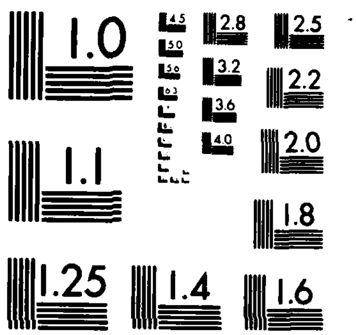
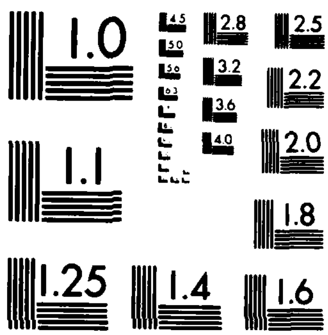
AD-A150 047 A TECHNIQUE TO OPTIMALLY LOCATE MULTILEVEL INTAKES FOR SELECTIVE WITHDRAW..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS HYDRA.. 1/1

UNCLASSIFIED M S DORTCH ET AL. NOV 84 WES/TR/HL-84-9 F/G 13/2 NL

END
FILMED
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

US Army Corps of Engineers

AD-A150 047

(12)

TECHNICAL REPORT HL-84-9

A TECHNIQUE TO OPTIMALLY LOCATE MULTILEVEL INTAKES FOR SELECTIVE WITHDRAWAL STRUCTURES

by

Mark S. Dortch, Jeffery P. Holland

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631
Vicksburg, Mississippi 39180-0631

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

November 1984

Final Report

Approved For Public Release, Distribution Unlimited

HYDRAULICS LABORATORY

Prepared for
DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

85 01 29 002

US Army Corps of Engineers

AD-A150 047

(12)

TECHNICAL REPORT HL-84-9

A TECHNIQUE TO OPTIMALLY LOCATE MULTILEVEL INTAKES FOR SELECTIVE WITHDRAWAL STRUCTURES

by

Mark S. Dortch, Jeffery P. Holland

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631
Vicksburg, Mississippi 39180-0631

November 1984

Final Report

Approved For Public Release, Distribution Unlimited

Prepared for

DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

85 01 29 002

HYDRAULICS LABORATORY

Destroy this report when no longer needed. Do not return it to the originator.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

20. ABSTRACT (Continued).

procedure is accomplished through the coupling of a reservoir thermal simulation model and a mathematical optimization algorithm. The report details the formulation of the design problem, input to the numerical procedure, constrains considered by the optimization procedure, and general use of the procedure. A case study illustrating the utility of the procedure for two optimization routines and the selection of one for the completed procedure are presented in detail.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report HL-84-9	2. GOVT ACCESSION NO. AD-A150047	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A TECHNIQUE TO OPTIMALLY LOCATE MULTILEVEL INTAKES FOR SELECTIVE WITHDRAWAL STRUCTURES		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Mark S. Dortch; Jeffery P. Holland		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Engineer Waterways Experiment Station; Hydraulics Laboratory; PO Box 631, Vicksburg, Mississippi 39180-0631		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS DEPARTMENT OF THE ARMY; US Army Corps of Engineers; Washington, DC 20314-1000		12. REPORT DATE November 1984
		13. NUMBER OF PAGES 46
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

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

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

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

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

As a result of increased public awareness and State and Federal legislation, water resources projects are being operated with a greater priority on water quality considerations. The use of a reservoir outlet works incorporating multilevel selective withdrawal intakes is a primary method for the control of reservoir in situ and release quality. Presented herein is a systematic numerical procedure whereby, for a given set of hydrothermal conditions, an optimum selective withdrawal intake configuration may be designed. The

(Continued)

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

PREFACE

This investigation was conducted as a part of the Flood Control Hydraulics Research and Development Program, sponsored by the Office, Chief of Engineers (OCE), US Army, administered by the Hydraulics Laboratory of the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, J. L. Grace, Jr., Chief of the Hydraulic Structures Division, and Dr. D. R. Smith, former Chief of the Reservoir Water Quality Branch (physical), directed and supervised this effort. Mr. M. B. Boyd, Chief of the Hydraulic Analysis Division, was the laboratory program manager and Mr. Tom Munsey of OCE was technical monitor of the Flood Control Hydraulics R&D Program.

Messrs. M. S. Dortch and J. P. Holland, Chief of the Reservoir Water Quality Branch, conducted this study and prepared the report. Mr. T. W. Reeves assisted in the numerical simulation testing. Drs. D. G. Fontane and B. Loftis, Colorado State University, assisted in the investigation as a contractor on numerical optimization.

Commander and Director of WES during this effort and the preparation and publication of this report was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

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

Multiply	By	To Obtain
acre-feet	1233.482	cubic metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres

A TECHNIQUE TO OPTIMALLY LOCATE MULTILEVEL INTAKES FOR SELECTIVE WITHDRAWAL STRUCTURES

PART I: INTRODUCTION

Background

1. As a result of increasing public awareness and State and Federal leg-

CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

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

Multiply	By	To Obtain
acre-feet	1233.482	cubic metres
cubic feet per second	0.02831685	cubic metres per second
feet	0.3048	metres

mathematical optimization routine because the quality of results and the rate of convergence (and, subsequently, the economy of the procedure) depend on the type of optimization scheme employed. Selection of an optimizer and recommendations for convergence criteria are based upon the results of an example application.

4. It is also intended that the technique be useful to persons concerned with hydraulic design as well as those involved with water quality control. The hydraulic constraints included in the procedure will require input from and feedback to those involved with hydraulic design. This interaction should result in a more effective and economical design for selective withdrawal structures.

5. In order to facilitate comprehension of the utility of the technique described herein, an elementary knowledge of simulation and optimization is appropriate. To this end, an overview of these concepts is presented in the next section followed by an application of the technique that demonstrates the potential utility of the procedure as a design tool.

A TECHNIQUE TO OPTIMALLY LOCATE MULTILEVEL INTAKES FOR SELECTIVE WITHDRAWAL STRUCTURES

PART I: INTRODUCTION

Background

1. As a result of increasing public awareness and State and Federal legislation, water resources projects are being operated with a greater priority on water quality considerations. Many proposed projects are being designed to operate for given water quality objectives. Furthermore, many existing projects are being retrofitted in order to meet water quality requirements.

2. The use of reservoir outlet structures incorporating multilevel selective withdrawal intakes is a primary method for the control of reservoir release quality. These structures permit release of water from various vertical strata in the reservoir, thereby allowing greater water quality control through blending or direct release. Although reservoirs may be operated for a variety of water quality objectives, the most common objective is maintenance of project release temperature in order to meet a prescribed downstream temperature. It is imperative, therefore, that the selective withdrawal intakes be placed in such quantity and location as to maximize the control of reservoir release temperature over a range of hydrologic, meteorological, and operational conditions. However, these intakes should be sited in a manner that is also cost-effective. An approach is therefore required that systematically determines the optimal number and locations of these intakes required to meet downstream temperature objectives for a range of conditions.

Objective and Approach

3. The objective of the work presented herein was to develop a technique that designers could use to determine the optimal number and locations of multilevel intakes required to satisfy release quantity and quality constraints for selective withdrawal structures. This is accomplished through the coupling of techniques for reservoir thermal/water quality simulation and mathematical optimization. Of particular importance is the selection of an appropriate

PART II: SOLUTION METHODOLOGY

Simulation/Optimization Approach

6. A system response model provides a means for assessing the state of a system (i.e., reservoir thermal structure) and measuring the effectiveness of given system operations in achieving the desired goals. Mathematical optimization provides the means to systematically evaluate alternatives (decision variables, i.e. multilevel intake locations) to determine the best policy or design without having to evaluate all the alternatives. An index of performance (objective function) provides the coupling between simulation and optimization necessary for realization of an "optimal" solution.

7. Reservoir thermal/water quality simulation codes can model the response of a given reservoir system to specified conditions. Because this effort considered a downstream temperature objective only, the reservoir code used herein simulated only temperature and will be referred to as the thermal model. The thermal model requires inputs of hydrologic and meteorological data to simulate the pattern of thermal stratification, or "state" of the reservoir, over a given duration of time. Algorithms simulating the operation of selective withdrawal structures for a specified intake configuration are used in the model to predict intake operations, reservoir flow distributions, and, subsequently, downstream release temperatures.

8. A scalar index of performance, the objective function, is used to measure the effectiveness of a specific intake configuration at meeting downstream temperature objectives. The objective function is computed based on the deviation of the predicted downstream release temperatures from the given downstream temperature objectives. Using a specified intake configuration and its corresponding objective function value as inputs the mathematical optimization routine considers alternative selective withdrawal intake configurations which, when simulated, produce smaller objective function values. Minimization of the objective function produces the optimal selective withdrawal intake configuration whose operation results in the minimum deviation of downstream release temperature from the given downstream temperature objective for a specified set of input conditions. The schematic in Figure 1 provides an overview of the approach. Comparison of results from repetition of this procedure for varying numbers of intakes allows determination of the optimum

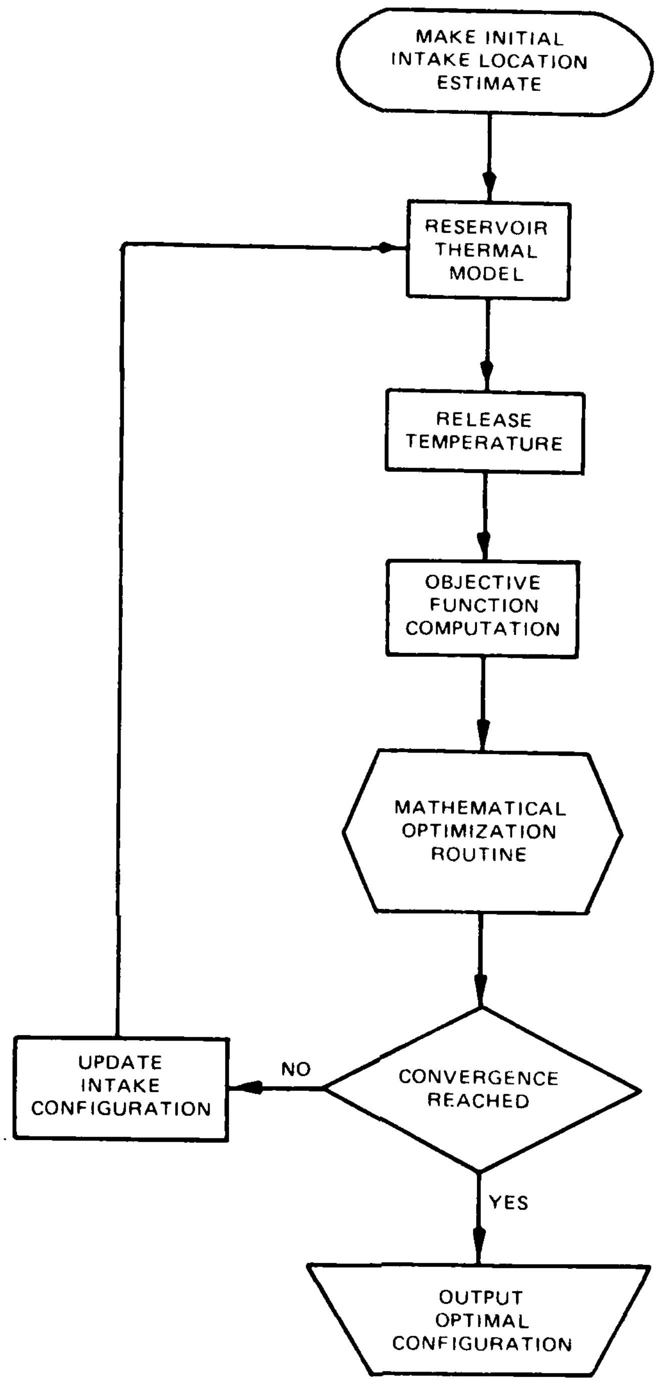


Figure 1. Schematic of simulation-optimization approach

number of intakes required for the given set of conditions. A description of the components of this procedure appears below.

Reservoir Thermal Model

9. Downstream release temperatures and in-lake temperature profiles were predicted using a reservoir thermal model. The model, WESTEX (Boyt 1982),

PART II: SOLUTION METHODOLOGY

Simulation/Optimization Approach

6. A system response model provides a means for assessing the state of a system (i.e., reservoir thermal structure) and measuring the effectiveness of given system operations in achieving the desired goals. Mathematical optimization provides the means to systematically evaluate alternatives (decision variables, i.e. multilevel intake locations) to determine the best policy or design without having to evaluate all the alternatives. An index of performance (objective function) provides the coupling between simulation and optimization necessary for realization of an "optimal" solution.

7. Reservoir thermal/water quality simulation codes can model the response of a given reservoir system to specified conditions. Because this effort considered a downstream temperature objective only, the reservoir code used herein simulated only temperature and will be referred to as the thermal model. The thermal model requires inputs of hydrologic and meteorological data to simulate the pattern of thermal stratification, or "state" of the reservoir, over a given duration of time. Algorithms simulating the operation of selective withdrawal structures for a specified intake configuration are used in the model to predict intake operations, reservoir flow distributions, and, subsequently, downstream release temperatures.

8. A scalar index of performance, the objective function, is used to measure the effectiveness of a specific intake configuration at meeting downstream temperature objectives. The objective function is computed based on the deviation of the predicted downstream release temperatures from the given downstream temperature objectives. Using a specified intake configuration and its corresponding objective function value as inputs the mathematical optimization routine considers alternative selective withdrawal intake configurations which, when simulated, produce smaller objective function values. Minimization of the objective function produces the optimal selective withdrawal intake configuration whose operation results in the minimum deviation of downstream release temperature from the given downstream temperature objective for a specified set of input conditions. The schematic in Figure 1 provides an overview of the approach. Comparison of results from repetition of this procedure for varying numbers of intakes allows determination of the optimum

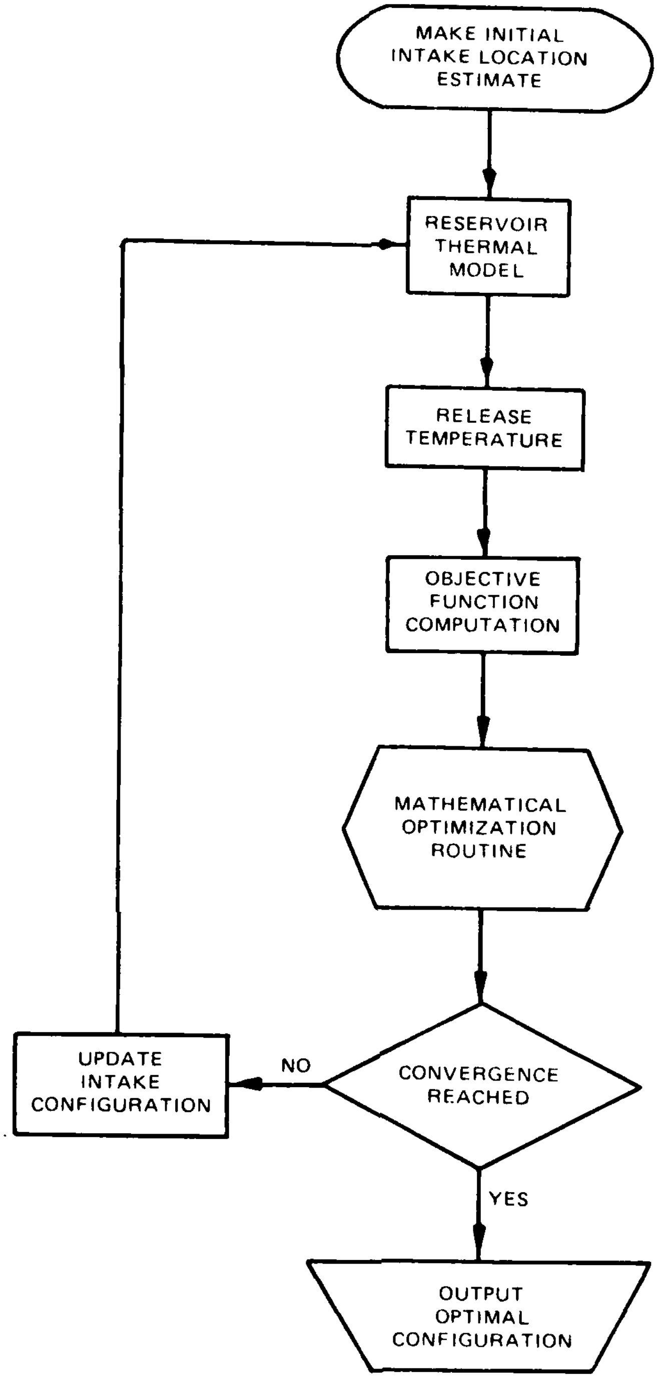


Figure 1. Schematic of simulation-optimization approach

number of intakes required for the given set of conditions. A description of the components of this procedure appears below.

Reservoir Thermal Model

9. Downstream release temperatures and in-lake temperature profiles were predicted using a reservoir thermal model. The model, WESTEX (Boyt 1982),

used in conjunction with this investigation was developed at the US Army Engineer Waterways Experiment Station (WES). The WESTEX model, which is based on the solution of the one-dimensional (vertical) thermal energy equation, provides a procedure for examining the balance of thermal energy imposed on an impoundment. This energy balance coupled with continuity is used to map vertical profiles of temperature in the time domain. The model includes computational methods for simulating heat transfer at the air-water interface, heat advection due to inflow and outflow, and internal dispersion of thermal energy.

10. In addition, a subroutine in the model, DECIDE, is used to simulate the operation of the selective withdrawal structure. For each time-step (generally 1 day), the DECIDE subroutine evaluates the thermal stratification of the reservoir, the desired downstream temperature objective, and the total flow to be released downstream. Based upon the operational constraints of the selective withdrawal structure, the DECIDE subroutine determines the combination of selective withdrawal intakes to be operated and the flows to be released through those intakes such that the release temperature is as close as possible to the downstream temperature objective. The operational constraints of the selective withdrawal structure considered by the DECIDE subroutine include hydraulic constraints on the intake operations such as minimum and maximum allowable flows, intake geometry, number of wet wells, and floodgate capacity. Hydraulic constraints are discussed further in this report (Appendix A). A discussion of the WESTEX model and its input data appears in a report by Holland (1982).

Objective Function

11. An objective function is a measure of system performance i[illegible]ng a goal for a set of inputs and decisions. The objective or goal of th[illegible]m under study is to minimize the deviation of reservoir release temperatures from the desired downstream (target) temperatures through the effective location of the selective withdrawal intakes. Thus the objective function for this work is a scalar index related to the deviation of release and target temperatures. The decision variables are the vertical locations of a specified number of selective withdrawal intakes. Minimization of the objective function produces the optimal intake configuration (i.e. intake locations) for given constraints, inputs, and downstream objectives.

the impact of limitations of the system on decisions. Constraints define the allowable flexibility for the decision variables by giving tolerable bounds for them. One type of constraint has already been discussed in paragraph 13. This constraint limits the optimization technique to the feasible search region within the lower and upper bounds of the pool. These bounds have a very obvious impact on the "optimal" intake configuration obtained.

18. There are more subtle constraints buried within the system state model (thermal model). These indirect constraints involve various hydraulic characteristics of the intake structure such as minimum and maximum permissible flows. The hydraulic constraints of the intake structure are encountered in subroutine DECIDE of the WESTEX code.

19. Based on given values for each time period of total release flow, reservoir thermal stratification, release temperature objective, and hydraulic constraints, subroutine DECIDE determines which intakes must be open and how much flow each must pass in order to come as close as possible to satisfying the total release flow and temperature objective desired. Subroutine DECIDE accomplishes these decisions through brute force logic.

20. The intake flows specified by DECIDE, which could be considered indirect decision variables (as opposed to the direct decision variables of the intake vertical locations), are very dependent upon the hydraulic constraints specified. These indirect decisions influence the release temperatures that affect the objective function; the objective function, in turn, drives the direct decisions of intake locations. Therefore the hydraulic constraints are of considerable importance in this technique. Appendix A is devoted to the discussion of the hydraulic constraints of the simulation model.

12. Several formulations for an objective function can be envisioned that relate the severity of these deviations or violations and, thus, the performance of a particular system in meeting downstream temperature objectives. The objective function used in this procedure is based on the sum of the squared deviation of release and target (objective) temperature over the simulated period. This formulation was chosen because minimization of the sum of squared deviations smooths deviations from the downstream objective temperatures over the simulation period. While this formulation may allow a greater number of deviations than other formulations, the severity of these individual deviations is reduced on the downstream system. This objective function can be mathematically stated as

$$F = \sum_{i=1}^{N} \left(T_{r_i} - T_{o_i}\right)^2 \qquad (1)$$

where

F = value for the objective function for the given intake configuration

N = number of time-steps or i periods in the total simulation period

Σ = summation over all time-steps

i = incremental counter for time-step

T_{r_i} = release temperature for period i

T_{o_i} = objective (target) temperature for period i

The release temperatures for each period i are obtained from the system state model (thermal model) based on a given set of input conditions and constraints. The objective temperatures for each period are specified as inputs to this formulation. The minimization of Equation 1, which provides the optimal intake configuration for the given constraint set, is achieved through the mathematical optimization routine.

Mathematical Search Techniques

13. The objective function and state model presented herein are nonlinear processes and require nonlinear search methods for optimization. In this context, there are both constrained and unconstrained nonlinear search methods. A constrained search method requires definition of the feasible

PART III: APPLICATION

Case Study Project Description

21. Use of this simulation/optimization procedure can best be demonstrated through its application to a specific case. Analysis of such an application will provide, in particular, an appreciation for costs, sensitivity, and effectiveness of the mathematical search techniques (described in paragraphs 13-16) under investigation.

22. The selective withdrawal intake structure at Beltzville Dam was selected for the case study. The primary reason for this selection was the availability of a data set that had been used numerous times to investigate various reservoir thermal modeling algorithms.

23. Beltzville Dam is the initial unit of a comprehensive plan for flood control and development of water resources of the Delaware River Basin. The project is located in the Lehigh River Basin on Pohopoco Creek in northeastern Pennsylvania (Figure 2). Total storage capacity of the reservoir is 68,260 acre-ft* when filled to spillway crest el 641.0.**

24. Flow through the dam is regulated by a gated intake tower (Figure 3) that contains two flood-control intakes (2.83 by 7.33 ft) located at the base of the structure (el 503.39), and a water quality control system, the intakes of which are located at various levels of the tower (Figure 4). These eight 2- by 4-ft water quality intakes pass flow into a divided wet well that converges into a single conduit with a 2- by 3-ft control gate. The flow exits the water quality control conduit (located between the two flood-control conduits) through a portal in the structure's transition section. A more complete description and analysis of the hydraulic aspects of this structure can be found in a report by Melsheimer (1969).

25. The case study consisted of three basic parts: (a) development of existing (as built) base operating conditions, (b) testing of the PM, and (c) testing of the CCS method. In both parts (b) and (c), the intake location technique was used (in conjunction with the specified search method) in an

---

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

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

search region as input. Unconstrained search methods may attempt to find a solution in a nonfeasible region (such as locating intakes above the maximum pool elevation). In order to incorporate constraints on the search region for an unconstrained optimization method, additional terms referred to as penalty functions are added to the objective function at nonfeasible points so that the unconstrained optimizer, in an effort to minimize the objective function, will find these points unattractive as solutions. Constrained search methods do not require the use of penalty terms in the objective function.

14. Three nonlinear optimization routines have been coupled with the WESTEX thermal model to search for optimum selective withdrawal intake elevations. Two of the routines are univariate searches that find the minimum of a function for one decision variable (i.e. one intake location). The first, a parabolic interpolation routine obtained from Boeing Computer Services (BCS), has been used to locate an additional level of intakes (two intakes at the same elevation) for an existing system due to project reformulation (Holland 1982). This routine was not used to locate multiple intakes due to search inefficiencies and therefore was not included in this effort.

15. The second univariate routine, a Golden Section line search, can be used as part of a cyclic coordinate search (CCS) for multiple decision variables (multiple intake elevations). In the CCS, an optimum elevation is obtained for a given intake using the Golden Section search while holding all other intake elevations constant. This action is continued for each of the intakes to be located until a given convergence criterion has been met. The Golden Section search is a constrained method; thus the decision variables (intake locations) are searched within given bounds.

16. The third optimization routine considered in this effort is a conjugate search that minimizes a function for multiple decision variables (i.e. multiple intake elevations) by Powell's Method (PM). PM is an unconstrained technique that searches for all the best decisions simultaneously. The numerical methodologies used as a basis for the Golden Section and PM routines are described in detail by Box, Davies, and Swann (1969). These two routines were obtained from Colorado State University.

Constraints

17. Constraints are part of the system state model that characterize

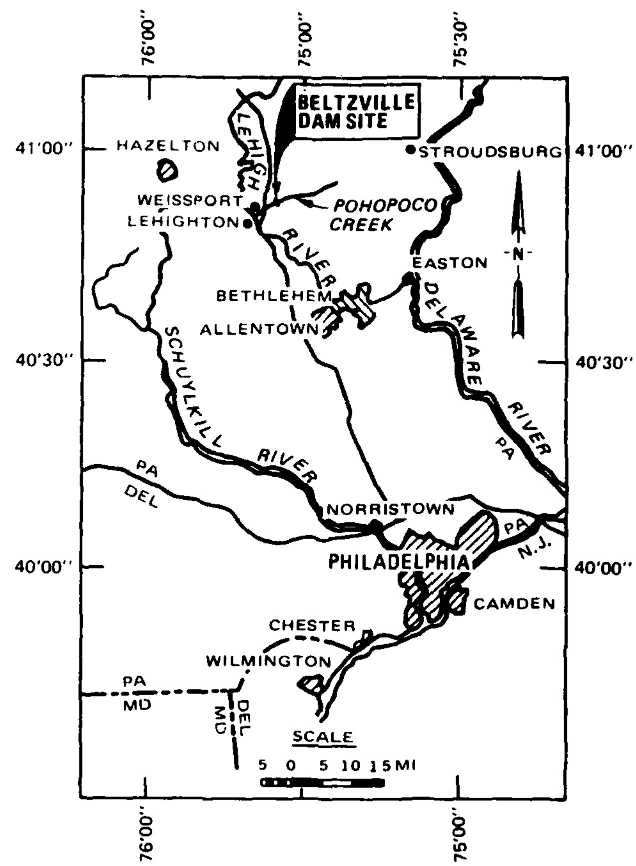


Figure 2. Vicinity map for Beltzville Dam

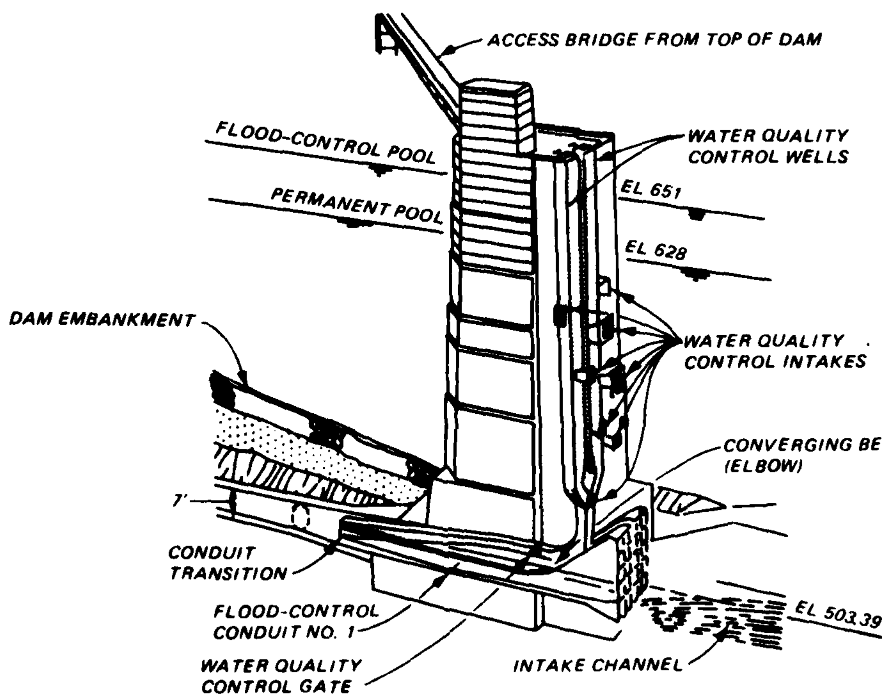


Figure 3. Details of Beltzville intake tower

the impact of limitations of the system on decisions. Constraints define the allowable flexibility for the decision variables by giving tolerable bounds for them. One type of constraint has already been discussed in paragraph 13. This constraint limits the optimization technique to the feasible search region within the lower and upper bounds of the pool. These bounds have a very obvious impact on the "optimal" intake configuration obtained.

18. There are more subtle constraints buried within the system state model (thermal model). These indirect constraints involve various hydraulic characteristics of the intake structure such as minimum and maximum permissible flows. The hydraulic constraints of the intake structure are encountered in subroutine DECIDE of the WESTEX code.

19. Based on given values for each time period of total release flow, reservoir thermal stratification, release temperature objective, and hydraulic constraints, subroutine DECIDE determines which intakes must be open and how much flow each must pass in order to come as close as possible to satisfying the total release flow and temperature objective desired. Subroutine DECIDE accomplishes these decisions through brute force logic.

20. The intake flows specified by DECIDE, which could be considered indirect decision variables (as opposed to the direct decision variables of the intake vertical locations), are very dependent upon the hydraulic constraints specified. These indirect decisions influence the release temperatures that affect the objective function; the objective function, in turn, drives the direct decisions of intake locations. Therefore the hydraulic constraints are of considerable importance in this technique. Appendix A is devoted to the discussion of the hydraulic constraints of the simulation model.

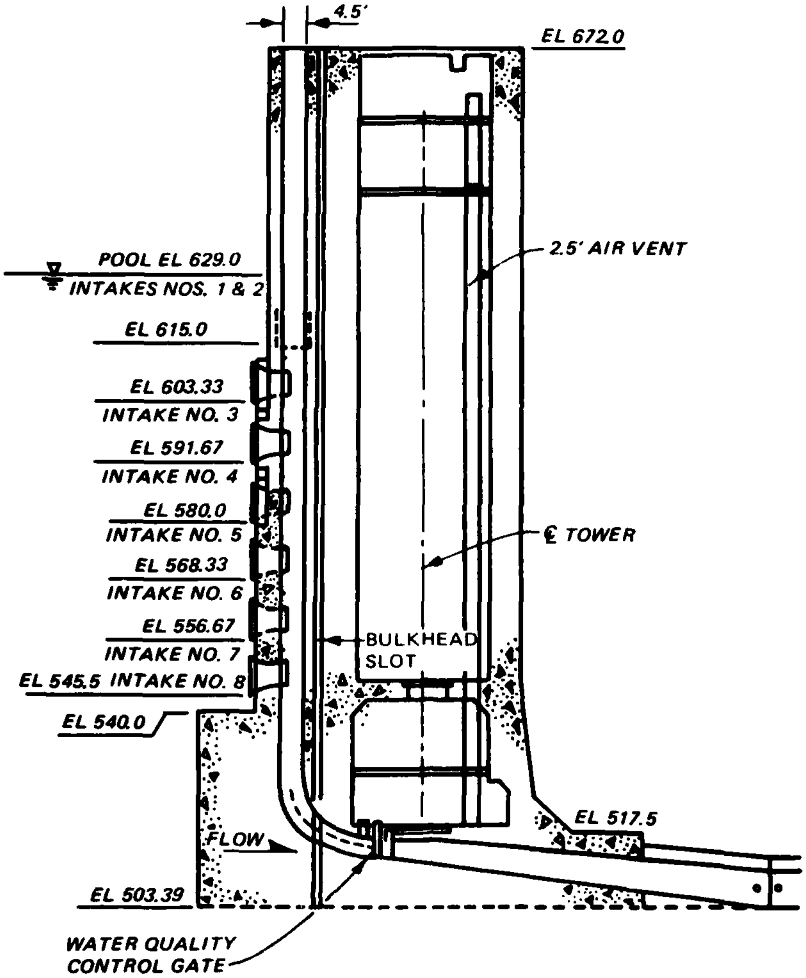


Figure 4. Details of water quality control system for Beltzville intake tower

effort to specify intake configurations that were more effective than the existing structure in meeting given water temperature objectives for the specific input conditions simulated. This should not suggest that the operation of the existing Beltzville structure is in general inferior to the "optimum" configurations generated by this technique; in fact, only a very finite subset of the range of operational, meteorological, and hydrological conditions expected at Beltzville was simulated. Rather, comparison of the results of parts (b) and (c) with existing conditions (part (a)) is intended to show the potential utility of the optimization technique discussed herein and, as such, does not constitute a rigorous investigation of potential designs. The input requirements and the results for each of these three parts are discussed in the next three sections.

PART III: APPLICATION

Case Study Project Description

21. Use of this simulation/optimization procedure can best be demonstrated through its application to a specific case. Analysis of such an application will provide, in particular, an appreciation for costs, sensitivity, and effectiveness of the mathematical search techniques (described in paragraphs 13-16) under investigation.

22. The selective withdrawal intake structure at Beltzville Dam was selected for the case study. The primary reason for this selection was the availability of a data set that had been used numerous times to investigate various reservoir thermal modeling algorithms.

23. Beltzville Dam is the initial unit of a comprehensive plan for flood control and development of water resources of the Delaware River Basin. The project is located in the Lehigh River Basin on Pohopoco Creek in northeastern Pennsylvania (Figure 2). Total storage capacity of the reservoir is 68,260 acre-ft* when filled to spillway crest el 641.0.**

24. Flow through the dam is regulated by a gated intake tower (Figure 3) that contains two flood-control intakes (2.83 by 7.33 ft) located at the base of the structure (el 503.39), and a water quality control system, the intakes of which are located at various levels of the tower (Figure 4). These eight 2- by 4-ft water quality intakes pass flow into a divided wet well that converges into a single conduit with a 2- by 3-ft control gate. The flow exits the water quality control conduit (located between the two flood-control conduits) through a portal in the structure's transition section. A more complete description and analysis of the hydraulic aspects of this structure can be found in a report by Melsheimer (1969).

25. The case study consisted of three basic parts: (a) development of existing (as built) base operating conditions, (b) testing of the PM, and (c) testing of the CCS method. In both parts (b) and (c), the intake location technique was used (in conjunction with the specified search method) in an

---

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

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

Base Conditions

26. Development of base conditions was necessary to provide a measure of the utility of the optimization techniques. The base conditions were developed by executing the WESTEX code in the verification mode. In verification mode, the outflow through each intake of the outlet structure is specified for each day of the simulation period; therefore subroutine DECIDE is not used. Vertical temperature profiles in the reservoir and mean daily release temperatures are the computed results of interest. Verification mode is used to evaluate the accuracy of the model when observed data exist or to test a particular predetermined intake operation scheme.

27. A data set for Beltzville Lake existed for 1972. The basic data, which can be found in a report by Marcinski (1975), consisted of the following:

- a. Mean daily meteorological data--wind speed, air temperature, dew point temperature, and cloud cover.
- b. Reservoir surface area and volume versus elevation.
- c. Mean daily inflow rates and temperatures.
- d. Mean daily outflow rates for each intake of the outlet structure.
- e. Intake elevations (see Figure 4).
- f. Observed in-lake temperature profiles recorded near the dam.

All of the above, with the exception of item f, are input data for the thermal model.

28. The observed temperature profile data were obtained between 18 May 1972 and 30 November 1972. The verification simulation was started on calendar day 138 (18 May) with an observed temperature profile and was stopped on calendar day 334 (30 November). The only model coefficients that must be input are β, the fraction of shortwave solar radiation absorbed in the 2.0-ft-thick surface layer, and λ, the extinction coefficient for the attenuation of shortwave radiation with depth. The values selected were $\beta = 0.50$ and $\lambda = 0.20\ ft^{-1}$. These values have been used with success in many other studies and tend to be representative of the clarity in many deep tributary reservoirs.

29. Computed and observed temperature profiles are shown in Figure 5. From this close agreement, it is apparent that the model is representative of the conditions simulated. The computed release temperatures for the "as-built

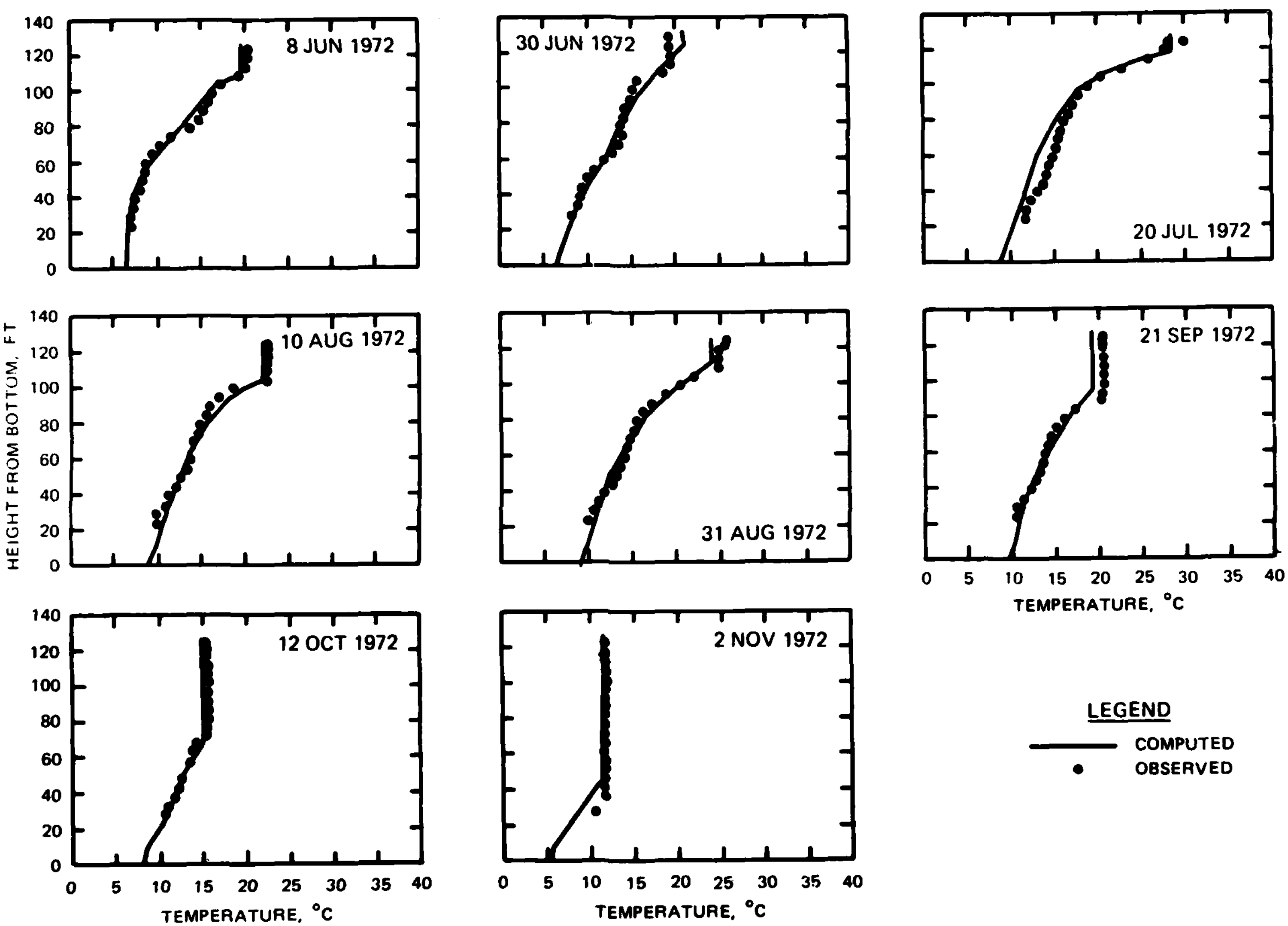


Figure 5. Predicted and observed temperature proviles for verification simulations of Beltzville Lake

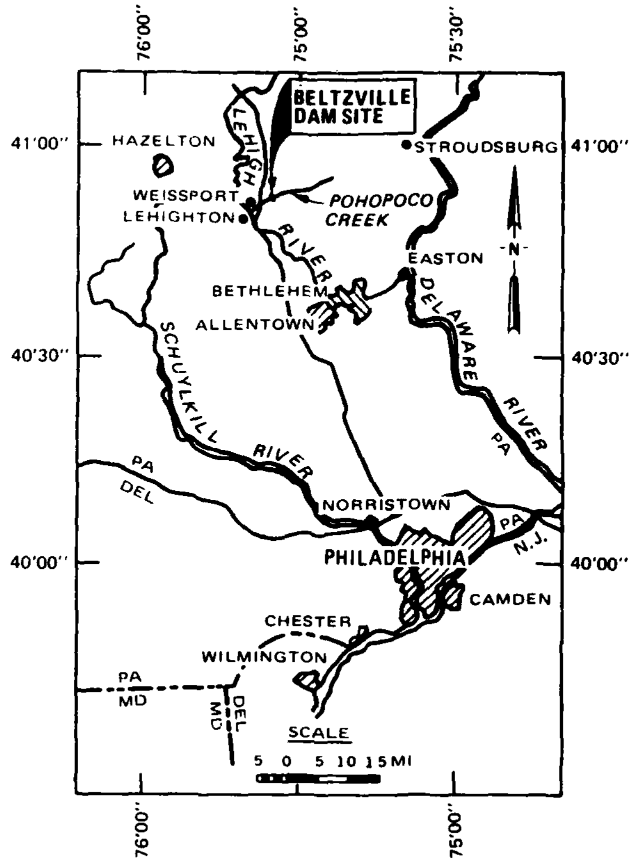


Figure 2. Vicinity map for Beltzville Dam

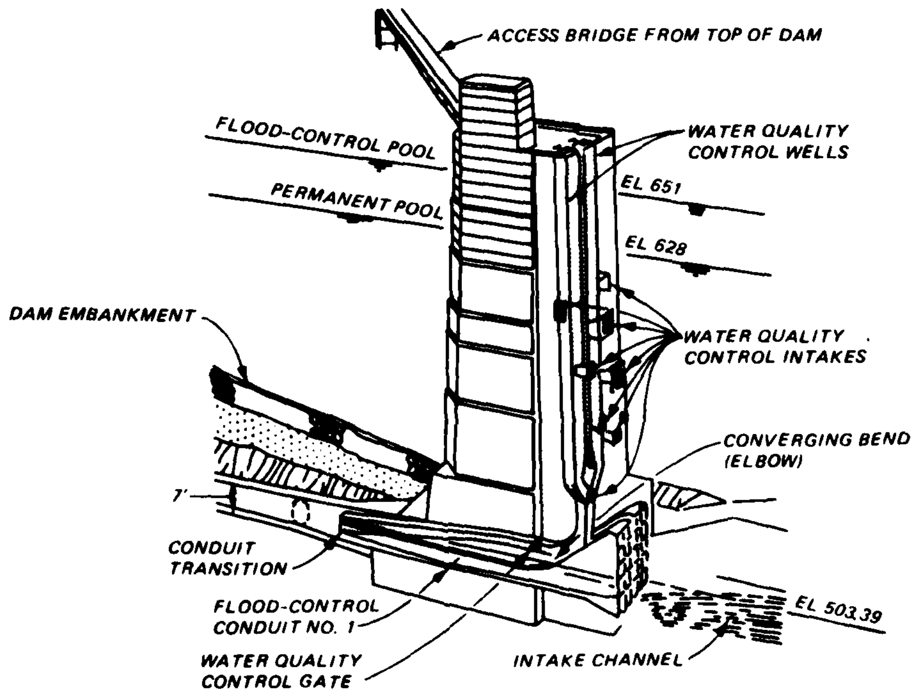


Figure 3. Details of Beltzville intake tower

and operated" conditions are shown in Figure 6. Observed release temperatures could not be found for comparison. The smooth curve shown in Figure 6 is a harmonic curve fit for the computed release temperatures of the form

$$T = A \sin (Bt + C) + D$$

where

T = average daily release temperature, °C

A = amplitude, °C

B = frequency, $\frac{2\pi \text{ rad}}{365 \text{ days}} = 0.017214$ rad/day

t = time, calendar day

C = phase angle, rad

D = mean annual release temperature, °C

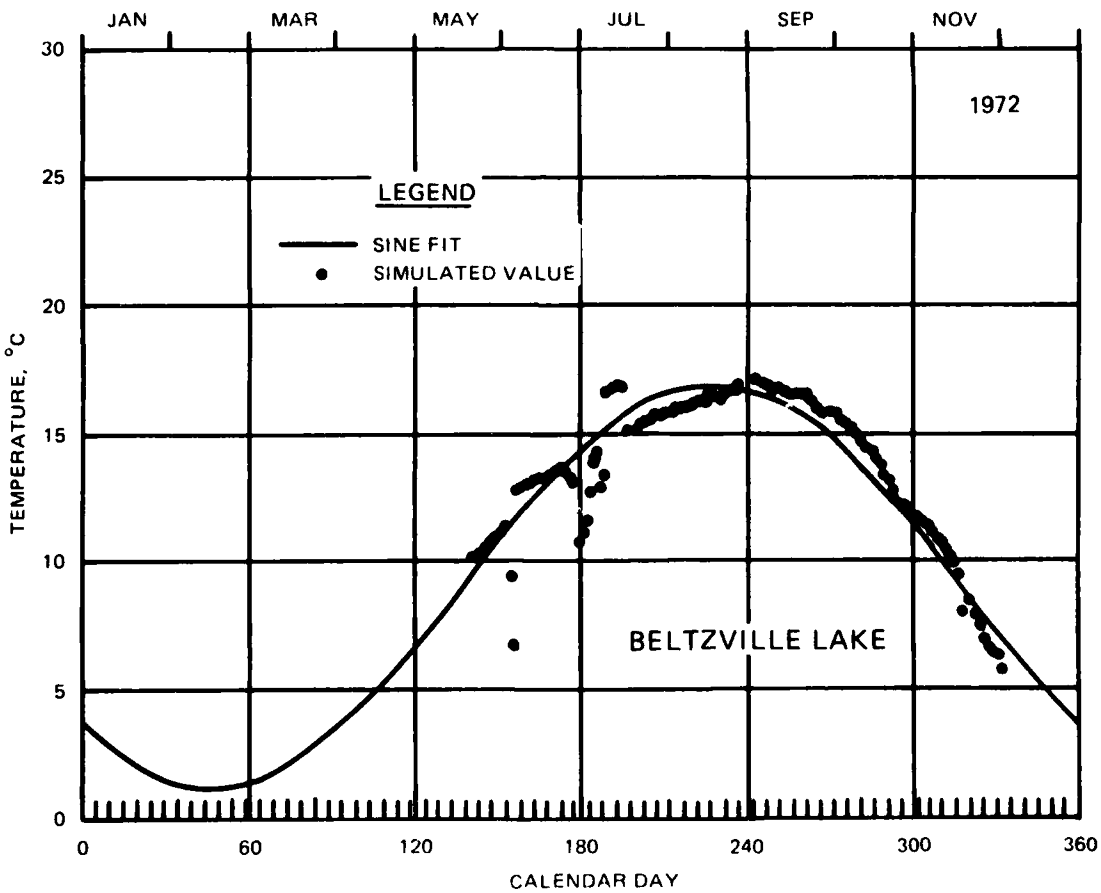


Figure 6. Verification mode simulated release temperatures for "as-built and operated" conditions with sine curve fit

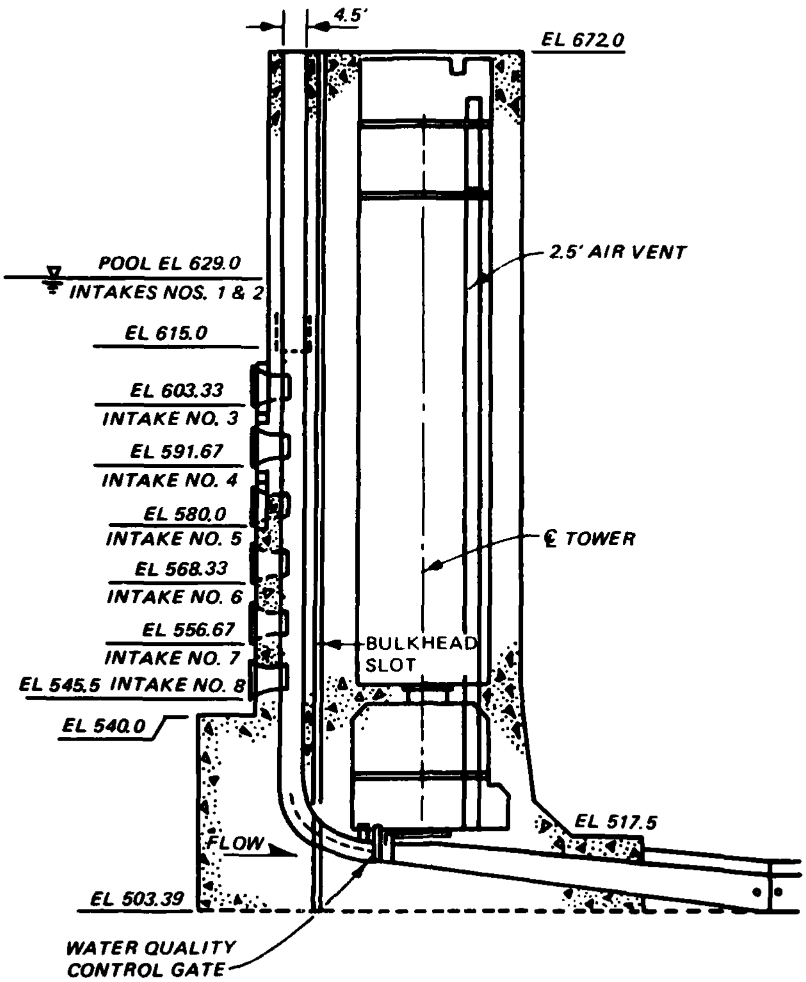


Figure 4. Details of water quality control system for Beltzville intake tower

effort to specify intake configurations that were more effective than the existing structure in meeting given water temperature objectives for the specific input conditions simulated. This should not suggest that the operation of the existing Beltzville structure is in general inferior to the "optimum" configurations generated by this technique; in fact, only a very finite subset of the range of operational, meteorological, and hydrological conditions expected at Beltzville was simulated. Rather, comparison of the results of parts (b) and (c) with existing conditions (part (a)) is intended to show the potential utility of the optimization technique discussed herein and, as such, does not constitute a rigorous investigation of potential designs. The input requirements and the results for each of these three parts are discussed in the next three sections.

The values for the coefficients based on regression analysis are

$A = -7.8467° C$

$C = 0.75519 \text{ rad}$

$D = 9.0826° C$

The harmonic curve was generated for the purpose of developing a release temperature equation that could be used as an objective for the optimization efforts. In this manner, a comparison of "as-operated" and optimized systems could be directly made.

30. Using the "as-built" intake locations and the harmonic temperature objective curve of the previous paragraph, the reservoir was simulated in the "prediction" mode. This mode, which invokes the use of subroutine DECIDE, is used to indicate how well a project might do in satisfying downstream temperature requirements. Results from simulation in this mode indicate the most effective methodology by which the project should be operated to meet the given temperature objectives.

31. The as-built intake locations used for the prediction mode simulations are shown in Figure 4. (The wet well in which each intake is located is indicated in Figure A2.) The intakes were simulated as specified by these figures with one exception; intake No. 8 (invert el 545.5) was not included. As will be discussed later, operation of the lower intakes was not necessary for the conditions simulated, thus removing the need for the inclusion of intake No. 8. Minimum and maximum flows for each of the selective withdrawal intakes were 0.0 and 150.0 cfs. Minimum and maximum flows used for the floodgate were 100.0 and 1,500.0 cfs. The required total release flows never exceeded this maximum flow for the floodgate for the simulated period.

32. The nature of the decisions from DECIDE are static and myopic; that is, the decisions of which intakes to open for any given day are based solely on the stratification, downstream flow, and release temperature objectives for that day. A dynamic decision process has been developed by coupling WESTEX to a dynamic programming optimization code (Fontane, Labadie, and Loftis 1982) that allows the decisions for each day to be based on the impact of present decisions on the objectives for the entire simulation period. For this study, however, the code was executed in the conventional (static-myopic decisions) prediction mode.

33. Figure 7 shows computed release temperatures obtained with the prediction mode, the as-built intake locations, and the objective temperature

Base Conditions

26. Development of base conditions was necessary to provide a measure of the utility of the optimization techniques. The base conditions were developed by executing the WESTEX code in the verification mode. In verification mode, the outflow through each intake of the outlet structure is specified for each day of the simulation period; therefore subroutine DECIDE is not used. Vertical temperature profiles in the reservoir and mean daily release temperatures are the computed results of interest. Verification mode is used to evaluate the accuracy of the model when observed data exist or to test a particular predetermined intake operation scheme.

27. A data set for Beltzville Lake existed for 1972. The basic data, which can be found in a report by Marcinski (1975), consisted of the following:

- a. Mean daily meteorological data--wind speed, air temperature, dew point temperature, and cloud cover.
- b. Reservoir surface area and volume versus elevation.
- c. Mean daily inflow rates and temperatures.
- d. Mean daily outflow rates for each intake of the outlet structure.
- e. Intake elevations (see Figure 4).
- f. Observed in-lake temperature profiles recorded near the dam.

All of the above, with the exception of item f, are input data for the thermal model.

28. The observed temperature profile data were obtained between 18 May 1972 and 30 November 1972. The verification simulation was started on calendar day 138 (18 May) with an observed temperature profile and was stopped on calendar day 334 (30 November). The only model coefficients that must be input are β , the fraction of shortwave solar radiation absorbed in the 2.0-ft-thick surface layer, and λ , the extinction coefficient for the attenuation of shortwave radiation with depth. The values selected were $\beta = 0.50$ and $\lambda = 0.20\ ft^{-1}$. These values have been used with success in many other studies and tend to be representative of the clarity in many deep tributary reservoirs.

29. Computed and observed temperature profiles are shown in Figure 5. From this close agreement, it is apparent that the model is representative of the conditions simulated. The computed release temperatures for the "as-built

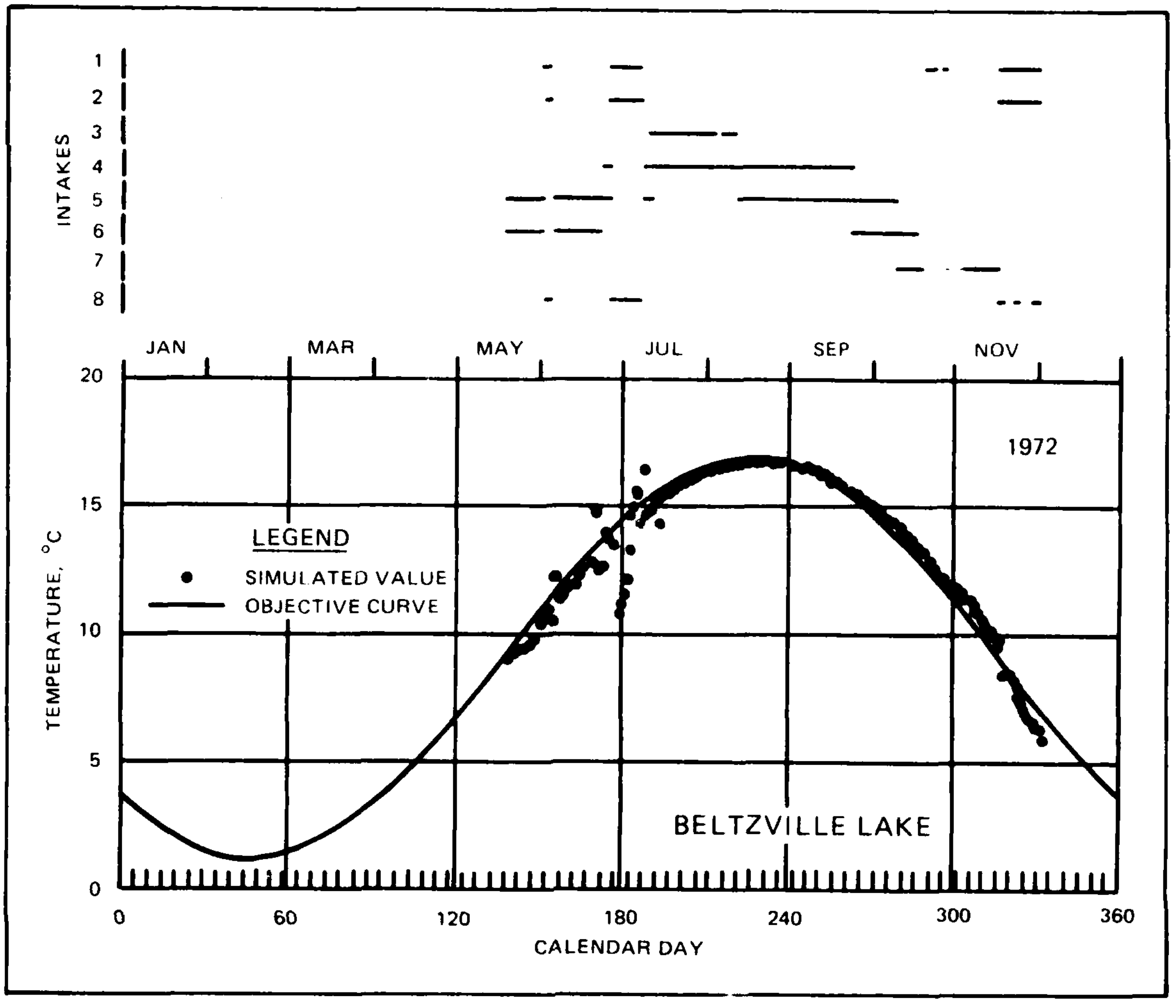


Figure 7. Prediction mode simulated release temperatures with sine curve objectives

curve of paragraph 29. Predicted intake operations are shown by the bar graph at the top of the figure. The intakes are numbered from the highest to the lowest in the pool. Therefore the two flood-control intakes, which were represented as a single intake, were assumed as intake No. 8. The two top intakes at the same elevation (Figure 4) were intakes Nos. 1 and 2. From Figure 7, it is apparent that the structure has no difficulty in meeting this temperature objective. This is reasonable since the curve was based on actual releases. If, however, this temperature objective curve was deemed unrepresentative of the majority of project release objectives, due, perhaps, to a revised temperature objective or project reformulation, additional assessment of intake locations would be required.

34. To assess the impact of a hypothetical revision in the project's

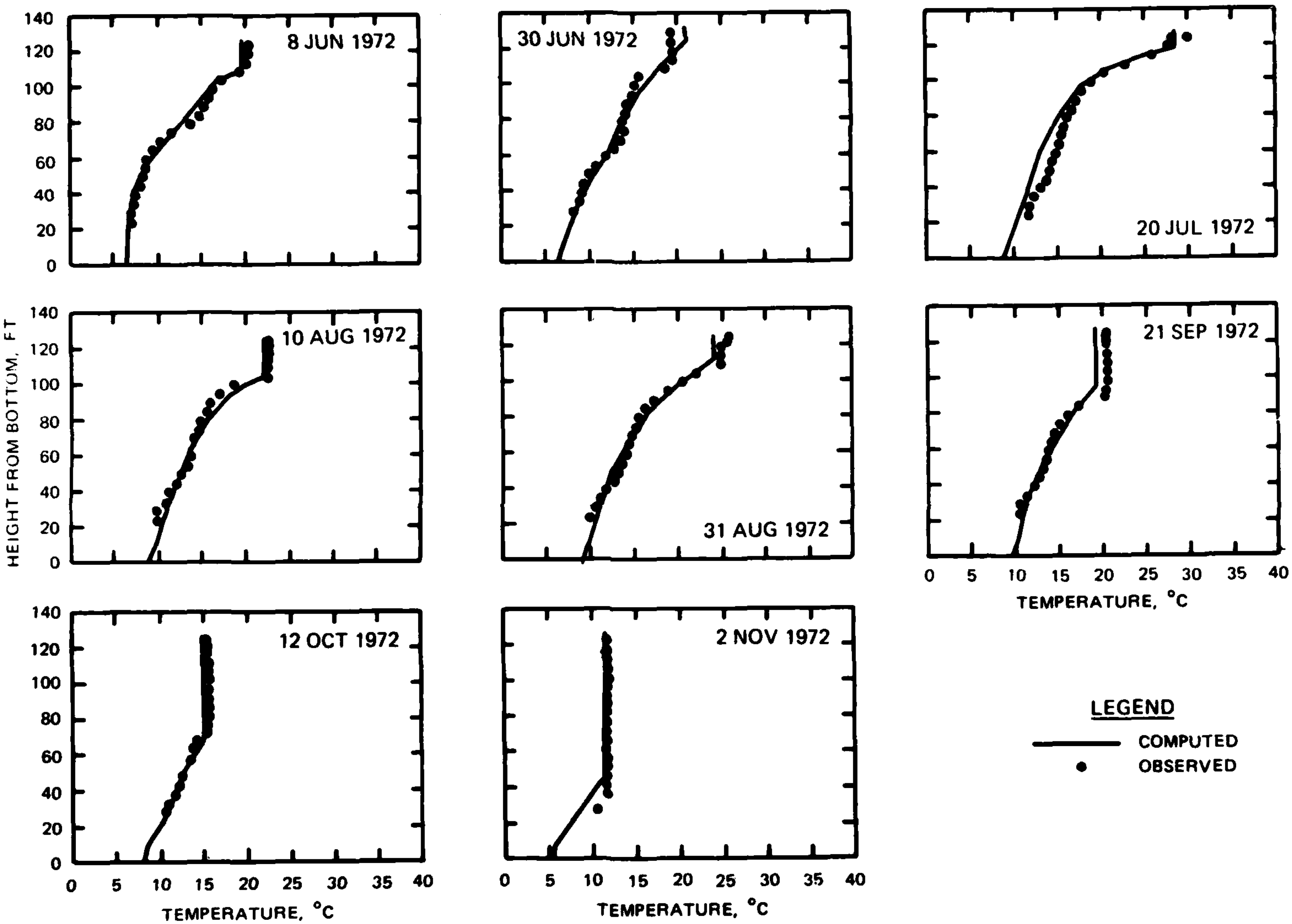


Figure 5. Predicted and observed temperature proviles for verification simulations of Beltzville Lake

temperature objectives, and thereby demonstrate the utility of the optimization procedure, a revised temperature objective curve was developed by reducing slightly the period and shifting the maximum point of the curve to earlier in the simulation period. The amplitude and mean annual temperature were increased such that the minimum and maximum temperatures were 4.0 and 22° C (as opposed to 1.2 and 16.9° C, respectively, for the original objective curve). Coefficients for the revised objective curve (in the form given in paragraph 29) were:

$A = -9.0°$ C

$B = 0.017952$ rad/day

$C = 0.90657$ rad

$D = 13.0°$ C

35. The as-built conditions were again simulated in prediction mode with the revised objective temperature curve. As indicated by Figure 8, the existing project would come close to satisfying this temperature objective most of the time for this study year. A sharp deviation from the objective occurred during early July due to the opening of the flood-control gates to accommodate a storm event. Figure 8 also shows that it was not necessary to use the three bottom intakes (5, 6, and 7) during the simulation period, thus indicating that fewer lower intakes would be needed for this temperature objective.

36. The sum of the squared deviation (SSD) of computed release temperature from the revised temperature objective was 1,160 for simulation of the existing structure. The SSD is also the objective function value, F (see Equation 1). This value will serve as a basis for evaluation of the optimization/simulation procedures.

Powell's Method of Conjugate Direction

37. A computer code of Powell's Method (PM; paragraph 16) was coupled with the WESTEX code. Because the PM is an unconstrained search technique, a penalty had to be added to the objective function whenever intake locations were considered that were outside the feasible region (above the maximum pool depth and below the reservoir bottom). The penalty function was

$$\text{Penalty} = 1000h \qquad (2)$$

and operated" conditions are shown in Figure 6. Observed release temperatures could not be found for comparison. The smooth curve shown in Figure 6 is a harmonic curve fit for the computed release temperatures of the form

$$T = A \sin (Bt + C) + D$$

where

T = average daily release temperature, °C

A = amplitude, °C

B = frequency, $\frac{2\pi \text{ rad}}{365 \text{ days}} = 0.017214$ rad/day

t = time, calendar day

C = phase angle, rad

D = mean annual release temperature, °C

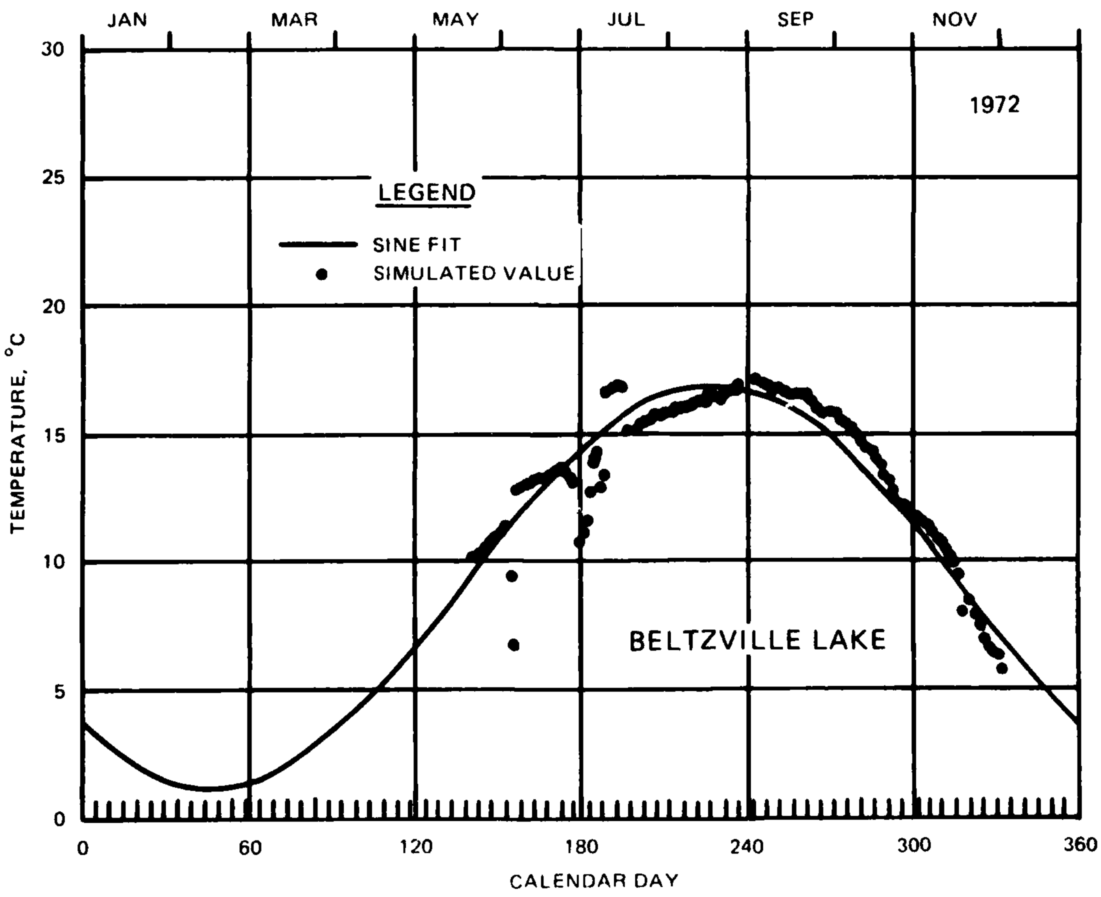


Figure 6. Verification mode simulated release temperatures for "as-built and operated" conditions with sine curve fit

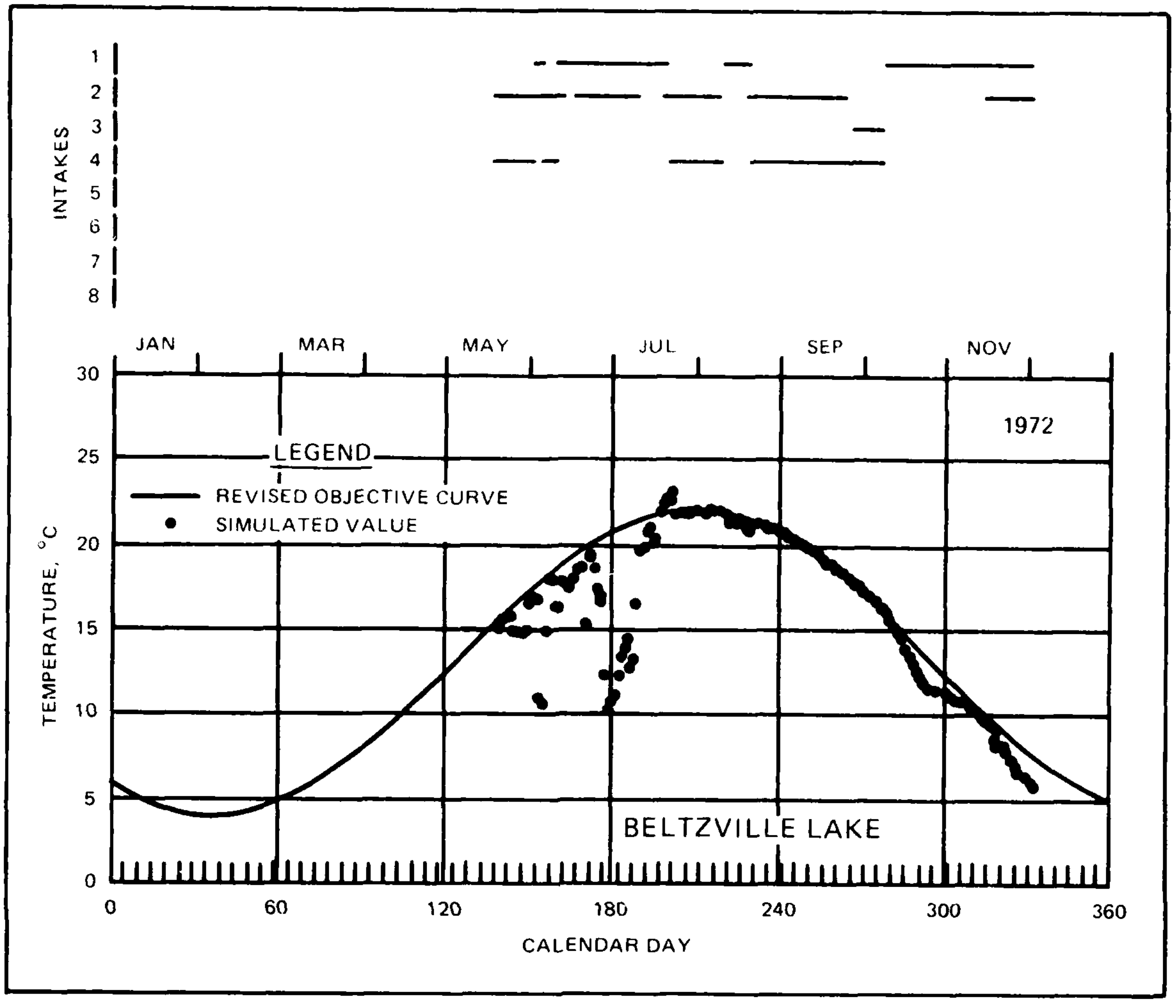


Figure 8. Prediction mode simulated release temperatures with revised sine cure objective

where h is the absolute value of the height of the intake above maximum pool or below the reservoir bottom.

38. The intakes were again ordered from the top to the bottom with the highest intake being intake No. 1. To aid convergence, the penalty function was also added to the objective function whenever the PM attempted to locate an intake of higher number above an intake of lower number. In this situation, the value of h was determined from the height differential between the two intakes. In addition to ordering, every other intake was specified as being in the same wet well of a dual wet-well system. Thus odd-numbered intakes (i.e., 1, 3, and 5) were in one well while even-numbered intakes were in the other.

39. The PM uses values of the objective function for determining search

The values for the coefficients based on regression analysis are

$A = -7.8467° C$

$C = 0.75519$ rad

$D = 9.0826° C$

The harmonic curve was generated for the purpose of developing a release temperature equation that could be used as an objective for the optimization efforts. In this manner, a comparison of "as-operated" and optimized systems could be directly made.

30. Using the "as-built" intake locations and the harmonic temperature objective curve of the previous paragraph, the reservoir was simulated in the "prediction" mode. This mode, which invokes the use of subroutine DECIDE, is used to indicate how well a project might do in satisfying downstream temperature requirements. Results from simulation in this mode indicate the most effective methodology by which the project should be operated to meet the given temperature objectives.

31. The as-built intake locations used for the prediction mode simulations are shown in Figure 4. (The wet well in which each intake is located is indicated in Figure A2.) The intakes were simulated as specified by these figures with one exception; intake No. 8 (invert el 545.5) was not included. As will be discussed later, operation of the lower intakes was not necessary for the conditions simulated, thus removing the need for the inclusion of intake No. 8. Minimum and maximum flows for each of the selective withdrawal intakes were 0.0 and 150.0 cfs. Minimum and maximum flows used for the floodgate were 100.0 and 1,500.0 cfs. The required total release flows never exceeded this maximum flow for the floodgate for the simulated period.

32. The nature of the decisions from DECIDE are static and myopic; that is, the decisions of which intakes to open for any given day are based solely on the stratification, downstream flow, and release temperature objectives for that day. A dynamic decision process has been developed by coupling WESTEX to a dynamic programming optimization code (Fontane, Labadie, and Loftis 1982) that allows the decisions for each day to be based on the impact of present decisions on the objectives for the entire simulation period. For this study, however, the code was executed in the conventional (static-myopic decisions) prediction mode.

33. Figure 7 shows computed release temperatures obtained with the prediction mode, the as-built intake locations, and the objective temperature

step and direction. Because the objective function in this problem can be weakly sensitive to the decision variables (intake locations) in some regions of the pool, it was necessary to use an amplification of F in the search procedures. Raising F to the fourth power allowed a practical application of PM.

40. The search process of PM continues until a specified solution convergence tolerance is satisfied. The convergence tolerance, ε, is a vertical distance; thus, if each intake location is within ε from the corresponding intake location found by the previous search, convergence has been reached. After making several test runs with different values of ε, it was found that a rather coarse convergence tolerance would have to be used. A value of 20 ft was used for ε during all multiple intake optimization runs; a value of 5 ft was used for optimization of single intake configurations. The PM optimizer would not converge for smaller values of ε.

41. The maximum search distance for each intake location must be specified for PM. Maximum search distances of 20 ft and 50 ft were used for the multiple and single intake optimizations, respectively. This distance affects the rate of convergence and thus the computer resources required for the use of this technique.

42. The PM was tested with both the original and revised temperature objectives, but only the results for the revised objective are discussed in detail. With the revised objective, the method was tested for one-, three-, and six-intake selective withdrawal systems. The optimal intake locations for each of these three configurations are presented in Table 1. Table 2 shows the central processor (CP) time for a Cyber 176 and the minimum objective

Table 1

Optimal Intake Locations Using Powell's Method

(Revised Temperature Objective)

Total Number of Intakes	Intake Center-Line Locations Above the Reservoir Bottom (el 503.39)					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
1	113.58					
3	115.31	107.15	71.08			
6	123.62	118.29	101.03	73.27	61.51	17.76

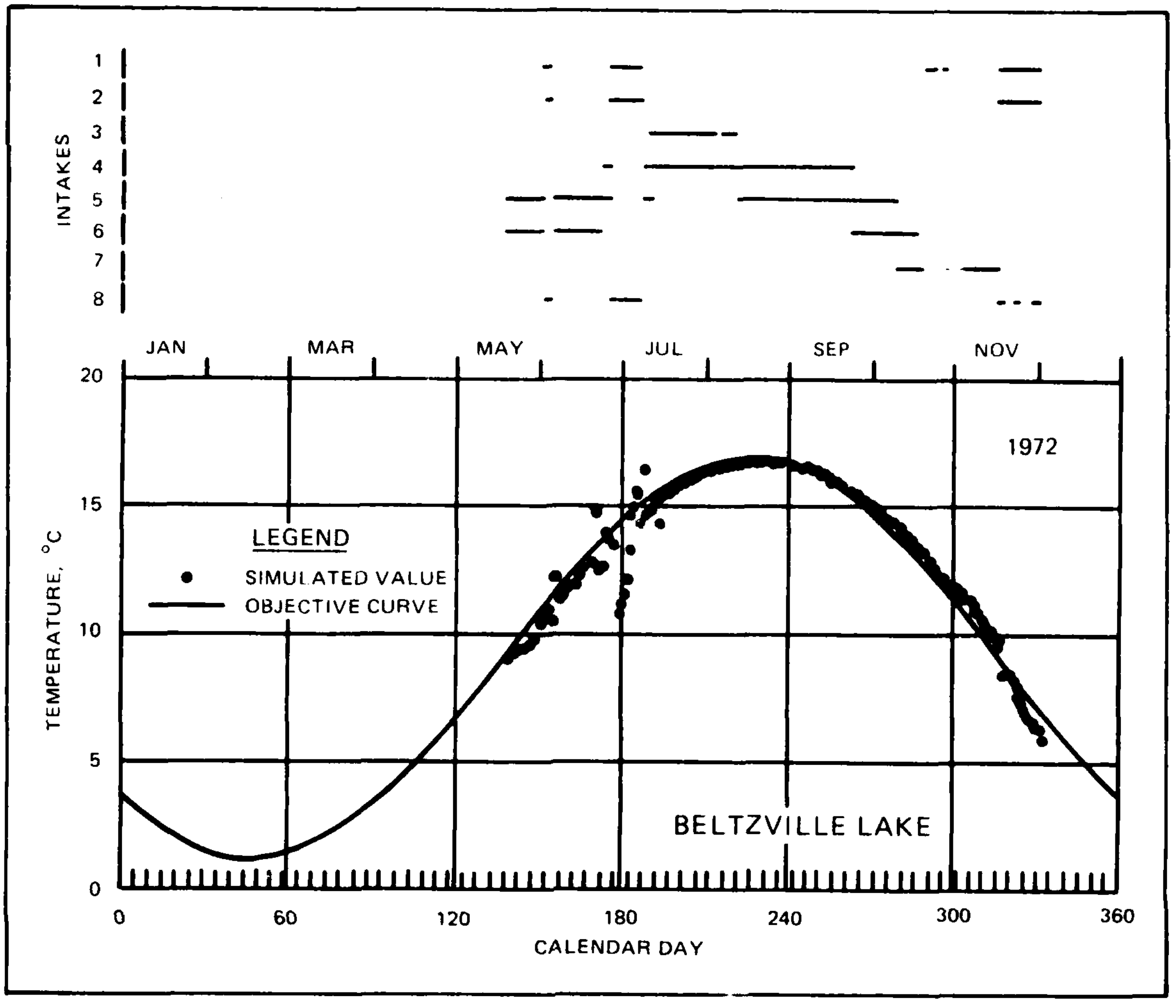


Figure 7. Prediction mode simulated release temperatures with sine curve objectives

curve of paragraph 29. Predicted intake operations are shown by the bar graph at the top of the figure. The intakes are numbered from the highest to the lowest in the pool. Therefore the two flood-control intakes, which were represented as a single intake, were assumed as intake No. 8. The two top intakes at the same elevation (Figure 4) were intakes Nos. 1 and 2. From Figure 7, it is apparent that the structure has no difficulty in meeting this temperature objective. This is reasonable since the curve was based on actual releases. If, however, this temperature objective curve was deemed unrepresentative of the majority of project release objectives, due, perhaps, to a revised temperature objective or project reformulation, additional assessment of intake locations would be required.

34. To assess the impact of a hypothetical revision in the project's

Table 2

Optimal Objective Function Values and Computation Times Using Powell's Method (Revised Temperature Objective)

Total Number of Intakes	F^*	CP Time sec
1	1,848	14.96
3	1,217	36.28
6	976	116.89

function values (F^*) for each optimized configuration. The CP time can become especially important when simulating multiple years and locating multiple intakes. The effectiveness of each intake configuration is measured by F^* ; the smaller F^* , the more effective the system in satisfying target temperatures.

43. As the number of intakes optimally located in the selective withdrawal system increases from one, the optimal objective function associated with the respective configurations, F^* , should decrease monotonically to some minimum. As an example, the results in Table 2 are monotonic. However, in the region near this minimum, the F^* values for successively increasing numbers of optimally located intakes will often approach a constant value which may be quite similar to the minimum observed F^* value. This region, referred to as a "flat spot" in the function, was believed to be caused by two phenomena: (a) the inclusion of additional intakes in each successive optimal intake configuration failed to increase the efficiency of the larger system in meeting the specified release temperature objectives when compared with an optimal system of lesser intakes--this is caused by the addition of system outflow flexibility which is not needed to achieve the "optimal" operational release strategy for the simulated conditions; and (b) the use of coarse convergence criteria which confuses the determination of an "optimal" intake configuration. As an example, testing of the PM with the original temperature objective revealed that F^* did not decrease monotonically as the intakes increased (Figure 9). This was attributed to the use of a coarse ε in regions where the F^* became less sensitive to the number of intakes. This could be remedied by starting a fine ε optimization run with the optimal intake locations obtained from a coarse ε optimization.

temperature objectives, and thereby demonstrate the utility of the optimization procedure, a revised temperature objective curve was developed by reducing slightly the period and shifting the maximum point of the curve to earlier in the simulation period. The amplitude and mean annual temperature were increased such that the minimum and maximum temperatures were 4.0 and 22° C (as opposed to 1.2 and 16.9° C, respectively, for the original objective curve). Coefficients for the revised objective curve (in the form given in paragraph 29) were:

A = -9.0° C

B = 0.017952 rad/day

C = 0.90657 rad

D = 13.0° C

35. The as-built conditions were again simulated in prediction mode with the revised objective temperature curve. As indicated by Figure 8, the existing project would come close to satisfying this temperature objective most of the time for this study year. A sharp deviation from the objective occurred during early July due to the opening of the flood-control gates to accommodate a storm event. Figure 8 also shows that it was not necessary to use the three bottom intakes (5, 6, and 7) during the simulation period, thus indicating that fewer lower intakes would be needed for this temperature objective.

36. The sum of the squared deviation (SSD) of computed release temperature from the revised temperature objective was 1,160 for simulation of the existing structure. The SSD is also the objective function value, F (see Equation 1). This value will serve as a basis for evaluation of the optimization/simulation procedures.

Powell's Method of Conjugate Direction

37. A computer code of Powell's Method (PM; paragraph 16) was coupled with the WESTEX code. Because the PM is an unconstrained search technique, a penalty had to be added to the objective function whenever intake locations were considered that were outside the feasible region (above the maximum pool depth and below the reservoir bottom). The penalty function was

$$\text{Penalty} = 1000h \tag{2}$$

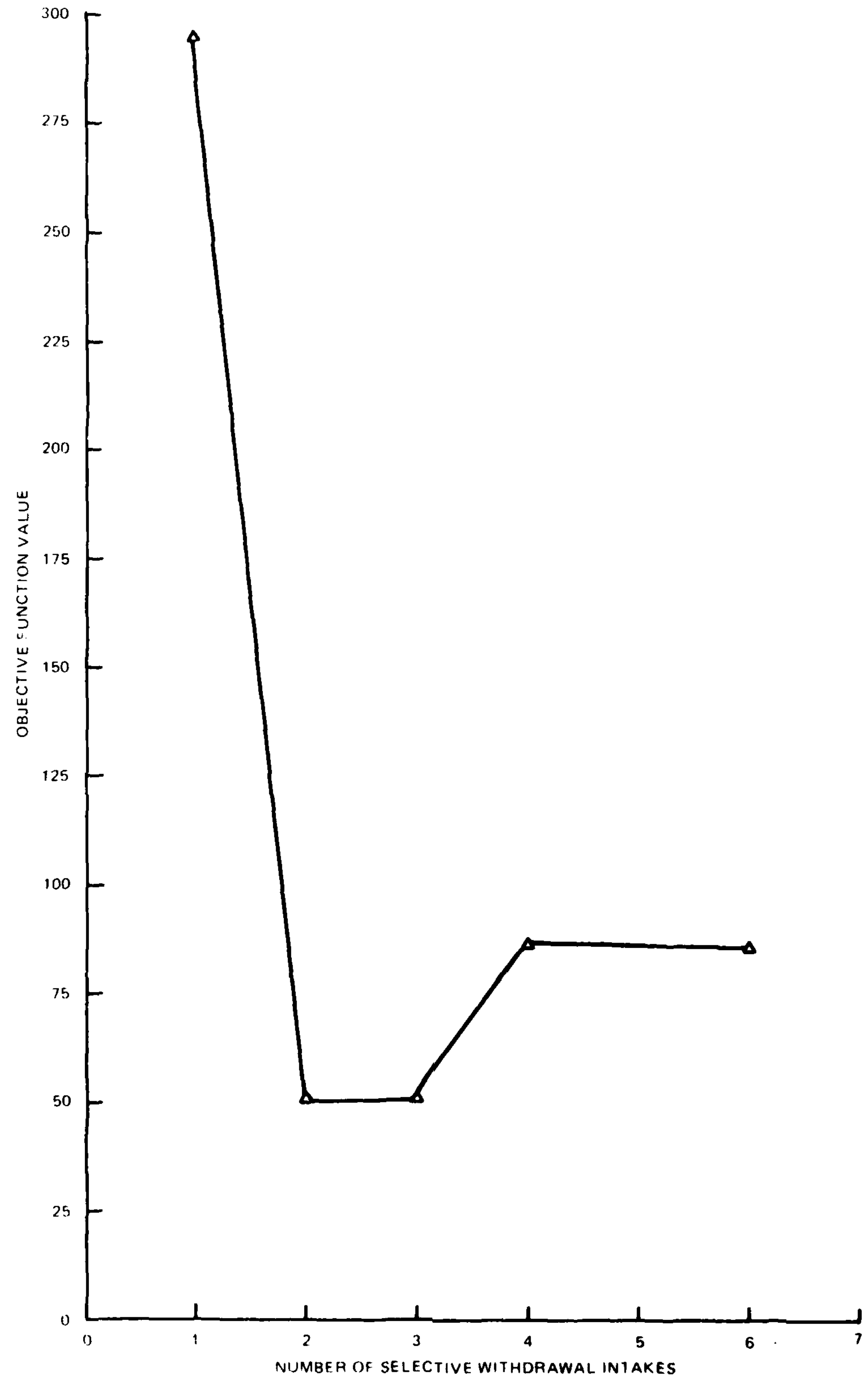


Figure 9. Optimal values of the objective function for various multilevel systems (original temperature objective) found using Powell's Method

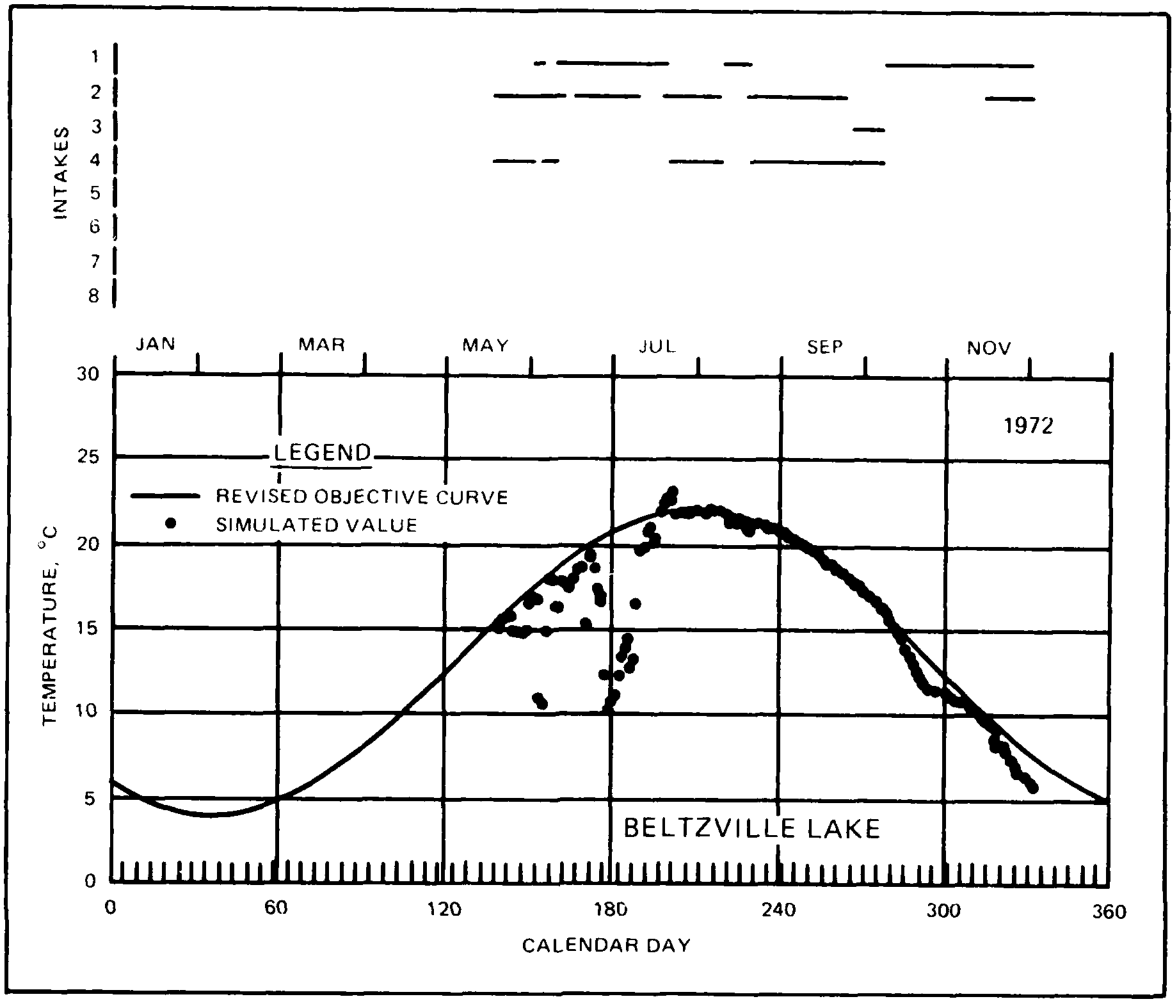


Figure 8. Prediction mode simulated release temperatures with revised sine cure objective

where h is the absolute value of the height of the intake above maximum pool or below the reservoir bottom.

38. The intakes were again ordered from the top to the bottom with the highest intake being intake No. 1. To aid convergence, the penalty function was also added to the objective function whenever the PM attempted to locate an intake of higher number above an intake of lower number. In this situation, the value of h was determined from the height differential between the two intakes. In addition to ordering, every other intake was specified as being in the same wet well of a dual wet-well system. Thus odd-numbered intakes (i.e., 1, 3, and 5) were in one well while even-numbered intakes were in the other.

39. The PM uses values of the objective function for determining search

44. It should be realized that the optimal intake locations generally have flexibility in their placement. For example, the lower intakes can often be moved 20 ft or more up or down within the hypolimnion while affecting the objective function very little due to the homogeneity of temperature in the hypolimnion. This physical sensitivity must be considered by designers during the use of this technique.

Cyclic Coordinate Search

45. A Golden Section line search was used with the cyclic coordinate search (CCS) investigated in this study. The CCS (see paragraph 15) optimizes one intake location at a time with the Golden Section line search while holding all other intake locations fixed. Convergence for an individual intake location is based on ε ; that is, the minimization of the objective function for an individual intake is accomplished when the intake location is within ε distance of the previous iteration. This process is continued for every intake to complete one cycle. Global search cycles are continued until an overall convergence criterion is met. The basis for the overall convergence criterion is the change in the optimal value of the objective function, ΔF^* . If F^* at the end of a cycle is within ΔF^* of the F^* value at the end of the previous cycle, convergence is satisfied and the search is complete. The value for ε and ΔF^* used in this study was 5.0.

46. Because the Golden Section line search is a constrained search, the search boundaries for each intake location must be specified. The lower and upper boundaries were defined as the reservoir bottom and the water-surface elevation. In a manner analogous to that used with the PM, the feasible search regions for each intake were further bounded by the elevation of the intakes immediately above and below, thus reducing computer resources.

47. The CCS was used to locate 1, 2, 3, 4, and 6-intake selective withdrawal systems, for the revised temperature objective. The optimal intake locations for the five systems (referenced to their total number of intakes) are given in Table 3. This method appears to give a consistent result for each system in that it locates the top three intakes at about the same elevations regardless of the total number of intakes. The locations of the bottom three intakes have a minor effect on the objective function and their "optimal" locations could be considered highly flexible with little adverse effect as mentioned in paragraph 44.

step and direction. Because the objective function in this problem can be weakly sensitive to the decision variables (intake locations) in some regions of the pool, it was necessary to use an amplification of F in the search procedures. Raising F to the fourth power allowed a practical application of PM.

40. The search process of PM continues until a specified solution convergence tolerance is satisfied. The convergence tolerance, ε , is a vertical distance; thus, if each intake location is within ε from the corresponding intake location found by the previous search, convergence has been reached. After making several test runs with different values of ε , it was found that a rather coarse convergence tolerance would have to be used. A value of 20 ft was used for ε during all multiple intake optimization runs; a value of 5 ft was used for optimization of single intake configurations. The PM optimizer would not converge for smaller values of ε .

41. The maximum search distance for each intake location must be specified for PM. Maximum search distances of 20 ft and 50 ft were used for the multiple and single intake optimizations, respectively. This distance affects the rate of convergence and thus the computer resources required for the use of this technique.

42. The PM was tested with both the original and revised temperature objectives, but only the results for the revised objective are discussed in detail. With the revised objective, the method was tested for one-, three-, and six-intake selective withdrawal systems. The optimal intake locations for each of these three configurations are presented in Table 1. Table 2 shows the central processor (CP) time for a Cyber 176 and the minimum objective

Table 1

Optimal Intake Locations Using Powell's Method

(Revised Temperature Objective)

Total Number of Intakes	Intake Center-Line Locations Above the Reservoir Bottom (el 503.39)					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
1	113.58					
3	115.31	107.15	71.08			
6	123.62	118.29	101.03	73.27	61.51	17.76

Table 3

Optimal Intake Locations Using Cyclic Coordinate Search

(Revised Temperature Objective)

Total Number of Intakes	Intake Center-Line Locations Above the Reservoir Bottom (el 503.39)					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
1	113.09					
2	121.00	110.3				
3	122.71	117.44	102.81			
4	123.14	119.22	101.55	59.27		
6	122.97	118.68	100.70	71.28	32.84	12.54

48. The optimal value of the objective function, F* , and the computation times for the respective optimal intake configurations are presented for each system in Table 4. These results are consistent with the expected monotonic trend and indicate that this method is well behaved. For the systems with more than three intakes, F* decreases very little with an increasing number of intakes. This again indicates that the operation of the bottom three intakes is of little importance for this case study. Computation time increases almost linearly with the number of intakes for CCS.

Table 4

Optimal Objective Function Values and Computation Times Using Cyclic Coordinate Search (Revised Temperature Objective)

Total Number of Intakes	F*	CP Time sec
1	1,849	8.10
2	1,159	44.27
3	987	82.13
4	967	144.41
6	967	165.35

Table 2

Optimal Objective Function Values and Computation Times Using Powell's Method (Revised Temperature Objective)

Total Number of Intakes	F^*	CP Time sec
1	1,848	14.96
3	1,217	36.28
6	976	116.89

function values (F^*) for each optimized configuration. The CP time can become especially important when simulating multiple years and locating multiple intakes. The effectiveness of each intake configuration is measured by F^* ; the smaller F^* , the more effective the system in satisfying target temperatures.

43. As the number of intakes optimally located in the selective withdrawal system increases from one, the optimal objective function associated with the respective configurations, F^* , should decrease monotonically to some minimum. As an example, the results in Table 2 are monotonic. However, in the region near this minimum, the F^* values for successively increasing numbers of optimally located intakes will often approach a constant value which may be quite similar to the minimum observed F^* value. This region, referred to as a "flat spot" in the function, was believed to be caused by two phenomena: (a) the inclusion of additional intakes in each successive optimal intake configuration failed to increase the efficiency of the larger system in meeting the specified release temperature objectives when compared with an optimal system of lesser intakes--this is caused by the addition of system outflow flexibility which is not needed to achieve the "optimal" operational release strategy for the simulated conditions; and (b) the use of coarse convergence criteria which confuses the determination of an "optimal" intake configuration. As an example, testing of the PM with the original temperature objective revealed that F^* did not decrease monotonically as the intakes increased (Figure 9). This was attributed to the use of a coarse ε in regions where the F^* became less sensitive to the number of intakes. This could be remedied by starting a fine ε optimization run with the optimal intake locations obtained from a coarse ε optimization.

49. The optimal intake locations obtained by CCS for each system (Table 3) were used with the simulation model in the prediction mode (simulation without optimization) to provide plots of the release temperatures predicted for each configuration. The simulated release temperatures for each configuration are plotted with the objective temperature curve in Plates 1-5. The intake operations are also indicated. The bottom intake (intake of largest number) is actually the floodgate. From Plates 1-5 it is again evident that only the top intakes are heavily operated for maintenance of the revised objective. Also, Plates 1-5 show that the greatest deviations between release and objective temperatures occurred when the floodgate was operated. This suggests that the selective withdrawal system flow capacity should be increased to avoid extensive use of the floodgate during the stratification season, thereby enhancing the project's ability to meet its prescribed downstream release temperature objections. Plots for the PM results showed results analogous to those for CCS and therefore are not presented herein.

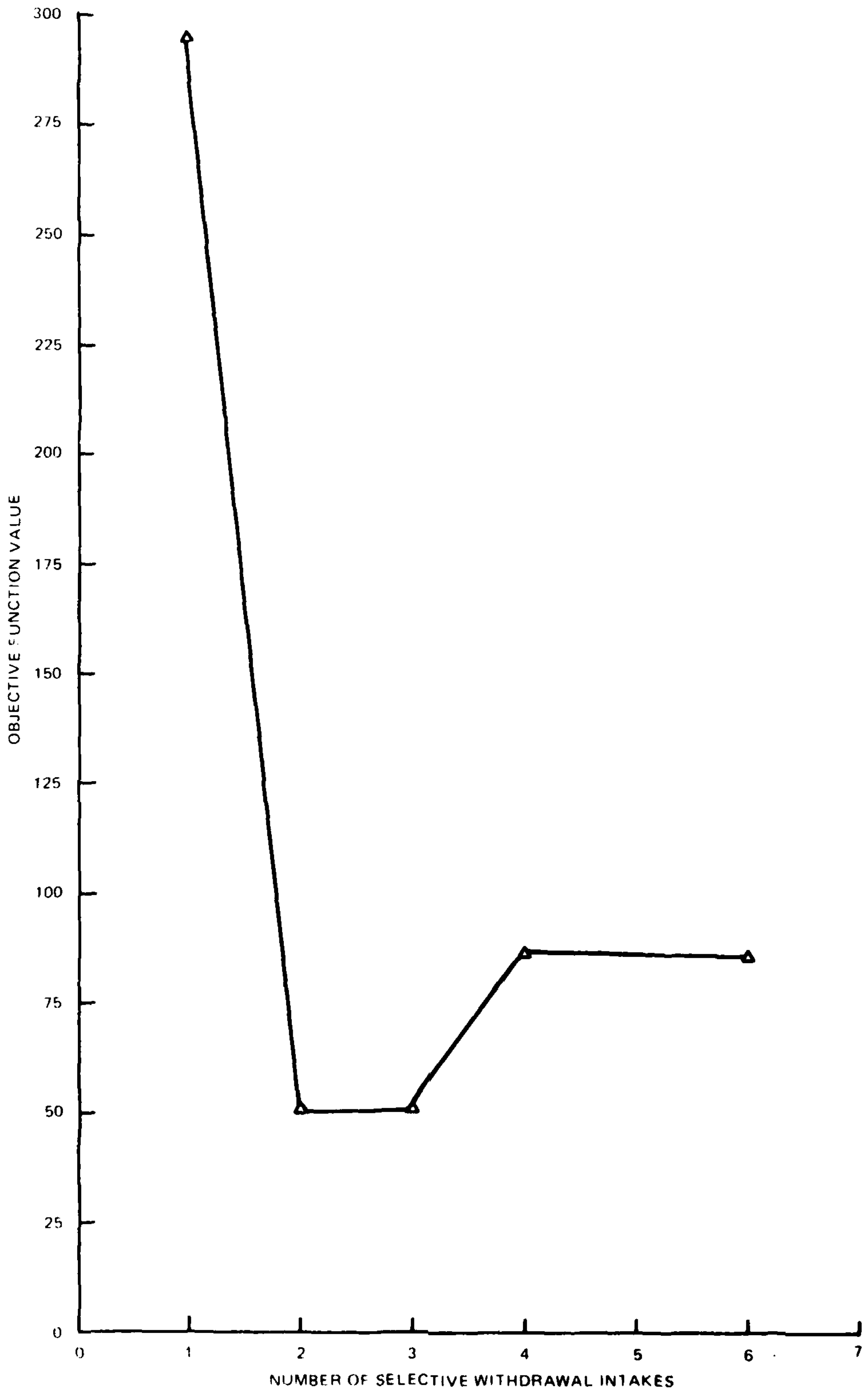


Figure 9. Optimal values of the objective function for various multilevel systems (original temperature objective) found using Powell's Method

PART IV: DISCUSSION

50. A comparison of the two optimization procedures can be made more easily with the aid of Figures 10 and 11. Figure 10 is a plot of F* (minimized objective function for a given number of intakes) versus the number of intakes. The PM was as effective as the CCS for the one- and six-intake systems but was less effective for the three-intake system. This is symptomatic of the irregular behavior of the PM near flat functional regions. This irregularity makes the method difficult to apply for this type of problem. When using the PM for this type of application, much care is required to assure the monotonic behavior that should characterize this problem. This special care creates uncertainty about the validity of declaring a given solution "optimum."

51. For systems with few intakes (i.e., one or two), CCS is cheaper to use. For systems with many intakes (three or more), PM is cheaper. This is evident from Figure 11 which compares the number of intakes located with the computation time required to optimize their locations for each method. This result would be expected based upon the methods of the two searches. PM expends considerable effort to determine search direction and distance simultaneously for all decision variables; however, fewer search steps are required. Conversely, while CCS expends less effort for each search step, it searches for only one decision variable at a time. This results in many search steps and the need for a cyclic procedure to consider all decision variables.

52. For the six-intake system, CCS required four complete cycles with a total of 108 search steps to converge. Each search step required computing the objective function for the simulation period. Thus 108 simulations were run to obtain the optimal intake locations. For this case, the simulation period was calendar days 138-334, 1972. Usually three or more study years would be used in this type of study. Thus requirements for computation time may be a consideration. However, with a highly efficient and relatively cheap reservoir simulation code, the computational burden can be quite reasonable as indicated by Tables 2 and 4 and Figure 11.

53. PM required three conjugate cycles with six line searches for each cycle for the six-intake system. It is not known how many function evaluations (each function evaluation requires simulation of the operating period) were required for each line search, but at least four would be required. Assuming at least 72 function evaluations with about 1.5 sec required for each

44. It should be realized that the optimal intake locations generally have flexibility in their placement. For example, the lower intakes can often be moved 20 ft or more up or down within the hypolimnion while affecting the objective function very little due to the homogeneity of temperature in the hypolimnion. This physical sensitivity must be considered by designers during the use of this technique.

Cyclic Coordinate Search

45. A Golden Section line search was used with the cyclic coordinate search (CCS) investigated in this study. The CCS (see paragraph 15) optimizes one intake location at a time with the Golden Section line search while holding all other intake locations fixed. Convergence for an individual intake location is based on ε ; that is, the minimization of the objective function for an individual intake is accomplished when the intake location is within ε distance of the previous iteration. This process is continued for every intake to complete one cycle. Global search cycles are continued until an overall convergence criterion is met. The basis for the overall convergence criterion is the change in the optimal value of the objective function, ΔF^* . If F^* at the end of a cycle is within ΔF^* of the F^* value at the end of the previous cycle, convergence is satisfied and the search is complete. The value for ε and ΔF^* used in this study was 5.0.

46. Because the Golden Section line search is a constrained search, the search boundaries for each intake location must be specified. The lower and upper boundaries were defined as the reservoir bottom and the water-surface elevation. In a manner analogous to that used with the PM, the feasible search regions for each intake were further bounded by the elevation of the intakes immediately above and below, thus reducing computer resources.

47. The CCS was used to locate 1, 2, 3, 4, and 6-intake selective withdrawal systems, for the revised temperature objective. The optimal intake locations for the five systems (referenced to their total number of intakes) are given in Table 3. This method appears to give a consistent result for each system in that it locates the top three intakes at about the same elevations regardless of the total number of intakes. The locations of the bottom three intakes have a minor effect on the objective function and their "optimal" locations could be considered highly flexible with little adverse effect as mentioned in paragraph 44.

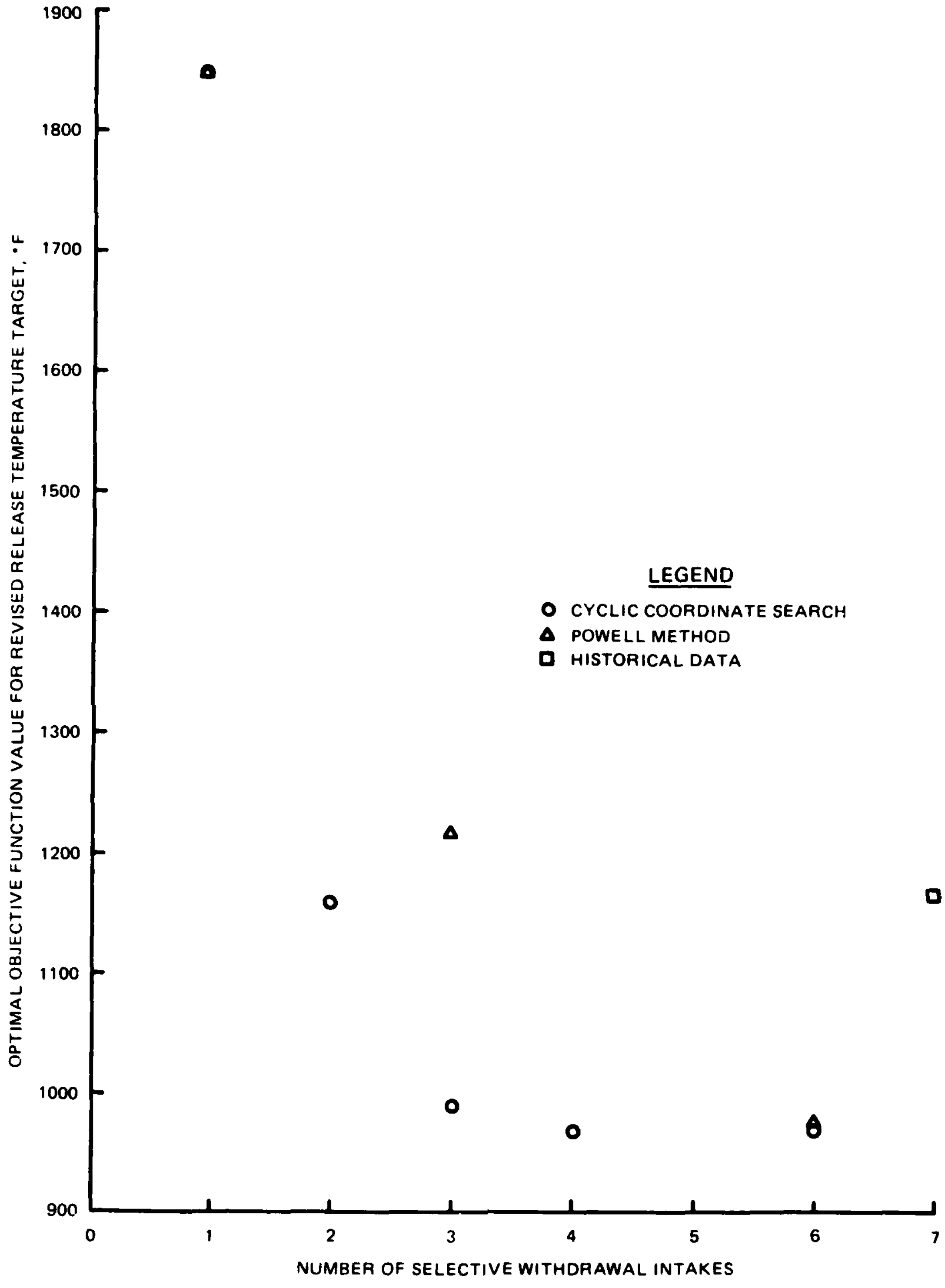


Figure 10. Optimal values of the objective function for multilevel intake configurations of varying number

Table 3

Optimal Intake Locations Using Cyclic Coordinate Search

(Revised Temperature Objective)

Total Number of Intakes	Intake Center-Line Locations Above the Reservoir Bottom (el 503.39)					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
1	113.09					
2	121.00	110.3				
3	122.71	117.44	102.81			
4	123.14	119.22	101.55	59.27		
6	122.97	118.68	100.70	71.28	32.84	12.54

48. The optimal value of the objective function, F^*, and the computation times for the respective optimal intake configurations are presented for each system in Table 4. These results are consistent with the expected monotonic trend and indicate that this method is well behaved. For the systems with more than three intakes, F^* decreases very little with an increasing number of intakes. This again indicates that the operation of the bottom three intakes is of little importance for this case study. Computation time increases almost linearly with the number of intakes for CCS.

Table 4

Optimal Objective Function Values and Computation Times Using Cyclic Coordinate Search (Revised Temperature Objective)

Total Number of Intakes	F^*	CP Time sec
1	1,849	8.10
2	1,159	44.27
3	987	82.13
4	967	144.41
6	967	165.35

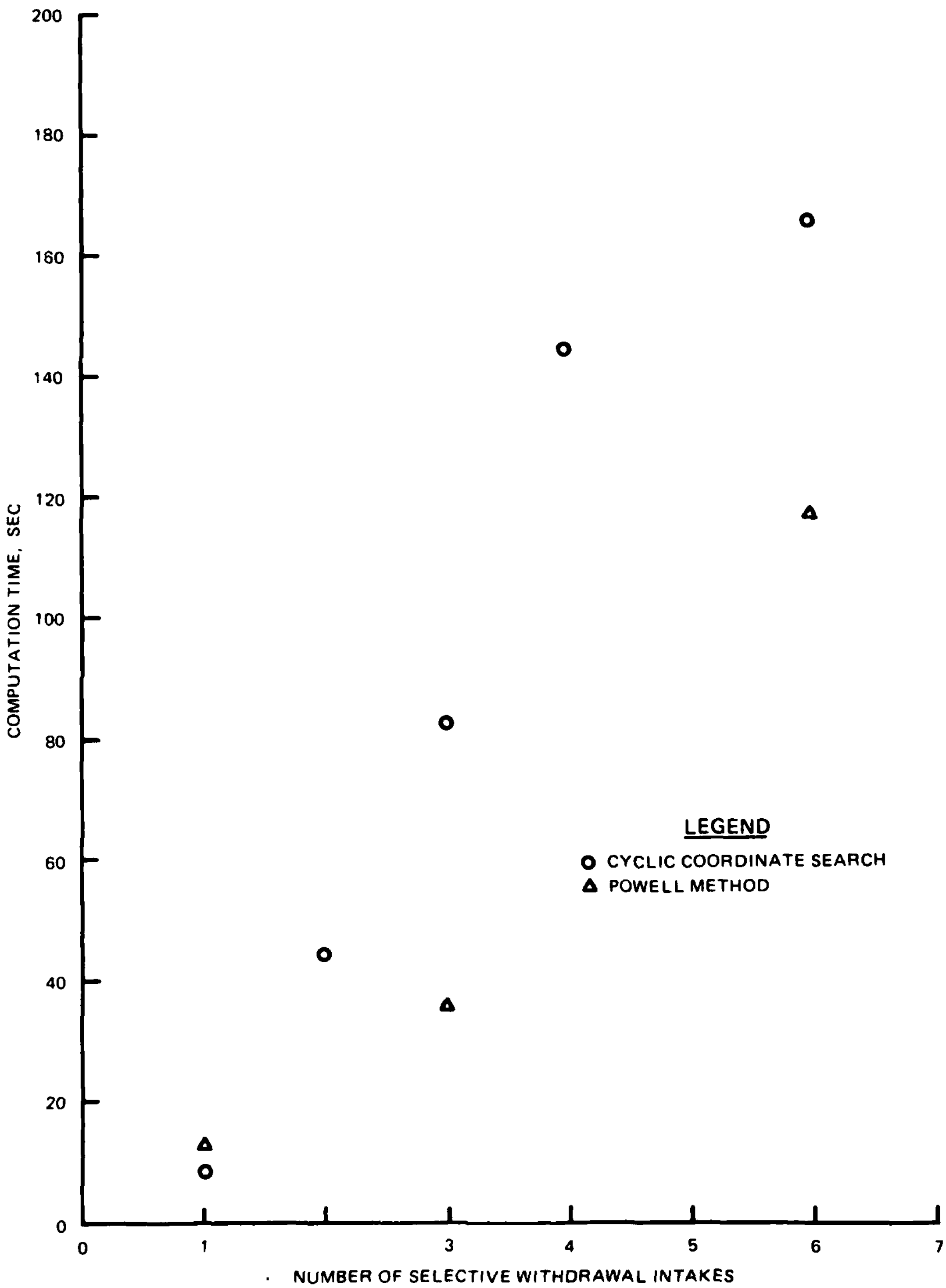


Figure 11. Computation time required to optimize multilevel intake configurations of varying number

49. The optimal intake locations obtained by CCS for each system (Table 3) were used with the simulation model in the prediction mode (simulation without optimization) to provide plots of the release temperatures predicted for each configuration. The simulated release temperatures for each configuration are plotted with the objective temperature curve in Plates 1-5. The intake operations are also indicated. The bottom intake (intake of largest number) is actually the floodgate. From Plates 1-5 it is again evident that only the top intakes are heavily operated for maintenance of the revised objective. Also, Plates 1-5 show that the greatest deviations between release and objective temperatures occurred when the floodgate was operated. This suggests that the selective withdrawal system flow capacity should be increased to avoid extensive use of the floodgate during the stratification season, thereby enhancing the project's ability to meet its prescribed downstream release temperature objections. Plots for the PM results showed results analogous to those for CCS and therefore are not presented herein.

simulation of the operating period (function evaluation), the PM would have required about 110 sec; PM was observed to require 116.9 sec for the six-intake configurations as compared with 165.4 sec for the analogous CCS run. Nonetheless, it is the opinion of the authors that although the PM is cheaper than the CCS for locating multiple intakes, the savings do not compensate for the difficulty and uncertainty imposed by using the Powell methodology.

54. Also shown in Figure 10 is the value of the objective function for the as-built project obtained through a prediction mode simulation with the revised temperature objective curve (see paragraphs 35 and 36). It is evident from Figure 10 that two selective withdrawal intakes optimally located (plus the floodgate) can do as well as the as-built seven intakes (plus floodgate) toward satisfying this release objective. Three optimal intakes do better than the as-built configuration. This demonstrates that the total number of intakes in a tower can be reduced through optimal placement, an action which could lead to cost savings. It must be noted, however, that this comparison is not rigorous, as noted in paragraph 25, since only a single set of input conditions was simulated. The existing project was designed for numerous other conditions not simulated herein. Rather, the results are presented strictly to illustrate the potential use of the technique for initial designs or project reformulation.

55. It is important to realize that optimal placement depends heavily upon hydraulic constraints, release objectives, and study years. For this test case, the release temperature objective was warm, the study year was wet, and maximum flow through a selective withdrawal intake was low (150.0 cfs). This resulted in the use of the floodgates during the summer to satisfy release flow constraints and demand (see Figure 8 and Plates 1-5). With the warm objective, low-level selective withdrawal intakes were not needed. If this had been a true design study, it would have been advisable at this point to consider increasing the capacity of the selective withdrawal intakes to prevent extensive floodgate flows during the summer. Further, for an actual study, as previously mentioned, one study year would not be sufficient. A variety of study years exhibiting wet, dry, warm, and cold conditions would be needed as a minimum.

PART IV: DISCUSSION

50. A comparison of the two optimization procedures can be made more easily with the aid of Figures 10 and 11. Figure 10 is a plot of F* (minimized objective function for a given number of intakes) versus the number of intakes. The PM was as effective as the CCS for the one- and six-intake systems but was less effective for the three-intake system. This is symptomatic of the irregular behavior of the PM near flat functional regions. This irregularity makes the method difficult to apply for this type of problem. When using the PM for this type of application, much care is required to assure the monotonic behavior that should characterize this problem. This special care creates uncertainty about the validity of declaring a given solution "optimum."

51. For systems with few intakes (i.e., one or two), CCS is cheaper to use. For systems with many intakes (three or more), PM is cheaper. This is evident from Figure 11 which compares the number of intakes located with the computation time required to optimize their locations for each method. This result would be expected based upon the methods of the two searches. PM expends considerable effort to determine search direction and distance simultaneously for all decision variables; however, fewer search steps are required. Conversely, while CCS expends less effort for each search step, it searches for only one decision variable at a time. This results in many search steps and the need for a cyclic procedure to consider all decision variables.

52. For the six-intake system, CCS required four complete cycles with a total of 108 search steps to converge. Each search step required computing the objective function for the simulation period. Thus 108 simulations were run to obtain the optimal intake locations. For this case, the simulation period was calendar days 138-334, 1972. Usually three or more study years would be used in this type of study. Thus requirements for computation time may be a consideration. However, with a highly efficient and relatively cheap reservoir simulation code, the computational burden can be quite reasonable as indicated by Tables 2 and 4 and Figure 11.

53. PM required three conjugate cycles with six line searches for each cycle for the six-intake system. It is not known how many function evaluations (each function evaluation requires simulation of the operating period) were required for each line search, but at least four would be required. Assuming at least 72 function evaluations with about 1.5 sec required for each

PART V: CONCLUSIONS AND RECOMMENDATIONS

56. Results of this study indicate that the coupled mathematical optimization and reservoir simulation approach can be used as an effective design tool for selective withdrawal structures. The methodology can be used to develop optimal vertical placement of intakes and to minimize the total number of intakes needed. This should result in more effective and economical designs.

57. The technique can be applied to new structures or retrofits of existing structures. Further, the technique can be applied in a fashion that allows optimal placement of new intakes in a structure while retaining existing intakes.

58. Of the two mathematical optimization techniques tested, the authors favor the cyclic coordinate search (CCS) with the Golden Section line search over Powell's Method (PM). The simplicity and reliability of the CCS method justify the computational costs imposed for locating large numbers of intakes.

59. The technique can be used with any reservoir simulation code provided that the code contains decision methods for intake operations (i.e., subroutine DECIDE). There should be provisions for hydraulic constraints also, as these affect the entire process. From the material presented herein, it should be apparent that this type of design methodology should include input and feedback from water quality, operations, hydrologic, and hydraulic design personnel. A design study should include multiple study years that cover a range of meteorological and hydrological conditions. In fact, it is for the investigation of multiple input conditions that the systematic nature of this technique is best applied.

60. It is recommended that this technique be extended to include an additional water quality parameter such as dissolved oxygen (DO). The easiest way to include DO in the objective function would be to impose a penalty each time the release DO is below the specified standard. However, the additional water quality parameter could also be considered more directly in the objective function (Poore and Loftis 1983).

61. The CCS method requires about of 15 to 20 simulations (function evaluations) per each intake to be located. When optimizing multiple intakes with multiple study years in each simulation, it is extremely important that the simulation model be efficient and relatively inexpensive as was the case

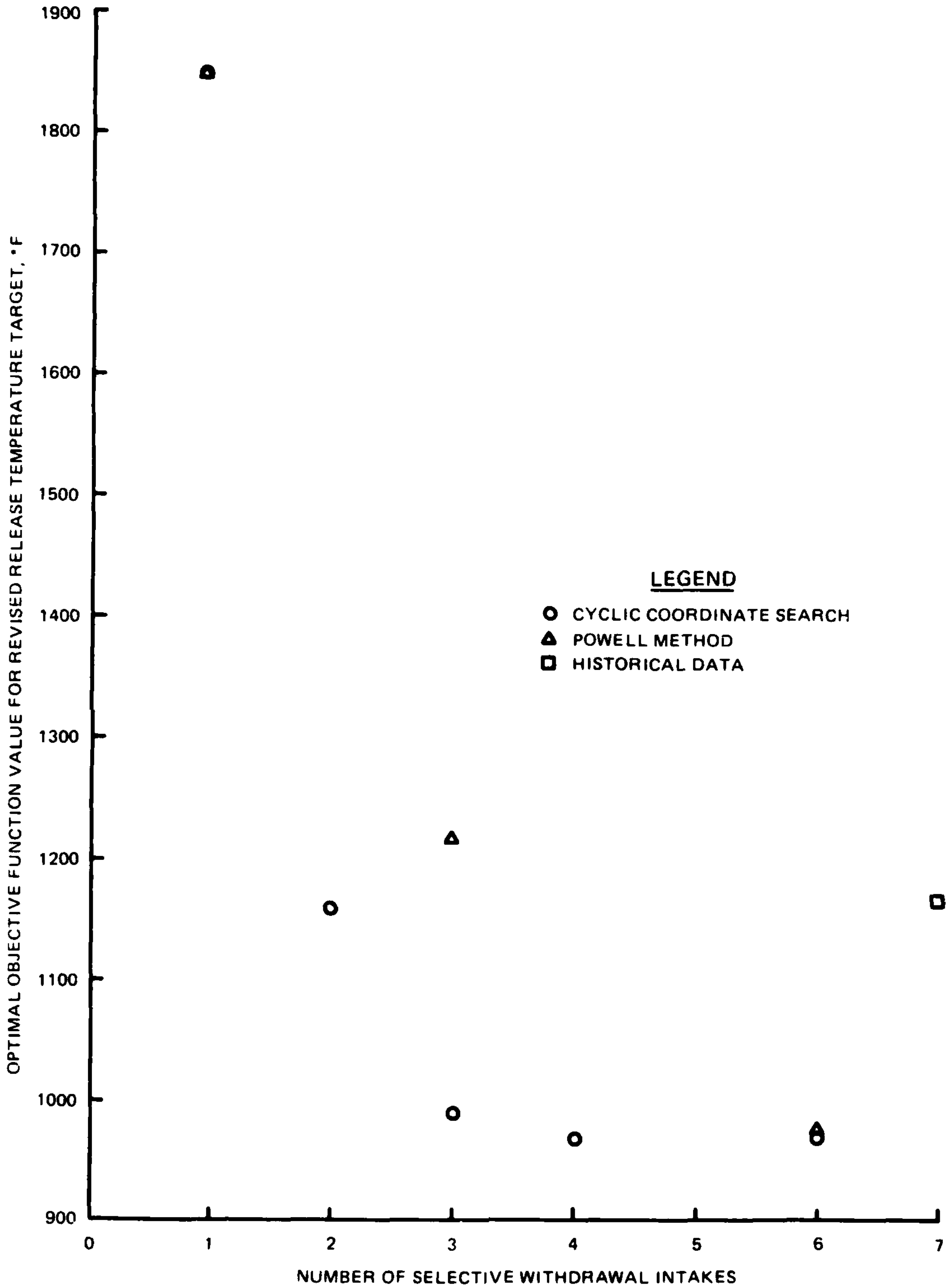


Figure 10. Optimal values of the objective function for multilevel intake configurations of varying number

in this study. The computational costs incurred in this case study were minor. Even if this had been an actual design study with multiple study years, the computational costs would have been inconsequential compared with the benefits derived. In any case, this procedure should be cheaper and more efficient than the older method of trying to manually determine adequate intake locations, especially for multiple operational and hydrothermal conditions. With optimally located intakes, it is easier to determine how many intakes are needed to satisfy given objectives, thus allowing construction savings while providing an effective design.

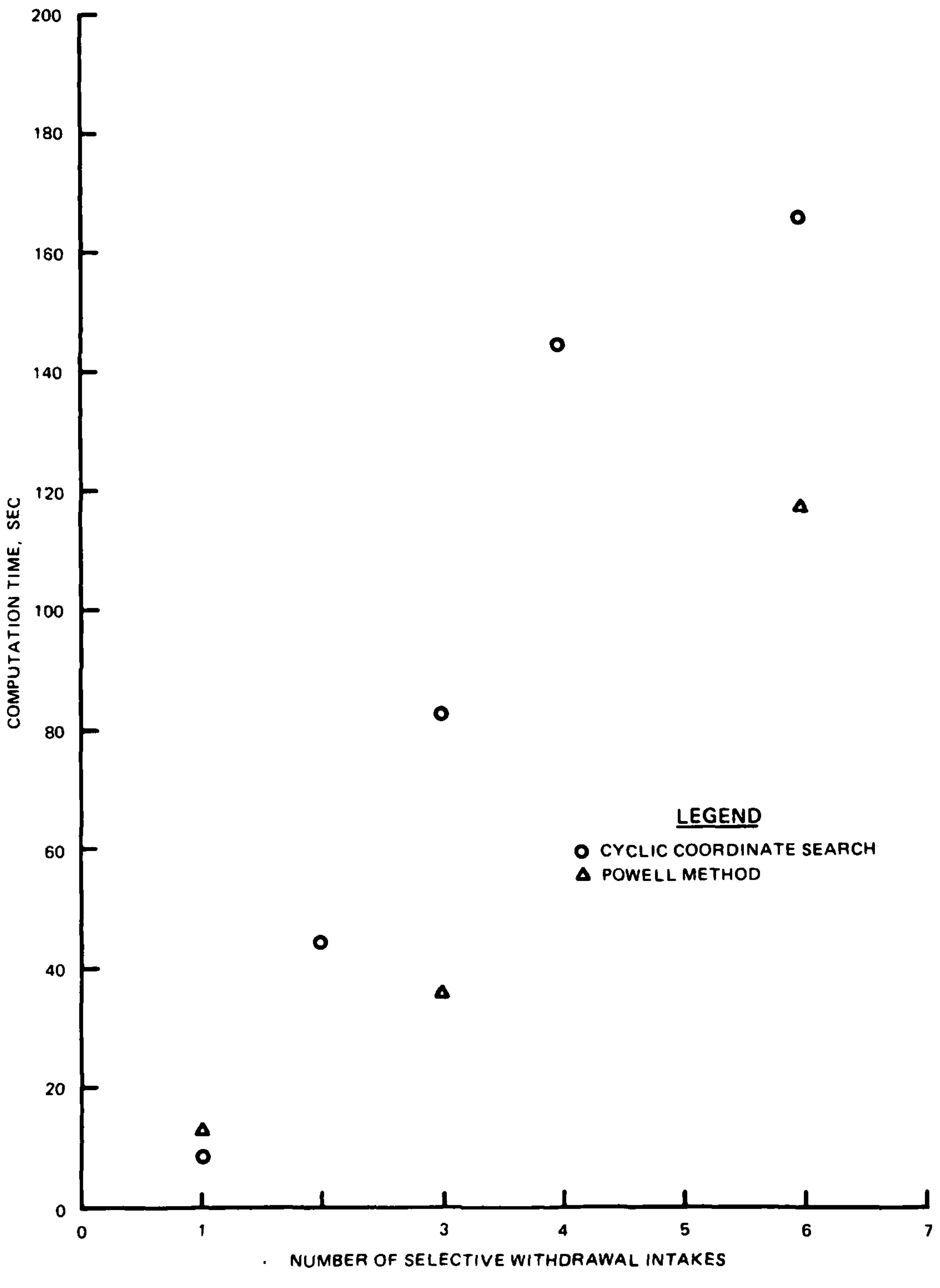


Figure 11. Computation time required to optimize multilevel intake configurations of varying number

REFERENCES

Box, M. J., Davies, D., and Swann, W. J. 1969. "Non-Linear Optimization Techniques," Imperial Chemical Industries Monograph No. 5, Oliver & Boyd, Publishers, Edinburgh, Great Britian.

Boyt, W. L. 1982. "Documentation for Computer Program WESTEX, Engineering and Computer Programs Library" (unpublished), US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Fontane, D. G., Labadie, J. W., and Loftis, B. 1982 (Feb). "Optimal Control of Reservoir Discharge Quality Through Selective Withdrawal; Hydraulic Laboratory Investigation," Technical Report E-82-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.; prepared by Colorado State University, Fort Collins, Colo.

Holland, J. P. 1982 (Apr). "Effects of Storage Reallocation on Thermal Characteristics of Cowanesque Lake, Pennsylvania; Numerical Model Investigation," Technical Report HL-82-9, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Marcinski, E. J. 1975 (May). An Evaluation of One-Dimensional Temperature Prediction Models for Reservoirs, M.S. Thesis, Department of Civil Engineering, Villanova University, Villanova, Pa.

Melsheimer, E. S. 1969 (Dec). "Outlet Works of Beltzville Dam, Pohopoco Creek, Pennsylvania; Hydraulic Model Investigation," Technical Report H-69-18, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

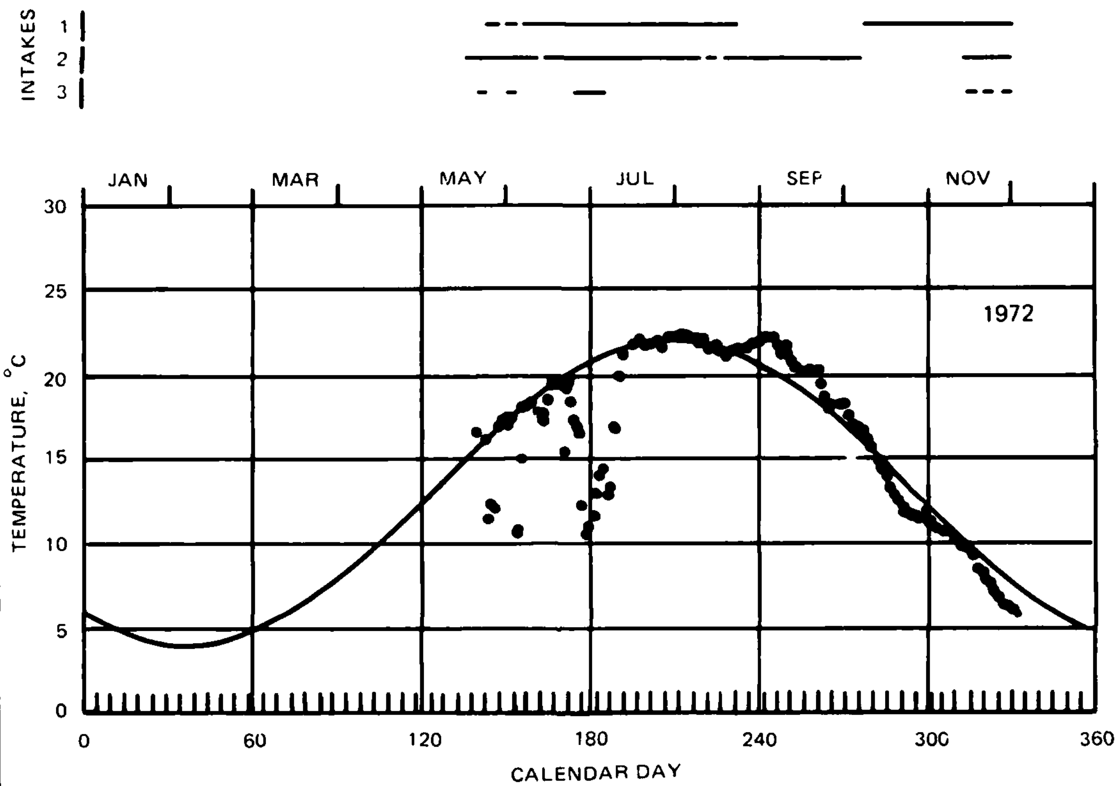
Office, Chief of Engineers, Department of the Army. 1980 (Oct). "Engineering and Design, Hydraulic Design of Reservoir Outlet Works," EM 1110-2-1602, Washington, DC.

Poore, A. B., and Loftis, B. 1983 (Mar). "Water Quality Optimization Through Selective Withdrawal," Technical Report E-83-9, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

simulation of the operating period (function evaluation), the PM would have required about 110 sec; PM was observed to require 116.9 sec for the six-intake configurations as compared with 165.4 sec for the analogous CCS run. Nonetheless, it is the opinion of the authors that although the PM is cheaper than the CCS for locating multiple intakes, the savings do not compensate for the difficulty and uncertainty imposed by using the Powell methodology.

54. Also shown in Figure 10 is the value of the objective function for the as-built project obtained through a prediction mode simulation with the revised temperature objective curve (see paragraphs 35 and 36). It is evident from Figure 10 that two selective withdrawal intakes optimally located (plus the floodgate) can do as well as the as-built seven intakes (plus floodgate) toward satisfying this release objective. Three optimal intakes do better than the as-built configuration. This demonstrates that the total number of intakes in a tower can be reduced through optimal placement, an action which could lead to cost savings. It must be noted, however, that this comparison is not rigorous, as noted in paragraph 25, since only a single set of input conditions was simulated. The existing project was designed for numerous other conditions not simulated herein. Rather, the results are presented strictly to illustrate the potential use of the technique for initial designs or project reformulation.

55. It is important to realize that optimal placement depends heavily upon hydraulic constraints, release objectives, and study years. For this test case, the release temperature objective was warm, the study year was wet, and maximum flow through a selective withdrawal intake was low (150.0 cfs). This resulted in the use of the floodgates during the summer to satisfy release flow constraints and demand (see Figure 8 and Plates 1-5). With the warm objective, low-level selective withdrawal intakes were not needed. If this had been a true design study, it would have been advisable at this point to consider increasing the capacity of the selective withdrawal intakes to prevent extensive floodgate flows during the summer. Further, for an actual study, as previously mentioned, one study year would not be sufficient. A variety of study years exhibiting wet, dry, warm, and cold conditions would be needed as a minimum.



LEGEND

REVISED OBJECTIVE CURVE

• SIMULATED RESULTS WITH TWO INTAKES AND FLOODGATE

SIMULATED RELEASE TEMPERATURES FOR OPTIMIZED INTAKE CONFIGURATIONS OF VARYING NUMBER WITH CYCLIC COORDINATE SEARCH TECHNIQUE

TWO INTAKES AND FLOODGATE

PLATE 2

PART V: CONCLUSIONS AND RECOMMENDATIONS

56. Results of this study indicate that the coupled mathematical optimization and reservoir simulation approach can be used as an effective design tool for selective withdrawal structures. The methodology can be used to develop optimal vertical placement of intakes and to minimize the total number of intakes needed. This should result in more effective and economical designs.

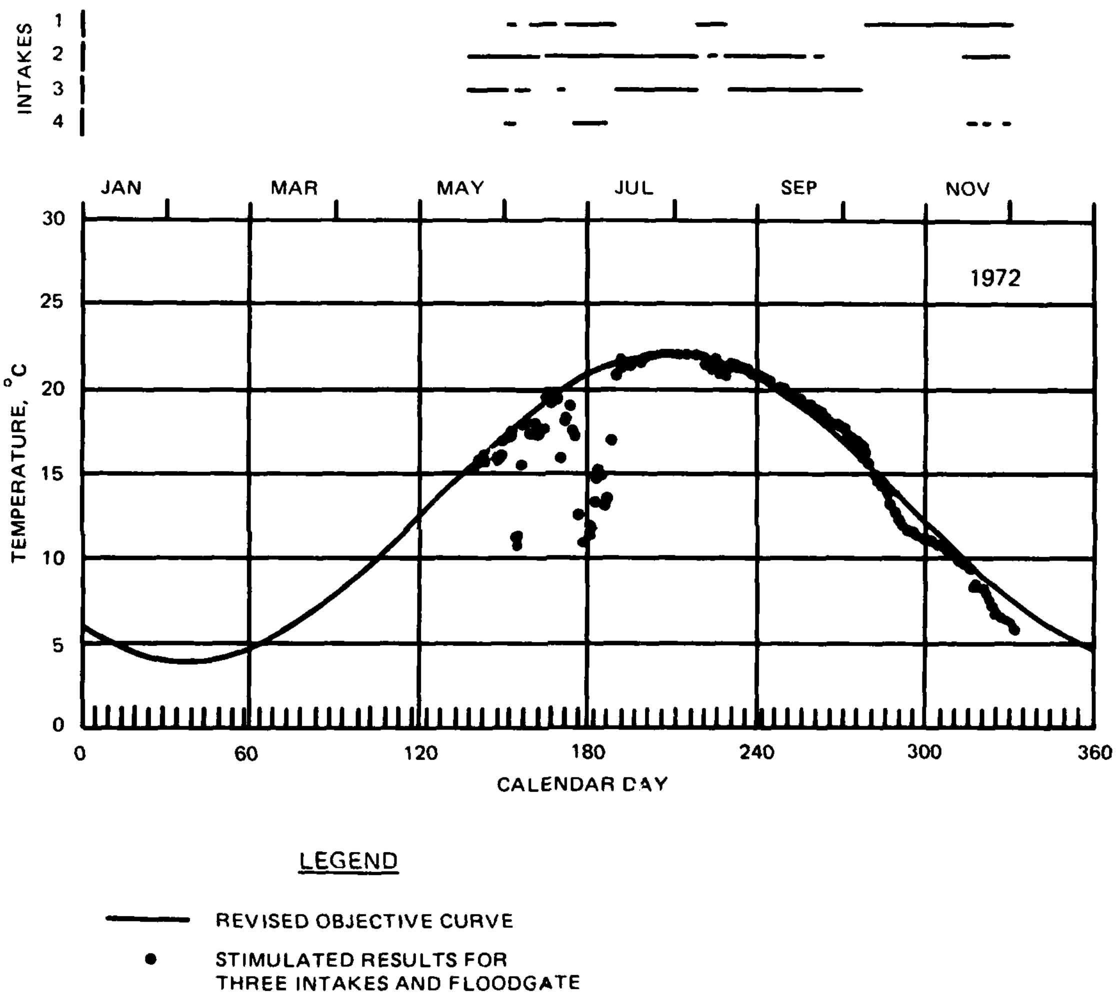
57. The technique can be applied to new structures or retrofits of existing structures. Further, the technique can be applied in a fashion that allows optimal placement of new intakes in a structure while retaining existing intakes.

58. Of the two mathematical optimization techniques tested, the authors favor the cyclic coordinate search (CCS) with the Golden Section line search over Powell's Method (PM). The simplicity and reliability of the CCS method justify the computational costs imposed for locating large numbers of intakes.

59. The technique can be used with any reservoir simulation code provided that the code contains decision methods for intake operations (i.e., subroutine DECIDE). There should be provisions for hydraulic constraints also, as these affect the entire process. From the material presented herein, it should be apparent that this type of design methodology should include input and feedback from water quality, operations, hydrologic, and hydraulic design personnel. A design study should include multiple study years that cover a range of meteorological and hydrological conditions. In fact, it is for the investigation of multiple input conditions that the systematic nature of this technique is best applied.

60. It is recommended that this technique be extended to include an additional water quality parameter such as dissolved oxygen (DO). The easiest way to include DO in the objective function would be to impose a penalty each time the release DO is below the specified standard. However, the additional water quality parameter could also be considered more directly in the objective function (Poore and Loftis 1983).

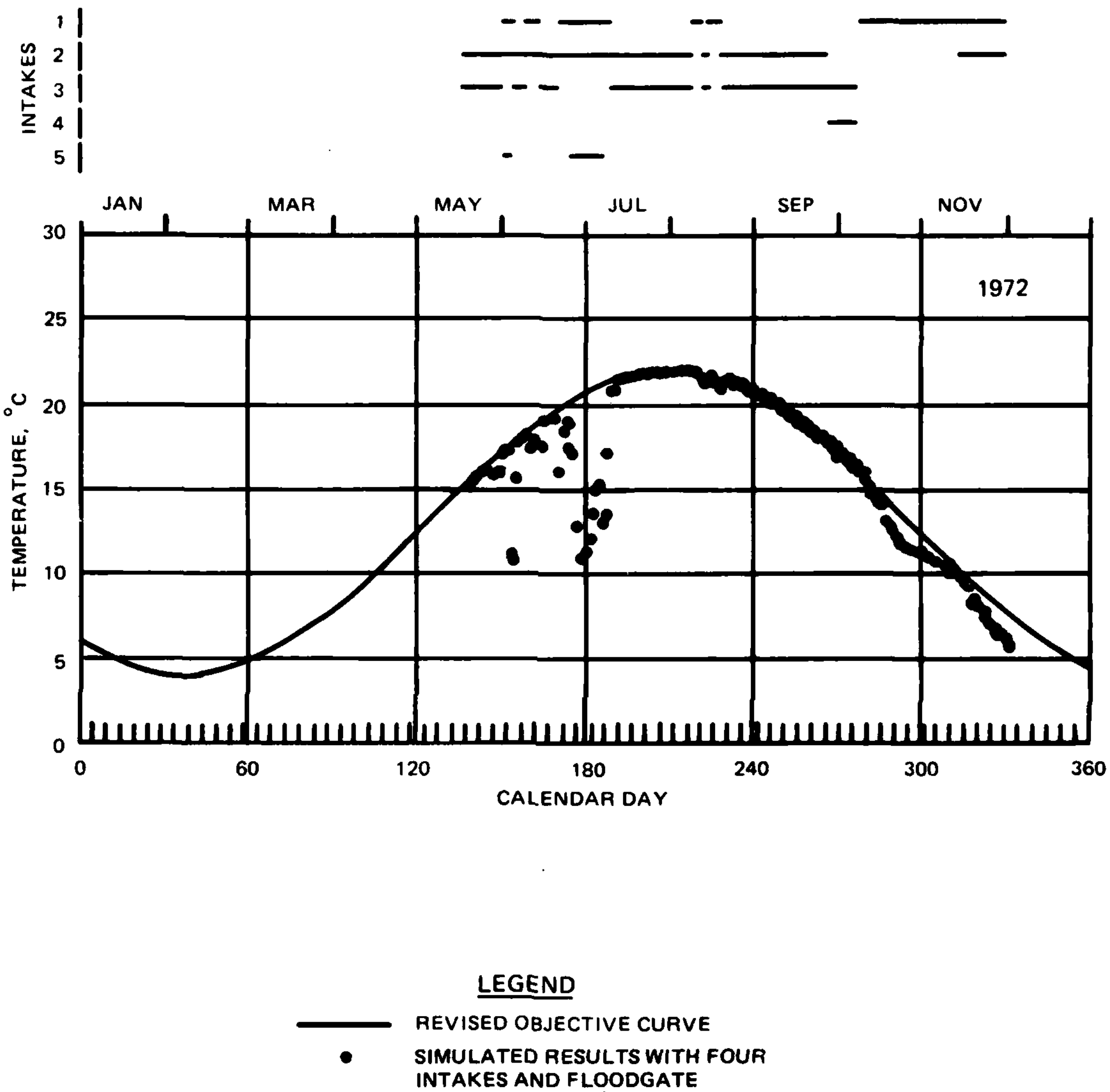
61. The CCS method requires about of 15 to 20 simulations (function evaluations) per each intake to be located. When optimizing multiple intakes with multiple study years in each simulation, it is extremely important that the simulation model be efficient and relatively inexpensive as was the case



SIMULATED RELEASE TEMPERATURES FOR
OPTIMIZED INTAKE CONFIGURATIONS
OF VARYING NUMBER WITH
CYCLIC COORDINATE SEARCH TECHNIQUE
THREE INTAKES AND FLOODGATE

PLATE 3

in this study. The computational costs incurred in this case study were minor. Even if this had been an actual design study with multiple study years, the computational costs would have been inconsequential compared with the benefits derived. In any case, this procedure should be cheaper and more efficient than the older method of trying to manually determine adequate intake locations, especially for multiple operational and hydrothermal conditions. With optimally located intakes, it is easier to determine how many intakes are needed to satisfy given objectives, thus allowing construction savings while providing an effective design.



SIMULATED RELEASE TEMPERATURES FOR OPTIMIZED INTAKE CONFIGURATIONS OF VARYING NUMBER WITH CYCLIC COORDINATE SEARCH TECHNIQUE

FOUR INTAKES AND FLOODGATE

PLATE 4

REFERENCES

Box, M. J., Davies, D., and Swann, W. J. 1969. "Non-Linear Optimization Techniques," Imperial Chemical Industries Monograph No. 5, Oliver & Boyd, Publishers, Edinburgh, Great Britian.

Boyt, W. L. 1982. "Documentation for Computer Program WESTEX, Engineering and Computer Programs Library" (unpublished), US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Fontane, D. G., Labadie, J. W., and Loftis, B. 1982 (Feb). "Optimal Control of Reservoir Discharge Quality Through Selective Withdrawal; Hydraulic Laboratory Investigation," Technical Report E-82-1, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.; prepared by Colorado State University, Fort Collins, Colo.

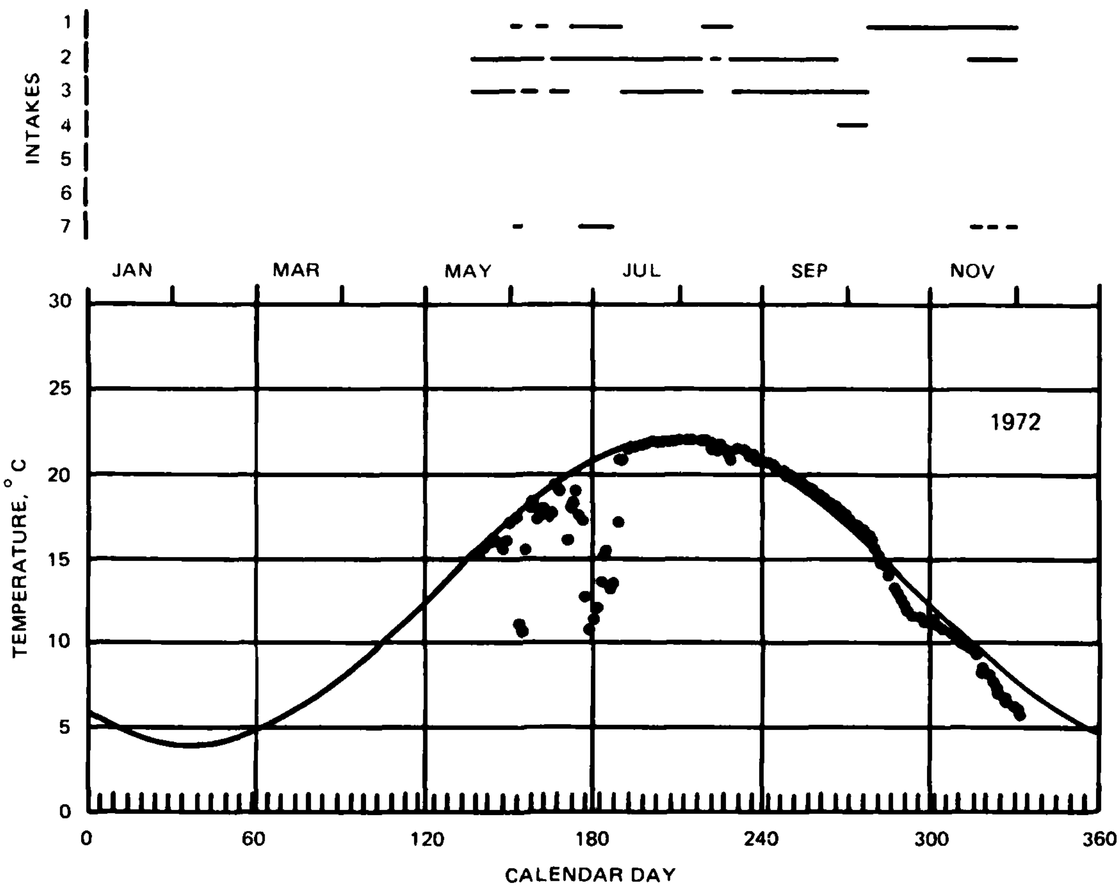
Holland, J. P. 1982 (Apr). "Effects of Storage Reallocation on Thermal Characteristics of Cowanesque Lake, Pennsylvania; Numerical Model Investigation," Technical Report HL-82-9, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Marcinski, E. J. 1975 (May). An Evaluation of One-Dimensional Temperature Prediction Models for Reservoirs, M.S. Thesis, Department of Civil Engineering, Villanova University, Villanova, Pa.

Melsheimer, E. S. 1969 (Dec). "Outlet Works of Beltzville Dam, Pohopoco Creek, Pennsylvania; Hydraulic Model Investigation," Technical Report H-69-18, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Office, Chief of Engineers, Department of the Army. 1980 (Oct). "Engineering and Design, Hydraulic Design of Reservoir Outlet Works," EM 1110-2-1602, Washington, DC.

Poore, A. B., and Loftis, B. 1983 (Mar). "Water Quality Optimization Through Selective Withdrawal," Technical Report E-83-9, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.



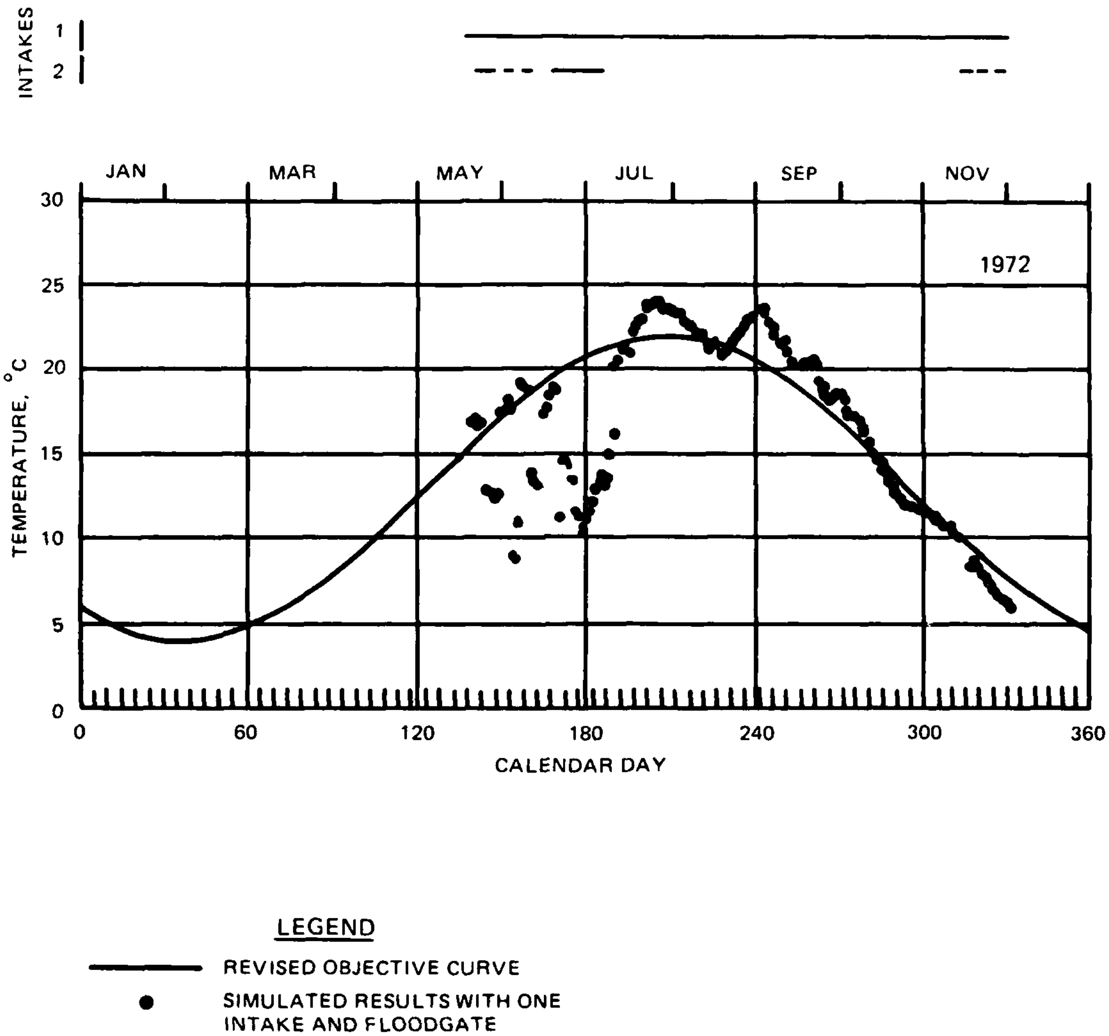
LEGEND

REVISED OBJECTIVE CURVE

SIMULATED RESULTS WITH SIX INTAKES AND FLOODGATE

SIMULATED RELEASE TEMPERATURES FOR OPTIMIZED INTAKE CONFIGURATIONS OF VARYING NUMBER WITH CYCLIC COORDINATE SEARCH TECHNIQUE

SIX INTAKES AND FLOODGATE



SIMULATED RELEASE TEMPERATURES FOR OPTIMIZED INTAKE CONFIGURATIONS OF VARYING NUMBER WITH CYCLIC COORDINATE SEARCH TECHNIQUE

ONE INTAKE AND FLOODGATE

APPENDIX A: HYDRAULICS OF SELECTIVE WITHDRAWAL INTAKE STRUCTURES

1. In this section, prevailing features of selective withdrawal intake structures are discussed in general, and the hydraulic constraints as formulated in subroutine DECIDE are presented. For a more detailed discussion of the hydraulics of selective withdrawal intake structures, see Chapter 6 of CE EM 1110-2-1602 (OCE 1980).*

General Features

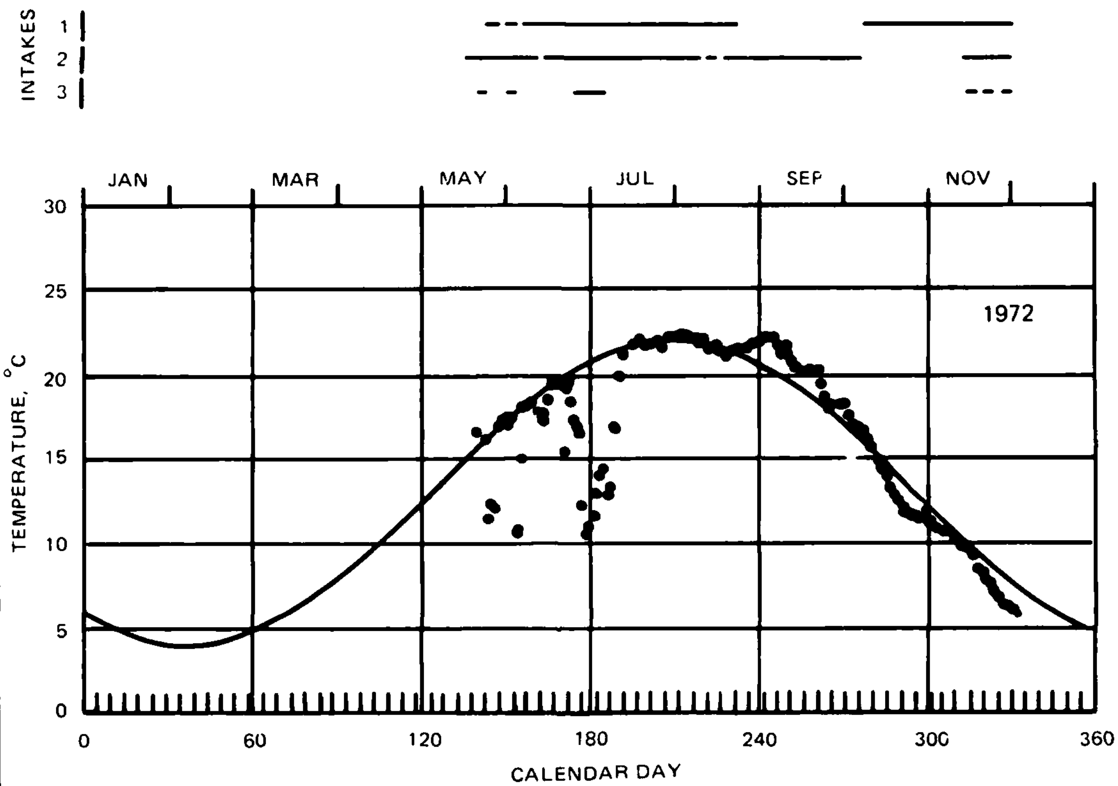
2. Selective withdrawal intake structures are basically composed of two systems: the selective withdrawal system and the flood-control system. The selective withdrawal system requires multilevel intakes or a variable intake elevation so that water of desired quality can be selectively withdrawn from various layers of a stratified pool. To economically accommodate multiple intakes in a common system usually results in a hydraulic capacity (maximum permissible flow) that is less than that needed for flood control, thus constituting the need for the flood-control system also.

3. Multiple selective withdrawal intakes usually pass the flow into a common collection well (wet well). A structure may have multiple wet wells, but the dual wet-well type is the most common. To assure water quality control, only one of the multilevel intakes should be open at a time in each wet well. However, simultaneous releases from different levels in the pool may be accomplished with multiple wet wells. Separate control gates or valves should be used downstream of each wet well to control the flow rate through the intake and wet well. Multiple wet wells eventually empty into a common conduit, stilling basin, or exit channel that enhance mixing of different quality waters. The combined flow capacity of all water quality wet wells will be referred to in this discussion as the selective withdrawal capacity.

4. The flood-control system provides for releases that exceed the capacity of the selective withdrawal system. The flood-control system typically consists of one or more intakes (usually all are at the same elevation near the reservoir bottom), gate passages, and a common outlet conduit or channel. The control gates or valves are located in the gate passage section. Dual

---

* See References at end of main text.



LEGEND

REVISED OBJECTIVE CURVE

● SIMULATED RESULTS WITH TWO INTAKES AND FLOODGATE

SIMULATED RELEASE TEMPERATURES FOR OPTIMIZED INTAKE CONFIGURATIONS OF VARYING NUMBER WITH CYCLIC COORDINATE SEARCH TECHNIQUE
TWO INTAKES AND FLOODGATE

PLATE 2

intakes, gate passages, and control gates transitioning into a single conduit is a very common flood-control configuration.

5. Some structures have separate flow controls for the selective withdrawal and flood-control systems. Others use the same flow control device for flood control and selective withdrawal. The two types will be referred to as separated and integrated systems, respectively, and are shown schematically in Figure A1. The intake structure for Beltzville Dam, Pohopoco Creek, Pennsylvania, is an example of a separated system (Figure A2). Figure A3 shows the intake structure at Taylorsville Dam (Salt River, Kentucky), which is an integrated system.

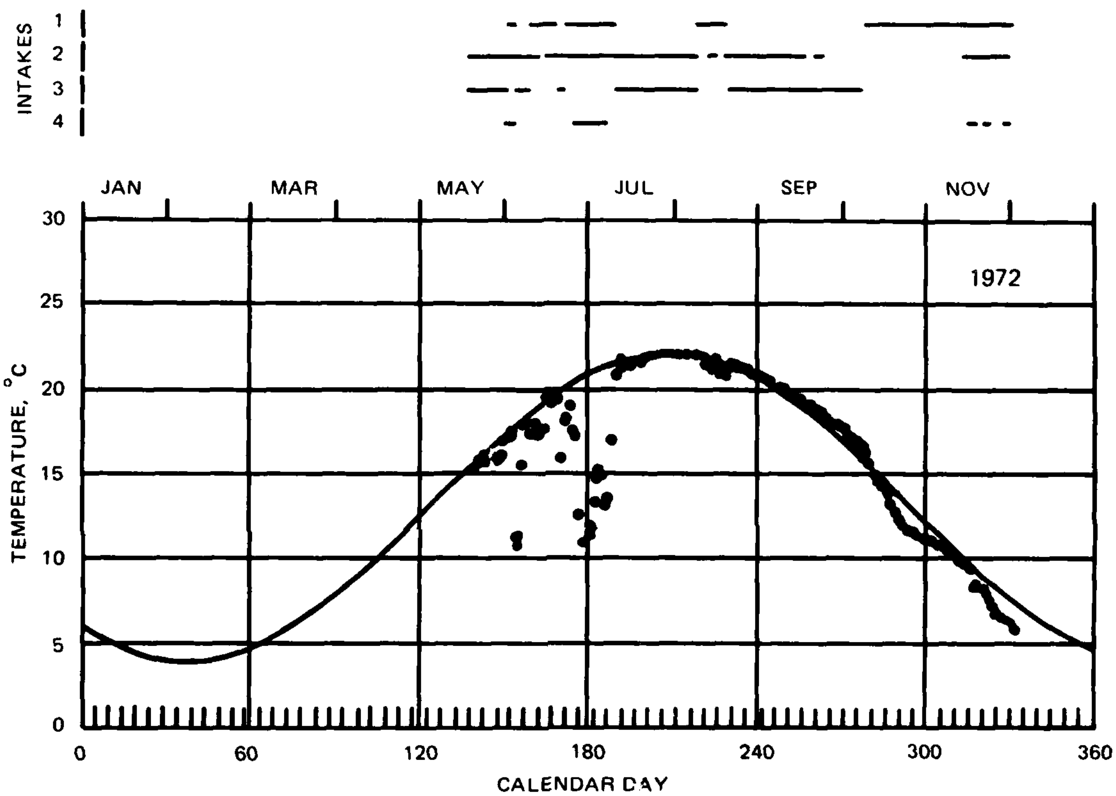
6. The wet wells empty into the flood-control gate passage of the integrated Taylorsville structure. It is possible to have flood-control and selective withdrawal releases simultaneously with either the separated or integrated system. However, with the linked wet well and flood gate passage of the integrated system, only one intake (either flood intake or water quality intake) should be open for each control gate to assure flow control.

7. Because of the size of some flood-control gates, significant discharge rates can be achieved at very small gate openings. To provide more manageable flow control for low discharge rates, a small low-flow gate or valve is often provided. This extra gate may be a part of the service gate or may be built into a pipe that bypasses the service gate. The important point here is that there is a minimum permissible discharge rate. A low-flow gate usually allows a lower minimum (controllable) flow than does a service gate.

Hydraulic Constraints of DECIDE

8. This section specifically addresses the physical and operational (hydraulic related) constraints of the intake structure that are encountered in subroutine DECIDE. The intake structure is assumed to have two wet wells for the selective withdrawal system and a flood-control system that is specified as either separated or integrated. The procedures in DECIDE seek which intake must be open, and the flows they must pass, to meet (as close as possible) the objective temperature and satisfy flow requirements. When the flow capacity of the selective withdrawal system is reached, the flood-control system is also used to fulfill flow requirements.

9. Blending can be accomplished in this routine only through the use



LEGEND

REVISED OBJECTIVE CURVE

STIMULATED RESULTS FOR THREE INTAKES AND FLOODGATE

SIMULATED RELEASE TEMPERATURES FOR OPTIMIZED INTAKE CONFIGURATIONS OF VARYING NUMBER WITH CYCLIC COORDINATE SEARCH TECHNIQUE

THREE INTAKES AND FLOODGATE

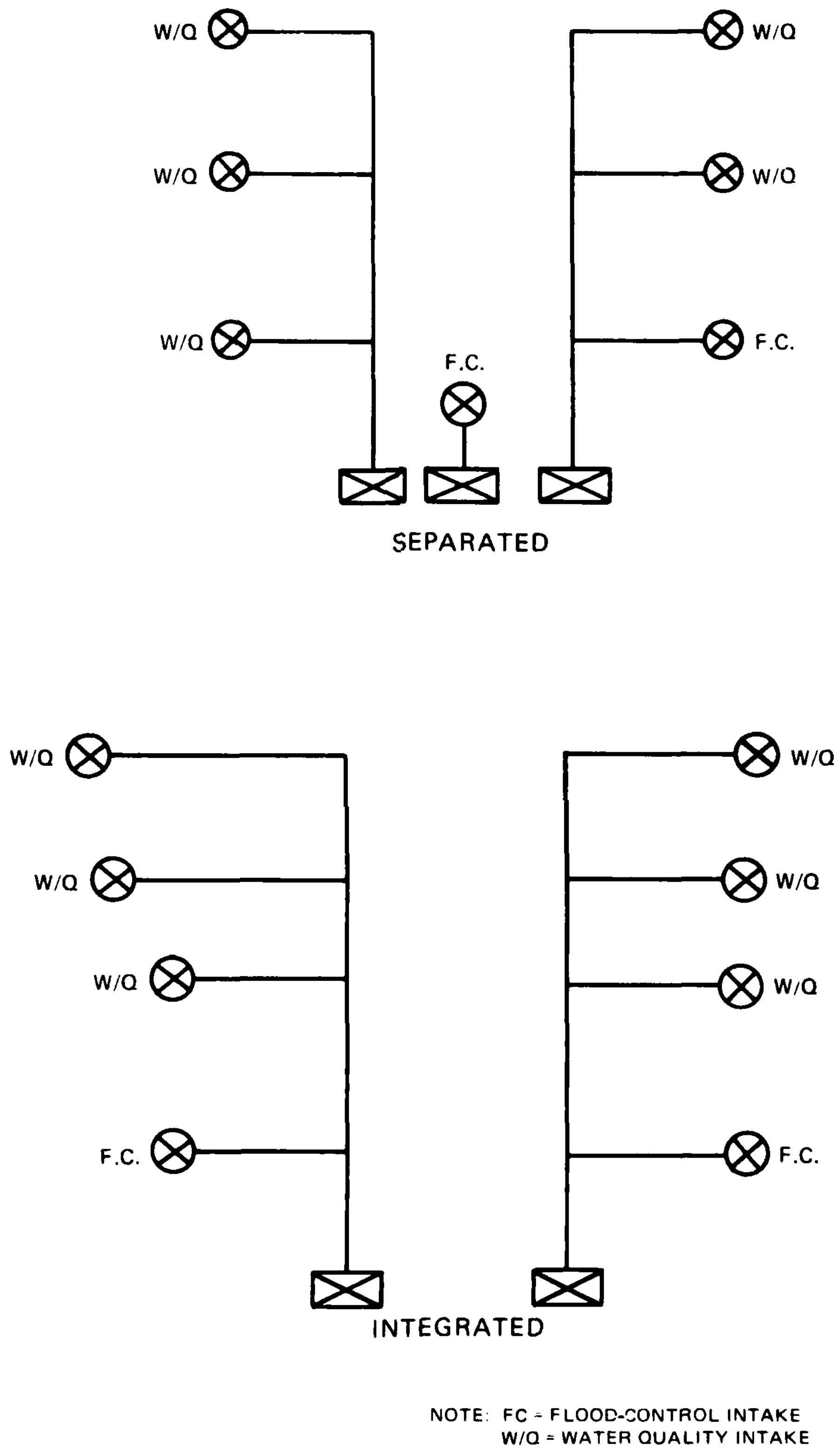
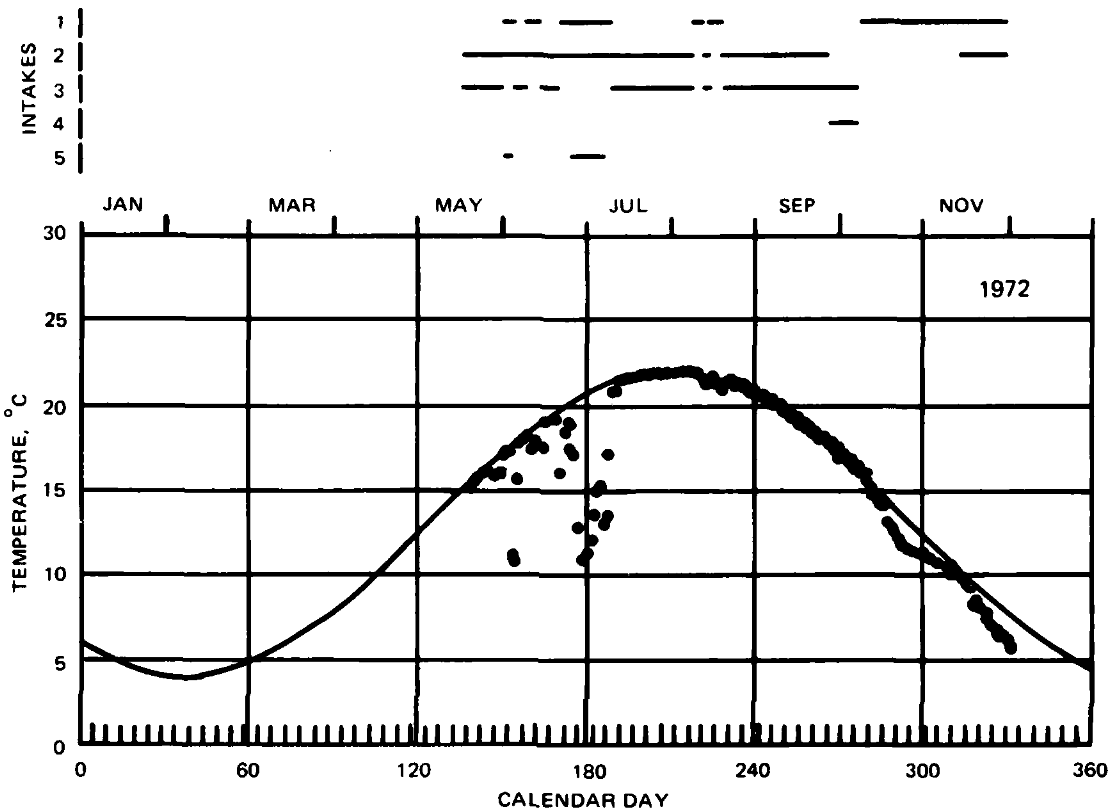


Figure A1. Schematic representation of separated and integrated flow control



LEGEND

REVISED OBJECTIVE CURVE

● SIMULATED RESULTS WITH FOUR INTAKES AND FLOODGATE

SIMULATED RELEASE TEMPERATURES FOR OPTIMIZED INTAKE CONFIGURATIONS OF VARYING NUMBER WITH CYCLIC COORDINATE SEARCH TECHNIQUE

FOUR INTAKES AND FLOODGATE

PLATE 4

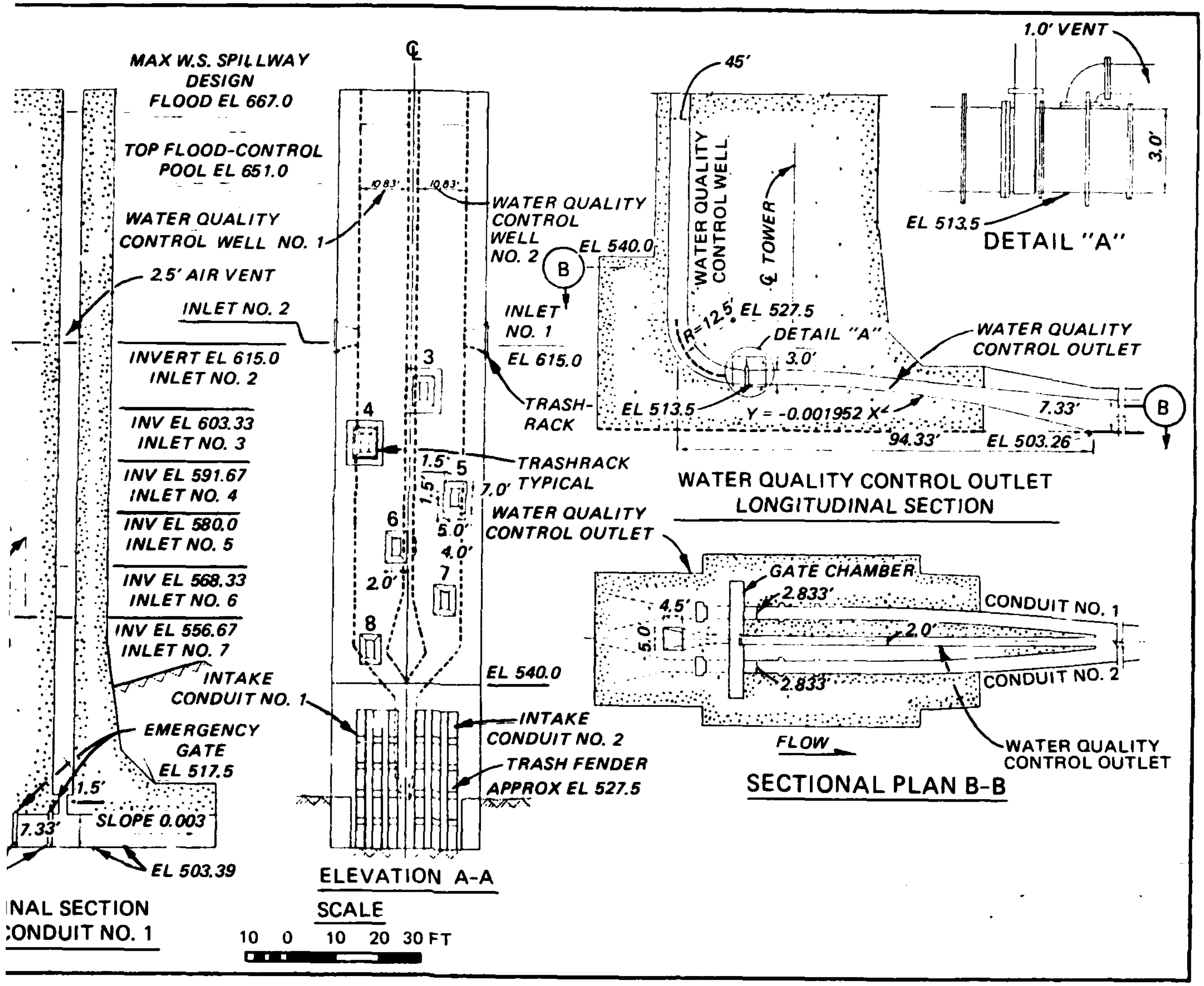
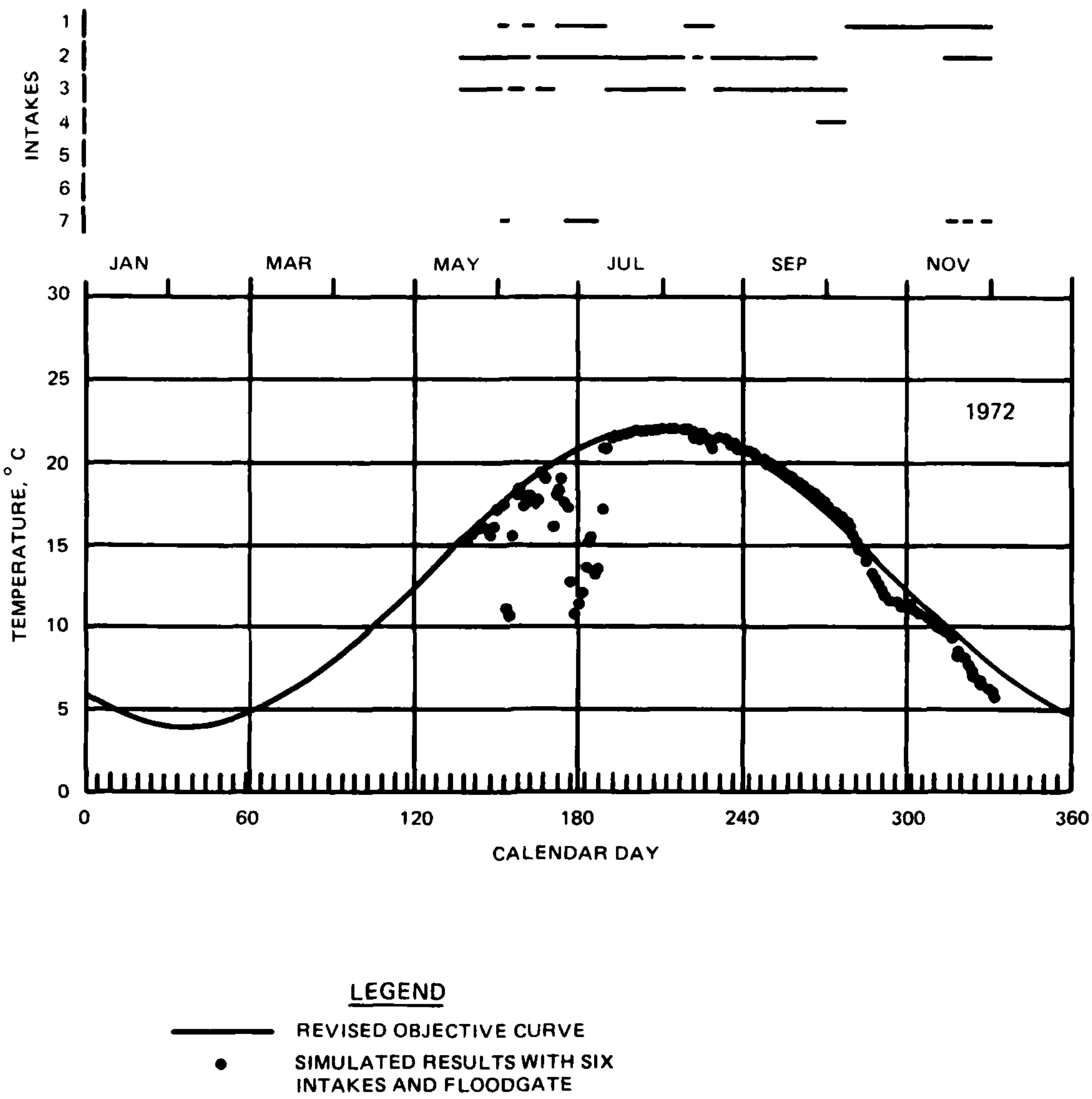


Figure A2. Beltzville Dam intake structure multilevel details



SIMULATED RELEASE TEMPERATURES FOR
OPTIMIZED INTAKE CONFIGURATIONS
OF VARYING NUMBER WITH
CYCLIC COORDINATE SEARCH TECHNIQUE
SIX INTAKES AND FLOODGATE

APPENDIX A: HYDRAULICS OF SELECTIVE WITHDRAWAL INTAKE STRUCTURES

1. In this section, prevailing features of selective withdrawal intake structures are discussed in general, and the hydraulic constraints as formulated in subroutine DECIDE are presented. For a more detailed discussion of the hydraulics of selective withdrawal intake structures, see Chapter 6 of CE EM 1110-2-1602 (OCE 1980).*

General Features

2. Selective withdrawal intake structures are basically composed of two systems: the selective withdrawal system and the flood-control system. The selective withdrawal system requires multilevel intakes or a variable intake elevation so that water of desired quality can be selectively withdrawn from various layers of a stratified pool. To economically accommodate multiple intakes in a common system usually results in a hydraulic capacity (maximum permissible flow) that is less than that needed for flood control, thus constituting the need for the flood-control system also.

3. Multiple selective withdrawal intakes usually pass the flow into a common collection well (wet well). A structure may have multiple wet wells, but the dual wet-well type is the most common. To assure water quality control, only one of the multilevel intakes should be open at a time in each wet well. However, simultaneous releases from different levels in the pool may be accomplished with multiple wet wells. Separate control gates or valves should be used downstream of each wet well to control the flow rate through the intake and wet well. Multiple wet wells eventually empty into a common conduit, stilling basin, or exit channel that enhance mixing of different quality waters. The combined flow capacity of all water quality wet wells will be referred to in this discussion as the selective withdrawal capacity.

4. The flood-control system provides for releases that exceed the capacity of the selective withdrawal system. The flood-control system typically consists of one or more intakes (usually all are at the same elevation near the reservoir bottom), gate passages, and a common outlet conduit or channel. The control gates or valves are located in the gate passage section. Dual

* See References at end of main text.

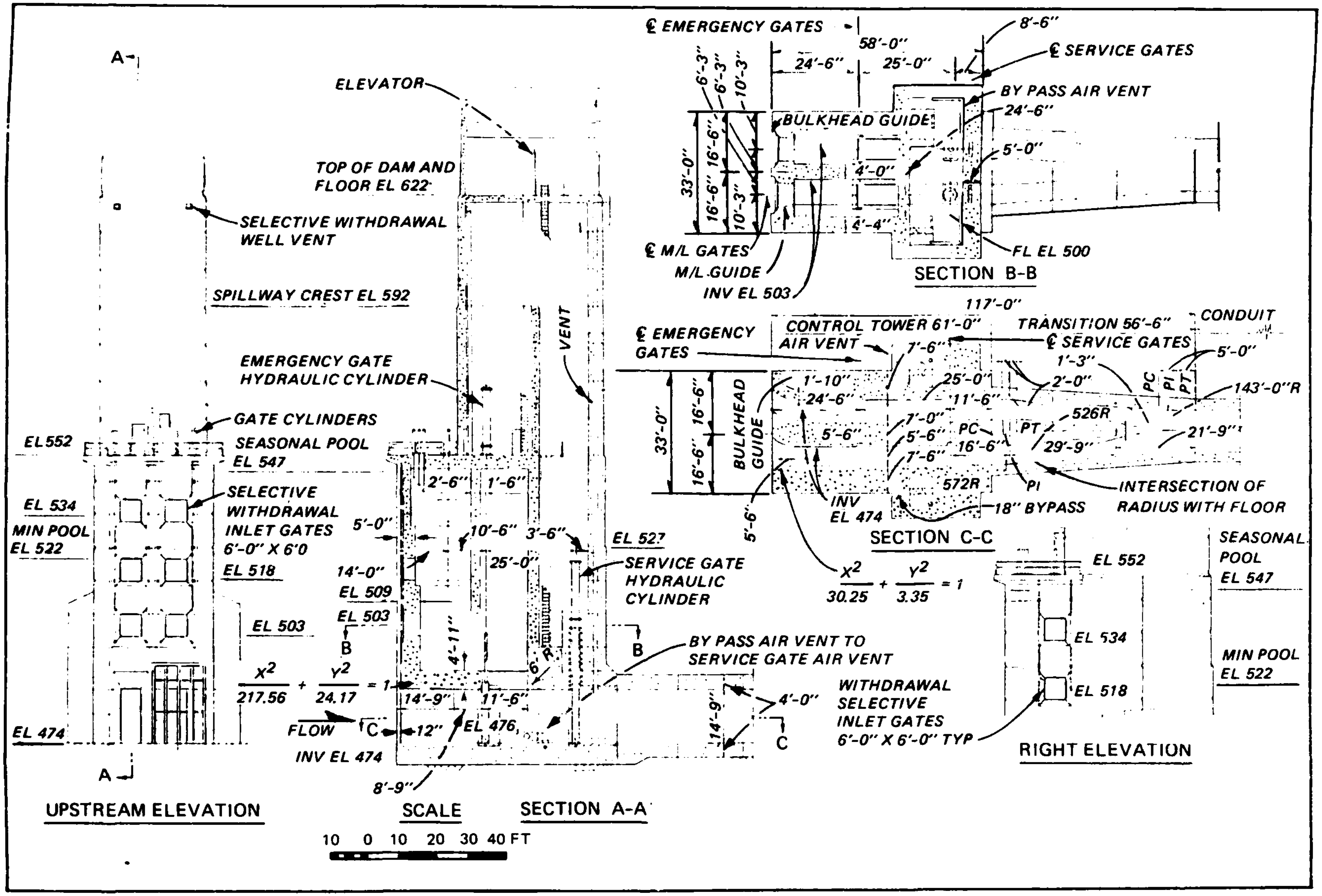


Figure A3. Taylorsville Dam intake structure details intakes, gate passages, and control gates transitioning into a single conduit is a very common flood-control configuration.

5. Some structures have separate flow controls for the selective withdrawal and flood-control systems. Others use the same flow control device for flood control and selective withdrawal. The two types will be referred to as separated and integrated systems, respectively, and are shown schematically in Figure A1. The intake structure for Beltzville Dam, Pohopoco Creek, Pennsylvania, is an example of a separated system (Figure A2). Figure A3 shows the intake structure at Taylorsville Dam (Salt River, Kentucky), which is an integrated system.

6. The wet wells empty into the flood-control gate passage of the integrated Taylorsville structure. It is possible to have flood-control and selective withdrawal releases simultaneously with either the separated or integrated system. However, with the linked wet well and flood gate passage of the integrated system, only one intake (either flood intake or water quality intake) should be open for each control gate to assure flow control.

7. Because of the size of some flood-control gates, significant discharge rates can be achieved at very small gate openings. To provide more manageable flow control for low discharge rates, a small low-flow gate or valve is often provided. This extra gate may be a part of the service gate or may be built into a pipe that bypasses the service gate. The important point here is that there is a minimum permissible discharge rate. A low-flow gate usually allows a lower minimum (controllable) flow than does a service gate.

Hydraulic Constraints of DECIDE

8. This section specifically addresses the physical and operational (hydraulic related) constraints of the intake structure that are encountered in subroutine DECIDE. The intake structure is assumed to have two wet wells for the selective withdrawal system and a flood-control system that is specified as either separated or integrated. The procedures in DECIDE seek which intake must be open, and the flows they must pass, to meet (as close as possible) the objective temperature and satisfy flow requirements. When the flow capacity of the selective withdrawal system is reached, the flood-control system is also used to fulfill flow requirements.

9. Blending can be accomplished in this routine only through the use

of the two wet wells, thus only one intake can be open in a wet well at any given time. The number of selective withdrawal intakes is specified, and each intake is identified as to belonging to wet well No. 1 or 2. The code is presently dimensioned for seven water quality intakes. All seven could be placed in the same well to simulate a single wet-well structure. However, at present, no blending in single wet-well structures can be simulated.

10. The minimum and maximum permissible flow, intake area, and vertical opening are specified for each water quality intake. For a water quality intake, the following operational constraints must be satisfied:

a. The intake must be submerged (water surface at or above top of intake) to be operated.

b. The desired flow must be greater than the intake's minimum permissible flow.

c. The desired flow must be less than the intake's maximum permissible flow. Each intake cannot release beyond its specified maximum.

The maximum permissible flow may be decreased by the program logic to prevent flow control from shifting from a downstream control gate to the intake. The intake elevation, the pool elevation, and the intake area are used to compute this maximum allowable flow. If this value is greater than the maximum permissible intake flow input by the user, then the latter is used as the intake flow constraint.

11. The flood-control system is used when the total desired flow rate exceeds the capacity of the selective withdrawal system. Additionally, the flood-control intakes might be used when the target temperature is cold, requiring the release of water near the bottom.

12. The flood-control system is configured with the intake(s) at the same elevation with either a single (separated system) or dual (integrated system) control gate(s). The elevation of the flood-control intake(s) is specified by the user. The flood-control system is specified as either separated or integrated. For the integrated system, the control gates are used for both flood control and selective withdrawal releases and the logic of the coding assures that only one intake is open (either a flood or water quality intake) in each of the two wet wells/gate passages.

13. A minimum and maximum permissible flow for the total flood-control system is specified by the user. The program assumes that there are two gate passages and control gates for an integrated system and that the capacity for

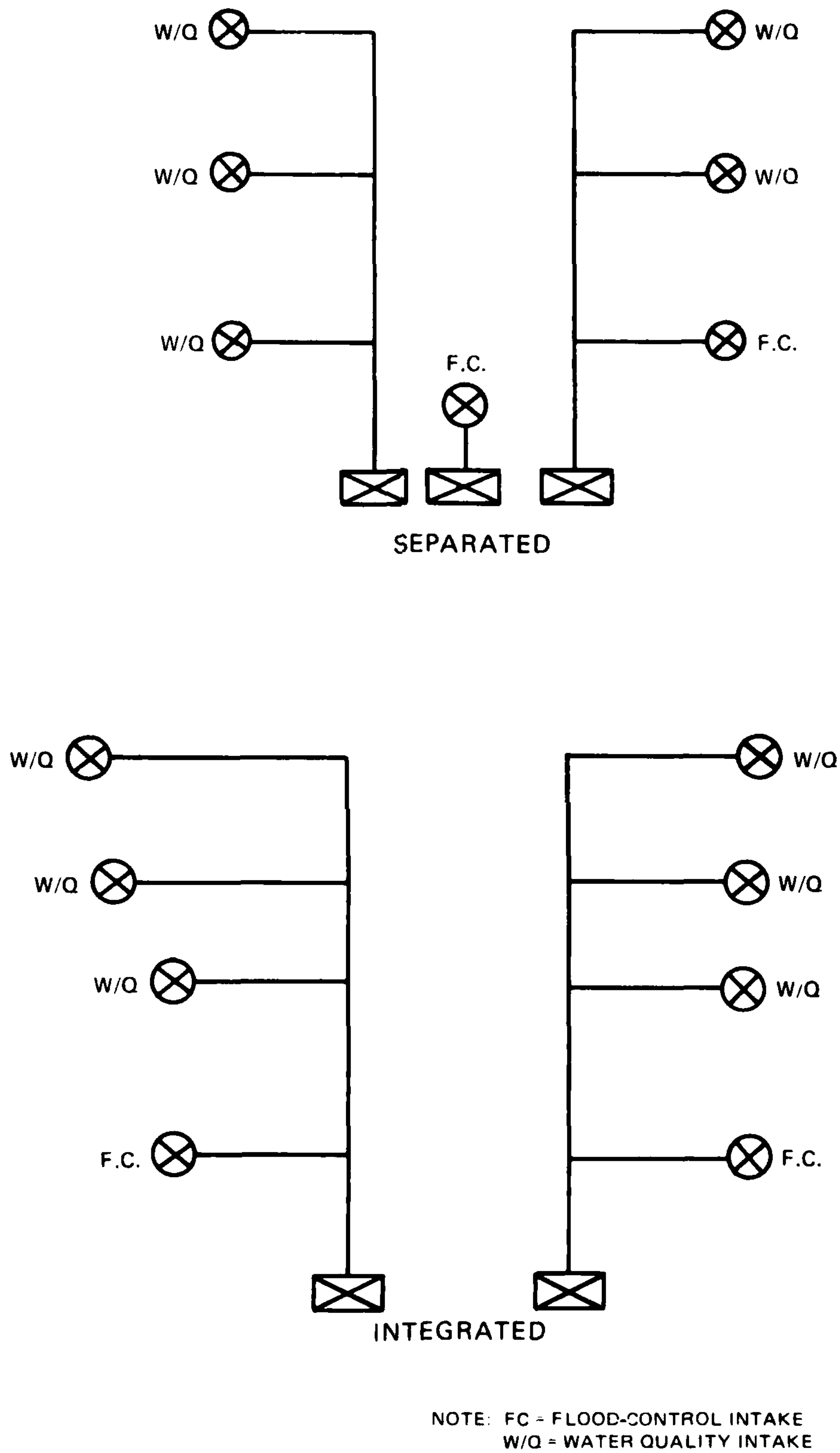


Figure A1. Schematic representation of separated and integrated flow control each flood-control gate passage is half the total flood-control capacity. The separated flood-control system is simulated with a single flood-control gate. Use of the flood-control system can be prevented by setting the minimum and maximum permissible flows greater than any flow that would be encountered.

14. The hierarchy of decision processes made in subroutine DECIDE is described by Figure A4. The subroutine is fairly general but does not include all the decision processes that might be desired. For example, it is preferable to maintain equal flow through both gates of a dual wet-well system. This operation helps to distribute the flow more evenly in the stilling basin thus enhancing stilling basin performance. DECIDE does not attempt to balance flow through both wet wells, although this option could be incorporated.

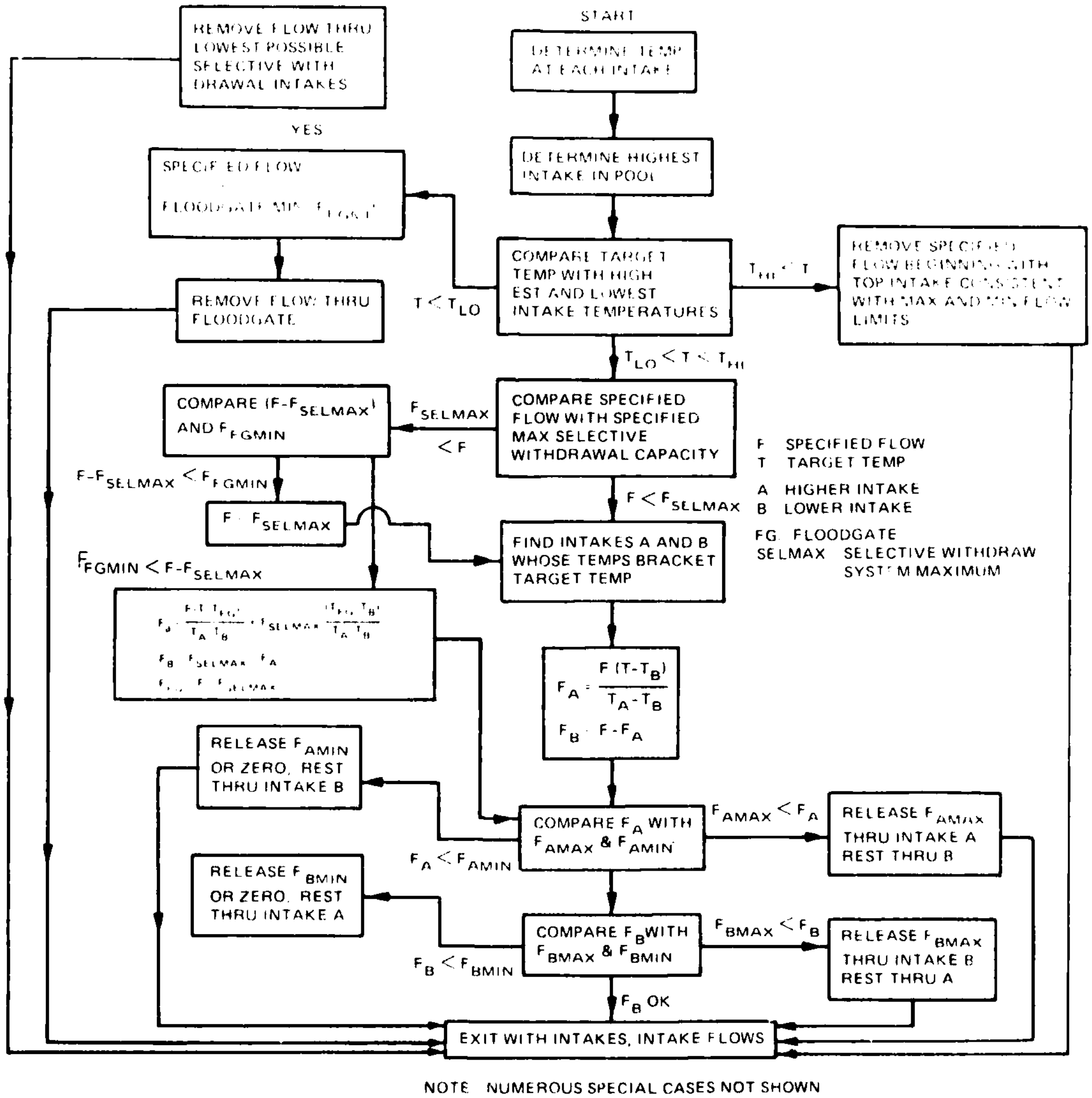


Figure A4. Flow chart for subroutine DECIDE

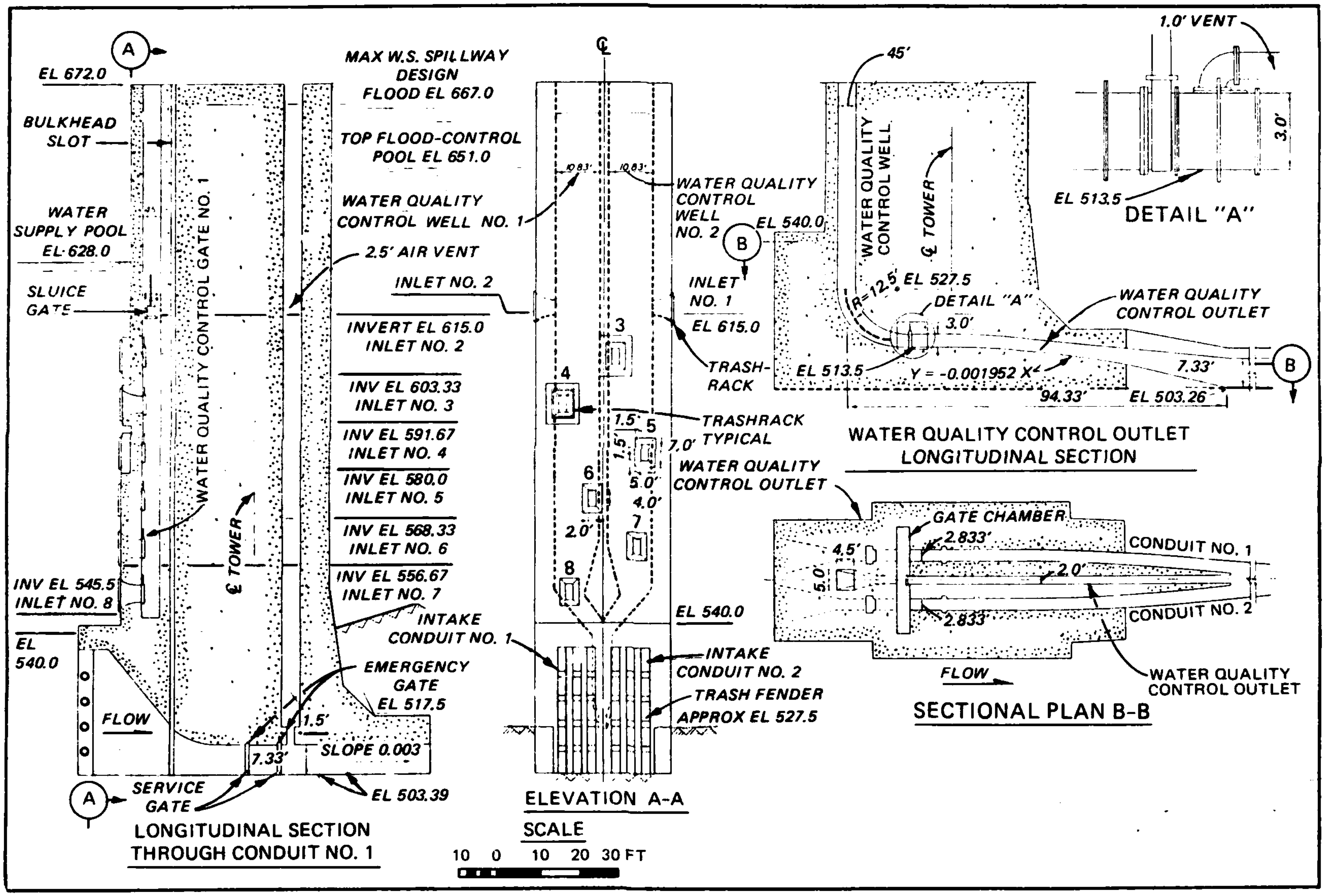


Figure A2. Beltzville Dam intake structure multilevel details

END

FILMED

3-85

DTIC

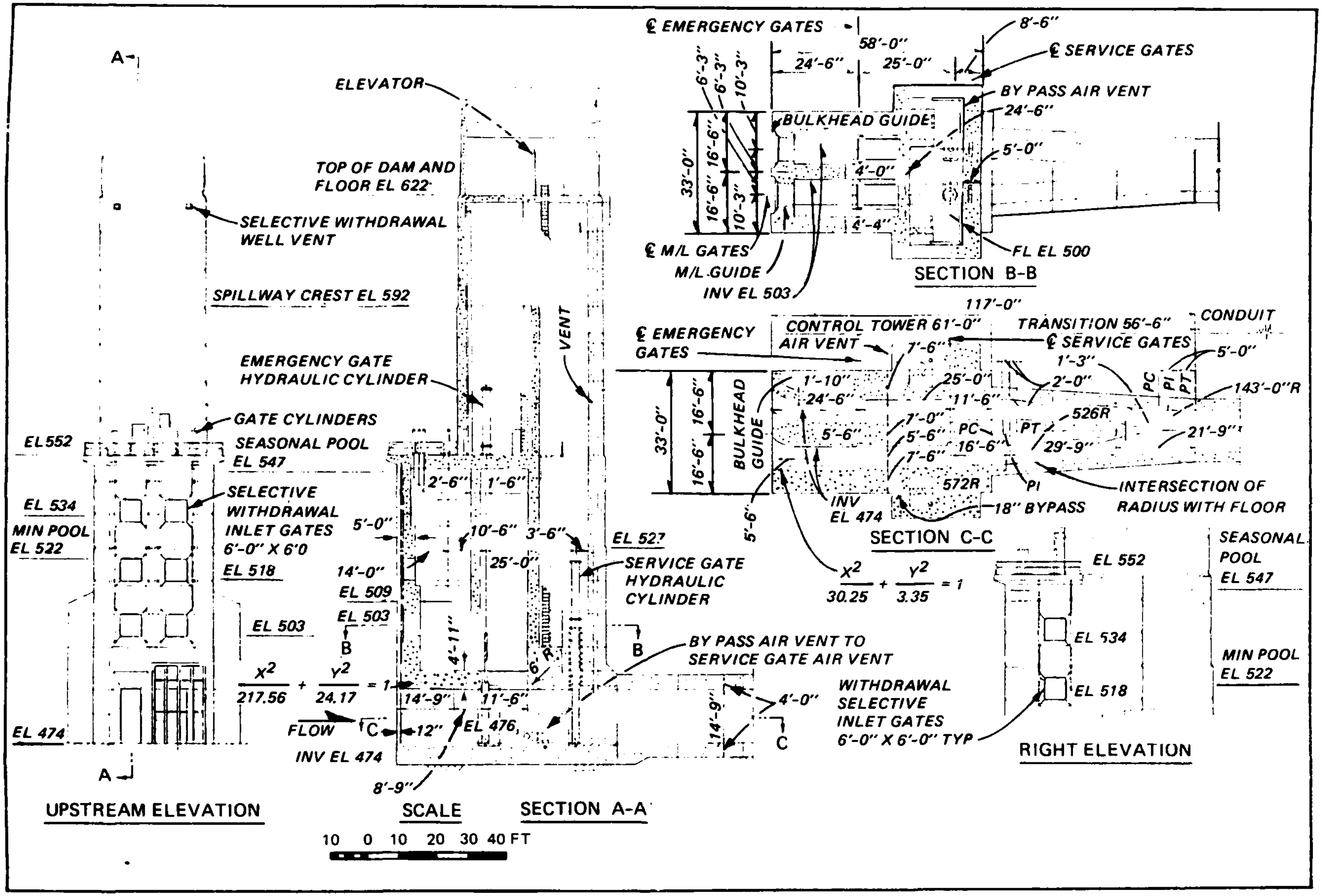


Figure A3. Taylorsville Dam intake structure details of the two wet wells, thus only one intake can be open in a wet well at any given time. The number of selective withdrawal intakes is specified, and each intake is identified as to belonging to wet well No. 1 or 2. The code is presently dimensioned for seven water quality intakes. All seven could be placed in the same well to simulate a single wet-well structure. However, at present, no blending in single wet-well structures can be simulated.

10. The minimum and maximum permissible flow, intake area, and vertical opening are specified for each water quality intake. For a water quality intake, the following operational constraints must be satisfied:

a. The intake must be submerged (water surface at or above top of intake) to be operated.

b. The desired flow must be greater than the intake's minimum permissible flow.

c. The desired flow must be less than the intake's maximum permissible flow. Each intake cannot release beyond its specified maximum.

The maximum permissible flow may be decreased by the program logic to prevent flow control from shifting from a downstream control gate to the intake. The intake elevation, the pool elevation, and the intake area are used to compute this maximum allowable flow. If this value is greater than the maximum permissible intake flow input by the user, then the latter is used as the intake flow constraint.

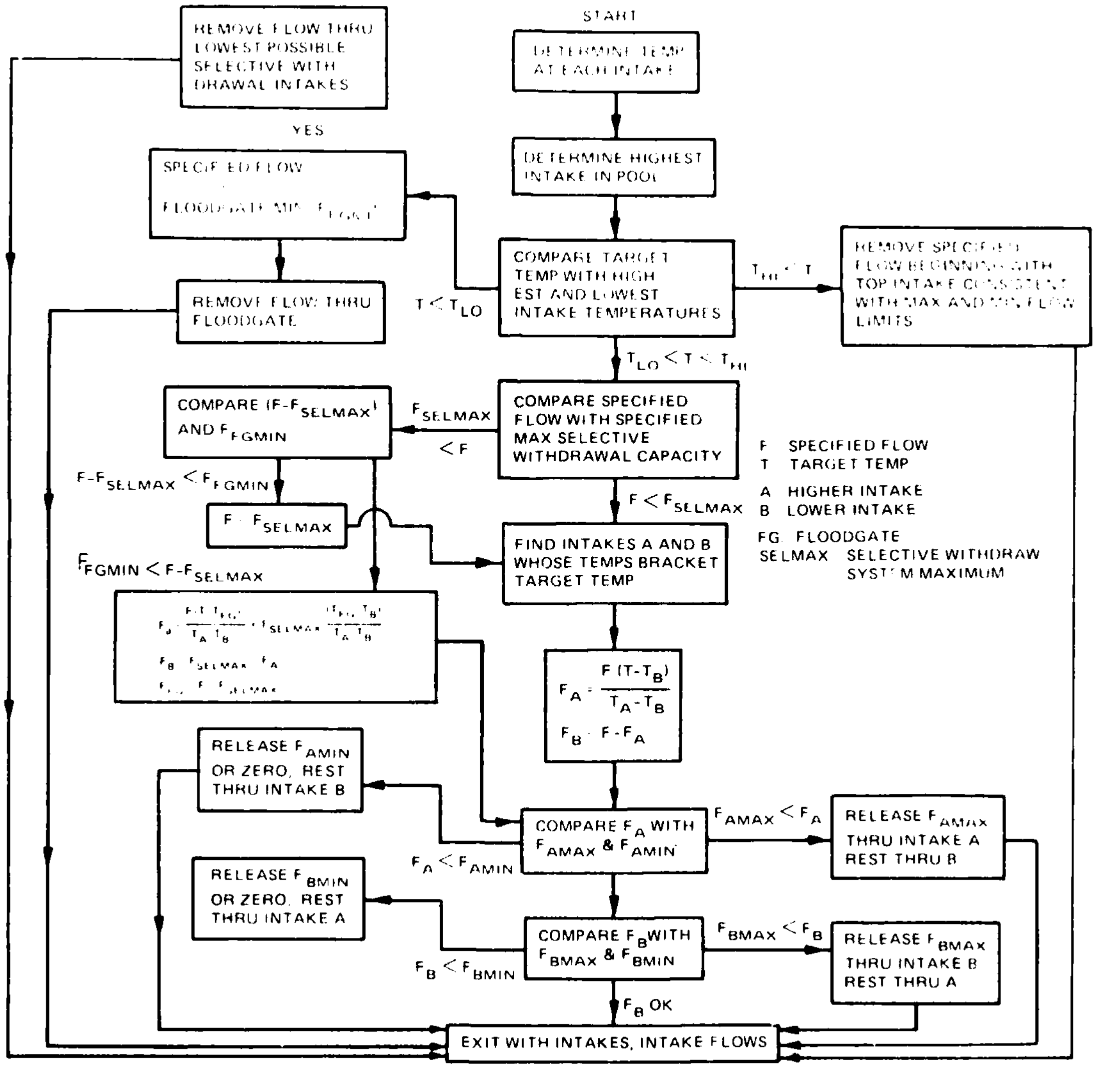
11. The flood-control system is used when the total desired flow rate exceeds the capacity of the selective withdrawal system. Additionally, the flood-control intakes might be used when the target temperature is cold, requiring the release of water near the bottom.

12. The flood-control system is configured with the intake(s) at the same elevation with either a single (separated system) or dual (integrated system) control gate(s). The elevation of the flood-control intake(s) is specified by the user. The flood-control system is specified as either separated or integrated. For the integrated system, the control gates are used for both flood control and selective withdrawal releases and the logic of the coding assures that only one intake is open (either a flood or water quality intake) in each of the two wet wells/gate passages.

13. A minimum and maximum permissible flow for the total flood-control system is specified by the user. The program assumes that there are two gate passages and control gates for an integrated system and that the capacity for

each flood-control gate passage is half the total flood-control capacity. The separated flood-control system is simulated with a single flood-control gate. Use of the flood-control system can be prevented by setting the minimum and maximum permissible flows greater than any flow that would be encountered.

14. The hierarchy of decision processes made in subroutine DECIDE is described by Figure A4. The subroutine is fairly general but does not include all the decision processes that might be desired. For example, it is preferable to maintain equal flow through both gates of a dual wet-well system. This operation helps to distribute the flow more evenly in the stilling basin thus enhancing stilling basin performance. DECIDE does not attempt to balance flow through both wet wells, although this option could be incorporated.



NOTE NUMEROUS SPECIAL CASES NOT SHOWN

Figure A4. Flow chart for subroutine DECIDE

END

FILMED

3-85

DTIC