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SELECTIVE WITHDRAWAL STUDIES FOR THE FISH HATCHERY OUTLETS AT PUEBLO DAM

Mathematical and Physical Models

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Engineering and Research Center
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16. ABSTRACT
Mathematical and physical models were used to evaluate the design of a proposed selective withdrawal outlet system for a fish hatchery downstream from Pueblo Dam, Colo. The mathematical model predicted that the reservoir would be stratified during a few months in the spring but would be isothermal during the summer and fall. The effects of an existing barrier dam were estimated by the mathematical model and by a physical model. The stratification patterns upstream from the barrier, predicted by the mathematical model, were used in a 1:60 scale hydraulic model to study conditions downstream from the barrier. The barrier acted as a skimmer, causing the flow of warmer water from higher levels in the reservoir to enter the region downstream from the barrier. The river outlets and municipal outlet operation in drawing down the isotherms caused warmer temperatures of withdrawal at the hatchery outlets. A higher hatchery outlet was recommended, in addition to the 3 hatchery outlets included in the preliminary design.

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by

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Commissioner

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The assistance of Mr. John Yearsley, Environmental Protection Agency, Water Quality Office, Portland, Oregon, in applying the mathematical model is sincerely appreciated.

The mathematical model used for the temperature predictions was developed by Water Resources Engineers, Inc., Walnut Creek, California.

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PURPOSE

These studies were performed to answer the following questions:

1. What will be the pattern of temperature stratification in Pueblo Reservoir, or will it stratify at all?

2. What effect will the existing barrier dam have on the temperatures of withdrawals at the fish hatchery outlets?

3. What effect will operation of the river outlets in Pueblo Dam have on the reservoir temperatures available at the fish hatchery outlets?

The preliminary design of the fish hatchery outlets was to be evaluated on the basis of the answers to these questions.

CONCLUSIONS

1. Application of the mathematical model for three reservoir conditions (high, intermediate, and low) predicted, in general, that the reservoir would be stratified from late March or early April until early July or early August, depending on the reservoir operation. According to the prediction, the reservoir would be isothermal the remainder of the year. Limited data from Lake Natoma in California suggested that some summer stratification might occur in Pueblo Reservoir; however, this could not be assured.

2. The mathematical model showed that the barrier dam caused warmer water to be available in the lower depths of the reservoir a few days later than if the barrier was not present. The hydraulic model clearly illustrated the effect of the barrier in skimming warmer water from the upper portion of the reservoir. Plugging the breach in the barrier accentuated this phenomenon.

3. Operation of the river outlets affected the temperature profile at the hatchery outlets to some degree by drawing down the isotherms. The extent of warming of the profile depends upon the discharge of the operating river outlet and its distance from the hatchery outlets.

4. To take advantage of the predicted temperature stratification in the reservoir, a higher outlet was recommended for addition to the hatchery selective withdrawal system. The recommended configuration consisted of outlets at elevations 4760 (1450.8),4785 (1458.5), 4810 (1466.1), and 4850 (1478.3) feet (meters).

5. The disposition of suspended sediment entering the reservoir will be determined by the concentration of suspended material. The mathematical model predicted that inflows from the Arkansas River would be warmer than the reservoir and flow at the reservoir surface. However, with high concentrations of suspended material, the density might be altered enough to cause interflows or bottom density currents. The barrier dam would either block or pass these currents, depending on their vertical location in the reservoir and their velocity through the reservoir.

6. Since the reservoir is expected to be isothermal during about 9 months of the year, and only weakly stratified during the remainder of the year, mixing and atmospheric reaeration should maintain adequate levels of dissolved oxygen.

APPLICATION

The temperature stratification predicted with the mathematical model for Pueblo Reservoir may apply, in a general sense, to other similar reservoirs. The results of the physical model study are unique to Pueblo Dam and Reservoir, however, the data and observations should provide some base for approaching similar problems.

INTRODUCTION

The idea of using selective withdrawal facilities to control the temperature of water supply to a proposed fish hatchery downstream from Pueblo Dam was first explored by the Colorado Department of Game, Fish, and Parks early in 1968. The hatchery was to be a joint venture of that agency with the U.S. Bureau of Sport Fisheries and Wildlife. By the latter part of 1968, the Bureau of Reclamation had developed a preliminary design for the selective outlets. The decision was then made to perform hydraulic model studies to evaluate this design.

Figure 1 shows hypothetical seasonal temperature variations in a typical deep reservoir. Normally, a reservoir would be filled during the spring runoff period, then drawn down during the summer and fall for power generation and water supply. Stratification similar to that shown in Figure 1 would exist under these circumstances. Control of downstream temperature by selective withdrawal would be most effective during the summer.

Pueblo Reservoir will be atypical in its operation. The reservoir will normally be full in late March or early April. Rapid drawdown will then occur, which will often result in the reservoir being at its minimum level by early June. The reservoir will remain low through the summer, with inflows being routed directly through the reservoir. This combination of relatively shallow depth and high through flow intuitively makes summer stratification unlikely.

When stratification does occur, selective withdrawal can be used very effectively to control downstream temperature and other water quality parameters. Figure 2 illustrates the mechanism of selective withdrawal in a general laboratory test. The outlet is located at middepth at the right side of the photographs. The top photograph shows the early deformation of a dye streak which was initially vertical. The primary withdrawal current is evident at the level of the outlet, with lesser upstream and downstream currents at other levels. The bottom photograph shows the status of water movement several minutes later. The thickness of the withdrawal layer depends primarily on the temperature profile, the vertical location of the outlet, and the discharge. Currents caused by inflow and suspended materials which alter the density will modify the withdrawal pattern, as will nearby structures or abrupt changes in the bottom geometry.

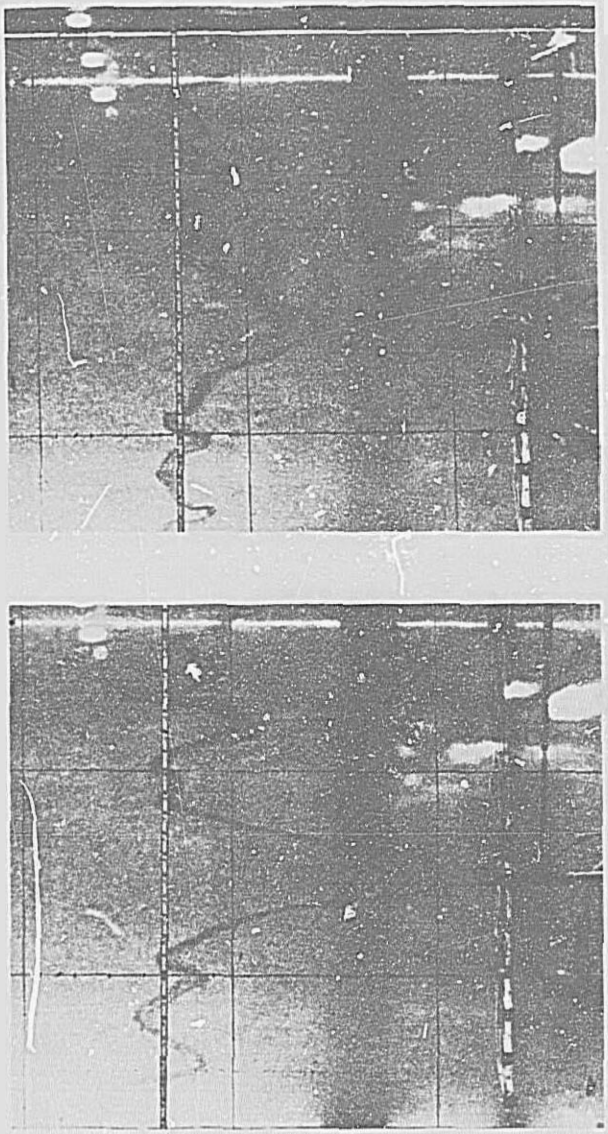

Figure 2. Selective withdrawal in general laboratory test. Top Photo P382-D-69412. Bottom Photo P382-D-69413

Pueblo Dam, Figure 3, near the city of Pueblo, Colorado, will consist of a massive head buttress concrete section about 1,750 feet (533.4 m) long, with earth embankments on each end which bring the total length of the dam to nearly 2 miles (3.2 km). The maximum height of the dam is approximately 175 feet (53.3 m). The uncontrolled overflow spillway is in the buttress section.

Outlets for several purposes are also in the buttress section, Figure 3. River outlets are in four locations. The fish hatchery outlets are about 140 feet (42.7 m) from the nearest river outlet, but immediately adjacent to the south outlet works, which will be used for municipal supply. The gorge outlet, farthest to the left, will have priority for operations.

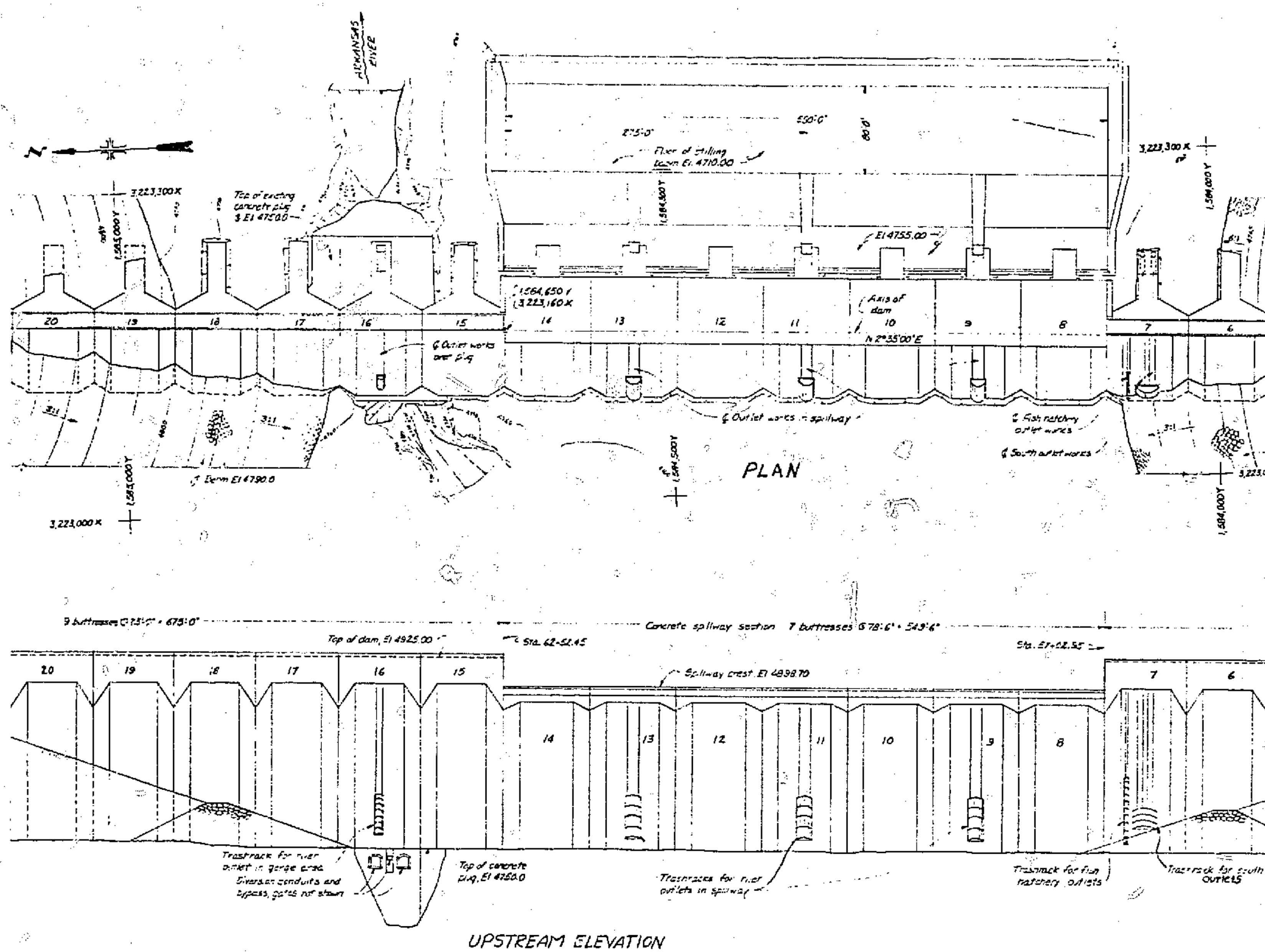

Figure 3. Pueblo Dam plan, elevation, and sections.

Figure 4 shows the existing Rock Canyon Barrier Dam which will be about 200 feet (61.0 m) upstream from the buttress section. This barrier was constructed to partially retain floods. A breach at the main channel, Figure 5, was designed to pass the downstream safe channel capacity. An access adit is also in the barrier, Figure 6.

The studies described in this report were conducted to determine the effects of the operation of various outlets and the presence of the barrier dam on reservoir temperatures available at the fish hatchery outlets.

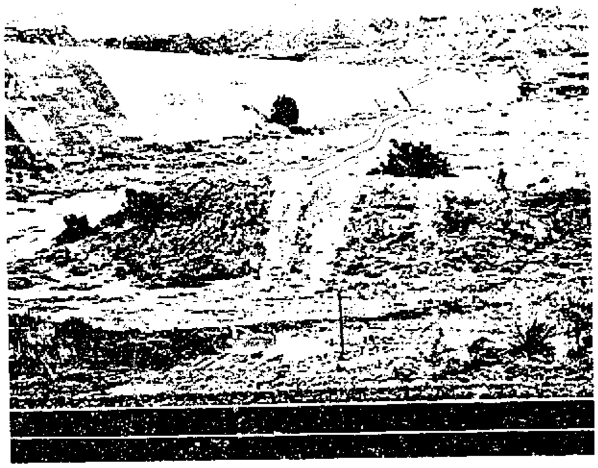

Figure 4. Existing Rock Canyon Barrier Dam, downstream side, looking north. Photo P382-D-69414

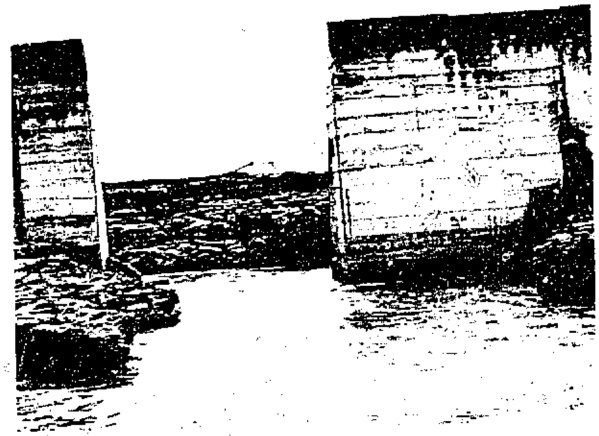

Figure 5. Main channel breach in Rock Canyon Barrier Dam, upstream side. Photo P382-D-69415

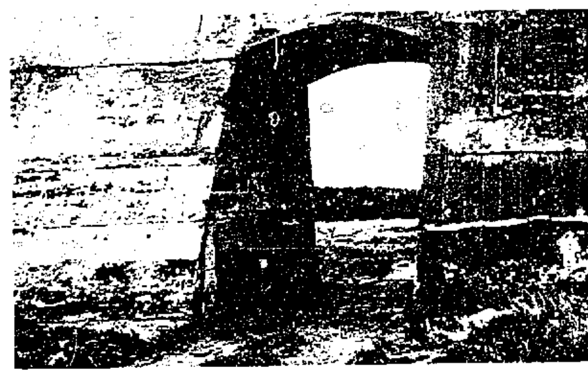

Figure 6. Access adit in Rock Canyon Barrier Dam, downstream side. Photo P382-D-69416

INVESTIGATION

Mathematical model

Background of development.—The mathematical model used in this study was developed by Water Resources Engineers, Inc., of Walnut Creek, California. The model was obtained by the Bureau of Reclamation from the Federal Water Quality Administration (now Water Quality Office, Environmental Protection Agency), Northwest Region, Portland, Oregon, and is presently considered to be in a verification stage.

A 1969 report to FWQA[1] summarizes the theory of the model and documents the computer program. An earlier report[2] describes the theory in detail.

General Theory.—Basically, the mathematical model performs energy and mass balances on horizontal finite elements or "slices," Figure 7. Transfer of heat and water is assumed to take place only in the vertical direction. For weakly stratified reservoirs or those with tilted isotherms, a recent version of the model allows dividing the reservoir into reaches. The computed

[1] "Mathematical Models for the Prediction of Thermal Energy Changes in Impoundments", Final Report, Water Resources Engineers, Inc., December 18, 1969

[2] "Prediction of Thermal Energy Distribution in Streams and Reservoirs", Final Report, Water Resources Engineers, Inc., June 30, 1967.

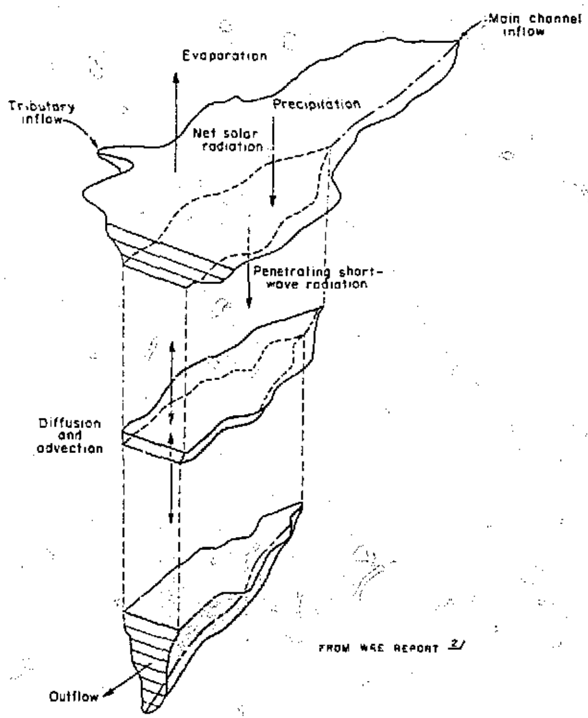

Figure 7. Heat and mass flow diagram for WRE prediction model.

conditions at the downstream end of a reach are used as the upstream boundary conditions for the next reach, etc. Pueblo Reservoir was not segmented into reaches for the present study.

Temperature profiles within the reservoir for any day of the analysis period are predicted along with the temperature of the outflow.

Hopefully, this very brief description of the mathematical model will not be misleading. The model is exceptionally general and detailed and accordingly very complex.

Data requirements.—Table 1 summarizes the input data required for the Pueblo Reservoir temperature prediction.

Table 1

Input Data Required for Temperature Prediction

Meteorological data	Hydrological data
Cloudiness Dry bulb temperature Wind speed Relative humidity	Inflow rate and temperature Outflow rate
Reservoir characteristics	
Elevation Outlet elevations Latitude and longitude Area—Elevation table Diffusion characteristics Evaporation formula coefficients Initial elevation, temperature, and temperature rate of change	

Other miscellaneous data are also required to run the program. the meteorological and hydrological data are generally input as daily values for the period of analysis. For an initial estimate of stratification in Pueblo Reservoir, average monthly values were used. Each daily value of data used in the computer program was assumed to be the average value for that month. Figure 8 shows the inflow temperature data used in the analysis conducted for March through November, as compared with temperatures measured in the Arkansas River over a 1-year period in 1969 and 1970. Meteorological data were from Pueblo Airport for 1968.

Limitations.—The accuracy of the temperature prediction depends very heavily on the quality of the input data. For example, the Pueblo prediction should be considered approximate because monthly averages for the meteorological and hydrological data were used. The proximity of the weather station to the reservoir is also an important factor. Also, the effects of short term variations are ignored. Wind mixing is not included except in a very general sense, and the effects of windstorms cannot be considered.

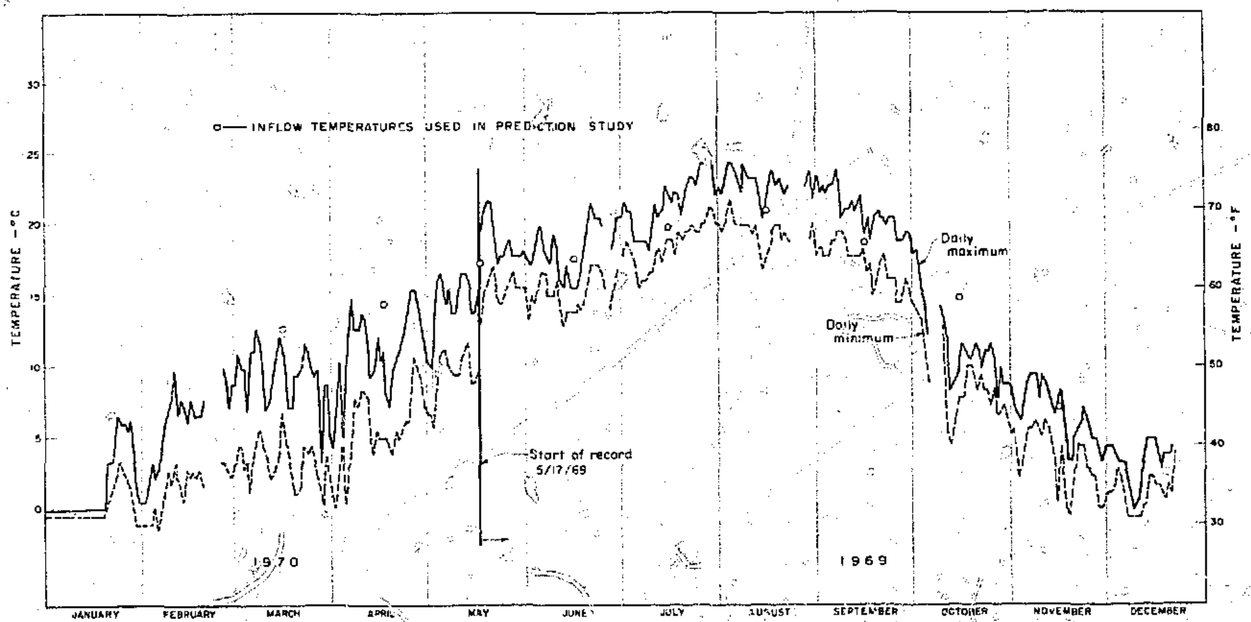

Figure 8. Arkansas River temperature data, 1969-70. Recording thermometer at Pueblo damsite.

The model will not simulate a reverse temperature gradient which often occurs in winter, usually under an ice cover. Density alterations caused by suspended materials cannot be simulated.

A diffusion coefficient must be chosen although the model does not appear to be too sensitive to variations in this parameter. The effect of high through-flow rates has not been studied in detail.

Pueblo Reservoir temperature prediction.—The predictions were started on March 1 with an assumed isothermal temperature of 39.2° F (4° C) and terminated on November 16 before formation of surface ice. Three representative reservoir conditions (high, intermediate, and low) and accompanying outflows were determined from projected reservoir operation studies. Runs were made to represent both a solid barrier dam (breach and adit closed) and complete removal of the barrier dam. The results of the prediction runs are shown in Figure 9. The effect of removal of the barrier dam is only of academic interest, since the design called for retaining the dam and plugging the breach and adit to block sediment from reaching Pueblo Dam.

The predictions show that warmer temperatures (say above 45° F) would be available earlier in the lower depths of the reservoir with the barrier dam removed. A general observation is that the deeper the reservoir, the longer the stratification persists. The need for a high outlet to guarantee a supply of warm water during the spring is evident. Also, though not evident from this prediction, a low outlet would be required to provide a warmer (39.2° F) supply from the winter inverse temperature gradient.

The period that the reservoir is isothermal will depend on the reservoir operation and depth.

Limited data were supplied by Region 2 in Sacramento, California, showing summer stratification in Lake Natoma (Nimbus Dam). Though shallow in depth with a high through flow, similar to Pueblo Reservoir, Lake Natoma exhibited a well-defined stratification near the surface. This suggested that Pueblo Reservoir might stratify to some degree in the summer and fall, notwithstanding the results of the mathematical prediction. However, since the Lake Natoma data were very limited, this cannot be assured.

An additional prediction run was made, using daily average data values. A year with nearly constant intermediate reservoir elevations was assumed, adjusted values of 1968 streamflow were used along with 1968 stream temperatures, and the outflows were computed according to the assumed reservoir elevations. The results of this prediction are shown in Figure 10.

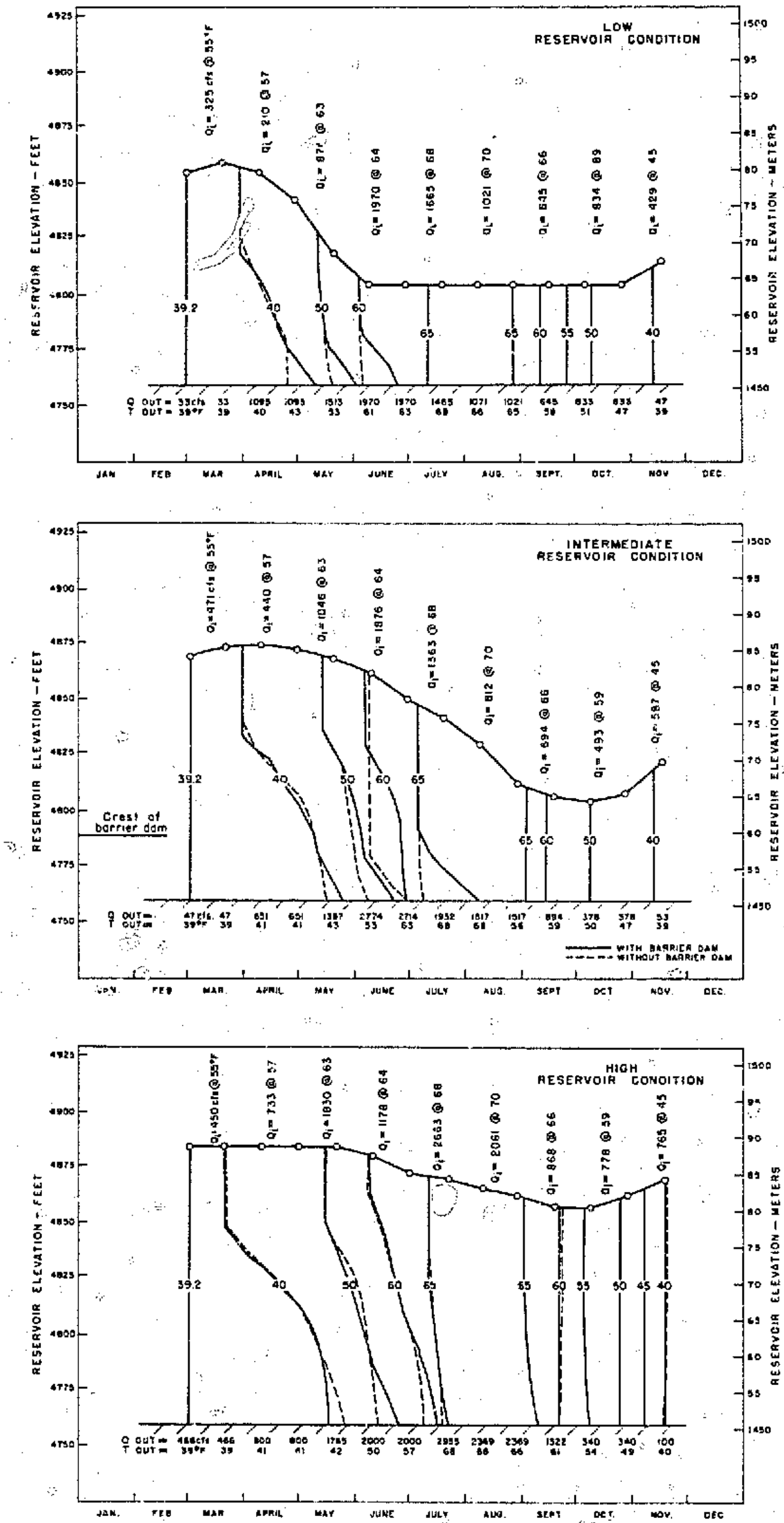

Figure 9. Pueblo Reservoir temperature prediction, using monthly average data.

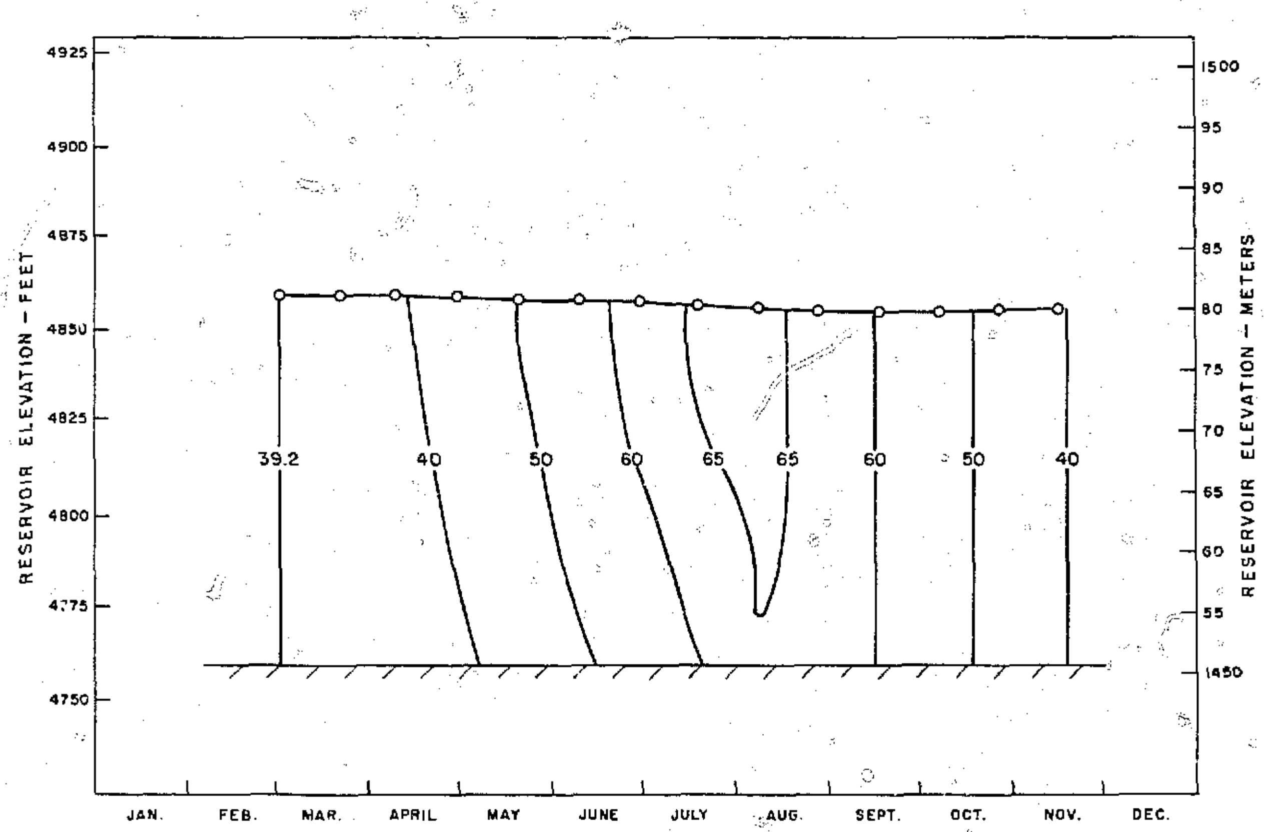

Figure 10. Pueblo Reservoir temperature prediction, using daily average data.

The computed stratification pattern is very similar to those of Figure 9, with some indication of stratification during the summer.

It must be noted that the prediction concerns temperatures UPSTREAM from the barrier. A physical model was used to determine detailed effects of the barrier and thus the temperature profiles DOWNSTREAM from the barrier.

Physical Model

Model and laboratory facilities.—Figure 11 is a view of the downstream portion of the 1:60 scale model. The plexiglass represents the upstream face of Pueblo Dam. Circular holes with slide gate controls were used to represent the outlets. No attempt was made to simulate the very small discharge from the fish hatchery outlets. A small portion of the earth embankment was represented on each side of the model. The prototype area covered by the model is outlined on Figure 12.

Water was discharged from the outlets into a collection trough, then discharged across a rectangular weir for measurement. The flow then entered a pump for recirculation to the upstream end of the model. The flow entered the model, flowed over a sill, then under an adjustable gate, Figure 13. The gate was found to be ineffective in controlling the stratification pattern because of mixing which occurred immediately downstream from the overflow sill.

Cold water was supplied from an adjacent flume with a refrigeration system, Figure 14. The arrangement of pipes and valves connecting the flume to the model allowed any portion of the recirculating flow to be passed through the cooling flume.

Instrumentation.—Thermistors installed in vertical arrays, as shown in Figure 15, were used to measure temperature profiles at various points in the model and in the inflow and outflow. Scans of the thermistors were initiated either manually or by a digital clock with available intervals of 1 minute to 1 hour. The starting time of the scan, thermistor numbers, and corresponding temperatures were recorded by a printer. A quartz thermometer was used to calibrate the individual thermistors. A temperature controller determined the temperature in the cooling flume.

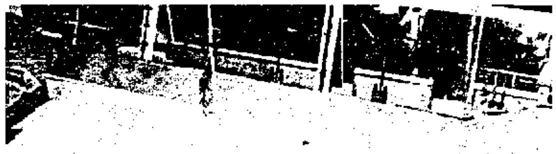

Figure 11. Interior view of 1:60 hydraulic model. Photo P382-D-69417

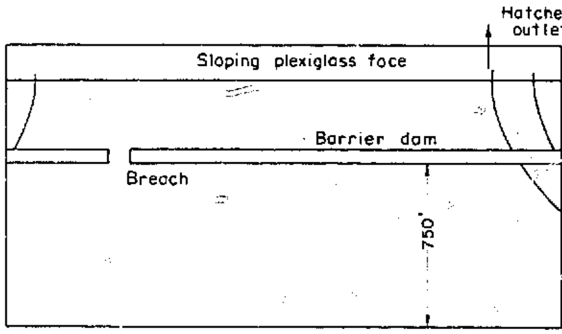

Figure 12. Prototype area included in model.

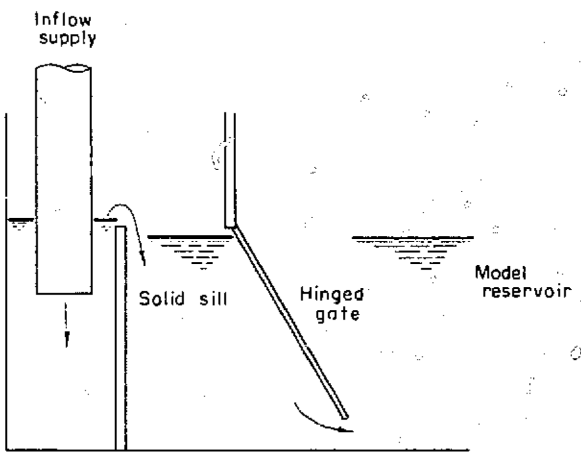

Figure 13. Model inflow apparatus.

Limitations.—The hydraulic model was limited to simulation of steady flow, primarily because only a small portion of the reservoir was represented. No storage was available to permit forming the proper relationships between inflow, outflow, and reservoir elevation. Inflow and outflow were equal for each test.

It was not possible to exactly duplicate the predicted temperature profiles; however, several representative profile shapes were studied. Because of the limited scanning rate of the instrumentation, it was not possible to trace rapid changes in the temperature profile, for example, immediately after opening an outlet gate.

The duration of each test was limited to a few hours because of warming of the model by heat transfer from the room and because of heat transfer and mixing within the stratified water body.

Test conditions and model operation.—The key to abbreviations which will appear in subsequent discussion of test results is as follows, in order of their location on the dam from left to right looking downstream:

GOW—Gorge outlet works
LROW—Left river outlet works
MROW—Middle river outlet works
RROW—Right river outlet works
FHOW—Fish hatchery outlet works
SOW—South outlet works

The GOW was normally given priority for operation, then the LROW, etc. Operation of the SOW was independent of operation of the river outlets. Tests were numbered according to the date (Test 0924 occurred on September 24). A summary of test conditions is given in Table 2.

Data processing and analysis.—As stated earlier, the temperature readings were recorded on printed tape. A short computer program was written to apply the necessary corrections to the thermistor readings. The printed tape was converted to punched cards for this purpose. Computer listings were used to plot the temperature profiles, from which test conclusions were drawn. Observations of the movement of dye tracers were also important in formation of the test results.

Preliminary hatchery outlet design.—Figure 16 shows the preliminary design of the fish hatchery outlet works. The total supply to the hatchery was to be 16 cfs (0.5 cms). Water could be withdrawn from any or all of the outlets, which were located at elevations 4760.63 (1451.0), 4785.63 (1458.7), and 4810.63 (1466.3) feet (meters). The valving arrangement would allow mixing of the separate withdrawals, with control according to temperature sensors in each of the three lines.

Test Results

First test series (breach and adit open).—The condition of primary interest was that of stratification at minimum reservoir elevation 4796.7 (1462.0 m), which

Figure 14. Refrigeration system for cold water supply. Photo P382-D-62875

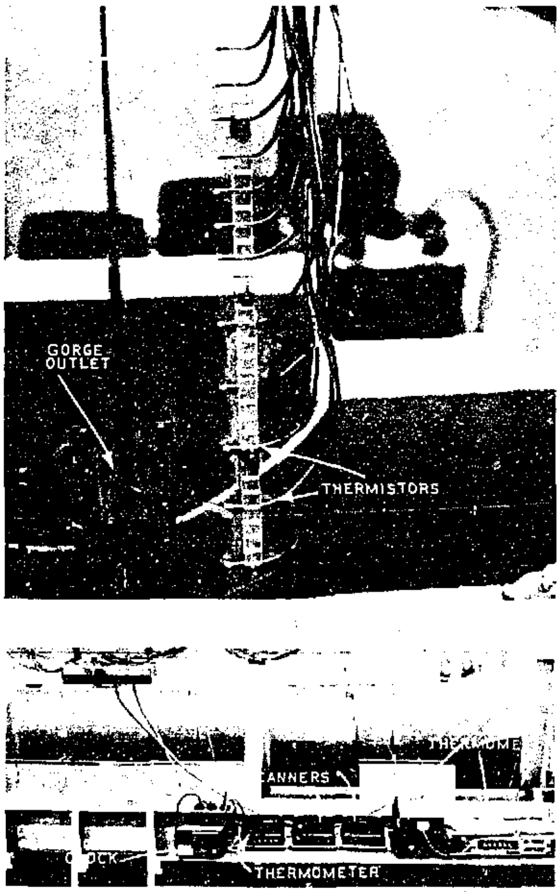

Figure 15. Temperature instrumentation. Top Photo P382-D-69418. Bottom Photo P382-D-69419

could occur during June. Tests 0924, 0930, 1002, and 1023 are for reservoir elevations at or near the minimum.

Test 0924, Figure 17, shows temperature profiles resulting from operation of the gorge outlet works (GOW) and the left river outlet works (LROW). At time 1352, 4 minutes after initiation of withdrawal from the GOW, the drawdown at the GOW is evidenced by warmer temperatures. A similar, lesser effect appears at the fish hatchery outlet works (FHOW). With operation of the LROW, the drawdown effect at the FHOW is appreciable. The temperature of the outflow shows the effect of the barrier dam skimming warmer water from higher elevations in the reservoir.

Test 0930, Figure 18, shows similar effects for a milder stratification with less discharge from the LROW. Test 1023, Figure 19, is similar, and shows smoothing of the GOW profile due to mixing downstream from the barrier. Note that the reservoir is essentially isothermal upstream of the barrier at Time 1309, while stratification persists downstream from the barrier.

Test 1002, Figure 20, shows the effects of withdrawal from the middle river outlet works (MROW). The drawdown and skimming effects are again apparent, with the most drawdown occurring at the FHOW. The warmer temperatures in the lower part of the profile at the FHOW may be due to heat transfer through the walls at the corner of the model.

Test 1014, Figure 21, shows the effects of a small withdrawal from a weak stratification with a reservoir elevation slightly greater than minimum. Some mixing of the profile, particularly at the GOW, is shown. This indicates that, even with small withdrawals, the breach in the barrier dam supplies only part of the demand, and some skimming occurs. This is also reflected in the outflow temperature.

Test 1007, Figure 22, describes increasing withdrawal from a well-stratified reservoir at intermediate depth. The profiles show mixing and warming of the hypolimnion as the withdrawal increases, with an accompanying rise in the lower boundary of the thermocline. Under these conditions, selective outlets for the hatchery would have no value if located below elevation 4810.

Test 1114, Figure 23, shows a cold hypolimnion located well below the crest of the barrier dam, with a very steep thermocline and relatively deep epilimnion. Cold water was introduced during the test. The effect of withdrawal was confined to the region below the crest of the barrier. For the "static" condition at Time 1020, warmer temperatures at the FHOW show that the layer of cold water is deeper at the gorge outlet, directly opposite the breach in the barrier. This effect also appears during withdrawal at Time 1050, along with the drawdown effect at both the GOW and the FHOW. Figure 24 shows the shape of the interface between the epilimnion and thermocline.

Test 1203, Figure 25, simulated a deep epilimnion extending below the barrier crest, and a thermocline

Table 2

Model Test Conditions

Test	Reservoir elevation feet (meters)	Discharge range cfs (cu m/sec)	Outlets operated	Comments
With breach and adit open:				
0924	4796.7 (1462.0)	500-2,000 (14.2-56.6)	GOW, LROW	Minimum reservoir
0930	4800 (1463.0)	500-1,000 (14.2-28.3)	GOW, LROW	
1002	4796.7 (1462.0)	500-1,000 (14.2-28.3)	MROW	
1007	4840 (1475.2)	500-5,000 (14.2-141.5)	GOW, LROW, MROW, RROW	
1014	4810 (1466.1)	500 (14.2)	GOW	
1023	4796.7± (1462.0)	500-1,000 (14.2-28.3)	GOW, LROW	
1114	4835-4845 (1473.7-1476.8)	4,000 (113.2)	GOW, MROW, RROW	
1203	4849 (1478.0)	1,900 (53.8)	GOW, LROW	
0127	4846 (1477.1)	1,095 (31.0)	GOW, LROW	
0129	4836 (1474.0)	300 (18.5)	SOW	
0317	4855-4817 (1479.8-1468.2)	2,000 (56.6)	GOW, LROW	
With breach and adit closed:				
0408	4854-4814 (1479.5-1467.3)	2,000 (56.6)	GOW, LROW	For comparison with 0317

extending to the reservoir bottom. During withdrawal, the thermistors upstream from the barrier showed cooling below the barrier crest, while those at the FHOW and GOW increased in temperature, except very near the reservoir bottom. Cooler water entering the model prior to Time 1320 was retarded by the barrier, with some flow through the breach to the GOW. The skimming effect of the barrier was again observed.

Test 0127, Figure 26, shows a relatively thick thermocline, with a well-developed epilimnion and hypolimnion. The static condition shows a relatively constant stratification throughout the model. Ten minutes of withdrawal markedly changed this pattern. Temperatures near the bottom of the reservoir remained relatively constant, but some mixing and cooling at the FHOW was noted. Warming at the GOW was due to drawdown. The cooling at the FHOW could not be explained.

Test 0129, Figure 27, was performed to determine the effects of withdrawal from the south outlet works (SOW) which will be used for municipal water supply. The outlet works was operated at its capacity of 300 cfs (8.5 cms). Temperatures at the FHOW were warmer than those at the GOW during withdrawal, due to drawdown as shown in Figure 28. In the upper portion of the reservoir, temperatures at the GOW and FHOW were cooler than those upstream from the barrier because of the inflow of warm water. The pattern at Time 0930 and the outflow temperature suggest that warmer water is being skimmed from the reservoir above the elevation of the barrier crest.

Conclusions from first test series.—The tests showed conclusively that the barrier dam acted to skim warmer water from the reservoir above the barrier crest, as shown in Figure 29. The extent of warming depended upon the stratification pattern and the discharge; most tests indicating warming of 1° C or less. Temperatures near an outlet are warmed because of the drawdown of higher layers during operation of the outlet, Figure 30. The extent of the drawdown influence is determined by the stratification pattern and the discharge.

In the early part of the study, removal of all or part of the barrier dam was considered a possibility. However, it was later decided that the barrier dam would be retained and that the breach and the access adit would both be plugged for the purpose of blocking sediment to the 100-year accumulation level.

Final test series.—The adit and breach, to elevation 4778 (1456.3 m), were plugged in the model with sand and gravel, Figure 31. A final series of model tests was performed to determine the effect of these closures on water temperatures at the fish hatchery outlets.

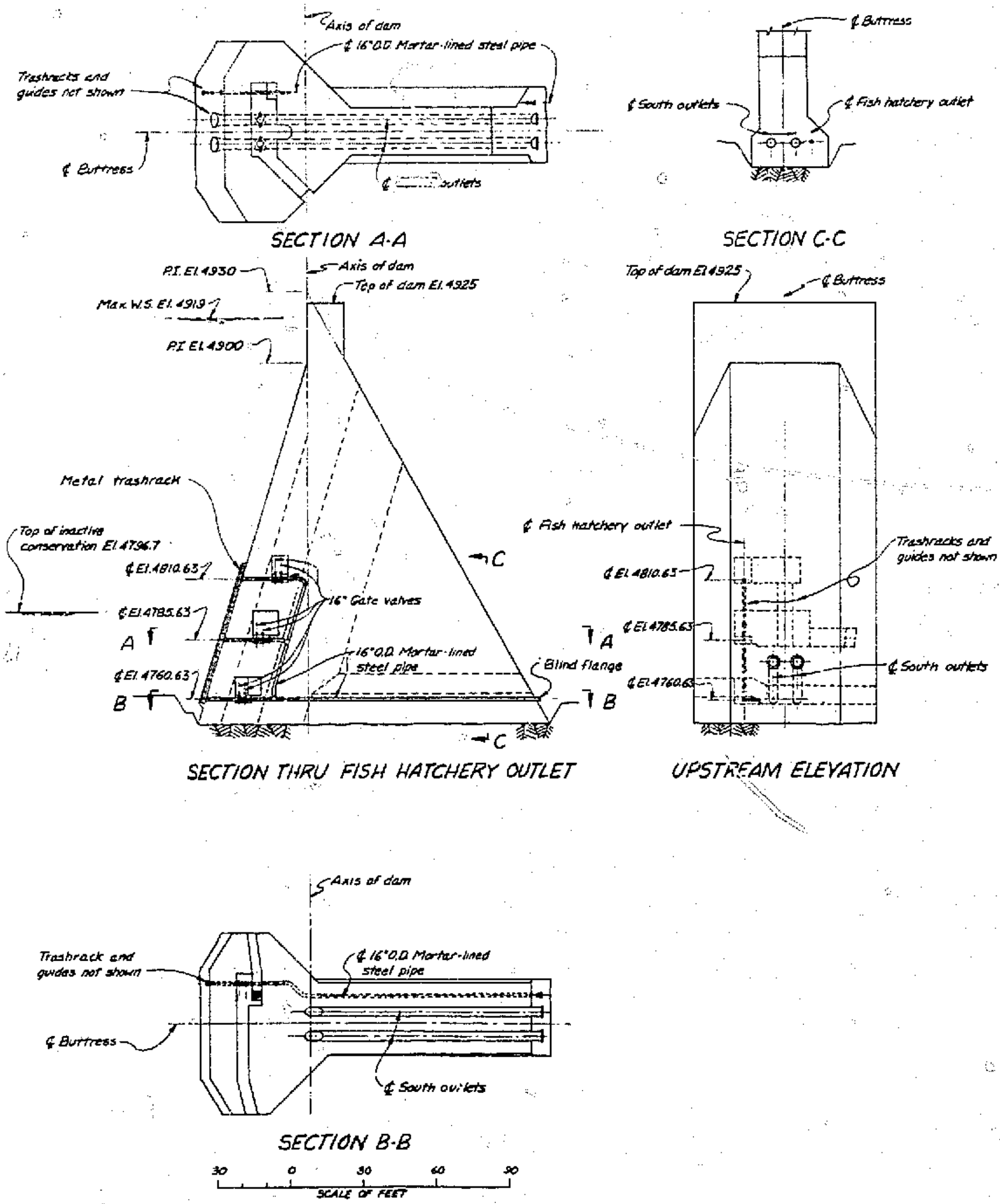

Figure 16. Preliminary design of fish hatchery outlet works.

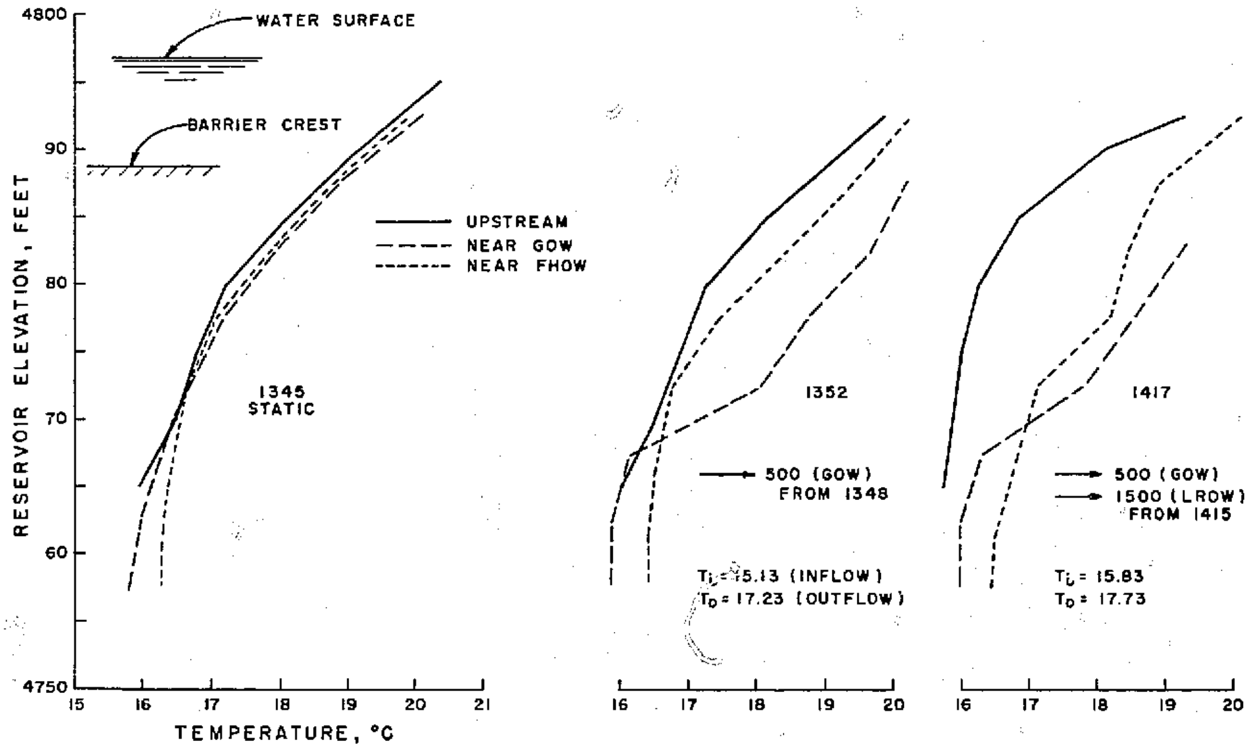

Figure 17. Test 0924.

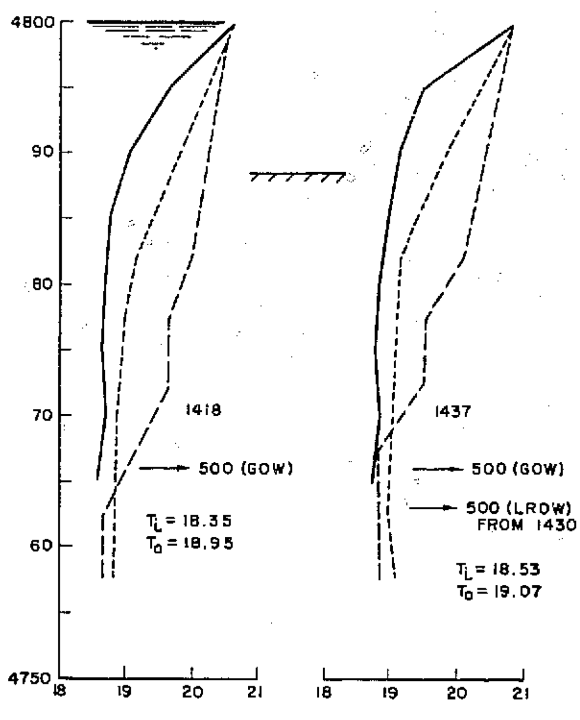

Figure 18. Test 0930.

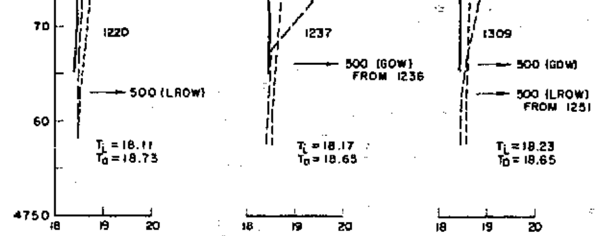

Figure 19. Test 1023.

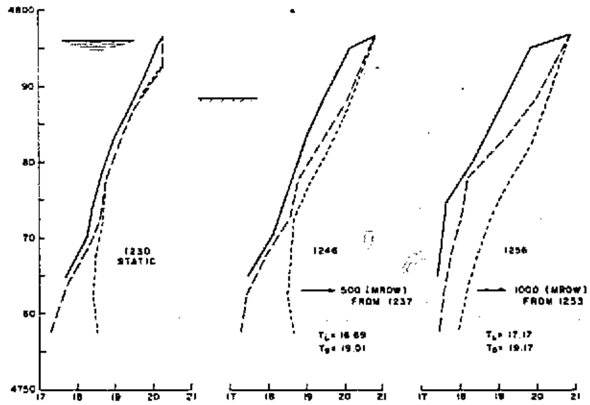

Figure 20. Test 1002.

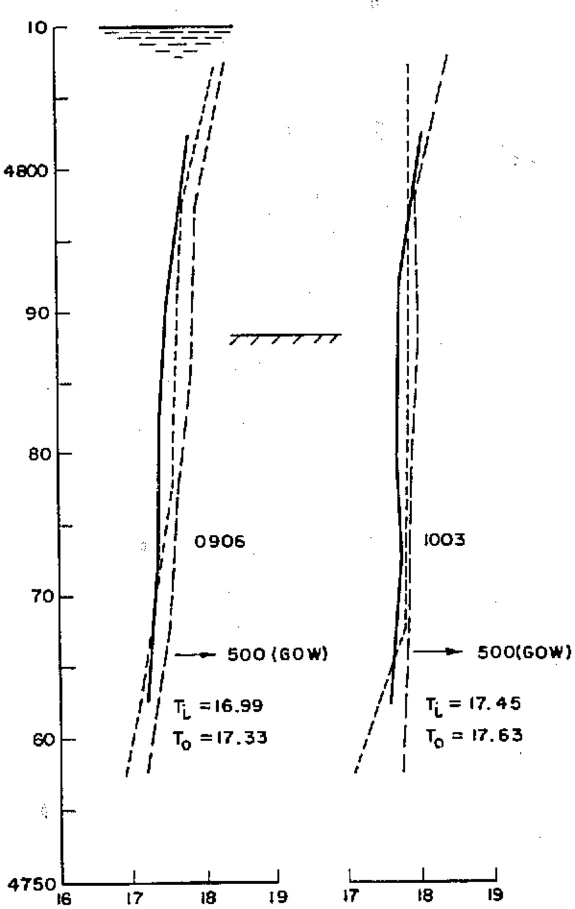

Figure 21. Test 1014.

Tests 0317 and 0408, Figure 32, with essentially identical temperature profile shapes, were performed with and without the closures, respectively.

Warmer temperatures downstream from the barrier were apparent for either condition, but, as expected, the difference was slightly more pronounced with the breach closed. Overall cooling of the hypolimnion was caused by the inflow of cold water prior to Time 1030. Apparently, the velocity or depth (or both) of the cold water inflow was sufficient to penetrate into the region downstream from the barrier dam. The temperature profiles show that temperatures at the upstream side of the barrier are cooler than either the FHOW or the upstream wall of the model. This suggests that cooler bottom flows may be impinging on the barrier, rising above the barrier, then sinking to the bottom again on the downstream side of the barrier.

Recommended Configuration of the Fish Hatchery Outlet Works

The mathematical and hydraulic model studies resulted in the recommendation that an additional, higher outlet be placed at elevation 4850 (1478.3 m). Even though this outlet would likely be above water most of the year, it would provide earlier withdrawals of warmer water for the fish hatchery. The recommended configuration therefore included outlets at invert elevations 4760 (1450.8), 4785 (1458.5), 4810 (1466.1), and 4850 (1478.3) feet (meters). The outlet pipes were also changed from 16-inch (40.6-cm) diameter to 30-inch (76.2-cm) diameter, with a resulting increase of total capacity from 16 cfs (0.5 cms) to 30 cfs (0.8 cms).

Other Water Quality Considerations

The question of the movement of suspended sediment was raised during the study. The mathematical model predicted that inflows from the Arkansas River would be warmer than the reservoir and thus flow at the reservoir surface. However, high concentrations of suspended material might sufficiently alter the density to cause interflows or bottom density currents. A density current of low velocity would probably be blocked by the barrier dam and deposition would occur upstream from the barrier. An interflow higher in the reservoir or a high-velocity bottom density current would tend to pass over the barrier. Also, large floods carrying large quantities of suspended material would tend to cause mixing of the reservoir with dispersion of the material throughout the depth.

Dissolved oxygen should normally be adequate at all times and at all locations in the reservoir, since the reservoir will be isothermal during most of the year with wind-induced mixing and accompanying atmospheric reaeration.

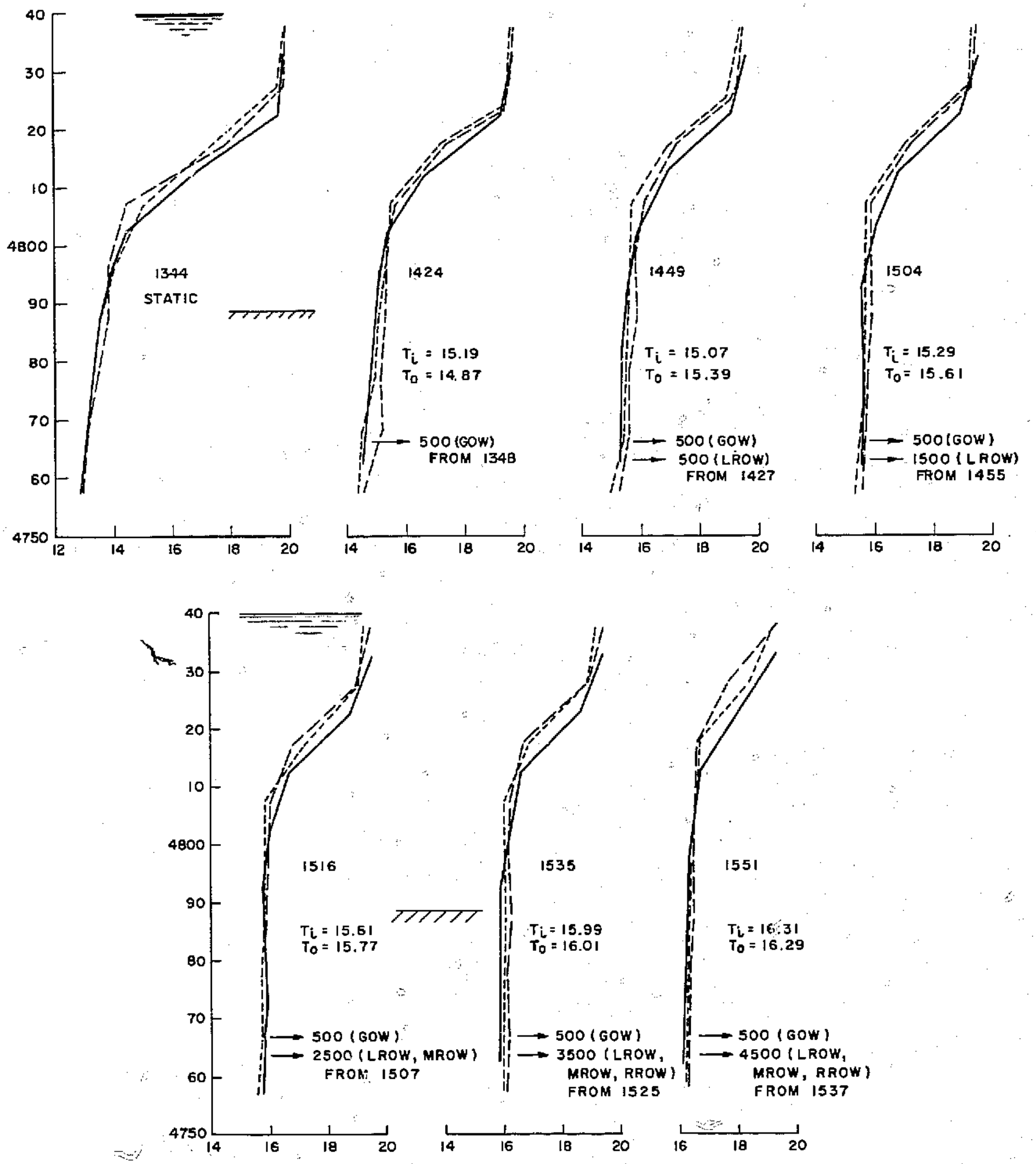

Figure 22. Test 1007.

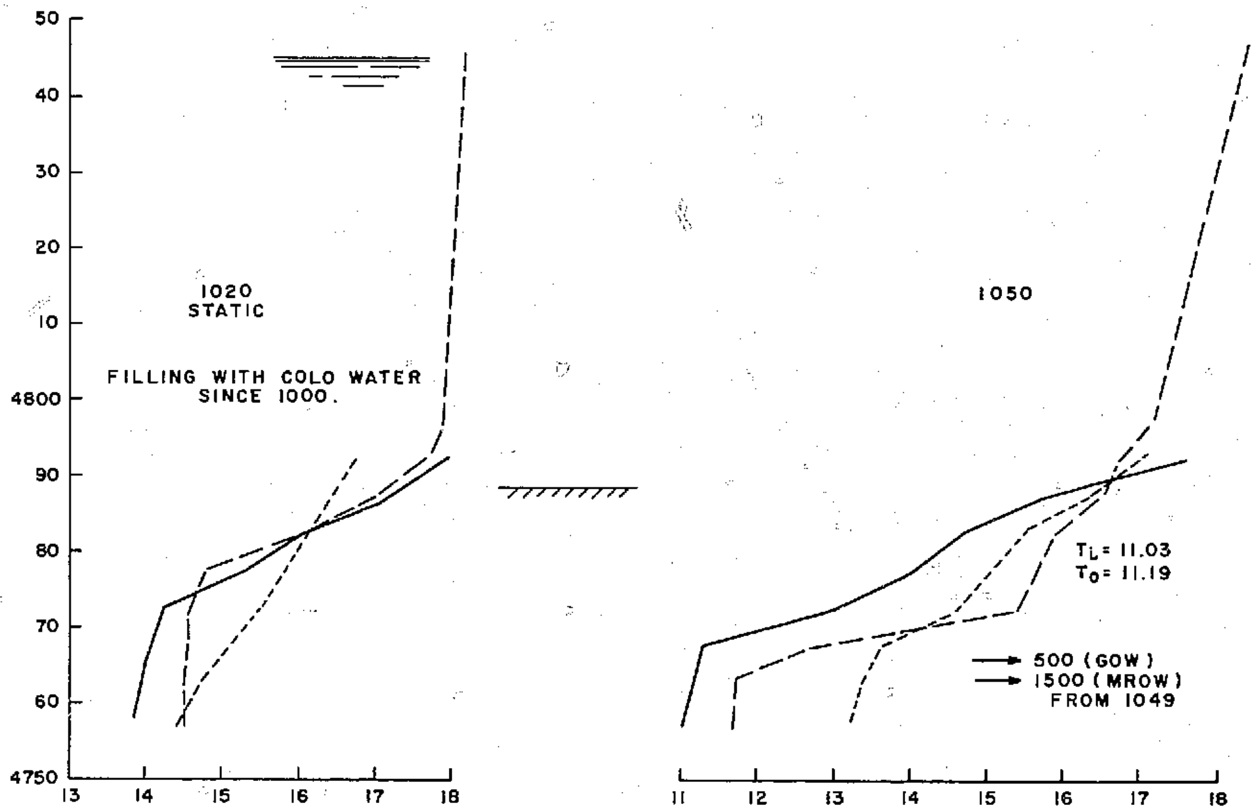

Figure 23. Test 1114.

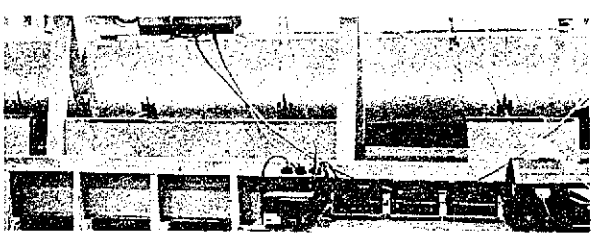

Figure 24. Interface shape due to drawdown at gorge outlet and middle outlet. Photo P382-D-69420.

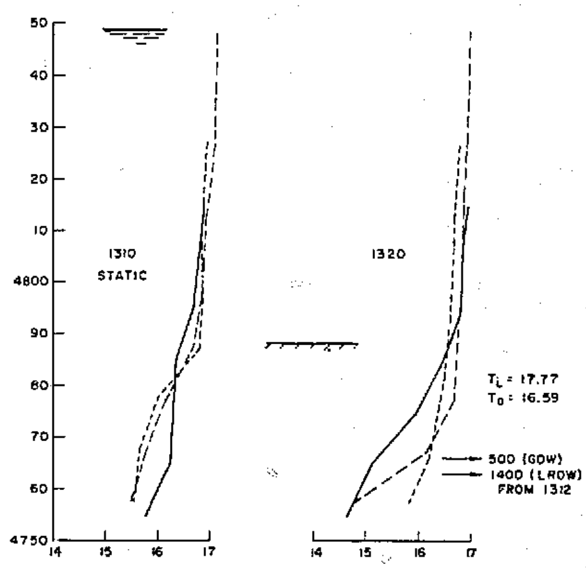

Figure 25. Test 1203.

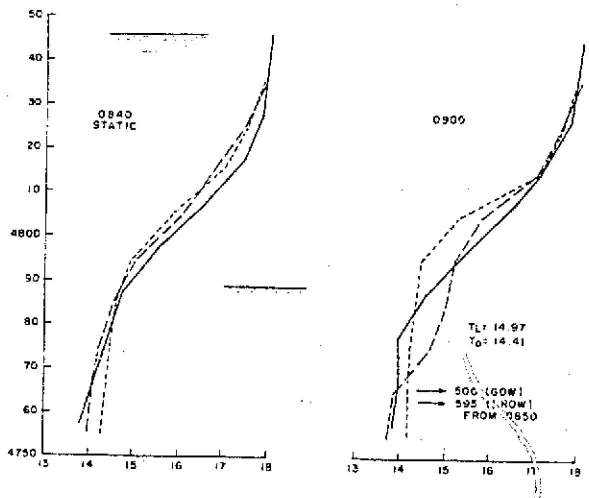

Figure 26. Test 0127.

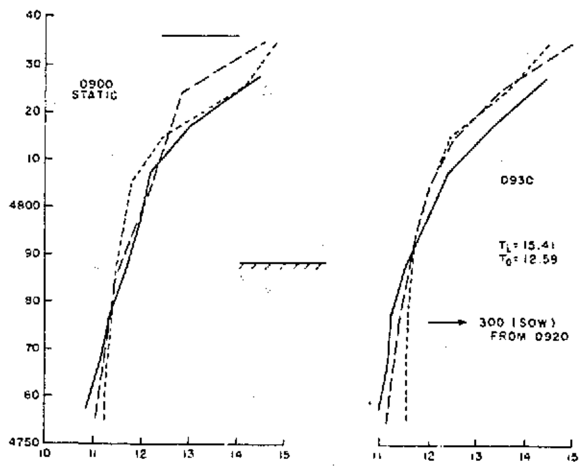

Figure 27. Test 0129.

Figure 28. Drawdown at south outlets. Photo P382-D-69421

Figure 29. Stratified flow pattern over Rock Canyon Barrier Dam. Photo P382-D-69422

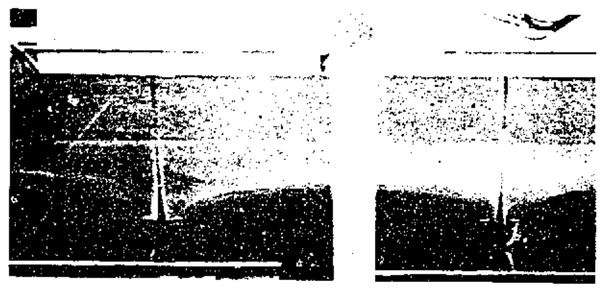

Figure 30. Drawdown at outlets. Photo P382-D-69423

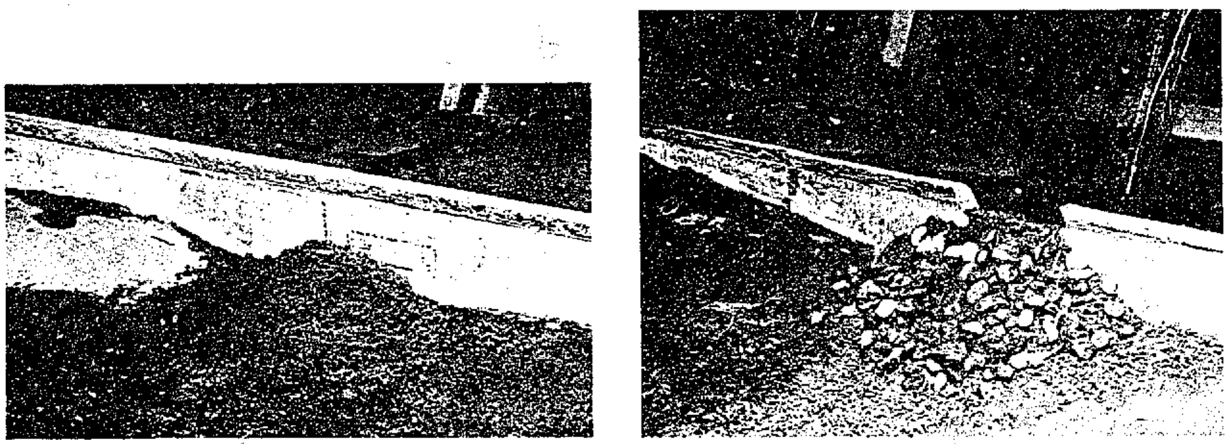

Figure 31. Plugs at access adit and breach. Left Photo P382-D-69424. Right Photo P382-D-69425.

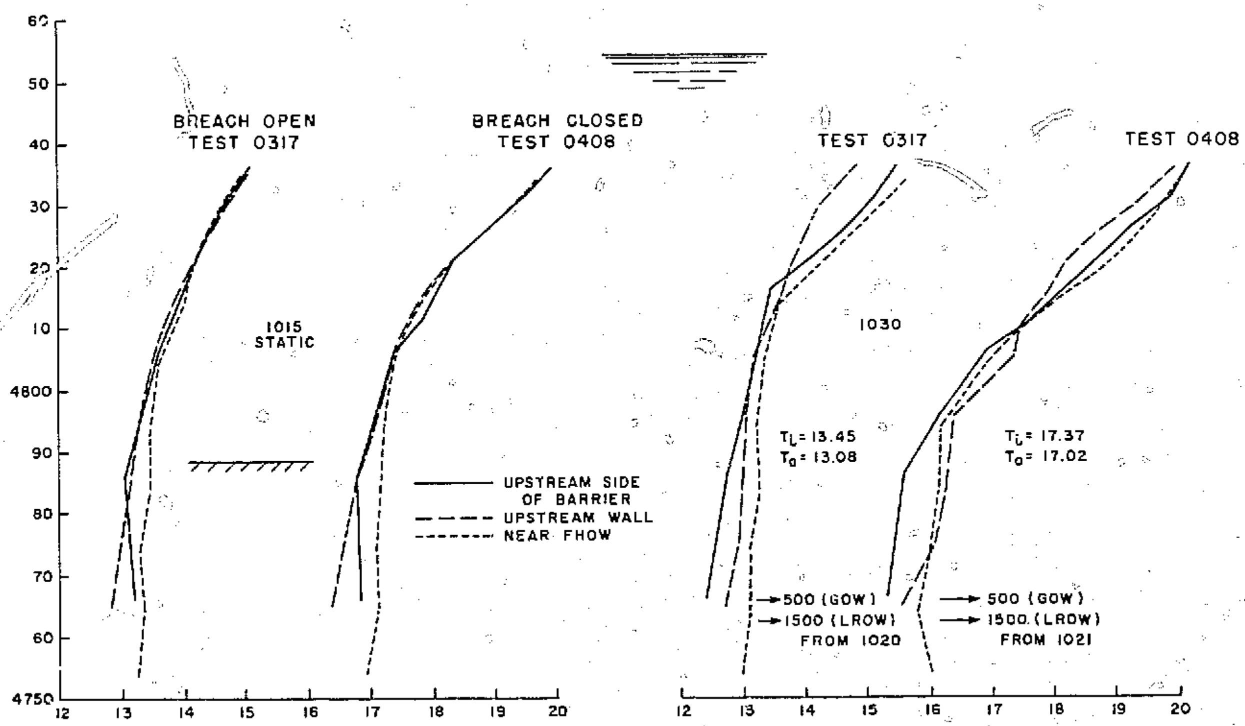

Figure 32. Test results showing effects of breach closure.

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^5	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	$*0.965873 \times 10^{-6}$	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	$*4.4482 \times 10^5$	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor) transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 839-300

ABSTRACT

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REC-ERC-71-32
King, D L
SELECTIVE WITHDRAWAL STUDIES FOR THE FISH HATCHERY OUTLETS AT PUEBLO DAM
Bur Reclam Rep REC-ERC-71-32, Div Gen Res, Aug 1971. Bureau of Reclamation, Denver, 18 p, 32 fig, 5 tab, 2 ref

DESCRIPTORS—/ *reservoirs/ *hydraulic models/ density currents/ water quality/ *selective level releases/ hydraulics/ stratification/ *thermal stratification/ stratified flow/ *mathematical analysis/ fish/ outlets/ simulation/ fish hatcheries/ *multilevel outlets/ *mathematical models/ water temperature IDENTIFIERS—/ Pueblo Dam, Colo

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