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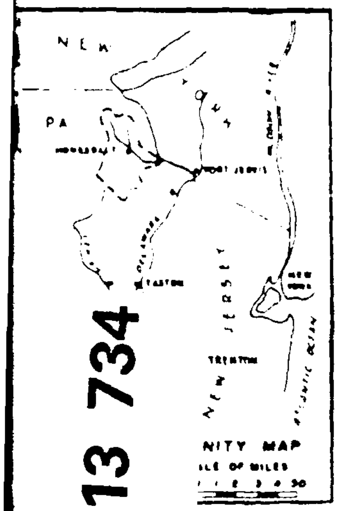

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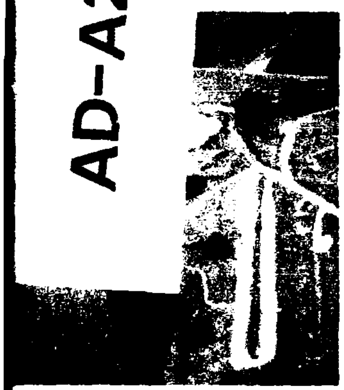

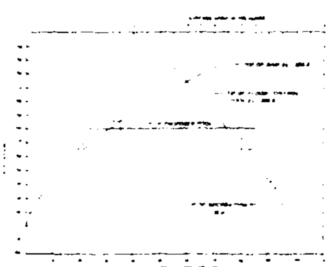

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TECHNICAL REPORT HL-89-20

THERMAL ANALYSIS OF PROMPTON RESERVOIR MODIFICATION, PENNSYLVANIA

Numerical Model Investigation

by

Richard E. Price, Jeffery P. Holland

Hydraulics Laboratory

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

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Hydrologic studies of the Delaware River Estuary have indicated that during low flow or drought periods, excessive salinity intrusion into the estuary may threaten water supplies in the Delaware River Basin. To assist in the prevention of this excessive salinity intrusion, additional water supply storage to Prompton Reservoir has been proposed. This additional storage would raise the pool and possibly affect the thermal stratification and subsequent release temperature from the dam. To address this concern, a one-dimensional numerical model was used to simulate existing conditions and conditions with the proposed pool modification. An optimization routine coupled to the model was used to identify the optimum number and location of ports to maintain release temperatures within the State of Pennsylvania Water Quality Criteria.

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19. ABSTRACT (Continued).

Results of the numerical simulations indicated a three-port structure with the ability to operate two ports simultaneously would meet the release criteria during a normal year. However, during a dry or drought year when the pool would be drawn down to meet downstream flow demands, a significant drop in the release temperature was predicted. To prevent this drop, two additional alternatives were examined: a submerged weir and lake destratification. The submerged weir did not improve the release temperature condition, but the destratification system when operated during the spring and early summer months did maintain release temperatures within criteria limits.

The recommendations for this study were a three-port structure with the ability to operate two ports simultaneously and a destratification system to be operated during years in which the water supply storage is used.

PREFACE

The numerical model investigation of the Prompton Reservoir, Pennsylvania, reported herein, was conducted by the US Army Engineer Waterways Experiment Station (WES) at the request of the US Army Engineer District, Philadelphia.

The investigation was conducted during the period October 1986 to May 1988 in the Hydraulics Laboratory (HL), WES, under the direction of Messrs. F. A. Herrmann, Jr., Chief, HL; J. L. Grace, Jr., former Chief, Hydraulics Structures Division (HSD); and G. A. Pickering, Chief, HSD; and under the direct supervision of Dr. J. P. Holland, Chief, Reservoir Water Quality Branch (RWQB). This report was prepared by Dr. R. E. Price, RWQB, and Dr. Holland and edited by Mrs. M. C. Gay, Information Technology Laboratory, WES.

Acting Commander and Director of WES during preparation of this report was LTC Jack R. Stephens, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
gallons	3.785412	cubic decimetres
horsepower (550 foot-pounds (force) per second)	745.6999	watts
miles (US statute)	1.609347	kilometres

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

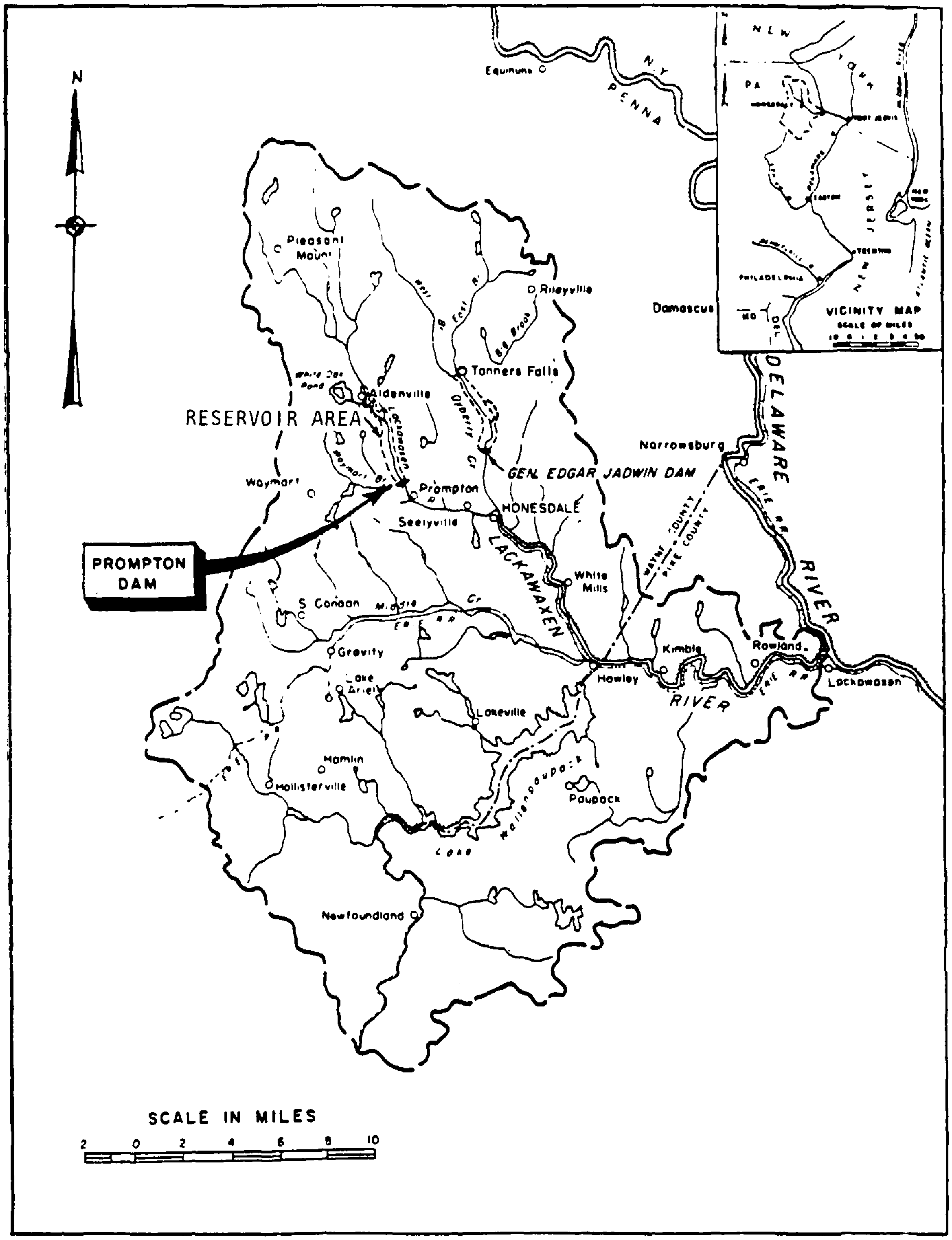

Figure 1. Location map for Prompton Reservoir

THERMAL ANALYSIS OF PROMPTON RESERVOIR MODIFICATION, PENNSYLVANIA

Numerical Model Investigation

PART I: INTRODUCTION

Background

1. Prompton Dam and Reservoir, which was authorized by the US Congress on 30 June 1948 to provide flood control on the Lackawaxen River, Pennsylvania, is located on the west branch of the Lackawaxen River 31 miles* above the confluence with the Delaware River in northeastern Pennsylvania (Figure 1). The existing 1,200-ft-long zoned earth-fill dam reaches a height of 140 ft above the streambed. The spillway, which is an uncontrolled perched-type open channel, is 50 ft wide at el 1205** with a maximum discharge capacity of 9,200 cfs. Normal releases are currently passed over a 30-ft weir at el 1125 and through an ungated morning-glory type drop inlet structure. A low-level coolwater intake with an invert located at el 1091 leads up to a low-level weir located in the center of the main weir. This 10-ft-wide low-flow weir has its crest at el 1122.8 and provides coolwater releases when the reservoir pool is between el 1125.0 and el 1122.8. The conduit through the dam has a maximum discharge capacity of 3,500 cfs. The existing outlet structure is shown in Figure 2.

2. Since the current project is ungated and therefore uncontrolled, no operation is required for the pool to remain at a constant elevation. Inflows from storm events cause a rise in the pool, but the normal pool is usually reached in a few days.

3. The west branch of the Lackawaxen River is classified by the State of Pennsylvania as high-quality water and is stocked with trout. A routine water quality monitoring program conducted by the US Army Engineer District, Philadelphia, also indicates that the existing reservoir water is of excellent

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* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

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

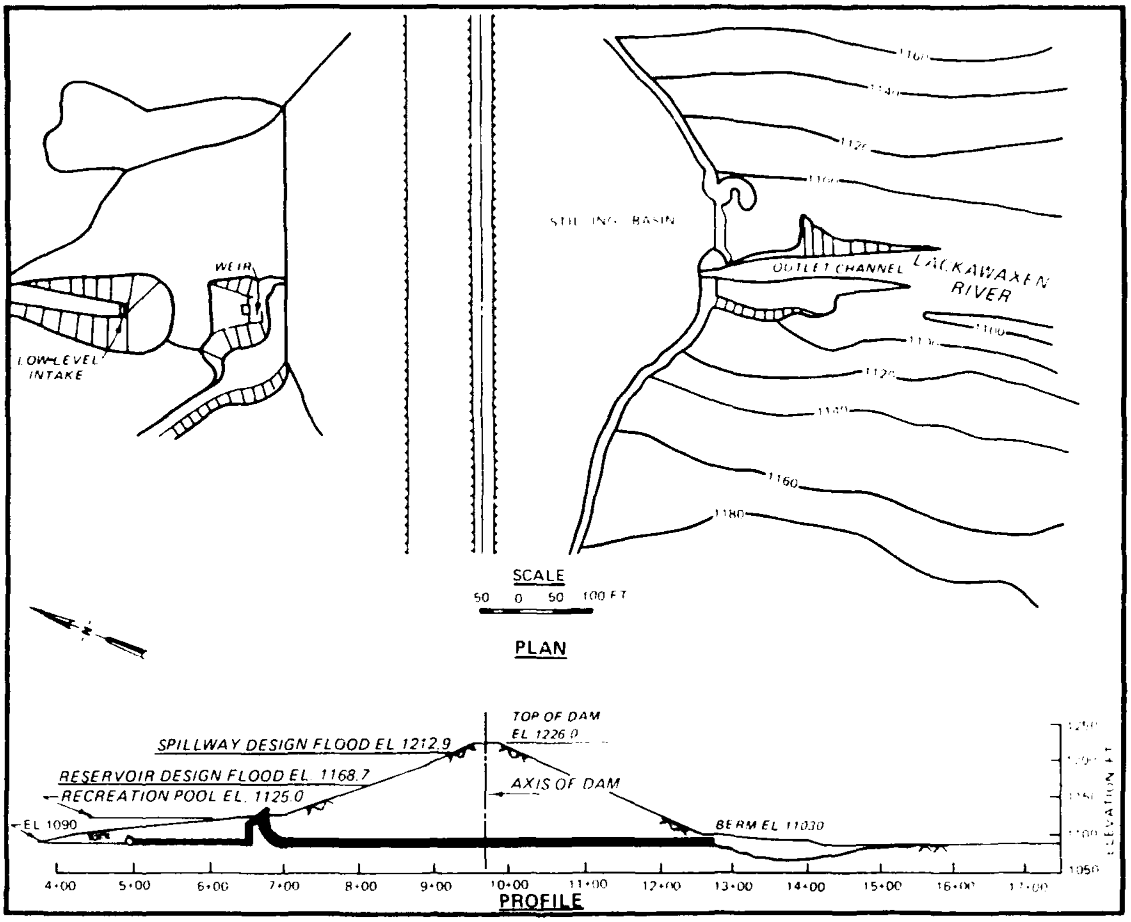

Figure 2. Plan and profile of existing outlet structure

quality. Water quality of the reservoir meets the Pennsylvania Department of Environmental Resources standards.

4. Hydrologic studies of the Delaware River Estuary conducted by the Philadelphia District indicated that during low flow or drought periods, excessive salinity intrusion into the estuary from the Delaware Bay to Trenton, NJ, would be possible. This excessive salinity intrusion would threaten both municipal and industrial water supplies in the Delaware River Basin. Therefore, a 3,000-cfs minimum flow objective at Trenton was deemed to be necessary by the Delaware River Basin Commission (DRBC) to prevent this excessive salinity intrusion. According to the Philadelphia District, the present reservoir storage capacity in the Delaware River Basin is not adequate to meet this low-flow objective. Given this, the DRBC felt a modification of Prompton Reservoir to increase water supply storage would help to meet the need for a 3,000-cfs minimum flow at Trenton to repulse the excessive salinity intrusion.

This increase would require raising the Prompton pool approximately 55 ft from el 1125 to el 1180, thereby adding 31,000 acre-ft of water for water supply (Figure 3). The DRBC could then request specific releases from Prompton Reservoir depending on flow conditions in the Delaware River at Trenton.

5. Concerns about raising the pool center on the impacts to the reservoir thermal stratification and on release temperature. Previous studies by Schneider and Price (1988) and Holland (1982) involving reallocation of water storage resources for water supply at different projects recommended additional selective withdrawal (SW) capability to maintain downstream temperature objectives. Since the Philadelphia District has determined that a new structure must be added to the Prompton project to provide operational control over releases, SW capability may be required to enable the selection of the temperature of release water to meet State standards. The vertical location of the desired temperature in the pool for release downstream will vary depending upon the depth of the pool, degree of thermal stratification, and time of year. Therefore simulation of the proposed operating conditions was necessary to identify design criteria for the suggested outlet structure.

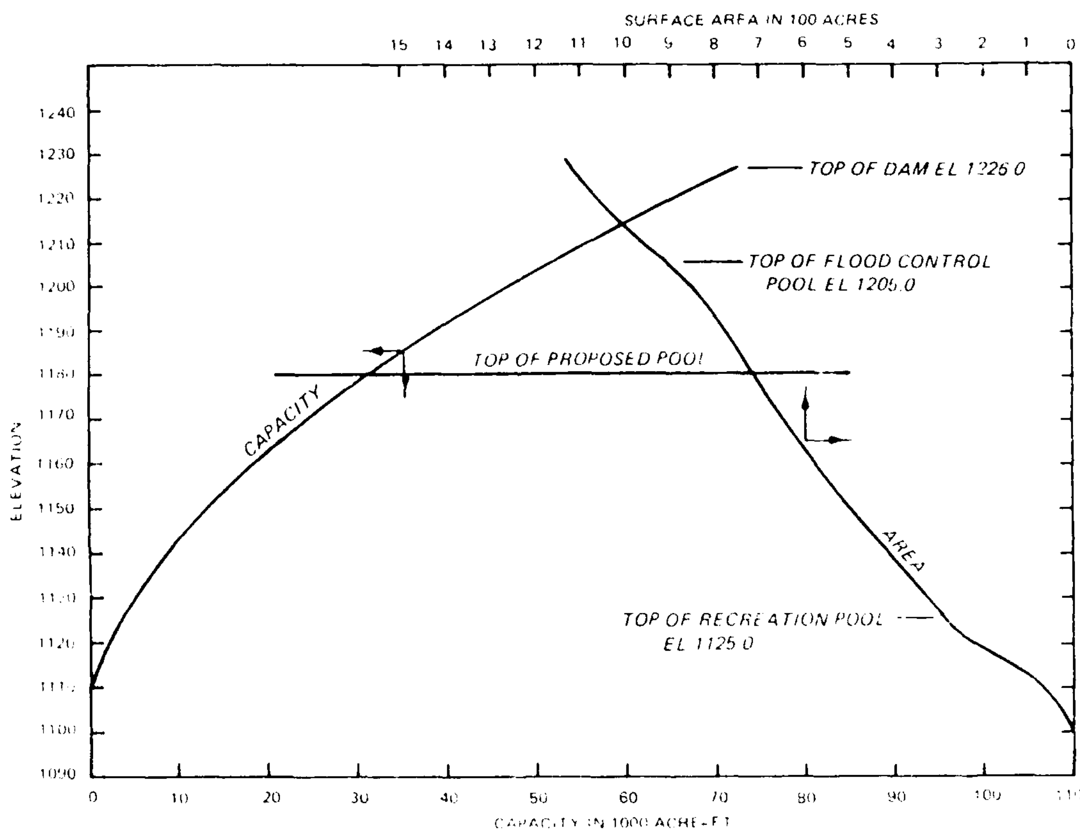

Figure 3. Capacity-area curve for Prompton Reservoir

Purpose and Scope

6. The Philadelphia District is currently investigating the modification of Prompton Dam to add the storage discussed in paragraph 4 for water supply and recreation purposes. This modification would raise the existing normal pool (3,355 acre-ft) from 35 ft deep (el 1125) to approximately 90 ft. Since the existing release structure consists of an uncontrolled weir at el 1125, a modification to the existing structure is necessary to provide the additional storage as well as the capability to release water on demand. To maintain release temperatures in accordance with State standards, the Philadelphia District determined that an SW structure was necessary.

7. This investigation was undertaken to identify the capacity, number, and location of SW ports in the modified structure to release temperatures within the criteria set by the State of Pennsylvania. This simulation used a numerical thermal simulation model coupled with numerical optimization routines. Adjustment of SW parameters (withdrawal angle) in the numerical model was made based on results obtained in a physical model. Various port configurations and capacities were then simulated to determine the optimum structure design for the given objective.

PART II: MATHEMATICAL METHODOLOGY

8. The in-lake and release temperature characteristics for Prompton Reservoir were modeled using a one-dimensional thermal simulation model. The model WESTEX, which was developed at the US Army Engineer Waterways Experiment Station (WES), was used to examine the balance of thermal energy within the reservoir. This one-dimensional model includes computational methods for predicting dynamic changes in thermal content of a body of water through simulation of heat transfer at the air-water interface, heat advection due to inflows and outflows, and internal dispersion of thermal energy. The reservoir is conceptualized as a series of homogeneous layers stacked vertically. The time-history of thermal energy in each layer is determined through solving for conservation of mass and energy at each time increment subject to an equation of state regarding density. The boundary conditions at the water surface and inflow and outflow regions are required to conduct these simulations. A numerical procedure for the withdrawal zone computation allows prediction of release temperature. Mathematical optimization routines are also coupled to this model enabling the systematic evaluation of optimal outlet configurations subject to specified release water temperature objectives. A more detailed discussion of the WESTEX model may be found in Holland (1982).

Thermal Model Inputs

9. The WESTEX model requires input data on the physical, meteorological, and hydrologic characteristics of Prompton Reservoir for each study year. Further, initial verification of the model requires determination of appropriate surface exchange and internal mixing coefficients. This verification procedure and the various inputs to the thermal model are described in the following paragraphs for this study.

Study Years

10. The years studied in this investigation were determined in consultation with the Philadelphia District and were based on inflow during the spring of each year. Along with normal hydrologic conditions, extreme conditions such as drought or flood periods should be modeled since these may

present the most difficulty in meeting State standards. Therefore, 1983 was chosen as an average year (84,275 acre-ft total inflow), 1984 as a wet year (89,619 acre-ft total inflow), and 1985 as a dry year (61,861 acre-ft total inflow). The daily inflow for these years is shown in Figure 4. Since the outlet operates as an uncontrolled weir, release quantity is based on pool elevation, which, in turn, is based on inflow quantity. Therefore, release rate traces the inflow rate. The impacts of meteorological and hydrologic conditions on the thermal stratification for each year are shown in Figure 5. In 1983, a typical stratification developed with the onset of summer, but the 1984 hydrologic conditions (high-flow year) prevented a significant level of stratification from developing. The 1985 conditions (dry year) permitted a strong stratification pattern to develop. Simulations during initial model verification were run from January through December, although optimization simulations were run only between 1 April and 1 December. During the 1 December to 15 February period the lake was isothermal; therefore, release temperature was not affected by port location. Subsequently, the releases during the period were unaffected by the SW design and were not included in the design optimization.

Meteorological Data

11. Meteorological data required by the WESTEX model consist of daily average values for air temperature, dew point, wind speed, and cloud cover. These data are available from the National Oceanic and Atmospheric Administration Local Climatological Data Monthly Summaries, which were provided by the Philadelphia District. The station used in the study was the Wilkes-Barre/ Scranton Airport weather station. In addition, daily air temperature during the week was available at Prompton Reservoir. Equilibrium temperatures, surface heat exchange coefficients, and daily average solar radiation quantities for the years of study were computed using the HEATEX program (Eiker 1977).

Release Temperature Criteria

12. The release temperature criteria* for Prompton Reservoir as set by the State of Pennsylvania are as follows:

* Personal communication, 30 November 1987, from Mr. Dave Erickson, US Army Engineer District, Philadelphia, Philadelphia, PA.

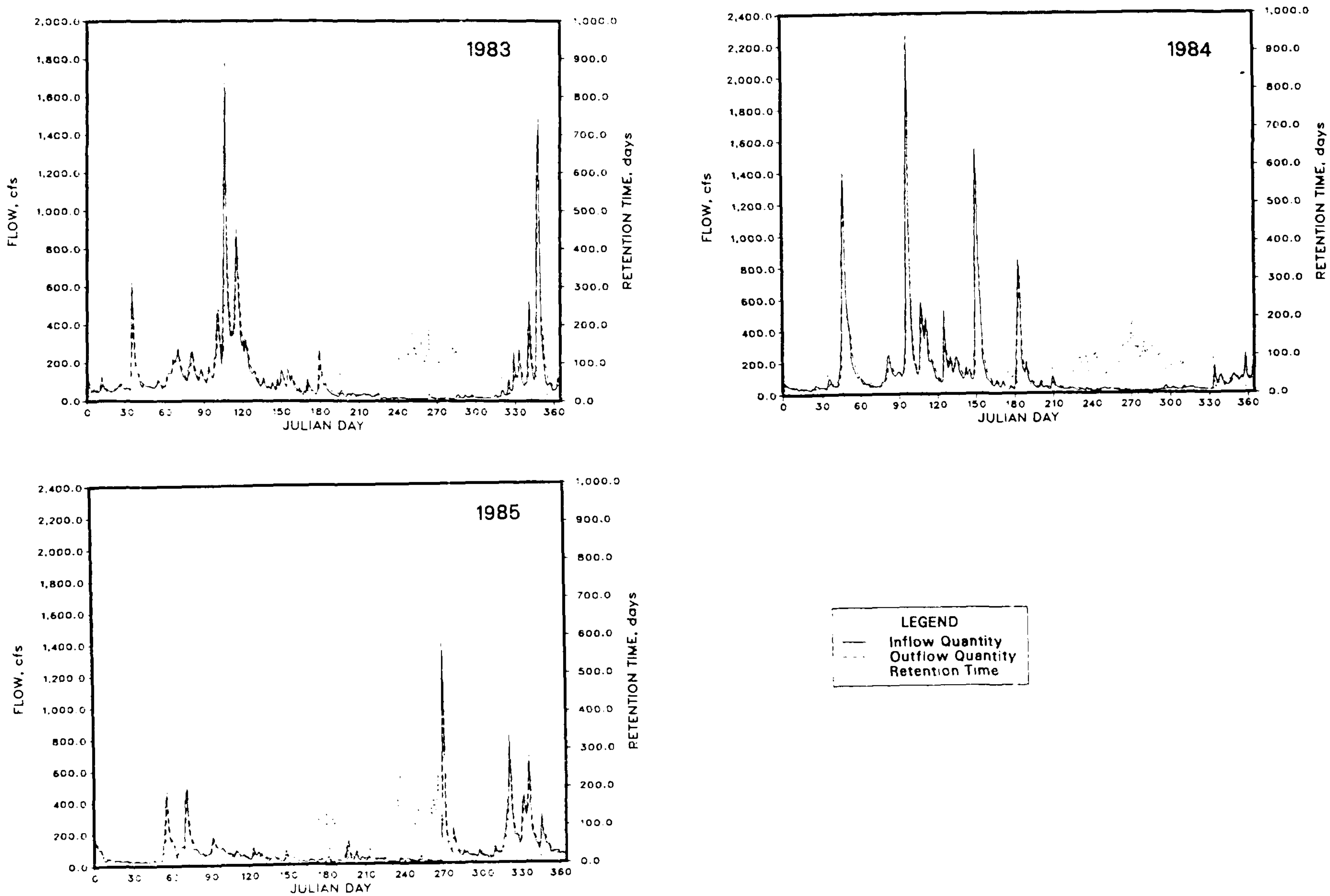

Figure 4. Daily inflow and outflow quantity for Prompton Reservoir

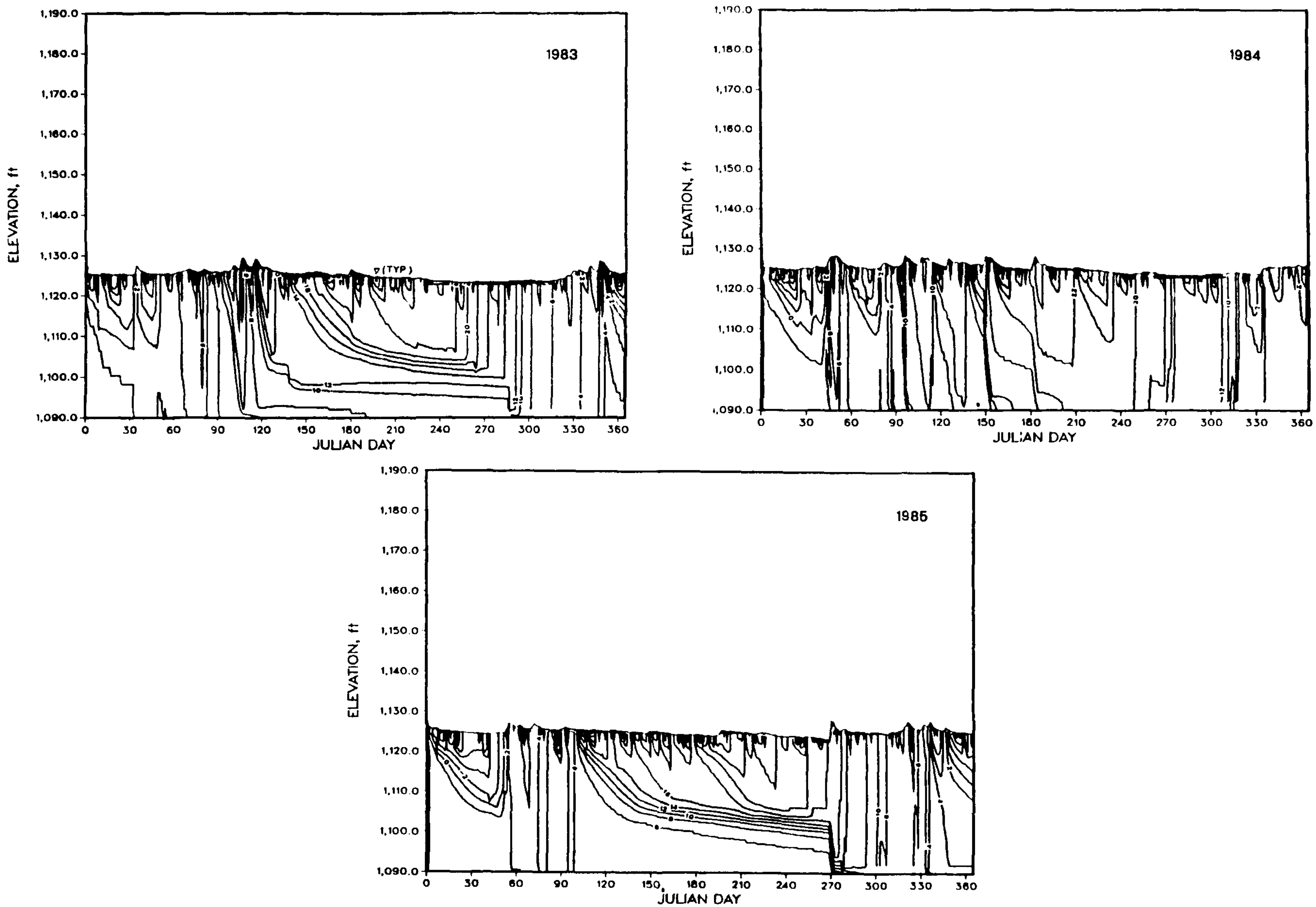

Figure 5. Reservoir temperature contours for 1983, 1984, and 1985
Note: Temperature contours given in degrees Centigrade.

Time of Year	Criteria
2/15 to 7/31	No rise when ambient temperature* is 74° F (23.3° C) or above; not more than 5° F (2.78° C) rise above ambient temperature until stream temperature reaches 74° F; not more than 2° F (1.1° C) change in any 1-hr period.
Remainder of year	No rise when ambient temperature is 87° F (30.5° C) or above; not more than 5° F (2.78° C) above ambient temperature until stream temperature reaches 87° F; not more than 2° F (1.1° C) change during any 1-hr period.

* Ambient temperature is defined as the stream temperature that would occur in the receiving basin prior to some discharge.

In addition, the Pennsylvania Fish Commission recommends that the release temperature from Prompton Reservoir be between 33° F (C.5° C) and 72° F (22.2° C) with 50° F (10° C) to 70° F (21.1° C) as the preferred range. The Commission also recommends no more than 2°-3° F (1.1°-1.6° C) change per hour or 5°-10° F (2.8°-5.5° C) change in 24 hr. For the purpose of this investigation, the slight difference between the State of Pennsylvania and the Pennsylvania Fish Commission criteria was considered insignificant. Therefore, the State criteria were used in this investigation.

13. Ambient conditions, on which these criteria are based, must be measured in situ. Since daily stream temperatures for the three study years were not available for this stream (or any nearby streams), a sine curve was fit through the 3 years of observed monthly inflow temperature data to obtain an estimate of ambient conditions. This sine curve function

$$T_t = 9.00 \times \sin(0.0174 \times D - 2.234) + 11.00 \qquad (1)$$

where

T_t = target temperature in degrees Centigrade

D = Julian day

was used to predict the daily target release temperatures from Prompton Reservoir. Predicted daily target release temperatures from Equation 1 and observed release temperatures for 1983, 1984, and 1985 (which, unfortunately, are very sparse) appear in Figure 6. All observed release temperatures were below the upper limit, with the target temperatures being somewhat warmer than observed in the fall.

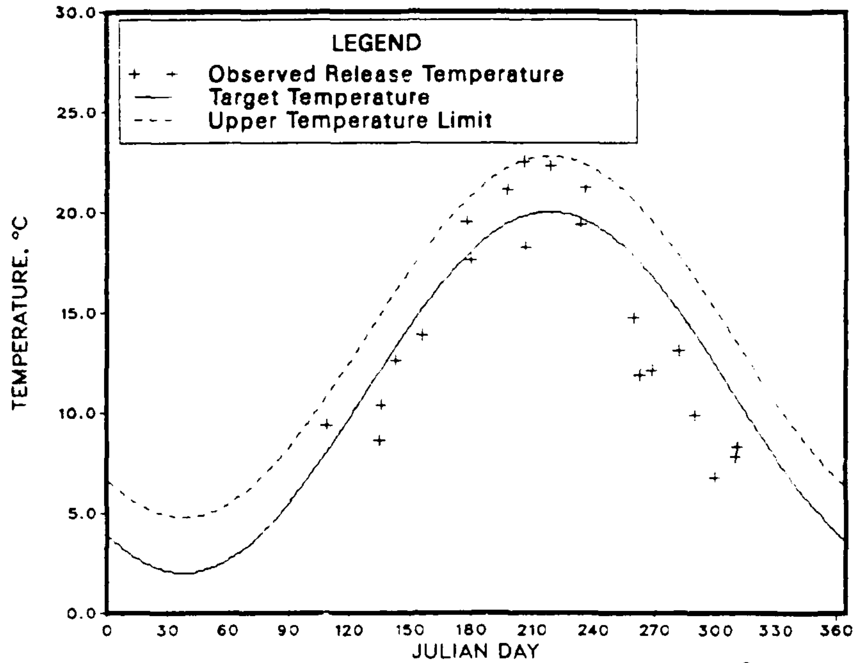

Figure 6. Observed, target, and upper limit release temperatures for Prompton Reservoir

Inflow Temperature

14. Daily inflow temperatures were not available for Prompton Reservoir. Therefore, monthly inflow temperatures, which were available for the 3 years of study, were used to develop a linear regression equation to predict daily inflow temperature. The independent variables used in the stepwise procedure included air and equilibrium temperature on the same day as the required inflow temperature and the air and equilibrium temperatures for the preceding 4 days. For example, the independent variables for Julian day 136 were the air and equilibrium temperatures for days 136, 135, 134, 133, and 132. Analyses using these 10 variables, along with inflow and logarithm of flow (natural and base 10), resulted in the following description of daily inflow temperature:

$$T_i = 0.8095(T_a) + 1.80 \qquad (2)$$

where

T_i = inflow temperature in degrees Centigrade on day i

T_a = air temperature in degrees Centigrade on day i

Of the variables for possible inclusion in the equation, air temperature on the day of the inflow was the most important. The value of R^2, which is an indicator of the amount of variance in inflow temperature that is accounted for by the equation, was 0.82.

Model Adjustment

15. The WESTEX model requires determination of dimensionless coefficients characterizing certain reservoir processes. Two hydrodynamic processes, representing entrainment of inflows and internal mixing resulting from circulation within the reservoir, are approximated through the application of mixing coefficients α_1 and α_2, respectively. The distribution of thermal energy absorbed into the pool through the air-water interface is governed by the coefficient for the percentage of incoming shortwave radiation absorbed in the surface layer β and a light extinction coefficient λ. These model coefficients were modified until simulated conditions most nearly matched field observations for the year 1983. The resultant model coefficients were as follows:

$$\alpha_1 = 0.05$$

$$\alpha_2 = 1.00$$

$$\beta = 0.99$$

$$\lambda = 0.99$$

16. Initial verification of the numerical model included comparison of predicted lake stage with observed lake stage, given historical inflow and outflow. These comparisons indicated that the model predicted within 0.1 ft of the observed stage in most cases. Initial comparison of temperature profiles with those observed was not as successful. The profiles indicated that not enough warming was occurring in the surface layers. Further analysis of the inflow data indicated that inflows from sta 4 (approximately 20,000 ft upstream from the dam) were much cooler than those from sta 3 (approximately 14,000 ft upstream from the dam), which is in the headwaters of Prompton Reservoir. The linear regression model (Equation 2) for inflow temperature was

then recomputed using equilibrium temperature and data from sta 3. The resulting equation was as follows:

$$T_i = 0.83(T_e) + 12.25 \qquad (3)$$

where T_e is the equilibrium temperature in degrees Centigrade. Computed daily inflow temperatures for 1983, 1984, and 1985 appear in Figure 7. The addition of this equation to the model improved the profiles so that they more closely matched the observed data. Further improvements were made using the observed air temperature at the project for computation of equilibrium temperature. Some deviations of predicted versus observed profiles may be due to the small volume of water located in the bottom layers (less than 2 percent of the volume is located in the bottom 10 ft) so that when withdrawal zones extended into the lower layers, the cooler water was exhausted quickly. Although some variation between the predicted and observed profiles existed, the general shape of the profiles matched the observed for 1983 (Figure 8). A reliability index (RI) that has been formulated (Martin 1986) was used to compare predicted with observed profile data. The closer the predicted profile is to the observed profile, the closer the RI is to 1.00. From previous studies (Schneider and Price 1988), an RI between 1.00 and 1.10 indicates good agreement of model and prototype profiles. The RI for these 1983 comparisons was 1.055.

Withdrawal Angle

17. In the WESTEX model, the withdrawal angle parameter must be set. This parameter, whose value was initially assumed to be 3.14 radians, is used to account for topographic effects on the withdrawal zone. At Prompton Reservoir the proposed structure will be located near the west bank end of the dam. This location may influence the limits of withdrawal by constricting the lateral area from which the structure may draw water. This in turn may cause the withdrawal zone to expand vertically, thus modifying the release temperature. Therefore, to promote accurate predictions with the numerical model, the effects of the local topography on this parameter were investigated in a physical model. The discussion and results of this investigation appear in Appendix A. This investigation indicated that the local topography has no

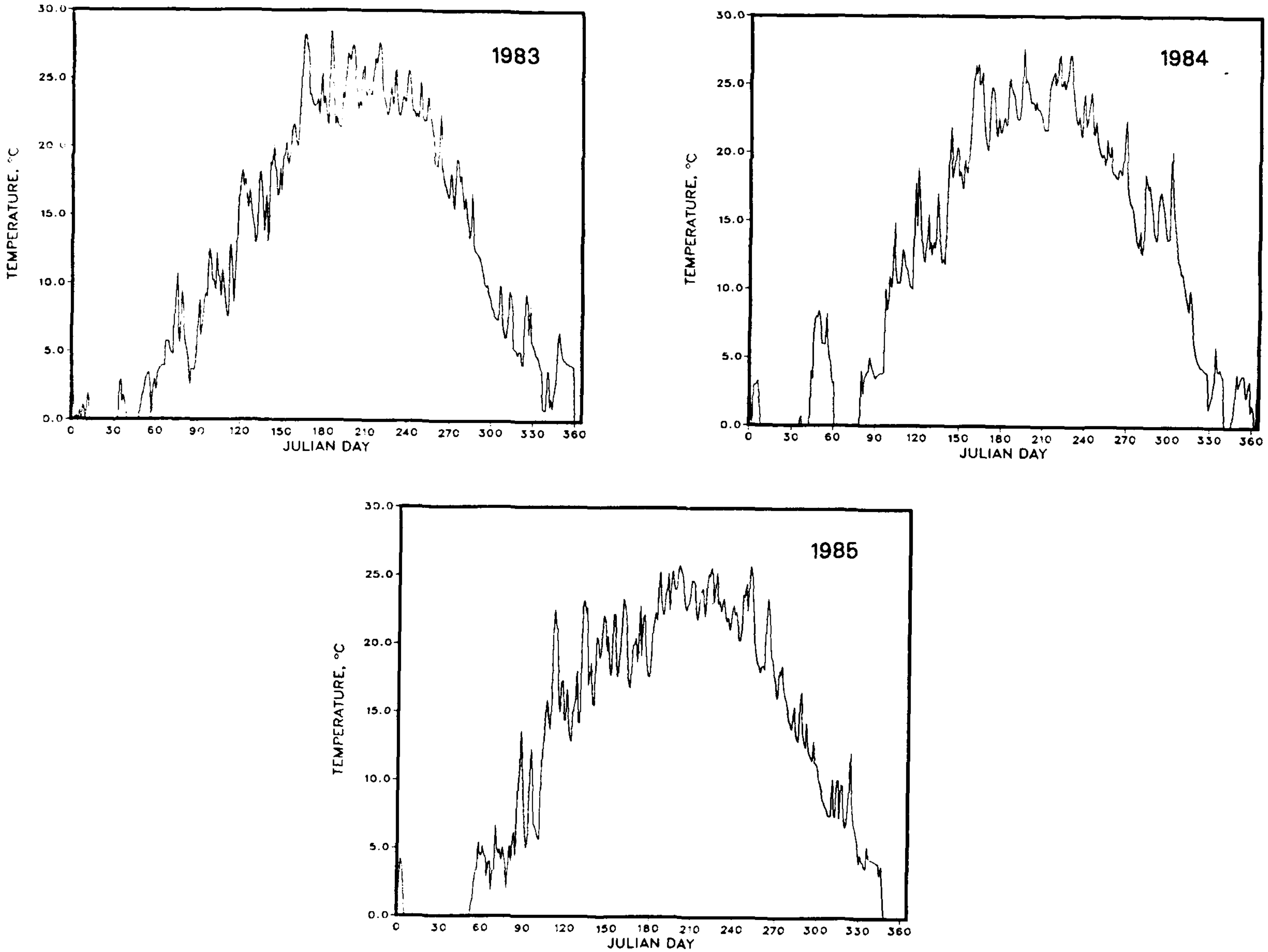

Figure 7. Predicted daily inflow temperature for Prompton Reservoir

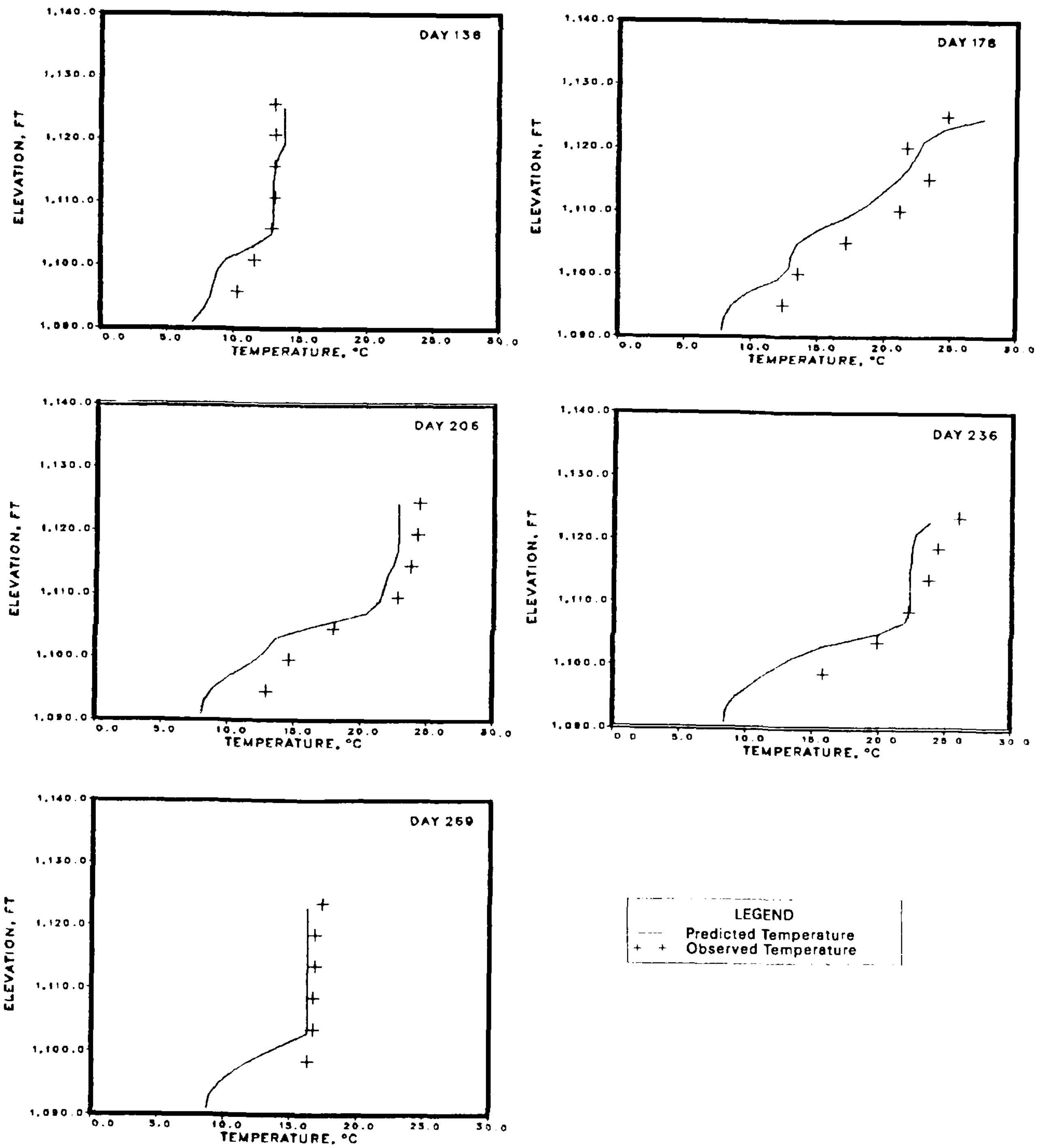

Figure 8. Predicted and observed temperature profiles for 1983

impact on the proposed structure at its current proposed location. Therefore, no modification of the withdrawal angle parameter was made in the numerical model.

Model Verification

18. The 1984 and 1985 data sets were used for verification of the model. Simulations with these data sets indicated the hydrologic conditions for these years matched the observed conditions well. Deviations between predicted and observed stages of the pool were usually less than 0.1 ft with a maximum of 0.3 ft. The comparison of predicted with observed temperature profiles for 1984 indicated the model predicted warmer temperatures during the early spring (day 109, 19 April) but matched the upper layers by day 180 (29 June), as shown in Figure 9. As with the 1983 data, the model predicted warmer hypolimnetic layers. This was probably due to the withdrawal limits extending into these layers (Figure 10) in the spring, causing evacuation of this cooler water. Since these layers contain a relatively small volume of water, and there is no other source of cool water (i.e., inflows), the hypolimnetic water that is released is replaced by warmer layers from above, thereby warming the overall profile. In contrast to the profiles collected in 1984, which was a high-flow year, 1985 profiles (Figure 11) were warmer than predicted during the spring. With the onset of summer, the predicted profiles more closely matched the observed profiles. The deviations occurring in the lower layers may again be attributed to the relatively small volume of water in these layers. The differences in the spring profiles may be due to errors in predicted inflow temperature or to the advective factors that dominate during the high inflow periods. The hydraulic residence time, which can be used as an indicator of an advectively dominated system, was very short during the spring. However, beginning in July, the residence time usually increased, allowing the system to become meteorologically dominated. For example, in the 1985 verification year, predicted profiles were consistently 3° to 4° C cooler than observed up to day 198 (17 July), after which much closer fits were observed. Simultaneously, the residence time began to increase about day 198 and peaked in October. The RI for all comparison profiles for 1984 was 1.051 and for 1985 was 1.098.

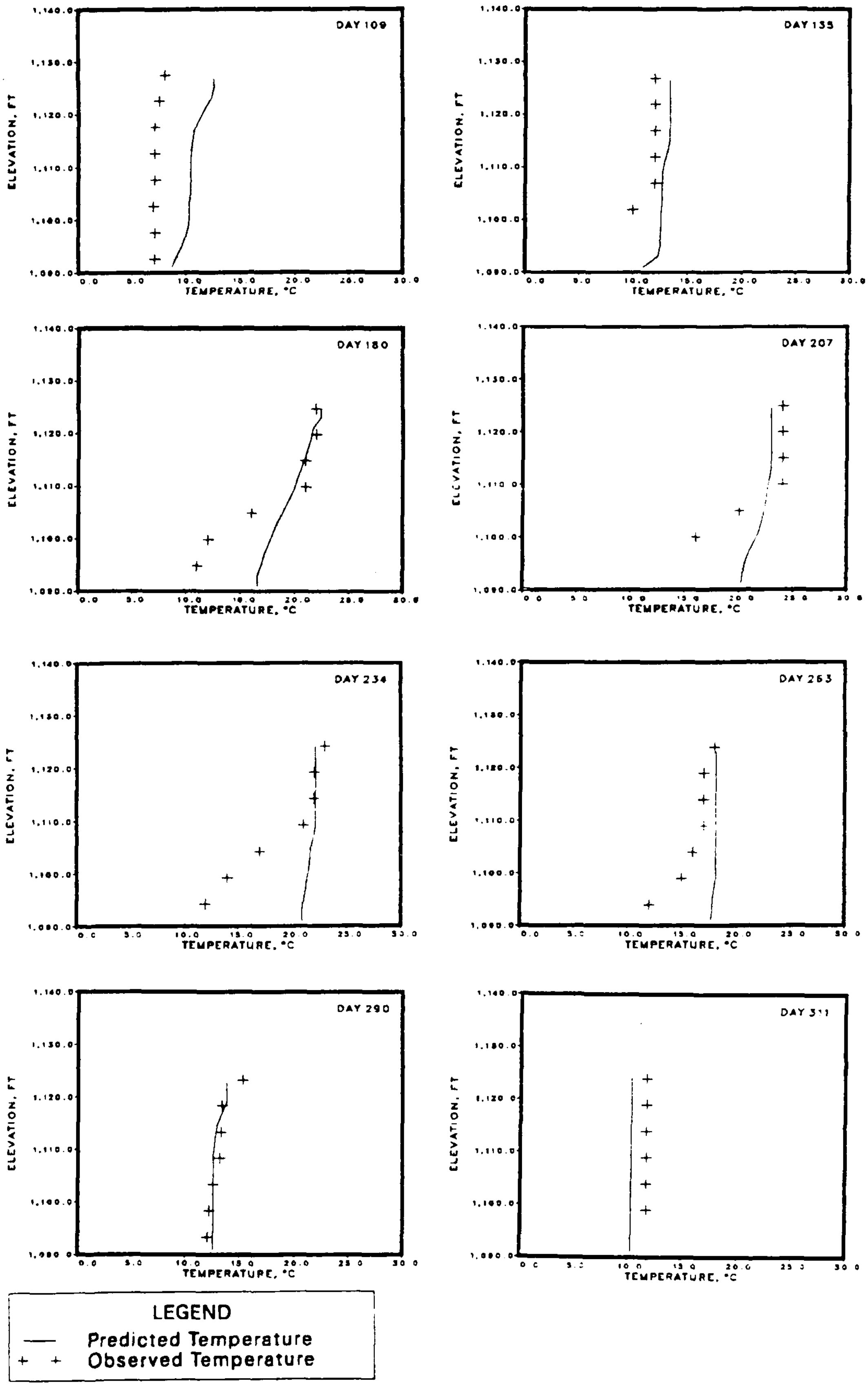

Figure 9. Predicted and observed temperature profiles for 1984

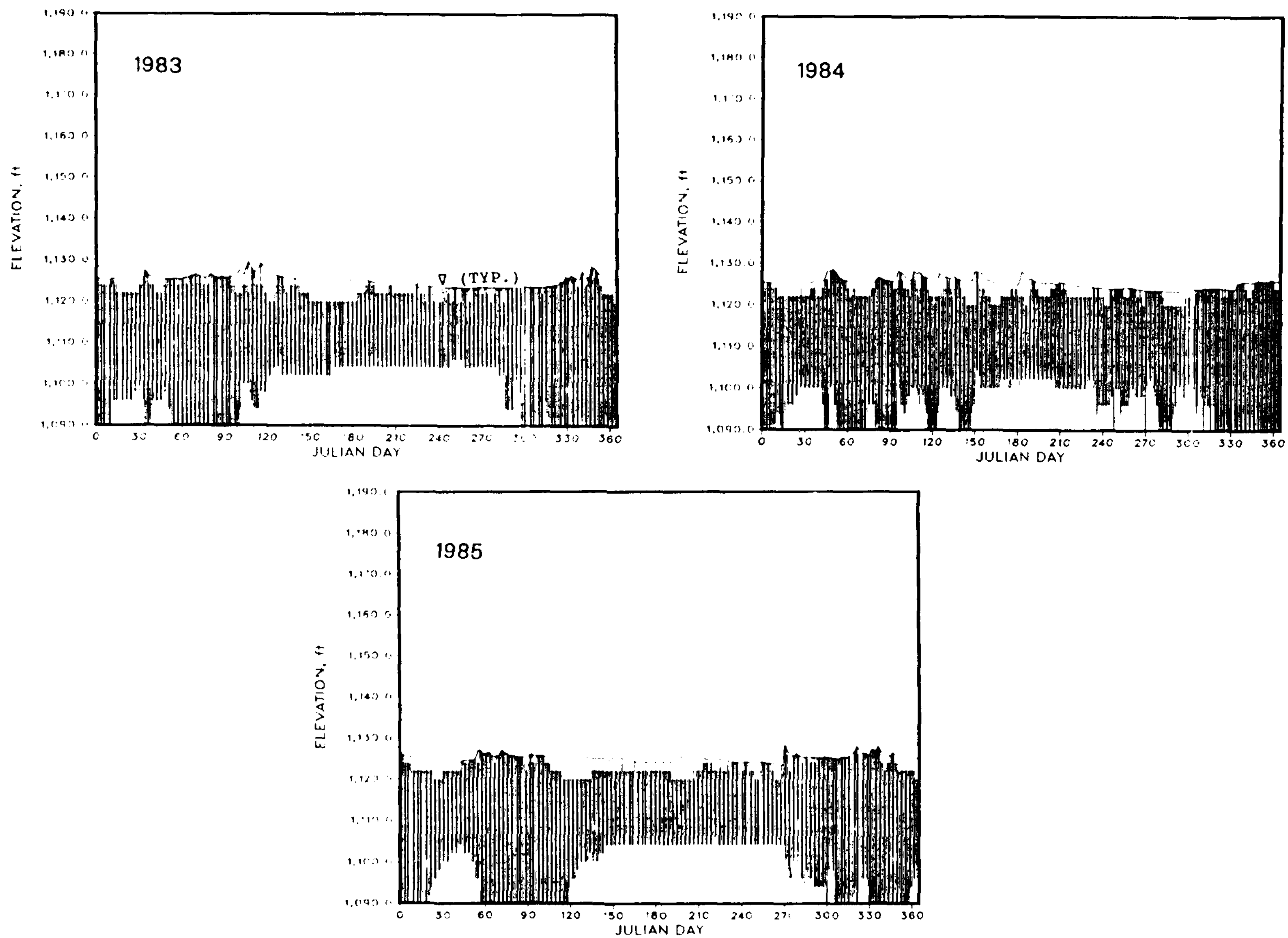

Figure 10. Withdrawal limits for 1983, 1984, and 1985. Band indicates extent of withdrawal zone

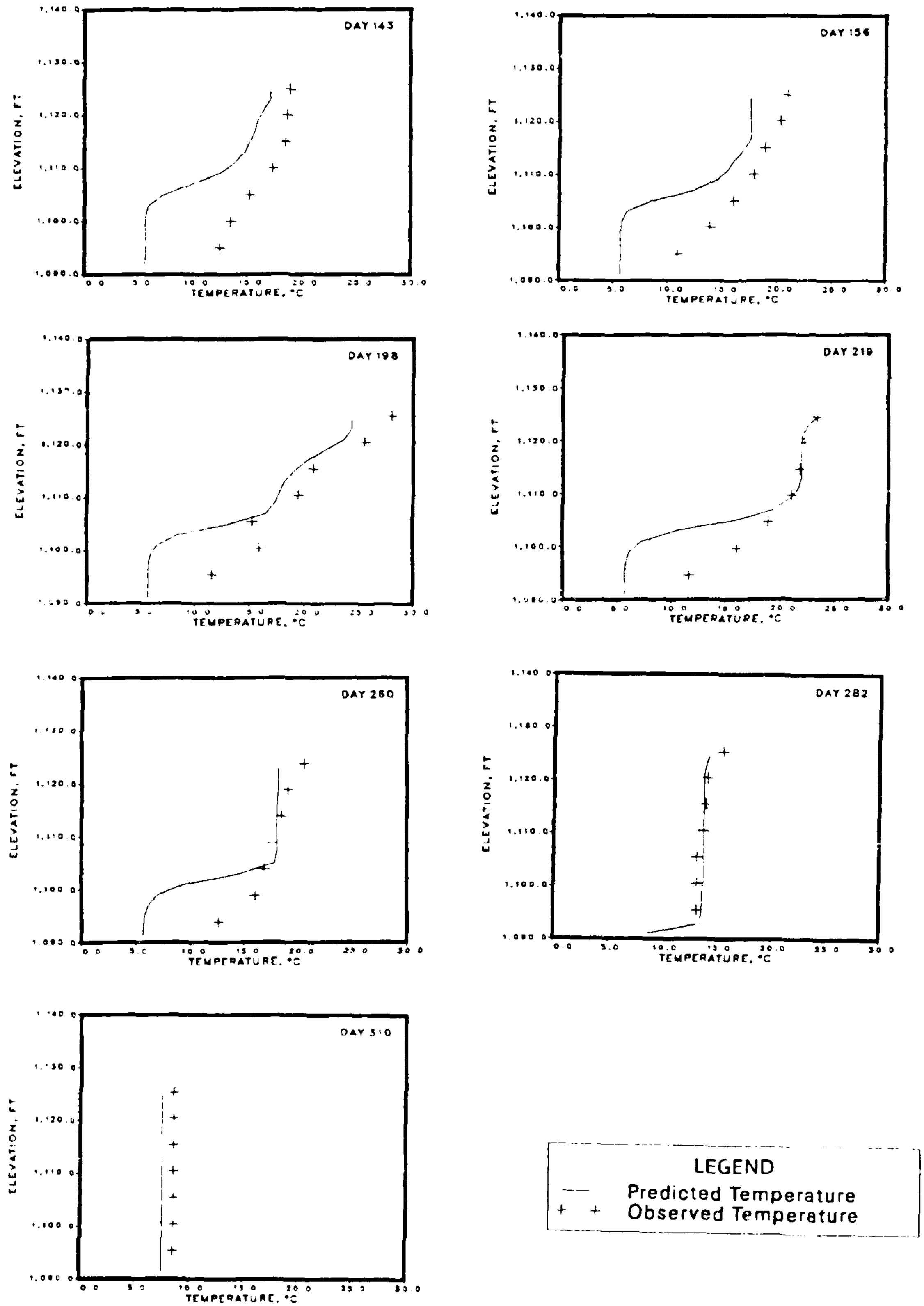

Figure 11. Predicted and observed temperature profiles for 1985

Release Temperature

19. As stated in paragraph 13, observed daily release temperatures for Prompton Reservoir were not generally available. Therefore, the model was used to simulate daily release temperatures using existing project conditions for comparison to the target temperatures. These comparisons appear in Figure 12. The predicted release temperature exceeded the target temperature during some periods in the spring of 1983 and 1984. However, these deviations were the result of large inflows mixing the entire lake. Once inflows began to decline during the summer, the day-to-day change in release temperature was minimal.

Operational Scenarios

20. The proposed pool raise is to provide additional water for release during drought conditions in the Delaware River Basin. To identify the timing and volume of flows required from Prompton Reservoir, the Philadelphia District used a Hydrologic Engineering Center (HEC) computer program to simulate 50 years (1927-1977) of operation with the raised pool. Examination of these simulations indicated there were four basic types of drawdown corresponding to the operations occurring in 1930, 1957, 1964, and 1965 (Figure 13). These scenarios are similar in that drawdown of the pool began in midsummer with the time to reach the minimum pool (el 1113) varying between 73 and 279 days. The minimum flow during the drawdown was 6 cfs with the maximum approaching 650 cfs. From the HEC simulations, it also appears that a drawdown occurred approximately every third year. When releases were not required, the pool was held constant at 1,180 ft with releases essentially equaling the inflow volume. For the purpose of this study, this was termed the level pool operating condition. Thus, for each of the three study years (1983, 1984, and 1985), five different operational scenarios were simulated: (a) level pool; (b) 1930 drawdown; (c) 1957 drawdown; (d) 1964 drawdown; and (e) 1965 drawdown.

Structure Configurations

21. Two discharge scenarios were simulated in the model: maximum discharge capacity of 220 cfs through a 7- by 8-ft port; and 325-cfs capacity

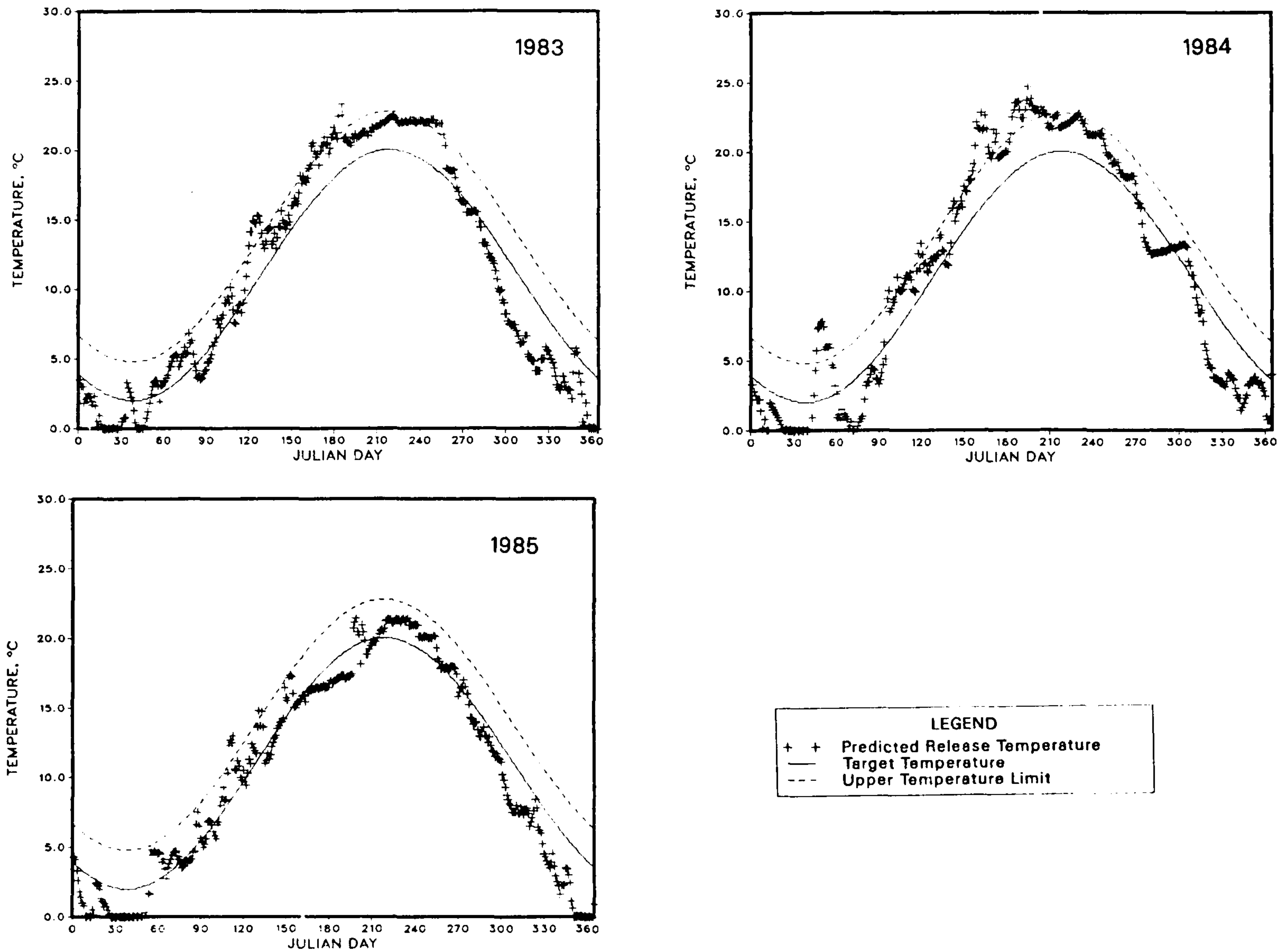

Figure 12. Predicted, target, and upper limit release temperatures for existing conditions

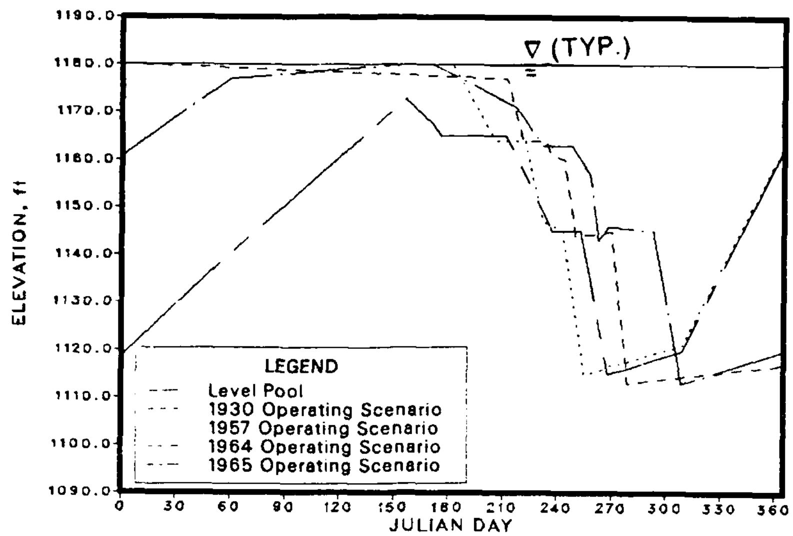

Figure 13. Operational scenarios for Prompton Reservoir

through an 8- by 8-ft port (the flows and port dimensions were specified by the Philadelphia District). These flow rates represent the 95 and 99 percent exceedence flow rates for the project. Two wet well configurations were also tested: a single wet well with only one port operating at a time and a dual wet well with simultaneous operation of two ports (one each per wet well). In the initial design optimization, the flood-control port was not allowed to operate simultaneously with other ports; however, in the simulations using the final design, the flood-control port was allowed to operate simultaneously although it did not significantly improve the ability to meet the release temperature objective. The flood-control outlet was defined as a 30- by 30-ft gate with an invert elevation of 1095.

Optimization Process

22. Design of an efficient outlet structure to meet the release temperature objectives under the raised pool conditions requires the determination of the number and location of additional intakes. This design process was greatly simplified by Dortch and Holland (1984), who coupled the WESTEX model to mathematical optimization techniques. This effectively allowed the consideration of numerous hydrologic, meteorological, physical, and operational conditions in the formulation of intake structure design. The use of the optimization techniques enhances structure design by allowing systematic

evaluation of the structure configurations needed in the design to meet the release temperature objectives. The systematic evaluation is carried out using an objective function as a measure of performance of each candidate system configuration. This function is discussed in the following paragraphs.

Objective Function Description

23. An objective function value is an index used to evaluate the degree to which releases from a given intake configuration meet a set of prescribed temperature objectives. In this study the objective function value was formulated as the difference between the predicted (model) release temperature for a given day and the target temperature for that day. This value was squared and summed for the period from 1 April to 1 December. The option to invoke mathematical penalties for a release temperature deviating from the prescribed temperature objective band also exists. For example, the release temperature for Prompton Reservoir is never to exceed 2.78° C above the ambient. Therefore, to penalize for deviations greater than 2.78° C above the ambient, these deviations were multiplied by 10, then squared and added to the objective function value. Because deviations below the ambient were not specified in the release criteria from the State of Pennsylvania, these deviations invoked no penalty. The target temperature and the upper temperature limit above which the penalty was imposed are shown in Figure 6.

24. The optimum capacity, location, and number of ports for the SW structure were determined by numerical optimization. This, in turn, involved minimization of the objective function value described in the previous paragraph. The optimized structure design consisted of selection of

a. Port capacity (220 or 325 cfs).

b. Number of wet wells (single or dual wet well).

c. Operating condition (level pool, 1930, 1957, 1964, or 1965 release scenarios).

d. Number of ports to locate (1, 2, 3, or 4*).

e. Optimum elevation for each port sited.

These data were input to the WESTEX model with the optimization routine. The

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* Initial optimization results indicated little improvement in objective function with more than four ports.

model then computed the objective function value for the initial elevation of the port(s). The optimization process then selected a new elevation of the first port for simulation. Upon completion of this simulation, the objective function value was compared to the previous objective function value and a new port elevation that was closer to the elevation with the lower objective function value was selected and simulated in the model. This process continued until the difference in elevation between the new and previous elevation did not exceed a predetermined value (4.0 ft in this study). This process was repeated for each input parameter listed to identify the optimum release structure for each set of conditions and structure configuration.

25. The two wet well configurations discussed previously (one or two wet wells) were included in this investigation to allow determination of the need for multiport blending operations to meet the release temperature objective. At the time of this study, the only accepted methodology within the Corps of Engineers for blending release water from two different elevations in the water column required the use of dual wet well systems. This convention was adhered to within this study. However, since the conclusion of this investigation, considerable research on multiport operations in a single wet well has been completed. This research indicates that density stratification in a reservoir can strongly affect efforts to achieve a desired blend of water from two elevations using a single wet well; however, these concerns can be overcome by construction of individual controls on each port to allow for partial opening of a port. Thus, a single wet well represents a potentially viable option for multiport release water quality operations that might merit future consideration by the Philadelphia District.

PART III: DISCUSSION OF RESULTS OF SYSTEM OPTIMIZATION

Optimization Results

26. The results of the optimization simulations are presented in Figures 14 through 18. The various operating scenarios were simulated in the order discussed in paragraph 20. In Figure 14, objective function values for each structure configuration of one, two, three, and four ports, both port capacities, and both wet wells for all 3 years of meteorological conditions are shown.

27. In the first series of tests, which simulated a level pool operating condition, there was little reduction of the objective function values by increasing the number of ports (Figure 14). The dual wet well configurations slightly improved the objective function values compared to the single well runs. The more pronounced differences were for the 1985 meteorological conditions. In a similar manner, the 325-cfs port capacity was slightly better than the 220-cfs capacity. The larger capacity provided more flexibility in meeting required release volumes for the release temperature objective. The slight difference between the one port and multiple ports (two, three, or four ports) suggested that one port would be sufficient with blending of releases through the flood-control port. However, it may be difficult to operate the flood-control gate at low flows (down to 6 cfs). Therefore, a two-port dual wet well structure with 325-cfs capacity of each port is the recommended structure for the level pool operation.

28. Simulation of the drawdown operating plans indicated much more difficulty in meeting the release temperature objective than for the level pool scenario. The order of magnitude difference in the objective function values (Figures 15 through 18) for several of the drawdown scenarios as compared to the level pool operation (Figure 14) indicated that in some cases the penalty function (described in paragraph 23) was used by the model. This penalty signified that some release temperatures exceeded the upper bound as set by the State.

29. Simulation of the 1930 operating rule curve (Figure 15) revealed the potential utility of the dual wet well. Simulation of the single wet well structures for 1983 resulted in larger objective function values than did either of the dual wet well designs. In addition, the 325-cfs port capacity

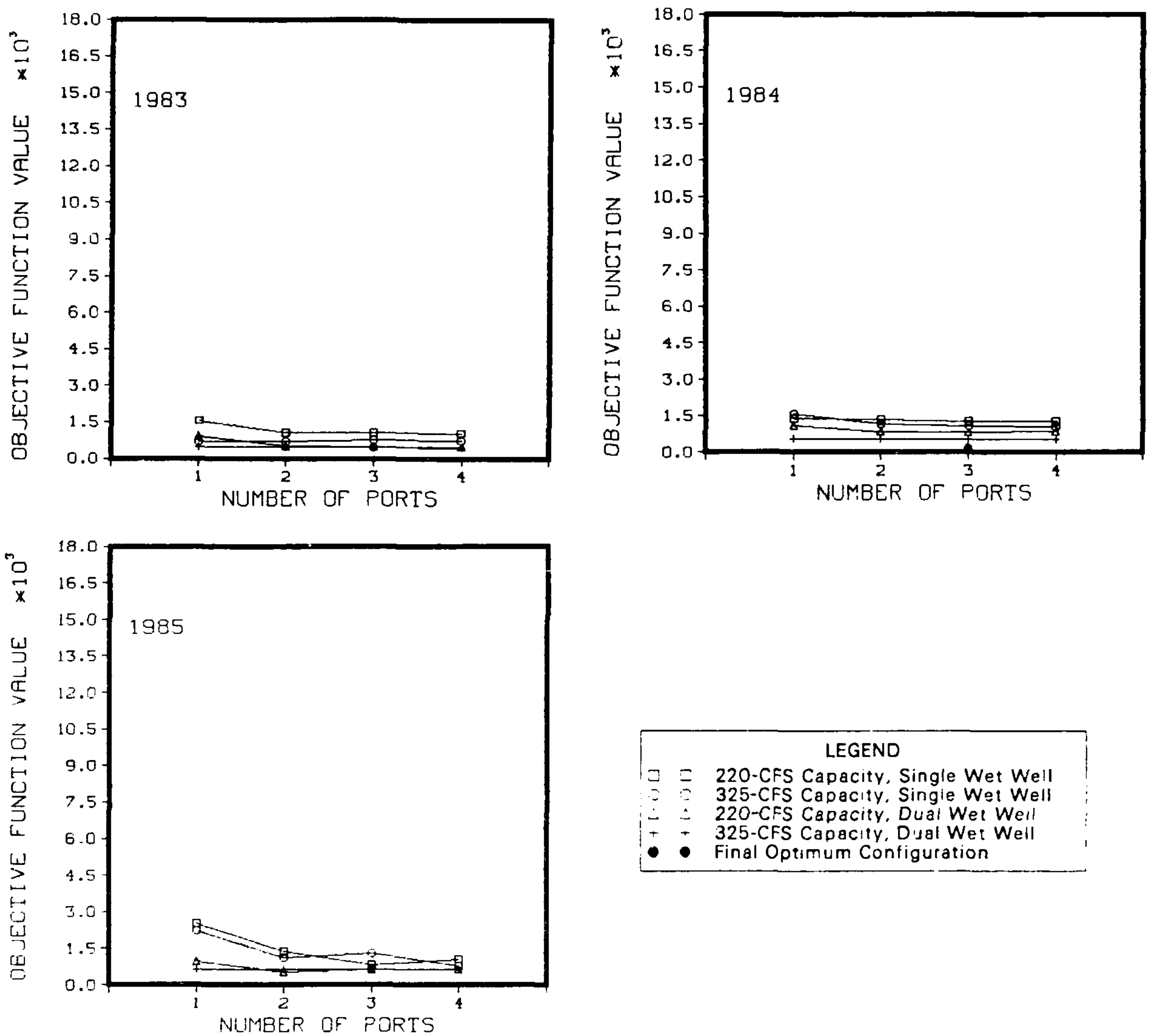


Figure 14. Optimization results for level pool operating scenario

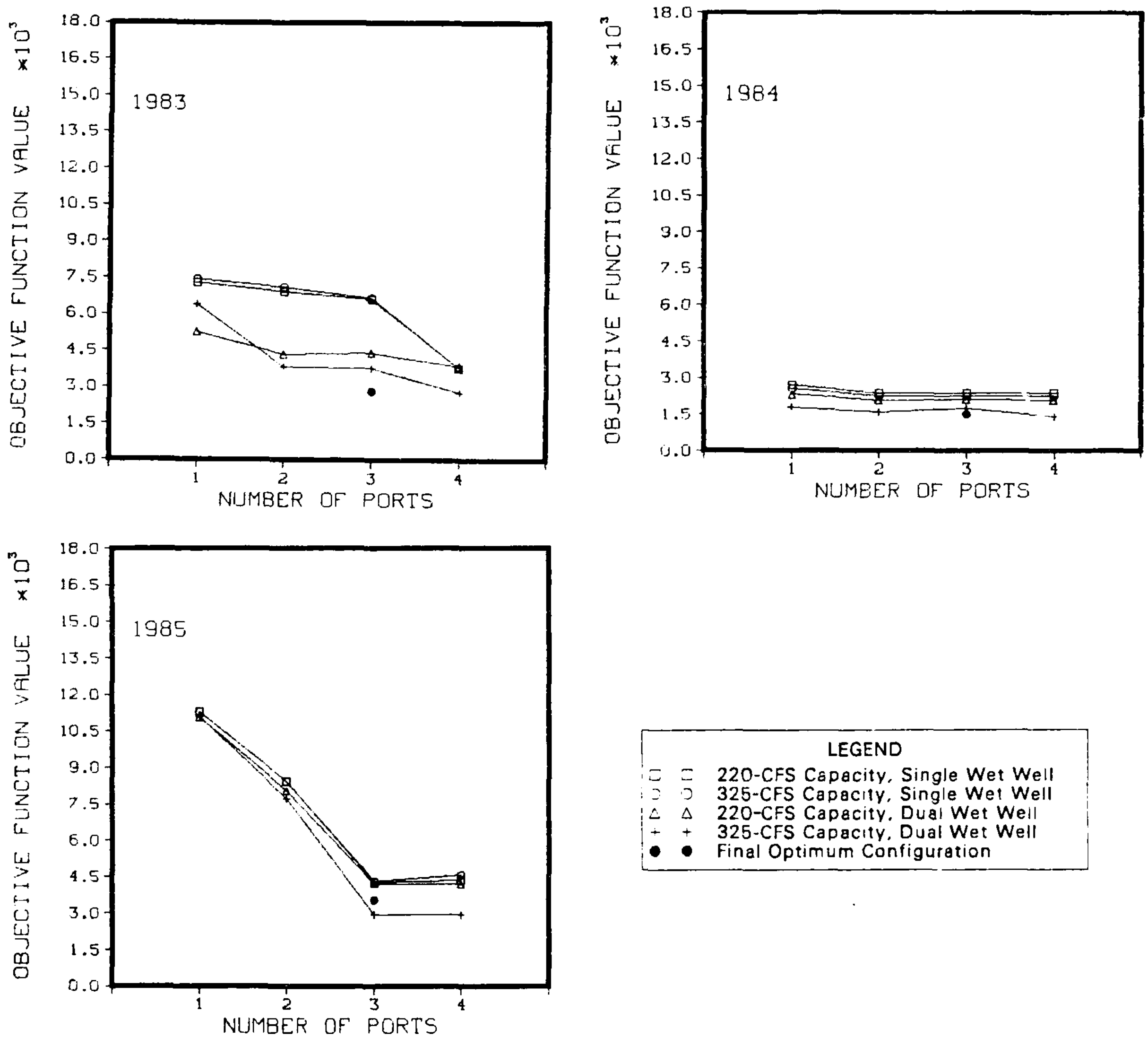


Figure 15. Optimization results for 1930 operating scenario

provided superior temperature control. The 1984 meteorological conditions, however, created no difficulty in meeting release temperature criteria for either the single or dual well design. Further, no apparent differences were observed between the 220- and 325-cfs port capacity runs. This is contrasted with the 1985 simulations, which were influenced more by the number of ports rather than number of wet wells. For 1985 conditions, three ports in a dual wet well with 325-cfs capacity per port was the optimum configuration.

30. Results of optimization simulations using the 1957 operating scenario (Figure 16) were similar to the 1930 operating scenario results. For the 1983 meteorological data, the increase in capacity to 325 cfs for the single wet well configuration improved the objective function value. However, the three-port, 325-cfs-capacity dual wet well appeared to be the optimum configuration for the 1957 operating scenario for the 1985 conditions.

31. The 1964 operating scenario (Figure 17) was influenced for all three meteorological years more by the addition of ports than by port capacity or number of wet wells. The minimal improvement in the objective function with addition of a third or fourth port indicates that for 1983 and 1984 a two-, three-, or four-port structure could be recommended. However, the three-port configuration minimized the objective function value for the 1985 operating conditions. Therefore, as with previous rule curves, the three-port, dual wet well, 325-cfs-capacity structure appeared to be the optimum configuration for the 1964 operational scenario.

32. The 1965 operating scenario (Figure 18) showed some variation between single and dual wet wells in 1983 and more variation in 1985. As with previous scenarios, release temperature control for 1984 meteorological conditions was equally good for the various combinations of number of ports, capacity, and number of wet wells. Therefore, for the 1983 and 1984 conditions, a two-, three-, or four-port dual wet well structure would provide similiar release temperature control. For the 1985 condition, the three-port, dual wet well structure was the optimum.

33. In general, the optimization results showed that the release temperature objective was not impacted by structural design for the 1984 meteorological conditions. Since the 1984 study year was considered a wet year with a number of storm events mixing the lake (an example of the 1984 stratification pattern will be shown later in Figure 21) to a more uniform temperature distribution from surface to the bottom, there was increased flexibility in

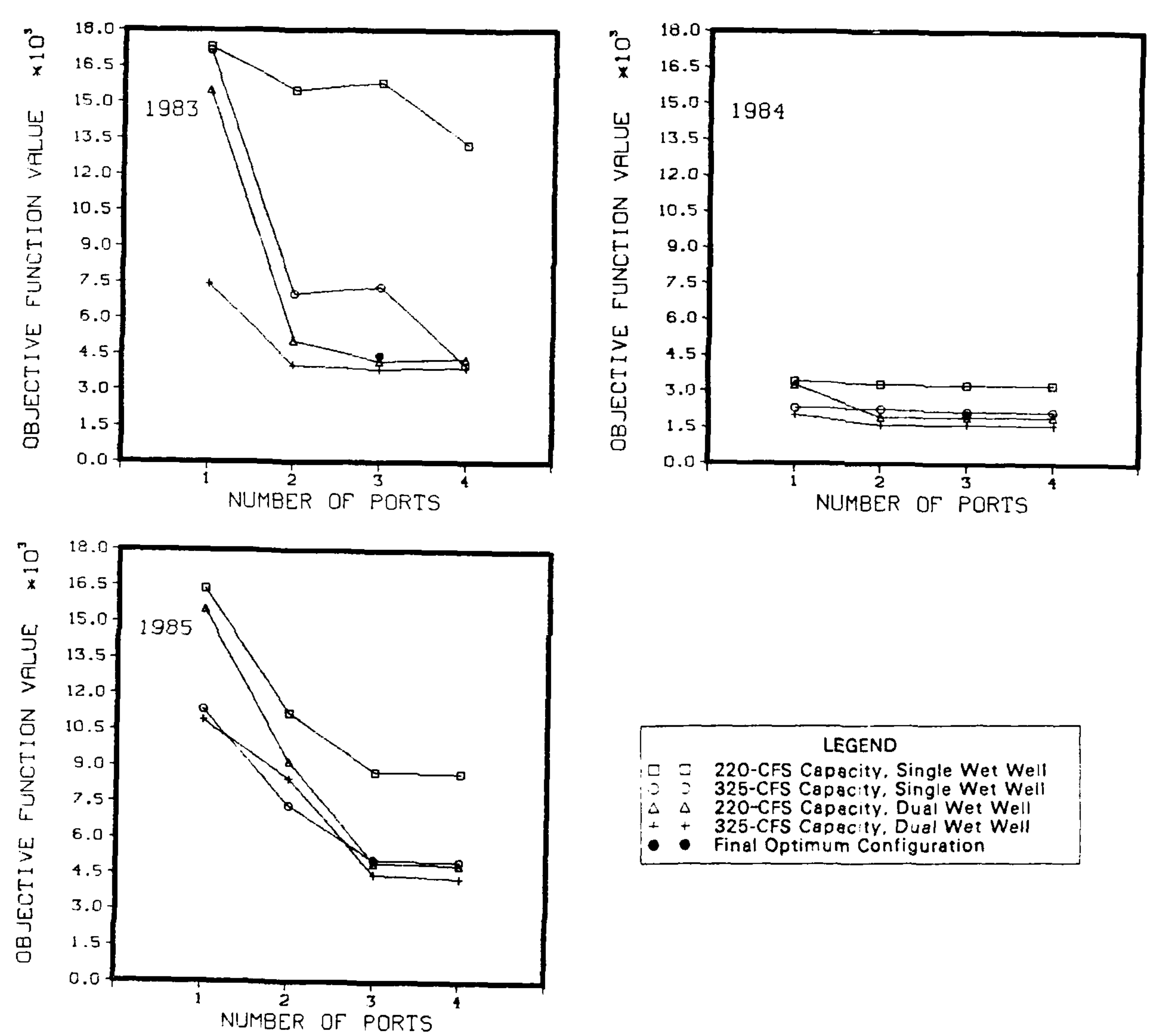


Figure 16. Optimization results for 1957 operating scenario

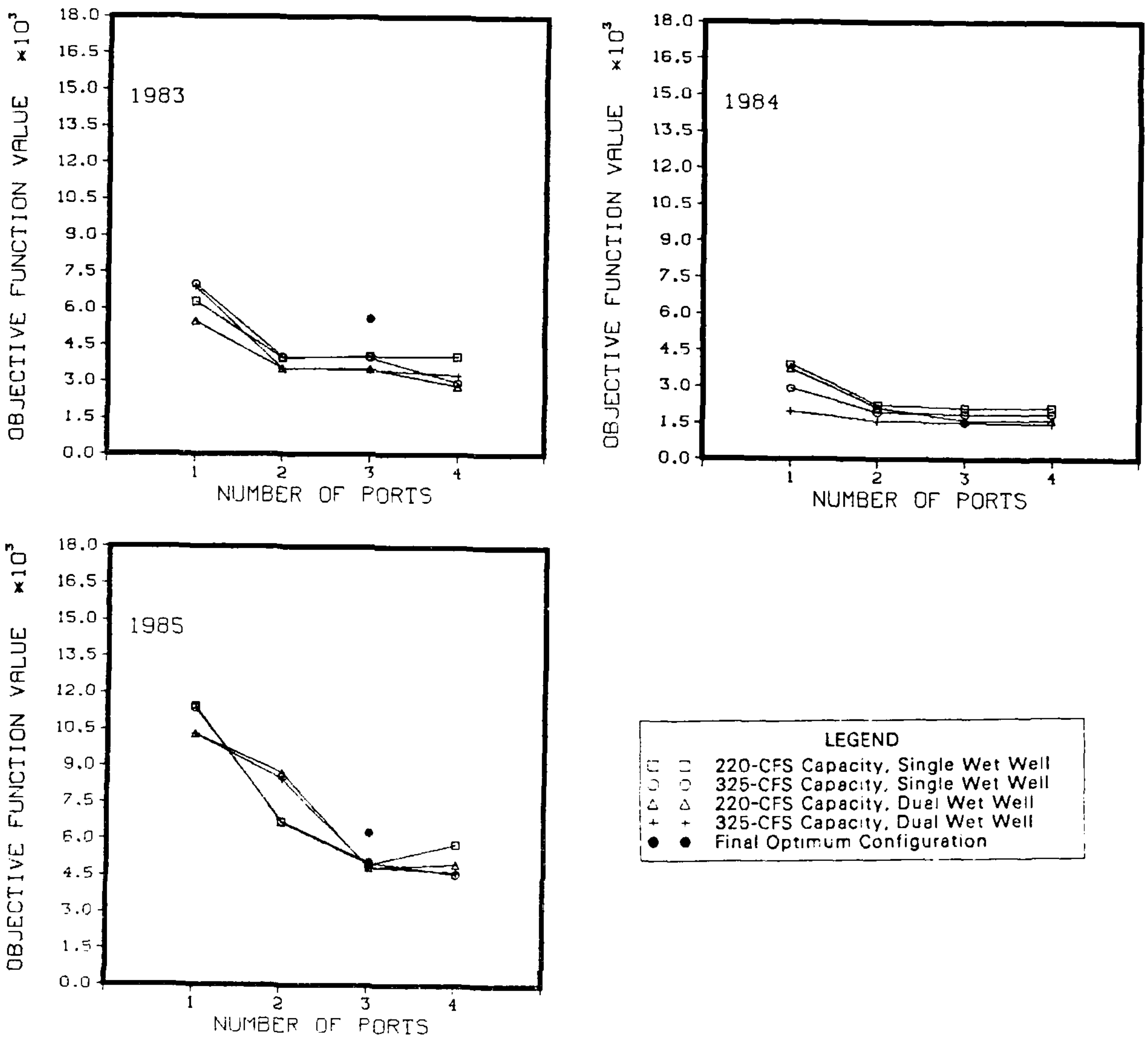


Figure 17. Optimization results for 1964 operating scenario

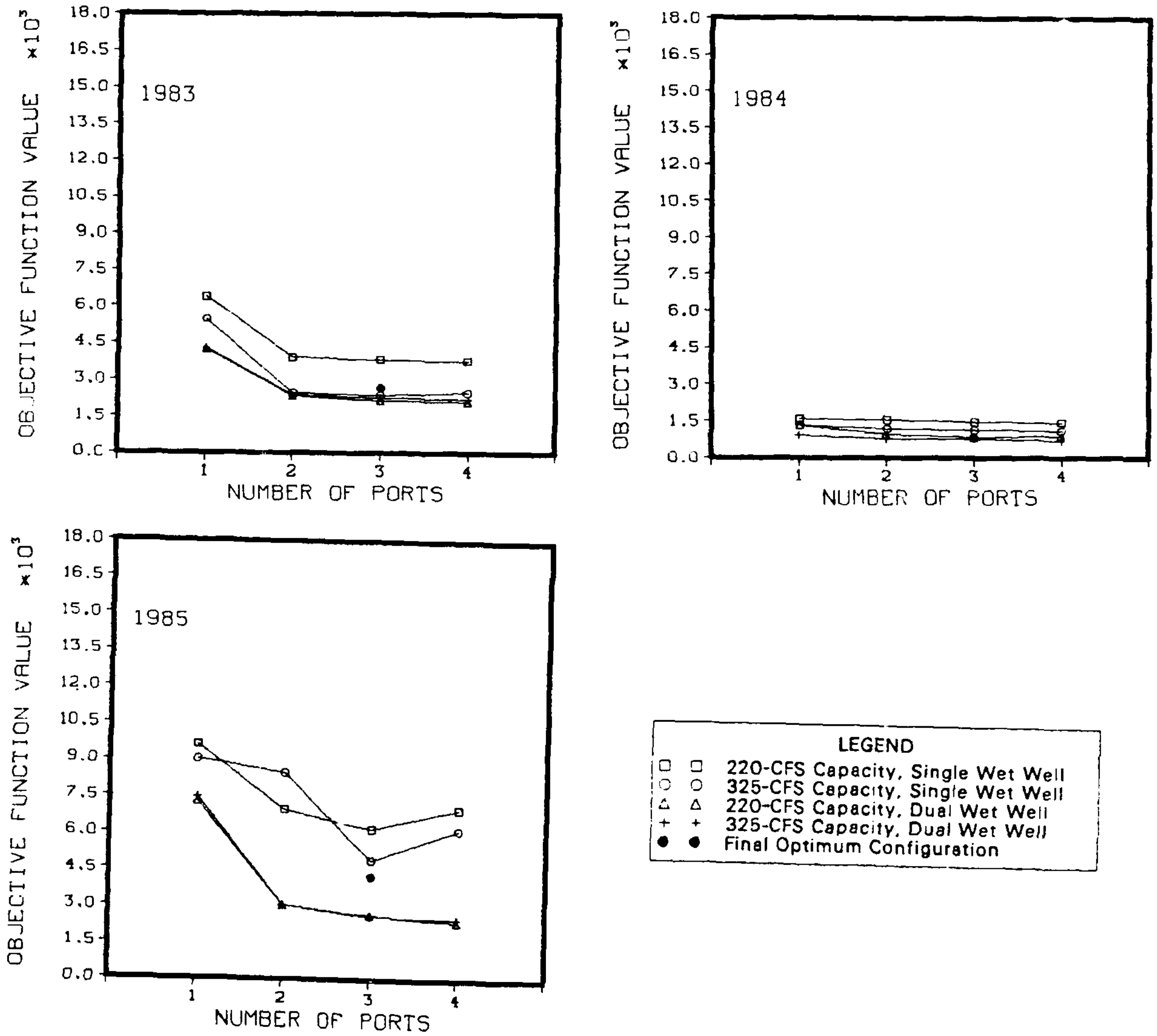


Figure 18. Optimization results for 1965 operating scenario

deciding where to locate a port. Therefore, with this pattern of stratification, there was a wider range of port elevations to choose from that provided the required thermal resource as opposed to that range for a stronger stratification that was essentially two layers. For example, during the optimization process, movement of a port would produce a corresponding change in the release temperature, hence a change in the objective function value. Due to the uniformity of the 1984 stratification patterns, the corresponding changes in the objective function due to modifying port elevation and capacity were small. Further, due again to this uniformity, very little benefit was derived from blending resources from differing elevations in the dual wet well configuration. Thus, little difference was noted between the wet well scenarios. Still, although increasing the number of ports had little impact on the objective function value for most operating scenarios, some improvement was observed with the 1957 and the 1964 operating scenarios with the two-port, 325-cfs-capacity dual wet well configuration. Therefore, this configuration is recommended for the 1984 meteorological conditions.

34. This configuration, however, was not recommended for the 1983 and 1985 study years. In both years, the stratification pattern was stronger than in 1984 and appeared more like a two-layer stratification. Thus, while movement of the location of a port within the epilimnion or the hypolimnion resulted in little change in the release temperature (hence little change in the objective function value), movement near the thermocline produced significant change in release temperature (and, therefore, impacted the objective function value). For the 1983 meteorological conditions, the ability to release water from two distinct pool elevations using a dual wet well resulted in better performance with all drawdown scenarios. Thus, with all drawdown scenarios using the 1983 study year, the two-port, dual wet well, 325-cfs-capacity configuration performed the best.

35. For the 1985 meteorological conditions, all drawdown scenarios were significantly impacted by the addition of ports. The trends observed with the 1983 optimization results were even more obvious for the 1985 results. Since the 1985 meteorological conditions were considered representative of a dry year, and stratification in the pool was stronger than in 1983 (essentially two layer), location of ports in each of the two layers provided enhanced flexibility in meeting downstream temperature requirements. The differences between the single and dual wet well results indicate that the ability to

blend between two elevations during the drawdowns will be beneficial during a strong stratification. The larger capacity (325 cfs) was beneficial in the 1930 and 1957 operational scenarios, but appeared to have little impact on the other two drawdown scenarios. Therefore, considering all operating scenarios of the 1985 meteorological conditions, the three-port, 325-cfs-capacity dual wet well configuration is the recommended design.

36. Since the purpose for the raising of the pool is to supply water downstream during drought conditions, the 1985 meteorological conditions would be somewhat representative of conditions under which a drawdown would most likely occur. Therefore, the structure configuration recommended from the 1985 simulations may be the most appropriate for meeting release temperature objectives under a drawdown of the reservoir.

Final Optimum Structure Design

37. The results of optimization determined an elevation for each port located for each given operating condition. Since each operating condition produced a slightly different set of elevations, determination of a final structure design was necessary to arrive at a recommended common design for all the conditions tested. The three-port, 325-cfs-capacity dual wet well was recommended for the 1985 meteorological conditions; thus, these results were included in the determination of the final design. Further, given that a drawdown could occur under weaker stratifications, the port configurations for the two-port, 325-cfs-capacity dual wet well for 1983 and 1984 as recommended in the previous section were also included in the design.

38. The final optimum configuration of ports was determined by consolidating the optimum center-line elevations as recommended in the previous paragraph. This consolidation resulted in three obvious groups of elevations. The upper port was determined from the average of the first grouping of condition-specific optimum ports, which ranged from el 1172.0 to 1175.0. The middle port was determined from the second group of port elevations, which ranged from el 1150.2 to 1164.0. The lower port was determined from the average of the third group of port elevations, which ranged from el 1132.7 to 1144.7. The following tabulation summarizes these results. The final optimum configuration was then used to simulate the release temperature for each of the study years and operating scenarios. Objective function results of these

Port	Range of Optimum Elevations	Elevation of Ports in Final Optimum Configuration	Number of Wet Wells
Upper	1172.0-1175.0	1174.2	1
Middle	1150.2-1164.0	1159.9	2
Lower	1132.7-1144.7	1141.7	1

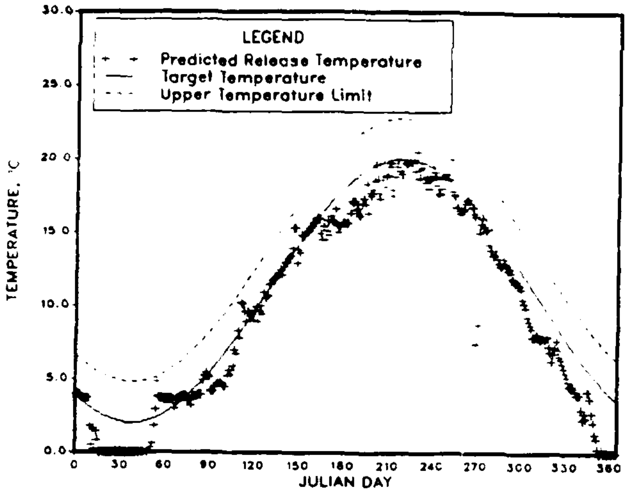
simulations, along with the previous dual wet well, 325-cfs port capacity results, appear in Figures 14 through 18 labeled as the final optimum configuration. The combining of port elevations to achieve a common optimum design resulted in a very slight increase in some objective function values over the individual optimum designs; however, this increase generally resulted in a negligible change in release temperature. There were three cases in which the final optimum configuration performed worse than the individual optimum configurations. Two of these were for the 1985 meteorological conditions with the 1964 and 1965 operational scenarios. Although the scenario-specific optimum port elevations for the 1964 operating scenario were within 3 ft of the final optimum configuration, the upper two final optimum ports were located at higher elevations than those scenario-specific configurations. During the drawdown, the higher port elevations required switching to lower ports sooner, thereby creating larger deviations in release temperature, and consequently a larger objective function value, than obtained for the scenario-specific simulations. The 1965 operational scenario began with a low pool and never allowed the pool to fill completely. Thus, the scenario-specific optimization results from this scenario recommended port elevations significantly lower than the final optimum configuration. Simulation of the 1983 meteorological conditions using the 1964 operational scenario with the final optimum configuration also resulted in a poorer objective function value compared to its individual optimum configuration. The final optimum configuration port elevations were 3 ft lower than the individual optimization simulation, resulting in deviations of release temperature similiar to those mentioned previously.

39. Results for individual operating conditions with the final optimum configuration indicated that the release temperature criteria can be easily met under the level pool operating conditions. The level pool operation with the 1985 meteorological conditions resulted in the largest objective function value among the three study years for this scenario. These conditions required that only two of the available three ports be operated as shown in

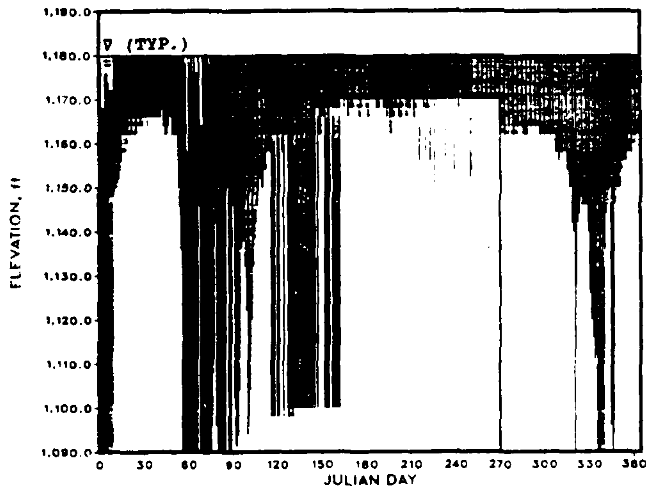
Figure 19; however, the release criteria were easily met with only minor deviations. The daily release temperature fluctuation was also reduced from the existing pool condition prior to pool raising (Figure 12).

40. When the drawdown operational scenarios were simulated, higher objective function values were computed. With the 1985 meteorological conditions and the 1964 operating scenario (the simulation resulting in the largest objective function value), all three ports were operated. The release temperature did not exceed the upper bound; however, during gate changes, a considerable drop in temperature was observed (Figure 20). When the drawdown began, the discharge increased from 20 to 92 cfs. This impacted the release temperature by expanding the withdrawal zone into the cooler hypolimnetic layers. However, the large deviation that occurred on day 202 (21 July, a 14.5° C drop) was due to a shift from the upper to the middle gate rather than being flow related. A similar situation occurred on day 245 (2 September) when flow was shifted from the middle to the lower port. This resulted in a release temperature drop of 13.4° C.

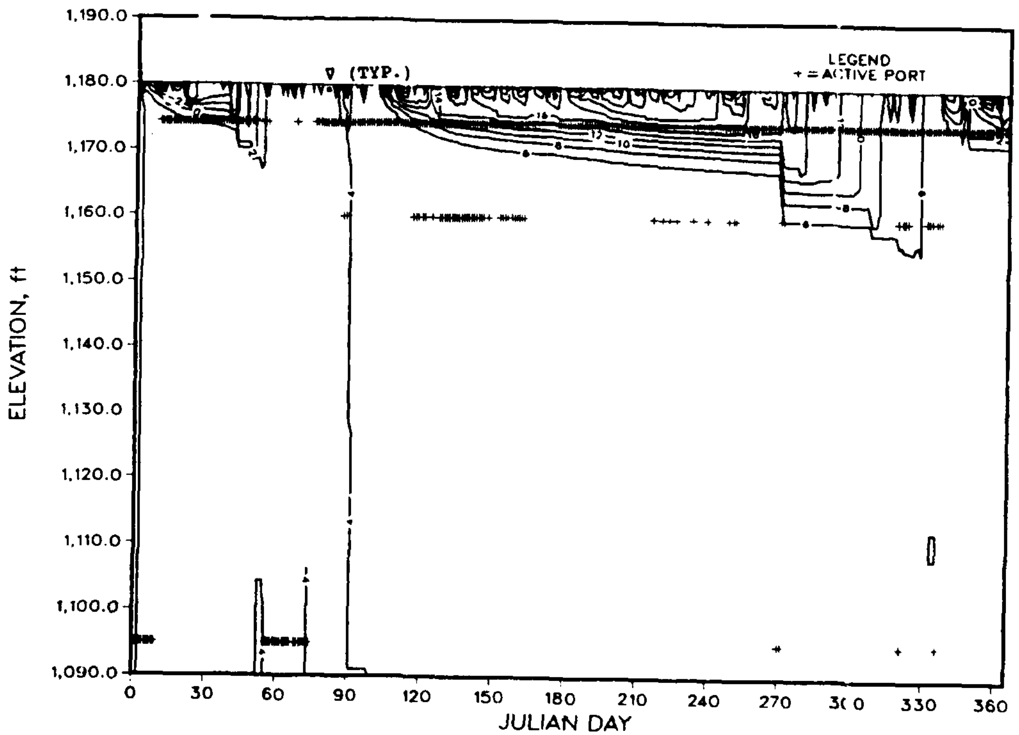
41. The 1984 meteorological conditions with the 1965 operating scenario, under which the final optimum configuration resulted in the lowest objective function value, were investigated next to determine if similar release temperature deviations occurred under the best operating conditions. Examination of the release temperature from this simulation (Figure 21) indicated similar trends to the simulation of 1985 meteorological data with the 1964 operating scenario. During January-March, reservoir temperatures were relatively uniform top to bottom; therefore, releases during this period were not affected by port operation. In addition, deviations above the release temperature objective were due to reservoir temperatures that were above the release temperature objective. When the flow was increased from 26 to 481 cfs on day 254 (11 September), the expansion of the withdrawal zone into the hypolimnion resulted in a cooler release temperature (3.9° C change). By day 256 (13 September), when the lower port was no longer submerged and all flow had to be released through the flood-control gates, the temperature dropped another 5.5° C. The remaining drawdown scenarios displayed similar results as indicated by the objective function values. When the discharge was increased, expansion of the withdrawal zone caused a drop in release temperature. With the falling pool and subsequent shift to lower gates, an even larger drop in release temperature was observed.



a. Release temperature

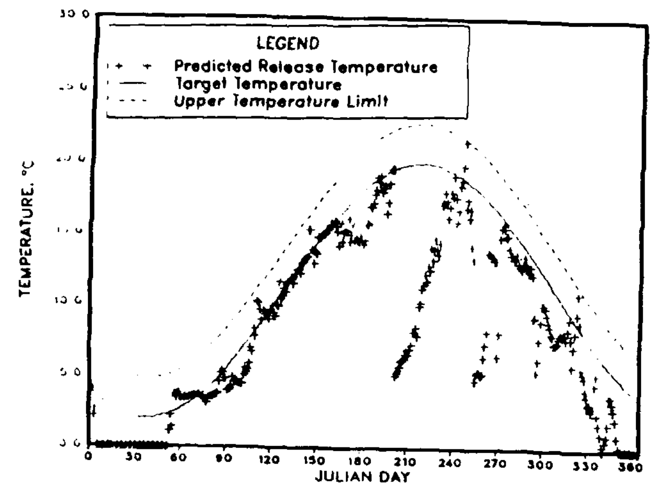


b. Withdrawal limits

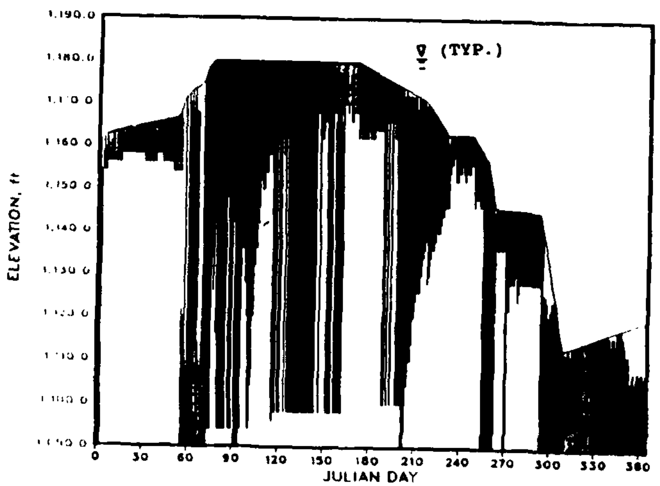


c. Temperature contours

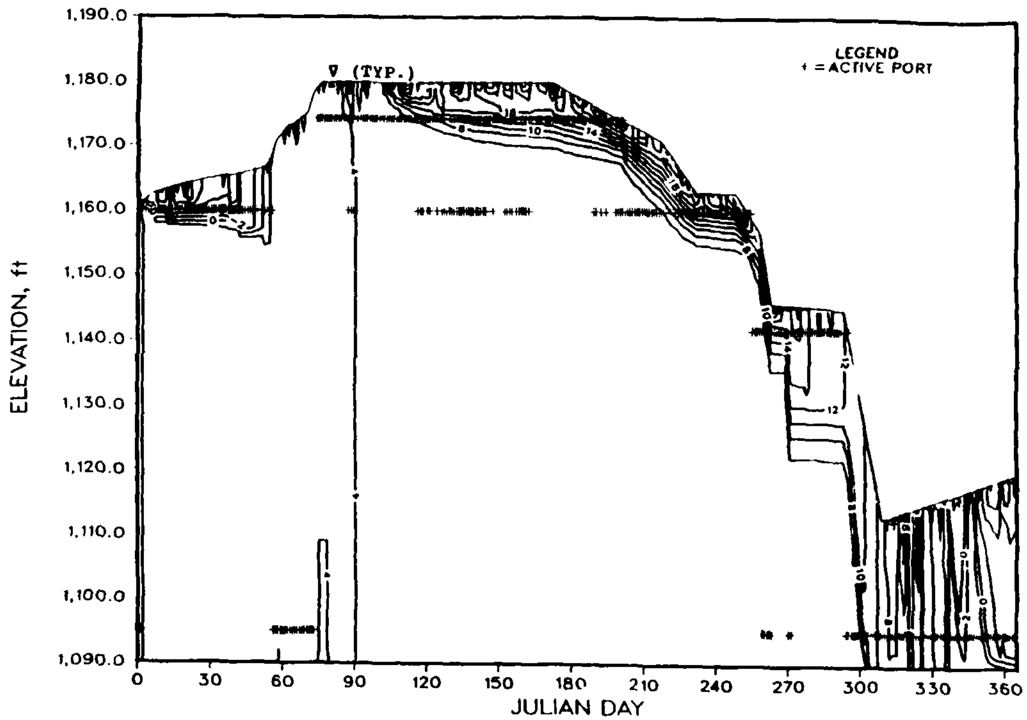
Figure 19. Reservoir and release conditions for level pool operating scenario with 1985 meteorological conditions



a. Release temperature

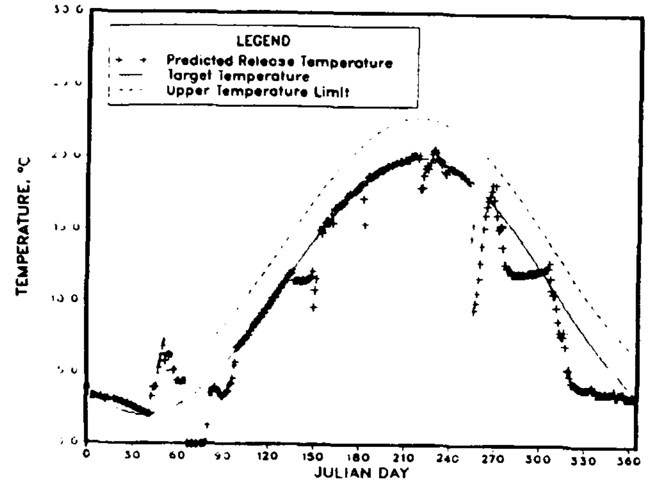


b. Withdrawal limits

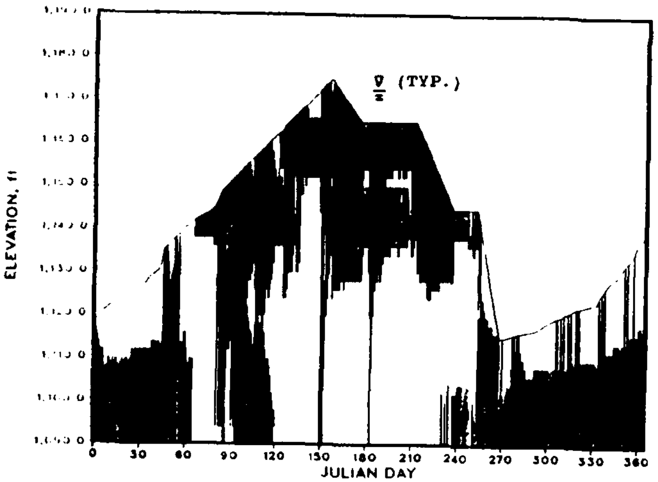


c. Temperature contours

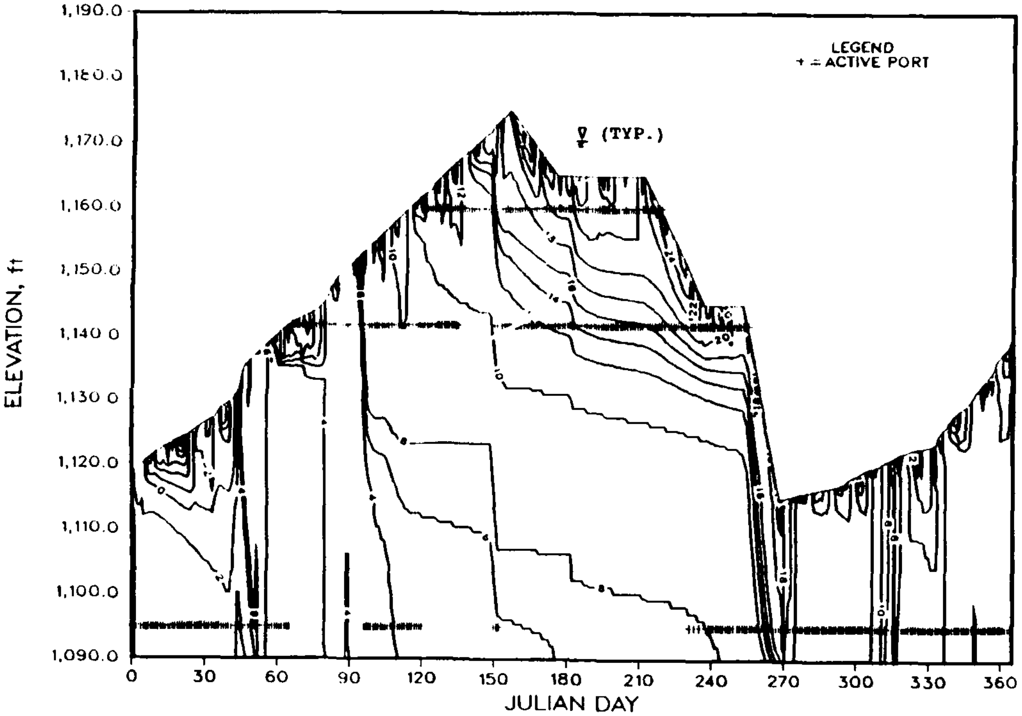
Figure 20. Reservoir and release conditions for 1964 operating scenario with 1985 meteorological conditions



a. Release temperature



b. *Withdrawal limits*



c. Temperature contours

Figure 21. Reservoir and release conditions for 1965 operating scenario with 1984 meteorological conditions

42. The temperature criteria as given by the State of Pennsylvania (paragraph 12) do not contain criteria for maximum allowable temperature deviations below the objective. Therefore, a meeting with the Philadelphia District was held 19 November 1987 to discuss these preliminary results. At this meeting, the temperature deviation was discussed and determined to be unacceptable. A number of alternatives were discussed; however, only two appeared to be feasible: a movable submerged weir and reservoir destratification. Analyses of those options are presented in the next two parts of this report.

PART IV: EVALUATION OF SUBMERGED WEIR

Background

43. Submerged weirs have been used on several projects to minimize the release of hypolimnetic water. The technique involves construction of an impermeable submerged weir upstream of the intake structure. The crest of the weir is located to constrict the lower withdrawal limit and thereby release predominantly epilimnetic water. For example, Clarence Cannon Dam, which is operated by the St. Louis District, was constructed with a submerged weir in front of the dam. This weir improves the quality of release by minimizing the depth of the withdrawal zone during hydropower releases. This concept works well for projects with minimum water level fluctuation. However, the weir is fixed; therefore, the range of pool elevations over which the weir is effective is limited. In addition, there is no provision for lowering the pool below the crest of the weir. At Prompton Reservoir, a moveable weir could possibly be designed into the proposed outlet structure. This is envisioned as a series of stop logs stacked in a bulkhead or gate slot. As the water level is dropped, the stop logs are removed to ensure submergence of the weir crest.

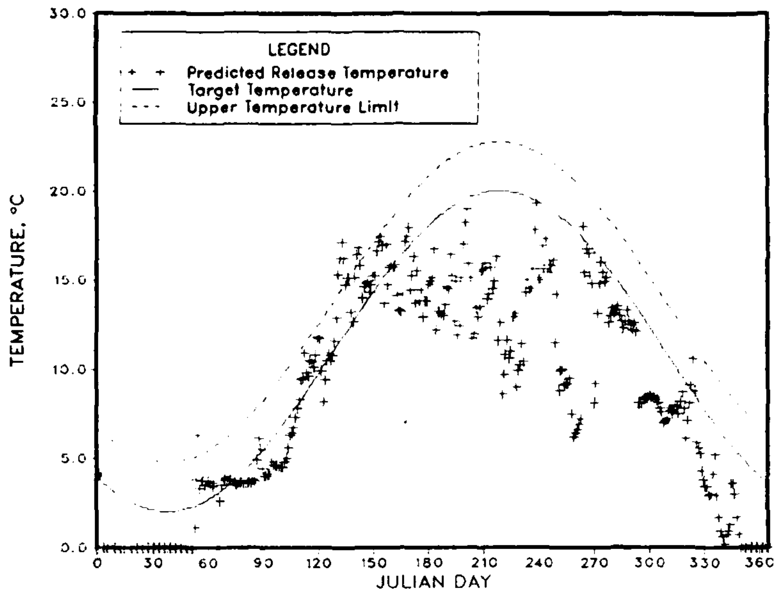
Modification to Numerical Model

44. The use of a moveable submerged weir to allow more epilimnetic water to be released during the drawdown to minimize the temperature drop when the discharge is increased was evaluated using the numerical model. The model was modified to use a moveable submerged weir as a release structure. Since the proposed structure would have a 30-ft-wide gate, a 30-ft-wide weir was conceptualized as a series of 2-ft-high gates (as suggested by the Philadelphia District) which were stacked in a single gate slot much like stop logs. Flow would be controlled by a gate in the wet well. As the discharge was increased during the drawdown scenario, and the pool dropped subsequently, the gates were pulled to always allow between 1 and 3 ft of water over the weir. During pool filling the gates were replaced, resulting in the same condition of 1 to 3 ft of submergence.

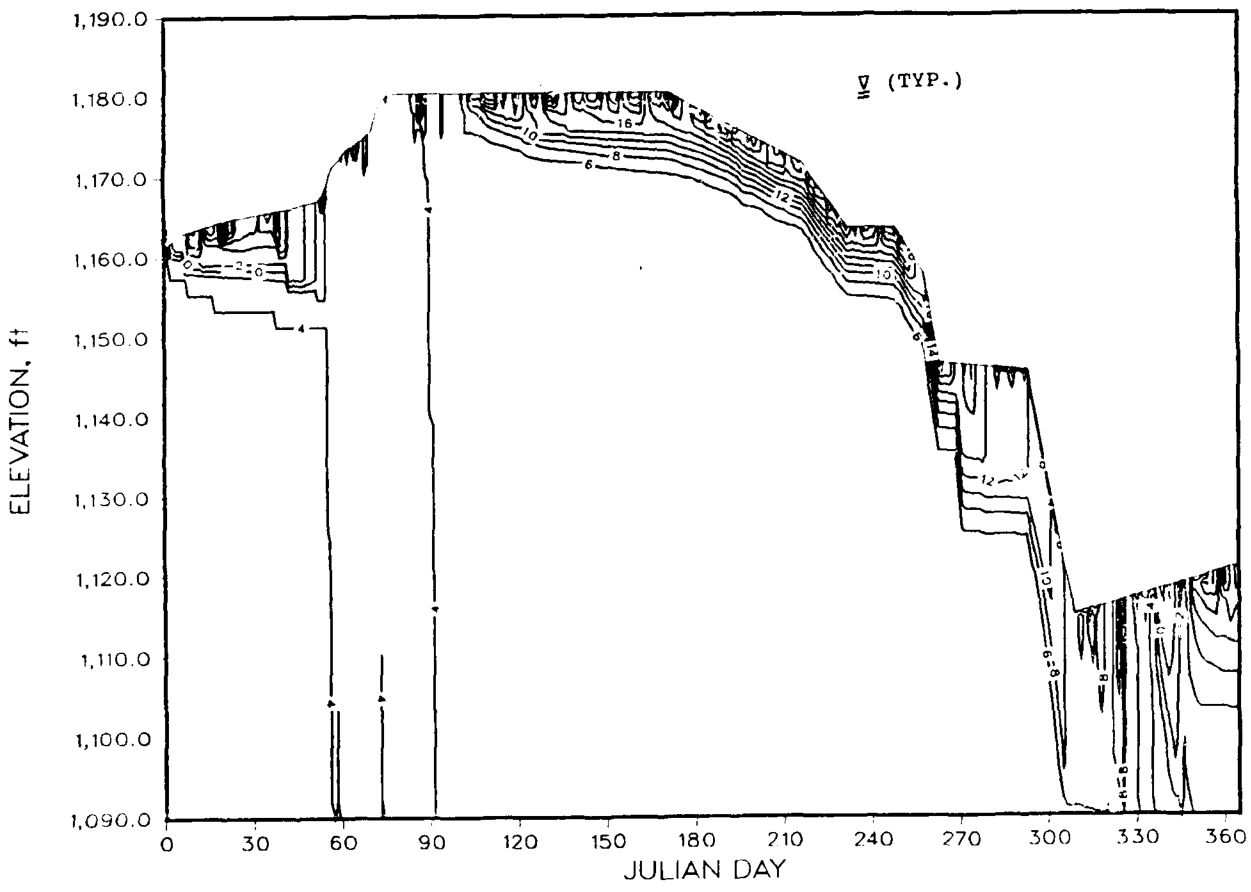
Results of Numerical Simulation Using a Submerged Weir

45. Using the 1985 meteorological conditions with the 1964 operating scenario, a simulation was run using only weir flows. These conditions were chosen since they represent the most difficult for the final optimum configuration to meet. The thermal stratification in the pool (Figure 22) was only minimally impacted by the weir flows and appeared very similar to the optimum condition as shown in Figure 20. However, as with previous drawdown scenarios, when the flow was increased, the withdrawal zone expanded, causing a drop in the release temperature. For example, on day 294 (21 October) the discharge was increased from 57 to 497 cfs, resulting in a release temperature drop from 12.0° to 8.1° C. In addition, a considerable degree of daily variation in release temperature was observed due to the loss of selective withdrawal control; and during the spring, the release temperature exceeded the upper limit on several occasions as a result of withdrawal from the surface layer during minimum flow events. Since this alternative did not satisfy release temperature requirements any better than previous port simulations, further simulations using other drawdown and meteorological conditions were suspended. Although a hybrid wet well consisting of both gates and a weir could minimize some of the fluctuation, the increase in the withdrawal zone when the drawdown occurs would still impact release temperature.

46. From this simulation it was apparent that large discharges during the stratified period produced considerable drops in temperature downstream no matter what type of release structure was used. Therefore, the drawdown scenarios create a problem that is bounded by resources rather than the type or design of the release structure. Thus, a second alternative involving modification of the thermal structure in the pool to reduce the release temperature fluctuation was evaluated.



a. Release temperature



b. Temperature contours

Figure 22. Reservoir and release conditions for 1985 meteorological conditions with 1964 operating scenario using a 30-ft submerged weir release structure

PART V: EVALUATION OF RESERVOIR DESTRATIFICATION

Background

47. The destratification of the pool may minimize fluctuation of the release temperature associated with the drawdown scenarios by modifying the in-reservoir temperature profile to near-uniform conditions (allowing for a minimal temperature difference between the surface and the bottom of the pool). This prevents the density stratification, which defines the limits for withdrawal zone formation. This makes the withdrawal zone extend from roughly surface to bottom regardless of discharge, and effectively makes the release temperature independent of discharge.

48. There are a number of destratification devices currently in use. These include mechanical pumps that transport surface water downward into the hypolimnion and aeration systems that release air bubbles near the bottom to create circulation cells as the bubbles rise to the surface. The method by which Prompton Reservoir would be destratified was not investigated. However, for this study, the model assumed that it could be destratified.

49. Using the destratification design guidance developed from previous research at WES (Holland and Dortch 1984), a lake destratification system could be designed. For example, three 40-hp surface mixers typically used in hydraulic mixing applications could destratify the entire lake in approximately 9 days.

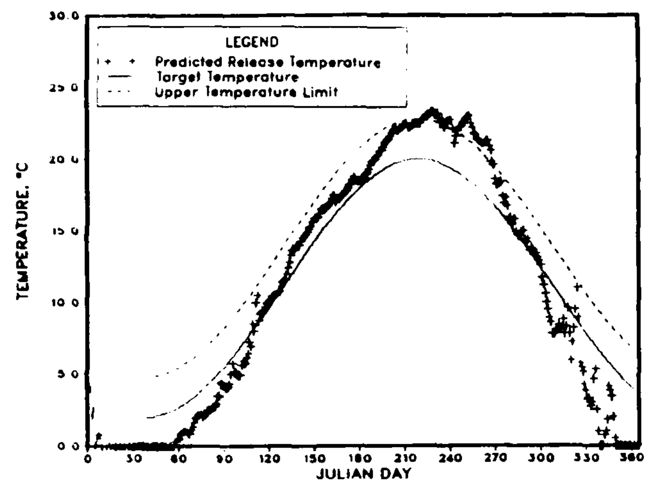
Modification to Numerical Model

50. To investigate the effects of destratification on release temperature, the numerical model was again modified to add a simplified destratification routine. Since previous research indicated that an 80 percent mixed condition is the design condition that is the most feasible (Dortch 1979), the model was modified to simulate an 80 percent mixed state throughout the entire reservoir. This was simulated by removing 80 percent of the volume of each layer in the reservoir, mixing these removed volumes together to a uniform temperature, and then adding the mixed volume back to the respective layer. A stable density profile was then enforced to achieve the destratified

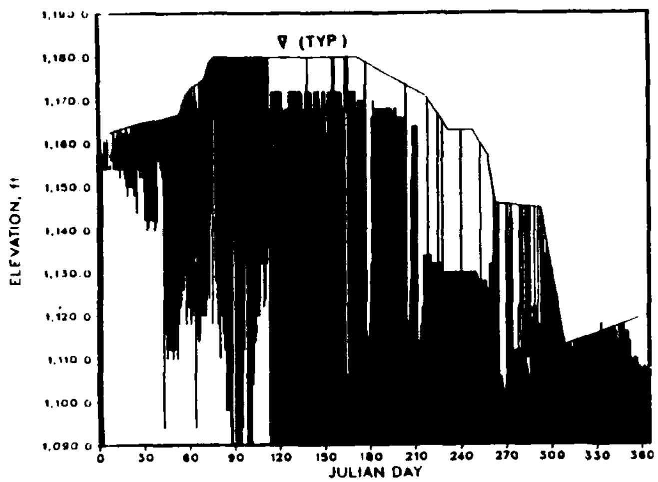
condition. For this study, this resulted in a surface-to-bottom temperature difference usually less than 6° C.

Results of Simulation Using Lake Destratification

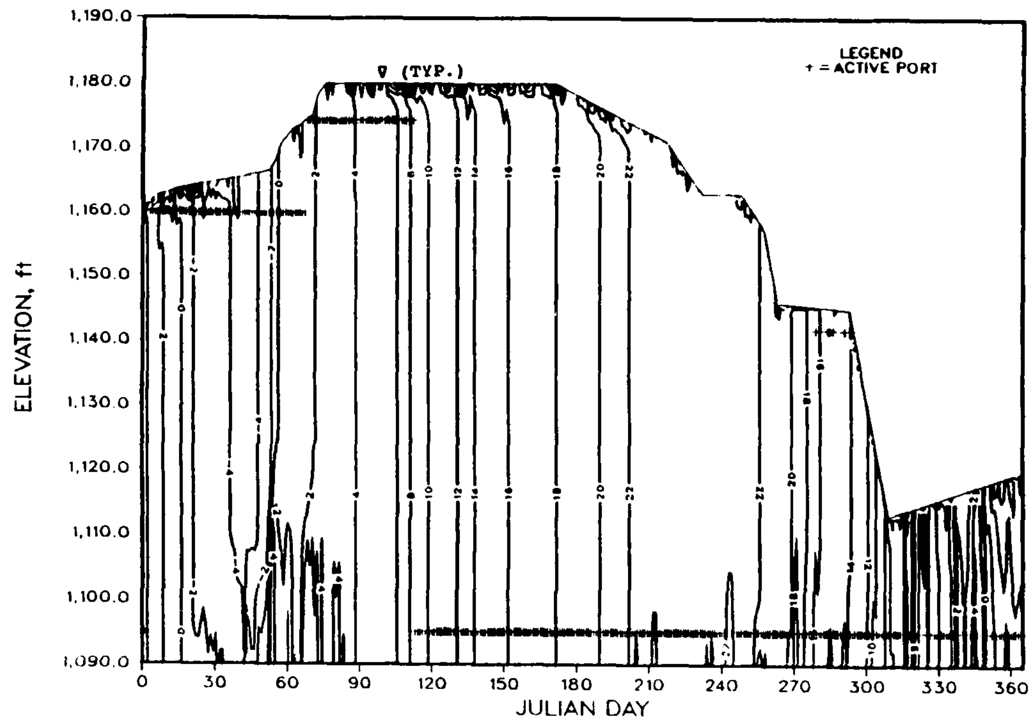
51. The 1985 meteorological condition with the 1964 operating scenario (as used with previous simulations) was used to investigate the impacts of the destratification system on release temperature objectives. The simulation with the destratification system operating from day 3 (3 January) to day 365 (31 December) reduced the release temperature fluctuations from those previously predicted (compare Figure 20 with Figure 23); however, the reservoir retained more heat, thereby exceeding the upper limit of the release criteria during the late summer. Since the destratification system is ineffective in the winter when little stratification exists, a second simulation was run in which the destratification routine was initiated on day 45 (14 February). Also, the previous simulations indicated that heat retention by the reservoir resulted in release temperature exceeding the objective. Therefore, the simulation was repeated with the destratification system operating only from day 45 through day 160 (9 June). The results of this simulation are given in Figure 24. The release temperature followed the objective temperature much more closely, deviating only when the highest port was no longer submerged and the operation switched to the next lower port. A similar temperature drop occurred with the switch from ports 2 and 3 to the flood-control gate operation. The spring destratification produced a weaker stratification prior to the drawdown, allowing the selective withdrawal capability of the structure to be used to meet the release temperature criteria. Prior to destratification, the release temperature deviations, which were 2.78° C above or below the objective temperature, occurred on 74 days. This was also reflected by the objective function value (5930). However, the use of the destratification system reduced the number of days the release deviated from the objective band to 10, which was also reflected in the objective function value (300). These 10 days were during the fall (mostly November) when the lake volume was relatively small as a result of the drawdown. This period was therefore more sensitive to meteorological conditions and was cooler than the objective temperature. Simulation of the remaining drawdown scenarios with destratification resulted in relatively low objective function values as well as reductions in the



a. Release temperature

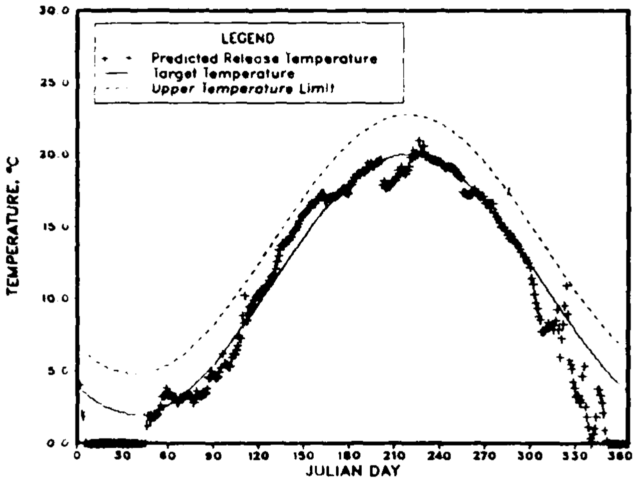


b. Withdrawal limits

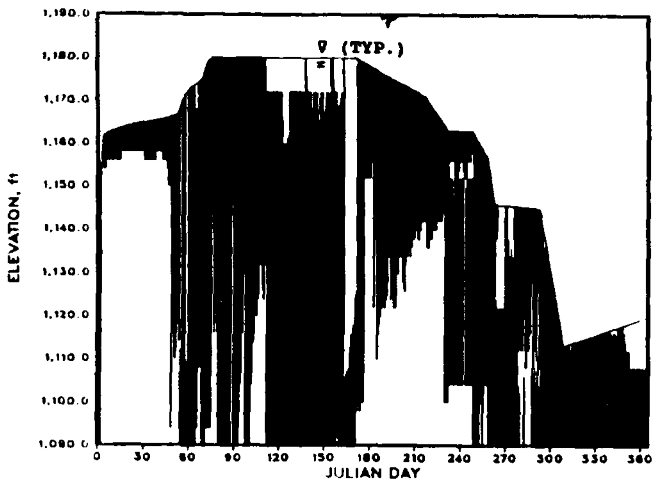


c. Temperature contours

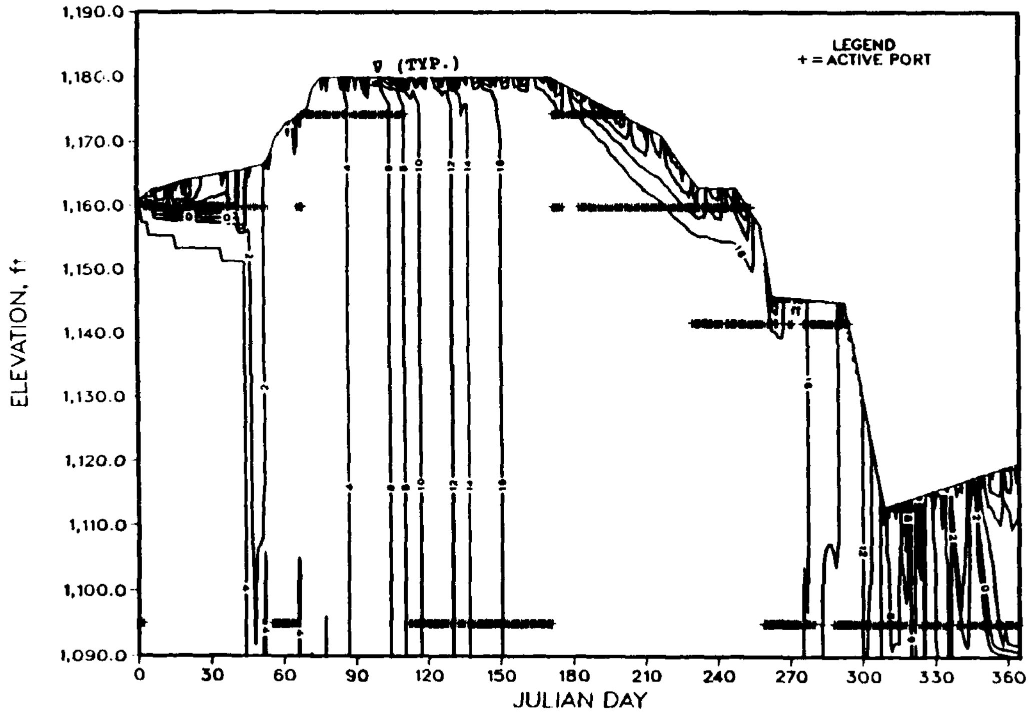
Figure 23. Reservoir and release conditions for 1964 operating scenario with 1985 meteorological conditions and destratification system operating from day 3 to day 365



a. Release temperature



b. Withdrawal limits



c. Temperature contours

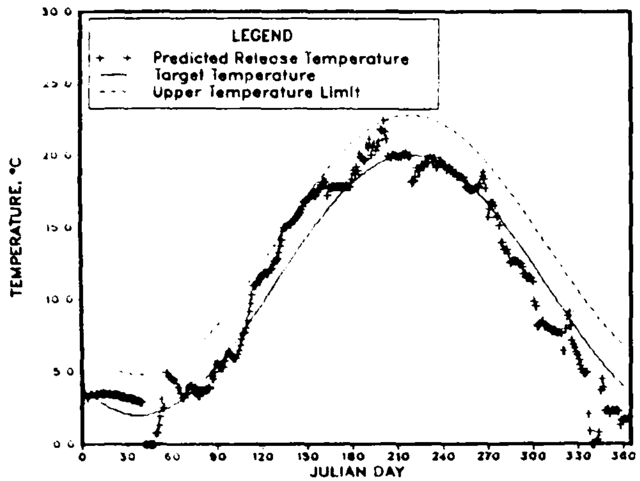
Figure 24. Reservoir and release conditions for 1964 operating scenario with 1985 meteorological conditions and destratification system operating from day 45 to day 160

number of days the release temperature deviated from the objective (Table 1). As with the 1985 simulation of the 1964 operating condition with the destratification system, most occurrences of the deviation were during the late fall (October-November) when the reservoir volume was small. All of the deviations were below (more than 2.78° C) the objective temperature with only two exceptions. The simulation using the 1985 meteorological conditions with the 1965 operating scenario resulted in warmer lake temperatures during the spring when the reservoir was filling; consequently, these releases were warmer than the release temperature objective (Figure 25). The simulation using the 1984 meteorological conditions with the 1964 operating scenario resulted in a larger objective function value than the same simulation without destratification due to fall releases that exceeded the upper limit of the target release temperature (Figure 26). Although these two simulations did not result in decreases in the objective function values, the number of days that deviations of release temperature from the objective occurred were reduced significantly from the same simulation without destratification. Further, the large release temperature changes associated with increased discharge or gate charges were eliminated through use of destratification.

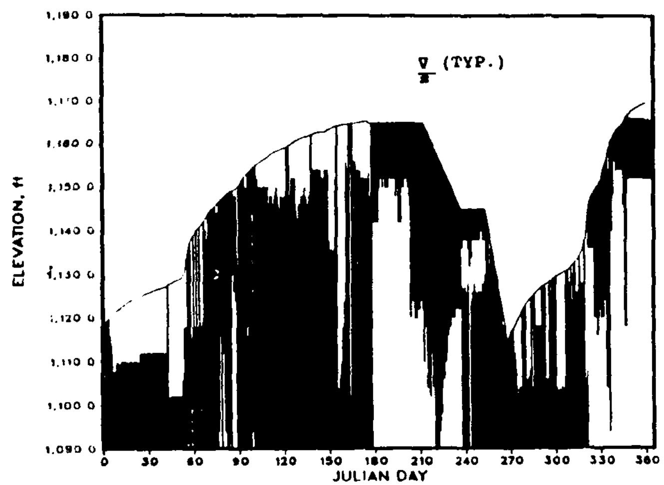
Table 1

Objective Function (OBF) Values and Number of Days of Release Temperature Objective Deviations With and Without Destratification

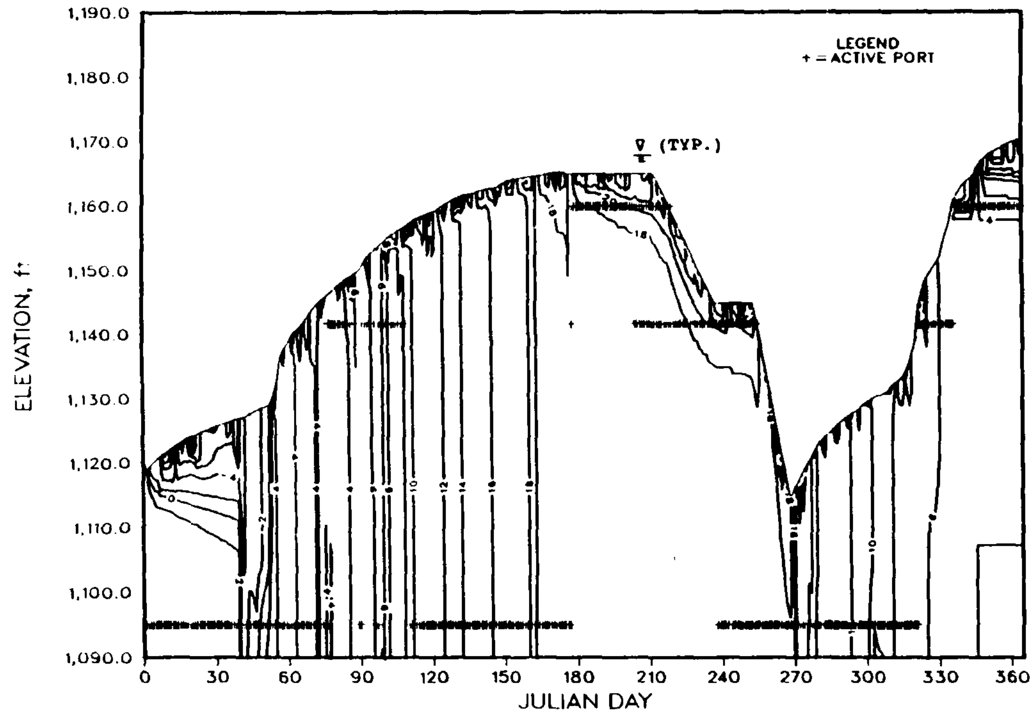
Meteorological Condition	Operating Scenario	Without Destratification days	Without Destratification OBF	With Destratification days	With Destratification OBF
1983	1930	61	2820	33	1920
	1957	82	4440	41	1900
	1964	93	5580	22	608
	1965	66	2650	35	907
1984	1930	46	1500	22	604
	1957	48	2050	27	536
	1964	42	1520	25	3170
	1965	35	848	25	576
1985	1930	39	3540	16	448
	1957	65	5100	4	321
	1964	74	5930	10	320
	1965	60	4210	17	4590



a. Release temperature

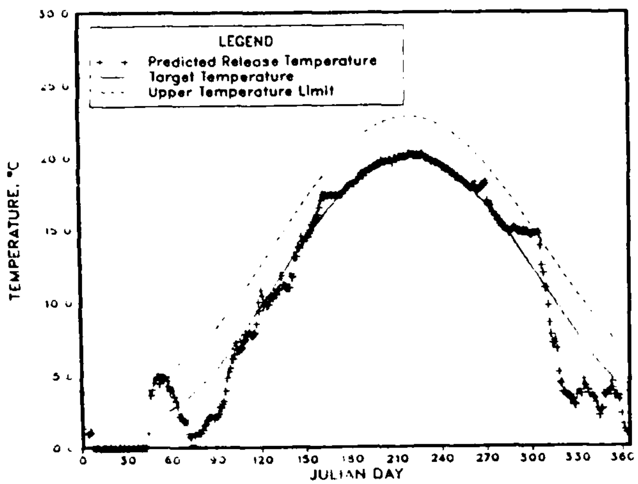


b. Withdrawal limits

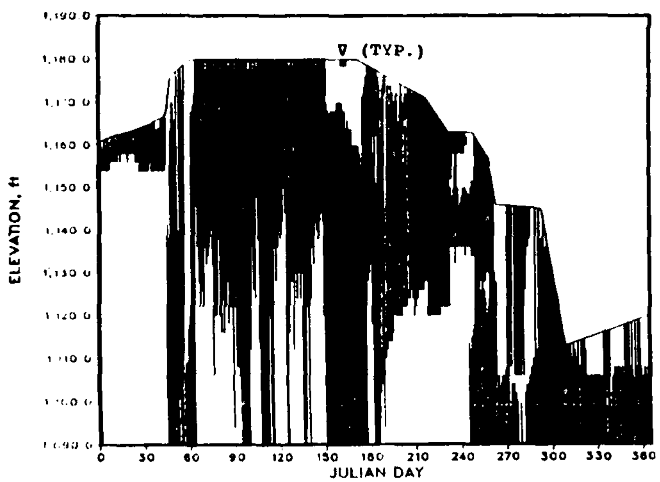


c. Temperature contours

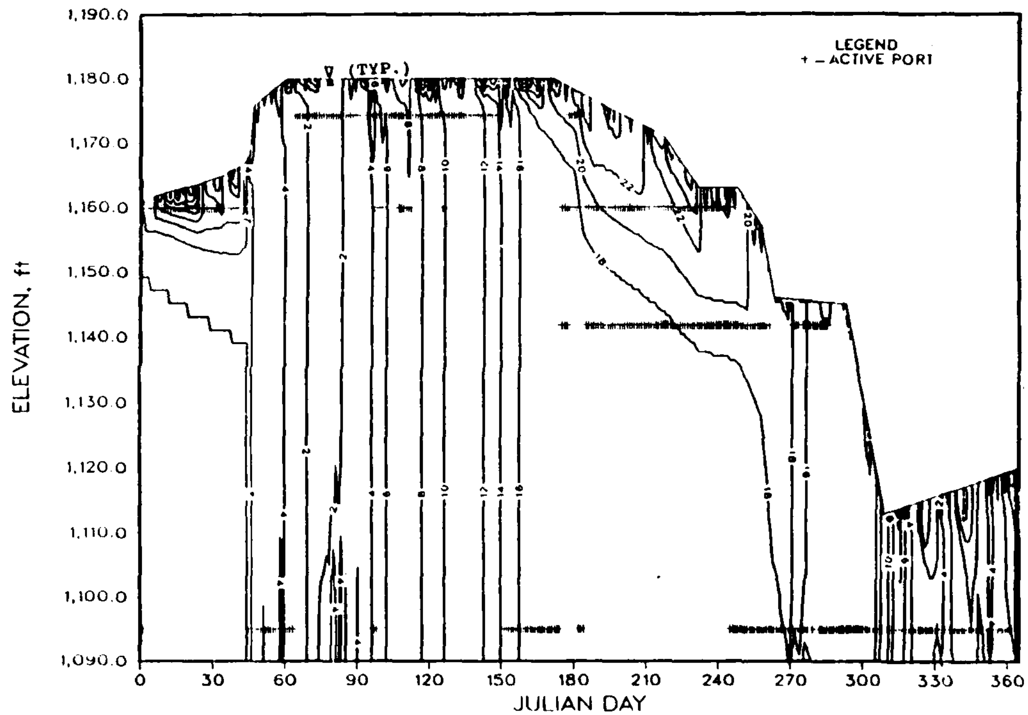
Figure 25. Reservoir and release conditions with 1965 operating scenario and 1985 meteorological conditions and destratification system operating from day 45 to day 160



a. Release temperature



b. Withdrawal limits



c. Temperature contours

Figure 26. Reservoir and release conditions with 1964 operating scenario and 1984 meteorological conditions and destratification system operating from day 45 to day 160

52. The results for these simulations indicate that the three-port dual wet well structure with 325-cfs capacity per port in combination with a lake destratification system will generally provide the control necessary to meet the release temperature criteria.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

53. The proposed increase in storage of Prompton Reservoir will require modification of the existing uncontrolled release structure. This proposed storage increase will raise the pool approximately 55 ft. In order to maintain acceptable release temperatures downstream, the modified structure was proposed with selective withdrawal capability. This investigation was undertaken to determine the optimum number, capacity, and location of selective withdrawal ports in the release structure. Using an optimization routine coupled to a one-dimensional thermal model, an optimum structure consisting of three ports with 325-cfs capacity per port in a dual wet well configuration was recommended. Upon closer examination of simulations of the release temperature from this structure, the level pool operating condition met the release temperature criteria; however, with initiation of any of the four drawdown scenarios, a considerable deviation in release temperature from the objective was observed as a result of increased release volume during the drawdown and its resulting shifts to lower ports.

54. Because the temperature deviation was deemed unacceptable by the Philadelphia District, two alternatives were examined. One alternative involved a submerged weir, configured as a stop log structure, which could be lowered with the pool; however, a considerable variation in daily release temperature was observed through its use. The second alternative involved the use of lake destratification to minimize the thermal stratification and thereby minimize the release temperature deviations associated with the drawdown. This alternative, in conjunction with multilevel selective withdrawal capability, met the release temperature criteria. This recommended three-port structure, in conjunction with a lake destratification system, will be required to meet release temperature objectives during all of the four drawdown scenarios. It is recommended that prior to construction of the new release structure, a more detailed investigation of destratification methods be conducted to determine operational guidance of the system.

55. Since the initiation of this investigation, considerable research has been conducted on the simultaneous operation of multilevel ports in a single wet well (as opposed to the operation of a single port in a single well as simulated in this investigation). Although this single wet well technology has not been fully integrated into design tools at this time, results of that

research indicate that a single wet well with the same total capacity as a dual wet well design would provide much of the same release temperature capabilities as a dual wet well provided that it has the ability to throttle flow through individual ports. However, there are some tradeoffs in operational flexibility with the use of a single wet well compared to a dual wet well design. This alternative may merit investigation.

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APPENDIX A: PROMPTON RESERVOIR NEAR-FIELD PHYSICAL MODEL INVESTIGATION

Purpose

1. Previous studies (Howington 1989; Dortch et al. 1976)* had indicated that local topography can influence the withdrawal characteristics. An undistorted-scale near-field physical model of the Prompton Reservoir in the vicinity of the proposed new release structure was constructed to evaluate the effect of the local topography upon the withdrawal characteristics of the project. By developing a site-specific description of withdrawal from the physical model results, these local effects were accounted for in a numerical model through adjustment of the withdrawal angle parameter. This information was used in conjunction with the numerical simulation to determine the optimum port configuration to meet release temperature requirements at the project.

Model Description

2. The scaling procedure used with these types of model studies is based on Froudian similitude. The model must be scaled such that the Froude number, which is the ratio of inertial to gravitational forces, is similar between the model and the prototype. This results in a length scaling that is equal to the established model scale. Since the minimum prototype length that needed to be reproduced was 100 ft (depth of the pool), the scale of 1 ft in the model to 50 ft in the prototype would allow use of a 2-ft-deep flume. Previous selective withdrawal work performed in physical models has used scales ranging from 1:40 to 1:100 (Howington 1989). The established scaling parameters follow (dimensions are in terms of length):

Dimension	Ratio	Scale Relation Model:Prototype
Length	$L_r = L$	1:50
Velocity	$V_r = L_r^{1/2}$	1:7
Discharge	$Q_r = L_r^{5/2}$	1:17,677
Density difference	$\Delta\rho_r = 1$	1:1

* References cited in this Appendix are included in the References at the end of the main text.

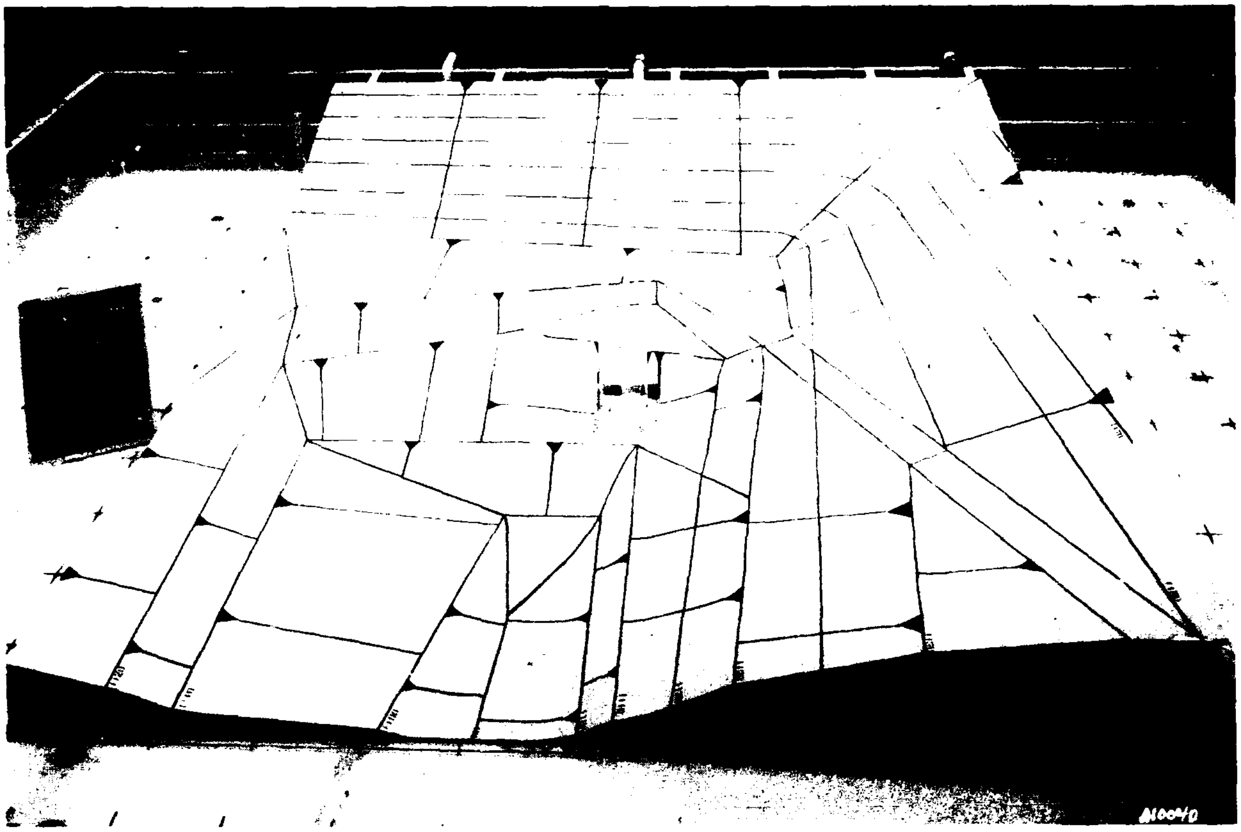


Figure A1. Prompton physical model

3. The physical model (Figure A1) was constructed to a 1:50 scale (model to prototype) in an 800-ft^3 flume and reproduced the area of the project within approximately 250 ft in all directions from the release structure. Previous selective withdrawal work had indicated that the topographic influences are limited laterally to the distance approximately equal to two withdrawal zones. Since the maximum withdrawal zone thickness could not exceed the maximum pool depth (90 ft), the topography had to extend at least 180 ft in all directions from the structure. The prototype intake structure was modeled to approximate external dimensions. Due to the uncertainty of the number and location of ports in the proposed structure, the front of the structure was removable to allow different locations, as well as sizes, of ports to be modeled. Initial tests were conducted using the three-port dual wet well structure recommended in paragraph 38 (main text). Since operation of the flood-control gate was not considered as part of the selective withdrawal system by the Philadelphia District, it was not modeled. Because the possibility for a dual wet well structure existed, the model structure was

constructed with a partition to simulate separate wet wells, each controlled by a gate valve. Total flow from the structure was controlled by a single gate valve downstream of a rotameter used to determine total flow in gallons per minute. Topography was reproduced using plywood and metal with the structure reproduced with Plexiglas.

Testing Procedure

4. Density stratification within the lake resulting from temperature stratification was simulated in the model using fresh and salt water. Since the densimetric Froude number similitude between the model and the prototype is significantly more dependent upon the density difference rather than the absolute water density, actual densities were not simulated. To achieve this density stratification, the flume was filled in layers. Salt water was added to represent the hypolimnion. Fresh water used to represent the epilimnion was added on top of the salt water using a moveable weir structure. Upon completion of filling, the stratification was allowed to stabilize. Then a vertical temperature and conductivity profile was taken at discrete intervals and used to compute a density profile. A particular port operation was then set and the desired flow from the port was measured using the rotameter. To determine the impacts of a range of flows, four flow rates were tested in this investigation (50, 100, 220, and 325 cfs corresponding to 1.27, 2.54, 5.58, and 8.25 gpm, respectively, in the model). The larger flow rates, 220 and 325 cfs, were the maximum flows under consideration by the Philadelphia District. To determine the shape and limits of the withdrawal zone, crystalline dye was dropped in front of the release structure. A fixed grid located in front of the operating port was used to measure the shape and limits of the withdrawal pattern. The dye streak displacement was filmed through the transparent flume walls with a video camera. This allowed the development of the withdrawal pattern to be accelerated or slowed to accurately determine the level of maximum withdrawal and the withdrawal limits.

5. The port geometry flow and test density profile were input into the numerical model SELECT (Davis et al. 1987) to compute withdrawal characteristics. This model contains the essential selective withdrawal parameters and computational procedures that are contained in the withdrawal routines in the WESTEX model. Therefore the withdrawal characteristic simulated by the SELECT

model would be the same as the WESTEX model. The SELECT model predicted values were compared to the physical model observed values to determine the impacts of the local topography.

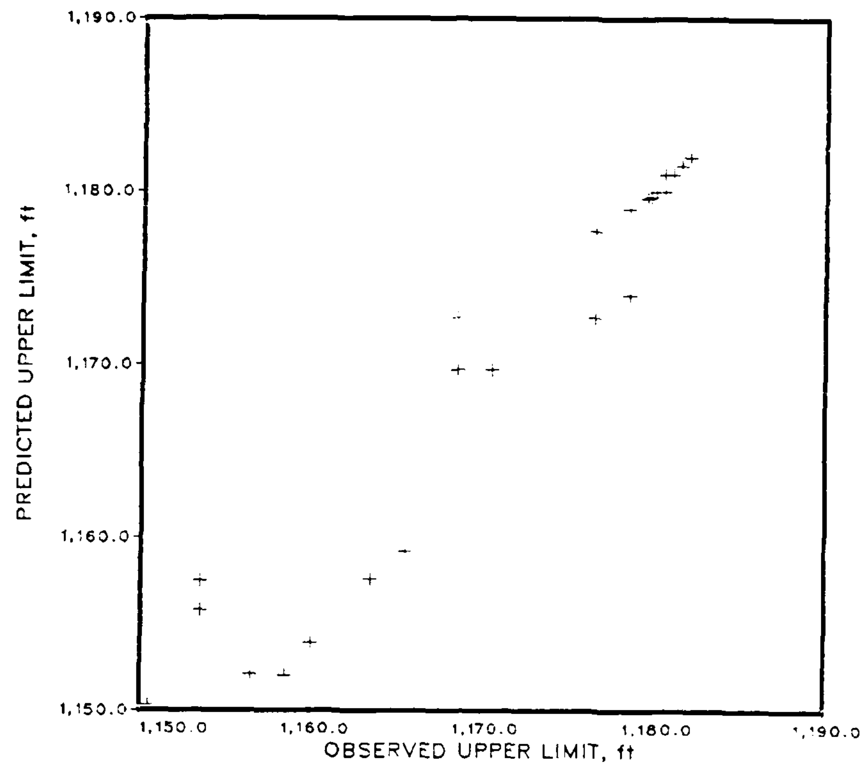
Results

6. Tests were completed for each of the three ports recommended by the WESTEX optimization results (paragraph 37, main text) using the four flow rates and a range of stratification patterns (from linear to two-layer). The two-layer stratification series with the uppermost port was conducted twice, yielding a total of 28 tests. The observed test conditions (port flow, elevation, and density stratified) were also simulated in the SELECT model.

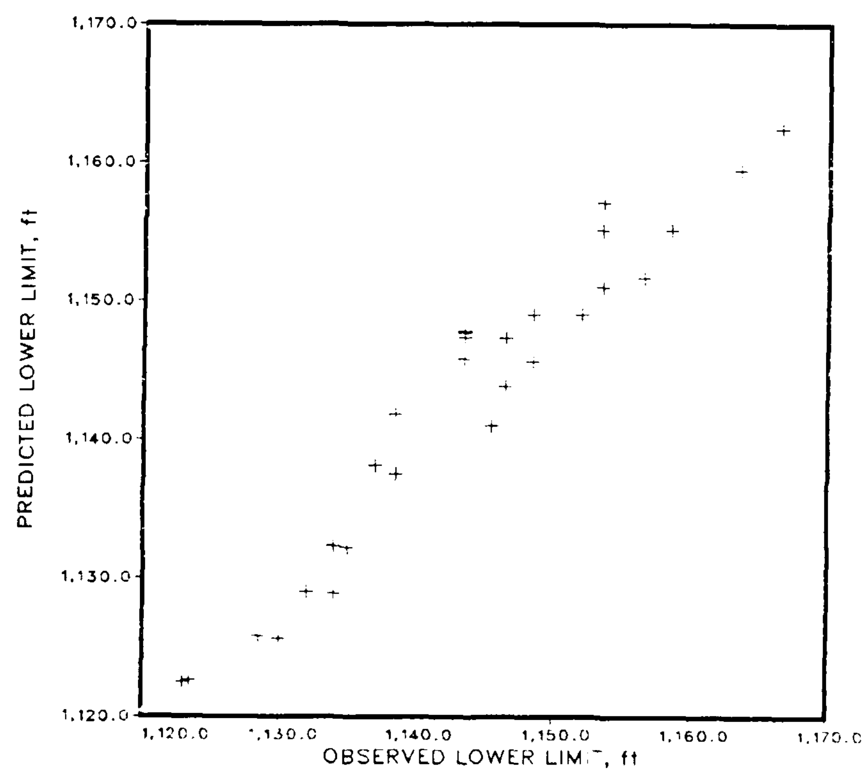
7. The results of the model investigation were analyzed by comparison of physical model observation to those predicted by the SELECT model. The comparison of the SELECT-predicted limit to the upper limit observed in the physical model (Figure A2) indicated the predictability improved as the limit approached the surface. This is probably a result of the limit extending to the upper boundary (surface) rather than an improvement in predictability. Once the upper limit reached the surface, location of the limit both in the numerical and physical model was dependent on the surface elevation. The maximum difference between the SELECT-predicted values and those observed in the physical model was 6.5 ft (prototype).

8. The comparison of the SELECT-predicted to observed physical model lower limit (Figure A2) was more accurate than that of the upper limit with the maximum difference between predicted and observed of 4.5 ft. As mentioned earlier (paragraph 1, Appendix A), local topography could have an influence on formation of the withdrawal zone. This could be manifested perhaps by the lower limit interacting with the bottom, thereby modifying the shape or upper limits of the withdrawal zone. Since the lower limit did not reach the bottom, the boundary had no impact on the withdrawal zone. In addition the comparison of the SELECT-predicted upper and lower limits to those observed in the physical model indicated good agreement requiring no modification to the assumed withdrawal angle.

9. The comparison of the elevation of maximum withdrawal (Figure A3) was much more variable with deviations of SELECT-predicted elevation from those observed in the physical model of up to 14.5 ft. However, the average



a. Upper limit comparison



b. Lower limit comparison

Figure A2. Comparison of predicted with observed limits of withdrawal

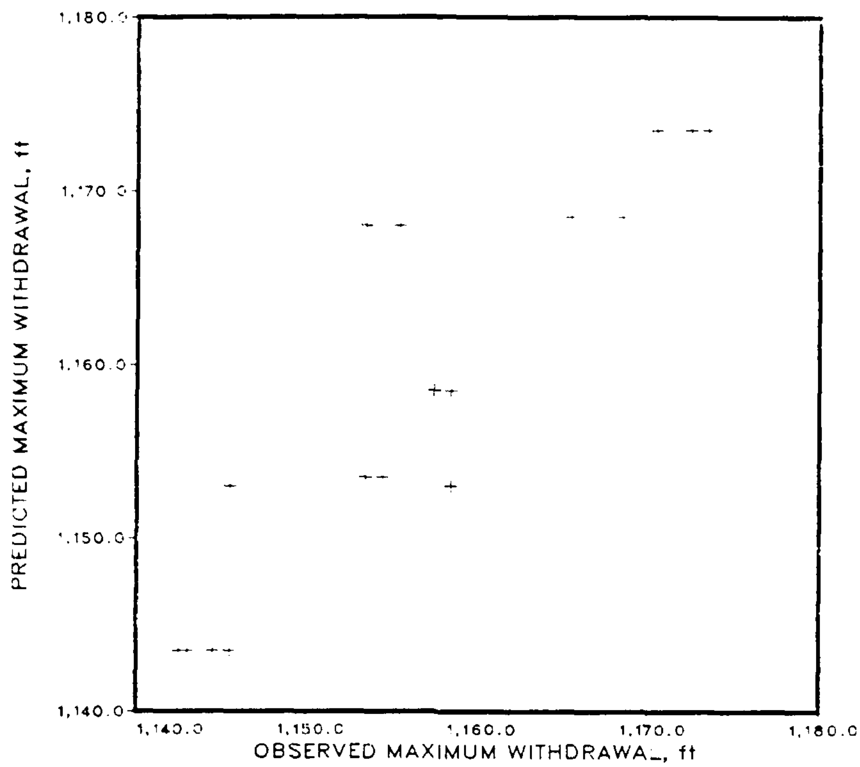


Figure A3. Comparison of predicted with observed maximum withdrawal

deviation was only 2.4 ft. The parabolic shape of the withdrawal zone made determination of the limits fairly precise. However, the layer of maximum withdrawal was much more difficult to determine since the maximum layer may extend over a range of 10 to 20 ft in the prototype. As with the limit comparison discussed previously, comparison of the SELECT-predicted layer of maximum withdrawal with those observed in the model indicated relatively good agreement.

10. The final comparison was that of the SELECT-predicted density with release density observed from the physical model (Figure A4). As with the previous comparison, the SELECT-predicted release density compared favorably with those observed from the physical model. The maximum difference observed (0.0005 g/cc) was just above the limits of detection (0.0002 g/cc), indicating good agreement between the numerical and physical model.

Conclusions

11. The key parameter, as discussed in paragraph 1 (Appendix A) used to

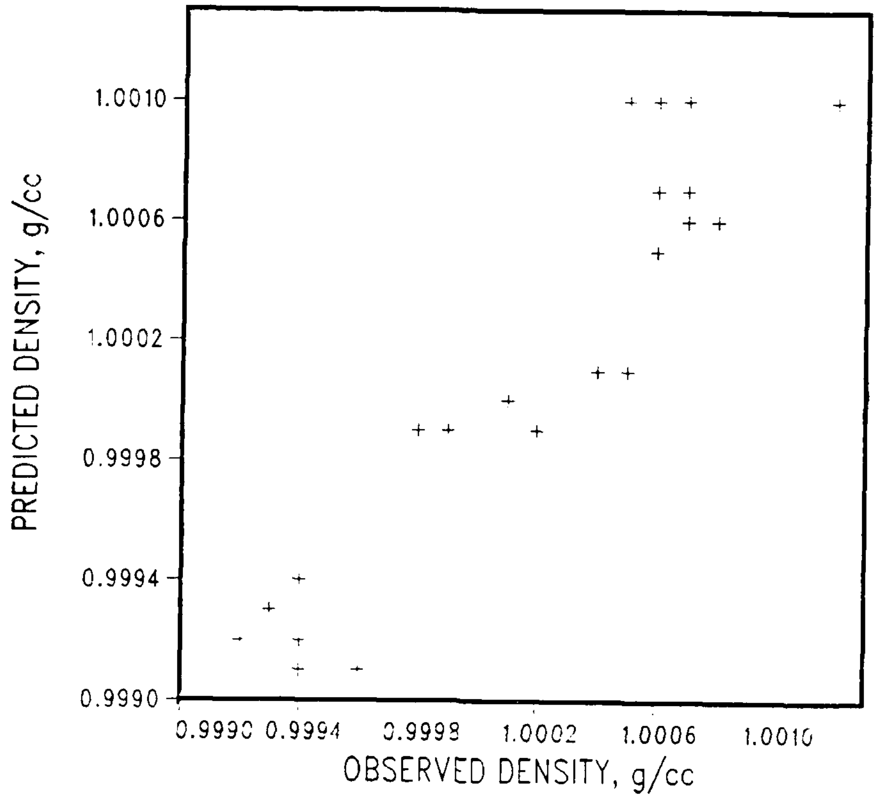


Figure A4. Comparison of predicted with observed release density

adjust the numerical model for local topography effect is the withdrawal angle. For the initial simulation in the SELECT model, the parameter was set at 3.14 radians, indicating a withdrawal angle of 180 deg in front of the structure. If there was an impact due to local topography, comparison of numerical model predictions with physical model results would indicate poor agreement. In this investigation, the comparison of the upper and lower limits and the layer of maximum withdrawal indicated relatively good agreement between the physical model and the SELECT predictions. The comparison of the release density with that predicted by the SELECT model also agreed well. Therefore, results of this investigation indicate that a withdrawal angle of 3.14 radians should be used in the WESTEX model.