SUMMERTIME WATER TEMPERATURE TRENDS IN STEAMBOAT CREEK BASIN, UMPQUA NATIONAL FOREST

by

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The Steamboat Creek basin drains 227 mi^2 (588 km^2) of steep forested terrain into the North Umpqua River of Southwest Oregon, 39 mi (63 km) northeast of Roseburg. Summer base flows for Steamboat Creek average 83 cfs (2.35 m^3/sec). Steamboat Creek and its tributaries are considered important to the production of summer-run steelhead; the basin has been closed to angling since 1932.

Harvesting has occurred in every subdrainage of the Steamboat Creek basin. Trees were routinely removed from riparian areas when harvesting in the basin began in 1955. Since the mid-1970s to early-1980s, however, buffer strips were left adjacent to streams. In addition, the floods of 1964-65 caused significant damage to riparian vegetation in the basin. This study was undertaken to: (1) determine long-term trends over the period 1969-90 of summertime water temperatures in the mainstem of Steamboat Creek, selected tributaries, and in Boulder Creek, an unharvested control stream in an adjacent watershed and (2) evaluate spacial patterns of maximum water temperatures in the Steamboat Creek basin during the summer of 1990.

Significant ($P \leq 0.10$) trends of decreasing maximum daily summertime stream temperatures on Steamboat Creek and tributaries occurred from 1969-90. In contrast, an unharvested control stream showed a small, but nonsignificant, increasing trend in stream temperatures. The largest decrease in maximum stream temperatures (7 to 11°F, 3.9 to 6.1°C) occurred on small streams with summer base flows less than 6 cfs (0.17 m^3/sec). These streams also had the

highest proportion of stream length adjacent to harvesting activities before 1974. The smallest decrease in maximum stream temperatures (0 to 3°F, 0 to 1.7°C) occurred on streams with little or no history of timber harvest activity along riparian areas, or at locations where summer base flows were greater than 15 cfs (0.42 m^3/sec).

Since no trends in either air temperature or streamflow were apparent over the 1969-90 period, regrowth of riparian vegetation that was previously removed by flooding, debris torrents, or streamside harvesting, appears to be the major cause of trends in decreasing maximum summer stream temperature. Regrowth of riparian vegetation provides shade over small streams, decreasing energy input to the stream from solar radiation.

Maximum daily stream temperatures in lower Steamboat Creek did not change significantly during the 1969-90 study period and stream temperature data in 1960 indicates that maximum stream temperatures in lower Steamboat Creek have historically been high. Any cooling effects by groundwater or tributaries are largely negated by the large volume of water in the main channel. Also, the large stream width renders riparian vegetation relatively ineffective in protecting the stream from solar radiation.

Minimum stream temperatures decreased during the 1969-90 study period for all of the long-term stations in the Steamboat Creek basin while the control stream showed a slight increasing trend. Similarly, diurnal stream temperature fluctuations decreased for several tributaries.

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SUMMERTIME STREAM TEMPERATURE TRENDS IN STEAMBOAT CREEK BASIN, UMPQUA NATIONAL FOREST

INTRODUCTION

Management History of Steamboat Creek Basin

Forested watersheds are valuable natural resources. When managed properly, these watersheds provide timber, habitat for wildlife and humans, clean air, recreation opportunities, and water of high quality for human use and aquatic life.

Maintenance of fishery resources and healthy stream ecosystems is important to the economy and culture of the Pacific Northwest. Stream temperature, because of its ability to regulate and influence aquatic life, plays a prominent role in the overall health of stream ecosystems.

Stream temperatures can increase significantly, particularly for small streams, when forest management practices remove riparian vegetation. Riparian vegetation can be removed either directly by harvesting (Brown 1970) or indirectly through road construction, harvesting and burning on unstable soils, which increase the opportunity for landslides or debris torrents (Swanson et al. 1987). In the Pacific Northwest, summer months coincide with the period in the life cycle of steelhead and salmon when fingerlings inhabit pools of small streams, making them vulnerable to high stream temperatures.

The Steamboat Creek basin in western Oregon is a major tributary of the North Umpqua river and drains a 227 mi^2 (588 km^2) forested watershed. The basin is an important source of timber as well as spawning and rearing habitat for native steelhead trout (Onocorhynchus mykiss). The basin is considered so essential to the production of summer-run steelhead in the North Umpqua River that the drainage has been closed to angling since 1932.

From the time timber harvesting in the basin began in 1955 to the end of 1990, 34% of the basin area had been harvested (USFS).

When logging in the basin began, stream channels often served as skid roads for log transport (Clare and Marston 1968 as cited in Dambacher 1991), clear-cut logging adjacent to streams often removed all riparian vegetation, and woody debris was removed from the stream channels.

In the winter of 1964-65, the basin experienced several major precipitation events with recurrence intervals of approximately 100 years. Mass soil failures and debris torrents were common and added to the loss of stream shade due to harvesting (Mikeal Jones, USDA Forest Service, Umpqua National Forest, Roseburg, Oregon; personal communication).

In the 1960s, several studies showed that the removal of riparian vegetation decreased stream shade, increased solar radiation energy input into the stream, and thus increased maximum summer temperatures (Levno and Rothacher, 1967; Brown, 1969; Brown and Krygier, 1970; Brown et al. 1971; Swift and Messer 1971). In 1969, Brown et al. (1971) made continuous summertime stream temperature measurements at several sites in the Steamboat basin and demonstrated the importance of riparian shade in maintaining low stream temperatures in summer. Increases in stream temperatures were found by measuring stream temperatures above and below clear-cuts. In the Steamboat Creek basin, the stream temperature of Cedar Creek increased 14°F (8°C), from 69 to 83°F (20 to 28°C), along a 4,200 ft (1,280 m) clear-cut. Brown (1969) showed that removing the shade above a small forest stream increased the solar heat load by nearly six times. Most of Steamboat Creek had summer stream temperatures higher than the optimum temperature for good survival rates and growth of summer steelhead (Brown et al. 1971).

With the results of the stream temperature studies in the 1960s and passage of the Oregon Forest Practices Act in 1972, the US Forest Service recognized a need for improved stream protection. In the Umpqua National Forest, bufferstrips were left along streams to varying degrees beginning in the mid-1970s. The Umpqua National Forest Land Management Plan of 1978 required leaving bufferstrips on all Class I, II and III streams. Timber sales prior to the 1978 management plan were not required to comply with the plan, hence it was not until the early-1980s that all harvesting management adjacent to streams provided bufferstrips (Mikeal Jones, Umpqua National Forest, Roseburg, Oregon; personal communication).

Study Objectives

Considering the high value of steelhead spawning habitat and high harvesting rates in the Steamboat Creek basin, it is important to understand the effects of streamside management practices on fish habitat. This study has two primary objectives:

1) to determine long-term trends, 1969-90, in summertime water temperatures in the mainstem of Steamboat Creek and selected tributaries, and in Boulder Creek, the control stream in an adjacent watershed, and

2) to evaluate spacial patterns of maximum water temperatures in the Steamboat Creek basin during the summer of 1990.

LITERATURE REVIEW

The survival rate of fish is affected by characteristics of the forest stream and riparian ecosystem. These characteristics, inturn, can be affected by forest management activities. Forest management activities such as timber harvesting on hillslopes and in riparian areas, road building, scarification and slash burning can influence physical and chemical characteristics of stream environments, change habitat quality, and change salmonid growth and survival (Hicks et al. 1991). The six most important ways forest management activities can alter salmonid habitat are by changing:

1) stream temperature and light levels,
2) streamflow,
3) the supply of large woody debris,
4) the supply of sediment and stability of streambanks,
5) dissolved oxygen concentration and
6) nutrient supply.

The impact on salmonid habitat and productivity by altering any of these stream characteristics can be difficult to predict because of interactions between them.

Stream Temperature and Light Level Effects on Salmonid Populations

Increases in stream temperature and light levels can affect salmonid populations primarily in two ways:

1) by changing salmonid food sources in the stream environment, and
2) by changing salmonid metabolism, development and activity.

Increasing temperature and light patterns in forest streams can be beneficial or deleterious to salmonid populations, depending on many factors whose combined effects are not fully understood.

Salmonid Food Sources

Organic matter becomes available to the stream environment from two main sources:

1) photosynthesis by aquatic plants in the stream such as

algae (aquatic primary production) and

2) terrestrial sources of organic matter (needles, leaves, wood, soil, grass).

Stream microorganisms colonize on and utilize organic matter from terrestrial sources. These microorganisms and aquatic plants, together called periphyton, become food for invertebrates which in turn become food for salmonids (Murphy and Meehan 1991).

Increased light and temperature generally cause higher production of periphyton (Murphy and Meehan 1991), although it is difficult to separate the influences of light and temperature (Beschta et al. 1987). This increase in production of periphyton is generally greater in small streams than in larger streams that are naturally more open to sunlight (Murphy and Hall 1981). Higher periphyton productivity also generally occurs after channels have stabilized to some degree and erosion inputs have diminished (Gregory et al. 1987).

Several studies have shown that removing streamside vegetation can increase invertebrate populations and, therefore, salmonid populations (Burns 1972; Aho 1976; Chapman and Knudson 1980; Murphy and Hall 1981; Hawkins et al. 1983; Bisson and Sedell 1984; Bisson et al. 1988; Holtby 1988). Murphy and Hall (1981) inventoried aquatic vertebrates and insect predators in old-growth and logged coniferous forests in the western Cascades of Oregon. Logged areas were clearcut without bufferstrips and later burned. Murphy and Hall (1981) made the following observations:

> "Effects associated with logging depended on stream size, gradient and time passed since harvest. Clearcut sections where the stream was still exposed to sunlight (five to 17 years after logging) generally had greater density, biomass and species richness of predators than old-growth (>450 years old) forested sections. Increases were greatest in small (first-order), high gradient (10-16%) streams where clearcut sites had both greater periphyton production and coarser streambed sediment than old-growth sites of similar size and gradient. Second-growth logged sections (12 to 35 years after logging), reshaded by deciduous forest canopy, had lower biomass of trout and fewer taxa than old-growth sites."

The lower biomass of trout and fewer taxa was attributed to a denser canopy in even-age, second-growth forest than in old-growth forest (Murphy and Meehan 1991).

Bisson and Sedell (1984) sampled salmonids in forested streams of western Washington during the low-flow summer period to compare salmonid population biomass in streams flowing through old-growth forests with those in areas recently clearcut down to the stream. Total salmonid biomass averaged 1.5 times greater after logging than in adjacent unlogged sections, however increases were not shared equally among species or age groups. Increased salmonid biomass was attributed to higher densities of invertebrates, earlier emergence of fry and prolonged growing season.

Salmonid biomass may increase in a local area of stream when the canopy is opened and periphyton production is increased, outweighing potential deleterious effects of removing riparian vegetation. However, cumulative downstream effects from many openings may reduce overall salmonid production and diversity in the watershed (Murphy and Meehan 1991).

Metabolism, Development and Activity

Salmonids are cold water fish with definite temperature requirements. Because fish are cold-blooded (poikilothermal), the temperature of their external environment determines their internal temperature and regulates metabolic rate. Therefore, water temperature changes directly influence the physiology and activity of fish. Also, the sensitivity of fish to temperature changes depends largely on their stage of development (Beschta et al. 1987).

Salmonids are tolerant of the temperature extremes they are likely to encounter over their lifespans and geographic ranges. The life stages of salmonid species that rear in fresh water seem especially tolerant of temperatures that are many degrees higher than they are likely to encounter (Beschta et al. 1987). However, salmonids have a lower level of thermal tolerance than other species less desirable to sportsmen (Lantz 1971).

Table 1 shows the lower lethal, upper lethal and preferred

Table 1. Lower lethal, upper lethal, and preferred temperatures (°C) for selected species of salmon and trout based on techniques to determine incipient lethal temperatures (ILT) and critical thermal maxima (CTM) (Bjornn and Reiser 1991).

Species	Lethal Temperature (°C) Lower Lethal[a]	Lethal Temperature (°C) Upper Lethal[b]	Preferred Temperature (°C)	Technique
Chinook salmon	0.8	26.2	12-14	ILT
Coho salmon	1.7	26.0	12-14	ILT
		28.8[c]		CTM
Sockeye salmon	3.1	25.8	12-14	ILT
Chum salmon	0.5	25.4	12-14	ILT
Steelhead	0.0	23.9	10-13	
Rainbow trout		29.4		CTM
		25.0		ILT
Brown trout		29.9		CTM
		26.7		ILT

[a] Acclimation temperature was 10°C; no mortality occurred in 5,500 min.

[b] Acclimation temperature was 20°C unless noted otherwise; 50% mortality occurred in 1,000 min.

[c] Acclimation temperature was 15°C.

temperatures based on laboratory studies for selected species of salmon and trout. Brett (1952) observed that salmonids generally avoid water temperatures above 59°F (15°C). Lethal temperatures have been defined and determined in two ways:

1) slow heating of fish to reveal the critical thermal maximum, CTM, and
2) abrupt transfer of fish between waters of different temperatures to show the incipient lethal temperature, ILT (Brett 1952; Becker and Genoway 1979; as indicated in Bjorn and Reiser 1991).

The lethal water temperatures in Table 1 were derived under laboratory conditions where fish were exposed to a given temperature for a long period of time. Lower lethal temperatures were determined using an acclimation temperature of 50°F (10°C) with no mortality occurring in 5,500 minutes (91.7 hours). The upper lethal values were determined by acclimating fish at 68°F (20°C) and using 50% mortality at 1,000 minutes (16.7 hours) as the endpoint. An exception to using the 68°F (20°C) acclimation temperature is Becker and Genoway (1979) who used an acclimation temperature of 59°F (15°C). Laboratory conditions are unlike natural conditions where summertime diurnal fluctuations can be as much as 14°F (8°C) (Brown et al. 1971).

Several studies indicate a decrease in invertebrate or salmonid populations following the loss of streamside vegetation and increases in stream temperature (Hall and Lantz 1969; Burns 1972; Moring and Lantz 1975; Culp and Davies 1983; Hartman et al. 1987). However, relationships between stream temperature and decreases in populations are not well defined because forest management activities can cause many changes to stream characteristics important to fish populations. These interactions make it difficult to determine the exact forest management activity that caused a particular impact on fish. In contrast to the studies just mentioned, which recorded decreases in populations, Bisson et al. (1988) found an increase in salmonid populations after removal of riparian vegetation with a resulting increase in stream temperatures. The following three studies, by Hall and Lantz (1969), Martin et al. (1986) and Bisson et al. (1988), discuss the changes in salmonid populations of natural streams following increased stream temperatures above the laboratory derived lethal limit for salmonids.

As part of the 15-year (1959-73) Alsea Watershed study, Hall and Lantz (1969) studied Needle Branch, a small central Oregon coastal stream with a mean summer minimum streamflow of 0.02 cfs (0.6 liters per second). The entire 175-acre (71 hectares) drainage was clearcut beginning mid-March 1966, while a second nearby watershed was partially clearcut leaving bufferstrips along the stream, and a third watershed remained unlogged. Considerable debris remained in the stream channel of Needle Branch Creek during the summer, causing significant decreases in dissolved oxygen content in both surface and intragravel water. In September, 1966 the larger debris was cleared from the stream channel. In October the watershed was completely burned to remove slash and prepare for reseeding, which occurred during the winter. In the upper canyon of the stream, the stream temperature rose rapidly during the fire from 55.4°F (13°C) to at least 82.4°F (28°C). Many juvenile coho salmon, cutthroat trout and sculpins were later found dead in this upper area due to the burn.

Annual suspended sediment yields for Needle Branch increased three to four times over pre-logging values. In 1967, the summer after logging and burning, daily maximum stream temperatures of 84 and 85°F (28.9 to 29.4°C) were common on clear, mid-summer days (George Brown, College of Forestry, Oregon State University, Corvallis, Oregon; personal communication). A maximum stream temperature of 86°F (30°C) and maximum diurnal fluctuation of 29°F (16°C) was recorded in 1967, compared to pre-logging maximums of 61°F (16°C) and 3°F (1.5°C) respectively. There was no apparent immediate mortality of fish associated with these extreme temperatures, which were above the 77°F (25°C) maximum reported to be lethal for coho salmon (Brett 1952). The number of juvenile coho salmon migrating to the ocean in the two years following logging were within the range of variation recorded before logging. However, in the two years following logging the resident cutthroat trout population decreased to approximately 25% of the pre-logging population. Moring and Lantz (1975) observed that the 1973 cutthroat-trout population was only 21% of the pre-logging average, while the two other watersheds in the study experienced slight increases over this same period. Although stream temperatures increased significantly and fish populations decreased after removing riparian vegetation, because of the many changes in the stream environment it is difficult to determine what exactly caused the population decrease.

In a different study, Martin et al. (1986) reported that juvenile coho salmon released in selected Mt. St. Helens streams during 1981 and 1982 suffered heavy summer mortality caused by high stream temperatures and unusually large diel temperature fluctuations. For example, in Bear Creek with less than 1% of its surface area shaded by plant cover, summer temperatures exceeded 77°F (25°C) during ten days in 1981 and 30 days in 1982. Bear Creek had diel temperature fluctuations greater than 29°F (16°C). These extreme thermal conditions resulted from lack of shading caused by widespread destruction of trees during the 1980 eruption of Mt. St. Helens or by removal of vegetation along streambanks during subsequent volcanic mudflows.

In a study similar to Martin et al. (1986) in the Mt. St. Helens blast area, Bisson et al. (1988) found contrasting results a few years later. Bisson et al. (1988) monitored habitat use and summer production of stocked underyearling coho salmon from 1983 to 1986 in three streams also affected by the 1980 eruption of Mount St. Helens. Two streams were in the blast area and one was on a volcanic mudflow terrace. Temperatures at the study sites reached 85°F (30°C) and there was relatively little submerged cover and little pool habitat. Despite these severe conditions, production rates of stocked coho salmon at all sites during the summer were equal to or greater than those measured in other streams of comparable size in the region. Bisson et al. (1988) suspected that an abundance of both terrestrial and aquatic food was partly responsible for the high summer production of stocked coho salmon. Since the 1980 eruption, there has been a notable increase in herb- and shrub-dominated riparian communities supporting abundant populations of invertebrates.

Under natural conditions of diurnal fluctuations, large populations of salmonids are able to withstand periodic, short-term exposures to temperatures that exceed upper lethal temperatures with minimal deleterious impact. However, these exposures can promote physiological stress which may reduce their resistance to predation and disease or inhibit their feeding and reproduction (Swift and Messer 1971). Fish (1948) observed that the temperature of the Columbia River at Bonneville reached an all time high of 75°F (24°C) in 1941. At the same time, a bacteria lethal to blueback salmon flourished and the 1941 run was almost decimated.

Although fish may survive at temperatures near the extremes of their suitable range, growth is reduced at low temperatures, because all metabolic processes are slowed, and at high temperatures, because most or all food must be used to maintain bodily functions and constant weight (Bjornn and Reiser 1991). In a laboratory study with juvenile rainbow trout, Wurtsbaugh and Davies (1977) found that when temperatures increased from 45 to 73°F (7 to 23°C), maintenance rations increased from 2.2 to 7.5% of body weight per day.

The growth rate of fish is affected by many factors including the size and metabolic requirements of the fish, water temperature, and the amount of food available to the fish (Elliot 1975b). Elliot (1975a) conducted laboratory studies of the growth rate of brown trout of various body weights (from 0.04 to 10.60 oz, 1 to 300 g) that were fed maximum rations. He found that for all body weights, the growth rate increased from 37.5°F (3°C) to a maximum growth rate at 55.5°F (13°C) (the optimum growth rate), then decreased to 0 growth rate at 67°F (19.5°C). The size of the fish determined the maximum growth rate; from 2.8% body weight per day for the 0.04 oz (1 g) size, to 0.4% body weight per day for the 10.6 oz (300 g) size. Wurtsbaugh and Davies (1977) observed under laboratory conditions that at maximum rations, increasing temperatures up to 62.5°F (17°C) improved rainbow trout growth by increasing the maximum food consumption rate.

Slight increases in late winter/early spring water temperature were found following logging in Carnation Creek, a coastal stream on Vancouver Island, British Columbia (Holtby 1988). These temperature increases accelerated the development of coho salmon embryos in the gravel and caused the early emergence of juveniles in the spring. Earlier emergence prolonged the growing season for the young salmon but increased their risk of being washed downstream during late-winter freshets. Warmer springtime stream temperatures were associated with earlier seaward migration of salmonid smolts, possibly resulting in decreased smolt-to-adult survivals. Following clearcutting of the entire Needle Branch Creek basin in the Oregon Coastal Range, Moring and Lantz (1975) reported a correlation between increased stream temperatures and a shift to earlier migration time for downstream cutthroat migrants.

Dambacher (1991) studied the distribution of juvenile steelhead (Onocorhynchus mykiss) in the Steamboat Creek basin. He observed a change in the activity of steelhead with a change in stream temperature. Both age 0 and >1 steelhead increased their use of riffle habitat exponentially in streams with higher temperatures. This higher stream temperature increased their metabolic rates and, therefore, increased their demand for food. The swifter streamflow in riffles provide a greater invertebrate drift. Smith and Li (1983), as indicated in Dambacher (1991), found that the benefit of a greater food supply could compensate for the greater energetic cost of faster swimming speeds in the riffle.

Dambacher (1991) also observed that densities of age 0 salmonids did not appear to be affected by the range of stream sizes studied or by channel roughness but were low in all channels with high stream temperatures. In the upper and lower segments of Steamboat Creek, where stream temperatures were the highest in the basin, densities of age 0 steelhead were one-fourth the densities of the basin average elsewhere. In the upper segment of Steamboat

Creek, many age >1 steelhead abandoned riffle habitats and apparently left the entire segment when stream temperatures were increasing to their summer maximum. Dambacher suggested that it was likely that the extreme summer temperatures limit the summer carrying capacity in that segment of the creek. The distribution of redside shiner in the Steamboat Creek basin also appeared to be greatly affected by stream temperature. Redside shiner occurred only in stream channels with maximum daily temperature regimes above 73°F (23°C).

In conclusion, there is no single factor that determines the production of fish populations in streams. Both habitat and food resources affect the survival and production of fish in streams, but they are both composed of many variables that vary spatially and temporally in importance (Gregory et al. 1987). Future studies on changes in stream habitat and food resources due to forest management activities must include the stream temperature variable. An understanding of the effect of logging on the entire stream ecosystem is essential if we are to be able to progress in understanding the narrower problem of logging impacts on fish production (Beschta et al. 1987).

Effects of the Stream Environment on Stream Temperatures

As water flows downstream, its temperature will change as a result of several factors that make up the heat balance of water (Beschta et al. 1987). The five primary processes that transfer energy in the stream environment are:

1) net radiation with the sky and vegetation,
2) evaporation with the air,
3) convection with the air,
4) conduction to the streambed, and
5) advection from incoming water sources such as groundwater or tributaries (Brown 1989, Sullivan et al. 1990).

The net rate of heat exchange per unit area of stream surface is shown in the following equation:

$$Nh = Nr \pm E \pm H \pm C \pm A$$

where Nh = net rate of heat exchange
Nr = net radiation
E = evaporation
H = convection
C = conduction
A = advection

The water temperature at any location within a stream system reflects a balance between heat input and heat loss. For a small stream, heat input is primarily determined by the amount of direct solar radiation reaching the stream (solar insolation) which varies daily and seasonally with the position of the sun and with shading by riparian vegetation or topography (Brown 1969). Additional energy sources might include longwave radiation from adjacent surfaces, advective heat, and inputs from condensation, convection and conduction. The major sources of heat loss are evaporation and long-wave radiation of energy to the sky and vegetation (Sullivan and Adams 1990). Heat loss is largely regulated by the difference between air and water temperature. Conduction to the streambed and groundwater in-flow also account for heat loss but are generally a small percent of the total energy budget during the summer.

There are many stream environment and climatic variables that affect the energy budget of a forest stream. Understanding these gains and losses of heat and the influence of the stream environment and climate provides the basis for understanding the relationship between the stream environment and stream temperatures.

Net radiation is the difference between total incoming and total outgoing all-wave radiation, which includes both short- and long-wave radiation (Brown 1969). Radiation transmits energy as an electromagnetic "wave" that releases energy when absorbed by an object. All objects above absolute zero radiate energy depending on their temperature and emissivity. Short-wave radiation from the sun transfers energy to the stream. The stream exchanges long-wave radiation with the atmosphere, primarily with water vapor and CO_2 (Adams and Sullivan 1990) but also with riparian vegetation near the stream.

The processes of evaporation and convection are similar in that both are affected by wind speed at the stream surface (Beschta et al. 1987). The latent heat of vaporization may be added or removed by condensation or evaporation depending on vapor pressure gradients at the stream-air interface (Brown 1969). Convection results from boundary layer conduction and subsequent transfer of this heat through displacement of masses of fluid. Convection depends on the temperature gradient and wind speed at the air-water interface.

Conduction, the transfer of heat from molecule to molecule, transfers heat between the water and the streambed (Brown 1969). Bedrock channels are more effective than gravel bed channels for conducting heat.

Advection is the result of heat exchange as tributaries or groundwater of different temperature mixes with the mainstem streamflow. Advection can either increase or decrease stream temperature (Sullivan et al. 1990).

Since the principle source of energy for heating small streams during summer conditions is solar insolation, riparian vegetation plays the greatest role in the rate at which solar energy reaches small forest streams (Beschta et al. 1987). A continuous canopy is very effective in intercepting direct solar radiation, limiting solar insolation to the stream (Brown and Krygier 1970) and depressing local air temperatures (Sullivan and Adams 1990). Solar radiation arrives at the stream surface either directly or by diffuse pathways due to scatter from clouds, vegetation or topographic features.

Removal of riparian vegetation along smaller streams (orders 1 through 4; Strahler 1957) can significantly increase diurnal and mean daily stream temperatures during the summer (Brown and Krygier 1970). The more canopy cover removed, the greater is the exposure of the stream to solar radiation energy and, thus, the greater the increase in stream temperature. For example, Brown et al. (1971) recorded a 13°F (7°C) increase in stream temperature following a clearcut in a 150-foot (46-meter) exposed section of a small stream (0.05 cfs, 1.4 liters/sec). Similarly, one year after clearcut logging on a small (0.01 cfs, 0.28 liters/sec) Oregon coastal stream, the annual maximum summer stream temperature increased 28°F (15°C) from 57 to 85°F (14 to 29°C) whereas in a nearby watershed where bufferstrips of brush and trees separated logging units from the stream, no changes in temperature attributed to clearcutting were observed (Brown 1970). This increase in maximum stream temperature signifies that leaving bufferstrips represents an effective means of preventing temperature change for many mountain streams.

The effectiveness of a bufferstrip to provide shade for a stream depends on canopy density, canopy height, species composition and stream width (Brazier and Brown 1973). Bufferstrip widths of 100 feet (30.5 meters) or more with mature trees generally provide the same level of shading as that of an old-growth forest (Beschta et al. 1987). Yet for small streams, a narrow strip of shrubs is also effective for providing adequate shade protection.

The extent to which a bufferstrip can shade a stream from solar insolation is determined by measuring its angular canopy density (ACD). Beschta et al. (1987) state:

> "whereas canopy density is usually expressed as a vertical projection of the canopy onto a horizontal surface, the ACD is a projection of the canopy measured at the angle above the horizon at which direct-beam solar radiation passes through the canopy. This angle is determined by the position of the sun above the horizon during that portion of the day during which solar heating of a stream is most significant (usually between 10 am and 2 pm in mid- to late-summer). Thus ACD can provide a direct estimate of the shading effects of streamside vegetation. Although it is possible for natural forest vegetation to have ACDs of 100%, indicating complete shading from incoming solar radiation, the ACD of old-growth stands in western Oregon generally falls between 80 and 90%."

After clearcutting streamside vegetation, the temperature recovery of a stream is largely dependent upon the rate of shade recovery through streamside revegetation (Beschta et al. 1987). Summers (1982) found a relationship between ACD and stand age for vegetation zones in western Oregon (Figure 1). He examined sites with small streams (Orders 1 to 3) that had been clearcut and burned

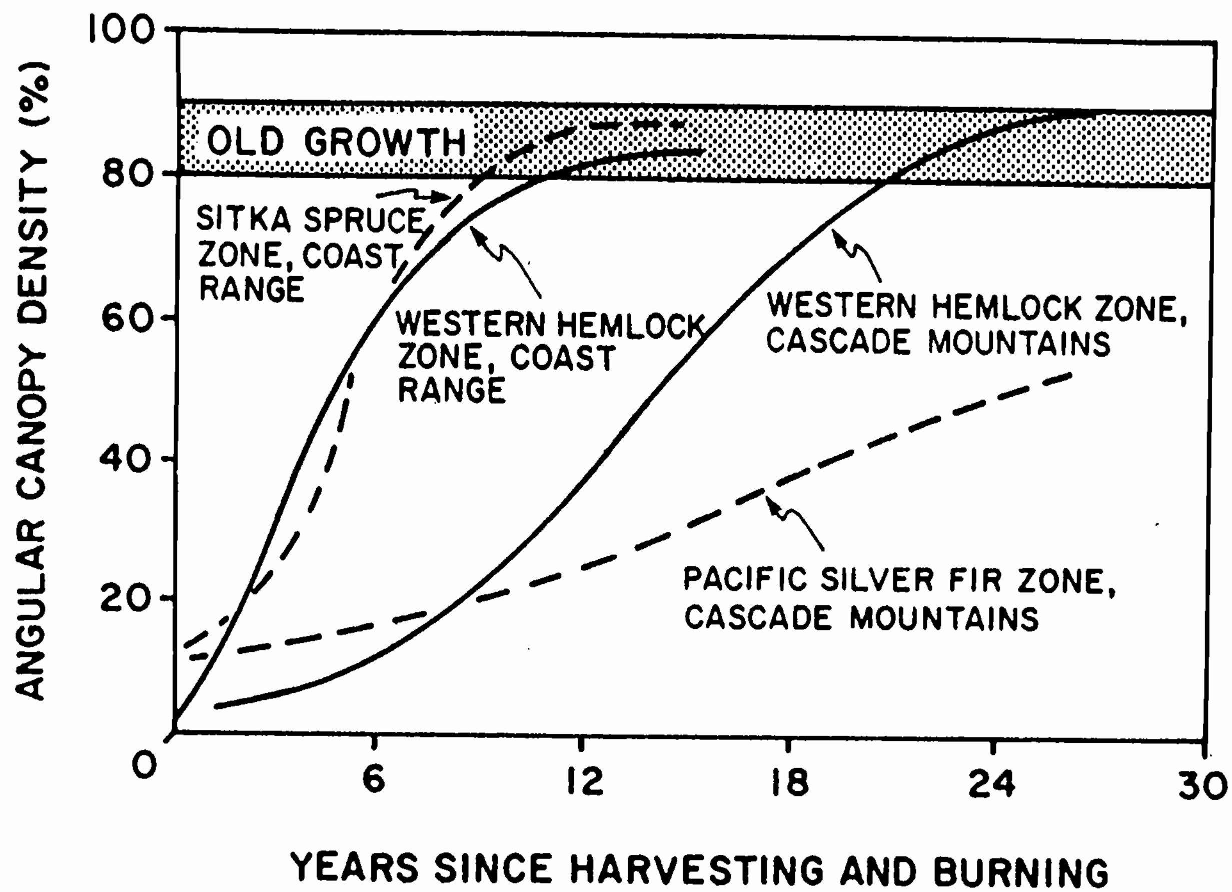

Figure 1. Relation between angular canopy density (ACD) and stand age for vegetation zones in western Oregon (Summers 1982 as in Beschta et al. 1987).

to evaluate the vegetation recovery. Sites in moist coastal ecosystems of the Pacific Northwest recover more rapidly than those in more arid ecosystems. Sites at lower elevations recover more rapidly than those at higher elevations. In the Western Hemlock and Sitka Spruce zones of the Coast Range, vegetation recovery to pre-harvesting and burning levels was reached in about 10 to 15 years while in the Western Hemlock zone of the Cascade Mountains, recovery was reached in about 20 to 25 years.

Regrowth of riparian vegetation after harvesting usually follows a predictive sequence of successional changes (Gregory et al. 1987). Riparian vegetation regrowth is initiated by regrowth of herbaceous plants, followed by shrubs and deciduous species which decrease solar insolation as they dominate the riparian vegetation. Solar insolation remains high for a few years after harvesting and declines with canopy closure over streams by deciduous tree species. As increased deciduous canopy cover increases ACD levels to above post-harvesting levels, solar insolation levels can decline to below pre-harvesting levels until conifers once again dominate the riparian canopy. This process can take up to 100 years to complete, assuming no major disturbances occur during that time interval.

The channel characteristics of a stream reach exposed to incoming solar radiation play a significant role in a stream's energy budget. These characteristics are stream surface area, discharge and type of streambed. As the amount of exposed surface area of a stream increases, so does the total solar energy input to the stream. Thus, the change in temperature of a stream following canopy removal is directly proportional to surface area and inversely proportional to discharge. These relationships are shown in a model developed by Brown (1972) to predict the maximum change in stream temperature (T) in °F expected from completely exposing a reach of stream with a given surface area in square feet (A), and discharge in cfs (Q) to the net rate of heat per unit area ($BTU/ft^2/min$) added to the stream (Nh). Nh, mostly shortwave solar radiation, can be easily determined from tables. This relationship can be expressed as: $\Delta T = \frac{Nh \times A}{Q} \times 0.000267$

where the constant (0.000267) converts discharge in cfs to pounds of water per minute in order that ΔT may be expressed in degrees Fahrenheit. A wide shallow stream will heat up faster than a narrow, deeper stream with the same discharge (Beschta et al. 1987).

The streambed can affect the amount of energy the stream will absorb. For shallow streams, significant amounts of solar insolation on a stream may be transmitted to the bottom. Up to 25% (Brown 1969) of the solar insolation may be absorbed by the streambed, especially if it is solid rock. This condition tends to lower and broaden the peak temperature and, after sunset, the streambed becomes a source of heat for the stream by conduction.

Since summertime stream temperatures are often well above the 47 to 55°F (8 to 13°C) typical of groundwater, the advective transfer of groundwater to small streams can have an important effect on preventing high stream temperatures (Adams and Sullivan 1990). This effect will depend on the rate of groundwater influx relative to the volume of flow into the stream, and on the groundwater temperature compared to that of the stream. Other cool water sources may come from a tributary stream or from an upwelling of stream water that has been cooled by flowing through the streambed (Beschta et al. 1987).

During the summer months in western Oregon, solar radiation levels are typically high because of long days, high sun angles, generally clear skies (Beschta et al. 1987) and warm air temperatures (Adams and Sullivan 1990). These factors in conjunction with low stream discharges lead to high summer stream temperatures. It is under these conditions that the streamside shading effects of forest vegetation become most significant in controlling stream temperatures. The timing of maximum stream temperatures follows by one to two months the timing of maximum solar radiation.

In winter, solar radiation levels at the stream surface are usually low, regardless of canopy cover (Beschta et al. 1987). At this time of year there are short days, low sun angles and usually cloudy weather. The low sun angles increase the proportion of solar energy reflected at the stream surface and also the shading effects from streamside vegetation and topography. In northern latitudes and at higher elevations, winter stream temperatures in exposed reaches may be cooler due to a loss of insulation from the surrounding forest and increased radiative cooling of the stream.

Superimposed on seasonal stream temperature patterns are diurnal temperature fluctuations (Beschta et al. 1987). Generally, diurnal fluctuations are greatest in the summer, in part because of low summer stream flows in the Pacific Northwest. Diurnal fluctuations are also greater in small streams without shade, due to the increased solar insolation. On exposed streams with summer flows of about 1 cfs (0.03 m^3/sec), diurnal fluctuations of 20°F (11°C) can occur. By comparison, the Willamette River, with a mean daily discharge of about 5000 cfs (141 m^3/sec), has a mean diurnal fluctuation in temperature of only 2°F (1.1°C) during August (Brown and Krygier 1967). Peak daily summer stream temperatures are usually reached in mid- to late-afternoon. Minimums are reached just before dawn.

After a stream has been heated following exposure to solar insolation, it will not cool as it flows through a shaded reach unless cooler surface or ground water enters the stream (Brown et al. 1971). Even though the direct solar radiation may be greatly reduced in the shaded reach, this radiation is still greater than long-wave radiation losses from the warm water and is likely to be greater than energy losses from evaporation, convection and conduction. In the Steamboat Creek basin, Brown et al. (1971) measured no reduction in temperature after a small stream heated to 80°F (27°C) in a clearcut passed through a 600-ft (183-m) shaded reach. If any cooling had occurred, it would have been due to groundwater advection.

Brown (1969) states that compared with solar radiation inputs, very little heat exchange at the surface of small forest streams results from evaporation and convection, because vapor pressure and temperature gradients close to the water are small and wind speeds are usually low. Brown's (1969) statement asserts that higher air temperatures following clearcutting are not the reason why stream temperatures rise on small streams. However, Adams and Sullivan (1990) suggest that air temperature can have a large influence on stream temperatures, particularly of larger streams.

Adams and Sullivan (1990) developed a model to explain the basic physics of forest stream heating. Their model uses ten environmental parameters:

1) mean air temperature,
2) air temperature fluctuations,
3) daily average solar insolation,
4) cloudiness,
5) view factor water-to-sky,
6) air velocity,
7) water vapor in the air,
8) stream depth,
9) groundwater influx and
10) groundwater temperature.

The predicted stream temperature is broken into two components, seasonal fluctuations in mean daily stream temperature and diurnal fluctuations in stream temperature about the daily means. Data from 24 streams and rivers of varying depth and riparian conditions in western Washington and Oregon verified that the fundamental patterns of stream temperature are strongly related to these factors (Sullivan and Adams 1990). Generally, stream temperatures were predicted within 3.6°F (2°C) by the model.

Adams and Sullivan (1990) describe the temperature pattern of natural streams as follows:

> "The stream temperature rises in a cyclic fashion and eventually establishes an equilibrium with the surrounding environment. The time to rise to this equilibrium is less than a day for small, shallow streams, to several days for large, deep streams. After reaching equilibrium, the diurnal fluctuations are smaller for the deep stream than for the shallow stream, and for all cases except streams shallower than 0.3 ft (0.1 m), the diurnal stream

temperature variations are less than the diurnal variations of the air temperature. As well, at the equilibrium the daily mean water temperature is very near the daily mean air temperature."

The energy transfers of this pattern are as follows:

"The energy loss from the stream due to evaporation and sky radiation increases rapidly with stream temperature. Evaporation loss increases exponentially with stream temperature. As the stream is heated by solar radiation and convection, a stream temperature, the equilibrium temperature, will always be reached where the energy losses will balance the energy gain for the day. When the stream is being heated to the equilibrium, the solar term dominates the energy budget, as found in actual measurements (Brown 1969; Brown and Krygier 1970)." (Adams and Sullivan 1990).

The model developed by Adams and Sullivan (1990) shows that the four most influential environmental variables regulating heat input and output and, therefore, determining stream temperature are local air temperature, stream depth, riparian canopy (controlling solar insolation) and groundwater inflow. Stream temperature regimes can be explained using these four characteristics which in themselves represent other stream characteristics. When a stream begins, the riparian canopy and groundwater inflow are the most influential variables. As the stream depth, width and total flow increase,

"there is some location in a watershed (threshold distance) where neither groundwater inflow nor riparian vegetation significantly influence water temperature and that water temperature is regulated primarily by air temperature."

In the Pacific Northwest, "the threshold distance appears to occur at about 30 to 60 km (19 to 37 mi) from the watershed divide where average stream depths are approximately 0.6 to 1 m (2 to 3.3 ft)."

Air temperature is important to stream temperatures because it affects most of the energy exchange terms influential in determining the equilibrium temperature in the Adams and Sullivan (1990) model. The effect of air temperature on the daily mean stream temperature is most significant. Throughout the year, the daily "mean water temperature tends to be within several degrees of the (daily) mean air temperature" regardless of stream size or riparian vegetation conditions (Sullivan and Adams 1990). Furthermore, the mean daily stream temperature equals the mean daily air temperature at the "threshold distance".

Besides groundwater, the other advective effect on stream temperature can be from tributaries. A tributary that is warmer or cooler than a main stream can change the temperature of the main stream. The predicted temperature of the main stream is adjusted with a mixing ratio using the temperature and discharge of both streams (Brown 1970):

$$\text{Adjusted temperature} = \frac{(Qt)(Tt) + (Qm)(Tm)}{(Qt) + (Qm)}$$

where Qt and Qm = discharge of the tributary and main stream, respectively, and

Tt and Tm = temperature of the tributary and mainstream, respectively.

Therefore, the warming of several headwater tributaries from harvesting or natural causes could raise the temperature in the main stream below (Swift and Messer 1971).

As stream order increases, however, the impact on temperature of tributaries entering a main stream generally decreases. Brown et al. (1971) found that increasing temperatures in a downstream direction in Steamboat Creek occurred in the wide unshaded main stream but was not due to the entry of warm tributary waters.

DESCRIPTION OF STUDY AREA

Location

The Steamboat Creek basin is a mountainous forested watershed on the west slope of the Cascade Mountains in southwest Oregon, 39 mi (63 km) northeast of Roseburg (Figure 2). The 227 mi^2 (588 km^2) basin drains into the North Umpqua River (longitude 122.7° W, latitude 43.3° N), 265 river mi (426 river km) from the Pacific Ocean. The basin is divided into two major drainages: Canton Creek, 62 mi^2 (161 km^2), and the area drained by Steamboat Creek above the confluence of Steamboat Creek and Canton Creek, 165 mi^2 (427 km^2). Canton Creek enters Steamboat Creek 0.5 mi (0.8 km) above the mouth of Steamboat Creek.

Land management within the Steamboat basin is divided between the Umpqua National Forest (UNF), the Bureau of Land Management (BLM) and private ownership. The North Umpqua Ranger District of the UNF manages 80% of the basin - 33% of the Canton Creek drainage and 98% of the area above the confluence of Steamboat Creek and Canton Creek. The 67% of the Canton Creek drainage not managed by the UNF is under BLM and private ownership. Two percent of the land above the confluence of Steamboat Creek and Canton Creek is under private ownership.

Boulder Creek, the control stream, is adjacent to and southeast of the Steamboat Creek basin and is managed by the North Umpqua Ranger District. The entire drainage is now a Wilderness Area and only a small portion of the head waters has been logged – less than 5% of the basin area. The basin drains a forested watershed covering 31.1 mi^2 (80.5 km^2) into the North Umpqua River, 15 river mi (24 river km) upstream from Steamboat Creek.

Timber Harvesting and Riparian Management

Road building and timber harvesting began in the Steamboat Creek basin in 1955 and expanded rapidly (Figure 3). Logging and road construction have occurred in all of the major drainages tributary to Steamboat Creek, although the impact on some has been

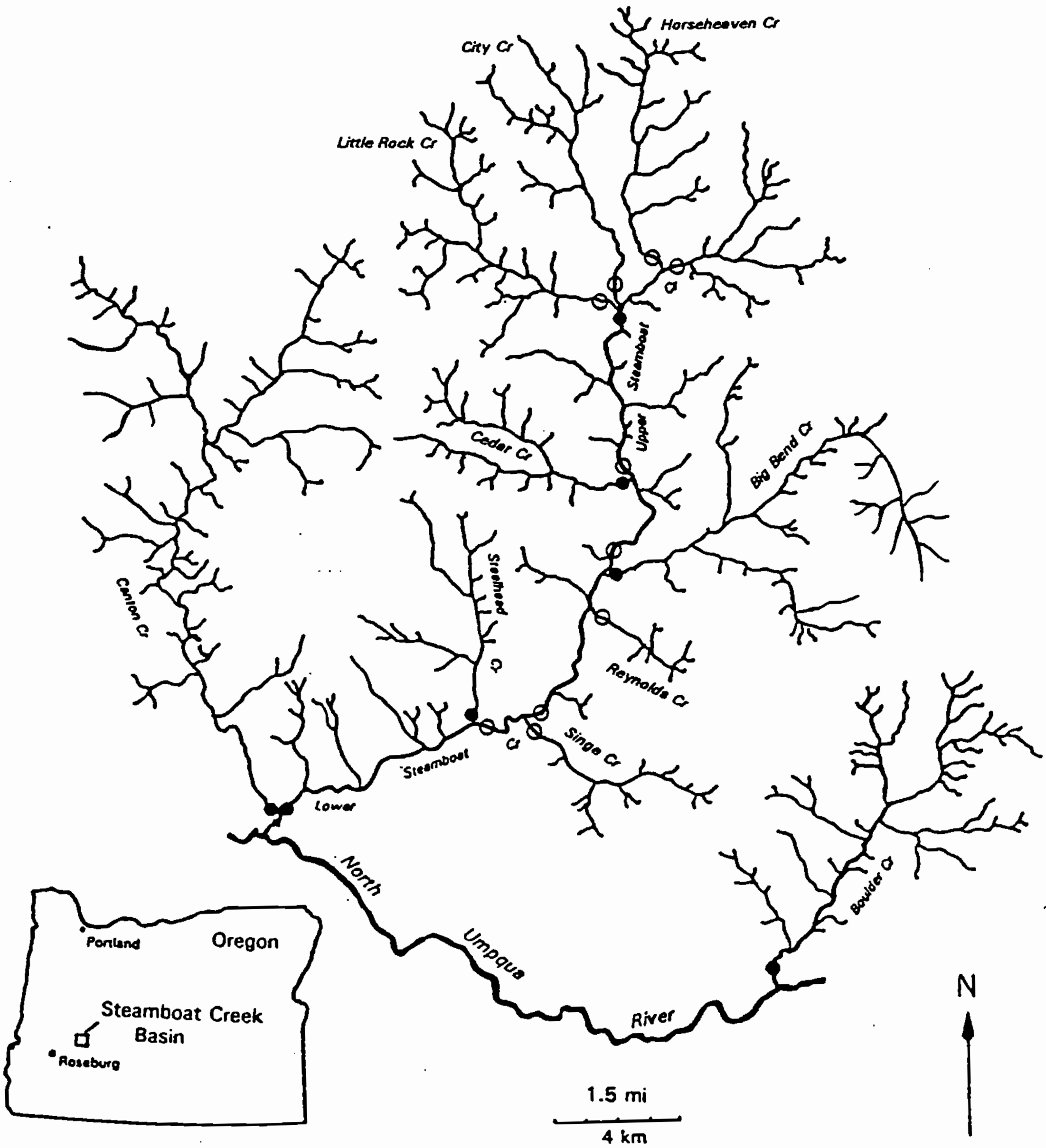

Figure 2. Location of stream temperature monitoring stations in Steamboat Creek and Boulder Creek basins. Solid circles indicate long-term (1969-90) monitoring stations; open circles indicate additional monitoring stations for the 1969 and 1990 summers (modified after Hostetler 1991).

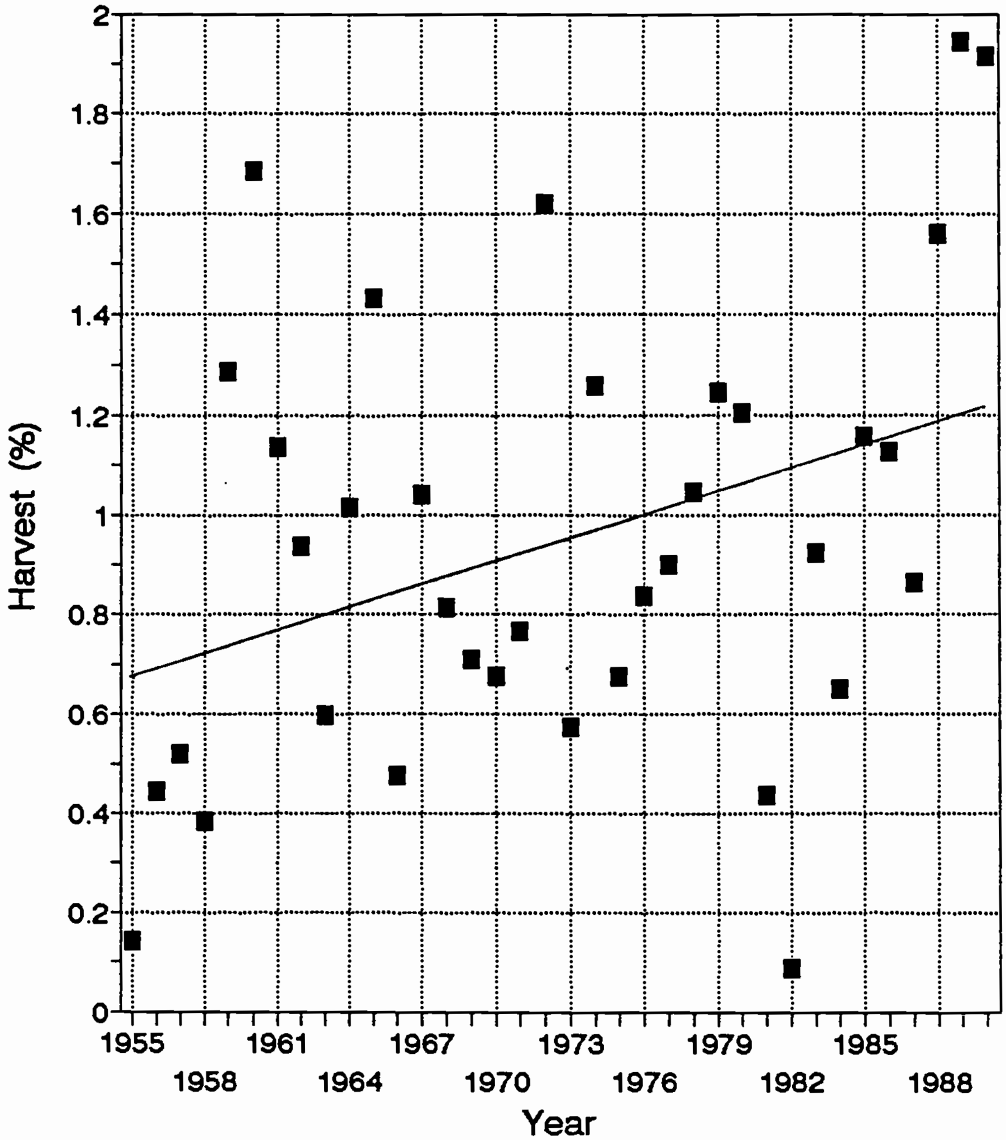

Figure 3. Annual percent of basin harvested for the Steamboat Creek watershed above Canton Creek, 1955-90.

much greater than others. From 1955 to 1990, 34% of the Steamboat Creek above Canton Creek basin was harvested (Table 2). The percentage of the area harvested in selected subdrainages of the Steamboat Creek basin ranges from 6.7% to 58.8% (Table 2). The proportion of Class I, II, and III stream lengths adjacent to harvest units for selected tributaries range from 0.0% to 35.7%, 1955 to 1988 (Table 2). Table B1 summarizes harvest patterns of selected subdrainages in the Steamboat Creek basin.

Topography, Soils and Geology

Topography in the Steamboat Creek basin is steep with elevations ranging from 1,180 ft (360 m) at the mouth of Steamboat Creek, to 5,930 ft (1,808 m) at Fairview Peak on the north divide between the Umpqua River and Willamette River watersheds. Elevations of stream temperature stations in the Steamboat Creek basin range from 1,190 ft (363 m) at Steamboat Creek above Canton Creek to 2,080 ft (634 m) at Steamboat Creek above Horseheaven Creek, 18.5 mi (28 km) upstream from the mouth of Steamboat Creek. Elevations in the Boulder Creek basin range from 1,600 ft (488 m) at the mouth, the location of the stream temperature station, to 6,170 ft (1,880 m) at Balm Mountain on the northeast divide.

Major soil types in the Steamboat Creek and Boulder Creek basins range from shallow gravelly loams to deep clays (Radtke and Edwards 1976). These soils are conducive to flashy runoff and low baseflow. The exception to this flow pattern is the headwaters of Big Bend Creek. This area is characterized by cirque topography with meadows and surface and subsurface soils of pumice, stonefields, talus, glacial till and gravelly and cobbly loams. Permeabilities are high and much of the precipitation is stored in these soils. Therefore, while Big Bend Creek covers only 13% of the Steamboat Creek basin area, it provides 35% of the summer baseflow (Table 3) and the coldest water in the basin, making Big Bend Creek a valuable tributary.

The Steamboat Creek and Boulder Creek basins lie in the Western Cascade Range as part of a deeply dissected belt of volcanic

Table 2. Timber harvest history of selected subdrainages in the Steamboat Creek basin.

Subdrainage	Basin area (acres)	Area Harvested 1955-90 (% of basin)	Total Lengths of Class I, II and III Streams (miles)	Proportion of Class I, II and III Stream Lengths Adjacent to Harvest Units (%)		
				1955-74	1974-88	Total 1955-88
Steamboat Creek Above Canton Creek	105,600	34.0	--	--	--	--
Steelhead Creek	9,950	38.0	21.5	1.0	9.6	10.6
Singe Creek	6,080	41.2	13.5	7.4	2.4	9.8
Reynolds Creek	7,150	58.8	14.0	35.5	0.2	35.7
Big Bend Creek	18,750	29.9	36.0	3.4	3.6	7.0
Cedar Creek	6,770	31.1	12.0	21.2	6.6	27.8
Little Rock Creek	9,640	26.6	18.0	17.2	1.1	18.3
City Creek	6,500	6.7	10.0	0.0	0.0	0.0
Horseheaven Creek	7,810	26.1	14.0	12.6	9.9	22.5

Table 3. Stream discharge data for Steamboat Creek, selected tributaries, and Boulder Creek, 1969-90.

Watersheds	Average Daily Discharge (cfs) for July and August 1969-90 (Summer Base Flow)	Average Daily Discharge as % of Steamboat Creek, June 25 - Sept. 6, 1969-90	Area of Subdrainage as % of Steamboat Creek Basin
Steamboat Creek	83.0	100.0	100.0
Canton Creek	26.0	31.0	27.0
Steamboat Creek Above Canton Creek	58.0	69.8	73.0
Steelhead Creek	6.8	8.2	6.9
Singe Creek	2.2	2.7	4.2
Reynolds Creek	3.3	4.0	4.9
Big Bend Creek	29.0	34.9	12.9
Cedar Creek	1.7	2.0	4.7
Steamboat Creek Below Little Rock Creek	15.0	17.9	22.9
Little Rock Creek	3.0	3.6	6.6
City Creek	2.5	3.0	4.5
Horseheaven Creek	5.7	6.9	5.4
Steamboat Creek Above Horseheaven Creek	4.5	5.4	10.6
Boulder Creek	11.0	13.3	18.8

formations forming the western slopes of the Cascade Range. These deformed pyroclastic rocks range in age from late Eocene to late Miocene as determined chiefly from fossil plants (Peck et al. 1964).

The exposed layers of bedrock in the Steamboat and Boulder Creek basins are primarily from the Little Butte Volcanic Series of the Oligocene and early Miocene. The majority of the two basins is composed of tuff, lapilli tuff, and less abundant drones and flows of dacite, andesite and rhyodacite. A two-mile wide path between Canton and Steamboat Creeks in a north-south direction is basaltic andesite and olivine basalt flows. The headwaters of Big Bend and Boulder creeks are part of the Sardine Formation, composed of pyroxene andesite and less abundant basalt and dacite, with tuff breccia, lapilli tuff and tuff. Along the western border of the Steamboat Creek basin and further west, the Little Butte Volcanic Series continues with andesite flows that dip downward to the east underlying the exposed Steamboat Creek bedrock. Below these andesite flows are rhyodacitic welded tuff that forms a unit at the base of the Little Butte Volcanic Series (Peck et al. 1964).

Stream Characteristics

Steamboat Creek is a fifth order basin (Strahler 1957 as cited in Dambacher 1991) at its mouth, with an average annual total sediment yield of 800 tons/mi^2 (280 metric tons/km^2) (Curtiss 1975). Streambeds throughout the basin vary from basalt bedrock to gravel. Some of the bedrock areas of Steamboat Creek cause the stream to be wide and shallow while exposed to the sun during the hottest portion of the day. Steamboat Creek generally flows in a southward direction from Little Rock Creek to Singe Creek with direct exposure to the noon sun (Figure 2). From Singe Creek to the North Umpqua River, Steamboat Creek generally flows in a southwest direction. As Steamboat Creek flows downstream and widens, the shading effectiveness of riparian vegetation and cooling influence of groundwater becomes less significant. It is common to see hardwoods along the streambanks of Steamboat Creek, indicating past disturbance of riparian vegetation. Boulder Creek generally flows in a south-southwest direction.

Flashy runoff and low summer baseflow are characteristic of streams in the Steamboat Creek and Boulder Creek basins. The average annual discharge of Steamboat Creek was 755 cfs (21.4 m^3/sec) during the study period, June 1969 to September 1990. The average monthly discharge distribution is illustrated in Figure 4. Peak flows generally occur between November and March due to the seasonal pattern of precipitation. Low flows generally occur from July through October. Only 2.7% of the annual discharge occurred from July through September during the study period. The average daily discharge for Boulder Creek and 13 locations in the Steamboat Creek basin for July and August is shown in Table 3. The average daily summer discharge at the mouth of Steamboat Creek is 83 cfs (2.4 m^3/sec).

Discharge extremes at the mouth of Steamboat Creek range from an instantaneous peak flow of 51,000 cfs (1,443 m^3/sec) and mean daily flow of 33,000 cfs (934 m^3/sec) on December 22, 1964, to a low mean daily flow of 30 cfs (0.85 m^3/sec) in September, 1973 (USGS stream discharge data). The highest mean daily flows during the study period were 21,000 cfs (594 m^3/sec) in January, 1971, 16,800 cfs (475 m^3/sec) in March, 1972, and 16,700 cfs (473 m^3/sec) in February 1986.

Boulder Creek had no continuous discharge record prior to September, 1986. The average annual discharge from 1986 to 1988 was 70.6 cfs (2.0 m^3/sec) (Hostetler 1991), 9.3% of the Steamboat Creek annual discharge. Based on spot measurements made from 1969 to 1985 and continuous measurements made from 1986 to 1988, the maximum recorded discharge of 2,203 cfs (62.4 m^3/sec) occurred in January of 1976 (Hostetler 1991) and the minimum recorded discharge of 3.0 cfs (0.08 m^3/sec) occurred in September of 1987 and again in September of 1988. Boulder Creek and Steamboat Creek have a similar seasonal discharge distribution.

The average of the July and August mean daily discharge at the mouth of Steamboat Creek for each year of the study period (1969-90) is shown in Figure 5. These average summer discharges range from a

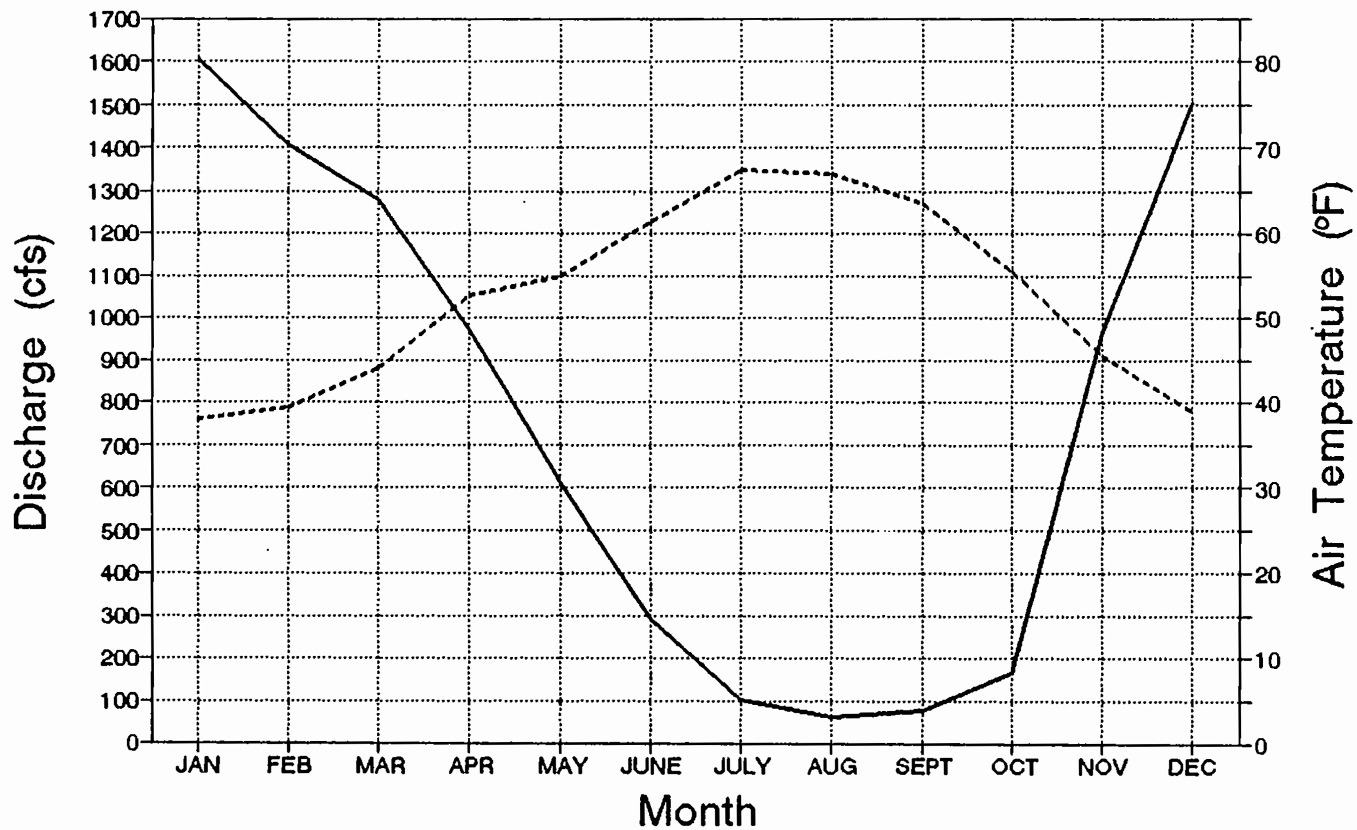

Figure 4. Mean monthly discharge at the mouth of Steamboat Creek, 1969-90, and mean monthly air temperature at Idleyld Park, 1988 and 1989.

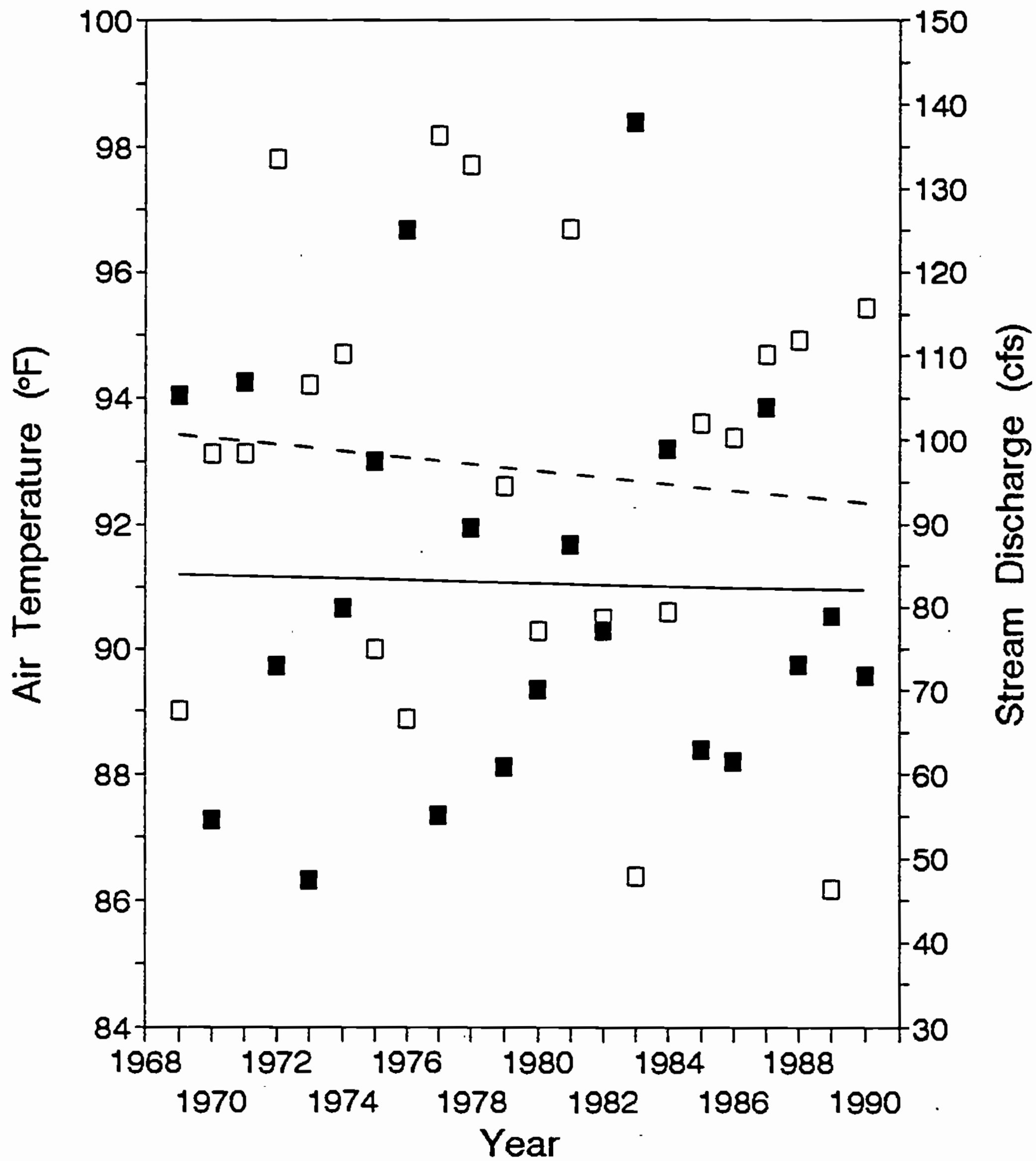

Figure 5. Maximum daily summer air temperatures at Idleyld Park (empty squares and dashed regression line) and mean daily summer discharge of Steamboat Creek (filled squares and solid regression line) in relation to time, 1969-90. Air temperature is the average of the 10 maximum daily air temperatures each year. Discharge is the average of the July and August mean daily discharge each year, 1969-90.

low of 48 cfs (1.4 m^3/sec) in 1973 to a high of 138 cfs (3.9 m^3/sec) in 1983. There is no significant change in the summer discharge trend over the study period.

Climate and Precipitation

The climate of western Oregon is maritime and is influenced strongly by the Coast and Cascade Range mountains. The amount and type of precipitation is closely related to elevation, especially in the Cascade Range. As elevation increases, precipitation and snowfall increase and air temperatures rapidly decrease (Franklin and Dyrness 1973). In the Steamboat Creek basin, summers are hot and dry with mild and wet winters. The air temperature range for the months of July and August are similar (Figure 4). Air temperatures are recorded at Idleyld Park, 16 mi (25 km) west of the mouth of Steamboat Creek. During the study period, 1969-90, the average maximum daily air temperature for July and August was 82°F (28°C) and the average minimum daily air temperature for July and August was 48°F (9°C). The highest recorded air temperature was 105°F (41°C) in July, 1970.

The average of the ten maximum daily air temperatures each year are illustrated in Figure 5. They show a general decrease of 1.1°F (2°C), 93.4 to 92.3°F (34.1 to 33.5°C), from 1969-90. Comparisons of summer air temperature and stream discharge each year in Figure 5 are useful because they can help explain abnormal summer stream temperatures. For instance in 1983, summer stream discharges were above average and summer air temperatures were below average. As a result, maximum stream temperatures in 1983 throughout the Steamboat Creek basin were below average.

Annual precipitation averages 55 in (1400 mm) at the mouth of Steamboat Creek (Brown et al. 1971). Nearly 70% of the precipitation occurs from November through March. Much of this precipitation is snow at the higher elevations. Snowfall can be followed by warm rains and elevated temperatures which create flashy storm flows (Dambacher 1991). Average annual precipitation for the months of July and August, combined, for the study period 1969-1990 was 1.8 in (46 mm), 3.3% of the annual precipitation (NOAA).

Maximum summer stream temperatures in the Steamboat Creek basin occur in the summer, anytime from late June to early September. Summer is the season of low cloud cover, high inputs of solar radiation, high summer air temperature and low stream discharge.

Vegetation

The vegetation of the Steamboat Creek and Boulder Creek basins is in the southern portion of the western hemlock (Tsuga heterophylla) zone, the most extensive vegetation zone in western Washington and Oregon and the most important in terms of timber production (Franklin and Dyrness 1973). Both basins are dominated by the subclimax species Douglas-fir (Pseudotsuga menzieii). The climax species are Western hemlock-western redcedar (Tsuga heterophylla-Thuja plicata). The following observations were made by Franklin and Dyrness (1973) as cited in McSwain (1987):

> Vegetation "communities are arranged along a moisture gradient within the forest. On the dry end of the scale (south facing slopes, well drained soils, the association found is Douglas-fir/oceanspray/ salal (Pseudotsuga menzieii/Holodiscus discolor/Gautheria shallon). Somewhat moister sites contain an overstory of western hemlock and Douglas-fir with an understory of Pacific Rhododendron and Oregon-grape (Tsuga heterophylla-Pseudotsuga/ Rhododendron macrophyllum/Berberis nervosa). The regional climax is the western hemlock/swoardfern (Tsuga heterophylla/ Polystichum munitum association). These climax stands generally include large quantities of Oregon oxalis (Oxalis oregana) and other shrubs such as vine maple, red huckleberry and evergreen huckleberry (Acer circinatum, Vaccinium parvifolium, and V. ovatum). On the wet end of the scale, one finds western hemlock/swoardfern-oxalis (Tsuga heterophylla/ Polystichum-Oxalis). Very wet stream sides and terraces are occupied by western redcedar (Thuja plicata)."

Hardwoods are not common except on disturbed sites or in riparian zones. Common hardwoods in the riparian zones are alder (Alnus spp.) and willow (Salix spp.).

Fish Populations and Distribution

Fish surveys in the Steamboat Creek basin during the summers of 1987 and 1988 were made by Dambacher (1991). The following observations were made:

> "The Steamboat Creek basin supports populations of winter- and summer-run steelhead (Oncorhynchus mykiss), and resident rainbow trout (O. mykiss), sea-run and resident cutthroat trout (O. clarki), coho salmon (O. kisutch), and chinook salmon (O. tshawytscha). Coho and chinook salmon use only the lower reaches of mainstem segments while steelhead, resident rainbow trout, and sea-run and resident cutthroat trout use both mainstem and tributary channels. Minor numbers of juvenile brown trout (Salmo trutta) and brook trout (Salvelinus fontinalis) were observed in the basin during the study. Redside shiner (Richardsonius balteatus), suckers (Catostomus spp.), Umpqua long-nose dace (Rhinichthys evermanni), and Umpqua squawfish (Ptychocheilus umpquae) occurred only in main channels, while sculpins (Cottus spp.), speckled dace (Rhinichthys osculus), and juvenile Pacific lamprey (Lampetra tridentata) were found in both tributary and mainstem channels."

Thirty-three miles (53 km) of stream channel on the mainstem of Steamboat Creek and seven tributaries were found to be important for summer rearing of age >1 juvenile steelhead (Dambacher 1991). These tributaries were Canton Creek, Steelhead Creek, Reynolds Creek, Big Bend Creek, Cedar Creek, Little Rock Creek and Horseheaven Creek. Average estimated number of steelhead age 0 for 1987 and 1988 was 197,230 and for steelhead age >1 was 21,315. Summer densities of age 0 and age >1 juvenile steelhead in the Steamboat Creek basin were generally low in comparison to other streams with low summer flow in the Western United States (Dambacher 1991).

The location of other fish species in 1987 and 1988 are provided by Dambacher (1991). Cutthroat trout were found throughout the majority of the area surveyed. Chinook salmon reared in the lower 4 mi (6.4 km) of Steamboat Creek and in the lower 0.4 mi (0.6 km) of Canton Creek but coho salmon reared only in the lower 0.4 mi (0.6 km) of Canton Creek. Redside shiner were observed in 8.5 mi (13.6 km) of the Steamboat Creek mainstem. In addition, a small number were observed several hundred feet into Cedar Creek and Canton Creek (Dambacher 1991).

HISTORICAL DATA AND METHODOLOGY

Stream Temperature Data

Daily maximum and minimum summer stream temperatures were recorded at 17 stream temperature monitoring stations: 16 stations in the Steamboat Creek basin and at one station on Boulder Creek in an adjacent basin (Figure 2). The 17 stations are composed of seven long-term stations where temperatures were monitored from 1969-90 and ten stations supplemental where stream temperatures were monitored only in 1969 and 1990 (Figure 2).

At the seven long-term stations, stream temperatures were recorded for most summers between 1969 and 1990 and used to statistically determine stream temperature trends. These long-term stations are: two on Steamboat Creek (Steamboat Creek above Canton Creek, Steamboat Creek below Little Rock Creek); four at the mouth of Steamboat Creek tributaries (Canton Creek, Steelhead Creek, Big Bend Creek, and Cedar Creek); and one at the mouth of Boulder Creek, the control stream, in an adjacent watershed. Maximum and minimum stream temperatures used in analysis for the seven long-term stations are listed in tables C1 to C7.

Measurements of summer stream temperatures (1959-62) at the gauging station near the mouth of Steamboat Creek are listed in Table D1. Also, measurements of afternoon stream temperatures in July, 1968, for selected locations throughout the Umpqua River basin are presented in Table D2.

The stream temperatures from the ten supplemental stations were compared to determine temperature trends from 1969-90 and, with temperatures from the seven long-term stations, to determine the spacial pattern of stream temperatures in 1990. The location of stations in the Steamboat Creek basin correspond with sites established and recorded by Brown et al. (1971) during a 1969 stream temperature study.

Since the 1969 Brown study, the six long-term stream temperature recording stations in the Steamboat Creek basin have been maintained by the USFS North Umpqua Ranger Station (NURS) in

Glide. However, during the summers of 1970 and 1971, stream temperatures for Canton Creek were recorded jointly by the BLM and the Oregon State Wildlife Commission, both in Roseburg. Stream temperatures for Boulder Creek were recorded during the study period (1969-90) by the Douglas County Water Resources Department (DCWRD), also in Roseburg.

Stream temperature data for the Steamboat Creek basin for 1969-87 and for Boulder Creek for 1969-88 were obtained from the Environmental Protection Agency's (EPA) national water quality data base (STORET). For Canton Creek, 1970-71, data was acquired from Oliver and Bauer (1971). Steamboat Creek basin stream temperature data for 1988-90 was obtained from the USFS Umpqua National Forest office in Roseburg. Boulder Creek stream temperature data for 1989 and 1990 and data at the gauging station near the mouth of Steamboat Creek from 1959-62 was acquired from the DCWRD. Stream temperatures in July, 1968, for selected locations throughout the Umpqua River basin were obtained from Lauman et al. (1972).

Where possible, missing summer stream temperatures for the long-term stations were estimated on time-sequenced graphs based on similar temperature patterns from other streams. Table E1 presents the percent of stream temperatures estimated for each long-term station.

In addition to the six long-term stations in the Steamboat Creek basin, ten thermograph sites were added for the summer of 1990 (Figure 2). Five of the sites were on Steamboat Creek (Steamboat Creek above Steelhead Creek, Steamboat Creek above Singe Creek, Steamboat Creek above Big Bend Creek, Steamboat Creek above Cedar Creek and Steamboat Creek above Horseheaven Creek), and five of the sites were at the mouth of five tributaries (Singe Creek, Reynolds Creek, Little Rock Creek, City Creek and Horseheaven Creek). The thermographs were checked weekly to bi-weekly with a hand-held thermometer for proper operation and accuracy. Thermographs were placed in moving water, out of direct sunlight and at least one foot below the water surface. The stream temperature stations were located within 0.1 mi (0.2 km) upstream from tributary junctions except for Steamboat Creek below Little Rock Creek, which is 1.3 mi (2.1 km) below Little Rock Creek, and Singe Creek, located 0.2 mi (0.3 km) above its mouth.

Streamflow Data

Streamflow at the long-term stream temperature stations were gathered to characterize the size of a stream and to evaluate possible relationships between streamflow and stream temperatures for the long-term stations during the study period. A United States Geological Survey (USGS) gauging station (station number 14316700) at the mouth of Steamboat Creek (below Canton Creek) provided continuous stream data for 1969-90. A DCWRD gauging station on Canton Creek, three miles above its mouth near Scaredman Creek campground, provided continuous streamflow data for 1980-90. Instantaneous streamflow data at the stream temperature stations of Steamboat Creek above Canton Creek, Steamboat Creek below Little Rock Creek, Steelhead Creek, Big Bend Creek and Cedar Creek were measured during the study period up to six times each summer by the NURS in Glide. Instantaneous flows from the remaining stations in the Steamboat Creek basin were recorded during the 1969 study by Brown et al. (1971). At the mouth of Boulder Creek, instantaneous stream flows were measured with current meters from 1975-84 and measured continuously by a gauging station from 1987-90 by the DCWRD in Roseburg.

Average daily streamflows at the mouth of Steamboat Creek for 1957-90 were obtained from the USGS in Portland, OR. Average daily streamflows for Canton Creek near Scaredman Creek campground for 1980-86 were obtained from the EPA's STORET data base in Ashville, NC, and for 1987-90 from the UNF office in Roseburg. Instantaneous streamflows from other locations in the Steamboat Creek basin for 1969-87 were obtained from the EPA's STORET data base in Ashville, NC, and for 1988-90 from the NURS in Glide. Boulder Creek streamflows for 1975-87 were obtained from the EPA's STORET data base and for 1988-90 from the DCWRD in Roseburg.

The area above the gauge near Scaredman Creek campground is 87%

of the Canton Creek basin. To estimate the streamflow at the mouth of Canton Creek, the 1980-90 gauged flows at Scaredman Creek were multiplied by (1/0.87) or 1.149, to represent streamflow for the entire Canton Creek basin. The estimated 1980-90 summer streamflow at the mouth of Canton Creek (as a percent of the streamflow at the mouth of Steamboat Creek) was regressed on the streamflow at the mouth of Steamboat Creek. Using this regression equation (r^2 = 0.09) and the gauged streamflow at the mouth of Steamboat Creek, daily streamflow was estimated for the mouth of Canton Creek for 1969-79. Streamflows at Steamboat Creek above Canton Creek were determined by subtracting the streamflow at the mouth of Canton Creek from the streamflow at the mouth of Steamboat Creek.

Boulder Creek streamflows for 1969-86 were estimated by the same regression technique used for Canton Creek. The 1987-90 gauged summer streamflows at the mouth of Boulder Creek (as a percent of the streamflow at the mouth of Steamboat Creek) were regressed on the streamflow at the mouth of Steamboat Creek. Using this regression equation (r^2 = 0.29) and streamflow at the mouth of Steamboat Creek, streamflow was estimated for the mouth of Boulder Creek for 1969-86.

For all the remaining long-term stations in the Steamboat Creek basin streamflows were estimated as a percentage of the streamflow at the mouth of Steamboat Creek. Instantaneous summer streamflows during the periods June 26 to September 6, 1969-90, at each site were divided by the average daily streamflow at the mouth of Steamboat Creek (when flows of Steamboat Creek were <125 cfs, <3.54 m^3/sec) to determine each station's percentage of flow at the mouth of Steamboat Creek. Table 3 lists the average daily discharge as a percent of Steamboat Creek for these stations. These values were multiplied by the average daily streamflow at the mouth of Steamboat Creek to determine the estimated daily flow for any summer day from 1969-90. Estimated flows were useful for the long-term stations, which were used to determine the relationship between stream temperature trends and stream flow. Streamflows used in analysis for the seven long-term stations are listed in tables C1 to C7.

Air Temperature Data

Air temperatures were obtained to evaluate possible relationships between stream temperatures and air temperatures for the long-term stations during the study period. Maximum and minimum air temperatures for the study period, June to September, 1969-90, were recorded at the National Oceanic and Atmospheric Administration (NOAA) weather observation station at Idleyld Park 4NE. This station is located 16 mi (25 km) west of the mouth of Steamboat Creek at an elevation of 1,080 ft (330 m), the same elevation as at the mouth of Steamboat Creek. This data was obtained from NOAA Climatological Data Summaries for Oregon. Air temperatures used in analysis for the seven long-term stations are listed in tables C1 to C7.

Maximum daily air temperatures at Idleyld Park 4NE for August, 1977, were estimated using regression analysis to determine the relationship of maximum daily air temperatures between the NOAA weather observation stations at Idleyld Park and at Roseburg KQEN radio station, located 21 mi (34 km) southwest of Idleyld Park. Roseburg KQEN had the most highly correlated maximum air temperature pattern with Idleyld Park of any weather observation station in the area. Maximum air temperatures for August, 1977, at Roseburg KQEN were among the highest of the decade. Therefore, maximum air temperatures for August in 1972 and 1978, also among the highest of the decade, were used to correlate the two stations. For the same days of the month of August in 1972 and 1978, the average of the two maximum daily air temperatures at Idleyld Park was regressed on the average of the two maximum daily air temperatures at Roseburg KQEN. This regression resulted in the following equation ($n = 62$; $r^2 = 0.95$; significance <0.01; Standard error of estimate = 2.2):

$$Y = 1.450 + 0.959X,$$

where Y = Idleyld Park maximum daily air temperature
and X = Roseburg maximum daily air temperature.

Timber Harvest Data

Timber harvest data was collected to study the relationship between timber harvesting and stream temperature trends in the Steamboat Creek basin. Annual totals of acres logged by subdrainage were obtained from the UNF office in Roseburg. A summary of this data is shown in Table 2.

Figure 3 illustrates the timber harvest trends in the Steamboat above Canton Creek basin. Available harvest data for Canton Creek was limited to UNF land, only 33% of the basin. Riparian management activities throughout the Canton Creek basin were similar to those of the Steamboat Creek above Canton Creek basin (Denny Pope, Forest Practices Officer, State Department of Forestry, Roseburg, OR; Frank Oliver, Wildlife Biologist, Bureau of Land Management, Roseburg, OR; personal communications). However, aerial photos indicate that harvesting rates have been higher in the Canton Creek basin than in the Steamboat Creek basin above Canton Creek.

Aerial Photography Analysis

Aerial photographs were studied to determine the relationship between riparian management activities and stream temperature trends. Aerial photographs of USFS land in the Steamboat Creek basin for 1974 (scale 1:70,000) and for 1988 (scale 1:40,000) were obtained from the UNF office in Roseburg. The length of stream adjacent to harvesting was measured and the percent of that length to the total tributary stream length was determined for the streams analyzed in this study (Table 2).

Instruments

Stream temperatures in the Steamboat Creek basin and Boulder Creek for 1969-87 were recorded with Partlow disk type thermographs. From 1988-90 temperatures in the Steamboat Creek basin were recorded with Ryan TempMentor 1.0 thermographs and in Boulder Creek with a Leopold Stevens digital thermograph.

The Partlow thermograph functions with a long liquid-filled tube extending into the water with a sensor at its tip. As the sensor changes temperature, the liquid in the tube expands and contracts affecting a bellows mechanism which, in turn, controls the upward or downward movements of the tracking pen. Temperature accuracy is within 1°F (0.55°C).

The Ryan TempMentor 1.0 thermograph digitally records temperatures that can be transferred to disks on an IBM or compatible computer. Data was recorded at intervals of ten or 20 minutes. Accuracy is +/- 0.54°F (0.3°C) and the temperature range is -25.6 to 158°F (-32 to +70°C). TempMentors were either submerged in the stream with the sensor as part of a waterproof case and secured in an eight-inch metal pipe with metal screens at both ends or secured on land with a remote sensor cable secured in the stream.

Streamflows measured at gauge stations used the manometer gauge system. All other streamflows were measured with Price or Pygmy current meters.

Statistical Analysis

Regression analysis and correlation among variables were considered to be "highly significant" at a probability level ≤ 0.01, "significant" at a probability level ≤ 0.10 and "not significant" at a probability level >0.10.

RESULTS AND DISCUSSION

1969-1990 Maximum Stream Temperature Trends

Maximum stream temperatures in the Steamboat Creek and Boulder Creek basins occurred in the summer when air temperatures were high and streamflows were low. For the seven long-term stream temperature stations in this study (Figure 1), the 15 highest maximum stream temperatures each year occurred between June 24 and September 6 during the study period, 1969-90. The annual maximum stream temperatures occurred between June 30 and August 26 and 90% of these temperatures occurred between July 12 and August 13.

Maximum stream temperatures in several Steamboat Creek basin tributaries and in upper Steamboat Creek (Steamboat Creek below Little Rock Creek) had significant or highly significant decreasing trends from 1969-90 while Boulder Creek, the control stream in an adjacent watershed, showed an increasing, but nonsignificant, trend from 1969-90 (Figure 6 and Table 4). Lower Steamboat Creek (Steamboat Creek above Canton Creek), showed no change in temperature from 1969-90. These trends occurred even though timber harvesting in the Steamboat Creek above Canton Creek basin had a statistically significant increasing trend from 1955-90 (Figure 3; regression slope = 0.015% area harvested per year; significance = 0.04).

Decreasing maximum stream temperatures occurred as a result of regrowth of riparian vegetation that had been removed by landslides or debris torrents in the mid-1960s or by timber harvest operations before the early-1980s. The regrowth of vegetation increased shade over streams, thus decreasing solar radiation input to the stream. When harvesting timber adjacent to streams, bufferstrips were left along the streams beginning in the mid-1970s and to varying degrees until the early-1980s, when they were always left. Regrowth of riparian vegetation lost due to landslides or debris torrents is not well documented in the Steamboat Creek basin.

Figures 7a and 7b show maximum 1969 and 1990 stream temperature changes for Steamboat Creek and selected tributaries compared to

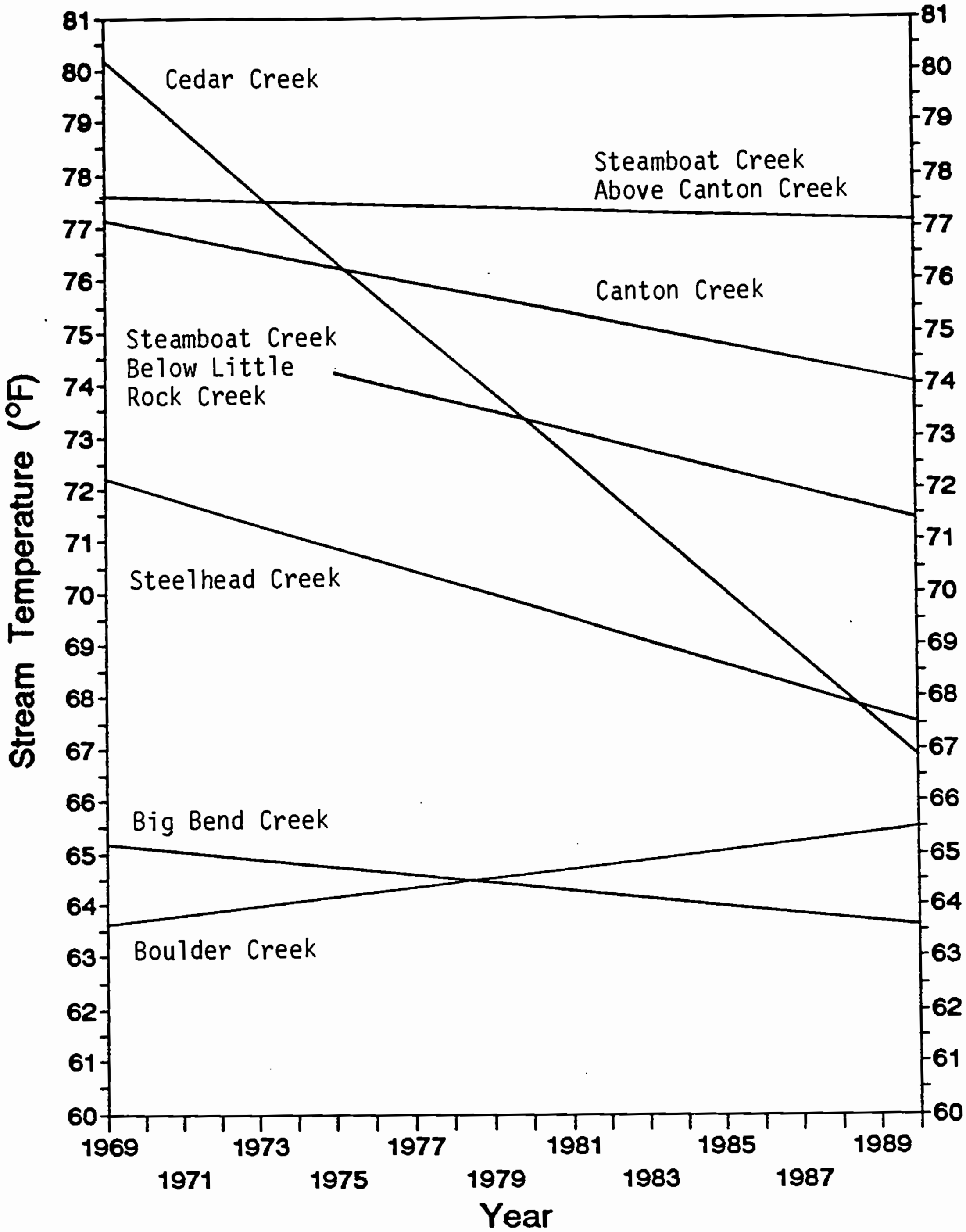

Figure 6. Linear regression trends of annual maximum stream temperatures over time (1969-90) for Steamboat Creek, selected tributaries, and Boulder Creek.

Table 4. Regression analysis summary of annual maximum stream temperatures over time (1969-90) for Steamboat Creek, selected tributaries, and Boulder Creek.

Stream Temperature Station	n	Slope (°F/year)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	16	-0.151	0.31	0.03	1.6
Steamboat Creek Above Canton Creek	21	-0.028	<0.01	0.75	2.5
Steelhead Creek	18	-0.223	0.40	0.01	1.7
Big Bend Creek	19	-0.074	0.04	0.42	2.4
Cedar Creek	15	-0.637	0.87	<0.01	1.8
Steamboat Creek Below Little Rock Creek	15	-0.186	0.22	0.08	1.8
Boulder Creek	16	0.090	0.05	0.39	2.7

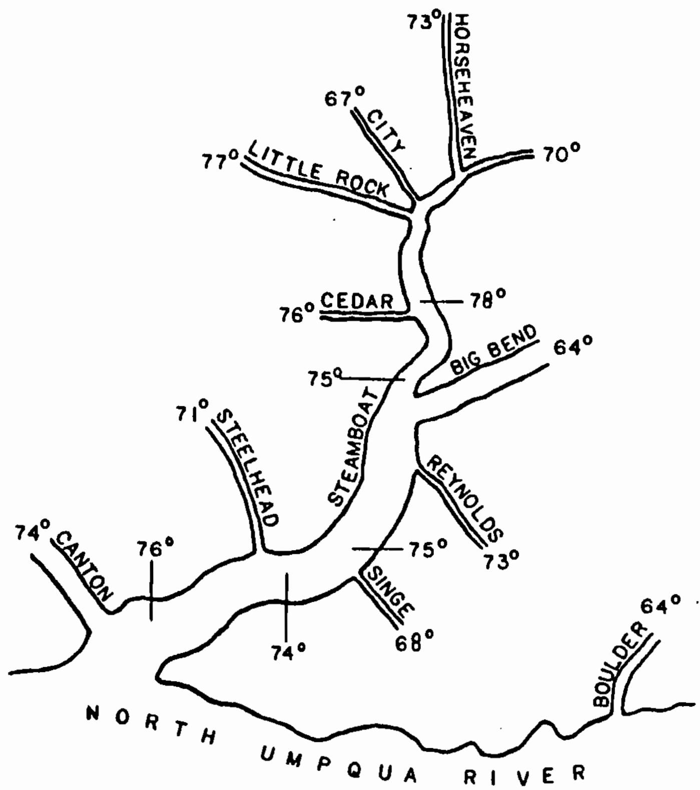

Figure 7A. Maximum stream temperatures (°F) on Steamboat Creek, selected tributaries, and Boulder Creek, July 27, 1969.
Maximum air temperature, Idleyld Park: 84°F
Stream discharge, Steamboat Creek: 84 cfs

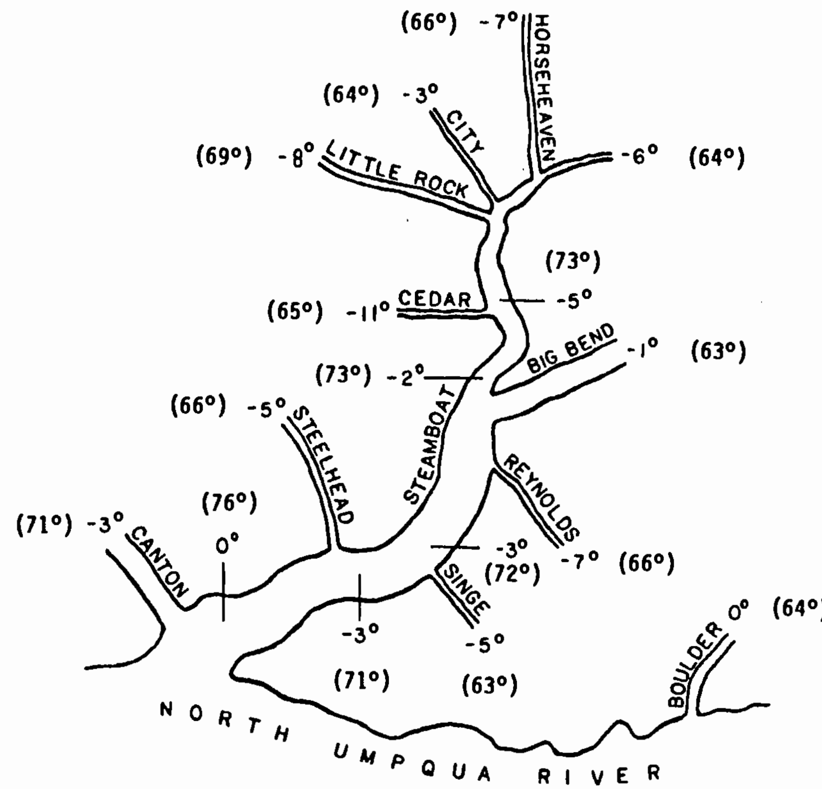

Figure 7B. Maximum stream temperatures (°F) on July 27, 1990, and temperature differences between July 27, 1969 and July 27, 1990, Steamboat Creek, selected tributaries, and Boulder Creek.
Maximum air temperature, Idleyld Park: 88°F
Stream discharge, Steamboat Creek: 66 cfs

Boulder Creek, the control stream, of which only a small portion of the headwaters had been harvested. Boulder Creek (11 cfs, 0.31 m^3/sec, summer baseflow) showed no change in maximum stream temperature between July 27, 1969 and July 27, 1990. Steamboat Creek above Canton Creek (58 cfs, 1.64 m^3/sec, summer baseflow) also showed no change since the stream is too large to be affected by cool groundwater. In addition, Steamboat Creek is very wide upstream of Canton Creek (50-60 feet, 15-18 m) so the stream is less affected by any improvements in riparian vegetation that may have occurred. However, on Steamboat Creek upstream from Steelhead Creek, maximum stream temperatures decreased. Furthermore, they decreased with increasing magnitude further upstream, to a maximum decrease of 6°F at Steamboat Creek above Horseheaven Creek (4.5 cfs, 0.13 m^3/sec, summer baseflow) where the response to the regrowth of riparian vegetation was high.

The maximum stream temperatures for all tributaries to Steamboat Creek were lower on July 27, 1990 than on July 27, 1969 (Figure 7b). The four tributaries with the largest decrease in maximum stream temperatures (between 7 and 11°F, -14 to -12°C, Figure 7b) were those that had the highest proportion of stream length adjacent to harvest units (12.6 to 35.5%; Table 2) during the years 1955-74. Before the mid-1970s, bufferstrips were generally not left along streams in the basin. Therefore, these streams are likely to have had the greatest regrowth of riparian vegetation that had been previously removed by timber harvesting. They also had the lowest summer baseflows, between 1.7 and 5.7 cfs (0.05 and 0.16 m^3/sec), causing temperatures in these tributaries to be the most responsive to the loss and then regrowth of riparian vegetation. These four tributaries are Reynolds Creek, Cedar Creek, Little Rock Creek and Horseheaven Creek (Figure 7b). Little Rock Creek had a significant debris torrent during the 1964 flood that removed riparian vegetation along most of its length, so the decrease in stream temperature for this stream may be attributed primarily to the regrowth of vegetation lost because of the debris torrent.

Steelhead Creek and City Creek had a moderate decrease in the maximum stream temperature (Figure 7b). Steelhead Creek (6.8 cfs, 0.19 m^3/sec, summer baseflow) had a maximum stream temperature decrease of 5°F (2.8°C), even though the proportion of stream length adjacent to harvest units before 1974 was only 1.0%. Also, City Creek (2.5 cfs, 0.07 m^3/sec, summer baseflow), which had no change in riparian vegetation due to timber harvesting, decreased 3°F (1.7°C). Only 6.7% (Table 2) of its basin area has been harvested with no harvesting adjacent to the stream.

Figure 8 shows the maximum stream temperatures on the mainstem of Steamboat Creek, using the temperatures from Figures 7a and 7b, in relation to distance from the basin divide for July 27, 1969 and July 27, 1990. Figure 8 illustrates the decrease in maximum stream temperatures from 1969 to 1990 given similar basin air temperatures, 84°F (29°C) and 88°F (31°C) respectively, similar streamflows at the mouth of Steamboat Creek, 84 cfs (2.4 m^3/sec) and 66 cfs (1.9 m^3/sec) respectively, and the same solar angle. If the streamflow in 1990 was the same as in 1969, even lower stream temperatures in 1990 would be expected.

The sharp decline in stream temperatures (7°F, 4°C) from Steamboat Creek above Big Bend Creek to Steamboat Creek below Big Bend Creek (Figure 8) is caused by the cold temperature and relatively high streamflow of Big Bend Creek. Brown et al. (1971) found that the July 27, 1969 streamflow of Big Bend Creek was 1.6 times higher than the streamflow of Steamboat Creek above Big Bend Creek. Both the 1969 and 1990 data indicate a 1°F (0.6°C) decline in stream temperatures from Steamboat Creek above Singe Creek to Steamboat Creek above Steelhead Creek. The cause of this 1°F (0.6°C) temperature decline is not known, but it is not due to the cooler temperature of Singe Creek since the streamflow of Singe Creek is only 5% of the streamflow of Steamboat Creek above Singe Creek (Brown et al. 1971). Singe Creek would have to be 23°F (13°C) cooler than the temperature of Steamboat Creek above Singe Creek in order to reduce the temperature of Steamboat Creek below Singe Creek 1°F (0.6°C) (Brown et al. 1971).

The maximum stream temperature trends indicated in Figure 7b

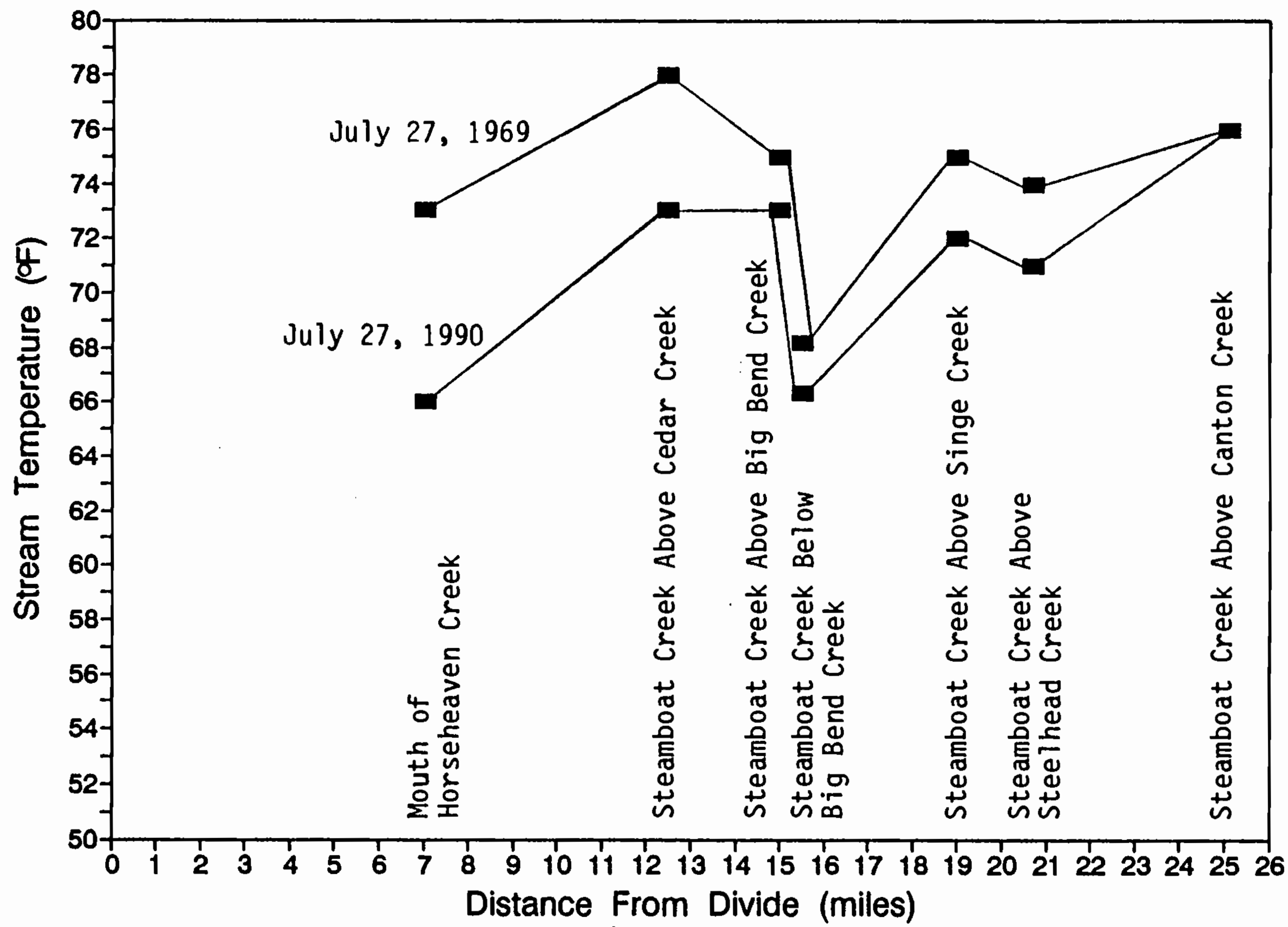

Figure 8. Maximum stream temperatures for Steamboat Creek in relation to distance from divide, July 27, 1969 and July 27, 1990.

are supported by regression analysis of annual maximum stream temperatures for the seven long-term stations (Figure 6). Scatterplots for each of these stations are illustrated in Figures F1 to F7.

Cedar Creek had the greatest decreasing trend in the annual maximum stream temperature over the 22-year study period (Figure 6). This trend (-0.64°F/year) was highly significant. Harvesting adjacent to Cedar Creek removed riparian vegetation along 21% of the stream from 1955-74 (Table 2). Much of this harvesting occurred in 1964 (Dudly Watson, USDA Forest Service, North Umpqua Ranger Station, Glide, Oregon; personal communication) along a three-quarter mile portion of the creek (6.3% of the stream length), 1.5 mi (2.4 km) above the mouth of Cedar Creek, where stream temperatures were recorded. This three-quarter mile section of the stream includes the lower portion of the North Fork of Cedar Creek and a portion below the intersection of the North and South Forks of Cedar Creek. Following timber harvesting of this reach, there was no natural regeneration of trees because of competition with grass. In 1972 and 1973, gabions were installed in the stream along this reach, and alder, willow and Douglas-fir trees were planted on the streambanks. After this restoration, the streambed aggraded with gravel, the riparian vegetation grew back and stream shading increased, decreasing solar radiation to the stream.

Summers (1982) found that, in the Western Hemlock Zone, the shading effect from riparian vegetation regrowth begins about five years after harvesting. On Cedar Creek, the maximum stream temperature for the summer began to decrease rapidly in 1978 (Figure A5), about five years after the planting of riparian vegetation during the restoration efforts. Summers (1982) also found that 20 years after harvesting, shading provided by the natural regrowth of vegetation increased to 80% of the preharvest level. On Cedar Creek, this effect seems to have occurred just ten years after the restoration efforts, since the annual maximum stream temperature appears to have leveled off at an average of 68.5°F (20.3°C) for the years 1983-90 (Figure A5). This shading effect on Cedar Creek may have occurred in ten years instead of the 20 years predicted by Summers (1982) because his sited only had natural regeneration. Also, the regrowth of riparian vegetation by natural regeneration at other pre-mid-1970s harvest units can be expected to have decreased annual maximum stream temperatures as well. The extent of the impact, if any, of the 1964 flood on Cedar Creek is not documented. However, if there had been an impact, any regrowth of vegetation could have contributed to the stabilizing of maximum stream temperatures beginning in 1984, 20 years after the flood. Cedar Creek has the lowest summer baseflow (1.7 cfs, 0.05 m^3/sec) of all the streams in the study, which may have contributed to Cedar Creek stream temperatures having the greatest response to the regrowth of riparian vegetation.

Steelhead Creek (6.8 cfs, 0.19 m^3/sec, summer baseflow) also had a highly significant decrease in annual maximum stream temperatures for the study period (-0.22°F/year), as illustrated in Figure 6. The proportion of stream length adjacent to harvesting before 1974 was only 1%. This harvesting occurred in a unit along 0.25 mi (0.4 km) of the stream on the south side, 1.25 mi (2 km) above the mouth of Steelhead Creek. It is difficult to determine if the decreasing trend in maximum stream temperatures is due to the regrowth of riparian vegetation lost by timber harvesting or of vegetation lost by landslides or debris torrents during the 1964 flood or at some other time. However, since 1955, 34% of the Steelhead Creek basin area has been harvested with associated roads having been built, increasing the chances of landslides or debris torrents.

Steamboat Creek below Little Rock Creek had the third greatest decrease (-0.19°F/year) in the annual maximum stream temperature. With a summer baseflow of 14.8 cfs (0.42 m^3/sec), this station may have a streamflow low enough to reflect decreasing temperatures of upstream tributaries. Also, the width of the stream may be small enough that temperatures are responding to the regrowth of riparian vegetation lost by the 1964 flood and the debris torrent that flowed down Little Rock Creek. The annual maximum stream temperatures in recent years (Figure F6) for this station are still higher than Cedar, Steelhead and Boulder Creeks.

Canton Creek is the last of the four long-term stations with a significant or highly significant decrease in annual maximum stream temperatures. Canton Creek (25 cfs, 0.7 m^3/sec, summer baseflow) had a significant decreasing regression slope of -0.15°F/year. Thus, after 22 years, Canton Creek should have decreased on average about 3.3°F (1.8°C) from 1969-90, very close to the value of 3°F (1.7°C) in Figure 7b.

Although the proportion of the Canton Creek stream length adjacent to timber harvest units was not recorded, communication with forest management personnel indicated that harvesting rates and management activities in the Canton Creek basin were similar to those of the Steamboat Creek above Canton Creek watershed (Denny Pope, Forest Practices Forester, State Department of Forestry, Roseburg, OR; Frank Oliver, Wildlife Biologist, Bureau of Land Management, Roseburg, OR; personal communications). This similarity indicates that the decrease in maximum stream temperatures during the study period for Canton Creek was caused by the regrowth of riparian vegetation lost due to timber harvesting, debris torrents, landslides, or a combination of the three. However, 1974 aerial photos indicate that harvesting rates in the Canton Creek watershed are higher than in the Steamboat Creek watershed above Canton Creek. These higher harvesting rates, if they are adversely affecting riparian vegetation, may extend the recovery time of stream temperatures in Canton Creek and its tributaries compared to streams of comparable size with lower harvesting rates since higher harvesting rates and associated road building may increase the opportunity for landslides or debris torrents (Swanson et al. 1987).

Of the three remaining long-term stream temperature stations, two had a decreasing annual maximum stream temperature regression slope (Big Bend Creek, -0.07°F/year; and Steamboat Creek above Canton Creek, -0.03°F/year), and one had an increasing regression slope (Boulder Creek, 0.09°F/year). However, none of these three regression slopes were statistically significant (Table 4).

The proportion of stream length for Big Bend Creek adjacent to harvest units is relatively low at 3.4% for the 1955-74 period and the summer baseflow of 29 cfs (0.8 m^3/sec) is the highest baseflow of all the tributaries. These characteristics may explain why there was no significant decrease in annual maximum stream temperatures for Big bend Creek.

Boulder Creek (11 cfs, 0.3 m^3/sec, summer baseflow), the control stream, was the only long-term stream temperature station which had an increasing annual maximum stream temperature trend, although it was small (slope = 0.09 °F/year) and not significant. However, the fact that Boulder Creek temperatures had not significantly decreased during a period when all of the remaining streams were decreasing provides supporting evidence that stream temperatures are recovering from land use and/or storm caused temperature increases.

Maximum stream temperatures at Steamboat Creek above Canton Creek remained high throughout the study period (Figures 6 and F2), especially during summers with high air temperatures and low streamflows. These high stream temperatures may be a continuation of a historical pattern in lower Steamboat Creek. On August 8, 1960, a stream temperature of 82°F (27.8°C) was recorded at the gauge station near the mouth of Steamboat Creek. The maximum air temperature for the day was above average at 102°F (39°C)(in Roseburg) and the streamflow at the gauge at the mouth of Steamboat Creek was below average at 50 cfs (1.4 m^3/sec).

Although the Steamboat Creek tributaries generally show a significant decreasing trend in annual maximum stream temperatures for the study period (Figures 6 and 7b), they do not result in a significant decrease in annual maximum stream temperatures at Steamboat Creek above Canton Creek. An exception to this pattern is at Steamboat Creek below Big Bend Creek, as illustrated in Figure 8. Beginning in the headwaters, Steamboat Creek gradually increases in temperature until it reaches Big Bend Creek, where the mean daily stream temperature equals the mean basin air temperature. The large volume and much cooler water of Big Bend Creek cools Steamboat Creek until it heats up again to the mean basin air temperature when it reaches Steamboat Creek above Canton Creek.

In 1968, stream temperatures were measured throughout the Umpqua River basin (Oregon State Game Commission 1972). With this data, summer stream temperatures at seven locations in the Steamboat Creek basin were compared to stream temperatures of 16 streams with similar streamflows located throughout the Umpqua River basin (Table D2). The stream temperatures were measured between July 24 and July 30, 1968, in the afternoon (Noon to 5:00 pm) with air temperatures 80°F (26.7°C) or above. Stream temperatures in the Steamboat Creek basin were average compared to other stream temperatures throughout the Umpqua River basin, except that the stream temperature for Cedar Creek was above average and the stream temperature for Big Bend Creek was below average. Therefore, the maximum stream temperatures at Steamboat Creek above Canton Creek, which have remained high throughout the 1969-90 study period (Figure 6), may represent maximum summer stream temperatures of other streams with similar streamflow throughout the Umpqua River basin.

Although maximum stream temperatures in the Steamboat Creek basin generally decreased during the study period, 1969-90, three long-term stream temperature stations indicate an increasing trend in maximum stream temperatures since the mid-1980s: Steelhead Creek (Figure F3), Big Bend Creek (Figure F4) and Steamboat Creek below Little Rock Creek (Figure F6). However, since 1983, maximum daily summer air temperatures also had an increasing trend (Figure 5) which may have caused the same trend in maximum stream temperatures.

In conclusion, regrowth of riparian vegetation that had been previously removed by timber harvesting, floods or debris torrents caused the largest decrease in annual maximum stream temperatures for streams in the Steamboat Creek basin with summer baseflows of 5.7 cfs (0.16 m^3/sec) or less (Figures 6 and 7b, and Table 4). Because there was no significant change in summer basin air temperature and stream discharge during the study period (Figure 5), the change in annual maximum stream temperatures can be attributed to the regrowth of riparian vegetation, indexed by "Year" in the regression analysis. Although timber harvesting adjacent to many of the tributaries continued after 1974 (Table 2), annual maximum stream temperatures decreased, indicating that bufferstrips were effective in shading these small streams.

The smallest changes in annual maximum stream temperatures during the study period generally occurred on streams with little or no history of timber harvest activity along the stream length (Boulder Creek, City Creek, and Big Bend Creek), or at stations with large summer baseflows (>15.5 cfs, 0.44 m^3/sec, summer baseflow). Although stream shading and/or groundwater inputs are probably of some importance to the temperature regime of small streams, the previous management history does appear to have greatly altered these temperatures.

Maximum Stream Temperature - Summer 1990 Spacial Pattern

The spacial pattern of maximum stream temperatures in the Steamboat Creek basin in 1990 is illustrated in Figure 9 using the average maximum daily stream temperatures for the ten warmest days at each station. Maximum stream temperatures in the basin for the summer of 1990 were generally above long-term averages as indicated by scatterplots of the annual maximum stream temperature for each of the seven long-term temperature stations (Figures F1 to F7). Those scatterplots show that maximum stream temperatures in 1990 were above average in relation to the linear regression line in each figure. Also, Figure 5 indicates that 1990 maximum stream temperatures may be above normal since the 1990 mean daily summer air temperature was above normal and mean daily summer stream discharge was below normal.

For 1990, maximum daily stream temperatures (Figure 9) on the mainstem of Steamboat Creek from above Canton Creek to below Little Rock Creek were between 73 and 79°F (22.8 and 26.1°C), with the highest temperature recorded at Steamboat Creek above Canton Creek. Maximum daily stream temperatures above 70°F (21.1°C) for Steamboat Creek tributaries were recorded on Little Rock Creek (73°F, 22.8°C), and Canton Creek (74°F, 23.3°C). All other stations in the

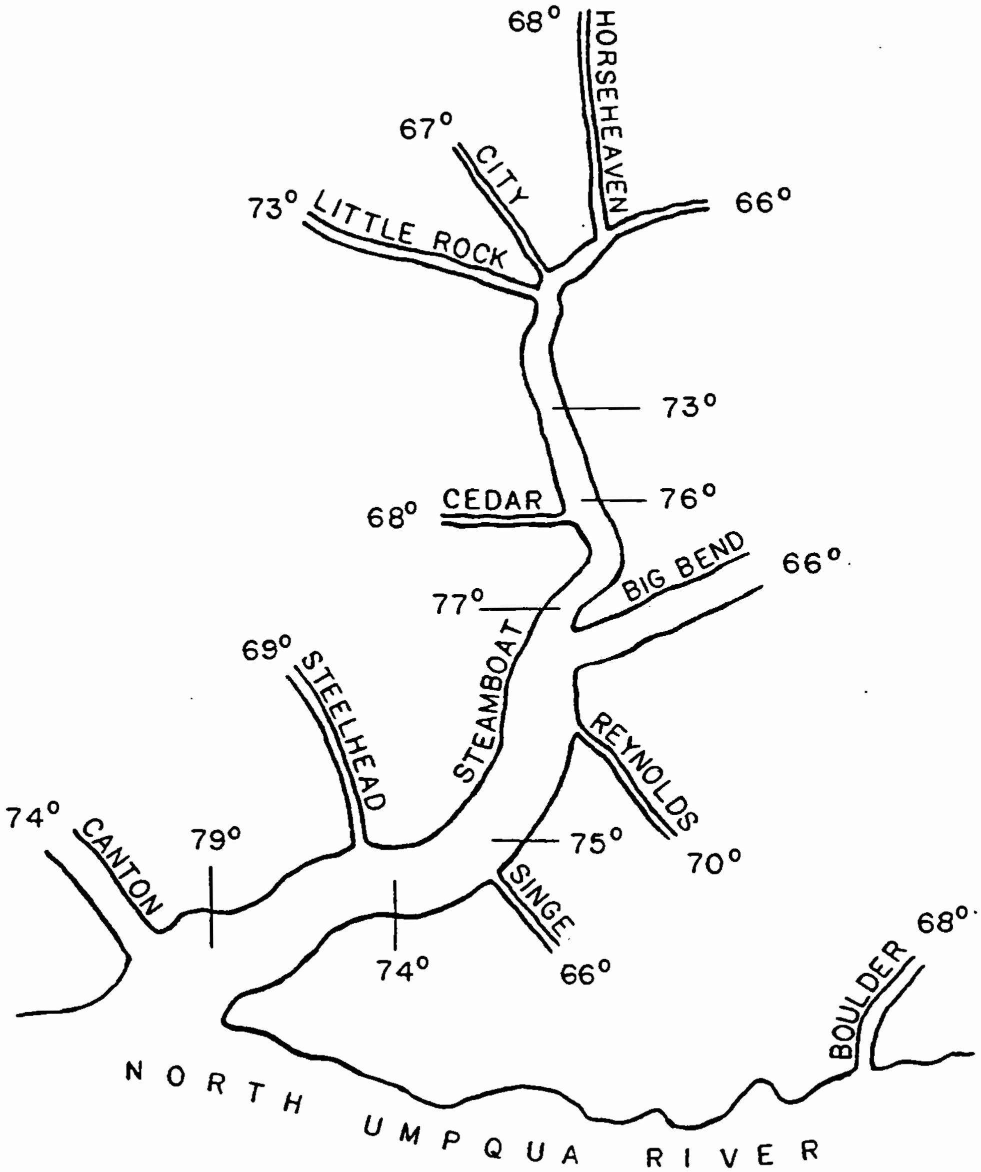

Figure 9. Average maximum daily stream temperatures (based on 10 warmest days) for Steamboat Creek, selected tributaries, and Boulder Creek, summer 1990.

Steamboat Creek basin and Boulder Creek had maximum daily stream temperatures between 66 and 70°F (18.9 to 21.1°C).

Maximum Stream Temperatures in Relation to Fish Tolerances

In Figure 10, linear regression lines illustrate trends in maximum stream temperatures (using the average of the ten maximum daily stream temperatures each year) and indicate the range of maximum stream temperatures at the end of the study period for all streams in the study (63 to 75.7°F, 17.2 to 24.3°C) were well above the preferred water temperature for steelhead salmon (50 to 55°F, 10 to 13°C; Bell 1986) based on laboratory studies. Stations with summer baseflows above 15 cfs (0.42 m^3/sec) have maximum stream temperatures above 70°F (21.1°C), with the exception of Big Bend Creek, which has the lowest maximum stream temperatures (63°F, 17.2°C). Maximum stream temperatures at Steamboat Creek above Canton Creek (75.7°F, 24.3°C) are at the upper lethal limit for steelhead trout (75°F, 23.9°C; Bell 1986). Long-term stations with summer baseflows between 1.7 and 11 cfs (0.05 and 0.31 m^3/sec) summer baseflow had maximum stream temperatures between 64.7 and 66.7°F (18.2 and 19.3°C), well below the upper lethal limit for steelhead salmon, but still about 12°F (6.7°C) above the preferred stream temperature.

Between July 10 and August 13, 1990, the station at Steamboat Creek above Canton Creek station experienced 29 days with the maximum daily stream temperatures exceeding 75°F (23.9°F). The average maximum daily stream temperature for the 29 days was 77.3°F (25.2°C), and the associated minimum daily stream temperatures averaged 66.6°F (19.2°C). The maximum daily stream temperature during the 29 days was 79.9°F (26.6°C) on July 13 with the stream temperature above 75°F (23.9°C) for nine hours. For 1990, maximum daily stream temperatures ≥ 75°F (23.9°C) occurred at the following locations:

Canton Creek, 2 days;
Steamboat Creek above Canton Creek, 29 days;
Steamboat Creek above Steelhead Creek, 2 days;

Steamboat Creek above Singe Creek, 4 days;
Steamboat Creek above Big Bend Creek, 15 days; and
Steamboat Creek above Cedar Creek, 13 days.

1990 maximum daily stream temperatures were generally above average. Thus, the 1990 maximum daily stream temperatures for the long-term stations in Figure 9 (using the average of the ten maximum stream temperatures in 1990) were, on average, 2.6°F (1.4°C) greater than would be predicted by the regression lines for the study period, 1969-90, in Figure 10 (using the average of the ten maximum stream temperatures each year).

Maximum Stream Temperature - Comparing Methods of Analysis

Maximum daily stream temperature trends for the seven long-term stations are illustrated in Figure 10 using the average of the ten maximum daily stream temperatures each year regressed on year. There is little difference in results when using as the dependent variables a single maximum stream temperature for each year (Table 4) or the average of the ten maximum daily stream temperatures for each year (Table 5). The one important difference is that the decreasing slope of maximum stream temperatures for Steamboat Creek below Little Rock is statistically significant using the one maximum stream temperature each year (significance = 0.08) but is not significant using the average of the ten maximum daily stream temperatures each year (significance = 0.13). Also, for some stations, the sample population (n) using the average of the ten maximum daily stream temperatures each year is less than the sample population using the one maximum stream temperature each year. This difference in sample population occurs where there is not enough measured data for ten maximum stream temperatures in a year or where it is inappropriate to estimate the data. Scatterplots of the average of the ten maximum daily stream temperatures each year for each of the seven long-term stations are provided in Figures G1 to G7.

Another comparison was undertaken to evaluate differences (if any) in maximum stream temperature trends when using a single

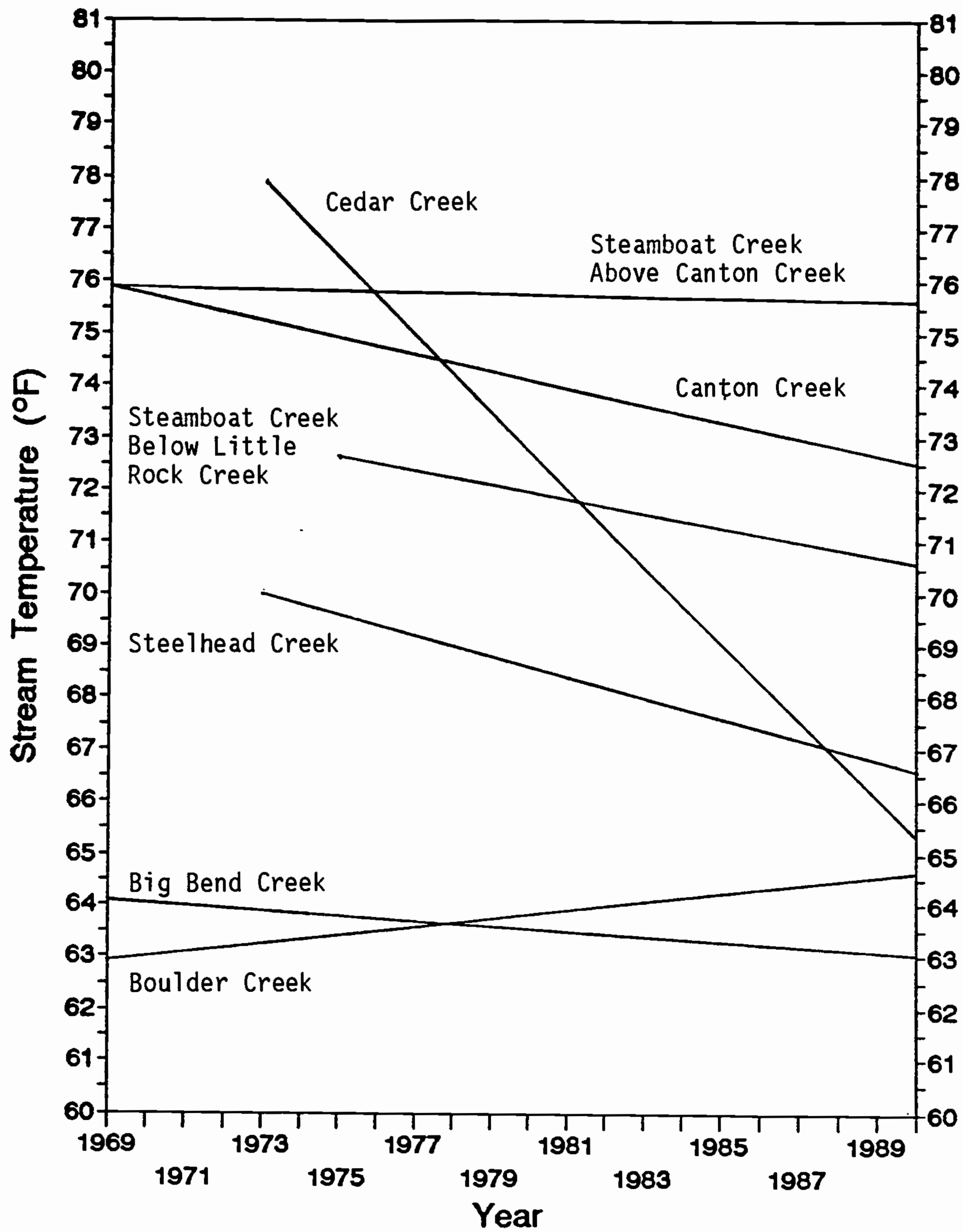

Figure 10. Liner regression trends of average maximum stream temperatures (based on 10 maximum temperatures of each year) over time (1969-90) for Steamboat Creek, selected tributaries, and Boulder Creek.

Table 5. Regression analysis summary of average maximum stream temperatures (based on 10 maximum daily temperatures of each year) over time (1969-90) for Steamboat Creek, selected tributaries, and Boulder Creek.

Stream Temperature Station	n	Slope (°F/year)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	15	-0.164	0.36	0.02	1.6
Steamboat Creek Above Canton Creek	18	-0.013	<0.01	0.90	2.6
Steelhead Creek	16	-0.199	0.32	0.02	1.5
Big Bend Creek	18	-0.053	0.02	0.57	2.4
Cedar Creek	13	-0.740	0.85	<0.01	1.6
Steamboat Creek Below Little Rock Creek	14	-0.144	0.18	0.13	1.6
Boulder Creek	16	0.084	0.05	0.39	2.5

maximum daily stream temperature each summer or the average of the five, ten, or 15 maximum daily stream temperatures each summer. Table 6 summarizes the analysis of regressing the one maximum stream temperature each summer on year and regressing the average of the five, ten and 15 maximum daily stream temperatures each summer on year. The sample population in the analysis for the four values in each of the seven stations are equal, so any difference between them is not due to a difference in sample size.

The four parallel slopes of the maximum stream temperature trends for each of the seven long-term stations are illustrated in Figures H1 to H7. These figures and the statistical analysis summary in Table 6 show that there is little difference in the slope between the four linear regression lines in each figure. However, for any given year, the average maximum stream temperature decreases as the number of days used in the analysis increases from one to 15. Also, the relationship between maximum stream temperature and years for Steamboat Creek below Little Rock Creek becomes less significant as the number of days used to calculate the average maximum stream temperatures increases.

The analysis to this point has focused on maximum daily stream temperatures each year. Using maximum daily stream temperatures is a useful way to evaluate the effects of forest management on stream temperature since it maximizes the coincidence of peak stream temperatures with cloudless days. Another approach would be to use a block of consecutive maximum daily stream temperatures each year. Using the consecutive maximum daily stream temperatures each year may be more useful when considering the biological effects of stream temperature on fish and other aquatic life.

For each of the seven long-term stream temperature stations, the average of the five, ten, and 15 consecutive maximum daily stream temperatures each year was regressed on the average of the five, ten and 15 maximum daily stream temperatures each year, respectively, to determine if there is a difference between these two analytical methods. Table 7 lists the results of this regression analysis and Figure 11 illustrates this relationship for

Table 6. Regression analysis summary of maximum stream temperatures (based on the 1, 5, 10 and 15 maximum daily temperatures of each year) over time (1969-90) for Steamboat Creek, selected tributaries, and Boulder Creek.

Stream Temperature Station	Number of Maximum Daily stream Temperatures Each Year	n	Y Intercept (°F)	Slope (°F/year)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	1	15	87.71	-0.15	0.30	0.03	1.66
	5	15	87.12	-0.15	0.34	0.02	1.53
	10	15	87.23	-0.16	0.36	0.02	1.57
	15	15	87.53	-0.17	0.42	<0.01	1.49
Steamboat Creek Above Canton Creek	1	18	76.57	<0.01	<0.01	0.95	2.58
	5	18	77.11	-0.01	<0.01	0.94	2.54
	10	18	76.85	-0.01	<0.01	0.90	2.56
	15	18	76.47	-0.02	<0.01	0.88	2.49
Steelhead Creek	1	16	86.18	-0.21	0.33	0.02	1.60
	5	16	84.83	-0.20	0.34	0.02	1.51
	10	16	84.51	-0.20	0.34	0.02	1.50
	15	16	83.84	-0.20	0.34	0.02	1.50
Big Bend Creek	1	18	70.29	-0.07	0.04	0.44	2.49
	5	18	68.96	-0.06	0.03	0.51	2.45
	10	18	67.73	-0.05	0.02	0.57	2.42
	15	18	67.26	-0.05	0.02	0.58	2.41
Cedar Creek	1	13	132.25	-0.73	0.83	<0.01	1.68
	5	13	133.00	-0.75	0.86	<0.01	1.57
	10	13	131.90	-0.74	0.85	<0.01	1.63
	15	13	130.75	-0.73	0.84	<0.01	1.63
Steamboat Creek Below Little Rock Creek	1	14	87.78	-0.18	0.28	0.05	1.49
	5	14	85.90	-0.16	0.24	0.08	1.56
	10	14	83.55	-0.14	0.18	0.13	1.61
	15	14	82.52	-0.14	0.15	0.17	1.73
Boulder Creek	1	16	57.37	0.09	0.05	0.39	2.70
	5	16	57.19	0.09	0.05	0.38	2.59
	10	16	57.06	0.08	0.05	0.39	2.54
	15	16	56.74	0.08	0.06	0.37	2.39

Table 7. Regression analysis summary of the average maximum stream temperatures (based on the 5, 10, and 15 consecutive maximum daily temperatures) over time (1969-90) for Steamboat Creek, selected tributaries, and Boulder Creek.

Stream Temperature Station	Number of Maximum Daily stream Temperatures Each Year	n	Y Intercept (°F)	Slope (°F/°F)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	5	12	0.33	0.991	0.97	<0.01	0.29
	10	12	3.35	0.947	0.94	<0.01	0.43
	15	12	2.33	0.960	0.88	<0.01	0.63
Steamboat Creek Above Canton Creek	5	18	1.25	0.980	0.99	<0.01	0.28
	10	18	-0.28	0.997	0.95	<0.01	0.58
	15	18	-1.86	1.016	0.94	<0.01	0.62
Steelhead Creek	5	16	-1.44	1.016	0.98	<0.01	0.26
	10	16	-2.33	1.025	0.97	<0.01	0.34
	15	16	-2.44	1.026	0.93	<0.01	0.50
Big Bend Creek	5	18	-0.61	1.008	0.99	<0.01	0.16
	10	18	-3.21	1.044	0.98	<0.01	0.35
	15	18	-0.61	0.981	0.95	<0.01	0.52
Cedar Creek	5	13	-0.32	1.000	0.99	<0.01	0.23
	10	13	1.51	0.971	0.99	<0.01	0.31
	15	13	-1.85	1.017	0.98	<0.01	0.57
Steamboat Creek Below Little Rock Creek	5	14	-10.07	1.133	0.95	<0.01	0.49
	10	14	-11.17	1.147	0.95	<0.01	0.47
	15	14	-3.74	0.938	0.90	<0.01	0.60
Boulder Creek	5	16	0.36	0.991	0.99	<0.01	0.19
	10	16	1.46	0.972	0.98	<0.01	0.34
	15	16	1.69	0.967	0.97	<0.01	0.39

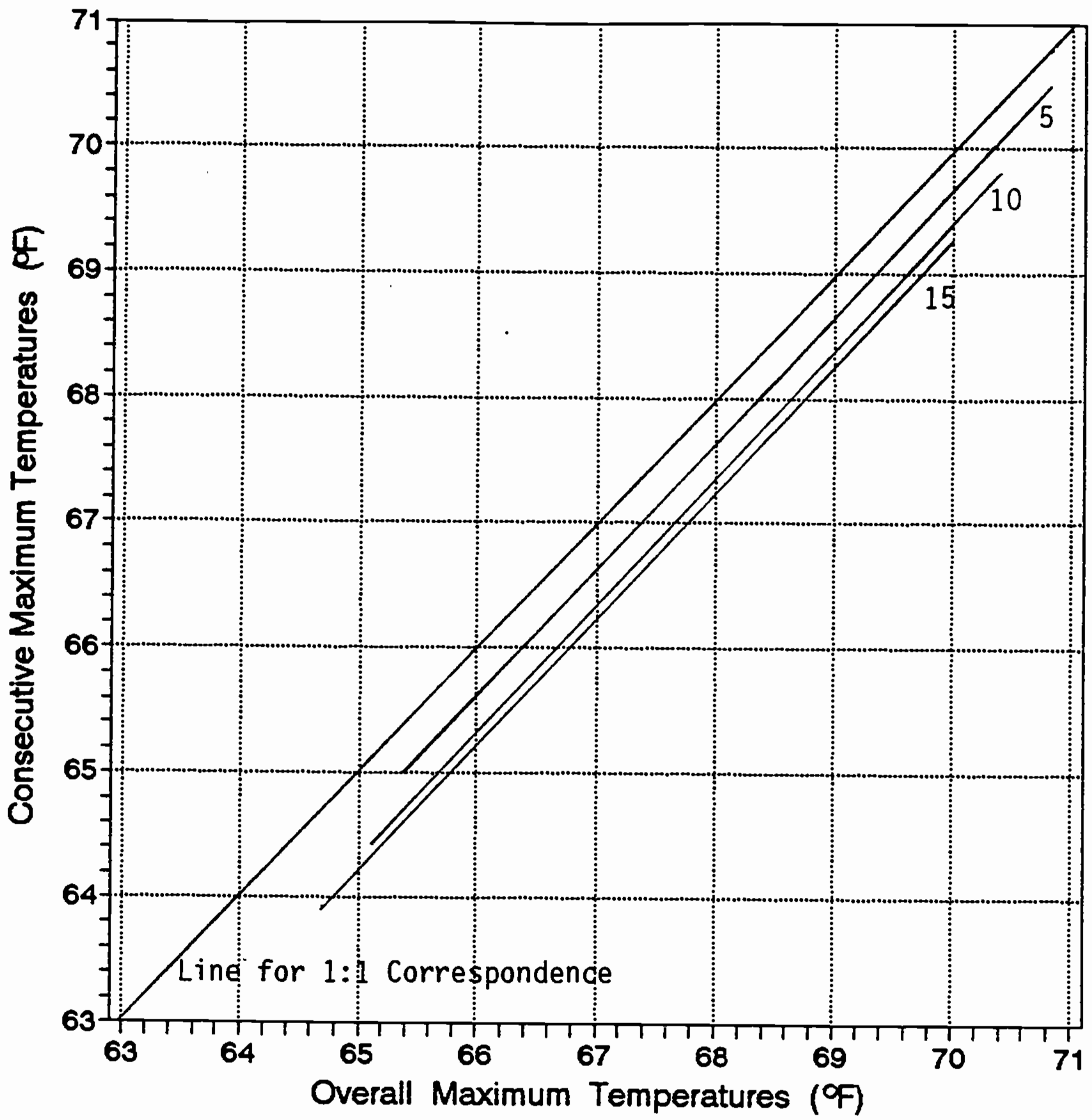

Figure 11. Linear regression lines of the 5, 10 and 15 consecutive maximum daily stream temperatures each year regressed on the 5, 10 and 15 maximum daily stream temperatures each year, Steelhead Creek, 1973-90.

Steelhead Creek, as an example. The parallel lines for Steelhead Creek in Figure 11 show that for any given year in the temperatures of interest, the stream temperature is lower for the consecutive maximum temperatures (Y axis) than for the maximum temperatures (X axis) as the number of days used each summer to determine the maximum value increases from five to 15 days each year. The slopes of all regression lines in the analysis are very close to 1.0°F/°F (Table 7), indicating a close relationship between the two methods. Also, all stations have slopes similar to each other, to within 0.044°F/°F. An exception is Steamboat Creek below Little Rock Creek, which has a deviation as large as 0.209°F/°F between regression lines. Steamboat Creek below little Rock Creek also has the largest variation in the Y intercept.

1969-90 Minimum Stream Temperature Trends

Figure 12 illustrates minimum stream temperature trends for the study period that were obtained by averaging the ten minimum daily stream temperatures associated with the ten maximum daily stream temperatures of each year, and regressing these minimum temperatures on year. Minimum stream temperatures decreased for all of the long-term stations in the Steamboat Creek basin while Boulder Creek, the control stream, shows an increasing trend. However, regression analysis in Table 8 shows that these trends are significant for only Steamboat Creek below Little Rock Creek and highly significant for only Cedar Creek. Cedar Creek had the most significant decrease in minimum and maximum stream temperatures over the 1969-90 period in comparison to the other long-term stations.

Minimum Stream Temperatures in Relation to Fish Tolerances

In Figure 12, the linear regression lines for minimum stream temperature trends indicate that the range of minimum stream temperatures at the end of the study period (55 to 65.9°F, 12.8 to 18.8°C) were well below the upper lethal water temperature for steelhead salmon (75°F, 23.9°C; Bell 1986). However, all these long-term stations had minimum stream temperatures above the

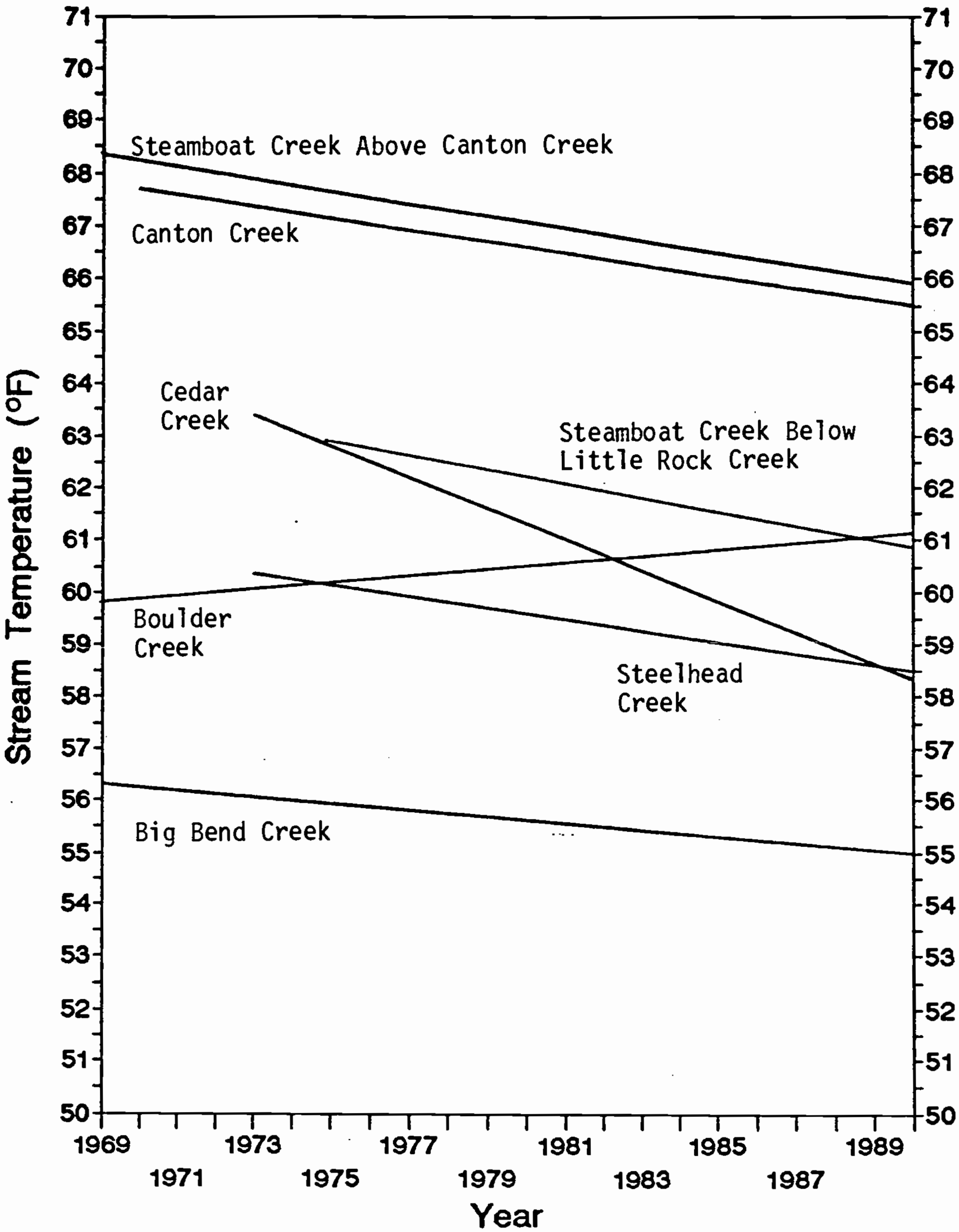

Figure 12. Linear regression trends over time (1969-90) of minimum stream temperatures using an average of the 10 minimum daily stream temperatures associated with the 10 maximum daily stream temperatures of each year for Steamboat Creek, selected tributaries, and Boulder Creek.

Table 8. Regression analysis summary of average minimum stream temperatures over time (1969-90) using the average of the 10 minimum daily stream temperatures associated with the 10 maximum daily stream temperatures of each year for Steamboat Creek, selected tributaries, and Boulder Creek.

Stream Temperature Station	n	Slope (°F/year)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	14	-0.108	0.19	0.12	1.5
Steamboat Creek Above Canton Creek	18	-0.115	0.11	0.19	2.1
Steelhead Creek	16	-0.111	0.12	0.19	1.6
Big Bend Creek	18	-0.058	0.05	0.38	1.7
Cedar Creek	13	-0.294	0.66	<0.01	1.1
Steamboat Creek Below Little Rock Creek	14	-0.141	0.21	0.10	1.4
Boulder Creek	16	0.060	0.04	0.44	2.0

preferred water temperatures for steelhead salmon (50 to 55°F, 10 to 12.8°C; Bell 1986) with the exception of Big Bend Creek, which was within the preferred range at 55°F (12.8°C). In 1990, the average of the ten minimum daily stream temperatures associated with the ten maximum daily stream temperatures of all the stations in this study exceeded the preferred stream temperature range for steelhead trout (50 to 55°F, 10 to 12.8°C; Bell 1986) (Tables C1 to C7).

Diurnal Stream Temperature Fluctuations

The relationships between maximum and minimum stream temperature trends are reflected in diurnal stream temperature fluctuations, illustrated in Figures I1 to I7 for each of the long-term stream temperature stations. The figures show as vertical lines the difference between the ten maximum daily stream temperatures each year and the average of the corresponding ten minimum daily stream temperatures. Maximum and minimum stream temperature trends previously analyzed are also shown in the figures, indicating the trends in diurnal fluctuations over time.

Diurnal fluctuations in Figures I1 to I7 were regressed on year, with the results listed in Table 9. Decreasing diurnal fluctuations over the study period were highly significant for Cedar Creek (slope = -0.45°F/year) and Canton Creek (slope = -0.11°F/year) and significant for Steelhead Creek (slope = -0.09°F/year). Cedar Creek had the largest decrease in diurnal temperature fluctuations over the study period, followed by Canton Creek and Steelhead Creek.

Figure 13 illustrates the relationship between the trends in diurnal temperatures and the trends in maximum stream temperatures for all seven long-term stations. This figure shows that Cedar Creek, Canton Creek and Steelhead Creek decreased in both maximum stream temperatures and diurnal fluctuations during the study period, although the decrease in fluctuation was not as great as the decrease in maximum stream temperature. Temporal trends for these three streams were significant or highly significant for both types of analysis. These results indicate that significant trends of decreasing maximum stream temperatures and diurnal fluctuations are

Table 9. Maximum diurnal stream temperature fluctuation in the summer of 1990, and regression analysis summary of maximum diurnal stream temperature fluctuation over time (1969-90) for Steamboat Creek, selected tributaries, and Boulder Creek. The daily stream temperature fluctuations are an average of the maximum minus the minimum daily stream temperature associated with the 10 maximum daily stream temperatures of each year.

		Regression Analysis				
Stream Temperature Station	Maximum Fluctuation Summer 1990 (°F)	n	Slope (°F/year)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	6.9	14	-0.105	0.54	<0.01	0.7
Steamboat Creek Above Canton Creek	10.9	18	0.098	0.13	0.15	1.6
Steelhead Creek	8.6	16	-0.088	0.23	0.06	0.9
Big Bend Creek	9.0	18	0.004	<0.01	0.94	1.5
Cedar Creek	7.4	13	-0.446	0.78	<0.01	1.2
Steamboat Creek Below Little Rock Creek	11.2	14	-0.004	<0.01	0.96	1.6
Boulder Creek	4.2	16	0.025	0.03	0.52	1.0
Average =	8.3					

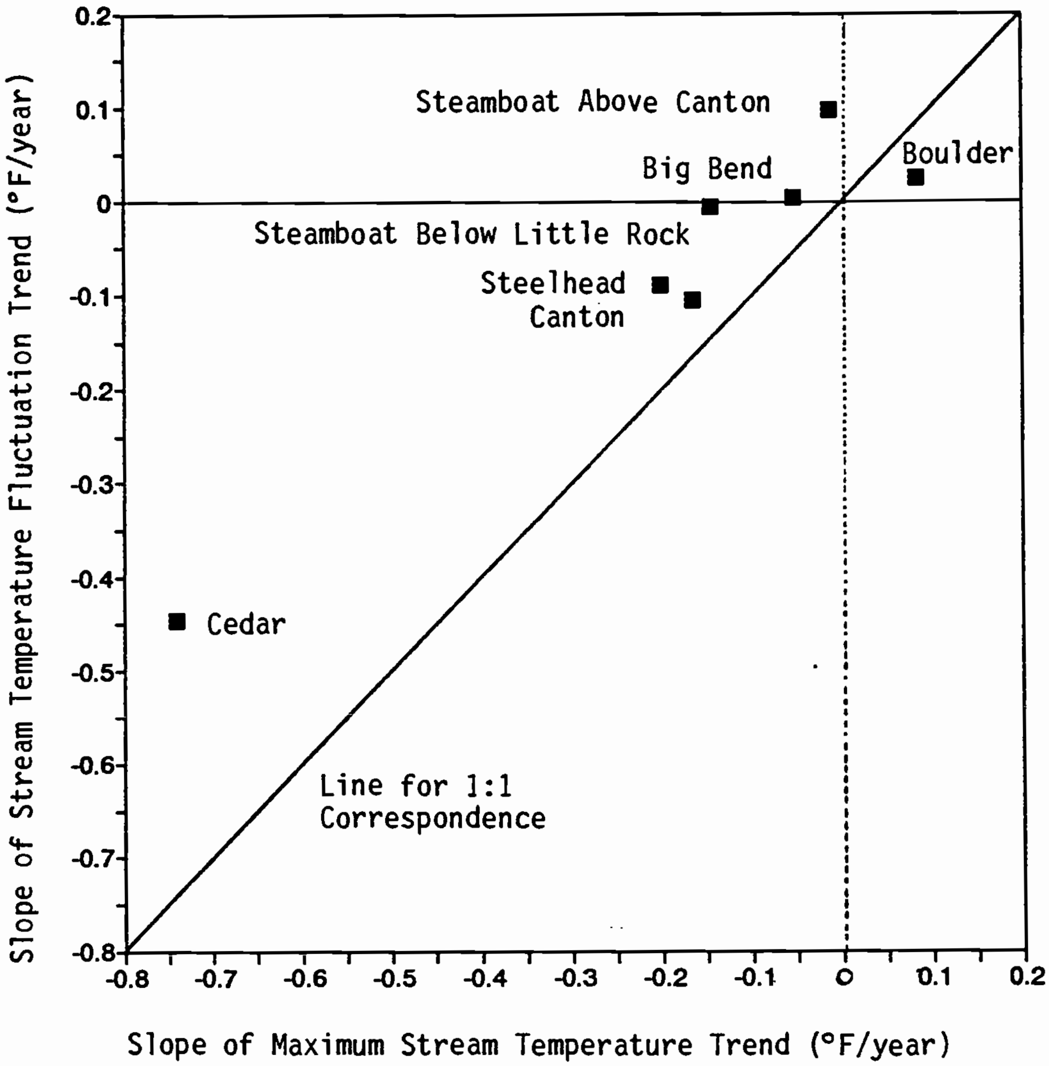

Figure 13. Relationship between the slope of the maximum summer diurnal stream temperature fluctuation trend and the slope of the maximum stream temperature trend (based on the average of the 10 maximum daily stream temperatures of each year) for Steamboat Creek, selected tributaries, and Boulder Creek over the period 1969-90.

occurring on tributaries of Steamboat Creek as a result of the regrowth of vegetation lost by timber harvesting, debris torrents or landslides. The other four stations in Figure 13 show relatively small diurnal fluctuations and maximum stream temperature trends and were not significant in either of the two types of analysis (Tables 5 and 9).

Table 9 lists the 1990 average diurnal fluctuation associated with the ten maximum daily stream temperatures each year for each of the long-term stations. This fluctuation averaged 8.3°F (4.6°C) for the seven stations. The two stations on Steamboat Creek, Steamboat Creek above Canton Creek and Steamboat Creek below Little Rock Creek, have the highest fluctuation at 10.9 and 11.2°F (6.1 and 6.2°C) respectively. This high fluctuation may be due to a high stream width/depth ratio at these locations causing greater response to solar radiation and basin air temperature conditions.

Boulder Creek has by far the lowest fluctuation at 4.2°F (2.3°C). A dense canopy cover over Boulder Creek, providing protection from incoming solar radiation by day and outgoing long-wave radiation by night, may be a factor in minimizing stream temperature fluctuation.

Maximum Stream Temperature in Relation to Stream Discharge

Table 10 lists the results from regressing maximum daily stream temperature (using the average of the ten maximum daily stream temperatures) on stream discharge (using the average of the ten average daily stream discharges associated with the ten maximum daily stream temperatures) for each year. The results show that this relationship is statistically significant for only two of the seven long-term stations: Steamboat Creek above Canton Creek (slope = -0.12°F/cfs) and Big Bend Creek (slope = -0.06°F/cfs). However, the "explained" variance (i.e., r^2) of maximum stream temperature related to stream discharge is fairly low, 16% for Steamboat Creek above Canton Creek and 27% for Big Bend Creek.

Table 10. Regression analysis summary of stream temperature versus discharge for Steamboat Creek, selected tributaries, and Boulder Creek, 1969-90. Stream temperature is calculated as the average of the 10 maximum daily stream temperatures each year; stream discharge is the average stream discharge for those days associated with the 10 maximum daily stream temperatures of each year.

Stream Temperature Station	n	Slope (°F/cfs)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	15	0.105	0.10	0.26	1.9
Steamboat Creek Above Canton Creek	18	-0.119	0.16	0.10	2.4
Steelhead Creek	16	-0.306	0.05	0.40	1.8
Big Bend Creek	18	-0.063	0.27	0.03	2.1
Cedar Creek	13	-7.720	0.20	0.12	3.7
Steamboat Creek Below Little Rock Creek	14	0.122	0.04	0.51	1.7
Boulder Creek	16	-0.470	0.08	0.28	2.5

Maximum Stream Temperature in Relation to Air Temperature

The correlation between maximum stream temperature and air temperature was significant or highly significant for four of the seven long-term stations. Table 11 lists the results of regressing the average of the ten maximum daily stream temperatures each year on the average of the ten maximum daily air temperatures (recorded at Idleyld Park) associated with the ten maximum daily stream temperatures each year. The three stations that were highly significant were Steamboat Creek above Canton Creek (slope = 0.35°F/°F), Big Bend Creek (slope = 0.24°F/°F) and Boulder Creek (slope = 0.32°F/°F). The one significant station was Steelhead Creek (slope = 0.16°F/°F). For the three highly significant stations, the linear regression slope is high with stream temperatures increasing 0.24 to 0.35°F (0.01 to 0.19°C) with each 1°F (.55°C) increase in air temperature. Also, the r^2 value for these three stations is relatively high with air temperature "explaining" 40 to 45% of the variation in maximum stream temperature.

Sullivan and Adams (1990) suggest:

> "there is some location in a watershed (threshold distance) where neither groundwater inflow nor riparian vegetation significantly influence water temperature and that water temperature is regulated primarily by air temperature."

In the Pacific Northwest, "the threshold distance appears to occur at about 30 to 60 km (19 to 37 mi) from the watershed divide where average stream depth averages approximately 0.6 to 1 m (2 to 3.3 ft)." Figure 24 in Sullivan and Adams (1990) shows that mean daily stream temperatures equal mean basin air temperatures at 12.4 mi (20 km) from the basin divide, in the Deschutes and Chehalis river basins in the western Cascade Range in Washington. However, for these basins, stream temperatures continue to rise and level off at 0.4°F (0.7°C) to 5.4°F (3°C) higher than the mean daily basin air temperature at approximately 19 to 37 mi (30 to 60 km) from the watershed divide. Figure 14 shows a similar relationship between mean daily stream temperature, mean daily basin air temperature and distance from divide in the Steamboat Creek basin. The watershed

Table 11. Regression analysis summary of stream temperature versus air temperature for Steamboat Creek, selected tributaries, and Boulder Creek, 1969-90. Stream temperature is calculated as the average of the 10 maximum daily stream temperatures each year; air temperature is the average of the 10 maximum daily air temperatures at Idleyld Park for those days associated with the 10 maximum daily stream temperatures of each year.

Stream Temperature Station	n	Slope (°F/°F)	r^2	Significance	Standard Error of Estimate (°F)
Canton Creek	15	0.210	0.17	0.13	1.8
Steamboat Creek Above Canton Creek	18	0.349	0.45	<0.01	1.9
Steelhead Creek	16	0.165	0.21	0.08	1.7
Big Bend Creek	18	0.241	0.40	<0.01	1.9
Cedar Creek	13	0.342	0.21	0.12	3.7
Steamboat Creek Below Little Rock Creek	14	0.171	0.19	0.12	1.6
Boulder Creek	16	0.317	0.40	0.01	2.0

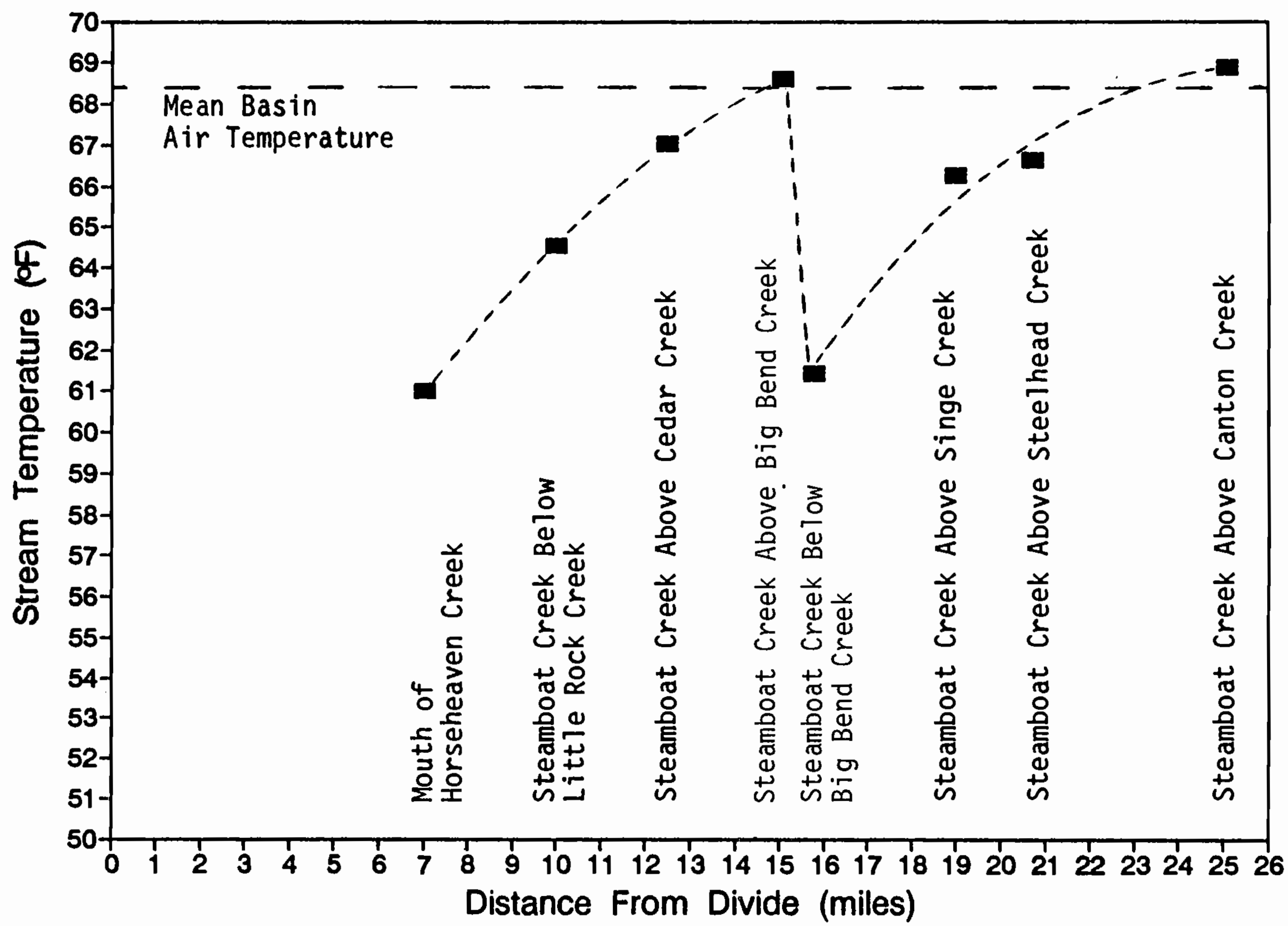

Figure 14. Mean daily stream temperatures for Steamboat Creek in relation to distance from divide and mean daily basin air temperature (68.3°F, Idleyld Park), July 7 to August 31, 1990.

divide for the Steamboat Creek basin is in the headwaters of Horseheaven Creek. As the water flows downstream from the divide, it increases in temperature until it reaches within 1°F (0.6°C) of the mean basin air temperature at Steamboat Creek above Big Bend Creek, 15 mi (24 km) distance from the watershed divide, at a depth of 0.8 ft (.24 m) and a width of 18 ft (5.5 m). Then, the large volume of cold water from Big Bend Creek flows into and cools Steamboat Creek. Steamboat Creek again warms as it flows downstream until its mean daily water temperature is within 1°F (0.6°C) of the mean daily basin air temperature at Steamboat Creek above Canton Creek. Here the average July and August, 1990, stream width is 50 ft (15.2 m) with a depth of 1.2 ft (0.4 m). Also, the mean daily stream temperature from July 7 to August 31, 1990, at the mouth of Canton Creek was 67.2°F (19.6°C), only 1.1°F (0.6°C) lower than the mean daily basin air temperature for the same period. The mouth of Canton Creek is 16 mi (25.7 km) from its divide and is 43 ft (13 m) wide and 1.4 ft (0.43 m) deep.

To illustrate the high correlation between air temperature and stream temperature, the 1990 summer mean daily air and water temperature relationships for the Steamboat Creek above Big Bend Creek station and Steamboat Creek above Canton Creek station are shown in Figures 15a and 15b, and Figures 16a and 16b respectively. Linear regression analysis indicates the relationships are highly significant for both Steamboat Creek above Big Bend Creek ($n = 56$; slope = 0.56°F/°F; $r^2 = 0.68$; significance < 0.01; standard error of estimate = 1.87°F) and Steamboat Creek above Canton Creek ($n = 56$; slope = 0.61°F/°F; $r^2 = 0.60$, significance < 0.01; standard error of estimate = 2.47). The regression slopes for both stations indicate that for each 1°F increase in mean daily basin air temperature, the mean daily stream temperature increases 0.6°F (0.3°C). The r^2 values for Steamboat Creek above Big Bend and Canton Creeks are relatively high, at 0.68 and 0.60 respectively.

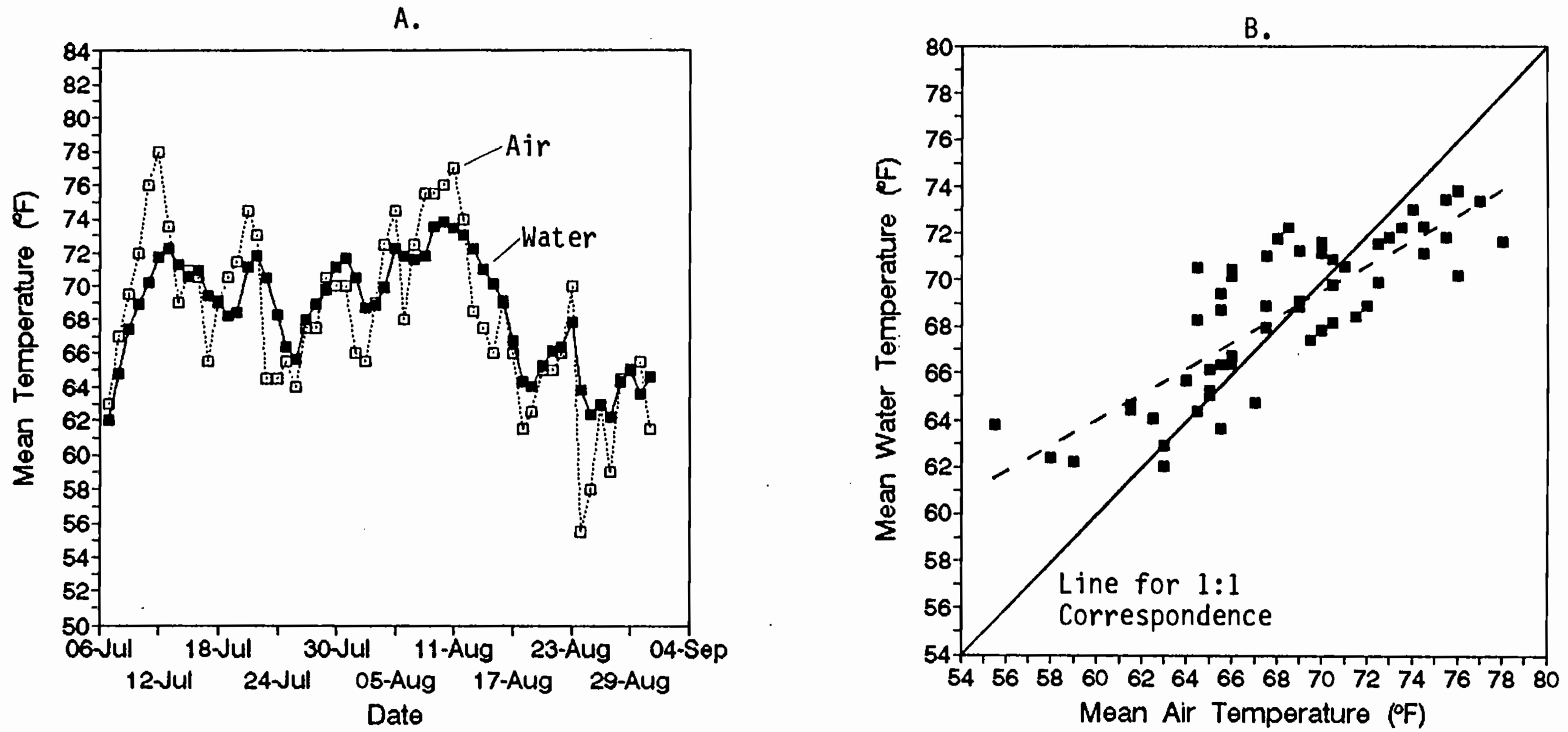

Figure 15. (A) Daily mean summer air temperature at Idleyld Park and daily mean summer water temperature at Steamboat Creek above Big Bend Creek, July 7 to August 31, 1990 and (B), relationship between mean daily summer water temperature and mean daily summer air temperature with linear regression line.

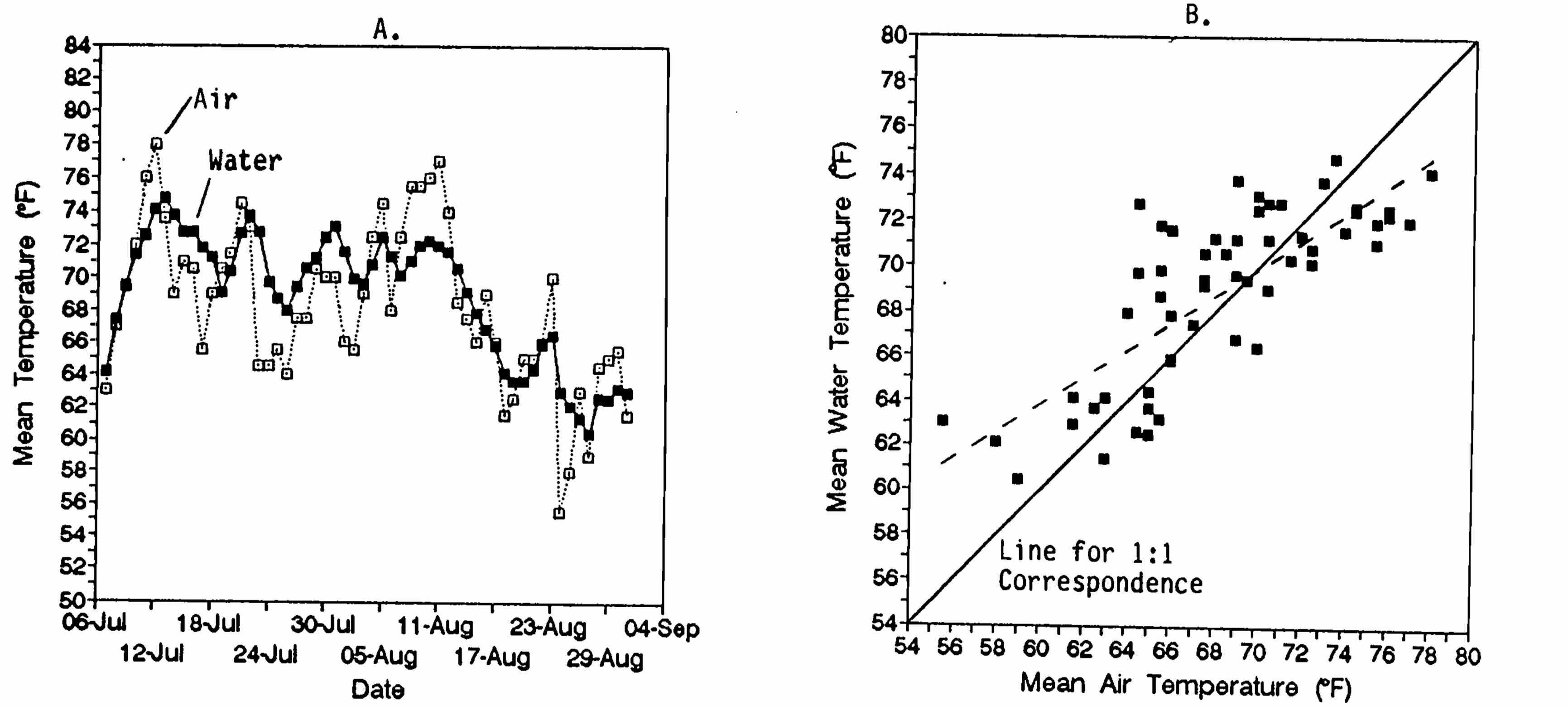

Figure 16. (A) Daily mean summer air temperature at Idleyld Park and daily mean summer water temperature at Steamboat Creek above Canton Creek, July 7 to August 31, 1990 and (B), relationship between mean daily summer water temperature and mean daily summer air temperature with linear regression line.

SUMMARY AND CONCLUSIONS

From 1969-90, significant trends of decreasing maximum daily summertime stream temperatures occurred on Steamboat Creek and tributaries. The decreasing stream temperature trend from 1969-90 was highly significant ($P \leq 0.10$) for Cedar Creek and Steelhead Creek and significant ($P \leq 0.10$) for Canton Creek and Steamboat Creek below Little Rock Creek. In contrast, Boulder Creek, the control stream, showed a small increasing trend in stream temperatures, though it was not significant ($P > 0.10$).

The decreasing maximum stream temperature trend is a result of regrowth of riparian vegetation lost to landslides, debris torrents, or timber harvesting before the mid-1970s and, to varying degrees, until the early-1980s. The regrowth provides shade over streams, decreasing energy input to the stream from solar radiation.

The largest decrease in maximum stream temperatures (7 to 11°F, 3.9 to 6.1°C) occurred on small streams with summer baseflows less than 6 cfs (0.17 m^3/sec) (Cedar Creek, Little Rock Creek, Horseheaven Creek, Reynolds Creek, Steamboat Creek above Horseheaven Creek). These streams also had the highest proportion of stream length adjacent to harvesting before 1974. The smallest decrease in maximum stream temperatures (0 to 3°F, 0 to 1.7°C) occurred on streams with little or no history of timber harvest activity along the stream length (Boulder Creek, City Creek, Big Bend Creek) or at locations with summer baseflows greater than 15.5 cfs (0.44 m^3/sec) (Canton Creek, Big Bend Creek and the main stem of Steamboat Creek from above Canton Creek to above Big Bend Creek).

Maximum daily stream temperatures in lower Steamboat Creek (Steamboat Creek above Canton Creek) did not change significantly during the 1969-90 study period. Any cooling effects by groundwater or tributaries are largely negated by the large volume of water in the main channel and by the large stream width, which renders riparian vegetation less effective in protecting the stream from solar radiation.

In a separate analysis, Hostetler (1991) also found generally decreasing trends in maximum stream temperatures for long-term stations throughout the Steamboat Creek basin from 1969 to 1989. However, in contrast to this study, Hostetler (1991), who used a different form of analysis, found decreasing maximum stream temperatures for Steamboat Creek above Canton Creek and no changes in maximum stream temperatures for Big Bend and Boulder Creeks.

In the nearby Salmon Creek watershed (drainage area = 325 km^2), Beschta and Taylor (1988) found a highly significant direct relationship between a cumulative index of forest harvesting throughout the basin and maximum stream temperatures over a 30-year period. This stream temperature and harvesting relationship is in contrast to results found in the Steamboat Creek watershed (drainage area = 588 km^2) where there was no change in maximum stream temperatures in the lower basin while harvesting rates throughout the basin increased.

Although maximum stream temperatures for most locations in the Steamboat Creek basin generally decreased during the study period, 1969-90, three long-term stream temperature stations indicate a slight increasing trend in maximum stream temperatures since the mid-1980s: Steelhead Creek, Big Bend Creek, and Steamboat Creek below Little Rock Creek. Since 1983, maximum daily summer air temperatures also had an increasing trend, which may have caused the increasing trend in maximum stream temperatures. During future summers with normal maximum air temperatures, maximum stream temperatures may continue their downward trend or level off in the Steamboat Creek basin. The larger streams may take longer than the smaller streams to level off since it will take longer for vegetation regrowth to provide significant shade to the larger streams. Maximum temperatures for Cedar Creek, the smallest stream in this study, already appear to be leveling off. The average annual maximum stream temperature since 1983 for Cedar Creek is 68.5°F (20.3°C). Continued stream temperature monitoring in the Steamboat Creek basin is necessary to determine future trends and their significance. Continued monitoring would also be useful to show stream temperature regimes before and after major flow events in the basin or stream temperature response, if any, to global or regional shifts in summertime temperatures.

Minimum stream temperatures decreased for all of the long-term stations in the Steamboat Creek basin while Boulder Creek, the control stream, shows a slight increasing trend. However, these downward trends in minimum stream temperatures are significant for only Steamboat Creek below Little Rock Creek and highly significant for only Cedar Creek. Cedar Creek had the most significant decrease in both minimum and maximum stream temperatures over the 1969-90 period in comparison to the other long-term stations.

Relationships between maximum and minimum stream temperature trends are reflected in diurnal stream temperature fluctuations. Over the study period, diurnal stream temperature fluctuation trends were as follows: decreasing and highly significant for Cedar Creek and Canton Creek and significant for Steelhead Creek; increasing but nonsignificant for Boulder Creek and Steamboat Creek above Canton Creek; and unchanged and nonsignificant for Big Bend Creek and Steamboat Creek below Little Rock Creek.

For the summer of 1990, air temperatures were above average and streamflows were below average, resulting in above average maximum stream temperatures. The highest stream temperature recorded was 79.9°F (26.6°C) on July 13 at Steamboat Creek above Canton Creek and the stream temperature was above 75°F (23.9°C), the upper lethal limit for steelhead trout based on laboratory studies (Bell 1986), for nine hours. Maximum daily stream temperatures reached 70°F (21.1°C) or above at nine of the 17 stream temperature monitoring stations in 1990; all of these stations are located on the mainstem of Steamboat Creek from above Canton Creek to below Little Rock Creek and also include Canton Creek, Little Rock Creek and Reynolds Creek. Maximum daily stream temperatures equaled or exceeded 75°F (23.9°C) at six stations: Canton Creek and the five stations on the mainstem of Steamboat Creek from above Canton Creek to above Cedar Creek. Similarly, in 1990, the average of the ten minimum daily stream temperatures associated with the ten maximum daily stream temperatures of all 17 stations exceeded the preferred stream temperature range for steelhead trout (50 to 55°F, 10 to 12.8°C; Bell 1986).

The correlation between maximum daily stream temperature and air temperature was highly significant for three of the seven long-term stream temperature stations: Steamboat Creek above Canton Creek (slope = 0.35°F/°F), Big Bend Creek (slope = 0.24°F/°F) and Boulder Creek (slope = 0.32°F/°F). The correlation between maximum stream temperatures and streamflow was significant for only two of the long-term stations: Steamboat Creek above Canton Creek (slope = -0.12°F/cfs) and Big Bend Creek (slope = -0.06°F/cfs). These correlations between maximum stream temperature and both air temperature and streamflow for the 22-year study period are highest for those stations with the smallest change in annual maximum stream temperature since there was no significant change in average summer air temperature and streamflow for the study period.

As Steamboat Creek flows downstream from its divide, it increases in temperature until it reaches within 1°F (0.6°C) of the mean basin air temperature at Steamboat Creek above Big Bend Creek, 15 mi (24 km) distance from the watershed divide. Also, the mean daily summer stream temperature at the mouth of Canton Creek, 16 mi (25.7 km) from its divide, was 67.2°F (19.6°C), only 1.1°F (0.6°C) lower than the mean daily basin air temperature for the same period. These relationships between mean daily stream temperature and mean daily air temperature in the Steamboat Creek basin are similar to those of Sullivan and Adams (1990) who found that mean daily stream temperatures equal mean basin air temperatures at 12.4 mi (20 km) from the basin divide in the Deschutes and Chehalis river basins in the western Cascade Range in Washington.

In spite of these high summer stream temperatures in the Steamboat Creek basin, no fish have been found dead due to high stream temperatures and the basin remains essential to the production of summer-run steelhead. However, Dambacher (1990) states that "the single most important factor limiting juvenile steelhead production in the Steamboat Creek basin is high summer water temperatures." Changes in forest management practices appear to have decreased maximum stream temperatures in the basin, particularly in upper Steamboat Creek and in tributaries. To ensure the productivity of juvenile steelhead, a policy of continued riparian protection and forest regrowth along streams needs to be continued.

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APPENDICES

APPENDIX A

Table A1. Unit Conversion Factors

°F	= 1.8°C + 32
1 mi	= 5,280 ft = 1.609 km
1 mi^2	= 2.59 km^2
1 acre	= 0.405 hectares
1 ft	= 0.305 meters
1 ft^3	= 0.0283 m^3 = 28.32 liters
1 oz	= 28.35 grams
1 in	= 25.4 mm
1 ton	= 0.908 metric tons

APPENDIX B

Table B1. Timber harvest history (1955-90) of selected subdrainages in the Steamboat Creek basin as a percent of the subdrainage area.

Year	Steamboat Creek above Canton Creek	Steel-head Creek	Singe Creek	Reynolds Creek	Big Bend Creek	Cedar Creek	Steamboat Creek below Little Rock Creek	Little Rock Creek	Horse-heaven Creek	City Creek
1955	0.14									
1956	0.44		0.18							
1957	0.52	1.18	0.76	0.70	0.20					
1958	0.38			1.69	0.64					
1959	1.28	0.41	1.41	3.82	1.81		0.57	1.96		
1960	1.69		1.12		1.39	0.37	2.60	4.48	2.42	0.46
1961	1.13	3.09	2.86	1.80	0.94		0.88		3.75	
1962	0.93	2.46	0.90	2.22	0.69	1.42	0.58	0.59		0.54
1963	0.60	0.58	0.69	0.73	0.60	1.49	0.72	1.20		1.88
1964	1.01			3.15	0.39		1.31	1.03	0.84	
1965	1.43	1.15		0.52	0.83	6.12	1.15	1.47	2.32	0.23
1966	0.47	1.44		2.20	0.21		0.26			
1967	1.04	1.02		1.48	1.20	1.70	0.86	0.94		1.00
1968	0.81	2.09	0.95	0.56	0.82	0.21	0.83		0.38	
1969	0.71		0.56	1.64	0.76		0.66		0.97	
1970	0.67			0.43	0.13		0.74			
1971	0.77		0.76	0.78	0.84	1.00	0.38	0.87		
1972	1.62	0.59	4.80	2.66	1.71	2.20	1.19			
1973	0.57		0.43	3.13	1.25					
1974	1.26	1.16		7.17	1.47		0.20		0.83	
1975	0.67	1.60		0.46	0.08		0.51		1.25	
1976	0.83	1.58	1.78	0.27			0.51		1.68	
1977	0.90	1.98	3.72	4.03	0.33					
1978	1.04	1.51	0.63	1.44	1.13	2.82	0.98	1.68		0.85
1979	1.24	0.97	7.63	0.08	1.07	1.42	0.91	0.61		0.51
1980	1.20	2.27	0.53	3.75	0.37	1.74	0.65	0.76		
1981	0.43	0.13		0.22	0.36		0.76		0.50	
1982	0.09	0.07			0.17		0.04			
1983	0.92	0.14	1.84	1.52	0.43	2.04	0.53		2.14	
1984	0.65	1.30	0.12	0.14	0.06	0.35	1.10	2.38	1.52	
1985	1.16	1.56		2.13	1.45	0.59	1.14	1.20	0.38	0.69
1986	1.13	5.49		2.13	0.61	1.00	0.35	0.45	0.93	
1987	0.86	0.56			0.63	3.57	0.75		2.32	
1988	1.56		6.68	2.21	1.81		1.50	0.83	3.74	
1989	1.95	2.84	2.39	2.28	3.04	0.27	1.44	3.18		0.37
1990	1.91	0.84	0.51	3.47	2.47	2.76	1.76	2.97	0.15	0.22
Total	34.04	38.01	41.24	58.81	29.90	31.08	25.87	26.61	26.13	6.74

APPENDIX C

Stream temperatures, air temperatures, and streamflows used in analysis for Steamboat Creek, selected tributaries, and Boulder Creek. Maximum stream temperatures are the average of the 1, 5, 10 and 15 maximum daily temperatures of each year. Consecutive maximum stream temperatures are the average of the 5, 10 and 15 consecutive maximum daily stream temperatures of each year. Minimum stream temperatures are the average of the 10 minimum daily stream temperatures for those days associated with the 10 maximum daily stream temperatures of each year. Air temperatures are the average of the 10 maximum daily air temperatures for those days associated with the 10 maximum daily stream temperatures of each year. Streamflows are the average of the 10 mean daily streamflows for those days associated with the 10 maximum daily stream temperatures of each year.

Table C1. Canton Creek, 1969-90.

Year	Stream Temperatures (°F)								Air Temperatures (°F)	Streamflows (cfs)
	Maximum				Consecutive Maximum			Minimum		
	1	5	10	15	5	10	15			
1969	75.0	74.2	73.8	73.5	73.6	73.3	72.1		86.0	24.2
1970	76.5	76.1	75.7	75.2				66.1	90.3	29.1
1971	79.0	78.2	77.6	77.1				68.6	90.5	27.9
1975	76.0	75.4	74.5	73.9	75.0	74.2	72.5	66.5	87.7	33.9
1977	76.0	75.2	74.9	74.6	75.2	74.7	74.4	67.5	95.9	11.4
1978	78.0	76.6	75.8	75.2	76.2	75.2	74.9	68.5	94.4	19.7
1979	76.0	75.8	75.0	74.3	75.8	74.4	73.8	66.7	90.7	17.9
1980	75.0	74.4	73.5	72.8	73.6	73.2	72.8	65.6	88.6	21.9
1981	76.0	75.3	74.4	73.7	75.3	74.4	73.3	67.8	94.6	20.3
1982	75.0	74.0	73.1	72.6	73.4	72.1	71.6	66.4	85.1	20.0
1985	75.0	73.8								
1986	72.0	71.4	70.4	69.9	71.2	70.4	69.9	62.9	91.2	15.1
1987	77.0	76.0	75.4	74.3	75.6	74.1	72.5	67.6	90.9	17.6
1988	73.4	72.9	72.5	71.8	72.7	72.2	71.7	65.0	91.5	22.2
1989	72.1	71.5	70.7	70.1	71.3	69.9	68.8	64.4	82.9	20.5
1990	75.6	74.7	74.1	73.7	74.0	73.1	72.7	67.2	94.1	20.2

Table C2. Steamboat Creek above Canton Creek, 1969-90.

Year	Stream Temperatures (°F)								Air Temperatures (°F)	Streamflows (cfs)
	Maximum				Consecutive Maximum			Minimum		
	1	5	10	15	5	10	15			
1969	76.0	75.4	75.1	74.7	75.4	74.8	74.5	67.6	85.4	53.8
1971	80.0	79.6								
1972	79.0	78.6	77.8	76.9	78.0	76.3	75.7	68.5	96.1	46.4
1973	80.0	79.0	78.5	78.0	79.0	78.2	77.6	67.4	93.7	33.2
1974	78.0	78.0								
1975	77.0	76.2	75.0	74.1	76.2	74.8	72.7	66.8	89.3	53.1
1976	77.0	76.2	75.4	74.7	76.0	75.2	74.4	66.3	86.9	49.0
1977	76.0	76.0	76.0	75.7	76.0	75.8	75.6	71.0	87.9	32.5
1978	76.0	75.4	74.7	74.5	75.4	74.7	74.3	69.4	95.4	44.4
1979	78.0	77.6	77.3	76.8	77.4	77.2	76.8	68.0	86.9	36.8
1980	77.0	77.0	76.4	75.8	76.6	76.3	75.8	67.9	89.0	45.7
1981	79.0	78.4	77.0	76.3	78.4	77.0	75.8	67.9	94.6	45.3
1982	77.0	76.2	75.6	75.1	75.6	74.7	74.1	66.6	81.8	42.9
1983	69.0	68.8	68.1	67.7	68.6	66.9	66.7	60.6	78.7	51.3
1984	76.0	74.0	73.1	72.5	73.6	72.3	71.8	64.9	86.7	65.2
1985	78.0	74.4								
1986	76.0	75.4	74.9	74.4	75.2	74.8	74.3	65.6	91.6	34.7
1987	80.0	79.2	78.3	77.1	78.2	76.5	75.0	67.8	92.5	38.3
1988	78.4	78.1	77.7	77.0	77.9	77.4	76.9	67.2	91.0	47.5
1989	76.8	75.5	74.6	74.2	75.1	74.1	72.9	65.0	83.5	42.2
1990	79.9	79.2	78.8	78.3	79.0	77.5	77.2	67.8	90.9	51.1

Table C3. Steelhead Creek, 1969-90.

Year	Stream Temperatures (°F)								Air Temperatures (°F)	Streamflows (cfs)
	Maximum				Consecutive Maximum			Minimum		
	1	5	10	15	5	10	15			
1969	71.0									
1973	71.0	70.6	70.3	70.0	70.6	70.0	69.6	59.4	93.8	4.1
1974	74.0	72.4								
1975	72.0	70.8	70.2	69.7	70.6	70.0	68.6	59.6	86.9	8.6
1976	69.0	68.2	67.6	67.1	68.0	67.1	66.6	58.1	86.7	5.8
1977	71.0	70.6	70.3	69.9	70.0	69.5	69.3	62.4	95.1	3.4
1978	70.0	69.2	68.7	67.9	69.2	67.7	66.5	59.9	95.2	5.4
1979	69.0	69.0	68.4	67.8	68.9	67.8	67.4	59.6	90.7	4.7
1980	70.0	69.8	69.2	68.5	69.2	68.8	68.3	61.2	89.1	5.7
1981	71.0	70.4	69.9	69.1	70.4	69.8	69.0	60.9	94.7	5.0
1982	72.0	70.8	70.4	69.9	70.2	69.2	68.8	62.2	82.2	4.8
1983	67.0	66.6	66.2	65.8	66.0	65.8	65.2	58.5	82.2	6.7
1984	66.0	65.4	65.1	64.7	65.0	64.3	63.9	56.9	83.2	7.6
1986	67.0	66.8	66.3	65.8	66.2	65.7	65.6	58.4	91.7	4.0
1987	68.0	66.8	66.3	65.7	66.6	65.7	64.7	57.1	89.6	4.7
1988	68.4	67.9	67.5	67.0	67.8	67.3	66.9	57.8	91.5	5.8
1989	67.1	66.8	66.3	65.8	66.5	65.2	64.1	58.4	81.8	5.4
1990	70.0	69.5	69.0	68.6	68.8	68.2	67.6	60.4	94.1	5.3

Table C4. Big Bend Creek, 1969-90.

Year	Stream Temperatures (°F)								Air Temperatures (°F)	Streamflows (cfs)
	Maximum				Consecutive Maximum			Minimum		
	1	5	10	15	5	10	15			
1969	64.0	63.8	63.3	62.9	63.8	63.0	62.7	55.2	82.8	32.8
1971	63.0	62.6	62.3	62.0	62.2	61.5	61.3	55.0	90.1	27.5
1972	64.0	63.0	62.5	62.1	63.0	61.4	60.6	54.3	92.1	29.4
1973	67.0	66.4	66.2	66.0	66.2	65.8	65.3	56.5	93.2	17.3
1974	66.0	65.2	64.5	63.7	64.8	64.5	63.7	56.3	94.2	23.9
1975	66.0	65.2	64.3	63.8	65.2	64.3	62.7	55.6	88.1	28.4
1977	70.0	69.6	69.2	68.8	69.6	69.1	67.8	59.1	94.8	12.8
1978	66.0	65.6	65.0	64.7	65.6	64.7	64.4	58.2	92.4	22.0
1979	62.5	62.4	62.2	61.8	62.3	61.9	61.6	57.2	89.5	20.2
1980	61.0	61.0	60.9	60.6	61.0	60.8	60.6	56.1	89.0	23.9
1981	66.0	66.0	65.5	65.1	66.0	65.4	64.6	57.4	94.2	22.9
1982	64.0	63.6	62.8	62.2	63.6	62.4	61.9	54.9	79.5	23.0
1983	60.0	60.0	59.7	59.4	59.8	59.3	58.9	53.5	71.7	104.1
1984	62.0	60.8	60.3	59.9	60.8	59.5	59.0	52.6	86.1	33.9
1985	64.0	62.4								
1986	62.0	61.9	61.6	61.2	61.7	61.4	61.1	53.7	91.9	17.8
1988	65.7	65.4	65.1	64.6	65.1	64.9	64.6	55.3	91.4	25.0
1989	63.3	62.8	62.5	62.2	62.4	61.5	60.5	54.3	81.5	23.7
1990	66.2	65.8	65.6	65.2	65.7	64.7	64.3	56.6	93.2	25.5

Table C5. Cedar Creek, 1969-90.

Year	Stream Temperatures (°F)								Air Temperatures (°F)	Streamflows (cfs)
	Maximum				Consecutive Maximum			Minimum		
	1	5	10	15	5	10	15			
1969	78.0									
1973	80.0	80.0	79.7	79.1	79.8	78.6	78.1	64.4	94.0	1.00
1978	77.0	76.0	75.0	74.5	75.6	74.4	74.1	61.1	93.8	1.28
1979	74.5	74.1	73.5	73.0	73.9	73.0	72.6	61.6	90.7	1.15
1980	74.0	73.2	72.6	72.1	72.6	72.3	72.1	61.3	89.2	1.37
1981	72.0	72.0	71.4	70.9	72.0	71.4	70.6	61.6	94.8	1.25
1982	73.0	72.2	71.3	70.8	72.2	70.7	70.1	60.9	80.4	1.22
1983	68.0	67.8	67.0	66.5	67.4	66.6	65.7	58.9	81.3	1.65
1984	69.0	68.4	67.8	67.4	68.0	67.2	66.6	60.0	84.1	1.80
1985	68.0	67.6								
1986	69.0	68.4	67.8	67.2	68.2	67.5	67.2	58.1	91.3	0.96
1987	70.0	69.2	68.5	67.8	68.5	67.4	65.8	58.5	91.3	1.16
1988	68.0	67.5	67.1	66.6	67.4	66.9	66.4	58.4	91.5	1.42
1989	66.9	66.4	66.0	65.6	66.3	65.4	64.4	58.9	81.8	1.32
1990	69.1	68.6	68.1	67.8	68.3	67.7	67.2	60.7	93.6	1.25

Table C6. Steamboat Creek below Little Rock Creek, 1975-90.

Year	Stream Temperatures (°F)								Air Temperatures (°F)	Streamflows (cfs)
	Maximum				Consecutive Maximum			Minimum		
	1	5	10	15	5	10	15			
1975	75.0	73.8	72.9	72.3	73.6	72.7	70.5	61.9	88.3	17.0
1976	73.0	71.6	70.9	70.3	71.0	70.3	69.8	60.1	86.9	13.1
1977	74.0	74.0	73.4	72.8	74.0	73.2	72.1	65.4	91.2	6.6
1978	74.0	73.2	72.7	72.2	72.8	71.9	71.5	64.0	95.2	11.6
1979	75.5	75.0	73.6	72.7	75.0	73.3	72.3	63.4	90.8	10.6
1980	75.0	73.8	72.9	72.0	72.8	72.5	71.9	62.6	89.1	12.4
1981	73.0	72.4	71.8	71.1	72.4	71.7	70.7	61.5	95.2	11.8
1982	73.0	72.0	71.2	70.5	72.0	70.4	69.9	61.0	82.2	12.0
1983	69.0	68.8								
1984	72.0	71.4	71.2	70.8	71.2	70.6	69.9	60.6	85.9	16.2
1986	70.0	69.4	68.9	68.5	69.4	68.6	68.3	62.1	91.3	8.7
1987	70.0	69.2	67.9	66.6	67.4	66.4	66.4	60.4	86.4	9.4
1988	73.4	72.8	72.3	71.7	72.4	72.1	71.6	60.2	92.9	13.2
1989	72.1	71.1	70.5	69.9	70.2	68.7	67.9	60.8	81.9	12.4
1990	74.1	73.5	73.2	72.9	73.3	72.2	71.9	62.0	93.4	12.7

Table C7. Boulder Creek, 1969-90.

Year	Stream Temperatures (°F)								Air Temperatures (°F)	Streamflows (cfs)
	Maximum				Consecutive Maximum			Minimum		
	1	5	10	15	5	10	15			
1969	64.0	64.0	63.5	63.0	63.8	63.2	62.7	59.7	83.5	10.8
1970	65.0	64.2	64.1	63.7	63.6	63.1	63.1	59.8	83.9	10.1
1971	66.0	65.6	64.8	64.3	65.6	64.8	64.3	61.1	86.0	10.5
1974	66.0	66.0	65.9	65.1	66.0	65.9	64.9	61.9	94.0	8.8
1975	61.0	60.6	59.8	59.5	60.6	59.7	59.0	57.4	87.1	9.8
1978	67.0	66.4	66.2	66.1	66.2	65.9	65.9	63.9	92.3	8.3
1979	64.5	63.6	63.3	63.1	63.6	63.2	63.0	61.4	85.1	6.2
1980	63.0	62.8	62.4	62.3	62.4	62.0	61.9	60.0	86.0	8.8
1981	63.0	63.0	62.5	62.3	62.8	62.5	62.3	59.7	89.5	7.4
1982	63.0	62.6	62.2	61.8	62.4	61.6	61.2	59.5	77.5	6.8
1983	59.0	59.0	59.0	59.0	59.0	59.0	58.6	56.5	79.5	11.1
1984	62.0	62.0	61.7	61.4	61.8	61.1	61.2	59.0	78.9	10.4
1987	68.0	67.7	67.1	66.3	67.2	66.2	65.2	61.9	89.2	7.2
1988	67.0	66.5	66.1	65.6	66.4	66.0	65.4	61.5	88.4	8.5
1989	66.0	65.3	64.9	64.4	65.2	64.2	63.0	60.8	80.7	10.4
1990	69.0	68.6	67.9	67.4	68.6	67.6	66.7	63.7	92.4	8.7

APPENDIX D

Historical Data Before 1969

Table D1. Stream temperature measurements at the streamflow gauge near the mouth of Steamboat Creek, 1959-62.

Date	Time	Stream temperature (°F)
6/11/59	10:00 am	58
6/23/59	3:05 pm	69
7/7/59	10:50 am	61
9/9/59	2:00 pm	63
9/21/59	1:30 pm	58
6/7/60	12:00 pm	54
6/22/60	2:30 pm	60
7/12/60	2:30 pm	72
7/28/60	3:20 pm	76
8/8/60	3:15 pm	82
9/1/60	11:20 am	59
9/19/60	11:25 am	59
6/1/61	12:45 pm	56
6/16/61	1:25 pm	66
6/28/61	11:00 am	62
7/14/61	2:30 pm	73
7/28/61	12:30 pm	71
8/10/61	1:30 pm	73
9/1/61	12:20 pm	64
9/15/61	10:50 am	60
9/29/61	1:30 pm	52
6/7/62	1:25 pm	57
6/21/62	2:35 pm	65
7/5/62	2:10 pm	68
7/19/62	3:00 pm	69
8/2/62	2:50 pm	71
8/23/62	3:05 pm	67
9/6/62	2:55 pm	66
9/20/62	4:10 pm	63

Table D2. Stream temperature, air temperature and streamflow at selected locations in the Umpqua River basin, 12 noon to 5:00 pm, July 24-30, 1968. Streams are listed in ascending order by streamflow.

Stream	Streamflow (cfs)	Stream Temperature (°F)	Air Temperature (°F)
* Cedar Creek	1.1	80	92
Elk Creek (USGS Gauge #14-3220)	1.5	75	80
Elk Creek (1 mi below USGS Gauge #14-3085)	1.5	81	94
Deadman Creek	1.5	77	89
* Steelhead Creek	2.0	67	91
* Boulder Creek	2.0	71	85
Pass Creek	2.5	67	90
Canton Creek above Pass Creek	3.0	64	90
Squaw Creek	5.2	67	87
Cavitt Creek (0.2 mi above mouth)	6.1	76	90
Rock Creek (0.3 mi above mouth)	6.5	80	91
Jackson Creek (0.4 mi above Squaw Creek)	7.5	70	87
* Steamboat Creek above Bend Creek	7.7	74	92
Rock Creek (2 mi above E. Fork Rock Creek)	13.0	76	89
* Canton Creek (0.5 mi above mouth)	13.0	74	91
* Big Bend Creek	14.0	65	92
Little River above Emile Creek	18.0	76	90
Jackson Creek (USGS Gauge #14-3077)	18.0	73	89
Rock Creek above Conley Creek	20.0	78	89
* Steamboat Creek above Canton Creek	20.0	74	88
Steamboat Creek (USGS Gauge #14-3167)	30.0	71	90
Little River below Cavitt Creek	35.0	78	90
Cow Creek (just below Crawford Creek)	39.0	76	80

* Also locations of 1990 stream temperature measurements.

Table E1. Percent of air temperatures and maximum and minimum stream temperatures used in analysis that were estimated, 1969-90. Maximum stream temperatures are the average of the 1, 5, 10 and 15 maximum daily stream temperatures of each year. Minimum stream temperatures are the average of the 10 minimum daily stream temperatures for those days associated with the 10 maximum daily stream temperatures each year. Air temperatures are the average of the 10 maximum daily air temperatures for those days associated with the 10 maximum stream temperatures of each year.

Stream	Air Temperatures (%)	Stream Temperatures (%)				
		Maximum				Minimum
		1	5	10	15	
Canton Creek	6.0	0.0	10.0	10.7	10.2	10.0
Steamboat Creek above Canton Creek	1.7	0.0	6.7	3.9	3.3	4.4
Steelhead Creek	4.4	0.0	0.0	1.3	0.8	1.3
Big Bend Creek	4.4	0.0	6.3	6.1	5.9	6.1
Cedar Creek	0.0	0.0	0.0	0.0	0.0	0.0
Steamboat Creek below Little Rock Creek	5.7	0.0	0.0	0.0	1.1	0.0
Boulder Creek	0.0	0.0	1.3	1.3	1.7	1.3

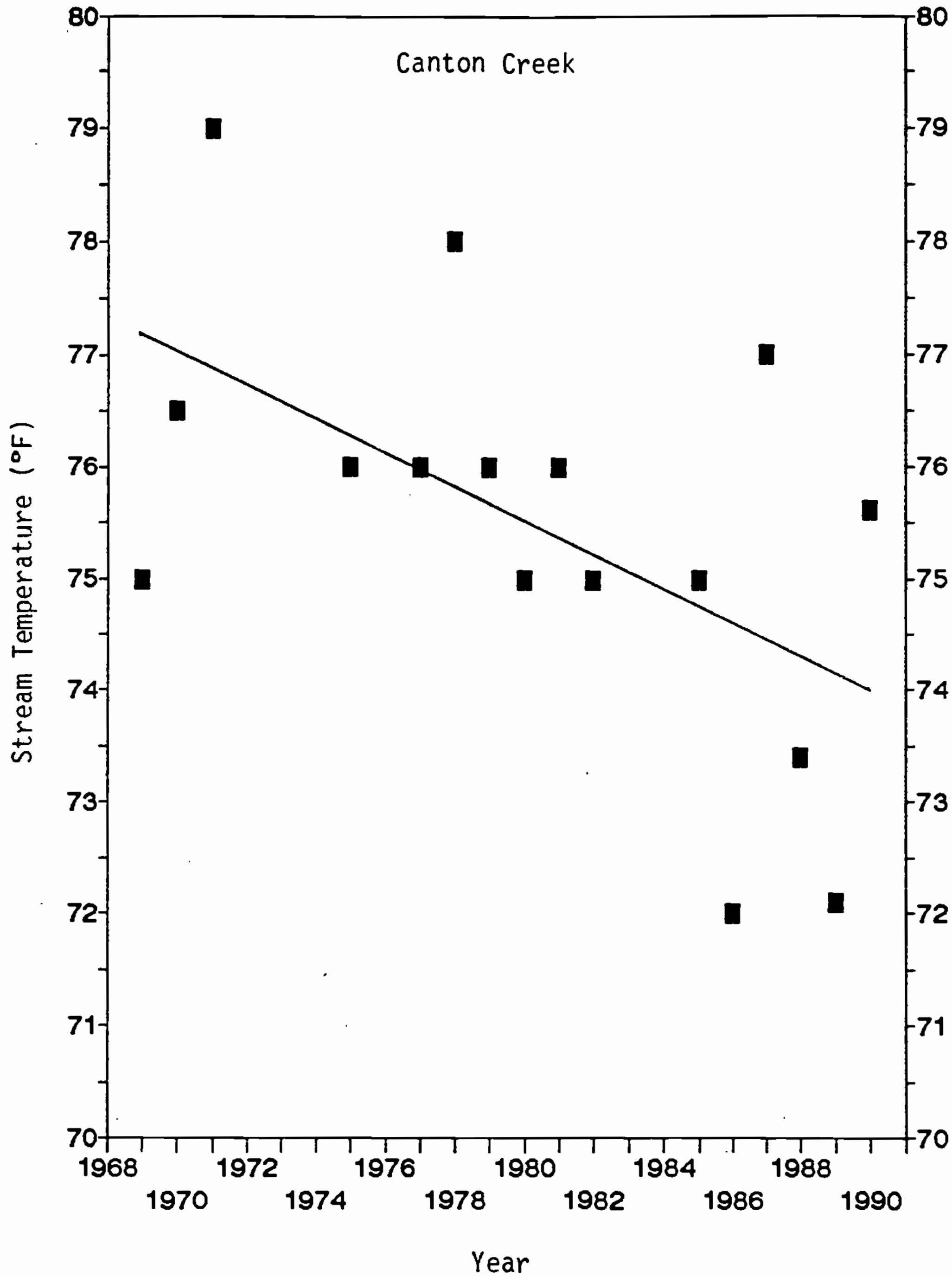

Figure F1. General trend (illustrated by regression line) of annual maximum stream temperatures over time (1969-90) for Canton Creek.

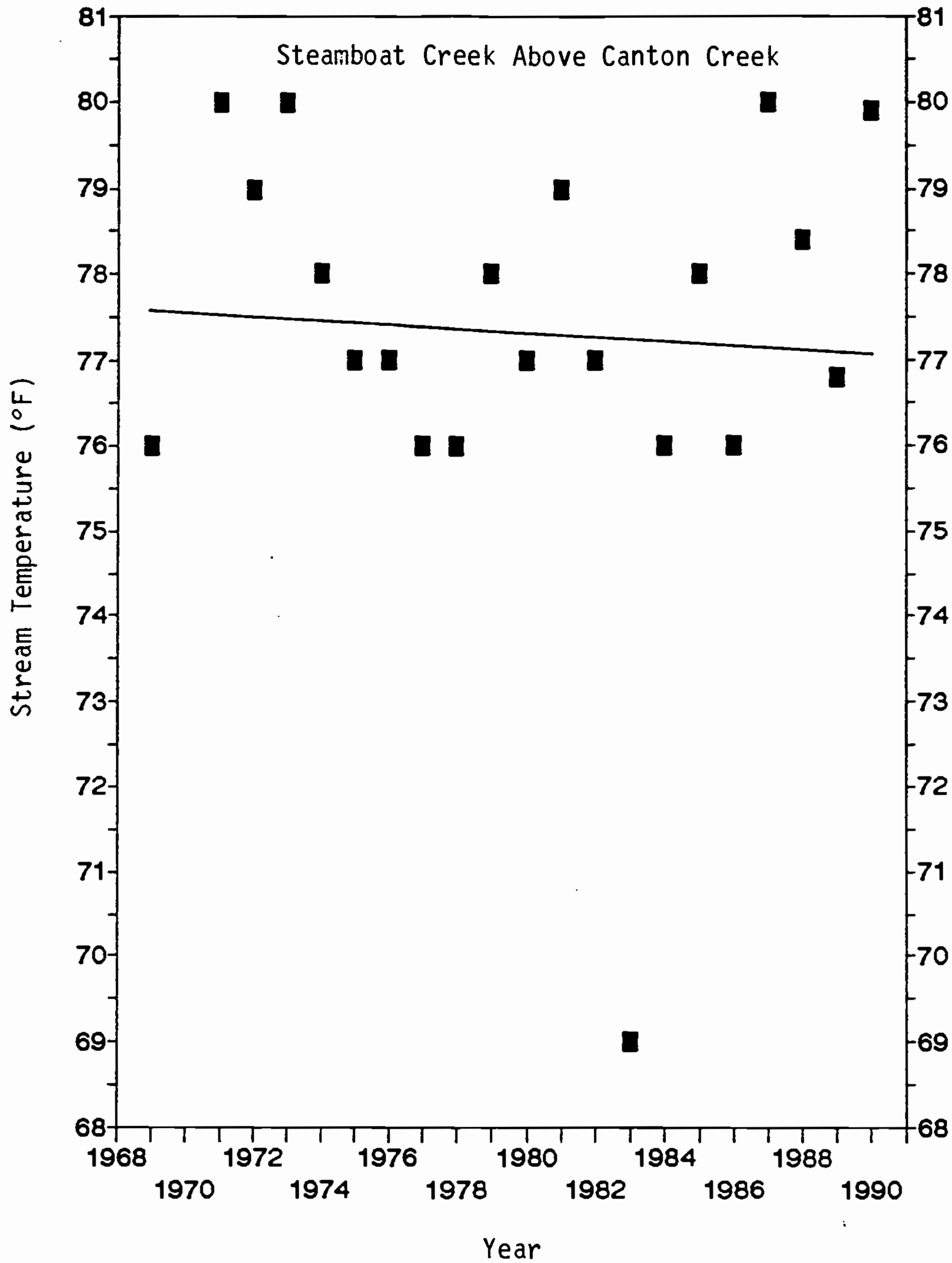

Figure F2. General trend (illustrated by regression line) of annual maximum stream temperatures over time (1969-90) for Steamboat Creek above Canton Creek.

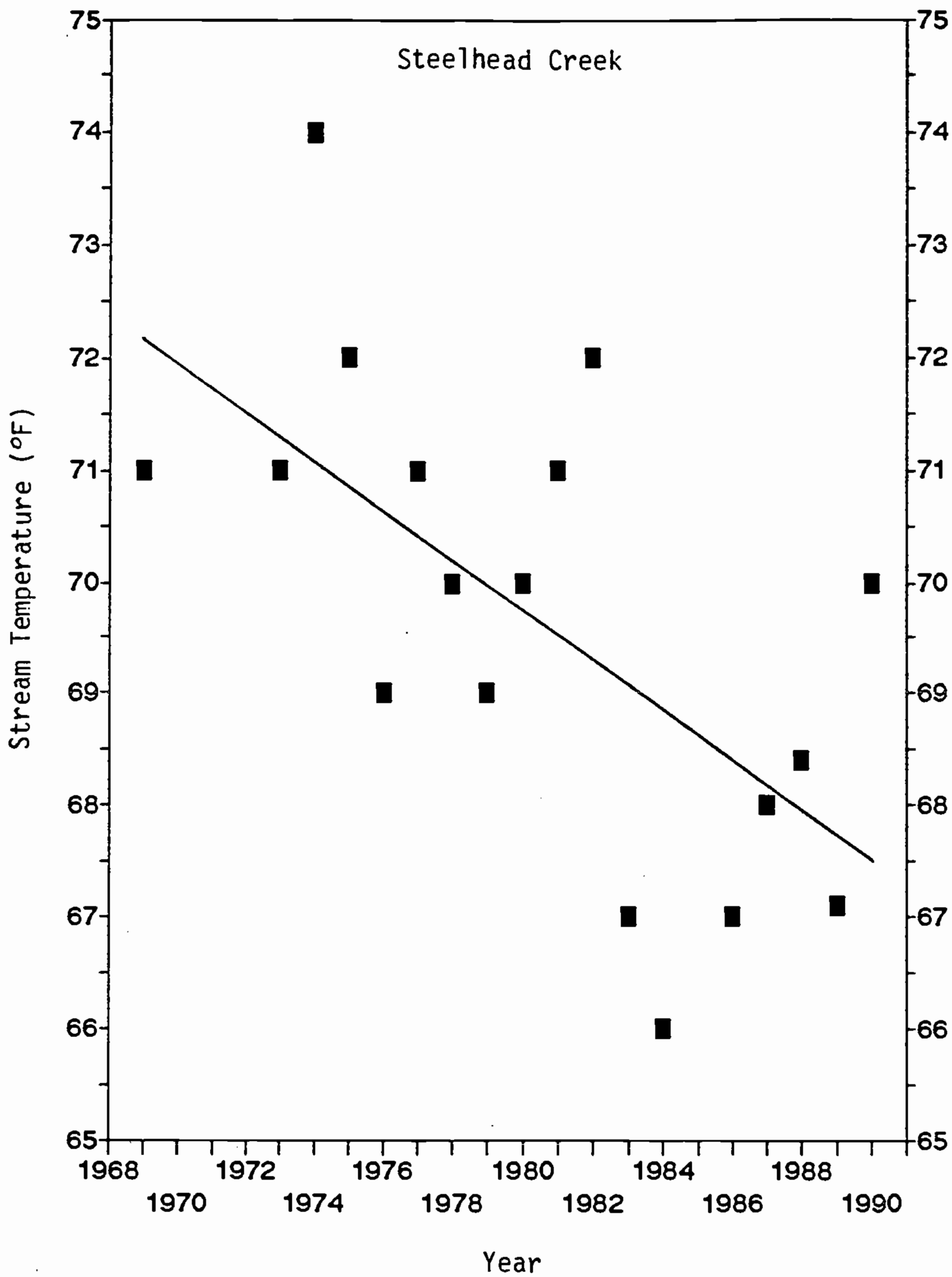

Figure F3. General trend (illustrated by regression line) of annual maximum stream temperatures over time (1969-90) for Steelhead Creek.

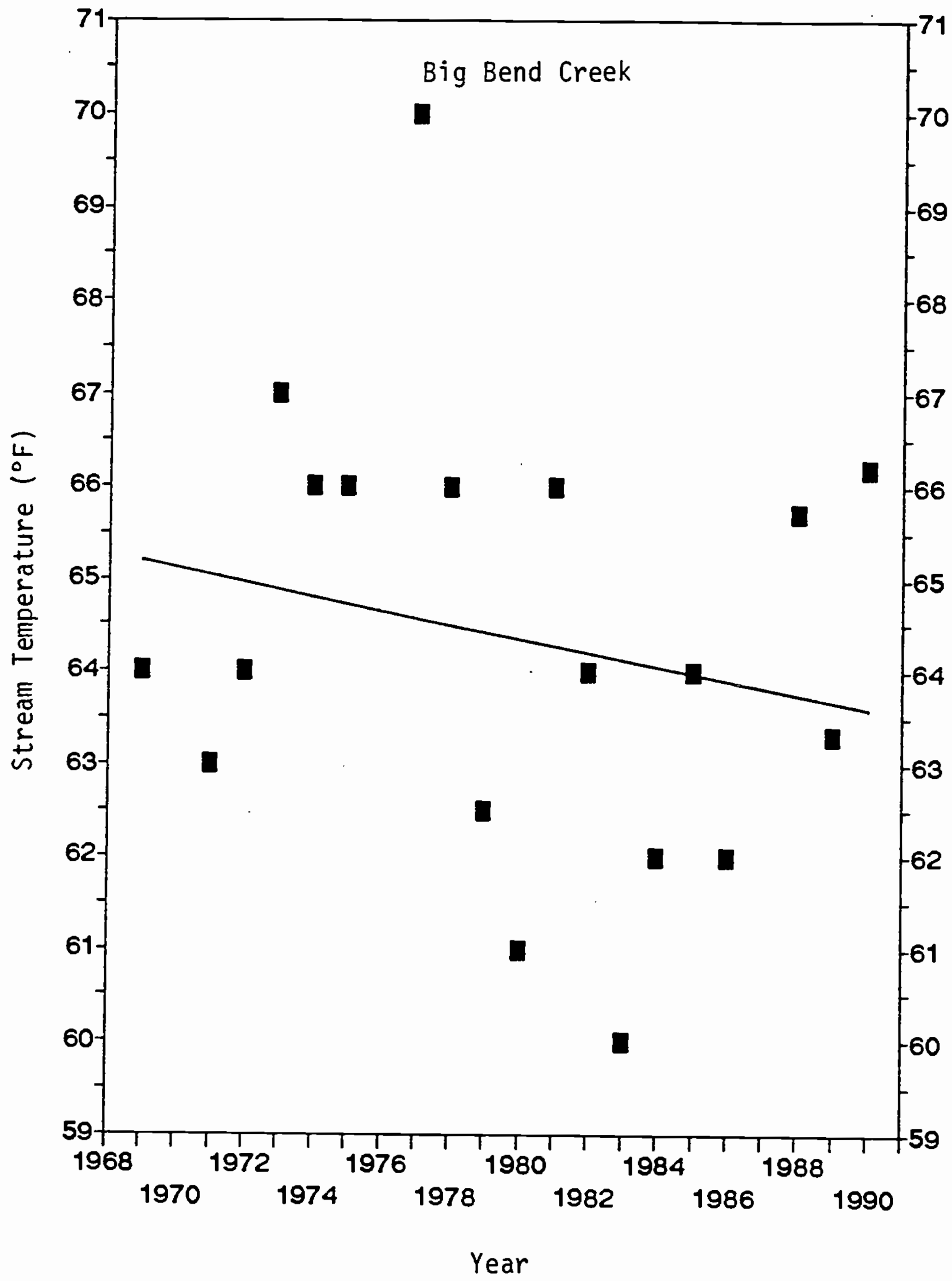

Figure F4. General trend (illustrated by regression line) of annual maximum stream temperatures over time (1969-90) for Big Bend Creek.

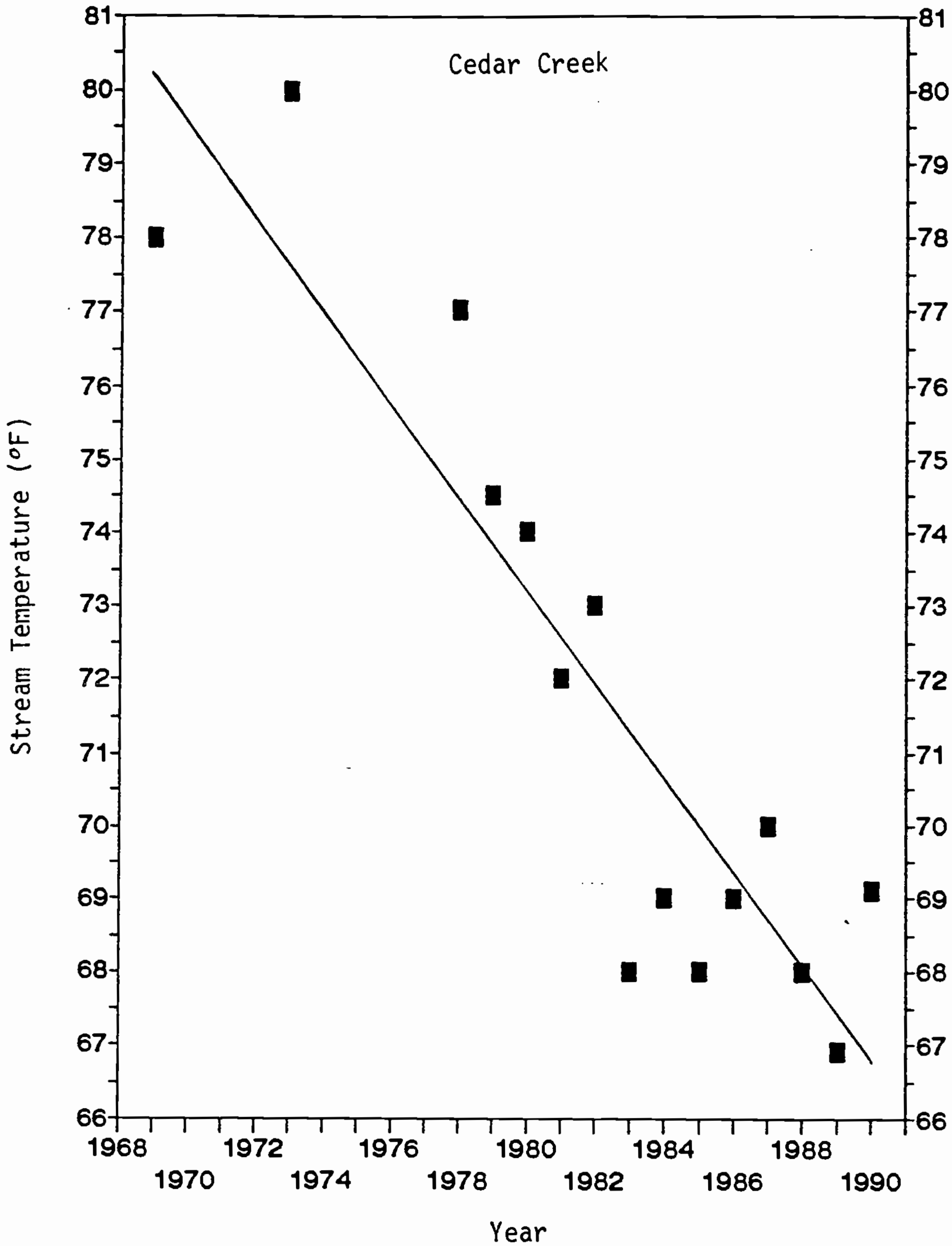

Figure F5. General trend (illustrated by regression line) of annual maximum stream temperatures over time (1969-90) for Cedar Creek.

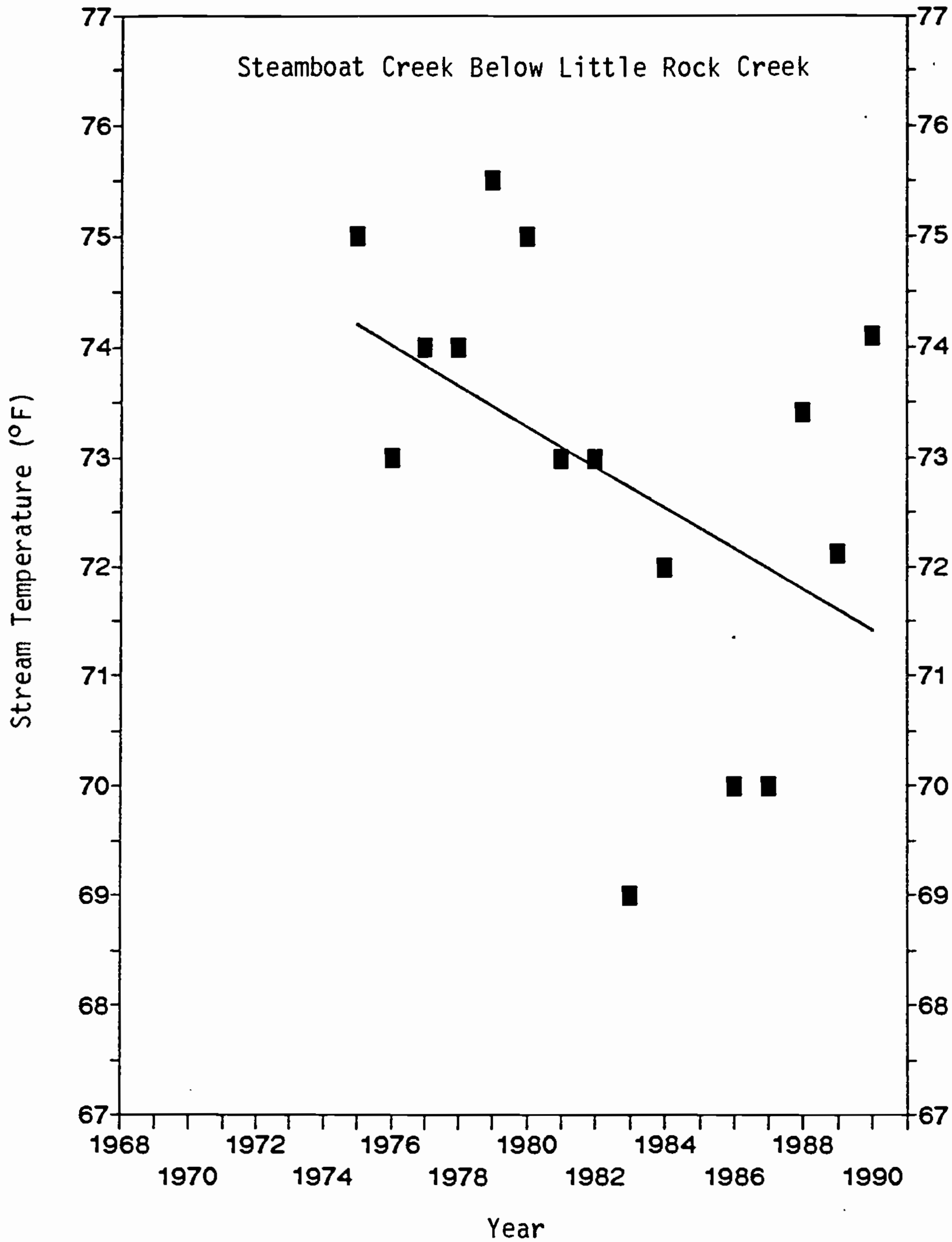

Figure F6. General trend (illustrated by regression line) of annual maximum stream temperatures over time (1969-90) for Steamboat Creek below Little Rock Creek.

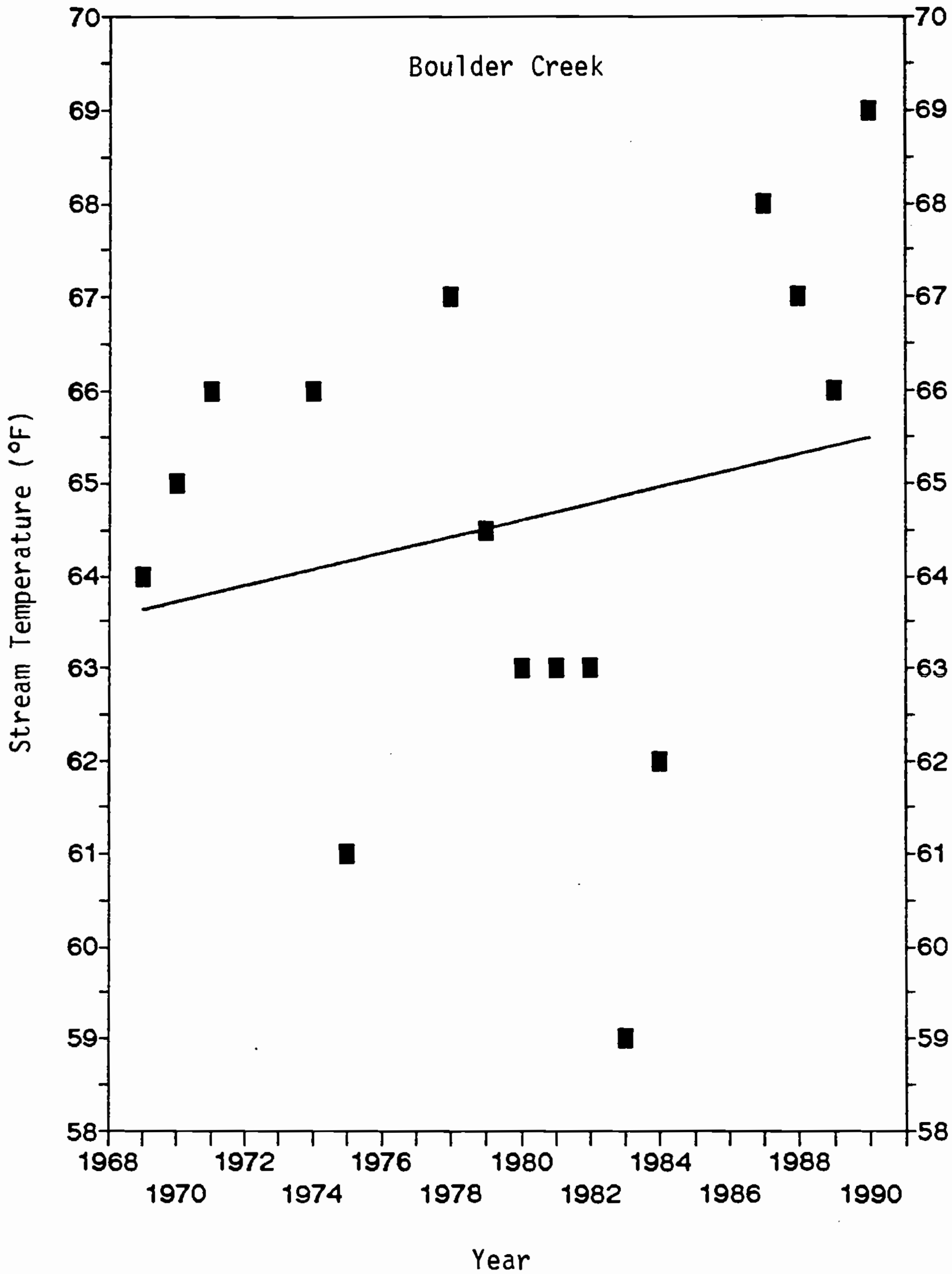

Figure F7. General trend (illustrated by regression line) of annual maximum stream temperatures over time (1969-90) for Boulder Creek.

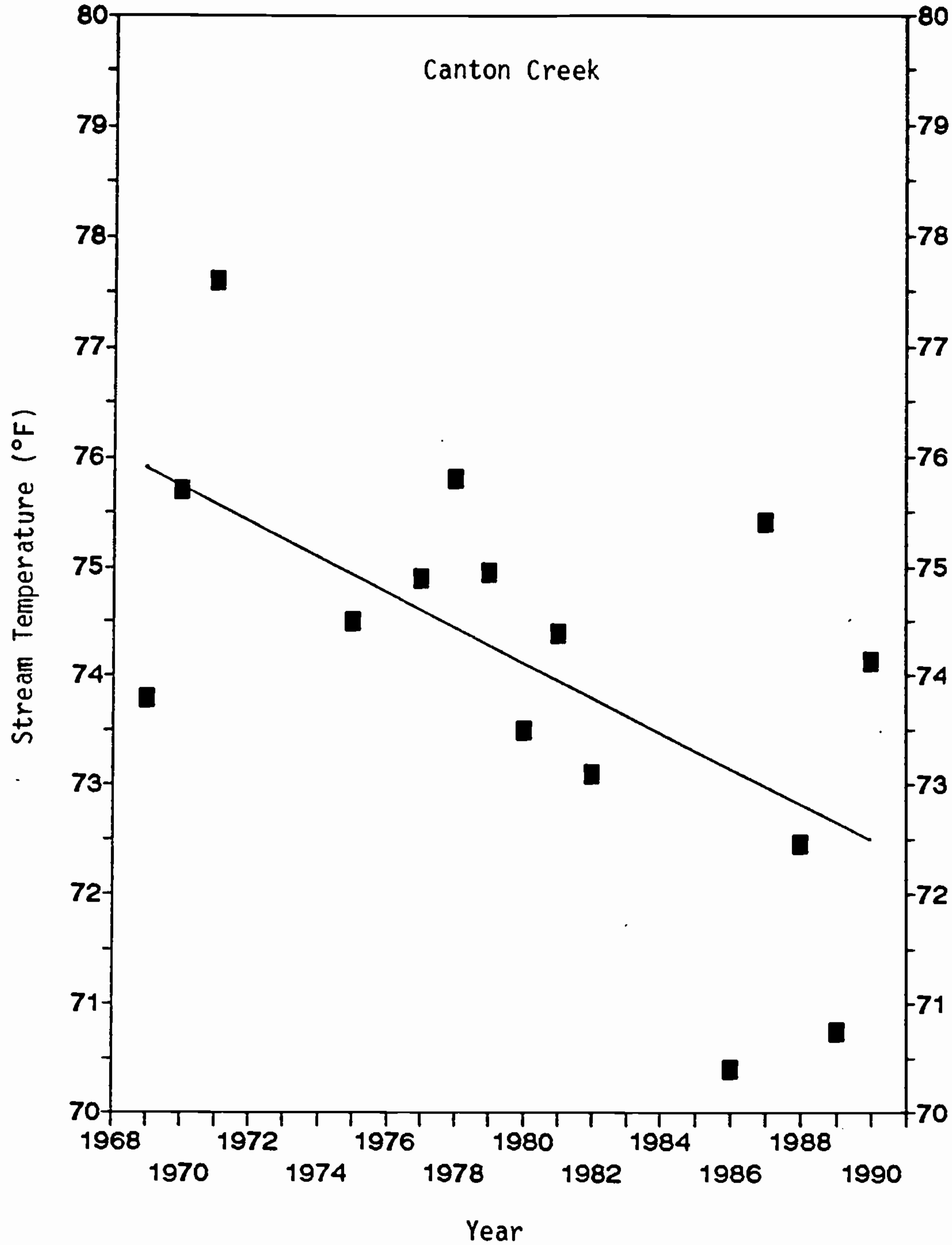

Figure G1. General trend (illustrated by regression line) over time (1969-90) of the average of the 10 maximum daily stream temperatures each year for Canton Creek.

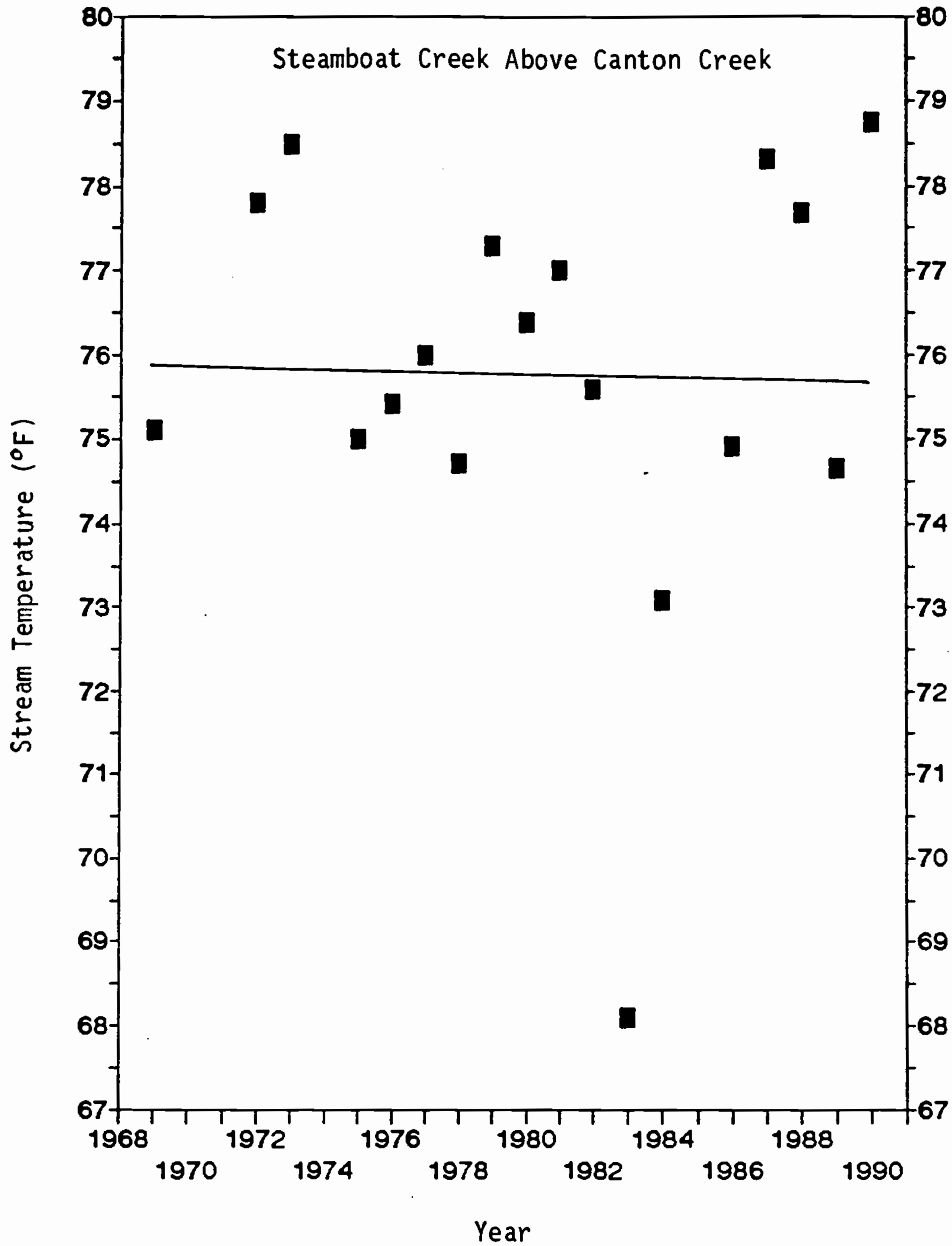

Figure G2. General trend (illustrated by regression line) over time (1969-90) of the average of the 10 maximum daily stream temperatures each year for Steamboat Creek above Canton Creek.

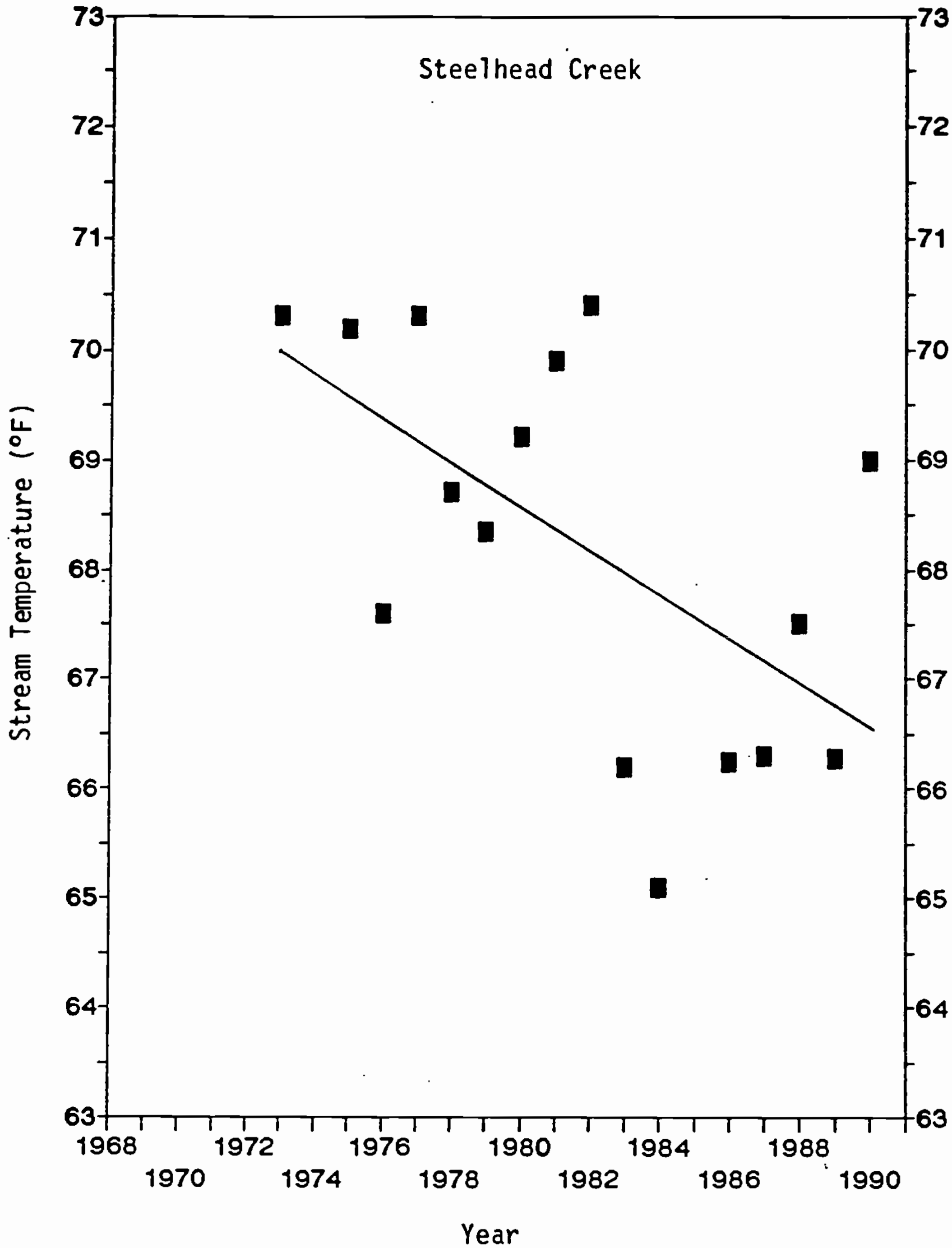

Figure G3. General trend (illustrated by regression line) over time (1969-90) of the average of the 10 maximum daily stream temperatures each year for Steelhead Creek.

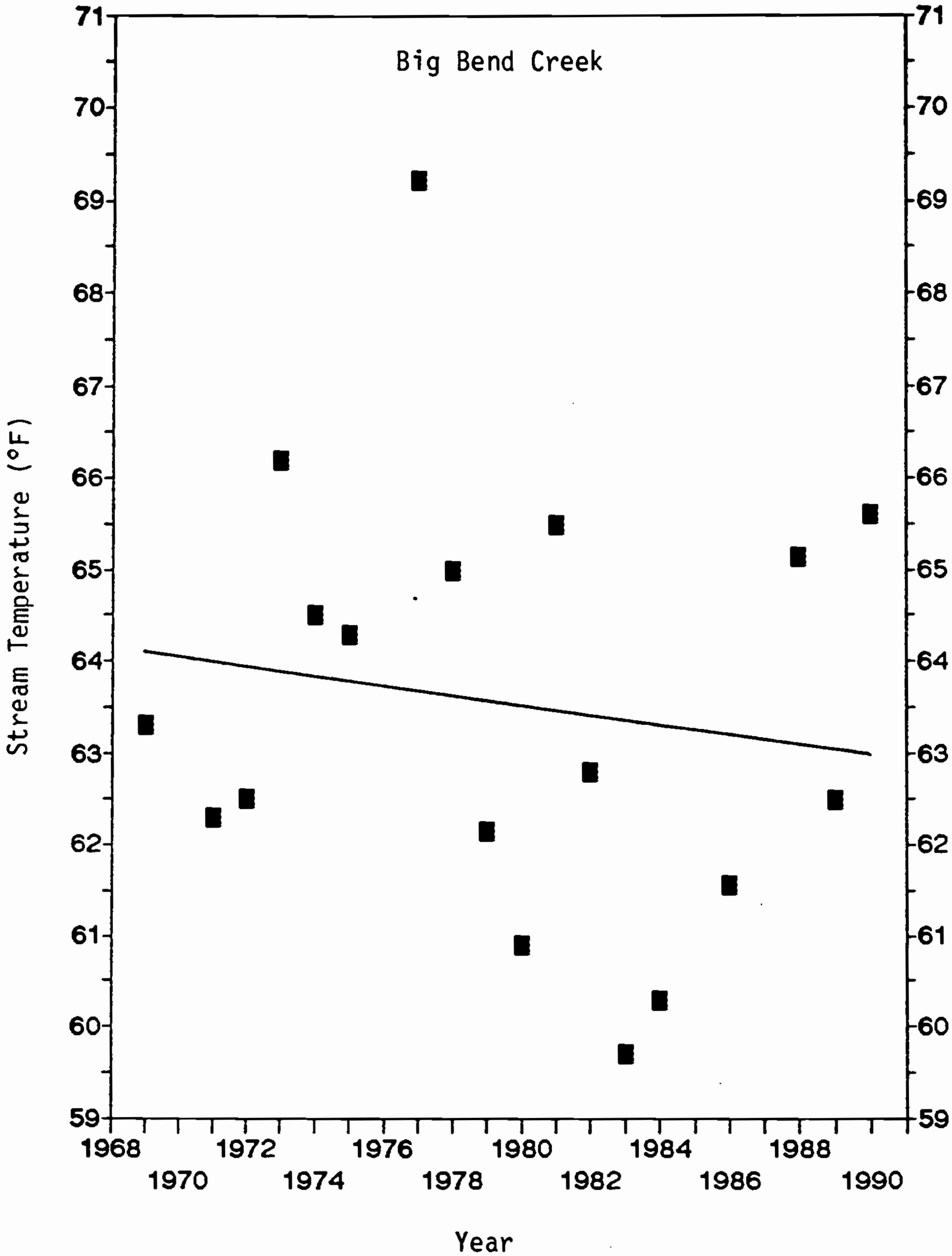

Figure G4. General trend (illustrated by regression line) over time (1969-90) of the average of the 10 maximum daily stream temperatures each year for Big Bend Creek.

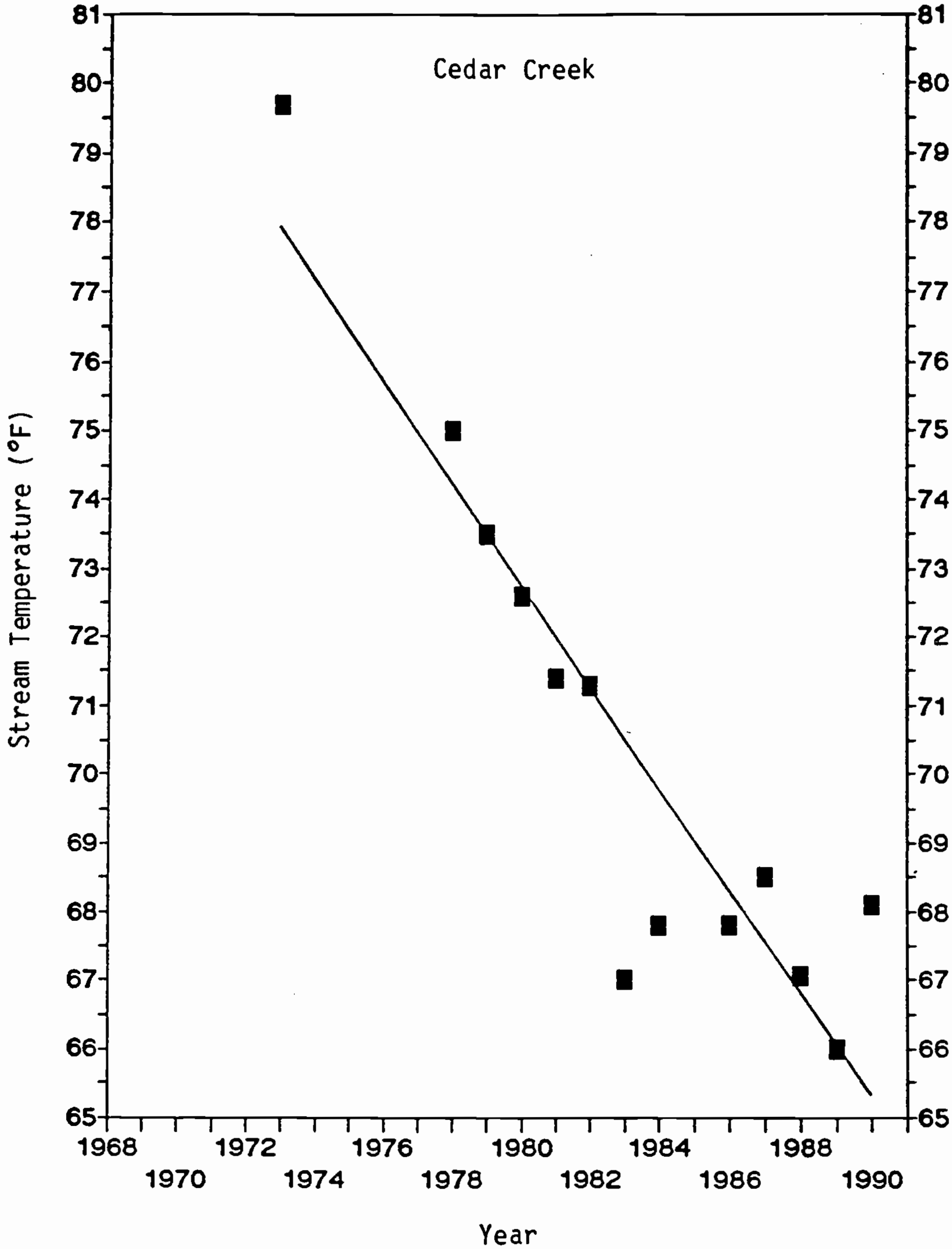

Figure G5. General trend (illustrated by regression line) over time (1969-90) of the average of the 10 maximum daily stream temperatures each year for Cedar Creek.

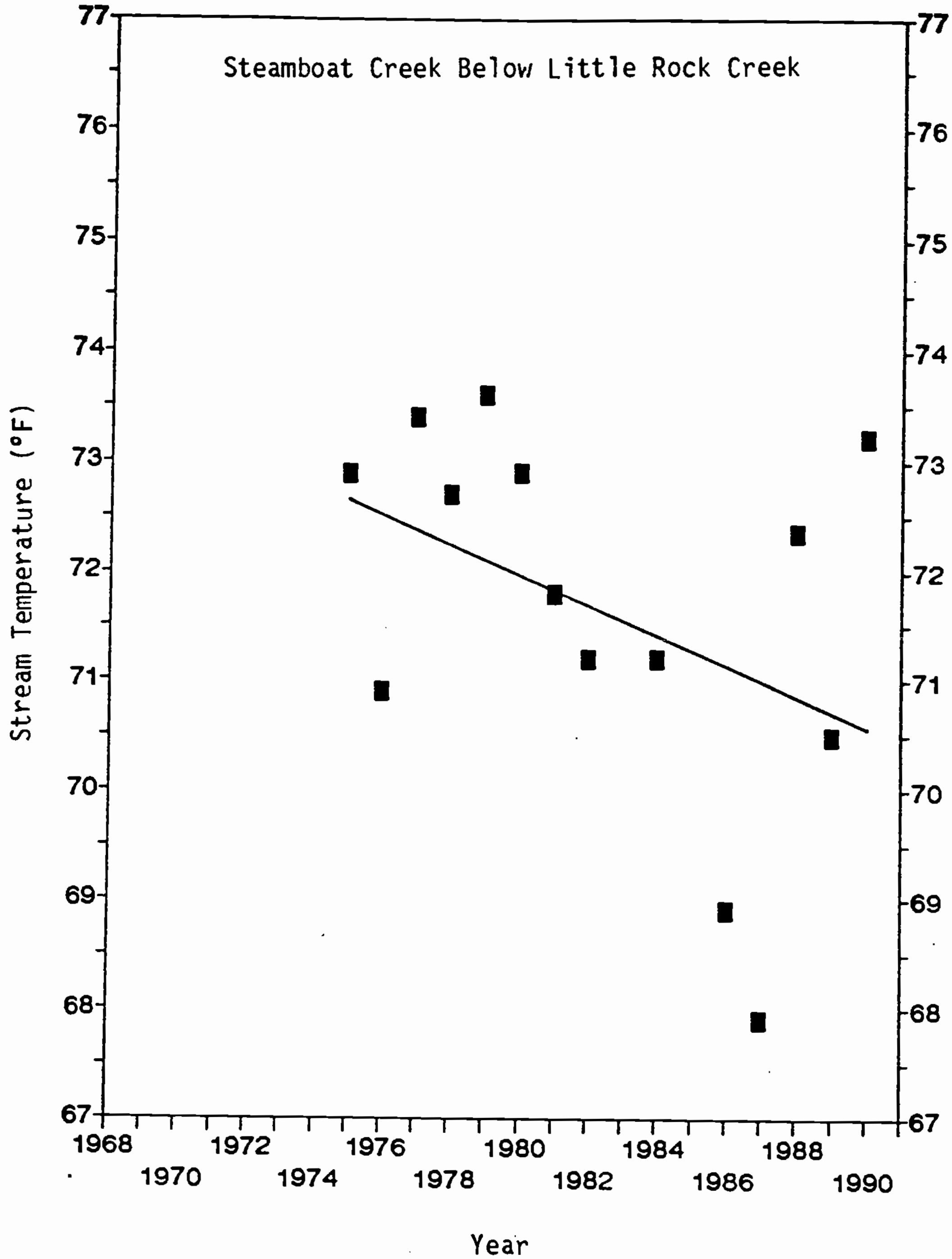

Figure G6. General trend (illustrated by regression line) over time (1969-90) of the average of the 10 maximum daily stream temperatures each year for Steamboat Creek below Little Rock Creek.

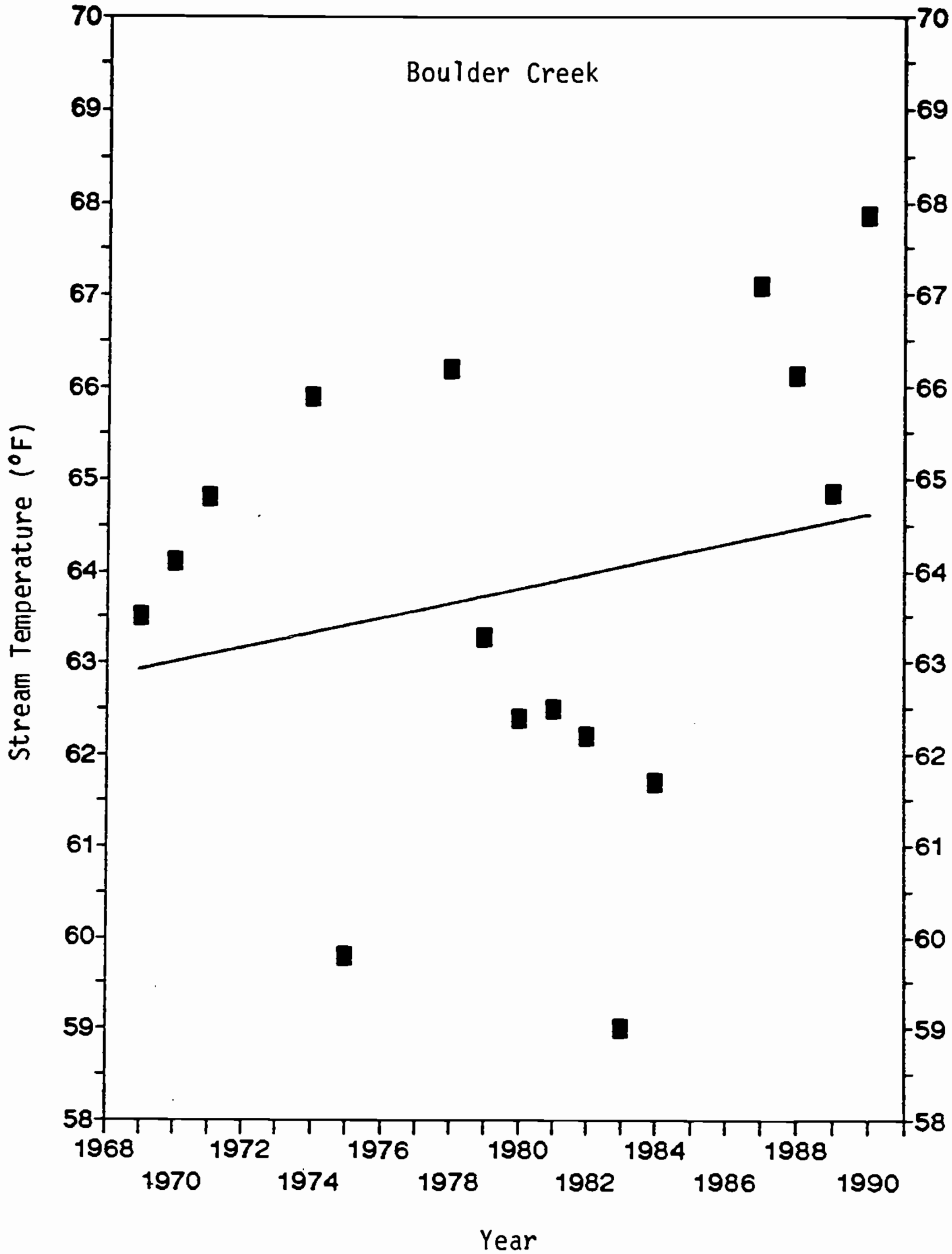

Figure G7. General trend (illustrated by regression line) over time (1969-90) of the average of the 10 maximum daily stream temperatures each year for Boulder Creek.

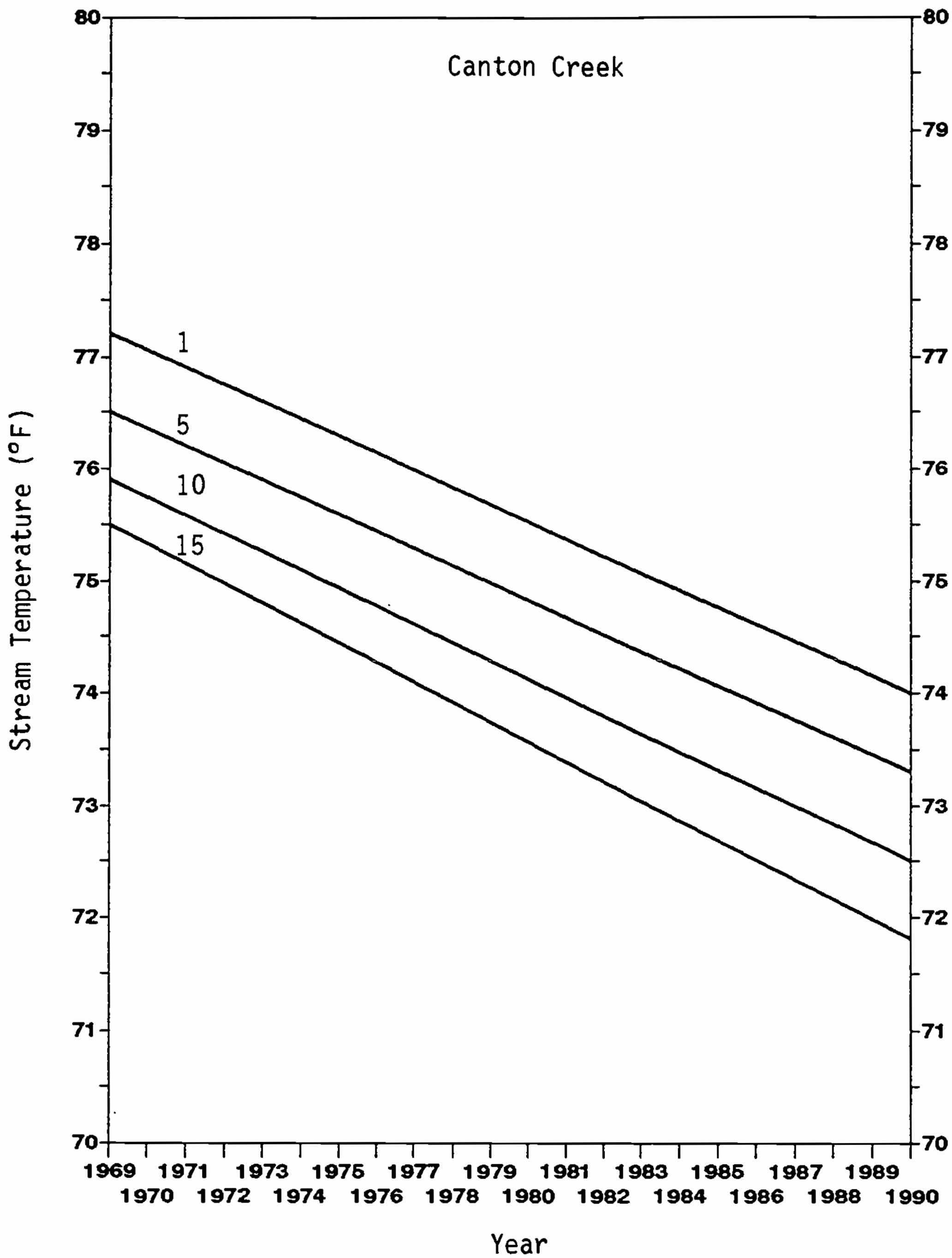

Figure H1. General trend of maximum stream temperatures (calculated from the 1, 5, 10, and 15 highest temperatures of each year) over time (1969-90) for Canton Creek.

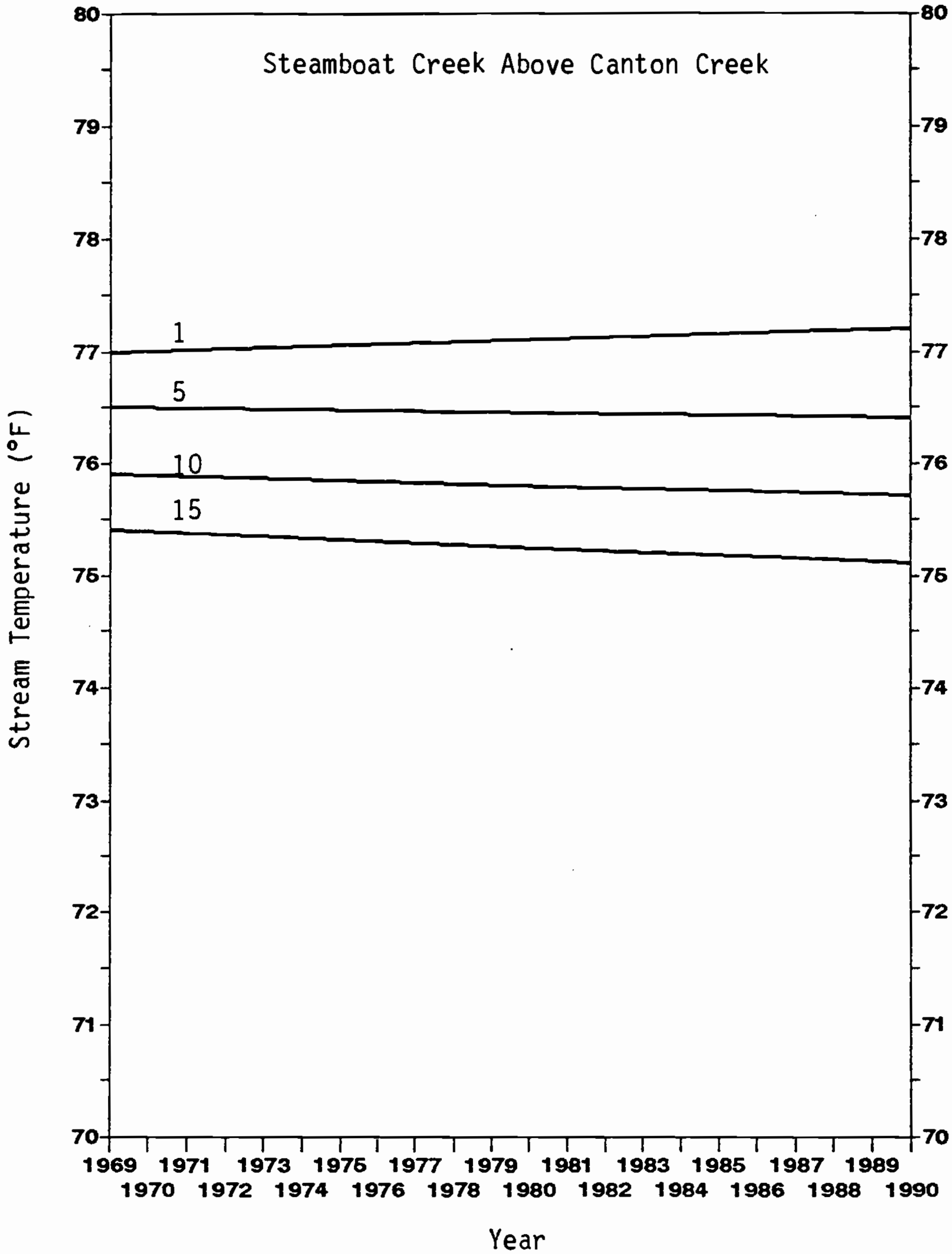

Figure H2. General trend of maximum stream temperatures (calculated from the 1, 5, 10, and 15 highest temperatures of each year) over time (1969-90) for Steamboat Creek above Canton Creek.

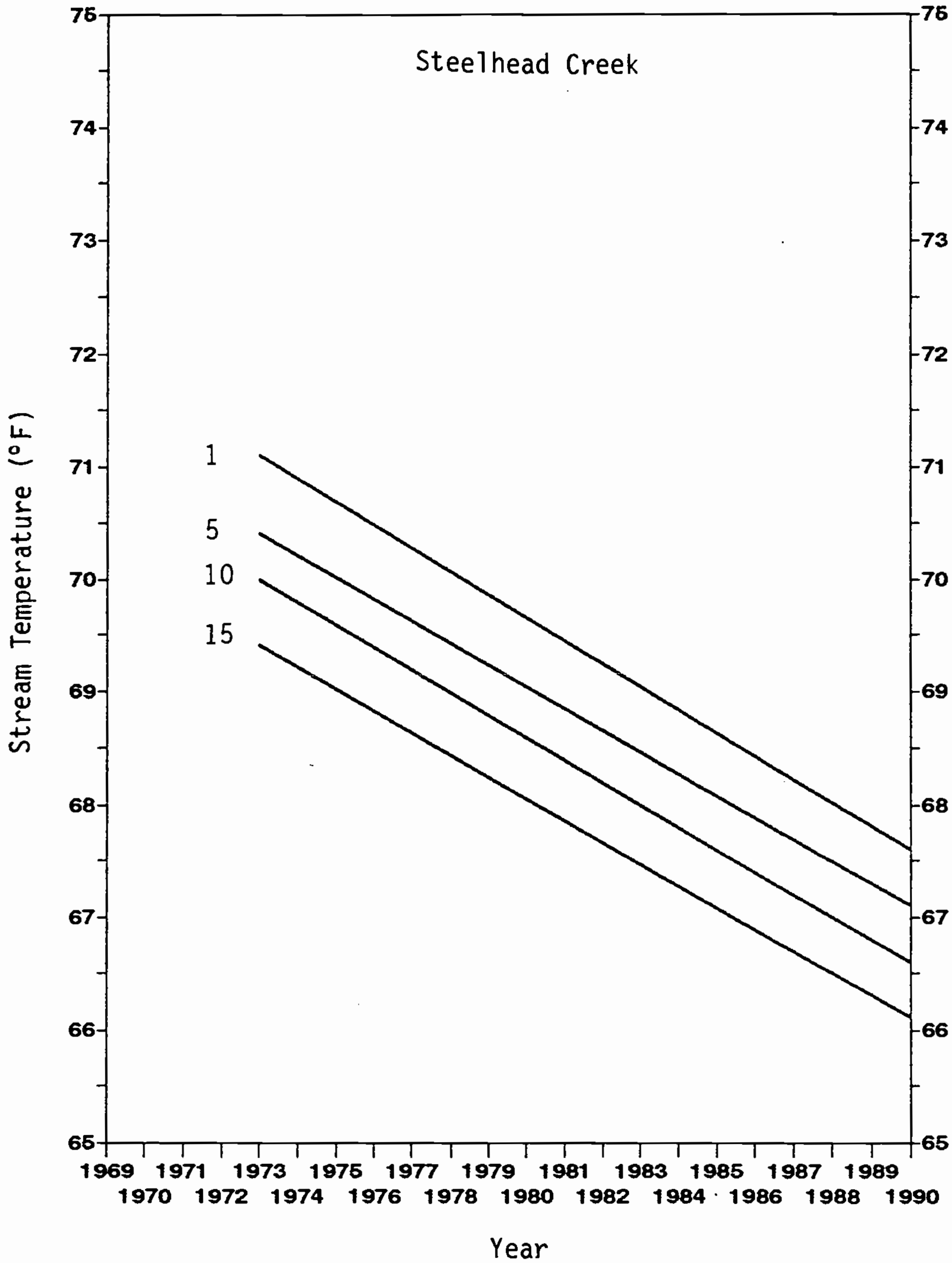

Figure H3. General trend of maximum stream temperatures (calculated from the 1, 5, 10, and 15 highest temperatures of each year) over time (1969-90) for Steelhead Creek.

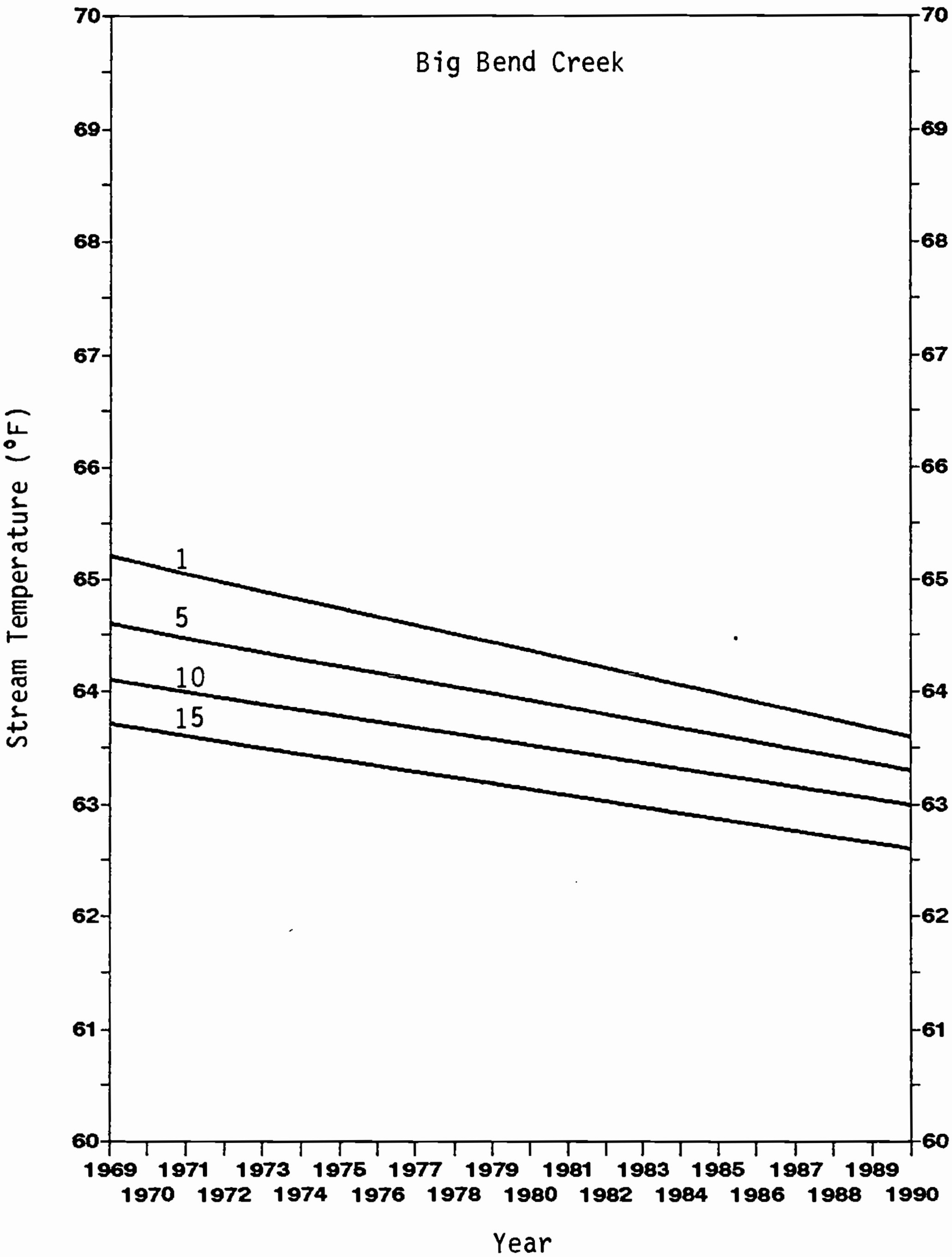

Figure H4. General trend of maximum stream temperatures (calculated from the 1, 5, 10, and 15 highest temperatures of each year) over time (1969-90) for Big Bend Creek.

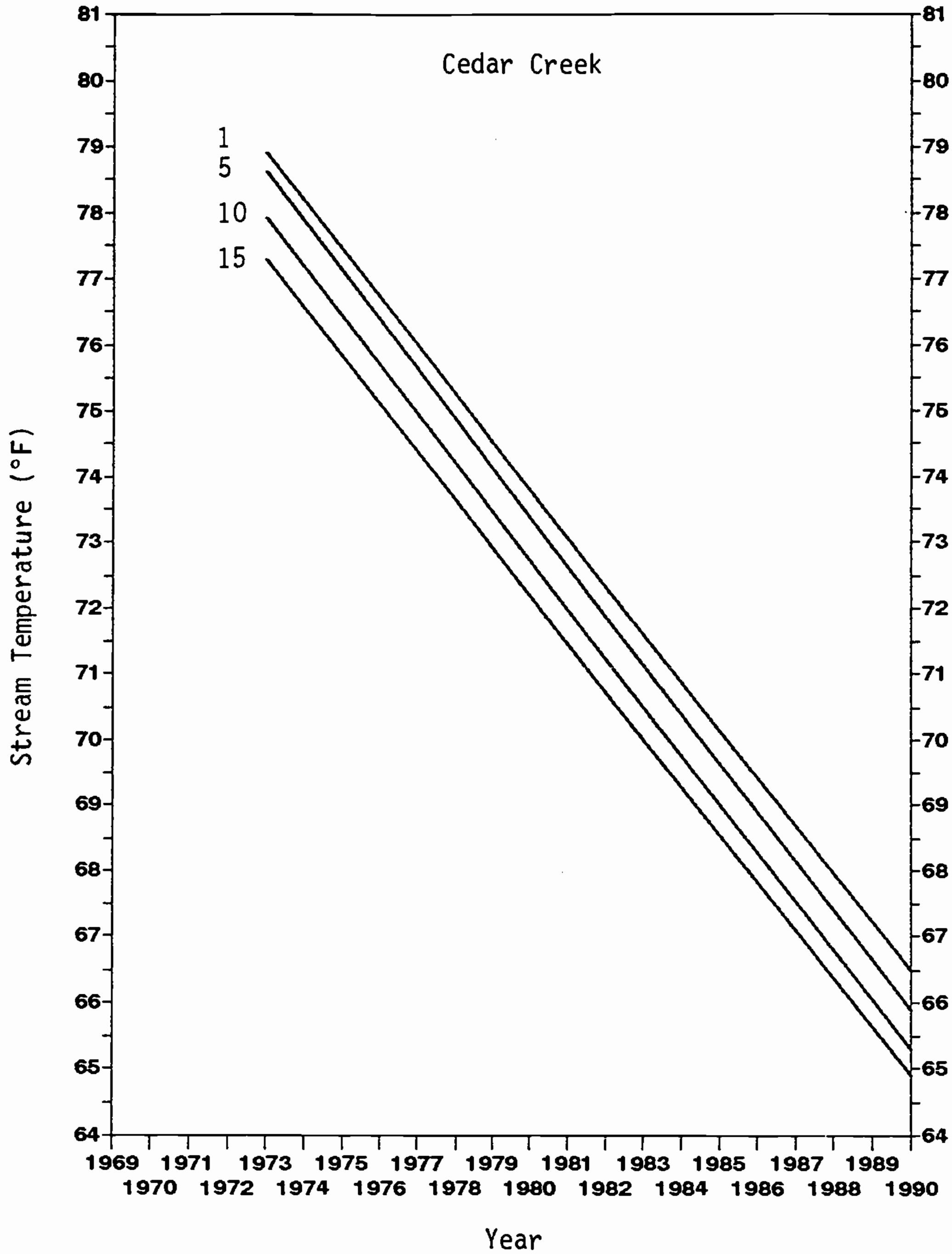

Figure H5. General trend of maximum stream temperatures (calculated from the 1, 5, 10, and 15 highest temperatures of each year) over time (1969-90) for Cedar Creek.

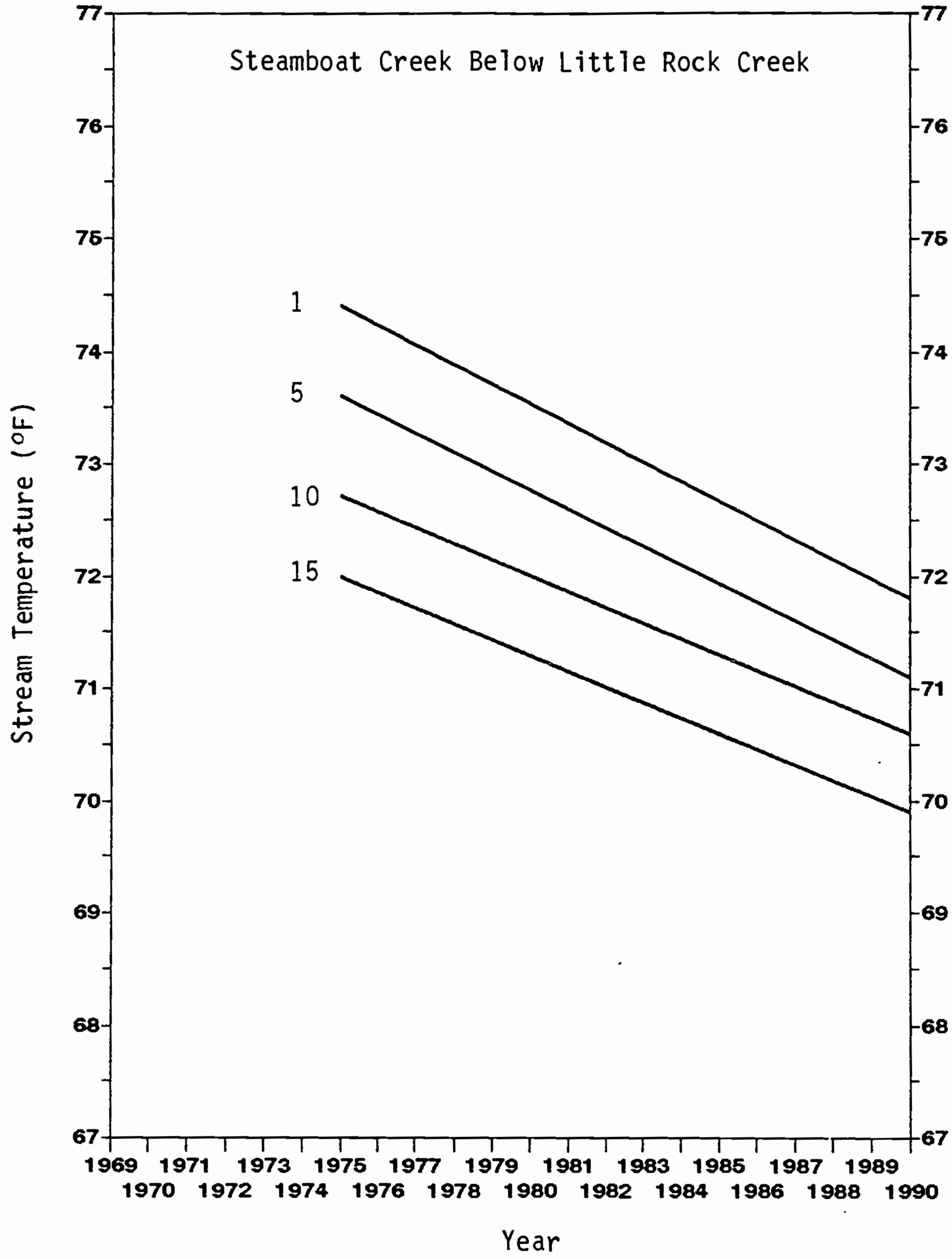

Figure H6. General trend of maximum stream temperatures (calculated from the 1, 5, 10, and 15 highest temperatures of each year) over time (1969-90) for Steamboat Creek below Little Rock Creek.

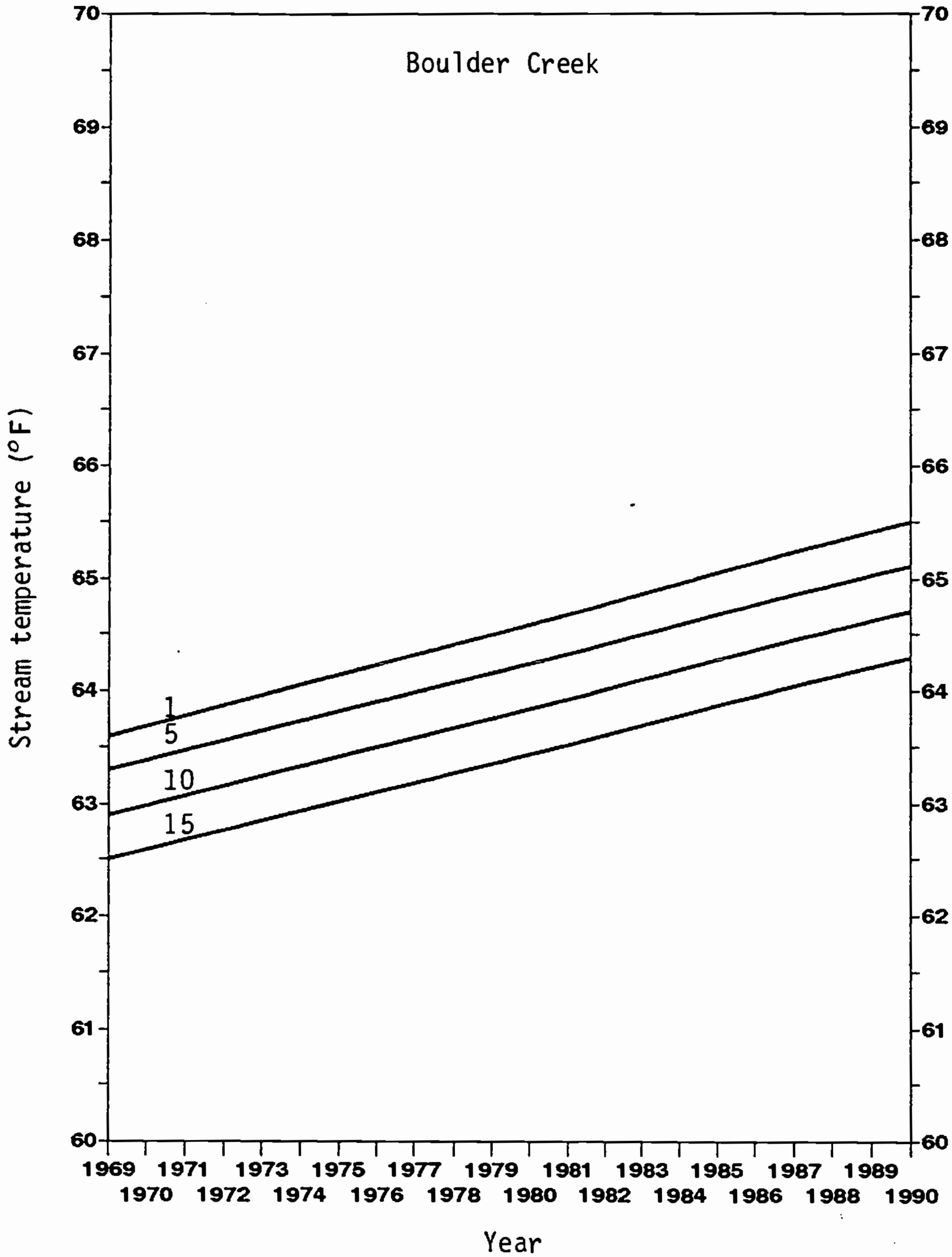

Figure H7. General trend of maximum stream temperatures (calculated from the 1, 5, 10, and 15 highest temperatures of each year) over time (1969-90) for Boulder Creek.

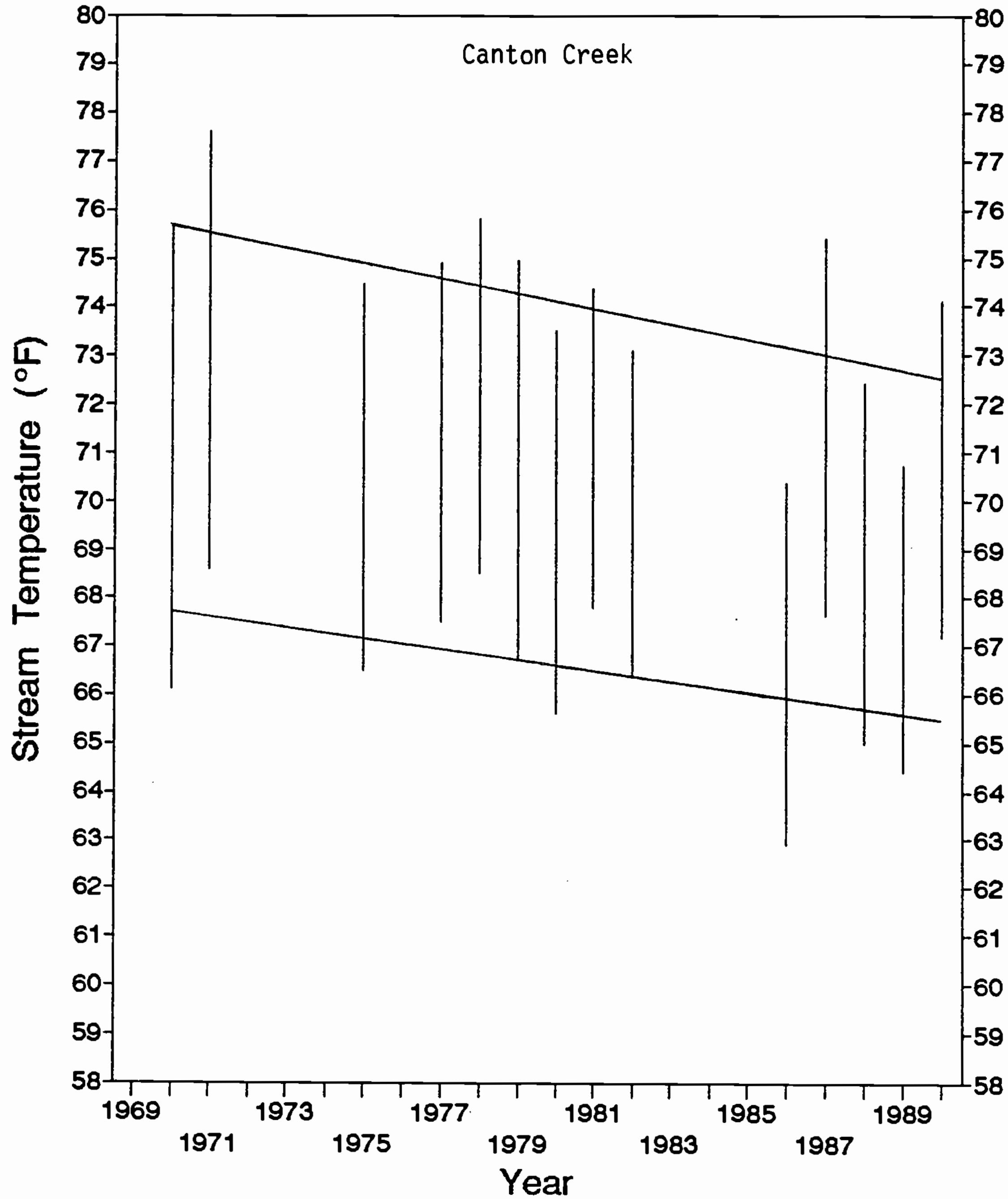

Figure I1. Diurnal fluctuations in daily summer stream temperature over time (1969-90) using the average of the 10 maximum daily stream temperatures each year and the average of the corresponding 10 minimum daily stream temperatures for Canton Creek. Regression lines of maximum and minimum daily stream temperatures are shown to illustrate trends.

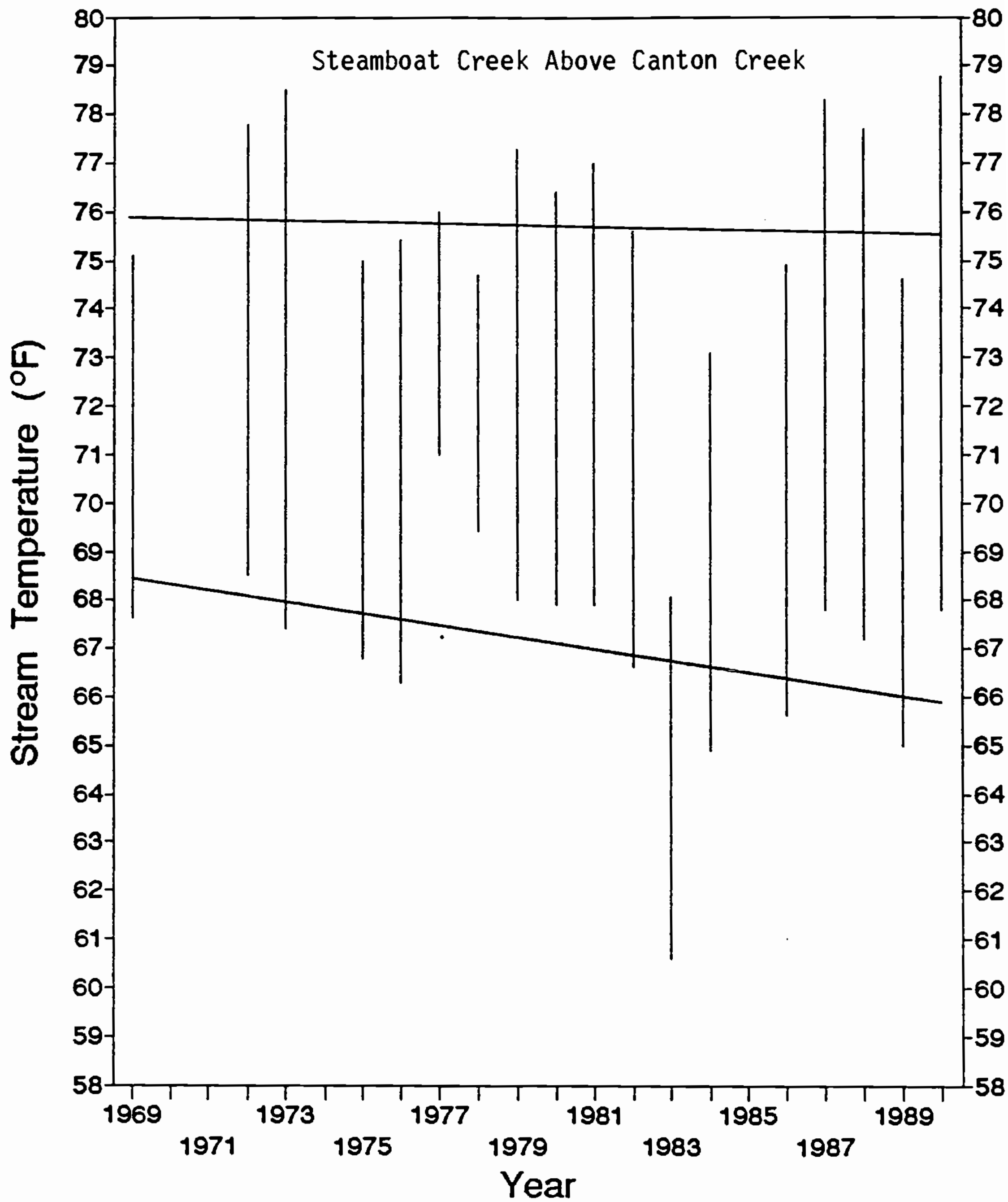

Figure I2. Diurnal fluctuations in daily summer stream temperature over time (1969-90) using the average of the 10 maximum daily stream temperatures each year and the average of the corresponding 10 minimum daily stream temperatures for Steamboat Creek above Canton Creek. Regression lines of maximum and minimum daily stream temperatures are shown to illustrate trends.

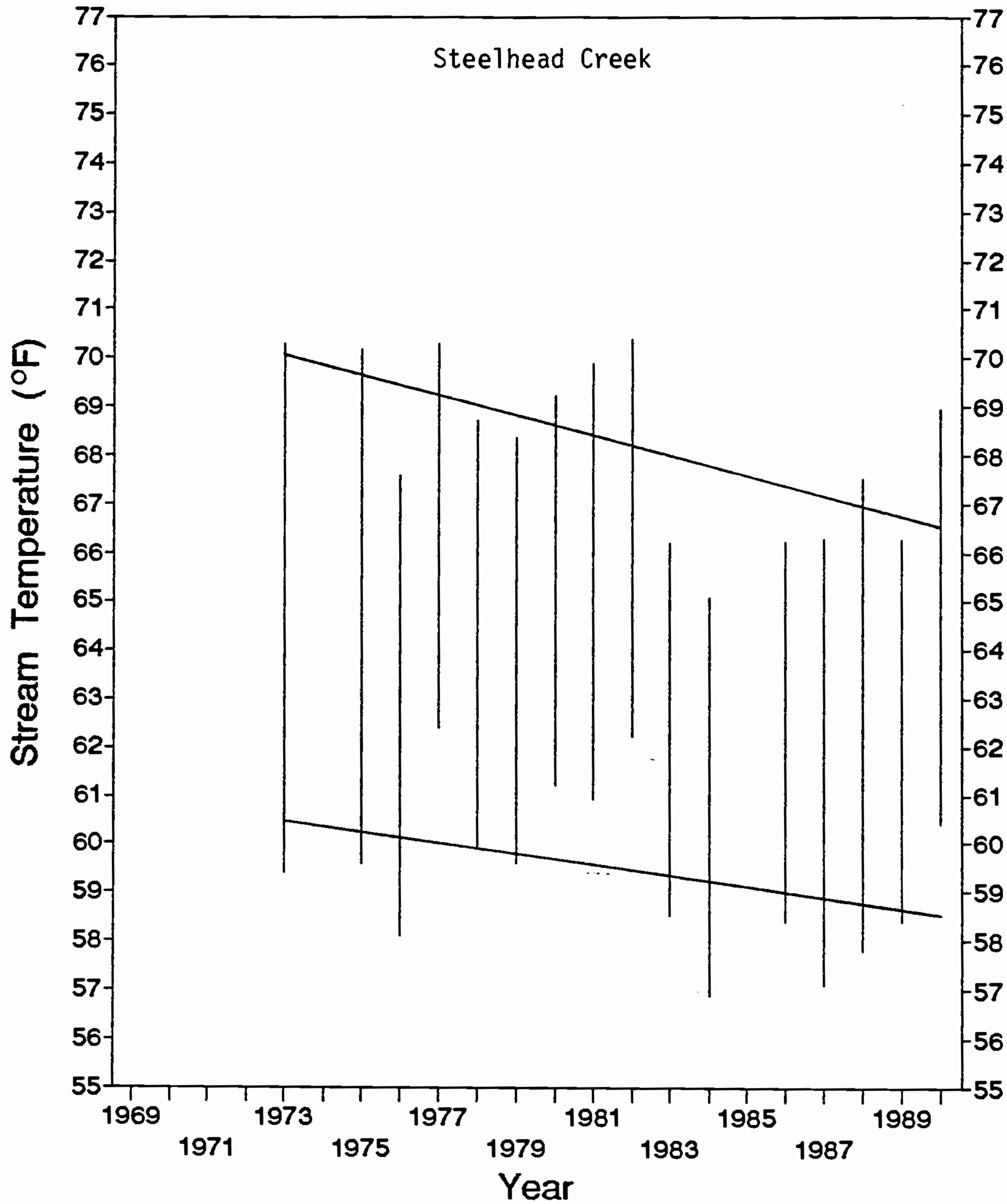

Figure I3. Diurnal fluctuations in daily summer stream temperature over time (1969-90) using the average of the 10 maximum daily stream temperatures each year and the average of the corresponding 10 minimum daily stream temperatures for Steelhead Creek. Regression lines of maximum and minimum daily stream temperatures are shown to illustrate trends.

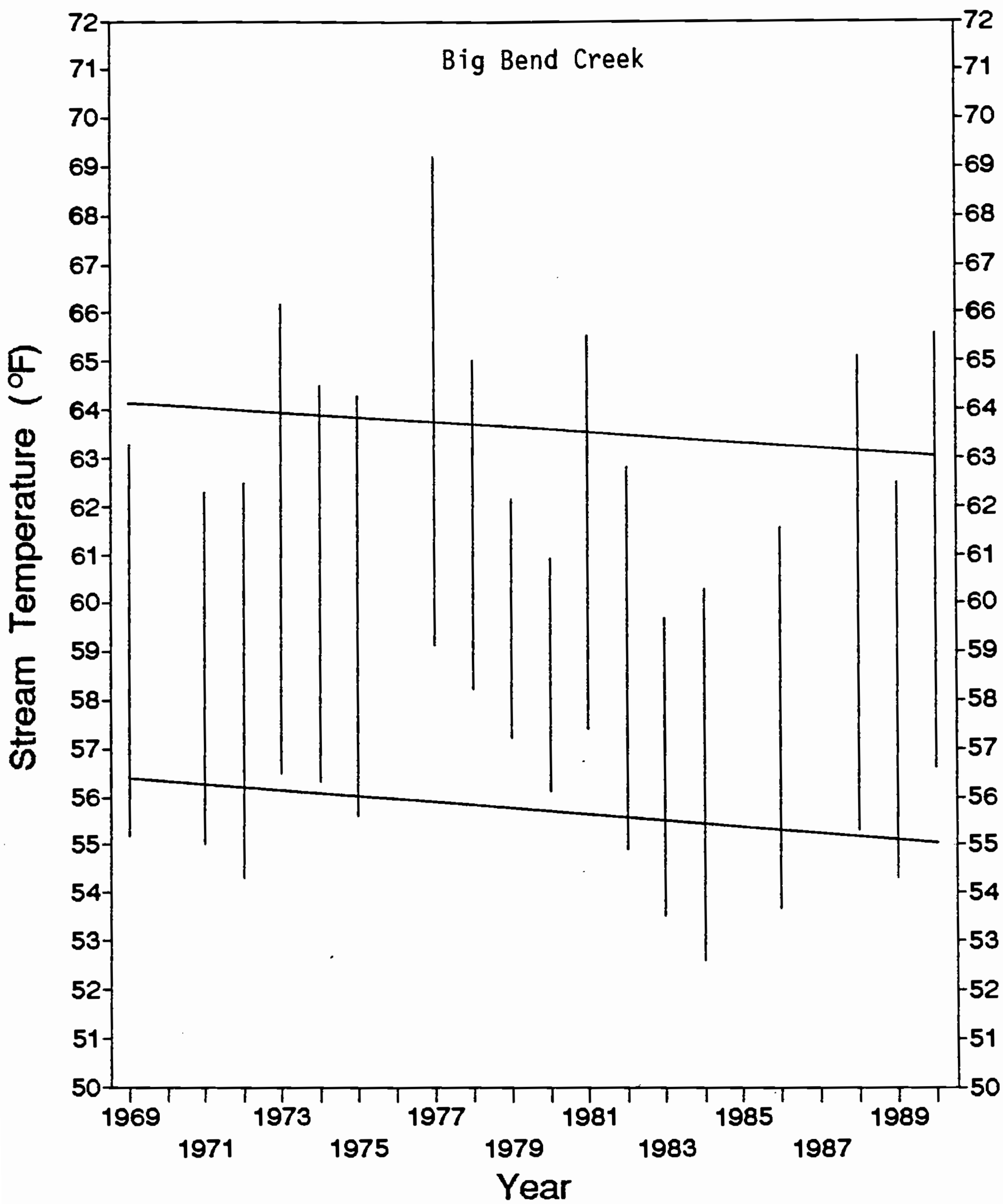

Figure I4. Diurnal fluctuations in daily summer stream temperature over time (1969-90) using the average of the 10 maximum daily stream temperatures each year and the average of the corresponding 10 minimum daily stream temperatures for Big Bend Creek. Regression lines of maximum and minimum daily stream temperatures are shown to illustrate trends.

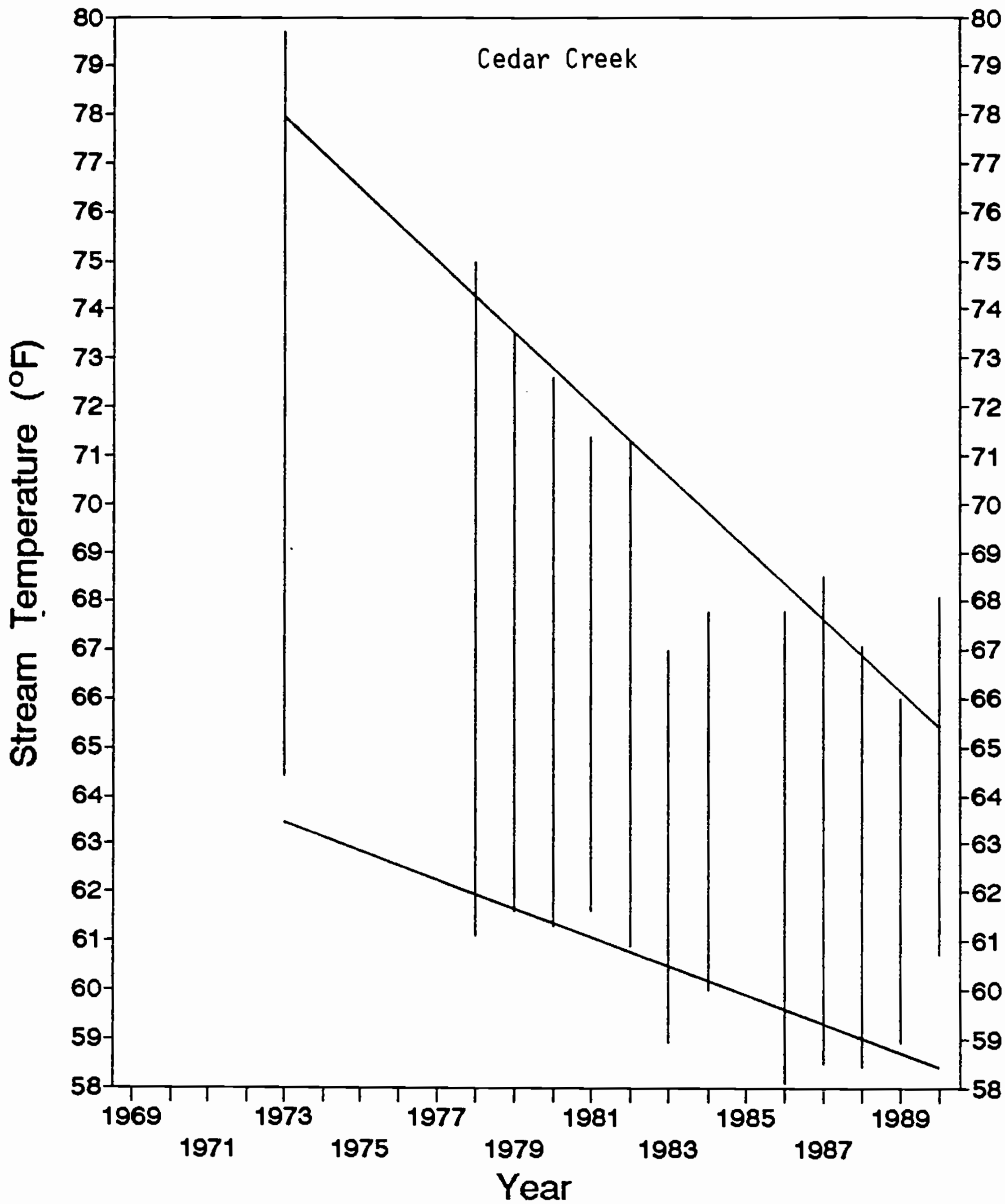

Figure I5. Diurnal fluctuations in daily summer stream temperature over time (1969-90) using the average of the 10 maximum daily stream temperatures each year and the average of the corresponding 10 minimum daily stream temperatures for Cedar Creek. Regression lines of maximum and minimum daily stream temperatures are shown to illustrate trends.

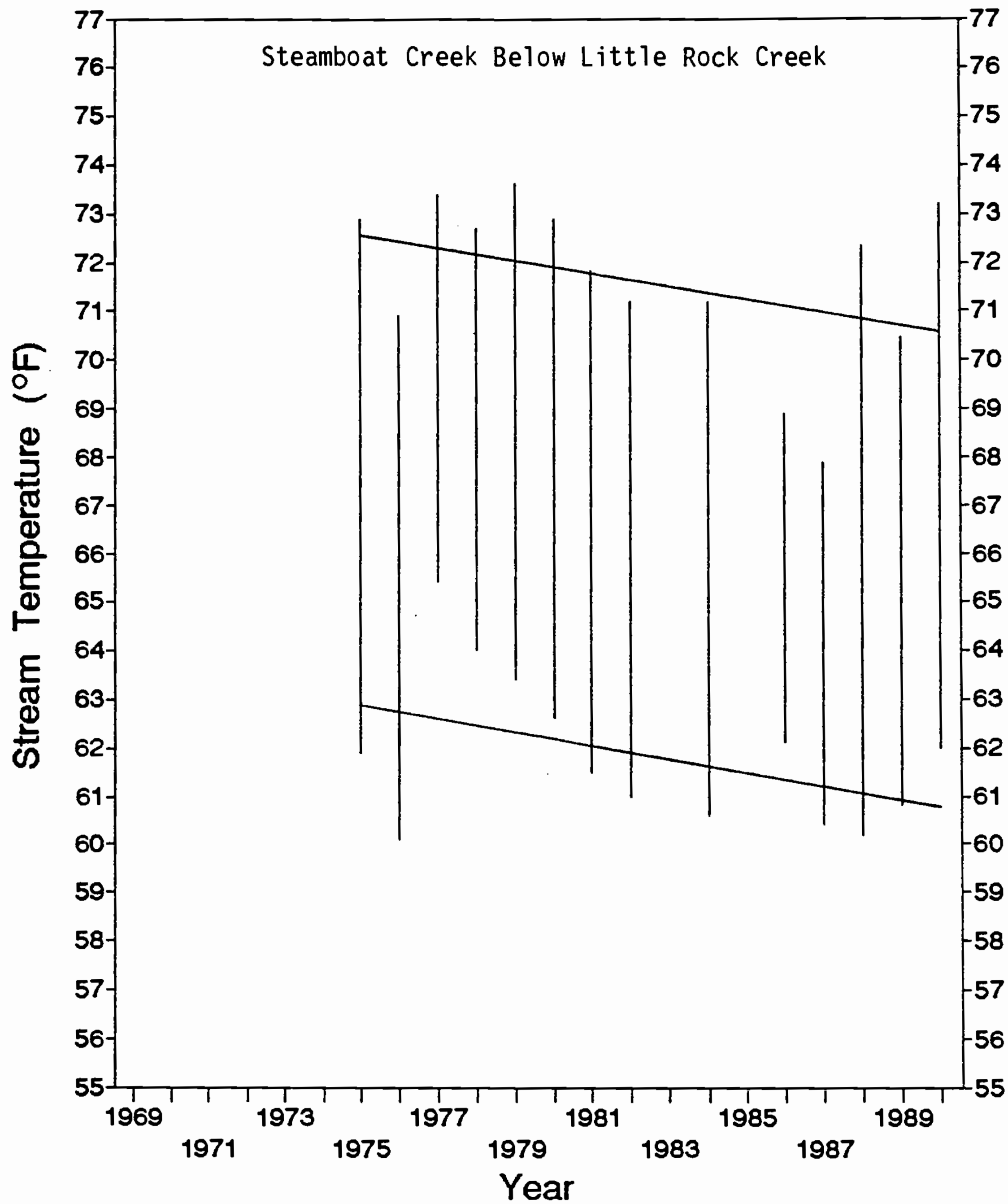

Figure I6. Diurnal fluctuations in daily summer stream temperature over time (1969-90) using the average of the 10 maximum daily stream temperatures each year and the average of the corresponding 10 minimum daily stream temperatures for Steamboat Creek below Little Rock Creek. Regression lines of maximum and minimum daily stream temperatures are shown to illustrate trends.

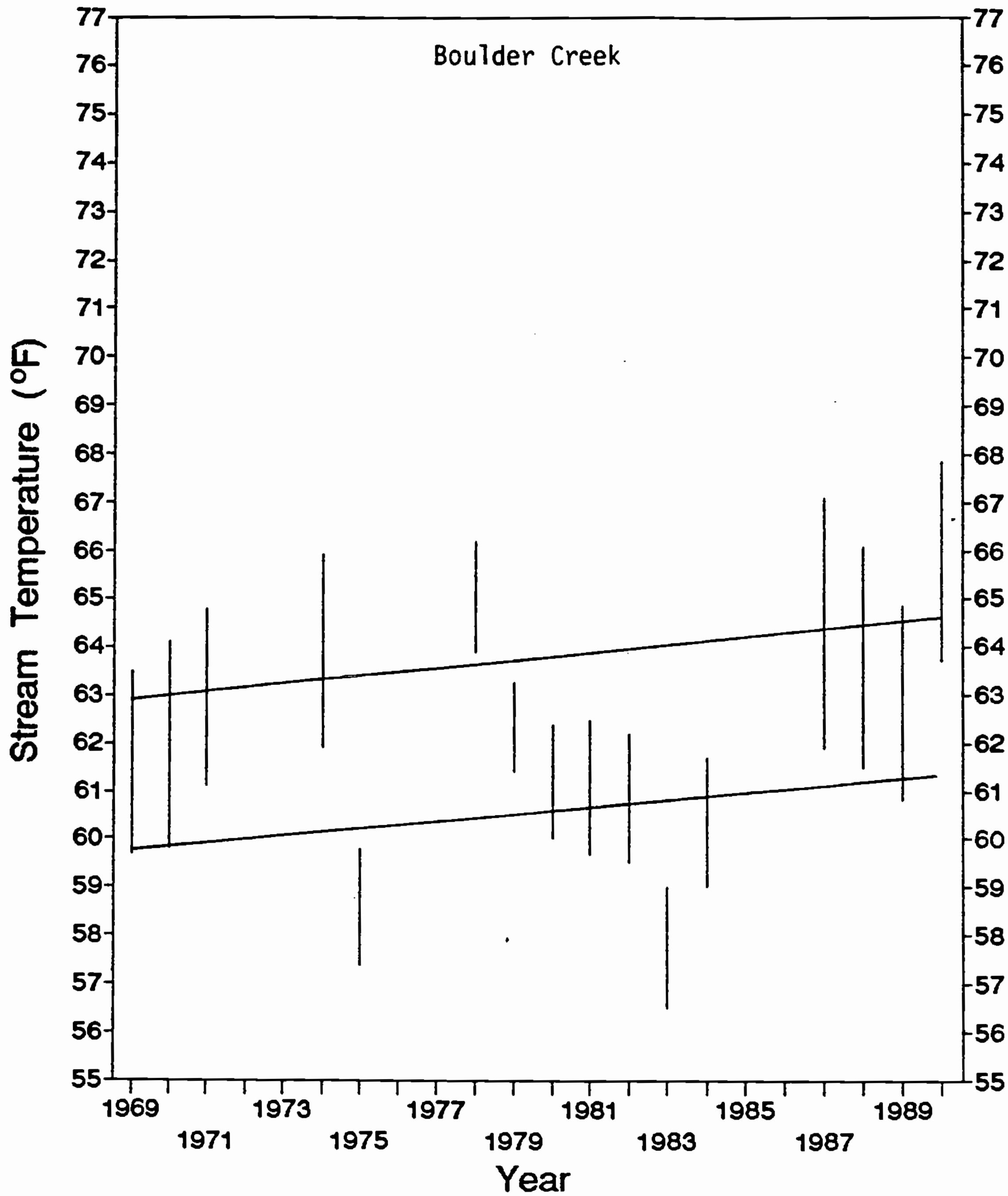

Figure I7. Diurnal fluctuations in daily summer stream temperature over time (1969-90) using the average of the 10 maximum daily stream temperatures each year and the average of the corresponding 10 minimum daily stream temperatures for Boulder Creek. Regression lines of maximum and minimum daily stream temperatures are shown to illustrate trends.