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EVALUATION OF RELEASE IMPROVEMENT TECHNIQUES FOR J. PERCY PRIEST RESERVOIR

by

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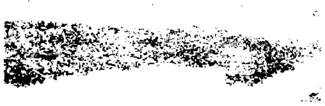

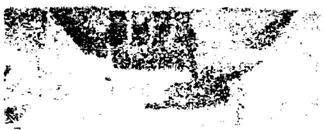

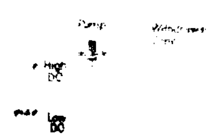

Dilution of Hydropower Release

US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

August 1988

Final Report

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The J. Percy Priest project, located on the Stones River near Nashville, TN, is experiencing problems with release water quality. A localized mixing system was proposed by the US Army Engineer District, Nashville, to resolve the problems. A pilot study and evluation of original design criteria were conducted. Formulas were valid for strong stratification, but underpredicted the efficiency of dilution in weak stratifications. An operation plan for a system of three, six, or nine pumps was developed using generalized project data and the numerical model SELECT. Additional alternatives to further enhance release quality using partial lake destratification and hypolimnetic aeration were also evaluated. Appendix A presents generalized temperature and dissolved oxygen profiles for the reservoir.

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Preface

The model study reported herein was conducted in the Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for the US Army Engineer District, Nashville (ORN). The field pilot study was completed by ORN.

This report was prepared under the direction of Mr. F. A. Herrmann, Jr., Chief, HL, and under the general supervision of Messrs. G. A. Pickering, Chief, Hydraulic Structures Division, and J. P. Holland, Chief, Reservoir Water Quality Branch. This report was prepared by Dr. R. E. Price, Reservoir Water Quality Branch.

COL Dwayne G. Lee, EN, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

Contents

Conversion Factors, Non-SI to SI (Metric)
Units of Measurement

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

Multiply	By	To Obtain
acre-feet	1233.482	cubic metres
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
miles (US statute)	1.609347	kilometres
horsepower (550 ft-lb (force) per second)	745.6999	watts
square miles	2.589998	square kilometres

EVALUATION OF RELEASE IMPROVEMENT TECHNIQUES FOR J. PERCY PRIEST RESERVOIR

Introduction

Water Reservoir

1. The J. Percy Priest Project, located outside Nashville, TN, on the Stones River, has experienced problems with the water quality of hydropower releases. During the annual stratification season (approximately May to November), the hypolimnion becomes devoid of oxygen creating a chemically reduced environment in which iron, manganese, and hydrogen sulfide become soluble. Upon hydropower generation, the oxidation of hydrogen sulfide creates a "rotten egg" smell downstream. The methodology selected for improving the quality of the release was to install a localized mixing system in the reservoir in front of the hydropower intakes. The primary objective of the localized mixing system was to increase the dissolved oxygen (DO) in the release to the State standard of 5 mg/l. Initial use of existing design criteria (Holland 1984) by personnel of the Hydraulics Laboratory, US Army Engineer Waterways Experiment Station (WES) indicated 8 to 10 direct-drive 40-hp* surface mixer units placed upstream of the hydropower intake would be required to meet a release DO of 5.0 mg/l. A pilot study to further refine design and operational criteria was undertaken by the US Army Engineer District, Nashville (ORN). The purpose of this report is to document results of field tests and the validity of the original design formulas (Holland 1984), and to better determine the number and location of pumps required to meet the desired release DO of 5.0 mg/l. ORN also requested additional information on destratification and hypolimnetic aeration alternatives that might be used to supplement the operation of the localized mixing system to further reduce iron, manganese and hydrogen sulfide concentrations in the releases.

Field Tests

2. Based on initial WES design criteria for the localized mixing system, ORN leased (for use in a pilot study) three Aqua-Aerobic 40-hp surface

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

mixers. The pumps, which were available for testing 31 August 1987, were standard design (off-the-shelf) surface direct-drive mixers (DDM) mounted in 10-ft-diam stainless steel foam-filled floats. Since the impacts of the exact positioning of the pumps were unknown, a series of field tests was conducted by ORN to further define operating criteria. These tests, which were conducted during the weeks of 31 August, 21 September, and 19 October 1987, consisted of varying the positions of the three pumps relative to the hydropower intake using a rectangular coordinate grid and varying the pumping rate by varying the number of pumps operating during a test. Hydropower discharge was constant at 4,600 cfs throughout all tests. Water quality data collected during the tests consisted of vertical profiles in the reservoir before and after each series of tests (daily, before and after all tests) and measurements in the tailwater during each individual test. A typical test routine involved collection of a vertical water quality profile in the reservoir (temperature, DO, pH, conductivity, redox potential, and selected chemical species), then monitoring of release water quality (same parameters as collected in the vertical profile) for initial conditions (release quality without pumps operating). A particular test (pump) configuration and pumping rate were then established and the temperature of the tailwater was monitored until it stabilized. Then water samples were collected downstream for analysis. During testing the week of 19 October, data were also collected in the reservoir near the pumps to describe the vertical mixing characteristics during operation. These tests, which consisted of vertical temperature profiles, were designed to determine the depth of penetration of the pumped jet into the hypolimnion.

Initial Design Criteria

3. The original computations performed by WES were based on the DO release objective of 5 mg/l. Using the following equation

$$(Q_r)(DO_r) = (Q_e)(DO_e) + (Q_h)(DO_h) \qquad (1)$$

where

Q = volume flux, ft/sec

DO = dissolved oxygen concentration, mg/l r, e, and h = release, epilimnion, and hypolimnion components of Q and DO, respectively

the required epilimnetic volume to be released was computed based on a normal generation flow of 4,600 cfs and average observed August thermal and DO profile (epilimnetic DO of 8.0 mg/l and hypolimnetic DO of 0.1 mg/l). From this, the required epilimnetic volume flux was 2,875 cfs. This computation assumed no reaeration occurred through the structure. To ensure that 2,875 cfs of epilimnetic water was available for withdrawal, the surface pumps had to force this volume through the thermocline and near, if not to, the lower limit of the withdrawal zone, which in this case was the bottom.

4. The theoretical volume flux at the thermocline Q_t was computed using this equation from Holland (1984)

$$\frac{Q_t}{Q_o} = 0.32 \frac{Z_t}{D_o} \tag{2}$$

where

Q_o = initial jet volume flux at pump, ft/sec

Z_t = distance from jet pumping outlet to thermocline, ft

D_o = initial jet diameter, ft

The criteria provided by Aqua-Aerobic Systems for each of the pumps used at J. Percy Priest were

D_o = 1.625 ft

Q_o = 45.0 cfs

V_o = initial jet velocity at the pump, 21.9 ft/sec

Examination of historical data indicated the minimum summer thermocline depth was usually 25 ft below the surface. Using Equation 2, the initial volume flux available at the thermocline for each pump was 220 cfs. Thus, approximately 13 pumps would be required to transport an epilimnetic volume flux of 2,875 cfs across the thermocline for the conditions evaluated.

5. An adequate depth of penetration is also essential to ensure that the epilimnetic volume flux penetrated deep enough to be withdrawn. The depth of penetration was computed using (Holland 1984)

$$\frac{Z_h}{D_t} = 1.66\ (Fr) - 0.66 \tag{3}$$

where

Z_h = depth of jet penetration into the hypolimnion as measured from the top of the thermocline, ft

D_t = diameter of the jet at the thermocline, ft

Fr = densimetric Froude number as computed by

$$\frac{V_t}{\left[\left(\frac{\Delta\rho}{\rho}\right) g D_t\right]^{1/2}} \tag{4}$$

where

V_t = jet velocity at thermocline, ft/sec

$\Delta\rho$ = absolute difference between jet (epilimnetic) and hypolimnetic densities, g/cc

ρ = jet density at thermocline (equal to density of epilimnion), g/cc

g = acceleration of gravity, 32.18 ft/sec^2

In the design computations, $\Delta\rho = 0.0029$, $\rho = 1.0000$ g/cc , $V_o = 21.9$ ft/sec , $D_o = 1.625$ ft , $Q_o = 45$ ft/sec , and Fr = 6.1 . Substituting these values into Equation 3, the depth of penetration was 71 ft below the thermocline, or 96 ft below the surface, which is essentially to the lower limit of withdrawal.

Verification of Design Formulas

6. The data collected during the three field studies were analyzed to determine the applicability of the initial formulas used in the design of the localized mixing system. Although there was no way to measure all the parameters used in the formulas, use of dilution calculations provided an indication of the key parameters. The dilution factor (DF) developed by Moon, McLaughlin, and Moretti (1979) provided an indirect measure of the epilimnetic volume flux across the thermocline (assuming 100 percent of the epilimnetic volume flux is withdrawn) based on the change in release quality before and after localized mixing. The dilution factor, which may also be interpreted as the dilution of the hypolimnion by the epilimnetic jet, is represented by

$$DF = \frac{Q_2}{Q_r} = \frac{\rho_o - \rho_1}{\rho_2 - \rho_1} \qquad (5)$$

where

DF = dilution factor

Q_2 = volume flux of epilimnion water released

Q_r = total volume flux or release volume

ρ_o = release water density during pumping

ρ_1 = release water density prior to pumping

ρ_2 = density of the epilimnetic water

The dilution factor was computed for each test and comparisons among individual tests made to determine the maximum dilution factor achieved. The particular test for each test series with the maximum dilution factor was adopted as the optimum location for the pumps for the tested conditions.

7. Equation 5 was used to compute the observed dilution factor of the release. Equation 2 was used to compute the predicted epilimnetic flux across the thermocline, which was then used to compute the predicted dilution factor. This assumed that 100 percent of the epilimnetic volume flux crossing the thermocline was entrained in the withdrawal zone and released. These computations (for the optimum pump location at each test period) yielded the following results:

Date	Observed DF	Predicted DF
2 Sep	0.171	0.173
24 Sep	0.244	0.202
22 Oct	0.540	0.260

An explanation of these results begins with the observation that the stratification in early September was stronger, more of a two-layer stratification than in late September or October. The equations used to predict volume flux across the thermocline (Equation 2) and depth of penetration (Equation 3) were developed from laboratory tests using a two-layer (approximating maximum) stratification. Therefore, as the stratification weakened in late September and October, the equations for the prediction of volume flux across the thermocline became less accurate. Since the strongest probable stratification was the initial design condition, and the observed depth of penetration and flux across the thermocline at a similar stratification (2 September) matched the original prediction, the design formulas were appropriate for this condition. The design formulas were not as appropriate for the weaker stratifications (24 September and 22 October) as shown by the inaccuracies in prediction of the DF.

8. The predicted dilution factor was based on the assumption that 100 percent of the epilimnetic volume pumped into the hypolimnion was released. From the field tests conducted the week of 19 October, vertical profiles in the reservoir near the pumps during operation indicated overpenetration of the epilimnetic jet. This was observed as a thermal plume that moved upstream along the bottom. Although it may have been possible that this plume was ultimately drawn into the hydropower intake, some loss of epilimnetic water was most likely occurring. Therefore, in the computation of the DF for this condition, the epilimnetic volume being released was somewhat less than that being pumped, resulting in a larger predicted value of the DF than should have been observed. This condition, therefore, indicates a loss of efficiency in the localized mixing system which could ultimately impact the reservoir thermal stratification.

9. The predicted DF was then used to compute predicted release quality according to the following formula:

$$X_p = (DF)(X_e - X_r) + X_r \tag{6}$$

where

X = water quality constituent (temperature or DO)

e, r, and p = epilimnetic, initial release quality without pumps, and predicted release with pumps operating for the given constituent

A comparison of the computed release quality and the observed release quality for the three test periods is shown in Table 1. The pump conditions are the same used to compute the DF shown above. The epilimnetic volume fluxes for two and three pumps were computed using the flow predicted for one pump and multiplying by two or three, respectively. This assumed that there were no synergistic effects among individual pumps.

Table 1

Observed and Predicted Release Temperature and DO with Varying Numbers of Pumps Operating

Date	No. of Pumps Operating	Temperature, °C		Dissolved Oxygen, mg/ℓ	
		Observed	Predicted	Observed	Predicted
9/2/87	1	16.53	16.39 (0.14)*	3.05	3.03 (0.02)
	2	17.13	16.98 (0.15)	3.26	3.28(-0.02)
	3	17.90	17.63 (0.27)	3.97	3.73 (0.24)
9/24/87	1	16.91	16.74 (0.17)	3.75	3.62 (0.13)
	3	18.28	17.55 (0.73)	4.46	4.00 (0.46)
10/22/87	1	14.53	14.49 (0.04)	4.10	3.90 (0.20)
	3	15.39	14.87 (0.52)	4.97	4.37 (0.60)

* The numbers in parentheses are the differences between the predicted and observed.

10. Although the predicted DF deviated considerably from the observed DF for the October tests, the actual deviation of the release temperature and DO was minimal. This was due to the relative range of temperature and DO differences between the epilimnion and hypolimnion in the pool. For example, in the 2 September tests, the temperature range was 15° C; but by October it was only 6° C. Therefore a 1° change in September, which was equivalent to a 6 percent change over the range, was not as significant as in October in which it was equivalent to a 16 percent change over the range. Thus, while the predicted DF for October was nearly 50 percent less than that observed, the smaller temperature range for this month resulted in a lessened impact of this error in predicting the pumped epilimnetic contribution to the total release.

11. Based on the foregoing analysis, the number of pumps shown in the following tabulation would be required to obtain (a) an epilimnetic release volume of 2,875 cfs (DF = 0.62) required to achieve 5 mg/l DO in the release;

Date	No. of Pumps 2,875 cfs	No. of Pumps 3,450 cfs
2 Sep	11	13
24 Sep	8	10
22 Oct	4	5

and (b) an epilimnetic release volume of 3,450 cfs (DF = 0.75) required to achieve the maximum dilution practicable* for release DO of 6.0 mg/l. This analysis was based on the observed profiles that were not as severe as the conditions used in the initial design computations discussed in paragraph 4. This analysis also did not take into account the reaeration that occurs through the release structure vacuum breaker system, which may reduce the epilimnetic volume flux required thus reducing the number of pumps required, to achieve the desired release DO. It is obvious from these data that the stronger the stratification (or the closer the stratification is to a two-layer stratification) the more pumps are required to achieve a given dilution of the total release.

Location of Pumps

12. The second objective of the three field tests was to determine the optimum spacing between pumps and their distances from the hydropower intake for maximum dilution. Equation 5 was used to compute the volumes of epilimnetic water pumped by all three pumps. Figures 1 and 2, which illustrate the relationship between spacing and DF, indicate that approximately 25 ft was the optimum spacing between pumps.

13. However, in Figure 3 for which the DF was considerably higher than all previous tests, 50 ft appears to have been the best spacing. The spacing of pumps was complicated by the fact that as the space increased, the distance from the hydropower intakes also increased. Therefore, the reduction in DF may be due to this distance rather than interference between pumps.

14. It should be noted that the pumps could not be physically located closer than 10 ft from each other (distance between pump outlets) because the diameter of their floats was 10 ft. Further, the entrainment of epilimnetic water would be maximized if the jets did not overlap prior to crossing the thermocline. The diameter of the jet as it crossed the thermocline was computed using the equation (Holland 1984)

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* Moon, McLaughlin, and Moretti (1979) have shown that increasing the pumping rate above that for a dilution of 0.75 did not significantly increase the DF.

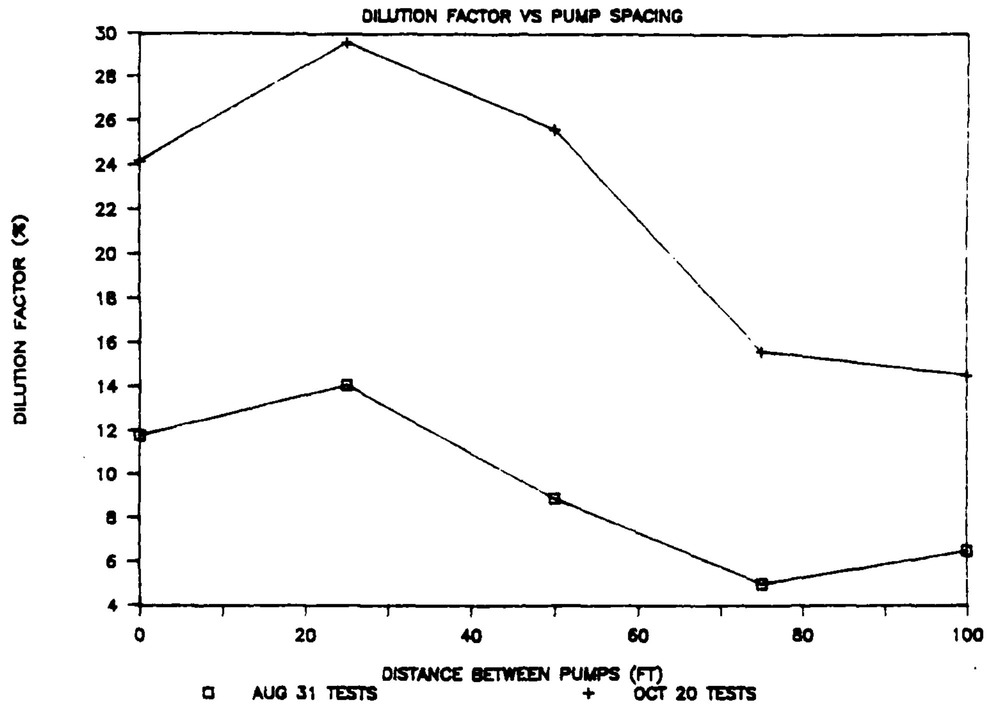

Figure 1. Dilution factor for pump spacing of 31 August and 20 October tests with pumps 50 ft in front of the dam

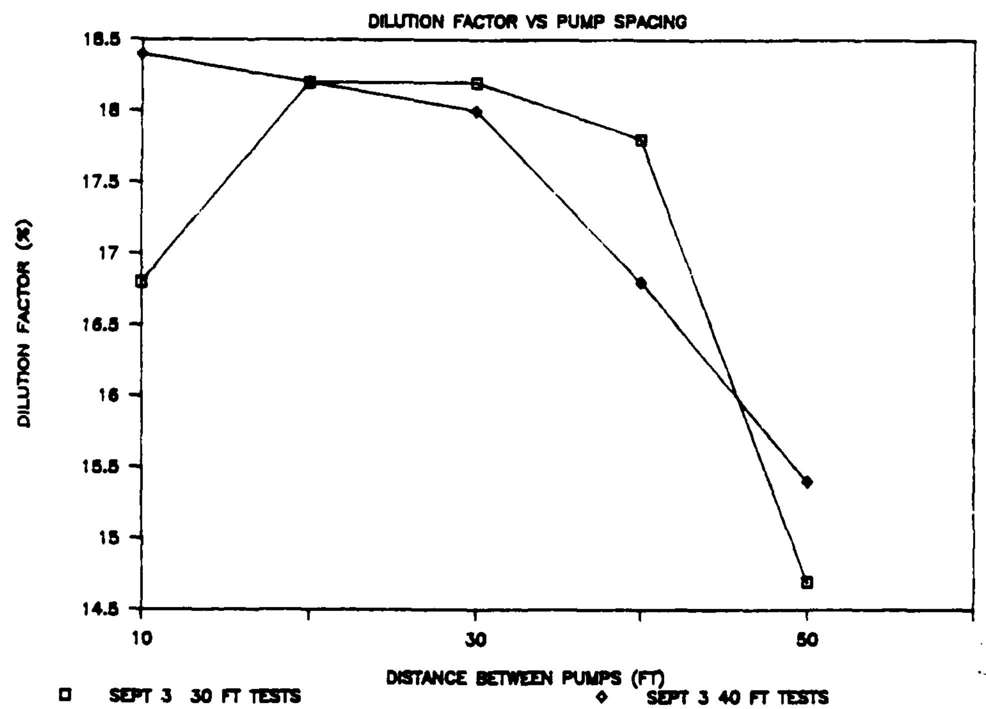

Figure 2. Dilution factor for pump spacing for 3 September tests, 30 and 40 ft in front of the dam

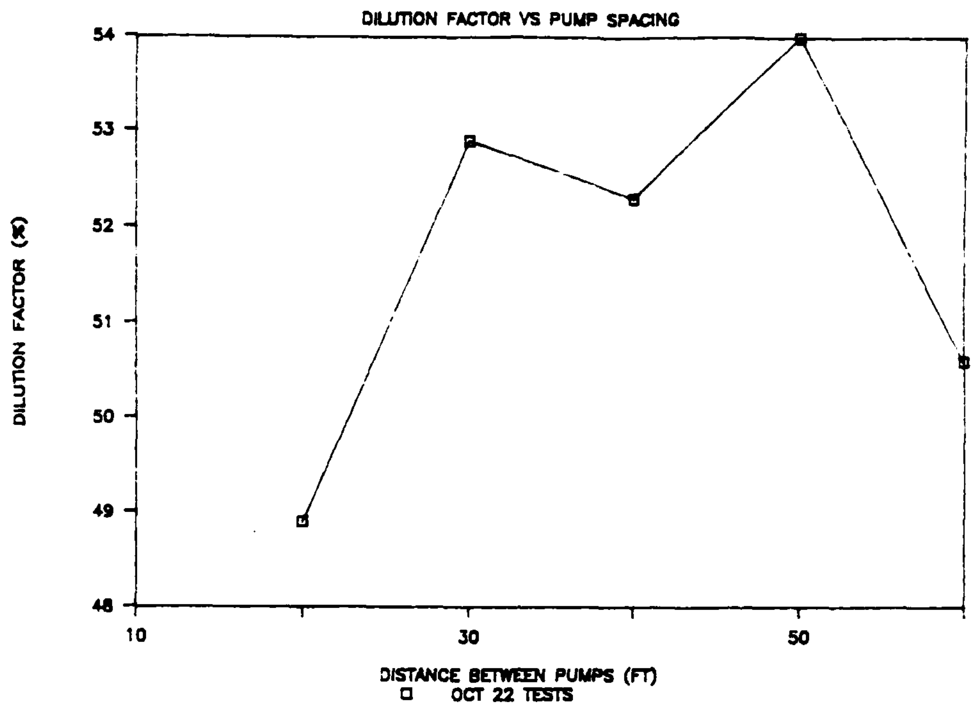

Figure 3. Dilution factor for pump spacing for 22 October tests, with pumps 60 ft in front of the dam

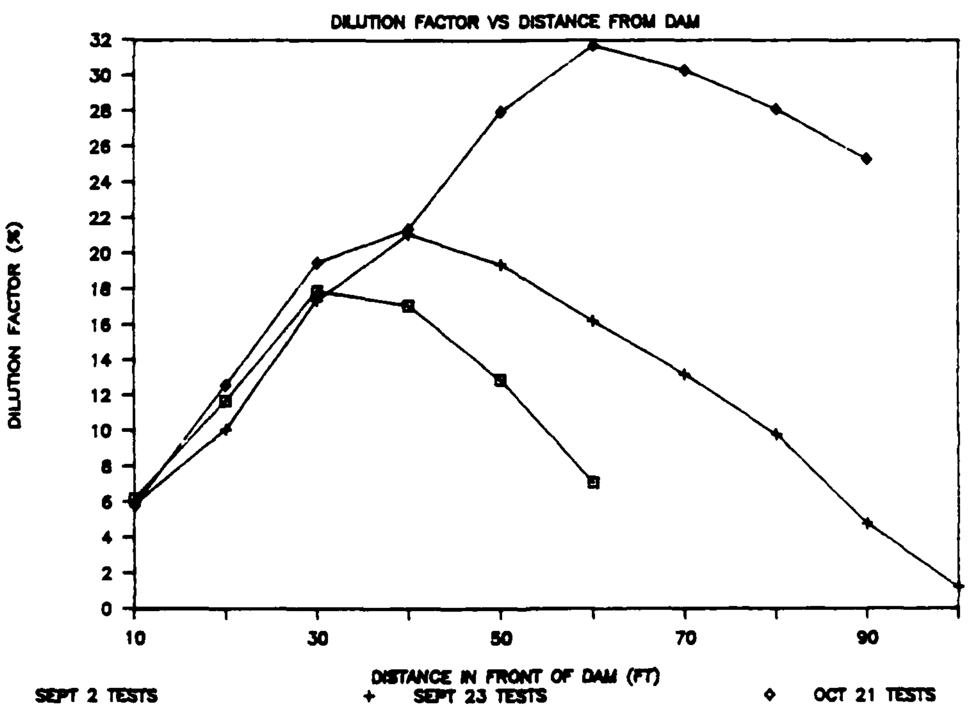

Figure 4. Dilution factor tests for pump distance from the dam with all three pumps clustered together

$$D_t = 0.30Z_t \tag{7}$$

For each test series the diameter D_t (jet diameter as it crossed the thermocline) was computed, and the diameters are shown in the following tabulation:

Date	Predicted Jet Diameter at the Thermocline, ft
2 Sep	9
24 Sep	9
22 Oct	13

Since the entrainment during the October tests was much greater than predicted (as indicated by the dilution factor), interference between jets appears to have been a minor problem. During August, when the stratification was the strongest, a minimum distance of 9 ft between pumps ensured no overlap of jets; however, since field tests indicated approximately 25 ft yielded a greater dilution, other factors must also have been involved in the dilution process. Given that these factors have not yet been identified, the minimum distance between jet outlets should remain at approximately 25 ft.

15. The field tests were also designed to locate the optimum distance of the pumps from the dam. A series of tests in which all three pumps spaced 10-ft apart were moved out from the dam in 10-ft intervals was used to identify the optimum distance. Comparing the DF for each location, it appeared (Figure 4) that the optimum region began at 30 ft; however, as the stratification weakened, the distance increased to 60 ft.

16. The pump spacing and distance in front of the dam were tested in a rectangular grid system; however, the hydropower withdrawal pattern would extend radially from the intake. Therefore, the pumps should be positioned radially from the hydropower intake rather than in a rectangular pattern.

Development of Pump Operation Plan

17. A generalized operating plan for the use of DDM pumps to improve release quality from J. Percy Priest was developed to include when and how many pumps to operate to achieve a given release quality objective. To develop the operating plan, the numerical model SELECT was (Davis et al. 1987) adjusted to the morphometric conditions at J. Percy Priest and verified against observed temperature and DO data. The hydropower intake at J. Percy Priest is approximately 60 ft high and 30 ft wide. The SELECT computational

procedure was developed with the assumption that the withdrawal structure functions as a point sink, meaning that the port dimensions are assumed small relative to the withdrawal zone thickness. The hydropower intake at J. Percy Priest funnels down to a 20-ft-diam penstock, approximately 30 ft behind the trashracks. This location was used to define the port dimensions for SELECT. The resulting port was 19.5 ft by 19.5 ft with a center-line elevation of 428.5 ft NGVD* and a withdrawal angle of 1.36 radians (corresponding to 78 degrees, the angle of the intake walls at the narrowest point in the intake). Seven profiles for which observed release temperature and DO were available were used to identify the precision of the SELECT code in predicting release quality. The comparison of observed with predicted quality (Table 2) indicates that the predicted release temperature was within a degree of the observed release temperature with an average difference of 0.6° C. The predicted DO was consistently lower than the observed, averaging 1.8 mg/l below that observed. Most of this error is due to the operation of the hydropower vacuum breaker system. The air intake on the vacuum breaker remains open at all times, allowing air to be entrained into the release flows, thereby increasing the release DO above that of the weighted average in the pool (on which SELECT predictions are based). Reaeration and turbine venting research (Wilhelms et al. 1987) indicates that approximately 30 percent of the DO deficit in the release can be satisfied by turbine venting. Examination of the SELECT data in Table 2 indicates that an average of approximately 27 percent of the DO deficit was satisfied by reaeration through the structure. Therefore, the predicted release DO was modified to reflect a 27 percent reduction in DO deficit to account for the reaeration by the vacuum breaker system. Using this technique on the predicted release DO in Table 2 resulted in an average deviation of 0.6 mg/l from the observed release DO.

18. The seasonal stratification cycle will impact operation of the pumps due to the varying density difference between the epilimnion and hypolimnion which impacts the penetration depth of the pumped epilimnetic jet. In addition, the depth of the thermocline impacts the epilimnetic volume flux into the hypolimnion in that the entrainment is a function of the velocity and depth of the thermocline. To predict the impacts of seasonal variation on

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

Table 2

SELECT Calibration Comparison

Date	Temperature		Dissolved Oxygen			
	Observed	Predicted	Observed	Predicted	Saturation Value	% Deficit Satisfied* by the Vacuum Breaker System
10/25/73	19.5	18.8	5.7	3.6	9.1	38.0
7/18/79	19.0	17.9	2.7	1.0	9.3	31.0
10/29/86	19.1	18.3	6.8	4.8	9.3	45.0
8/31/87	15.3	15.5	2.7	1.1	9.9	12.0
9/21/87	15.9	15.8	3.3	1.6	9.8	21.0
10/20/87	14.4	14.1	3.9	2.4	10.1	20.0

* DO deficit satisfied = 1 - ((DO saturation - DO observed)/(DO saturation - DO predicted)).

pump performance, the observed thermal and DO profiles for each month from April through October were generalized. This was accomplished by defining a curve which best fit the profile for the period of record of data for each month for temperature and DO (Appendix A). SELECT predictions of release temperature and DO were then made using these generalized profiles and a release of 4,600 cfs. Release DO was adjusted to account for reaeration from the vacuum breaker system as discussed in paragraph 17. Equation 3 was used to predict the epilimnetic volume flux for each generalized profile. The epilimnetic volume flux was then used to compute the DF. Equation 6 was then used to predict release quality with three, six, and nine pumps operating. The comparison of the predicted release without and with pumps appears in Table 3.

19. A generalized localized mixing operating plan to improve release quality during hydropower generation was developed based on the SELECT predictions. Without localized mixing, the release DO drops to 3.4 mg/l in July and does not significantly recover until October. However, the release DO objective is to maintain 5 mg/l DO in the release. Following this release quality criterion, the pumps would be placed in operation in June with six pumps

Table 3

Predicted Release Temperature and Dissolved Oxygen for Generalized Monthly Profiles

Month	Predicted Release Temperature, °C			
	0 pumps	3 pumps	6 pumps	9 pumps
April	13.34	13.86	14.38	14.90
May	14.44	15.36	16.28	17.20
June	14.92	16.48	18.00	19.60
July	15.96	17.91	19.85	21.81
August	17.36	19.15	20.94	22.73
September	18.03	19.37	20.71	22.05
October	16.98	17.88	18.78	19.68
	Predicted Release Dissolved Oxygen, mg/l			
Month	0 pumps	3 pumps	6 pumps	9 pumps
April	7.3	7.7	8.1	8.5
May	5.3	5.9	6.7	7.4
June	3.5	4.3	5.0	5.8
July	3.4	4.2	4.9	5.7
August	3.5	4.3	5.0	5.8
September	3.4	4.2	4.9	5.7
October	4.0	4.8	5.6	6.4

operating. In July, all nine pumps are required. By October, six pumps are all that are necessary to maintain the release DO. By November, operation of the pumps would not be necessary.

20. The above plan was based on several generalizations; therefore, some caution is advised in application of these results. The generalized profiles used in the SELECT predictions do not account for extreme conditions for which operation of the system would be less effective. The profiles do not account for the maximum temperature reached in the epilimnion during the summer (approximately 29.0° C) or an extremely shallow thermocline that would reduce the ability of a given number of pumps to deliver the epilimnetic volume flux required to meet the release DO objective. The port description used in SELECT, although not a theoretically appropriate description due to the point sink assumption, appears to be adequate; however, the number of comparisons that were performed to verify it were minimal.

Alternatives to Augment Localized Mixing

21. As stated in paragraph 1, the objectives of this report are to provide ORN with design verification and operational guidance for a localized mixing system on J. Percy Priest. In addition, ORN requested an evaluation of partial lake destratification and hypolimnetic aeration alternatives that may be used in conjunction with the localized mixing system to improve the hypolimnetic DO prior to release.

22. The analysis of the localized mixing system discussed above concerned a system that operated only when the hydropower facility was in operation. A localized destratification of J. Percy Priest Reservoir in the vicinity of the dam could be accomplished using surface pumps that operate on a continuous basis. This technique would maintain a well mixed volume of water that would have a relatively uniform temperature profile and allow greater reaeration potential in the hypolimnetic water but only in the vicinity of the dam. For purposes of this analysis, an area 2,100 ft by 2,100 ft by 90 ft deep in front of the dam, having an approximate volume of 9,200 acre-ft was considered for localized destratification. This is equivalent to 24 hours of continuous generation at maximum capacity (4,600 cfs) from J. Percy Priest. Using Holland and Dortch (1984) to compute the time to destratify this area with an initial density difference of 0.0029 g/cc, two

40-hp pumps in continuous operation would destratify the area in 96 hours; 6 pumps in 32 hours; and 8 pumps in 24 hours. Under weaker stratifications, shorter periods of time would be required. The formulas used to compute the destratification time were developed from data on whole-lake destratification systems. Since these formulas were applied to only a portion of the lake, it is difficult to predict the effectiveness of this type of system. Therefore, extreme caution should be exercised in application of this technique.

Partial Lake Destratification

23. The localized destratification could be extended to destratify a larger portion of the lake. The morphometry of the reservoir is such that the pool begins to narrow as it approaches the dam. There is a constriction in the pool approximately 1 mile upstream of the dam. This area, approximately 1 square mile, covers approximately 5 percent of the total lake area at el 490. The total volume of the pool at this elevation is 391,990 acre-ft. If 1-square-mile area was assumed to contain approximately 10 percent of the volume, then the area to be destratified would contain 39,199 acre-ft. This volume would be released in 4.3 days with continuous generation at 4,600-cfs capacity. A 16-hp axial flow pump of a design similar to that used by Robinson et al. (1982) generates 143 cfs of discharge at a exit velocity of 2.85 ft/sec. The time required for one of these pumps to destratify 39,199 acre-ft of water with various density differences between the epilimnion and hypolimnion was computed using Holland and Dortch (1984). These computed times appear below:

Density Difference, g/cc	Time, days
0.0001	13.2
0.0005	21.0
0.0010	25.6
0.0015	28.7
0.0020	31.2
0.0025	33.2

Although multiple pumps would reduce the time for destratification, the pumps would have to be started in the spring with the initiation of stratification to minimize the density difference which the pumps would have to overcome. There may also be a significant warming of this area of the lake due to the partial destratification. As with the localized destratification, methods to predict the impacts of a destratification system designed using total lake criteria, but purposely underdesigned to destratify only a portion of the lake, are currently unavailable and caution is advised in their application.

Hypolimnetic Aeration

24. Hypolimnetic aeration is a technique used to increase DO in the hypolimnion without affecting the thermal stratification. Although there are a variety of devices used with this technique, the type of device discussed here is a partial airlift type system (LIMNO) similar to that manufactured by Aqua-Technique, Inc. (formerly Atlas Copco). A more complete discussion of hypolimnetic aeration and oxygenation devices is given in Holland and Tate (1984). The design of a hypolimnetic aeration system requires an estimate of the rate of oxygen consumption in the hypolimnion. In this study, the elevation of the thermocline was determined by examination of monthly thermal profiles for the year 1979. Beginning in March, the lake began to stratify with the strongest stratification being reached in August. Once the thermocline became well defined, it remained relatively constant at approximately 30 ft below the surface (el 460.0). The hypolimnion was defined as the area below the 30-ft depth. The volume of the hypolimnion, approximately 111,000 acre-ft, was estimated from the elevation volume curve as provided by ORN. Using five observed profiles from March through July 1979, the hypolimnetic oxygen consumption was computed as shown below:

	Hypolimnetic Oxygen Consumption for 1979	
Time Period	kg/day	mg/l/day
3/7 to 3/27	14,232	0.13
3/27 to 4/16	16,406	0.15
4/16 to 6/5	14,680	0.13
6/5 to 7/18	5,820	0.05

Once the hypolimnion becomes anoxic, the DO deficit cannot be determined from DO data. The lower layers of the hypolimnion became depleted of DO during the latter part of June and early July; therefore the rate for the last time period is undoubtedly inaccurate. It should also be noted that the DO deficit will vary on an annual basis according to meteorological and hydrological conditions.

25. The rate of oxygen consumption for the J. Percy Priest hypolimnion is comparable with those of other reservoirs reported in the literature. An

oxygen consumption of 0.13 mg/l/day is equivalent to 0.91 mg/l/week. Lorenzen and Fast (1977) report values of 0.24 to 2.30 mg/l/week for various lakes in California, New York, Ohio, and Wisconsin. It should also be noted that rates for lakes with hypolimnetic aeration displayed significantly higher depletion rates than prior to hypolimnetic aeration. This may be due to resuspension of sediments that subsequently increases the DO demand.

26. The LIMNO unit(s) is sized for the site-specific DO demand and lake depth. According to design criteria provided by Aqua-Technique, Inc., the DO demand as discussed above of 14,000 to 16,000 kg/day oxygen would require approximately six of the largest units to provide adequate reaeration to maintain DO in the hypolimnion. Specific costs for this size of system would vary due to site-specific installation; however, Aqua-Technique uses an approximate cost of $60.00 to $70.00 per kg oxygen to estimate system costs.* This estimate includes costs for all the equipment required for installation and operation. This equates to $1,120,000 for a system capable of delivering 16,000 kg oxygen per day at J. Percy Priest Reservoir.

27. The use of a localized hypolimnetic aeration system to aerate only the area near the dam, much like the localized destratification technique discussed above, would reduce the cost of the system. A system designed to deliver 1,400 to 1,600 kg oxygen per day or 10 percent of the demand would be in the medium to large size range, but would require only one unit. This would reduce the cost approximately an order of magnitude to approximately $130,000.

28. Although the above computations were performed with the objective of maintaining 5 mg/l DO in the hypolimnetic water being released, some benefit would be achieved by hypolimnetic aeration even with an undersized unit. Brunnsviken Lake in Sweden experienced high levels of hydrogen sulfide in the hypolimnion. Installation of a small hypolimnetic aeration system successfully removed the hydrogen sulfide even though the hypolimnion remained anaerobic (Lorenzen and Fast 1977). However, such is not the case with iron and manganese. Bernhardt (1974) reported that 2 mg/l DO was required to prevent iron and manganese from coming into solution in the hypolimnion. Thus, a system designed to deliver only 2 mg/l DO may control

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* Personal communication with Mr. R. S. Geney, Aqua-Technique, Inc., on 9 March 1988.

hydrogen sulfide, iron, and manganese in releases from J. Percy Priest.

29. There are several concerns with hypolimnetic aeration that could not be adequately addressed without site-specific field investigations. The first involves the potential for gas supersaturation in the release. Fast et al. (1975) reported nitrogen gas supersaturation of 150 percent relative to the surface with a LIMNO hypolimnetic system. Therefore, gas supersaturation of the water released from the hydropower penstock is highly possible. The second concern applies only to the localized hypolimnetic aeration technique. Once the hypolimnion outside the region of localized aeration becomes anaerobic, the rate of oxygen consumption for this water is unknown. As water is released through the hydropower project, water from upstream in the reservoir that has not been aerated by the localized hypolimnetic system will move downstream into the influence of the hypolimnetic aerator. The contact time required for the hypolimnetic aerator to satisfy the DO deficit of this water may be longer than that computed above. Therefore, the hypolimnetic DO requirements for this type of system may be highly variable. The last concern involves the variability of the data used to compute the DO deficit. Since only five profiles for one year were used to compute the deficit, some caution in application of these results is advised. If further consideration is given to a hypolimnetic aeration system, a more detailed field investigation is recommended.

Recommendations

30. Based on the above analysis, the following recommendations are offered:

a. For a localized mixing system that is designed to overcome the most difficult late summer stratification (strong stratification with shallow thermocline and the vacuum-breaker system closed), it is recommended that a system consisting of 13 pumps spaced approximately 25 ft apart in a radial pattern 40 ft from the hydropower intake be installed. This will provide the desired release DO of 5 mg/l under the given design criteria of epilimnetic DO of 8.0 mg/l and hydropower release of 4,600 cfs.

b. For a system designed to function in a generalized or average set of thermal conditions (normal spring or fall stratification with the thermocline at an average depth and the vacuum breaker system open, satisfying approximately 27 percent of the DO deficit), it is recommended that a localized mixing system consisting of 9 pumps spaced approximately 25 ft apart in a radial pattern 40 ft from the hydropower intake be installed. The operating plan for this system was discussed above.

c. For further improvement in release quality by reduction of concentration of hydrogen sulfide, iron, and manganese, it is recommended that use of a small localized hypolimnetic aeration system located near the hydropower intake be further investigated as a means of augmenting the water quality enhancement of the localized mixing system.

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Appendix A: Generalized Temperature and Dissolved Oxygen Profiles for J. Percy Priest Reservoir

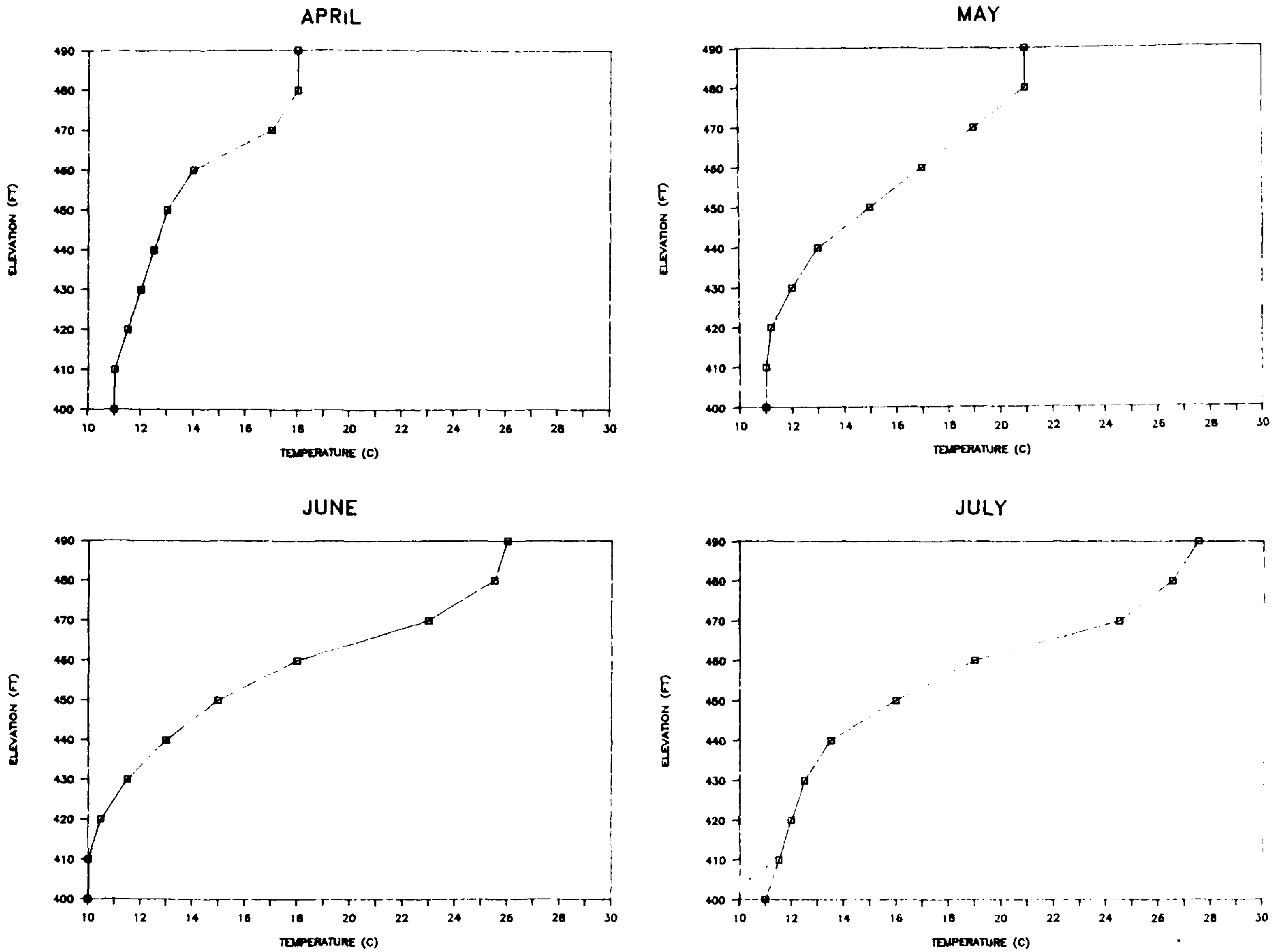

Figure A1. Generalized temperature profiles, April-October (Continued)

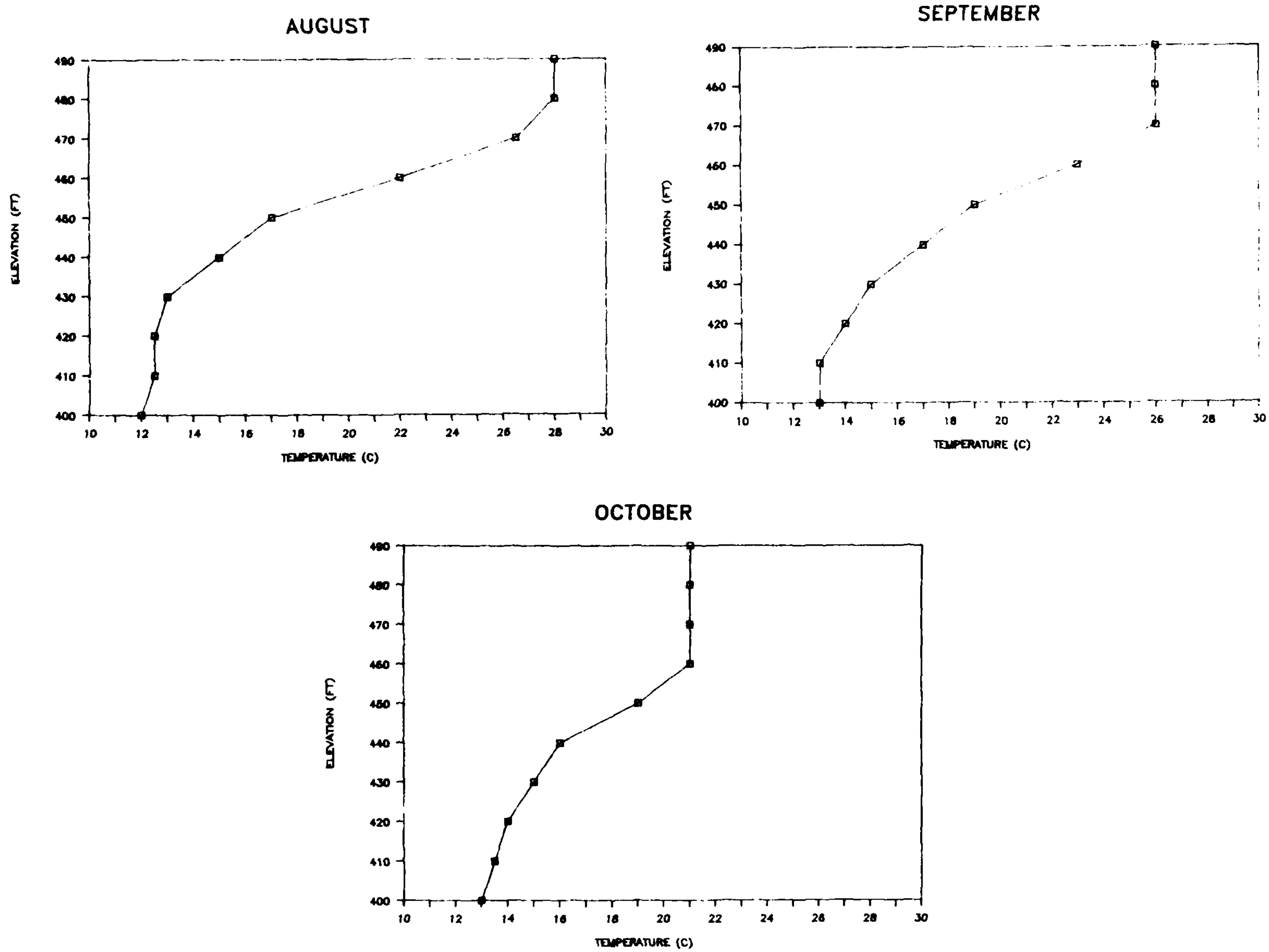

Figure A1. (Concluded)

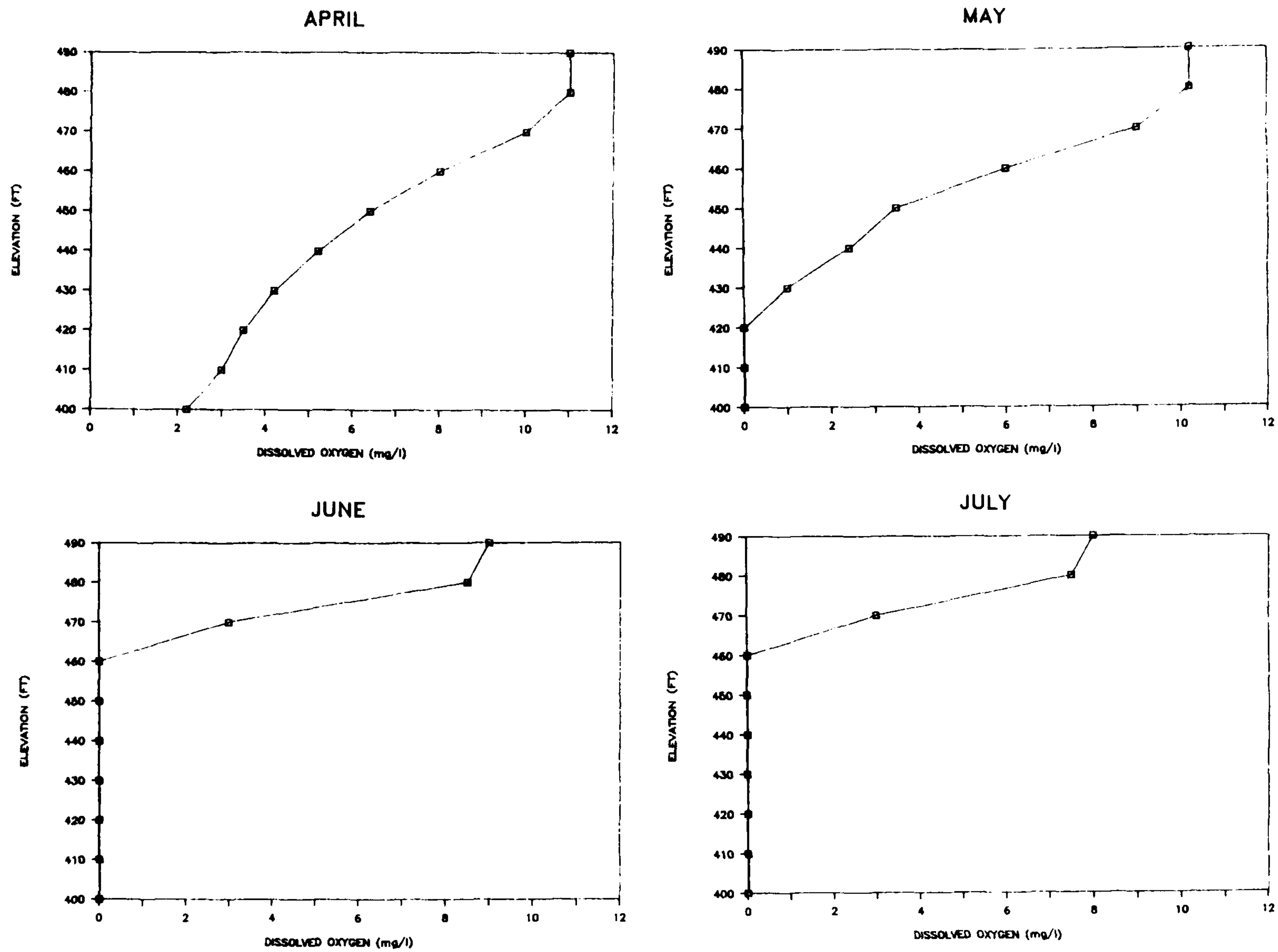

Figure A2. Generalized dissolved oxygen profiles, April-October (Continued)

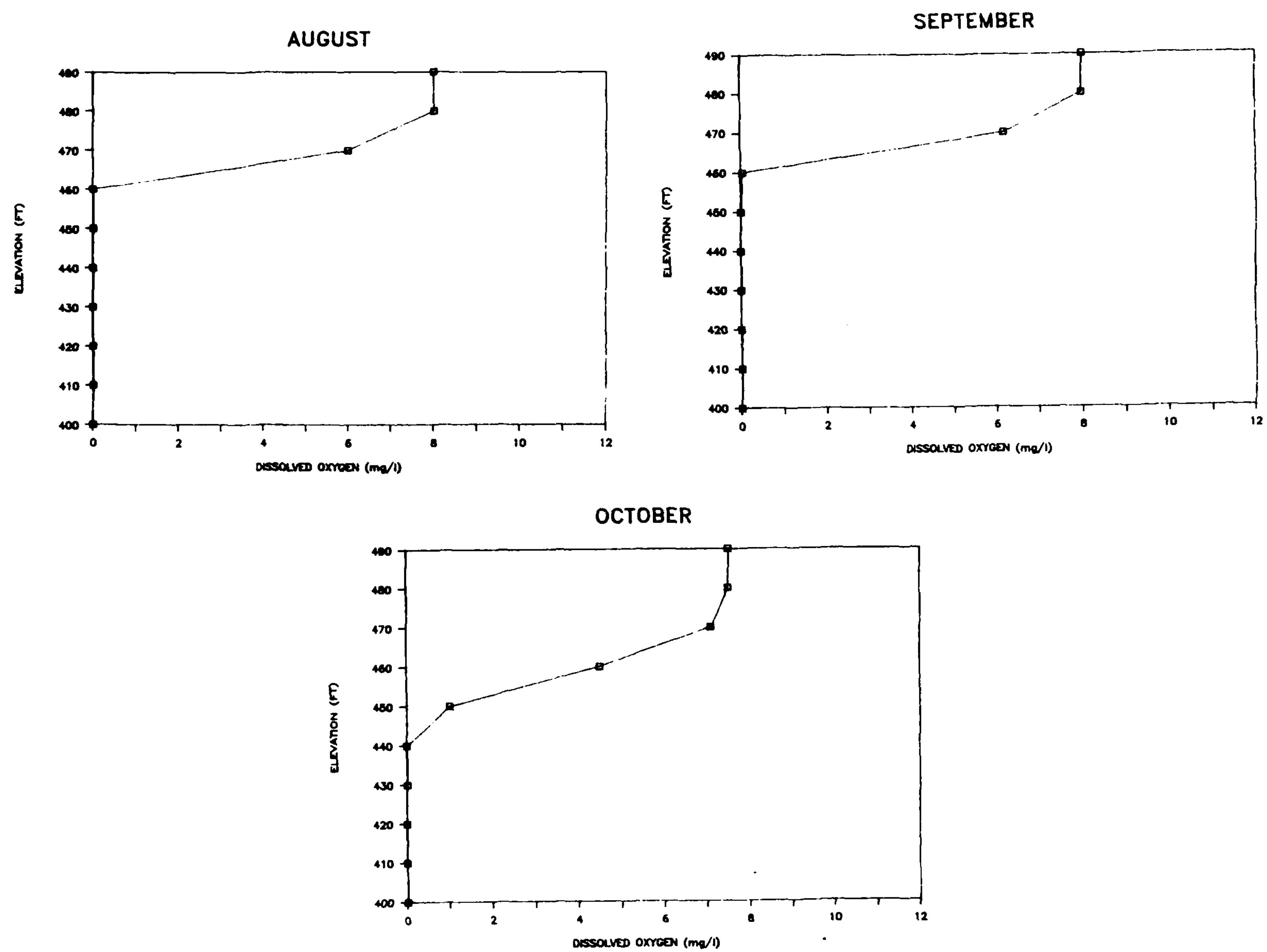

Figure A2. (Concluded)