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WASHINGTON STATE DEPARTMENT OF WATER RESOURCES

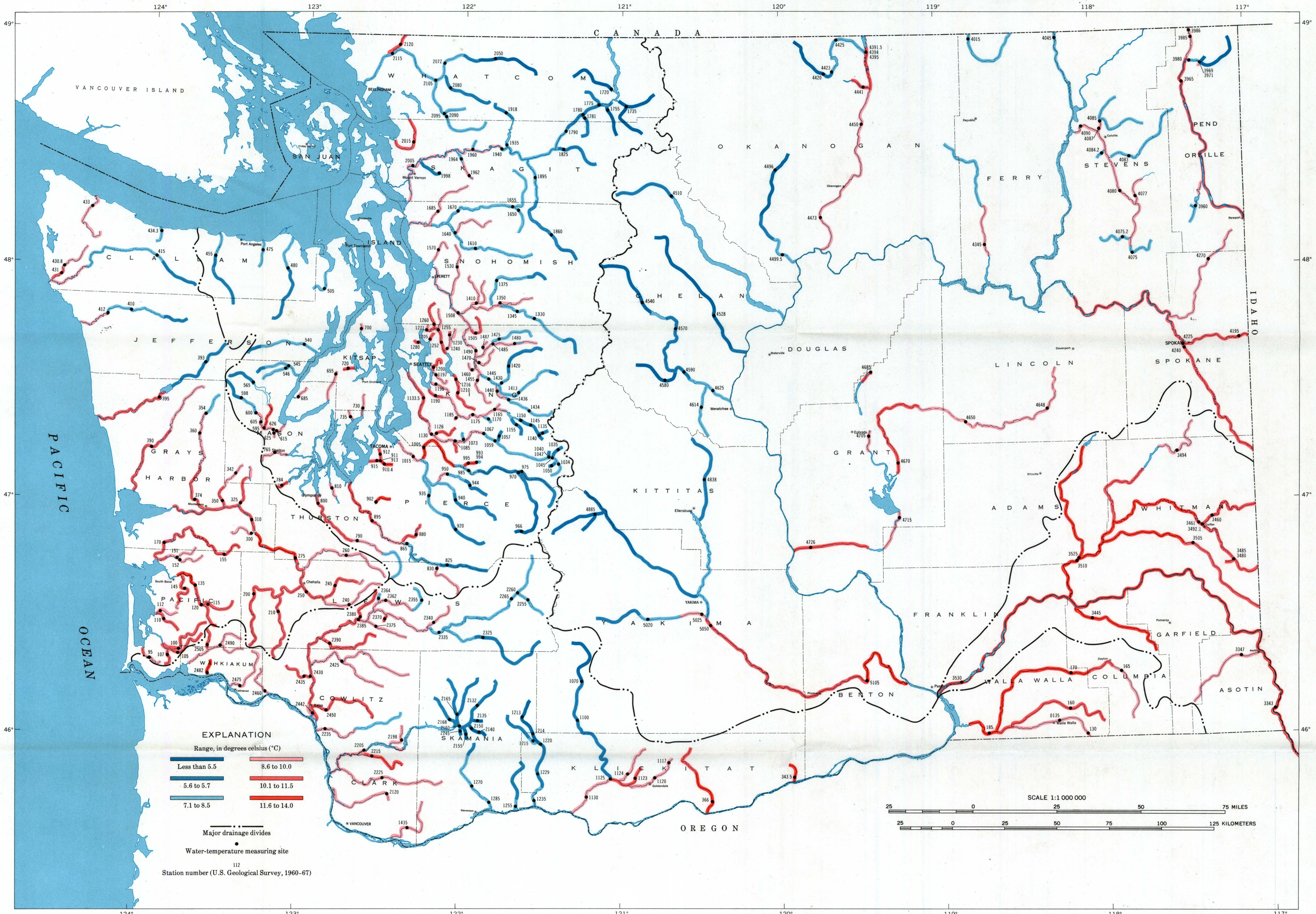

FIGURE 2.—AVERAGE OF THE MEDIAN ANNUAL STREAM TEMPERATURE FOR THE PERIOD 1960-67

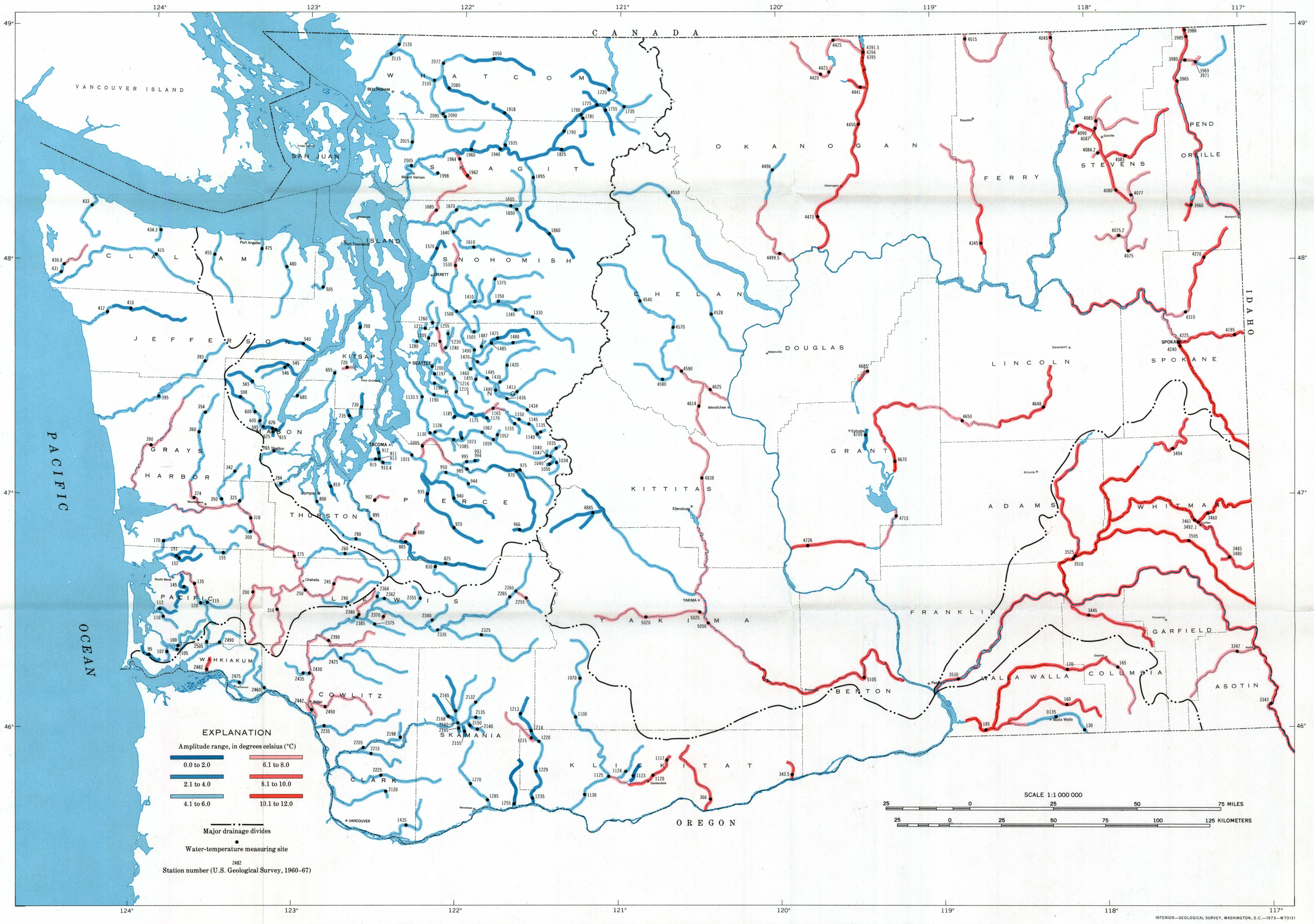

FIGURE 3.—AVERAGE OF THE ANNUAL AMPLITUDE OF STREAM TEMPERATURES FOR THE PERIOD 1960-67

INTRODUCTION

The temperature of a stream generally changes seasonally and follows a definite periodic pattern. In addition to the seasonal temperature variations are minor sporadic fluctuations due to diurnal changes and chance events. These cyclic temperature patterns and minor oscillations are caused by the effects of meteorological and physical phenomena such as solar radiation, wind velocity, air temperature, vapor pressure, water surface exposed, depth of water, temperature of the source water, magnitude and rate of streamflow, mixing, shading, impurities in the water, surface and subsurface inflow, orientation of the stream, and albedo of the water surface.

Temperature is one of the most important water-quality parameters. Many physical as well as chemical and biological properties of water are a function of temperature.

Fishery agencies are interested in water temperatures, because temperature changes may have an adverse effect on aquatic life. Fish and other aquatic animals exist at or near the temperature of the water surrounding them. Unlike warm-blooded animals, they cannot maintain fixed body temperatures when the temperature of the water varies widely. With rising temperatures biological activity increases, the rate of biological processes rise, and energy consumption increases. The elevated water temperatures increase respiratory activity which in turn increases oxygen uptake and carbon dioxide discharge by fish. Thus, the dissolved-oxygen content of the water declines and at some temperature (depending on the fish species; Burrows, 1963) the oxygen concentration is insufficient to meet the higher demands of the fish.

Although the effect of temperature on the biota of a stream is an important consideration, it is not the only factor that is important in the thermal environment of a stream. The effect of temperature on domestic water supplies, industrial water for cooling and other purposes, sediment transport (Colby and Scott, 1965, p. 1–25), irrigation, and on many other factors must also be considered when a stream is to be utilized for optimum financial, recreational, and esthetic benefits.

The purpose of this study was to gain an understanding of the magnitudes, geographic distribution, and time variations in temperatures of streams in Washington, as defined by major drainage areas (fig. 1). The information provides a basis for evaluating the streams relative to their use for fish propagation, and for municipal, industrial, and agricultural supply.

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METHOD OF ANALYSIS

Water temperatures of streams in Washington may be defined, on an annual basis, by means of the Fourier analysis. The analysis reduces the temperature-time curves to Fourier coefficients. The simplest Fourier (harmonic) equation is the sin curve,

$$T = \overline{M} + A[\sin(bx+c)]$$

(Burington, 1954, p.29), where T is the temperature in °C (degrees Celsius), $\overline{M}$ is the median annual temperature, A is the amplitude that defines the maximum variation, c is the phase coefficient in radians, b is a constant equal to 0.0172 ($2\pi/365$) radians per day, and x is the day of the year with January 1st as day 1. Collings (1969) provides detailed information on this method, its application, and reliability.

The harmonic coefficients, $\overline{M}$, A and c have been calculated for 318 stream-temperature measuring sites in the State. None were calculated for the main stem of the Columbia River because of regulation of flow for use by hydroelectric plants and irrigation projects. Data used for this study included those from thermographs, once-daily observations, and intermittent temperature measurements. Of the data from intermittent measurement sites, only those sites with at least eight well-spaced measurements throughout the year (most sites had a greater number) were used. For the analysis all data for the period from January 1, 1960, through December 31, 1967, were used.

MEDIAN ANNUAL AND ANNUAL AMPLITUDE OF STREAM TEMPERATURES

A plotting of the average for the period 1960–67 of the median annual stream temperatures is shown in figure 2, and the annual amplitude for the average of the period is shown in figure 3.

The median annual stream temperature in the Snake River drainage is higher than that of the other major drainages, as is the stream temperature amplitude. The Snake drainage is influenced by comparatively warm summers, cold winters, and only small temperature-moderating effects from ground-water inflow. Therefore, stream temperatures more nearly reflect seasonal air temperatures. Lower median annual temperatures result from the cooler climate of the higher altitudes in the western and northern parts of the Upper Columbia drainage and in the easternmost part of the Puget Sound drainage (along the Cascade Mountains). Also these mountainous areas generally have only small amounts of ground-water inflow which, combined with the cooler climate, results in greater (than other areas) amplitudes of stream temperatures. Streams in the east-central, lowland, part of the Puget Sound drainage, an area underlain by unconsolidated sands and gravels that form near-surface aquifers, have relatively constant temperature, or relatively low stream-temperature amplitudes. Streams in the southern part of the Pacific Ocean drainage have temperatures that are representative of an area that, in general, has only a small amount of ground-water inflow, a mild climate, and is at a low altitude.

Collins (1925, p. 101) asserts that as air temperatures increase, or decrease, so do water temperatures. In order to compare air temperatures and stream temperatures, the median annual air temperatures and the annual amplitude of air temperatures were computed from the U.S. Weather Bureau's 30-year normal. The data for the plots (figs. 4 and 5) were obtained by fitting the harmonic curve to the monthly normal air temperatures recorded at 171 weather stations (U.S. Weather Bureau, 1967, table 1) and by drawing lines of equal air-temperature coefficients.

By comparing figure 2 with figure 4 a definite relation, except for a few anomalies, is shown to exist between median annual stream temperatures and median annual air temperatures. For example, lower stream temperatures (fig. 2) in the mountainous area of the Upper Columbia River and the Puget Sound drainage, show the effect of the cool air temperatures (fig. 4).

The amplitudes of stream and air temperatures also show an interrelationship in the high-altitude mountain area. Stream-temperature amplitudes (fig. 3) are from 2.1° to 4°C (Celsius) and air-temperature amplitudes (fig. 5) are from 8.1° to 10°C. The magnitude of the differences (range) both being 1.9°C but the air temperature is 6°C higher.

Air- and stream-temperature amplitudes are more nearly equal in the Pacific Ocean and Snake River drainages than they are in the high altitude mountain area, or in the Puget Sound drainage. For example, the Snake River drainage has air-temperature amplitudes (10.1° to 12°C) within the range of stream-temperature amplitudes (8.1° to 12°C), whereas in the mountain area such "overlap" of air-temperature and stream-temperature amplitudes do not occur (8.1° to 10°C and 2.1° to 4°C, respectively).

The annual air-temperature amplitudes are not as great in the lower areas of the Pacific Ocean and Snake River drainages as in the mountain areas. In the lower Snake River drainage area air-temperature amplitudes range from 10.1° to 12°C (fig.5), whereas in the mountain areas amplitudes range from 8° to 10°C. However, water-temperature amplitudes in the mountain areas range from 8.1° to 12°C (fig. 3); this is indicative of low base flows which generally result from little ground-water inflow.

MEDIAN ANNUAL MAXIMUM AND MINIMUM STREAM TEMPERATURES

Median annual maximum and minimum stream temperatures are shown in figures 6 and 7, respectively. The maximum stream temperatures generally reflect the influence of air temperatures. This is shown by the higher stream temperatures in the eastern part of the State and by lower temperatures in the western part.

The minimum stream temperatures are generally lower in the eastern than in the western drainages. Few streams in western Washington, except those in the mountains of the west-central Puget Sound drainage, have minimum temperatures as low as 0° to 1.5°C. Several streams in the southwest corner of the Pacific Ocean drainage and central part of the Puget Sound drainage have minimum temperatures of 4.6° to 6°C. The majority of streams in the eastern drainages of the State have minimum temperatures of 0° to 1.5°C.

VARIABILITY OF STREAM-TEMPERATURE CHARACTERISTICS

The phase coefficient, c, may be used to determine the time of occurrence of maximum or minimum temperatures and is related to the physical and environmental characteristics of a stream.

Table 1 lists average phase coefficients for the five major drainages. The Pacific Ocean and Lower Columbia River drainages have the same "c" value (4.18 radians), whereas that of the Puget Sound drainage, 4.19 radians, is only slightly different. This means that the maximum occurrence is on about day 213 (August 1), and the minimum occurrence is on about day 30 (January 30). Those drainages encompass mainly the western part of the State. The Upper Columbia and Snake River drainages in the eastern part of the State have an occurrence of maximum temperatures on days 208 (4.28 radians) and 202 (4.37 radians), respectively, averaging day 205 (July 24).

The standard deviations of the coefficients, c, A, and $\overline{M}$ (table 1), are not error terms but show the variability of streams in each drainage and indicate the stream-temperature characteristics of that drainage.

Generally, climatic differences between eastern and western Washington are reflected in the coefficients in table 1. Because the Lower Columbia River drainage spans both the eastern and western parts of the State (fig. 1), however, it was necessary to divide its drainage into two sections, one from stations 130 to 1255, and the other from stations 1270 to 2505 (fig. 7). This resulted in the following coefficients:

Stations	c, radians	Standard deviation	A, °C	Standard deviation	$\overline{M}$, °C	Standard deviation
130 through 1255	4.30	0.25	6.0	2.5	8.7	2.6
1270 through 2505	4.12	.13	5.1	1.3	8.4	2.2

The $\overline{M}$ and A change only slightly from values in table 1 but the phase coefficient shows the break between eastern and western Washington, the eastern area's average phase coefficient (4.30 radians) being 10 days earlier than that of the western area (4.12 radians). This may be a general indication of the difference between the semiarid eastern climate and the maritime western climate. The maritime climate characteristically has its warmest months later in the year than the semiarid continental climate.

The average median temperature of streams in each of the five drainages was calculated from the cofficients in table 1 and plotted on figure 8. The harmonic curves of figure 8 show a large amplitude of stream temperatures for the Snake River drainage and a relatively low amplitude for the Puget Sound drainage. Also shown is a shifting upward of the curve for the Pacific Ocean drainage in relation to that of the Puget Sound drainage. The curve for the Pacific Ocean drainage shows a higher annual median and annual amplitude of stream temperatures than does that for the Puget Sound drainage; however, both have nearly the same average phase coefficient probably because both are representative of maritime climates.

REMARKS

A cursory examination of the maps reveals that several streams have anomalous temperature patterns. Many of these temperature patterns are due to natural influx of hot or cold water from springs—flow from a warm spring affects temperatures at station 1123 in the Lower Columbia River drainage and a cold spring affects temperatures at station 1073 in the Puget Sound drainage. The influence of large ground-water inflow and the effect of urbanization is shown at stations 911 through 915 in the Puget Sound drainage. Cultural eutrophication of lakes, artificial channelization of streams and many other factors also modify natural stream temperatures.

Stream temperatures are an important factor in water quality; more sophisticated temperature studies will be conducted on the major streams and analyzed at a later date. Further analysis will be made to determine which physical and meteorological factors have the greatest influence on stream temperatures and to what extent urbanization affects stream temperatures.

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Table 1.—*Average stream-temperature coefficients and their variability, by drainage*

Drainage area	c (radians)	Standard deviation S_c (radians and approximate days)	A (°C)	Standard deviation S_A (°C)	$\overline{M}$ (°C)	Standard deviation $S_{\overline{M}}$ (°C)
Pacific Ocean	4.18	0.12 (7 days)	5.3	1.1	10.9	2.7
Puget Sound	4.19	.20 (12 days)	4.7	1.1	8.5	1.7
Upper Columbia River	4.28	.12 (7 days)	7.7	1.8	8.5	1.9
Lower Columbia River	4.18	.20 (12 days)	5.4	1.8	8.5	2.4
Snake River	4.37	.16 (9 days)	9.8	1.2	11.4	.8

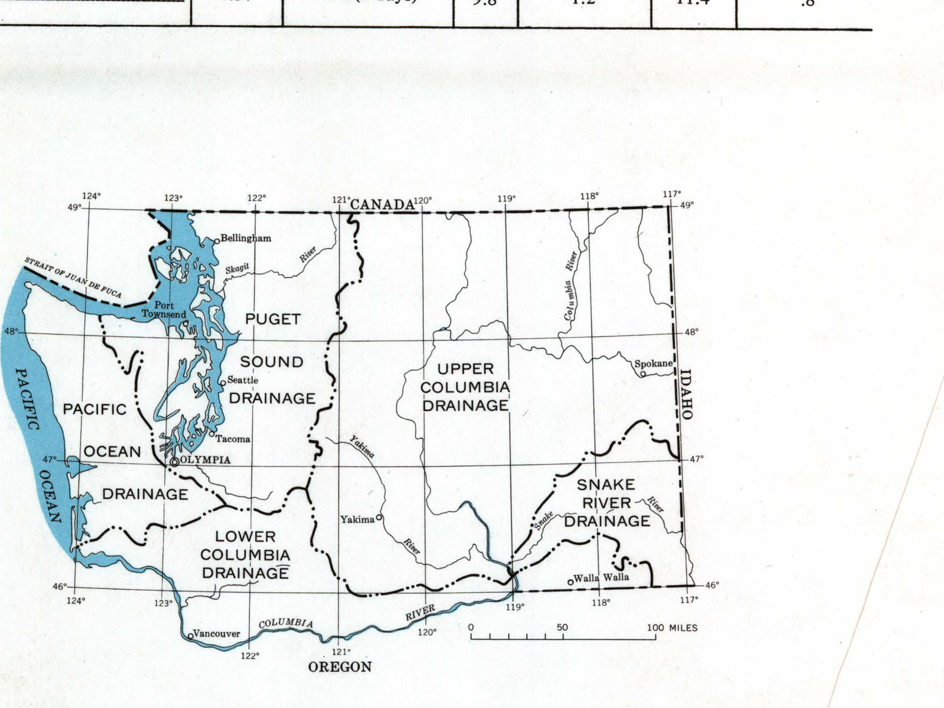

FIGURE 1.—MAJOR DRAINAGE AREAS IN WASHINGTON STATE

STREAM TEMPERATURES IN WASHINGTON STATE

By

M. R. Collings and G. T. Higgins

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