# AN EVALUATION OF WATER TEMPERATURE AND ITS EFFECT ON JUVENILE STEELHEAD TROUT IN GEOTHERMALLY ACTIVE AREAS OF BIG SULPHUR CREEK

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Abstract. A water temperature study in geothermally active areas of Big Sulphur Creek was conducted to evaluate the suitability of habitat for juvenile steelhead trout. Portions of the Big Sulphur Creek drainage have been classified as lethal, marginal, or satisfactory based on a comparison of recorded temperatures and a review of literature concerning the effects of high temperatures on steelhead. Results indicate that stream temperatures in 4.1 miles of Big Sulphur Creek between The Geysers geothermal energy development and Squaw Creek increase to lethal levels during the summer months due to natural geothermal activity and reduced streamflow. Few steelhead have been collected in this area. Stream temperatures in Big Sulphur Creek upstream from natural geothermal activity and in Squaw Creek remain at satisfactory levels through the summer. Numerous steelhead have been collected in these areas and in Big Sulphur Creek downstream from Squaw Creek.

## INTRODUCTION

Big Sulphur Creek, located within The Geysers Known Geothermal Resource Area (KGRA), is a tributary to the Russian River and provides spawning and nursery habitat for steelhead (*Salmo gairdneri*). Fishery investigations in 1974 indicated a low juvenile steelhead population in Big Sulphur Creek from the vicinity of present geothermal energy development at The Geysers to the mouth of Squaw Creek, 4.1 miles downstream (Figure 1). LeGore (1975) reported juvenile steelhead to be "virtually absent" in the 4.1-mile section of stream but "plentiful" upstream and downstream during the spring and summer. Price (1975) found no steelhead in 3.1 miles of stream immediately downstream from the development area but found populations of steelhead upstream and downstream during the fall. Nongame fish populations were also estimated to be lower between the development and Squaw Creek than in other areas of Big Sulphur Creek (Price 1975).

Although it has been postulated that geothermal development may be adversely affecting fish fauna (White 1974, 1975), the natural occurrence of hot springs and steam fumaroles in this area appears to be an important factor

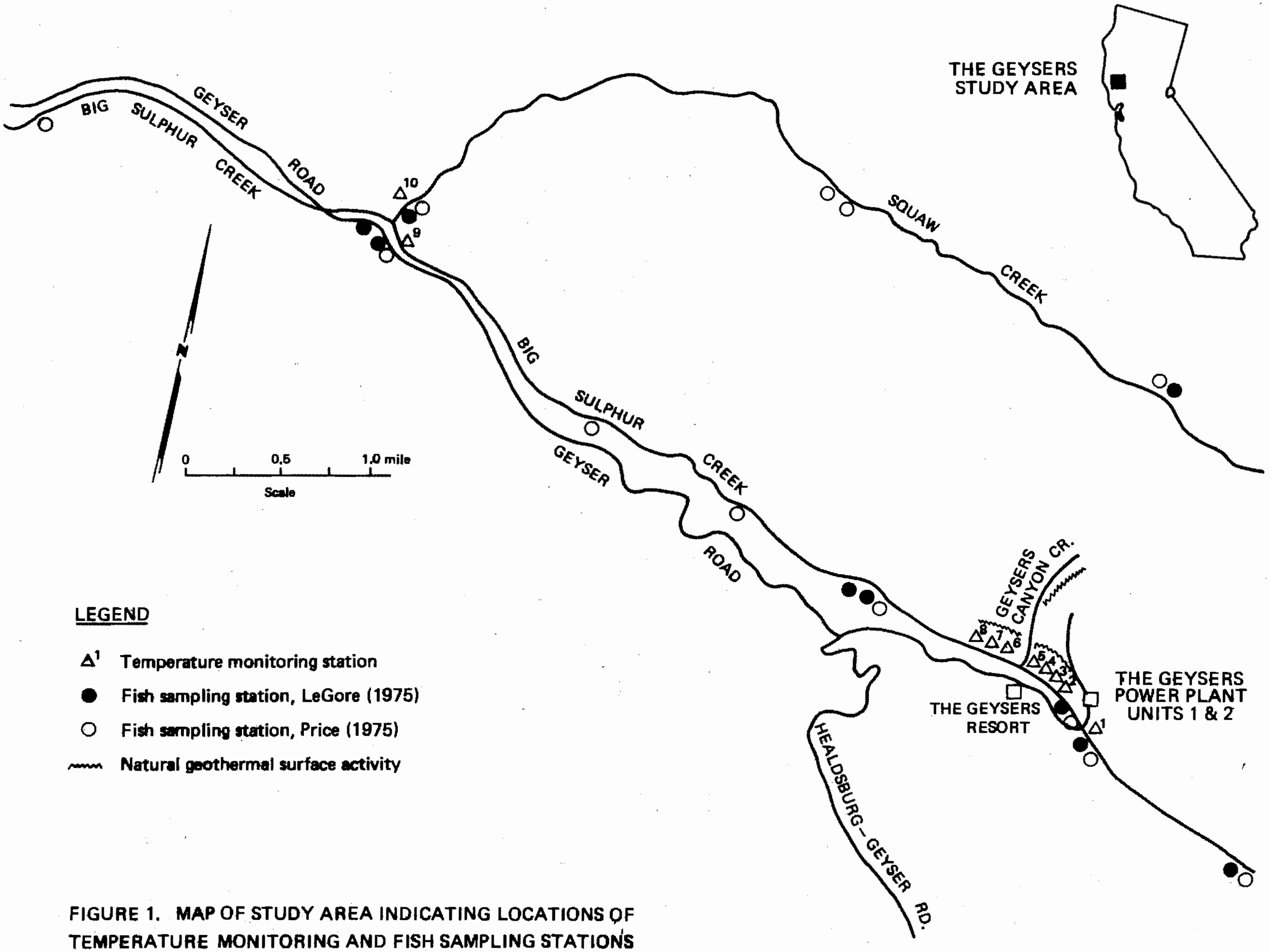


FIGURE 1. MAP OF STUDY AREA INDICATING LOCATIONS OF TEMPERATURE MONITORING AND FISH SAMPLING STATIONS

which may be limiting fish populations. As early as 1924, Allen and Day (1927) documented the occurrence of hot springs and fumaroles in the Big Sulphur Creek streambed as well as in the surrounding Geysers area. More recently, the occurrence and nature of The Geysers steam field, hot springs, and fumaroles have been discussed by McNitt (1963), Moxham (1969), and Ramey (1970). Big Sulphur Creek water temperature is influenced by several natural hot springs discharging warm water into the creek and by natural fumaroles adjacent to the creek which warm the streambed. Warm water is not discharged from steam wells or power plants into Big Sulphur Creek or its tributaries; all condensate is reinjected into the steam field. Although accidental spills of condensate have occurred infrequently, these incidents do not increase water temperature, and due to their short duration, the spills are quickly flushed out of the area.

LeGore (1975) stated that the absence of juvenile steelhead downstream from the geothermal development appears to be due to the natural occurrence of ammonia and natural summer increases in water temperature. Preliminary water quality investigations indicate that ammonia concentrations reach lethal levels during the summer and fall in portions of Big Sulphur Creek downstream from the geothermal development (Griffin and Sharp 1975; LeGore 1975; Price and Griffin 1975).

The thermal requirements of fishes and the limiting effects which temperature may have on fish have been reviewed by numerous researchers (Belding 1928; Brett 1956, 1959, 1970; Jones 1964; Mihursky and Kennedy 1967; Dunham 1968; Lantz 1971; Snyder and Blahm 1971; Sylvester 1972a; Brown 1974). High water temperature may act as a lethal factor and exert limiting effects on the distribution of fish in a stream (Brett 1956). Sublethal effects of high temperature may also exert considerable control on the distribution and success of a species (Dunham 1968).

Because of the great ecological importance of temperature and the absence of juvenile steelhead in Big Sulphur Creek between The Geysers and Squaw Creek, a study was implemented to evaluate the possible thermal influence of natural hot springs, fumaroles, and warm streambeds on steelhead habitat in this area. The objective of the present work is to determine from a water temperature standpoint the suitability of habitat for juvenile steelhead in Big Sulphur Creek between The Geysers development and Squaw Creek during the spring, summer, and fall.

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## METHODS

Nine water temperature monitoring stations were established in Big Sulphur Creek, and one station was established in Squaw Creek (Figure 1). Station 1 was located in Big Sulphur Creek upstream from the geothermal development and the area of visual natural geothermal activity. Stations 2-8 were located in the creek adjacent to areas of visual natural geothermal activity. Station 9 was located in Big Sulphur Creek above its confluence with Squaw Creek, downstream from all visual natural geothermal activity. Station 10 was located in Squaw Creek.

A calibrated Ryan thermograph, capable of recording water temperatures from 0 to 30.0°C continually for 45 days, was placed in the stream at each station on April 29, 1975. Once each month, the thermograph charts were removed and replaced with new ones. A reference water temperature was measured with a laboratory thermometer at each station during thermograph servicing. This measurement was used to check thermograph calibration. The date, time, and reference temperature were recorded on both the old and new thermograph charts. All thermographs were removed on October 22, 1975.

A Hewlett-Packard digitizer and 9830 programmable calculator were used to reduce the thermograph chart data. A program was developed to read out any temperature point on a chart to the nearest 0.01°C and the time duration between any two points on a chart to the nearest $1.0 \times 10^{-9}$ of a day (24-hour period). Daily maximum and minimum temperatures were determined on the digitizer. The temperature readouts were rounded to the nearest 0.5°C. Ryan thermographs are accurate to ±0.5°C with proper calibration.

Total monthly durations of temperatures exceeding 28.0 and 26.5°C (critical temperatures designated in the literature as lethal to steelhead trout) were determined by accumulating daily durations above each of these two temperatures with the digitizer. From duration data, the mean lengths of time in minutes that temperatures exceeded 28.0 and 26.5°C daily were calculated on a monthly basis, considering only those days that had temperatures exceeding 28.0 and 26.5°C.

The total monthly durations of temperatures exceeding 20.0°C (designated in the literature as a temperature above which sublethal effects to steelhead trout may be expected) and the total monthly duration that each thermograph chart operated were determined with the digitizer. From this duration data, the percentage of total recording time that temperatures exceeded 20.0°C was calculated.

Based on a review of the literature concerning the effects of high temperature on steelhead and the temperature data collected in this study (daily maximum temperatures and durations or exposure times of steelhead to high temperatures), each temperature station was classified with respect to its suitability of habitat for juvenile steelhead. Stations reaching a maximum temperature of greater than 28.0°C were classified as lethal and considered to cause total mortality of exposed steelhead. Stations reaching a maximum temperature in the range of 26.5 to 28.0°C were classified as marginal and considered to cause the mortality of at least some of the exposed steelhead. Stations with temperatures that did not reach a maximum of 26.5°C or higher were classified as satisfactory and not considered to directly cause the mortality of steelhead.

## RESULTS

All daily maximum and minimum water temperatures recorded during the study can be obtained from the authors. Table 1 lists by station the maximum temperature recorded each month, and Table 2 presents a monthly classification of stations with respect to their suitability of habitat for juvenile steelhead based on the temperatures listed in Table 1. The number of days during which the maximum temperature was lethal (>28.0°C) or marginal (≥26.5°C but ≤28.0°C) are listed on a monthly basis by station in Tables 3 and 4, respectively. The mean length of time that temperatures exceeded 28.0 and 26.5°C daily are listed on a monthly basis by station in Tables 5 and 6, respectively. The percentages of time that temperatures exceeded 20.0°C are listed on a monthly basis by station in Table 7. Figures 2-11 graphically present daily maximum and minimum temperatures and their relationships with the temperature classification system.

## DISCUSSION

### General Thermal Tolerance Considerations

As previously mentioned, the thermal requirements of various fish species and the limiting effects that temperature may have on a species have been studied in the laboratory by many researchers. Before discussing the effects of high temperature on steelhead, some general definitions and findings of such laboratory studies should be considered.

Brett (1956) stated that the "lethal temperature" is theoretically conceived as that temperature which 50 percent of a population could withstand for an infinite time. At the lethal temperature and beyond, there is a period of tolerance before death known as the "resistance time" (Fry 1947). By virtue of the resistance time, fish are able to tolerate diurnal fluctuations exceeding lethal temperatures (Fry et al., 1946). Between the upper and lower lethal temperatures is found the "preferred temperature" for each species. Fry (1947), defined "preferred temperature" as the temperature range in which a given population will congregate when given the choice of an infinite range of temperatures.

Lethal temperature limits and the preferred temperature of a species can be altered through the process of acclimation to changing environmental temperatures. As the acclimation temperature increases, the lethal and preferred temperatures progressively increase (Brett 1956). This process allows a species to survive over an extended temperature range.

A review of the literature concerning the effects of high temperature on steelhead-rainbow trout shows considerable variation between the results of different researchers. This may be partially due to differences under which laboratory studies were conducted. Brett (1952) stated that the lethal temperatures reported by researchers have been based upon temperature exposures varying from several hours to a week. Additionally, uncontrolled variables such as water chemistry, season, day length, acclimation level, physiological condition, size, age, sex, reproductive condition, nutritional state, and genetic history of test fish may influence the lethal temperature determined in the laboratory (Brown 1974).

## Thermal Tolerance of Steelhead

In light of these definitions and considerations, the temperature tolerance of steelhead-rainbow trout can be discussed. Table 8 summarizes the upper lethal temperatures and preferred temperatures of steelhead that have been reported in the literature. Resistance times at several lethal temperatures are summarized in Table 9. It should be noted that rainbow trout have been observed surviving in temperatures as high as 29.5°C (Embody 1921; Soldwedel 1968); however, the times of exposure to high temperatures were not reported in these studies.

Data presented in Table 9 were used to predict lethality of maximum temperatures recorded at the temperature stations in Big Sulphur and Squaw Creeks. In order to use this table, it was necessary to determine not only the magnitude and duration of lethal temperatures recorded at each station (Tables 1 and 3-6), but also the temperature to which the fish were believed to be acclimated. Alabaster and Downing (1966) reported that the resistance times for trout held at a constant 15.0°C for eight days prior to testing were nearly equivalent to the resistance times of trout held at temperatures fluctuating between 11.0 and 19.0°C on 24- and 48-hour cycles, when tested at 26.5°C. Therefore, it was assumed in the present study that steelhead at any one time were acclimated to a temperature at least as high as the minimum temperature being recorded, and probably near the daily mean tempera ture. This generally corresponded to an acclimation temperature near 20.0° C. Thus, the temperature classification system defined in the methods section of this report was established based on data in Table 9 and data extracted from thermograph charts (Tables 1 and 3-6).

## Sublethal Effects of High Temperatures on Steelhead

Sublethal effects of high temperatures on steelhead include increased metabolic rates and decreased scope for activity (Fry 1947, 1957; Brett 1956, 1959, 1970, 1971; Sylvester 1972a), decreased food utilization and growth rates (Donaldson and Foster 1941; Warren and Davis 1967; Brett 1970, 1971; Lantz 1971; Warren 1971), reduced resistance to disease and parasites (Belding 1928; Wales 1938; Ordal and Pacha 1963; Lantz 1971; Snyder and Blahm 1971; Holt et al., 1975; Udey et al., 1975), increased sensitivity to some toxic materials (Belding 1928; Macek et al., 1969; Lantz 1971; Cairns et al. 1973; MacLeod and Pessah 1973), interference with migration (Smith and Elwell 1961; Dunham 1968; Lantz 1971; Snyder and Blahm 1971), reduced ability to compete with more temperature resistant species (Titcomb 1926; Macan 1961; Dunham 1968; Snyder and Blahm 1971), and reduced ability to avoid predation (Sylvester 1972b; Coutant 1972a, 1972b, 1973).

Although temperatures less than 26.5°C are not assumed to directly cause the mortality of steelhead in the Big Sulphur Creek drainage, temperatures consistently above 20.0°C are assumed to cause sublethal stress. Such stress could result in decreased production and indirect mortality. Snyder and Blahm (1971) reporting on the work of Brett (1959) stated that steelhead can exist at temperatures above 20.0°C, but only at the expense of feeding, growth, maturation, and migration.

A review of the literature indicates that temperatures below 20.0°C are best suited for the success and production of steelhead-rainbow trout. Mantelman (1958), summarizing Russian research, indicated that the range of 12.0 to 20.0°C was most favorable for food consumption and growth of rainbow trout. Schaeperclaus (1933) reported that growth rates were best at temperatures from 15.0 to 20.0°C. Aiken (1971) reported that growth was maximum at 12.0 to 16.0°C for rainbow trout on low fat diets and maximum at 16.0 to 20.0°C for trout on high fat diets. Coche (1967) concluded that, for his stock of juvenile steelhead, temperatures between 20.0 and 24.0°C were responsible for high maintenance requirements and low conversion efficiency of food into growth. Dickson and Kramer (1971) reported that rainbow trout held at 25.0°C refused to feed.

Dickson and Kramer (1971) reported that the scope for activity of hatchery and wild rainbow trout was maximum at 15.0 and 20.0°C, respectively, and slightly less at 25.0°C. However, Fry (1948 cited by Brett 1956) reported that the scope for activity increased throughout the 5.0 to 25.0°C range of temperatures tested. The reported increase in scope for activity at temperatures above 20.0°C may be part of an avoidance or escape mechanism from high temperatures, as suggested by Frank and Meyer (1971).

Table 7, indicating the percentage of time that stream temperatures exceeded 20.0°C at each station, was developed in an attempt to present a comparison of sublethal conditions between the stations in different months. Stations which had temperatures greater than 20.0°C for less than 50 percent of the time in any one month are not expected to cause significant sublethal effects in that month, unless that station reached a marginal or lethal maximum temperature.

All sublethal effects mentioned earlier are assumed to be occurring in the Big Sulphur Creek drainage. One effect in particular, increased sensitivity to toxic materials at increased temperatures, warrants discussion. Lantz (1971) stated that organisms subjected to toxic materials are less tolerant of temperature extremes. The occurrence of ammonia, as well as other compounds with potential toxic effects to fish, in the Big Sulphur Creek drainage has been documented by Price and Griffin (1975), Griffin and Sharp (1975), and LeGore (1975). It appears that ammonia and other toxic materials may be interacting with high temperatures and producing mortality at temperatures lower than would be expected.

## Thermal Conditions and Distribution of Steelhead

Water temperatures in Big Sulphur Creek upstream from visual natural geothermal activity, represented by Station 1, were satisfactory through the spring, summer, and fall (Tables 1 and 2). From a water temperature standpoint, this section of stream is suitable as a nursery area for juvenile steelhead throughout the year.

Stream temperatures immediately increase to lethal and marginal levels during the summer months as the stream flows through the area of natural geothermal activity, as represented by Stations 2-8 (Tables 1 and 2). During the summer, temperatures appear to remain at lethal and marginal levels through the entire 4.1 miles of stream below The Geysers, as indicated by temperatures recorded at Station 9. The fact that no lethal temperatures were recorded at Station 3 indicates that other portions of this 4.1-mile stream section may also reach only marginal levels. However, it is unlikely that steelhead could exist in such marginal areas in midsummer due to the large number of days that marginal temperatures were recorded at Station 3 (Table 4).

In this 4.1-mile stream section, satisfactory temperatures occur from fall through late spring. Marginal temperatures were not recorded until May 29 or 30 at Stations 6-9, and mid-June at Stations 2, 4, and 5. Temperatures returned to satisfactory levels near the end of August or beginning of September at all stations except at Station 8, where a marginal temperature was recorded as late as September 24. Thus, from a temperature standpoint, this section of stream is suitable as a steelhead nursery area only from fall through spring.

Water temperature in Squaw Creek, represented by Station 10, were satisfactory except in July when three days of marginal temperatures were recorded. However, the magnitude and duration of these marginal temperatures (Tables 1 and 6) were not believed to be sufficient enough to cause significant mortality. Thus, it appears that from a water temperature standpoint Squaw Creek provides suitable nursery habitat for juvenile steelhead throughout the year.

The temperature classifications applied to the Big Sulphur Creek drainage coincide with the results of the recent fishery investigations of LeGore (1975) and Price (1975). During those studies, healthy populations of juvenile steelhead were found in areas designated as satisfactory in the present work. Generally, limited numbers of steelhead were found in marginal areas, and no steelhead occurred in lethal areas. In the spring, summer, and fall of 1974, juvenile steelhead were collected in Big Sulphur Creek upstream from The Geysers development, downstream from the confluence of Big Sulphur and Squaw Creeks, and in Squaw Creek (LeGore, 1975; Price, 1975).

In the 4.1 miles of Big Sulphur Creek between The Geysers and Squaw Creek, steelhead populations appear to vary with seasonal changes in water temperature. Temperature data collected in the present study indicated that temperatures in the spring are satisfactory for steelhead. LeGore (1975) documented steelhead inhabiting this stream section in May 1974, although the number of steelhead collected was small relative to numbers collected upstream and downstream.

In June and July, temperatures reach marginal and lethal levels in the 4.1-mile stream section below The Geysers, and the habitat becomes unsuitable to juvenile steelhead. In June 1974, LeGore (1975) found no steelhead inhabiting this area. In July 1974, he collected juvenile steelhead only at the station located immediately upstream from Squaw Creek.

Apparently as temperatures increase to marginal and lethal levels, steelhead inhabiting this stream section must either move to cooler waters or succumb to high temperatures. During the present study, several dead juvenile steelhead were collected in this area during midsummer. A limited number of steelhead may be able to survive within this stream section during the summer by seeking inflow from cool-water springs that may exist. Two explanations for the occurrence of steelhead immediately upstream from Squaw Creek in July (LeGore 1975) can be presented. First, a cool-water spring may exist and supply suitable habitat for a limited number of steelhead. Secondly, steelhead surviving the summer in the cooler waters of Squaw Creek and Big Sulphur Creek downstream from Squaw Creek may move upstream and utilize the lethal area of Big Sulphur Creek on days when temperatures do not reach marginal and lethal levels.

It appears that, when water temperatures decrease to satisfactory levels during the fall in the 4.1-mile stream section below The Geysers, steelhead are able to reinhabit this area. In October 1974, Price (1975) found no steelhead in the first 3.1 miles of stream below The Geysers but estimated a population of 739 juvenile steelhead in the mile of stream above Squaw Creek. Apparently these fish moved upstream from summer nursery areas in Squaw and Big Sulphur Creeks, as temperatures once again became satisfactory in the fall.

## Factors Affecting Stream Temperature

Big Sulphur Creek downstream from The Geysers Units 1 and 2 receives natural heat input from hot springs, steam fumaroles, and warm streambeds. The locations of greatest heat input extend along the north bank of Big Sulphur Creek for several hundred feet on either side of Geyser Canyon Creek, the location of Stations 2-8, and are documented by Allen and Day (1927), McNitt (1963), and Moxham (1969). In this area, springs discharge warm water into the creek, and streamside steam fumaroles and thermal surface activity heat the banks and streambed.

The magnitude of spring temperatures and the discharge from hot springs that have been measured and estimated by Allen and Day (1927), McNitt (1963), and LeGore (1975), and instantaneous streamflow measurements made at several locations in Big Sulphur Creek as part of the present study (Table 10) indicate that hot springs alone do not represent the significant heat input factor. It appears that steam fumaroles and other streamside surface thermal activity significantly heat the streambed and, in turn, the waters of Big Sulphur Creek.

The heat input from natural geothermal activity occurs year-round; however, its effect on stream temperatures and aquatic life becomes significant only during the summer months. As streamflows in Big Sulphur Creek drastically decrease in the spring and summer (Table 11), geothermal heat input has a greater effect on stream temperatures. Reduced flows result in a greater exposure of each mass of water to the heated substrate, due to both a slower travel time and a greater surface to volume ratio. This resulting greater influence of geothermal heat input at low flows, combined with increased solar radiation striking the water surface and warmer air temperatures during the summer months, creates conditions favorable to the attainment of lethal maximum water temperatures. The water of Big Sulphur Creek receives its initial boost in temperature from geothermal heat input as it flows through the geothermally active area at The Geysers. Stream temperatures generally remain elevated for 4.1 miles downstream to Squaw Creek due to the high exposure of the stream to solar radiation through this stream section.

Although flows remain low during the fall, decreased solar radiation and air temperatures partially compensate for the geothermal heat input, and water temperatures decrease to satisfactory levels. During the winter, flows increase greatly (Table 11) and provide further compensation.

## CONCLUSIONS

Big Sulphur Creek is a unique coastal steelhead stream. During the winter when stream temperatures and water quality are satisfactory throughout the length of the stream, adult steelhead are able to move upstream into and through the geothermally affected section. Adult steelhead are able to spawn above and possibly within this area (although this is unknown). The adult steelhead then return to the Russian River and eventually the ocean before Big Sulphur Creek temperatures reach marginal or lethal levels and before ammonia levels become toxic. The young steelhead which hatch within the geothermally active stream section or drift downstream into it are able to survive here until marginal and lethal temperatures begin to occur in late May or by the middle of June. At that time, in order to avoid death, the juveniles must seek the cooler, fresher waters of upstream areas, downstream areas, Squaw Creek, or cool springs. As temperatures decrease in fall, juvenile steelhead can once again utilize the areas of satisfactory water quality in the section of stream between The Geysers and Squaw Creek.

The same unique situation on a smaller scale has been discovered in one other stream in The Geysers KGRA (Price and Kubicek, 1976, unpublished). Sulphur Creek, a tributary to Kelsey Creek which drains into Clear Lake approximately 17 miles to the north, receives significant inflow from a hot sulfur spring. In early summer, no fish were found inhabiting the stream for several hundred feet below the spring, although rainbow trout were collected upstream and downstream. Conditions immediately downstream from the spring were unsuitable from water temperature and water quality standpoints. Apparently, rainbow trout from Kelsey Creek and lower Sulphur Creek move upstream past the sulfur spring at high flows during the winter to spawn. By midsummer, Sulphur Creek upstream from the spring becomes dry, and the trout must migrate out or die.

Steelhead management practices in Big Sulphur Creek have included the attempted chemical control of nongame fish species to improve steelhead habitat (Pintler and Johnson 1958). Beneficial results from such attempts were short-lived. Recent studies have shown that portions of Big Sulphur Creek are unsuitable as habitat for steelhead from a water quality standpoint (Griffin and Sharp 1975; LeGore 1975; Price and Griffin 1975) and, in the present study, from a water temperature standpoint. These findings should be considered in evaluating future steelhead management programs in the Big Sulphur Creek drainage.

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Table 1. Monthly maximum water temperatures (°C) recorded at stations in the Big Sulphur Creek drainage in 1975.

| Station | April-May | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 1 | 23.5 | 25.5 | 25.5 | 25.5 | 21.0 | 17.5 |
| 2 | 25.0 | 26.5 | 30.0* | 30.0 | 26.0 | 20.5 |
| 3 | 24.5 | 25.5 | 28.0 | 26.5 | 24.0 | 19.5 |
| 4 | 25.0 | 27.0 | 30.0* | 30.0 | 26.5 | 22.0 |
| 5 | 24.5 | 26.5[a] | 29.5[a] | 29.5[a] | 26.0 | 21.0 |
| 6 | 26.5 | 28.0 | 30.0* | 29.5 | 27.0 | 22.5 |
| 7 | 27.0 | 29.0 | 30.0* | 29.5 | 27.5 | 23.0 |
| 8 | 27.5 | 29.5 | 30.0* | 29.5 | 28.5 | 23.0 |
| 9 | 27.0 | 29.0 | 30.0 | 29.0 | 25.5 | 18.0 |
| 10 | 24.5 | 25.0 | 26.5 | 26.0 | 24.0 | 20.5 |

[a]Estimated value based on the maximum temperature recorded during each of the two time periods: June 7 to July 9 and July 10 to August 13.

*Maximum temperature was >30.0°C.

Table 2. Monthly classification of water temperature stations in the Big Sulphur Creek drainage with respect to their suitability of habitat for juvenile steelhead in 1975.[a]

| Station | April-May | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 1 | S | S | S | S | S | S |
| 2 | S | M | L | L | S | S |
| 3 | S | S | M | M | S | S |
| 4 | S | M | L | L | M | S |
| 5 | S | M | L | L | S | S |
| 6 | M | M | L | L | M | S |
| 7 | M | L | L | L | M | S |
| 8 | M | L | L | L | L | S |
| 9 | M | L | L | L | S | S |
| 10 | S | S | M | S | S | S |

[a]S = Satisfactory (maximum temperature <26.5°C)
M = Marginal (maximum temperature ≥26.5°C but ≤28.0°C)
L = Lethal (maximum temperature >28.0°C)

Table 3. Total number of days during which the maximum water temperature was >28.0°C (lethal classification)/and total number of days temperatures were recorded, by station and month in the Big Sulphur Creek drainage in 1975.

| Station | April-May | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 1 | 0/33 | 0/30 | 0/31 | 0/26 | 0/21 | 0/6 |
| 2 | 0/33 | 0/28 | 12/31 | 11/31 | 0/30 | 0/5 |
| 3 | 0/33 | 0/13 | 0/23 | 0/31 | 0/30 | 0/20 |
| 4 | 0/33 | 0/30 | 10/31 | 10/30 | 0/30 | 0/21 |
| 5 | 0/33 | 0/6[a] | 0/0[b] | 0/18[b] | 0/30 | 0/9 |
| 6 | 0/33 | 0/6[c] | 16/23 | 3/20 | 0/30 | 0/20 |
| 7 | 0/33 | 1/30 | 16/31 | 11/31 | 0/26 | 0/16 |
| 8 | 0/33 | 3/30 | 14/23 | 7/18 | 1/30 | 0/21 |
| 9 | 0/33 | 1/30 | 10/31 | 2/31 | 0/30 | 0/4 |
| 10 | 0/33 | 0/30 | 0/31 | 0/31 | 0/30 | 0/21 |

[a]Although daily maximum temperatures could not be determined, the maximum for the time period, June 7 to July 9, was recorded as marginal.

[b]Although daily maximum temperatures could not be determined, the maximum for the time period, July 10 to August 13, was recorded as lethal.

[c]Although daily maximum temperatures could not be determined, the maximum for the time period, June 7 to July 8, was recored as marginal.

Table 4. Total number of days during which the maximum temperature was ≥26.5°C but ≤28.0°C (marginal classification)/and total number of days temperatures were recorded, by station and month in the Big Sulphur Creek drainage in 1975.

| Station | April-May | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 1 | 0/33 | 0/30 | 0/31 | 0/26 | 0/21 | 0/6 |
| 2 | 0/33 | 2/28 | 10/31* | 6/31* | 0/30 | 0/5 |
| 3 | 0/33 | 0/13 | 6/23 | 2/31 | 0/30 | 0/20 |
| 4 | 0/33 | 2/30 | 13/31* | 11/30* | 1/30 | 0/21 |
| 5 | 0/33 | 0/6[a] | 0/0[b]* | 6/18[b]* | 0/30 | 0/9 |
| 6 | 1/33 | 2/6[c] | 5/23* | 6/20* | 4/30 | 0/20 |
| 7 | 1/33 | 17/30* | 9/31* | 11/31* | 3/26 | 0/16 |
| 8 | 3/33 | 17/30* | 5/23* | 3/18* | 7/30* | 0/21 |
| 9 | 2/33 | 11/30* | 13/31* | 10/31* | 0/30 | 0/4 |
| 10 | 0/33 | 0/30 | 3/31 | 0/31 | 0/30 | 0/21 |

[a]Although daily maximum temperatures could not be determined, the maximum for the time period, June 7 to July 9, was recorded as marginal.

[b]Although daily maximum temperatures could not be determined, the maximum for the time period, July 10 to August 13, was recorded as lethal.

[c]Although daily maximum temperatures could not be determined, the maximum for the time period, June 7 to July 8, was recorded as marginal.

*Lethal maximums were also recorded.

Table 5. Mean daily length of time in minutes that water temperatures were >28.0°C, by station and month in the Big Sulphur Creek drainage in 1975.

| Station | April-May | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 263 | 263 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 339 | 340 | 0 | 0 |
| 5 | 0 | 0 | -[a] | -[a] | 0 | 0 |
| 6 | 0 | 0 | 391 | 302 | 0 | 0 |
| 7 | 0 | 197 | 385 | 372 | 0 | 0 |
| 8 | 0 | 243 | 351 | 285 | 221 | 0 |
| 9 | 0 | 395 | 321 | 302 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 |

[a]Lethal maximums were recorded, but the duration could not be determined.

Table 6. Mean daily length of time in minutes that water temperatures were >26.5°C, by station and month in the Big Sulphur Creek drainage in 1975.

| Station | April-May | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 116 | 372* | 432* | 0 | 0 |
| 3 | 0 | 0 | 302 | 186 | 0 | 0 |
| 4 | 0 | 302 | 430* | 399* | 163 | 0 |
| 5 | 0 | -[a] | -[a]* | 255* | 0 | 0 |
| 6 | 163 | 232 | 547* | 328* | 116 | 0 |
| 7 | 209 | 229* | 491* | 435* | 291 | 0 |
| 8 | 186 | 347* | 516* | 427* | 305* | 0 |
| 9 | 279 | 344* | 392* | 389* | 0 | 0 |
| 10 | 0 | 0 | 81 | 0 | 0 | 0 |

*Indicates that temperatures above 28.0°C (lethal classification) were recorded, and thus, the times include durations of both marginal and lethal maximums.

[a]Marginal maximums were recorded, but the duration could not be determined.

Table 7. Percentage of time that water temperatures were >20.0°C at stations in the Big Sulphur Creek drainage in 1975.

| Station | April-May | June | July | August | September | October |
|---|---|---|---|---|---|---|
| 1 | 11.1 | 46.1 | 52.2 | 48.3 | 4.1 | 0 |
| 2 | 12.7 | 59.1M | 88.4L | 80.8L | 47.6 | 17.3 |
| 3 | 13.0 | 61.9 | 79.4M | 54.4M | 34.7 | 0 |
| 4 | 17.4 | 72.6M | 92.2L | 92.3L | 73.2M | 10.0 |
| 5 | 12.5 | 53.6M | -L[a] | 74.6L | 59.9 | 20.1 |
| 6 | 23.9M | 70.3M | 100.0L | 92.5L | 83.5M | 14.4 |
| 7 | 25.4M | 80.8L | 93.9L | 96.8L | 93.1M | 24.0 |
| 8 | 32.4M | 90.6L | 95.2L | 98.6L | 87.2L | 12.7 |
| 9 | 29.3M | 75.9L | 88.4L | 74.8L | 34.5 | 0 |
| 10 | 10.4 | 29.5 | 40.1M | 42.5 | 28.5 | 0.7 |

M - Marginal temperatures were recorded.
L - Lethal temperatures were recorded.
a - The duration could not be determined.

Table 8. Upper lethal and preferred temperatures of steelhead-rainbow trout, *Salmo gairdneri* (see text for definition of terms).

| Factor | Acclimation Temperature (°C) | Temperature (°C) | Length of Test (hrs.) | Reference |
|---|---|---|---|---|
| Upper lethal temperature | 11.0 | 24.0 | 24 | Black (1953) |
| | 12.0 | 23.5 | - | Threinen (1958) |
| | 12.0 | 24.92 | 24 | Charlon et al. (1970) |
| | 14.0 | 25.22 | 24 | Charlon et al. (1970) |
| | 16.0 | 25.41 | 24 | Charlon et al. (1970) |
| | 18.0 | 25.31 | 24 | Charlon et al. (1970) |
| | 20.0 | 25.82 | 24 | Charlon et al. (1970) |
| | 24.0 | 26.35 | 24 | Charlon et al. (1970) |
| | 15.0 | 25.3 | 16.5 | Alabaster (1962) cited by Charlon et al. (1970) |
| | 20.0 | 26.6 | 16.5 | Alabaster (1962) cited by Charlon et al. (1970) |
| | 15.0 | 25.0-26.0 | - | Bidgood and Berst (1969) |
| | - | 23.5-26.5 | - | Angelovic et al. (1961) |
| | - | 24.0-29.0 | - | McAfee (1966) |
| Preferred temperature | 10.0 | 15.0-17.0 | | Javaid and Anderson (1967) |
| | 15.0 | 17.0-19.0 | | Javaid and Anderson (1967) |
| | 20.0 | 21.0-23.0 | | Javaid and Anderson (1967) |
| | 10.0 | 15.0 | | Garside and Tait (1958) |
| | 15.0 | 13.0 | | Garside and Tait (1958) |
| | 20.0 | 11.0-12.0 | | Garside and Tait (1958) |
| | 18.0 | 17.0-20.0 | | McCauley and Pond (1971) |
| | 14.0-18.0 | 13.0-19.0 | | Mantelman (1958) |
| | - | <21.0 | | McAfee (1966) |
| | 12.0 | 14.4 | | Cherry et al. (1975) |
| | 15.0 | 16.9 | | Cherry et al. (1975) |
| | 18.0 | 18.1 | | Cherry et al. (1975) |
| | 21.0 | 20.1 | | Cherry et al. (1975) |
| | 24.0 | 22.0 | | Cherry et al. (1975) |

Table 9. Resistance times in minutes for steelhead-rainbow trout, *Salmo gairdneri*.

| Life Stage | Acclimation Temperature (°C) | Test Temperature (°C) 31.0 | 30.5 | 30.0 | 29.5 | 29.0 | 28.5 | 28.0 | 27.5 | 27.0 | 26.5 | 26.0 | 25.5 | 25.0 | 24.0 | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Juvenile | 18.0 | - | - | - | 20 | 50 | - | 100 | - | 300 | 3000 | - | - | - | - | Alabaster and Welcomme (1962)[a] |
| Juvenile | 15.0 | - | - | - | - | - | - | - | 100 | | - | - | 1000 | - | - | Alabaster and Downing (1966)[a] |
| Juvenile | 20.0 | - | - | - | - | - | - | 100 | - | - | 1000 | - | - | - | - | Alabaster and Downing (1966)[a] |
| Juvenile | 15.0 | - | - | - | - | - | - | 24 | - | 75 | - | - | - | - | - | Ebel et al. (1971)[a] |
| Juvenile | 15.0 | 6 | 16 | - | 32 | 50 | - | 75 | 108 | 158 | 333 | - | - | - | - | Coutant and Dean (1972)[b] |
| Juvenile | 15.0 | - | - | 5 | - | 15 | - | 30 | - | 100 | - | 250 | - | - | - | Becker (1973) |
| Juvenile | 15.0 | - | - | <10 | - | - | - | - | - | - | - | - | - | >5760 | - | Bidgood and Berst (1969) |
| Yearling | 20.0 | - | - | - | - | 54 | - | 104 | - | 423 | - | - | - | - | - | Craigie (1963)[a,c] |
| Yearling | 20.0 | - | - | - | - | 70 | - | 158 | - | 572 | - | - | - | - | - | Craigie (1963)[a,d] |
| Yearling | 20.0 | - | - | - | - | 42 | - | 83 | - | 363 | - | - | - | - | - | Craigie (1963)[a,e] |
| Yearling | 20.0 | - | - | - | - | 61 | - | 112 | - | 357 | - | - | - | - | - | Craigie (1963)[a,f] |
| Adult | 16.0-19.5 | - | - | - | - | 30 | - | 40 | - | 68 | - | 175 | - | - | 1500 | Coutant (1970)[b] |

[a] Median resistance times.
[b] Geometric mean resistance times.
[c] Fish reared in soft water, tested in soft water.
[d] Fish reared in soft water, tested in hard water.
[e] Fish reared in hard water, tested in soft water.
[f] Fish reared in hard water, tested in hard water.

Table 10. Instantaneous flow measurements made at several locations in the Big Sulphur Creek drainage on December 11, 1975.

| Location | Flow (cfs) |
|---|---|
| Big Sulphur Creek, Temperature Station 1 | 5.93 |
| Big Sulphur Creek, Temperature Station 8 | 6.58 |
| Big Sulphur Creek, Temperature Station 9 | 7.64 |
| Squaw Creek, Temperature Station 10 | 3.06 |
| Big Sulphur Creek below confluence with Squaw Creek | 10.82 |

Table 11. Average stream flow in Big Sulphur Creek, approximately 7.5 miles downstream from its confluence with Squaw Creek, 1960-1971 (from Pacific Gas and Electric Company, 1974).

| | | | | | |
|---|---|---|---|---|---|
| January | 687.9 cfs | May | 63.1 | September | 4.9 cfs |
| February | 501.5 cfs | June | 26.6 | October | 32.4 cfs |
| March | 278.1 cfs | July | 9.9 | November | 128.7 cfs |
| April | 213.4 cfs | August | 6.3 | December | 414.7 cfs |

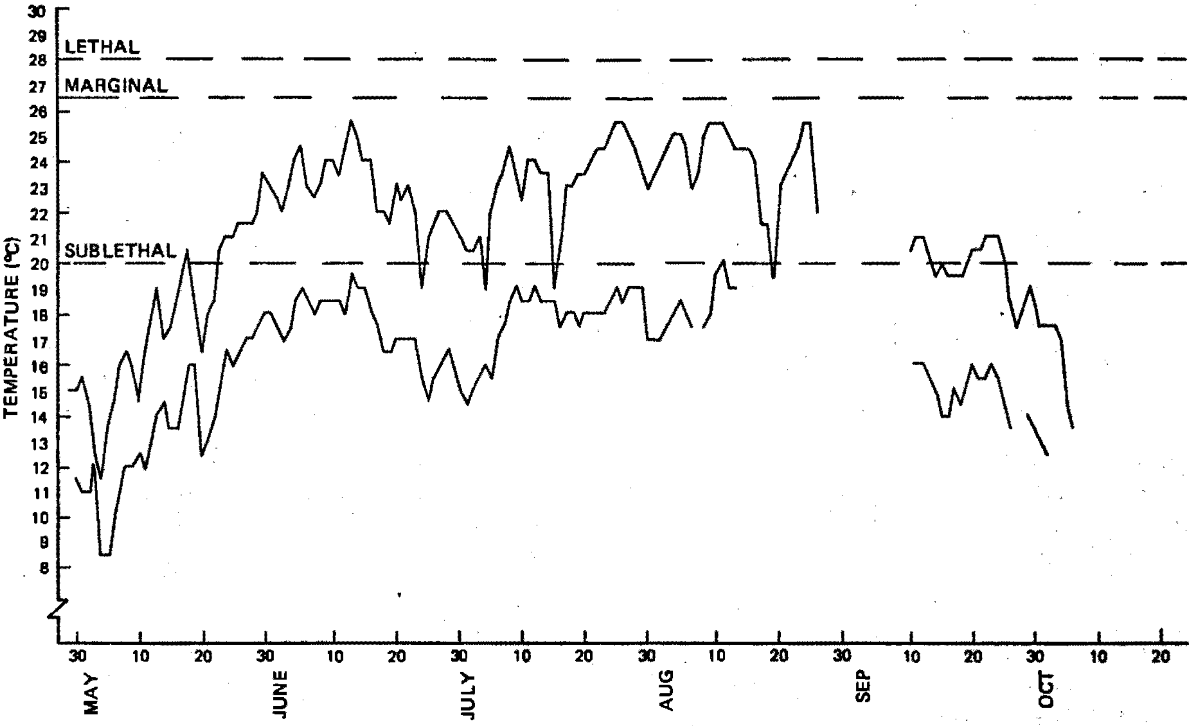


FIGURE 2. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 1 IN BIG SULPHUR CREEK

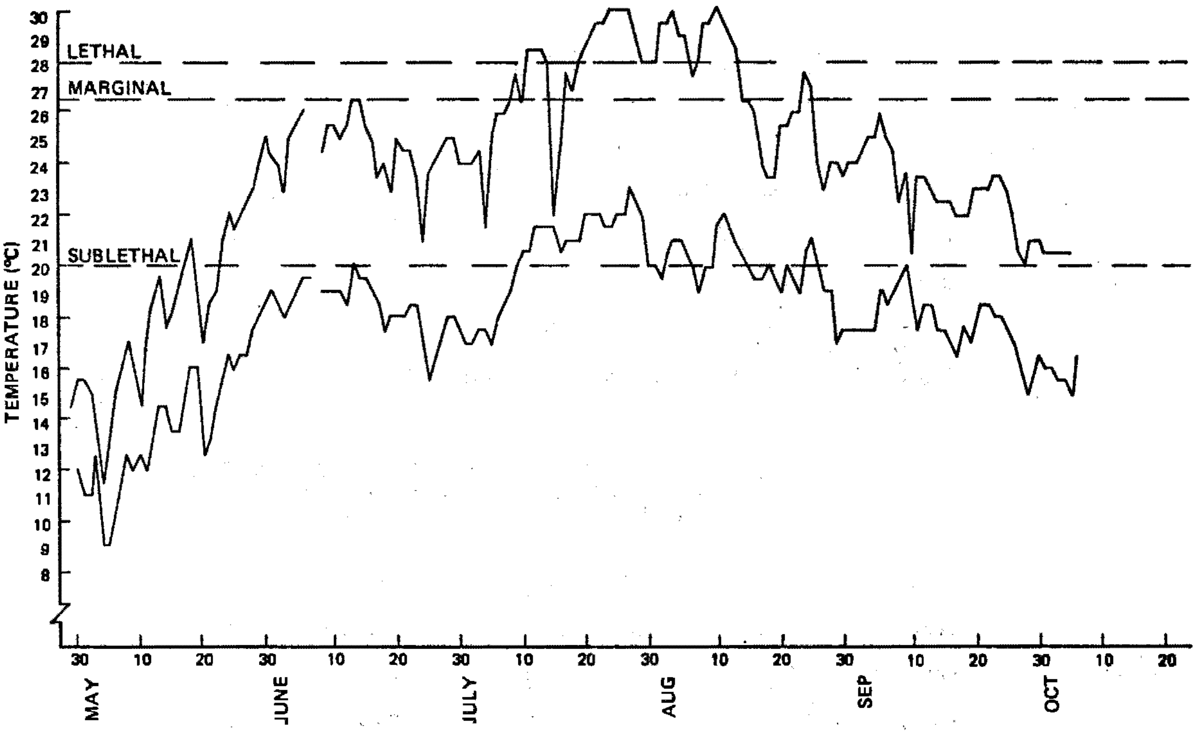


FIGURE 3. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 2 IN BIG SULPHUR CREEK

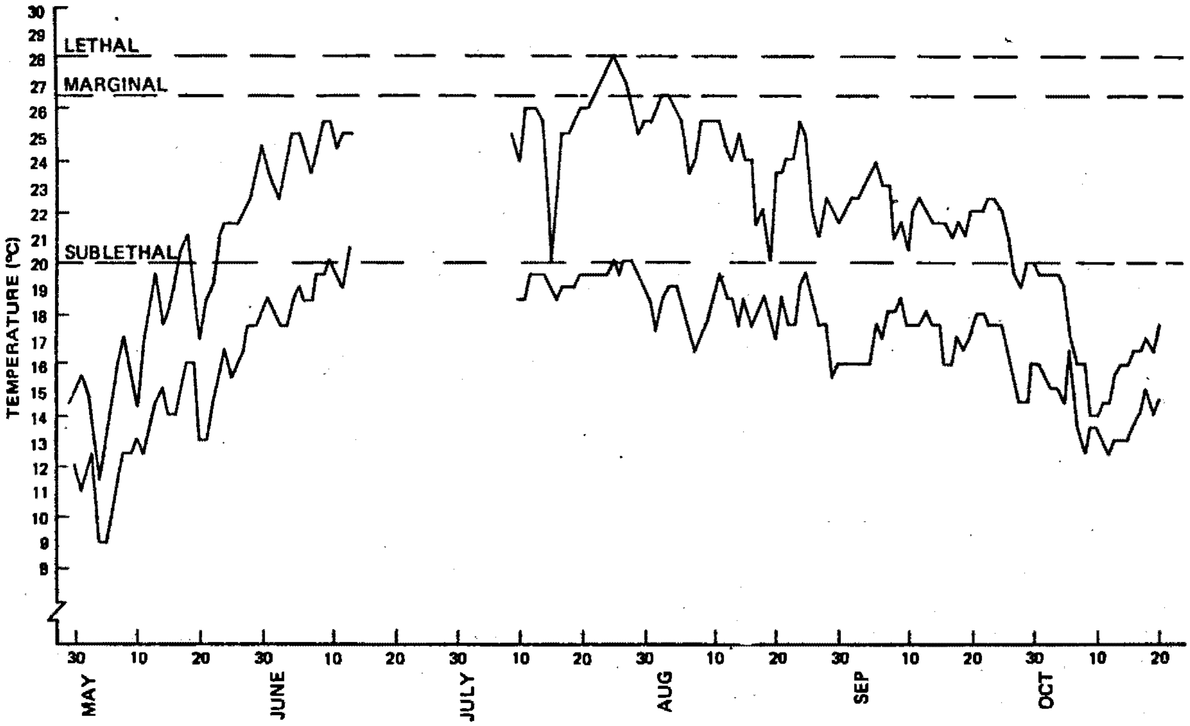


FIGURE 4. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 3 IN BIG SULPHUR CREEK

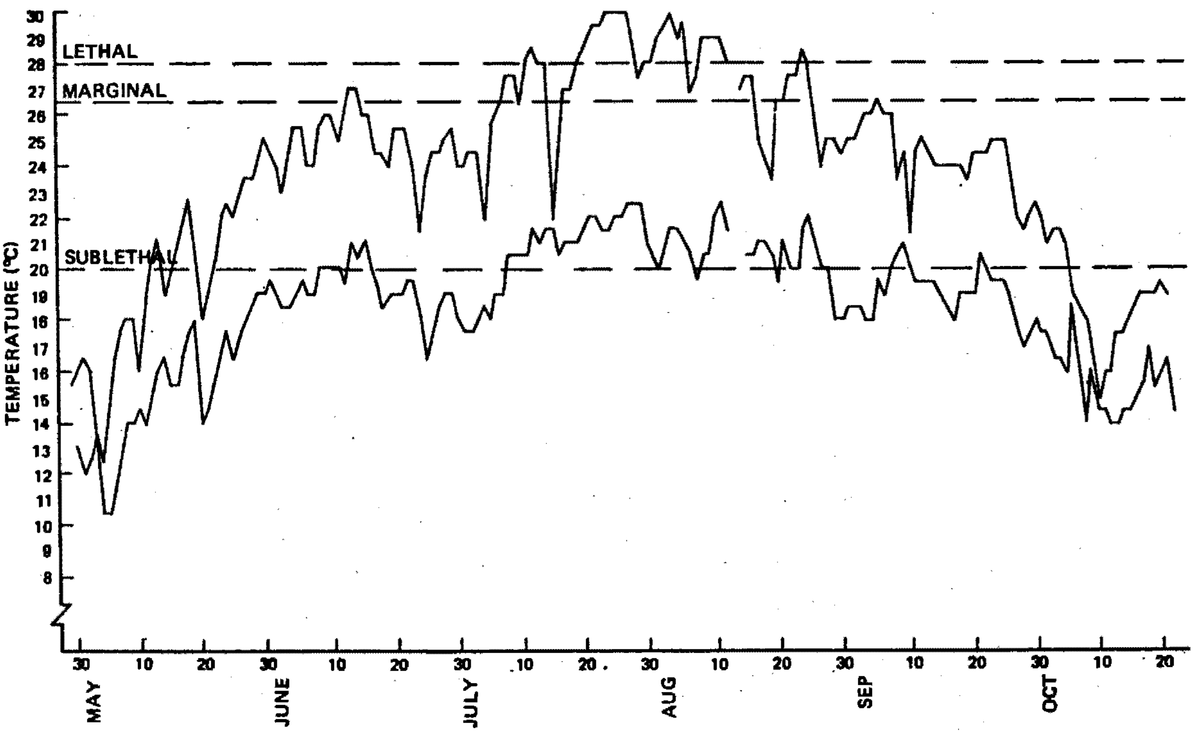


FIGURE 5. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 4 IN BIG SULPHUR CREEK

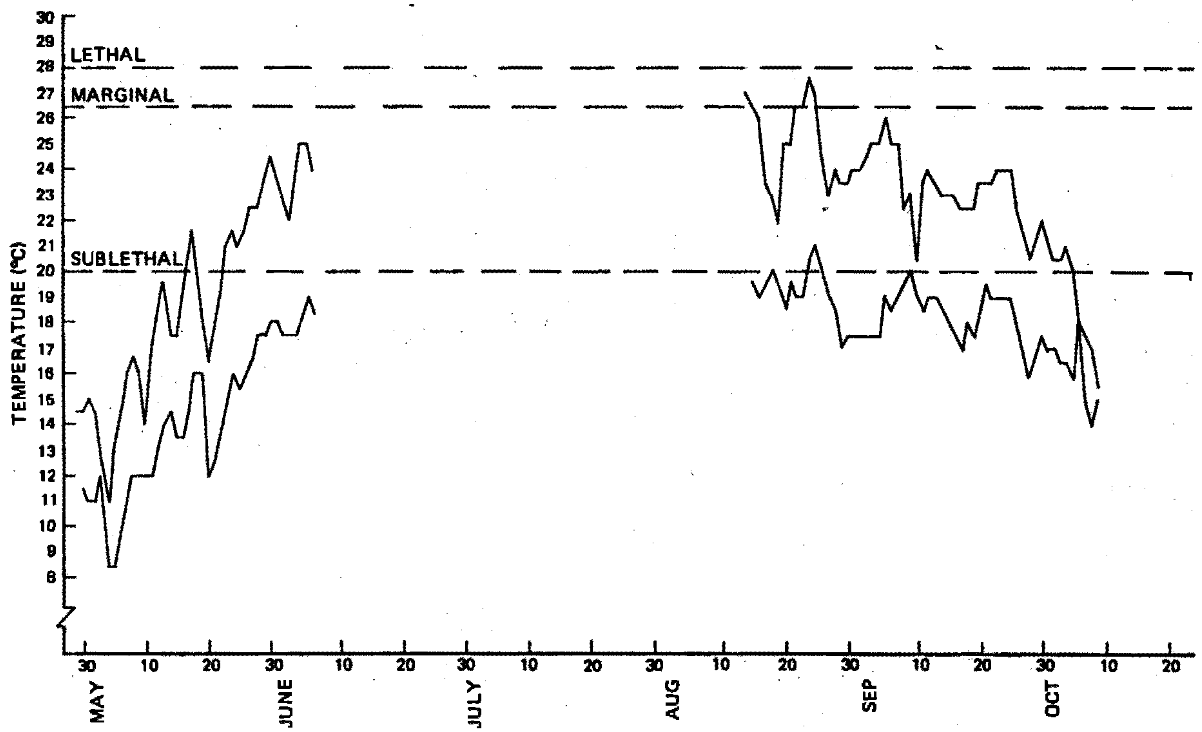


FIGURE 6. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 5 IN BIG SULPHUR CREEK

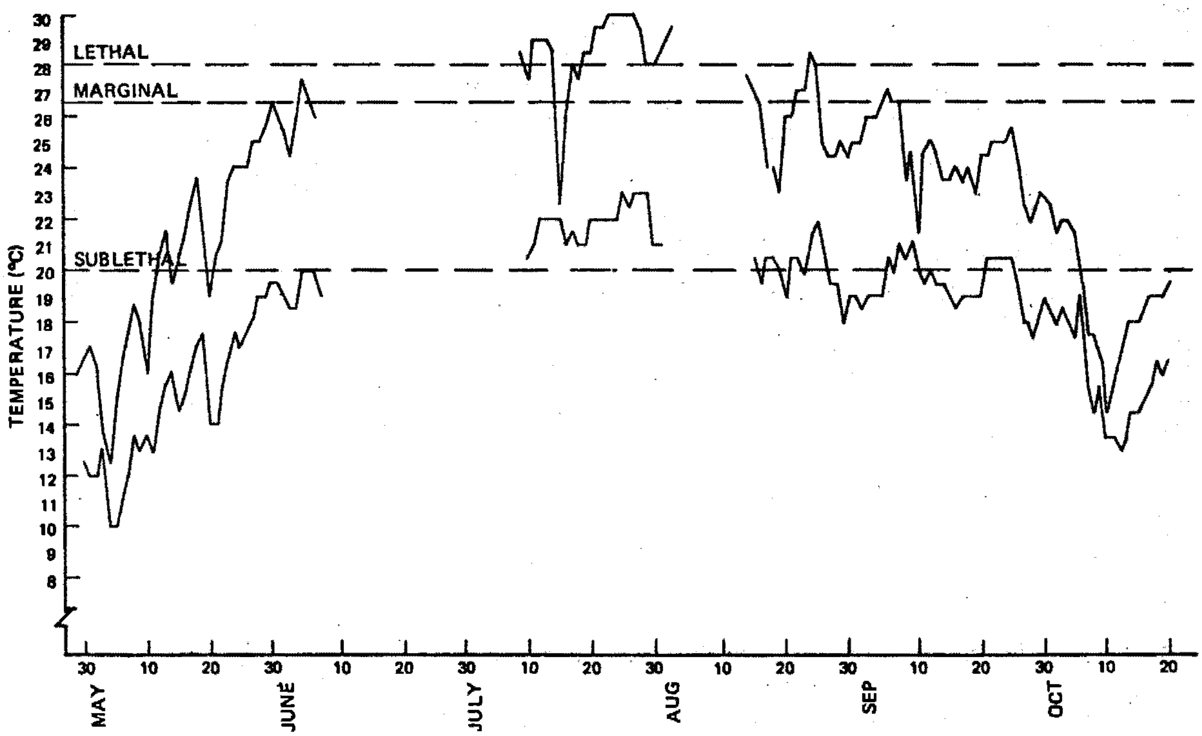


FIGURE 7. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 6 IN BIG SULPHUR CREEK

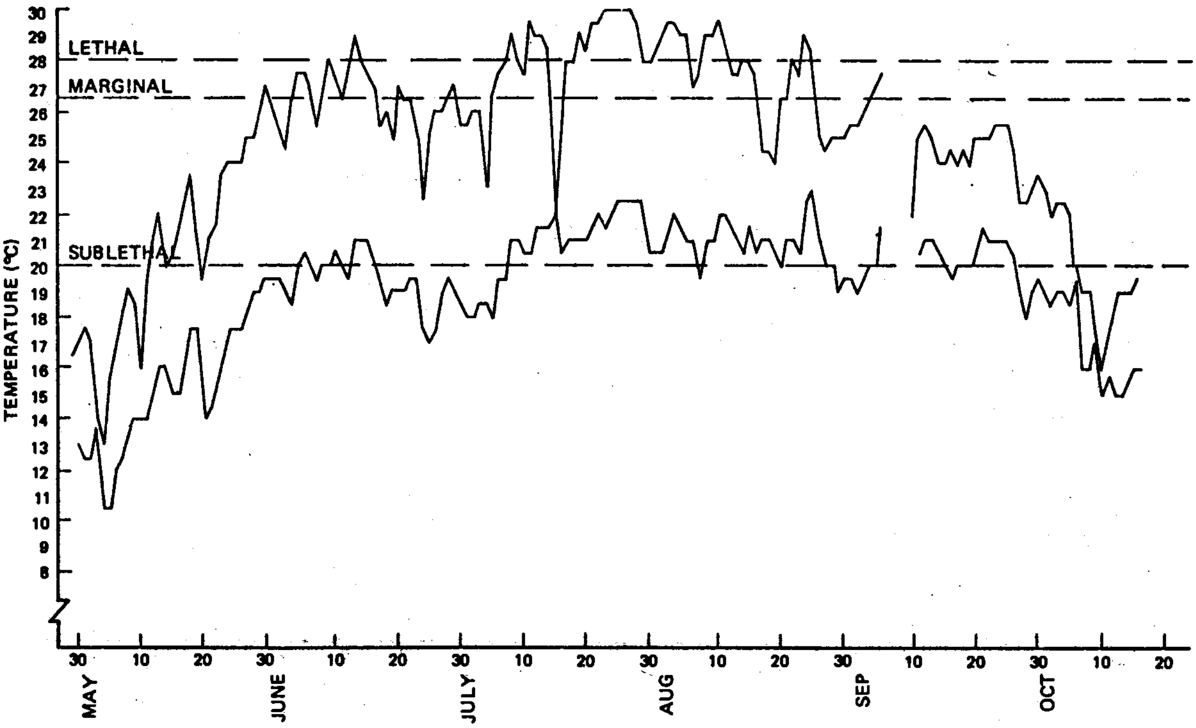


FIGURE 8. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 7 IN BIG SULPHUR CREEK

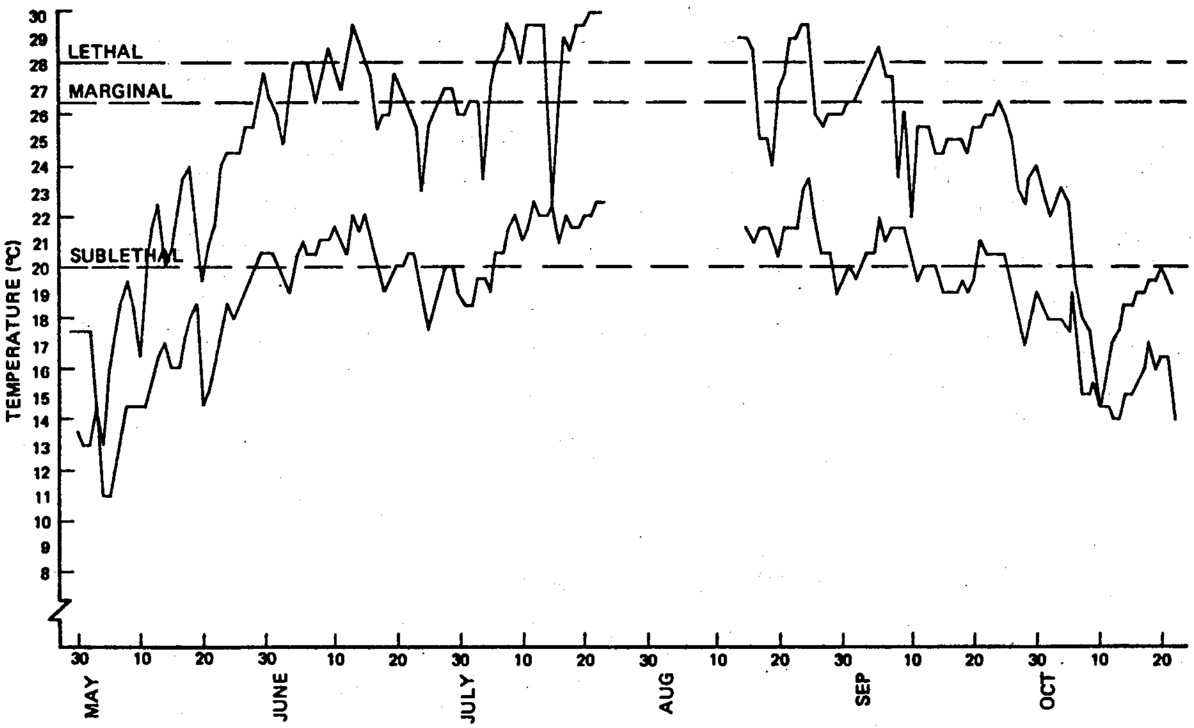


FIGURE 9. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 8 IN BIG SULPHUR CREEK

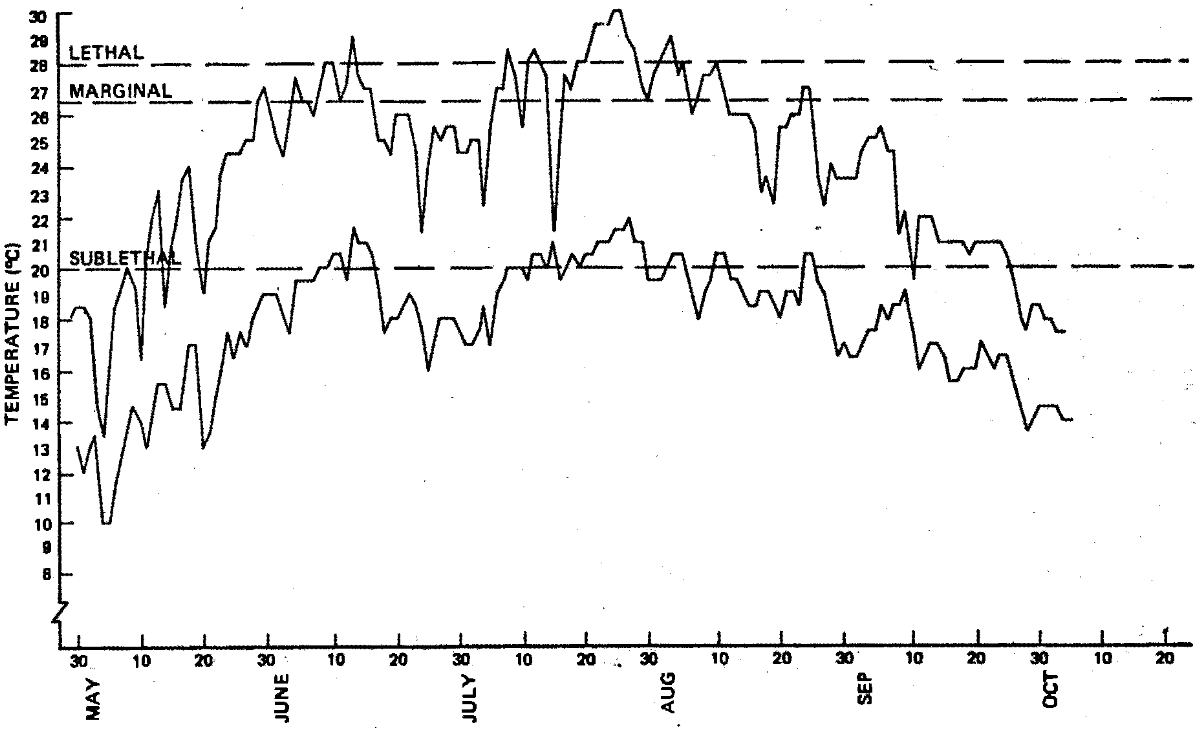


FIGURE 10. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 9 IN BIG SULPHUR CREEK

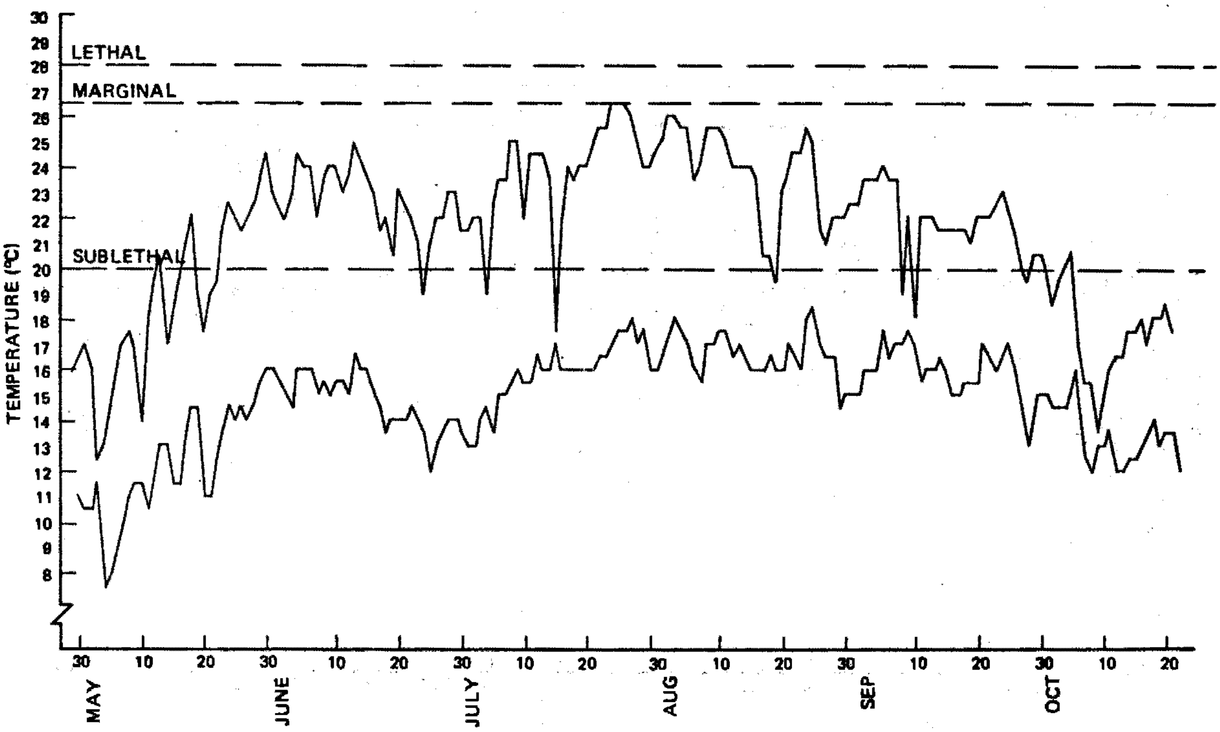


FIGURE 11. DAILY MAXIMUM AND MINIMUM WATER TEMPERATURES IN 1975 AT STATION 10 IN SQUAW CREEK