat exchange, internal mixing, and advection

processes are simulated separately and their effects are introduced sequentially at specified time intervals. A simplified flow chart of the numerical simulation procedure is presented in Figure 13.

Surface Heat Exchange

53. The mathematical model employs an approach to the evaluation of surface heat transfer developed by Edinger and Geyer.[9] This 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:

$$H = K(E - \theta) \tag{13}$$

where

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

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

E = equilibrium temperature, $^\circ$F

θ = surface temperature, $^\circ$F

The computation of equilibrium temperature and heat exchange coefficient is based solely on meteorological data as outlined by Edinger, Duttweiler, and Geyer.[11]

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

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

For every day of meteorological data, the seven heat exchange terms can

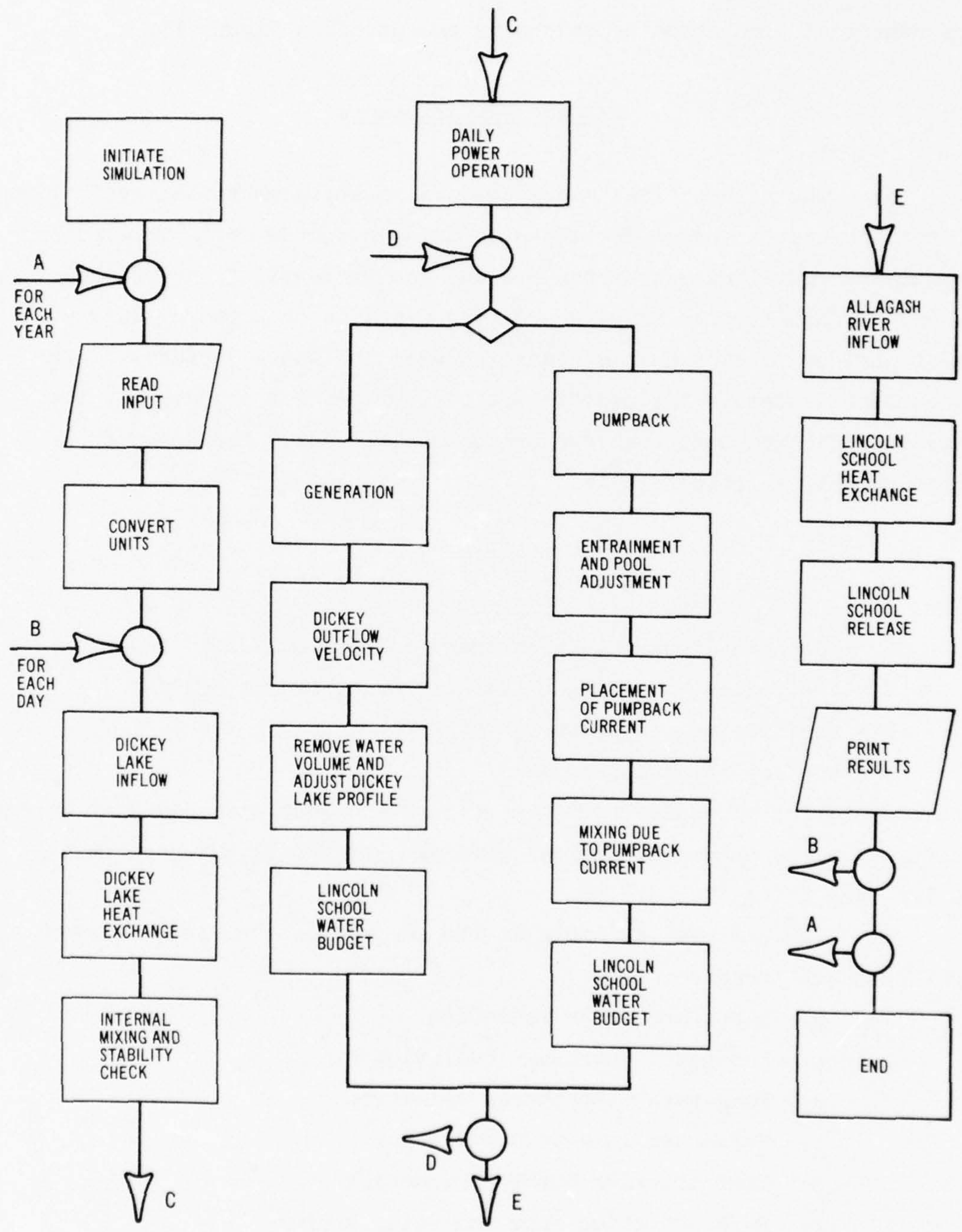


Figure 13. Mathematical model flow chart

be evaluated, the net heat exchange computed and then expressed in terms of an equilibrium temperature and an exchange coefficient.

55. All of the surface heat exchange processes, with the exception of shortwave radiation, affect only approximately the top few feet of the lake. Shortwave radiation penetrates the water surface and increases the temperature at greater depths. Based on laboratory investigations, Dake and Harleman[10] have suggested an exponential decay with depth for describing the heat flux due to shortwave penetration.

56. The surface heat exchange concepts are implemented in the model by the exponential penetration of a percentage of the incoming shortwave radiation and the placement of the effect of all other sources of surface heat exchange into the surface layer. This procedure can be expressed mathematically by the following two equations:

$$H_s = K(E - \theta) - (1 - \beta)S \qquad (14)$$

$$H_i = (1 - \beta)Se^{-\lambda z_i} \qquad (15)$$

where

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

β = shortwave radiation absorbed in the surface layer, percent

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

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

e = natural logarithmic base (2.7183)

λ = heat absorption coefficient, ft^{-1}

z_i = depth below surface, ft

57. Equations 14 and 15 are applied to the Dickey Lake temperature profile once during each one-day time step. A shorter time step was evaluated as discussed in Appendix A but was not selected for use. The net heat exchange rate into each layer is computed and converted to a temperature change. The temperature changes are used to determine an updated temperature profile for Dickey Lake. Numerically, Lincoln School Lake is assumed to remain thoroughly mixed. Thus, surface heat exchange in Lincoln School Lake is effected by converting the total heat exchange

rate as indicated in Equation 13 to a temperature change. The temperature change is then added to the existing Lincoln School Lake temperature once during each one-day time step.

Inflow

58. The process of inflow into a lake is simulated by the placement of inflow quantity and quality at that layer in which the density of the lake corresponds most nearly to the density of the inflow. Research efforts and physical model studies at WES have indicated the existence of entrainment-induced density currents that flow upstream along the surface into the turbulent mixing zone caused by the inflow. Entrainment is implemented in the model by augmenting the inflow quantity with a volume from the surface layer. Characteristics of inflow and entrained flow are averaged; and mixed values of density, temperature, and other water-quality parameters are determined. The mixed density is used to determine placement of the total quantity and mixed quality. Simulation of the inflow process displaces upward a volume equal to the total inflow quantity. This upward displacement is reflected in the model by an increase in the water-surface elevation. A corresponding decrease in water-surface elevation occurs as a result of the outflow simulation process.

59. The volume of the entrained current is generally expressed as a percentage of the inflow quantity. Prior flume studies at WES indicated that this percentage ranges from 5 to nearly 250. The percentage is thought to be a function of the entering velocity, depth, density, and density within the lake, and is therefore a function of the densimetric Froude number. However, analytical relationships have not been completed.

60. As indicated previously in the discussion of the Dickey-Lincoln School Lakes distorted model, the inflow current in Dickey Lake has no appreciable effect on the temperature profile in the vicinity of Dickey Dam. The same conclusion was reached numerically by simulation with various inflow temperatures. Simulations with inflow temperatures

(a) as provided by NED, (b) with a constant value of 0°C throughout the simulation period, or (c) with a constant value of 100°C produced identical temperature profiles within the accuracy of the model output. Thus, it was shown that due to the large volume of Dickey Lake, the inflow process has a minimal effect on the heat budget of the lake at the dam. However, the inflow process must be retained in the model in order to maintain the water budget. The minimal effect of inflow on the heat budget allowed the flow quantity from many inflow points to be lumped together and treated as a single inflow point with total flow quantity and flow-weighted average temperature. Lumping of inflows decreases computer storage requirements and run time.

Internal Dispersion

61. The internal dispersion process is represented by an internal mixing scheme based on a simple diffusion analogy. Internal mixing transfers heat and other water-quality constituents between adjacent layers. The magnitude of the transfer between two layers is a percentage of the total transfer required to completely mix the two layers. This percentage is a mixing coefficient which is defined for every layer. Data input includes values of the mixing coefficient at the top and at the bottom of the lake. An exponential fit between the two extreme values is used to determine the appropriate coefficient at each layer.

Outflow

62. The outflow component of the model incorporates the selective withdrawal predictive techniques developed at WES[5] for submerged weir flow. However, the selective withdrawal description was modified to include characteristics unique to the Dickey Lake intake structure (paragraphs 17-21. Transcendental equations defining the location of the zero-velocity limits are solved with a half-interval search method. The location of the zero-velocity limits is functionally dependent on configuration of the withdrawal device, release flow rate, and density structure

within the lake. With knowledge of the limits of the withdrawal zone, the velocity profile due to outflow can be determined. The flow from each layer is then computed as the product of the velocity in the layer and the width and thickness of the layer. A flow-weighted average is applied to the temperature profile to determine the value of the release temperature for each time step. For the constant discharge rates proposed during periods of generation, the physical models indicated that the withdrawal zone was fully established almost immediately after initiation of withdrawal. Additionally, release densities were constant throughout a generation period. Therefore, in the mathematical model the release temperature is assumed constant throughout a generation period.

Operation Schedules

63. Because the generation and pumpback flows change markedly within the period of a day (Table 1) and the rates of these flows affect withdrawal and pumpback characteristics, it was not adequate to use daily average flows for generation and pumpback operations. Daily average flow routings are quite adequate for less dynamic reservoirs, such as water supply and flood control projects. For this model, the scheduled generation and pumpback flow rates and durations are used rather than daily averages. The Julian day number, the modes of operation (generation or pumpback), flow rates, durations of flow, and elevations of the withdrawal or pumpback device are input for each day that a change in the operation schedule occurs. The flow rates are used in computing withdrawal and pumpback characteristics, while the duration and rate of flow are used to budget generation and pumpback volumes.

Lincoln School Lake

64. Lincoln School Lake is modeled numerically by maintaining heat and water budgets in the lake and is assumed to remain fully mixed throughout the year. This assumption is supported by physical model observation, and it allows further simplifying assumptions to

be made with respect to advection and heat exchange in the lake. Once during each day of simulation the volume of water in the lake is adjusted to sequentially account for (a) Allagash River volume which is not pumped back, (b) Dickey Lake generation volume which is not pumped back, (c) Lincoln School Lake volume which is pumped back, and (d) Lincoln School Lake volume which is released downstream. The net contributions of volume from the Allagash River and Dickey Lake at the respective temperatures are added to the Lincoln School Lake volume, producing a mixed value of temperature. The daily heat budgeting is completed by applying Equation 13 to the final surface area of Lincoln School Lake to account for surface heat exchange at the air-water interface. The schematic shown in Figure 14 describes the budgeting of heat and mass in Lincoln School Lake.

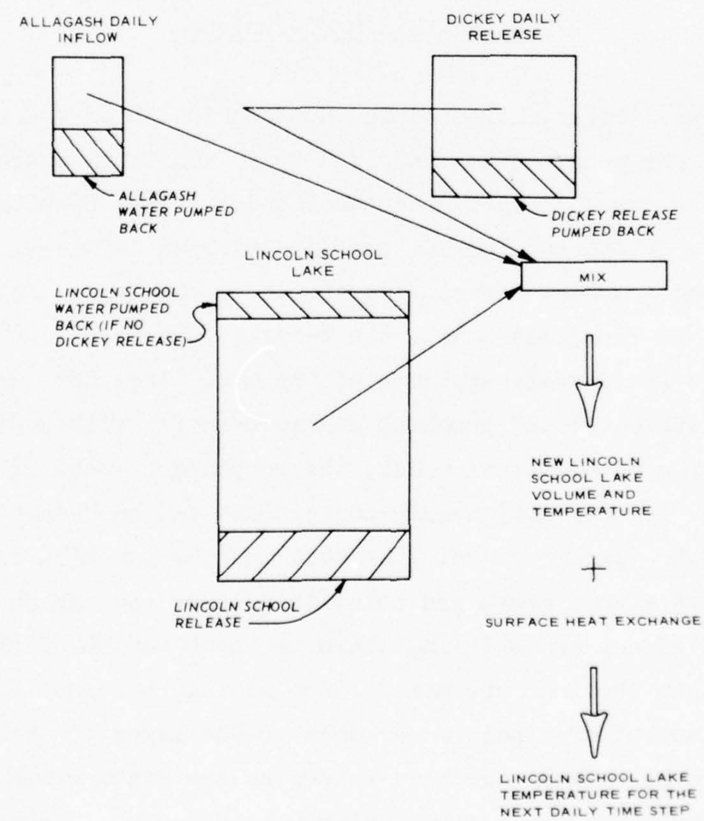


Figure 14. Simulation of reregulation

Pumpback Quality

65. The quality (temperature) of the pumped flow can be influenced by three water sources: the Allagash River, releases from Dickey Lake just prior to pumpback, and Lincoln School Lake. As previously discussed (paragraph 44), the Allagash River was found to contribute to the quality of pumped flow. The amount of contribution is described by Equation 11. The remainder of the water pumped back can consist of either Dickey Lake release or Lincoln School Lake water. If generation occurs before pumpback on the same day, then the remainder will consist of Dickey Lake release water; otherwise, Lincoln School Lake water constitutes the remainder. The temperature of the pumped flow is determined from a volume-weighted average of the constituents.

Pumpback Mixing Technique

66. As previously indicated in the description of the physical model results, the pumpback current is a two-dimensional phenomenon (Figure 11) that causes longitudinal variations in the density structure of Dickey Lake. Different thermal profiles existed in the vicinity of the dam than those observed farther upstream in the lake. As the mathematical model is one-dimensional, the decision was made to simulate the thermal profile immediately upstream of the dam, since this profile controls the withdrawal and pumpback characteristics within Dickey Lake.

67. In the mathematical model, the pumpback current is placed in the layer whose density most nearly corresponds to the density of the pumpback current. In the vicinity of the dam, the pumpback current actually affects a zone above and below this layer (paragraph 48). To represent this effect and still maintain the heat budget of the lake, the layers within the zone are mixed. The mixing technique employed is based on the concept of a portion of each of the layers in the pumpback zone being removed, mixed together, returning the mixed water to the layers in the zone, and then mixing within each layer. The portion of water removed and mixed from each layer is computed by multiplying a

mixing coefficient (a number between 0 and 1) times the volume of the layer. The mixing coefficients were determined using data from the distorted physical model (paragraph 49). Density profiles were measured before and after pumpback. By analyzing the difference in these profiles, the mixing coefficients necessary to apply to the initial profile to yield the final profile were computed.

68. Mixing coefficients were computed for each of the pumpback operation tests conducted in the distorted model. Analysis of the mixing coefficients revealed that the coefficients could be considered symmetrical about the pumpback current inflow layer. Additionally, a constant magnitude of the coefficients could be used throughout the stratification cycle. For a given pumping rate, the mixing coefficients could be assumed equal for pumpback over or under the weir. For three reversible units pumping 20,000 cfs, the coefficients were found to be approximately twice the magnitude of those determined for pumpback with a single reversible turbine (7,000 cfs). This difference was attributed to the greater velocity of the current with pumped flow of 20,000 cfs. An equation was developed to predict the mixing coefficient in a layer as a function of the distance of that layer from the pumpback current inflow layer:

$$\eta_i = Ae^{-BX_i} \tag{16}$$

where

η_i = mixing coefficient

i = layer

A = 0.067 for 3 reversible units
  = 0.033 for 1 reversible unit

B = 0.118

X_i = distance from the pumpback current inflow layer to layer, i

69. To represent the pumpback mixing technique within the mathematical model, the following sequence of computational steps is employed. The depth of the zone affected by the pumpback current is computed by Equation 12, and this zone is distributed about the layer

of pumpback placement. The mixing coefficient for each layer in the zone is computed by Equation 16, the amount of each layer to be mixed is computed as the product of the mixing coefficient and the layer volume, and the portions from the layers are mixed together. The mixed water is returned to the layers and each layer is individually mixed.

PART V: DISCUSSION

70. A one-dimensional, numerical simulation model was developed for prediction of temperature within and downstream of Dickey-Lincoln School Lakes. Physical hydraulic models were used to obtain an improved understanding and description of the hydrodynamic response of the lakes to pumped-storage hydropower operations. Descriptions from the physical models were incorporated into the mathematical model to enhance the predictive capabilities. Sensitivity analyses were conducted to determine the effects on temperature of the various algorithms developed from the physical model studies. Discussions of the sensitivity analyses are presented in the following paragraphs. It should be noted that the results of these sensitivity analyses are unique to the Dickey-Lincoln School Lakes project.

71. Information obtained from the Dickey Lake intake model (Part II) was used to modify the mathematical description of the selective withdrawal characteristics (paragraphs 17-21). The effect that these modifications have on the predicted release temperatures from Dickey and Lincoln School Lakes is presented in Plates 5a and 5b, respectively. The dashed-line circle represents a base condition of release temperature computed without the use of the selective withdrawal modifications. The solid line plots the deviation in temperature from the base condition as a result of the selective withdrawal modifications. The base and perturbed conditions are plotted over the cycle of a year (360° = 1 year) starting on 1 January positioned at the scaled axis and rotating in a counterclockwise direction. Hydrologic and meteorologic data for 1953, furnished by NED, and operational conditions for six turbines (generation flow 60,000 cfs and pumpback flow 20,000 cfs, Table 1) were used to conduct all the sensitivity analyses. As shown by Plate 5a, the selective withdrawal modifications of the mathematical model had the effect of decreasing the Dickey Lake release temperature by a maximum of about $3^\circ C$. The reregulation pool attenuated this effect to a maximum of approximately $2^\circ C$ (Plate 5b). Although these modifications did not create drastic changes in the release temperature, the

changes are significant and cannot be overlooked.

72. The ability of the reregulating pool to warm and cool the releases from Dickey Lake is demonstrated by Plate 6. The surface heat exchange expected in Lincoln School Lake tends to drive the water temperature toward equilibrium with the atmosphere. During the strong stratification period, the releases from Lincoln School Lake should be as much as 5°C warmer than the Dickey Lake release. Other factors contributing to the heat exchange characteristics of the reregulation pool are the influence of the Allagash River, the contribution of the Dickey release, the amount of release and pumpback from Lincoln School, and the fully mixed conditions of the lake (Figure 14). Descriptions of these water budgeting processes in Lincoln School Lake were developed from hydrodynamic model results (Part III) for use in the mathematical model. For example, the hydrodynamic model was used to determine the contribution of the Allagash River to the pumped flow from Lincoln School Lake (paragraphs 39 and 44). The Allagash River water that is not pumped back contributes to the heat budget of Lincoln School Lake. The difference in the Lincoln School release temperature while allowing the pumpback of Allagash River water (using Equation 11) compared with not allowing any pumpback of Allagash water is plotted in Plate 7. This plot demonstrates the importance of providing a reasonable mathematical description of the advected heat into or out of Lincoln School Lake.

73. Physical understanding of the pumped flow characteristics was obtained from both the undistorted- and distorted-scale model results. Two basic features of the pumped flow are entrainment of Dickey Lake water into the pumpback jet and mixing within Dickey Lake created by the pumpback current. A description of these features was considered necessary to provide reasonable predictions of thermal profiles within Dickey Lake. The entrainment and pumpback mixing algorithms of the mathematical model did affect the development of thermal profiles in Dickey Lake. However, the effect of the entrainment phenomena (described in paragraphs 25 and 26) on the release temperature from Dickey Lake was very small (Plate 8a) and the effect on the release from Lincoln School Lake was practically undetectable (Plate 8b). With a

lake as large as Dickey, entrainment had a small effect on the thermal profile which resulted in an almost unnoticeable difference in the release temperature. The pumpback mixing algorithm discussed in Part IV (paragraphs 66-69) had an apparent warming effect (Plate 9a) on the Dickey release compared with the base condition of no mixing of the pumpback current within the Dickey thermal profile. This warming trend was damped in Lincoln School Lake as shown by Plate 9b. The pumpback current mixing technique resulted in a deepening of the metalimnion, thus providing a larger zone for the release of warm water. The spikes on the plots of Plates 8 and 9 are due to a mathematical anomaly resulting from a slight lead in the development of the thermal profile for the perturbed condition as compared with the base condition.

74. Simulations were conducted with pumpback over the gates and under the gates to evaluate the effect of pumpback location on release temperatures. Although some variation in the temperature profiles for the two conditions was observed, the differences in the release temperatures were negligible as shown by Plate 10. Therefore, these results indicate that there is no advantage to pumping back lower in the pool versus pumping back high (over the weir).

75. Definition of the selective withdrawal characteristics of Dickey Lake had by far the greatest impact on release temperatures. Variations in the pumpback characteristics only slightly affected release temperatures. This was attributed to the large volume of Dickey Lake and large zone of withdrawal that existed with the generation flows. The release temperature is a flow-weighted function of the temperatures within the zone of withdrawal; however, release temperature is less sensitive to variations in the temperature profile for a large withdrawal zone. For different release conditions causing a smaller withdrawal zone, variations in the temperature profile due to pumpback could cause more significant differences in release temperatures.

76. Simulations were conducted with the effects of the restrictive topography on selective withdrawal removed (paragraphs 16, 18, and 19) to determine the variation in release temperature from the base condition which includes the topographical effect. The perturbation

plot of Plate 11a demonstrates that the release temperatures from Dickey Lake are increased 1/2 to 2°C during the peak stratification season. This increase is damped in Lincoln School Lake to an increase of 1/2 to 1°C (Plate 11b). Comparison of Plates 5a and 11a shows that the topographical effect accounts for about half of the total variation from the condition of no selective withdrawal modifications. With excessive topographical contraction, selective withdrawal can be completely prevented as shown by Kao.[12] As mentioned previously, the topography only partially influenced selective withdrawal from Dickey Lake, and selective withdrawal was not eliminated.

77. Results of this model study and sensitivity analyses are unique to the Dickey-Lincoln School Lakes project and should not be interpreted to apply to other pumped-storage projects.

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Table 1

Operational Modes Tested

Operational Mode	Dickey Generation Flow	Pumpback Flow	Lincoln School Generation Flow*
3 conventional and 3 reversible turbines	60,000 cfs for 4.4 hr a day, 5 days per week, start at noon	20,000 cfs for 6 hr a night, 7 nights per week, start at 11 p.m.	16,000 cfs varied from 6 to 12 hr a day, 5 to 7 days per week, start at 9 to 11 a.m.
3 conventional and 1 reversible turbines	40,000 cfs for 4 hr a day, 5 days per week, start at noon	7,000 cfs for 6 hr a night, 7 nights per week, start at 11 p.m.	16,000 cfs varied from 6 to 12 hr a day, 5 to 7 days per week, start at 9 to 11 a.m.

* Lincoln School base generation flow was 1000 cfs for times not noted above. The duration and frequency of releases from Lincoln School Lake were dependent upon the magnitude of the Allagash inflow that was being simulated.

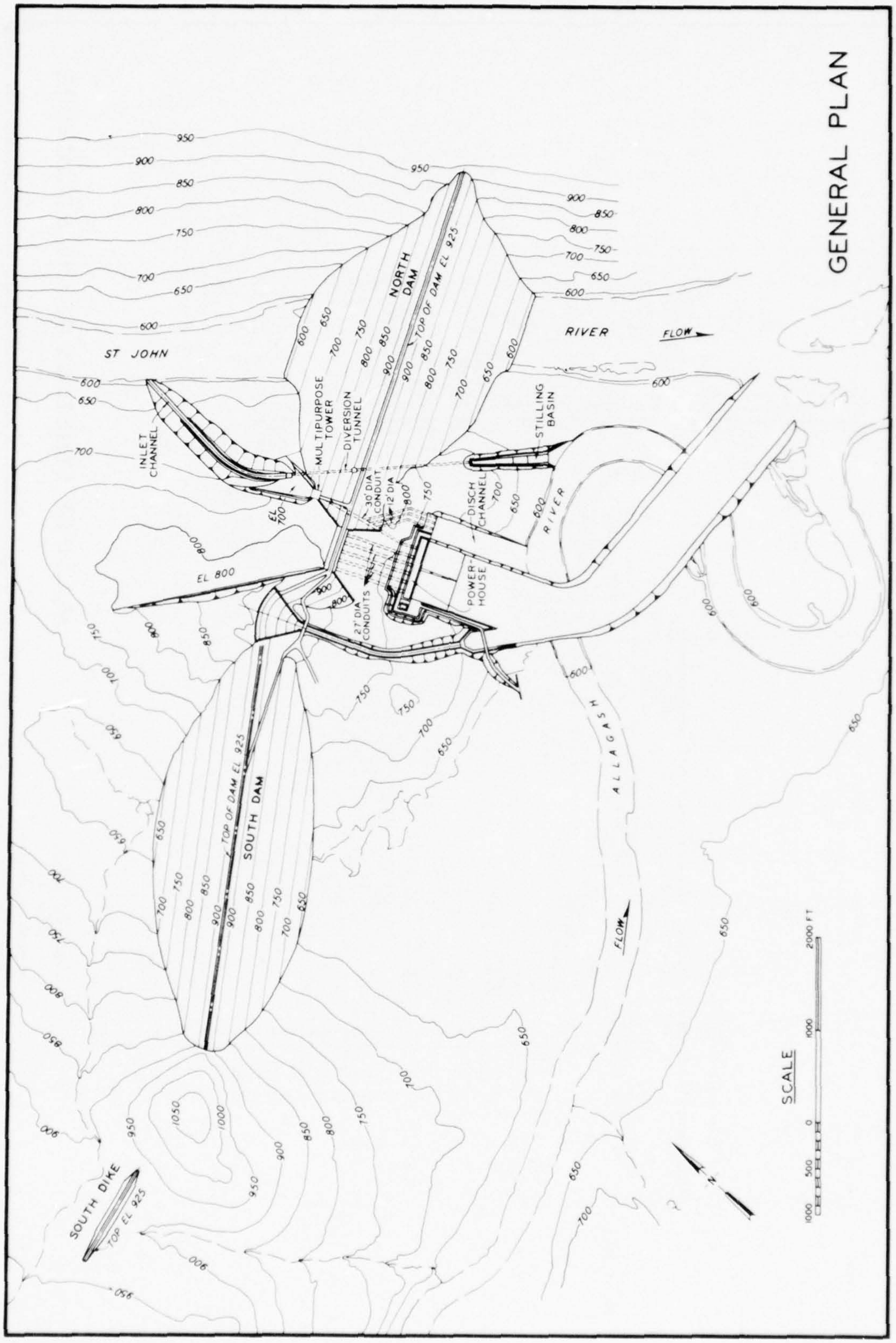
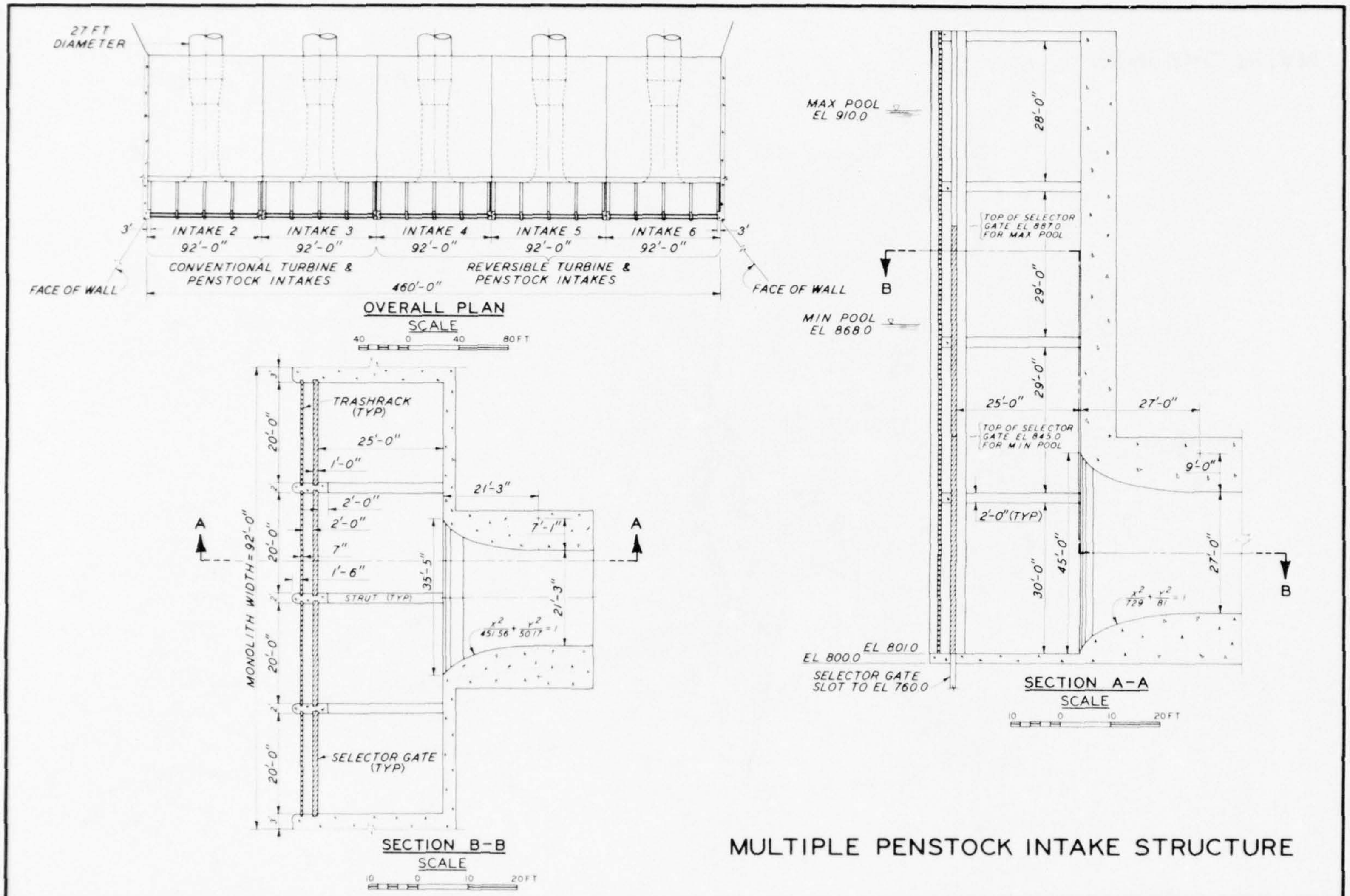
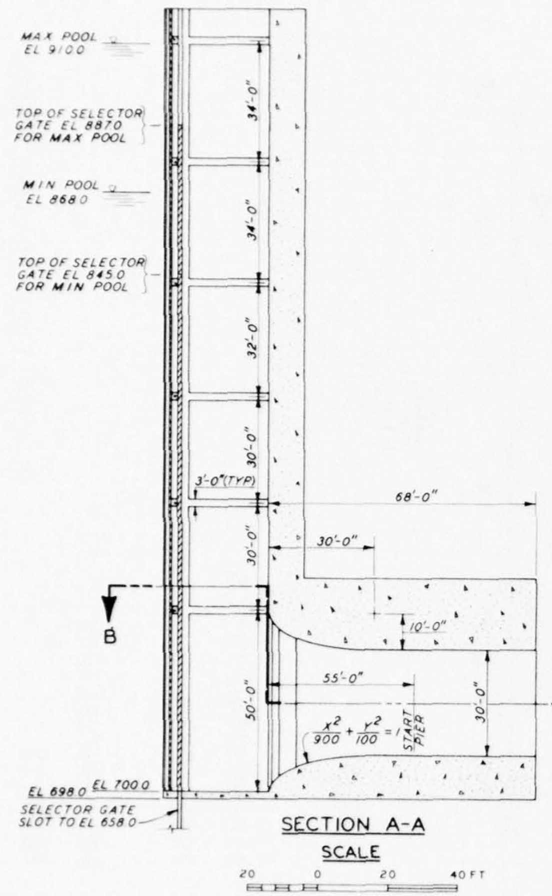

GENERAL PLAN
NORTH DAM
TOP OF DAM EL 925
SOUTH DAM
TOP OF DAM EL 925
SOUTH DIKE
TOP EL 925
ST JOHN
RIVER
FLOW
ALLAGASH
FLOW
INLET CHANNEL
MULTIPURPOSE TOWER
DIVERSION TUNNEL
30' DIA CONDUIT
12' DIA
27' DIA CONDUITS
POWER-HOUSE
DISCH CHANNEL
STILLING BASIN
EL 700
EL 800
SCALE
1000 500 0 1000 2000 FT
N

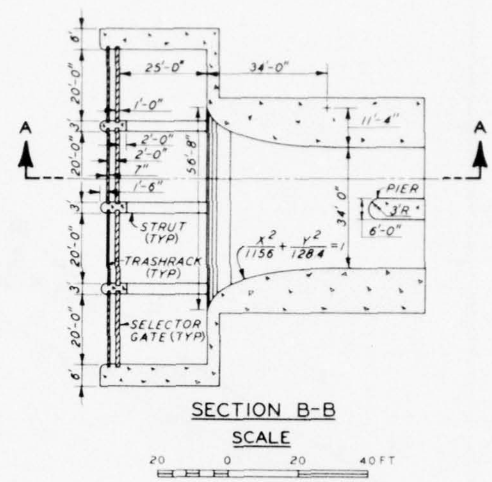
PLATE 1



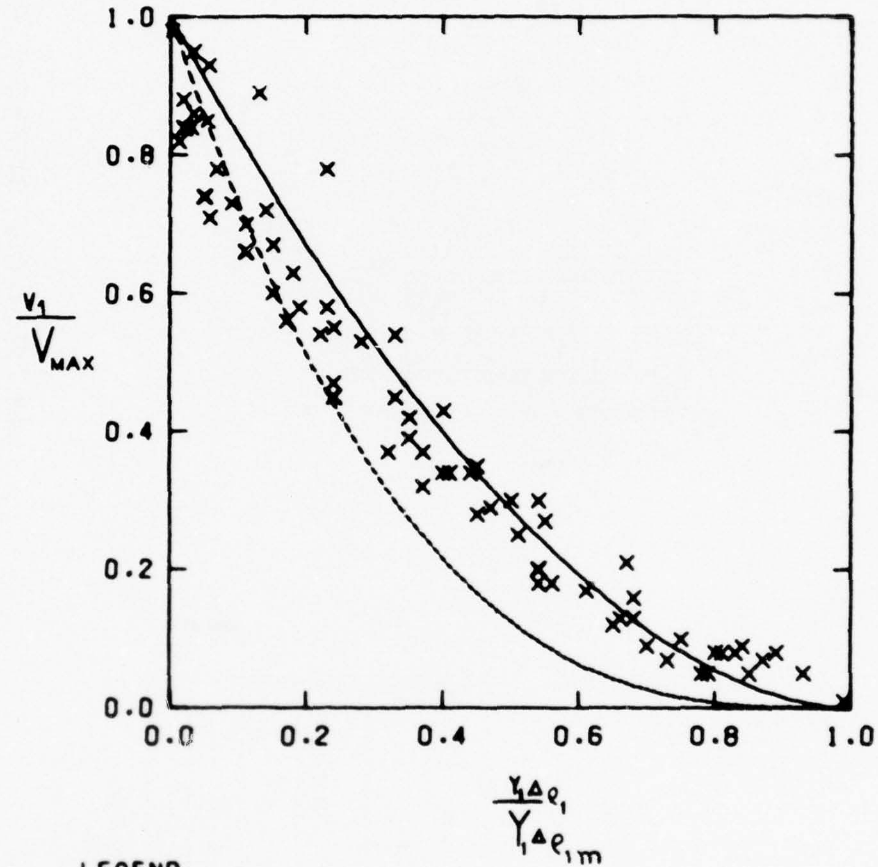
MULTIPLE PENSTOCK INTAKE STRUCTURE

PLATE 2





MULTIPURPOSE INTAKE STRUCTURE



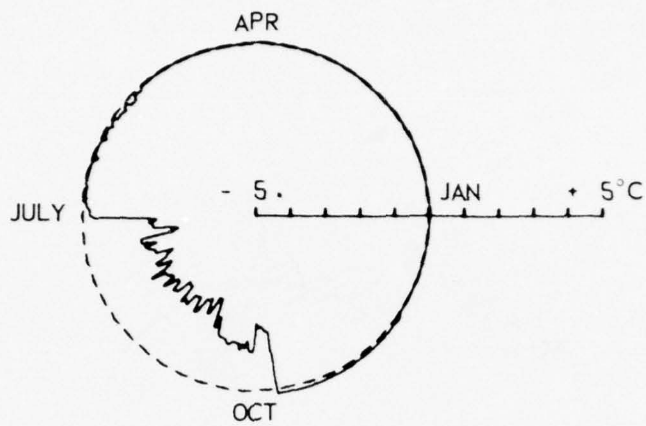
LEGEND

——— EXPONENTIAL FIT OF MODEL DATA

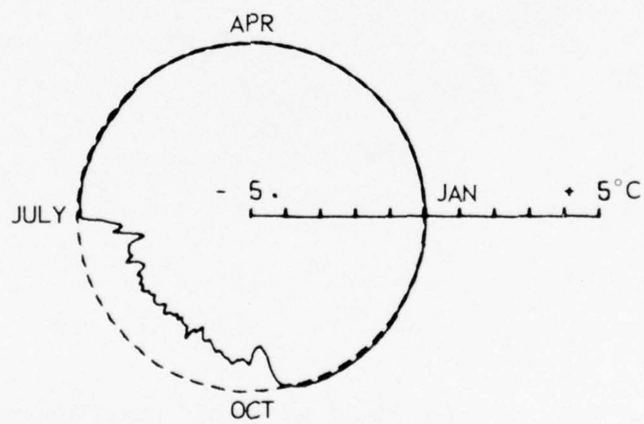
- - - - - WES GENERALIZED RESULTS

X - MODEL DATA

DICKEY LAKE INTAKES MODEL
DIMENSIONLESS VELOCITY
DISTRIBUTION



a. DICKEY LAKE

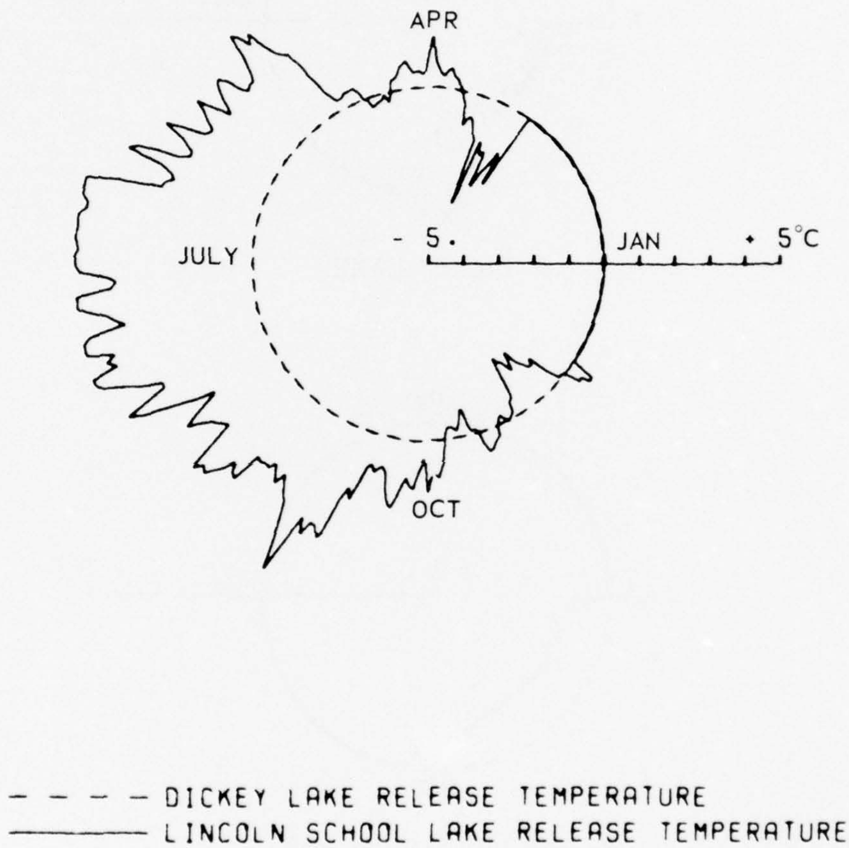


b. LINCOLN SCHOOL LAKE

– – – – NO SELECTIVE WITHDRAWAL MODIFICATIONS
——— ALL MODEL MODIFICATIONS

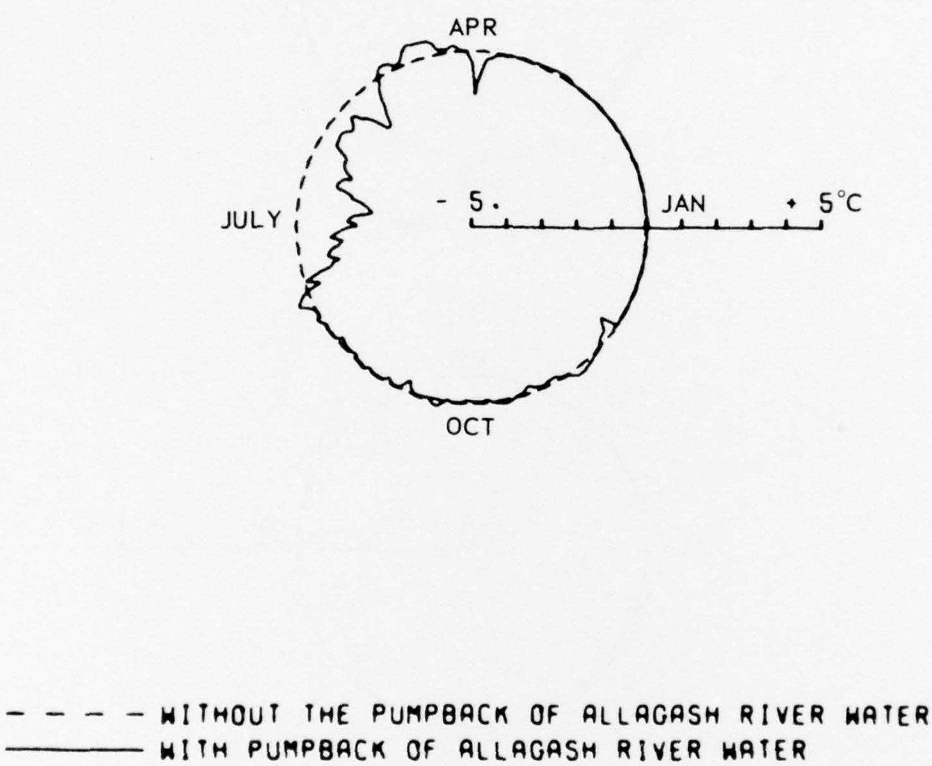
DICKEY-LINCOLN SCHOOL LAKES
RELEASE TEMPERATURES

WITH AND WITHOUT SELECTIVE WITHDRAWAL MODIFICATIONS



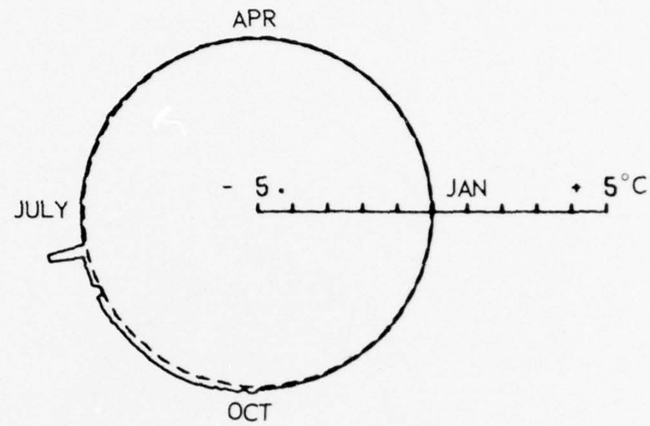
COMPARISON OF DICKEY AND LINCOLN SCHOOL LAKES RELEASE TEMPERATURES

WITH ALL MODEL MODIFICATIONS

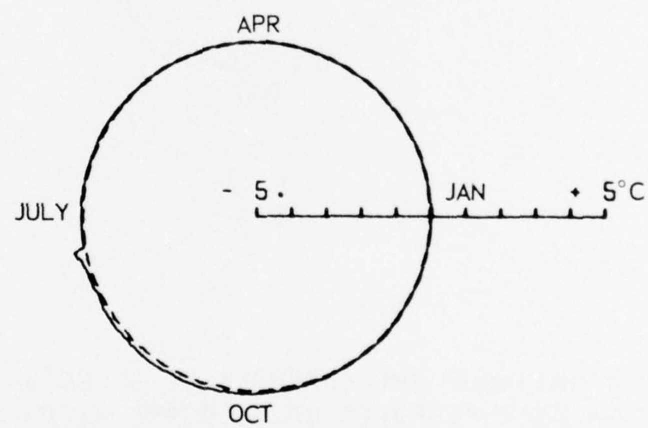


LINCOLN SCHOOL LAKE RELEASE TEMPERATURE

WITH AND WITHOUT THE PUMPBACK OF ALLAGASH RIVER WATER



a. DICKEY LAKE

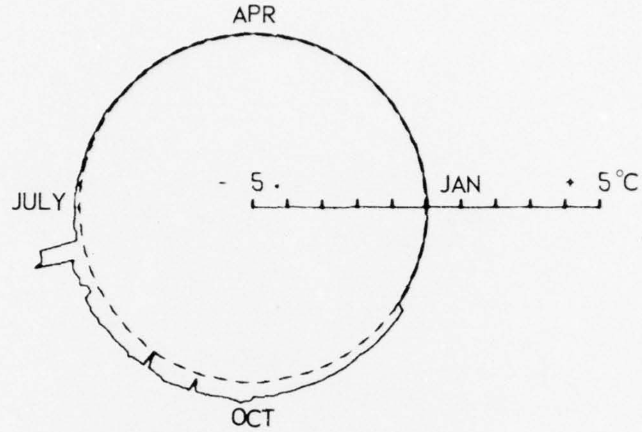


b. LINCOLN SCHOOL LAKE

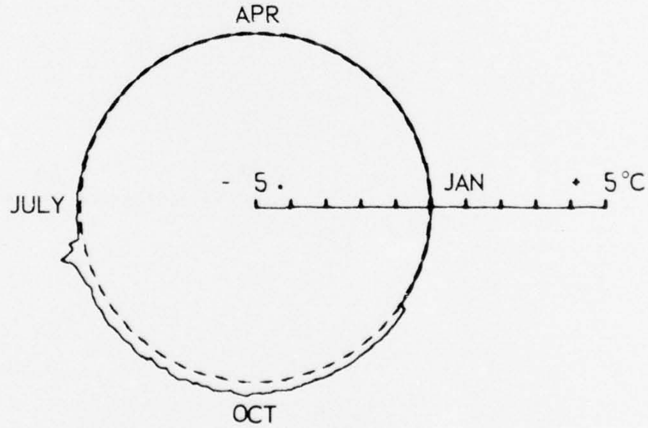
– – – – PUMPBACK WITHOUT ENTRAINMENT
———— PUMPBACK WITH ENTRAINMENT

DICKEY-LINCOLN SCHOOL LAKES
RELEASE TEMPERATURES

PUMPBACK WITH AND WITHOUT ENTRAINMENT



a. DICKEY LAKE

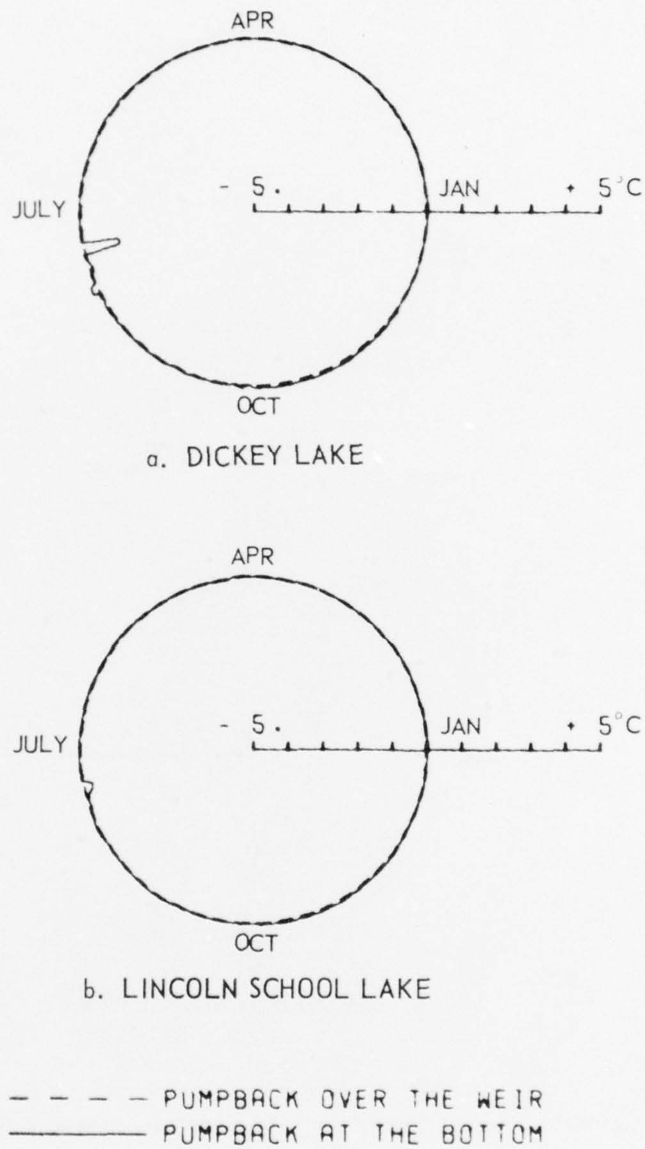


b. LINCOLN SCHOOL LAKE

- - - - WITHOUT MIXING OF PUMPBACK CURRENT
——— WITH MIXING OF PUMPBACK CURRENT

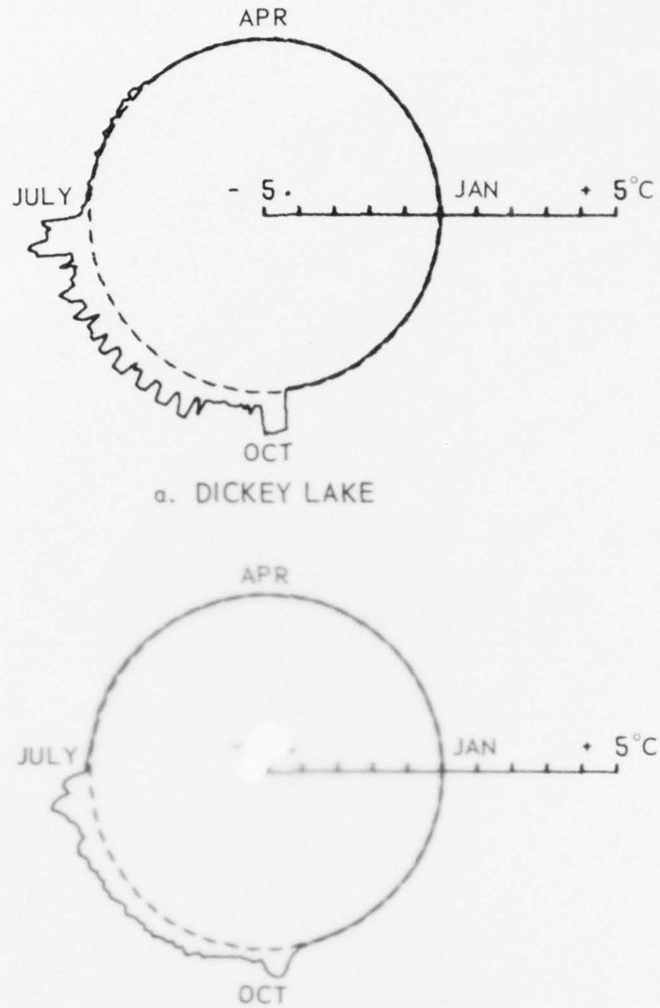
DICKEY-LINCOLN SCHOOL LAKES
RELEASE TEMPERATURES

WITH AND WITHOUT MIXING OF PUMPBACK CURRENT



DICKEY-LINCOLN SCHOOL LAKES
RELEASE TEMPERATURES

PUMPBACK OVER THE WEIR AND
AT THE BOTTOM



a. DICKEY LAKE

b. LINCOLN SCHOOL LAKE

- - - - WITH EFFECT OF TOPOGRAPHY
——— WITHOUT EFFECT OF TOPOGRAPHY

DICKEY-LINCOLN SCHOOL LAKES RELEASE TEMPERATURES

WITH AND WITHOUT TOPOGRAPHICAL EFFECT ON SELECTIVE WITHDRAWAL

APPENDIX A: TIME STEP FOR HEAT EXCHANGE COMPUTATIONS

1. The purpose of this analysis was to determine the appropriate time step for applying the surface heat exchange in the numerical simulation model. Conventionally, one-dimensional reservoir thermal simulation models employ a daily time step. Harleman and Hurley[13*] compared three hourly and daily surface heat exchange inputs in a one-dimensional model. They found variations in surface temperatures of 2-3°C over a day. Additionally, they noted that diurnal temperature fluctuations affected primarily the upper 2-4 m of the lake. Their results showed that the surface temperatures and thermal profiles based on three hourly inputs fluctuated about the values predicted with average daily input. Since the mathematical model for Dickey-Lincoln School Lakes incorporates the simulation of generation and pumpback with a time step less than one day, the need for a similar time step for surface heat exchange input was evaluated.

2. Numerical simulations of Dickey Lake were made using an hourly and a daily time step for surface heat exchange input. Plate A1 shows daily values and mean hourly values (24-hr period) of Dickey Lake release temperatures. Plate A2 compares typical thermal profiles for the daily time step with selected hourly profiles. Plate A3 shows, for one simulation day, the fluctuations of the hourly surface temperatures about the daily value. Plate A4 shows, for a stratification period, the fluctuations of the mean hourly release temperatures compared with the daily values. Analysis of these results yielded conclusions similar to those of Harleman and Hurley.[13] The effects of the hourly time step were small and restricted to the upper portion of the profile. The effect on the release temperature from Dickey Lake was minimal.

3. Based on the results of the simulation, a daily time step was chosen for surface heat exchange input for the Dickey-Lincoln School numerical model. Since this model computes the effect of individual processes on the total heat budget of the lake and then applies these

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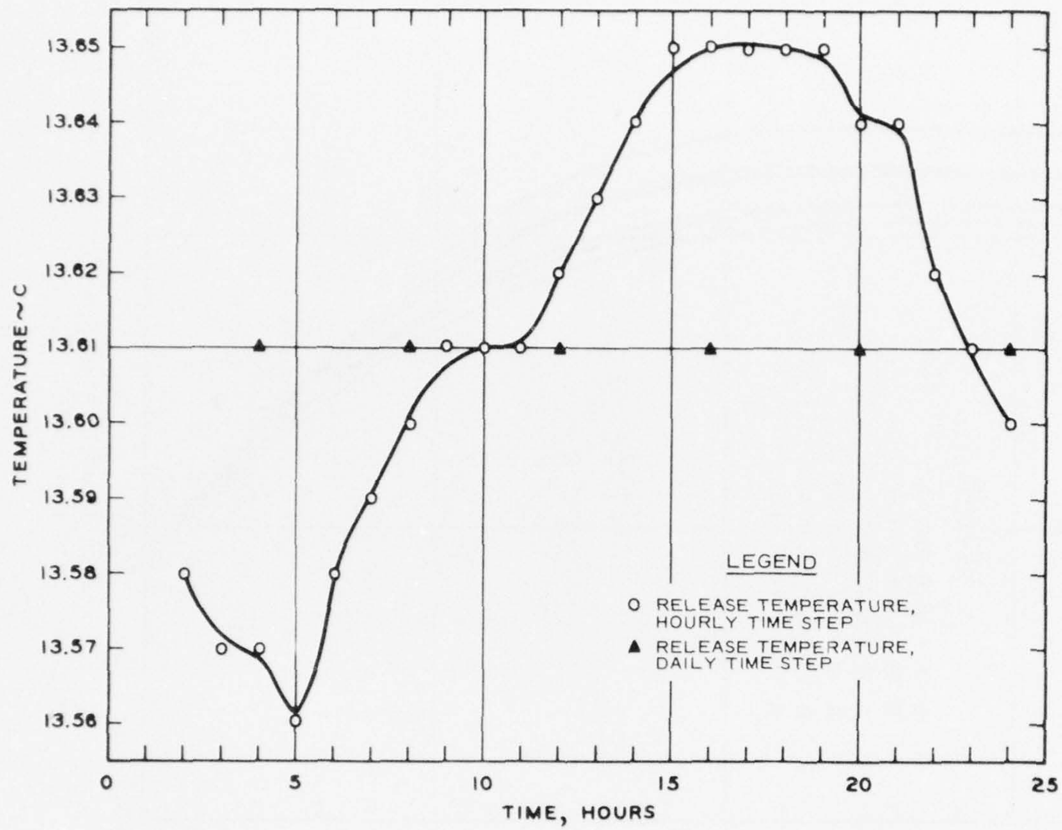
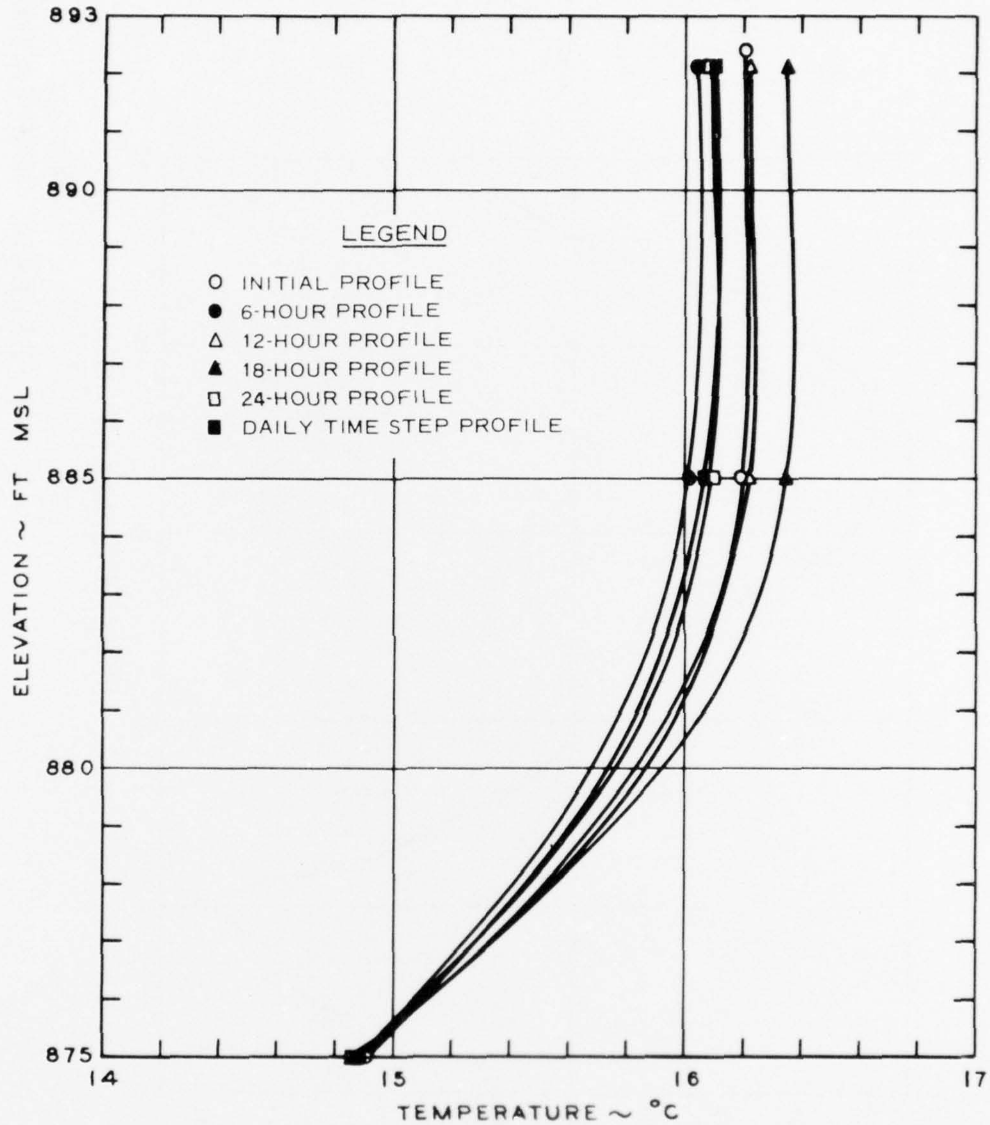
* See references at end of main text.

effects sequentially, the model can easily handle different time steps for each process. This means that a daily time step for surface heat exchange input and a shorter time step for generation or pumpback can be used. Additionally, the use of a daily time step versus a shorter time step for surface heat exchange input results in a computational time savings and a reduction in input data requirements. If surface heat exchange input were to be required for a time step less than daily, that input (equilibrium temperatures and exchange coefficients) would have to be derived from daily values. This derivation would be accomplished by curve-fitting an assumed functional relationship to the daily values.[14] The computed hourly input may or may not be representative of the actual hourly fluctuations. Finally, these functional relationships ensure that the hourly values fluctuate symmetrically about the daily average value.



DICKEY LAKE

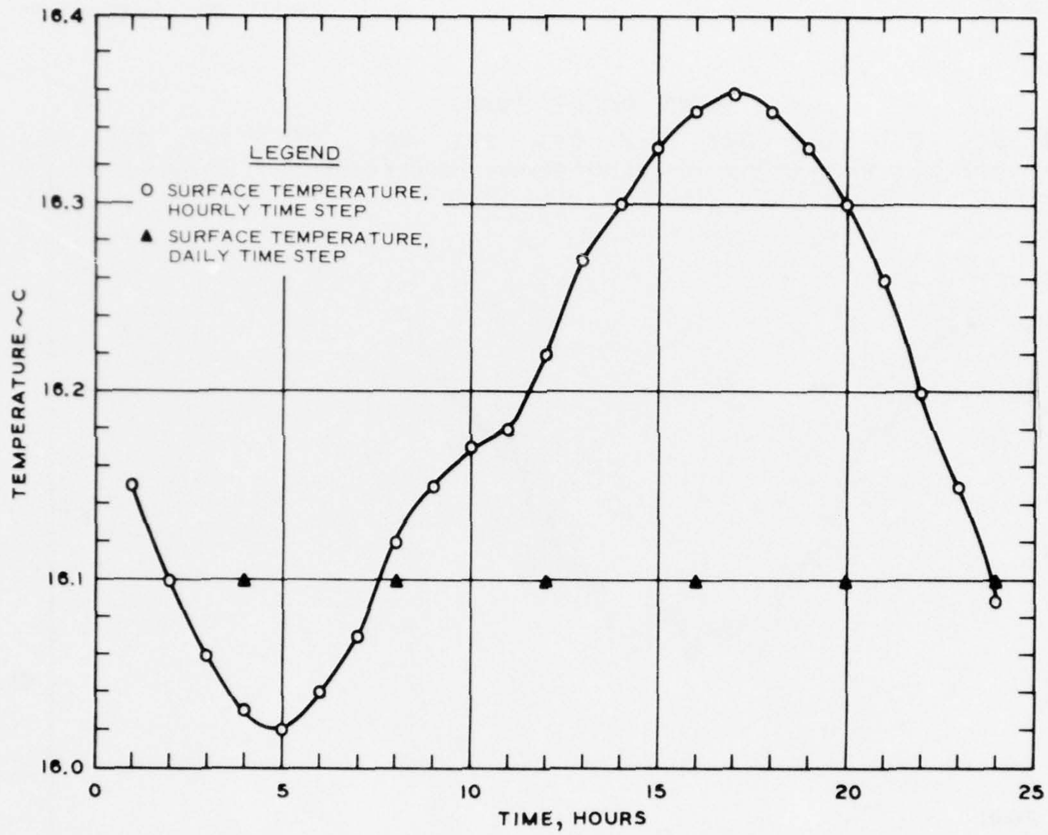
RELEASE TEMPERATURES



DICKEY LAKE

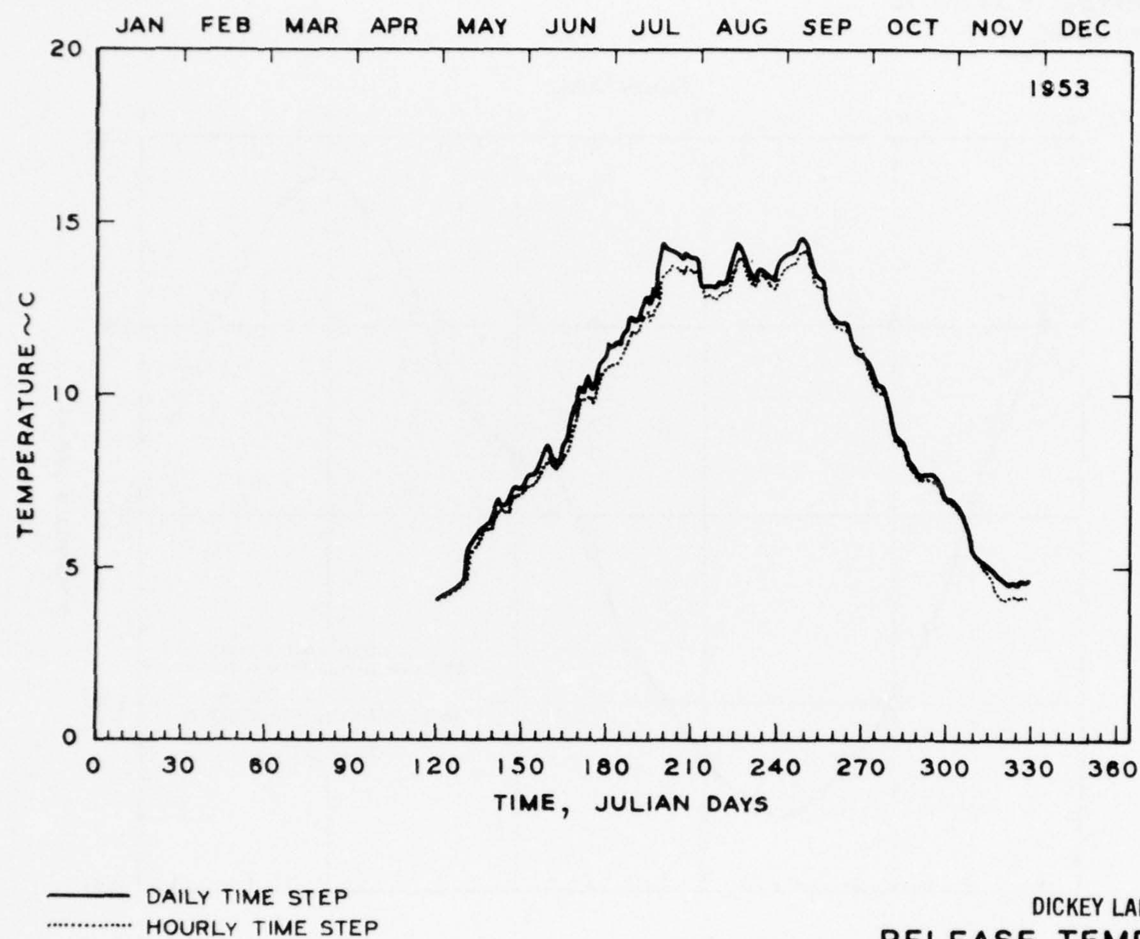
VARIATION OF TEMPERATURE PROFILE OVER 24 HOURS

PLATE A2



DICKEY LAKE

SURFACE TEMPERATURES



DICKEY LAKE

RELEASE TEMPERATURE

APPENDIX B: NOTATION

A	0.067 for 3 reversible units; 0.033 for 1 reversible unit
b	Weir length, ft
B	0.118
D	Interflow thickness at a particular station, ft
e	Natural logarithmic base (2.7183)
E	Equilibrium temperature, °F
g	Acceleration due to gravity, 32.2 ft/sec^2
H	Net rate of surface heat transfer, Btu/ft^2/day
H_i	Rate of heat absorbed in layer i, Btu/ft^2/day
H_s	Heat transfer rate into or out of surface layer, Btu/ft^2/day
H_w	Head on the weir for free flow or depth of flow over the weir for submerged flow, ft
i	Layer
K	Coefficient of surface heat exchange, Btu/ft^2/day/°F
p	Exponent in the selective withdrawal dimensionless velocity distribution equation
Q	Discharge over weir, cfs
Q_c	Volume flow rate of the pumpback current, cfs
Q_e	Volume rate of the entrained flow, cfs
Q_o	Volume flow rate of water pumped, cfs
Q_A	Allagash River inflow, 1000 acre-ft/day
S	Total incoming shortwave radiation rate, Btu/ft^2/day
v_1	Local velocity in the zone of withdrawal at a distance y_1 below the elevation of the maximum velocity V_{max}, fps
v_2	Local velocity in the zone of withdrawal at a distance y_2 above the elevation of the maximum velocity V_{max}, fps
V_{max}	Maximum velocity in the zone of withdrawal, fps
V_w	Average velocity over the weir, fps
W	Average reservoir width at the elevation of the pumpback current in the vicinity of the dam, ft
X_i	Vertical distance from the pumpback current inflow layer to layer i, ft
y_1	Vertical distance from the elevation of the maximum velocity V_{max} to that of the corresponding local velocity v_1, ft

y_2	Vertical distance from the elevation of the maximum velocity V_{max} to that of the corresponding local velocity v_2, ft
Y_1	Vertical distance from the elevation of the maximum velocity to the lower limit of withdrawal, ft
Y_2	Vertical distance from the elevation of the maximum velocity to the upper limit of withdrawal or the free surface for weir flow, ft
Y_1'	Modified vertical distance from the elevation of the maximum velocity to the lower limit of withdrawal, ft
z_i	Depth below surface, ft
Z_o	Vertical distance from the elevation of the weir crest to the lower limit of the zone of withdrawal, ft
β	Shortwave radiation absorbed in the surface layer, percent
Δt	Pumping period
$\Delta\rho$	Density difference of the epilimnion and hypolimnion, g/cc
$\Delta\rho_1$	Density difference of fluid between the elevations of the maximum velocity and the corresponding local velocity v_1, g/cc
$\Delta\rho_{1m}$	Density difference of fluid between the elevations of the maximum velocity and the lower limit of the zone of withdrawal, g/cc
$\Delta\rho_w$	Density difference of fluid between the elevations of the weir crest and the lower limit of the zone of withdrawal, g/cc
ε	Entrainment coefficient
η_i	Mixing coefficient
θ	Surface temperature, ^oF
λ	Heat absorption coefficient, ft^{-1}
ρ_c	Average density of the pumpback current, g/cc
ρ_e	Average density of the entrained flow, g/cc
ρ_o	Density of the pumped water, g/cc
ρ_w	Density of fluid at the elevation of the weir crest, g/cc
σ	Percent of Allagash River water to the total pumped flow

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.

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Dickey-Lincoln School Lakes hydrothermal model study; hydraulic laboratory investigation, by Mark S. Dortch, Bruce Loftis, Darrell G. Fontane, [and] Steven C. Wilhelms. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report H-76-22)
Prepared for U. S. Army Engineer Division, New England, Waltham, Massachusetts.
Includes bibliography.

1. Dickey-Lincoln School Lakes. 2. Hydraulic models. 3. Mathematical models. 4. Pumped storage. 5. Reservoir systems. 6. Stratified flow. 7. Thermal stratification. 8. Water temperature. I. Fontane, Darrell G., joint author. II. Loftis, Bruce, joint author. III. Wilhelms, Steven C., joint author. IV. U. S. Army Engineer Division, New England. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report H-76-22)
TA7.W34 no.H-76-22