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MATHMATICAL SIMULATION OF TEMPERATURES IN DEEP IMPOUNDMENTS

Verification Tests of the Water Resources Engineers, Inc. Model - Horsetooth and Flaming Gorge Reservoirs

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Successful use of predictive mathematical models requires verification of the accuracy of the models by applying them to existing situations where the prediction can be compared with reality. A Corps of Engineers' modification of a deep reservoir thermal stratification model developed by Water Resources Engineers, Inc., was applied to two existing Bureau of Reclamation reservoirs for verification. Diffusion coefficients used for the Corps' Detroit Reservoir were found to apply to Horsetooth Reservoir in Colorado, for which very good computer input data were available. The Detroit diffusion coefficients gave a reasonable simulation of Flaming Gorge Reservoir in Wyoming and Utah, which has very complex and variable physical characteristics and for which only average-quality computer input data were available.

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MATHEMATICAL SIMULATION OF TEMPERATURES IN DEEP IMPOUNDMENTS

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CONTENTS

CONTENTS—Continued

LIST OF TABLES

LIST OF FIGURES

PURPOSE

This report is part of a research project to find a mathematical model for predicting temperatures in impoundments that is both reasonably accurate and generally applicable throughout the U.S. Bureau of Reclamation's (USBR) area of operation. The temperature structure of a reservoir is of major importance to the quality of water both within the impoundment and in releases to the stream below. Therefore, the ability to predict the temperature regimen in an impoundment is valuable, both for planning the outlets and operating criteria of a proposed reservoir and for evaluating the environmental effects of various courses of action on an existing reservoir.

The studies discussed in this report evaluate the predictive capability of the model developed by Water Resource Engineers, Inc. (WRE), using prototype data from Flaming Gorge and Horsetooth Reservoirs as examples of large Bureau reservoirs.

Several other temperature prediction models are available, including those developed by MIT[8]* and the Hydrologic Engineering Center (HEC) of the Corps of Engineers.[5] These other models will be investigated and reported on as time permits.

CONCLUSIONS

1. The diffusion coefficients determined by the Corps of Engineers to apply to their Detroit Reservoir gave excellent simulation of 1965 temperature profiles for Horsetooth Reservoir and acceptable simulation of 1965 temperatures in Flaming Gorge Reservoir. Input data were of high quality in the former case and of only average quality in the latter case.

2. The authors concluded that the computer programs for the "initial" and "segmented" versions of the WRE model were excessively difficult to run and, therefore, attempts to verify these versions were abandoned.

3. Application of the Corps of Engineers' version of the WRE model was successful.

4. In the authors' opinions, the state-of-the-art of mathematical prediction of temperatures in reservoirs is as follows:

a. A reliable model for weakly stratified reservoirs remains to be developed.

b. Choosing correct "effective diffusion" coefficient in the WRE model could be a major problem.

c. Inadequate documentation and problems encountered in switching the model from one brand of computing machinery to another (e.g., from IBM to CDC) are major problems.

APPLICATION

The results of this study should be of general interest to anyone involved in prediction of temperatures in streams and reservoirs and of specific interest to investigators using this or other forms of the WRE model.

INTRODUCTION

The initial development of the WRE model for the California Department of Fish and Game was reported in 1967.[2] Verification of this version of the model was based on data from TVA's Fontana Reservoir.

In 1969, WRE issued a final report[3] to the Federal Water Pollution Control Administration (FWPCA) which described a version of the model which allowed segmenting the reservoir for simulation of weak stratification and tilted isotherms. After FWPCA completed its contract with WRE, the USBR obtained this version. This version, in addition to allowing simulation of weakly stratified reservoirs, also included selective withdrawal theory. The base simulation studies were conducted using data from the USBR Hungry Horse Reservoir in Montana. The simulation for weak stratification was applied to the Bureau's Lake Roosevelt behind Grand Coulee Dam.

The Corps of Engineers, North Pacific Division, issued a report in 1970[4] documenting a modification of the unsegmented WRE model. This version has been used quite extensively by the Corps (e.g., Detroit, Applegate, Dworshak, and Libby Reservoirs) and was obtained by the Pacific Northwest Regional Office of the USBR, who in turn provided it to the Denver Office. The Pacific Northwest Region performed a

*Numbers refer to references listed at the end of this report.

successful verification test on Anderson Ranch Reservoir and has applied the model for prediction of temperatures in the new Teton Reservoir.

In this report, the three versions described above are referred to as the "initial version," the "segmented version," and the "Corps' version," respectively.

THE MODEL

General Theory

The model theory is described in detail in a report[4] by the Corps' North Pacific Division as well as in two WRE reports[2 3] and a paper by Orlob and Selna[9]; a brief summary follows.

The basic assumption of this model is that all transfers of water and heat within the impoundment take place in the vertical direction; i.e., the impoundment is idealized as a one-dimensional system, Figure 1. The water mass is divided into horizontal, finite elements or "slices." The mathematical model then computes mass and energy balances for these elements from data on the inflows, outflows, reservoir characteristics, and meteorological parameters.

Mass transfers within the impoundment are carried out by advection along the vertical axis. An inflow enters the system at an elevation where the resident water has the same temperature, thus causing an upward flow in all the slices above this level. Similarly, outflows cause a downward flow through all the slices above the outlet. The most recent versions of the model incorporate a selective withdrawal theory in the computation of outflow temperature.

The transfer of heat energy is accomplished by four primary mechanisms: advection by inflows and outflows, radiant energy flux at the air-water interface, convective mixing associated with surface cooling, and "effective diffusion."[9] The first three mechanisms involve relatively straight-forward computations. The net energy passing the air-water interface is determined from an energy budget involving net short- and long-wave radiation delivered through the interface, long-wave radiation from the water body to the atmosphere, energy loss by evaporation, and sensible heat transfer between the water and the overlying airmass. Convective mixing associated with surface cooling (e.g., spring or fall "overturn") is handled by a convective mixing mode in the model program that is initiated when any element has a lower computed temperature than one below it.

The fourth energy transfer mechanism is more complex and constitutes the crux of the model. Orlob and Selna[9] explain it as follows:

> "The term 'effective diffusion' as it is used herein connotes a process of mixing of fluid masses and their associated properties which is analogous statistically to that of the more classical molecular diffusion, but proceeds at a much greater rate. It may be taken to include molecular diffusion, eddy viscosity, and certain larger fluid motions of the random sort which cannot otherwise be described as simple advection. To a limited extent 'effective diffusion' may also be used to describe the spatial nonuniformities of shear flows, sometimes designated as 'advective dispersion'."

In the model, the process is represented by an empirically determined "effective diffusion coefficient" which is assumed to vary in both time and space. More will be said about this coefficient later.

Finally, the FWPCA version of the WRE model allows the option of segmenting a weakly stratified impoundment in which the isotherms are tilted along the longitudinal axis. The computed conditions at the downstream end of a segment are then used as the

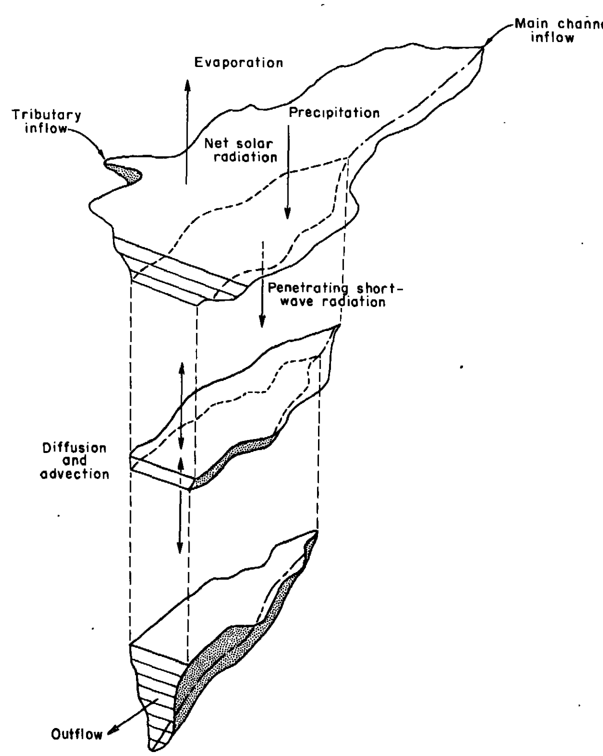

Figure 1. Heat and mass flow diagram for WRE model (from[2]).

upstream boundary conditions for the next segment. The Corps' version of the model, however, does not contain this option.

Data Requirements

The input data required for this model are summarized in Table 1 and discussed in more detail below.

Meteorological.—The five parameters listed in Table 1 are most commonly used with this model,[4] but others may be substituted. Dew point or relative humidity may be used in place of wet bulb temperature in the evaporation calculations. Of course, when evaporation is measured directly, it is possible to eliminate the need for windspeed and barometric pressure as well as any of the humidity data. Cloudiness, which is used in the computation of net short- and long-wave radiation, is unnecessary when these quantities are measured directly. Finally, barometric pressure can be measured either directly or estimated in the program from data on the impoundment's altitude and geographical location.

Inflow and outflow.—The measurement of these parameters is relatively simple. It should be emphasized, however, that data are necessary for all outlets and all inflows, both main and tributary. Small, ungaged streams, springs, and other miscellaneous inflows are sources of error.

Reservoir characteristics.—Three parameters warrant further discussion here: the solar extinction depth, the evaporation coefficients, and the effective diffusion coefficient.

Depending on the turbidity of the water, the model generally uses an assumed vertical distance in which short-wave solar energy is absorbed (usually from 1 to 10 meters). In practice, a depth within this range is specified as a constant in the model. It would be desirable to use Secchi disk determinations of the solar extinction depth at various times of the year. These determinations could be made on the prototype impoundment or, in the case of a proposed reservoir, on a similar reservoir.

To compute the evaporation rate, E, the model uses an equation that requires the specification of two coefficients, A and B. The equation is of the form:

$$E = (A+BV)\,(e_o - e_a) \qquad (1)$$

Table 1

INPUT DATA REQUIRED FOR TEMPERATURE PREDICTION

Data file	Parameter	Units,	Frequency (Δt = 1 day)
Meteorological	Cloudiness	percent (decimal)	Daily average
	Wind velocity	meter/sec	Daily average
	Dry bulb temperature	^oC	Daily average
	Wet bulb temperature	^oC	Daily average
	Barometric pressure	mb	Daily average
Inflow (for each inflow)	Inflow rate	cfs	Daily mean
	Inflow temperature	^oF	Daily average
Outflow (for each outlet)	Outlet elevation	feet	Constant
	Outflow rate	cfs	Daily mean
Reservoir characteristics	Elevation of bottom	feet	Constant
	Latitude and longitude	degrees	Constant
	Elevation-area table	acres and feet	Constant
	Initial surface elevation	feet	Single value
	Initial temperature profile	feet versus ^oF	Single value
	Solar extinction depth	—	*
	Evaporation coefficients	—	*
	Diffusion coefficients	—	*

*See discussion under "Reservoir Characteristics."

where V is the wind velocity, e_o is the saturation vapor pressure of the air at the temperature of the water surface, and e_a is the water vapor pressure. The evaporation coefficients are best derived from experience on either the prototype or a reservoir of similar characteristics.

Typical values used in these studies were: A = 0.0 meter/sec^{-1}mb^{-1} and B = 2.6 x 10^{-9}mb^{-1}. These coefficients may be dispensed with entirely if evaporation rate measurements are available for the impoundment under consideration.

As explained above, the effective diffusion coefficient represents a rather complex process of mixing within the impoundment. WRE[3] assumes that effective diffusion is primarily dependent upon wind mixing in the epilimnion, gravitation stability in the area of the thermocline, and deep water turbulence in the hypolimnion. The minimum effective diffusion takes place at the thermocline itself where the temperature (density) gradient, and thus the gravitational stability, are maximum. The maximum effective diffusion usually occurs at or near the surface of the impoundment where the amount of wind mixing is greatest. WRE therefore proposes that the functional form of the effective diffusion coefficient be as follows:

$$A(z,t) = A_o e^{-\eta(z_s - z)} \qquad z_E < z \quad , \qquad (2\text{-A})$$

$$A(z,t) = bE^{-a} \qquad z_H < z < z_E, \qquad (2\text{-B})$$

$$A(z,t) = c \qquad z < z_H \qquad (2\text{-C})$$

where E is the gravitational stability, z_s is the water surface elevation, and z_E and z_H are the elevations at which $E \sim 10^{-6}$ meters^{-1} and $E = (b/c)^{1/a}$, respectively. The value of η is chosen so that $e^{-\eta(z_s - z_E)} = \frac{b}{A_o}(10^{-6})^{-a}$, where A_o is the effective diffusion at the surface of the impoundment. Because of the difficulty of determining A_o, the Corps of Engineers' version of the model makes A_o = c and η = 0, while the values of E that define elevations z_E and z_H are made equal and are called E_c, the critical stability. The functional form of the effective diffusion coefficient thus becomes:

$$A(z,t) = c \qquad E \leq E_c \qquad (3\text{-A})$$

$$A(z,t) = bE^{-a} \qquad E > E_c \qquad (3\text{-B})$$

where $E_c = (b/c)^{1/a}$. At present, the constants a, b, and c must be determined empirically, using observed temperature profiles from the prototype or a similar impoundment.

Limitations

The accuracy of the model output is directly dependent upon the quality of the input data. For example, when mean daily values are supplied for some parameters and hourly values for others, a model response at the shorter time step should be interpreted with caution. The model is insensitive to events of a shorter duration than the simulation time step being used.

To achieve an accurate mass balance and to properly account for advected heat energy, it is imperative that the amounts and temperatures of all inflows to the impoundment, as well as the amounts of all outflows, be included in the computations. The meteorological and hydrological data should be synoptic and should be obtained directly from the prototype impoundment. When it is necessary to use synthesized data or data from a different but similar impoundment, proper caution should be maintained in interpreting the results of the model simulation.

The effective diffusion coefficient plays a crucial role in the functioning of the model. The continuous function form of this coefficient as shown in equations 3-A and 3-B is the one recommended by WRE.[3] This functional form is based on the gravitational stability of the water, E, as defined by:

$$E = -\frac{1}{\rho}\frac{\partial \rho}{\partial z} \qquad (4)$$

where ρ is the water density and z is the elevation. The model computes the density of the water solely on the basis of temperature so that density alterations caused by suspended or dissolved materials are not taken into account. When using the continuous function form, the choice of the value for E_c, the critical stability, has a major effect on the shape of the temperature profile. As mentioned previously, wind mixing in the epilimnion is included in only a very general way because of the difficulty of determining the value of A_o, the effective diffusion coefficient at the surface.

A step function form of the effective diffusion coefficient has been considered by WRE[3], but was rejected in favor of the continuous function form.

At present, the relatively poor level of understanding of the mechanics of internal mixing makes it necessary to obtain the effective diffusion coefficient from observed temperature data on either the prototype or a similar reservoir. This necessity constitutes a major constraint on the use of the model for predicting temperatures in a proposed reservoir, because there is no certainty that the effective diffusion coefficient is representative of the proposed impoundment.

The Corps' version of the WRE model includes a subroutine (CURFIT) that fits a least-squares curve to the elevation-area table to improve interpolation. The model is very sensitive to the order of the equation that is used in this curve fitting. A sixth-order equation was necessary for accurate results in the Flaming Gorge tests, while a second-order equation sufficed for Horsetooth.

The final point to be considered is that the original program[4] obtained from the Pacific Northwest Regional Office was written for use on an IBM computer and had to be translated to run on the CDC computer used in this study. Because of storage limitations in the CDC computer, it was also necessary to trim the PLOT subroutine. The function of this subroutine is to print out graphs of various run parameters and simulation results. In this study, only the function of plotting the temperature profiles for each day of simulation output was used.

HORSETOOTH RESERVOIR VERIFICATION

Physical Characteristics of the Reservoir

A map of Horsetooth Reservoir is shown as Figure 2, with typical cross sections shown in Figure 3. The elevation versus area and volume curves for the reservoir are shown in Figure 4.

Horsetooth Reservoir, a feature of the Bureau's Colorado-Big Thompson Project, is located approximately 4 miles southwest of Fort Collins, Colo. The reservoir lies in a north-south-oriented trough bounded by ridges. Spring Canyon, Dixon Canyon, and Soldier Canyon Dams block natural drainage routes through the eastern ridge, while Horsetooth Dam and Satanka Dike close the north end of the trough. All of these structures are earthfill.

At maximum capacity, the water surface elevation is 5430 feet, resulting in a pool approximately 6.5 miles long and 0.5 mile wide with a surface area of 1,875 acres and a volume of 151,000 acre-feet.[10]

The Charles Hansen Feeder Canal, which enters near the southwest end of the reservoir, provides the main flow. During 1965, this flow ranged from 0 to 516 cfs.

The reservoir has two outlets: the Dixon Creek Feeder Canal supplied from Soldier Canyon Dam, and the Charles Hansen Canal supplied from Horsetooth Dam. These outflows ranged from 0 to 28 cfs and from 0 to 889 cfs, respectively, in 1965. Figure 5 graphs the inflows with inflow temperatures and the outflows. It should be noted that Horsetooth Reservoir was designed primarily for irrigation storage and that consequently there is a distinct cycle of filling and drawing down of the pool. The reservoir is filled during the months of April, May, and June, while the withdrawal period is August, September, and October.[10] In 1965, total reservoir volume varied from approximately 60,715 to 112,456 acre-feet (reservoir elevation 5373.40 to 5410.00 feet).

The outlets are located at elevation 5293 feet in Horsetooth Dam and elevation 5270 feet in Soldier Canyon Dam. The elevation of the reservoir bottom is at approximately 5212 feet.

Limnological Characteristics

Kenneth J. Stimpfl's thesis[10] describes a 1964-65 water-quality study of Horsetooth Reservoir, and is the basis for the following discussions.

Figure 6 shows superimposed temperature profiles at two reservoir sampling stations established by Stimpfl in 1965. Station 2 was located in the deep water behind Spring Canyon Dam, and Station 3 was similarly located behind Horsetooth Dam (Stimpfl's Station 1 was not used in this verification study).

These profiles show that the reservoir was isothermal in early April. Stratification was first noted on June 16, 1965, and reached a maximum in late July and early August when the thermocline occupied the 5- to 10-meter stratum. By September 7, the thermocline had been depressed to the 10- to 14-meter stratum. Stratification had almost completely decayed by October 30, and the reservoir was again relatively isothermal in early December. Station 2 (the upper end of the reservoir) lagged somewhat behind Station 3 (the lower end) in the depression of the thermocline. Stimpfl attributes the rapid depression of the thermocline at Station 3 to the large withdrawal of water during the late summer and early fall. During the winter months, the reservoir was covered by ice.

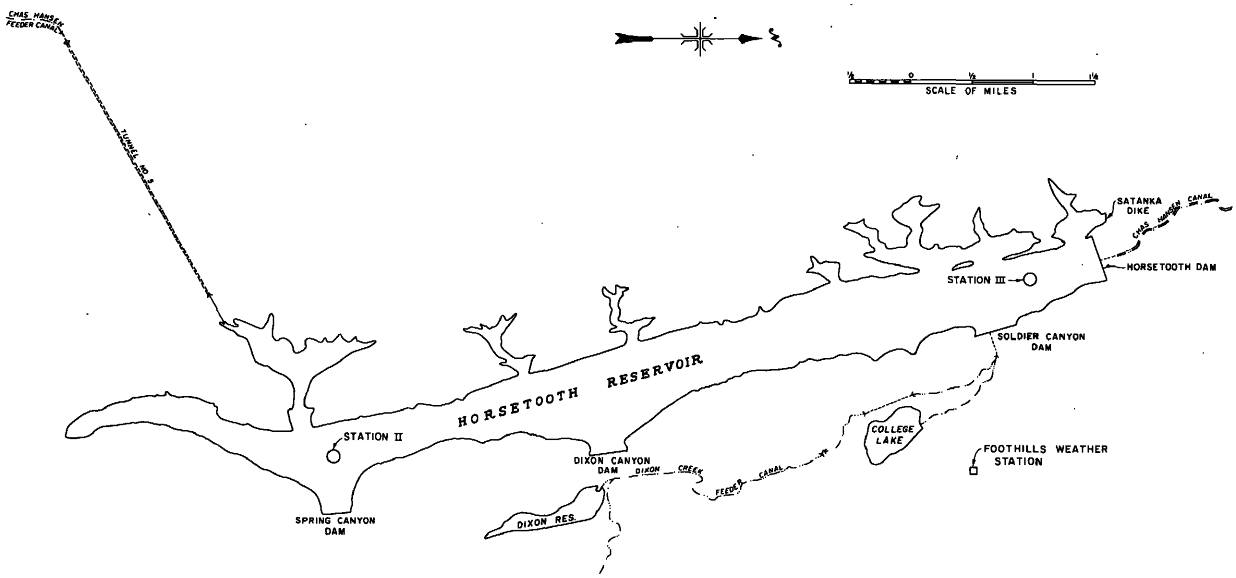

Figure 2. Map of Horsetooth Reservoir.

In summary, these temperature profiles indicate that the reservoir "turns over" twice a year, producing isothermal conditions in the late fall before the ice cover forms, and again in the early spring after the ice breaks up. Horsetooth Reservoir should therefore be classified according to Hutchinson[6] as a dimictic lake.

Dissolved oxygen profiles for 1965 indicate a depletion of hypolimnetic dissolved oxygen as the summer progresses. After the fall and spring overturns, however, oxygen is restored to the hypolimnion indicating that complete mixing takes place at these times.

Available Data

The year 1965 was selected for the Horsetooth Reservoir verification study. Data were compiled from three sources.

Nine temperature profiles at each of two stations in the reservoir were obtained from Stimpfl's thesis.

Meteorological data for 1965 were obtained from the records of the Colorado State University Foothills Weather Station. Twice daily, values of dew point temperature, dry bulb temperature, cloud cover, atmospheric pressure, and windspeed were available for use in the model verification. The location of Foothills Weather Station is shown on the map in Figure 2.

Data on the outflows, inflows, inflow temperatures, and the physical characteristics of the reservoir were obtained from the Lower Missouri Region of the USBR. Daily outflows were measured at Soldier Canyon and Horsetooth Dams. Daily inflows and inflow temperatures were measured in the Charles Hansen Feeder Canal at the Big Thompson wasteway about 9 miles upstream from Horsetooth Reservoir. Inflow temperatures for 1965 were not available, so records from April 22, 1969, through April 21, 1970, were used and assumed to be comparable to 1965.

Verification Tests

Evaporation function.—Because evaporation data were not available for these tests, Equation 1 (see Reservoir Characteristics) was used to calculate the evaporation rate. The values used for coefficients A and B were 0.0 meter/sec^{-1} mb^{-1} and 2.6 x 10^{-9} mb^{-1}, respectively.

Solar extinction.—No data on solar extinction were available for the Horsetooth tests, so a solar extinction depth of 10.0 meters was assumed.

Thermal diffusion.—The model represents this complex process with an "effective diffusion" coefficient. This coefficient, in turn, can have a variety of functional forms. In the Horsetooth verification tests, three different types of functions were used: the exponential function suggested by WRE (Equation 3), a constant value, and a step function. The 13 trials which were made using these three basic functions are summarized in Table 2.

The results of the first three trials are plotted with the observed temperature profiles in Figure 6. With the exception of Nos. 6 and 13, all the other trials gave

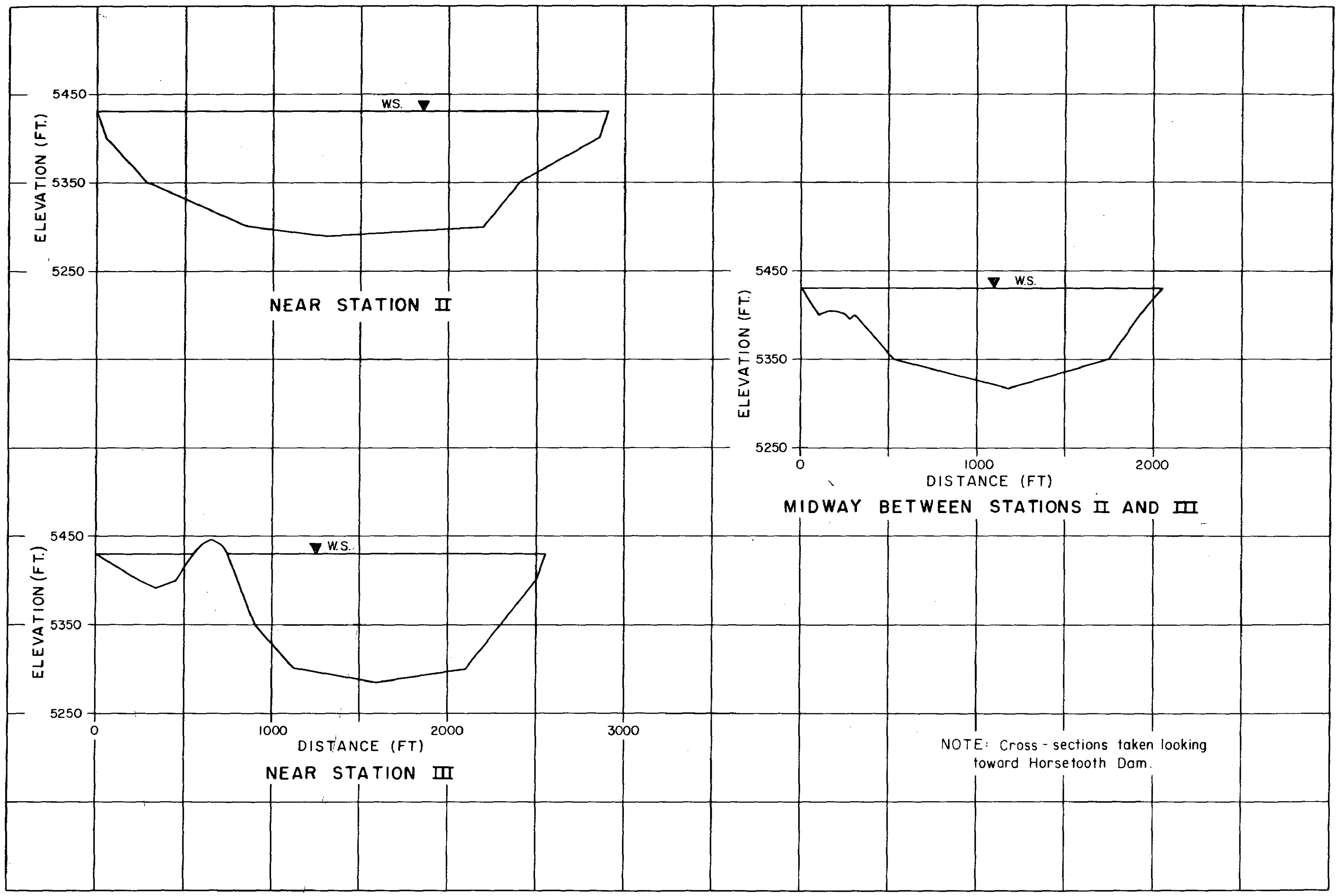

Figure 3. Typical cross sections—Horsetooth Reservoir.

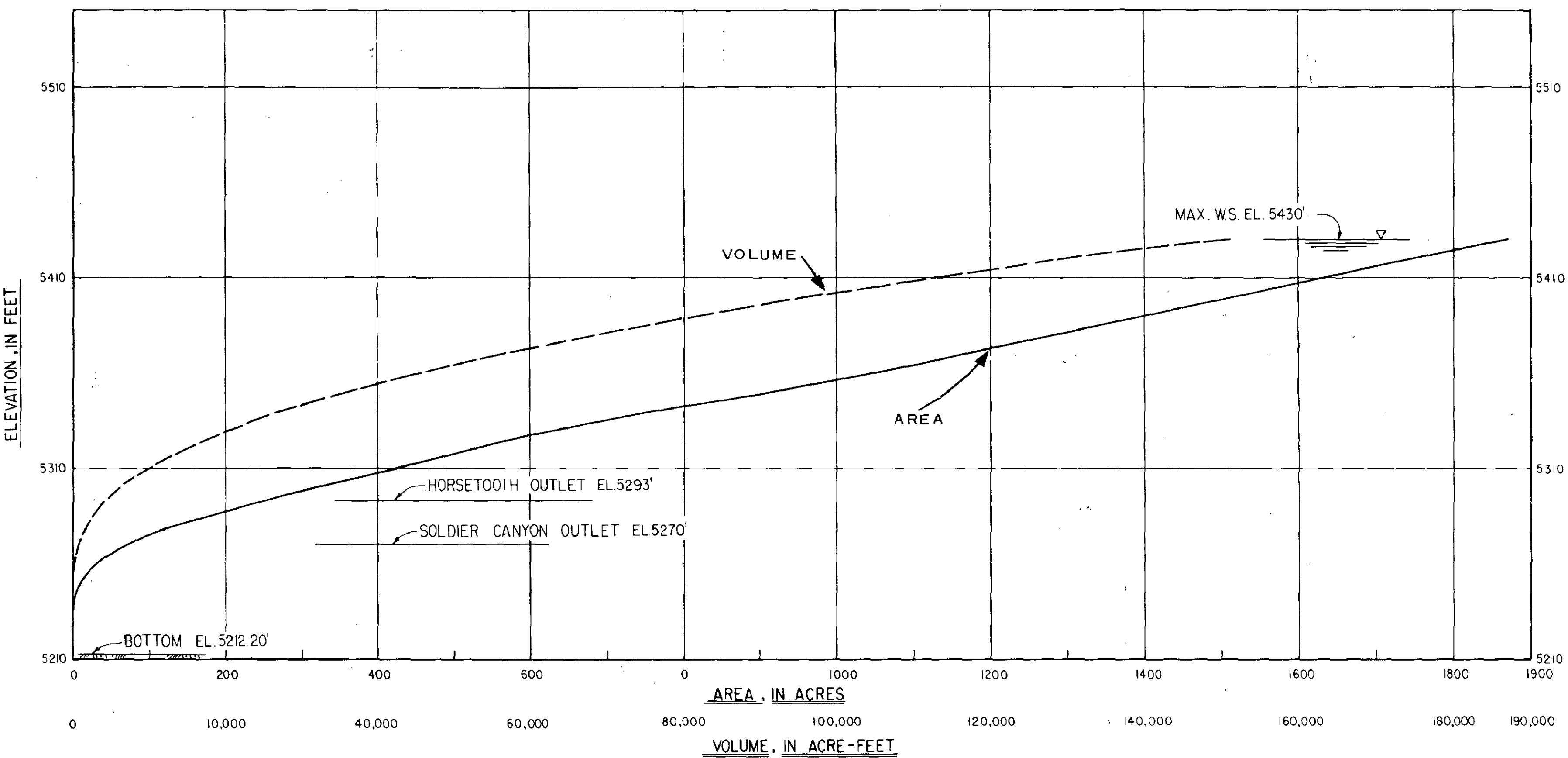

Figure 4. Elevation versus area and volume—Horsetooth Reservoir.

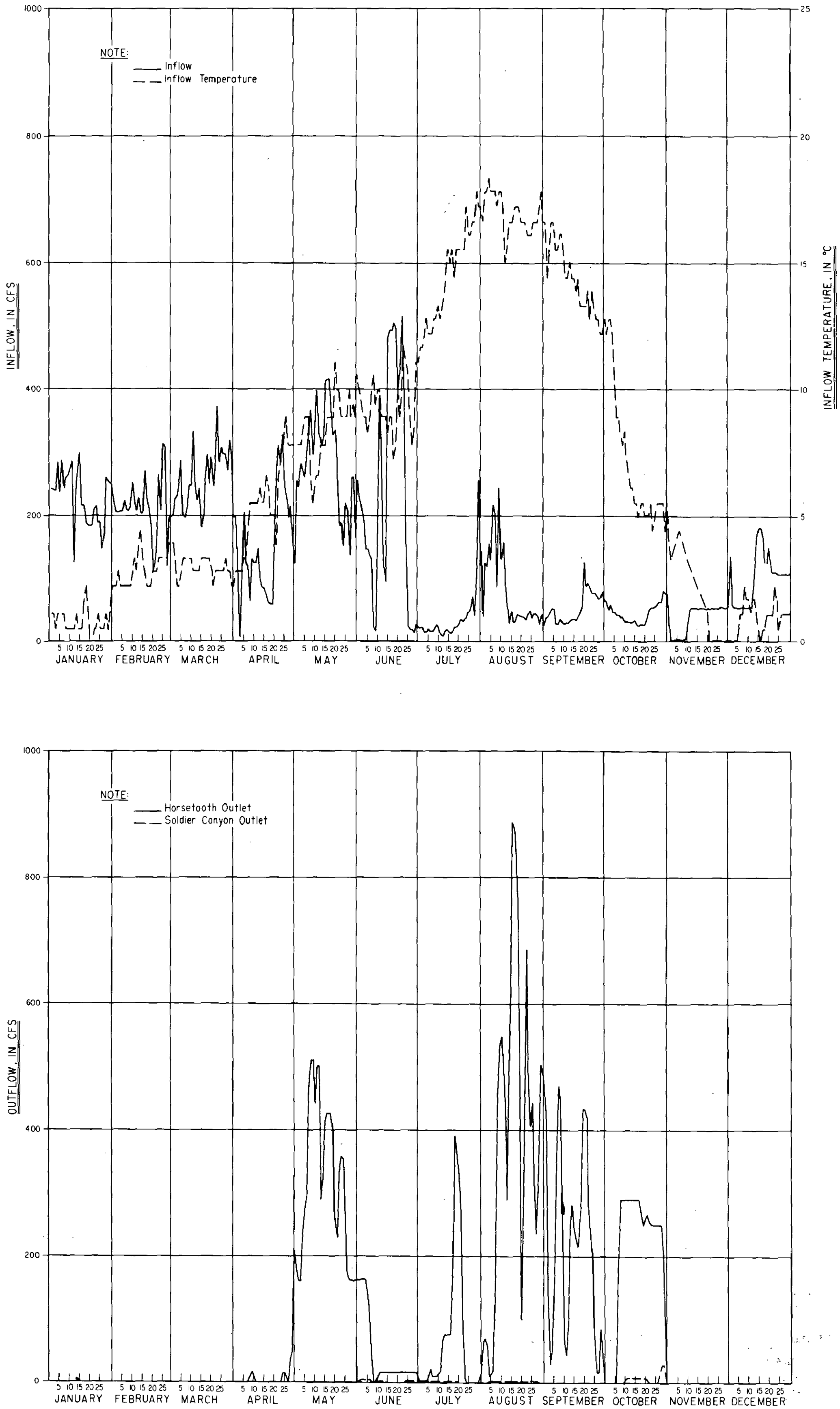

Figure 5. Horsetooth Reservoir inflows, inflow temperatures, and outflows—1965.

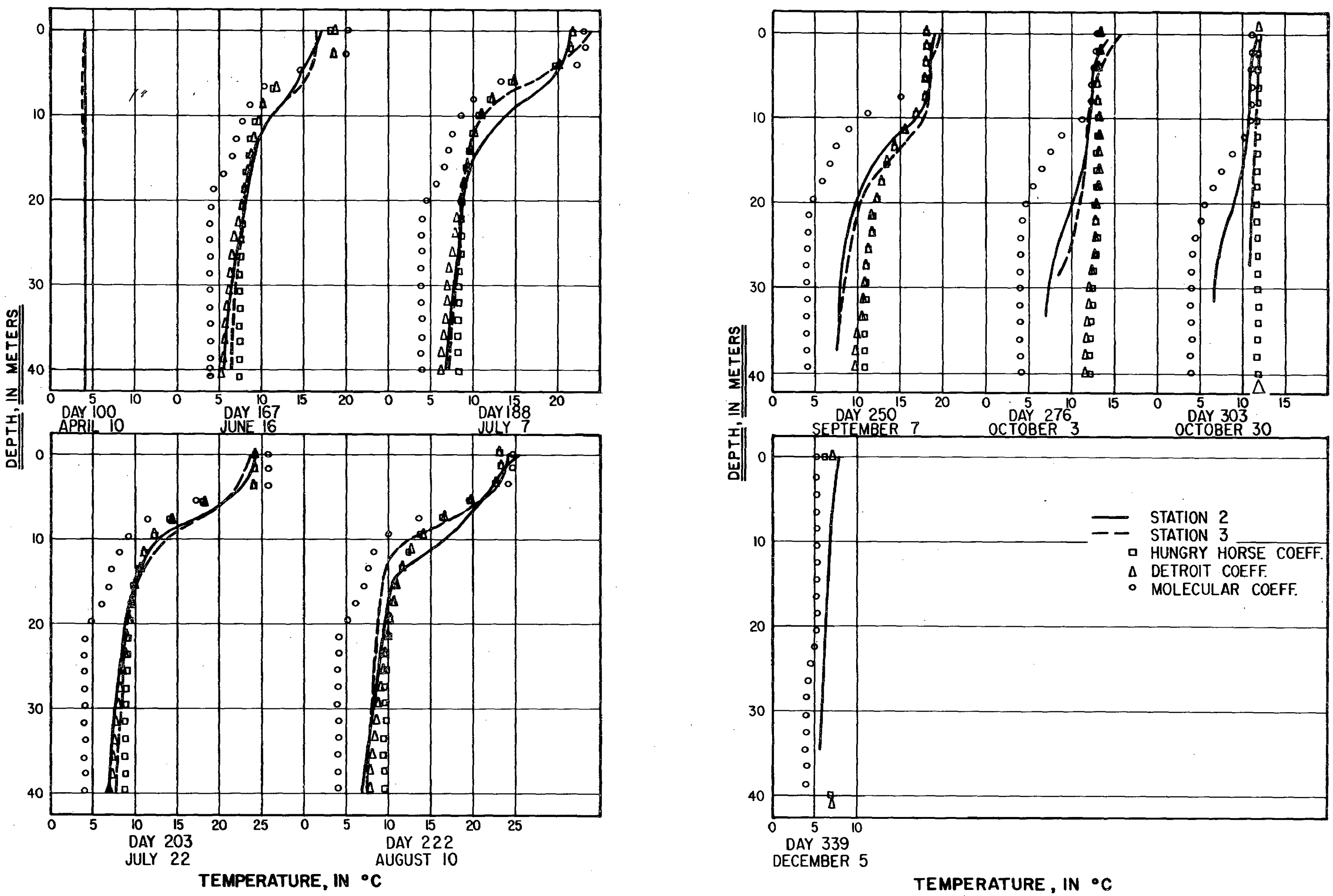

Figure 6. Observed and simulated temperature profiles, Horsetooth Reservoir—1965.

Table 2

HORSETOOTH VERIFICATION TRIALS

Trial	GMIN*	Function type	Parameters	Remarks
1	-0.1	Exponential	$E_c = 9.0 \times 10^{-7}$ $a = 0.7$ $c = 2.5 \times 10^{-1}$	WRE suggested values from Hungry Horse Reservoir
2	-0.1	Exponential	$E_c = 1.75 \times 10^{-5}$ $a = 0.7$ $c = 3.0 \times 10^{-2}$	WRE suggested values from Detroit Reservoir
3	-0.1	Constant value	$A(z,t) = 1.4 \times 10^{-7}$	Molecular diffusion (D_m) only
4	-0.1	Constant value	$A(z,t) = 1.5 \times 10^{-6}$	MIT estimate of molecular plus turbulent diffusion ($11 \times D_m$)
5	-0.01	Constant value	$A(z,t) = 1.5 \times 10^{-6}$	
6	-0.01	Step	$A(z,t) = 1.4 \times 10^{-7}$ $A(z,t) = 2.5 \times 10^{-1}$	$z \leqslant$ thermocline elevation $z >$ thermocline elevation
7	-0.01	Step	$A(z,t) = 1.4 \times 10^{-7}$ $A(z,t) = 2.5 \times 10^{-1}$	$z \leqslant$ elevation 56 meters $z >$ elevation 56 meters
8	-0.01	Step	$A(z,t) = 1.4 \times 10^{-7}$ $A(z,t) = 2.5 \times 10^{-1}$	$z \leqslant$ elevation 50 meters $z >$ elevation 50 meters
9	-0.01	Step	$A(z,t) = 1.4 \times 10^{-7}$ $A(z,t) = 2.5 \times 10^{-1}$	$z \leqslant$ elevation 58 meters $z >$ elevation 58 meters
10	-0.01	Step	$A(z,t) = 1.4 \times 10^{-7}$ $A(z,t) = 0.1 \times 10^{-9}$	$z \leqslant$ elevation 58 meters $z >$ elevation 58 meters
11	-0.01	Constant value	$A(z,t) = 0.0$	
12	-0.01	Exponential	$E_c = 9.0 \times 10^{-7}$ $a = 0.7$ $c = 1.4 \times 10^{-7}$	
13	-0.01	Step	$A(z,t) = 2.5 \times 10^{-1}$ $A(z,t) = 1.4 \times 10^{-7}$	$z \leqslant$ elevation 58 meters $z >$ elevation 58 meters

*Minimum allowable thermal gradient; controls convective mixing mode.

results very similar to those obtained in Trial 3. Trial 6 involved circular reasoning in calculating the thermocline elevation; consequently, the temperature profile was nearly isothermal throughout the simulation period. Trial 13 resulted in temperature profiles that were too warm in the lower layers.

The three trials plotted in Figure 6 are:

Trial 1.—Equation 3 with coefficients obtained by WRE for Hungry Horse Reservoir, Montana;
Trial 2.—Equation 3 with coefficients obtained by WRE for Detroit Reservoir, Oregon;

Trial 3.—The effective diffusion coefficient set equal to the coefficient of molecular diffusion of heat in water (i.e., turbulent diffusion is disregarded entirely).

Disregarding turbulent diffusion (Trial 3) resulted in simulated temperature profiles that were too cold in the thermocline and hypolimnion regions; i.e., too little heat was diffused into the lower layers of the reservoir. These results indicate the need for some diffusion mechanism in addition to molecular diffusion.

Trial 2 gave the best simulation of the observed profiles. Although Trial 1 was nearly identical to Trial 2 in the upper layers, the hypolimnion temperatures were up to 2^{o} C warmer during the period of maximum thermal stratification.

Even Trial 2, however, failed to accurately simulate the observed hypolimnion temperatures during the period of fall overturn (approximately day 250 through day 303). The model compressed this overturn period into less than a month, showing isothermal conditions to exist by early October. This "accelerated cooling in the fall of the year" has been noted in both WRE reports[2 3] and in the paper by Orlob and Selna.[9] The cause of this behavior is not known.

Summary

Compiled data for the year 1965 for Horsetooth Reservoir, Colorado, were used in verification runs of the Corps' version of the WRE model. Thirteen trials were completed and the best agreement with observed temperature profiles was obtained using WRE's exponential effective diffusion coefficient function as derived for Detroit Reservoir, Oregon. The model results closely paralleled the measured temperature profiles, except during the period of fall cooling, when they indicated an accelerated overturn. This accelerated fall cooling seems to be an inherent problem with the WRE model which has yet to be explained.

FLAMING GORGE RESERVOIR VERIFICATION

Physical Characteristics of the Reservoir

A map of the reservoir is shown as Figure 7, with typical cross sections shown in Figure 8. The elevation versus area and volume curves for the reservoir are shown in Figure 9.

Flaming Gorge Reservoir is quite atypical. The downstream reaches are in deep, steep canyons while the upstream reaches are located in a plains region. For this reason, the temperature profiles might be expected to vary considerably according to location in the reservoir. Application of the segmented version of the WRE model seemed appropriate; however, difficulties with this version resulted in a decision to switch to the Corps of Engineers' version.

Outflows from the reservoir have historically been entirely through the power turbines. During the test year 1965, outflows ranged from about 300 cfs to about 4,000 cfs.

Primary inflow is from the Green River with measured tributary inflows from Henry's Fork and Black's Fork. U.S. Geological Survey (USGS) records for 1965 show Green River flows varying from 300 to 16,700 cfs, Henry's Fork flows from 40 to 200 cfs, and Black's Fork flows from 20 to 1,680 cfs. Mean flows were 2,712, 260, and 236 cfs, respectively. Figure 10 graphs the outflows and inflows with inflow temperatures. For use in the model, the two primary tributary inflows were added together, and the temperatures were combined into a weighted average, Figure 11.

During 1965, total reservoir volume varied from approximately 0.5 to 2.5 million acre-feet (reservoir elevation 5900-6000 feet).

The power turbine intake is located in the concrete arch dam at elevation 5850. The reservoir bottom is approximately at elevation 5600 at the dam.

Limnological Characteristics

A joint report issued by the Utah State Department of Fish and Game and the Wyoming Game and Fish Commission in 1968,[1] describes a 1965-66 post-impoundment study of the reservoir.

Figure 12 shows temperature profiles at various stations throughout the reservoir for 1965 indicating significant differences during weak stratification, but only minor differences during strong stratification. The joint report showed that the canyon reaches lagged behind the plains reaches during both the warming and cooling cycles.

The profiles on Figure 12 also show that in the deeper reaches of the reservoir the temperature in the bottom 100-150 feet remains at 35^{o}-40^{o} F throughout the year.

Two periods of mixing, or "overturns," are indicated. The first occurs in late December or early January

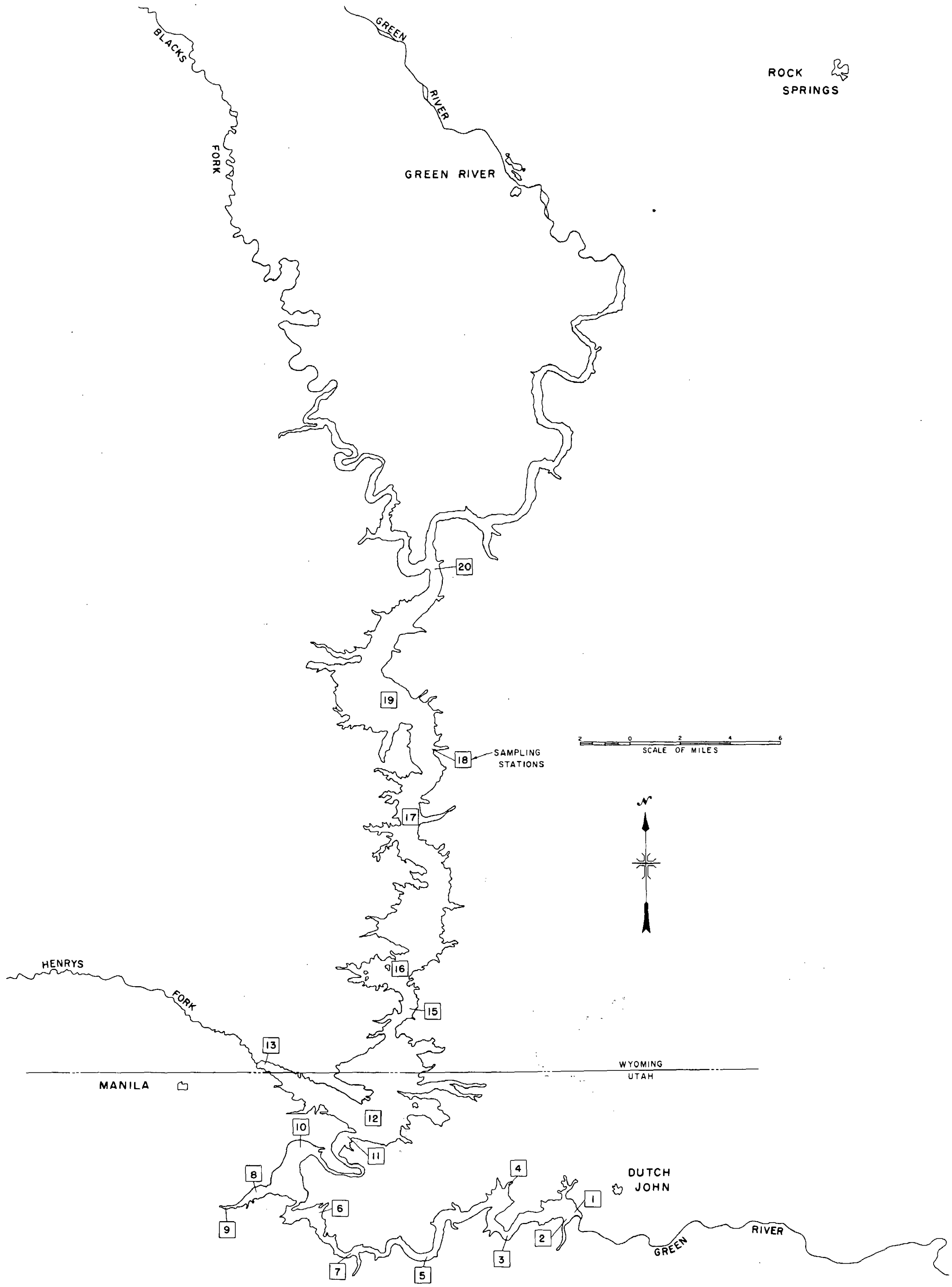

Figure 7. Map of Flaming Gorge Reservoir.

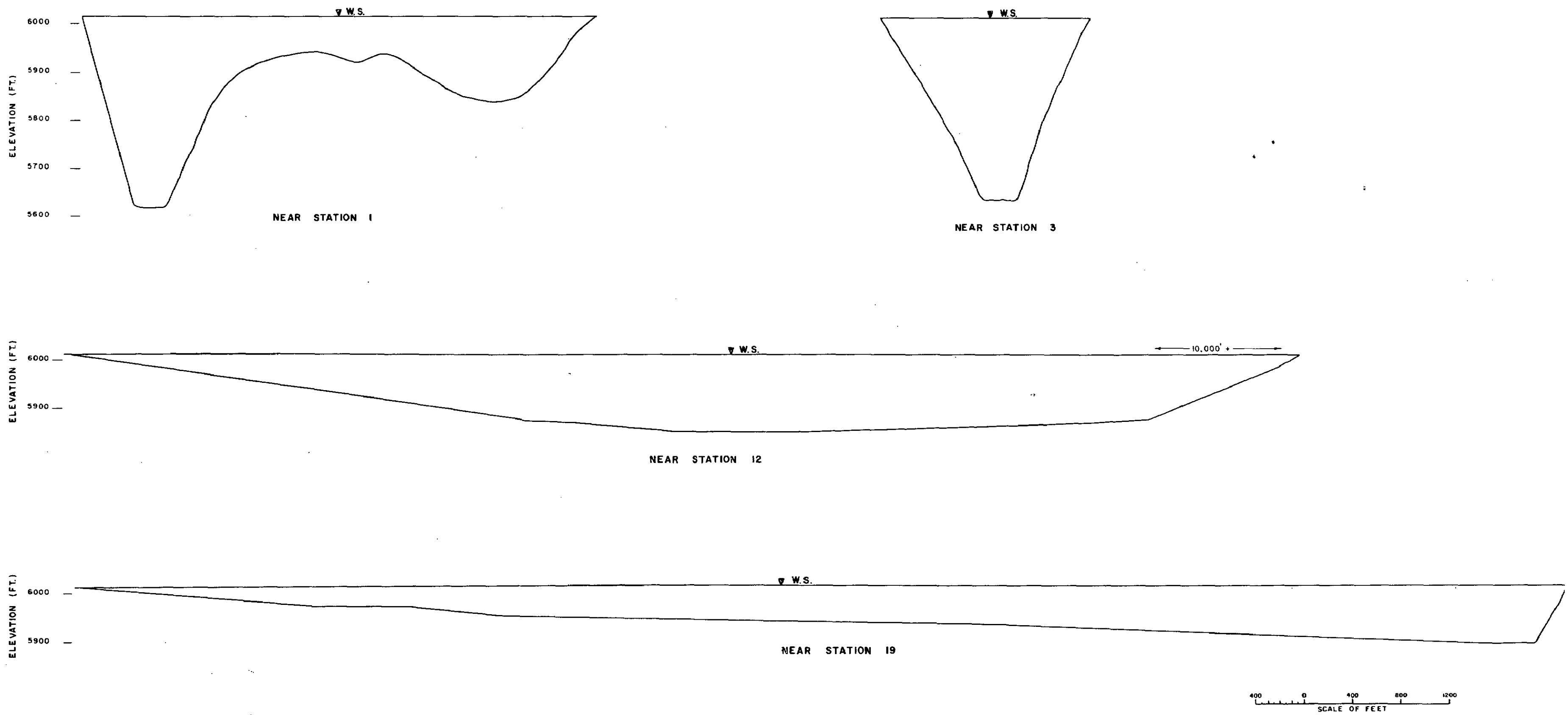

Figure 8. Typical cross sections—Flaming Gorge Reservoir.

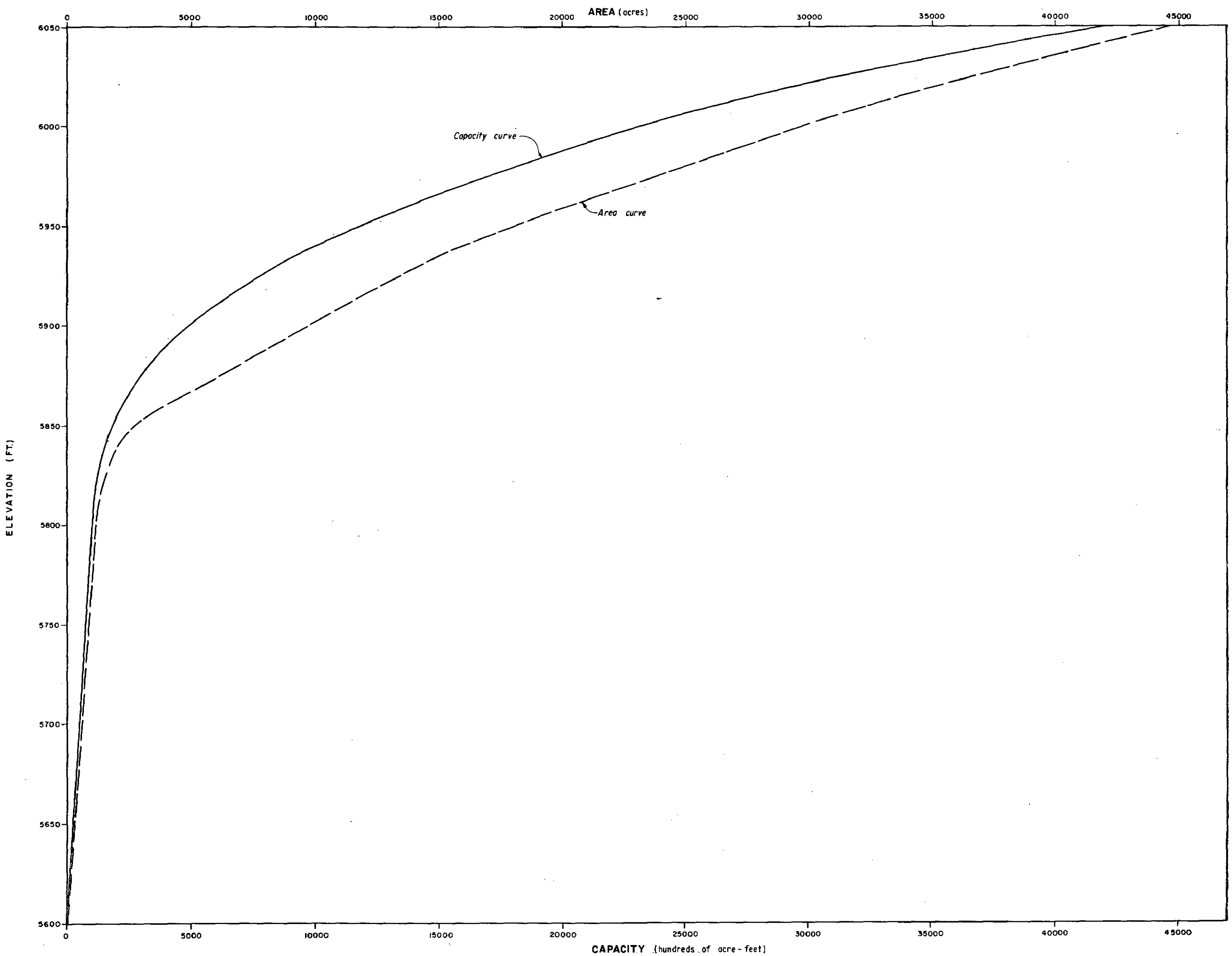

Figure 9. Elevation versus area and volume—Flaming Gorge Reservoir.

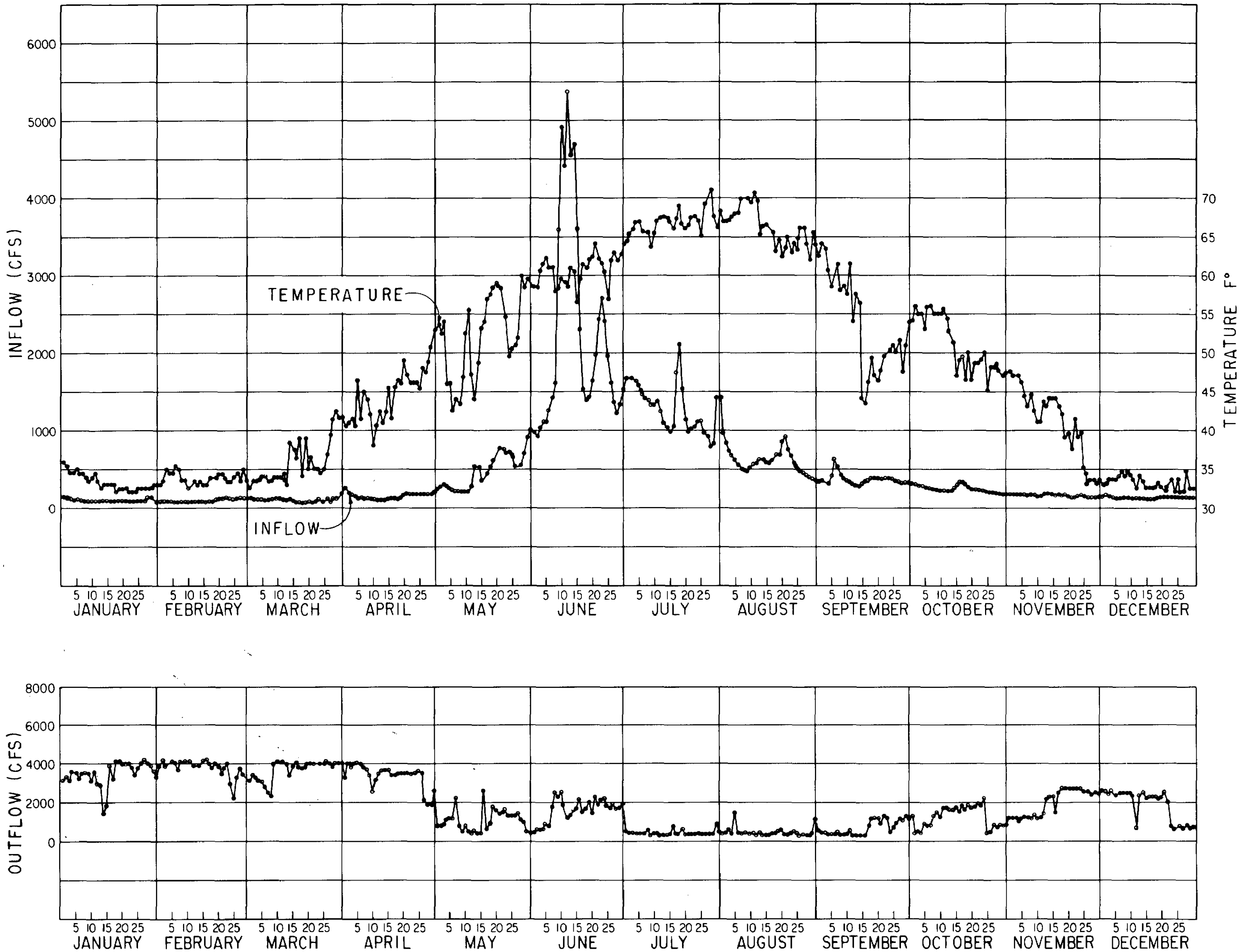

Figure 10. Flaming Gorge Reservoir inflows, inflow temperatures, and outflows—1965.

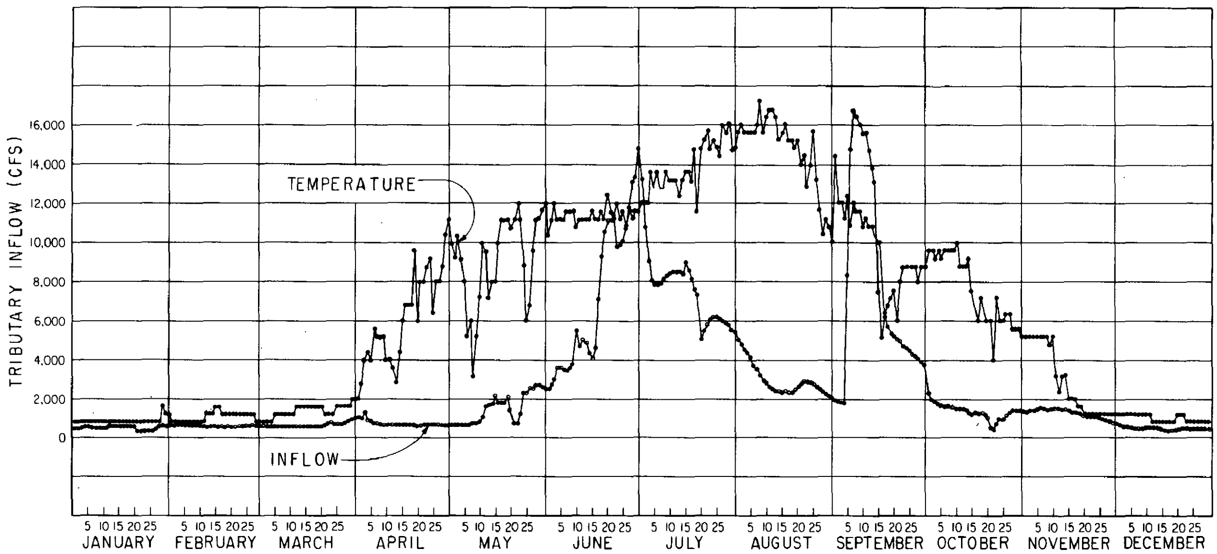

Figure 11. Flaming Gorge Reservoir tributary inflows and temperatures—1965.

when the reservoir becomes isothermal but before the ice cover forms. The second occurs in late March or April after the ice cover is gone. This suggests that the hypolimnion would become regenerated with dissolved oxygen at these times. However, the year-round persistence of a bottom layer of low DO and higher concentrations of other chemical parameters in the downstream portion of the reservoir show that complete mixing does not take place. The upper surface of this layer, the "chemocline," is immediately below the power turbine intake at the dam and intersects the reservoir bottom several miles upstream.

Density differences due to dissolved solids were neglected in this simulation. Furthermore, isotherms were assumed to be horizontal with the entire reservoir represented by a single station at the dam.

Available Data

Meteorological data.—Dry and wet bulb air temperatures and windspeed were determined from data taken at Flaming Gorge Dam. Cloud cover was extracted from microfilm records for the Rock Springs, Wyo., weather station.

The data taken at Flaming Gorge were daily readings at a specific time and not daily averages. Thus they are deficient since daily averages should be used. Furthermore, the meteorological data apply to only one point on the reservoir, whereas weather conditions are widely variable as suggested by the different types of terrain in which the reservoir is located.

As is often the case, the available meteorological data were less than optimum for application of the WRE model.

Inflows and outflows.—The sources and quantities of the inflows and outflows have already been described. The Black's Fork tributary inflows and temperatures are somewhat deficient because the measurements were taken about 100 miles from the point at which the tributary enters the reservoir. Also miscellaneous tributary inflows and outflows caused by seepage, etc. are not measured and are thus neglected.

Verification Tests

Reservoir characteristics.—Input data included a tabulation of elevation versus surface area. Also an isothermal temperature of 39.2° F (4° C) was assumed on the first day of analysis, April 10.

Evaporation.—Evaporation from the reservoir water surface was calculated according to Equation 1 (see Reservoir Characteristics), with $B = 2.6 \times 10^{-9}\ mb^{-1}$.

Surface absorption of heat.—Absorption of short-wave solar radiation in the surface layers of the reservoir was assumed to be exponential with the extinction depth set at 8.0 meters.

Thermal diffusion.—The significance of the effective diffusion coefficient has been discussed earlier in this report, which described the equation:

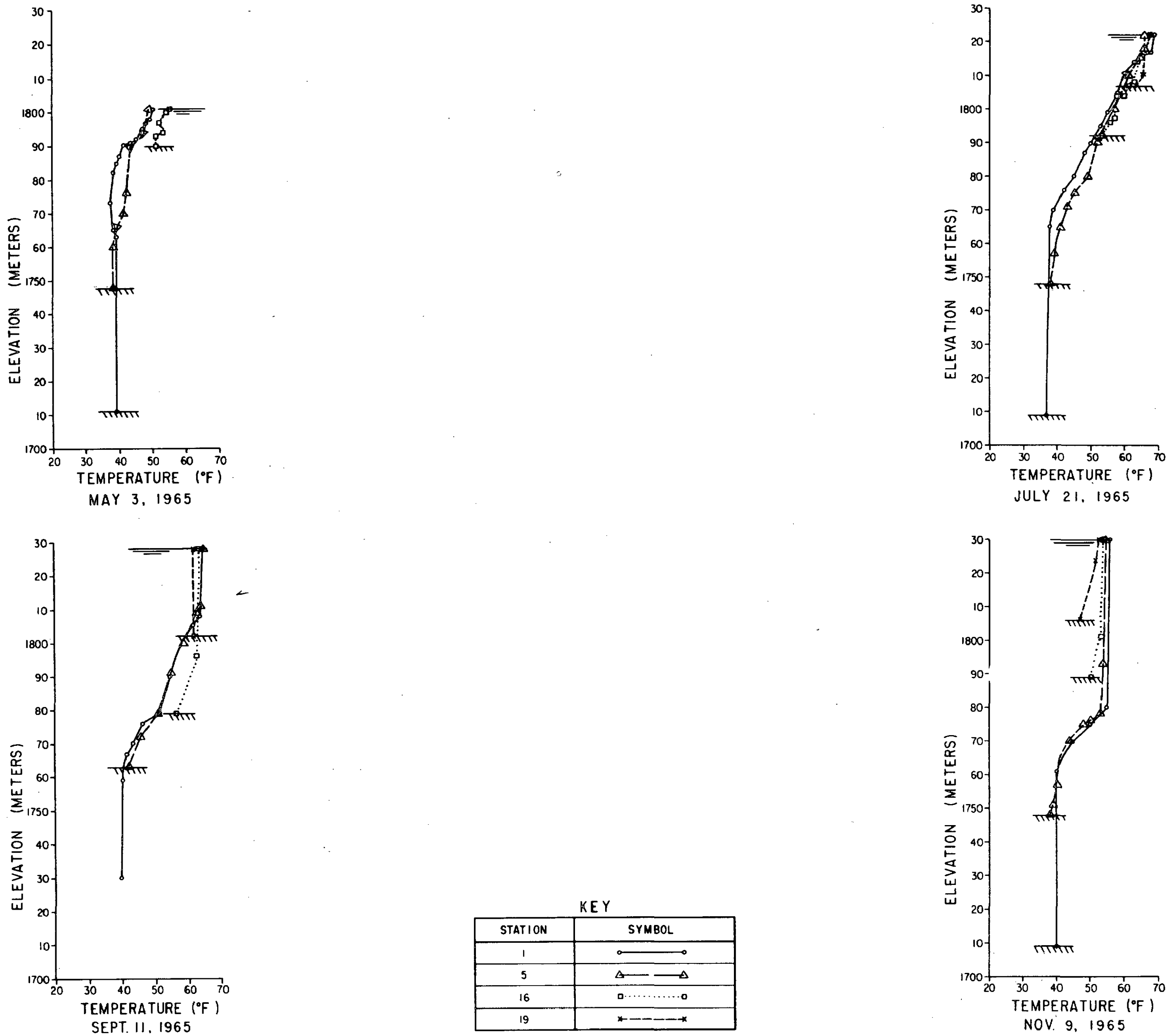

Figure 12. Observed temperature profiles in Flaming Gorge Reservoir—1965.

$$Dc = A_2 E^{A_3}, \text{ and}$$

$$Dc = A, \text{ for } E \leq E_c,$$

where E_c is the critical stability; A_1, A_2, and A_3 are empirical coefficients (corresponding to c, b, and a, respectively, in Equations 3-A and 3-B). Numerous computer runs were made with trial values for solution of this equation. The first two trials consisted of values recommended by WRE based on studies[4] in the Northwest. These values were:

	Hungry Horse	Detroit
E_c =	9.0×10^{-7}	1.75×10^{-5}
A_1 =	2.5×10^{-1}	3.0×10^{-2}
A_2 =	1.5×10^{-5}	2.0×10^{-5}
A_3 =	-0.7	-0.7

A_2 is the effective diffusion coefficient. For comparison, molecular diffusion of heat in water is approximately 1.4×10^{-7} meter^2/sec.

Results of this trial using the Hungry Horse coefficients are shown in Figure 13, in comparison with the measured temperature profiles at Station 1 near the dam. The simulation is reasonably accurate (except for unexplained anomalies in the observed profiles early in the season) until after June when the predicted profiles begin to grow progressively warmer than the observed profiles. Surface temperature predictions were 6^o-10^o too warm on July 30 and August 18, but were otherwise reasonably accurate. Representation of the thermocline is very poor after about October 10, which agrees with previous experience. The well-defined thermocline in the observed data, even in December, is also thought to be connected with the dissolved solids concentration in the hypolimnion of the prototype, which is not considered in the mathematical model.

The second simulation run, using the coefficients from Detroit Reservoir, showed an improvement in the prediction, Figure 14. Again, errors in prediction of surface temperature occurred on July 30 and August 18. The observed surface temperatures are essentially constant at 69^o-70^o from June 22 through August 18, while the computed temperatures increase from 68^o to 78^o during the same period. Data from subsequent years suggest that the observed surface temperatures are more probably correct.

Another run was made to simulate the effect of diffusing more heat downward from the surface of the reservoir. A constant (not variable with stability) coefficient of 5×10^{-2} meter^2/sec was used, compared with coefficients up to two orders of magnitude less in the epilimnion for the previous two runs. Figure 15 shows improvement in the prediction of surface temperatures for July 30 and August 18; however, the additional downward diffusion of heat caused serious error along the remainder of the profile.

Summary

Considering deficiencies in accuracy of data and the complex shape of the reservoir, it was decided that the simulation using the Detroit diffusion coefficients should be accepted as a reasonable verification of the model.

Figure 16 compares the observed and simulated outflow temperatures for the profiles of Figure 14. The maximum difference is 6^o F, which approximately reflects the difference between the temperature profiles at the level of the outlet. Figure 16 also compares the outflow temperatures with the reservoir temperatures at the level of the outlet. The simulated outflow temperatures are essentially equal to the reservoir temperatures at the level of the outlet because the general linearity of the computed profile results in prediction of a symmetrical withdrawal layer. However, the observed outflow temperatures tend to be cooler (up to about 2^o F) than the corresponding reservoir temperatures. The authors can offer no basis for this difference.

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10 Stimpfl, Kenneth J., "Changes in the Quality of Water Impounded in Horsetooth Reservoir," M.S. Thesis, Colorado State University, May 1966

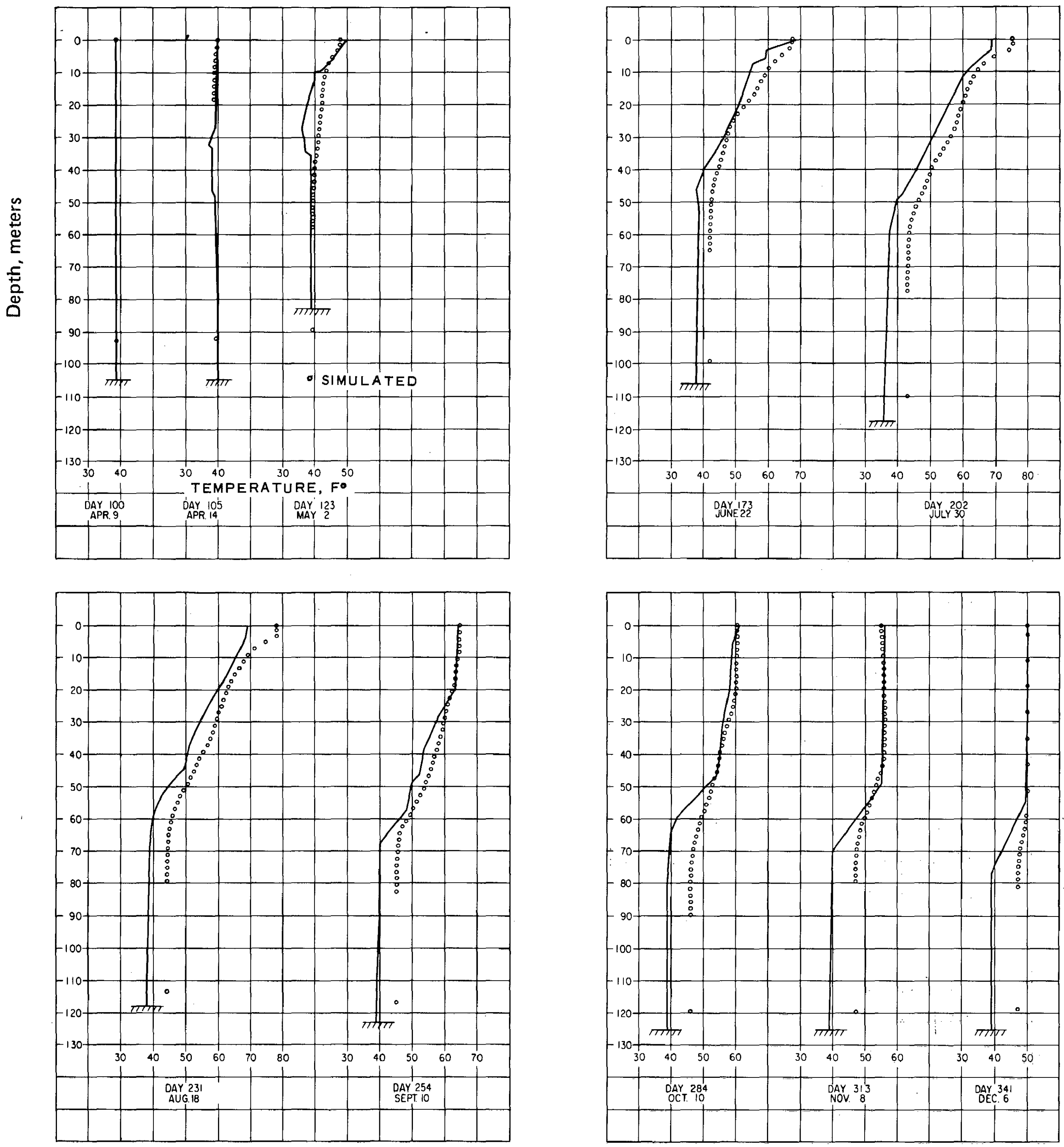

Figure 13. Observed versus simulated profiles at Station 1, using Hungry Horse diffusion coefficients.

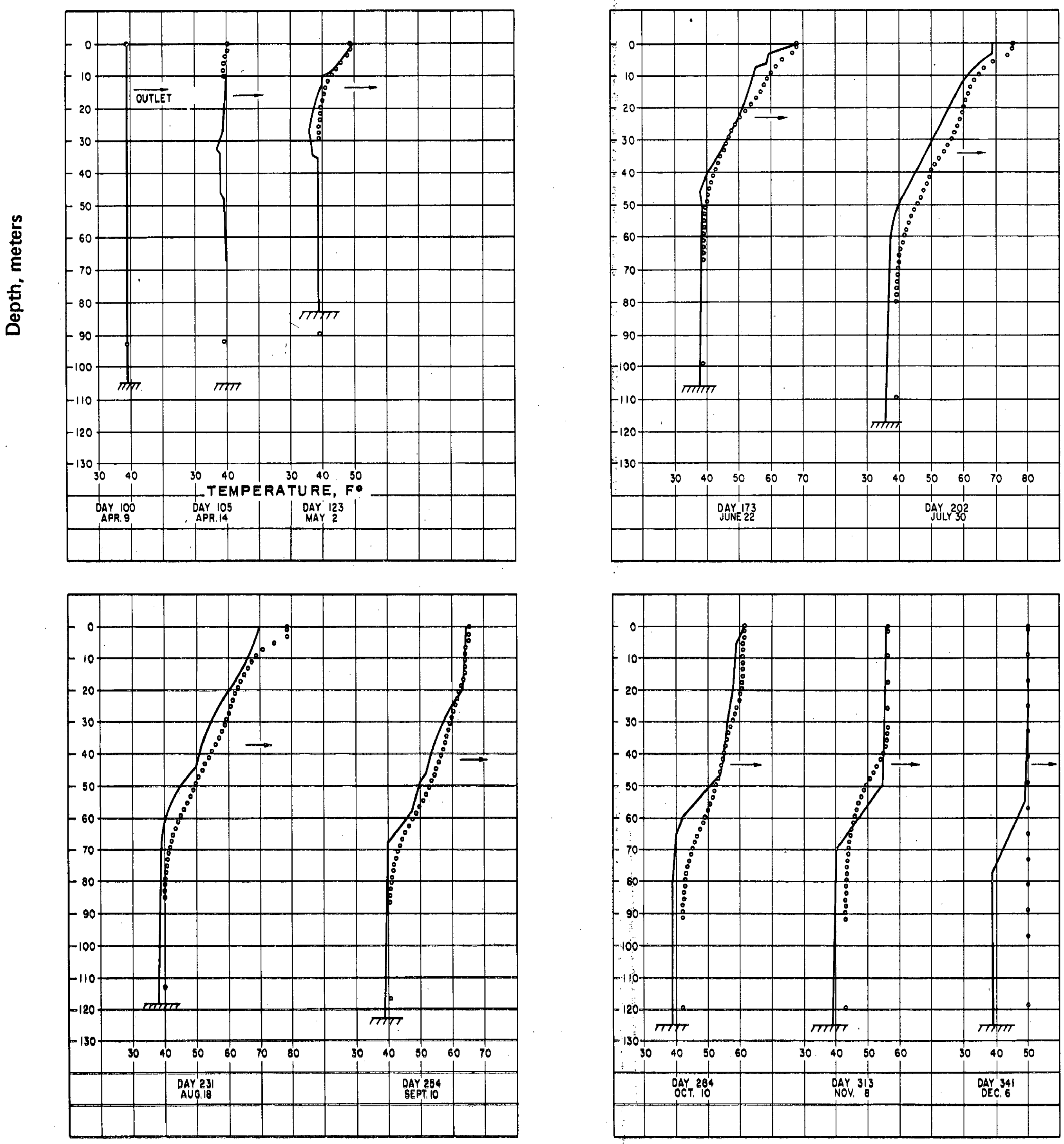

Figure 14. Observed versus simulated profiles at Station 1, using Detroit diffusion coefficients.

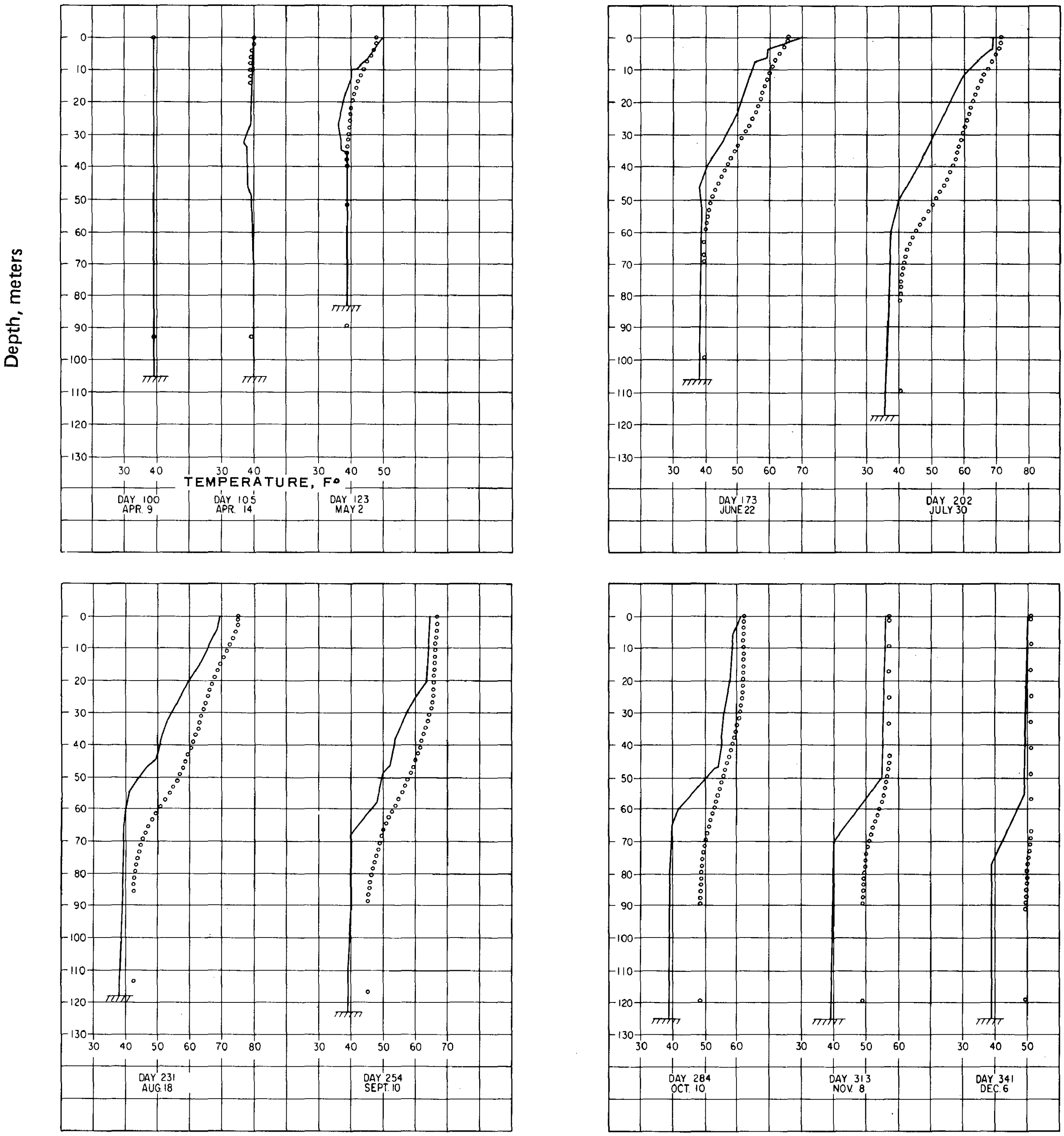

Figure 15. Observed versus simulated profiles at Station 1, using constant diffusion coefficient of 5 x 10^{-2} meter^2/sec.

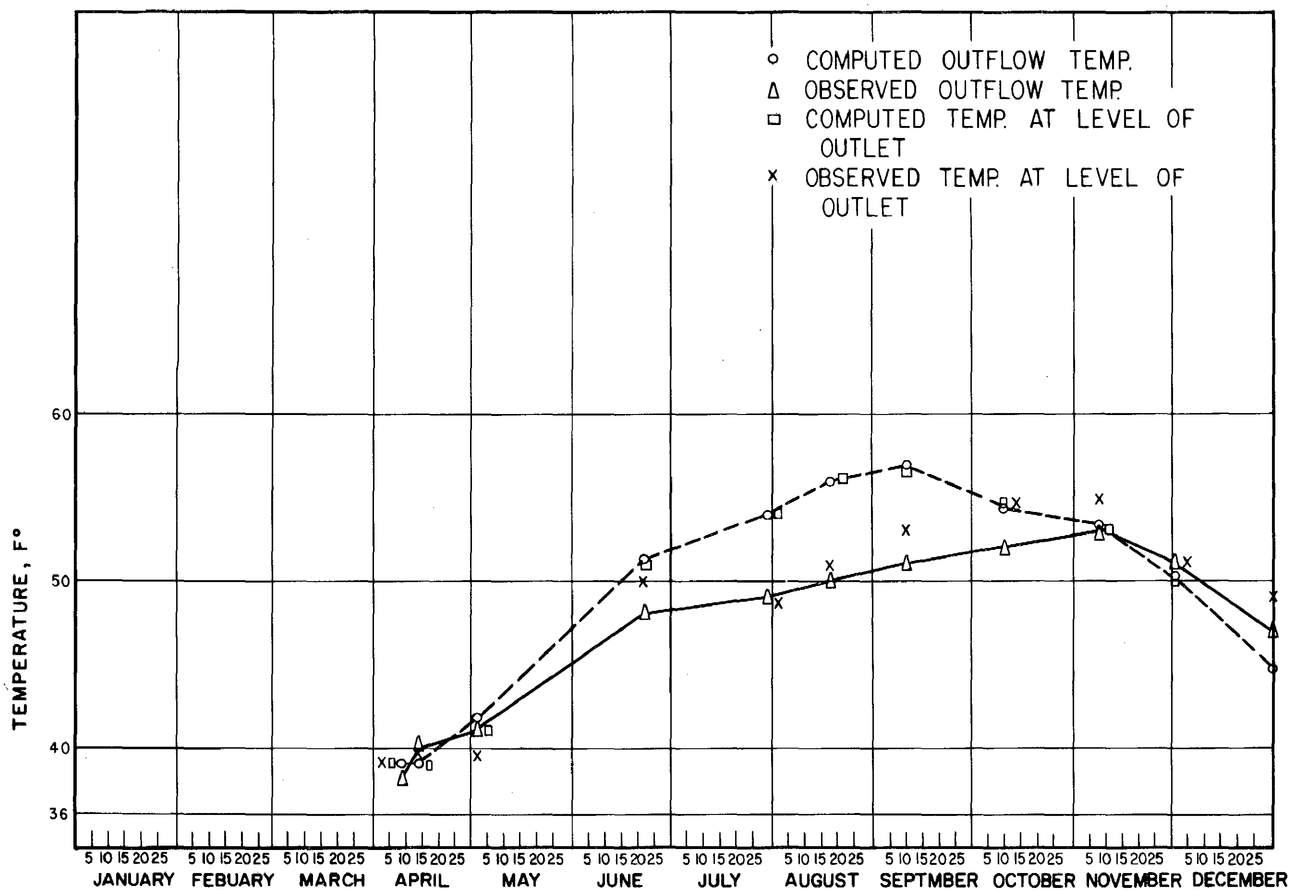

Figure 16. Observed versus simulated outflow temperatures—1965.

APPENDIX

APPENDIX

DOCUMENTATION OF COMPUTER PROGRAM—CORPS OF ENGINEERS VERSION OF WRE MODEL

The computer program for the Corps' version of the WRE model is documented in the Hydraulics Problem Area of the Bureau of Reclamation Engineering Computer System (BRECS). The program identification number is 1522-WRECORPS. The documentation includes a program index entry in the BRECS manual and a program description with references to the Corps and WRE user's manuals.

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	1.12985×10^6	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

ABSTRACT

Successful use of predictive mathematical models requires verification of the accuracy of the models by applying them to existing situations where the prediction can be compared with reality. A Corps of Engineers' modification of a deep reservoir thermal stratification model developed by Water Resources Engineers, Inc., was applied to two existing Bureau of Reclamation reservoirs for verification. Diffusion coefficients used for the Corps' Detroit Reservoir were found to apply to Horsetooth Reservoir in Colorado, for which very good computer input data were available. The Detroit diffusion coefficients gave a reasonable simulation of Flaming Gorge Reservoir in Wyoming and Utah, which has very complex and variable physical characteristics and for which only average-quality computer input data were available.

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