SULTAN RIVER PROJECT
FINAL REPORT

TEMPERATURE AND TURBIDITY STUDIES FOR SPADA LAKE AND THE SULTAN RIVER

PUBLIC UTILITY DISTRICT NO. 1
SNOHOMISH COUNTY, WASHINGTON

BECHTEL CIVIL & MINERALS, INC.
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SUMMARY

The Stage II development for the Sultan River Project in Snohomish County, Washington, involves raising Culmback Dam, constructing a tunnel and pipelines, and building a powerhouse on the Sultan River. A comprehensive program of data acquisition, analysis, and numerical simulation was conducted to evaluate the effects of the Stage II development on water temperature and turbidity in the discharges from Spada Lake. Results were used to assess the potential effects on fisheries and the city of Everett's water supply.

Measurements of reservoir inflow and outflow temperatures, discharges, and turbidities, as well as reservoir temperature and turbidity profiles and complete meterological data were obtained to calibrate and verify a numerical model. This extensive, high-quality data base reduced many of the uncertainties associated with previous studies of this type reported in the literature. Improvement and extension of the M.I.T. reservoir model made possible year-round simulation of both temperature and turbidity. Calibration and verification of the model resulted in a high level of confidence in the numerical results.

TEMPERATURE

Temperature simulations were performed for the existing Stage I reservoir and for the raised Stage II reservoir with a deep intake (Elevation 1366 ft) and a surface withdrawal intake. Although the outflow temperatures follow similar trends, some differences were noted between Stages I and II.

Predictions of Stage II power tunnel outflow temperatures, with the intake at Elevation 1366, were compared with the historical record at the city of Everett's Diversion Dam on the Sultan River. The results showed that outflow temperatures from the raised reservoir in the June-September period would be 2 to 3^{o}C colder than existing recorded minimum conditions. In contrast, surface withdrawal intake resulted in power tunnel outflow temperatures within, or at most slightly above, the range of recorded temperatures recorded at the Diversion Dam, which significantly improved the temperature regime in the Sultan River in comparison with the deep intake at Elevation 1366, as far as potential effects on fisheries are concerned.

During winter and early spring, outflow temperature ranges would be practically the same in all cases since the reservoir is isothermal, and little heating occurs in the river or reservoir.

Temperature simulation results show that a surface withdrawal intake for the power tunnel would provide temperature variations in the Sultan River below the city of Everett's Diversion Dam similar to those presently occurring in the river's North and South Forks. The warmest temperature will occur about one month earlier in the year than with existing conditions, and the outflow temperature will closely follow the pre-Culmback Dam thermal regime.

A surface intake is simple to operate, with the operation determined solely by the reservoir water level. For most years, only one change in the intake level should be necessary between June and October.

TURBIDITY

Major winter storms are a principal factor in causing turbidity events in Spada Lake. Flooding caused by winter storms brings in large quantities of suspended fine clay particles. Erosion in Culmback Gulch, wave-induced erosion along the reservoir shoreline, and erosion from exposed banks do not contribute significantly to reservoir turbidity as compared with flood flows of the Sultan River's principal tributaries. The North Fork is now the primary source of turbid inflows. The increase in reservoir volume (from 34,600 to 154,900 acre-feet, or more than four times the existing volume) is the principal factor in understanding the general differences in turbidity behavior between the existing and raised reservoir following a turbidity event.

With a larger reservoir, the initial turbidity levels in the reservoir and in the discharge after an event will be lower than existing levels for about two to four weeks. Numerical simulation, based on the 1979-80 winter data, shows a reduction in the outflow turbidity immediately after a major turbidity event to about half the level of the outflow turbidity from the existing reservoir. However, turbidity in the raised reservoir outflows will remain at a slightly higher level (between 2 to 3 NTU's greater) for about three to four months, compared with the existing reservoir.

With the Stage II reservoir, the turbidity of outflows with either the surface withdrawal intake or the intake at Elevation 1366 will be practically the same until stratification develops in the spring. After reservoir stratification develops in late spring, the surface withdrawal intake turbidity will be lower than with an intake at Elevation 1366 ft. During the late spring and summer months, outflow turbidities using a surface withdrawal scheme will be about the same as for the existing reservoir under the same meteorologic and hydrologic conditions. The location of the intake level had practically no effect on predicted turbidities for the low-level outlet.

The surface withdrawal intake not only provides a better thermal regime in the Sultan River than the intake at Elevation 1366, but it also reduces turbidity in the power releases from the raised reservoir. The surface withdrawal concept is, therefore, the logical choice for the power tunnel intake for the Stage II development of the Sultan River Project.

Section 1

INTRODUCTION

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1.1 PURPOSE

The Stage II Development for the Sultan River Project in Snohomish County, Washington, involves raising Culmback Dam, constructing a tunnel and pipelines, and building a powerhouse on the Sultan River. A comprehensive program of data acquisition, analysis, and numerical simulation was undertaken to evaluate the effects of the Stage II Development on the water temperature and turbidity in the discharges from Spada Lake so that the possible impacts on fisheries and the water supply for the city of Everett could be assessed.

1.2 SCOPE

The scope of the study described in this report is as follows:

- Collect sufficient field data on meteorology, flows, temperatures, turbidities, and other water quality parameters for Spada Lake, for verification of a mathematical model of the temperature and turbidity distribution within the reservoir and in the outflows from the reservoir
- Develop and verify a mathematical model
- Use the mathematical model to simulate the temperature and turbidity within the Stage II reservoir and in the outflows from the reservoir
- Develop and verify a streamflow temperature model for the reach between Culmback Dam and the Diversion Dam, and simulate the temperature changes in the low-level releases from the Stage II reservoir as it flows down the Sultan River to the Diversion Dam

- Compare the simulated temperatures of the Stage II reservoir outflows with historical streamflow temperatures

- Compare simulated turbidities in the Stage II reservoir outflows with the turbidity in the exisiting outflow

Collection, reduction, and analysis of the data is described in Section 2 of this report. Development and verification of the mathematical models for reservoir temperature and stream temperature simulation is described in Section 3. Results of the reservoir temperature studies are presented in Subsections 4.1 and 4.2; Subsection 4.3 presents the results of the stream temperature simulation. Finally, the existing turbidity variations in Spada Lake, verification of the mathematical model for turbidity, and prediction of turbidity variations in the Stage II reservoir are presented in Section 5.

1.3 DESCRIPTION OF EXISTING AND PROPOSED PROJECTS

The existing project, shown on Figure 1-1, provides a firm water supply for the city of Everett, Washington. Culmback Dam, constructed on the Sultan River in 1965, forms Spada Lake, a small reservoir with a surface area of about 800 acres and a volume of about 34,500 acre-ft at the normal operating level, El. 1360. The average inflow to Spada Lake is about 745 cfs.

The flow out of Spada Lake passes over a morning glory spillway (crest El. 1360) or through a low-level outlet controlled by a Howell-Bunger valve (centerline El. 1241, tunnel intake centerline El. 1250). Releases from the lake then flow downstream to the city of Everett's Diversion Dam where diversions are made to Lake Chaplain, a re-regulating and secondary storage reservoir.

Stage II of the Sultan River Project will develop the hydroelectric potential of the Sultan Basin without impairing the water supply resources of the basin. A schematic plan of the proposed project is depicted in Figure 1-2. Culmback Dam will be raised, increasing the water level in

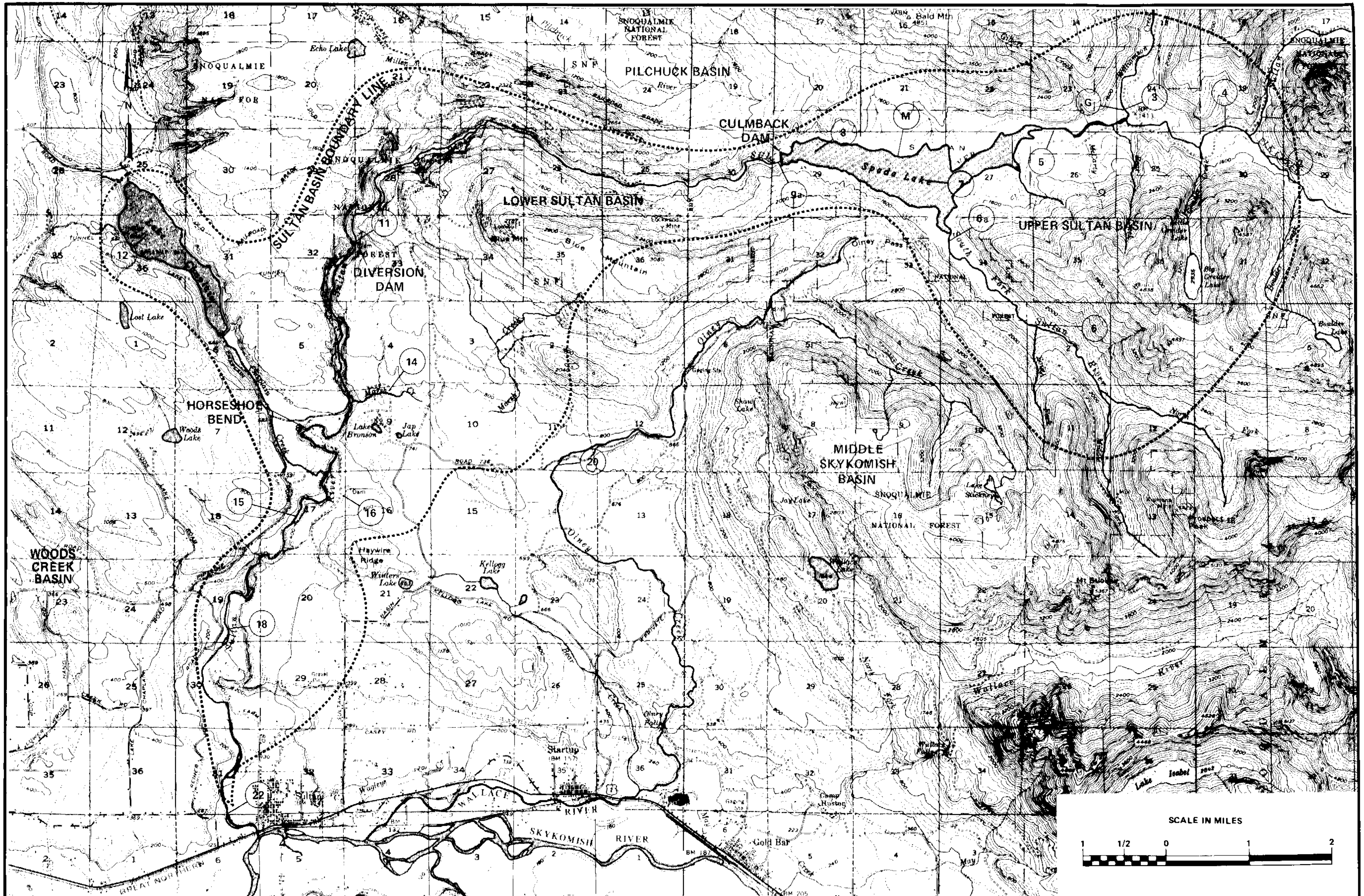


Figure 1-1 Sampling Stations, Sultan Basin

SULTAN RIVER PROJECT
GENERAL PLAN

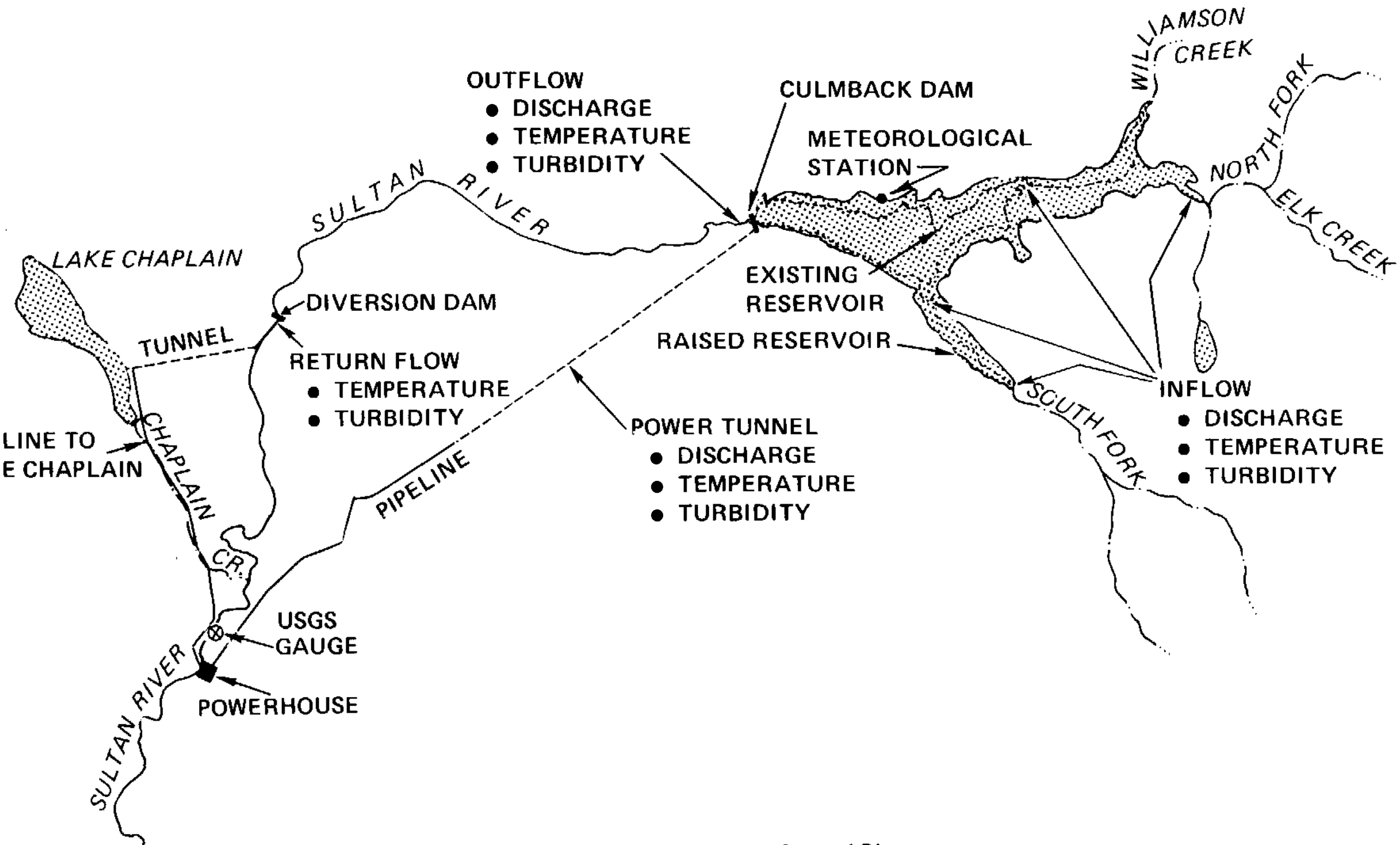


Figure 1-2 Sultan River Project, General Plan

Spada Lake 90 ft to El. 1450. Raising the dam will more than quadruple the reservoir storage volume. The principal release from the raised reservoir will pass through a tunnel and pipeline to a powerhouse, located on the Sultan River about 5.4 miles below the city of Everett's Diversion Dam. A pipeline from the powerhouse to Lake Chaplain will furnish the city's water supply requirements. Flow augmentation to satisfy fish requirements in the reach between the Diversion Dam and the powerhouse will be made by backflowing water from the pipeline outlet structure at Lake Chaplain through the existing Diversion Tunnel to the Sultan River as shown on Figure 1-2. In addition, it is assumed that a minimum release of 20 cfs will be made through the low-level outlet works at Culmback Dam.

1.4 RIVER REACHES FOR COMPARISON OF EXISTING AND RAISED RESERVOIR TEMPERATURE REGIMES

For the existing project, the temperature regime in the Sultan River below Culmback Dam is determined by the temperature of water released from Culmback Dam and the subsequent heating or cooling of the water as it flows downstream to the confluence with the Skykomish River. At present, releases from the low-level outlet combine with spills over the morning glory spillway in a common outlet tunnel and flow into the Sultan River at the base of the Culmback Dam (Station 9A on Figure 1-1). In general, there is relatively little spill from mid-July through September, so the releases in summer usually come from the lowest levels which contain the coldest water in the reservoir. As the flow passes downstream, heat exchange with the atmosphere causes the water temperature to increase or decrease, depending on the time of year. Based on past records, the water temperature increases about 2°F between Culmback Dam and the Diversion Dam (Station 11 on Figure 1-1) during the summer months. Daily river temperatures have been taken by the city of Everett at the Diversion Dam since construction of Culmback Dam in 1965. This record was used as the benchmark against which changes in temperature were measured. The Diversion Dam is the only station for which long-term records on the Sultan River are available.

The temperature regime will be much more complex for raised reservoir conditions. To help maintain resident trout fisheries between Culmback Dam and the Diversion Dam, a flow of 20 cfs will be released from the low-level outlet at Culmback Dam. The temperature of these releases has been obtained from the reservoir model and the temperature rise between Culmback Dam and the Diversion Dam has been predicted using a streamflow temperature model. Data necessary to extend the stream temperature model from the Diversion Dam to the powerhouse site were not available. Consequently, comparison with the Diversion Dam temperature record formed the basis for evaluating temperature changes in the Sultan River for the entire reach between the Diversion Dam and the powerhouse.

Discharges passing the Diversion Dam will mix with fishwater return flows from the Diversion Tunnel. The temperature of the fishwater return flow will be the same as the power tunnel outflow temperatures. A mixed temperature for the reach between the Diversion Dam and the powerhouse site was estimated, using the water temperature of the fishwater return flow as obtained from the reservoir model and the temperature of the water in the Sultan River at the Diversion Dam as determined from the stream temperature model.

The water temperatures of releases at the powerhouse will be virtually the same as those leaving Spada Lake, and were obtained from the numerical model used for simulating the reservoir temperatures. The temperatures at the proposed powerhouse site were compared to the historical record obtained by the city of Everett at the Diversion Dam.

Section 2

FIELD DATA ACQUISITION AND REDUCTION

Section 2

FIELD DATA ACQUISITION AND REDUCTION

2.1 RESERVOIR TEMPERATURE AND TURBIDITY

2.1.1 General

The numerical model for simulating the reservoir temperature and turbidity accounts for the flow of water, suspended material, and heat into and out of the reservoir. The field data acquisition program was therefore designed to monitor the discharge, temperature, and turbidity of the reservoir inflows and outflows as well as the distribution of temperature and turbidity within the reservoir. Local meteorology was monitored because heat exchange with the atmosphere and wind mixing were the principal factors in determining the changes in temperature within the reservoir. Table 2-1 lists all of the stations shown on Figure 1-1 and summarizes the data collected at each station. Measurement of discharge, water temperature, and meteorological parameters followed standard procedures; the methodology, instrumentation, and data reduction for these parameters are described briefly in subsequent paragraphs in this section. Turbidity, however, presented a special problem and is discussed below.

2.1.2 Turbidity

Turbidity is an optical property of water. To model turbidity requires that it be related to some physical quantity that can be described mathematically, e.g., the concentration of suspended solids or of biologic matter causing the water to be turbid.

Turbidity is expressed in terms of the amount of light that is scattered by material suspended in the water. Measurement of turbidity by scattering

Table 2-1

SUMMARY OF WATER QUALITY SAMPLING STATIONS
FOR THE SULTAN BASIN

Station No.	Location	Stage	Temperature	Turbidity	Water Quality[d]
1.	North Fork, not used in this study				
2.	Elk Creek	USGS Gauge	City[a]	City[a]	
3.	Williamson Creek	USGS Gauge	City[a]	City[a]	
4.	North Fork, above Williamson Creek	Stage Recorder USGS Gauge Weight Gauge	City[a]	City[a]	
5.	North Fork, Entrance to Spada Lake		Continuous recorder	ISCO Sampler	X
6.	South Fork, Bridge	Stage Recorder USGS Wire Weight Gauge	City[a,b]	City[a,b]	X
6A.	South Fork, Entrance to Spada Lake		Continuous[b] recorder	ISCO[b] Sampler	
7.	Spada Lake, midlake		Profiles	Profiles	X
8.	Spada Lake, near the log boom		Profiles	Profiles	X
9A.	Outlet of Culmback Dam	(c)	Continuous recorder	ISCO Sampler	X
11.	Diversion Dam	Stage Recorder	Continuous recorder	ISCO Sampler	X
12.	Lake Chaplain		Profiles	Profiles	X
14.	Marsh Creek				X
15.	USGS Gauge, Sultan River	USGS Gauge			X
16.	City of Sultan Water Supply				X
18.	Sultan River, below Powerhouse site				X
22.	Town of Sultan				X

Notes: (a) "City" designates once daily reading by the city of Everett.
(b) Recorders moved to Station 6 during winter for ease of access.
(c) Stage recorder at Culmback Dam to record Spada Lake levels.
(d) "Water Quality" designates collection of periodic samples for analysis of chemical and biological constituents.

of light is called nephelometry, and the standard unit of turbidity is expressed as Nephelometric Turbidity Units (NTU's). The definition of the NTU is based on a standard solution of Formazin polymer as described in the 14th Edition of Standard Methods, AWWA (1975). Proper use and evaluation of turbidity measurements requires a basic understanding of the interaction between some physical properties of the sample and the characteristics of the instrument used to produce a turbidity measurement. In general, there is no unique relationship between turbidity and suspended solids concentration, because turbidity, as measured by a nephelometer, depends on the characteristics of the suspended particles as well as upon the individual instrument characteristics. The relative importance in nephelometry of such factors as the total number, size and geometric shape of the suspended particles, the spectral distribution of the incident radiation, and the instrument design is discussed by Austin (1973) and Vanous (1978).

If the particles causing turbidity are of the same material and fairly uniform in size, then the relationship between turbidity and NTU is linear. This fact is supported by Mie (1908) who showed that the amount of scattering caused by uniform-size, spherical particles is linearly related to the number of particles. Data by Lobring and Booth (1974) and Locher et al. (1976) show that there is a linear relationship between turbidity readings and the total suspended solids concentration for different "standard" materials, the slope of the lines being different for each material. Data obtained in this study showed that there was a linear relationship between turbidity in NTU and suspended solids concentration for Spada Lake. Consequently, modeling turbidity in the numerical model could be accomplished in terms of Nephelometric Turbidity Units instead of concentration of suspended solids. In this study, turbidity is the property that was modelled because turbidity is the accepted parameter on which comparison of existing and future water quality will be based.

In general, different instruments do not read the same NTU value for a given sample even if they have been calibrated with the same Formizin standard because of differences in nephelometer design among instrument manufacturers. Therefore, all turbidity measurements obtained in this study were obtained with the same instrument, a battery-powered nephelometer manufactured by Resources Technology, Inc., Gainsville, Florida.

2.1.3 Reservoir Inflows

The North and South Forks of the Sultan River are the two principal sources of inflow into Spada Reservoir. The United States Geological Survey (U.S.G.S.) established gauging stations with wire-weight gauges on the North Fork at Station 4 (Figure 1-1), and the South Fork at Station 6 in 1976. Gauging stations with hourly recording gauges were also established by the U.S.G.S. on Williamson Creek (G on Figure 1-1) and on Elk Creek, Station 2. Because the small drainage areas and mountainous terrain lead to short duration, highly peaked runoff events, Leupold and Stevens Type F stage recorders were installed on the North and South Forks at Stations 4 and 6, respectively, to supplement the U.S.G.S. recording stations. The installation on the North Fork is shown on Figure 2-1. Reservoir inflows were calculated by combining the stage data obtained on the North and South Forks with the Williamson Creek data and with hydrologic estimates of flows from several small ungauged areas which make up about 15 percent of the catchment area.

Inflow temperatures were obtained with clock-wound, mechanical thermographs supplied by Weather Measure Inc., Sacramento, California (Model T601-AS-22). To obtain continuous stream temperature records as close to the reservoir as practicable, the thermographs were installed on the North Fork at Station 5 (Figure 1-1) and on the South Fork at Station 6A.

Turbidity measurements were obtained by using automatic sequential samplers manufactured by ISCO Inc., Lincoln, Nebraska. These samplers, shown in Figure 2-3 were located at Stations 5 and 6, and obtained pumped samples at pre-selected, programmed intervals. Turbidities were measured with a battery-

Figure 2-1 Stage Recorder Installation, North Fork

Figure 2-2 Thermograph Installation, Low-level Outlet at Culmback Dam

powered, portable nephelometer manufactured by Resources Technology Inc. (RTI), Gainsville, Florida. During periods of high turbidity, the samplers were serviced Monday, Wednesday, and Friday of each week. A more detailed description of the field operation was presented by Locher, Elder, and Ryan (1980).

2.1.4 Reservoir Outflows

Lake levels were monitored with a Leupold-Stevens, Type F, stage recorder to obtain the head on the morning glory spillway and the head on the Howell-Bunger outlet valve. Rating curves for the morning glory spillway and Howell-Bunger valve were developed to compute the reservoir outflow. The rating curve for the spillway was developed on the basis of model study data for Culmback Dam (Acre and Higgins, 1962) and on data from other morning glory spillways. The outlet valve rating curve was derived from U.S. Army Corps of Engineers Hydraulic Design Criteria (1973) and included the effects of system headlosses.

Outflow temperature and turbidites were measured at Station 9A, located at the outlet of Culmback Dam. A mechanical, clock-wound thermograph, shown on Figure 2-2, was used to obtain a continuous record of outflow temperature. Turbidities were obtained using the ISCO automatic sequential sampler as depicted on Figure 2-3.

2.1.5 Reservoir Profiling

Measurements of temperature and turbidity in the reservoir as a function of depth were made approximately every two weeks at Station 8, and about every month at Station 7 (see Figure 1-1). Station 8 is located near the log boom at the lower end of the reservoir, and Station 7 is located about midway between Culmback Dam and the upper end of the reservoir. Measurements were obtained with a Hydrolab Model 8002, a battery-powered field instrument capable of measuring temperature, dissolved oxygen, pH and conductivity *in situ*. Samples for turbidity were obtained with a grab sampler and turbidity measurements were made with the RTI nephelometer.

Figure 2-3 Servicing Automatic Sequential Pump Sampler

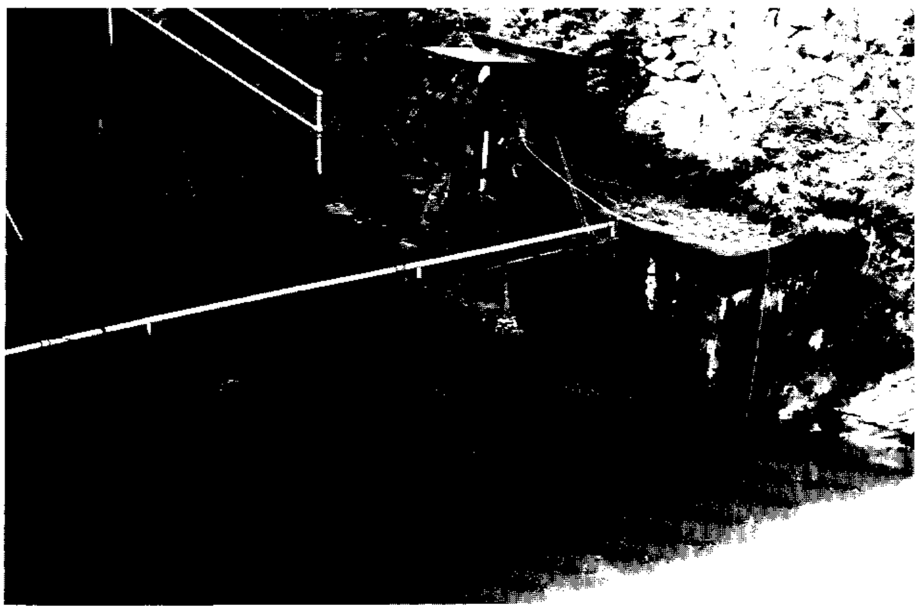


Figure 2-4 Diversion Dam. Intake to Diversion Tunnel and Instrumentation

The reservoir profiles indicated the spatial and temporal distribution of temperature and turbidity within the reservoir and provided a check on the capability of the numerical model to simulate conditions in the reservoir.

2.2 METEOROLOGY

Exchange of heat between the lake and the atmosphere is controlled by the meteorological conditions. Most previous investigators in reservoir temperature simulation have used meteorological data from neighboring sites, or have generated the data using empirical formulae. This procedure creates uncertainty in the validity of the simulation. Reliable and accurate site meteorology is therefore essential for estimating correctly the fluxes through the lake surface. A meteorological station located at M on Figure 1-1 was established to obtain wind speed and direction, solar radiation, precipitation, relative humidity, and air temperature.

An electronic weather station (EWS) manufactured by Climatronics Corp., Bohemia, NY, was supported by mechanical units to ensure reliability. The mechanical units consisted of a Weather Measure Hydrothermograph Model H311S which measured temperature and relative humidity, a Model R401 mechanical pyranograph which measured solar radiation, a weighing pan rain gauge (Model 6032 distributed by Weathertronics, Sacramento CA) and a Measurement Research Inc. (MRI) mechanical unit for wind speed and direction.

2.3 DIVERSION DAM INSTRUMENTATION

To assist in the calibration of the stream temperature model, water and air temperature measurements were obtained at the Diversion Dam with a Weather Measure Model T601S-16 thermograph. The turbidity of the flows diverted to Lake Chaplain was obtained with an ISCO sampler (Figure 2-4). Stage recorders were installed to monitor the discharge over the Diversion Dam as well as the quantity diverted to Lake Chaplain.

2.4 QUALITY ASSURANCE

One of the most important and often neglected aspects of a data acquisition program is obtaining assurance that all of the data are of good quality. To ensure that all of the temperatures were measured with respect to a common datum, each thermograph was checked with a mercury calibration thermometer when the charts were changed each week. The Hydrolab was calibrated with the same thermometer, and temperatures measured with this instrument were compared in the field with the thermographs and the mercury thermometer. The field crew was required to maintain a log book wherein all periodic checks on instrumentation calibration were recorded.

A sling psychrometer and calibrated thermometer were used to check the meteorological station during each weekly visit. Internal calibration checks of the electronic weather station were also made weekly. Data from the two solar radiation devices and the two rain gauges were cross-checked each week.

The field turbidimeter was supplied with calibration standards. Both the instrument zero and calibration were checked prior to obtaining each set of turbidity readings. Standard Formizin solutions were used in the lab to ensure agreement with the supplied standards.

2.5 DATA REDUCTION

All of the chart records from the stage and temperature recorders were reduced by hand, coded and keypunched, providing hourly values for further analyses. Turbidity values and hourly values of the meteorological parameters were also reduced and keypunched.

In some instances, there were gaps in the inflow water temperature records caused by instrument problems. These gaps were bridged by using the stream temperature model described in Section 3 of this report, the meteorological observations, and the daily temperature readings obtained by the city of Everett at Stations 4 and 6 on the North and South Forks, respectively. In this manner, complete records of inflow temperatures were made available for the numerical simulation of the reservoir temperatures.

A water balance for Spada Lake was performed to check the inflow and outflow data used in the numerical simulation. Inflows were computed by combining the hourly stage data obtained on the North Fork (Station 4) and the South Fork (Station 6) with the U.S.G.S. stage data for Williamson Creek and with estimates of flows from several small ungauged areas. Outflows were calculated using the reservoir water surface elevation and the rating curves for the morning glory spillway and the Howell-Bunger valve outlet. A computer program used these data, the observed precipitation, and estimates of evaporation based on the meteorological data to calculate the daily variation in lake level. The calculated lake elevations were then compared with the observed lake levels. In general, the agreement was within ± 1.5 ft, which was satisfactory, given that a consistent error of 30 cfs for a month's time in the inflow or outflow results in more than a 2 ft change in water surface elevation, and that the area-capacity-elevation curve shown on Figure 2-5 was based on a map with 10 ft contour intervals.

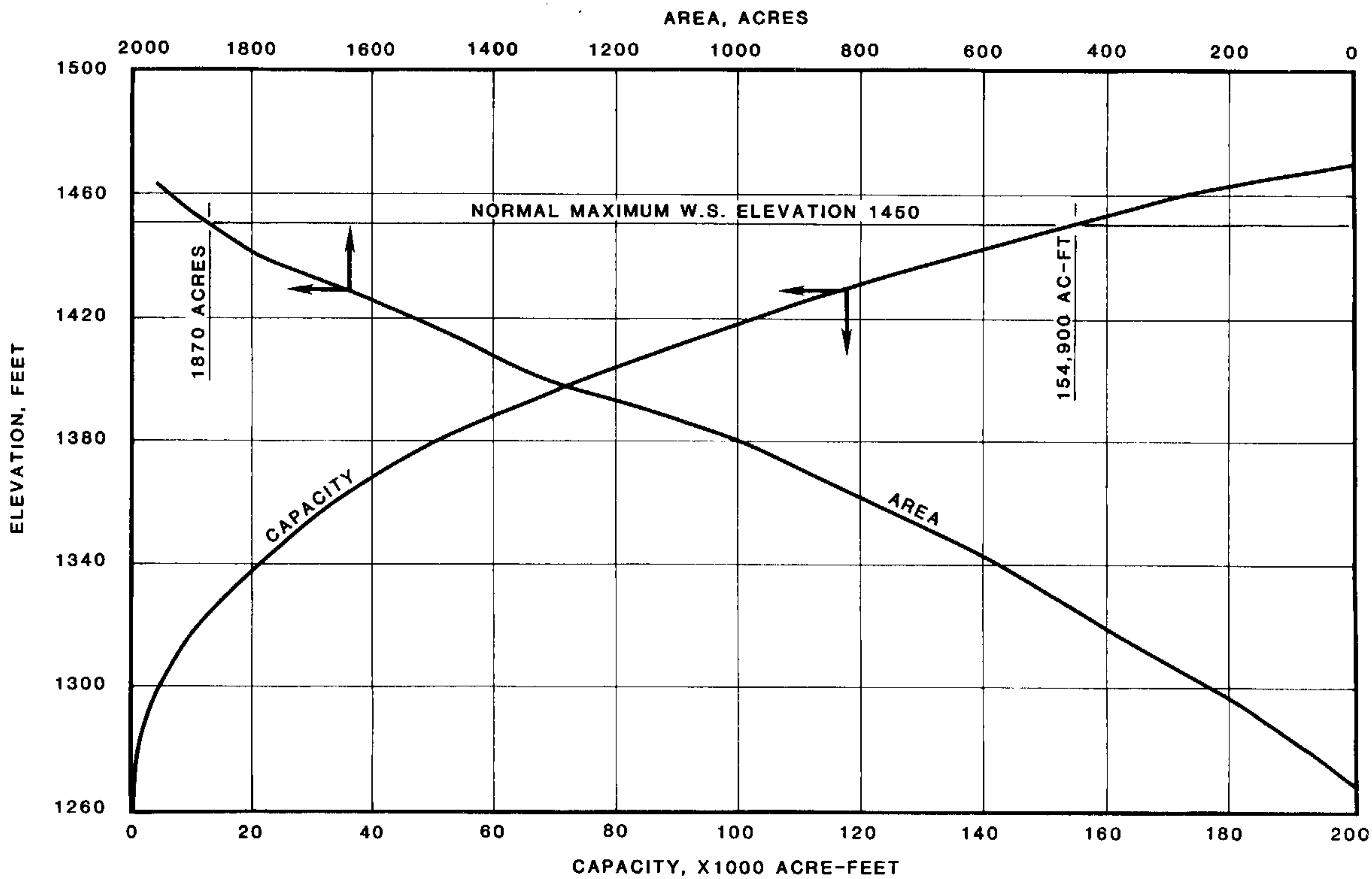


Figure 2-5 Spada Lake, Area-Capacity Curve

Section 3

NUMERICAL MODEL FOR TEMPERATURE AND TURBIDITY

Section 3

NUMERICAL MODEL FOR TEMPERATURE AND TURBIDITY

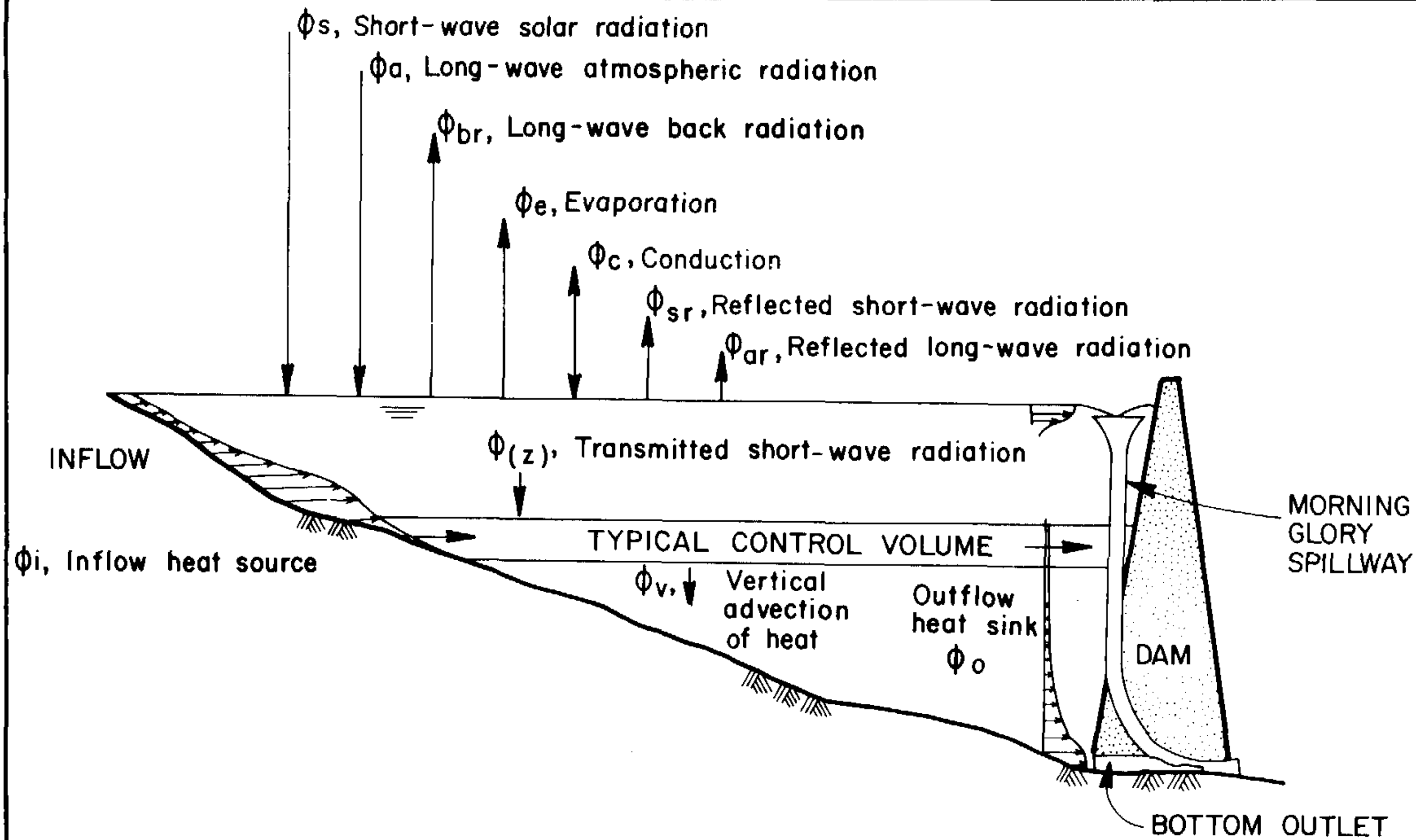
3.1 THE M.I.T. RESERVOIR MODEL

The time variation of temperature and turbidity in Spada Reservoir was simulated using an expanded and modified version of the M.I.T. reservoir model. This model was originally developed by Huber, Ryan and Harleman (1972). Major improvements to the basic model were made for simulating turbidity in the reservoir as well as the turbulent mixing induced by the action of winds, the formation, growth and melting of an ice cover, and the inflow and outflow dynamics.

The M.I.T. model is a one-dimensional (vertical variations), time dependent, variable area model for simulating the temperature distribution in a reservoir. The basic structure and key elements of the model are illustrated in Figure 3-1. The model incorporates surface heat fluxes, internal transmission and absorption of solar radiation, the distribution of inflows and outflows, and the resulting vertical advection within the reservoir. A basic assumption of the model is that horizontal temperature variations are negligible (i.e., the thermal structure of the reservoir can be described by a one-dimensional, heat balance equation in the vertical direction). Detailed descriptions of this model can be found in Ryan and Harleman (1971) and Huber et al. (1972).

3.2 MODIFICATIONS TO THE M.I.T. TEMPERATURE MODEL

Surface heat fluxes are key parameters in the temperature model. The principal fluxes are solar radiation, longwave atmospheric and back radiation, and evaporation and conduction. Minor modifications were necessary to



<u>SULTAN RIVER PROJECT</u>
<u>RESERVOIR TEMPERATURE SIMULATION</u>

Figure 3-1 Definition Sketch: Principal Elements of the MIT Model for Stratified Reservoirs as Applied to Spada Lake

correctly simulate some of the fluxes for Spada Lake. These modifications are discussed in Subsections 3.2.1 through 3.2.4. Subsections 3.2.5 and 3.2.6 describe improvements to the model for simulating the effect of wind mixing and the development of an ice cover, respectively. Subsection 3.2.7 describes the treatment of the inflow dynamics. Finally, Subsection 3.2.8 describes the modifications to the model for improved treatment of the outflow dynamics.

3.2.1 Solar Radiation

Measurements of solar radiation were taken with a silicon cell radiometer, and a mechanical pyranograph. The spectral response of the silicon cell radiometer was in the 0.35–1.15 μ range; the range for the pyranograph was 0.36–2.0 μ. Evaluation of the data obtained with these instruments presented problems. For example, the silicon cell radiometer was calibrated under clear skies during the summer in Arizona against an Eppley instrument with a spectral response in the 0.28–2.80 μ range. Use of this instrument in the Pacific Northwest (where thick cloud cover, atmospheric haze, and effects of a different latitude result in an incoming radiation spectrum significantly different from the calibration spectrum) lead to incorrect (low) measurements of the short wave radiation. For conditions observed at Spada Reservoir, a correction was made in the model to the measured short wave radiation to account for the change in the calibration factor based on a comparison of the data obtained from the silicon cell radiometer and the mechanical pyranograph.

3.2.2 Long Wave Radiation

The original M.I.T. model used the Swinbank formula (1963), adjusted for cloud cover, to estimate long wave atmospheric radiation. In general, this formula is satisfactory for the air temperatures usually observed in moderate climates, but it appears that the Swinbank formula underestimates the radiation flux at temperatures below 0°C. Consequently, the Swinbank formula was replaced by the Idso-Jackson (1969) formula which is considered more suitable for year-round simulations in areas characterized by long periods of near-zero temperatures. As shown by Findikakis et al. (1980), the Idso-Jackson formula provides a better estimate in the temperature range -10 to 10°C. No adjustment was necessary for longwave back radiation.

3.2.3 Evaporation and Heat Conduction

Evaporative losses were estimated in the original model using a Lake Hefner type formula (Marciano and Harbeck, 1954). The original Lake Hefner formula is based on daily estimates of the evaporation and daily averages of the wind speed, air and water temperature, and represents the best fit through data obtained under various conditions of atomospheric stability. To account for the effect of atmospheric stability and improve the estimate of the evaporation and conduction losses especially in simulations with time steps smaller than one day, the constant in the evaporation formula was expressed as a function of atmospheric stability and the value of the constant under neutral conditions (Deardorff, 1968).

Conductive heat transfer was estimated in the original model using the Bowen ratio approach. The effect of atmospheric stability on conductive heat transfer was accounted for in a manner similar to that for evaporation losses.

3.2.4 Absorption and Transmission of Short-Wave Radiation Within the Reservoir

The transmission of short-wave radiation was computed in the M.I.T. model by assuming that a fraction of the incident solar radiation is absorbed at the surface and that the transmission into the reservoir decays exponentially with depth. The exponential decay of the transmitted short-wave radiation was computed as a function of an extinction coefficient. Using a single extinction coefficient for the entire spectrum of incident radiation gives only an approximation to the actual rate of energy transmission into the water, because the extinction coefficient is actually a function of the wave length of the incident radiation. The long wave lengths (i.e., the infrared radiation) penetrate to a much smaller depth than the shorter wave lengths. This effect is usually accounted for by assuming that approximately forty percent of the incident short-wave radiation is absorbed at the surface. Because of the effect of the annual variation of the atmospheric mass on the incoming solar spectrum (and thus on the fraction of the short-wave radiation which is absorbed at the surface) a slightly different approach was taken in this study. It was assumed that the short-wave radiation which is absorbed at the surface is equal to the fraction of the total solar radiation reaching the water surface with a wavelength greater than 0.74 μ. On the basis of data presented by Jerlov (1965) this approach seems reasonable. With this assumption, and using data on the spectral distribution of solar radiation under different atmospheric mass conditions published by Nikolskii (1973), the fraction of the short-wave radiation absorbed at the surface was expressed as a linear function of the atmospheric mass.

The extinction coefficient used in the M.I.T. model was a bulk coefficient for the entire spectrum and accounted for the effort of different physical processes causing attenuation of the incident radiation flux. These processes include attenuation by pure water, scattering by suspended particles, absorption by suspended particles and absorption by biologic matter. These last three components of the extinction coefficient have high variability depending on the characteristics and quantity of suspended solids and biologic matter in the water, and are site-dependent. The principal contributors to the extinction coefficient in Spada Lake appear to be scattering and absorption by suspended particles. Biologic activity is low because of the lack of nutrients in the water.

The most widely used practical method for measuring light attenuation is the Secchi disk. The Secchi disk is a standardized disk, 8 inches in diameter, which is gradually lowered into a water body. The depth at which the disk is no longer visible is called the Secchi depth. Different investigators have obtained satisfactory estimates of the extinction coefficient by computing it as inversely proportional to the Secchi disk depth. A commonly used value of the constant of proportionality is 1.7 as proposed by Poole and Atkins (1929). Secchi disk depth observations in Spada Lake have shown a variability over the lake. Observations at Station 7 in the shallow upper end of the reservoir have indicated generally lower values of the Secchi disk depth during the summer than observations at Station 8 near the dam. Best results were obtained using the Station 8 Secchi disk values, and increasing the constant of proportionality to 3.4 to account for the more turbid shallow areas.

Secchi disk depth measurements were made in the field approximately every two weeks. To account for variations of the Secchi disk depth, and consequently of the extinction coefficient between field observations, direct interpolation between observations at Station 8 was used.

3.2.5 Wind Mixing

The version of the M.I.T. model presented by Octavio et al. (1977) included the effects of wind mixing in a relatively simple manner. For Spada Lake, a more sophisticated approach was necessary.

Winds cause turbulent mixing in the upper layers of water bodies. Typically, a mixed surface layer of uniform temperature is formed, which deepens under the continuous action of the wind. The exchange of heat at the surface is thus coupled with the wind-induced mixing. The rate of growth of the mixed layer can be estimated by writing a one-dimensional turbulent kinetic energy equation and a heat balance equation for the mixed layer. These equations were integrated over the depth of the layer and then combined to yield the rate of deepening the layer. An accurate estimate of the rate of production of turbulent kinetic energy and the associated dissipation in the epilimnion is an important factor in the prediction of the growth of the mixed layer.

The main mechanisms of production of kinetic energy in the mixed layer are the action of the wind stress at the surface, convection due to surface cooling, and wave breaking.

The energy which is available for turbulent mixing below the wave mixed layer depends not only on the intensity of the wind but also on the wind pattern. Short duration, interrupted winds — characterized by frequent changes in direction — are not as effective in contributing to the growth of the mixed layer as are constant direction, uninterrupted winds, because a higher percentage of the energy input from intermittent winds is used to develop surface waves. This energy is dissipated near the surface and is not available for deepening the mixed layer.

The production rate of turbulent kinetic energy below the wave zone due to wind action was estimated using the Tucker and Green (1977) method, but modified to allow for the energy required for wave build-up during intermittent winds. Hourly wind values were used in the computations.

The energy dissipation rate in the mixed layer below the wave zone was estimated on the basis of dimensional arguments, using appropriate length and velocity scales. These scales are different for turbulent motions generated by different mechanisms, e.g., wind and convective mixing due to surface cooling. The processes described above, as well as the definition of some terms used in this subsection, are illustrated in Figure 3-2.

The turbulent kinetic energy and the heat balance equations were solved with an iterative scheme. Each iteration had three stages. The first stage consisted of solving the heat balance equation. In the second stage, any convective instabilities found in the temperature profile were removed. Finally, the temperature profile which had been obtained from the first two stages was mixed layer by layer starting from the top, until the entire net gain of mechanical energy had been used to increase the potential energy

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Definition Sketch. Physical Processes Affecting the Growth of the Wind-Mixed Layer

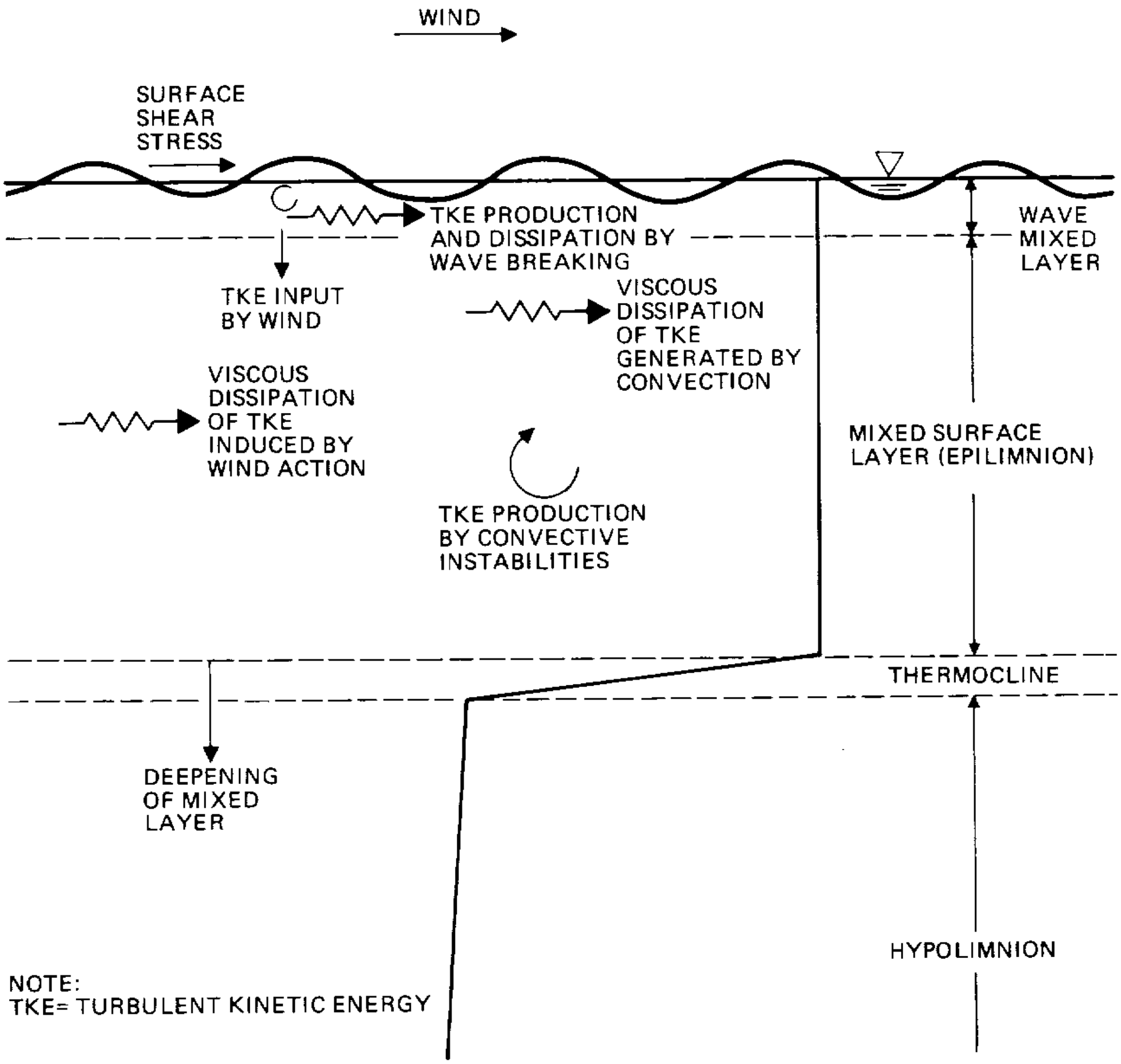

Figure 3-2 Definition Sketch: Physical Processes Affecting the Growth of the Wind-Mixed Surface Layer

of the water column. Thus, a new temperature and depth were obtained for the mixed layer. Computing the surface heat fluxes based on the new water surface temperature and then using these heat fluxes in the heat balance equation results in a different surface temperature than that for the original temperature profile. This iteration cycle was repeated until convergence for the mixed layer temperature was achieved. The first two stages of this process are featured in the original M.I.T. temperature model. The scheme was implemented by using a modified version of the algorithm developed by Octavio et al. (1977).

3.2.6 Ice Cover Formation and Melting

In order to simulate the formation, growth, and eventual melting of the ice cover which may form during the winter, a solution for the temperature distribution in the ice cover was developed. Temperature variations in the ice cover were described by the standard heat conduction equation. Boundary conditions used were:

- Constant water temperature at the ice-water interface (equal to 0°C)
- Heat flux at the ice-air interface was estimated by considering all the physical processes that add to or take away from the system
- The temperature at the ice-air interface (as well as throughout the cover) cannot exceed zero

A key parameter in the estimation of the heat flux at the ice-air interface was the albedo of the ice surface, which can vary significantly depending on the condition of the surface, including the presence or absence of snow, and the effect of melting. These effects were included in the simulation.

The time variation of ice thickness can be estimated by solving a heat balance equation for the ice cover. The rate of heat conduction from the water underneath the ice cover was obtained by solving the heat diffusion equation in the thermal water boundary layer underneath the ice cover. These equations were solved numerically using one-dimensional quadratic finite elements.

A critical factor in the simulation of the onset of the ice cover is the proper accounting of the wind mixing effect. If wind mixing in the surface layer is underestimated, the simulated water surface temperature decreases at a faster rate than the observed, resulting in an early formation of ice in the reservoir. For example, in Spada Lake, if the effect of wind mixing is neglected, the simulation produces an ice cover 12 days earlier than it actually occurred. Accounting for the wind mixing effect substantially improved this aspect of the simulation.

Once formed, the ice cover acts as an insulating blanket on the reservoir. The only significant heat input into the ice-covered reservoir is from warmer streams discharging into the reservoir and from a small fraction of the short-wave radiation which penetrates the ice cover. The latter effect on the surface heat fluxes was also included in the model.

3.2.7 Inflow Dynamics

The M.I.T. model treats inflows in a relatively simple manner. The inflow is assumed to entrain a prescribed amount of water from the surface layers. The resulting mixed inflow temperature determines the level at which the plume enters the reservoir. The mixed inflow is assumed to have a Gaussian velocity profile with a standard deviation related to the inflow depth. Modifications were made to the model to improve the estimation of the amount of entrainment, and the velocity distribution in the inflow plume. River inflows were simulated in the model in four phases, surface mixing, plunging, underflow, and intrusion. Figure 3-3 illustrates these phases.

Surface Mixing. At the entrance to the reservoir, the inflows, although often buoyant (positively or negatively), expand vertically so that they remain both on the surface and attached to the bottom. If the reservoir

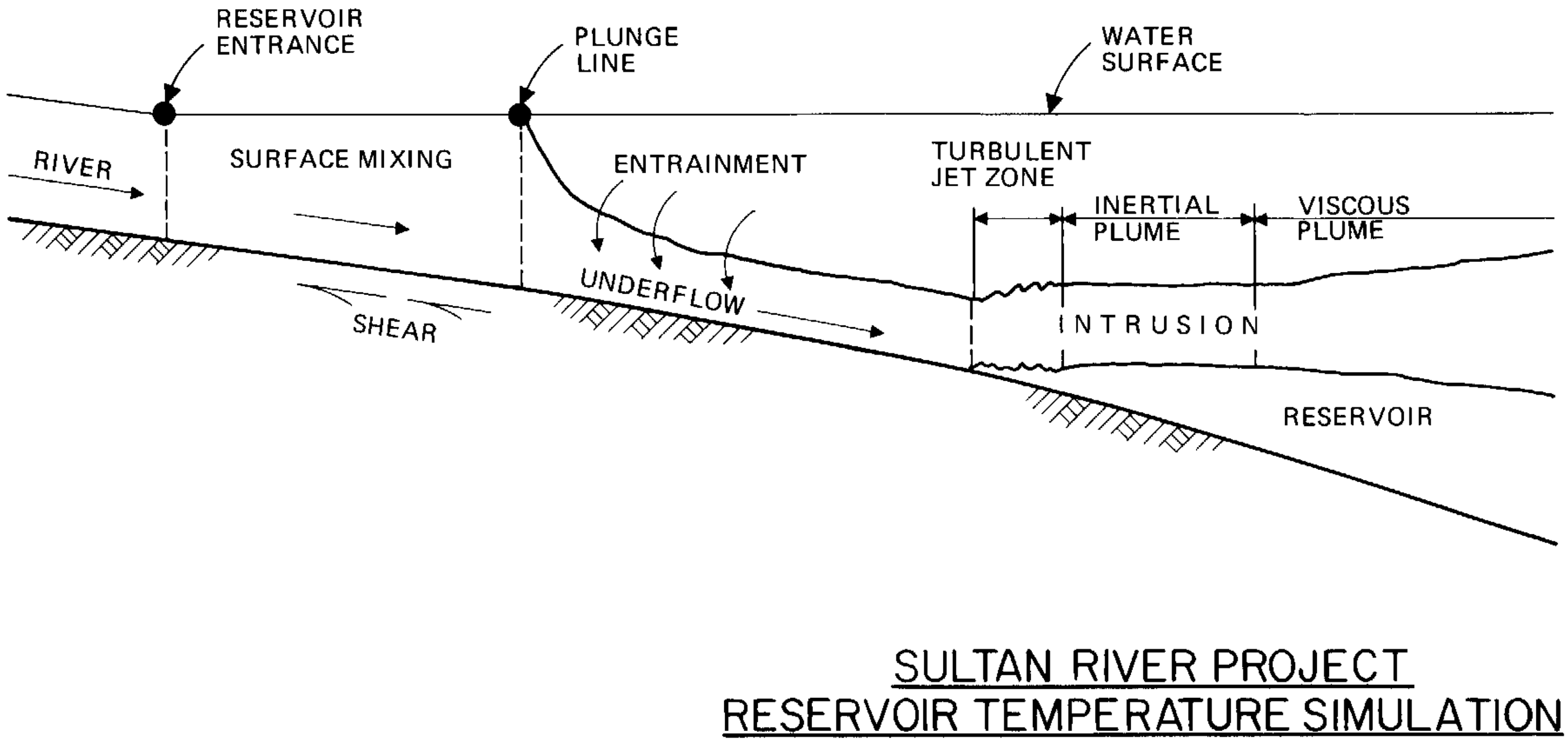

Figure 3-3 Definition of Terms and Processes, Inflow Dynamics

topography permits, the inflow will entrain reservoir water through its lateral boundaries. Standard integral jet analysis was used to estimate dilution. When the plume width equalled the reservoir width, no further dilution was allowed.

Plunge Line. As a buoyant inflow moves into the reservoir, the plume velocity decreases, until at some point there is a balance between inertial and buoyancy effects. In this region the inflow either plunges below the reservoir surface and flows along the bottom as an underflow, or is detached from the bottom, floats and spreads across the reservoir surface as a surface intrusion. The location of this change in inflow behavior is called the plunge line. The location and depth of the plunge line, and flow conditions downstream from the plunge line, were determined using an approach similar to Fisher et al. (1979).

Underflow. When a river inflow plunges, it moves downward along the sloping reservoir bottom to a depth at which its density is the same as the reservoir density (neutral buoyancy level). At this depth the inflow moves into the reservoir as an intrusion. For very cold inflows, the underflow may move along the bottom to the dam.

The underflow was analyzed as a steady, gradually varied flow with a constant internal Froude number at each depth. Though a steady state analysis was used at each time step, the underflow characteristics were allowed to change in response to changing river and reservoir conditions since the time scale for equilibrium adjustment of the underflow was less than the time scale for river and reservoir changes. The entrainment rate was estimated by writing a simple steady state turbulent kinetic energy equation for the underflow layer. The governing equations for the underflow were integrated numerically starting from the plunge line and moving downstream until the underflow had reached the level of neutral buoyancy.

Inflow Intrusion. Once the inflow reaches the level of neutral buoyancy, it becomes detached from the bottom and flows horizontally as an intrusion layer into the reservoir. The estimation of the growth of the intrusion layer was based on the work of Chen (1980). The thickness at the intrusion layer was obtained as a function of the total flow, viscosity, local density gradient, and the travel time from the point of detachment from the bottom until the intrusion reaches the dam.

This scheme does not account for the effect of ambient turbulence which is likely to produce further spreading of the intruding layer and modify its profile. An approximate description of the outcome of this process was obtained by assuming that the velocity distribution in the intrusion layer is Gaussian, with a standard deviation equal to half the computed intrusion layer thickness.

Diurnal Fluctuations. The M.I.T. model typically used inflow temperatures averaged over the time step (usually one day). However, in Spada Reservoir the summer inflow temperatures often exhibited a diurnal fluctuation of 2°C or more, which could result in distributing the inflow over a large range of depths (as large as 15 m), compared to the calculated intrusion thickness (typically 1-2 m). To account for such diurnal effects, the observed hourly inflow temperatures were used. However, performing the complete sequence of inflow dynamics computations for each hour would have increased the computational effort substantially. Therefore, average inflow temperatures over the time step were used to compute the average intrusion layer thickness and entrainment rate for the time step. The hourly inflow temperatures were used to calculate the intrusion levels for each hour. The flow distribution for each hour's inflow was then computed on the basis of the average conditions for the time step. Finally, the vertical distribution of the total inflow for a given time step was obtained by superposition of the hourly flow distributions.

3.2.8 Outflow Dynamics

Modifications to the M.I.T. reservoir model were made to account for two factors which affect the outflow dynamics, and which were not considered in the original model:

- The effect of the reservoir bottom on the withdrawal layer thickness and the velocity distribtuion for a bottom outlet
- The possibility, under certain conditions, of withdrawal from both sides of the thermocline as suggested by recent experimental work

The growth of the withdrawal layer for the bottom outlet and the associated velocity distribution were estimated by applying the results of theoretical and experimental studies of Monkmeyer et al. (1977) and Lawrence (1979) on selective bottom withdrawal. It was assumed that, in the immediate vicinity of the outlet, the flow is axisymmetric and that further away from the outlet it becomes two-dimensional and uniform in the lateral direction. The growth of the withdrawal layer thickness in the axisymmetric flow zone was computed using an empirical expression proposed by Lawrence (1979). The estimate of the further growth of the withdrawal layer in the two-dimensional flow zone was based on the work of Monkmeyer et al. (1977).

The approach described above is based on the assumption that the reservoir is lineraly stratified. However, this is seldom the case. Typically, the thermal structure of the reservoir consists of a uniform temperature epilimnion and a weakly stratified hypolimnion which are separated by a thermocline. A steep thermocline may act as a barrier and restrict the withdrawal from both the hypolimnion and the epilimnion. Selective withdrawal from two layer fluids has been studied in recent years by several investigators. The work of Jirka and Katavola (1979) was used to determine whether the withdrawal layer from the bottom outlet extends into the epilimnion, and if so, to determine the fraction of the total outflow withdrawn from the epilimnion.

The ratio of the flow withdrawn from the epilimnion over the flow withdrawn from the hypolimnion was computed as a function of the density difference between epilimnion and hypolimnion, the outflow velocity, the size of the outlet, the distance of the outlet from the thermocline and the thickness of the thermocline. It was assumed that the velocity distribution in the upper layer is uniform and that the velocity distribution in the lower layer is described by the sine-exponential profile proposed by Monkmeyer et al. (1977). At the interface of the two layers, the velocities computed for each layer must be equal.

A test for the possibility of withdrawal from both the epilimnion and the hypolimnion was also incorporated in the treatment of the spillway outflow dynamics. The same basic approach was used as for the bottom outlet, with some modification to account for the characteristics of a spillway flow. The velocity profile in this case was assumed to be uniform in the wind mixed layer, where the temperature is uniform, and to have a Gaussian form below the mixed layer.

3.3 TURBIDITY SIMULATION

3.3.1 Relationship Between Turbidity and Suspended Solids

Turbidity is an optical property of water which is usually measured in terms of the amount of light scattering at a certain angle relative to a light source. This approach to turbidity measurement is characterized as nephelometry, and the accepted turbidity unit is the Nephelometric Turbidity Unit (NTU) which is defined in Standard Methods, 14th Ed., AWWA 1975.

To simulate turbidity variations, it is necessary to relate the turbidity to the substances which cause it. The predominant cause of turbidity in Spada Lake is the presence of fine clay particles in suspension. The amount of light scattering and consequently the turbidity measurements depend on the total number, the size distribution, and the geometry of the suspended particles. A mathematical relationship between turbidity measurements and the concentration of suspended particles of different sizes and different material may be rather complex. However, if the turbidity-causing particles are of the same material and fairly uniform in size, then the relationship between turbidity and the total amount of suspended solids is approximately linear. Analysis of concurrent turbidity and suspended solids measurements in Spada Lake justified the use of a linear assumption (Figure 3-4).

3.3.2 Formulation

Variations in turbidity were simulated by solving a one-dimensional, mass balance equation for the total concentration of suspended particles. The assumption of linearity between turbidity and the concentration of suspended solids facilitated the simulation, since all data for suspended solids in the inflows and in the reservoir were in terms of Nephelometric Turbidity Units.

Turbulent transport of suspended particles was described with an eddy diffusion model. The eddy diffusivity coefficient for the turbidity was computed as a function of the length scale associated with turbulent mixing and the turbulent kinetic energy. The vertical distribution of turbulent kinetic energy in the reservoir was estimated by solving a one-dimensional energy equation. The same assumptions regarding the generation and dissipation of turbulence which were discussed in Subsection 3.2.5 were made in the formulation of this energy equation. In addition, it was assumed that there was no turbulent transport of energy or production of energy in the hypolimnion. The effect of gravitational settling of suspended particles on the turbidity in the reservoir was accounted for by adding a constant settling velocity to the vertical advective velocity in the turbidity transport equation, and adding a sink term, proportional to the settling velocity, to account for settling on the slopes and the bottom of the reservoir. The settling velocity of suspended particles in water depends on the density, size and shape of the particles, and the kinematic

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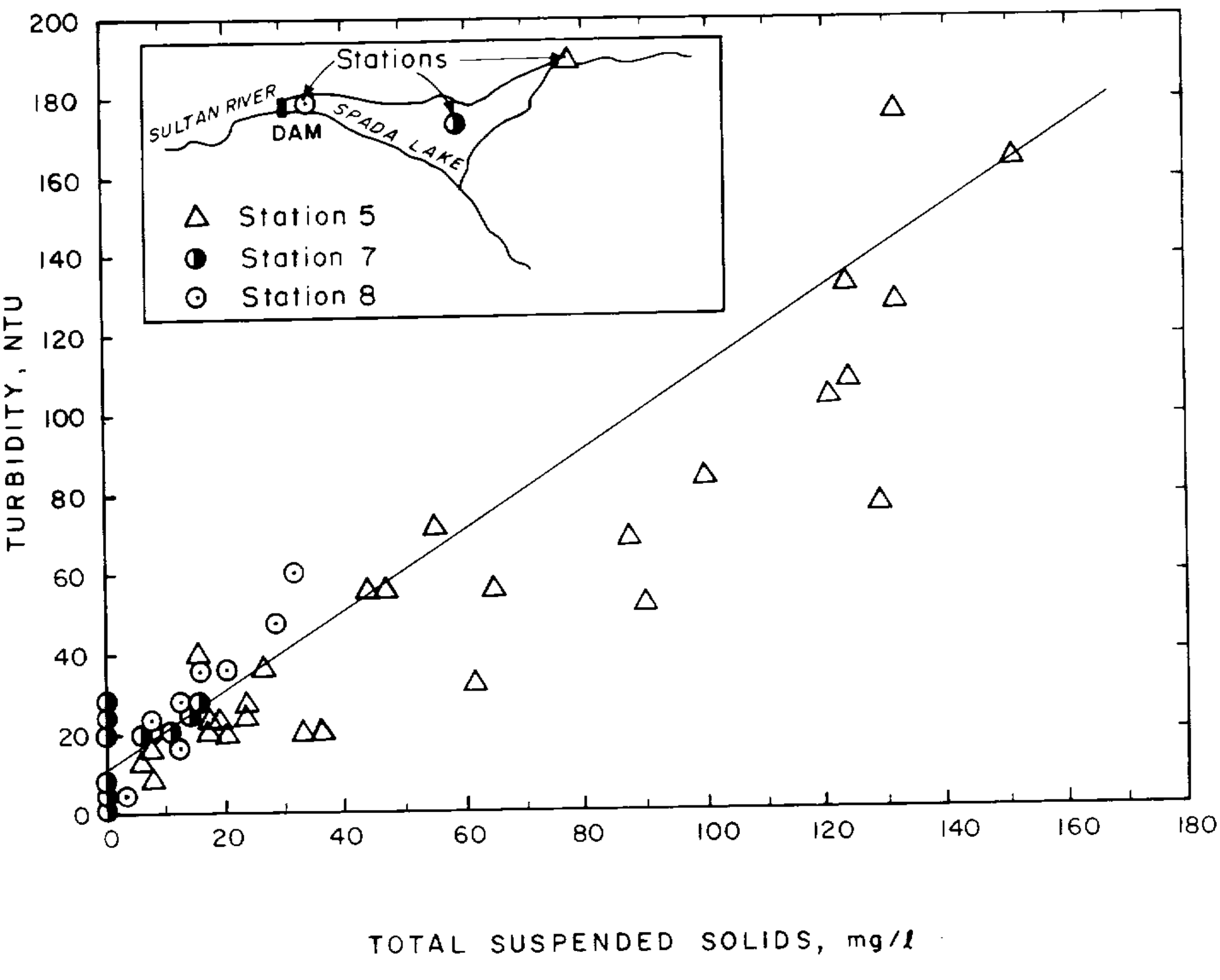

Figure 3-4 Relationship Between Turbidity and Suspended Solids Concentration

viscosity of the water. It was assumed that the settling velocity of the turbidity causing suspended particles in Spada reservoir is 0.4 m/day for a water temperature of 20°C. This is the settling velocity of spherical particles of diameter 2.2 μ, as computed from Stokes' law (for particles of specific gravity 2.7). This also would be the settling velocity of disc-shaped (Lerman et al. 1974) particles of diameter 5.3 μ and ratio of radius over thickness equal to 10. Field observations in Spada Lake have indicated that typically 60-80 percent of the suspended particles are less than 5 μ in size. Microscopic observations indicate that the particles are more like plates than spheres, as is typical for clay materials.

In the simulation, the settling velocity was varied as a function of the water temperature which affects the kinematic viscosity. Thus, for example, the settling velocity used at 5°C water temperature was approximately equal to two-thirds of the settling velocity at 20°C.

3.4 TEMPERATURE CALIBRATION

3.4.1 Results

The set of meteorological and water temperature data collected from 31 May, 1979 through 30 September, 1980 were used to calibrate the model. Calibration consisted of comparing the simulated with the observed temperature profiles in the reservoir and the observed reservoir outflow temperatures. Good agreement between simulated and observed temperature values indicated that the reservoir model with the modifications described in Section 3.2 was capable of accurately simulating the different physical processes which affect the thermal structure of the reservoir. This agreement provided the confidence and assurance necessary to use the model for prediction of the temperature distribution in the raised reservoir.

Figures 3-5 and 3-6 show the simulated and the observed (at Station 8) surface temperatures and temperatures at 4, 10, and 20 meters below the reservoir water surface for 1979 and 1980, respectively. The agreement

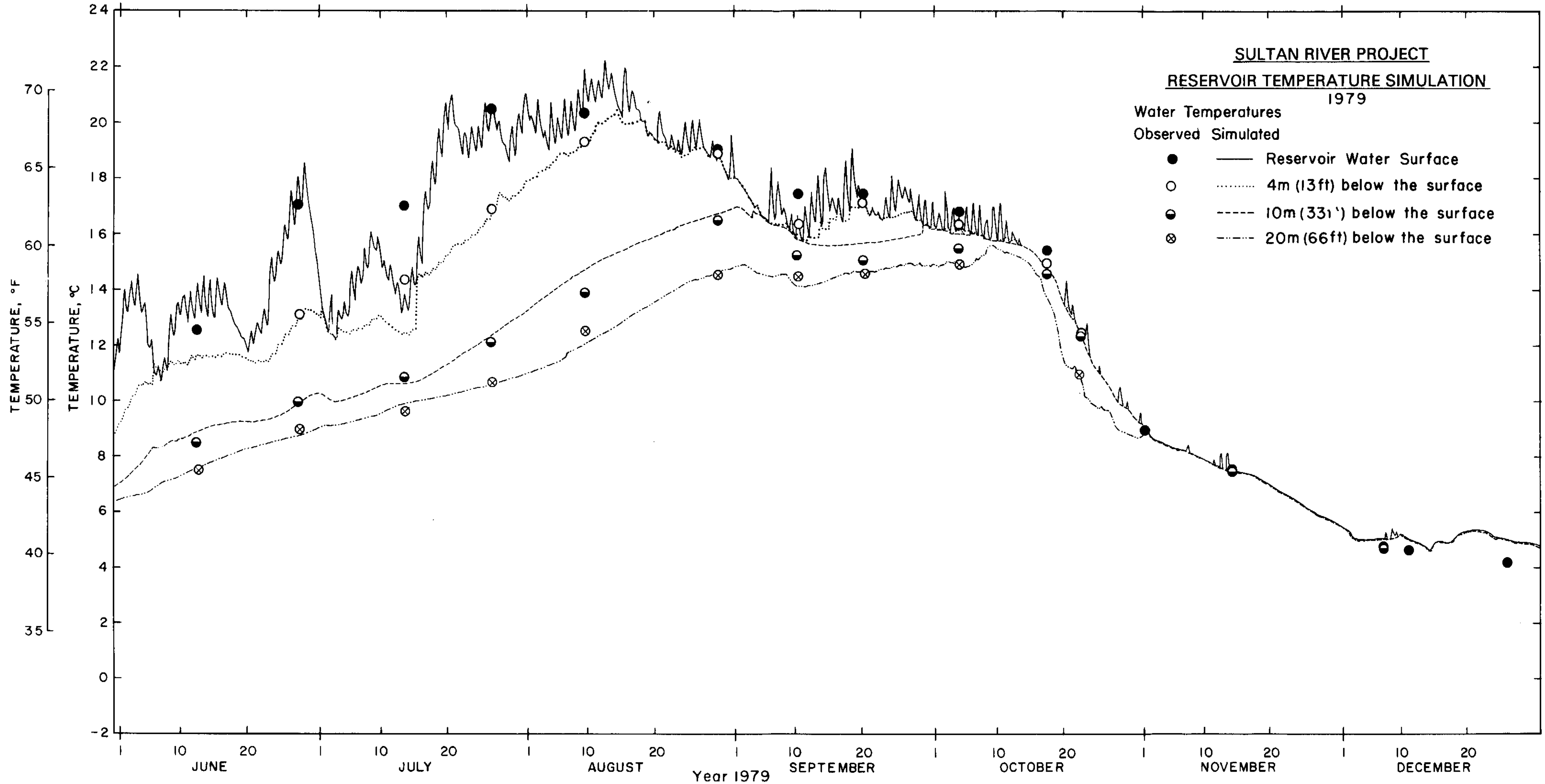

Figure 3-5 Comparison of Observed and Simulated Temperatures in Spada Lake, June-December 1979

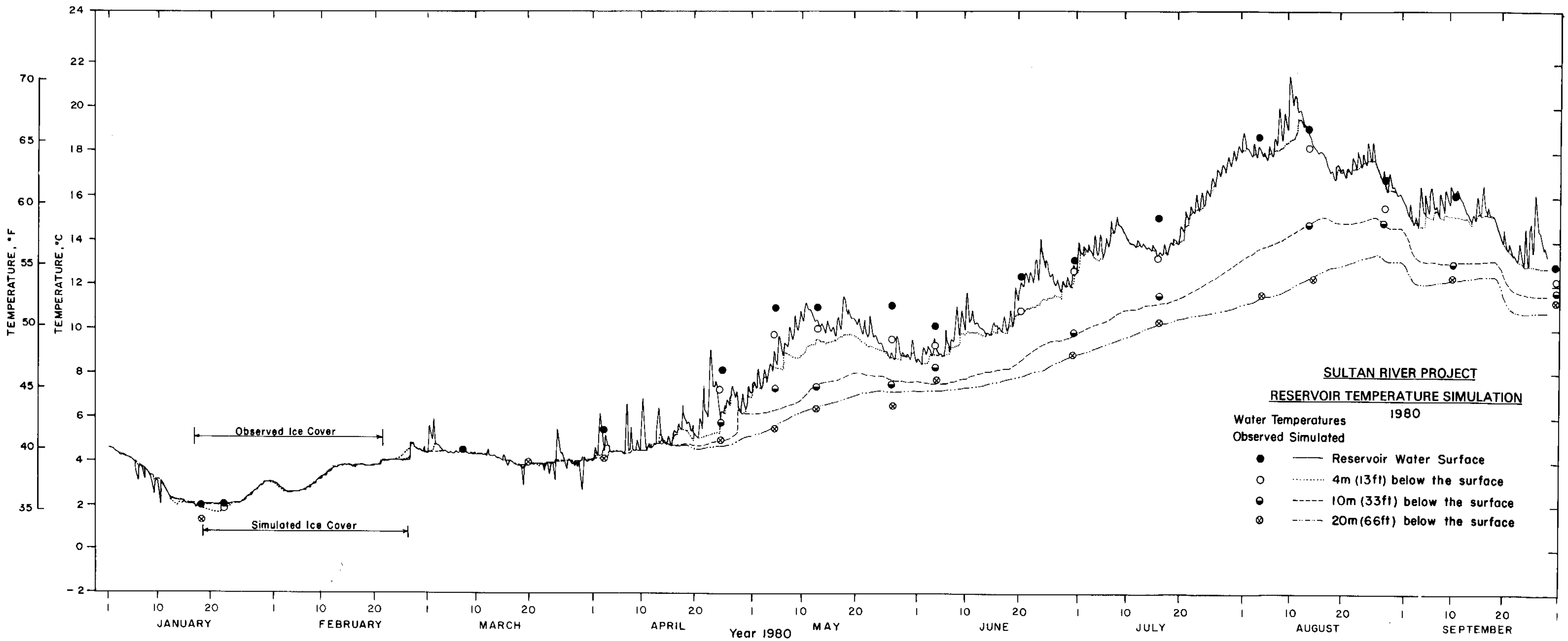

Figure 3-6 Comparison of Observed and Simulated Temperatures in Spada Lake, January-September 1980

between simulated and observed values is considered excellent. Noticeable features of the simulation shown in these figures are (a) the proper modeling of the thermal mixing during the fall which was made possible by the introduction of the wind mixing algorithm described in Subsection 3.2.5 and (b) the accurate prediction of the time of the formation and melting of the ice cover in the winter, which was made possible by using the approach described in Subsection 3.2.6.

A comparison of the observed and simulated temperature profiles in Spada Lake at different days during the simulation period is depicted on Figures 3-7 and 3-8. These profiles show clearly that the overall agreement is excellent. Figures 3-5, 3-6, 3-7, and 3-8 demonstrate conclusively that both the spatial and the temporal distribution of temperature in the reservoir are being simulated correctly.

Figures 3-9 and 3-10 compare the simulated temperature of outflows through the Howell-Bunger valve with the daily observations obtained by the City of Everett. Since the city's temperatures are recorded to the nearest degree Fahrenheit, the agreement is excellent. When the morning glory spillway is in operation, the outflow temperature is a mixture of the spillway and low-level outlet releases. Figure 3-11 shows the simulated outlet temperature during two periods of spill in comparison with temperature records obtained at Station 9A. Again, the agreement is considered excellent. These results show that the formulation of the reservoir outflow dynamics discussed in Subsection 3.2.8 closely simulates withdrawal of fluid from the appropriate layers in the reservoir and provides further evidence that the model is satisfactorily simulating the reservoir thermal behavior.

3.4.2 Limitations of 1979 Simulation

Upon completion of the calibration of the reservoir model for 1979 and most of 1980, it was concluded that using the 1979 data as input for simulation of the raised reservoir temperature regime would not produce "typical" results because the summer of 1979 was unusually hot and dry. The warm weather and lack of rainfall in the late summer of 1979 resulted in low inflows, which in turn caused reservoir drawdown to the second lowest level recorded since 1968 (Table 3-1).

The combination of a low reservoir level and clear, warm days, caused unusual heating of the remaining small body of water ($\approx$13,500 acre-feet) and abnormally high outflow temperatures in September and October of 1979. The fact that the 1979 outflow temperatures were exceptionally high in September and October is illustrated graphically on Figure 3-12. This figure depicts all of the available temperature data for releases through the Howell-Bunger valve for the June-December period that have been recorded by the city of Everett since the recording began in mid-August of 1976. The data were recorded to the nearest degree Fahrenheit. Undoubtedly, the 1979 temperatures are not "typical". To obtain more representative results, it was decided to simulate 1978 conditions. The 1978 conditions were selected because some reservoir profile data for 1978 were available from a previous study, and because the data shown on Figure 3-12 indicate that the 1978 temperatures were more typical than those observed in 1979.

3.4.3 Reservoir Temperature Simulation for 1978

The only meteorological data available for 1978 were daily maximum and minimum air temperatures, daily precipitation and thrice daily observations of cloud cover (beginning June 17th, 1978) collected by the city of Everett. The use of meteorological data from other sites on the reservoir temperature simulation was not considered a reliable procedure unless a relationship between meteorology at Spada Lake and the other site could be established. Therefore, data from Seattle taken during 1978-1980 were correlated statistically with the available 1979-1980 meteorological data obtained at Spada Lake to establish the necessary relationship between conditions at the site and at Seattle. Hourly values of solar radiation, relative humidity, and air temperature for 1978 were then synthesized by using the available 1978 Seattle data and the statistical relationships derived from correlating the 1979-1980 Seattle and project site data.

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Reservoir Temperature Profiles Comparison of Simulated and Observed Temperatures for 1980.

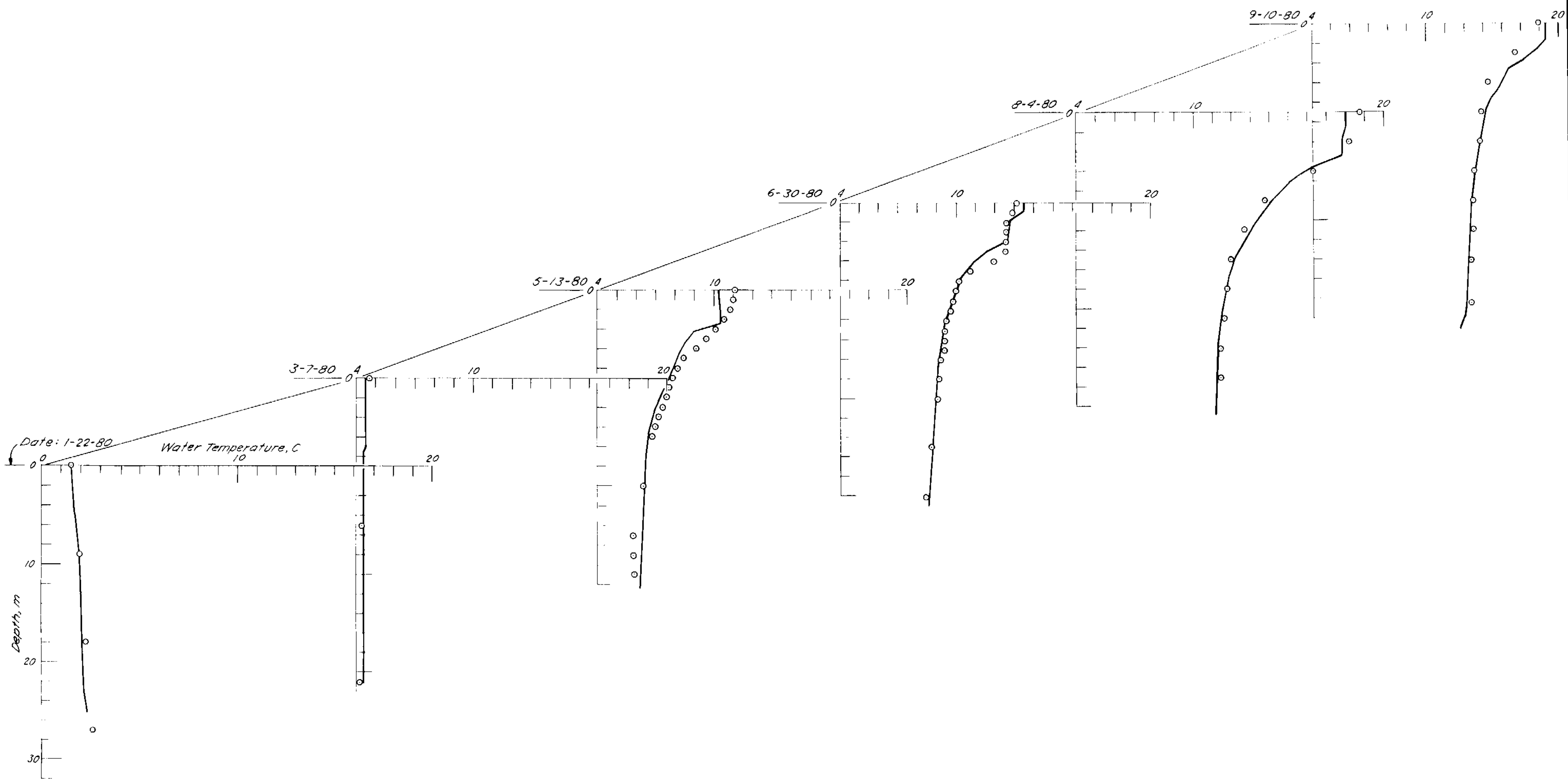

Figure 3-8 Water Temperature Profiles in Spada Lake: Simulated and Observed Temperatures, 1980

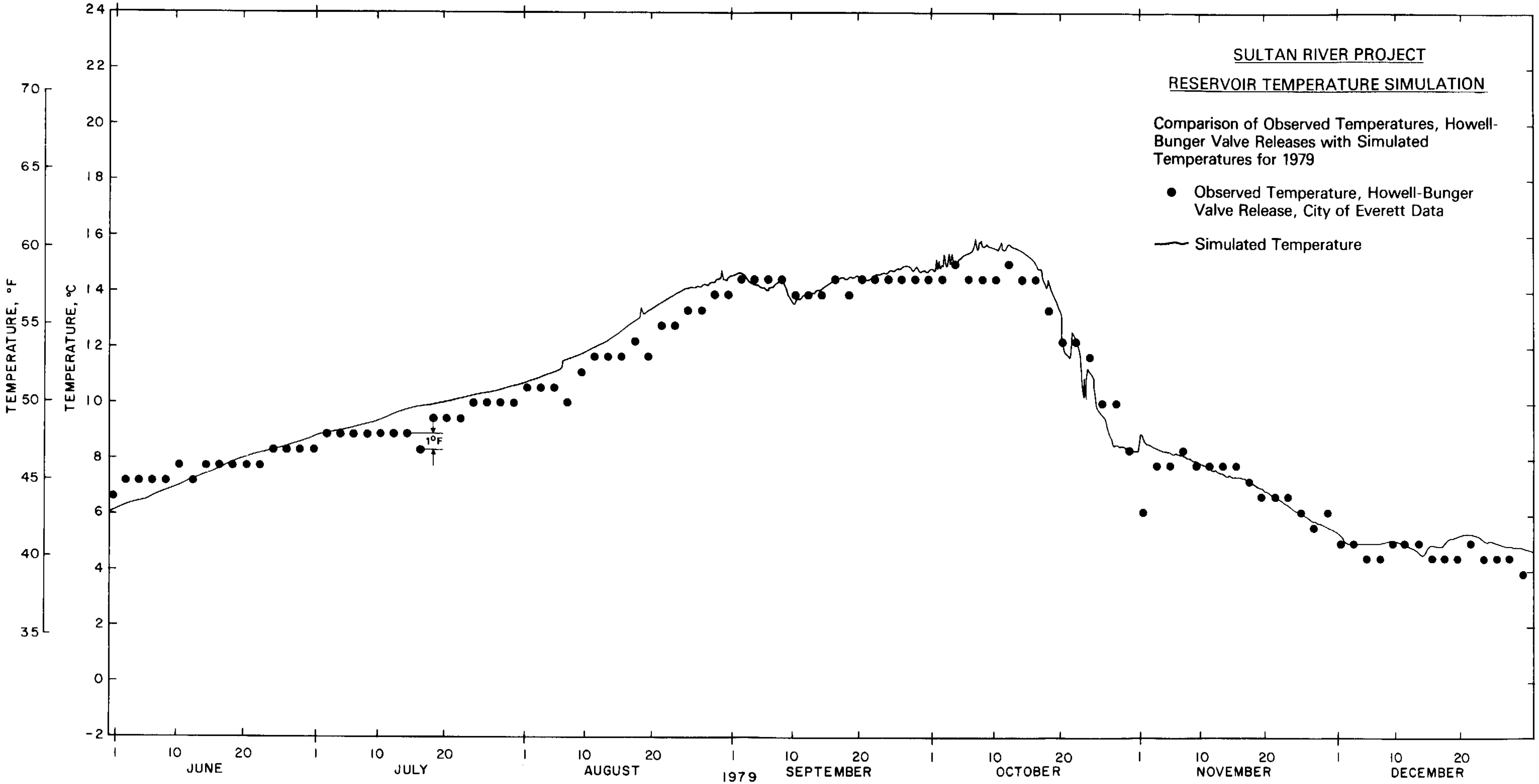

Figure 3-9 Existing Reservoir Outlet Temperatures: Simulated Temperature of Howell—Bunger Valve Releases and City of Everett Observed Temperatures, 1979

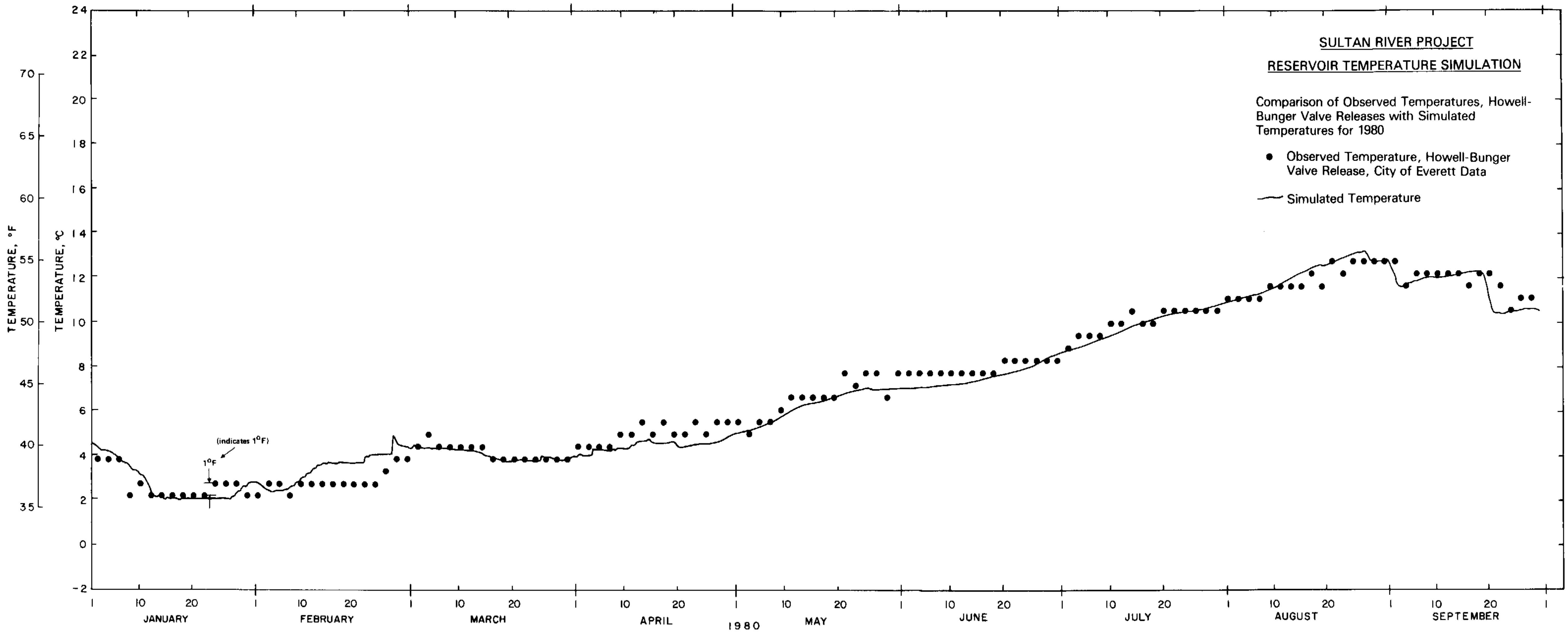

Figure 3-10 Existing Reservoir Outlet Temperatures: Simulated Temperature of Howell-Bunger Valve Releases and City of Everett Observed Temperatures, 1980

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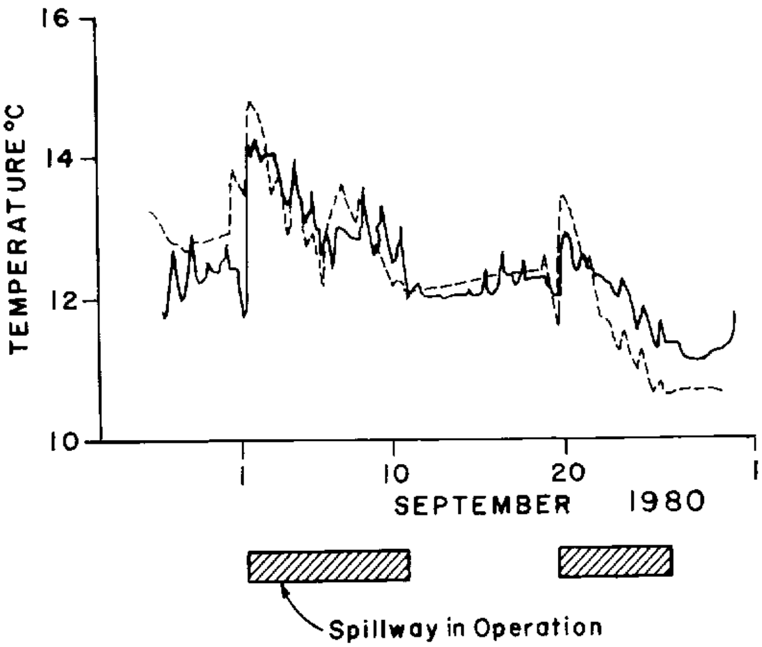

Comparison of Simulated and Observed
Reservoir Outflow Temperatures

—— Record from Station 9A

---- Simulated Temperature Combined Spillway and Howell Burger Valve Releases.

Figure 3-11 Comparison of Simulated and Observed Temperatures, Combined Outflow from Spillway and Howell-Bunger Valve, Existing Reservoir, September 1980

Table 3-1

CULMBACK DAM, MINIMUM RESERVOIR DRAWDOWN
1968-1979

Year	Reservoir Water Surface Elevation	Month and Day of Occurrence
1968	1350.38	Aug 23
1969	1331.08	Sep 16
1970	1343.98	Sep 2
1971	1350.92	Mar 22
1972	1332.72	Nov 1
1973	1331.30	Sep 19
1974	1310.50	Nov 6
1975	1344.65	Oct 3
1976	1334.22	Nov 15
1977	1339.08	Feb 10
1978	1351.40	Nov 1
1979	1326.55	Oct 16

Reservoir inflows were estimated from the city of Everett's daily stage readings on the North and South Forks (Stations 4 and 6, respectively), the U.S.G.S. data from Williamson Creek and estimates of flows from ungauged drainage areas. Outflows were calculated from the city of Everett's records of lake level, valve opening, and the rating curves for the morning glory spillway and Howell-Bunger valve outlet developed for the 1979 study.

Daily stream temperature readings for the North and South Forks at Stations 4 and 6 were available from the city of Everett. Diurnal variations in the inflow temperature were generated using these readings, the synthesized 1978 site meteorology, and the stream temperature model.

The results of the simulation of temperatures in Spada Lake for 1978 are depicted on Figure 3-13. The agreement between the predicted and the

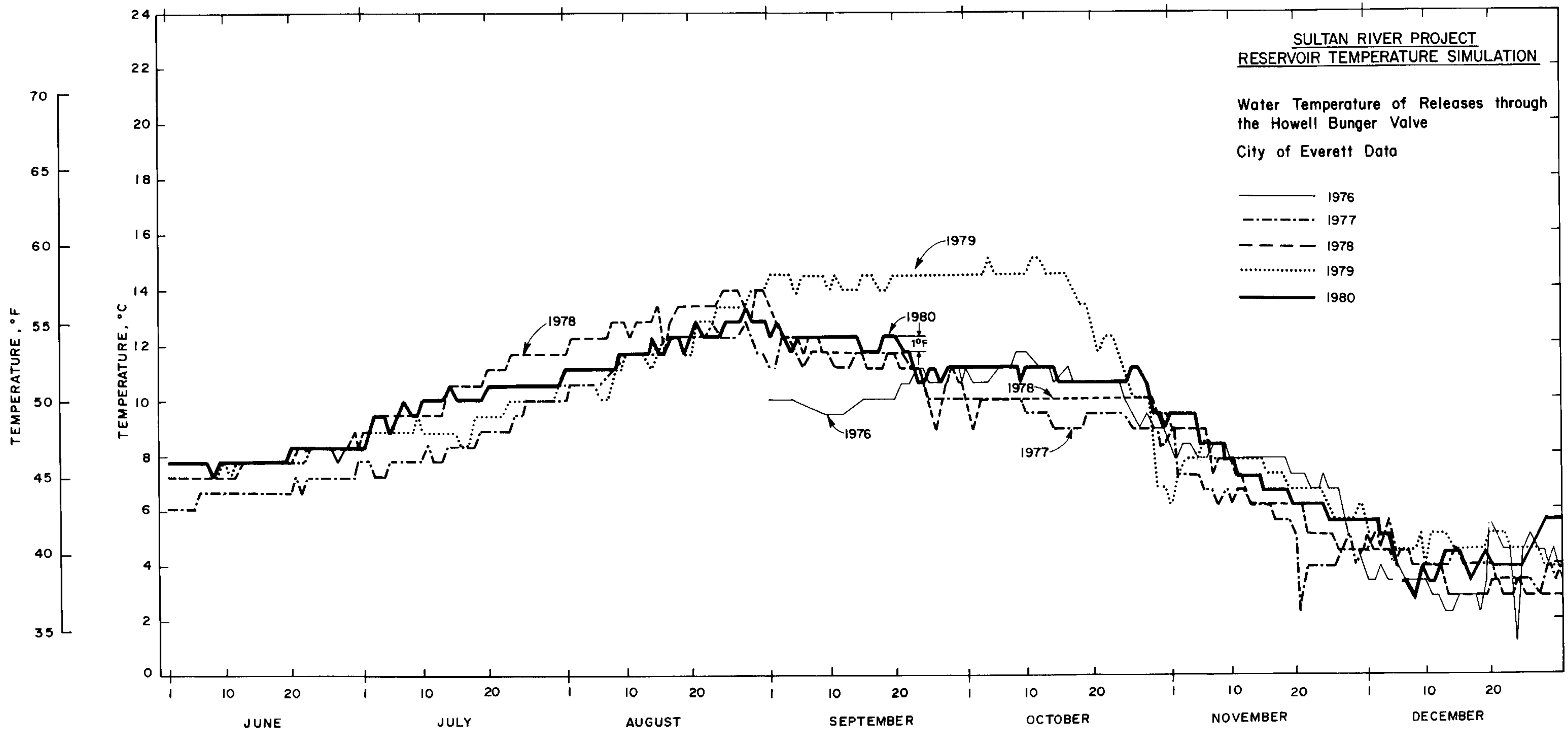

Figure 3-12 Water Temperature of Releases through the Howell-Bunger Valve, City of Everett Data 1976-1980

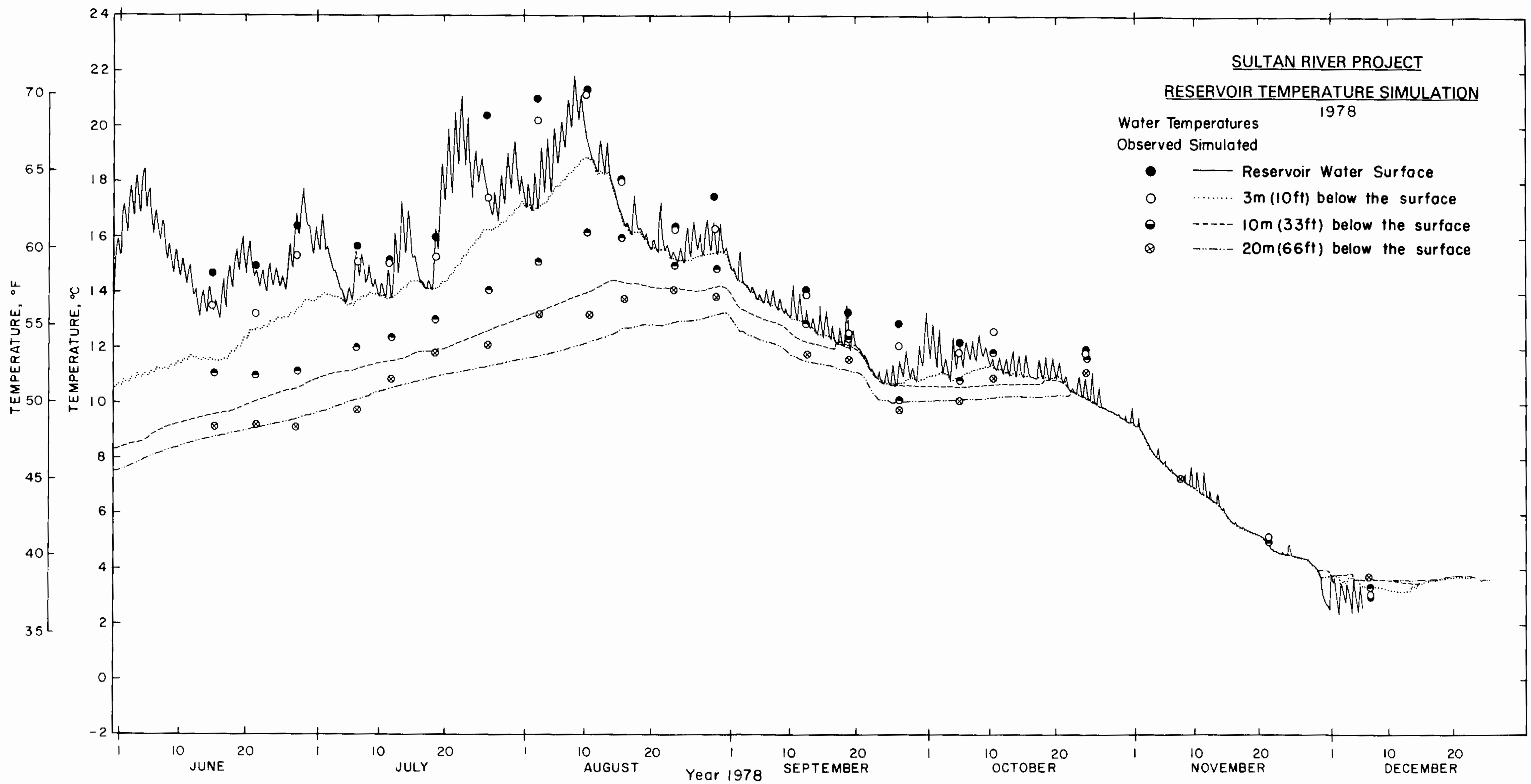

Figure 3-13 Comparison of Observed and Simulated Temperatures in Spada Lake, June—December 1978

observed temperatures was generally satisfactory, although the agreement was not as good as the 1979 simulation, probably because the meteorology for 1978 was synthesized, rather than measured at the site. In particular, the simulated lake surface temperatures were lower than the observed temperatures during late July and the first half of August. This result is probably caused by the relatively poor correlation obtained for air temperatures above 80°F. Lower air temperatures led to a lack of heat input in the first half of August which was then reflected in predicted reservoir temperatures in the last half of August and early September being lower than the observed values.

A comparison of the observed and simulated outflow temperature from the Howell-Bunger valve for 1978 is shown on Figure 3-14. The agreement is considered good. It is clear that the 1978 simulation produces results that are similar to the recorded outlfow temperatures shown on Figure 3-12, for 1976, 1977, 1978, and 1980.

On the basis of comparing the observed and simulated temperatures for 1978, it was concluded that the synthesized 1978 record was a satisfactory representation of a typical year's temperature record.

3.4.4 Comparison of 1980 and 1978 Simulations

The outflow temperature variations from Spada Lake during 1980 were practically the same as those for 1978, as shown on Figure 3-12. City of Everett observations of lake surface temperature for 1978 and 1980 (not shown here) were also similar. Results of the simulated outflow temperatures were also very similar as may be seen by comparing Figures 3-10 and 3-14. On the basis of comparing these data with all of the available data, it was therefore concluded that both the 1978 and 1980 simulations would be representative of typical conditions for Spada Lake. Since the 1980 data were not complete, the 1978 simulation thus provides information during October and November of a typical year as the reservoir cools in the fall.

To provide as comprehensive and complete a picture of expected conditions in the raised reservoir as practicable, simulations of raised reservoir performance with the data to October 1st, 1980 were obtained and compared with the 1978 and 1979 data. These results, discussed in Section 4 of this report show that the 1980 and 1978 simulations of the raised reservoir are also similar and that the 1978 and 1980 data together provide a valid set of typical conditions with which predictions and comparisons of temperatures in the raised reservoir can be made.

3.5 STREAMFLOW TEMPERATURE MODEL

3.5.1 Formulation of the Model

The time variation of water temperature in the reach of the Sultan River between Culmback Dam and the Diversion Dam was simulated using a one-dimensional stream temperature model which accounts for temperature variations in the longitudinal direction. This model was also used to fill in missing pieces of record on the North and South Forks as mentioned in Subsection 2.5. The model is based on the assumption that there is complete mixing over the stream depth and in the lateral direction; it also accounts for advection and heat fluxes at the water surface. The heat flux estimates were based on the meteorological data obtained from the meteorological station located on Spada Lake. The calculations of heat fluxes were made in a manner similar to that described in Subsection 3.2.

The Sultan River between Culmback Dam and the Diversion Dam was divided into five reaches to account for variations in channel slope, geometry, and orientation of the reach. The incoming short-wave solar radiation was adjusted to account for effects of shade from the steep canyon walls and tree-lined banks, and the orientation of the stream with respect to the direction from the sun. For simulation of periods of missing record in the North and South Forks data (Stations 5 and 6A), only one or two reaches were necessary to obtain satisfactory results. Mean velocities and depths of flow were computed using the surveyed cross-sections at Station 4 on the North Fork,

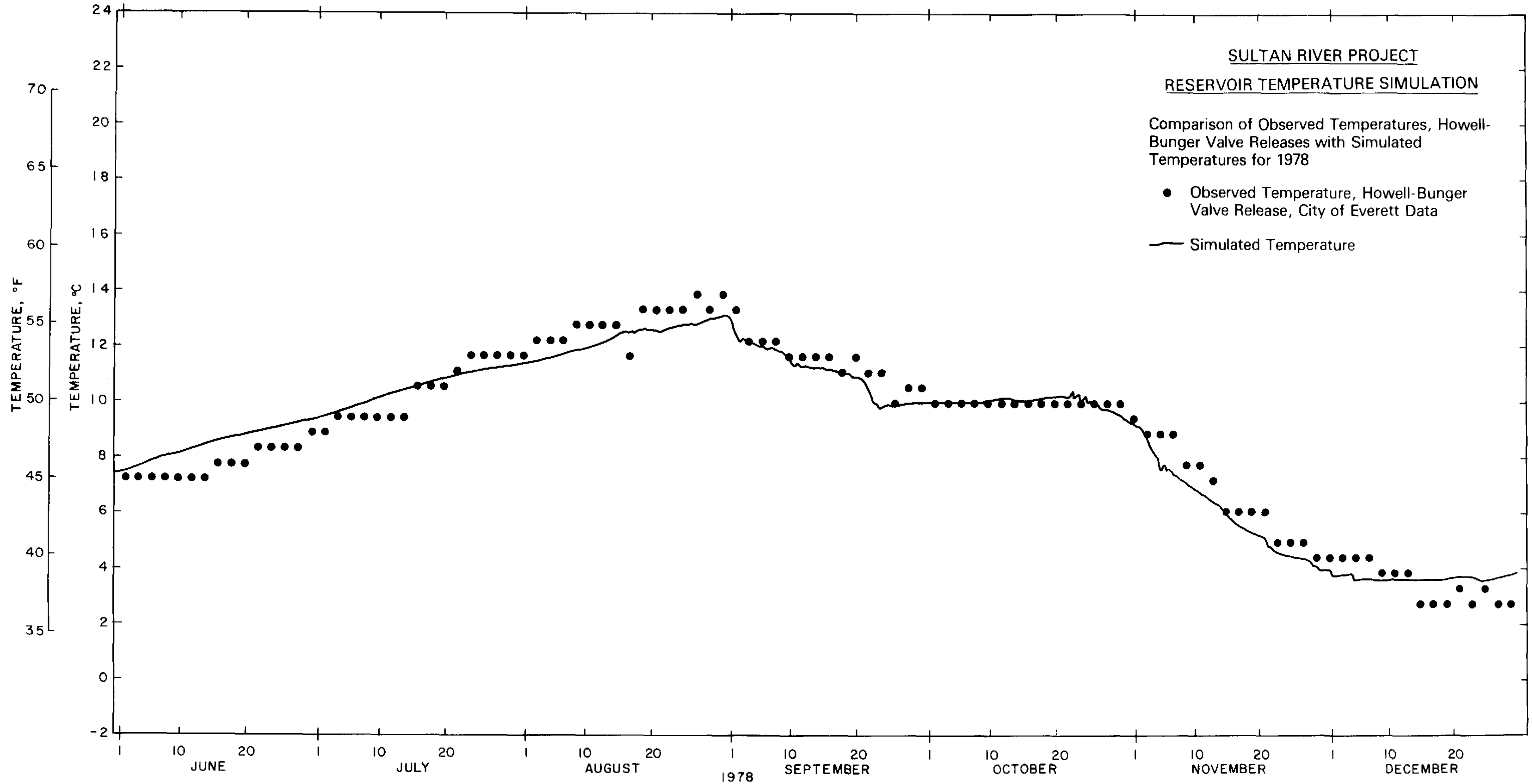

Figure 3-14 Existing Reservoir Outlet Temperatures: Simulated Temperature of Howell-Bunger Valve Releases and City of Everett Observed Temperatures, 1978

Station 6 on the South Fork, and at the Startup Gauge, a discontinued U.S.G.S. gauge located on the Sultan River about 5.2 miles downstream from Culmback Dam. Mean velocities and depths in other reaches of the river were computed using Manning's equation and the ratio of the channel slope in the reach to the channel slope at the U.S.G.S. gauge. Because no detailed survey of the river was available, it was assumed that Manning's "n" and the stream width were approximately the same in all reaches.

The computation of streamflow velocities and depths was based on an assumption of quasi-steady flow, e.g., for the reach between Culmback and the Diversion Dams, the flow in the entire reach adjusts to changes in releases from Culmback Dam within a time period shorter than the time step used in the simulation (4 hours, in this case). This assumption was justified on the basis of the stage records obtained at the Diversion Dam and the stage records and records of Howell-Bunger valve operation at Culmback Dam which showed that the travel time in the reach was 1-1/2 to 2 hours. Estimates of travel time on the North Fork were made using the stage recorder at Station 4 and a temporary recorder installed at Station 5. The reach on the South Fork is only about 1.4 miles long; the travel time is very short.

Inflows to the model to fill in data gaps were obtained from the stage records on the North and South Forks. Temperatures on the North and South Forks were obtained from the city of Everett data when appropriate. Inflows to the stream temperature model at Culmback Dam were obtained from the simulated outflow from Culmback Dam. Inflow temperatures at Culmback Dam were also obtained from the reservoir model.

3.5.2 Calibration

For the North and South Forks, the model was calibrated using the city of Everett's data, meteorological data, and the continuous temperature records obtained at Stations 5 and 6A. The model was then used to bridge gaps in the records at 5 and 6A when necessary.

For the reach between Culmback Dam and the Diversion Dam, the model was calibrated using meteorological data, the outflow discharge and temperature at Culmback Dam, and the observed water temperatures at the Diversion Dam (Station 11). Meteorology used in the simulation was based on data obtained from the meteorological station at Spada Lake. A comparison of air temperature records obtained from the meteorological station and a continuous air temperature recorder at the Diversion Dam showed that maximum air temperatures at Spada Lake tended to be slightly higher and minimum air temperatures tended to be slightly lower than the corresponding air temperatures at the Diversion Dam. Further analysis of the meteorological data did not appear to be justified, because a comparison of results using air temperatures from Spada Lake and the Diversion Dam made relatively little difference in the simulated stream temperatures. Cross sections used in this study were based on data obtained at the discontinued U.S.G.S. Gauging Station (Startup gauge) located approximately 5.2 miles downstream from Culmback Dam, and on several sections obtained from a previous study of the Sultan River which were located between Culmback Dam and the Startup station. Extensive surveys of river cross-sections required for a detailed description of the remainder of the reach were not available.

Because of the lack of a complete description of the river geometry and because of variations in meteorological conditions along the river reach, not as much confidence can be placed in the absolute values of the simulated stream temperatures as in the simulation of the reservoir temperatures. However, the calibration results shown on Figure 3-15 are quite satisfactory. Furthermore, the calibration did extend over a rather wide range of flows from about 80 cfs to 330 cfs. It is concluded that the stream temperature model will produce results that are a reliable indication of the temperatures of low-level releases from the raised reservoir in the reach between Culmback Dam and the Diversion Dam.

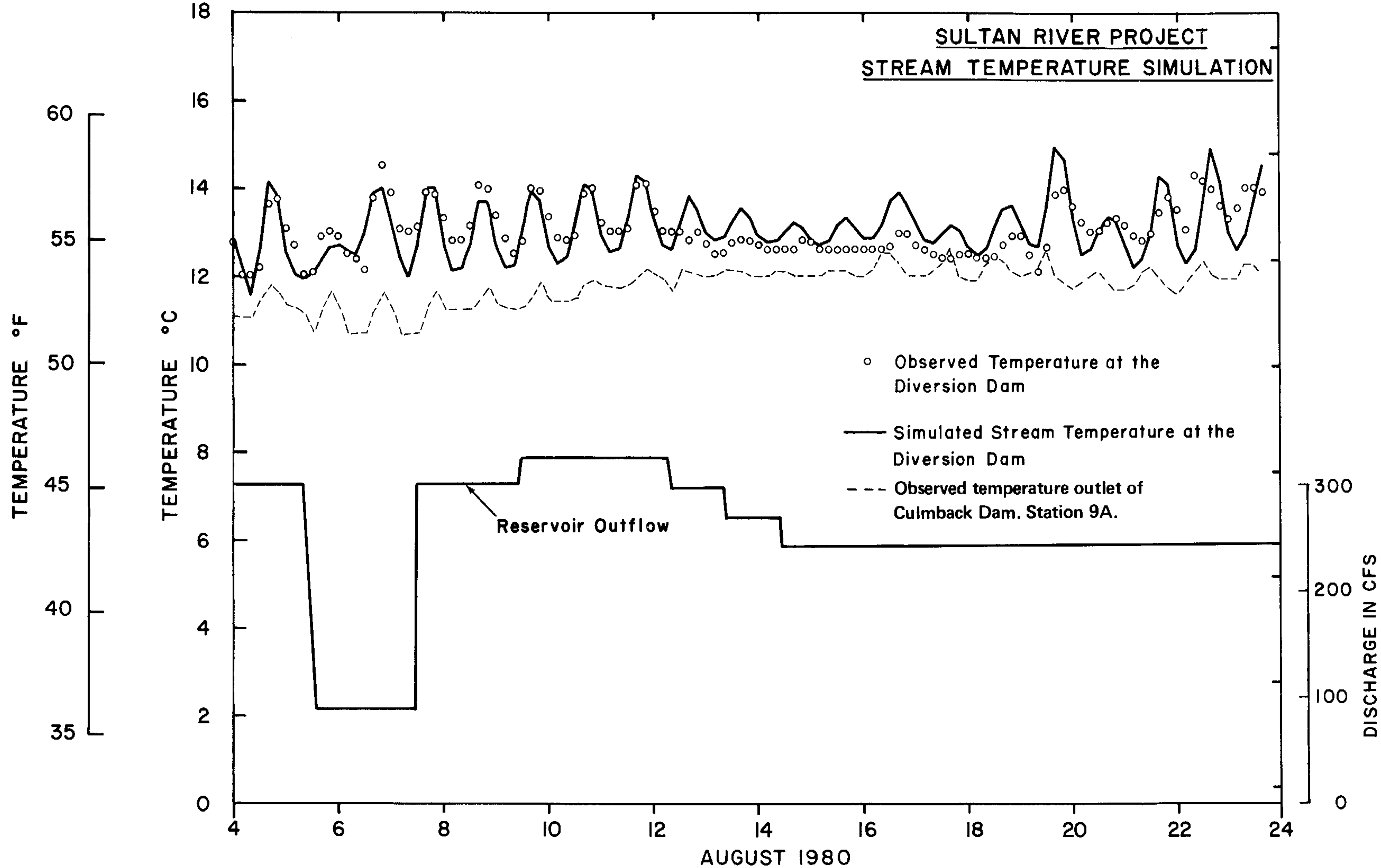

Figure 3-15 Calibration of Stream Temperature Model: Comparison of Observed and Simulated Temperatures at the Diversion Dam

Section 4

DISCUSSION OF RESULTS: TEMPERATURE SIMULATION

Section 4

DISCUSSION OF RESULTS: TEMPERATURE SIMULATION

4.1 EXISTING AND RAISED RESERVOIR TEMPERATURES, INTAKE EL. 1366

4.1.1 Comparison of Reservoir Outlet Temperatures Power Tunnel (Intake El. 1366) with Existing Reservoir

The intake structure originally proposed for the power tunnel is depicted on Figure 4-1, which is a copy of the FERC Exhibit L drawing, Sheet 28. The intake centerline is at El. 1366 or 84 feet below the spillway crest (El. 1450) for the raised reservoir. Figure 4-2 compares the simulated outflow temperatures from the Howell-Bunger valve for the existing reservoir with the simulated power tunnel outflow temperatures for the raised reservoir using the 1978-1980 data. The individual years are compared separately at reduced scale and superposed to depict the general trends in the simulations. Results for the raised reservoir were calculated using the same meteorological conditions and inflows as for the existing reservoir. Outflows from the raised reservoir were determined from the reservoir operation studies using the FERC license application rule curves and the observed inflows. No operation for flood control was considered.

Although the outflows from the existing and raised reservoirs shown on Figure 4-2 follow similar trends, in each case there are significant differences between the two systems. The temperature of the outflow from the raised reservoir exhibits less variation from year to year, the outflow is several degrees colder throughout summer and early fall and the peak outflow temperature occurs later than for the existing reservoir. The behavior is explained by the fact that the volume in the raised reservoir is about four times larger than the existing reservoir, but the surface area through which the principal heat transfer occurs is only twice as great.

Both reservoirs start at the same initial temperature in the spring, but the smaller reservoir heats up more rapidly. Not only does it take longer to warm the raised reservoir but it also takes longer to withdraw the larger volume of cold water contained in the raised reservoir. Hence, the outflow from the raised reservoir will be colder for a longer period of time in comparison with the existing reservoir.

In typical years, the maximum outflow temperature from the existing reservoir occurs during the last week in August, as shown on Figure 3-12, whereas the maximum outflow temperature from the raised reservoir using the intake shown on Figure 4-1 would occur sometime around the end of October. This result is a consequence of the fact that the raised reservoir cools more slowly in the fall, which provides a supply of warmer water for a longer period of time in the raised reservoir in comparison with the existing reservoir.

It should be noted that the existing reservoir has delayed the occurrence of the peak temperature in comparison with the natural stream conditions. This result is illustrated by comparing the mean stream temperature for the period 1969-1979 obtained from data collected by the city of Everett at Station 4 on the North Fork with the mean stream temperature for the same period at the Diversion Dam as shown on Figure 4-3. The natural stream temperature tends to peak about August 10th, while the temperature at the Diversion Dam peaks three weeks later, about September 1st.

4.1.2 Comparison of Power Tunnel Outlet Temperatures (Intake Elevation 1366) with Historical Record at the Diversion Dam

To assess the potential impact of the temperature changes caused by raising the dam on the Sultan River temperature regime, the power tunnel outlet temperatures must be compared with data obtained in the Sultan River. Because the principal release from the raised reservoir will occur at the powerhouse, the temperature changes anticipated in the reach below the

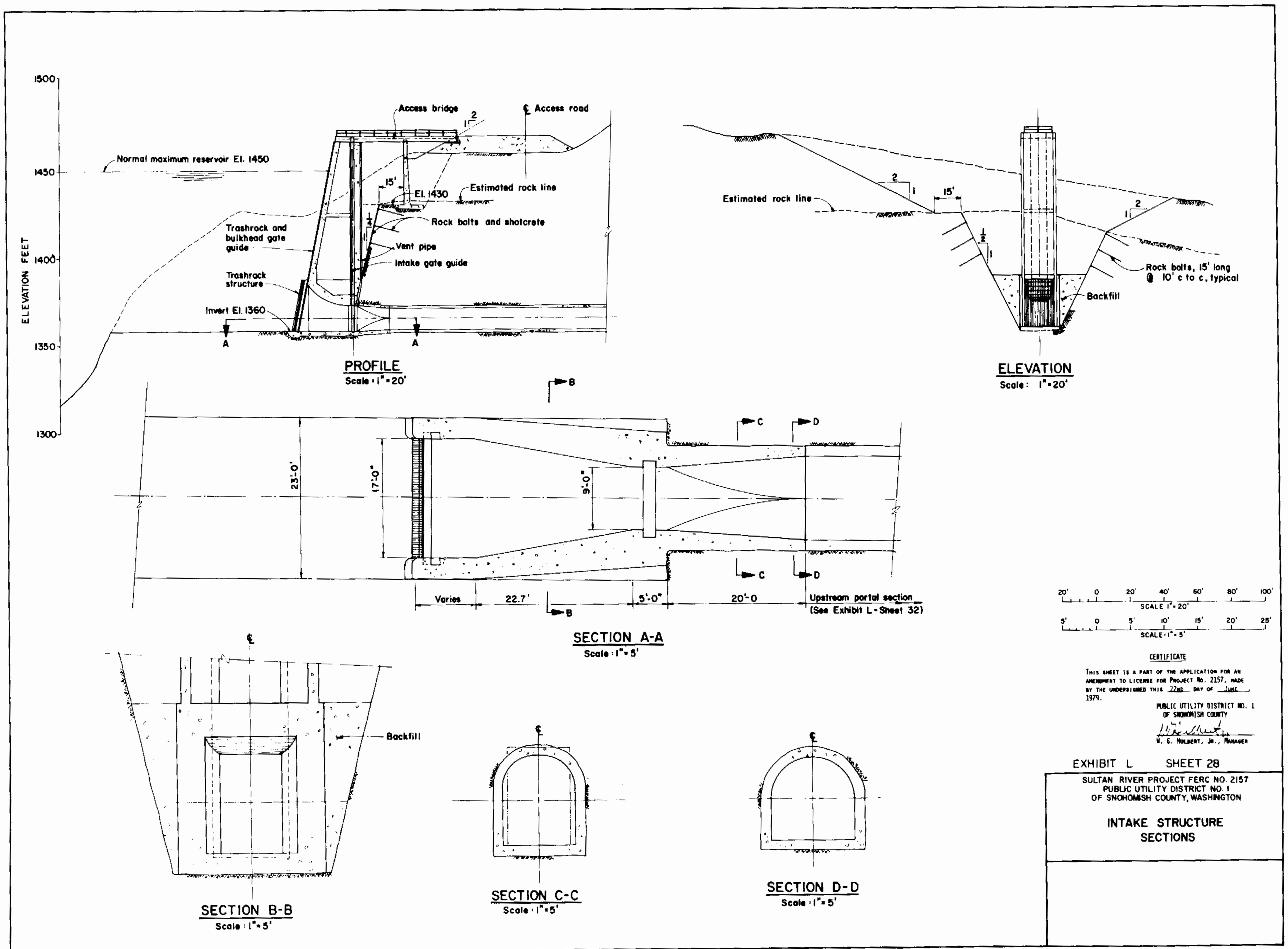

Figure 4-1 Intake Structure. Intake Elevation 1,366. Copy of Exhibit L Drawing Amendment to FERC License Application

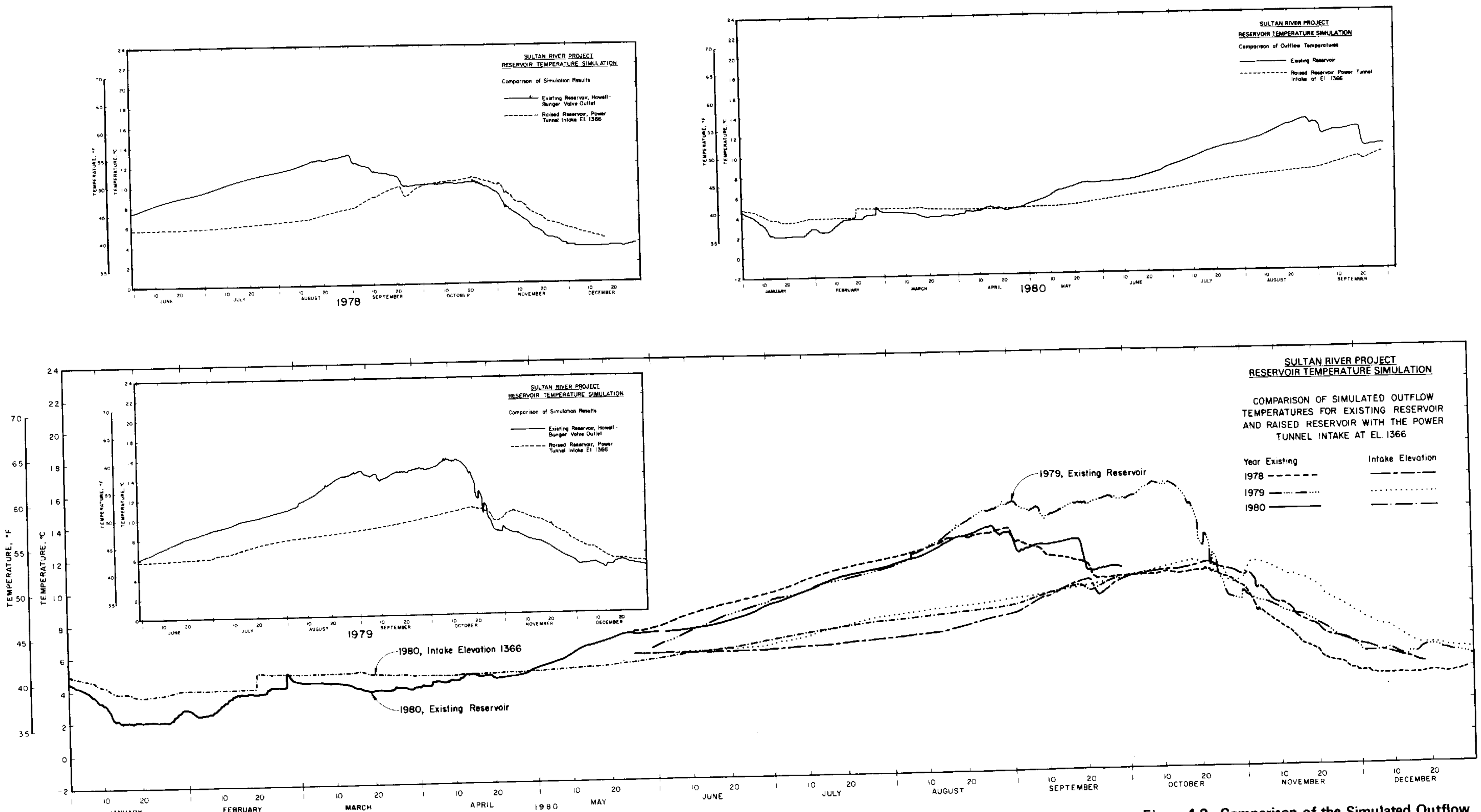

Figure 4-2 Comparison of the Simulated Outflow Temperatures for the Existing Reservoir and for the Raised Reservoir with the Intake at Elevation 1,366

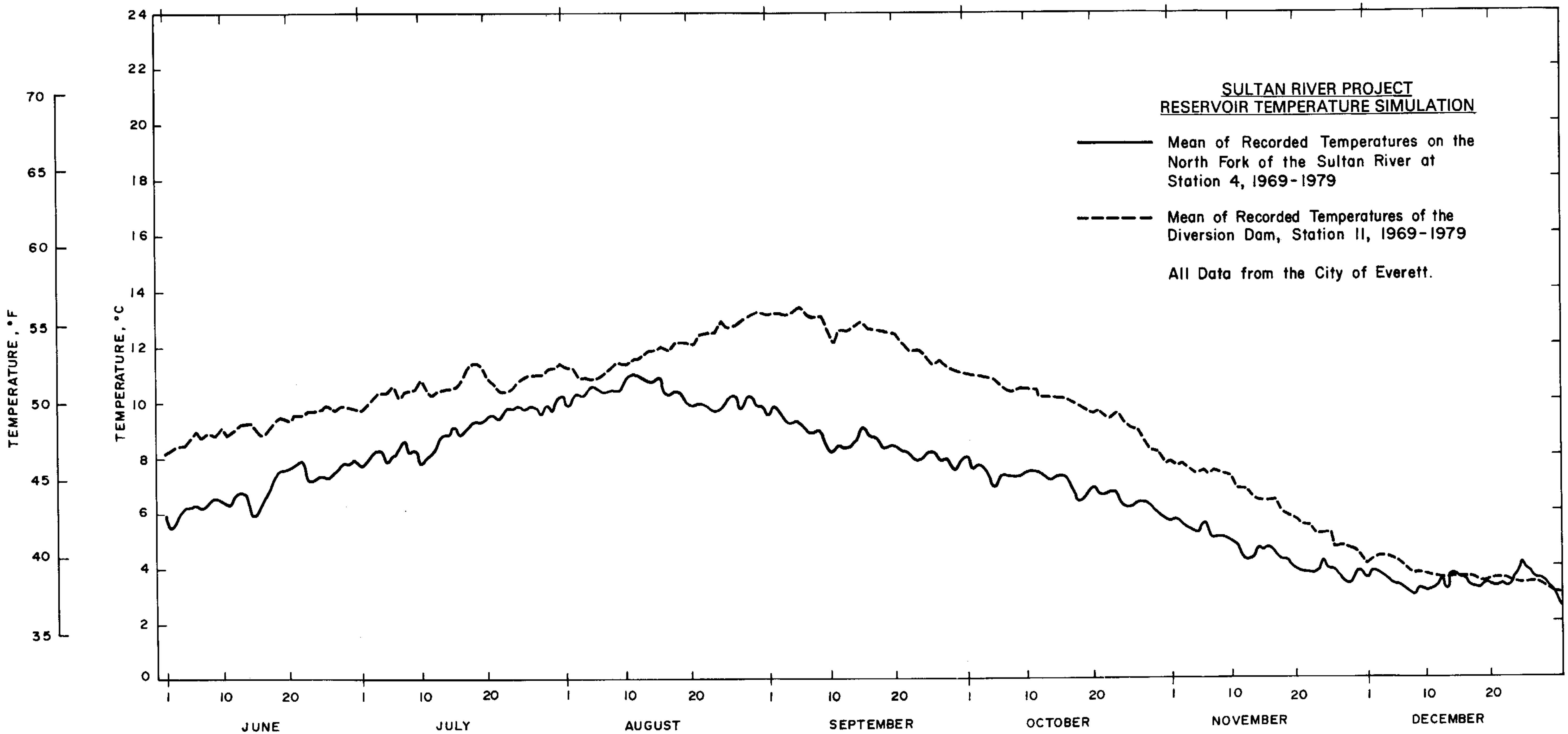

Figure 4-3 Mean of Recorded Temperatures on the North Fork of the Sultan River, City of Everett Data, 1969-1979

powerhouse will be considered first. As discussed previously in Subsection 1.4, the historical record of temperatures obtained by the city of Everett at the Diversion Dam will be assumed representative of existing conditions in the Sultan River below the Diversion Dam.

Figure 4-4 depicts the maximum, minimum, and average temperature obtained by the city of Everett at the Diversion Dam for the period 1969-1979. The shaded area on the figure delineates the range between the maximum and minimum recorded temperatures. The temperature variations for releases at the powerhouse predicted by the numerical simulation for the intake at El. 1366 using the 1978-1980 conditions are also shown on Figure 4-4.

The power tunnel outlet temperatures are lower than the average river temperatures from mid-May through September and near average in mid-October. For "typical" conditions, as indicated by the 1978 results, the temperatures are only slightly above average in November and December. In general, with the power tunnel intake located at El. 1366, the water temperature in the Sultan River below the powerhouse would be 2 to 2.5°C below the minimum of recorded temperatures from July through mid-September, while in October, November, and December, the outflow temperature would be within or slightly above the range of recorded temperatures.

During the winter and early spring, the temperatures in the existing and raised reservoirs would be in the same range because in both cases the reservoir becomes isothermal in winter. As shown by comparing the two curves for this period shown on Figure 4-2, the outflow temperatures for both the existing reservoir and the raised reservoir with the intake at El. 1366 would be nearly the same from January through April.

The winter river temperatures at the Diversion Dam are practically the same as the outflow temperatures because relatively little heating of the stream flow occurs in winter. Consequently, for all practical purposes, the winter temperature regime for "typical" conditions on the Sultan River below the powerhouse should be approximately the same for the proposed project as for the existing project with the intake as depicted on Figure 4-1.

4.2 SURFACE WITHDRAWAL INTAKE

4.2.1 Surface Withdrawal Concept

A review of the results of the temperature simulation for the raised reservoir with the intake configuration depicted on Figure 4-1 indicated potential adverse impacts on fisheries in the Sultan River. Figure 4-4 showed that the predicted outflow temperatures with the intake at El. 1366 were below the normal range of temperatures as measured by the city of Everett at the Diversion Dam throughout the summer and into the early fall months.

To alleviate these low temperatures, several variations of a multi-level intake were considered. A multi-level intake would permit withdrawal and mixing (if required) of water from the appropriate level or levels within the reservoir to obtain temperatures better suited to fish life. There are numerous (and expensive) multi-level intake designs reported in the literature. However, operating such an intake to meet specific temperatures can be difficult, and studies conducted by others have shown that operation to meet specified temperatures early in the summer may result in failure to meet these objectives later in the season, depending on the meteorology for the particular year. This type of operation also requires continuous monitoring of inflow, reservoir, and outflow temperatures.

After considering several alternatives, a surface withdrawal concept was developed. A surface withdrawal intake is extremely simple to use and avoids the operational difficulties described above. Figure 4-5 depicts a schematic layout of the surface withdrawal scheme. A set of stoplogs or some other type of adjustable leaf gate would be placed in front of the opening so that water would be withdrawn from a surface layer approximately 30 feet deep. The stoplogs act as a skimming weir with the weir crest at

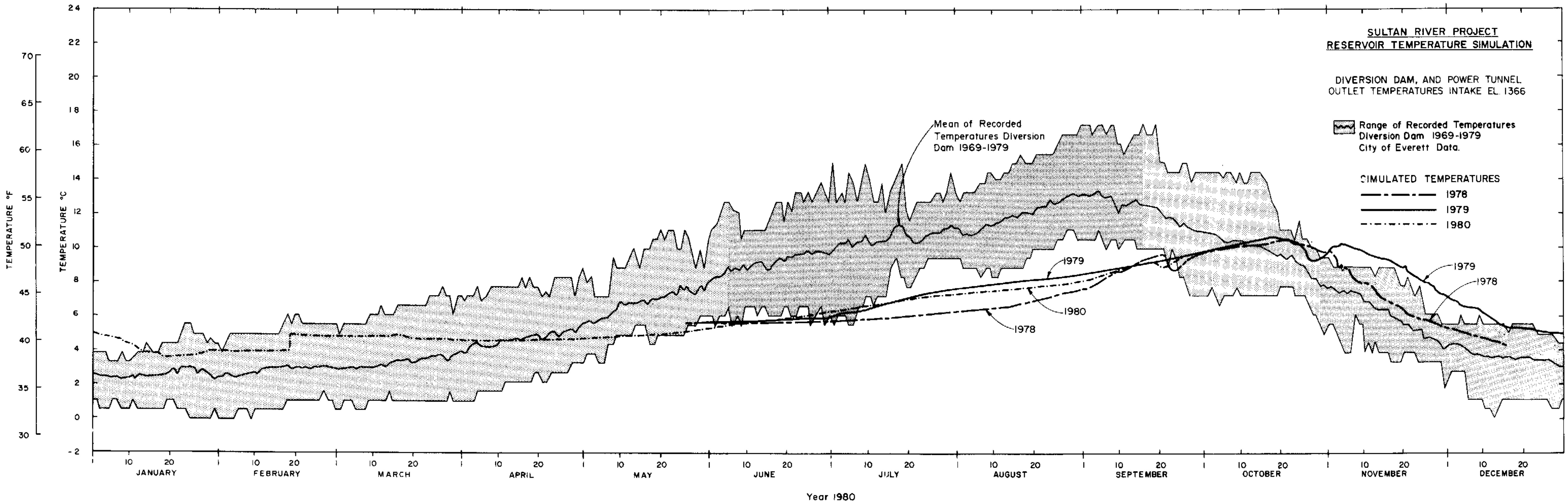

Figure 4-4 **Comparison of the Simulated Temperature of Releases through the Power Tunnel, Intake Elevation 1,366, with Temperatures Recorded at the Diversion Dam by the City of Everett**

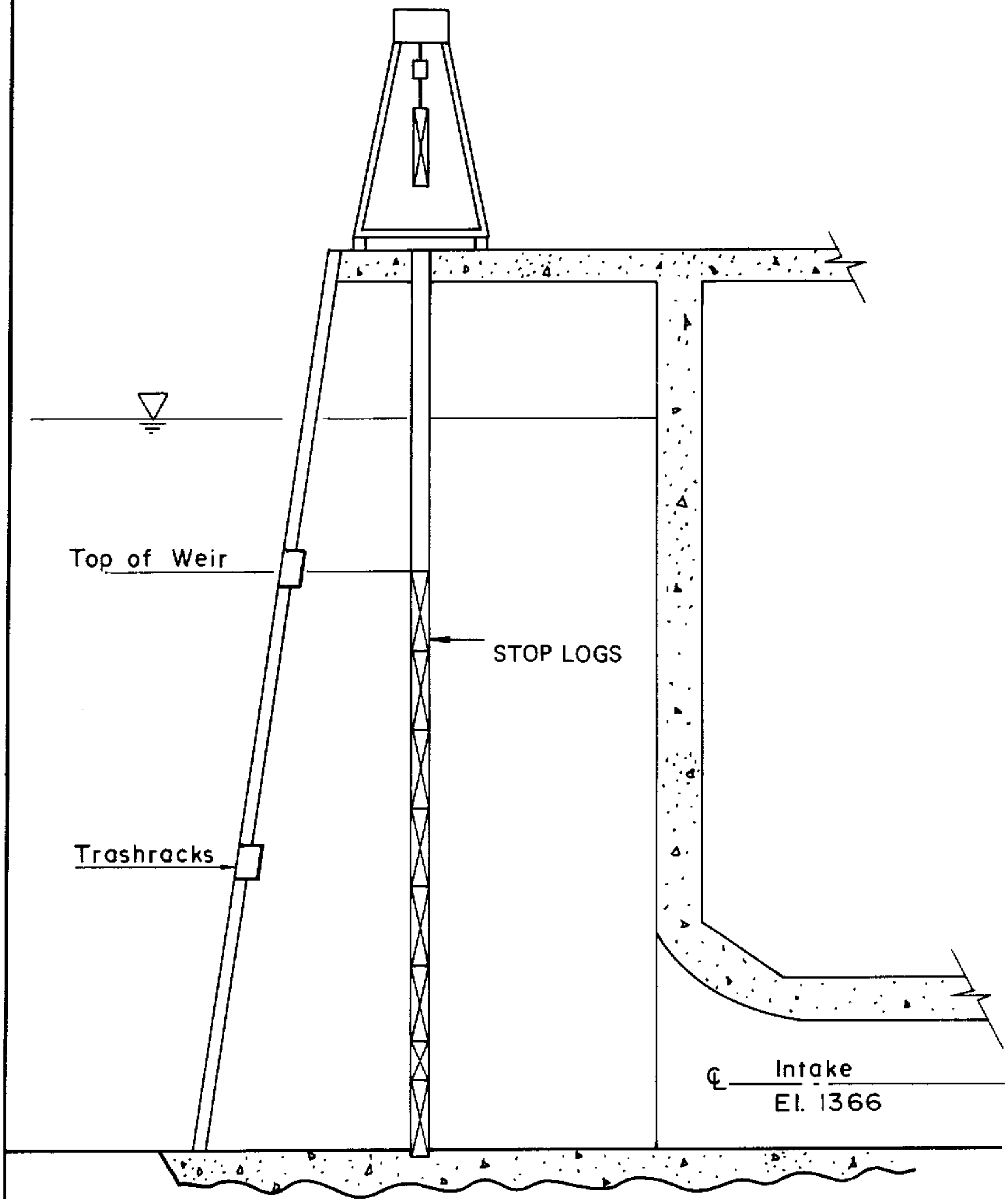

Figure 4-5 Conceptual Layout of a Surface Withdrawal Intake

the top of the stoplogs. The height of the individual stoplogs used in this study was about 10 feet and the withdrawal layer thickness was maintained as the reservoir elevation changed by adding or removing stoplogs. Operation was governed by water level in the reservoir with a minimum of 13 feet of water being maintained over the top stoplog. Because the water level in the proposed reservoir changes slowly, stoplogs should have to be removed or added only two to three times each year. Variations in the outflow temperature would then be governed by the site meteorology and reservoir inflow temperature.

4.2.2 Results of Simulations with the Surface Withdrawal Intake

The simulated 1978-1980 temperatures for the power tunnel outflow, using the surface withdrawal intake, are depicted on Figure 4-6, together with the city of Everett's data obtained at the Diversion Dam. The predicted temperatures for 1978 and 1980 lie generally within the range of temperatures recorded by the city of Everett during the period 1969-1979 and do not become lower than the mean 1969-1979 temperature until late August or early September. For 1979, the predicted temperatures are always equal to or above the 1969-1979 mean temperature obtained from the city of Everett's data. From June through September, the 1978 and 1980 outflow temperatures (indicative of typical conditions) are significantly higher than those obtained with an intake at El. 1366 as illustrated on Figures 4-7 and 4-8 for the typical years, 1978 and 1980.

For 1979, the simulated reservoir operation began with the water level in the reservoir at El. 1438.5 on 31 May. The top stoplog was at El. 1417.3. Two stoplogs were removed on October 15th when the water surface reached El. 1433.7, dropping the weir crest to El. 1397.6. A similar scheme was used in simulating the 1978 and 1980 temperatures. Only one change in the intake level was required from June through October for 1978 and 1979. The removal of the stoplogs causes an abrupt drop in the outflow temperature as noted on Figures 4-9 and 4-10. Once the reservoir becomes isothermal, no

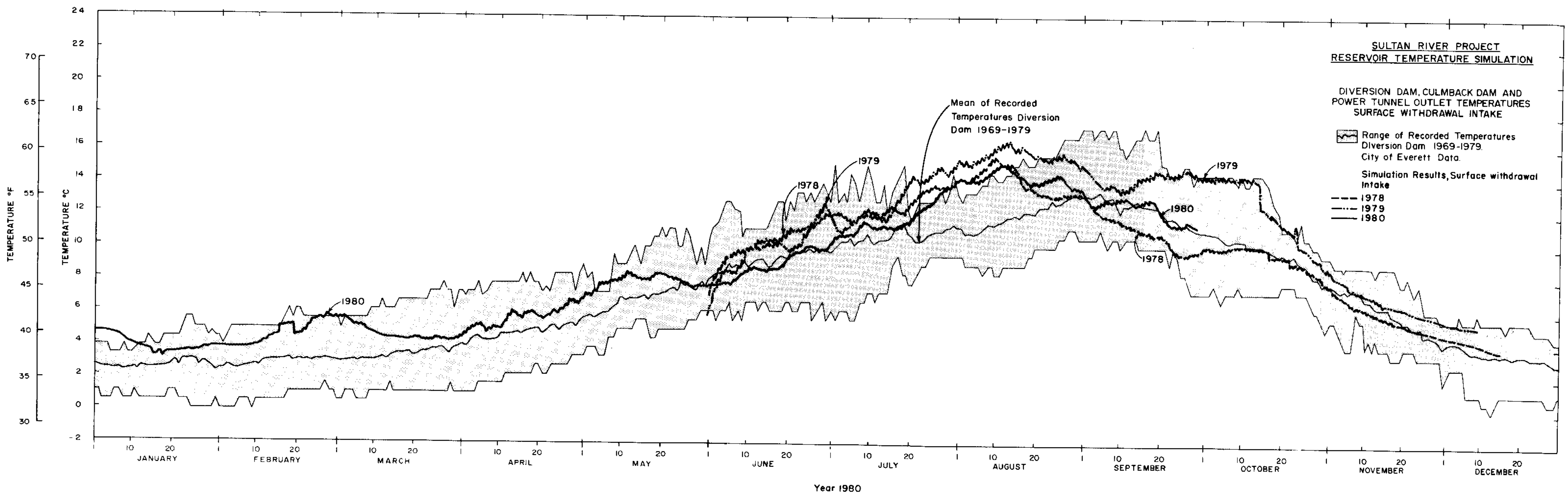

Figure 4-6 **Comparison of the Simulated Temperature of Releases through the Power Tunnel, Surface Withdrawal Intake with Temperatures Recorded at the Diversion Dam by the City of Everett**

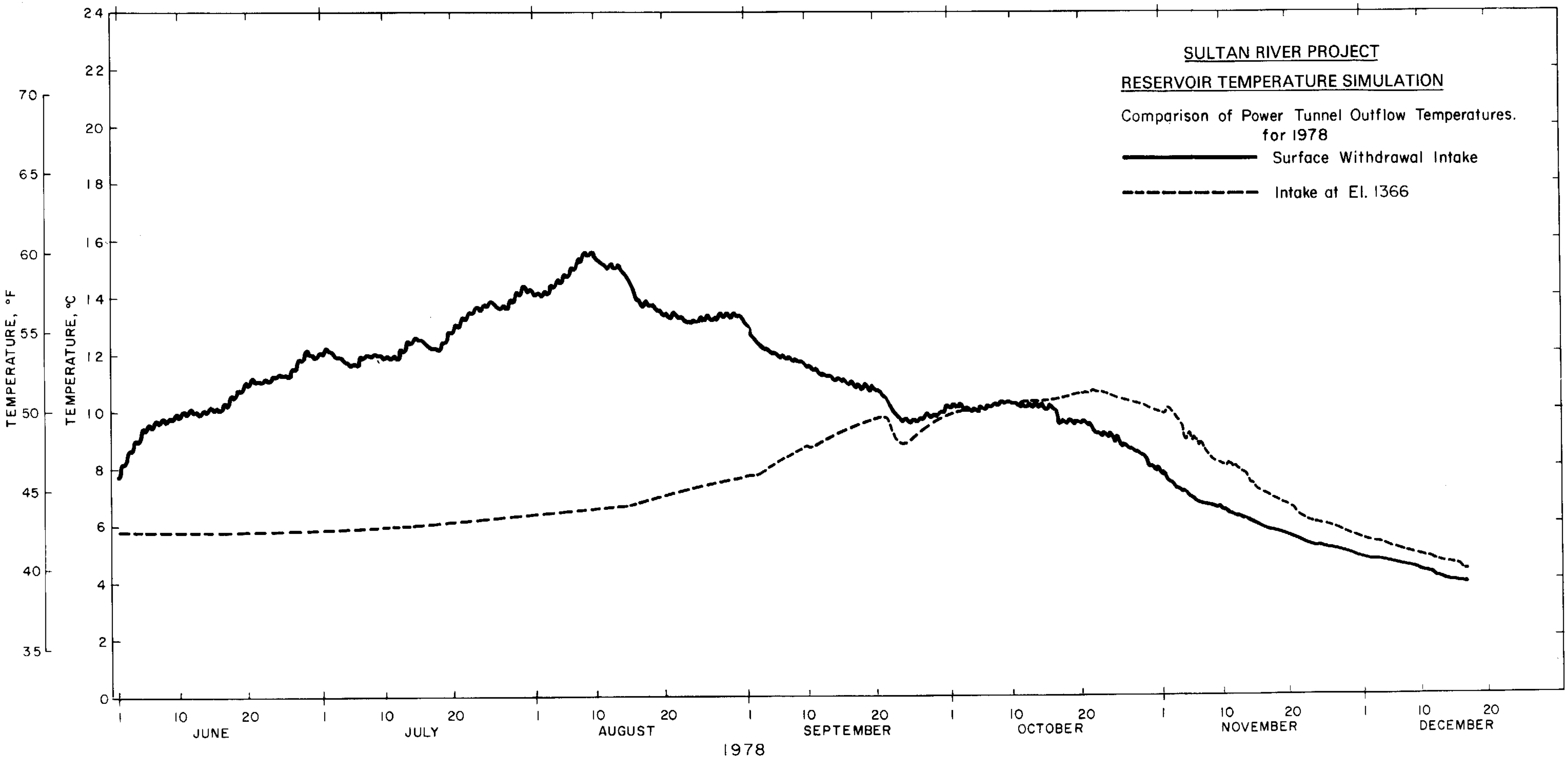

Figure 4-7 Comparison of Power Tunnel Outflow Temperatures, Surface Withdrawal Intake and Intake at Elevation 1,366, 1979

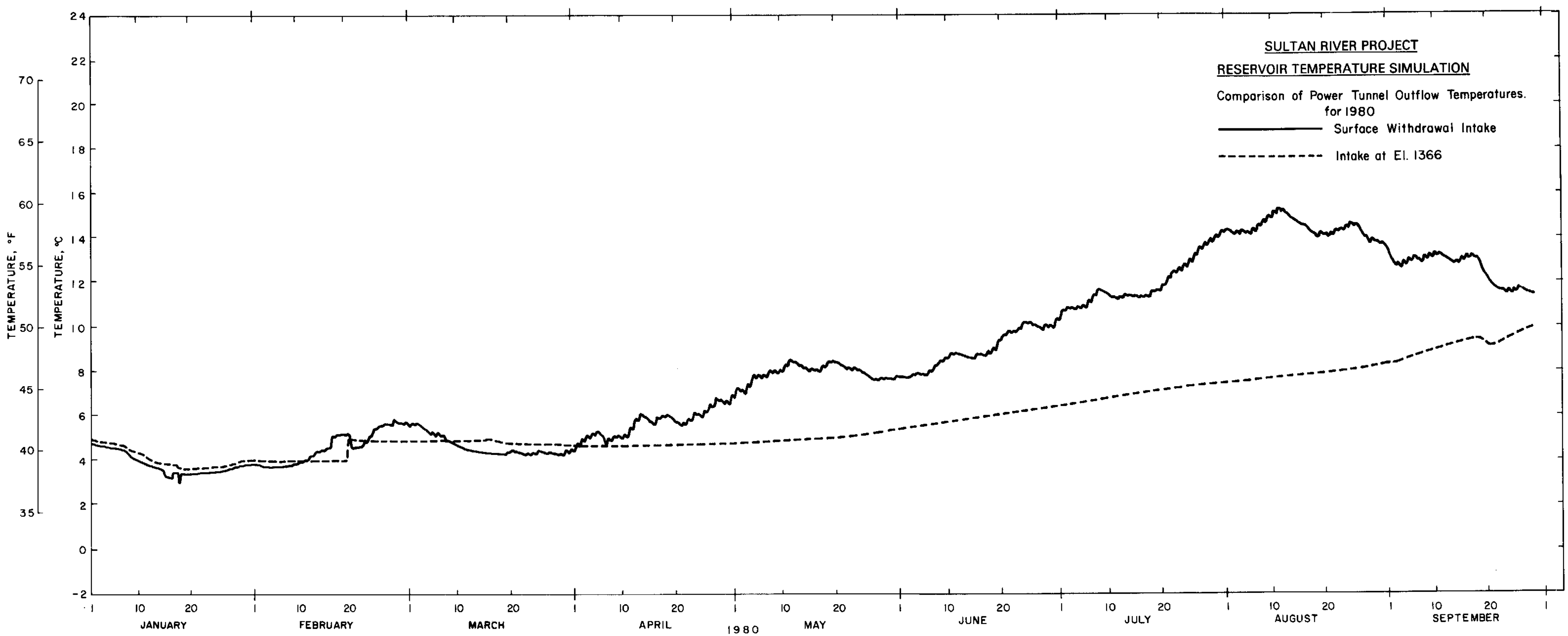

Figure 4-8 **Comparison of Power Tunnel Outflow Temperatures, Surface Withdrawal Intake and Intake at Elevation 1,366, 1980**

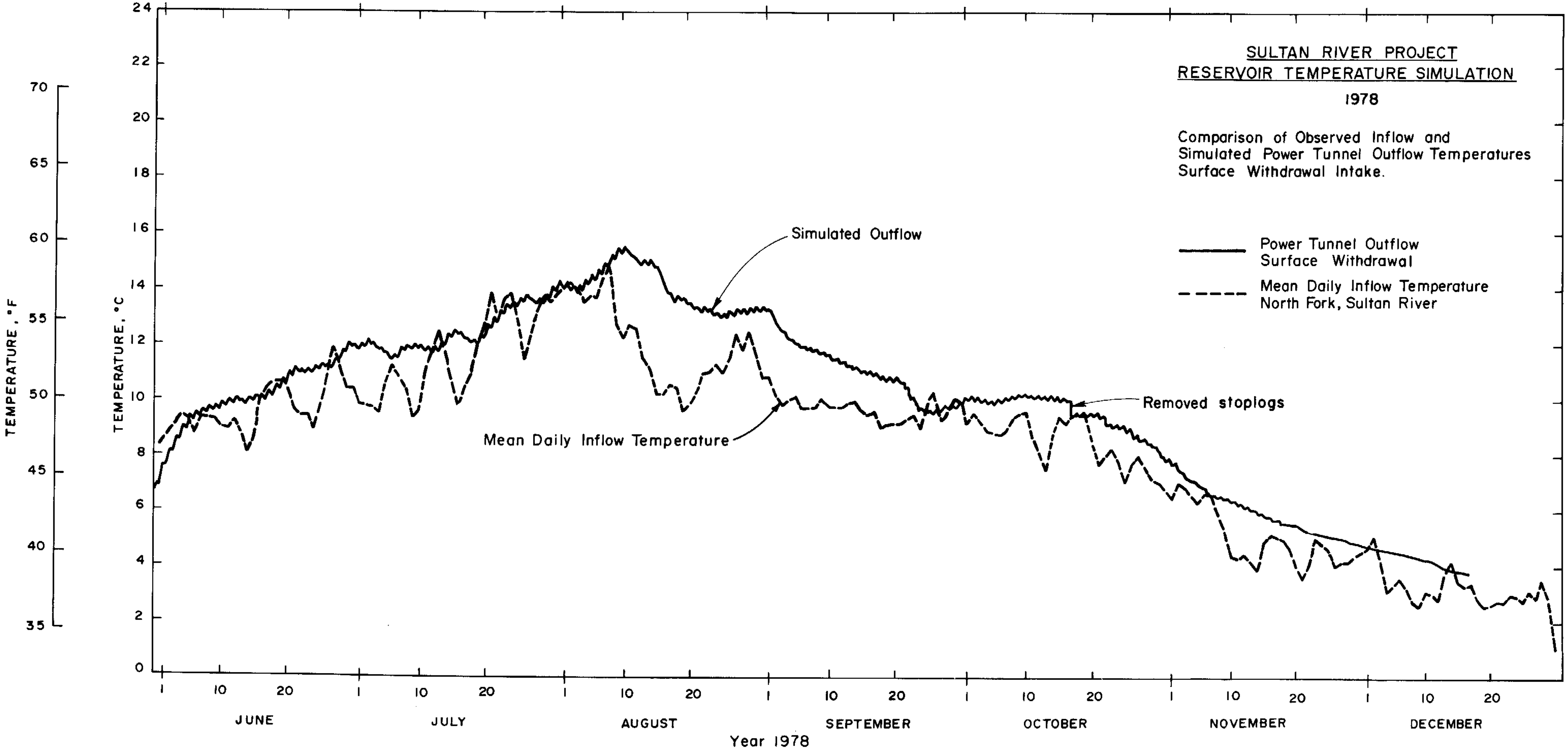

Figure 4-9 Comparison of the Observed Spada Lake Inflow Temperatures with the Simulated Power Tunnel Outflow Temperatures, Surface Withdrawal Intake, 1978

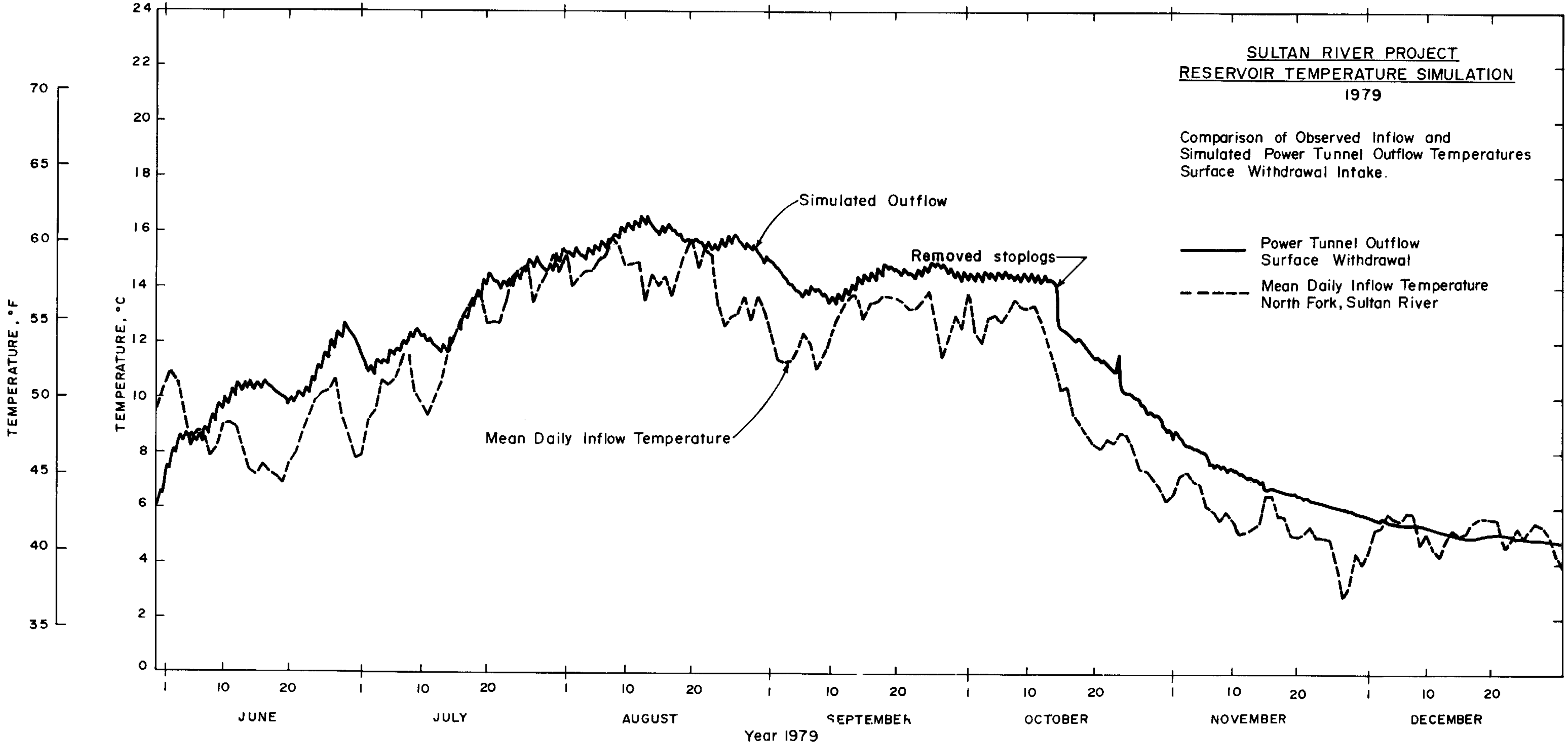

Figure 4-10 Comparison of the Observed Spada Lake Inflow Temperatures with the Simulated Power Tunnel Outflow Temperatures, Surface Withdrawal Intake, 1979

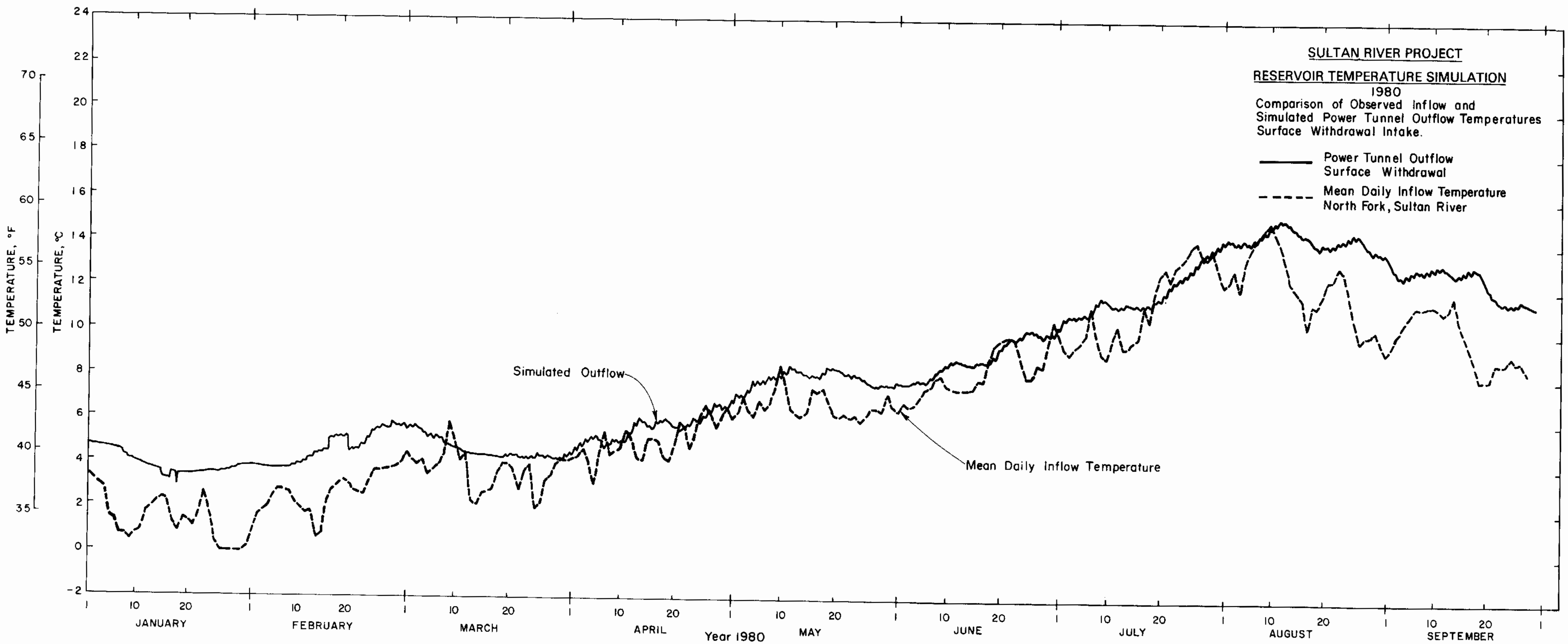

Figure 4-11 Comparison of the Observed Spada Lake Inflow Temperatures with the Simulated Power Tunnel Outflow Temperatures, Surface Withdrawal Intake, 1980

further operation to control the temperature is required or is possible. Until stratification begins in the spring, the weir crest can be set low enough to permit satisfactory hydraulic operation (in terms of water level) during the winter months.

Although the simplicity of the operation is important, the most important feature of the surface withdrawal scheme is the resulting outflow temperatures. Rather than trying to meet a specific temperature criterion, this scheme lets the naturally occurring meteorological conditions determine the temperature variation. The withdrawal layer is thick enough that the water in the warm, surface layer is mixed with water in the lower, cooler layers resulting in outflow temperatures that are close to the naturally occurring reservoir inflow temperatures.

Figures 4-9, 4-10, and 4-11 depict the mean daily inflow temperature for 1978, 1979, and 1980, respectively, in comparison with the predicted outflow temperatures from the surface withdrawal intake. In general, the predicted outflow temperatures are close to or slightly above the mean daily reservoir inflow temperatures. This implies that the outflow temperature variation will follow natural conditions as governed by the site meteorology and reservoir inflow temperatures. Outflow temperatures slightly higher than average inflow temperatures are desirable to help compensate for the natural temperature rise in the stream that would have occurred in the Sultan River in its natural condition as it flowed from the reservoir site to the Diversion Dam. Consequently, the outflow temperatures from the surface withdrawal intake will be close to the natural conditions that would have occurred before Culmback Dam was constructed. In fact, Figures 4-9, 4-10, and 4-11 show that the peak in the outflow temperatures, using the surface withdrawal intake, occurs practically at the same time as that which would occur naturally in the unregulated stream.

It is concluded that the surface withdrawal intake will provide a temperature regime throughout the entire year that will be comparable to existing conditions as far as the magnitude of the temperature is concerned. Also, the pattern or variation in temperature will actually be closer to naturally occurring conditions that existed prior to the construction of Culmback Dam.

4.3 RAISED RESERVOIR — LOW LEVEL OUTLET TEMPERATURES

4.3.1 General

Releases from the low-level outlet of the raised dam will be used to help maintain the resident trout fisheries located in the reach between Culmback Dam and the Diversion Dam. These releases (20 cfs) will be withdrawn from the lowest reservoir levels, which is the coldest part of the reservoir. Figures 4-12, 4-13, and 4-14 depict the simulated water temperature of low-level releases from the raised reservoir using the 1978, 1979, and 1980 data, respectively, and show that the temperature of these releases will be generally much colder than existing conditions from May through September.

As the cold, relatively small flows released from the raised dam flow downstream, heat transfer with the atmosphere will cause a rise in temperature during the summer months, and a decrease in temperature during cold winter periods. The numerical model described in Subsection 3.5 was used to predict this temperature variation throughout the year to provide as complete a comparison of existing and future temperature regimes in the river reach between Culmback and the Diversion Dam as practicable.

Calibration of the stream temperature model was discussed in Subsection 3.5.2. Results of the calibration, shown on Figure 3-15, show satisfactory agreement between simulated and observed water temperatures over a range of flows from about 80 cfs to 330 cfs. Extension to flows around 20 cfs does represent an extrapolation of the model, but the results, discussed in the following section, follow trends consistent with the changes expected for lower river flows.

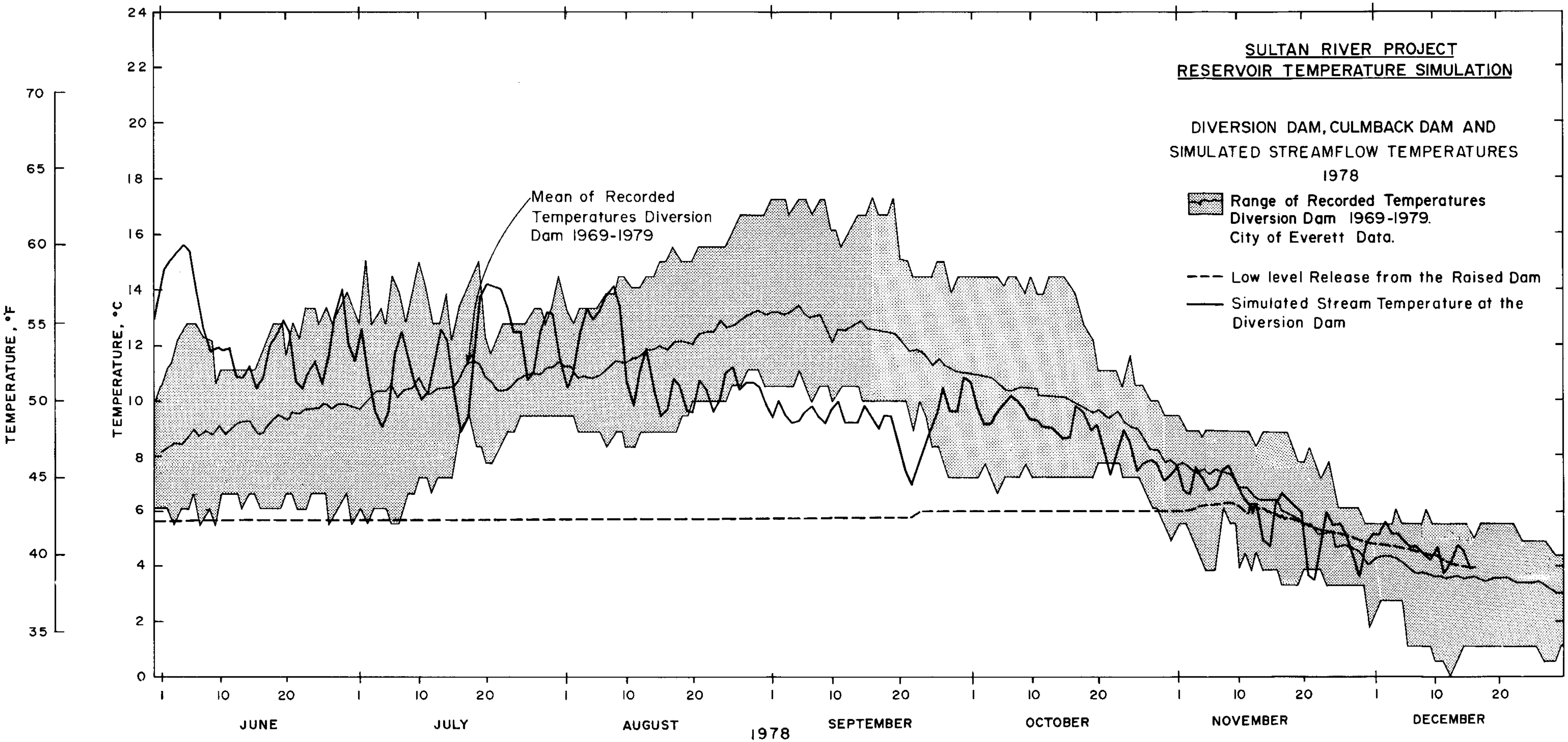

Figure 4-12 Streamflow Temperature Model. Comparison of Results for Temperature of Low-Level Releases from Culmback Dam Routed to Diversion Dam with Temperatures Recorded at the Diversion Dam by the City of Everett for 1978

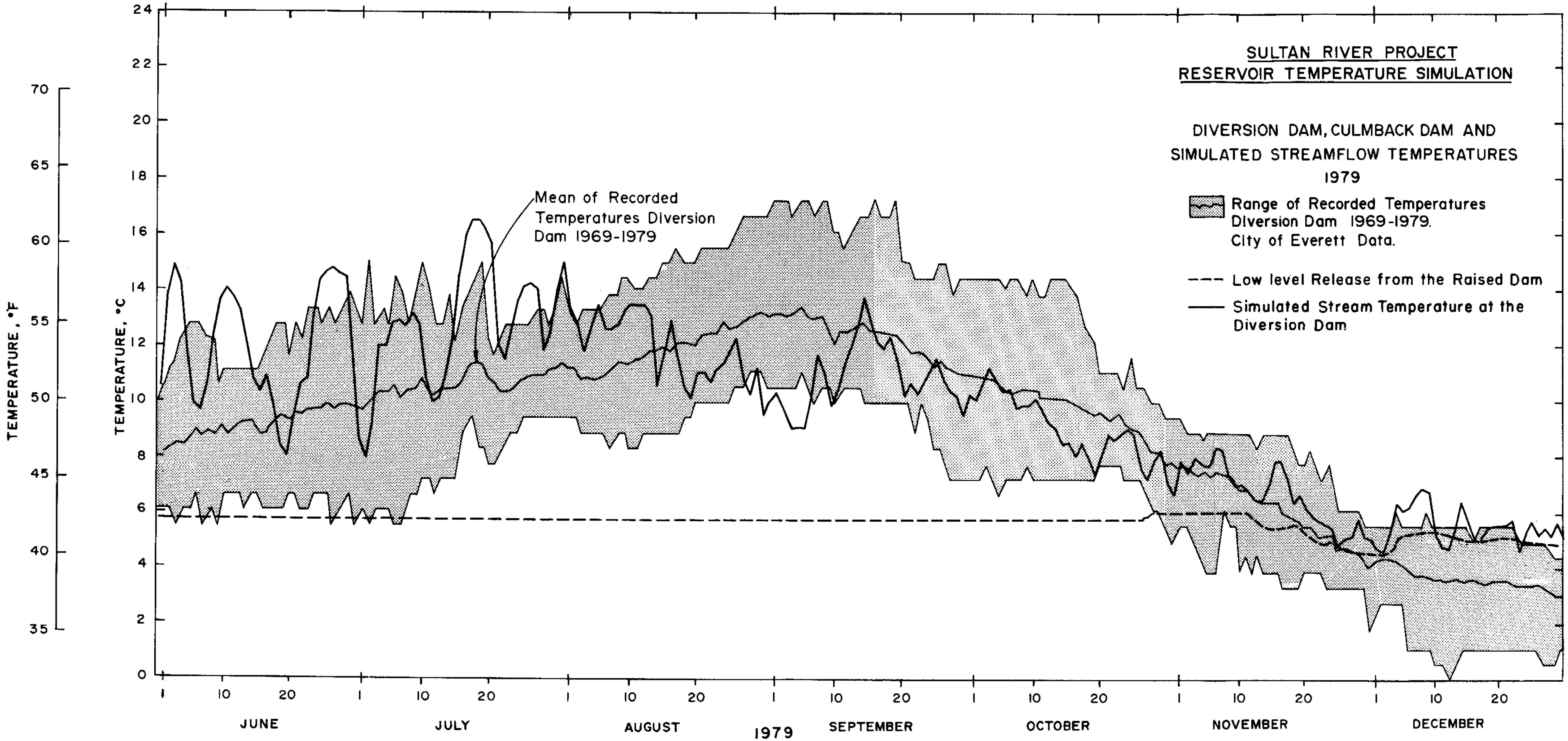

Figure 4-13 Streamflow Temperature Model. Comparison of Results for Temperature of Low-Level Releases from Culmback Dam Routed to Diversion Dam with Temperatures Recorded at the Diversion Dam by the City of Everett for 1979

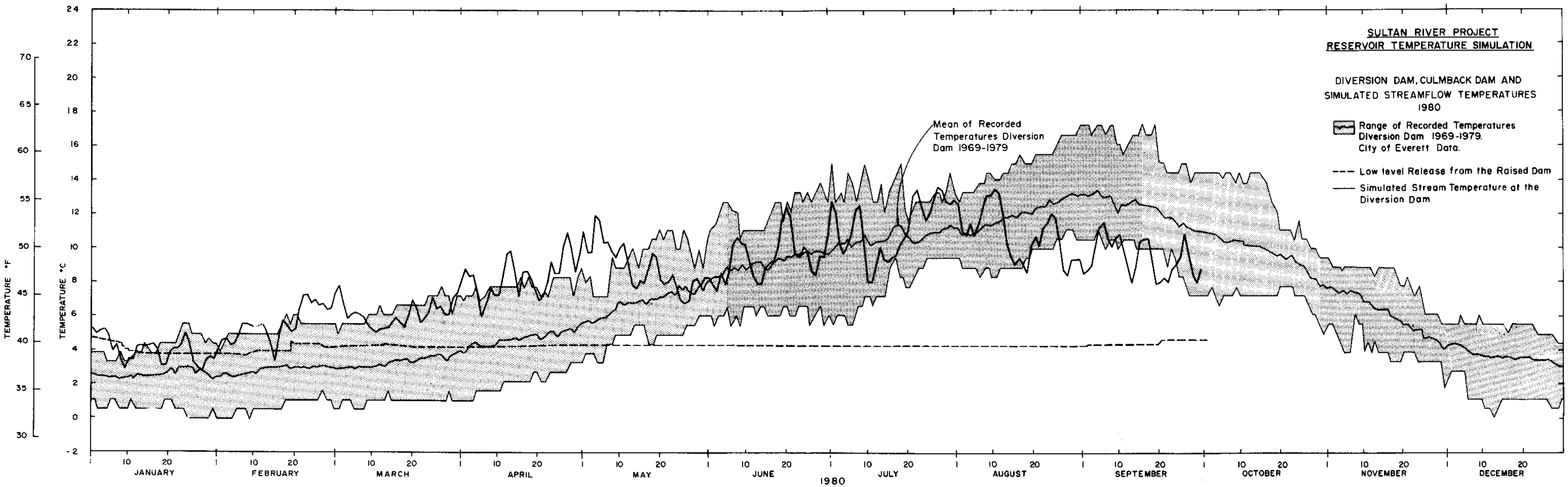

Figure 4-14 Streamflow Temperature Model. Comparison of Results for Temperature of Low-Level Releases from Culmback Dam Routed to Diversion Dam with Temperatures Recorded at the Diversion Dam by the City of Everett for 1980

4.3.2 Results of Stream Temperature Simulation — Culmback Dam to Diversion Dam

Figures 4-12, 4-13, and 4-14 depict the results of the stream temperature simulation using the 1978, 1979, and 1980 data, respectively. In each case, the solid line is the mean daily temperature of the low-level release when it arrives at the Diversion Dam; the dashed line is the temperature of the low-level release at Culmback Dam. The reason for the large fluctuations in the mean daily temperatures is that the low flows are rather sensitive to changes in daily meteorological conditions.

As anticipated, the temperature increase during the summer months for the small, low-level releases from the raised dam is greater than that for the existing dam, as may be seen by comparing Figure 3-15 with Figures 4-12, 4-13, and 4-14. In general, for June through mid-August, the results show that temperatures in the upper one-third of the Sultan River between the raised dam and the Diversion Dam will be colder than existing conditions. In the middle one-third, the water temperature will be nearly the same as existing conditions, and in the lower one-third, the stream temperatures will be above average conditions at the Diversion Dam.

The general trend in these simulated stream temperatures at the Diversion Dam is the same as that for the natural stream temperatures shown on Figure 4-3, which is not surprising, since both are dominated by short-term local meteorology. Consequently, in September, the simulated temperatures at the Diversion Dam are lower than existing temperatures because the existing dam delays the peak temperatures, as noted previously in Subsection 4.1.1.

In October, November, and December, the stream temperatures are expected to be about the same as the average of the city of Everett's measurements as shown on Figures 4-12 and 4-13. In the winter and early spring, the stream temperature at the Diversion Dam will be at or above the average conditions. It should be emphasized that the above results apply only to the low-level releases from the raised reservoir. Inflows to the Sultan River between Culmback Dam and the Diversion Dam will change these temperatures. There is no reliable information regarding either the quantity or temperature of those inflows. Tributary flows will, however, bring the temperature of releases from the raised reservoir closer to existing conditions.

4.3.3 Temperature Regime between the Diversion Dam and the Powerhouse

The temperature of the fishwater return flows introduced at the Diversion Dam by backflowing the existing diversion tunnel was discussed in Subsection 4.2.2. A comparison of Figure 4-6 with Figures 4-12, 4-13, and 4-14 shows that from May through mid-August the simulated streamflow temperatures at the Diversion Dam are comparable to those in the fishwater return flows. The fishwater return flows are typically two to four times the flow released from the raised dam. The mixed temperature downstream from the Diversion Dam must be between the stream flow temperature and the fishwater return flow temperature, but will be much closer to the temperature of the fishwater return flows. A more precise temperature estimate cannot be given because of the effects of tributary inflows on the low-level release just discussed. Tributary inflows between the Diversion Dam and the powerhouse will also mix with the river flow and bring the river temperatures closer to normal conditions. Consideration of the quantity and temperature of both the low-level releases and the fishwater return flows leads to the conclusion that effects of the low-level release on the temperature regime below the Diversion Dam are minimal, and that, for practical purposes, the temperature of the flows below the Diversion Dam will be essentially the same as the fishwater return flow shown on Figure 4-6.

Section 5

TURBIDITY

Section 5

TURBIDITY

5.1 EXISTING VARIATIONS IN TURBIDITY, SPADA LAKE

The city of Everett has been recording turbidities on the North and South Forks of the Sultan River, Williamson Creek, Elk Creek, the surface of Spada Lake at Culmback Dam, and in the Howell-Bunger valve releases on a daily basis (weather permitting) since October 1976. These data provide a general, qualitative picture of past turbidity variations in Spada Lake.

Historically, the principal influx of turbidity enters Spada Lake during and immediately following one or two major storms that usually occur sometime between the first of November and the end of January. The occurence of highly turbid inflows will be referred to in this report as a "turbidity event." Some turbidity events also occur in the early fall or late winter, but as a general rule, these events are small in comparison with those associated with the major frontal storms that occur in the winter.

Turbidity events on the tributaries to Spada Lake are short-lived because the relatively small drainage areas and mountainous terrain make the runoff floods of very short duration, with high peak flows in comparison with normal daily discharges. The turbidity in the inflow rises quickly to values about 100 to 300 NTU and then drops rapidly with recession of the flood to values less than 10 NTU. Most of the turbidity enters the lake in two or three days, depending on the duration of the storm.

After the turbidity event, the dilution by relatively clean inflows in conjunction with some settling, gradually lowers the lake turbidity.

In the existing lake, dilution usually takes place rather quickly because the monthly inflow volumes following the storm are of the same order of magnitude as the volume of storage in the lake. Snowmelt in the spring and early summer provides a source of clear inflows which generally reduces the lake turbidity to 1 or 2 NTU by early June.

5.2 TURBIDITY EVENT, 1979-1980

The turbidity event which occurred in December of 1979, Figures 5-1 and 5-2, is representative of previous events and provided the data necessary to verify the numerical model. The turbidity event took place over a period of 6 days, beginning December 13th, 1979. There were two distinct periods of rainfall. In the first period, about 11 inches of rain were recorded at the meteorological station between 6:00 AM, December 13th and 7:00 AM on December 15th; in the second period, about 4.5 inches of rain fell between 4:00 PM, December 16th and about midnight, December 17th. Runoff in the first period was increased by melting about a 1-inch water equivalent of snow on the basin.

The variation in lake level during this turbidity event also is depicted on Figure 5-1. The daily readings obtained by the city of Everett are shown and indicate the inadequacy of daily readings in describing such events on this basin. The total volume of inflow from December 13th through December 20th was about 78,500 acre-ft, or about 2.3 times the storage volume of Spada Lake at El. 1360 (spillway crest). The estimated peak hourly inflow was 14,200 cfs past Station 5 on the North Fork and about 2,900 cfs on the South Fork.

Most of the turbidity entered the lake via the North Fork. The city of Everett's data show that the Williamson Creek drainage basin was the principal source of the turbidity. City data obtained on Elk Creek and on the North Fork at Station 4 show that relatively little turbidity came from the upper reaches of the Sultan Basin. Measurements at Station 5 showed peak turbidities of about 160 NTU, while during the first two

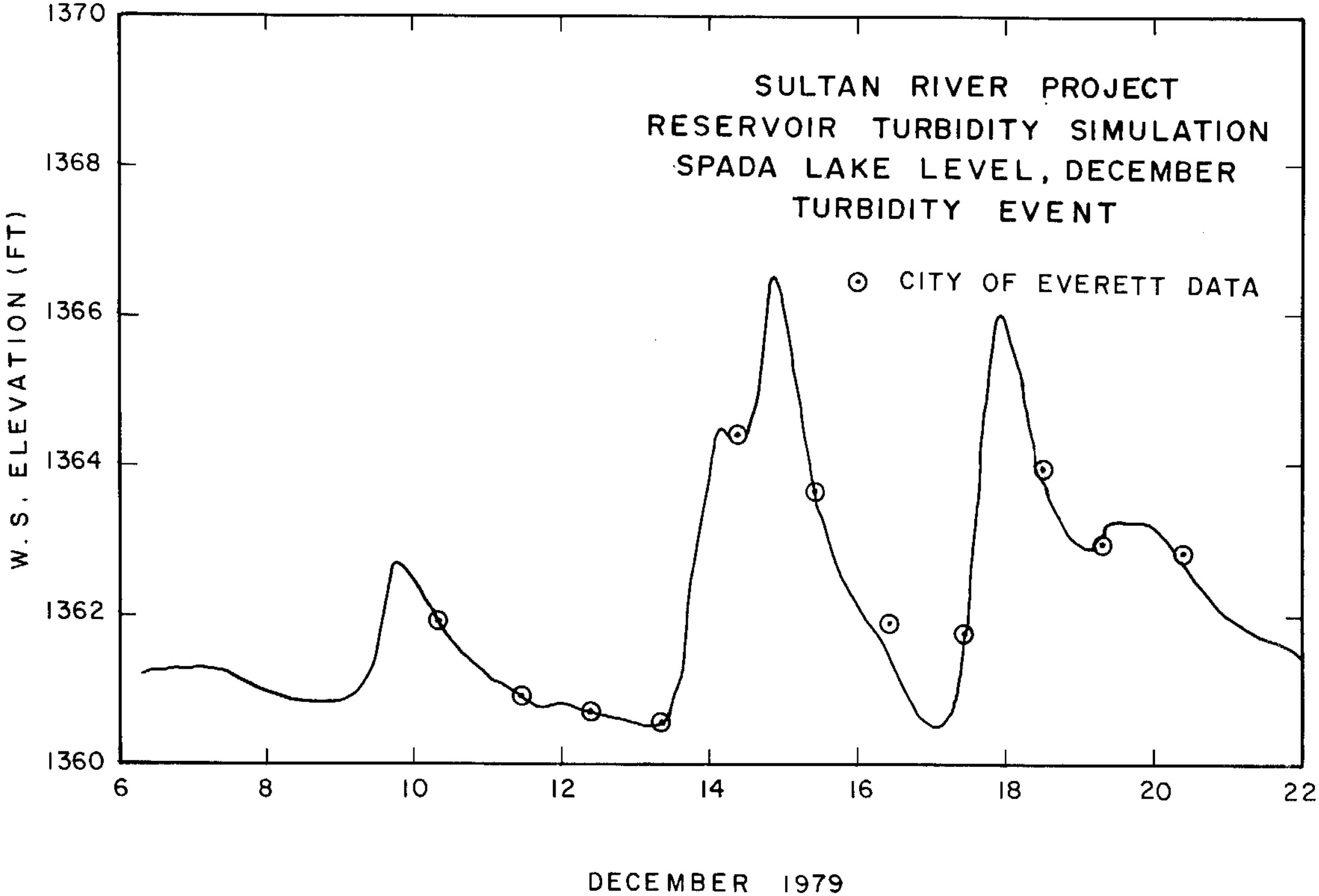

Figure 5-1 Variation in Spada Lake Level During the Turbidity Event of December 1979

days of the event, measurements on the South Fork at Station 6 never exceeded 20 NTU. During the latter part of the storm, there was one sharp peak of about 50 NTU on the South Fork. Two hours before and two hours after this peak, the turbidities on the South Fork were less than 15 NTU. The South Fork was not a significant contributor to turbidity during this event.

Turbidity profiles in Spada Lake taken on December 20th show that the lake turbidity was about 50 NTU, in comparison with 4 NTU on November 14th. The turbidity profiles taken December 18th, 20th, and 26th at Stations 7 and 8 (not shown here) indicate that some local turbidity probably entered Spada Lake via Culmback Gulch, a small gully located on the north side of Spada Lake approximately 800 ft upstream from Culmback Dam. The inflow volume from this 50-acre drainage area was small in comparison with other inflows. This inflow entered the bottom layers of the lake and was evacuated quickly through the low-level outlet. Rapid evacuation of the lower levels in the reservoir was effected by the city's operating procedures during and following the turbidity event. The city fully opened the Howell-Bunger valve and the 48 inch slide valve on December 16th discharging approximately 1,470 cfs; on December 18th, the city fully closed the slide valve and reduced the outflow from the Howell-Bunger valve. At an outflow rate of 1,470 cfs, the lake volume between the lake bottom and about El. 1295 was evacuated in less than one day. It was concluded that any contribution to the overall lake turbidity from Culmback Gulch was not significant, but that Culmback Gulch was probably responsible for some of the locally high peak turbidities observed at the reservoir bottom near the dam.

On December 22nd, after the second rainstorm of December 16th and 17th, the city of Everett fully opened both the Howell-Bunger valve and the 48-inch slide valve to draw down the lake, and reduce the volume of turbid water in storage. The slide valve was closed on December 31st; the Howell-Bunger valve was set at about 1/4 open on January 3rd, 1980. The lake then began to refill, beginning the dilution phase of the turbidity cycle.

The dilution of Spada Lake was interrupted by a minor turbidity event that occurred January 12th, 1980 and another on February 6th, 1980. Neither of these two events will be discussed further. There were several other small increases in turbidity that occurred in March and April of 1980, but these variations cannot be classified as major turbidity events. Another minor turbidity event occurred in September 1980. This event did not influence the verification of the turbidity model and will not be described in detail in this report.

5.3 VERIFICATION OF TURBIDITY FORMULATION

Agreement between the observed and simulated values of lake turbidity provides the confidence necessary to use the numerical model to predict turbidity in the raised reservoir. The two principal unknowns involved in the turbidity simulation were the turbulent diffusion coefficient, which governs the rate at which the turbidity spreads or mixes within the reservoir, and the fall velocity, which governs the rate at which the turbidity settles out of the reservoir. Both unknowns are bounded by physical constraints. The magnitude of the turbulent diffusion coefficient is limited by the amount of turbulent kinetic energy produced either by wind action at the surface or by the internal flows in the reservoir. The magnitude of the fall velocity is limited by the size distribution of the material causing the turbidity. Estimates of the diffusion coefficient were made using the formulation described in Subsection 3.3. Estimates of the fall velocity were made on the basis of particle size distributions. The initial estimates were then adjusted slightly to provide a "best fit" to the observed data.

The fall velocity used in this study was 0.4 meters per day at 20°C. Particle size distributions from samples taken in December 1980 and early 1981 were obtained by filtering and weighing, by Coulter Counter, and by hydrometer tests. Results of the analyses showed that the median particle size was about 2-5 μ. Estimates of the fall velocity from data presented by Lerman et al. (1974) show that the fall velocity used in this study is compatible with the size of the particles measured in the field.

Consideration was also given to sources of turbidity other than that carried into the reservoir by major tributary inflows. However, it does not appear that other sources such as erosion in Culmback Gulch, wave-induced bank erosion, or sheet flow over exposed reservoir banks contributed measureable quantitites of turbidity in comparison with that carried by the North and Sourth Forks. This conclusion was based on two mass balance studies of reservoir turbidity. Figure 5-2 depicts the simulated surface and bottom turbidities in the reservoir from November 1st, 1979 through September 30th, 1980, together with the surface and bottom turbidities taken from the observed turbidity profiles. These results were computed using only inflow turbidities as measured on the North and South Forks of the Sultan River. An independent calculation treating the reservoir as a simple mixing tank and using the measured inflow turbidities produced calculated reservoir turbidities immediately after the event that agreed with the reservoir model and field observations. These two analyses demonstrated conclusively that the turbidity in the reservoir entered the reservoir through its two principal tributaries.

This result is in agreement with an extensive study of reservoir turbidity for the Hills Creek Reservoir conducted by Oregon State University (1971) which also found that effects of wave-induced bank erosion and flow over exposed banks were negligible contributors to reservoir turbidity.

Some of the bottom turbidity measurements taken during the event are higher than the simulated turbidities, as shown in Figure 5-2. These observations were probably influenced by the local inflows from Culmback Gulch as discussed in Subsection 5.2. and may not be indicative of turbidity effects caused by the North and South Fork inflows.

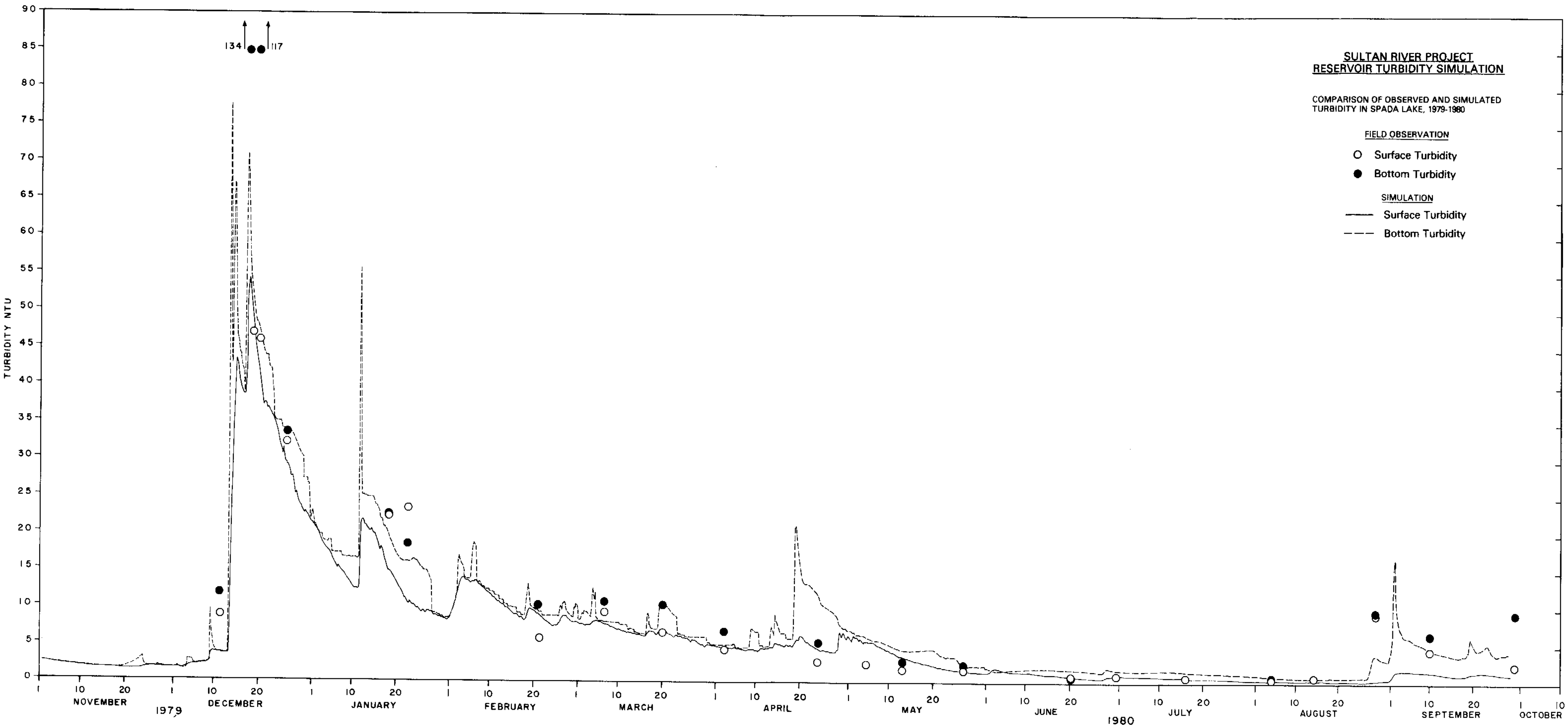

Figure 5-2 **Comparison of Observed Surface and Bottom Turbidities in Spada Lake with Simulated Turbidities, November 1979-September 1980**

The high values of bottom turbidity which were simulated at the beginning of December and January turbidity events deserve some comment. In both cases, these high bottom turbidities were caused by the fact that the termperature distribution in the lake and the inflow temperature were such that the highly turbid inflows entered the lower levels of the lake, thereby causing high bottom turbidity to appear in the simulation. The bottom turbidity then decreased rapidly for three reasons. First, the Howell-Bunger valve withdrew from the lowest layers in the lake, evacuating turbid water; second, the duration of the most turbid tributary inflows was short, so that the bottom layer was soon replaced by succeeding inflows which were less turbid; and third, mixing and diffusion within the reservoir further reduces locally high turbidities. Since such short duration effects of bottom turbidity have been observed in the lake, this result shows that the model is simulating the observed physical phenomenon. These high bottom turbidities do not occur in the Howell-Bunger valve releases because the low-level outlet withdraws water form several layers in the reservoir, not just from the bottom-most layer.

On the basis of the agreement between the observed and simulated values of turbidity in Spada Lake as shown on Figure 5-2, it was therefore concluded that the model is a satisfactory predictor of turbidity in the raised reservoir.

5.4 PREDICTION OF TURBIDITY FOR THE RAISED RESERVOIR

5.4.1 General

All of the results for the raised reservoir were based on the recorded 1979-1980 inflows and outflows as determined from the reservoir operation studies using the FERC license application rule curves and the 1979-80 inflows. Operation for flood control was not considered and no attempt was made to mitigate the reservoir turbidity. Most of the discussion which follows will be confined to the surface withdrawal intake. The intake at El. 1366 (Figure 4-1) will be mentioned only for purposes of comparison when appropriate.

There are several major factors which should be kept in mind when comparing the turbidity behavior in the existing and raised reservoirs. First, the storage volume in the raised reservoir is more than four times that in the existing reservoir. Second, practically all of the releases from the proposed reservoir will pass through the power tunnel intake; only 20 cfs will be released through the low-level, while all normal releases from the existing reservoir are made through the low-level outlet. Third, there was relatively little spill in the simulation of the raised reservoir operation. For the existing reservoir, more than 66,000 acre-ft, about two times the existing storage volume passed over the morning glory spillway during the turbidity event between December 13th and December 20th, 1979.

The increase in reservoir volume is the principal factor in understanding the general differences in turbidity behavior between the existing and raised reservoir following a turbidity event. In simulating the raised reservoir, the same amount of turbidity enters a much larger reservoir. Since the reservoir is well mixed during the turbidity event, the incoming turbidities will be diluted more in the raised reservoir than in the existing reservoir, and the overall turbidity in the raised reservoir shortly after the turbidity influx will be less. This result is illustrated in Figure 5-3 which compares the turbidity of outflows from the existing reservoir with the predicted turbidity from the surface withdrawal intake for the raised reservoir.

However, the turbidity of the reservoir outflows through the surface withdrawal intake remains at a somewhat higher level for a longer period of time than is the case for the existing reservoir. Because the turbidity becomes rapidly mixed in the reservoir, the turbidity behavior becomes analogous to the passage of a flood through a reservoir. Just as the peak flood discharge is reduced, so is the overall turbidity. Similarly, just as the recession of the flood hydrograph is stretched out over a

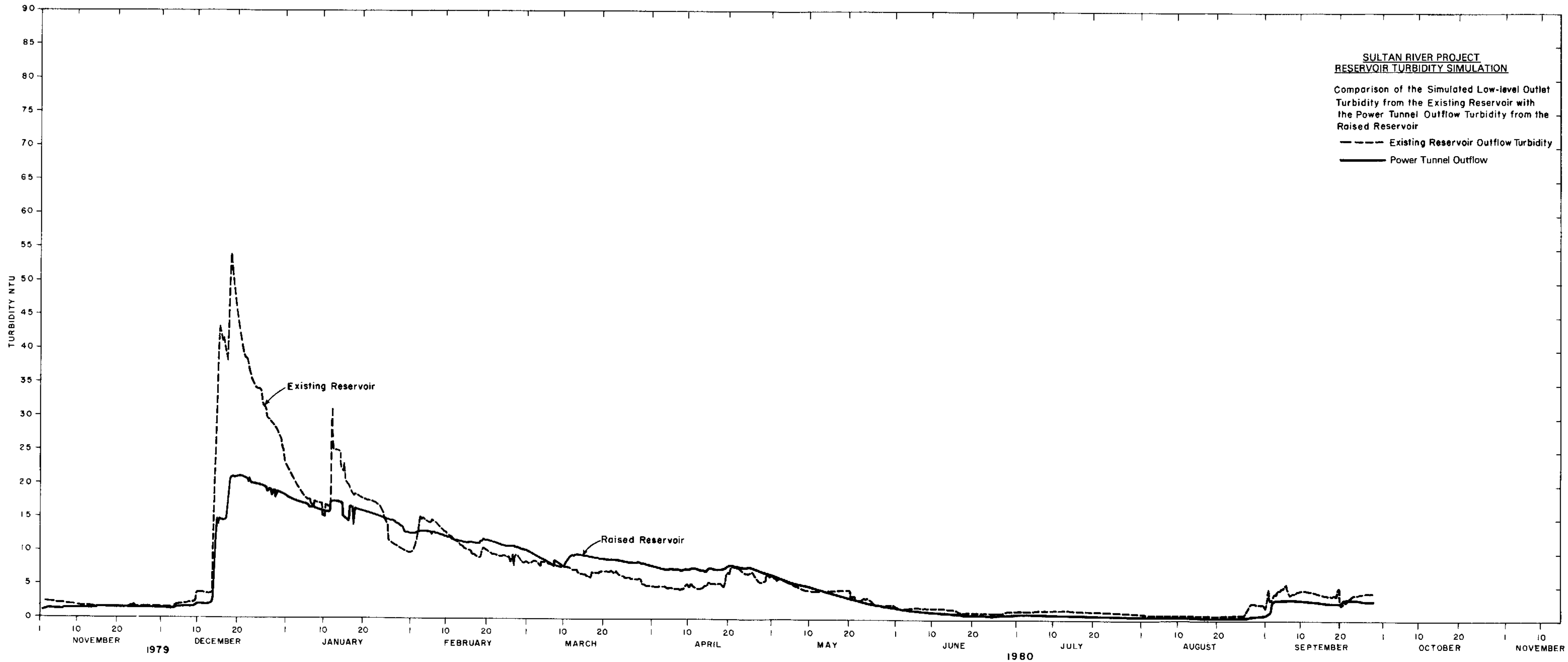

Figure 5-3 Comparison of Simulated Outflow Turbidities from the Existing Reservoir with Turbidity of Releases through the Power Tunnel Using a Surface Withdrawal Intake

longer period of time than would have occurred without the reservoir so is the recession in the turbidity level similarly delayed by passage through the reservoir. In general, the larger the reservoir, the more the flood peak is attenuated and the longer is the recession period. Similarly, the larger the reservoir, the lower the overall initial turbidity, but the longer the persistence of high turbidity in the outflow.

5.4.2 Comparison of Outflow Turbidities: Intake at El. 1366 and Surface Withdrawal Intake

A comparison of the turbidity of the power tunnel outflows with the intake at El. 1366 and with a surface withdrawal intake is depicted on Figure 5-4. The turbidity for both cases is practically the same as long as the reservoir is well mixed because mixing and diffusion make the reservoir turbidity nearly uniform from top to bottom. Effects of settling make the turbidity in the outflow from the surface withdrawal intake slightly lower than those from the intake at El. 1366. The turbidities remain similar until late April when stratification effects become significant. After the reservoir stratifies, the inflows enter the reservoir at or near the surface instead of mixing throughout the reservoir. The dilution caused by the clear inflows, combined with the effects of settling, results in less turbid layers near the surface and less turbidity in the power tunnel outflow. Consequently, the turbidity of outflows from the surface intake is less than the turbidity of outflows from the deeper intake at El. 1366, as shown on Figure 5-4.

5.4.3 Discussion of Predicted Reservoir Turbidity, Surface Withdrawal Intake

Figure 5-3 shows that the predicted turbidities of releases through the power tunnel using the surface withdrawal intake are lower than those made from the existing reservoir from the beginning of the turbidity event on December 12th until approximately January 25th. From January 25th through February 15th, the outflow turbidities for the two cases vary with respect to each other, because the effects caused by the two minor turbidity events are more significant in the existing reservoir. After February 15th, the outflow turbidities from the raised reservoir are about 2 or 3 NTUs greater than those from the existing reservoir through about April 20th.

After April 20th, the model shows that turbidities from the surface withdrawal intake in the raised reservoir are nearly the same as those in the releases from the existing reservoir even though the average turbidity in the raised reservoir is greater than that in the existing reservoir. This result is a consequence of two factors.

The first factor is the effect of settling. The releases through the Howell-Bunger valve in the existing reservoir come from the lowest levels in the reservoir. The lowest levels are the most turbid because the turbid inflows tend to enter the reservoir at low elevations and material continuously settles into these layers from overlying layers. In the raised reservoir, the surface intake withdraws from the upper layers of the reservoir. The upper layers are generally the least turbid layers in the reservoir because as material settles out of these layers, there is no resupply.

The second factor is the effect of stratification. After reservoir stratification begins in April, the cleaner inflows enter the intermediate and upper layers of the reservoir. In the existing reservoir, withdrawal is analogous in general to dealing off the bottom of a deck of cards. The lowest and most turbid layers are evacuated first. Cleaner inflows which mix within the reservoir are not withdrawn until the layers below them are evacuated. For the raised reservoir, the situation is analogous to dealing off the top of the deck, with additional cards (the inflows) being slipped into the deck near the top. Hence, the least turbid water, including most of the clean, spring, and summer inflows are withdrawn through the surface intake. Together, these two factors make the surface withdrawal intake the most logical choice as far as minimizing turbidity in power tunnel releases from the raised reservoir.

The turbidity in both the existing and raised reservoir with the surface withdrawal intake will be below 5 NTU by May 5th. Table 5-1 lists the outflow turbidities from the existing and raised reservoir conditions for comparison.

TABLE 5-1

COMPARISON OF OUTFLOW TURBIDITY
EXISTING RESERVOIR AND POWER TUNNEL OUTFLOWS, RAISED RESERVOIR

Date	Existing Reservoir	Power Tunnel El. 1,366	Power Tunnel Surface Intake
1 Jan	28.2	20.3	18.2
1 Feb	10.0	13.9	12.7
1 March	8.5	12.1	10.3
1 April	5.0	8.3	7.9
1 May	6.5	7.8	6.6
1 June	2.2	6.2	1.9
1 July	1.2	2.1	0.7
1 Aug	1.0	1.3	0.4
1 Sept	2.2	0.9	1.0
1 Oct	4.2	2.6	2.7

5.4.4 Turbidity, Low-Level Releases from the Raised Reservoir

Turbidity in the releases from the low-level outlet from the raised reservoir follow closely the turbidity of releases from the power tunnel outlet except for a sharp peak that occurs at the beginning of the January turbidity event as shown on Figure 5-5. The sharp peak is a consequence of the same phenomenon discussed in the case of the existing reservoir: turbid inflows enter at the lowest level in the reservoir as governed by the reservoir and inflow temperatures. After about April 25th, the inflow enters the reservoir at intermediate levels. Because of the reservoir stratification, the low-level release of 20 cfs can remove only a small part of the storage volume below the power tunnel intake. Therefore, further dilution takes place very slowly. Effects of settling also tend to maintain higher levels of turbidity near the bottom. Consequently, turbidity in the low level release remains above 5 NTU throughout the simulation period. As expected, the location of the intake level for the power tunnel had practically no effect on the predicted turbidities for the low-level outlet.

5.4.5 Accumulation of Turbidity

A series of simulations was run to determine whether there would be any carry-over of turbidity from one year to the next. The results indicated that there was no discernable effect, and for typical conditions the raised reservoir will dilute sufficiently each year so that there will be no significant accumulation of turbidity in the raised reservoir.

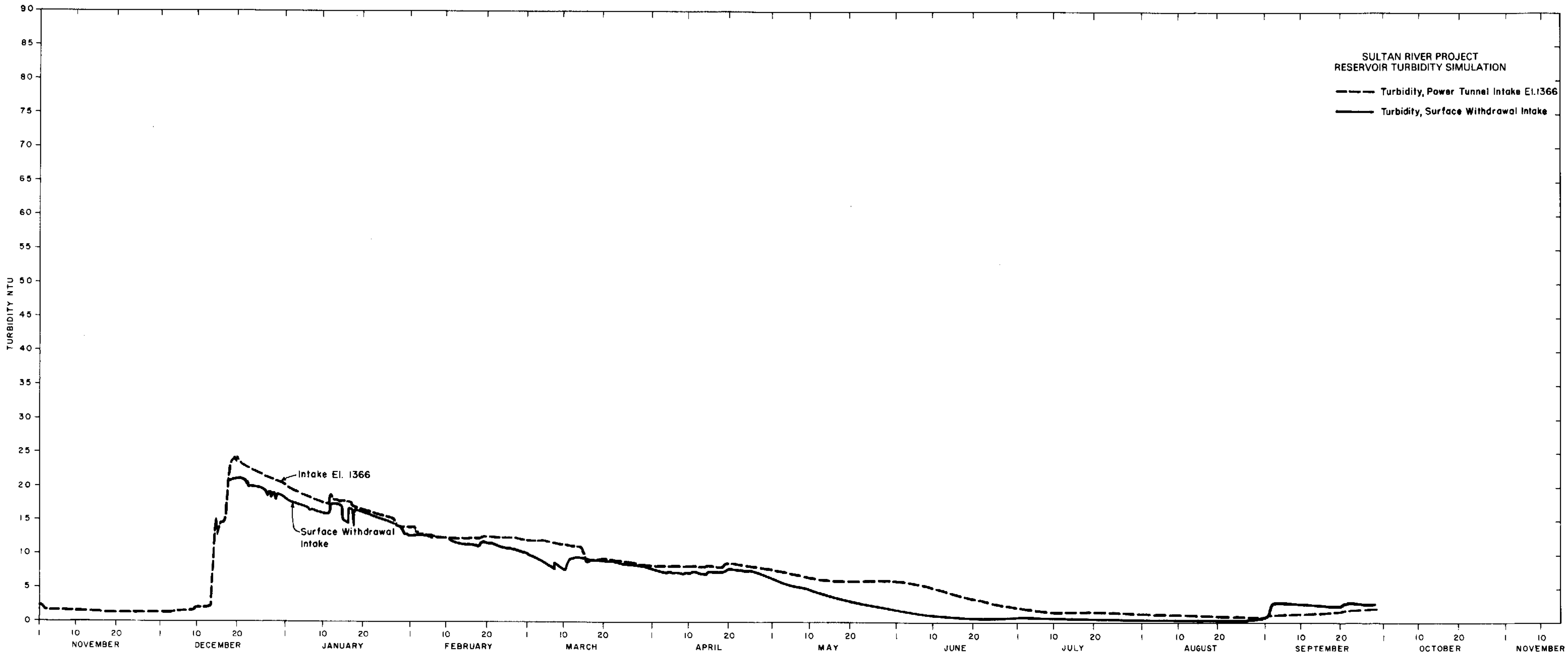

Figure 5-4 Comparison of Simulated Outflow Turbidities, Raised Reservoir, Intake at Elevation 1,366 and Surface Withdrawal Intake

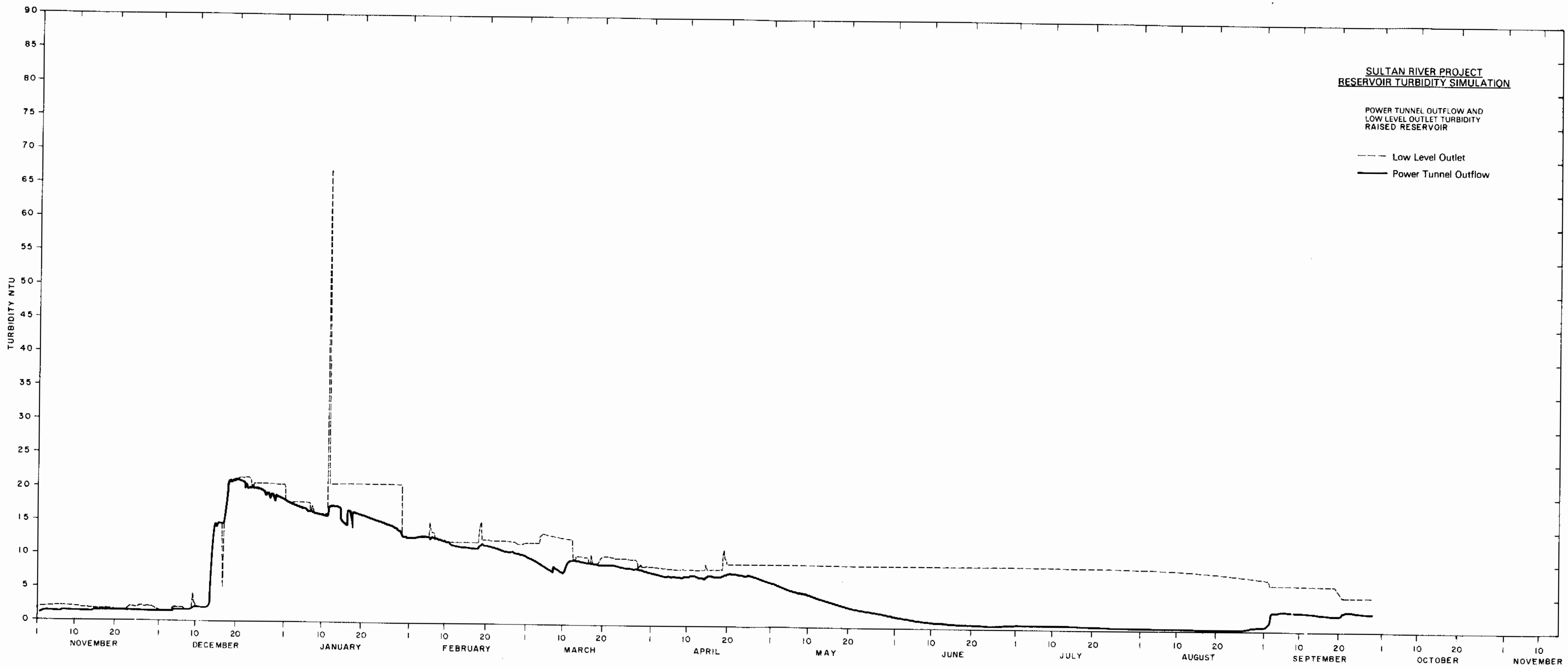

Figure 5-5 Simulated Turbidities. Surface Withdrawal Intake and Low-Level Outlet, Raised Reservoir

Section 6

CONCLUSIONS

Section 6

CONCLUSIONS

Improvements to the M.I.T. reservoir model made possible the prediction of temperature and turbidity in the raised reservoir for evaluation of potential project impacts on water quality and fisheries in the Sultan River.

Calibration and verification of the model necessary to assure confidence in the predicted results were excellent. The extensive and high quality data base obtained to calibrate and verify the numerical model reduced many of the uncertainties associated with previous studies of this type.

Predictions of power tunnel outflow temperatures with the intake at El. 1366 as shown on the FERC Exhibit L drawing, Sheet 28 (Figure 4-1), were compared with the historical record at the city of Everett's Diversion Dam on the Sultan River. The results showed that outflow temperatures from the raised reservoir in the June-September period would be 2 to 2.5°C colder than existing conditions. In general, the power tunnel outflow temperature for June through September would be below the minimum temperatures recorded at the Diversion Dam from 1969 to 1979 as shown on Figure 4-4.

A surface withdrawal intake resulted in power tunnel outflow temperatures that are expected to be within, or at most slightly above, the range of temperature recorded at the Diversion Dam. Temperatures in June, July, and August are most likely to be above the mean of the 1969-1979 temperatures recorded at the Diversion Dam, significantly improving the temperature regime in the Sultan River in comparison with the intake at El. 1366. Power tunnel outflow temperatures with a surface withdrawal intake are compared with the temperatures recorded at the Diversion Dam in Figure 4-6.

The temperature variation of outflows from the power tunnel with a surface withdrawal intake will follow the naturally occurring temperature of the North and South Forks of the Sultan River throughout the year as illustrated on Figures 4-9, 4-10, and 4-11. The peak outflow temperature will occur earlier in the year than for the existing conditions, and the outflow temperature will follow closely the thermal regime that existed prior to the construction of Culmback Dam.

The surface intake is simple to operate. Operation is determined by the reservoir water level. For most years, only one change in intake level should be necessary between June and October. At most, three to four changes per year may be required.

The turbidity of release through the power tunnel with the surface withdrawal intake will be lower than those that would have occurred under existing conditions immediately following a turbidity event. For about three to four months after the turbidity event, the turbidity will be about 2 to 3 NTU greater in the raised reservoir in comparison with the existing reservoir as depicted in Figure 5-3.

On the basis of existing data, it appears that during the late spring and summer months, outflow turbidities using a surface withdrawal scheme during typical years will be about the same as for the existing reservoir under the same meteorologic and hydrologic conditions.

The turbidity of outflows with either the surface withdrawal intake or the intake at El. 1366 is practically the same until stratification develops in the spring. After the reservoir stratification develops in late spring, the outflow turbidities from the surface withdrawal intake will be lower than those with the intake at El. 1366.

The surface withdrawal intake not only provides a better thermal regime in the Sultan River than the intake at El. 1366, but it also reduces turbidity in the power releases from the raised reservoir. The surface withdrawal concept is therefore the logical choice for the power tunnel intake for the Stage II development of the Sultan River Project.

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