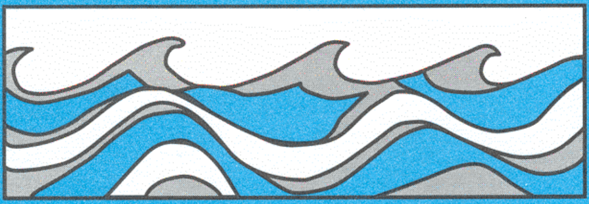
University of Washington
Department of Civil and Environmental Engineering

STREAM TEMPERATURE STUDY, NORTH FORK SNOQUALMIE RIVER, WASHINGTON

R. E. Nece



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Charles W. Harris Hydraulics Laboratory
Department of Civil Engineering
University of Washington
Seattle, Washington 98105

STREAM TEMPERATURE STUDY, NORTH FORK SNOQUALMIE RIVER, WASHINGTON

by

Ronald E. Nece

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Technical Report No. 23

Completion Report
on
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Budget No. 10E-3992-3006
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TABLE OF CONTENTS

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The work was performed by Ronald E. Nece (Principal Investigator), Professor of Civil Engineering, and by William J. Stolte and Clarence J. Garrison, Research Assistants in Civil Engineering. Mr. Stolte in particular prepared much of the field data for presentation in this report.

ABSTRACT

The upper basin of the North Fork of the Snoqualmie River was used for a study of stream temperatures in the headwater regions of a typical Pacific Northwest mountain river. Water temperature, stream flow, and climatological data are given for the heating season of calendar year 1967.

A simplified procedure is suggested for predicting water temperatures at a given station on such a stream. The suggested procedure uses a typical heat energy-budget approach; a number of terms usually considered in heat budget calculations are omitted, while provision is made for consideration of groundwater temperatures. The accuracy of the suggested simple scheme remains to be verified because stream travel times required in the calculations have yet to be obtained on the study river.

Measurements of air temperatures and of solar radiation in the test basin indicate that these variables may indeed be satisfactorily predicted on the basis of conventional data obtained at the federal weather station in the same general region.

Key words: water temperature*, hydrology, micro-meteorology*

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The work described in this report is a study of stream water temperatures in the upper reaches of a typical Pacific Northwest mountain river.

The original objective of the study, initially viewed as having a long-term period of data collection, was to record changes in downstream water temperatures caused by the construction of a dam on the stream, with subsequent controlled releases from the impoundment. Natural state (pre-construction) temperatures were to be correlated with regional climatological conditions; the study was to be carried through reservoir filling stages and coupled with information gathered on reservoir temperatures in order to evaluate the effects of the dam on downstream water temperatures. This particular incentive was furnished because of the plans of the United States Corps of Engineers to construct dams on the Middle Fork and on the North Fork of the Snoqualmie River, on the western slope of the Cascade Mountains. The dams were in the "pre-authorization" stage when the study was proposed. After the study was formally initiated, however, it became apparent that actual construction dates for these proposed dams would be deferred longer than originally anticipated; accordingly, study objectives were changed.

Emphasis was concentrated on those factors which influence temperatures in a mountain river. One objective was to see if relatively simple calculation methods could be devised for formulating predictions of stream temperatures in the upper reaches of such rivers. This involved consideration of the temperature of the ground water flow, an aspect of stream temperatures that has not received much prior attention. A second objective was to learn how well conventional available weather data, measured at a station in the same general mountain area, could be employed at a different locality in water temperature prediction calculations.

Field measurements of stream water temperatures were obtained beginning April, 1966, and were continued through August, 1967. Records are quite complete for most of this period, with largest gaps in the data occurring in February and March, 1967. Limited climatological data were obtained in the late summer and early autumn of 1966 and throughout the summer of 1967. These data were confined to the drainage basin of the North Fork of the Snoqualmie River, as study efforts were concentrated on the smaller of the two areas involved in the original proposal. Emphasis is on data obtained during the river heating season (May-August) of 1967.

Field data obtained are summarized in this report; data acquisition methods and locations are described. Attempts to develop a computational procedure for predicting stream temperature variations as functions of assumed climatological conditions and streamflows are described. The procedure considers stream travel time and ground water effects in "heat budget" calculations, in addition to such climatological factors as solar radiation, air temperature, etc. These factors are incorporated with methods which have been presented by other investigators. No actual calculations are presented, because at this time more work needs to be done in some particular areas before the calculation procedures can be tested properly. Results of this phase of the study are therefore inconclusive. The question of transferral of some climatological data from one area to another was checked in more detail, with results presented and discussed.

II. DESCRIPTION OF FIELD AREA

Stream temperatures were obtained at the United States Geological Survey gaging station on the North Fork of the Snoqualmie River, near Snoqualmie Falls, Washington.

The drainage area above the gaging station is 64.0 square miles. The average discharge, based on a 25-year period of record, is 491 cfs; the maximum discharge during the period of record (1929-49, 1961-66) is estimated as 15,800 cfs, and the minimum observed discharge is 30 cfs (10).*

The location of the drainage basin is shown in Fig. 1, and the basin is outlined on Fig. 2. At the gaging station the river flows southerly, but the basin has a predominately east-west orientation. Elevations range from an altitude of 1,130 feet at the gaging station to over 5,000 feet at the divides at the upper (eastern) end of the basin. The basin therefore contains some mountain areas above timberline; mountain lakes on some tributaries are at general elevations of 4,000 feet and remain frozen until the late spring.

The major streams in the basin are the North Fork and three tributaries: Phillippa, Sunday, and Lennox Creeks. Stream lengths and drainage areas are listed in Table I. Upstream from the confluence of Lennox Creek and the North Fork the basin is mostly forested, although some logging has taken place. In the lower basin logging operations have been rather extensive on both sides of the river, and in the summer of 1967 extensive logging operations were carried out in the lower Phillippa Creek and Sunday Creek areas. In the summer months the shade provided by trees along the main river was not considered excessive. Except in the narrow valley in the 2 - 3 miles immediately upstream from the gaging station, shading from surrounding topography is also negligible along the lower stem of the main river. Observations from aerial photographs of the basin indicate that some tributaries are denuded of vegetation which would provide shade.

The North Fork is a typical Pacific Northwest mountain river. The usual succession of pools, rapids, etc., invalidates any rigorous use of the

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*Numbers in parentheses refer to references listed in the Bibliography.

more common uniform-flow equations of open-channel hydraulics. The stream bed is of rounded gravel and cobbles; during low periods much of the bed area is exposed. At high flows, discharges cover the bed and are confined between steep banks. The elevation at the confluence with Lennox Creek, 11.1 miles upstream from the gaging station, is approximately 1550 feet; in the lower basin, the average drop of the North Fork is 38 feet per mile, or an average slope of about 0.007.

Stream temperatures were also obtained at the USGS gaging station on the Middle Fork of the Snoqualmie River, near Tanner. This thermograph was installed at the beginning of the project because the first of the two dams to be constructed on the upper branches of the Snoqualmie is planned for the Middle Fork. The gaging station is located 9 air miles (south and slightly east) of that on the North Fork, at an elevation of 780 feet. The average discharge, from a 5-year period of record, is 1,247 cfs; maximum and minimum flows during this period are 22,800 cfs and 140 cfs, respectively.

River temperature data were thus available from two streams, providing a comparison of water temperatures for discharges from two contiguous basins having rather similar characteristics but different areas. Temperature characteristics of the two streams are quite comparable.

III. SCOPE AND METHODS OF DATA ACQUISITION

Water Temperatures

Stream temperatures were obtained by continuously recording Foxboro Model 40 filled thermal system thermographs. Instrument housings were installed within USGS gaging station shelters; the 100-foot liquid-filled capillary tubes connecting the immersed bulb and the helical sensing element in the recorder were threaded through a combination of steel and plastic pipes to prevent damage to the tubes. The immersed bulbs were each enclosed in a length of 1-1/2-inch pipe, open at the lower end and perforated to allow adequate water circulation past the bulb; these pipes were rigidly mounted so that the sensing bulb would be at least one foot below the water surface during low flow periods. Ink-line recordings were obtained on charts driven by a 35-day wind mechanical clock. The temperature range of the recorder is 0-100°F; charts have 1-degree F divisions.

The thermographs were routinely checked and calibrated against temperatures measured by hand-held mercury thermometers and by thermistor-sensor telethermometers. The latter were also used to verify that the streams were indeed fully mixed as far as temperatures were concerned, and that for local measurements in flowing water (i.e., at the thermograph bulb site) observed temperatures were insensitive to whether the thermograph bulb itself was shaded or not. These measurements indicated that the thermograph reading (with any calibration corrections) could be considered the average temperature of the water in the entire cross-section of the stream, independent of instantaneous shade conditions, the expected situation for highly turbulent mountain streams.

Stream Flow

Unpublished stream flow data for the North Fork were made available by the Surface Water Branch of the United States Geological Survey. The discharges listed are 'provisional' values of the average daily flows; values when published for the 1967 water year may vary slightly if revisions are necessary in the rating curve at the North Fork station.

Climatological Data

Two 'weather stations' were established in the drainage basin. One was approximately 1/4-mile from the gaging station, at elevation 1250 in a relatively flat, logged-off area on a bench to the east of the river; the other was near the confluence of Lennox Creek and the North Fork, at elevation 1560, again in a logged area. Both sites were selected to be free of shading from trees or topography, so that solar radiation measurements would be free of local shadow effects. The Lennox Creek site was selected as being most representative of the entire basin; further, access to the upper basin was not convenient in terms of establishing and servicing another station. The two weather stations were established for a brief period at the end of the summer, 1966. They were removed in early October as a safety precaution prior to the start of hunting season and were reestablished in the spring, 1967. Records obtained at the two stations were nearly the same. Each station housed a thermohygrograph and a pyrheliograph.

The thermohygrographs were Kahlsico Model WE-24-01 units, equipped with a 30-day hand-wind clockwork-driven recording drum; temperature range of the unit is 50°C, and the charts have 0.5°C divisions. A continuous record of the relative humidity was also obtained. The instruments were mounted inside conventional instrument shelters.

Solar radiation on a horizontal surface was measured by Belfort Model 5-3850 pyrheliographs, mounted on top of the instrument shelters. Recorded values were considered to be the net incoming short-wave insolation. The units were equipped with 7-day hand-wind mechanical clockwork drive; the chart range is 3 calories/sq. cm. per minute, over a 3-inch chart height.

Climatological data were limited to the three measurements indicated, on the assumption that the data would suffice for the most important 'climatological' terms in heat-budget calculations. No wind or precipitation data were considered.

Ground Water Temperature

It is expected that the temperature of ground water inflow plays an important role in stream temperatures in the upper reaches of rivers. While it is often assumed that ground water temperatures remain constant over the year, at a temperature approximating the mean annual air temperature of the region, such assumptions are more valid for ground water flows at some distance below the ground surface and might not be so valid in the mountain area under study as far as ground water inflow to the streams is concerned. Accordingly, a limited program of weekly water temperature measurements at selected seepage sites was initiated during the summer of 1967; some of the sites were at roadside cuts, others were closer to the river. Measurements were taken with the thermistor-probe thermometer; the thermistor sensor was inserted into a hole dug into the soil in the seep, the soil replaced, and the temperature recorded after the instrument had come to equilibrium.

Ground water temperature measurements made in the lower Phillippa Creek area were taken as representative of values for the lower basin area. Some apparent anomalies in values were recorded at particular sites. In August, one series of measurements was made well upstream from the confluence of Lennox Creek and the North Fork. Results from these measurements are discussed briefly in the following paragraph.

General Comments, Data Trends

Field data for the 1967 calendar year are listed in Table II and are plotted in Fig. 3. Seasonal trends in the data are evident from the curves plotted in Fig. 3. The summer of 1967 was exceptionally warm and dry. This fact is indicated indirectly by the long recession curve on the hydrograph at the North Fork gaging station; from July 26 through August 20, for example, there was essentially a constant drop in stage at the North Fork gaging station, with the recorder indicating no rises in stage exceeding 0.02-foot per day.

Stream temperature data during the winter are intermittent because access to the gaging station was limited by snow; servicing of the thermograph was not performed routinely. Data at the North Fork station were otherwise obtained routinely except for the periods June 23-30 and July 2-20, when the recorder malfunctioned. The values plotted in Fig. 3 and listed in Table II for these two intervals are extrapolated from data at the Middle Fork station. As justification for this step, Table III is incorporated in the data summary; shown are data for the North Fork and the Middle Fork stations for the months of June and July, 1966, from which the agreement between the two stations is evident.

Air temperature data listed are based upon readings obtained at the Gaging Station site because the hygrothermograph at the Lennox Creek station sustained a number of shut-downs. When both hygrothermographs were operating, results at the two stations were in close agreement. The precision of air temperature readings was uncertain; inconsistencies were noted in response of the hygrothermographs to changes in air temperature in comparison to the response of mercury thermometers and battery-powered thermistors. Such discrepancies involved time lags in instrument response, were not observed to have any consistent trends, and were usually of magnitude less than 1°F; accordingly, no corrections were applied to instrument readings.

Solar radiation data listed were obtained at the Gaging Station instrument because this site had a more complete record. Agreement between pyrheliograph readings was good on clear days, understandably not so good on days of partial overcast sky conditions. These data are considered again in more detail in Section IV.

Diurnal variations in relative humidity at both weather stations were quite consistent. The relative humidity data are not plotted, but are listed in Table II in the form of the number of hours during the day during which the average relative humidity was a value less than 100 percent. A 100 percent value was reached for all nights. The duration for the less-than-100 percent average was derived from the difference between the mid-point on the falling and rising limbs of the relative humidity versus time record; the time to achieve equilibrium conditions of relative humidity during either daytime or evening was between one and two hours.

Ground water temperatures at the sites in the lower Phillippa Creek area measured in June, July, and August averaged 53°F, with a range of ± 2°F. The one set of readings in the upper basin (during August) yielded an average value of 48°F; these latter readings were obtained both for ground seeps and in small, but sheltered, streams. The difference in values is not surprising, and tends to be in line with the assumption that ground water temperatures approximate mean annual air temperatures; the mean air temperatures are undoubtedly lower at the higher elevations. No significant trend in ground water temperatures with time was observed at any of the measurement locations during the data period, which as shown in Fig. 3 comprised the heating period for the river waters. No data are available on the basin to give figures for mean annual air temperatures.

Ground water temperatures at one site in the lower basin averaged 47°F during the June - August period. This site was approximately 3 river miles downstream from the confluence of Phillippa Creek; a possible explanation is an artesian condition linking this site to ground water sources at a much higher elevation. The differences observed in the ground water temperatures over the basin would seem to preclude the use of a single value for the entire drainage basin for use in heat budget calculations.

The curves in Fig. 3 indicate very obvious connections between some of the variables. Average stream temperatures rise throughout the summer heating period, reaching peak values in late August. This is indicated also in Fig. 4, in which average river temperatures are plotted for both 1966 and 1967; while trends are comparable for the two years, and peak temperatures occur at about the same time, the greater total heating during 1967 is evident. Stream temperatures during the early part of the heating season are noticeably lower than ground water temperatures, reflecting the fact that during this time river flow is due primarily to surface run-off of snow melt from the upper basin.

Diurnal variations in river temperature increase with increased solar radiation and decrease with increased stream flows. An illustration of the former is clearly evident in Fig. 3 for the dates July 26-27, during which time there was very little change in stream flow; the two dates in question were overcast, and river diurnal temperature variations decreased markedly. It is difficult to isolate the effects of solar radiation and diurnal variations in air temperature because the two correlate closely in this near-mountain region; their relative importance in heating of river waters can best be demonstrated by actual heat budget calculations.

The peak discharges during May and June were associated with increases in snow-melt run-off due to both precipitation and high temperatures. Observed lower diurnal temperature fluctuations during these higher flows depended in part upon the higher average stream velocities (producing a shorter time during which the water could be exposed to heating) and in part upon the greater depths, hence water volumes in the river. Depending upon variations in stream cross-section with discharge, the amount of water to be heated by exposure to atmospheric factors (e.g., solar radiation and air temperature) varies with respect to the available area of water-air interface at the water surface.

Diurnal water temperature fluctuations, when significant, followed the pattern indicated in Fig. 5. Maximum water temperatures occurred at about 1800 hours, minimum values in the morning from about 0800 to 0900 hours. This pattern indicates the significance of time of exposure to heating or cooling experienced by the river flow during its travel upstream of the thermograph. Also, the normalized temperature pattern appears to be rather independent of stream flow rate. The discharge hydrograph shown on the same figure is typical of those observed from the stage recorder trace for the period June 13 through

July 5, during which time there were daily fluctuations in stream flow following periods of precipitation and late snow-melt runoff. These daily fluctuations, of course, do not appear on Fig. 3. It is noted that maximum discharges occurred in the early morning hours, sometime shortly after midnight, and minimum flows between 1500 and 1800 hours; flow rate and water temperature diurnal variations for these conditions were almost entirely out of phase.

The trends noted above can be explained on physical grounds; it is also evident that the various factors leading to an observed variation with time of river temperature at a particular location interact in a complex fashion, perhaps more so for a mountain stream such as the river under study than for many other rivers investigated in other, prior studies. Consideration of the various items in attempting to formulate a suitable mathematical model for temperature predictions is discussed in Section V.

IV. SPATIAL CORRELATION OF CLIMATOLOGICAL DATA

Station Locations

Standard local climatological data were available (7) from the U. S. Environmental Science Services Administration station at Stampede Pass, Washington. The Stampede Pass station is approximately 29 air miles southeast of each of the two weather stations established in the basin, is at a greater elevation, and is situated on the crest of the Cascade Mountains. The Stampede Pass station thus would experience the same general regional climatological conditions, but not the same strictly local conditions experienced in the basin of the North Fork of the Snoqualmie River; it is, however, the only complete station in the general topographical region, and is the logical choice for the purposes of the study. Ground cover conditions in the general vicinity are comparable. Data from the Seattle station, while available, were not compared with those in the North Fork basin because of the common discrepancies in cloud cover which exist between the Puget Sound basin and the Cascade Mountains.

The locations of the three weather stations for which data are compared are listed below.

Station	Longitude	Latitude	Elev.
Stampede Pass (ESSA)	121°20'W	47°17'N	3958
Gaging Station	121°42'W	47°36'N	1250
Lennox Creek	121°35'W	47°40'N	1560

Air temperature and solar radiation data were the only ones studied, as these two factors are most important in heat budget calculations in the 'maritime' climate of the Pacific Northwest. The Stampede Pass air temperatures are compared in the following with those obtained at the Gaging Station hygrothermograph. Local correlations between Lennox Creek and Gaging Station data are also indicated; these data are somewhat limited because of sporadic malfunctioning of the instrument at the Lennox Creek site.

Air Temperatures

A comparison of daily average air temperatures at Stampede Pass and at Gaging Station is given in Fig. 6; daily maximum and daily minimum values are indicated in Fig. 7. Data from August, September and early October, 1966, are included; the 1967 data cover the months of April through July. August 1967 data are somewhat limited, and there are no data for September; access to the North Fork basin was limited in the late summer of 1967 because of forest fire danger.

The three sets of data plotted on Figs. 6 and 7 have the same general trend. In all cases the lower values are those obtained in April and early May, 1967, during which time average daily values were generally 40°F or less; temperatures at the (lower) Gaging Station location were consistently higher. The presence of the snow cover at higher elevations is accounted for in this consistent variation. In late summer, when average temperatures are highest, and snow has gone from the ground at the higher as well as at the lower station, average daily temperatures at the two stations became more nearly equal and the daily minimum temperatures at the Gaging Station tend to become less than those at Stampede Pass.

The line indicating equality of temperature between the two stations is shown in all plots, as is the straight line corresponding to the temperatures at the Gaging Station being 9.6°F greater than those at Stampede Pass. The 9.6° differential is computed on the basis of a mean lapse rate (temperature decrease) of 3.6°F per 1000-foot increase in elevation (6).

As might be expected, the daily average values tend to correlate better than do either the maximum or minimum values, and daily maximum values correlate better when temperatures are higher. This generally occurs in the late summer; data in Fig. 7 are indicative of a fairly well mixed atmosphere due to turbulent air currents for which the standard lapse rate provides a fairly accurate relationship between the two stations. Again, in the late summer, the data of Fig. 7 indicate lower minimum temperatures at Gaging Station than at Stampede Pass; evening and early-morning conditions indicate a lower degree of mixing, and the cooler air closer to the ground, influenced by surface cooling of the ground, tends to flow into and remain in the lower valleys. The condition is not simply one of temperature inversion. Maximum temperatures occurred near 1500 hours; minimum values usually occurred near 0600 at Gaging Station.

The limited data given show the difficulty in obtaining simple relationship between temperatures at a particular site and those obtained and recorded routinely at an established weather station. Empirical correlation equations might be obtained, but these could well mask the physics of the problem; no such equations are presented here. Within the 50°F span of daily average temperatures plotted in Fig. 6, a variation one-half that of the standard lapse rate would be reasonably good; this estimate would be good during the summer months when net water heating is taking place. A working estimate for maximum daily temperatures would be to use the standard lapse rate. Fig. 7 indicates no such simple relationship for minimum temperatures; a first estimate would be to assume a 1:1 correspondence between the minimum temperatures at the two stations. Any further refinement does not seem justified.

The data of Fig. 8 indicate the correlation between daily maximum and daily minimum temperatures, for a limited number of days, between Gaging Station and Lennox Creek. A 1.1°F temperature differential is indicated on the plots to indicate the predicted difference in temperatures based upon the standard lapse rate. Both maximum and minimum values are in quite close agreement, indicating the more localized similarity in climatological values.

Solar Radiation

Solar radiation was measured directly in the test area, as discussed previously. Radiation is not measured at weather stations, but the cloud cover is recorded on a daily basis. The procedure followed was to compute solar radiation based upon recorded cloud cover at Stampede Pass and then to compare the computed value with that measured by the pyrheliographs in the study basin.

The procedure followed was that outlined by Rafael (8); the method is well adapted to engineering-type calculations. Rafael presents curves of effective insolation for any cloud cover and solar altitude, with the net insolation (i.e., accounting for reflectivity, or albedo, of the water) on a horizontal water surface being expressed in terms of Btu $hr^{-1}ft^{-2}$. Computed incoming (not net) radiation values should be approximately five percent higher than indicated (8). The steps outlined below were used to calculate net insolation values for Stampede Pass.

Curves of solar altitude versus hour of the day were plotted for a number of dates; dates used were at 10-day intervals before and after June 21, with the final time span selected from March 3 to October 9. Results were replotted to yield curves of average daily solar angle versus calendar date and of total hours of sunlight versus calendar date. The first of these two curves, used in conjunction with Rafael's curves (Fig. 4, reference 8) for the recorded cloud cover at Stampede Pass on a particular day, gave a calculated average effective insolation for the day, in Btu $hr^{-1}ft^{-2}$. This value, multiplied by the total hours of sunlight, gave the calculated total solar radiation for the day in Btu ft^{-2}.

These final daily total values were compared with results obtained from integration of the pyrheliograph records. No latitude correction was made in the calculations.

Comparison of results is indicated in Fig. 9, on which both Gaging Station and Lennox Creek pyrheliograph data are plotted in terms of Btu $ft^{-2}day^{-1}$ versus the computed value of Btu $ft^{-2}day^{-1}$ using Stampede Pass cloud cover data. Cloud cover ranges are indicated for the plotted points. Data are restricted to calendar year 1967. It is immediately evident from Fig. 9 that the correspondence between computed and measured values was much better for clear days at Stampede Pass than for cloudy days. This correspondence verifies what is expected because in the general region when clear skies occur they are more wide-spread in their occurrence than are cloudy skies.

Localized effects of clouds are evident. On clear days the Lennox Creek and Gaging Station readings were nearly identical, again as expected. Agreement among the three stations generally decreased with increased cloud cover. Calculated values using Stampede Pass cloud cover tend to be somewhat higher than the measured values on clear days; a partial explanation for this is the neglect of any correction for latitude difference between the stations, as well as neglecting any decrease in available sunlight hours due to shading from the surrounding hills which occurred near sunrise and near sunset for the stations in the study area.

The conclusion drawn from Fig. 9 is that it is a reasonable calculation procedure to apply solar radiation values computed from conventionally reported cloud cover data to a particular site in the same general region. When solar heating is greatest, and would have greatest influence on raising water temperatures, agreement is best; when agreement is poorer the total solar heating is reduced and effects in heat-budget calculations would likewise be reduced. Again, this is not a new result, but in particular a verification for the mountain region.

V. WATER TEMPERATURE PREDICTION METHOD

An original objective of the current study was to develop a simple calculation scheme adequate for predicting water temperatures in a stream comparable to that investigated--namely, the upper reaches of a typical Pacific Northwest mountain river. The instrumentation and data accumulation methods already outlined were selected to provide suitable input, as well as a check on, calculation methods.

The two general methods which have been developed for water temperature prediction are the energy budget approach and the method of equilibrium temperatures and exponential decay of temperature increments. The basic elements of the two methods have been summarized by Zeller (11). The energy budget approach was selected for the current study primarily because it was felt that the relatively simple and limited field data obtained could not justify more elaborate mathematical procedures; in addition, the equilibrium temperature approach makes use of energy budget-type calculations.

The energy budget approach attempts to equate the net exchange of heat between a body of water and its surroundings to changes in water temperature. The literature cited here is typical of that available for stream temperature studies; the examples selected are relatively recent and are of regional background. Stream temperature prediction methods, all based on the energy approach, have been presented by Rafael (8), Delay and Seaders (4), and Brown (1). Common to all three studies is a numerical integration of a time rate of change of temperature function; a common form of writing the relationship is

$$\frac{dT}{dt} = \frac{Q_t A + \dot{m}_i (T_i - T)}{m_w} \qquad (1)$$

where: T = mean water temperature of the water mass

t = time

A = area over which heat energy transfer occurs

m_w = total water mass

$\dot{m}_i, t_i$ = mass rate and temperature of any "tributary" inflow water

Q_t = total surface heat transfer rate

The factors involved in the Q_t term are discussed in more detail below. It will be noted here that the term Q_t depends in part upon T, so that numerical solution of Eq. 1 is a trial process.

In references (8), (4), and (1), Eq. 1 is applied to discrete-length reaches of the stream, and in each reach the flow, water temperature, and climatological conditions are considered to be homogeneous. Rafael (8) presented calculations applicable to the shallow reservoirs on the main stem of the Columbia River, in which the reservoirs are considered to be fully mixed; Delay and Seaders (4) presented calculations for the South Umpqua River, in Oregon; Brown (1) studied small forested streams.

The solution of Eq. 1, in the form presented, in essence observes the changes in temperature of a particular mass of water as it responds to the various heat inputs while moving downstream. The calculation procedures do not consider variations in discharge over the reach; in their studies Delay and Seaders, as well as Brown, treat discharge and heat input due to ground water flows as lumped quantities to be added at the upstream end of the reach. (This procedure would be appropriate for a discrete heat source, such as condenser cooling water being discharged into a stream). For large rivers, where ground water inflows are negligible, the procedure would be valid. In small streams, however, where ground water inflows are significant, gross simplification in Eq. 1 can lead to difficulties; Brown attributed some large prediction errors to an inexact treatment of groundwater.

Implicit in the relationship is the length of time during which the water in the reach is exposed to the ambient meteorological conditions. This "travel time" depends upon discharge-velocity relationships for the river, where the average values to be used over the reach must be determined from field measurements. The "A" term in Eq. 1 is also based upon stage-discharge-river width relations for the reach; the water surface area is used almost exclusively as the area over which heat transfer occurs, with heat transfer across the bottom and wetted banks ignored.

Equation 1 may be deduced from the convective turbulent diffusion equation consistent with assuming a one-dimensional flow in a reach of constant cross-sectional area. The general form below is given in (3).

$$\frac{\partial \overline{C}_A}{\partial t} + \frac{U \partial \overline{C}_A}{\partial x} = \frac{\partial}{\partial x} \left(E_T \frac{\partial \overline{C}_A}{\partial x}\right) + \frac{r_A}{\rho} \qquad (2)$$

where: $\overline{C}_A$ = time average concentration over a cross-section of a diffusing substance

U = average velocity in the x-direction

E_T = longitudinal dispersion coefficient

r_A = production rate of the diffusing substance

ρ = mass density of the fluid

Equation 2 may be rewritten with water temperature T replacing the concentration term. All terms of Eq. 2 as rewritten must have dimensions of degrees/unit time. The "r_A" term enters as the heat transfer term, and may be replaced by two individual terms accounting for heat transfer through the water surface and heat input due to ground water inflow. For an incremental reach having a surface width w and an average depth y, an average water temperature of T, and assuming that all heat input through the surface is absorbe by the water, the last term on the right hand side of Eq. 2 may be replaced by

$$\frac{Q_t}{\rho c y} + \frac{\partial Q_G}{\partial x} \; \frac{\partial x \, (T_G - T)}{w \; y \; dx} = \frac{Q_t w \; dx}{\rho \; c \; y \; w \; dx} + \frac{\partial Q_G}{\partial x} \; \frac{(T_G - T}{w \; y}$$

where: c = specific heat

$\frac{\partial Q_G}{\partial x}$ = ground water inflow per unit length of channel

T_G = temperature of ground water

Similarly, the longitudinal dispersion coefficient may be replaced by D_T, a thermal turbulent-diffusion coefficient. The revised equation then becomes

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} - \frac{\partial}{\partial x} (D_T \frac{\partial T}{\partial x}) = \frac{Q_t \ w \ dx}{\rho c \ y \ w \ dx} + \frac{\partial Q_G}{\partial x} \frac{(T_G - T)}{w \ y} \tag{3}$$

It is desirable to simplify Eq. 3 if possible, and the third term is considered. Expanding, the third term of Eq. 3 is

$$- D_t \frac{\partial^2 T}{\partial x^2} - \frac{\partial D_t}{\partial x} \frac{\partial T}{\partial x}$$

For turbulent flows mass and heat diffuse at equal rates (3), and thus values of longitudinal dispersion coefficients should be considered in trying to obtain an order of magnitude comparison of the terms. Fischer (5) lists values of dimensionless dispersion coefficients obtained in various laboratory flumes and in natural rivers; these results are used to estimate a value of D_T for the North Fork of the Snoqualmie River.

For natural streams which approach the configuration of the North Fork, Fischer lists dimensionless dispersion coefficients having values near 600.

$$600 = \frac{E_t}{rU_*} \tag{4}$$

where: r = hydraulic radius

U_* = friction velocity

Letting the hydraulic radius be replaced by a typical depth of 2 feet, and using a represantative slope of 0.01, the value of E_T is approximately 970, say 1000, $ft^2 \ sec^{-1}$ or 0.13 $mi^2 \ hr^{-1}$. (Again it is emphasized that this is at best only a representative value, and that it does not attempt to give any actual average over the wide variations in stream character encompassed in the section of river studied).

Representative values (typical of conditions during summer months) are listed here as selected for an order of magnitude analysis of the terms on the left-hand side of Eq. 3: $U = 3$ ft sec^{-1} = 2 mph, $\Delta T = 10^{\circ}$F as both a diurnal variation at a station and as an estimated difference in temperatures between two stations 15 miles apart. Assuming linear variations throughout, the following values result:

$$\frac{\partial T}{\partial t} \approx \frac{10}{(\frac{1}{2} \times 24)} \approx \frac{10}{12} \equiv 0.83 \ {}^{\circ}\mathrm{F\ hr}^{-1}$$

$$U \frac{\partial T}{\partial x} \approx (3) \frac{(10)}{(15)} \approx 2.0 \ {}^{\circ}\mathrm{F\ hr}^{-1}$$

$$D_T \frac{\partial^2 T}{\partial x^2} \approx E_T \frac{\partial^2 T}{\partial x^2} \approx (0.13)\left(\frac{1}{15}\right) \left(\frac{10}{15}\right) \approx .006 \ {}^{\circ}\mathrm{F\ hr}^{-1}$$

The diffusion term is seen to be small, and, if D_T is not treated as a spatial variable, the entire diffusion term may be eliminated so that Eq. 3 is now reduced to

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = \frac{Q_t \ W \ dx}{\rho \ c \ y \ w \ dx} + \frac{\partial Q_G}{\partial x} \ \frac{T_G - T}{wy} \tag{5}$$

The two terms on the left side are the local and the convective water temperature change terms, and together form the material derivative, DT/Dt, which is the time rate of change of temperature experienced by a particular mass of water moving with the flow.

One practical numerical solution of Eq. 5 involves the consideration of finite times and finite reaches; let the time increment be the travel time Δt for a reach of length Δx. The value of T is the average value experienced by the water flowing in the reach; if the groundwater temperature is assumed constant, then $(T_G - T)$ is treated as a constant for the reach. Assuming the finite values, Eq. 5 becomes

$$\Delta T = \frac{Q_t \; W \;\; \Delta x \;\; \Delta t}{\rho \; c \; y \; w \;\;\; \Delta x} + \frac{\Delta Q_G}{\Delta x} \; \frac{(T_G - T) \; \Delta t}{w \; y}$$

$$\Delta T = \frac{Q_t \; A}{\rho c \; Q} + \frac{\Delta Q_G \; (T_G - T)}{Q} \tag{6}$$

Equation 6 becomes Eq. 1 upon substitution of proper units for ρc and for Q_t. ΔT is the temperature change of the particular slug of water moving downstream. It would be desirable to have a direct solution for $\partial T/\partial t$ because recorded temperatures are measured at a station. Separate consideration of the local and convective terms in Eq. 5 involves trial procedures comparable to methods used in solving Eq. 6. It is concluded that the general calculation procedures laid out by Delay and Seaders (4) may be most appropriate for the present study, when modified as shown below.

The trial procedure, for a known initial temperature, is to assume a final downstream temperature and thus obtain a working value for T, compute Q_t (which in part depends upon T), calculate ΔT and check the assumed variation; successive iterations are needed to close the solution. The discharge Q is the sum of the initial discharge plus one-half the ground water inflow entering in the reach.

The procedure as outlined applies to a reach of stream; some further simplification is needed to obtain initial temperature values at the headwaters. Calculations are to be started at an "apparent origin," which has been located arbitrarily at a point midway between the "map source" and the first confluence of a headwater tributary with another tributary. At the apparent origin, the initial stream temperature is assumed to be a constant at all times and is taken as

$$T_{\text{source}} = \frac{T_{\text{ground water}} + T_{\text{snow melt}}}{2} \tag{7}$$

For the basin of the North Fork of the Snoqualmie, using the upper basin ground water temperature, the initial temperature is (1/2) (48 + 32) = 40°F. Upstream of the confluence of Lennox Creek and the North Fork, all ground water temperatures will be assumed 48°F; downstream, in the lower basin, 53°F. The estimate of the intial temperature seems reasonable for the heating season which is the time of concern in the water temperature calculations.

All stream flows are to be computed on a basis that discharge is proportional to drainage area; in this way, for a known or assumed discharge at the gaging station flows are established in all streams in the basin. Inflow between tributaries will be taken as linearly distributed groundwater.

The travel times involved in tracing a particular water mass from the headwaters to the temperature recording station cannot be theorized, but will be found by direct field measurement. The measurement procedure to be followed is that outlined by Buchanan (2), and involves fluorescense measurements in observing the downstream motion of a cloud of rhodamine B dye injected at some upstream point. The direct determination of travel times over the entire basin by this procedure is impractical, so the following simplification is introduced; effective average stream velocities will be assumed to be the same over the entire basin at the same time. The effect of steeper slopes in the upper reaches is compensated for by smaller depths, increased effective roughness, etc.

All travel times are to be based on measured values on the main stem of the North Fork, between the confluence with Lennox Creek and the confluence with Phillippa Creek. The measurement will be made at typical flows at the gaging station so that a "rating" may be obtained. Such measurements were planned for the summer of 1967; when the necessary equipment became available, however, it was in the late summer when access to the area was severely restricted because of forest fire danger. Further, at this time the stream flows were very low (see Fig. 4), so that results could have been extrapolated to higher flows only with much uncertainty. As a consequence no travel time measurements were made, and any calculations made to date can depend only upon assumed travel times.

The other 'hydraulic' term to be determined for use in Eq. 6 is the water surface area, A. Aerial photographs obtained from the U. S. Forest Service were studied, but these did not provide sufficient accuracy, understandably so in the upper reaches. Stream width measurements were obtained and correlated with simultaneous discharges at the gaging station for a number of points along the North Fork and for some points on Lennox and Phillippa Creeks. These data are on file and will serve as the basis for calculations.

Discussion of all terms entering the working Eq. 6 has been concluded except for the surface heat transfer term, Q_t. It is on this term that attention is placed in an effort to simplify the calculations as much as possible and as justified. The surface heat transfer (rate) term may be expressed as follows, where all the Q's are in Btu $\mathrm{ft}^{-2}\ \mathrm{hr}^{-1}$:

$$Q_t = Q_s - Q_r - Q_b - Q_e - Q_h + Q_v \tag{8}$$

where: Q_s = incoming solar radiation

Q_r = reflected solar radiation

Q_b = back radiation or net energy lost from the water by exchange of long-wave radiation between the water body and the atmosphere

Q_e = heat lost through evaporation

Q_h = heat lost through conduction from the water to the atmosphere

Q_v = heat advected by precipitation falling on the surface

These terms are discussed below briefly; all have been discussed at great length in the literature, and the question here is how many of the terms may be simplified or eliminated. Some other factors not considered here are heat stored in the stream bottom and the possibility of surrounding topography behaving as a heat source. Neglect of the former could lead to evening water temperatures which are too low because the mostly gravel stream beds would retain heat from the exposure to sunlight during the day. The second point is considered to be unimportant because of the combination of relatively low (average) daytime air temperatures and forested slopes and canyon walls near the stream; an example where local terrain effects are important and have been studied is presented by Seaders (9).

The solar radiation terms are by far the most important ones involved in the heating process. Rafael (8) has combined Q_s and Q_r into a single function, the effective insolation, suitable for practical engineering calculations. The methods involved, and some results obtained on the current study, have been discussed in Chapter IV. The $(Q_s - Q_r)$ term to be used as a component of Q_t in Eq. 6 likewise is to be found by Rafael's methods.

Again following Rafael's method, the effective long-wave back radiation term is calculated as follows:

$$Q_b = 1.66 \times 10^{-9} (T^4 - \beta T_a{}^4) \tag{9}$$

where: T = absolute water temperature (mean value for reach), degrees Rankine

T_a = absolute air temperature, degrees Rankine

β = atmospheric radiation factor

Rafael presents a figure relating β, cloud cover, and the vapor pressure; the latter can be determined from relative humidity values, either known or assumed, coupled with the known elevation.

Common forms for the Q_e and Q_h terms are given below.

$$Q_e = C_1 U (e_w - e_a) \tag{10}$$

$$R_H = \frac{Q_h}{Q_e} = C_2 p \frac{(T - T_a)}{(e_w - e_a)} \tag{11}$$

where: U = wind speed (usually above still water)

$C_{1,2}$ = constants (dimensional)

p = atmospheric pressure

e_w = saturation vapor pressure of air

e_a = actual vapor pressure of air

R_H = Bowen's ratio, commonly taken as 0.61

There are no well-defined procedures for evaluating evaporative heat losses from flowing water. No attempts were made to measure any wind speeds, and a logical first approximation would be to use the river velocity. Because relative humidities are quite high at all times, and reach the 100% value for all nights in the study area, the evaporative heat loss would be small during the day and zero at night. The sensible (conducted) heat term would likewise be small, and for most days would have an opposite sign from the evaporation term. Differences between air and water temperatures are small at night, and so the conducted heat term (while no longer possible of being computed from the Bowen ratio expression) is again small. The Q_e and Q_h terms tend to compensate each other during the day, and are zero or small at night; they have been eliminated from heat budget calculations for the present system.

Rainfall has not been considered separately, so the Q_v term in Eq. 8 also is not considered.

In summary, changes in stream temperature calculated by Eq. 6 involve only these three methods of heat transfer: 1) effective solar radiation, strictly a warming phenomenon, independent of water temperature; 2) net long-wave back radiation, which depends upon the differences between water and air temperature, and can account for either warming or cooling; 3) ground water temperature, which is usually a cooling agent. The transfer of climatological data used in determing the first two terms has already been justified in Chapter IV. The calculations for the solution of Eq. 6 follow a slug of water from an apparent source and through a number of discrete reaches, each involving a trial solution. For an assumed diurnal climatological--stream discharge relationship, the method allows calculations of the temperature at particular stations for different times, once the travel times have been established. Because these travel times have not been measured for the North Fork of the Snoqualmie River no detailed trial calculations are presented in this report. The actual validity of the method has not been tested, so results are inconclusive. Some preliminary trial calculations, using measured weather data and stream flows, gave reasonable diurnal variations, but these used uncertain travel times.

In conclusion, the calculation procedure detailed above does not present anything really new. Elimination of some heat transfer terms has been justified. Ground water influence is dealt with to a greater degree than in other known studies. The method does not throw much light on a rapid procedure for estimating seasonal average temperatures; it is, however, most well suited for predicting discrete temperature values at selected times during the water heating season.

VI. CONCLUSIONS

The upper basin of the North Fork of the Snoqualmie River has been used for a study of stream temperatures in the headwater regions of a typical Pacific Northwest mountain river. Water temperature, stream flow, and climatological data have been presented for the heating season of calendar year 1967.

A procedure has been presented for predicting river temperatures at a given station on a stream. The calculation method uses a typical energy-budget approach, with the number of surface heat transfer terms limited and with groundwater inflows definitely considered. The validity of using conventionally available regional weather data for detailed application at a specific site has been checked.

The accuracy of the calculation procedure presented has not been suitably checked because necessary travel time values have not yet been measured in the test basin. It is hoped that such measurements can be made in the future, along with accompanying numerical checks on the calculation procedures. Data presented in this report will provide the basis for such future calculations.

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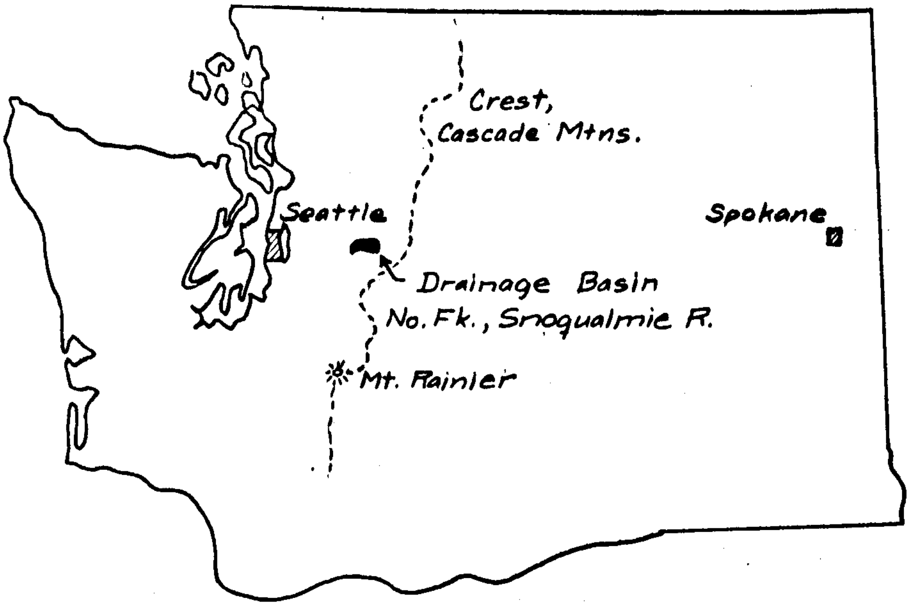
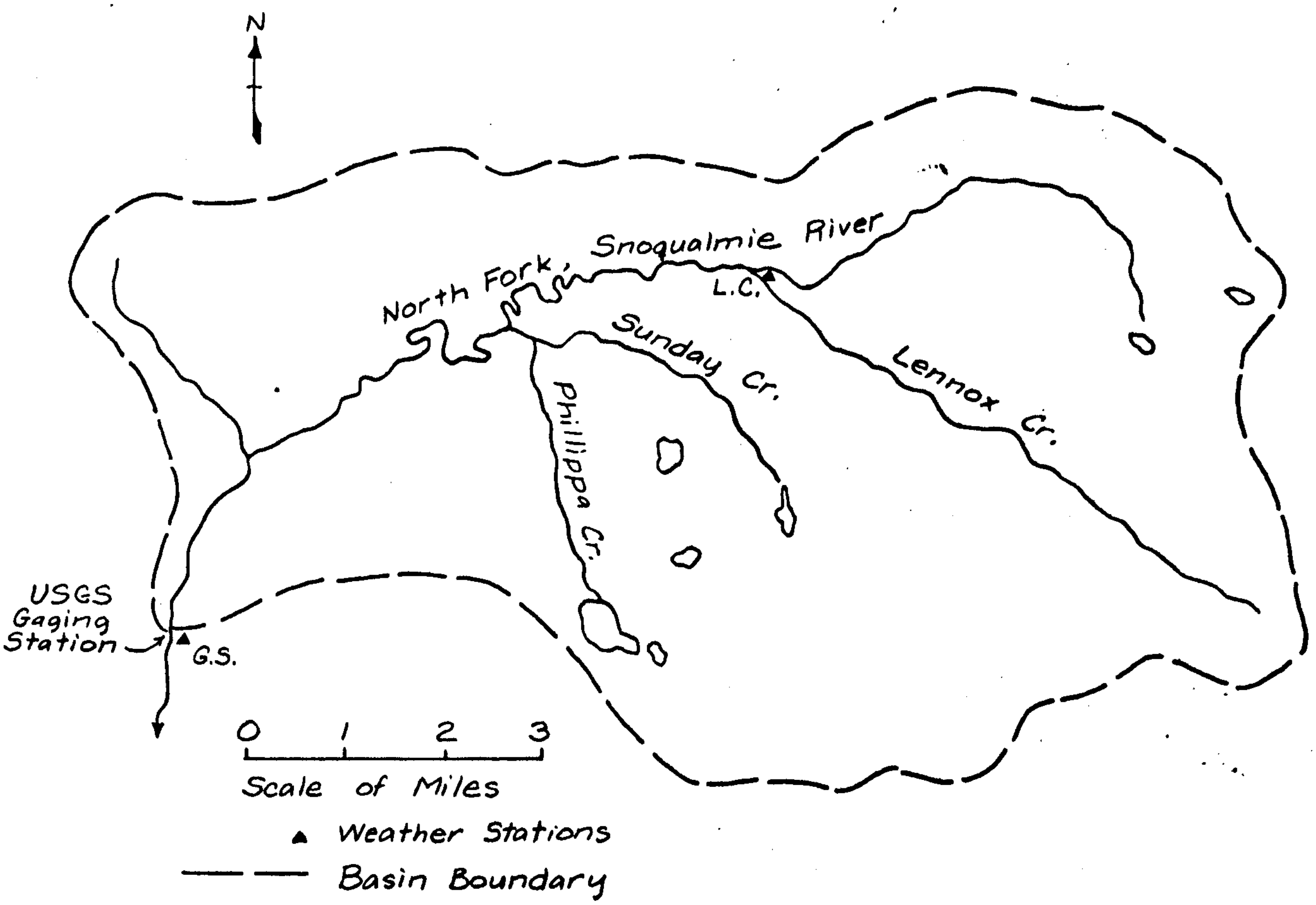


Figure 1



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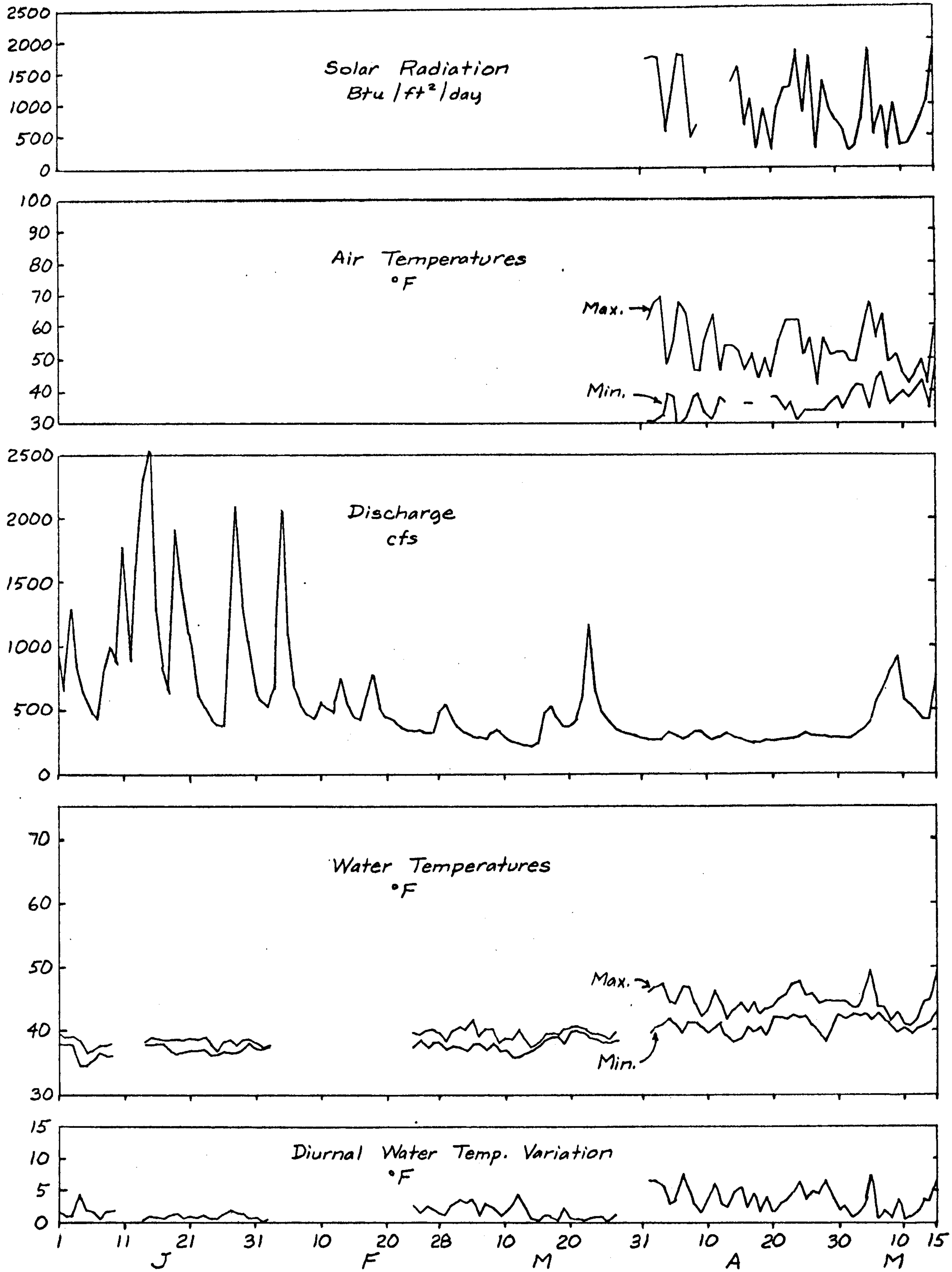
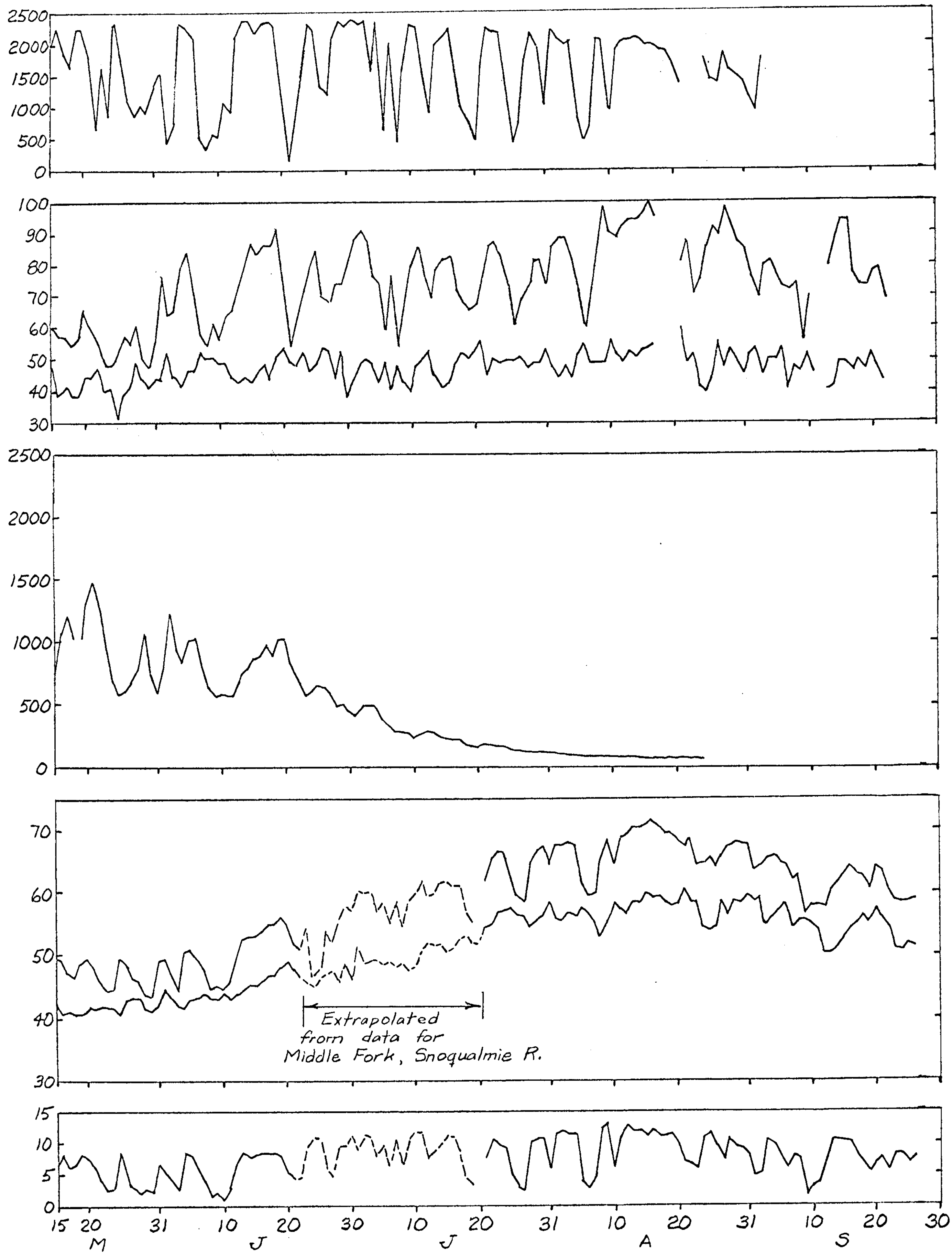

Solar Radiation
Btu / ft² / day
2500
2000
1500
1000
500
0
Air Temperatures
°F
Max.
Min.
100
90
80
70
60
50
40
30
Discharge
cfs
2500
2000
1500
1000
500
0
Water Temperatures
°F
Max.
Min.
70
60
50
40
30
Diurnal Water Temp. Variation
°F
15
10
5
0
1
11
21
31
10
20
28
10
20
31
10
20
30
10
15
J
F
M
A
M

Figure 3a



2500
2000
1500
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100
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80
70
60
50
40
30
2500
2000
1500
1000
500
0
70
60
50
40
30
Extrapolated
from data for
Middle Fork, Snoqualmie R.
15
10
5
0
15
20
31
10
20
30
10
20
31
10
20
31
10
20
30
M
J
J
A
S

Figure 3b

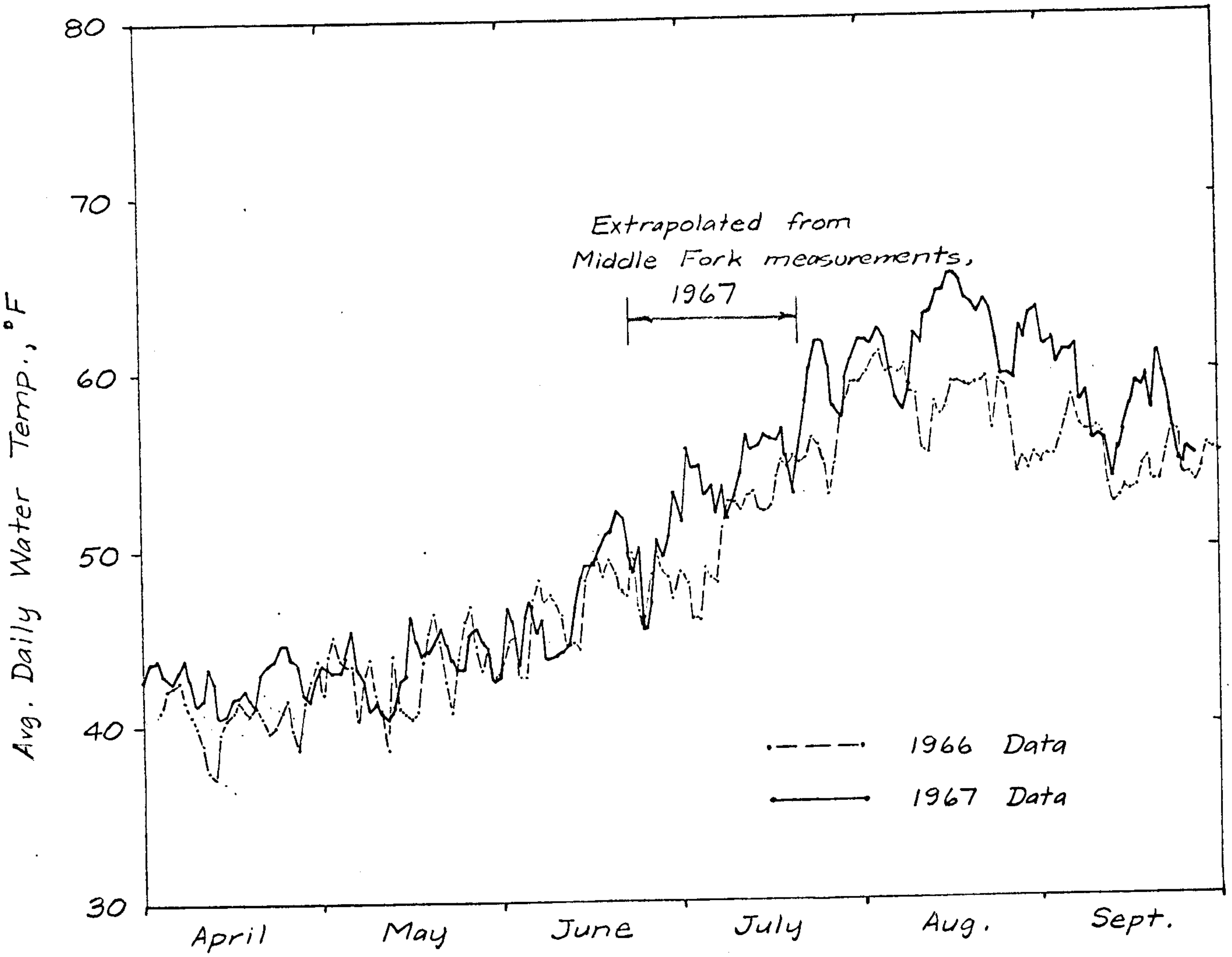


Figure 4

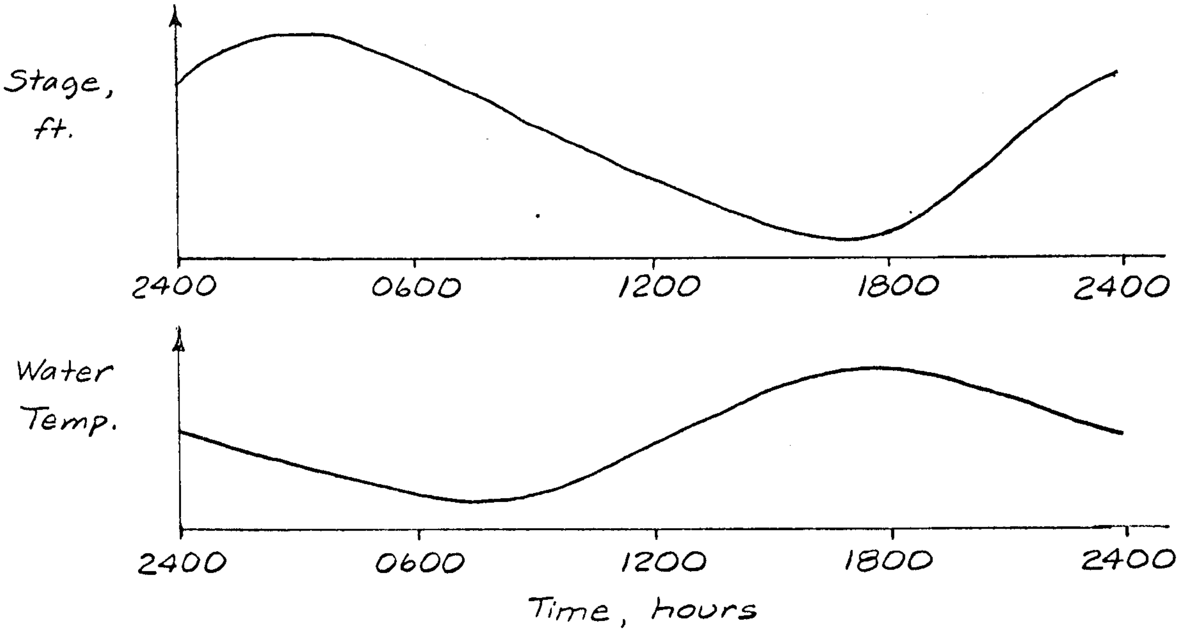


Figure 5

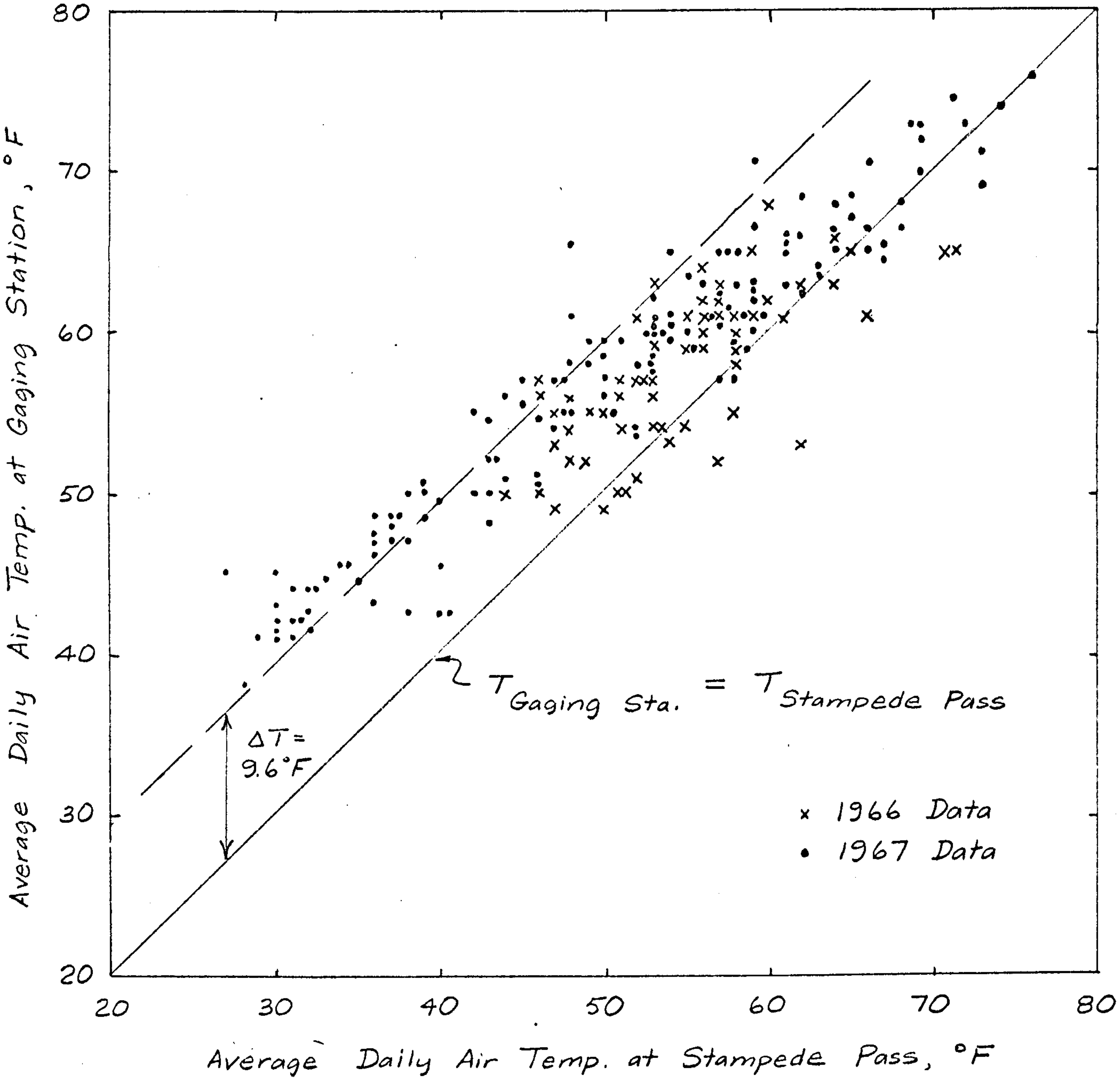
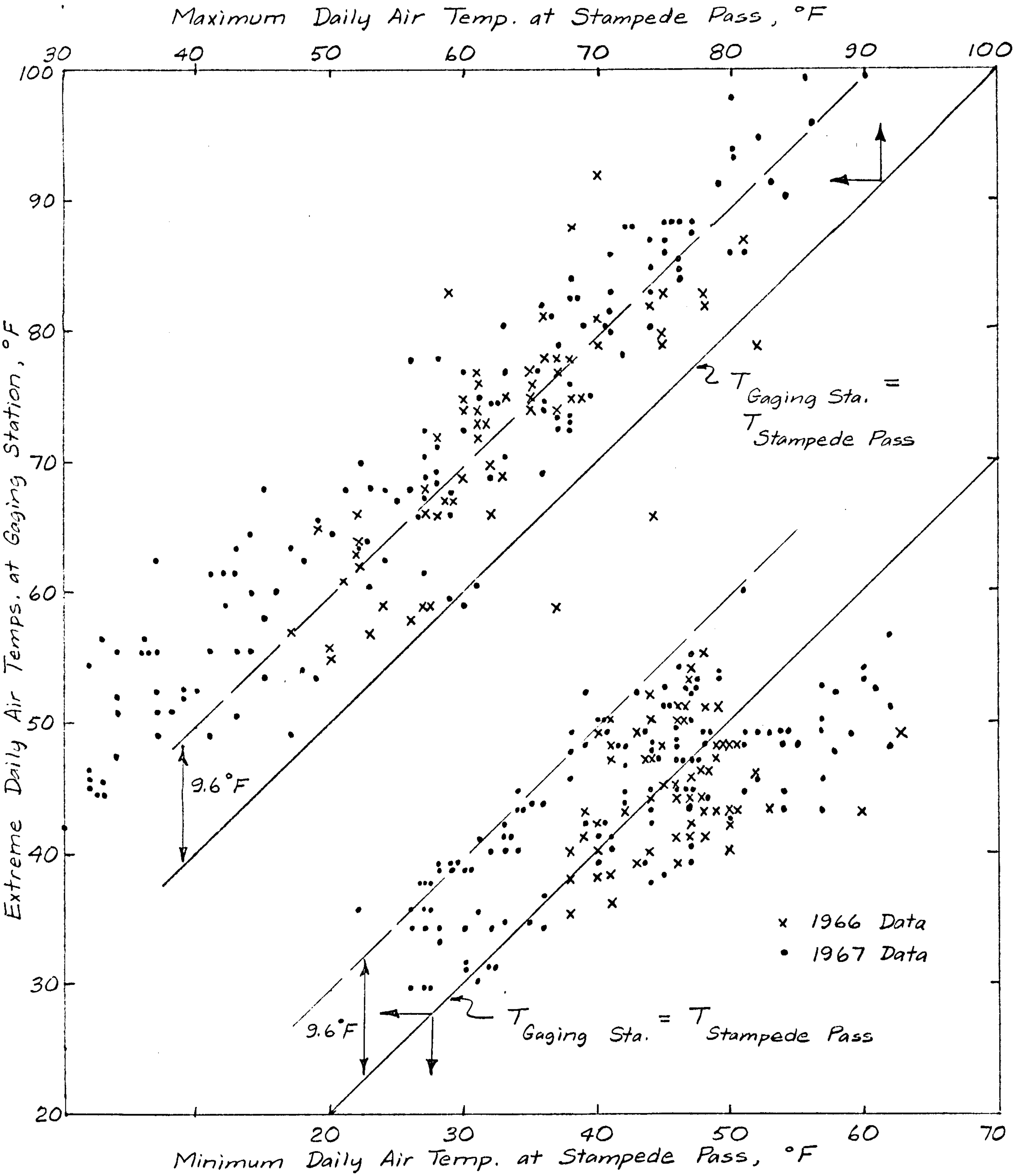

80
70
60
50
40
30
20
20
30
40
50
60
70
80
Average Daily Air Temp. at Gaging Station, °F
Average Daily Air Temp. at Stampede Pass, °F
ΔT = 9.6°F
$T_{Gaging\ Sta.} = T_{Stampede\ Pass}$
× 1966 Data
• 1967 Data

Figure 6



Maximum Daily Air Temp. at Stampede Pass, °F
30
40
50
60
70
80
90
100
Extreme Daily Air Temps. at Gaging Station, °F
100
90
80
70
60
50
40
30
20
$T_{Gaging\ Sta.} = T_{Stampede\ Pass}$
9.6°F
9.6°F
$T_{Gaging\ Sta.} = T_{Stampede\ Pass}$
× 1966 Data
• 1967 Data
20
30
40
50
60
70
Minimum Daily Air Temp. at Stampede Pass, °F

Figure 7

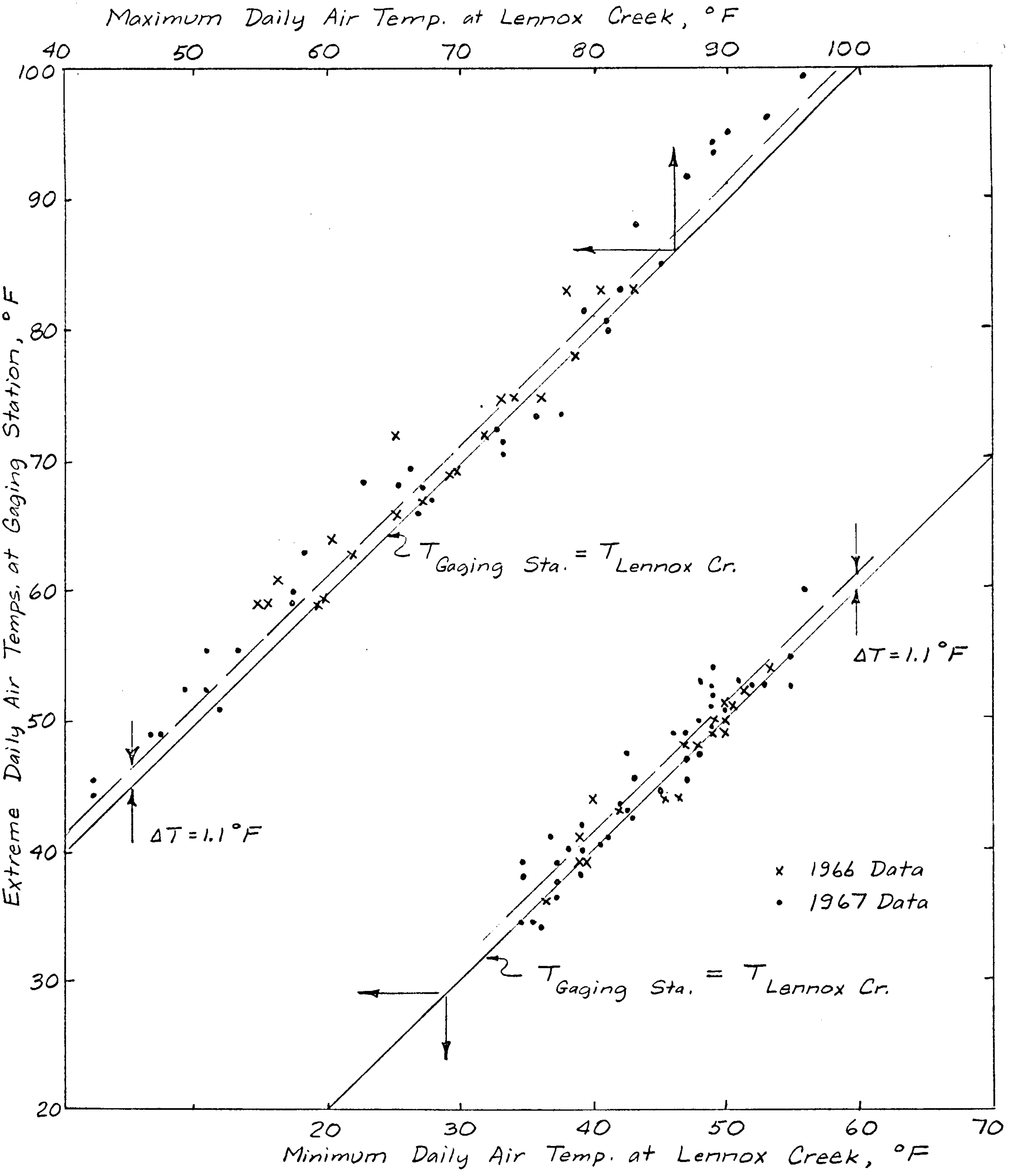

Maximum Daily Air Temp. at Lennox Creek, °F
40
50
60
70
80
90
100
Extreme Daily Air Temps. at Gaging Station, °F
100
90
80
70
60
50
40
30
20
T_Gaging Sta. = T_Lennox Cr.
ΔT = 1.1 °F
ΔT = 1.1 °F
T_Gaging Sta. = T_Lennox Cr.
× 1966 Data
• 1967 Data
20
30
40
50
60
70
Minimum Daily Air Temp. at Lennox Creek, °F

Figure 8

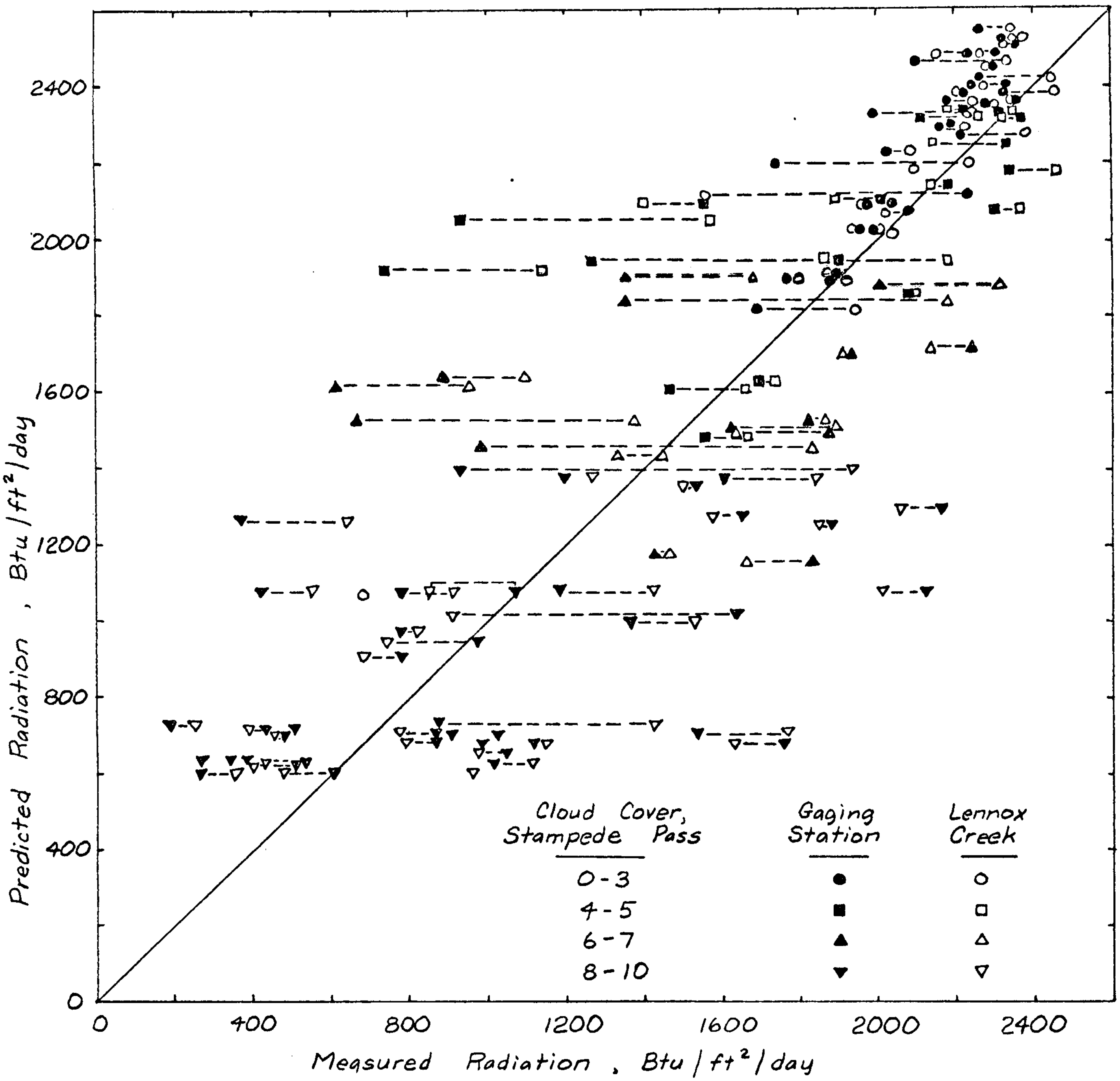

Predicted Radiation, Btu/ft²/day
Measured Radiation, Btu/ft²/day
0
400
800
1200
1600
2000
2400
Cloud Cover, Stampede Pass
Gaging Station
Lennox Creek
0-3
4-5
6-7
8-10

Figure 9

TABLE I

Drainage Basin Areas, Stream Lengths

Drainage Areas

Region	Area - Mi^2	% of Total
Lennox Cr. Sub-basin, u.s. of confluence with N.F. Snoq.	14.7	23.0
No. Fork Snoqualmie Sub-basin, u.s. confluence w. Lennox Cr.	11.8	18.5
Main Stream, Lennox Cr. to Phillippa Cr.	5.3	8.3
Phillippa Cr. - Sunday Cr. Sub-basin	17.1	26.7
Main Stream, d.s. of Phillippa Cr.	15.1	23.5
	64.0	100.0

Stream Lengths - Miles (Major Tributaries)

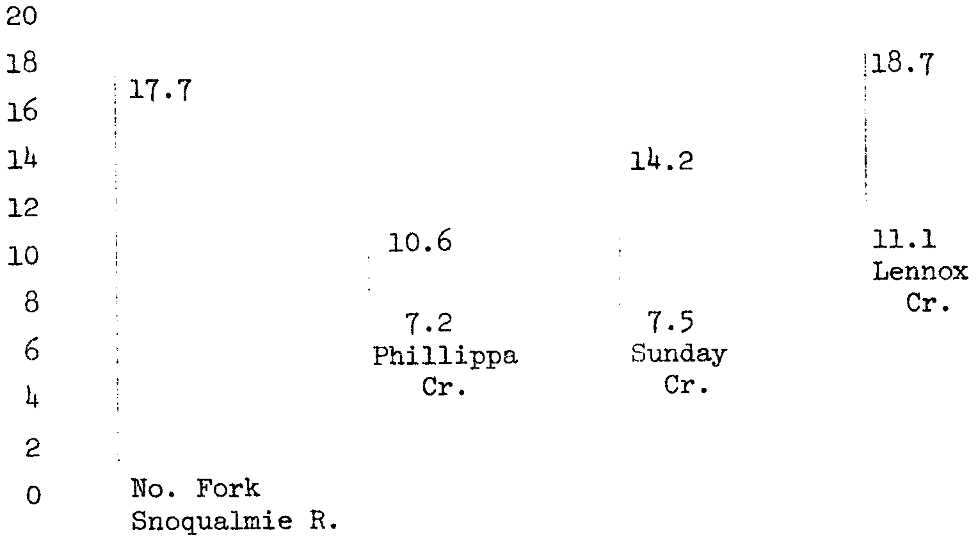


TABLE II-A

Stream Flow and Water Temperature Data, 1967
North Fork Snoqualmie River

Date		Water Temperatures - °F			Avg. Daily Q	Date		Water Temperatures -°F			Avg. Daily Q
		Max.	Min.	Diurnal Var.	cfs			Max.	Min.	Diurnal Var.	cfs
Jan.	1	39.5	38.1	1.4	1,040	Feb.	1	37.2	37.1	0.1	538
	2	39.0	38.0	1.0	650		2	37.6	37.2	0.4	508
	3	39.0	38.0	1.0	1,300						
	4	38.4	34.6	3.8	814						
	5	36.7	34.7	2.0	610						
	6	37.0	35.3	1.7	484						
	7	37.6	36.8	0.8	426						
	8	37.8	36.2	1.6	773						
	9	37.9	36.1	1.8	968						
	10	--	--	--	846						
	11	--	--	--	1,780						
	12	--	--	--	892						
	13	--	--	--	1,640						
	14	38.2	38.0	0.2	2,310						
	15	39.0	38.0	1.0	2,540						
	16	38.9	38.0	0.9	1,290						
	17	38.7	37.9	0.8	826						
	18	37.9	36.9	1.0	635						
	19	37.9	36.7	1.2	1,910						
	20	37.6	36.8	0.8	1,430						
	21	37.9	36.9	1.0	844						
	22	37.8	37.0	0.8	630						
	23	38.0	37.0	1.0	516						
	24	37.0	36.2	0.8	440		24	39.8	37.5	2.3	337
	25	36.9	36.2	0.7	394		25	39.7	38.3	1.4	347
	26	38.1	36.9	1.2	374		26	40.0	37.6	2.4	337
	27	38.3	36.7	1.6	1,050		27	40.1	38.1	2.0	318
	28	37.9	36.7	1.2	2,090		28	39.4	38.0	1.4	479
	29	38.4	37.2	1.2	1,330						
	30	38.7	38.1	0.6	1,050						
	31	38.0	37.1	0.9	660						

Date		Water Temperatures °F			Ave. Daily Q cfs	Date		Water Temperatures °F			Ave. Daily Q cfs
		Max.	Min.	Diurnal Var.				Max.	Min.	Diurnal Var.	
Mar.	1	38.3	37.1	1.2	542	Apr.	1	46.0	39.5	6.5	258
	2	40.0	37.3	2.7	416		2	46.9	40.4	6.5	258
	3	40.6	37.2	3.4	354		3	47.2	41.0	5.8	272
	4	40.1	36.9	3.2	315		4	44.3	41.7	2.6	315
	5	41.7	37.9	3.8	294		5	44.2	40.9	3.3	300
	6	39.1	38.0	1.1	286		6	47.0	39.6	7.4	277
	7	40.1	37.1	3.0	269		7	46.7	41.1	5.6	292
	8	40.2	38.0	2.2	303		8	44.0	41.1	2.9	322
	9	38.4	37.0	1.4	328		9	42.0	40.5	1.5	322
	10	38.8	37.0	1.8	280		10	43.1	39.8	3.3	289
	11	38.5	35.9	2.6	253		11	46.3	40.3	6.0	262
	12	40.1	35.9	4.2	235		12	44.0	41.0	3.0	280
	13	38.9	36.4	2.5	223		13	41.8	39.1	2.7	307
	14	37.3	37.0	0.3	214		14	43.1	38.1	5.0	288
	15	38.0	37.8	0.2	238		15	44.3	38.9	5.4	265
	16	39.5	38.4	1.1	479		16	42.9	40.5	2.4	250
	17	39.7	39.0	0.7	524		17	44.4	39.8	4.6	246
	18	39.3	39.2	0.1	436		18	42.3	40.7	1.6	246
	19	40.2	38.0	2.2	360		19	43.2	39.2	4.0	252
	20	40.3	39.8	0.5	357		20	43.9	42.1	1.8	250
	21	40.4	40.0	0.4	408		21	45.0	42.0	3.0	265
	22	40.1	39.9	0.2	603		22	45.7	41.9	3.6	265
	23	39.7	39.0	0.7	1,170		23	47.1	42.2	4.9	271
	24	39.5	38.7	0.8	655		24	47.8	41.7	6.1	288
	25	39.0	38.5	0.5	476		25	45.6	42.0	3.6	310
	26	38.7	38.5	0.2	412		26	45.9	40.9	5.0	299
	27	39.7	38.5	1.2	354		27	44.1	39.5	4.6	290
	28	--	--	--	328		28	44.6	38.1	6.5	299
	29	--	--	--	309		29	44.6	40.7	3.9	290
	30	--	--	--	294		30	44.5	42.5	2.0	277
	31	--	--	--	277						

Date	Water Temperatures °F			Ave. Daily Q cfs	Date	Water Temperatures °F			Ave. Daily Q cfs
	Max.	Min.	Diurnal Var.			Max.	Min.	Diurnal Var.	
May 1	44.6	41.9	2.7	277	June 1	49.2	44.1	5.1	812
2	43.4	42.6	0.8	289	2	47.1	43.0	4.1	1,227
3	43.7	42.2	1.5	310	3	44.6	42.0	2.6	940
4	45.3	42.5	2.8	349	4	50.4	41.8	8.6	838
5	49.3	41.8	7.5	414	5	51.0	43.0	8.0	1,010
6	43.5	42.9	0.6	565	6	49.3	43.2	6.1	1,024
7	43.7	41.7	2.0	695	7	48.0	43.9	4.1	814
8	41.2	40.6	0.6	778	8	44.3	43.1	1.2	630
9	42.9	39.6	3.3	904	9	45.0	43.0	2.0	578
10	40.9	40.4	0.5	588	10	44.7	43.7	1.0	578
11	40.8	39.7	1.1	529	11	46.0	43.1	2.9	565
12	41.9	40.2	1.7	488	12	49.9	43.6	6.3	569
13	44.4	40.8	3.6	436	13	52.4	44.3	8.1	685
14	44.7	41.2	3.5	444	14	53.0	45.1	7.9	796
15	49.6	42.8	6.8	722	15	53.1	45.1	8.0	868
16	49.0	40.8	8.2	1,066	16	54.0	45.8	8.2	898
17	47.1	40.9	6.2	1,220	17	54.9	46.8	8.1	975
18	46.6	40.7	6.9	1,031	18	55.0	46.9	8.1	898
19	48.9	40.7	8.2	1,038	19	56.1	48.1	8.0	1,003
20	49.4	41.8	7.6	1,330	20	54.5	49.0	5.5	1,017
21	47.6	41.6	6.0	1,498	21	51.8	47.7	4.1	814
22	45.8	41.8	4.0	1,269	22	50.9	46.5	4.4	720
23	44.5	41.8	2.7	968	23	54.5*	45.5*	9.0*	583
24	44.7	41.8	2.9	695	24	46.1*	45.2*	10.9*	610
25	49.4	40.7	8.7	592	25	47.9*	46.1*	10.8*	660
26	48.0	43.0	5.0	615	26	54.0*	47.0*	6.0*	650
27	46.2	43.2	3.0	685	27	52.0*	47.3*	4.7*	596
28	45.4	43.2	2.2	790	28	55.3*	45.9*	9.4*	492
29	43.9	41.5	2.4	1,073	29	57.9*	48.4*	9.5*	500
30	43.4	41.3	2.1	735	30	57.0*	46.0*	11.0*	452
31	49.1	42.3	6.8	588					

Date	Water Temperatures °F			Ave. Daily Q cfs	Date	Water Temperatures °F			Ave. Daily Q cfs
	Max.	Min.	Diurnal Var.			Max.	Min.	Diurnal Var.	
July 1	60.2	51.3	8.9	414	Aug. 1	67.3	55.9	11.4	109
2	60.0*	48.8*	11.2*	484	2	67.4	55.6	11.8	103
3	60.0*	49.1*	10.9*	480	3	67.9	56.5	11.4	99
4	57.0*	49.0*	8.0*	480	4	67.4	56.1	11.3	95
5	58.3*	48.7*	9.6*	377	5	61.3	57.8	3.5	92
6	55.1*	49.0*	6.1*	334	6	59.5	56.8	2.7	90
7	58.8*	48.2*	10.6*	291	7	60.0	55.4	4.6	88
8	54.7*	48.4*	6.3*	284	8	65.3	53.0	12.3	86
9	58.3*	47.6*	10.7*	264	9	68.7	55.4	13.3	81
10	59.9*	48.4*	11.5*	235	10	64.6	58.6	5.8	79
11	62.0*	50.6*	11.4*	262	11	68.4	57.7	10.7	78
12	59.2*	52.0*	7.2*	294	12	69.4	56.9	12.5	76
13	60.0*	51.5*	8.5*	280	13	70.3	58.4	11.9	73
14	61.4*	51.5*	9.9*	246	14	70.4	58.4	12.0	70
15	61.7*	50.7*	11.0*	228	15	70.9	59.9	11.0	69
16	61.1*	51.1*	11.0*	216	16	71.3	59.3	12.0	67
17	61.0*	52.7*	8.3*	207	17	70.5	59.5	11.0	63
18	57.1*	52.9*	4.2*	189	18	69.5	58.5	11.0	61
19	55.2*	51.9*	3.3*	170	19	69.4	58.1	11.3	60
20	--	51.9*	--	172	20	68.0	58.3	9.7	58
21	62.0	54.4	7.6	187	21	67.5	60.6	6.9	59
22	65.3	55.0	10.3	168	22	68.5	58.2	6.3	63
23	66.4	56.9	9.5	160	23	64.5	58.6	5.9	60
24	66.1	57.1	9.0	155	24	64.9	54.3	10.6	57
25	62.6	57.7	4.9	146	25	65.5	54.0	11.5	
26	59.4	56.6	2.8	136	26	64.0	54.8	9.2	
27	58.4	56.3	2.1	133	27	66.0	58.6	7.4	
28	64.5	54.5	10.0	127	28	67.2	56.4	10.8	
29	66.8	55.3	10.5	116	29	67.8	58.6	9.2	
30	67.2	56.5	10.7	113	30	67.7	58.6	9.1	
31	64.6	58.7	5.9	110	31	67.6	59.5	8.1	

Date	Water Temperatures °F			Ave. Daily Q cfs	Date	Water Temperatures °F			Ave. Daily Q cfs
	Max.	Min.	Diurnal Var.			Max.	Min.	Diurnal Var.	
Sept. 1	63.6	58.8	4.8		Oct.				
2	64.2	59.2	5.0						
3	65.4	55.0	10.4						
4	65.7	56.1	9.6						
5	64.7	57.2	7.5		5	50.5	--	--	
6	64.2	58.2	6.0		6	50.0	49.3	0.7	
7	62.0	54.2	7.8		7	50.0	49.2	0.8	
8	62.4	55.3	7.1		8	52.1	48.3	3.8	
9	56.6	55.3	1.3		9	52.7	49.8	2.9	
10	57.6	54.8	2.8		10	52.0	51.0	1.0	
11	57.9	54.2	3.7		11	50.2	49.9	0.3	
12	57.5	50.1	7.4		12	49.9	49.0	0.9	
13	60.8	50.4	10.4		13	48.9	48.4	0.5	
14	61.7	51.5	10.2		14	49.1	47.3	1.8	
15	63.0	52.9	10.1		15	49.1	46.3	2.8	
16	64.2	54.2	10.0		16	50.9	48.0	2.9	
17	63.0	55.0	8.0		17	49.8	46.5	3.3	
18	62.8	56.4	6.4		18	48.3	47.2	1.1	
19	60.2	55.2	5.0		19	48.1	45.6	2.5	
20	64.2	57.6	6.6		20	47.5	45.0	2.5	
21	63.3	56.0	7.3		21	47.8	46.5	1.3	
22	60.2	54.4	5.8		22	46.8	45.9	0.9	
23	58.8	50.8	8.0		23	46.1	44.9	1.2	
24	58.6	50.6	8.0		24	45.4	44.2	1.2	
25	58.8	52.0	6.8						
26	58.9	51.4	7.5						

* Estimated values, determined as follows:
Min. Temp. = Min. Temp. on Middle Fork, Snoqualmie R.
Diurnal Temp. Variation = Diurnal Temp. Variation on Middle Fork + 1°F.

Table II - B
Climatological Data - "Gaging Station" - 1967

Date	Air Temperatures °F		Rel. Humidity		Solar Rad.	Cloud Cover (Stampede)
	Max.	Min.	Percent	Hours	Btu-ft^{-2}da^{-1}	
Apr. 1	62	30	42	11	1708	0
2	68	30	33	10	1742	0
3	70	31	35	10	1701	3
4	48	39	86	17	572	10
5	56	38	52	6	1173	8
6	68	29	39	9	1790	0
7	64	31	32	9	1771	7
8	45	38	90	17	480	10
9	46	39	84	13	649	10
10	56	33	50	8	--	10
11	64	31	44	8	--	2
12	46	38	64	11	--	10
13	54	36	63	4	--	10
14	54	--	41	5	1354	10
15	52	--	41	8	1601	6
16	46	36	59	5	642	10
17	52	36	74	9	1096	10
18	44	--	97	13	306	10
19	50	--	70	8	948	9
20	44	38	93	7	314	10
21	56	38	56	9	948	10
22	62	34	40	10	1236	7
23	62	36	45	9	1273	8
24	62	31	40	10	1863	10
25	51	34	86	10	823	10
26	56	34	46	11	1753	9
27	42	34	98	13	299	10
28	56	34	56	9	1373	9
29	51	36	61	8	904	10
30	52	38	57	8	723	10

Date	Air Temperatures °F Max.	 Min.	Rel. Humidity Percent	 Hours	Solar Rad. Btu-ft^{-2}da^{-1}	Cloud Cover (Stampede)
May 1	52	34	68	7	605	10
2	49	40	76	5	262	10
3	49	42	84	7	373	8
4	59	41	58	8	779	9
5	68	34	52	9	1889	4
6	56	44	79	11	517	10
7	64	46	57	8	978	9
8	49	36	84	1	269	10
9	51	38	58	9	1015	10
10	46	39	84	6	336	10
11	42	38	88	6	380	10
12	46	40	74	5	517	10
13	50	43	65	8	775	9
14	42	34	56	9	1055	10
15	60	48	50	9	1882	8
16	57	39	33	13	2240	6
17	57	42	43	11	1871	7
18	54	38	50	12	1646	8
19	57	38	40	11	2225	3
20	66	44	35	12	2165	8
21	60	44	43	11	1819	7
22	55	48	72	8	661	7
23	48	40	60	12	1635	9
24	48	41	60	5	867	10
25	50	31	48	9	2339	4
26	58	39	28	14	1760	10
27	55	41	52	10	1122	10
28	61	49	53	3	867	10
29	50	44	87	8	1030	10
30	47	41	89	11	904	10
31	56	44	62	9	1347	6

Date	Air Temperatures °F Max.	Min.	Rel. Humidity Percent	Hours	Solar Rad. Btu-ft^{-2}da^{-1}	Cloud Cover (Stampede)
June 1	77	44	61	16	1528	8
2	64	52	90	9	432	10
3	66	44	68	4	786	9
4	80	41	41	10	2314	4
5	84	46	41	12	2262	2
6	70	46	53	11	2114	9
7	58	52	74	10	531	10
8	54	50	94	7	299	10
9	62	50	73	7	554	10
10	56	48	82	6	506	10
11	64	49	63	7	1066	9
12	66	44	65	7	930	8
13	74	43	58	8	2103	4
14	80	44	50	10	2369	4
15	87	43	37	9	2387	1
16	84	46	42	12	2184	5
17	86	48	43	10	2303	2
18	86	44	44	11	2332	3
19	92	51	44	11	2244	2
20	72	54	65	7	1192	9
21	54	49	99	6	173	10
22	62	48	83	10	867	10
23	72	52	63	5	1354	6
24	80	46	51	10	2306	4
25	85	48	50	10	2214	4
26	70	53	59	5	1358	10
27	68	52	68	10	1184	8
28	74	44	52	10	2000	5
29	74	52	49	11	2321	3
30	80	38	46	10	2258	0

Date	Air Temperatures °F		Rel. Humidity		Solar Rad.	Cloud Cover
	Max.	Min.	Percent	Hours	Btu-ft^{-2}da^{-1}	(Stampede)
July 1	88	43	41	10	2343	0
2	90	48	42	11	2295	2
3	88	49	37	9	2358	0
4	76	48	52	9	1546	5
5	74	42	50	11	2365	3
6	59	48	88	13	605	7
7	77	40	49	9	2007	6
8	54	47	95	11	472	10
9	69	42	52	9	1609	8
10	80	39	45	10	2306	5
11	86	47	42	10	2277	3
12	78	49	56	12	1535	10
13	69	52	71	13	923	5
14	79	44	42	12	1989	3
15	82	40	40	12	2096	0
16	83	42	44	12	2221	2
17	72	47	53	12	1690	6
18	68	51	66	13	993	10
19	66	50	75	11	793	10
20	68	52	71	5	474	10
21	75	55	51	8	1621	7
22	86	44	45	10	2257	0
23	87	49	41	10	2183	1
24	83	48	45	9	2183	0
25	74	49	54	7	1247	5
26	60	49	86	8	412	9
27	69	50	64	5	742	5
28	73	47	48	9	1740	2
29	82	48	40	11	2183	0
30	82	48	46	11	1927	6
31	74	53	56	7	979	7

Date		Air Temperatures °F		Rel. Humidity		Solar Rad.	Cloud Cover
		Max.	Min.	Percent	Hours	$\text{Btu-ft}^{-2}\text{da}^{-1}$	(Stampede)
Aug.	1	86	47	34	8	2208	0
	2	88	44	32	10	2077	5
	3	88	48	32	11	1989	3
	4	82	44	46	11	2020	0
	5	72	51	63	9	879	6
	6	60	54	84	9	486	10
	7	68	48	67	8	686*	9
	8	84	48	45	10	2083*	0
	9	98	48	29	11	2033*	3
	10	90	56	49	10	954*	10
	11	88	52	39	10	1884*	0
	12	92	49	37	11	2003	0
	13	94	52	32	10	2022	0
	14	94	50	35	13	2072	0
	15	96	52	35	12	2022	0
	16	100	53	28	12	1991	1
	17	95	54	32	11	1966	0
	18	--	--	32	11	1897	2
	19	--	--	32	12	1878	2
	20	--	--	47	12	1691	5
	21	81	60	45	8	1329	6
	22	88	49	41	10	--	0
	23	70	51	67	8	--	8
	24	75*	41*	53*	9*	--	2
	25	86*	39*	45*	9*	1777	0
	26	92*	44*	45*	10*	1422	7
	27	89*	55*	46*	10*	1372	8
	28	98*	47*	37*	10*	1827	7
	29	93*	53*	58*	10*	1559	5
	30	87*	48*	63*	10*	1465	4
	31	85*	45*	60*	10*	1409	5

Date	Air Temperatures °F		Rel. Humidity		Solar Rad.	Cloud Cover
	Max.	Min.	Percent	Hours	Btu-ft^{-2}da^{-1}	(Stampede)
Sept. 1	76*	51*	62*	9*	1122	6
2	69*	53*	83*	7*	917	9
3	80*	45*	55*	8*	1771	0
4	81*	50*	67*	7*		1
5	76*	50*	65*	9*		9
6	73*	53*	60*	6*		9
7	72*	40*	63*	7*		6
8	74*	47*	68*	7*		7
9	56*	46*	97*	12*		10
10	70*	52*	90*	14*		10
11	--	45*	--	--		10
12	--	--	--	--		2
13	79*	40*	50*	8*		2
14	88*	41*	35*	7*		0
15	94*	49*	35*	6*		0
16	94*	48*	35*	7*		0
17	77*	46*	65*	7*		3
18	73*	49*	70*	8*		6
19	73*	47*	80*	7*		8
20	78*	52*	70*	6*		1
21	79*	47*	70*	7*		5
22	69*	43*	58*	6*		4
23						0
24						0
25						1
26						0
27						0
28						0
29						10
30						10

*Lennox Creek Data

TABLE III

Stream Temperatures, North Fork and Middle Fork
Snoqualmie River, June - July 1966

(Water Temperatures in °F)

Date	North Fork			Middle Fork		
	Max.	Min.	Diurn. Var.	Max.	Min.	Diurn. Var.
June 1	47.0	42.5	4.5	48.5	42.5	6.0
2	46.5	43.5	3.0	44.5	43.5	1.0
3	43.0	42.3	.7	43.8	42.3	1.5
4	43.3	42.0	1.3	44.3	42.3	2.0
5	52.0	42.3	9.7	54.2	43.0	11.2
6	52.0	44.5	9.5	54.3	44.5	9.8
7	49.0	45.0	4.0	50.7	44.5	6.2
8	49.8	44.8	5.0	50.5	44.5	6.0
9	49.0	44.8	4.2	50.5	44.2	6.3
10	47.0	45.3	1.7	47.0	45.2	1.8
11	45.5	43.2	2.3	44.3	43.0	1.3
12	46.3	43.0	3.3	46.8	43.0	3.8
13	45.0	43.5	1.5	45.5	43.3	2.2
14	52.3	44.0	8.3	54.0	44.3	9.7
15	53.5	45.0	8.5	55.5	45.0	10.5
16	52.3	46.7	5.6	53.8	46.3	7.5
17	49.0	46.7	2.3	49.7	46.5	3.2
18	52.8	46.2	6.6	54.5	46.0	8.5
19	50.0	47.2	2.8	50.5	47.2	3.3
20	50.0	45.5	4.5	51.3	45.2	6.1
21	48.5	46.0	2.5	50.0	45.2	4.8
22	54.0	45.8	8.2	54.8	46.0	8.8
23	47.1	45.7	1.4	49.0	48.2	0.8
24	46.6	44.2	2.4	48.3	46.1	2.2
25	53.2	44.0	9.2	52.9	45.9	7.0
26	53.2	46.7	6.5	53.0	48.2	4.8
27	50.5	47.1	3.4	51.1	49.0	2.1
28	50.0	47.0	3.0	49.5	48.0	1.5
29	50.1	44.0	6.1	52.3	50.1	2.2
30	52.5	45.0	7.5	52.9	47.0	5.9

(Water Temperatures in °F)

Date	North Fork Max.	North Fork Min.	North Fork Diurn. Var.	Middle Fork Max.	Middle Fork Min.	Middle Fork Diurn. Var.
July 1	50.0	46.4	3.6	50.9	47.9	3.0
2	46.7	45.7	1.0	47.9	47.0	0.9
3	46.4	45.8	0.6	47.2	46.8	0.4
4	53.1	45.1	8.0	51.8	46.3	5.5
5	50.0	47.0	3.0	50.3	48.2	2.1
6	49.6	46.8	2.8	49.6	47.7	1.9
7	55.7	47.0	8.7	53.6	48.0	5.6
8	57.4	48.5	8.9	57.1	50.0	8.1
9	57.7	48.9	8.8	58.0	50.3	7.7
10	55.0	49.5	5.5	55.3	51.0	4.3
11	56.9	49.3	7.6	54.8	50.5	4.3
12	57.2	49.3	7.9	57.1	50.5	6.6
13	54.0	50.7	3.3	53.9	51.4	2.5
14	53.9	50.4	3.5	53.3	51.4	1.9
15	54.9	50.1	4.8	54.3	50.9	3.4
16	57.9	50.5	7.4	56.0	51.9	4.1
17	59.1	51.1	8.0	59.9	52.9	7.0
18	58.9	50.9	8.0	58.3	53.0	5.3
19	58.8	52.1	6.7	57.9	53.2	4.5
20	58.9	51.2	7.7	60.3	51.0	9.3
21	60.0	50.3	9.7	61.2	51.2	10.0
22	60.1	52.9	7.2	61.1	52.2	8.9
23	59.2	52.9	6.3	60.2	52.8	7.4
24	56.3	53.9	2.4	58.0	53.7	4.3
25	55.0	51.1	3.9	56.0	52.0	4.0
26	58.9	51.0	7.9	61.3	51.0	10.3
27	62.4	53.2	9.2	63.1	53.1	10.0
28	63.1	54.3	8.8	63.9	54.0	9.9
29	63.8	55.1	8.7	64.3	55.0	9.3
30	63.6	55.8	7.8	63.9	55.9	8.0
31	63.7	56.1	6.6	64.3	56.2	8.1