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# An Approach to Reservoir Temperature Analysis

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**14. ABSTRACT**
Several mathematical models for analyzing reservoir temperature stratification involving examination of hourly temperature changes have been developed. Use in practical applications is limited because of large amounts of observational data required. There is an increasing use of reservoir storage for bridging drought periods that requires examination of many combinations of reservoir storage levels and seasonal inflow patterns. Selecting a few representative years for analysis is not possible because thirty or more years of data are required. This approach is practical only if a long computation interval, such as one month, may be used. Observational data needed in existing models are ordinarily not available. A practical model must use generalized data such as average air temperature and average radiation. A generalized model must be capable of making releases through specific outlets or automatically selecting the outlets that will maintain outflow temperatures within a desired range as long as possible and leave the temperature of the remaining stored water at an optimum value. A compute program has been developed that conforms to these requirements and automatically calibrates the model.

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Papers in this series have resulted from technical activities of the Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution with the Corps of Engineers.

# AN APPROACH TO RESERVOIR TEMPERATURE ANALYSIS

Leo R. Beard[1] and R.G. Willey[2]

## INTRODUCTION

The rapidly increasing public interest in and need for water quality management has brought out many technical problems for which solution techniques do not exist. The increased demand on available water supplies has greatly complicated problems of water quantity regulation during the past 10 or 20 years. Related problems associated with water quality regulation are more complex by at least an order of magnitude.

Probably the most effective means of water quality regulation, other than controlling the input of pollutants to a stream system, is the regulation of quality by means of surface reservoir storage. The dominant quality factor that controls the hydromechanics of reservoir regulation is water temperature. Considerable progress has been made in understanding the mechanics of reservoir stratification, as illustrated in references cited below, but a great deal of development is yet required for an adequate solution of water resource development problems involving reservoir stratification.

In the case of large surface reservoirs, the seasonal variation of temperature and quantity of reservoir inflows and outflows and the seasonal variation of heat exchange with the atmosphere have complex effects on the reservoir state. Furthermore, the facts that the state of a reservoir at

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the start of a season can differ in different years and that the outflows and inflows can differ in different years complicate the problem. As a consequence, a great many combinations of reservoir state, inflow and outflow quantities, and temperatures must be considered in most reservoir water quality studies. It is not sufficient simply to examine the operation of a reservoir during one critical period, because it is difficult to determine the critical combination of factors except by examining the various results produced by a large number of combinations of the dominant factors.

At the present state of the art, the most effective approach to the design of reservoirs for quality control is to specify reservoir characteristics and output requirements, to simulate the operation of the reservoir for a large number of conditions, and to examine the results. In order to do this, it is necessary to construct a simulation model that is reasonably realistic and yet simple enough for application purposes.

A large amount of the information needed for theoretical evaluation of energy exchanges is ordinarily not available. Furthermore, many aspects of the energy exchange phenomena are not well understood or do not apply in any simple manner to conditions at an actual reservoir. The amount of reflection of solar radiation and the amount of evaporation energy absorbed from the air (rather than from the water) are examples of this. For this reason, even though a simulation model can be designed to conform with the physical laws reasonably well, it ordinarily must be calibrated on the basis of observed data.

## MODEL REQUIREMENTS

A practical model must be capable of accepting the types of data that are readily available generally, must be capable of simulating conditions over long periods of time, must respond easily to various outflow controls, and must be easy to calibrate where observed data are available. In some reserovirs, it may be necessary to perform operation studies for periods longer than 50 or 100 years in order to assure that critical combinations of conditions are represented. In order to do this with reasonable amounts of computation, it is almost mandatory that the basic computation interval be in the order of one month.

Meteorological variables considered must be restricted to variables such as average monthly temperature, average monthly clear-weather radiation, total monthly evaporation, etc. Short-term variations in winds, temperatures, cloud cover, etc., cannot feasibly be considered, unless their average effect over a period as long as a month could be represented by an index that is easy to obtain from available data.

The model must have flexibility in the specification of outlet releases. In calibrating the model for historical conditions, it would be necessary to specify the amount of release for each outlet during each interval. In applying the model to planning problems, it will be necessary to specify the total outflow, but also specific amounts for particular outflow levels, such as penstock intake levels. The model must be capable of automatically selecting the levels from which releases must be made in order to meet the target temperatures. It would also be desirable for the model to automatically determine a target temperature within the specified range of acceptability that would result in the optimum state of the reservoir at the end of each interval.

## NATURE OF THE HEC MODEL

A reservoir temperature stratification model has been developed at The Hydrologic Engineering Center (HEC) of the Corps of Engineers. The model has been developed specifically to satisfy the needs described above and is based on a greatly simplified energy budget computation. There are six calibration coefficients each associated with an energy exchange function. These are described in detail in the following section.

The reservoir is divided into horizontal layers of uniform thickness equal to any integral number of feet or meters. It is necessary to specify the storage capacity at the top of each layer and the storage capacity at the bottom of each level of outlets. Although it is known that water released from a particular outlet comes from both above and below the outlet invert, releases as computed in this model are made from the lowest water above the intake invert of each outlet. It is considered that this approximation will have minor effect on computation accuracy, because water ordinarily blended from higher and lower levels would have approximately the same temperature as the water at the invert level.

The exchange of energy between the reservoir and the atmosphere is assumed to affect only the top 10 meters of water, except for diffusion within the reservoir, which is computed separately. The exchange is considered to affect water temperatures linearly, with maximum effect at the surface and zero effect at 10 meters depth. Three factors are considered in the energy exchange computation. These are solar radiation, evaporation, and a combination of conduction and long-wave radiation expressed as a function of the difference between air temperature and water temperature. All three exchanges are computed before stability and diffusion computations are made. In doing this, the exchange that is a function of air temperature is based on the water surface temperature at the start of the computation interval. Equations for these exchanges are described below.

The depth of the thermocline is considered in this model to be a function of the minimum temperatures that occur during any period. Based on a calibration coefficient, a temperature is selected that is intermediate between the average air temperature and the minimum air temperature for the computation interval. Water is then mixed from the surface downward until the surface water temperature equals this intermediate air temperature and is further mixed, if necessary, until no lower levels contain warmer water than exists at higher levels. This computation is constrained to temperatures above 4° C, corresponding to the maximum density of water. If water is cooled below this, the temperature of each layer from the surface downward is allowed to go negative until an amount of energy equal to that required to form ice has been extracted from that layer.

A rather simple diffusion computation has been found to work reasonably well where observed temperature profiles have been reconstituted. This simply consists of incomplete mixing of adjacent layers over a 10-meter range, starting from the bottom and proceeding upward through the reservoir one layer at a time. The degree of mixing is controlled by a calibration coefficient. The mixing process is done five times per month.

It is recognized that there is some mixing between inflow water and reservoir water that is warmer than the inflow water, as the inflow water descends into the reservoir to seek its temperature level. Based on a calibration coefficient, a constant percentage of mixing occurs with each layer as the inflow water descends. Its temperature is consequently modified upward, and the water ultimately reaches a reservoir level at a temperature somewhat warmer than the original inflow temperature.

In some cases, inflow during a period as long as a month can exceed the total reservoir contents. When this happens, computation on a monthly interval becomes very unstable. In order to preserve computational stability, it is possible to specify that the computation be divided into any number of actual parts and that only a fraction of the water and energy amounts be computed in each part. Thus the partial computations would be repeated the specified number of times before the quantities for the entire computational interval are printed out.

Where there is latitude in selection of outlets for releasing water of the required temperature, the two outlets closest together that can blend water of the required temperature are selected. In this manner, maximum choice of temperatures can be made subsequently. This criterion can be changed, if desired.

A provision is included to output release quantities and temperatures on tape and to accept inflow quantities and temperatures from tape so that studies for tandem reservoirs can be made in a single computer run.

## COMPUTATION PROCEDURE

Use of the HEC model has been facilitated by the detailed instructions in reference 2 for the preparation of computer input data. The computations are performed automatically for an entire operation study. They account for the energy in each layer and the energy and water transferred into and out of each layer of the reservoir. The reservoir must be subdivided into a number of horizontal layers of equal specified depth. After defining the initial state, the procedure for each month can be outlined as follows:

a. Calculate the transfer of energy between the water and the atmosphere by the following equation:

$$E_1 = C_1 \ (T_A - T_W) \ (S_{10}/2) \tag{1}$$

where:

$E_1$ = Energy transferred to the top 10 meters of storage in acre-ft-degrees F (thousand cubic meters-degrees C)

$C_1$ = A calibration coefficient between 0 and 1

$T_A$ = Monthly average air temperature in degrees F (degrees C)

$T_W$ = Water surface temperature in degrees F (degrees C)

$S_{10}$ = Storage in the top 10 meters of depth in acre-feet (thousand cubic meters)

b. Calculate the energy transferred to the water from solar radiation by the following equation:

$$E_2 = KC_2 \ (R) \ (A) \ (ND) \tag{2}$$

where:

$E_2$ = Energy transferred to the top 10 meters of storage in acre-feet-degrees F (thousand cubic meters-degrees C)

K = A conversion constant = .0036 for english units (.002 for metric units)

$C_2$ = A calibration coefficient between 0 and 1

R = Solar radiation in langleys per day (figure 1)

A = Reservoir surface area in acres (thousand square meters)

ND = Number of days in the computation period

c. Calculate the energy removed from the water by gross lake evaporation by the following equation:

$$E_3 = C_3 (H_E) (V_E) \tag{3}$$

where:

$E_3$ = Energy removed from the top 10 meters of storage in acre-feet-degrees F (thousand cubic meters-degrees C)

$C_3$ = A calibration coefficient between 0 and 1

$H_E$ = Latent heat of vaporization plus approximate heat to warm water = 1062 BTU per pound (590 calories per gram)

$V_E$ = Volume of water evaporated in acre-feet (thousand cubic meters)

d. The coefficients in equations 1, 2 and 3, along with the three coefficients in equations 4, 5 and 8, can be determined from recorded data. The energy calculated in equations 1, 2 and 3 is transferred in the order discussed, to (or from) the top 10 meters of reservoir water as a function of depth, linearly decreasing from the top layer to a value of zero at 10 meters depth.

e. Rainfall on the water surface is added to the reservoir volume at the average temperature of the top layer, and evaporation volume is subtracted from the top layer.

f. Any thermally unstable layers are thoroughly mixed as are all layers that are warmer than a temperature specified by the following equation:

$$T = T_A - C_4 (T_A - T_M) \tag{4}$$

where:

$T$ = Resultant epilimnion temperature in degrees F (degrees C)

$C_4$ = A calibration coefficient between 0 and 1

$T_A$ = Monthly average air temperature in degrees F (degrees C)

$T_M$ = Monthly minimum air temperature in degrees F (degrees C)

This criterion is intended to account for the tendency of the thermal profile to be isothermal in the epilimnion, attributing the phenomenon principally to air temperature changes that cool the surface water intermittently, causing it to descend a short distance.

g. If the reservoir inflow is cooler than the surface temperature, it will descend and partially mix with the upper layers. The temperature of each layer and the temperature of the inflow that results from the exchange of energy between the inflow and the reservoir volume at each level is calculated by use of the following equations:

$$T'_L = T_L + C_5 (T_{avg} - T_L) \tag{5}$$

$$T'_I = T_I + C_5 (T_{avg} - T_I) \tag{6}$$

where:

$C_5$ = A calibration coefficient between 0 and 1

$T_L$ = Temperature at layer L in degrees F (degrees C)

$T_I$ = Temperature of inflow in degrees F (degrees C)

$T_{avg}$ = Average (weighted by volume) of inflow temperature and temperature of layer L in degrees F (degrees C)

The calculations involving equations 5 and 6 must be repeated for each layer. The inflow is thus warmed slightly as it descends to a level where the temperature equals the modified inflow temperature, but never descending below water which has a temperature of maximum water density (4°C). It is then added to the reservoir, and all warmer water is raised.

h. The temperature changes resulting from the vertical diffusion of energy can be calculated by the following equations:

$$T_{av} = \frac{\Sigma\ T_L\ V_L}{\Sigma\ V_L} \tag{7}$$

$$T_L' = T_L\ (1 - C_6) + T_{av}\ C_6 \tag{8}$$

where the summation is over 10-meter ranges and:

$T_{av}$ = Average temperature of all layers within a 10 meter range

$T_L$ = Temperature at layer L in degrees F (degrees C)

$V_L$ = Volume in layer L in acre-feet (thousand cubic meters)

$C_6$ = A calibration coefficient between 0 and 1

The calculation involving equations 7 and 8 must be repeated for each set of layers 10 meters thick, starting at the bottom of the reservoir and proceeding upward a layer at a time. This process is done five times per month.

i. The releases assigned to specific outlets are made by withdrawing the required quantity from the storage available immediately above the outlet invert level, accounting for the total released quantity and energy.

j. The temperature limits which apply to the remaining required release can be calculated as follows:

$$T'_{max} = (T_{max}\ Q_T - Q_1 T_1) \ / \ (Q_T - Q_1) \qquad (9)$$

$$T'_{min} = (T_{min}\ Q_T - Q_1 T_1) \ / \ (Q_T - Q_1) \qquad (10)$$

where:

$T_{max}$ = Maximum desirable release temperature for total release in degrees F (degrees C)

$Q_T$ = Total required release in acre-feet (thousand cubic meters)

$Q_1$ = Release required through specific outlets in acre-feet (thousand cubic meters)

$T_1$ = Temperature of water released through specific outlets in degrees F (degrees C)

$T_{min}$ = Minimum desirable release temperature for total release in degrees F (degrees C)

k. The target temperature of the remaining required release can be calculated by the following equation:

$$T = \left[E - T_3\ (V - Q)\right] \ / \ Q \qquad (11)$$

where:

T = Target temperature of the remaining release in degrees F (degrees C)

E = Reservoir energy above the lowest usable outlet in acre-feet-degrees F (thousand cubic meters-degrees C)

$T_3$ = The average of the succeeding 3 months maximum and minimum temperature requirements in degrees F (degrees C)

Q = Remaining release required during the current month in acre-feet (thousand cubic meters)

V = Reservoir volume remaining above the lowest usable outlet in acre-feet (thousand cubic meters)

Equation 11 has been derived so the remaining release (Q) can be withdrawn at a level such that the average temperature of the water remaining above the lowest usable outlet is changed to equal the average temperature of the three succeeding months maximum and minimum temperature requirements. If the target temperature calculated with equation 11 is outside the desirable range calculated with equations 9 and 10, the closest temperature limit is adopted as the target temperature.

l. An attempt should be made to release the target temperature calculated from equation 11 by examining the energy that could be released through the highest usable outlet below where the target temperature exists in the reservoir and the lowest usable outlet above that level. The water released through these two outlets is mixed so as to match the target temperature. If it becomes necessary to use other outlets also, lower and higher outlets are used as required. If it is found that this process does not satisfy the target temperature, the release will be withdrawn only from the one outlet which will produce water with a temperature closest to the target temperature.

m. The end-of-month storage and the temperature of the water in each layer is determined by redistributing the reservoir water to fill all the "empty spaces" resulting from the release.

n. The above computation procedure should be repeated for each month of record.

## MODEL CALIBRATION

Model coefficients can be derived automatically on the basis of minimizing the sum of squares of errors in temperature between computed and observed profiles. Observed profiles must extend from the surface downward to any depth for which data are obtained. Any number of observed profiles can be used for a single model calibration. Errors are measured between computed and observed temperatures for each level and each profile. Computed temperatures are interpolated for the date of the observed profile by linear interpolation between end-of-month temperatures at the depth corresponding to the depth of the observed temperature.

A gradient optimization technique is used. Coefficients are specified arbitrarily and are changed by the computer in accordance with the resulting effect on minimizing the standard error of computed temperatures. The optimization procedure is described in reference 1.

It is not necessary to calibrate the model for all coefficients. Fixed values for any of the coefficients can be prespecified, and the computer will change only the remaining coefficients. In order to evaluate results of calibration easily, comparison of the computed and observed profiles is printed out. An example of this is illustrated in figure 2. An example of reconstitution of reservoir temperatures over a period of 3 years is illustrated in figure 3.

## APPLICATION

The reservoir temperature model was used for studying temperatures in a tandem system of reservoirs on the Yuba River. The Yuba River, located in north central California, drains 1340 square miles of the northern Sierra Nevada. The streamflow temperature on the Yuba is important not only for fish and game propagation but also for agricultural uses. Spawning salmon require temperatures in the low fifties while rice in the central valley requires warmer irrigation water. Fortunately their most critical needs are in different seasons. However, satisfying these differing temperature requirements may require a multilevel intake structure. For this reason it was desired to study various intake structures for Marysville Reservoir, a proposed reservoir near the mouth of the Yuba River.

The Yuba River temperature problem is further complicated by the existence of two reservoirs upstream from the Marysville site, Englebright and Bullards Bar Reservoirs (figure 4). Bullards Bar, the most upstream reservoir, has been recently inundated by a larger reservoir, New Bullards Bar, which is about 600 feet deep and has a surface area of 4800 acres. Englebright is a smaller impoundment with a depth of 260 feet and a surface area of 815 acres.

In order to form some basis for selecting model coefficients for reservoirs where temperature data are not available, calibration studies were made for the five reservoirs listed in table 1, for which good temperature data exist. The use of the derived calibration coefficients for each of the Yuba River Reservoirs will be described below.

Hydrologic design studies for Marysville Reservoir were based on observed data for 31 years from 1924 to 1954 and included operation studies of existing reservoirs. It was desired to perform detailed water temperature studies for the same period, using the same flow and evaporation data. For three years (1963 to 1966) the California Department of Fish and Game collected very detailed temperature data in the Yuba River basin from above Bullards Bar Reservoir to below Marysville Reservoir, including most of the major tributary inflow temperatures.

Since New Bullards Bar is three times as deep and has 30 times as much volume as Bullards Bar (figure 5), the model calibration used for Bullards Bar is not necessarily valid for New Bullards Bar. The calibration for New Bullards Bar was therefore based on the average calibration coefficients derived from historical temperature profile data at the five reservoirs listed in table 1.

The Bullards Bar inflow temperatures for 1963 to 1966 were graphically correlated (figure 6) on a seasonal basis with the monthly average and minimum air temperatures for the city of Marysville, and the resulting relation was used to estimate New Bullards Bar inflow temperatures for 1924 to 1954 from the Marysville air temperature data for the same period. Using these estimates, and the hydrologic and meteorological data available, the outflow temperatures from New Bullards Bar were calculated based on a selected target temperature criterion. This outflow temperature criterion was varied in an attempt to meet required temperatures below Marysville Dam.

In addition to the outflow from New Bullards Bar, the Englebright inflow includes Middle Yuba and South Yuba streamflow. The observed streamflow temperatures for each tributary were correlated with Marysville air temperatutes as in the case of New Bullards Bar inflow temperatures. The outflow from New Bullards Bar is split between a power tunnel and the release to the river. The tunnel release does not change temperature appreciably before entering Englebright, but the river release travels 10 miles before entering Englebright and therefore will change to a temperature somewhere (assumed half-way) between the New Bullards Bar release temperature and the average air temperature.

The model calibration for Englebright was derived from the historical temperature profiles for 1963 to 1966. Using these estimates, and the hydrologic and meteorological data available, the outflow temperatures from Englebright were calculated. A temperature selection criterion was not necessary, because Englebright has only one outlet (a penstock with a fixed power demand) and an ungated spillway.

In addition to the outflow from Englebright, the Marysville inflow includes streamflow from Deer and French Dry Creeks. The observed streamflow temperatures for each tributary were correlated with Marysville air temperatures as in the case of New Bullards Bar inflow temperatures. The model calibration for Marysville was based on the average calibration coefficients derived from historical temperature profile data at the five reservoirs listed in table 1. Using these estimates, and the hydrologic and meteorological data available, the outflow temperatures from Marysville were calculated for the entire period based on the target temperature criterion shown in figure 7 and a selected outlet configuration.

Although design studies are not yet complete, preliminary results of a simulation study are shown in figure 7. Although averages shown for the 31 years are usually within the required range of outflow temperatures, temperatures during some critical periods are not satisfactory, and studies of additional operation schemes are yet to be made. It was found that for the simulations tried, little difference in the release temperatures resulted at Marysville Reservoir whether three or a greater number of intake levels were used. Also, differences in the operation of New Bullards Bar Reservoir had little effect on outflow temperatures at Marysville.

## CONCLUSIONS

It is certainly recognized that reservoir temperature stratification models exist that are more acceptable from a theoretical standpoint than the model described herein. However, this model was designed to accept data generally available and to solve complex problems with a reasonable amount of computation. The model shows considerable promise and is capable of achieving reasonably good reconstitutions of observed reservoir temperatures. Considerably more application experience is needed in order to improve the reliability of model calibration. In particular, it would be beneficial to generalize the calibration coefficients on the basis of reservoir characteristics, geography, etc.

## ACKNOWLEDGMENT

The reservoir temperature stratification model described herein was developed in The Hydrologic Engineering Center of the Corps of Engineers. During the development of the model, suggestions were received from numerous individuals, and data for testing were received from numerous agencies, particularly the Sacramento District and the North Pacific Division of the Corps of Engineers.

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TABLE 1

| Test Reservoir | Main Tributary | State | Years Tested |
|---|---|---|---|
| Detroit | N. Santiam River | Oregon | 3 (1965 - 1967) |
| Lookout Point | M.F. Willamette River | Oregon | 4 (1964 - 1967) |
| Bullards Bar | N. Yuba River | California | 3 (1963 - 1966) |
| Englebright | Yuba River | California | 3 (1963 - 1966) |
| Pine Flat | Kings River | California | 4 (1965 - 1969) |

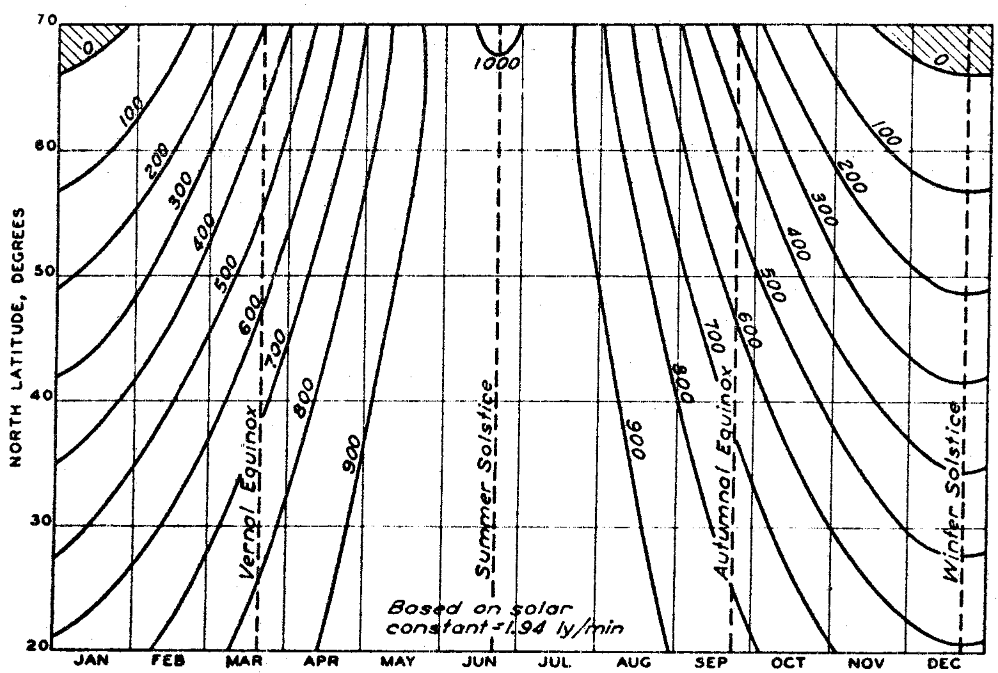


Figure 1. Daily solar radiation outside the earth's atmosphere, in langleys. (U. S. Army Corps of Engineers - EM 1110-2-1406)

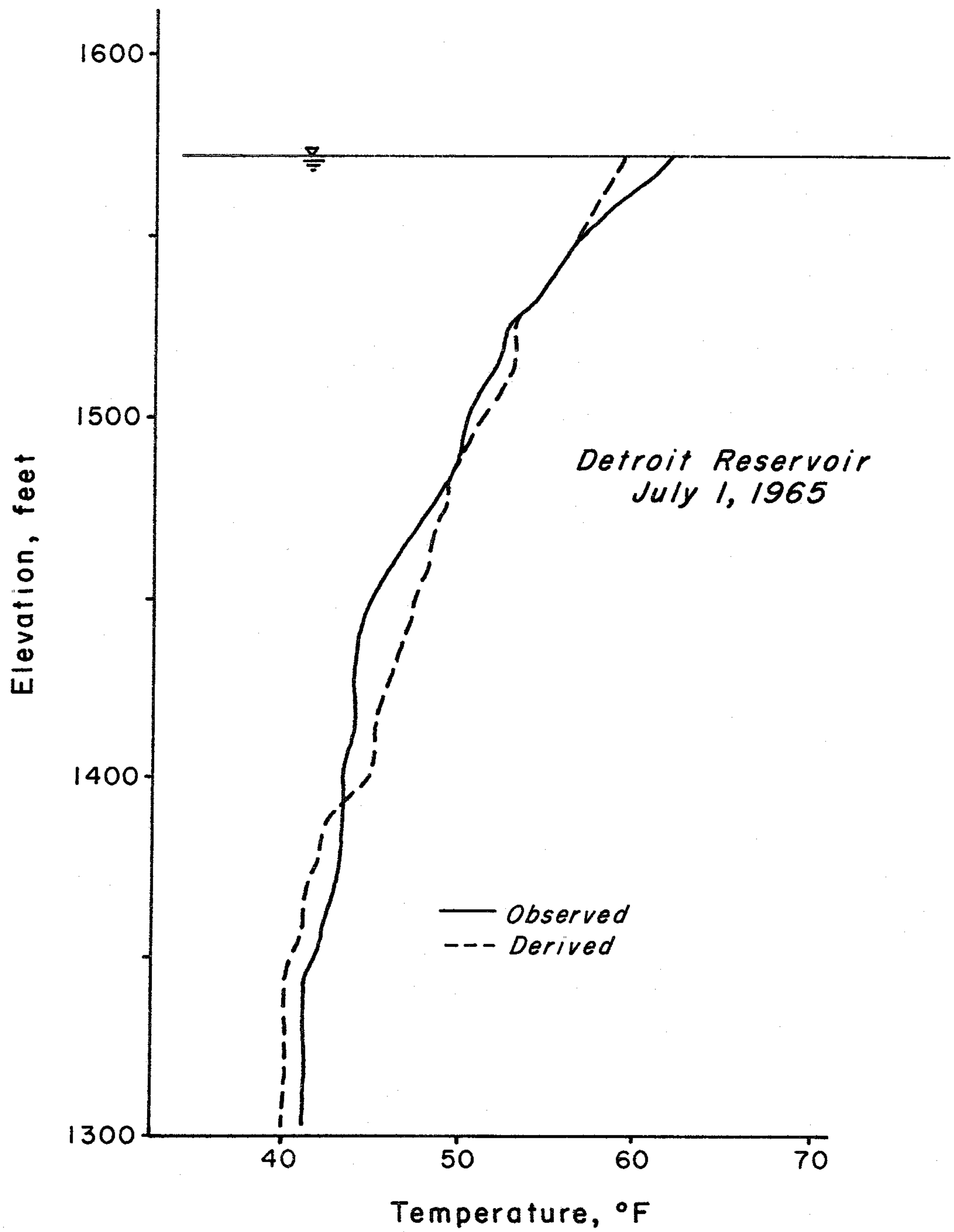


Figure 2. DERIVED AND OBSERVED TEMPERATURE PROFILES

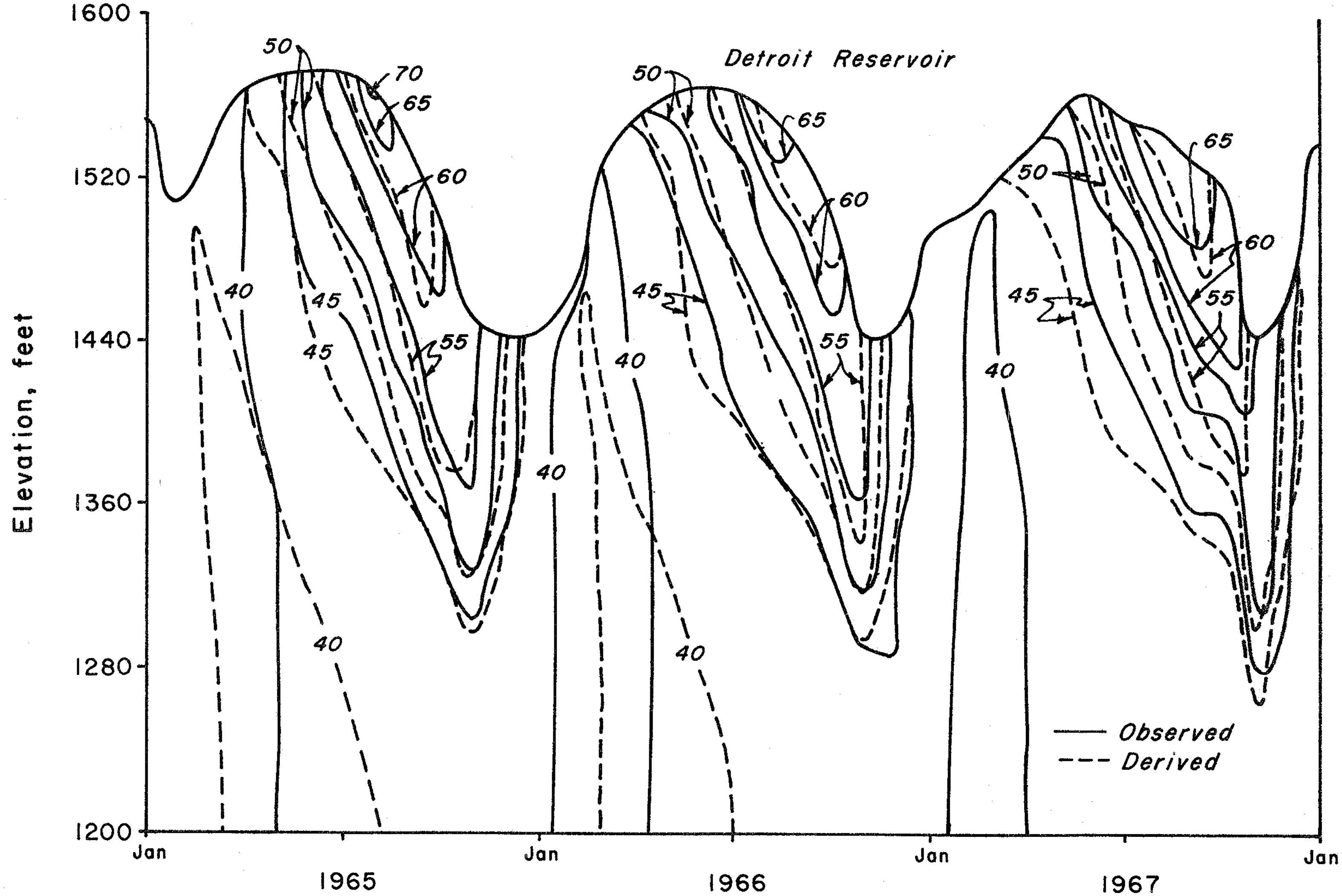


Figure 3. DERIVED AND OBSERVED ISOTHERMS

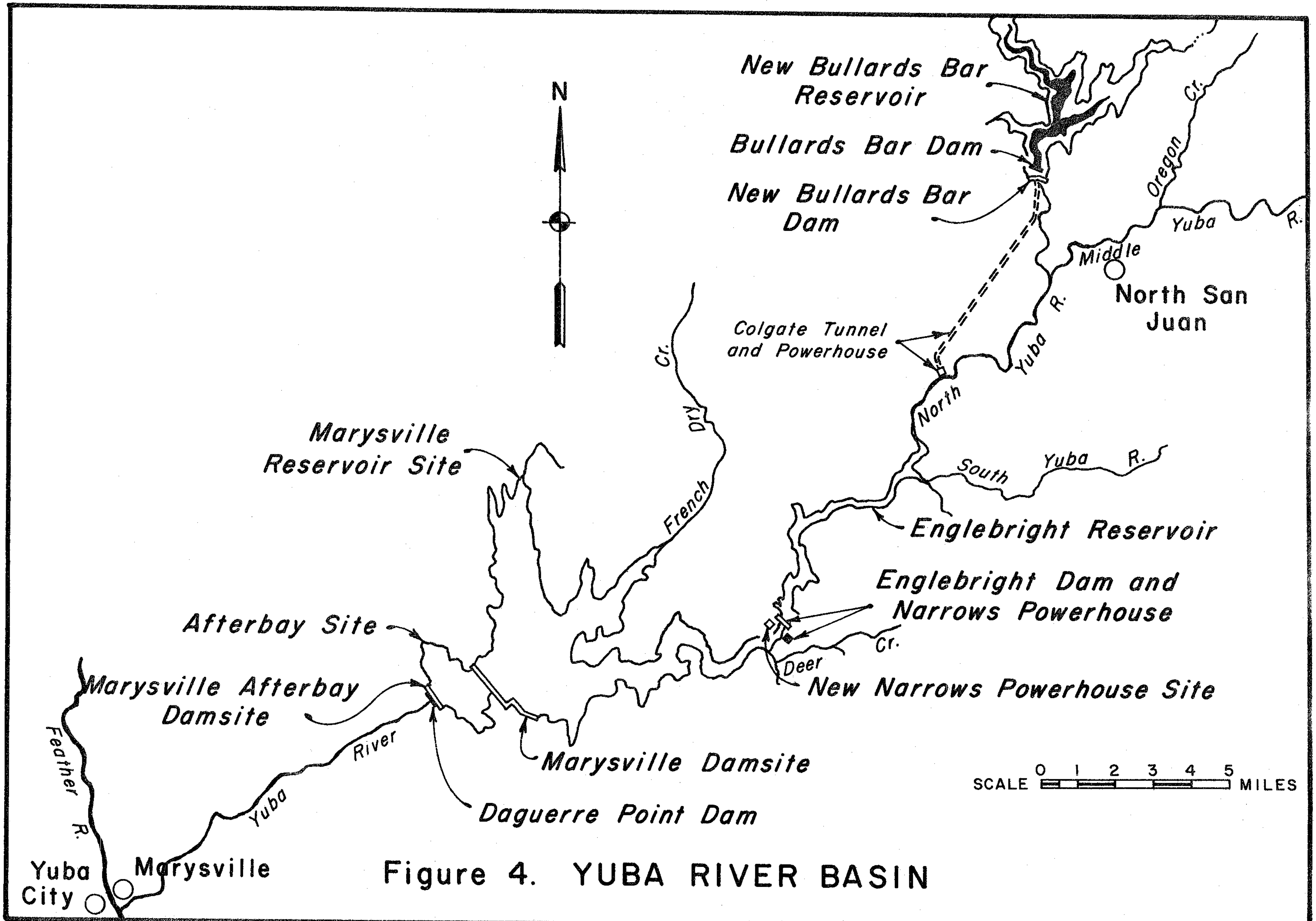


Figure 4. YUBA RIVER BASIN

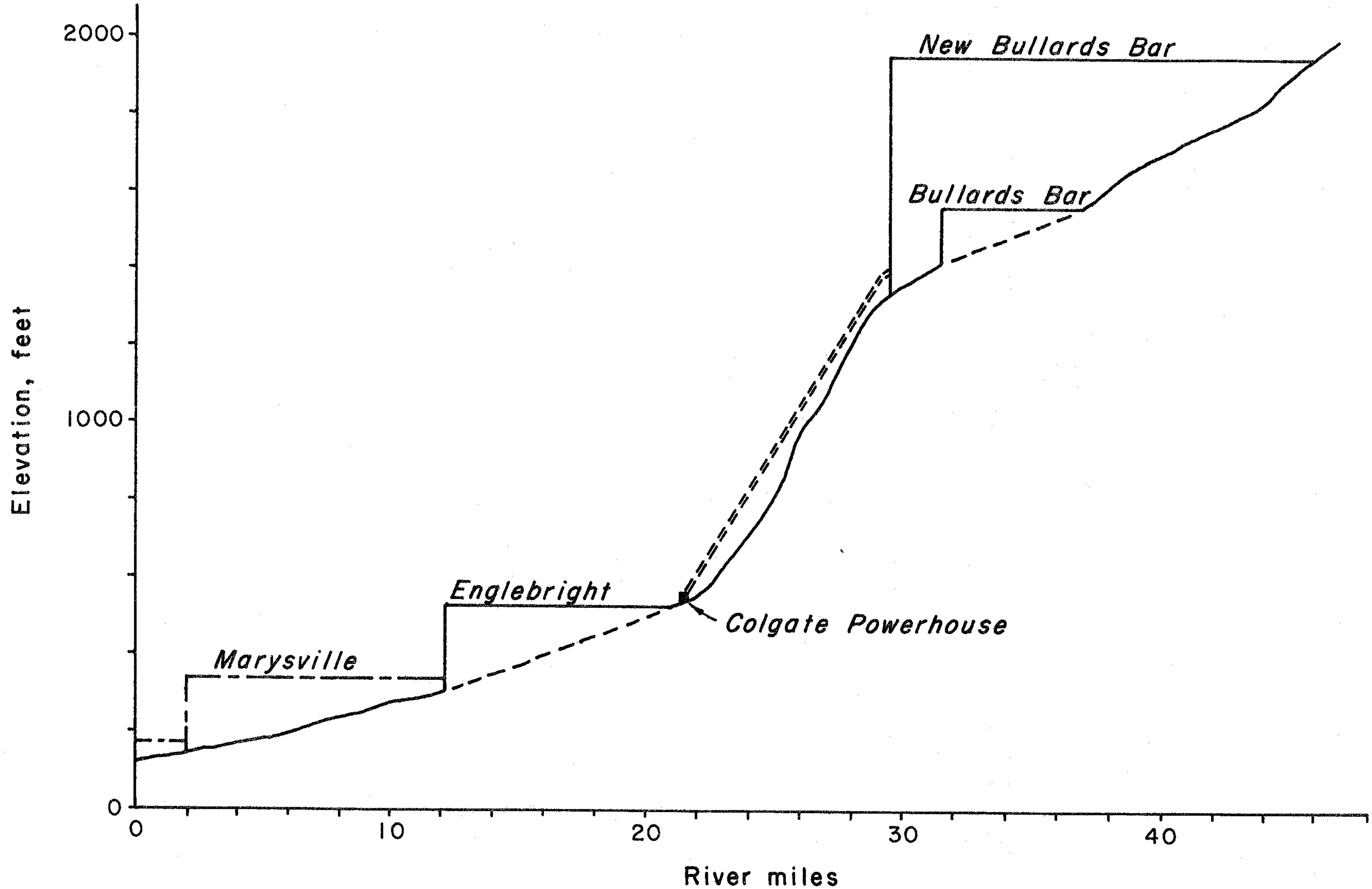


Figure 5. YUBA RIVER PROFILE

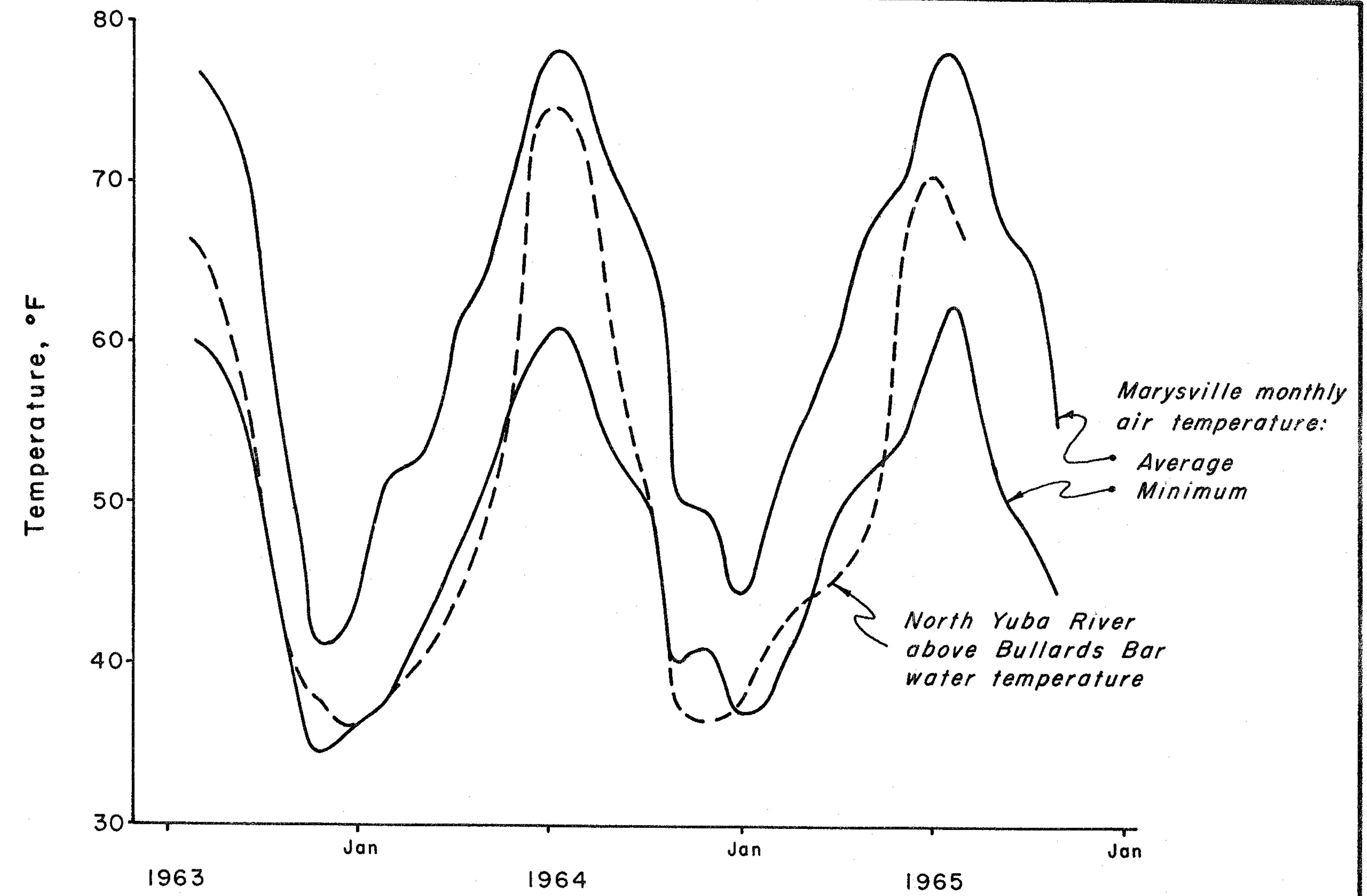


Figure 6. STREAMFLOW TEMPERATURE VERSUS AIR TEMPERATURE

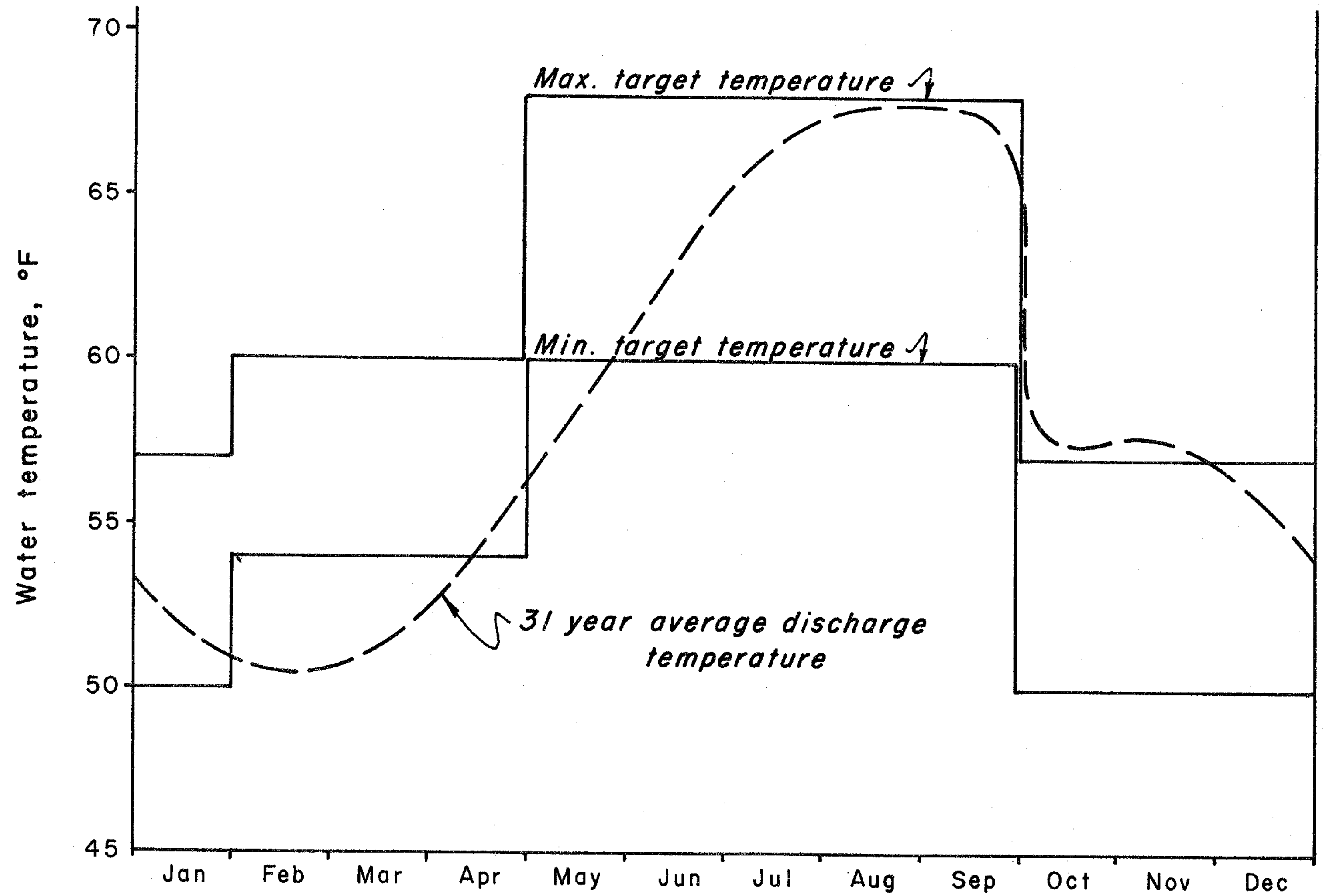


Figure 7. TARGET TEMPERATURE CRITERIA AND SIMULATED RELEASE TEMPERATURES AT MARYSVILLE
(Temperature criteria from Calif. Dept. of Fish and Game)

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