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GEOLOGICAL SURVEY

SIMULATION OF STREAMFLOW TEMPERATURES IN THE YAKIMA RIVER BASIN, WASHINGTON, APRIL-OCTOBER 1981

By John J. Vaccaro

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CONTENTS

APPENDICES

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
inches (in.)----------------------	25.4	millimeters (mm)
	2.540	centimeters (cm)
	0.0254	meters (m)
feet (ft)-------------------------	0.3048	meters (m)
miles (mi)------------------------	1.609	kilometers (km)
square miles (mi^2)----------------	2.590	square kilometers (km^2)
acres-----------------------------	4047.	square meters (m^2)
acre-feet (acre-ft)---------------	1233.	cubic meters (m^3)
	0.001233	cubic hectometers (hm^3)
cubic feet per second (ft^3/s)------	0.02832	cubic meters per second (m^3/s)
	28.32	liters per second (L/s)
centimeters (cm)	0.3937	inches (in.)
meters (m)------------------------	3.281	feet (ft)
kilopascal (kPa)-------------------	0.1450	pounds per square inch ($lb/in.^2$)

Degrees Celsius to degrees Fahrenheit: $^{o}F = 9/5^{o}C + 32$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "mean sea level." NGVD of 1929 is referred to as sea level in this report.

SIMULATION OF STREAMFLOW TEMPERATURES IN THE YAKIMA RIVER BASIN, WASHINGTON, APRIL TO OCTOBER 1981

By John J. Vaccaro

ABSTRACT

The effects of storage, diversion, return flow, and meteorological variables on water temperature in the Yakima River, in Washington State, were simulated, and the changes in water temperature that could be expected under four alternative-management scenarios were examined for improvement in anadromous fish environment. A streamflow-routing model and Lagrangian streamflow temperature model were used to simulate water discharge and temperature in the river. The estimated model errors were 12 percent for daily discharge and 1.7°C (degrees Celsius) for daily temperature.

A sensitivity analysis for the simulation of water temperatures showed that the effect of reservoir outflow temperatures diminishes in a downstream direction. A 4°C increase in outflow temperatures results in a 1.0°C increase in mean irrigation season water temperature at Umtanum in the upper Yakima River basin, but only a 0.01°C increase at Prosser in the lower basin. The influence of air temperature on water temperature increases in a downstream direction and is the dominant influence in the lower basin. A 4°C increase in air temperature over the entire basin resulted in a 2.34°C increase in river temperatures at Prosser in the lower basin and 1.46°C at Umtanum in the upper basin. Changes in wind speed and model wind-function parameters had little effect on the model-predicted water temperature.

Of four alternative-management scenarios suggested by the U.S. Bureau of Indian Affairs and the Yakima Indian Nation, the 1981 reservoir releases maintained without diversions or return flow in the river basin produced water temperatures nearest those considered as preferable for salmon and steelhead trout habitat. The alternative management scenario for no reservoir storage and no diversions or return flows in the river basin (estimate of natural conditions) produced conditions that were the least like those considered as preferable for salmon and steelhead trout habitat.

INTRODUCTION

The Yakima River and its main tributaries, located in east-central Washington (fig. 1), are highly regulated by storage reservoirs and diversion canals. The regulated streamflow in the basin is extensively used and reused for the irrigation of over 500,000 acres, as well as for municipal and industrial uses. Diversion of water has caused the Yakima River to go dry at times at several locations. At some locations in the river, water temperatures are elevated because of the interaction between diversion-induced flow depletion, high air temperatures, low water velocities, and some high-temperature return flows. These elevated river temperatures have caused thermal blocks to the migration of anadromous fish, loss of habitat and spawning grounds for anadromous and native fish, and fish kills.

Objectives

In 1981 the Yakima Indian Nation and the U.S. Geological Survey undertook a cooperative study with the following objectives: 1) to estimate the effects of storage, diversion, return flows, and meteorological parameters (air temperature and wind speed) on the mean daily temperature of the Yakima River at selected locations for the irrigation season from April 1 through October 31, 1981; 2) to provide a means of studying the effects of potential management alternatives on the river temperature; and 3) to provide data for possible evaluation of the potential for enhancing the fish habitat in the basin by managing streamflows. The use of a streamflow-temperature model for the Yakima River basin was determined to be the best means to achieve the objectives.

Approach

The approach consisted of four general steps: 1) acquisition of data, 2) calibration and verification of a basin streamflow-routing model, 3) calibration, verification, and sensitivity testing of a basin temperature model, and 4) operation of the two models and analysis of results.

The data for the study were acquired in several ways: 1) compilation, checking, and storage of streamflow discharge and reservoir storage information; 2) measurement of synoptic air and water temperatures at more than 70 sites at bimonthly intervals during the 1981 irrigation season; 3) installation, operation, and analysis of 11 Geological Survey thermographs (continuous recorders of water temperature) and field checks of 15 existing U.S. Bureau of Reclamation (USBR) thermographs, and analyses of the thermograph records; 4) determination of stream geometry at selected points in the basin; and 5) compilation, checking, storage, and analysis of air-temperature and wind-speed data for 20 existing meteorological (HM) stations. These factors are discussed in more detail in the section "Hydraulic, Meteorological, and Temperature Data".

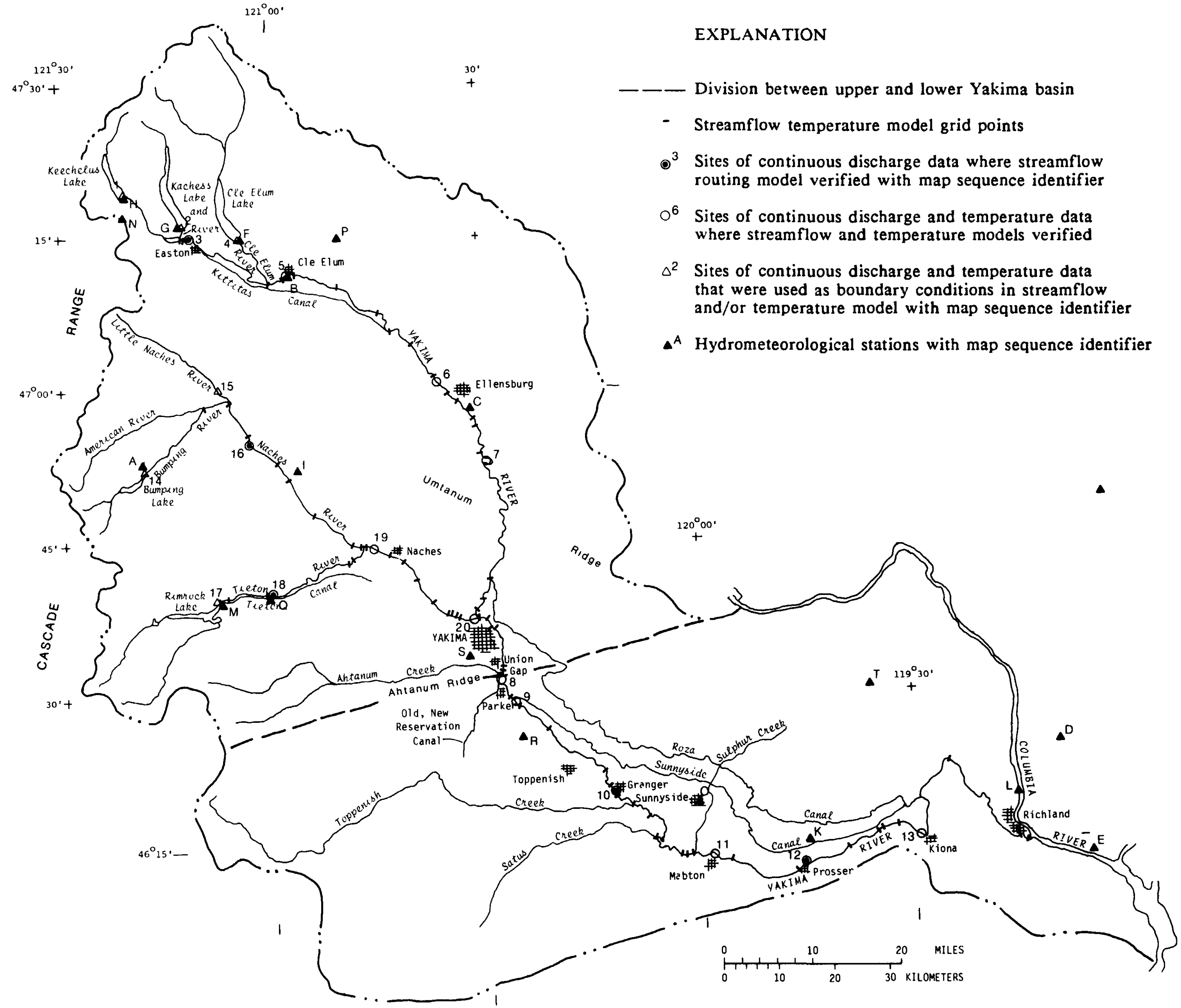

FIGURE 1.--Yakima River basin showing location of hydrometeorological stations, major geographic features, and river sites where water temperature was computed.

The Streamflow Synthesis and Reservoir Regulation model, SSARR, (U.S. Army Corps of Engineers, 1971) was chosen for use in this study and was calibrated and verified for the basin. This streamflow-routing model was selected because it can accommodate large data sets economically while producing reliable results. The model has been used in a previous study (Vaccaro, 1982) of the Yakima River upstream of Parker, Wash., so for this study it was calibrated and verified only for the Yakima River below Parker. The model was operated to simulate daily streamflow discharges under several management alternatives; the simulated discharges were then used, along with water temperature and meterological data, as input to a temperature model.

The one-dimensional Lagrangian temperature model of Jobson (1980a) was the model selected to simulate water temperatures. In this model, a parcel (volume) of water is followed as it moves through the river system. The initial temperature of the parcel and subsequent temperature changes are computed and tracked directly. Thus, a time history of the temperature and the contribution of each source to the temperature changes in each parcel is obtained. The model and its calibration and verification are discussed further in the "Simulation of Stream Temperatures" section.

Finally, the streamflow-routing and temperature models were operated using conditions that existed during the 1981 irrigation season and using four alternative scenarios that represent four levels of deregulation in the Yakima River basin. The operation of the models for the conditions that occurred in 1981 and the discharges and temperatures simulated for these conditions will hereafter be referred to as simulated conditions or values.

DESCRIPTION OF STUDY AREA

The Yakima River basin, which encompasses some 6,100 square miles, is located in southwest-central Washington (fig. 1). It is bordered on the north and west by the Cascade Range and on the east and south by lower divides that separate it from the Columbia River valley. Altitudes in the basin range from about 8,000 feet in the Cascades to about 400 feet near the mouth of the Yakima River. The basin contains 8 large streams, numerous small streams, 5 major storage reservoirs, over 80 canals, 5 diversion dams, 15 major return flows, and numerous smaller return flows.

The major rivers in the basin head at high altitudes in the Cascades, where the precipitation is over 100 inches per year. The basin is divided at several locations by ridges and hills. For instance, the Ahtanum Ridge near Parker divides the basin into upper and lower parts that are topographically, hydraulically, and climatologically different. The lower part, where the river slope is low, is in an arid environment that receives less than 10 inches of precipitation per year and has an average annual air temperature of about 10°C. In the upper part the average annual air temperature is about 6°C and the precipitation ranges from over 100 inches in the Cascades to about 13 inches near Ellensburg, Washington. The river in the upper part has a medium to high slope and passes through forest lands and deeply incised canyons. The river in the lower part follows a meandering course through a hilly and flat topography.

Agriculture is the predominant economic activity in the basin. Approximately 2,400,000 acre-feet of water is diverted for irrigation of about 500,000 acres; 45 percent of the water is eventually returned to the river system.

HYDRAULIC, METEOROLOGICAL, AND TEMPERATURE DATA

The simulation of streamflow and water temperature by deterministic numerical models requires the following data: 1) hydraulic data to calibrate and verify the streamflow-routing model and for comparison with simulated values computed under the management scenarios; hydraulic data include stream discharge, canal discharge, return flows, local inflow, and stream geometry relationships; 2) meteorological (HM) data for those processes that control the heat transfer between the water surface and the atmosphere; and 3) thermal regime data (synoptic and continuous) to be used in defining heat sources to the river and upstream boundary conditions, and in the calibration and verification of the model. For reference purposes, each key river site that is discussed and analyzed, and each meteorological data site that is presented in this report has been assigned a map sequence identifier on figure 1. Throughout this report, these numbers follow site names.

Hydraulic Data

Mean daily discharges were available for 42 stream sites (see Appendix A for listing) on the Yakima, Naches, Tieton, Cle Elum, and Kachess Rivers and their tributaries. Twenty-five of the sites were equipped with continuous flow recorders and the other 17 with staff gages; the latter group were mostly on small streams. Discharge measurements were made at all sites throughout the 1981 irrigation season to rate the gages.

Discharge data for streamflow sites on the Yakima, Naches, and Tieton Rivers were used for calibration, verification, and comparison with the values simulated by the streamflow-routing model for observed and alternative scenario conditions. Upstream reservoir outflow data were used as boundary conditions for the model. Tributary inflows were used as input to the routing model and as the discharge portion of the heat-loading sources for the temperature model.

Mean daily discharges were available for all major canals and over 95 percent of the minor canals that divert from rivers. Appendix B lists gaged canals for which records were used in this study.

All major surface return flows were included in the models. Mean daily discharges were available from gages on the major surface return flows. Discharge measurements were made throughout the 1981 irrigation season to help define the ratings at these sites. A list of all surface return-flow sites incorporated in the study is given in Appendix C. The discharges and temperatures of the return flows are important because they can be a heat load to the rivers.

In the upper part of the basin the minor and poorly defined return flows were estimated by return-flow routing models as described in Vaccaro (1982). In this estimation method, a percentage of the discharge from each diversion is put into a specific reach of the river. The return-flow water is then routed in these reaches (both the surface- and ground-water return flows) and the routed water is summed at selected locations. These summed values are treated as an aggregated tributary inflow.

The term 'local' as used in this report is defined as the ungaged discharge for a particular reach of the river bounded by continuous streamflow gaging locations. It is an estimate of the natural ungaged discharge and consists of ungaged surface runoff, ground-water discharge and recharge, ungaged diversions and returns (which are assumed to be negligible), and errors in the gaged flows. A local is computed for a reach of a river as the downstream observed discharge value minus the upstream observed discharge value, plus diversions in that reach minus surface- and ground-water return flows and tributary inflow in that reach. Locals for the upper part of the Yakima River basin were given in Vaccaro (1982). Equations for computing locals for the lower basin above Kiona, Wash., are given in Appendix D. The locals in the lower basin were considered to be entirely of ground-water origin because all major surface-water return flows, diversions, and streams are gaged; however, the locals probably include some small ungaged surface-water return flows. Because of the lack of information on the distribution of the locals between gaging locations, the locals were considered as tributaries that were input at the location at which the local was estimated.

Required inputs for the streamflow and temperature models are the discharge, velocity or area, and width of the river at predetermined grid points. The SSARR model computes only the first of these, discharge. A streamflow model that computes the other parameters--velocity, area, and width--would require an extensive data-collection program and large computer costs. This is especially true when operating such a model for a complete irrigation season of 214 days and over a spatial domain of some 300 river miles.

Therefore, measured discharges at gaging stations were used in conjunction with other discharge-related data (area, width, depth, and velocity) under a variety of flows to establish regression relationships between discharge and the other hydraulic parameters at the gaging stations. Relationships at intermediate river locations were based on interpolated values from the upstream and downstream control relationships. The interpolation scheme was based on the physical configuration of the river and river geometry data when available. Interpolation to intermediate points was not a linear, but a weighted interpolation scheme. Where possible, values of width, depth, and velocity at intermediate points for different discharge values were compared with observed data.

The above relationships were established for all river grid points used in the temperature model and were used in a processing computer program. The processing program operated on the SSARR-computed discharge values at these grid points and produced the mean daily velocity, area, and width at each grid point for each of the 214 days of the 1981 irrigation season for regulated streamflow conditions and streamflow conditions under the four scenarios.

Meteorological Data

To compute the transfer of energy between the water and the atmosphere, a complete meteorological data base is desirable but rarely available. The equipment, installation, time, and data processing on a scale necessary for this study would be too costly. Consequently, the equilibrium temperature approach, which has been shown by other investigators (Jobson and Yotsukura, 1973) to yield good results, was used in this study. In the equilibrium temperature approach only a minimum of meteorological data are needed, specifically, wind speed and the equilibrium water temperature (which in this study is approximated by the air temperature). The equilibrium temperature approach is discussed in more detail in the "Heat Addition" section.

There were 20 existing HM stations in or near the basin, operated by the National Weather Service (NWS), USBR, Battelle Pacific Northwest Laboratory, and the Washington State University Agricultural Research Station. The sites are shown in figure 1 and listed in Appendix E.

Air Temperature

Of the 20 meteorological stations, mean daily air-temperature data from all but Othello (J) and Naches-Cliffdell (I) were used in the study. Missing values were synthesized either by regression analysis or by averaging the daily extremes. Due to the spatial and temporal variability of air temperature and topographic changes in the basin, a representative HM station could not be defined for individual river reaches. Thus, the daily air temperature for each model grid point was obtained by using a bivariate interpolation scheme (IMSL, 1982) and data from the four nearest HM stations (fig. 1). Values from four HM stations were used for interpolation to suppress regional trends; local variations were then assumed to be adequately represented. Two methods were used to estimate the reasonableness of the interpolated values. The first method, which tested for a regional fit, consisted of computing the lag-4 cross-correlation coefficient between the 214 daily temperatures from the 18 HM stations and selected river-grid points, all of which represent a multivariate time series (Salas and others, 1980). These correlation coefficients were then checked for their fit in the regional structure. The second method, which was site-specific, compared interpolated air temperatures for the river grid points with air temperatures measured at the river grid points during the synoptic surveys. This analysis showed that the interpolated air temperatures were within about ±2°C with a maximum estimated error of about 4°C.

Monthly averages of air temperatures for three river locations during the 1981 irrigation season are given in table 1, along with 1981 irrigation season monthly averages for three NWS HM stations and the long-term averages at two of the HM stations. The data from the three NWS stations are representative air temperatures of different positions of the basin and of the three river sites.

TABLE 1.--Monthly and seasonal mean air temperatures measured at three meteorological stations and predicted at three sites along the Yakima River for the period April 1 to October 31, 1981

[Values in degrees Celsius; numbers and letters in parenthesis refer to map sequence identifiers shown on figure 1]

Site	Apr	May	June	July	Aug	Sept	Oct	1981 irrigation season
Ellensburg[1] (C)	8.4	13.0	15.0	19.0	21.5	14.4	7.5	14.1
Yakima River at Ellensburg[2] (6)	8.2	12.7	14.8	18.7	21.4	14.5	7.4	14.0
Yakima WSO[1] (S)	9.8	13.7	16.5	20.5	22.8	16.4	9.3	15.6
(Historic)[3]	9.7	14.4	18.1	21.5	20.3	16.3	10.1	15.8
Yakima River at Union Gap[2] (8)	10.0	14.1	16.8	20.8	23.0	16.7	9.5	15.9
Prosser 4 NE[1]	10.4	14.0	16.6	20.0	22.3	16.5	9.8	15.7
(Historic)[3] (K)	10.3	14.6	18.2	21.3	20.5	17.0	10.9	16.1
Yakima River[2] at Prosser (12)	10.1	13.8	16.3	19.6	21.9	16.2	9.7	15.4

[1]National Weather Service meteorological site.
[2]Location of river sites for which air temperature was predicted by interpolation.
[3]Historic is the monthly mean air temperature at the meteorological station for the complete historical record.

Wind Speed

Wind-speed data were available at only four locations in or near the basin. Wind speed is usually more variable (spatially and temporally) than air temperature. However, daily mean values at the four sites and the lag-4 cross-correlation coefficients showed that there was some mutual dependence between sites. Because of a lack of information on wind speed and available methodologies, the basin was initially partitioned into three subbasins on the basis of topography. Next, either the daily wind speeds for a representative HM station were assigned to a subbasin and all model grid points in that subbasin used these daily wind speeds, or else three stations were assigned to a subarea and wind speed at specific river locations was estimated using linear two-dimensional interpolation or extrapolation.

Temperature Data

Air and water temperatures were measured synoptically and bimonthly at over 70 sites in the basin during the April-October 1981 irrigation season, including the mouths of all major inflows into the Yakima, Naches, and Tieton Rivers and all gaging-station sites in the basin. There were 26 thermograph stations (fig. 1) on streams in the basin during the study period, 11 of which were operated by the Survey and 15 by the USBR. They were located at all upstream model boundaries, at the mouths of the major inflows to the rivers, and at sites along the major rivers for calibration and verification of the temperature model. At each thermograph station, the temperature distribution in the cross section was observed at least once to determine if adjustments in the recorded temperature were needed to account for spatial variation of water temperature over the cross section. In general, temperature differences in the cross section were less than 0.5°C, and therefore no adjustments were required. The measurement error of the thermograph was estimated to be 0.5°C.

The synoptic measurements and thermograph records were used to construct a daily-temperature data base for most inflows. Harmonic analysis methodology as presented by Steele (1974) was used to synthesize missing daily mean values for the 1981 irrigation season. This method has given reliable estimates (Higgins and Hill, 1973, and Gilroy and Steele, 1973). The r-squared values for the harmonic analysis synthesis ranged from 0.43 to 0.92, and most of the values were about 0.77. The lowest values were for the smaller inflows. Correlation techniques were also tested, but were found in general to be inadequate. A harmonic analysis of a synoptic record gives an equation for a sine wave that describes the temperature over a 1-year cycle. The inherent errors in a sine wave description of water temperature values are that (1) early and late values in the year can be computed as negative, when they should, in reality, be at or close to 0°C (ice conditions), and (2) the inherent variation of temperatures is filtered out. To account for low or negative values the synoptic and continuous recorded data were checked for the lowest 1981 observed values. This check showed that when the inflow temperatures generated by the harmonic analysis were lower than a limiting value they could be set equal to that value. This limiting value was estimated to be 3.7°C for the Naches River basin and 5.0°C for the Yakima River basin.

The locals consist of surface runoff and ground water and were estimated at several river sites. Temperature data were not available for these discharges, so temperature values were estimated on the basis of the principal source (ground water or surface runoff) of the discharge. For locals that were estimated to be principally of surface-runoff origin, the prior 4-day moving average of the air temperature (at the inflow location of that discharge) was assigned as the water temperature value; other methods were tested and the 4-day average was found to be the best estimator. Values which were less than the limiting values (3.7° or 5.0°C) were constrained to be equal to the limiting values. The water temperature of those locals that consisted principally of ground-water origin was set equal to either the annual average or irrigation-season average air temperature, depending on whether the ground water originated from irrigated or nonirrigated areas. As with surface runoff, the air temperature values were obtained at the inflow location of the discharge. The above method has been used by other investigators and has been shown to give a good estimate (Edinger and Geyer, 1965; H. Jobson, oral commun., 1982).

For many of the smaller streams the errors in air and water temperatures estimated by harmonic analyses of synoptic temperature measurements were judged to be too large. Therefore, more accurate means of synthesizing these values were investigated, despite the fact that the smaller streams account for less than 5 percent of the flow in the entire Yakima River system. The similarity of the results of harmonic analysis of air and water temperature suggested that the prior 4-day moving average of the air temperature at the location of these small streams could be used as the stream temperature estimator. The discharges of these streams were generally unregulated, low (about 2 to 15 ft^3/s), and highly variable. Computed values were checked against synoptic data and agreed well. This methodology is physically reasonable, because the larger variability in water temperature of the small streams, which is generally masked by harmonic analysis, is accounted for. All larger tributaries and regulated tributaries had at least partial continuous water-temperature records, and in those cases harmonic analysis was used to synthesize missing values.

STREAMFLOW-ROUTING MODEL

General

The SSARR streamflow-routing model simulated mean daily discharge at selected river locations for the 1981 irrigation season. Streamflow routing in the SSARR model is based on the storage/continuity method of routing discharge from an upstream point to a downstream point. The required equation form and parameters are discussed fully in the SSAAR User Manual (U.S. Army Corps of Engineers, 1972) and, for application to the Yakima River basin above Parker, Wash., in Vaccaro (1982). In this study, the configuration of the model was extended to the mouth of the Yakima River. Streamflow was computed at selected locations below Kiona, the last gaging station on the river; however, because there are no continuous discharge data downstream of Kiona, the reliability of the simulated discharges below Kiona cannot be checked.

The lower basin model (below Parker) included all major inflows greater than about 5 ft^3/s into the Yakima River and all the diversions. Discharge was computed at 24 points, 22 of which are at inflows or outflows. The 22 inflows or outflows include four canals, four locals, and 14 that are either tributaries or return flows. Where possible, return flows were aggregated to facilitate model tractability and to enhance data-handling characteristics. Also, two canals below the Kiona gaging station were aggregated as a single outflow. The four locals correspond to the four reaches in the river that have upstream and downstream continuous daily-discharge data. The first local is for the Yakima River at Granger, with Parker as the upstream control; the second is for the Yakima River at Mabton with Granger upstream; the third is for the Yakima River at Prosser with Mabton upstream; and the fourth local was computed for the Yakima River at Kiona with Prosser upstream. As previously discussed, the locals were input at the river site for which they are named and were not distributed between uptream and downstream locations. Further, the estimated locals were not adjusted for the different simulations in this report because the locals include possible errors in the observed daily discharge data used to estimate the locals and account for the estimates of surface-water and ground-water return flows.

The lower-basin routing model was calibrated to values of observed mean daily discharge at the four sites discussed above (fig. 1) for the months of April and August 1981, and was verified on observed daily discharge values for the other 5 months in the 1981 irrigation season. Verification results for the simulation of observed mean daily discharges in the lower basin are presented in table 2.

TABLE 2.--Verification results of simulating observed mean daily discharges for 5 months of the 1981 irrigation season for the Yakima River at Granger, Mabton, Prosser, and Kiona, Wash.

[Values in cubic feet per second unless otherwise noted; number in parenthesis refers to map sequence identifiers shown in figure 1]

Site	Period	Mean daily discharges: Observed	Predicted	Error[1]	Standard deviation of residuals[2]	Observed mean daily discharge,[3] in percent
			Yakima River			
At Granger (10)	5-month	906	914	8	50	6
	May	1,234	1,238	4	82	7
	June	829	835	6	39	5
	July	651	650	-1	38	6
	September	693	695	2	38	5
	October	1,114	1,108	-6	38	3
At Mabton (11)	5-month	1,878	1,874	-4	187	10
	May	2,046	2,045	-1	348	17
	June	1,859	1,876	17	158	8
	July	1,515	1,509	-6	111	7
	September	1,814	1,808	-6	74	4
	October	2,154	2,136	-18	113	5
At Prosser (12)	5-month	819	814	-5	236	29
	May	1,015	1,011	-4	457	45
	June	569	587	18	182	32
	July	370	366	-4	128	35
	September	634	626	-8	87	14
	October	1,496	1,479	-17	130	9
At Kiona (13)	5-month	1,957	1,940	-17	311	16
	May	2,090	2,106	16	610	29
	June	1,843	1,782	- 61	210	11
	July	1,488	1,488	0	170	11
	September	1,894	1,880	-14	125	7
	October	2,463	2,441	-22	170	7

[1] Average difference between observed and simulated mean daily discharges for the specified period.

[2] Standard deviation of the residuals represents an estimate of mean daily error.

[3] This column defines a percentage of error based on the mean daily discharge and the 5-month or monthly averages.

Error Analysis

Model simulation of observed conditions in the upper basin is basically a second verification of the upper basin model developed and verified previously by Vaccaro (1982). Estimated daily error for the upper basin model is about 8 percent, which is less than the 12 percent estimated during the prior study. The smaller error can be attributed to a greater number of available discharge records for small streams, canals, and return flows, which previously had been aggregated in the upper-basin locals. Also, flows in the 1981 irrigation season were less variable than those used in the 1982 study.

Analysis of table 2 shows that the simulated daily discharges for the lower basin have an estimated root mean square error of 17 percent. The differences between the standard deviations of the daily residuals at the different sites are dependent on four factors: 1) magnitude and variability of river discharge values; 2) magnitude of inflows, mainly represented by return flow; 3) computation of locals on a daily basis without a time lag; and 4) downstream propagation and accumulation of errors. As one moves downstream, the flow in general becomes higher and more variable due to inflows. However, at the Prosser gaging station, which is directly downstream from a major diversion dam and canal, the streamflow is greatly reduced. Below Prosser, streamflow once again increases in amount and variability. For these reasons, the potential error in the computed results near Prosser is greater (when expressed as a percentage) than at other sites along the river (table 2). Hydrographs of the observed and simulated mean daily-discharge values for the 1981 irrigation season for the four verification sites in the lower basin are presented in figures 2 through 5. In the following sections only the observed discharge values are presented for comparison with the computed values from the four scenarios. This is done for three reasons, the first being that the predicted values are similar to the observed (table 2). Secondly, simulation of observed values is for calibration and verification, that is, parameter identification and error analysis. Thus, the simulated values will have an error associated with them which should be considered when they are compared to the observed values—actual values will be compared, not changes. Lastly, this type of analysis is the same as in a report by Vaccaro (1983) on unregulated flow in the Yakima River basin, so that values can be compared between this report and the previously published report.

The timing of streamflow in the lower basin is generally reproduced by the streamflow model (figs. 2 through 5). The important streamflow characteristics needed for Lagrangian temperature-model input are the velocity and volume of a parcel of water. The parcel volume is determined by the discharge at the upstream boundary and the discharges of inflows and outflows. Consequently, the accuracy of the parcel volume is only as accurate as the data which produced it. The calculation of locals is based on river, return flow, and diversion discharge data. Thus, errors in all of these components will be reflected in the locals. Therefore, discharge errors which do not affect the streamflow model results, due to the inclusion in the locals, can affect the temperature model simulations. This is because the parcel volumes and the size of inflows (which can be heat loads) will have an error of the same order of magnitude as the errors in discharge data.

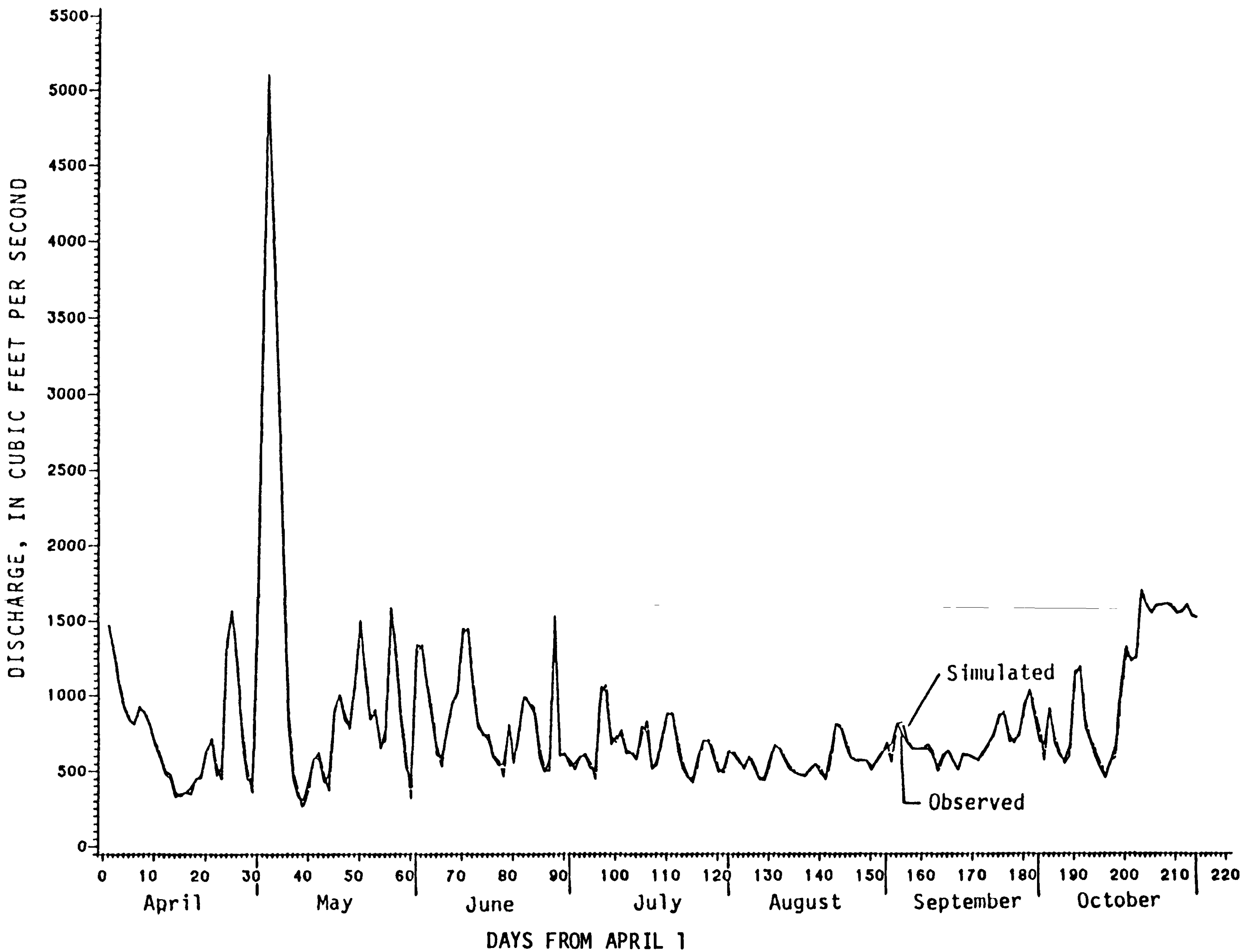

FIGURE 2.--Mean daily observed and simulated discharges of the Yakima River at Granger (10) for the period April 1 to October 31, 1981.

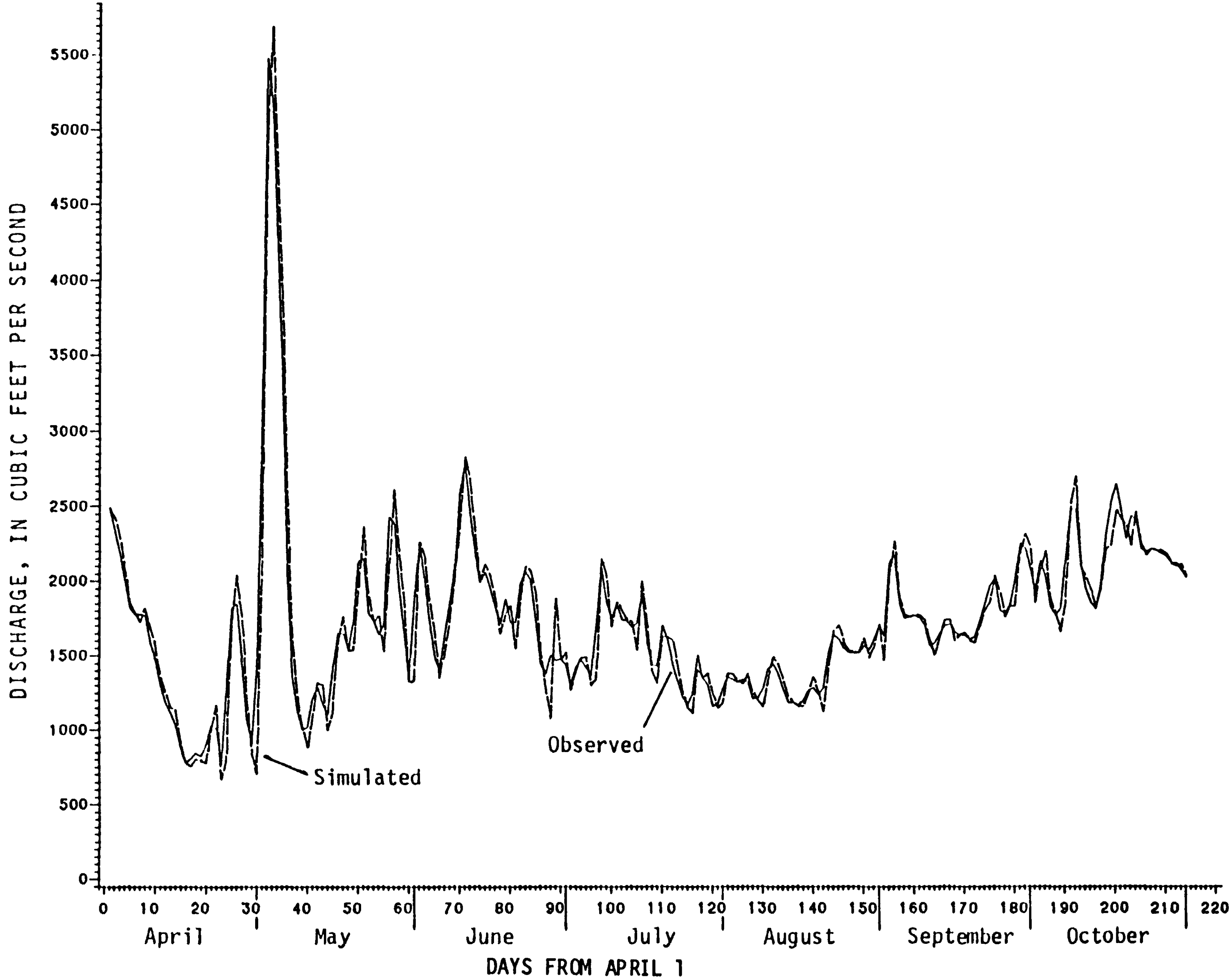

FIGURE 3.--Mean daily observed and simulated discharges of the Yakima River at Mabton (11) for the period April 1 to October 31, 1981.

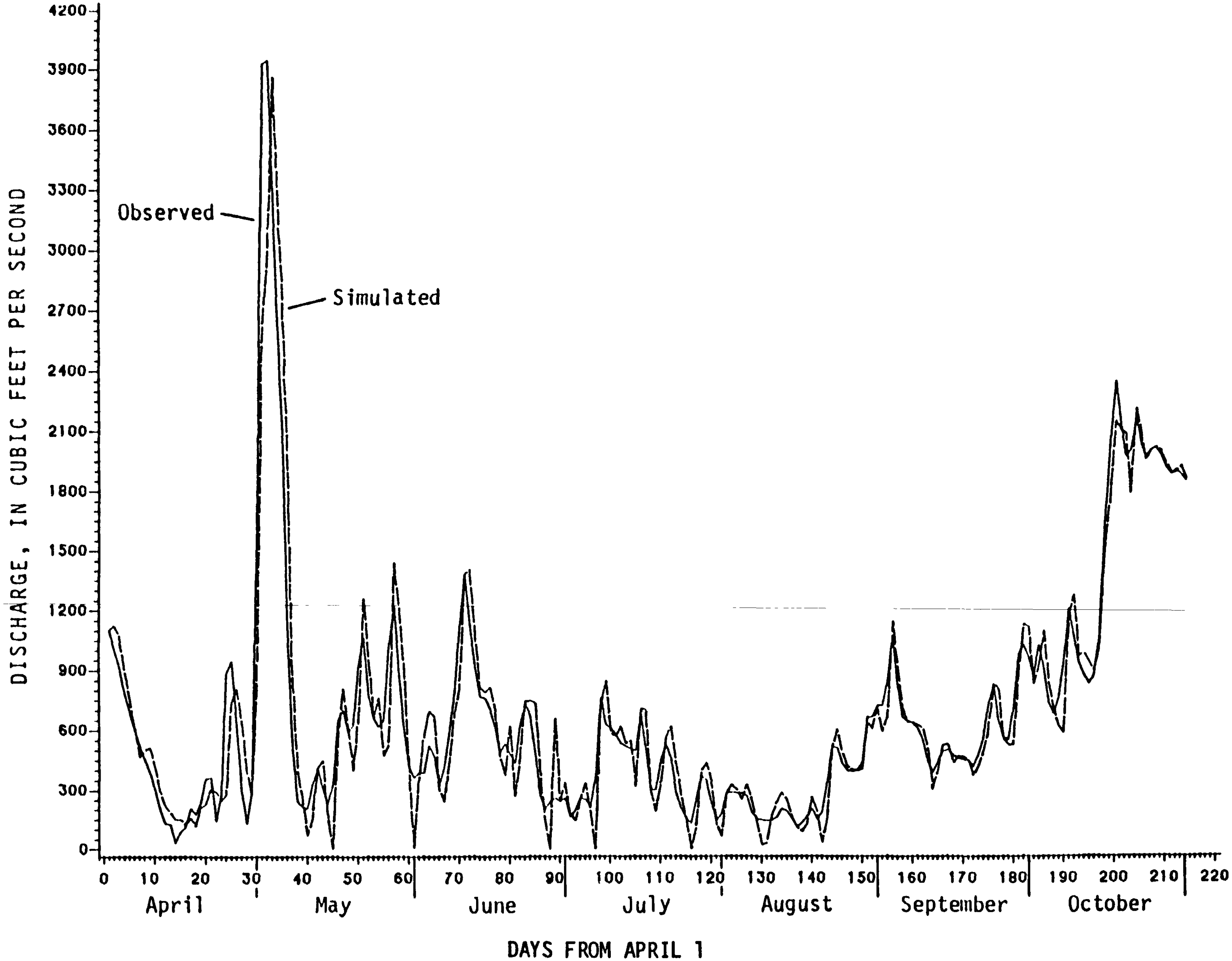

FIGURE 4.--Mean daily observed and simulated discharges of the Yakima River at Prosser (12) for the period April 1 to October 31, 1981.

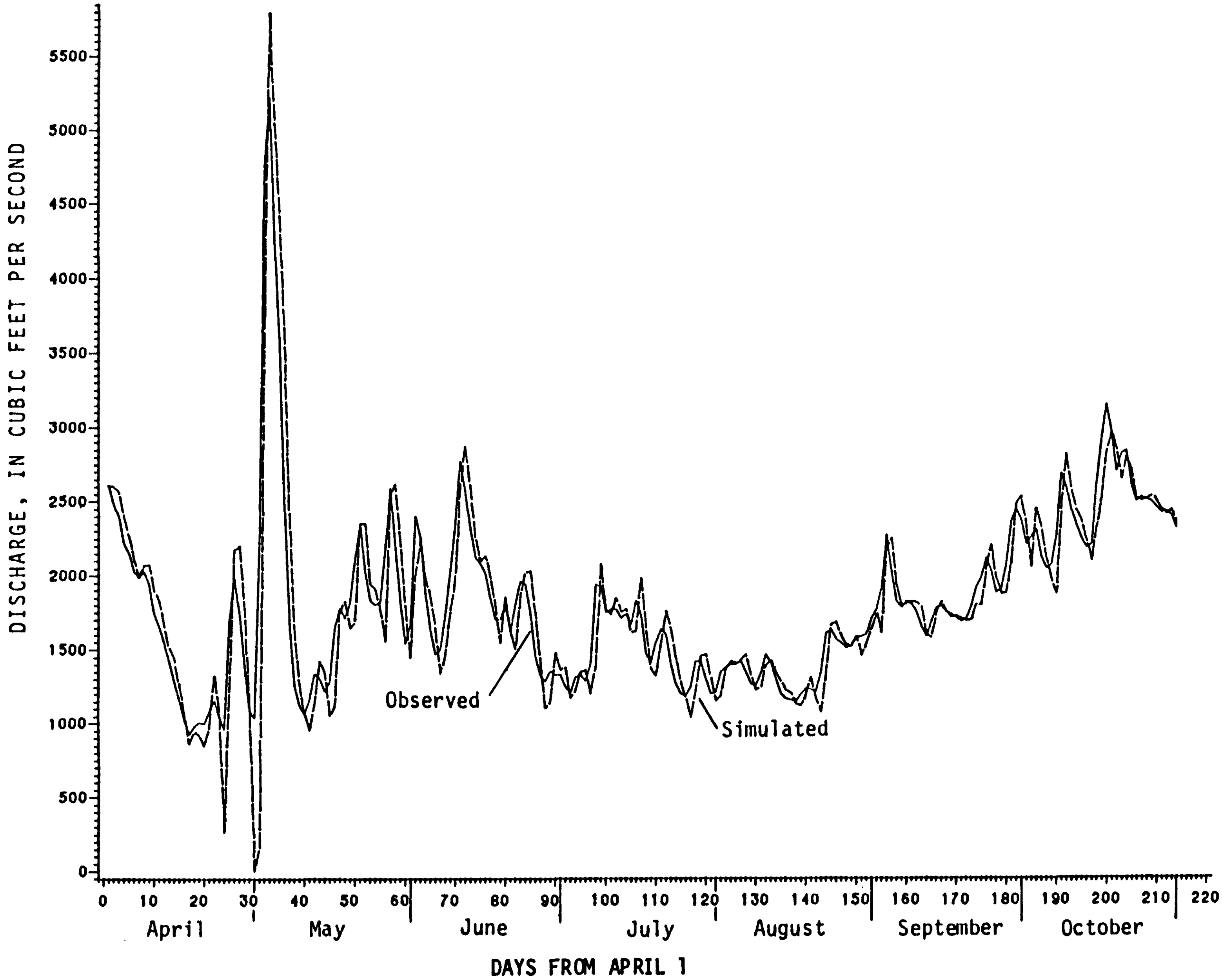

FIGURE 5.--Mean daily observed and simulated discharges of the Yakima River at Kiona (13) for the period April 1 to October 31, 1981.

SIMULATION OF STREAM TEMPERATURES

A numerical model was used in this study in order to analyze the effect of water storage, diversion, and return flows on the downstream temperatures, and to allow simulation and analysis of management alternatives that might affect the temperature of the river. Model selection was based on the size of the Yakima River basin, data-handling characteristics, and model simplicity. A Lagrangian numerical temperature model (Jobson, 1980a,b) that computes unsteady temperatures was the model selected for this study.

Lagrangian Temperature Model

In the Lagrangian temperature model, the solution to the convective- diffusion equation is based on a moving reference frame, where a parcel of water is tracked as it moves through the river system. The model simulates the effects of the variations in velocity in a flow cross section (Fisher, 1973) by longitudinal dispersion. Numerical dispersion and instabilities that are the result of simulating convection in Eulerian models do not generally occur with a Lagrangian model. In the operation of the model, a parcel of water is assigned an initial temperature at the upstream model boundary. The parcel is next advected downstream, where tributaries, diversions, return flows, and locals with their associated loads are added to or subtracted from the parcel. Concurrently, atmospheric heat exchange acts on the parcel. An Eulerian grid system is retained in the Lagrangian model to input the stream velocity, inflow and outflow, channel geometry, and meteorological parameters. As a parcel moves downstream it obtains its characteristics by considering which grid points it has passed and by interpolation to the grid points bounding the river reach in which the parcel is residing. Further, as this parcel moves through the river system its initial temperature, T_o, at time zero when it entered the system is known and all the changes in the temperature from T_o are stored and kept track of. Thus, on any day one can determine the number of parcels in the river system, the initial temperature of each, the temperature changes due to heat addition, the current temperature, and its travel time to its current location. Also, a single parcel can be tracked through the system and the same characteristics listed above can be determined for any day until the parcel leaves the system. This helps in describing, especially graphically, the physical processes effecting streamflow, both spatially and temporally.

The one-dimensional form of the convective-diffusion equation solved in the Lagrangian model is given by Jobson (1980a, p. 6) as

$$T = T_o - \int_o^t \frac{\partial \overline{u'T}}{\partial \xi} dt' + \int_o^t P\, dt', \qquad (1)$$

where T is the cross-sectional average temperature after a time change of t; T_0 is the initial temperature at time zero when a parcel first enters the system at the upstream boundary; ξ is the Lagrangian distance coordinate; $\overline{u'T}$ is the cross-sectional average value of the product of the local instantaneous velocity and temperature (the representation of longitudinal dispersion), and P is the cross-sectional average value of the addition of heat per unit time. Note that the advective term does not appear in equation 1. Representation of the dispersion and heat addition processes and the discretization of the river system are described in the next three subsections.

Dispersion

The dispersion term (Jobson, 1980a, p. 7) is written as

$$\int_0^{\Delta t} \frac{\partial \overline{u'T}}{\partial \xi}\, dt = \frac{DQQ_{k-1}\, AU\, \Delta t\, (T_{k-1} - T_k) + DQQ_k\, AU\, \Delta t\, (T_{k-1} - T_k)}{\forall_k} \quad (2)$$

where A is the unsteady cross-sectional area of the river, U is the unsteady reach-averaged velocity, Δt is the model time step, $\forall$ is the parcel volume, T is as defined earlier, the subscript k represents parcel k, and DQQ represents the flow rate of water between parcels divided by the discharge (represented by the product of A and U). A detailed description of the dispersion term and its representation of the physical process can be found in Jobson (1980a, 1980b) and Fischer (1969).

Heat Addition

The heat addition term approximates point sources, such as a tributary inflow, and a distributed source representing the rate of exchange of energy at the water surface. The point sources are model inputs defined at grid points, as discussed previously in the "Hydraulic, Meteorological, and Temperature Data" section. The surface-exchange portion of the heat addition term is approximated by a net surface-exchange expression

$$P_{SE} = k(T-T_A) \quad (3)$$

where k is the kinematic surface-exchange coefficient and T_A is the air temperature.

Approximating the surface exchange by the above expression is a parameterization method utilized in determining the rate of exchange of some transportable quantity. This method is generally used in modeling studies (Pond, 1975) that require easily identifiable, measurable, and reproducible parameters. The formulation and implementation of the above surface-exchange expression can be found in Jobson (1980a) and Edinger and Geyer (1965).

The value of K in equation 3 is evaluated with the expression (Jobson, 1980a, p. 35),

$$K = 4\varepsilon\sigma \quad (T+273.16)^3 + \rho LW \left[\frac{\partial e_o}{\partial T} + \gamma\right] \tag{4}$$

where ε is the emissivity of water (0.97 dimensionless, σ is the Stefan-Boltzmann constant 1.171×10^{-7} (cal/cm^{2}day(K)^4), 273.16 converts to the Kelvin temperature scale when T is in Celsius, ρ is the density of water (1 g/cm^3), L is the latent heat of vaporization (595.9-.545T cal/g), W is the empirical wind function, e_o is the saturation vapor pressure of air at a temperature equal to that of the water surface (kilopascals), and γ is the psychrometric constant (0.06 KPa/^{o}C). The slope expression $\frac{\partial e_o}{\partial T}$ is represented by (Jobson, 1980a, p. 35)

$$\frac{\partial e_o}{\partial T} = 1.1532 \times 10^{11} \text{ exponent } [-4271.1/(T+242.63)] \ /(T+242.63) \tag{5}$$

Equation 4 is based on the equilibrium temperature approach and needs only two meteorological parameters for its solution, air temperature and wind speed. The expression for the surface-exchange coefficient has only one unknown variable, the wind function. The wind function incorporates the wind speed and is defined as

$$W = a - NV \tag{6}$$

where a is a constant, N is a heat transfer coefficient, and V is the wind speed, in meters per second (m/s). The values of a and N are the only variables that can be adjusted during the temperature model calibration. Values as presented by Jobson (1980a) of a = 0.302 cm/d kPa and N = 0.113 cm/d (m/s) kPa were generally used in the temperature model for lack of information.

The heat addition due to tributary inflow is approximated by the following relationship,

$$DEL = (TRIBT_i*TRIBV_i + T_k*\mathcal{V}_k)/(\mathcal{V}_k + TRIBV_i)-T_k \tag{7}$$

where TRIBT is the temperature of the ith tributary, TRIBV is the inflow volume of the ith tributary over the model time step, DEL is the temperature change due to tributary inflow, and $\mathcal{V}_k$ and T_k are as previously defined.

Discretization

To facilitate modeling and data handling, the Yakima River basin was subdivided into four subbasins: Tieton, Naches, upper Yakima, and lower Yakima. Each subbasin was then modeled separately. The Tieton subbasin was discretized by use of 7 grid points, the Naches by 21 grid points, the upper Yakima by 32 grids, and the lower Yakima by 24 grid points (fig. 1; appendix F). The required input data were obtained at each grid point in the manner previously discussed in the data section. Also, as previously discussed, several of the sources were aggregated at grid points.

In this method, the Naches subbasin model requires input from the Tieton subbasin, the upper Yakima subbasin model requires the Naches subbasin model output as part of its input, and the lower Yakima subbasin model requires the upper-basin model output.

Calibration

Calibration of a model is the adjustment of model parameters, within a physically reasonable range, until an acceptable match between observed and simulated values is obtained. Observed values were chosen for calibration from a representative period, April through June 1981, because: 1) day-to-day reservoir outflow temperatures were relatively constant, yet there was a net rise in these water temperatures of 8°C over the period; 2) air temperatures during the period included both the lowest for the 1981 irrigation season and also some high temperatures (about a 16°C range); 3) diversions included both the lowest and highest of the irrigation season; 4) return flows were established by the end of the period; 5) there was a large variation in the outflow volumes from the five reservoirs; and 6) the period did not include the low-flow months, which are used in verifying the model.

The temperature model has only two parameters—the parameters in the wind function, equation 4. Sensitivity analysis showed that these parameters were relatively insensitive (less than 0.8°C mean change in stream temperatures) to 80 percent changes in the parameters. Thus, because of the lack of information about both parameter values and meteorological data and their sensitivities, the values presented in Jobson (1980a) were chosen for most of the model of stream reaches. The only exceptions were for the first seven grid points of the upper basin model, where the values were decreased by 75 percent. The decrease was found to improve the model fit. The change is physically realistic because the upper reach of the river is narrow and heavily forested on both banks and is consequently much more shaded than the lower parts.

The lack of parameters in the temperature model allows the calibration process to be a test of the conceptual and numerical representation of the physical processes and variables. These variables include water velocity, air temperature, tributary temperatures, and cross-sectional area. During the calibration certain tests were performed. A 4-day moving average (4-DY) model was tested against a harmonic-analysis model and was found to be best for estimating the temperature of small streams. The temperature of the locals consisting principally of ground water was also tested. First, average annual or irrigation season average air temperatures at the local sites were used. Next, these values were adjusted upwards and downwards by 2.2°C, which represented a change ranging from 13 to 19 percent. The effects on the simulated temperatures at selected sites were small, generally less than 0.3°C; thus, the original temperatures were used and are given in Appendix F.

Width and velocity relationships were also studied during calibration. The regression relationships established are not exact, as can be expected. A 20-percent error in widths was compatible with the discharge-width prediction equations, and a 10-percent error in velocity was felt to be physically reasonable. Adjustment of the widths and velocities by the potential error affected the results by only about 0.1 to 0.5°C; therefore, original estimates were used. The reasons for the small variations in simulated temperatures is the dominance of external factors and the quantity of water in the river.

Verification

Verification statistics for eight river sites are given in table 3. The statistics are presented for the complete irrigation season rather than just the July-October period because 1) no change in parameters occurred, and 2) the determination of small tributary and local inflow temperature values can be considered a dual verification. In addition, even though the calibration and verification results were of the same order, the predictions in the early part of the irrigation season were not as good as in the later part. Thus, the error estimate is a conservative one.

The verification results from the upper basin models indicated to the author that the lower basin model need not be calibrated, but only verified. Thus, the lower basin model was verified for the 1981 irrigation season under the following two conditions: constant temperatures (ground-water source) for the locals, and 4-day moving average for the locals. Also, temperatures of three small inflows—for Frazer Road drain, Corrall Canyon Creek (drain), and the aggregated Snipes, Bull, and Spring Creeks inflows--were based on the 4-DY method prior to model operation. These inflow temperatures, excluding the locals, were the only ones not based on a thermograph record. The results of these two simulations were nearly the same due to the size ofthe locals and the dominance of air temperature in the energy budget; that is, the locals have little effect on simulated temperatures. The results for the verification simulation with the constant-temperature locals are presented in table 3 because the constant-temperature locals more accurately represent a local consisting mainly of ground water. Actual local temperatures will

TABLE 3.--Verification results of simulating observed mean daily temperature for the 1981 irrigation season

[Values in degrees Celsius; number in parenthesis refers to map sequence identifiers shown in figure 1]

Site	Error[1]			
	Mean	Standard deviation	Minimum	Maximum
Naches River near Naches (19)	-0.27	1.5	-9.0	3.9
Yakima River:				
at Cle Elum (5)	-.37	1.39	-6.3	2.6
at Ellensburg (6)	1.5	1.13	-2.7	4.1
at Umtanum (7)	.81	1.08	-2.2	3.9
at Union Gap (8)	1.12	1.04	-2.3	3.0
near Parker (9)	.82	1.73	-4.5	4.8
at Mabton[2] (11)	.54	1.06	-3.0	3.8
at Mabton[3] (11)	.47	1.07	-2.4	3.3
at Kiona[2] (13)	.38	1.10	-2.4	3.8
at Kiona[3] (13)	.37	1.10	-2.5	3.8

[1]Values computed for the 1981 irrigation season from the daily residual, which is defined as the observed minus simulated mean daily water temperature.

[2]Values computed from model simulation that used the simulated daily streamflow temperatures for the Yakima River near Parker for the upstream boundary condition.

[3]Values computed from model simulation that used the observed daily streamflow temperatures for the Yakima River at Parker for the upstream boundary condition.

vary at times because the locals at times do consist of surface runoff. The lower basin temperature model was operated with both the observed and simulated daily temperature values for the Yakima River near Parker as the upstream boundary condition. The results of the simulation using the observed water temperature record near Parker are also shown in table 3. They show that the error that propagates downstream in the upper basin has little influence in the lower basin.

Errors can be assessed for specific locations or for the entire basin. The latter can be calculated as the root-mean-square of all the errors at specific locations. The application of this method to the data for table 3 yields an estimated mean daily error of 1.7°C. Note that when comparing mean monthly observed and simulated values, the differences are much smaller. Error assessment is also discussed in conjunction with simulation results in the "Simulations" section.

Observed and simulated mean daily water temperatures for several locations on the main stem of the Yakima River are shown in figures 6 through 11. Also, listed in Appendix F are the aggregated inflow and outflow points used in the model and the type of temperature record used for the inflows.

Errors in the modeling of streamflow temperatures in the Yakima basin can be attributed to the following six sources: 1) inaccuracies in the input air temperatures; 2) inaccuracies in inflow and outflow discharge data and temperatures (including locals); 3) approximations in the equations for computing surface heat transfer at the air-water interface; 4) assuming that air temperature can approximate equilibrium temperature; 5) estimating depths and widths; and 6) excluding some physical processes—for example, bank shading, heat storage in impoundments, and streambed heat conduction. Also, the larger-than-observed day-to-day variation in simulated temperatures is due to a combination of the above sources. Considering the above sources of error, the model is still able to predict temperatures adequately and responds correctly to the parameters, variables, boundary conditions, and heat loads. In general, simulated daily values fall within the recorded diurnal range at thermograph sites. Therefore, when comparing the changes in statistics of the computed daily values for the different scenarios, the differences are realistic and give a better guide than an actual predicted value. Thus, the predicted regulated temperature values are used for comparisons and changes in temperature are discussed in relation to the effects of the scenarios and not so much the actual predicted value.

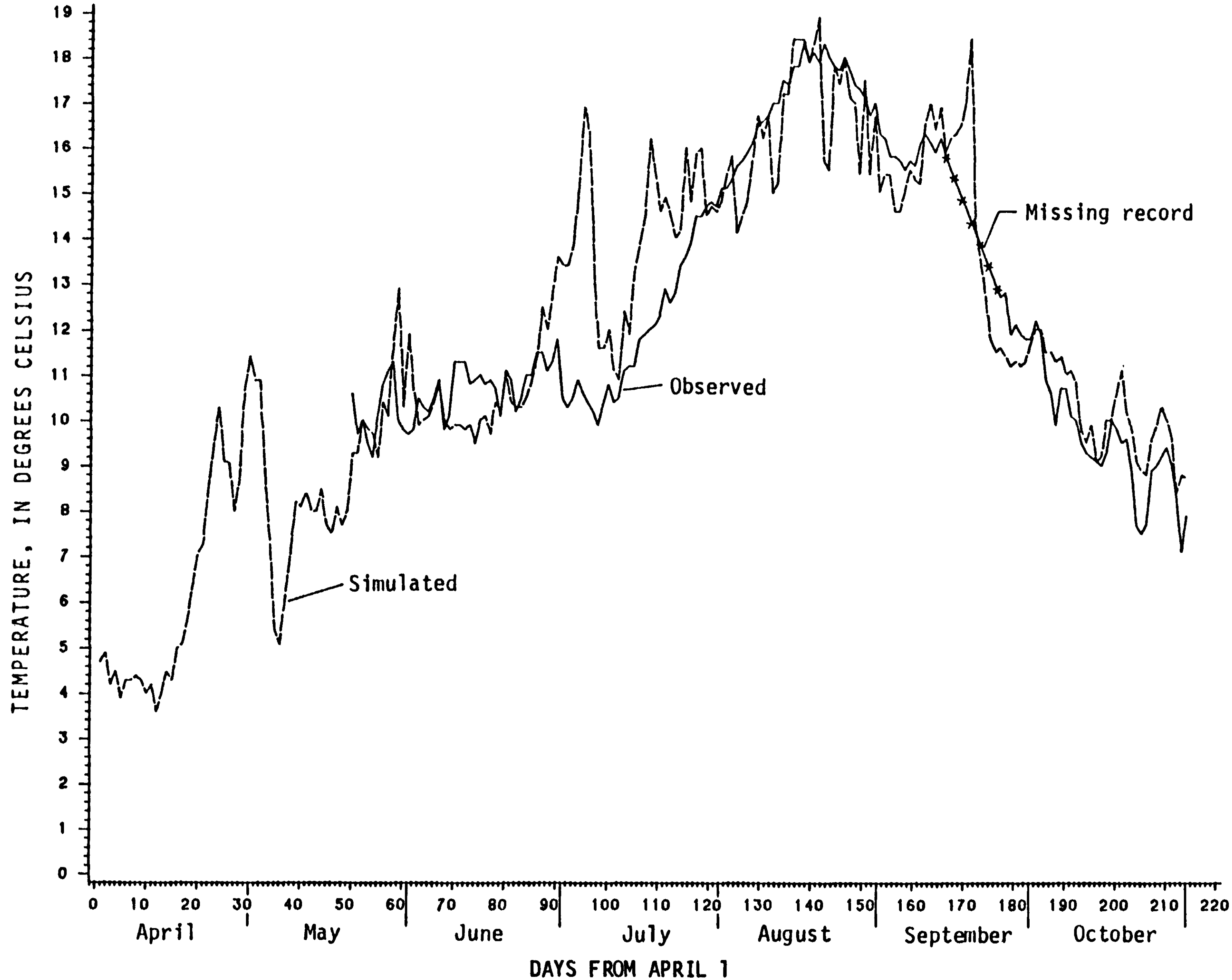

FIGURE 6.--Mean daily observed and simulated temperatures of the Yakima River at Cle Elum (5) for the period April 1 to October 31, 1981.

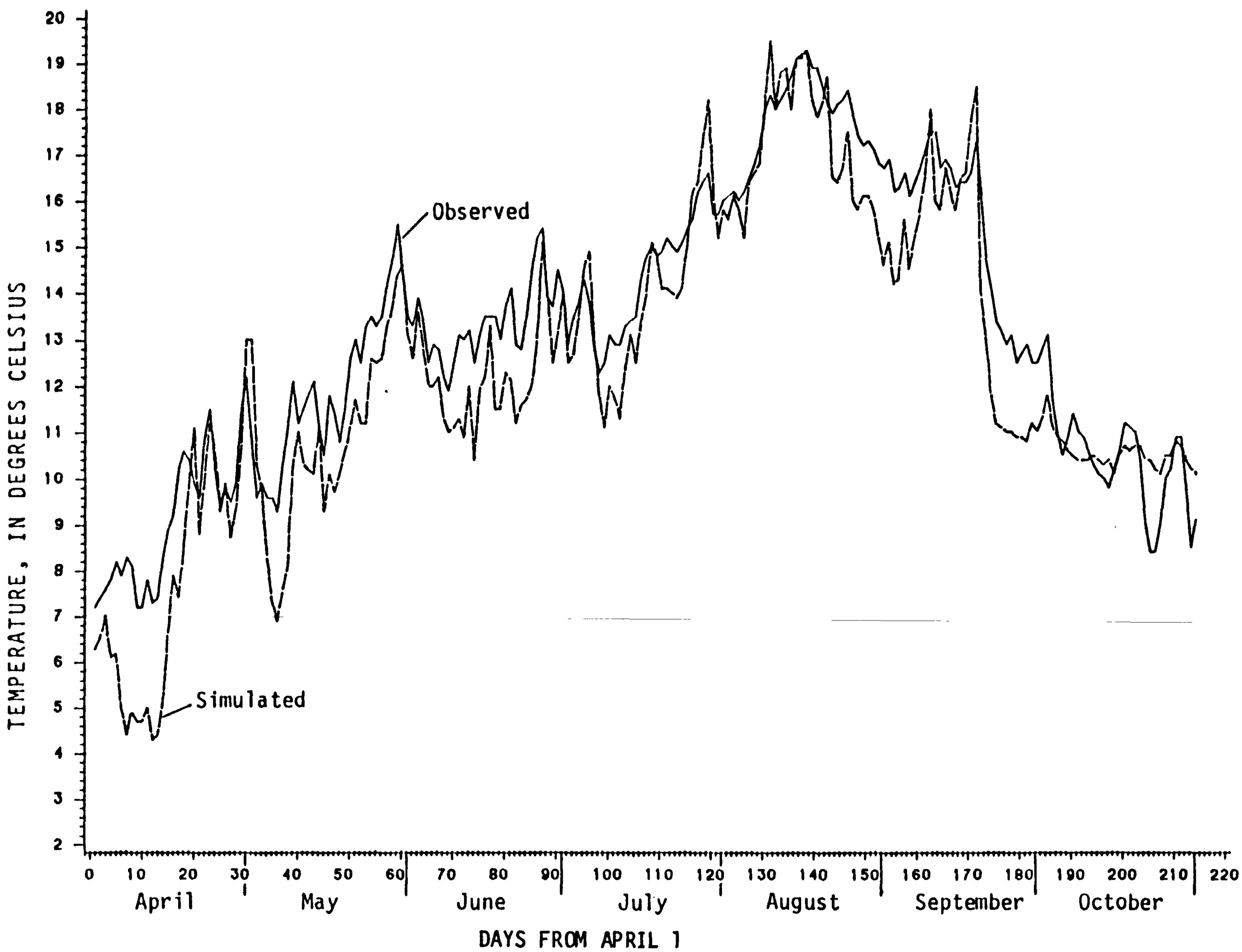

FIGURE 7--Mean daily observed and simulated temperatures of the Yakima River at Umtanum (7) for the period April 1 to October 31, 1981.

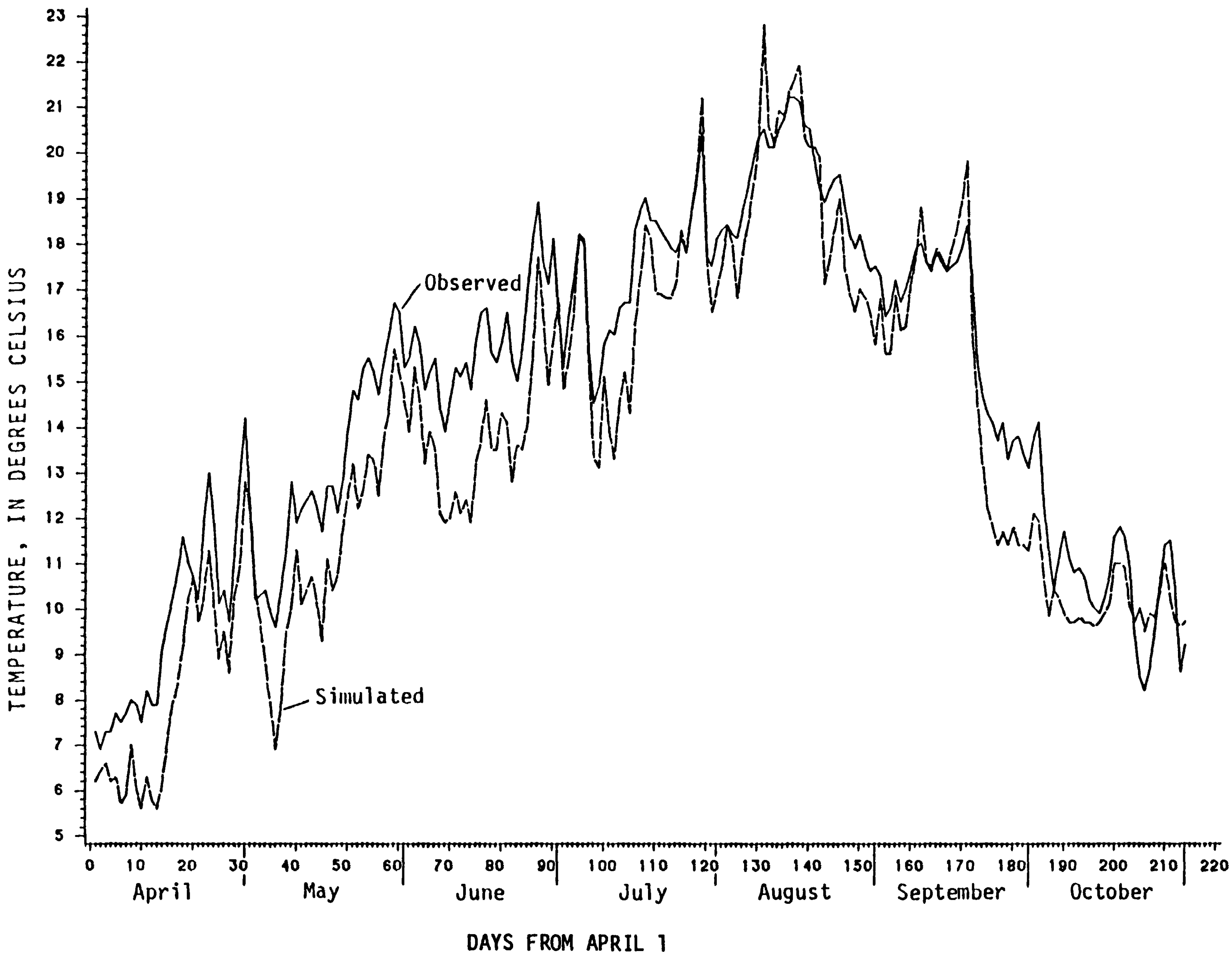

FIGURE 8.--Mean daily observed and simulated temperatures of the Yakima River at Union Gap (8) for the period April 1 to October 31, 1981.

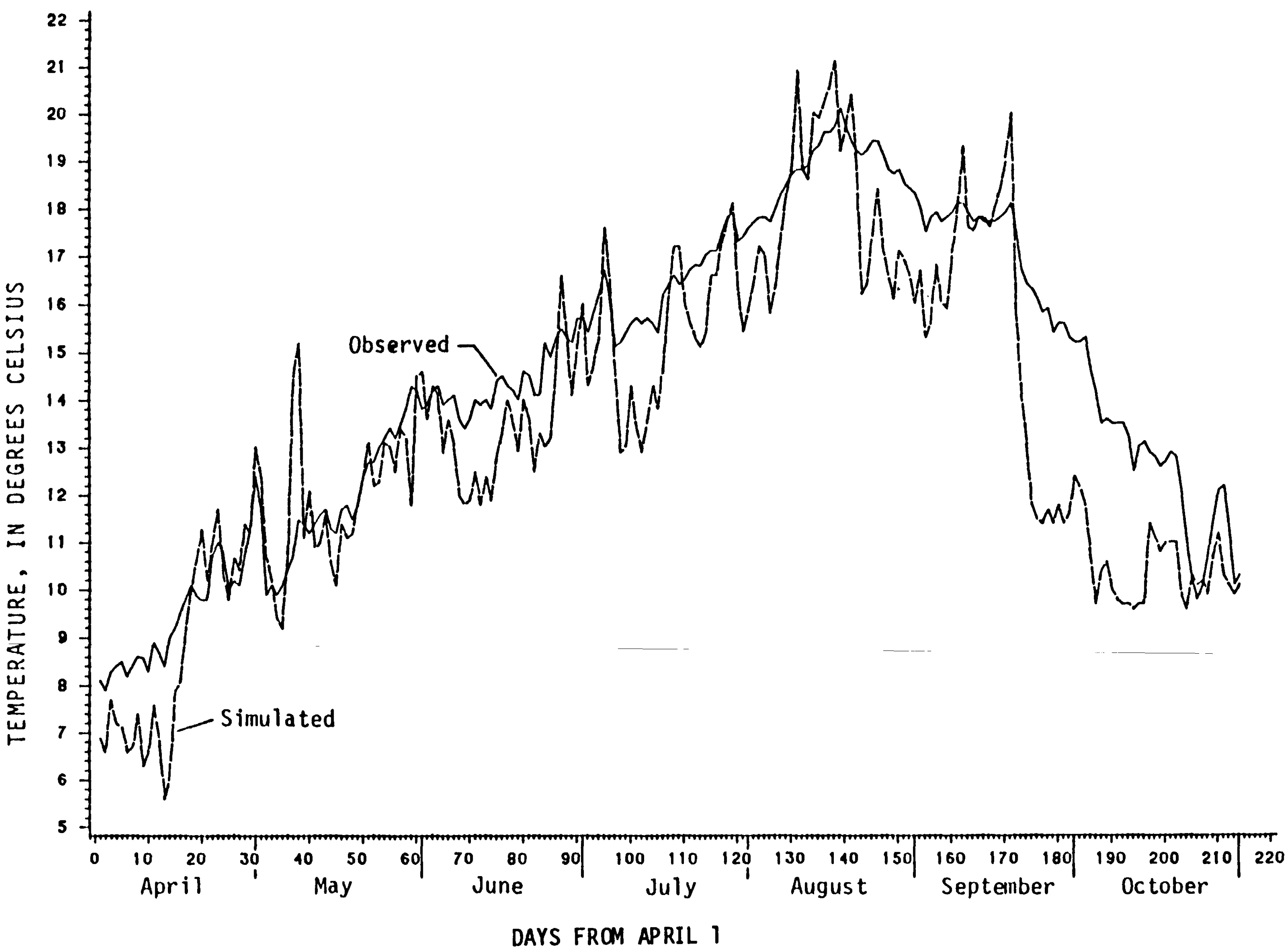

FIGURE 9.--Mean daily observed and simulated temperatures of the Yakima River near Parker (9) for the period April 1 to October 31, 1981.

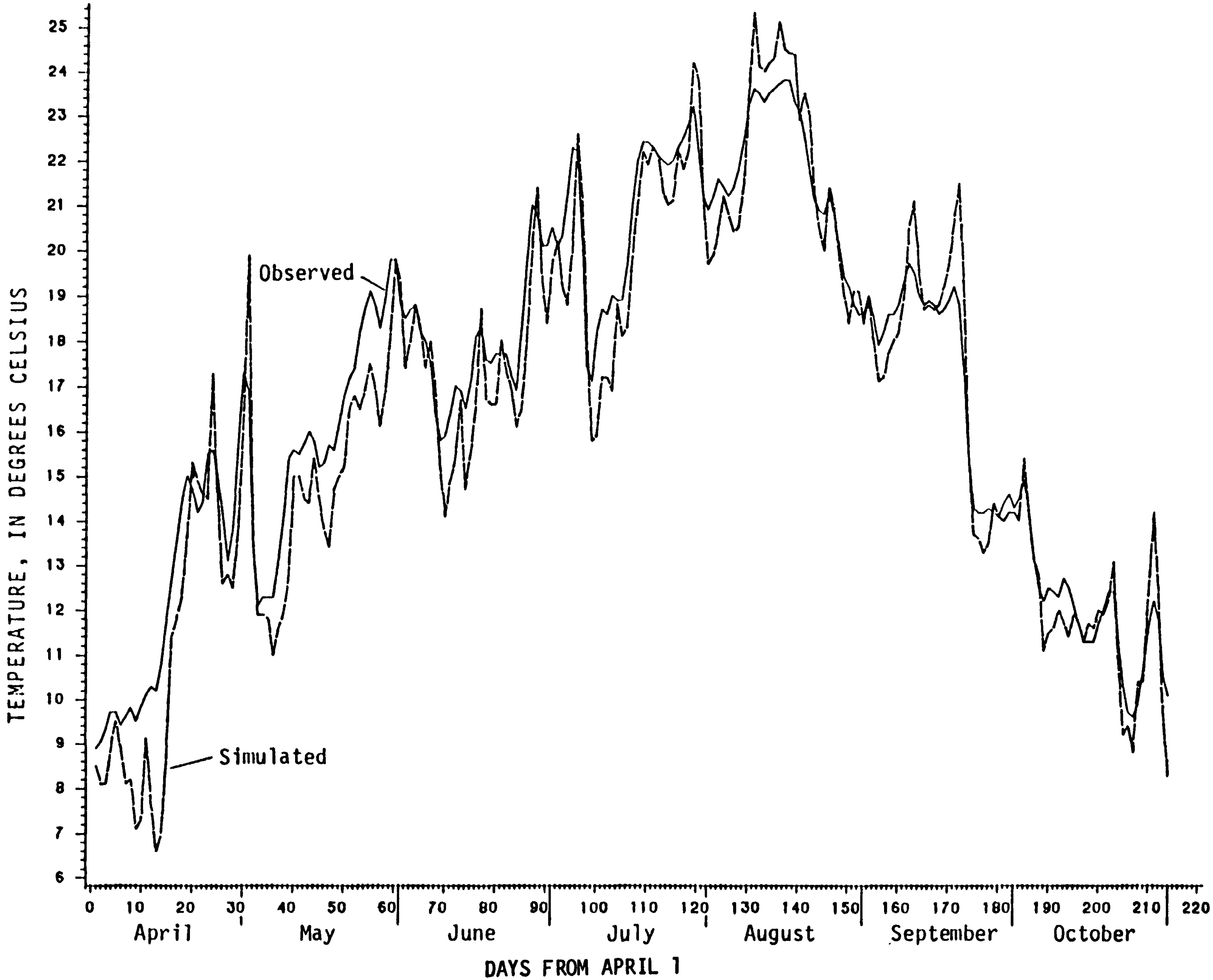

FIGURE 10.--Mean daily observed and simulated temperatures of the Yakima River at Mabton (11) for the period April 1 to October 31, 1981.

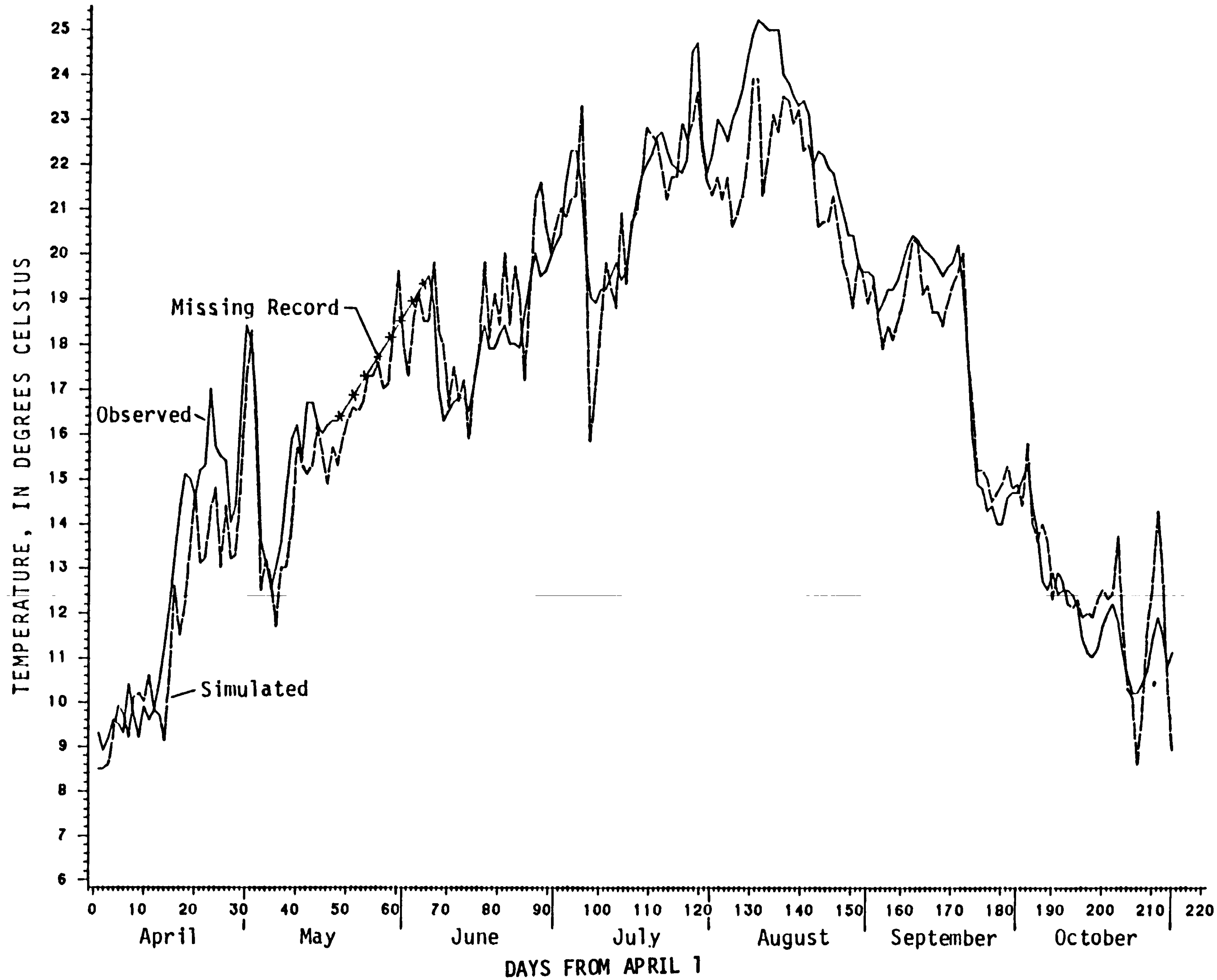

FIGURE 11.--Mean daily observed and simulated temperatures of the Yakima River at Kiona (13) for the period April 1 to October 31, 1981.

Sensitivity Analysis

Model sensitivity was studied by making a change in a variable or parameter value and observing the effects on the simulated temperatures. A sensititivity analysis can 1) determine data collection needs and accuracy, 2) determine important components of the system, 3) help to define the transference of errors through the system, and 4) define the importance of the variables and parameters and model acceptability. A sensitivity analysis of the variables and parameters was previously completed for the streamflow- routing model and is discussed in Vaccaro (1982). A similar sensitivity analysis was performed for the variables and parameters of the streamflow temperature model as part of this study and is a simplified example of what can be an in-depth analysis.

Analysis focused on four variables/parameters that basically determine the temperatures in the river system: air temperature, wind speed, coefficients in the heat-transfer equation (eqn. 6), and upstream boundary conditions (reservoir outflow temperatures). The other variables that enter into the temperature simulation (stream discharge, velocity, width and cross-sectional area, and tributary temperatures) were analyzed for sensitivity in the calibration process. The sensitivity analysis was used to 1) check the conceptual model, 2) determine relative sensitivities to meteorological inputs, and 3) estimate the effects of reservoir storage (because reservoir storage is a component of the system, and sensitivity of outflow temperatures on downstream temperatures can be analyzed). The last aspect essentially analyzes the effects of reservior storage, with the 1981 irrigation season operating rules, on streamflow temperatures.

The effects of a change in a parameter or variable are shown in tables 4 and 5. The results for the Yakima River are presented in a downstream order, to enable estimation of the downstream importance of the variable on river temperature.

Air temperature is the most important variable, and its importance increases as a parcel moves downstream. This is physically reasonable and complements the conceptual model of the system. Therefore, accurate air temperatures along the river are a necessity, and it is important that small-scale spatial variability as well as regional trends in air temperature be accounted for. The change in temperature ($\pm 4^{o}C$) used in the sensitivity analysis is equal to the estimated maximum error in interpolated air values. Considering the mean daily model error of $1.7^{o}C$ and comparing it with the mean sensitivity of $1.6^{o}C$ for air temperature (given in table 4) further supports the conclusion in the previous section that inaccuracies in interpolated air temperatures for model grid points could be a primary source of model error.

Simulated temperatures are relatively insensitive to wind speed. A change in wind speed of 1 meter per second (table 4) corresponds to a 20- to 70-percent change in that variable. The wind function and wind speed sensitivities in table 4 indicate that the accuracy of wind speed for the Yakima River basin model need be only about ± 50 percent.

The operation of the reservoirs most likely affects downstream temperatures by affecting the discharge rate rather than the outflow temperatures. This can be seen by examining the sensitivity of water temperatures to reservoir and air temperatures presented in tables 4 and 5.

TABLE 4.--Sensitivity of computed streamflow temperatures at selected river locations for a predetermined variable change for the 1981 irrigation season

[Values in degrees Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Variable[1]	Statistic[2]	Tieton River at mouth	Naches River at mouth (20)	Yakima River: at Easton (3)	at Cle Elum (5)	at Ellensburg (6)	at Umtanum (7)	at mouth Naches R	at Union Gap (8)	at Prosser (12)	at Kiona (13)
Air temperature (+4°C)	Mean	1.67	1.28	0.50	1.49	1.50	1.46	2.02	1.66	2.34	1.7
	SD	.81	.33	.49	.66	.54	.36	.44	.30	.70	.52
	Max	3.7	2.4	3.0	3.3	3.0	2.5	3.5	2.5	3.9	3.5
	Min	.5	.6	.0	.2	.7	.8	.9	.8	.1	.4
Wind speed (+1 meters per second)	Mean	.08	.09	.02	.05	.08	.10	.16	.14	.02	.00
	SD	.21	.13	.07	.10	.14	.14	.19	.16	.13	.09
	Max	.9	.5	.2	.5	.4	.4	.6	.6	.4	.3
	Min	-.5	-.3	-.3	-.2	-.3	-.3	-.3	-.2	-.3	-.2
a,N[3] (increased by 80 percent)	Mean	.31	.39	.05	.18	.35	.46	.68	.57	.06	.01
	SD	.74	.46	.26	.33	.56	.57	.71	.60	.47	.29
	Max	3.3	2.0	.8	1.3	1.8	2.0	2.5	2.4	1.7	1.0
	Min	-1.5	-.8	-.8	-.7	-1.0	-.8	-.8	-.6	-1.2	-.7

[1] This column defines the variable that was changed and by how much it was changed for the sensitivity analysis.

[2] Mean is the average difference for the 1981 irrigation season between the simulated and the simulated observed with the variable changed; SD is the standard deviation of the differences; max is the maximum or largest difference between the two simulations over the 1981 irrigation season; and min is the minimum or smallest difference between the two simulations.

[3] a is a constant, and N is the heat-transfer coefficient in the wind-function equation $W = a - NV$ (see p. 20 of text).

TABLE 5.--Sensitivity of computed streamflow temperatures at selected river locations for a predetermined change in reservoir outflow temperatures for the 1981 irrigation season

[Values in degrees Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Variable[1]	Statistic[2]	Naches River at mouth	Tieton River at mouth (20)	Yakima River: at Easton (3)	at Cle Elum (5)	at Ellensburg (6)	at Umtanum (7)	at mouth Naches R	at Union Gap (8)	at Prosser (12)	at Kiona (13)
Bumping Lake (+4°C)	Mean	0.46									
	SD	.56									
	Max	2.1									
	Min	.0									
Rimrock Reservoir (+4°C)	Mean		2.03					0.12	0.22	0.00	0.00
	SD		.96					.18	.32	.32	.02
	Max		3.5					1.2	1.4	.1	.1
	Min		.0					.0	.0	.0	.0
Lake Keechelus (+4°C)	Mean			1.44	0.22	0.06	0.04				
	SD			.72	.32	.09	.07				
	Max			3.0	1.5	.4	.3				
	Min			.0	.0	.0	.0				
Lake Cle Elum (+4°C)	Mean				1.53	1.46	.96	.57	.35	.01	.00
	SD				1.04	.95	.78	.55	.38	.02	.02
	Max				3.7	3.0	2.4	1.8	1.2	.1	.1
	Min				.0	.0	.0	.0	.0	.0	.0
Lake Kachess (+4°C)	Mean			1.02	.16	.05	.03	.02	.01	.00	.00
	SD			.89	.28	.10	.07	.04	.04	.01	.01
	Max			2.6	1.2	.5	.4	.2	.3	.1	.1
	Min			.0	.0	.0	.0	.0	.0	.0	.0
All reservoirs (+4°C)	Mean			1.02	1.69	1.51	1.00	.70	.58	.01	.01
	SD			.89	.99	.95	.79	.53	.38	.04	.03
	Max			2.6	3.7	3.0	2.4	1.8	1.5	.3	.2
	Min			.0	.0	.0	.0	.0	.0	.0	.0

[1]This column defines the variable that was changed and by how much it was changed for the sensitivity analysis.

[2]Mean is the average difference for the 1981 irrigation season between the simulated and the simulated observed with variable change; SD is the standard deviation of the differences; max is the maximum or largest difference between the two simulations over the 1981 irrigation season; and min is the minimum or smallest difference between the two simulations.

SIMULATIONS

The streamflow and temperature models were operated using four scenarios for the 1981 irrigation season: 1) 1981 reservoir releases but without diversions or returns; 2) no reservoir storage, no diversions, and no returns (estimate of natural conditions); 3) 1981 reservoir releases, but all diversions in the Yakima River basin reduced by an amount necessary to reduce the return flow for each diversion by 50 percent (for example, if 40 percent of some diversion is return flow, then 50 percent of that return flow was added back to the river system at the model grid diversion location, and in the case of aggregated diversions that have the same percentage of diverted water going to return flows, then 50 percent of that return flow was added back to the river at the location of the aggregated diversions); 4) 1981 reservoir releases, but the diversions of Roza Canal at 11 mile, Sunnyside Canal, New and Old Reservation Canal, Chandler Canal, and three smaller canals were each reduced by an amount necessary to reduce their return flows by 50 percent; these are the major returns below the gaging station at Yakima River near Parker. The reduction in return flows can be considered as increased irrigation efficiency. The reductions would then amount to an assumed increase in irrigation efficiency of about 22 percent. Thus, less water is diverted from the river and return flows are reduced. This results in more water being in the river system upstream of the return flow points; however, the total amount of water in the complete system is the same.

The four scenarios will hereafter be referred to, respectively, as: 1) reservoir releases only, 2) unregulated, 3) 50 percent basin, and 4) 50 percent Parker. The observed discharges and temperatures will be referred to as observed or regulated values, and the simulated values for the observed conditions during the 1981 irrigation season will be referred to as simulated regulated. These four simulations represent different degrees of deregulation in the basin. Scenario 4 represents the least deregulation and scenario 2 the most deregulation (unregulated simulation). Scenario 1 falls between 2 and 4 and represents the total effect that diversions and returns have on streamflow and streamflow temperature in the basin. Although scenario 3 falls between 1 and 4, it does not address the total effect of diversions and returns, but a possible effect of increased irrigation efficiency. The simulated temperatures for the 1981 irrigation season were used as a base for comparison.

The four scenarios were used to estimate best obtainable water temperatures at selected sites in the basin, the natural water temperature, and the water temperature at selected sites with reduced return flows. These simulations further define the effects of reservoir storage and diversions and returns on streamflow temperature.

Figures 12 through 18 show the observed and simulated discharges for the four scenarios at selected sites; figures 19 through 27 show the simulated streamflow temperatures for the same scenarios. Tables 6 through 15 present statistics on the mean daily discharge and streamflow temperature values for selected stations. Air-temperature data for three NWS meteorological stations (table 1) are typical of the upper, middle, and lower parts of the Yakima River basin and are of value in comparing air and water temperatures at these sites.

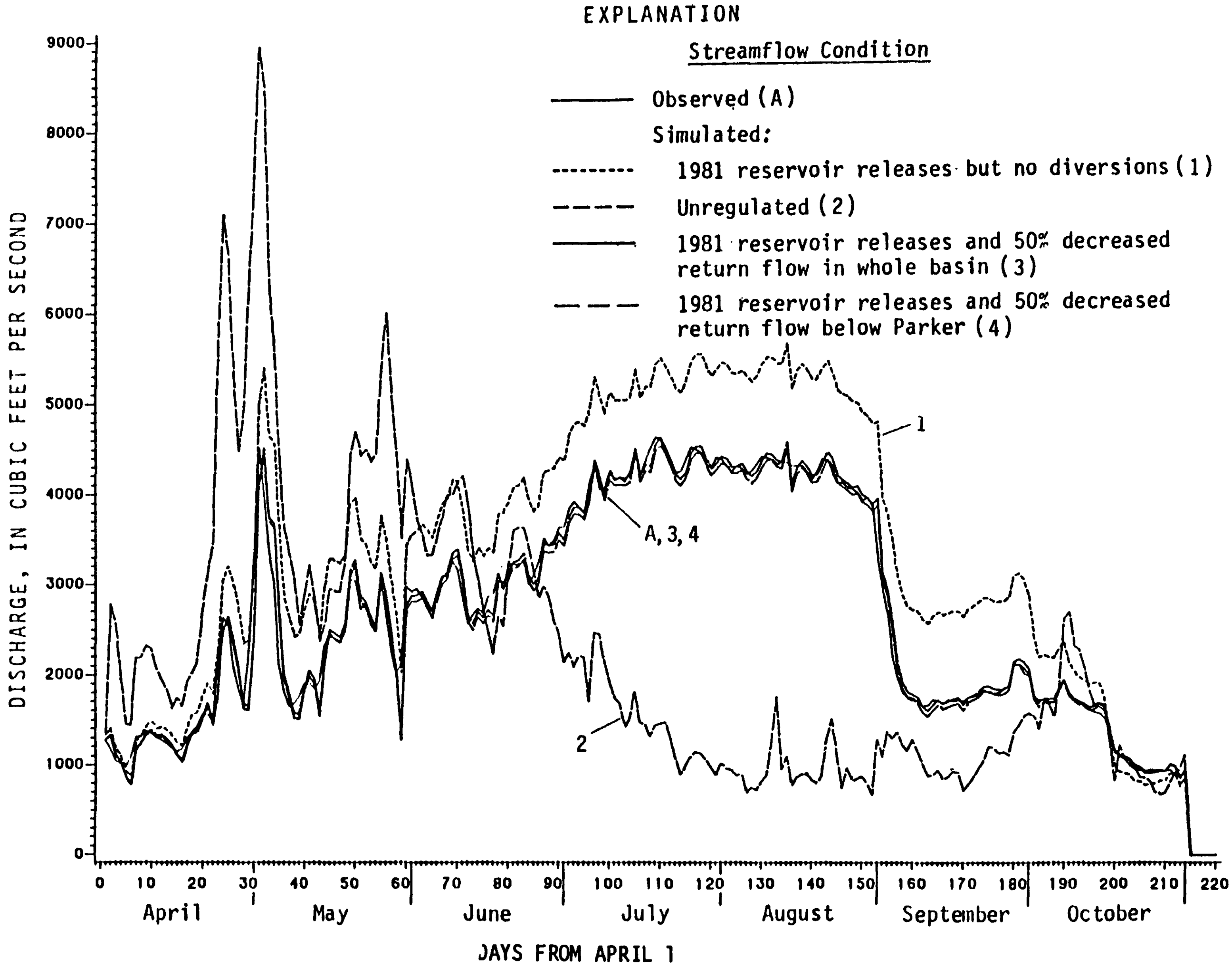

FIGURE 12.--Observed and simulated mean daily discharges of the Yakima River at Umtanum (7) for the period April 1 to October 31, 1981.

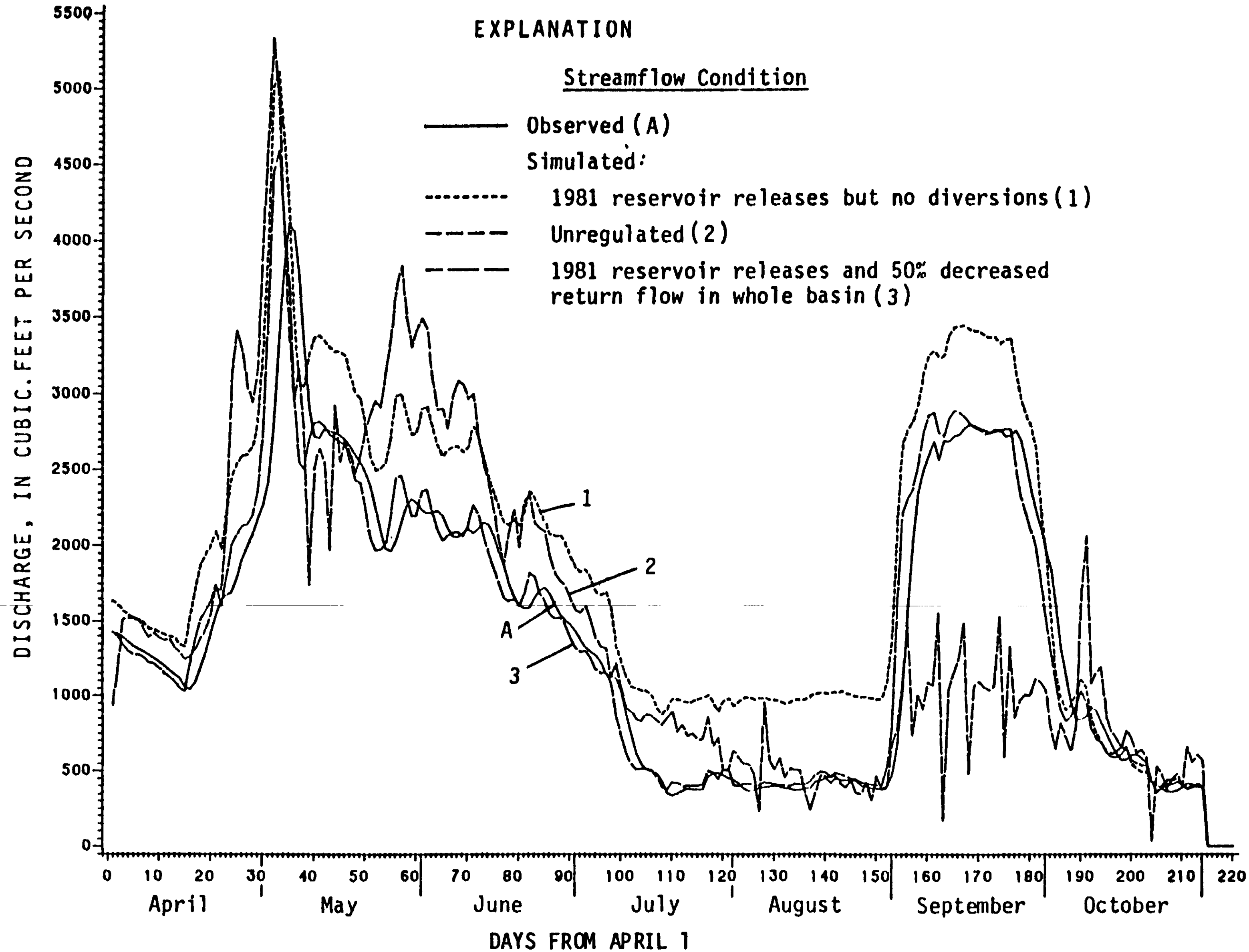

Figure 13.--Observed and simulated mean daily discharges of the Naches River at mouth near Yakima (20) for the period April 1 to October 31, 1981.

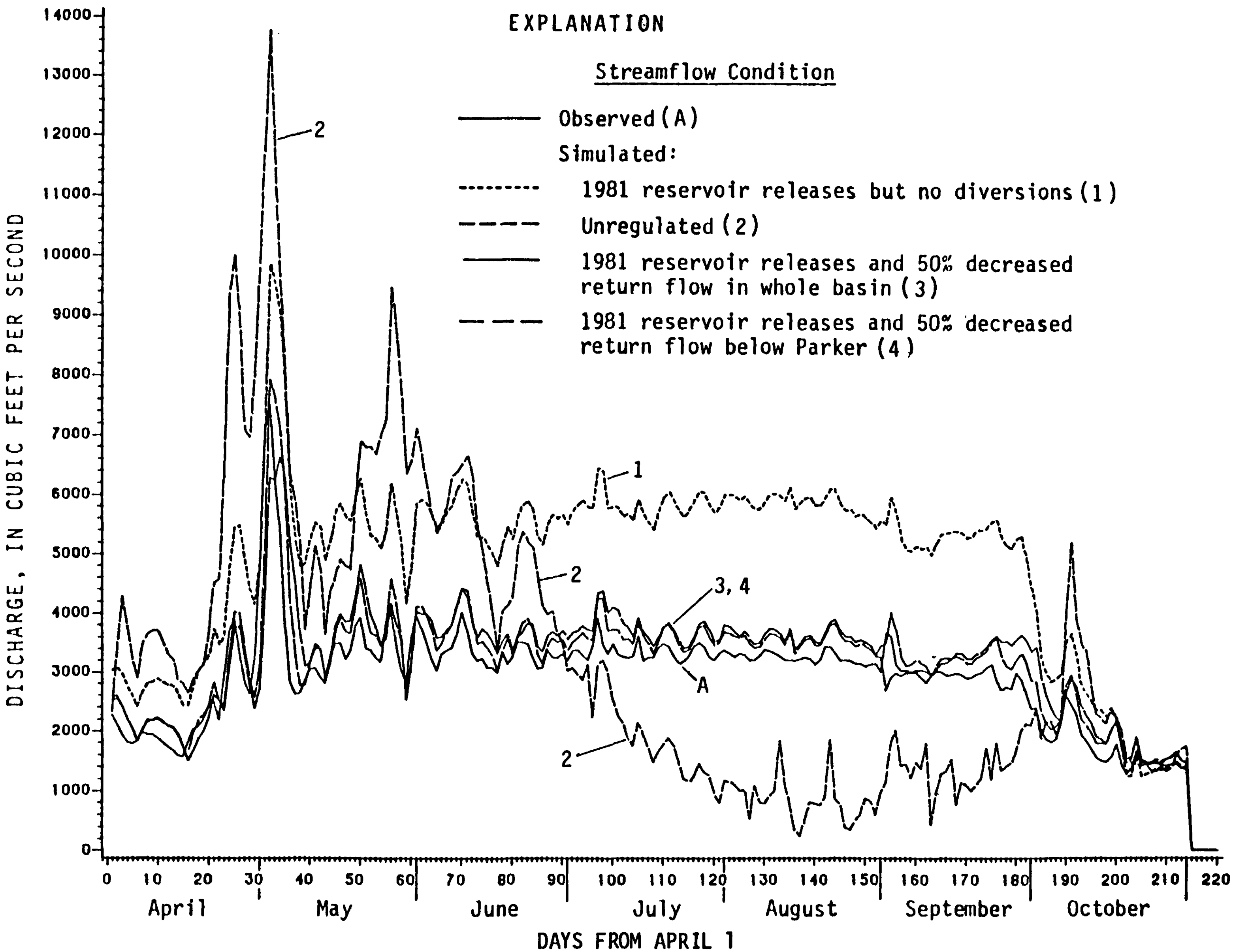

FIGURE 14.--Observed and simulated mean daily discharges of the Yakima River at Union Gap (8) for the period April 1 to October 31, 1981.

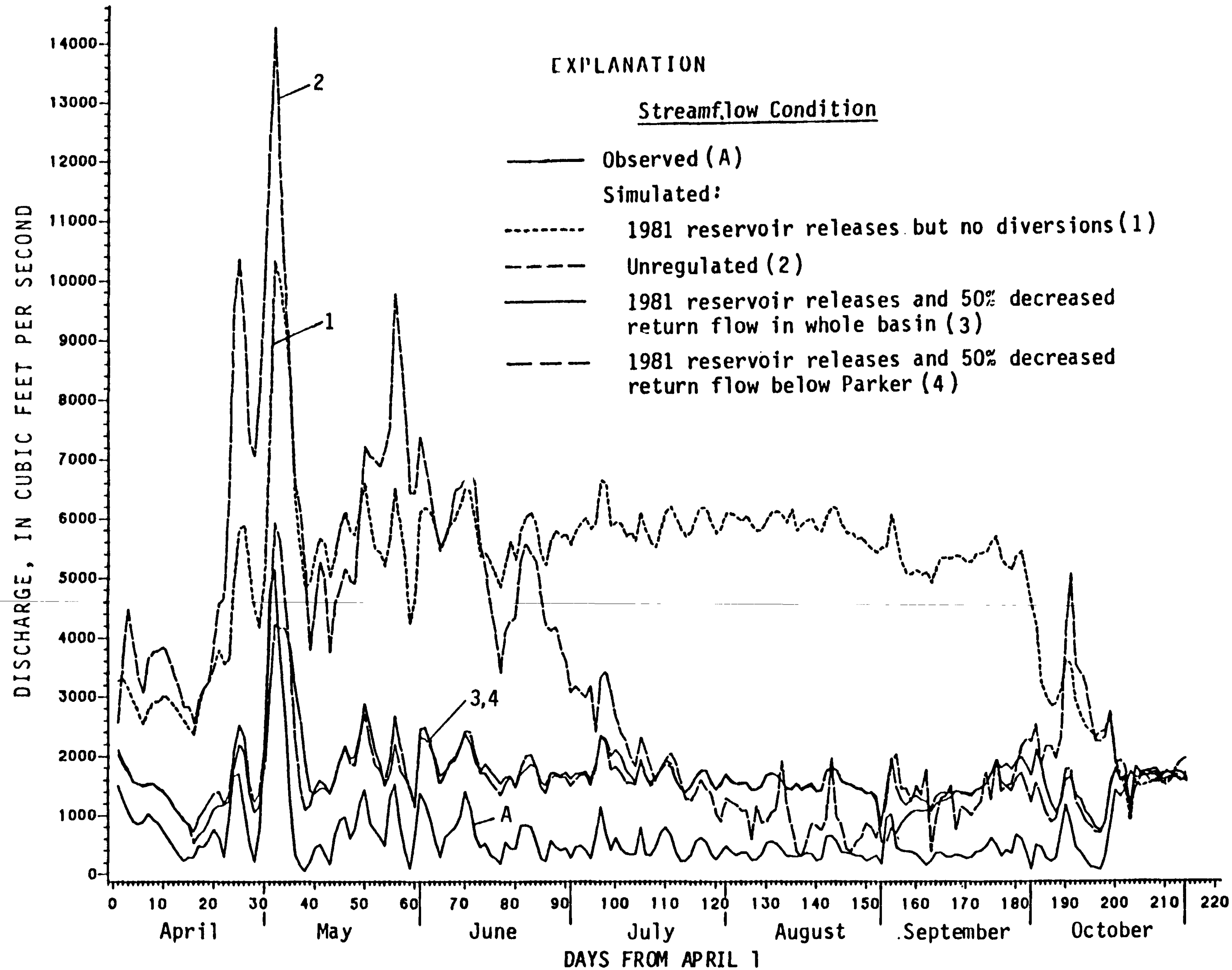

FIGURE 15.--Observed and simulated mean daily discharges of the Yakima River near Parker (9) for the period April 1 to October 31, 1981.

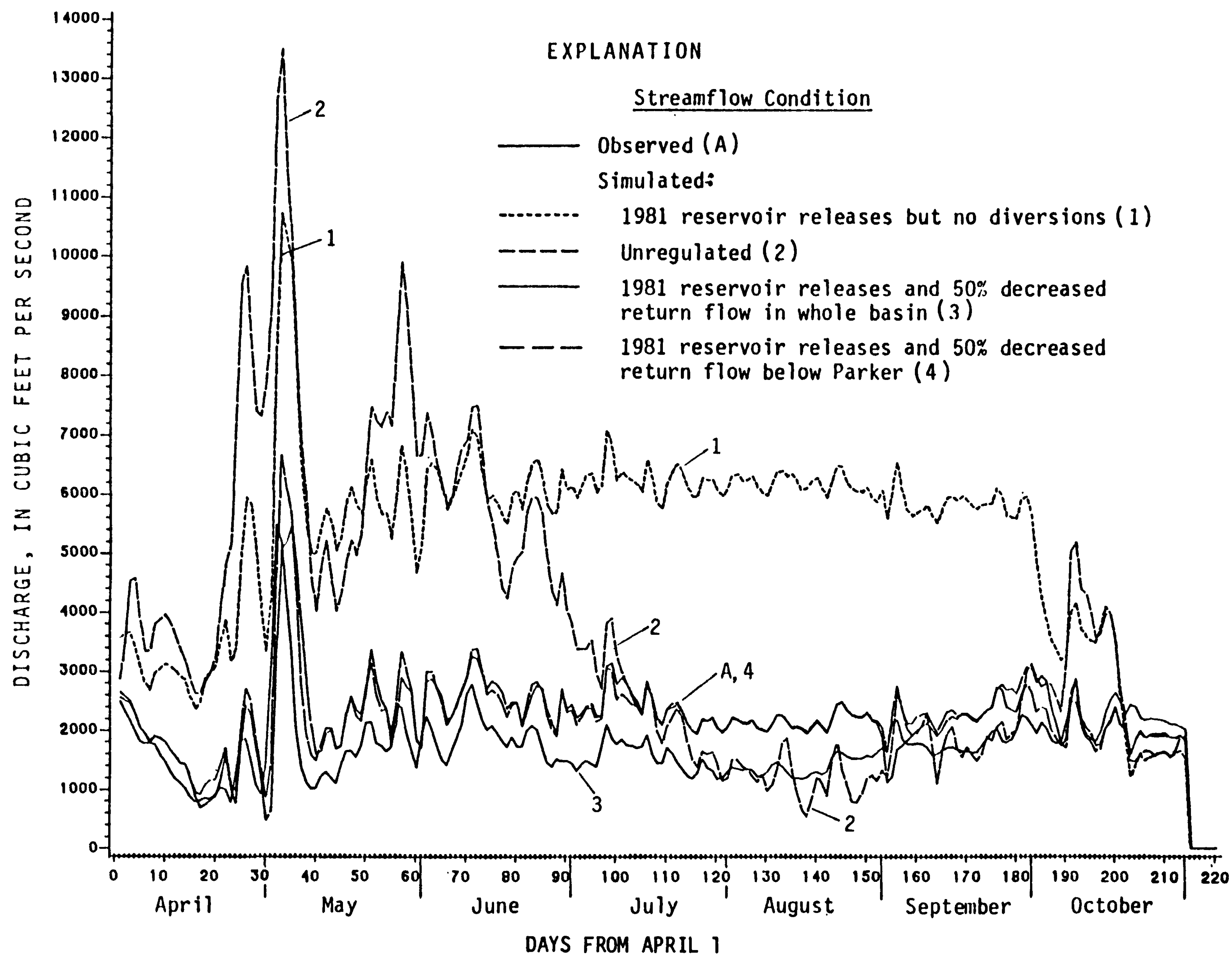

FIGURE 16.--Observed and simulated mean daily discharges of the Yakima River at Mabton (11) for the period April 1 to October 31, 1981.

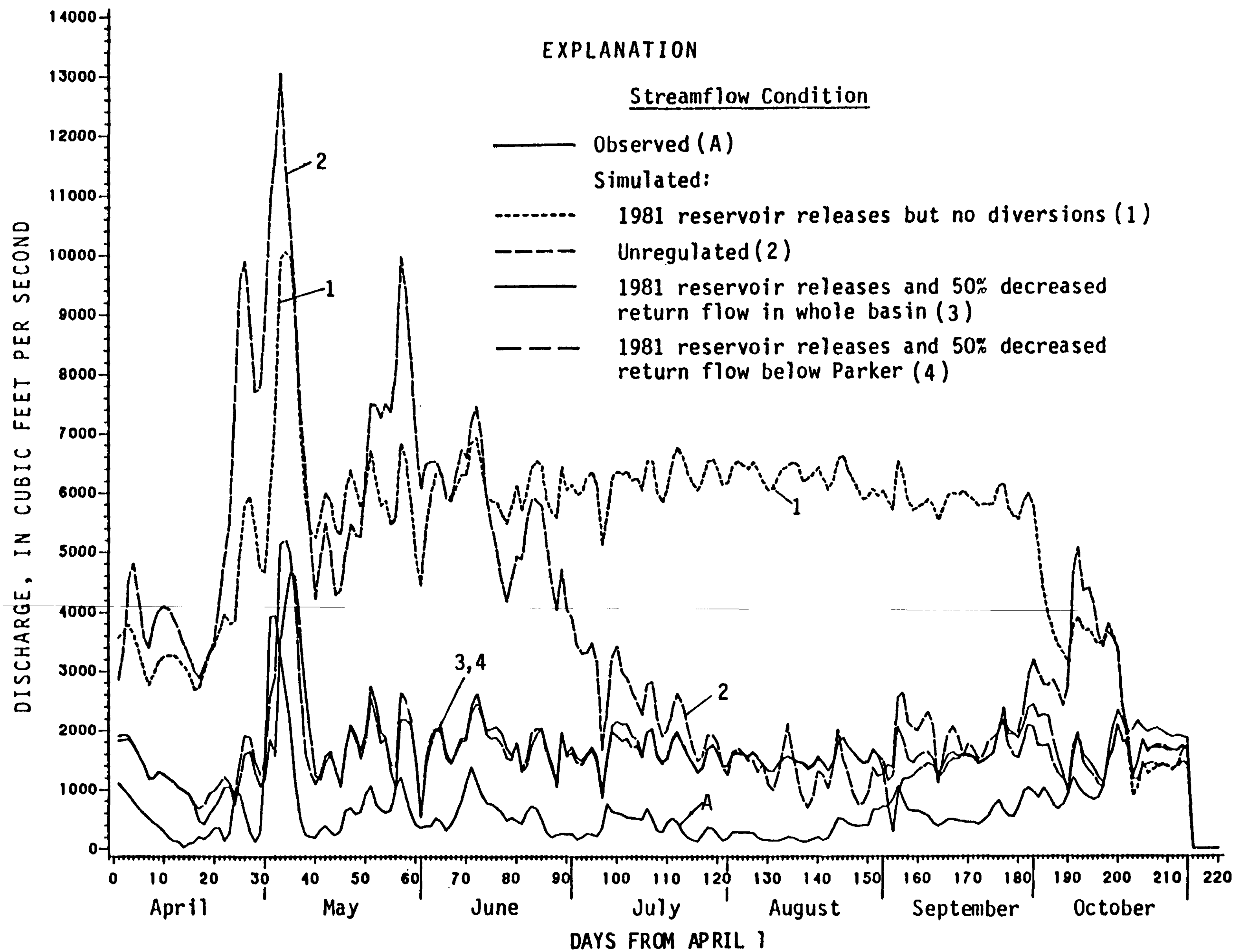

FIGURE 17.--Observed and simulated mean daily discharges of the Yakima River at Prosser (12) for the period April 1 to October 31, 1981.

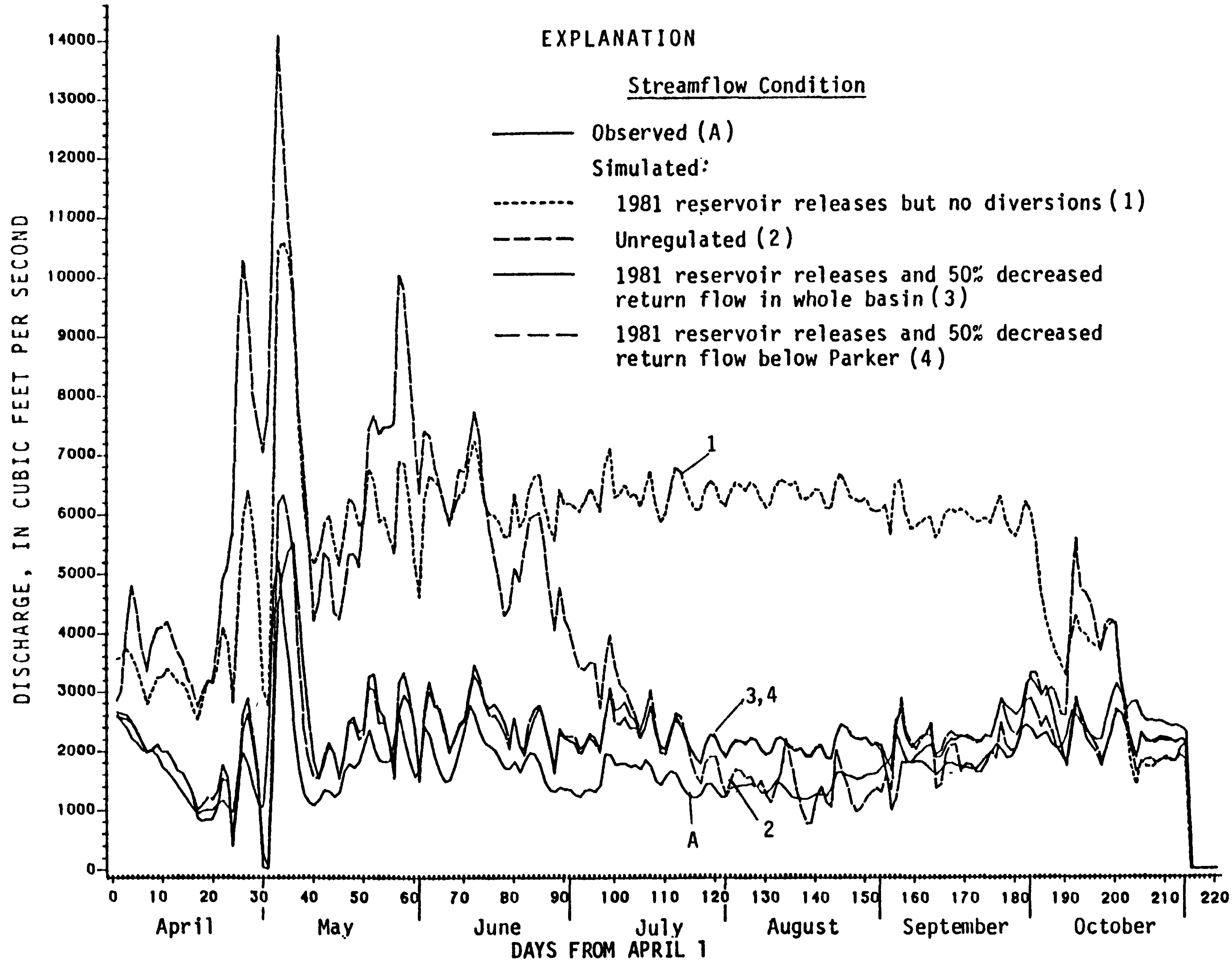

FIGURE 18.--Observed and simulated mean daily discharges of the Yakima River at Kiona (13) for the period April 1 to October 31, 1981.

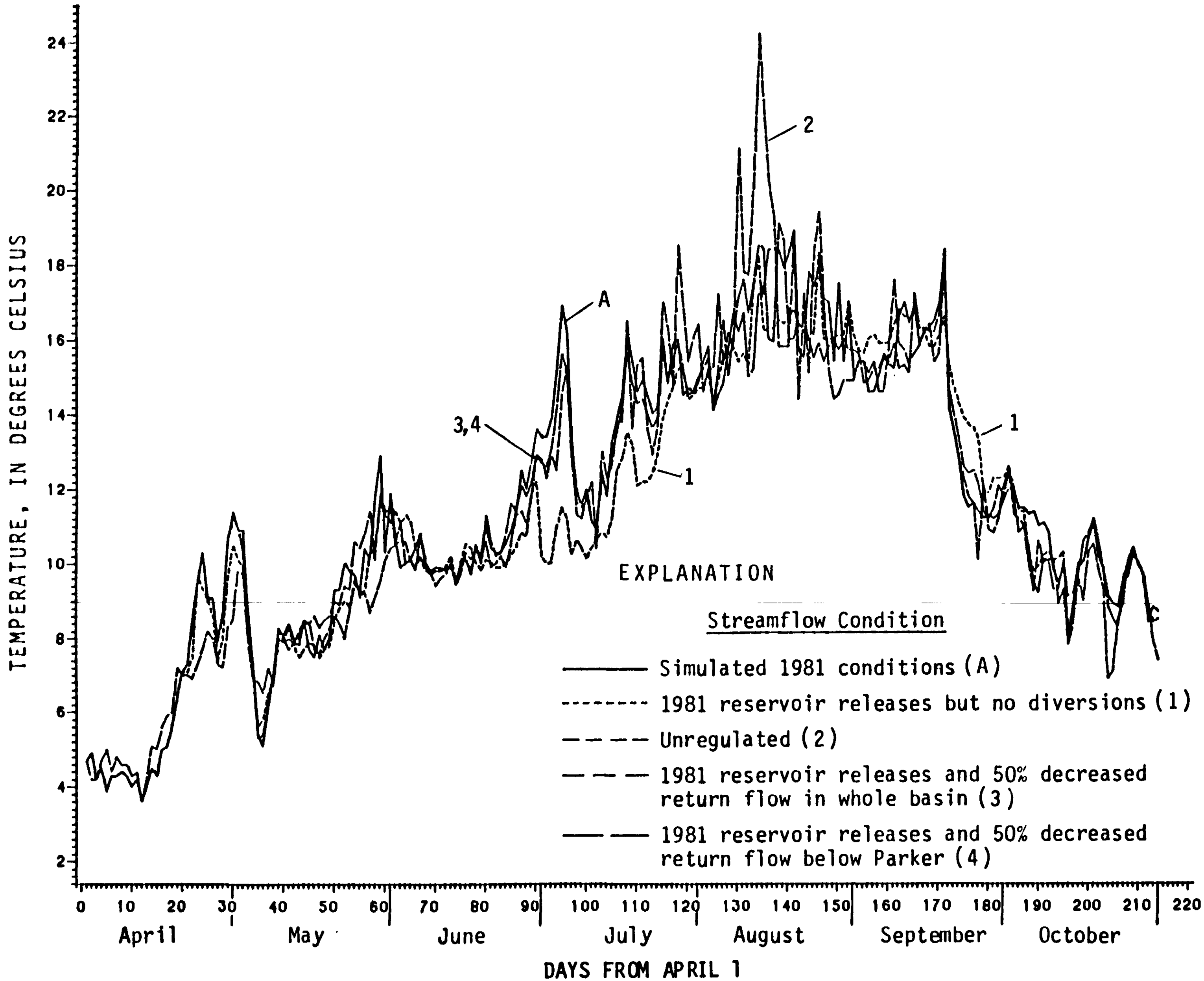

FIGURE 19.--Simulated daily temperatures of the Yakima River at Cle Elum (5) for the period April 1 to October 31, 1981.

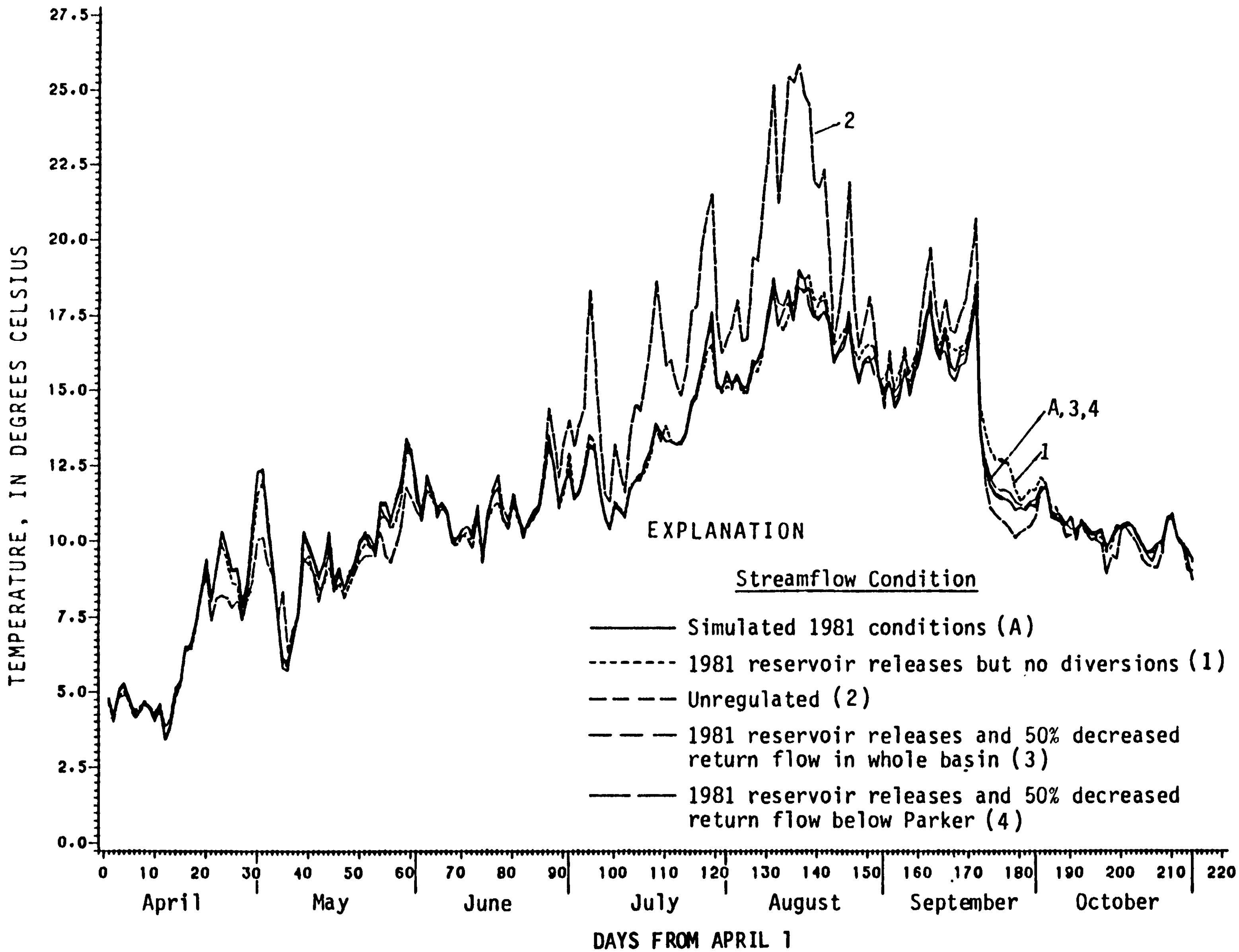

FIGURE 20.--Simulated daily temperatures of the Yakima River at Ellensburg (6) for the period April 1 to October 31, 1981.

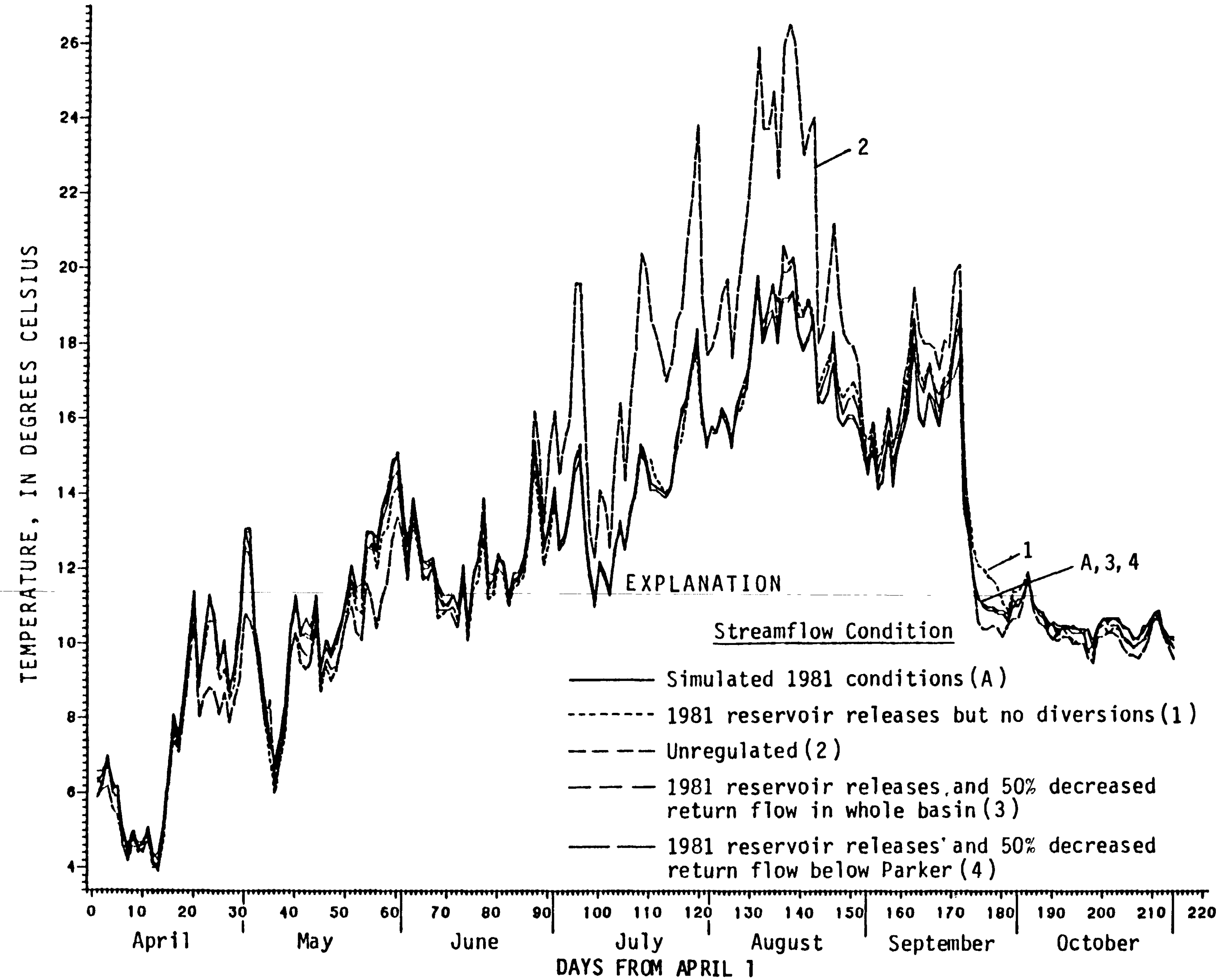

FIGURE 21.--Simulated daily temperatures of the Yakima River at Umtanum (7) for the period April 1 to October 31, 1981.

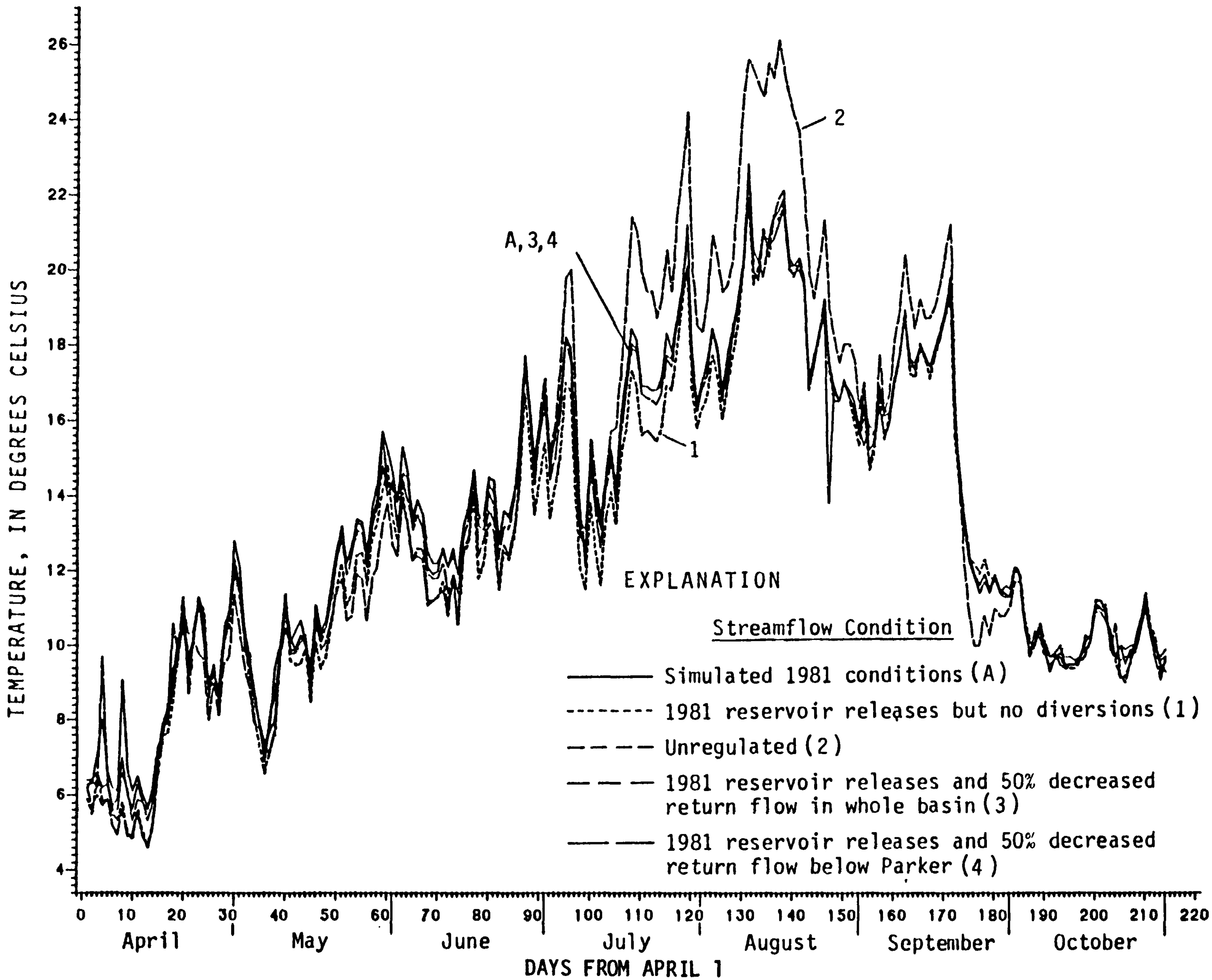

FIGURE 22.--Simulated daily temperatures of the Yakima River at Union Gap (8) for the period April 1 to October 31, 1981.

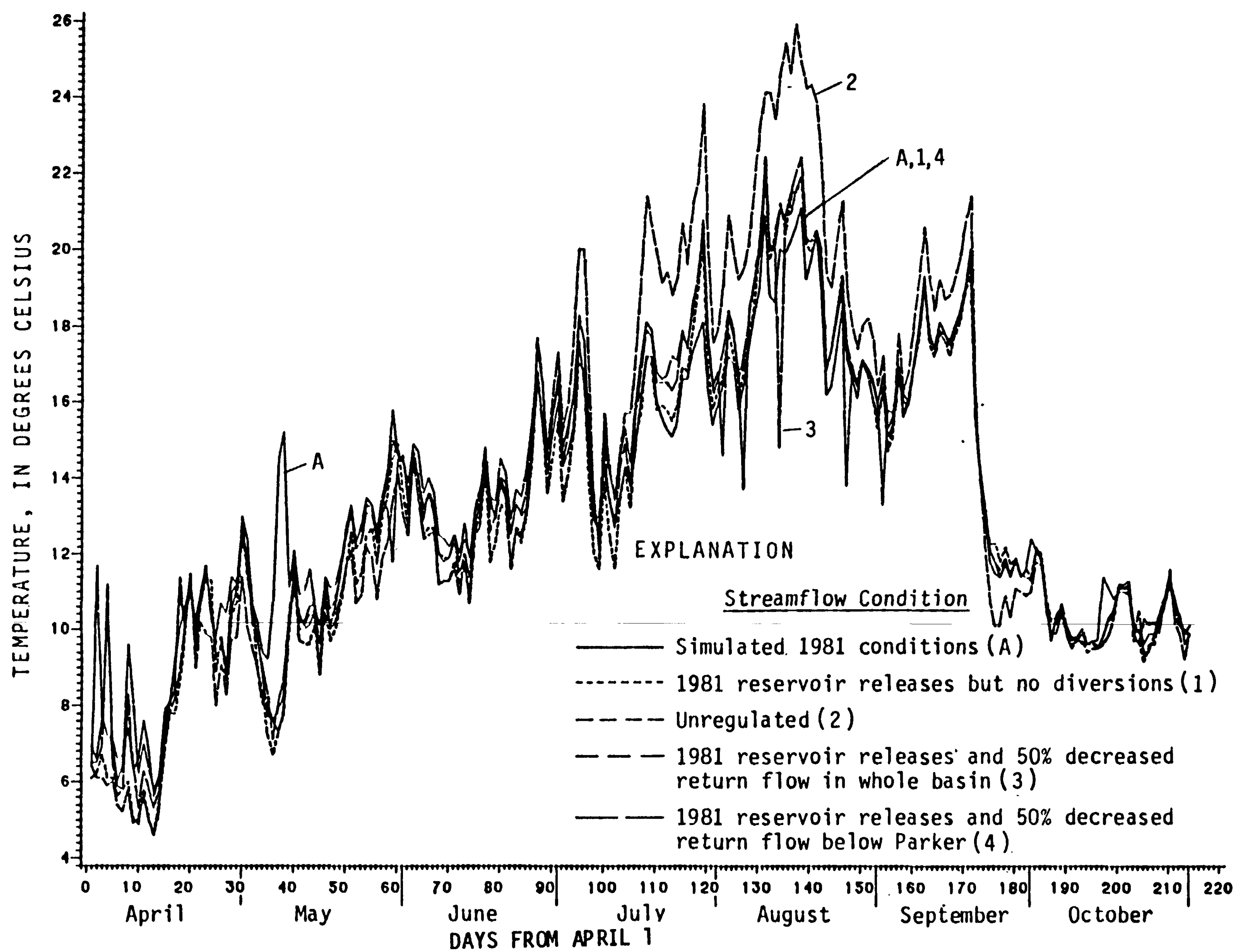

FIGURE 23.--Simulated daily temperatures of the Yakima River near Parker (9) for the period April 1 to October 31, 1981.

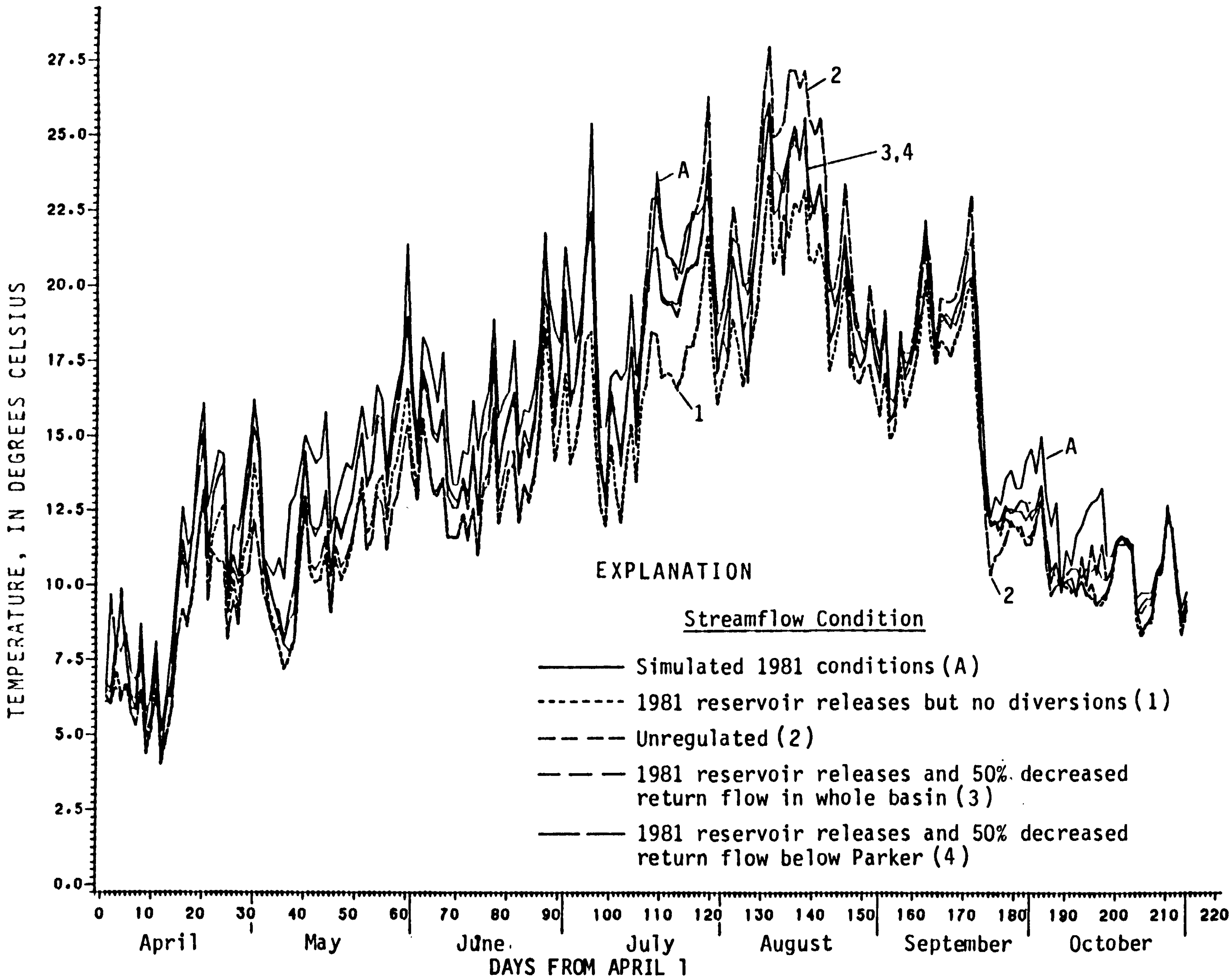

FIGURE 24.--Simulated daily temperatures of the Yakima River at Granger (10) for the period April 1 to October 31, 1981.

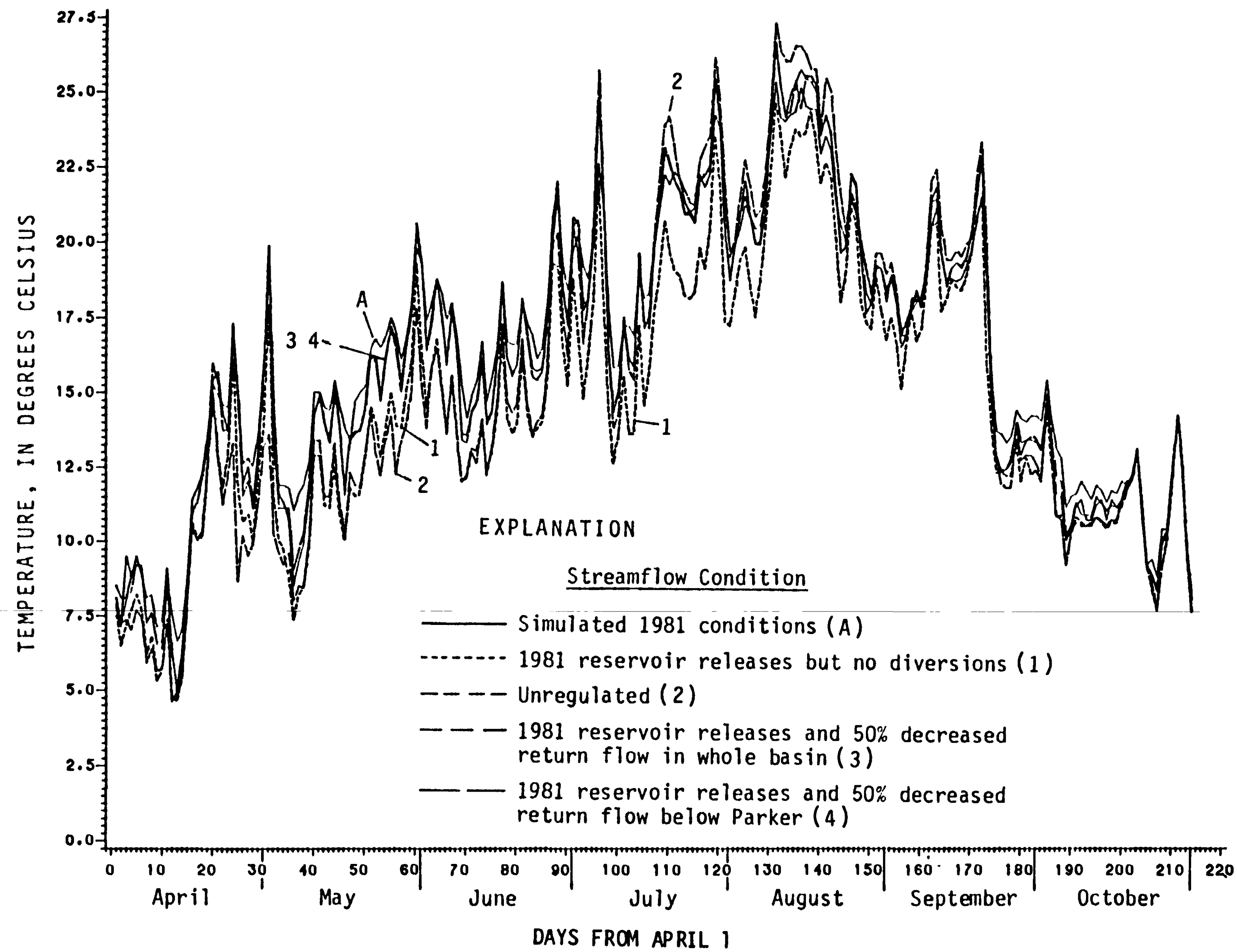

FIGURE 25.--Simulated daily temperatures of the Yakima River at Mabton (11) for the period April 1 to October 31, 1981.

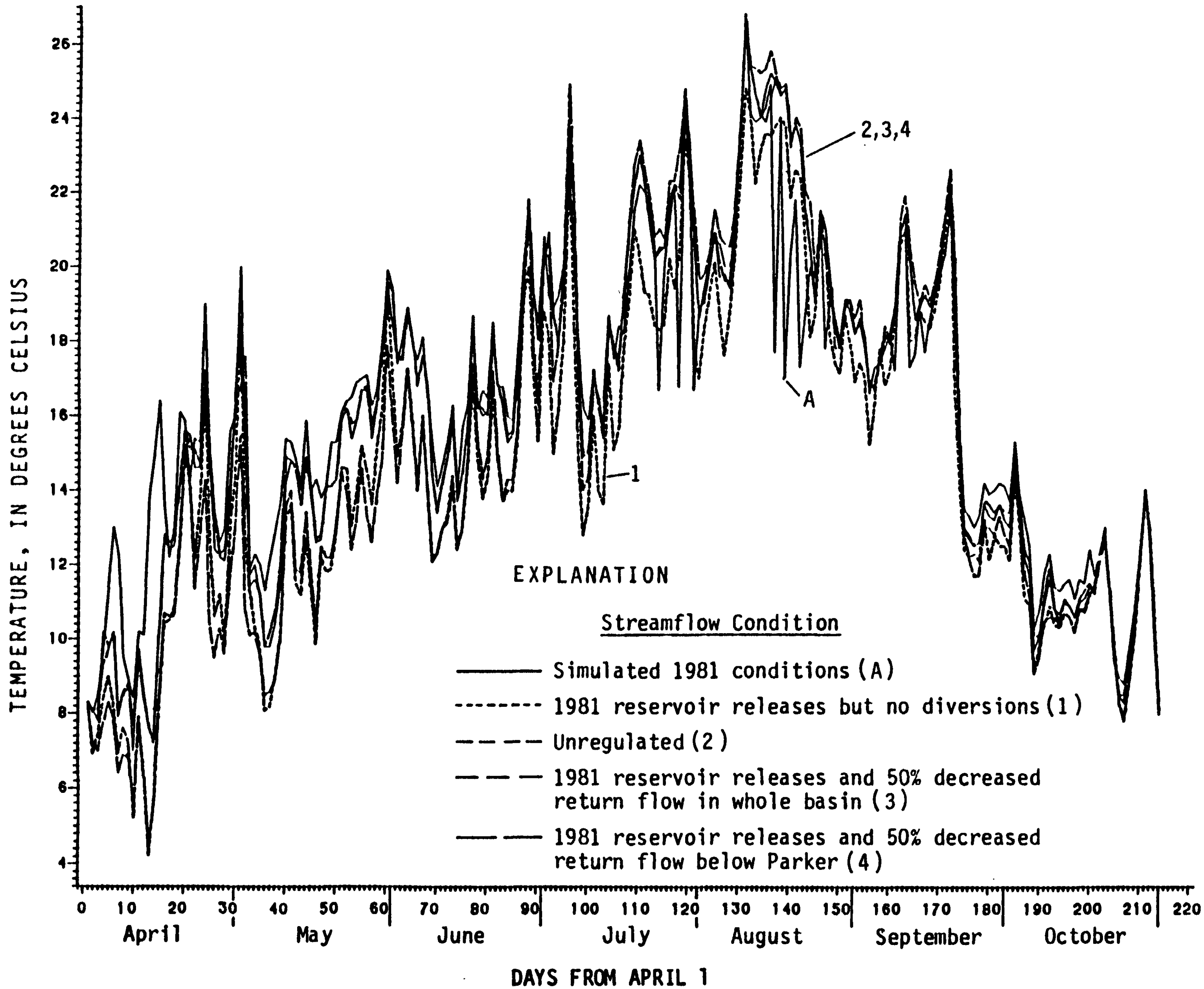

FIGURE 26.--Simulated daily temperatures of the Yakima River at Prosser (12) for the period April 1 to October 31, 1981.

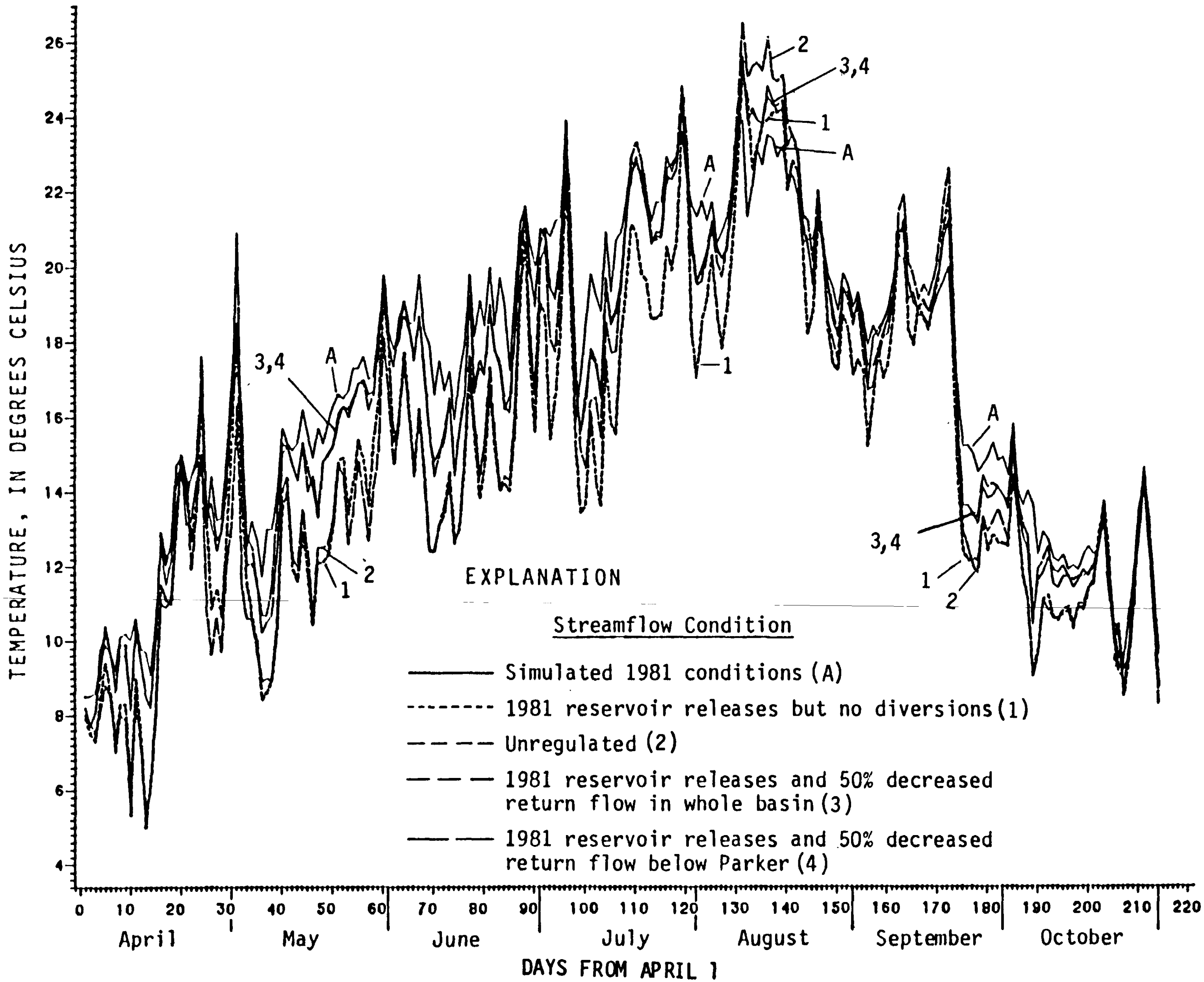

FIGURE 27.--Simulated daily temperatures of the Yakima River at Kiona (13) for the period April 1 to October 31, 1981.

TABLE 6.--Statistics of observed and simulated mean daily discharges for the 1981 irrigation season for the Yakima River at Umtanum (7)

[Values in cubic feet per second unless otherwise noted; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	2,694	1,538	2,516	3,066	4,273	4,207	1,877	1,327
	SD[1]	1,198	542	670	294	223	226	289	378
	Maximum	4,628	3,274	4,531	3,638	4,628	4,428	2,928	1,925
	Minimum	870	980	1,628	2,557	3,799	3,285	1,635	870
Simulated									
1981 reservoir releases and no diversions	Mean	3,396	1,740	3,338	3,841	5,183	5,266	2,882	1,464
	SD	1,490	688	772	342	247	223	331	639
	Maximum	5,672	3,191	5,392	4,418	5,551	5,672	3,955	2,402
	Minimum	763	862	2,012	3,257	4,654	4,779	2,557	763
No reservoir storage and no diversions (unregulated)	Mean	2,224	3,146	4,258	3,225	1,533	943	1,100	1,392
	SD	1,558	1,871	1,591	589	482	242	228	585
	Maximum	8,946	7,491	8,946	4,208	2,454	1,742	1,570	2,691
	Minimum	665	1,328	2,353	2,118	870	665	697	670
1981 reservoir releases; all return flows decreased by 50 percent	Mean	2,653	1,454	2,516	2,985	4,181	4,176	1,870	1,334
	SD	1,187	463	763	297	232	167	361	368
	Maximum	4,555	2,590	4,461	3,498	4,555	4,503	3,045	1,915
	Minimum	770	770	1,269	2,486	3,668	3,812	1,531	849
1981 reservoir releases; return flows below Parker decreased by 50 percent	Mean	2,711	1,483	2,580	3,056	4,255	4,256	1,934	1,361
	SD	1,205	474	763	298	232	168	366	379
	Maximum	4,627	2,636	4,519	3,572	4,627	4,583	3,127	1,952
	Minimum	788	788	1,320	2,557	3,743	3,889	1,595	861

[1] Standard deviation.

TABLE 7.--Statistics of observed and simulated mean daily discharges for the 1981 irrigation season for the Yakima River at Union Gap (8)

[Values in cubic feet per second unless otherwise noted; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	2,945	2,348	3,818	3,319	3,347	3,226	2,952	1,696
	(historic)	(4,428)	(5,200)	(7,400)	(6,800)	(3,900)	(3,300)	(2,600)	(1,800)
	SD[1]	862	763	1,210	237	154	97	242	357
	Maximum	7,490	4,740	7,490	4,010	3,910	3,440	3,660	2,588
	Minimum	1,280	1,570	2,630	2,980	3,150	2,990	2,360	1,280
Simulated									
1981 reservoir releases and no diversions	Mean	4,843	3,359	5,926	5,545	5,802	5,819	5,242	2,195
	SD	1,544	919	1,365	347	220	174	268	852
	Maximum	9,824	5,476	9,824	6,241	6,420	6,105	5,936	4,056
	Minimum	1,240	2,398	4,145	4,781	5,384	5,407	4,425	1,240
No reservoir storage and no diversions (unregulated)	Mean	3,257	4,701	6,783	4,983	1,948	838	1,410	2,180
	(historic)	(5,414)	(7,600)	(12,000)	(9,600)	(3,700)	(1,500)	(1,400)	(2,100)
	SD	2,500	2,368	2,422	1,071	720	361	399	922
	Maximum	13,761	9,993	13,761	6,642	3,199	1,856	2,128	5,169
	Minimum	238	2,322	3,647	3,015	807	238	430	1,315
1981 reservoir releases; all return flows decreased by 50 percent	Mean	3,215	2,459	4,099	3,624	3,627	3,527	3,245	1,914
	SD	933	603	1,356	337	214	122	225	439
	Maximum	7,926	4,019	7,926	4,393	4,250	3,814	3,996	2,944
	Minimum	1,448	1,677	2,506	3,033	3,310	3,295	2,849	1,448
1981 reservoir releases; return flows below Parker decreased by 50 percent	Mean	3,250	2,355	4,102	3,710	3,749	3,584	3,227	2,011
	SD	885	543	1,035	255	233	145	249	532
	Maximum	6,626	3,790	6,626	4,413	4,364	3,886	3,627	3,428
	Minimum	1,443	1,506	2,611	3,298	3,400	3,249	2,680	1,440

[1] Standard deviation.

TABLE 8.--Statistics of observed and simulated mean daily discharges for the 1981 irrigation season for the Yakima River near Parker (9)

[Values in cubic feet per second unless otherwise noted; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	684	816	1,134	598	475	357	406	995
	(historic)	(1,943)	(3,200)	(4,300)	(3,700)	(790)	(330)	(330)	(950)
	SD[1]	650	481	1,275	306	205	120	200	635
	Maximum	5,150	2,180	5,150	1,394	1,134	649	1,019	1,730
	Minimum	38	208	38	168	206	170	83	66
Simulated									
1981 reservoir releases and no diversions	Mean	4,952	3,488	6,146	5,696	5,921	5,869	5,282	2,250
	SD	1,581	986	1,471	407	254	209	273	805
	Maximum	10,328	5,878	10,328	6,490	6,636	6,182	6,049	4,234
	Minimum	894	2,362	4,239	4,822	5,490	5,416	4,553	894
No reservoir storage and no diversions (unregulated)	Mean	3,367	4,831	7,003	5,134	2,068	888	1,450	2,235
	SD	2,569	2,420	2,520	1,129	733	380	438	852
	Maximum	14,265	10,377	14,265	6,932	3,423	1,961	2,280	5,060
	Minimum	282	2,553	3,748	3,071	886	282	374	1,114
1981 reservoir releases; all return flows decreased by 50 percent	Mean	1,656	1,477	2,299	1,789	1,684	1,506	1,429	1,401
	SD	619	452	1,242	315	213	174	201	383
	Maximum	5,938	2,522	5,938	2,486	2,335	1,805	1,955	1,813
	Minimum	700	713	1,091	1,332	1,389	819	1,085	700
1981 reservoir releases; return flows below Parker decreased by 50 percent	Mean	1,633	1,344	2,238	1,803	1,732	1,483	1,348	1,472
	SD	533	426	889	231	230	217	389	351
	Maximum	4,229	2,199	4,229	2,367	2,337	1,778	1,973	2,091
	Minimum	518	518	1,177	1,465	1,385	536	536	738

[1] Standard deviation.

TABLE 9.--Statistics of observed and simulated mean daily discharges for the 1981 irrigation season for the Yakima River at Prosser (12)

[Values in cubic feet per second unless otherwise noted; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	694	466	1,015	569	370	297	634	1,496
	SD[1]	633	380	1,046	289	177	173	196	561
	Maximum	3,942	1,623	3,942	1,374	760	718	1,070	2,342
	Minimum	31	31	201	198	128	108	385	676
Simulated									
1981 reservoir releases and no diversions	Mean	5,313	3,688	6,388	6,069	6,210	6,278	5,874	2,672
	SD	1,609	886	1,435	377	319	206	211	1,227
	Maximum	10,057	5,928	10,057	6,925	6,763	6,629	6,534	5,043
	Minimum	872	2,695	4,436	5,436	5,102	5,901	5,532	872
No reservoir storage and no diversions (unregulated)	Mean	3,723	4,913	7,319	5,584	2,406	1,288	1,990	2,600
	SD	2,492	2,192	2,418	1,014	674	355	452	1,172
	Maximum	13,060	9,902	13,060	7,458	3,474	2,119	3,184	5,082
	Minimum	682	2,860	4,207	3,874	1,241	682	1,118	1,163
1981 reservoir releases; all return flows decreased by 50 percent	Mean	1,655	1,285	2,185	1,772	1,613	1,531	1,629	1,564
	SD	572	379	1,182	322	249	131	248	273
	Maximum	5,196	1,924	5,196	2,610	2,005	1,881	2,135	2,105
	Minimum	673	673	529	1,044	851	1,306	1,153	1,034
1981 reservoir releases; return flows below Parker decreased by 50 percent	Mean	1,632	1,162	2,116	1,781	1,663	1,516	1,530	1,644
	SD	566	404	1,019	306	281	137	458	312
	Maximum	4,656	1,852	4,656	2,431	2,152	1,873	2,430	2,264
	Minimum	413	413	524	1,119	906	1,309	295	932

[1] Standard deviation.

TABLE 10.--Statistics of observed and simulated mean daily discharges for the 1981 irrigation season for the Yakima River at Kiona (13)

[Values in cubic feet per second unless otherwise noted; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	1,819	1,561	2,090	1,843	1,488	1,391	1,894	2,463
	SD[1]	600	522	1,029	392	239	161	223	269
	Maximum	5,220	2,610	5,220	2,770	1,940	1,710	2,440	3,140
	Minimum	933	933	1,070	1,290	1,190	1,150	1,590	2,040
Simulated									
1981 reservoir releases and no diversions	Mean	5,422	3,604	6,381	6,222	6,333	6,335	5,968	3,100
	SD	1,595	957	1,730	411	276	178	232	1,172
	Maximum	10,602	6,407	10,692	7,238	7,085	6,676	6,578	5,589
	Minimum	1,425	2,531	2,748	5,537	5,846	6,025	5,601	1,425
No reservoir storage and no diversions (unregulated)	Mean	3,831	4,777	7,343	5,775	2,556	1,345	2,060	3,000
	SD	2,470	2,120	2,517	1,102	746	329	463	1,124
	Maximum	14,093	10,301	14,093	7,733	3,954	2,180	3,333	5,607
	Minimum	747	2,739	4,207	4,005	1,208	747	1,310	1,637
1981 reservoir releases; all return flows decreased by 50 percent	Mean	2,279	1,798	2,818	2,476	2,233	2,102	2,292	2,244
	SD	675	655	1,360	411	268	137	282	271
	Maximum	6,339	2,902	6,339	3,446	2,980	2,435	2,890	2,911
	Minimum	262	262	1,472	1,595	1,779	1,864	1,644	1,748
1981 reservoir releases; return flows below Parker decreased by 50 percent	Mean	2,258	1,679	2,762	2,483	2,283	2,089	2,185	2,329
	SD	656	697	1,157	366	303	143	494	345
	Maximum	5,526	2,638	5,526	3,271	3,039	2,422	3,220	3,106
	Minimum	26	26	1,502	1,687	1,759	1,843	988	1,732

[1] Standard deviation.

TABLE 11.--Statistics of observed and simulated mean daily streamflow temperatures for the 1981 irrigation season for the Yakima River at Umtanum (7)

[Values in degress Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	13.2	9.0	11.9	13.4	14.4	17.7	15.4	10.4
	SD[1]	3.1	1.5	1.7	.8	1.2	1.0	1.8	1.1
	Maximum	19.3	12.2	15.5	15.4	16.6	19.3	17.5	13.1
	Minimum	7.2	7.2	9.3	11.9	12.3	16.0	12.5	8.4
Simulated									
Simulated regulated	Mean	12.4	7.6	10.8	12.2	14.0	17.1	14.2	10.6
	SD	3.4	2.5	2.0	1.1	1.8	1.4	2.5	.4
	Maximum	19.5	13.0	14.6	15.1	18.2	19.5	18.5	11.8
	Minimum	4.3	4.3	6.9	10.4	11.1	14.6	10.8	10.1
1981 reservoir releases and no diversions	Mean	12.4	7.3	10.3	11.9	14.0	17.6	14.9	10.3
	SD	3.7	2.5	2.1	1.0	1.7	1.5	2.6	.5
	Maximum	20.2	12.6	14.2	14.6	17.8	20.2	19.1	11.9
	Minimum	4.0	4.0	6.0	10.1	11.0	15.4	10.9	9.7
No reservoir storage and no diversions (unregulated)	Mean	13.3	6.8	10.0	12.3	17.3	21.1	14.9	10.2
	SD	5.1	2.0	1.6	1.6	2.8	3.3	3.4	.5
	Maximum	26.5	10.8	13.4	16.2	23.8	26.5	20.1	11.7
	Minimum	4.1	4.1	6.2	10.1	12.3	14.8	10.2	9.5
1981 reservoir releases and all return flows decreased by 50 percent	Mean	12.5	7.6	10.9	12.3	14.2	17.5	14.5	10.4
	SD	3.6	2.6	2.2	1.1	1.8	1.6	2.8	.4
	Maximum	20.6	13.0	15.1	15.4	18.4	20.6	19.0	11.8
	Minimum	3.9	3.9	6.6	10.4	11.1	14.6	10.6	9.8
1981 reservoir releases and return flows below Parker decreased by 50 percent	Mean	12.5	7.7	11.1	12.4	14.2	17.2	14.2	10.6
	SD	3.4	2.6	2.1	1.1	1.7	1.5	2.5	.4
	Maximum	19.7	13.1	15.0	15.1	18.3	19.7	17.9	11.8
	Minimum	4.2	4.2	6.7	10.6	11.2	14.5	10.7	9.9

[1] Standard deviation.

TABLE 12.--Statistics of observed and simulated mean daily streamflow temperatures for the 1981 irrigation season for the Yakima River at Union Gap (8)

[Values in degress Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	14.6	9.6	13.0	15.9	17.4	19.3	16.2	10.7
	SD[1]	3.7	2.0	2.1	1.2	1.4	1.2	1.8	1.4
	Maximum	21.2	14.2	16.7	18.9	20.4	21.2	18.4	14.1
	Minimum	6.9	6.9	9.6	13.9	14.5	17.4	13.1	8.2
Simulated									
Simulated regulated	Mean	13.5	8.0	11.4	13.9	16.5	18.9	15.4	10.2
	SD	4.0	2.1	2.2	1.5	1.9	1.9	2.8	0.7
	Maximum	22.8	12.8	15.7	17.7	21.2	22.8	19.8	12.1
	Minimum	5.6	5.6	6.9	11.9	13.1	15.8	11.3	9.5
1981 reservoir releases and no diversions	Mean	12.9	7.6	10.5	12.8	15.3	18.5	15.3	10.1
	SD	4.0	2.4	2.1	1.4	2.1	2.0	2.6	0.8
	Maximum	21.9	12.3	14.8	16.7	20.0	21.9	19.2	12.1
	Minimum	4.6	4.6	6.6	10.6	11.5	15.3	11.4	9.1
No reservoir storage and no diversions (unregulated)	Mean	13.8	7.4	10.3	13.1	18.1	21.6	15.6	10.1
	SD	5.2	2.2	1.7	1.8	2.9	3.0	3.8	0.7
	Maximum	26.1	11.4	13.8	17.6	24.2	26.1	21.2	11.7
	Minimum	4.6	4.6	7.1	10.6	12.3	16.3	10.0	9.0
1981 reservoir releases and all return flows decreased by 50 percent	Mean	13.3	8.1	11.0	13.5	16.1	18.8	15.3	10.1
	SD	4.6	2.2	2.0	1.5	2.0	1.9	2.7	0.7
	Maximum	22.5	12.2	14.8	17.3	20.9	22.5	19.2	12.1
	Minimum	5.3	5.3	7.0	11.4	12.6	15.6	11.3	9.3
1981 reservoir releases and return flows below Parker decreased by 50 percent	Mean	1.34	8.3	11.1	13.9	16.4	18.6	15.4	10.2
	SD	3.9	1.9	2.2	1.4	1.9	1.9	2.7	0.7
	Maximum	21.9	11.9	15.6	17.4	20.1	21.9	19.5	12.1
	Minimum	5.7	5.7	7.4	11.9	12.1	13.8	11.3	9.4

[1] Standard deviation.

TABLE 13.--Statistics of observed and simulated mean daily streamflow temperatures for the 1981 irrigation season for the Yakima River near Parker (9)

[Values in degress Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	14.4	9.5	12.0	14.4	16.4	18.9	17.1	12.5
	SD[1]	3.2	1.1	1.3	0.6	0.8	0.6	1.0	1.5
	Maximum	20.1	12.4	14.3	15.7	17.9	20.1	18.1	15.3
	Minimum	7.9	7.9	9.9	13.4	15.1	17.7	15.2	9.8
Simulated									
Simulated regulated	Mean	13.4	8.7	12.0	13.5	15.4	18.1	15.4	10.4
	SD	3.5	2.1	1.5	1.2	1.5	1.7	2.9	.7
	Maximum	21.1	13.0	15.2	16.6	18.1	21.1	20.0	12.1
	Minimum	5.6	5.6	9.2	11.8	12.9	15.8	11.4	9.6
1981 reservoir releases and no diversions	Mean	13.0	7.8	10.7	12.9	15.4	18.6	15.3	10.2
	SD	4.0	2.4	2.1	1.4	2.1	2.0	2.7	.8
	Maximum	22.1	12.8	14.9	16.8	20.1	22.1	19.3	12.1
	Minimum	4.6	4.6	6.7	10.7	11.6	15.3	11.4	9.1
No reservoir storage and no diversions (unregulated)	Mean	13.8	7.5	10.5	13.2	18.0	21.3	15.7	10.2
	SD	5.1	2.2	1.7	1.8	2.8	2.8	3.9	.7
	Maximum	25.9	11.5	14.1	17.7	23.8	25.9	21.4	11.8
	Minimum	4.6	4.6	7.3	10.7	12.4	16.4	10.1	9.2
1981 reservoir releases and all return flows decreased by 50 percent	Mean	13.4	8.5	11.3	13.6	16.1	18.7	15.3	10.3
	SD	3.9	2.3	2.0	1.5	2.0	2.1	2.8	.7
	Maximum	22.4	12.4	15.0	17.5	20.8	22.4	19.7	12.1
	Minimum	5.3	5.3	7.1	11.4	12.6	14.8	11.4	9.5
1981 reservoir releases and return flows below Parker decreased by 50 percent	Mean	13.5	8.9	11.4	14.0	16.4	18.4	15.3	10.3
	SD	3.8	2.1	2.2	1.4	1.8	2.3	2.8	.7
	Maximum	21.9	13.0	15.8	17.5	20.5	21.9	19.7	12.2
	Minimum	5.8	5.8	7.6	11.9	12.1	13.7	11.3	9.5

[1] Standard deviation.

TABLE 14.--Statistics of observed and simulated mean daily streamflow temperatures for the 1981 irrigation season for the Yakima River at Prosser (12)

[Values in degress Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed[2]	Mean	16.9	12.2	16.1	18.0	20.8	21.7	17.3	11.9
	SD[1]	4.0	2.6	2.3	1.4	1.7	1.7	2.1	1.3
	Maximum	23.8	17.3	19.8	21.0	23.2	23.8	19.7	14.9
	Minimum	8.9	8.9	12.1	15.8	17.1	18.6	14.1	9.6
Simulated									
Simulated regulated	Mean	16.3	12.8	15.3	17.2	19.4	20.6	17.0	11.6
	SD	3.8	2.9	2.2	1.8	2.3	2.6	2.5	1.6
	Maximum	26.5	19.0	20.0	21.3	24.3	26.5	21.5	15.3
	Minimum	8.0	8.0	11.3	14.0	15.9	17.0	13.0	8.4
1981 reservoir releases and no diversions	Mean	14.8	9.8	12.8	15.1	17.8	20.6	16.4	10.8
	SD	4.4	3.2	2.7	2.0	2.7	2.5	3.1	1.5
	Maximum	24.8	16.5	19.2	20.0	23.4	24.8	21.9	14.2
	Minimum	4.2	4.2	8.1	12.2	12.8	16.9	12.1	7.8
No reservoir storage and no diversions (unregulated)	Mean	15.4	9.4	12.5	15.3	20.0	22.1	17.2	10.9
	SD	5.1	2.9	2.2	2.3	3.0	2.6	3.4	1.6
	Maximum	26.8	15.2	17.9	21.3	24.9	26.8	22.6	14.3
	Minimum	4.4	4.4	8.5	12.1	14.0	18.0	11.7	7.8
1981 reservoir releases and all return flows decreased by 50 percent	Mean	16.1	11.3	14.6	16.8	19.8	21.7	17.2	11.2
	SD	4.5	3.1	2.6	2.0	2.6	2.6	3.0	1.6
	Maximum	26.6	17.2	19.6	21.8	24.5	26.6	22.1	14.8
	Minimum	7.2	7.2	9.8	13.4	14.9	17.8	12.5	8.3
1981 reservoir releases and return flows below Parker decreased by 50 percent	Mean	16.1	11.4	14.5	16.9	19.8	21.8	17.2	11.2
	SD	4.5	3.1	2.6	2.0	2.6	2.6	3.1	1.5
	Maximum	26.6	16.7	19.9	21.8	24.4	26.6	22.1	14.6
	Minimum	7.0	7.0	9.8	13.5	15.0	17.8	12.5	8.3

[1] Standard deviation.

[2] Record is for Yakima River at Mabton and used as estimate for Prosser.

TABLE 15.--Statistics of observed and simulated mean daily streamflow temperatures for the 1981 irrigation season for the Yakima River at Kiona (13)

[Values in degress Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Streamflow conditions	Statistic	Irrigation season	Apr	May	June	July	Aug	Sept	Oct
Observed	Mean	17.3	12.6	15.4	18.1	21.3	22.8	17.9	12.0
	SD[1]	4.4	3.0	1.6	1.2	1.5	1.7	2.4	1.3
	Maximum	25.2	18.4	18.0	20.2	24.7	25.2	20.4	15.3
	Minimum	8.9	8.9	12.5	16.3	18.9	19.6	14.0	10.2
Simulated									
Simulated regulated	Mean	16.9	11.6	15.7	18.7	21.0	21.5	17.7	12.3
	SD	4.1	2.4	1.9	1.4	1.8	1.5	2.0	1.6
	Maximum	23.9	17.1	19.6	21.6	23.6	23.9	20.3	15.8
	Minimum	8.5	8.5	11.7	15.9	15.8	18.8	14.5	8.6
1981 reservoir releases and no diversions	Mean	15.1	10.3	13.1	15.3	18.1	20.8	16.5	11.3
	SD	4.3	3.0	2.7	2.0	2.7	2.6	3.1	1.6
	Maximum	25.2	16.7	19.2	20.7	23.6	25.2	21.9	14.4
	Minimum	5.3	5.3	8.4	12.4	13.4	17.1	12.1	8.5
No reservoir storage and no diversions (unregulated)	Mean	15.5	9.8	12.8	15.5	20.0	22.0	17.3	11.3
	SD	4.9	2.8	2.3	2.3	2.8	2.7	3.3	1.5
	Maximum	26.5	15.0	18.1	21.6	24.8	26.5	22.6	14.5
	Minimum	5.0	5.0	8.9	12.4	14.6	17.5	11.8	8.3
1981 reservoir releases and all return flows decreased by 50 percent	Mean	16.5	11.5	15.0	17.6	20.3	21.7	17.4	12.0
	SD	4.2	2.8	2.2	1.8	2.3	2.2	2.6	1.4
	Maximum	25.6	17.6	19.8	21.4	24.3	25.6	21.2	15.3
	Minimum	7.7	7.7	10.7	14.4	15.6	18.2	13.3	9.5
1981 reservoir releases and return flows below Parker decreased by 50 percent	Mean	16.5	11.6	15.0	17.6	20.2	21.7	17.4	11.9
	SD	4.3	2.8	2.5	1.8	2.3	2.2	2.7	1.3
	Maximum	25.5	16.7	20.9	21.5	24.3	25.5	21.2	15.0
	Minimum	7.7	7.7	10.2	14.4	15.6	18.1	13.1	9.2

[1] Standard deviation.

Each scenario is discussed in the next four subsections and is followed by a discussion of the effects of the four scenarios on fisheries.

Scenario 1: Reservoir Releases Only

This simulation (scenario 1) estimates streamflow and streamflow temperatures in the basin with current reservoir operating rules, but with no diversions or returns; that is, an attempt to determine the effects of current diversions and returns on water temperatures in the basin.

The overall effect of removing diversion in the basin for the 1981 irrigation season is shown graphically in figure 28. Note that the greatest streamflow augmentation occurs in the lower basin where reservoir outflow temperatures have the least influence. However, it is under this management scenario that water temperatures are optimum and flow quantities were more than sufficient to provide the suggested instream flow values for the preservation of fish habitat (U.S. Bureau of Reclamation, 1979, p. 157).

Scenario 2: Unregulated Conditions

In this scenario the models were operated to simulate unregulated streamflow conditions, in essence, no reservoir storage, diversions, or returns (scenario 2). The computed results estimate the natural streamflow and streamflow temperatures that would have occurred during the 1981 irrigation season. Discharge and temperature data for selected sites are shown in figures 12 through 27 and statistics appear in tables 6 through 15.

The simulated unregulated temperatures are, in general, higher than those calculated in other scenarios during August and September. This difference, however, is not as pronounced below Parker (9) (see figs. 23, 24, and 27) as it is above Parker. The statistics presented in table 7 show that the 1981 irrigation year was dryer than normal; for example, the historic unregulated irrigation-season mean discharge for the Yakima River at Union Gap (8) is 5,414 ft^3/s, compared with the 1981 unregulated mean discharge of 3,257 ft^3/s. However, tables 7 and 8 show that the regulated discharges were generally higher than historic regulated values during August and September. In addition, the day-to-day variation in August and September was less than the historic regulated flows (Vaccaro, 1982).

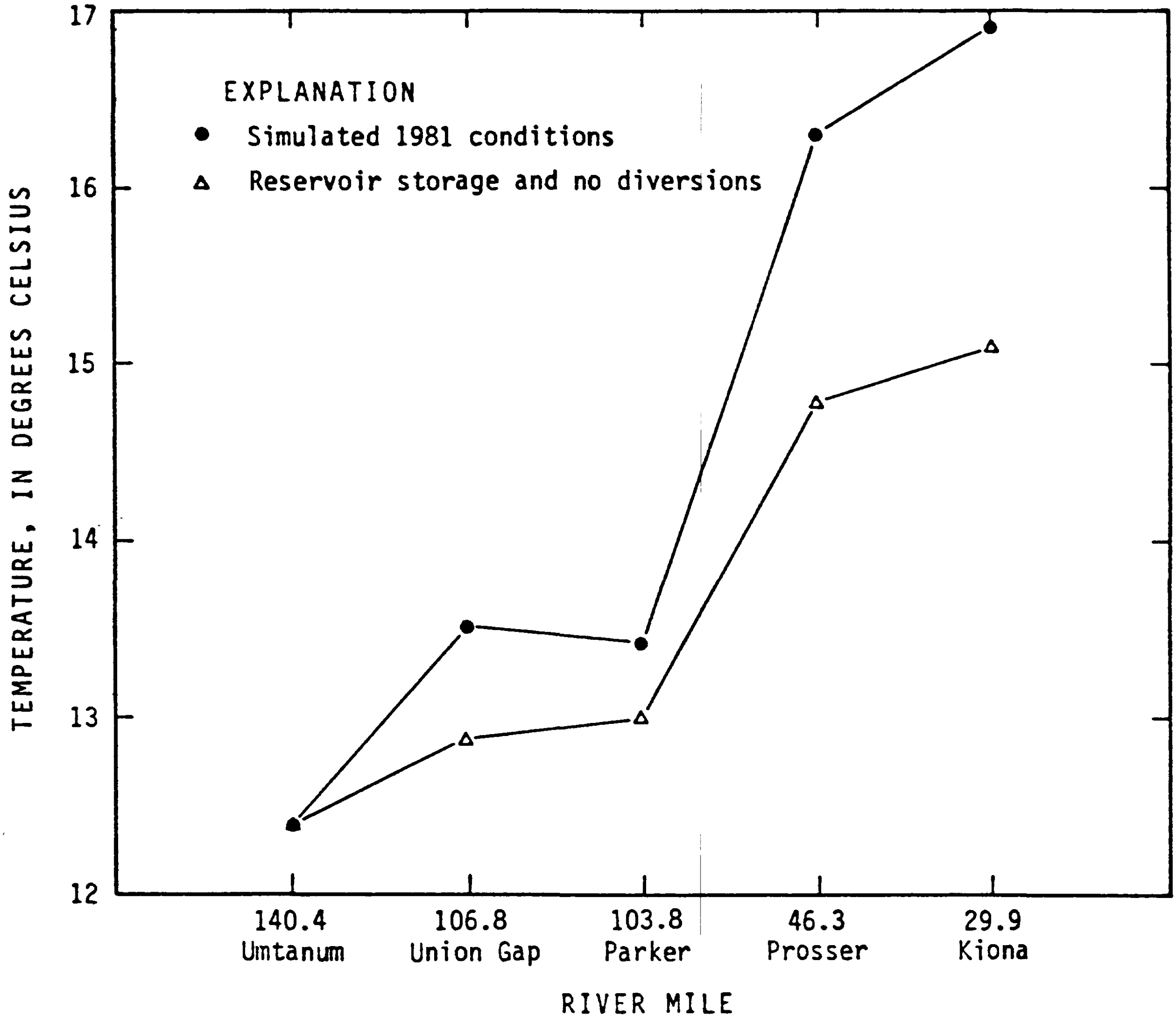

FIGURE 28.--Mean simulated 1981 irrigation-season streamflow temperatures for observed conditions and for conditions of 1981 reservoir releases and no diversions.

The daily mean air temperature for the three sites given in table 1 and the water temperature for three nearby river sites for both regulated and unregulated simulations (representing the current management temperature and the estimate of natural temperatures for 1981) are shown graphically in figures 29 through 31. Downstream of Parker (9), atmospheric heating or surface-heat exchange dominates the energy budget and temperatures from both simulations are similar, even though there is a large difference between flow quantities and traveltimes for the two conditions. At the Ellensburg (6) site (fig. 29) there are large differences between the water temperatures for the two conditions; also, the unregulated streamflow temperature pattern closely follows that for air temperature. These differences are less pronounced at Union Gap (8) (fig. 30), and by the time a parcel of water from the Yakima River at Martin (1) reaches Prosser (12) the differences are minimal (fig. 31). Figure 31 shows that the two water-temperature hydrographs match the air temperature closely. Furthermore, the similarity occurs despite a large difference in the traveltimes. This is shown in figure 32, which presents the total traveltime for a parcel of water leaving the Yakima River at Martin (1) location to reach the Yakima River at Prosser (12) site on any day for the 1981 irrigation season for regulated and unregulated conditions. Thus, the previous paragraph and the above analysis indicate that during this August-September period regulated streamflow temperatures were probably lower than normal regulated temperatures, and simulated unregulated temperatures were probably higher than normal unregulated temperatures.

Because the variation in unregulated streamflow temperatures at Prosser (12) closely tracks that in air temperatures (closer than regulated conditions), the tributary effects (especially with no return flow) are less for the unregulated scenario than for the other scenarios. Thus, the assumptions in the discussion above and in the sensitivity analysis are verified. The effects of surface exchange and tributary inflow for the observed and unregulated streamflow conditions can be analyzed for the 1981 irrigation season by comparing the simulated daily temperatures at a river site of a parcel of water with the initial temperature that parcel had when it left the Yakima River at Martin (1) and with the changes induced on the parcel by surface exchange processes and tributary inflows. Figures 33 and 34 graphically show these effects for a parcel of water arriving at the Yakima River at Prosser (12) site. Thus, the resulting simulated temperatures will represent different effects for observed and unregulated conditions.

The major effects of unregulating streamflow are: 1) decreased variability in temperatures in a downstream direction, and 2) a diminished range between simulated regulated and unregulated mean August temperatures. These are shown graphically in figure 35, which presents both the mean irrigation season and the August monthly streamflow temperatures at the five comparison sites for simulated regulated and unregulated conditions.

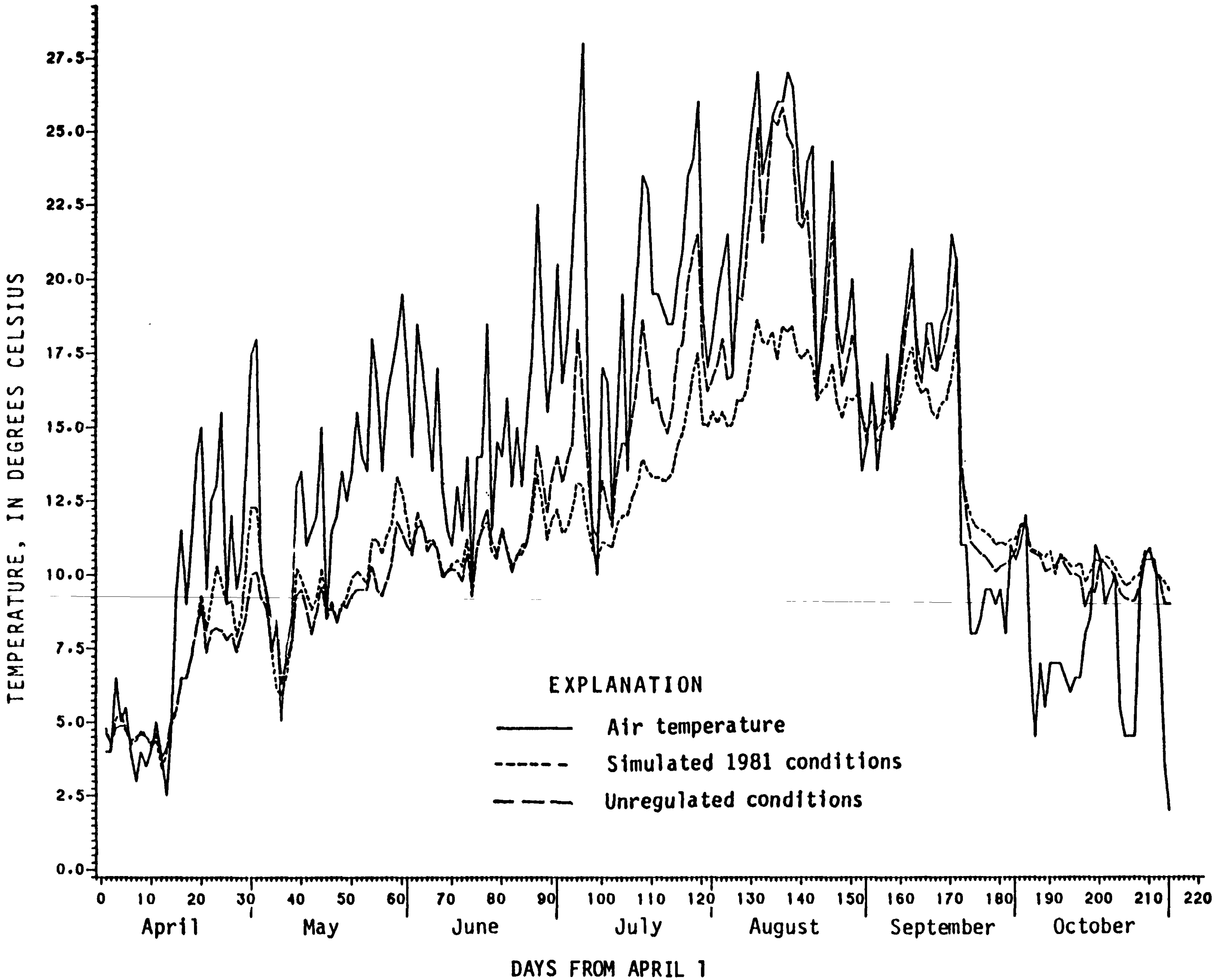

FIGURE 29.--Air and water temperatures for the Yakima River at Ellensburg (6) for observed and unregulated streamflow conditions during the 1981 irrigation season.

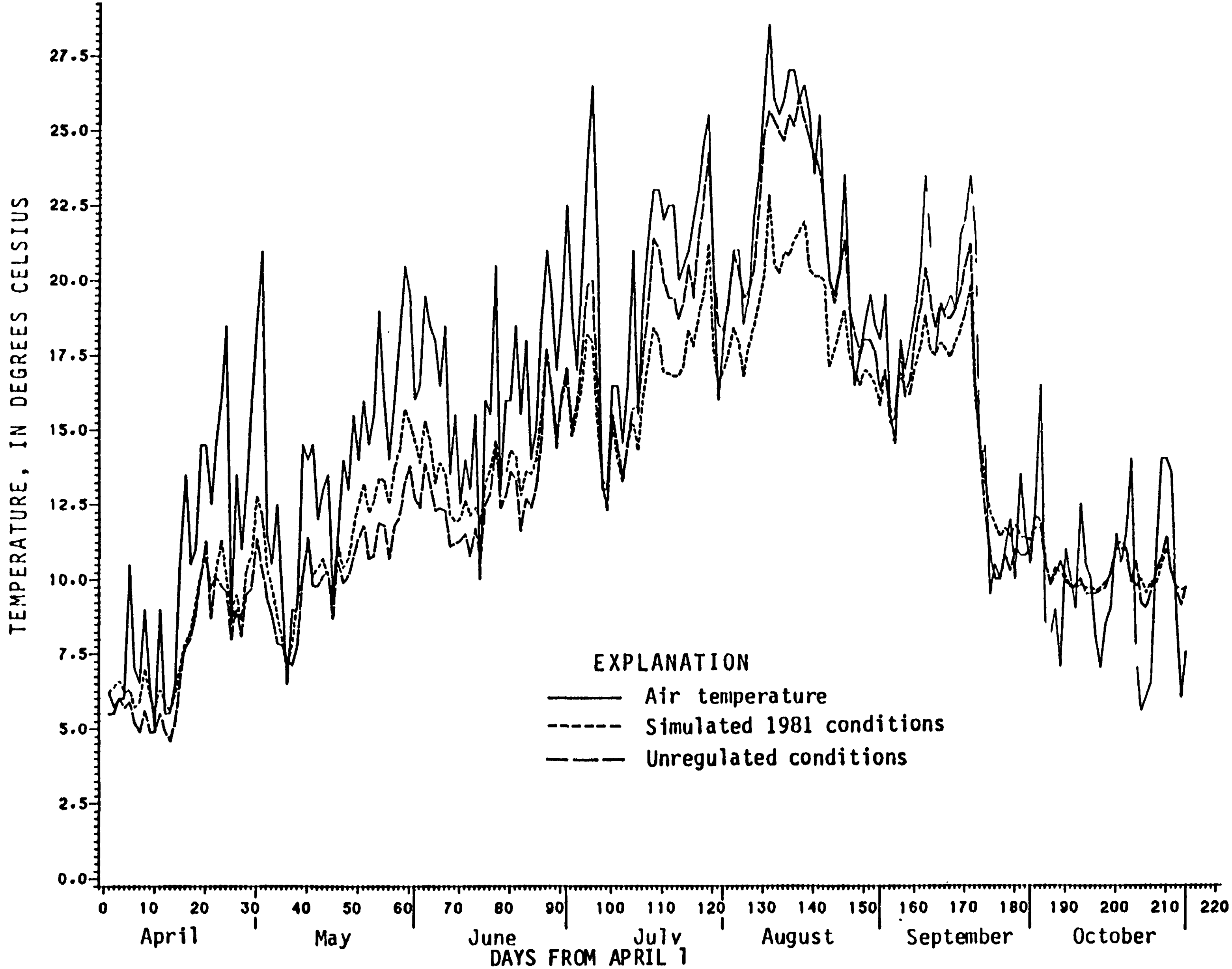

FIGURE 30.--Air and water temperatures for the Yakima River at Union Gap (8) for observed and unregulated streamflow conditions during the 1981 irrigation season.

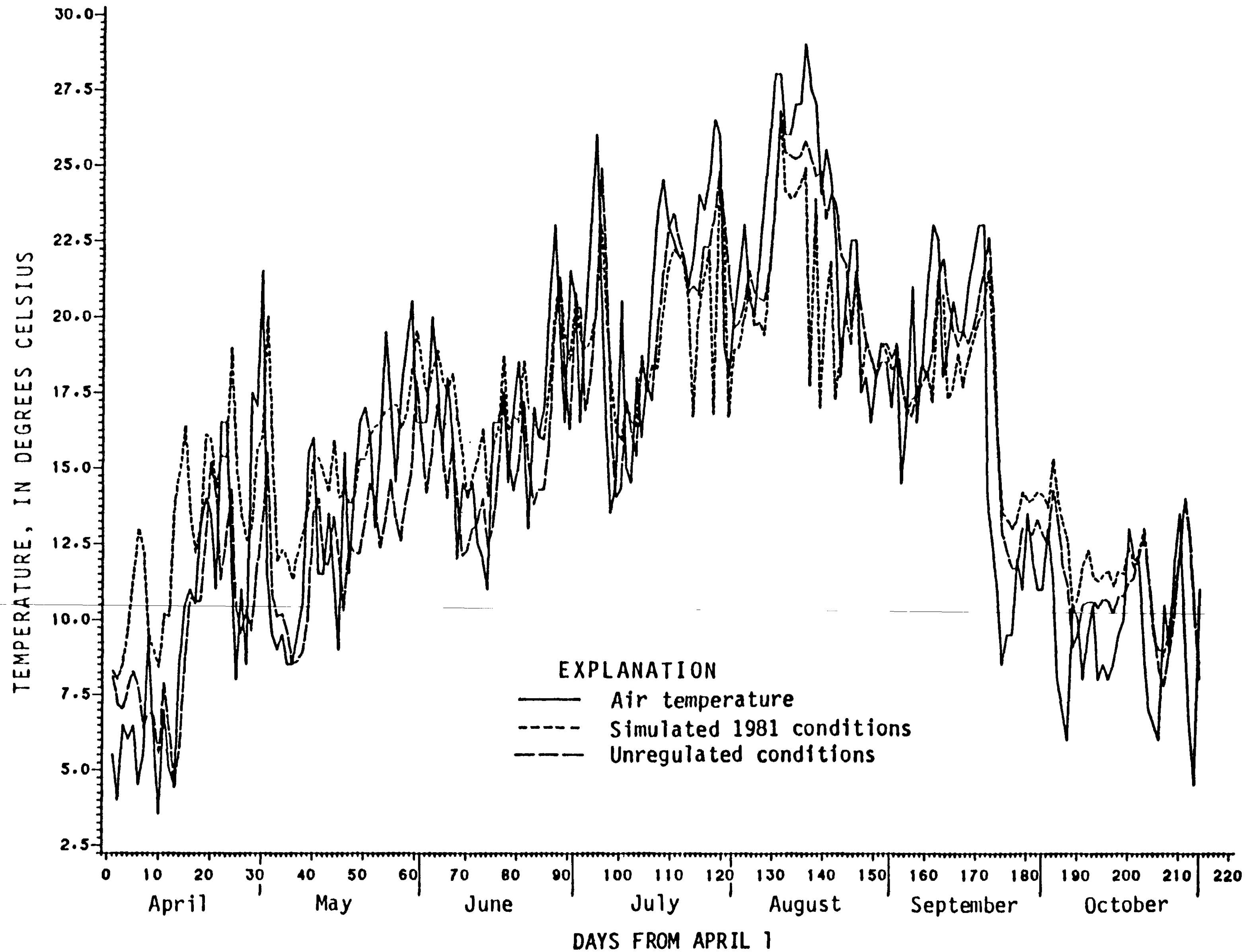

FIGURE 31.--Air and water temperatures for the Yakima River at Prosser (12) for observed and unregulated streamflow conditions during the 1981 irrigation season.

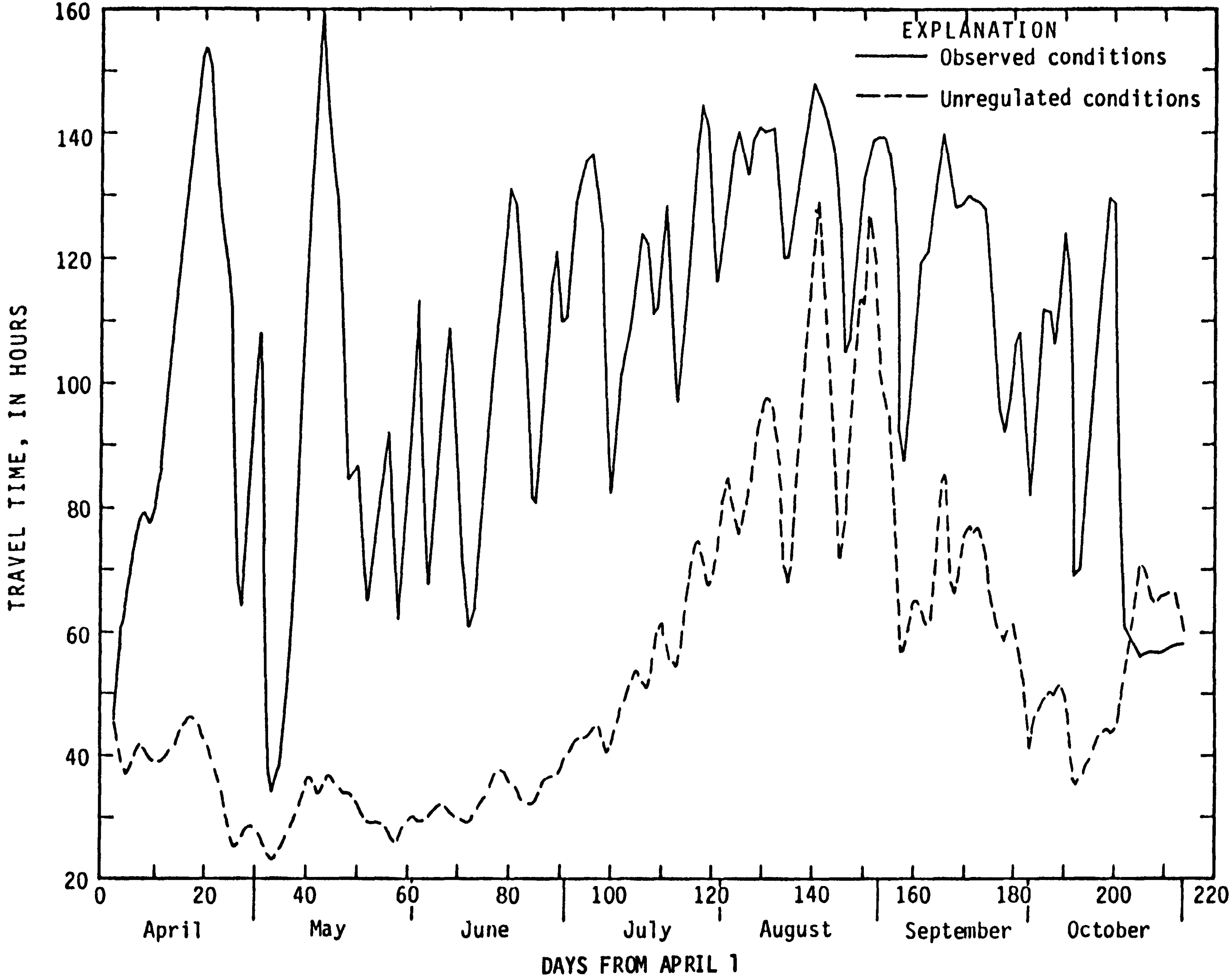

FIGURE 32.--Computed traveltime from the Yakima River at Martin (1) to the Yakima River at Prosser (12) for observed and unregulated streamflow conditions for the period April 1 to October 31, 1981.

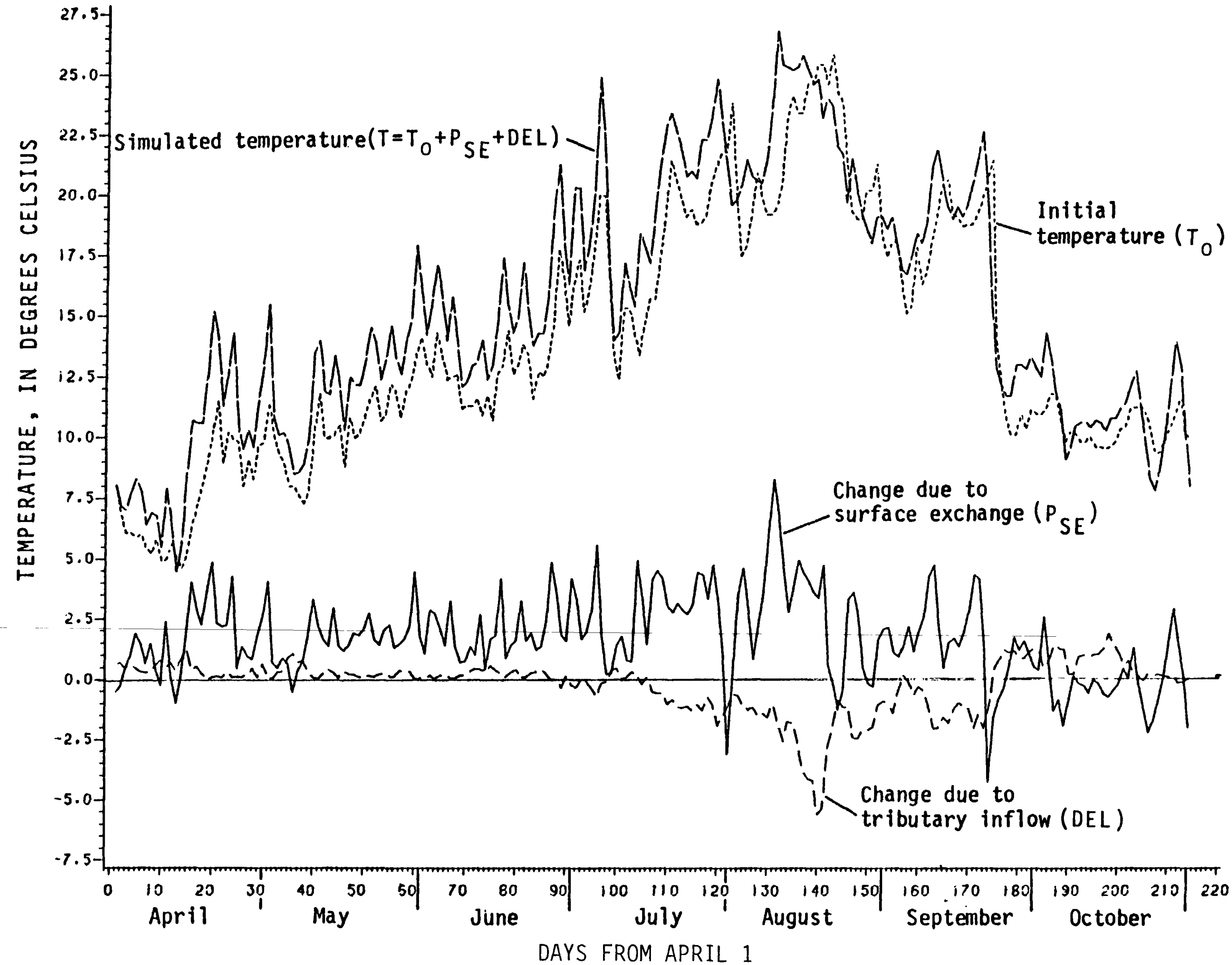

FIGURE 33.--Temporal variation in streamflow temperature of a parcel of water at the Yakima River at Prosser (12) for observed streamflow conditions for the period April 1 to October 31, 1981.

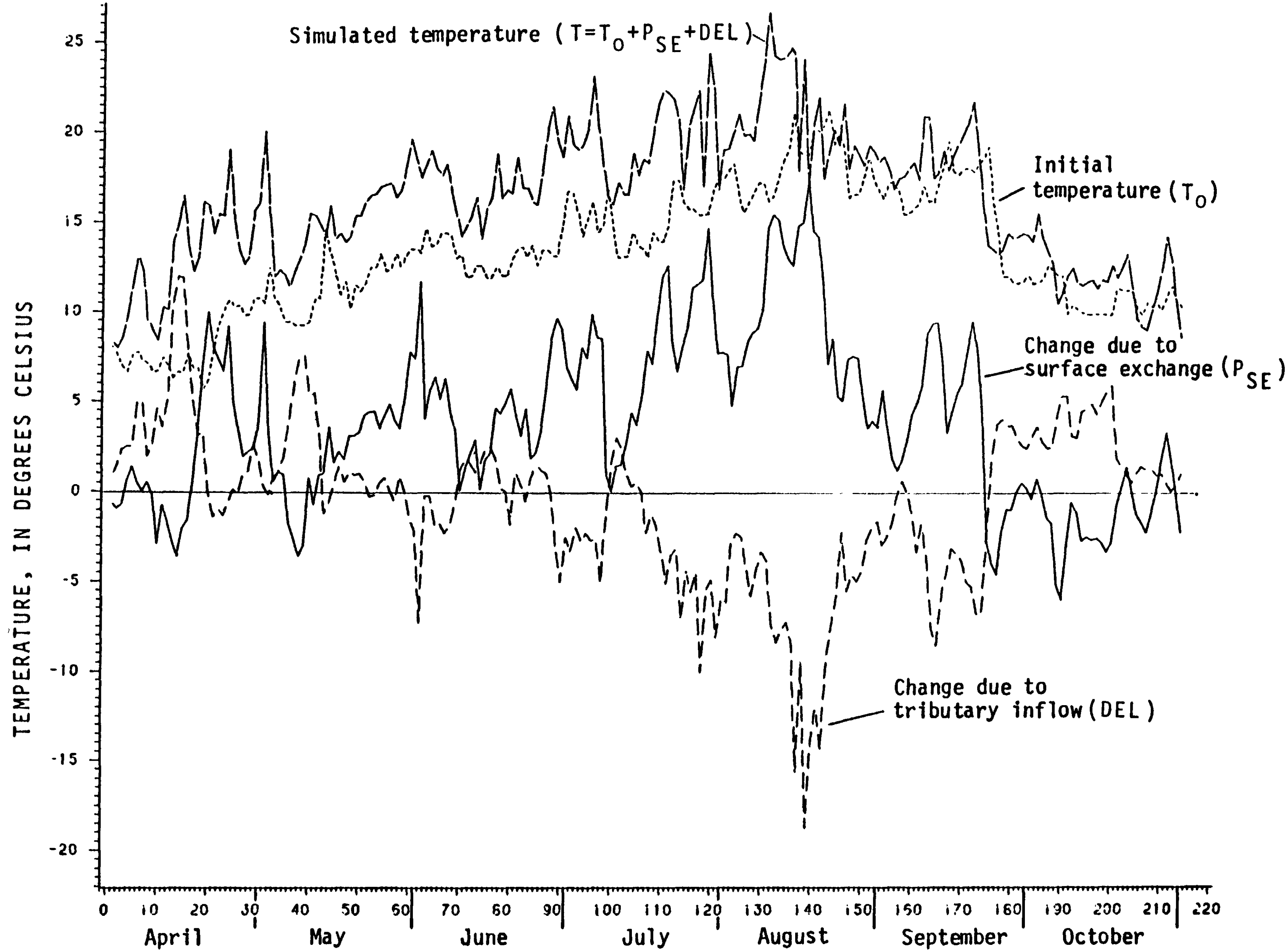

FIGURE 34.--Temporal variation in streamflow temperature of a parcel of water at the Yakima River at Prosser (12) for unregulated streamflow conditions for the period April 1 to October 31, 1984.

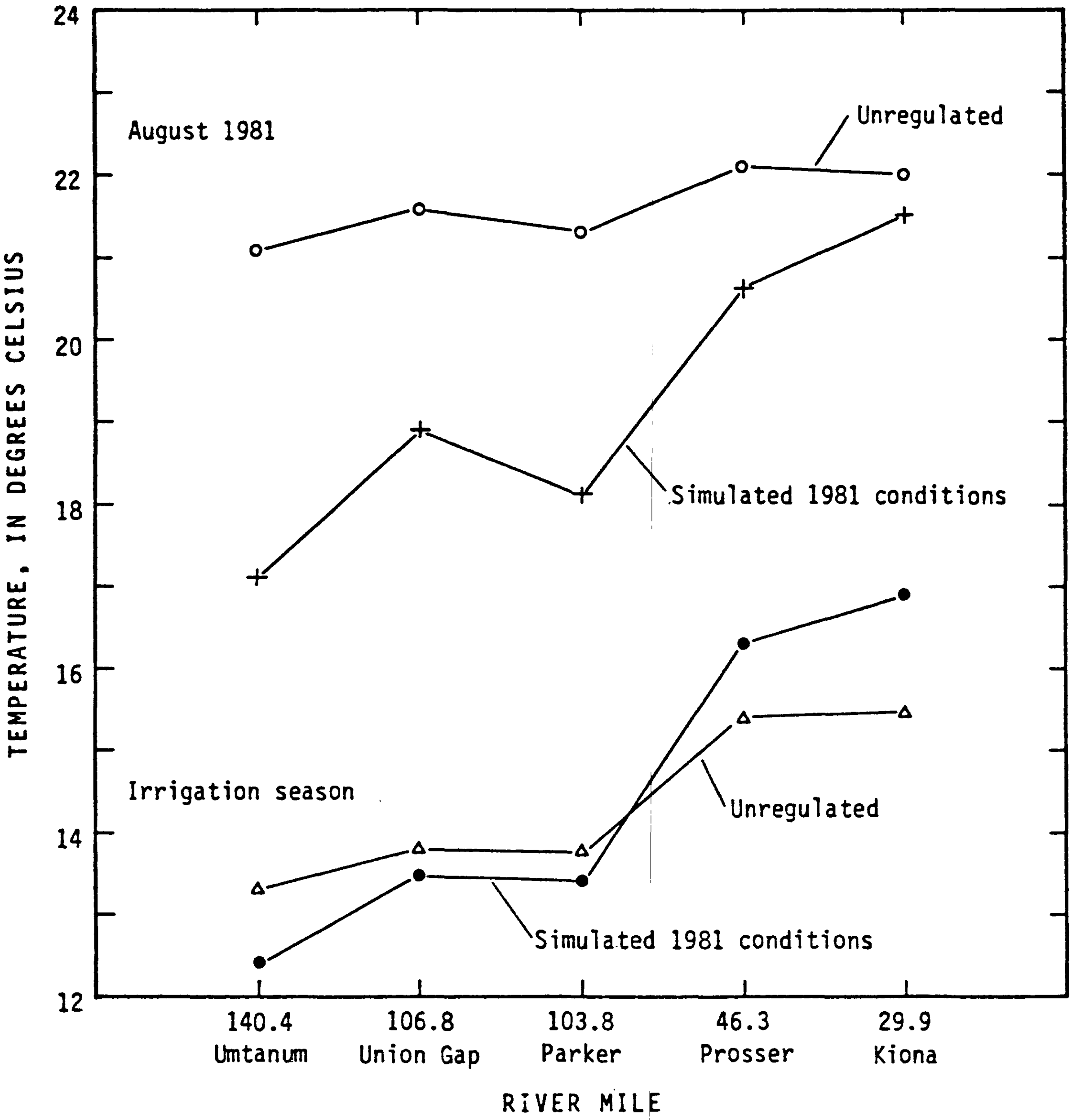

FIGURE 35.--Comparison of mean 1981 irrigation season and mean August 1981 temperatures simulated for observed and unregulated streamflow conditions.

Scenario 3: Fifty-Percent Basin

Scenario 3 estimates the effects of partial deregulation throughout the whole basin. The partial deregulation is considered to represent an increase in irrigation efficiency of about 22 percent; that is, the amount by which return flows are reduced is merely not diverted. This results in not only the same amount of water in the river system, but also more water upstream from the return flow points. Thus, only the timing and location of the discharge quantities were different from the 1981 regulated values. This difference can be seen best by examination of tables 6 through 10 and figures 12 through 18, where, for example, at Union Gap (8) the mean observed 1981 irrigation season discharge was 2,945 ft^3/s, compared with 3,215 ft^3/s for this simulation. The largest differences in flow quantities occur near Parker (9) and at Prosser (12). These two sites are directly below diversion dams and the effects of decreased diversion quantities are more apparent. Had the sites been farther downstream, the observed flows would have been higher due to return flows.

The water temperatures simulated for this scenario and for regulated conditions are nearly identical at all sites (figs. 19 through 27). The differences between monthly means of simulated regulated temperatures and the temperatures from this simulation are smaller than the model error. For example, the September mean observed, simulated regulated, and 50-percent basin temperatures of the Yakima River at Union Gap (8) are 16.2°, 15.4°, and 15.3°C, respectively. The 0.8°C difference between observed and simulated is greater than the 0.1°C difference between simulated regulated and 50-percent basin. However, as discussed in the verification subsection, changes between the simulated regulated and scenario values are appropriate in estimating effects. Thus, the 0.1°C change is a good estimator of the magnitude (small in this case) and sign of the changes from regulated conditions for this management alternative as simulated by the model.

The similarity between this scenario and the one with simulated regulated flows can be attributed to several factors. First of all, the decrease in return flows results in more water in the river from the point of diversion to the return flow point. This water has a slightly faster traveltime through the system than under the regulated flow conditions, mainly in the upper basin, and will undergo less heating; for example, see table 12.

Next, the major return flows in the lower basin, such as Toppenish, Satus, and Sulfur Creeks, are generally cooler than the river water at the return point. This is shown graphically in figure 36 for the water temperature for the Yakima River at Mabton (11), Toppenish Creek, and Satus Creek. Also, some of the smaller return flows consist partly of native ground water, which is at times cooler than the river water, and water that percolates through the soil zone, which is cooled by the process of infiltration. Therefore, after a parcel of water in this scenario reaches the lower basin, it is moved at a lower velocity than in the upper basin, it undergoes warming at nearly the same rate as regulated flow, and it does not receive as much of the cooling effect of large return flows due to the decrease in return flows. Thus, the water is heated to about the same temperature.

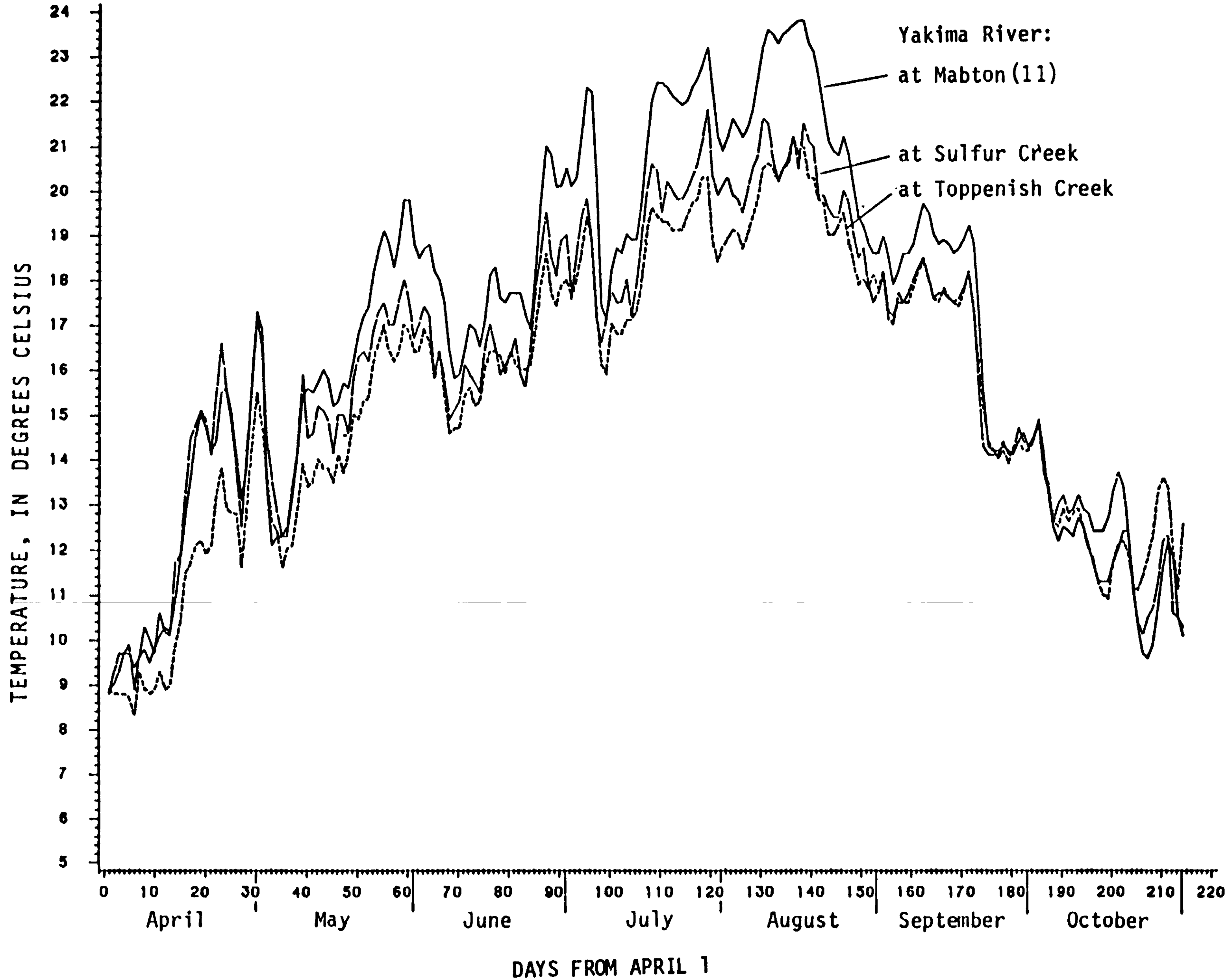

FIGURE 36.--Observed temperatures of the Yakima River at Mabton (11), Sulfur Creek, and Toppenish Creek for the 1981 irrigation season.

The reasons discussed above for the similarity of water temperatures between this scenario and the simulated regulated condition can be shown graphically. The initial temperature, the temperature change due to surface exchange processes, the temperature change due to tributary inflow, and the resulting simulated temperature of parcels of water located in the Yakima River below Easton on August 20, 1981, are shown in figure 37. The traveltime for these parcels of water is shown in figure 38. Figure 38 shows that there is a faster traveltime through the upper basin, and figure 37 shows that downstream of Parker (12) (river mile 103) surface exchange processes dominate in determining water temperature.

Scenario 4: Fifty-Percent Parker

Scenario 4 estimates the effects on water temperature, mainly in the lower basin, of reducing diversions at Roza Canal at 11 mile, New and Old Reservation Canals, Sunnyside Canal, Snipes and Allen Canal, Chandler (Kiona) Canal, Columbia Canal, and Richland Canal by an amount necessary to reduce return flows downstream of the Yakima River near Parker (9) by 50 percent, while maintaining the 1981 reservoir releases.

Examination of the discharge data (tables 6 through 10) results in similar conclusions about streamflow as were made for scenario 3; that is, more flow was in the river than for regulated conditions, and the timing of flows were altered (figs. 12 through 18).

Water temperatures for this scenario were similar to those for the simulated regulated scenario and scenario 3 (figs. 19 through 22). Water temperature differences were minor in the lower basin and the magnitude of the differences decreased in the downstream direction. As in scenario 3, the reasons for the similarities are the dominance of surface exchange processes in determining streamflow temperatures in the lower basin and the decreased effects of cool return flows.

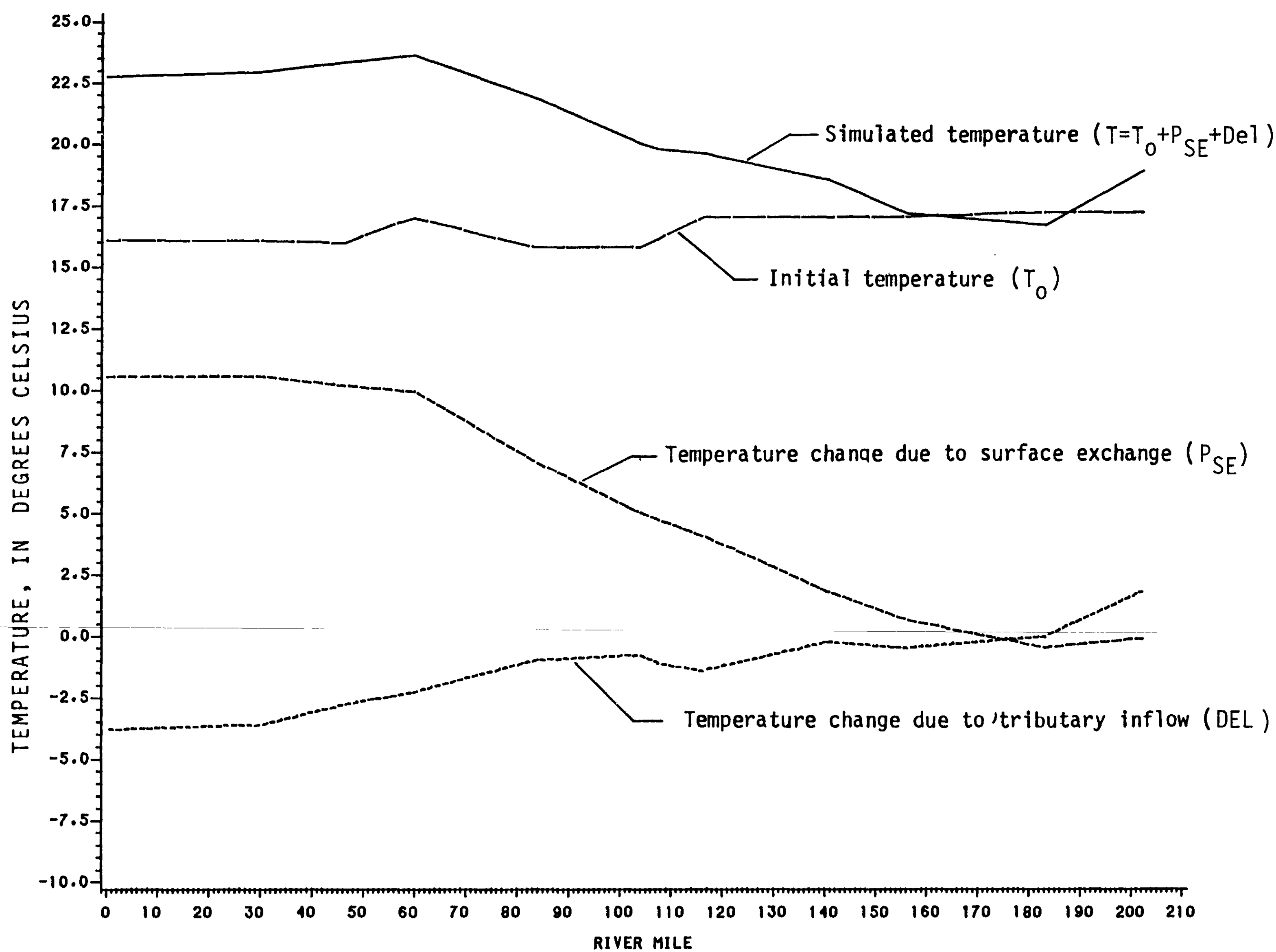

FIGURE 37.--Longitudinal variation in temperature of a parcel of water on August 20, 1981, for model simulation representing 50-percent decreased return flows in the basin.

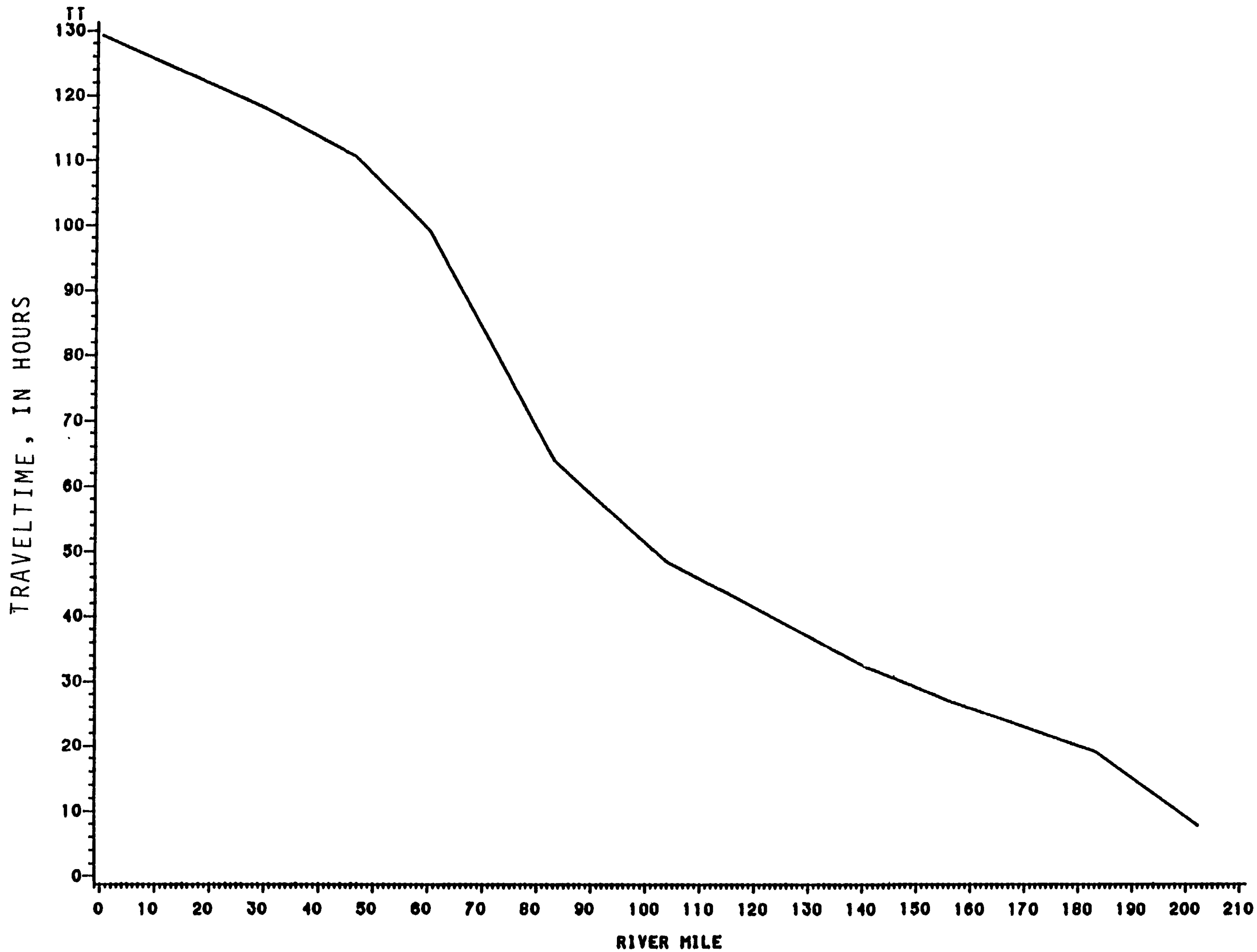

FIGURE 38.--Traveltime of a parcel of water from Easton on August 20, 1981, for model simulation representing 50-percent decreased return flows in the basin

WATER TEMPERATURE PERTAINING TO FISHERIES

Water temperature is an important factor during life stages of fish because it affects the growth rate and the concomitant size of a fish, the feeding rate, aging processes, disease susceptibility, food digestion, and availability of food. Water temperature (table 16) is a critical factor for survival of fish. Therefore, in order to provide data for possible evaluation of the potential for enhancing the fish habitat in the basin by managing streamflow, additional statistics for the mean daily water temperatures for the regulated simulation and the four scenarios are presented in this section.

In order to help define the variation in temperatures in the basin under the four scenarios, the frequency of occurrence of daily temperatures is presented in table 17. This table is of particular help in defining the occurrence of high temperatures. Seven-day mean daily low and high values of water temperatures are given in table 18. These values are presented because 7-day mean daily streamflow values are commonly used in fisheries management. Also, 7-day mean temperature values will be a good estimator of extremes and this period is longer than the traveltime through the system. Table 18 indicates that the high temperatures (which occur in August) will persist under the current and alternative scenarios. The frequency analysis and the 7-day mean high values also show a reduction in the amount of time that critical high temperatures are present in the stream under the four management scenarios, but very little reduction in the daily maximums.

TABLE 16.--Important water temperatures for life stages of selected anadromous fish[1]

[Values in degrees Celsius]

Fish	Life-stage	Accli-mation	Thermal death point	Optimum or preferred	Delayed life stage
Chinook salmon fry	Rearing	10	24.3		
	--do.--	20	25.1		
Coho salmon fry	--do.--	10	23.7		
	--do.--	20	25.0		
All salmon species	Migration			7.2-15.6	
	Spawning			5.8-12.8	5.5, 14.0
	Rearing			10.0-15.6	
	Incubation		15.7-16.5	0.0-12.8	
	All stages			9.5-13.9	
Chinook:					
Spring	Migration			3.3-13.3	21.1
Fall	--do.----			10.6-19.5	21.1
All	Spawning			5.5-14.0	
Coho:					
Adult	Migration			7.2-15.6	
Adult	Spawning			4.4-9.5	
Juvenile	Migration			7.2-16.7	
Steelhead trout	All		23.9	7.2-14.5	
	Spawning			3.9-9.5	

[1] From Brett (1956), Environmental Protection Agency (1971), and Bell (1973).

TABLE 17.--Frequency analysis of observed and model simulated mean daily water temperatures for selected temperature ranges for four sites along the Yakima River during the 1981 irrigation season

[Number in parenthesis refers to map sequence identifiers shown on figure 1]

Temperature range, in degrees Celsius	Frequency of occurrence, in percent					
			Scenario[2]			
	Observed	Predicted[3]	1	2	3	4
			Yakima River at Umtanum (7)			
0.0 - 5.0		4	4	4	4	3
5.1 - 10.0	17	12	19	21	14	11
10.1 - 13.0	32	46	39	33	43	45
13.1 - 15.6	25	18	16	9	17	20
15.7 - 21.0	26	21	22	24	22	21
21.1 - 24.9				6		
25.0 - 29				2		
			Yakima River near Parker (9)			
0.0 - 5.0			2	2		
5.1 - 10.0	11	15	22	23	20	18
10.1 - 13.0	23	35	32	31	29	29
13.1 - 15.6	28	20	14	8	19	19
15.7 - 21.0	38	29	27	27	30	32
21.1 - 24.9		1	2	8	2	1
25.0 - 29				1		
			Yakima River at Prosser[4] (12)			
0.0 - 5.0			0.5	0.5		
5.1 - 10.0	6	6	14	13	9	9
10.1 - 13.0	16	17	26	26	20	20
13.1 - 15.6	17	19	19	17	18	17
15.7 - 21.0	43	48	33	27	39	40
21.1 - 24.9	18	10	8	14	13	13
25.0 - 29.0		1		3	1	1
			Yakima River at Kiona (13)			
0.0 - 5.0				0.5		
5.1 - 10.0	6	7	12	12	7	7
10.1 - 13.0	17	15	24	23	16	17
13.1 - 15.6	15	16	22	20	20	20
15.7 - 21.0	40	44	33	28	43	42
21.1 - 24.9	20	18	8	13	14	13
25.0 - 29.0	2		1	4	1	1

[1]Values rounded.

[2]Scenario 1, 1981 reservoir storage, no diversions; scenario 2, unregulated conditions; scenario 3, all return flows decreased by 50 percent; scenario 4, return flows below Parker, decreased by 50 percent.

[3]Predicted values for the 1981 observed conditions.

[4]Observed record for Yakima River at Mabton is used as estimate for Yakima River at Prosser.

TABLE 18.--Seven-day mean daily low and high streamflow temperatures for selected sites on the Yakima River for the 1981 irrigation season

[Values in degrees Celsius; number in parenthesis refers to map sequence identifiers shown on figure 1]

Site	Observed		Predicted regulated		1981 reservoir storage only		Unregulated		All return flows decreased by 50 percent		Return flows below Parker decreased by 50 percent	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Umtanum (7)	7.6	18.9	4.6	18.8	4.3	19.5	4.4	24.8	4.5	19.4	4.6	18.8
Union Gap (8)	7.4	20.8	6.0	21.2	5.1	20.9	5.0	25.3	5.8	21.0	6.4	20.7
Parker (9)	8.3	19.6	6.6	20.2	5.2	21.0	5.2	24.8	6.0	21.1	6.7	21.0
Prosser (12)	9.4	23.6	10.2	24.5	6.3	23.6	6.2	25.6	8.2	24.9	8.2	25.1
Kiona (13)	8.4	24.9	9.1	23.0	7.2	23.9	6.8	25.5	8.8	24.3	8.9	24.3

SUMMARY AND CONCLUSIONS

A streamflow-routing and a streamflow temperature model were calibrated and verified for the Yakima River basin. A sensitivity analysis of the basin temperature model was used to estimate which parameters and variables were most important in the realization of streamflow temperatures in the Yakima River basin, and to determine the effects that reservoir water temperatures have on downstream water temperatures. The models were used to simulate 1981 irrigation-season streamflow and temperature both for historical conditions and for conditions under four alternate management scenarios representing different levels of deregulation of streamflow. The deregulation was accomplished by decreasing the quantities of return flows, diversions, and flow regulation by reservoirs in the basin. The four alternate scenarios were 1) 1981 reservoir releases and no diversions or return flows; 2) unregulated streamflow with no storage, no diversion, and no return flows; 3) 1981 reservoir releases with all diversions reduced by an amount necessary to reduce all return flows by 50 percent; and 4) 1981 reservoir releases with appropriate diversions reduced by an amount necessary to reduce return flows below Yakima River near Parker by 50 percent. The first scenario was the most effective in increasing streamflow and decreasing water temperature in the entire basin; the second scenario was the least effective.

The following paragraphs describe where the major effects of each scenario occurred and what those effects were, the major results of the sensitivity analysis, and the important general conclusions.

The first scenario represents the total effect of diversions and return flows on the streamflow and stream temperature regime in the basin under current, 1981, operating rules. This scenario was the most effective in increasing streamflow and decreasing water temperature in the entire basin. The mean irrigation-season discharge increased by 702 ft^3/s (cubic feet per second) to 3,396 ft^3/s at Umtanum (7), by 4,619 to 5,313 ft^3/s at Prosser (12), and by 3,603 to 5,422 ft^3/s at Kiona (13). Except for the October minimum daily discharges at Umtanum (7) and Union Gap (8), all monthly mean, maximum daily, and minimum daily discharges increased. The mean irrigation-season temperatures decreased at all locations; the magnitude of the change increased in a downstream direction. Mean monthly temperatures generally decreased throughout the basin, except for August near Parker (9) and for August and September at Umtanum (7) where the increases were about 0.5°C. The decreases ranged from 0.0°C in July at Umtanum (7) to 2.9°C in July at Kiona (13).

The second scenario was an estimate of natural streamflow and stream temperatures for the 1981 irrigation season. The second scenario was least effective for increasing streamflow and decreasing temperature in the river basin. The mean irrigation-season discharge was decreased by 470 ft^3/s to 2,224 ft^3/s at Umtanum (7) and increased by 312 to 3,257 ft^3/s at Union Gap (8) and by 2,012 to 3,831 ft^3/s at Kiona (13). The mean August discharges were decreased by 3,264 ft^3/s to 943 ft^3/s at Umtanum (7), 2,388 to 838 ft^3/s at Union Gap (8), and 46 to 1,345 ft^3/s at Kiona (13). However, near Parker (9) and at Prosser (12) where observed flows are especially low due to diversion, mean August discharges were increased by 531 ft^3/s to 888 ft^3/s and 991 ft^3/s to 1,288 ft^3/s, respectively. The mean irrigation-season temperatures generally increased in the downstream direction to Parker and decreased downstream of Parker (9). The mean monthly temperatures for August were increased by as little as 0.5°C at Kiona (13) and as much as 4.0°C at Umtanum (7).

The third scenario depicts the net effects of decreasing diversion to reduce all return flows by 50 percent and represents an assumed increase in irrigation efficiency by about 22 percent. This scenario was the second most effective for increasing streamflow and decreasing stream temperatures. The mean irrigation-season discharge of the Yakima River was increased by 439 ft^3/s to 2,258 ft^3/s near the mouth at Kiona (13). The effects on the mean irrigation-season temperature varied from 0.1° at Union Gap (8) near Yakima to 0.4°C at Kiona (13). Mean monthly temperatures increased, ranging from 0.0°C at Union Gap (8) to 0.2°C at Prosser (12) in September, and from 0.0°C at Kiona (13) to 0.3°C at Union Gap (8) in April, except for a decrease of 1.4°C at Prosser (12) in April.

The fourth scenario is similar to the previous one except that the assumed increased irrigation efficiency is only for the lower river basin, where the Yakima River first enters the Yakima Indian Reservation. This scenario was the third most effective for increasing streamflow and decreasing stream temperature. In management scenario 4, the mean irrigation-season discharge increased by 41 ft^3/s to 2,653 ft^3/s at Umtanum (7), by 972 to 1,656 ft^3/s at Parker (9), and by 460 to 2,279 ft^3/s at Kiona (13). The two smallest computed monthly minimum daily discharge values, excluding Kiona (1), were 529 ft^3/s in May and 673 ft^3/s in April at Prosser (12); which are significant increases over the observed monthly minimum daily discharges for both Parker (9) and Prosser (12), where discharges were less then 400 ft^3/s for all months of the irrigation season except October and as low as 31 ft^3/s in April at Prosser (12). Mean monthly temperatures both increased and decreased. The increases ranged from 0.0°C in April at Umtanum (7) to 1.1°C in August at Prosser (12), and the decreases were as much as 1.5°C, in April at Prosser (12).

The sensitivity analysis indicated that water temperature at any point in the basin is affected more by air temperature and reservoir outflow temperatures than by other factors. The effects of the reservoir release temperatures are moderate in the upper basin and negligible in the lower basin. Air temperature is the dominant factor in the lower basin. Reservoir outflow temperature and air temperature changes had significantly more effect on computed temperatures than changes in the hydraulic variables, wind speed, and model parameters. The effect of tributary inflow and return flow on water temperature is included in the different simulations.

In general, the temperature regime in the Yakima River basin upstream of Parker (9), Washington, appears to be adequate for maintaining temperatures preferred by anadromous fish. In the basin below Parker (9), water temperatures under all conditions were at times higher than those preferred by fish. Examination of the temperatures simulated by the model indicates that little reduction in the high temperatures would occur during August for any of the conditions studied, and for July and September, temperatures would at times be higher than those preferred by fish. However, these temperatures were generally lowered under all but the unregulated flow scenario. The July and September flow quantities for all scenarios varied less than the observed flows. Results from the four scenarios indicate that higher flow quantities and an improved temperature regime for fish could possibly be achieved during part of the low-flow period of the irrigation season in the lower river basin. The frequency of occurrence of high temperatures was generally reduced under the alternative scenarios; however, the 7-day mean daily high temperatures were not.

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APPENDIX A.--Stream-gaging sites in Yakima River basin for which discharge records were used in study

[Number in parenthesis are map-sequence identifiers shown in figure 1]

Station name	USGS or USBR station No.
Ahtanum Creek at Union Gap	12502500
American River near Nile	12488500
Buckskin Creek	12494200
Bumping River near Nile (14)	12488000
Cherry Creek	12493005
Cle Elum River near Roslyn (4)	12479000
Cle Elum River above French Cabin Creek	
Cowichee Creek	12494100
Golf Creek	
Kachess River near Easton (2)	12476000
Kauzlarich Creek East Fork	
Kauzlarich Creek South Fork	
Little Naches River near Nile (15)	12488501
Manashtash Creek	12483500
Naches River near Cliffdell (16)	12487000
Naches River near Naches (19)	12494000
Nile Creek	12489100
Oak Creek	
Rattlesnake Creek	12489200
Reecer Creek	
Satus Creek	12507660
Sorrenson Creek	
Sulfur Creek	12508850
Swauk Creek	12480800
Taneum Creek	12482000
Teanaway River below Forks	12478900
Tieton River at Tieton Canal Headworks (18)	12492500
Tieton River at Tieton Dam (17)	12491500
Toppenish Creek	12507508
Wenas Creek	12485960
Wide Hollow Creek	12500445
Wilson Creek	12484000
Yakima River at Cle Elum (5)	12479500
Yakima River at Easton (3)	12477000
Yakima River at Ellensburg (6)	12483500
Yakima River at Granger (10)	12506600
Yakima River at Kiona (13)	12510500
Yakima River at Mabton (11)	12508990
Yakima River at Prosser (12)	12509500
Yakima River at Umtanum (7)	12484500
Yakima River at Union Gap (8)	12503000
Yakima River near Martin (1)	12474500
Yakima River near Parker (9)	12505000

APPENDIX B.--Gaged canals in Yakima River basin for which records were used in study

Station name	USGS or USBR station No.
Anderson Canal	12483402
Blue Slough Canal	12510003
Boise Cascade Canal	12510008
Broadway Canal	
Bull Canal	12480015
Cascade Canal (new)	12480007
Cascade Canal (old)	12480006
Chandler Canal	12503002
City of Cle Elum M. and I. Canal	
City of Ellensburg M. and I. Canal	12480012
City of Yakima Irrigation Canal	12493003
City of Yakima M. and I. Canal (Gleed)	12493009
Clark Canal	12493012
Cobb Upper Side Canal	12493803
Columbia Canal	12501003
Congdon Canal	12493006
Ellensburg Mill and Feed Canal	12480012
Ellensburg Power Canal	12480006
Ellensburg Town Canal	12480009
Emerick Canal	12483401
Fogarty and Dyer Canal	
Foster Naches Canal	12493013
Fredericks and Hunting Canal	12483304
Frutivale Power Canal	12493002
Gleed Canal	12493008
Hubbard Granger Canal	12510006
Kelly and Lowry Canal	12493010
Kennewick Canal	12509600
Kiona Canal	12502001
Kittitas Canal	12476500
Knoke Canal	
Mill and Sons Power Canal	12480005
Moxee Company Canal	12510007
Naches Cowichee Canal	12493004
Naches Selah Canal	12490000
Nile Valley Canal	12483305
O'Connor Canal	
Old Union Canal	12493001
Reservation Canal (Old-New)	12503500
Richartz Canal	12510004
Richland Canal	12501004

(continued)

APPENDIX B.--Gaged canals in Yakima River basin for which records were used in study--Continued

Station name	USGS or USBR station No.
Roza Canal at 11.0 mile	12481301
Roza Power Canal at Roza Dam	12489600
Selah Moxee Canal	12481102
Simcoe Creek Canal	12506331
Sinclair and Cobb Canal	12493802
Snipes and Allen Canal	12508001
South Naches Channel Company Canal	12493011
Stanfield Canal	
Stevens Canal	12483302
Sunnyside Canal	12504500
Taylor Canal	12481101
Tenant Canal	12493801
Tieton Canal	12492000
Tjossem Canal	12480011
Union Gap Canal	12510005
Vertrees No. 1 Canal	
Vertrees No. 2 Canal	
Wapatox Power Canal	12493500
Westside Canal	12480008
Woldale Canal	12480010
Younger Canal	

APPENDIX C.--Gaged return-flow sites in Yakima River basin for which records were used in study

Station name	USGS or USBR station No.
Amon Wasteway	
Bichfield Drain	12500420
Bull Pasture Creek	
Corral Creek	12510200
Coulee Drain	12507560
East Toppenish Drain	12505350
Frazer Road Drain	12508997
Granger Drain	12505450
Green Valley Drain	
Griffen Lake Outlet	
Griffen Road Drain	
Marion Drain	12505500
Roza Power Plant Return	
Satus Drain 302	12508660
Satus Drain 303	12508690
Snipes Creek	12509820
South Drain	12508630
Spring Creek	12509700
Subdrain 35	12505410
Wamba Road Drain	12509492

APPENDIX D.--Equations used to compute daily ungaged inflow for the four locals in the lower basin

Granger local equals

Yakima River at Granger minus Yakima River near Parker plus Snipes and Allen Canal minus E. Toppenish drain minus Subdrain-35.

Mabton local equals

Yakima River at Mabton minus Yakima River at Granger minus Granger, Marion, Coulee, South, Griffin Road, Green Valley, Satus 302, Griffin Lake, and Satus 303 drains minus Toppenish, Satus, and Sulfur Creeks.

Prosser local equals

Yakima River at Prosser minus Yakima River at Mabton plus Chandler canal minus Frazer drain.

Kiona local equals

Yakima River at Kiona minus Yakima River at Prosser minus Spring, Snipes, Bull, and Corrall Canyon Creeks minus Chandler Power Return.

APPENDIX E.--Meteorological stations and mean air temperatures for 1981 irrigation season

NWS ident. No.[1]	Name	Map sequence indent.[2]	Elevation (ft)	Longitude	Latitude	Operator	temperature (1981 irr- gation season
969	Bumping Lake	A	3440	1211800	465200	USBR	9.8
1504	Cle Elum	B	1930	1205700	471100	NWS	13.2
2505	Ellensburg	C	1408	1203300	465800	NWS	14.1
2542	Eloplia	D	700	1191000	462400	NWS	16.0
4154	Kenniwick	E	390	1190600	461300	NWS	17.5
4394	Lake Cle Elum	F	2255	1210400	471440	USBR	12.0
4406	Kachess Lake	G	2270	1211200	471600	USBR	11.4
4414	Keechelus Lake	H	2475	1212020	471920	USBR	10.0
5713	Naches-Cliffdell	I	2300	1205600	465200	USBR	8.3
6215	Othello[3]	J	1190	1190300	464800	ARS	14.9
6768	Prosser	K	903	1194500	461500	ARS	15.7
7015	Richland	L	373	1191600	461900	NWS	18.0
7038	Rimrock Reservoir	M	2730	1210800	463900	USBR	12.3
8009	Stampede Pass[3]	N	3958	1212000	471700	NWS	8.6
8207	Sunnyside	O	747	1200000	461900	NWS	16.8
8300	Teanaway	P	2080	1205000	471440	USBR	12.1
8442	Tieton-Headworks	Q	2280	1210000	464016	USBR	13.4
8959	Wapato	R	841	1202500	462600	NWS	16.5
9465	Yakima[3]	S	1052	1203200	463400	NWS	15.6
	Hanford[3]	T	733	1193600	463000	Battelle Co.	18.1

[1] National Weather Service identification number.

[2] Letters refer to map sequence identifiers shown on figure 1.

[3] Sites with wind speed data.

APPENDIX F.--Locations, names, and aggregations of inflows and outflows that were used in streamflow-temperature models

River mile	Grid No.	Station name	Type of temperature record used for inflow loading sources[1]
Tieton Basin: Time step = 4 hours			
20.8	1	Rimrock Outflow	T
17.2	2		
14.4	3	Tieton Canal	
14.2	4	Headworks local	4DY
2.6	5	Cobb, Sinclair, and Tenant Canals	
2.2	6	Oak Creek	HA
0.0	7		
Naches Basin: Time step = 2 hours			
60.4	1	Burping Lake Outflow	T
48.1	2	American River	HA
44.6	3	Little Naches	T
36.5	4	Anderson and Emerick Canals	
36.0	5	Cliffdell local	4DY
31.0	6	Nile, Fredrick and Hunting, and Stevens Canals	
28.0	7	Nile and Rattlesnake Creeks	T
19.5	8		
18.4	9	Naches-Selah Canal	
17.5	10	Tieton River	C
17.1	11	Wapatox Canal	
16.8	12	Naches-Selah return, Naches local, small returns	4DY
14.9	13	Foster and Naches, Clark Canals	
13.9	14	S. Naches, Kelley and Lowry Canals	
9.4	15	City Yakima (Gleed), Gleed, Morrisey, Congdon Canals	
6.1	16	Wapatox Power return, E. and N. Forks Kauzlarich Creek	T
3.6	17	Naches-Cowchee and City Yakima Irrigation Canals	
3.3	18	Buckskin Creek	T
2.8	19	Cowichee Creek	T
2.5	20	Fruitvale and Old Union Canals	
.5	21	Tieton Canal Return (A), small returns at mouth	A (12.0°C)
0.0	22		

★ GPO 1986-693-359

APPENDIX F.--Locations, names, and aggregations of inflows and outflows that were used in streamflow-temperature models--Continued

River mile	Grid No.	Station name	Type of temperature record used for inflow loading sources[1]
Upper Yakima: Time step = 4 hours			
214.5	1	Lake Keechelus Outflow (Yakima R. at Martin)	T
203.5	2	Kachess River	T
202.5	3	Kittitas Canal	
202.	4	Easton local	4DY
185.6	5	Cle Elum River	T, HA
183.1	6	City of Cle Elum M & I Canal	
183.0	7	Kittitas Return (A) Cle Elum local	4DY
182.0	8	Younger and O'Connor Canal	
176.1	9	Teanaway River	T
169.4	10	Swauk and Taneum Creek	4DY
166.2	11	Westside, Knocke, and Cascade Canals	
162.	12	Ellensburg Power, Cascade Pump, Mills and Sons, Ellensburg Town, Woldale, and City Ellensburg M & I Canals	
157.1	13	Ellensberg Mill and Feed	
155.8	14	Ellensburg returns, local	A (11.5°C)
154.1	15	Manashtash, Reecer Creeks	4DY
152.5	16	Bull, Fogarty and Dyer, Vertrees #1, #2, and Tjossen Canals	
149.9	17	Stanfield Canal	
147.0	18	Wilson, Cherry, and Sorenson Creeks	4DY
142.0	19	Small returns at Umtanum and Kittitas return (B)	A (12.0°C)
140.4	20	Umtanum local	A (12.0°C)
127.9	21	Roza Canal	
122.9	22	Selah-Roxee, Taylor Canals	
117.3	23	Wenas, Golf Creek	T
116.3	24	Naches River	C
115.2	25	Boise-Cascade, Union Gap, Richartz, Moxee, Hubbard and Granger, Blue Slough Canals	
113.3	26	Roza Power Return	T
107.5	27	Wide Hollow Creek	T, HA
107.6	28	Small returns at Union Gap, Tieton Canal return (B), Union Gap Canal return	4DY
106.9	29	Ahtanum Creek	T
106.0	30	Union Gap local	4DY
105.0	31	Sunnyside, New and Old Reservation Canals	
103.7	32	Parker local	A (12.0°C)
103.0	32a.		

APPENDIX F.--Locations, names, and aggregations of inflows and outflows that were used in streamflow-temperature models--Continued

River mile	Grid No.	Station name	Type of temperature record used for inflow loading sources[1]
Lower Yakima: Time step = 4 hours			
103.7	1	Yakima River near Parker	C
97.	2	Snipes and Allen Canals	
86.1	3	E. Toppenish drain	T
83.2	4	Subdrain 35	HA
83.0	5	Granger local	A (16.6°C)
82.6	6	Granger, Marion drains	HA
80.4	7	Toppenish Creek	T
77.0	8	Coulee Drain	HA
69.5	9	Satus Creek, South Drain	T
65.1	10	Griffin and Green Valley Drains	HA (Same as grid No. 11)
62.4	11	Satus 302 and Griffin Lake Drains	HA
61.0	12	Sulfur Creek, Satus 303 Drain	T
59.8	13	Mabton local	A (16.6°C)
55.9	14	Frazer Drain	HA
47.0	15	Chandler Canal	
46.3	16	Prosser local	A (16.6°C)
40.0	17	Spring, Snipes, and Bull Creeks	4DY
35.8	18	Chandler Return	HA
34.9	19	Kiona Canal	
33.5	20	Corral Canyon Creek	4DY
29.9	21	Kiona local	A (16.6°OC)
18.0	22	Columbia, Richland Canals	
2.1	23	Amon Wasteway	HA
0.0	24	mouth	

[1]Record types are defined as:
- T - thermograph record;
- 4DY - record based on 4-day moving average of air temperature at that grid;
- HA - record based on harmonic analysis of synoptic water-temperature measurements;
- C - computed from lagrangian temperature model; and
- A - constant temperature approximating an average air temperature.