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Pool Morphology of Redwood Creek, California

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ABSTRACT

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Quantitative evaluation of the longitudinal profile in combination with field observation of pools in the lower 18 km of Redwood Creek suggest: 1) the majority of pools are associated with large roughness elements (LRE's) such as bedrock outcrops and large organic debris, and these pools are significantly deeper (0.77 m mean depth compared to 0.42 m for pools not associated with LRE's, at the 0.5 level of significance); and 2) pool to pool spacing averages 3.8 channel widths, considerably lower than 5 to 7 channel widths commonly reported for undisturbed alluvial channels lacking LRE's. An analysis of four different reaches of alluvial channels showed that 65% of the variability of pool depth can be explained by the variability of heights of upstream and downstream riffles.

A total of seven cold pools were found in the lower 18 km of Redwood Creek. The cold pools form where effluent, cool groundwater or mainstream water cooled by intragravel flow, seeps into the channel and does not mix rapidly with the warmer mainstream water. Mixing may be retarded by large organic debris, which also helps shape the pool by inducing scour during relatively high flow events, or by mid- or side-channel bars. Temperature measurements showed that the

pools consistently maintain water temperatures several degrees cooler than the main stream.

Groundwater and surface water are intimately related in the fluvial system, and baseflow is often provided by a series of point sources as well as more diffused sources. Discrete seeps, along with intragravel flow are the source of cold water for the formation of cold pools. Discharge measurements suggest that baseflow may be locally increased by about 20%. However, the effluent water soon enters the intragravel flow system of the main channel, and the discharge returns to that measured upstream of the point source of groundwater outflow.

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INTRODUCTION

Purpose

Pool morphology of Redwood Creek was investigated to better understand 1) "cold pools" - which maintain summer water temperatures several degrees cooler than the main stream; 2) the relationship between large roughness elements (LRE's) and pool formation and depth; 3) the balance between erosion in pools and deposition on riffles; and 4) pool to pool spacing in Redwood Creek. Furthermore, discharge measurements were used to determine the significance of point sources of groundwater to summer low flow.

Methods

During the summers of 1982 and 1983, a total of seven cold pools were investigated in the lower 20 kilometers of Redwood Creek. Location of each was mapped on 1:6000 aerial photographs. At each site, morphologic maps were made, cross sections and longitudinal profiles were surveyed, water temperature measurements were frequently taken, and continuously recording thermographs were placed in both the cold pool and the mainstream. Discharge measurements were also taken with a pygmy current meter both above and below the pools to establish the percent increase of flow, in order to determine the amount of groundwater flow contributing to the cold pool formation.

The longitudinal profile of the lower 18 kilometers was surveyed by transit, in cooperation with a team from Redwood National Park, Arcata, in August of 1983. During the survey, field observations were made as to whether the pools were associated with large roughness elements (LRE's). In September of 1983, a regression line was fitted to the longitudinal profile data. This regression analysis was used as a basis for the development of two methods to more objectively define pools.

Once the pools were identified, field notes were used in combination with the profile to determine the percentages of pools associated with LRE's and the effect of LRE's on pool depth. In order to determine whether there is a relationship between the heights of the upstream and downstream riffles and the depth of the intervening pool, a multivariate regression analysis was done on data obtained from longitudinal profiles of four different reaches of gravel channels.

Previous Studies

The hydrology and geology of the Redwood Creek basin has been intensively studied since 1972. The studies were primarily focused on the effects of timber harvesting on the portion of the basin which lies within Redwood National Park. Most of these studies were conducted under the auspices of the Forest Geomorphology Project of the

U. S. Geological Survey, and were headed by Dr. Richard Janda (Kelsey and others, 1981a). The project investigated a number of related topics: hillslope erosion, the effects of logging on sediment yield, sediment transport in the main channel and its tributaries, and geomorphological changes in the channel form due to increased sediment loads and recent storms. The major papers which have been a result of these investigations include the following: Colman (1973); Harden and others (1978, 1981); Iwatsubo and others (1975, 1976); Janda and others (1975); Janda (1975, 1976, 1978); Kelsey and others (1981a,b); Lee and others (1975); Madej and Kelsey (1981); Nolan and others (1976a,b); Nolan (1979); and Pitlick (1982). A geological map of the basin was prepared by Harden and others (1982).

"Cold pools" in Redwood Creek were first documented during the summer of 1981. Reid (1961) speculated that springs at the bottom of pools may produce cold pools. Bilby (1984) identified four distinct types of areas of cool water in a fifth order tributary. These areas were termed lateral seeps, pool bottom seeps, cold tributary mouths and flow through bed.

The importance of cold pools and cool water areas in maintaining anadromous fish habitat during summer flows is duscussed by Bilby (1984); Jones (1980); and Keller and others (1983).

The effect of large organic debris (LOD) on pool morphology has been discussed by Keller and others (1981); Keller and Swanson

(1979); Keller and Tally (1979); and Tally (1980).

Techniques of distinguishing pools and riffles have been developed by Leopold and others (1964); Richards (1976); Yang (1971); and Wolman (1955).

The spatial variability of groundwater contributions to base flow has been little explored. Anderson and Burt (1978) found that hollows in the hillslope topography contribute significant amounts of throughflow to the channel. Huff and others (1982) found by conducting simultaneous measurements along a stream reach, that topography alone cannot explain the variations of input. Harrison and Clayton (1970) suggest that both channel morphology and stream competency may be significantly affected by seepage of water into or out of the channel. Little is known about the basic relations between the influent and effluent groundwater flow, intragravel flow of water in the stream channel, and channel form and processes.

Source Area

General Description

The mouth of Redwood Creek is located near the town of Orick on the coast of northwestern California (Fig. 1). The NNW-trending Redwood Creek basin drains 730 km^2. It has a drainage basin length of approximately 90 km and a width of 7-11 km. The altitude ranges from mean sea level to 1600 m (Iwatsubo and others, 1975).

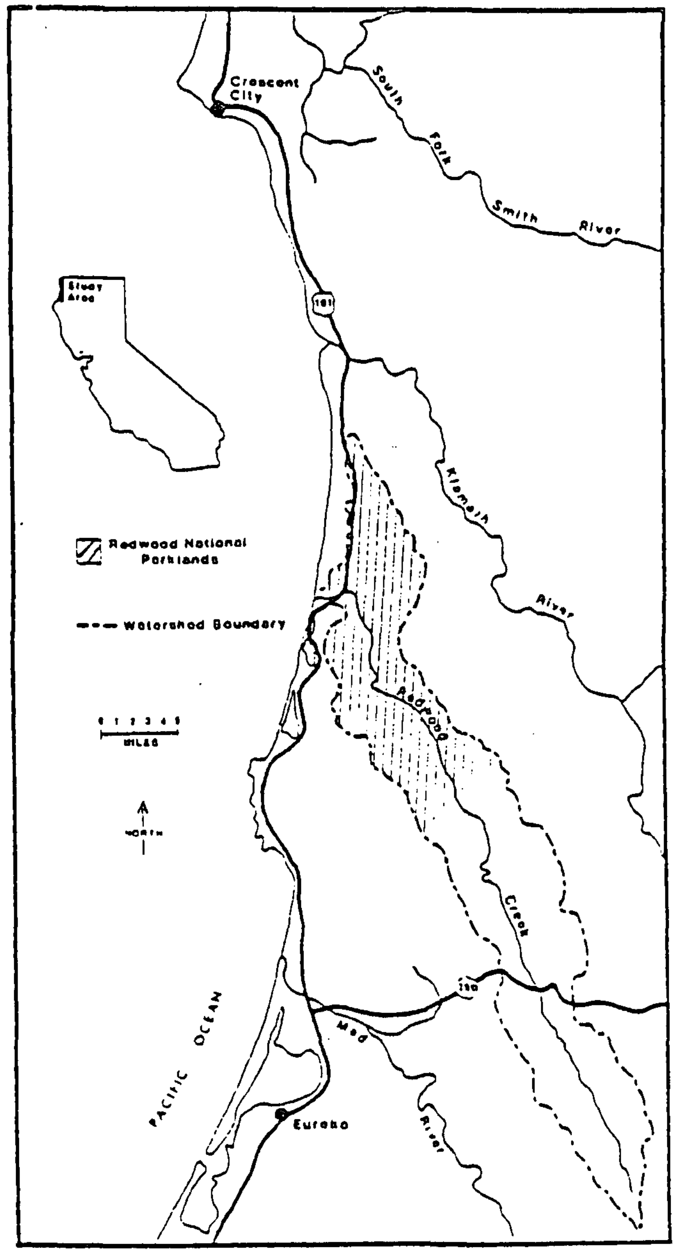


Figure 1. Location map of Redwood Creek watershed (after Pitlick, 1982).

Within the Redwood Creek basin, there are seventy-four tributary basins drained by second or higher order streams which flow directly into Redwood Creek. Most tributaries of the basin are characteristically low order, high gradient streams draining small watersheds. Their channels are, in general, deeply incised and have narrow, discontinuous flood plains. Average stream gradients range from 0.05 to 0.03 (Pitlick, 1982).

The Redwood Creek valley is structurally controlled by the Grogan fault for most of its course, which causes it to be straight to slightly sinuous. The floodplain is discontinuous and narrow, with widths in excess of 60 m uncommon, except for areas between Minor Creek and Mill Creek, near the mouth of Lacks Creek (Iwatsubo and others, 1975), the Tall Trees Grove area, and between McArthur Creek and Orick (Fig. 2).

This study covers the lower 20 km of the Redwood Creek channel, between the Tall Trees Grove and Hayes Creek. This area is entirely within the Redwood National Park boundaries (Fig. 3). The profile of Redwood Creek is shown in Figure 4, with a 50x vertical exaggeration. The slope of the channel averages 0.002 through this reach. The low flow stream bed is composed primarily of sandy, pebble gravel, but the high flow terraces are composed of cobble gravel.

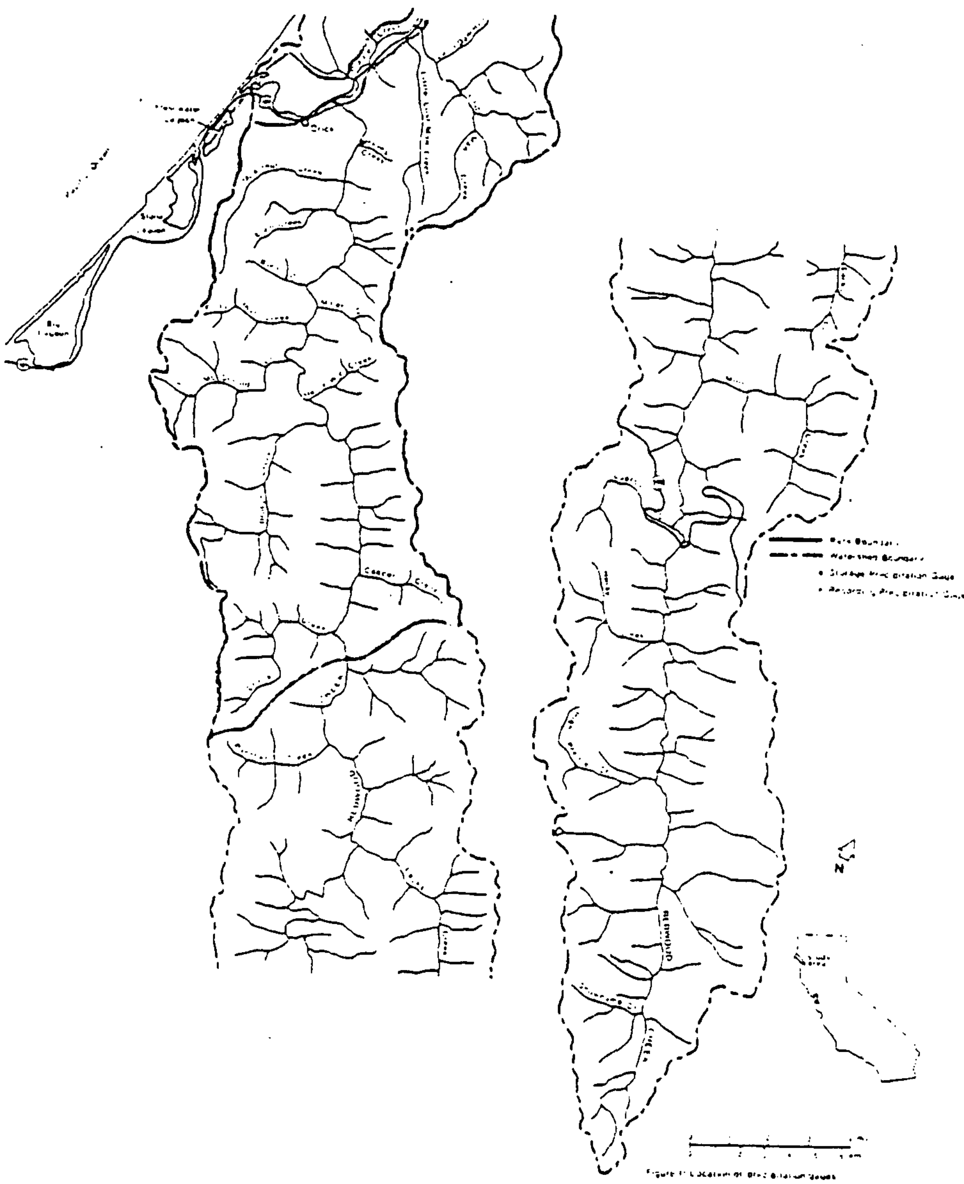


Figure 2. Redwood Creek watershed (after Kelsey and others, 1981a).

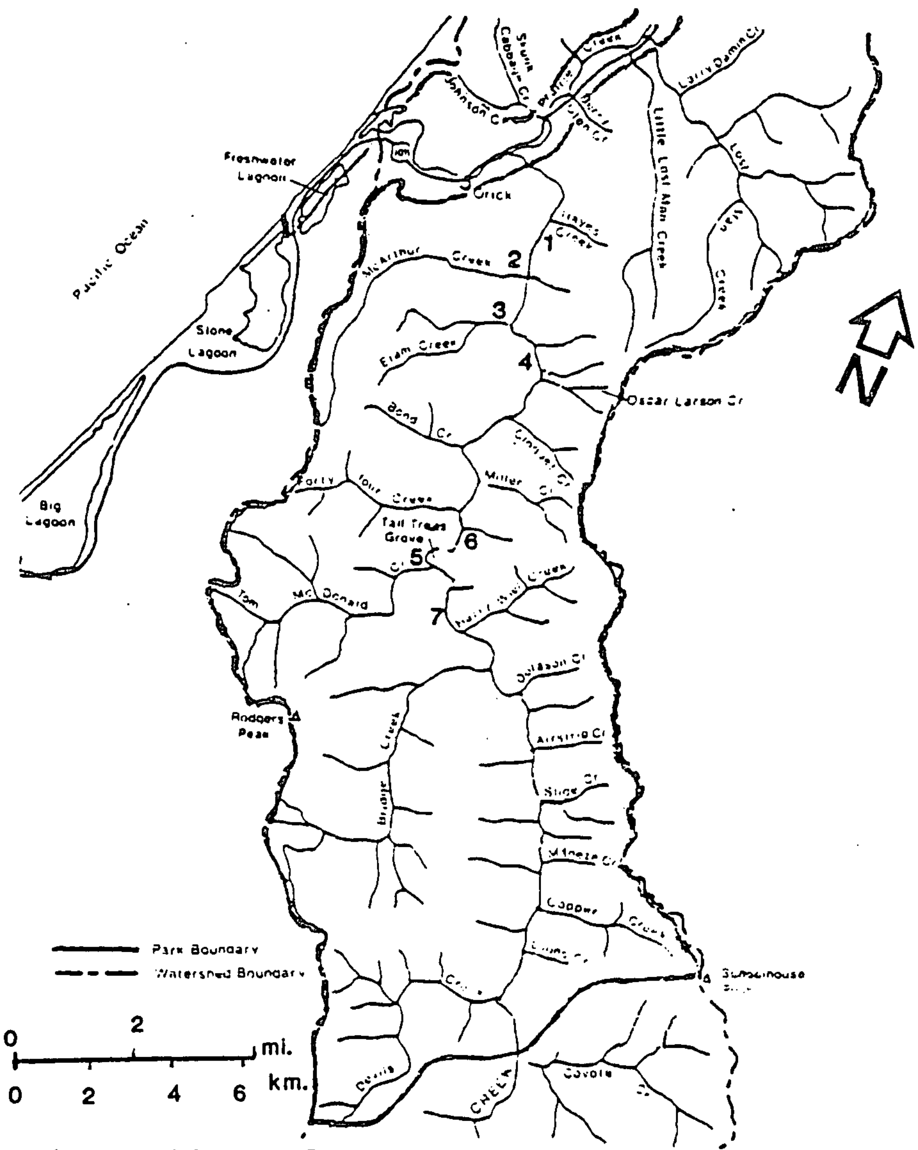


Figure 3. Lower third of Redwood Creek basin. Numbers refer to locations of cold pool sites: 1) Hayes Creek Cold Pool; 2) Footbridge Cold Pool; 3) Elam Creek Cold Pool; 4) Jeremiah Cold Pool; 5) Swimmin' Coon Cold Pool; 6) Tall Trees Cold Pool; and 7) Emerald Cold Pool.

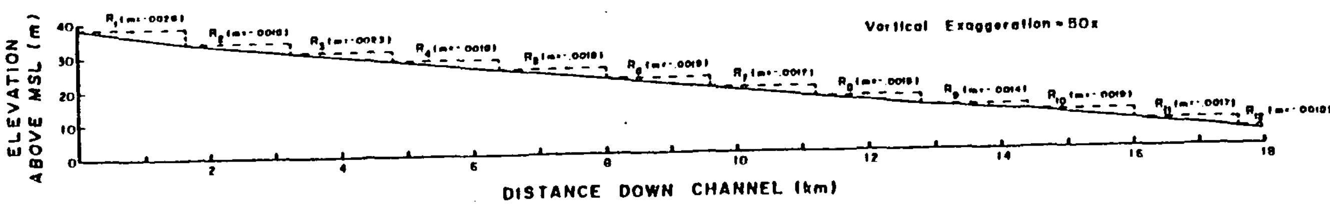


Figure 4. Longitudinal profile of the lower 18 km of Redwood Creek, surveyed August, 1983. Reach "R" refers to an individual reach, as shown in Plate I.

Vegetation and Land Use History

Prior to the initiation of timber harvesting, 85% of the Redwood Creek basin was forested. Mixed stands of old growth redwood and Douglas-fir covered the coastal northern third of the basin, while mixed Douglas fir and hardwood forest was found in the drier inland two-thirds of the basin. The other 15% of the basin was covered by prairie grasses and oak woodland (Janda and others, 1975).

Today, over 65% of the basin has been logged. The majority of the upper basin was logged in the 1950's and the 1960's in response to the post-World War II housing boom. Timber harvesting in the lower basin started later, but by the mid-1960's the area was also being intensively logged (Kelsey and others, 1981a).

By the mid-1970's, less than 25% of the basin's old growth timber remained (Agee, 1980). The majority of this gained protection when the lower 40% of the Redwood Creek basin was included in the expansion of Redwood National Park in 1978. However, timber harvesting is still the major land-use upstream of the park.

Climate

There is a strong seasonal variation in climate in the Redwood Creek area. The mean annual precipitation of 200 centimeters (80 inches) occurs primarily between November and March, rainfall is very infrequent in the summer (Janda, 1978). Coastal fog, however, covers the lower third of the basin on most of the summer mornings, and often does not lift throughout the day. The fog plays an important role in maintaining the redwood forest by increasing the soil moisture and decreasing evapotranspiration.

Major flood-producing storms occurred throughout northern California in 1953, 1955, 1964, 1972, and 1975 (Pitlick, 1982). Peak discharges of greater than 1274 m^3 per second (45,000 cfs) were recorded at the mouth of Redwood Creek for each of these storm events (Harden and others, 1978). The flood of 1964 caused widespread landsliding and change in channel form. The geomorphic changes were unequalled by any other flood since 1950 (Pitlick, 1982).

Discharges during the summer months of this study (1981, 1982, and 1983) averaged 1.32 m^3 per second at the junction of Hayes Creek and Redwood Creek, approximately four kilometers inland from the mouth.

General Geology

Tectonic Setting:

Throughout most of the Mesozoic and well into the Cenozoic, active subduction of the Farallone plate beneath the North American plate occurred along the northwestern coast of North America. During the Miocene, the convergent plate boundary evolved into a transform strike-slip plate boundary as a result of the northward migration of the Mendocino triple junction between the Pacific, North American, and Gorda plates (Atwater, 1970). The emergence of the present-day coastal ranges followed this shift from a subduction type boundary to a transform boundary.

Herd (1978) has presented evidence that a line of recently active right-slip fault zones, that diverge from the San Andreas just south of Hollister, bypasses the Mendocino triple junction. The line of faults are claimed to isolate a small northwestern-elongate plate from the North American continent. This newly recognized plate -the Humboldt plate - is converging northwestward against the Gorda plate, which is being thrust beneath it. If Herd is correct, the Redwood Creek basin is situated at the transform boundary between the North American plate and the Humboldt plate (Fig. 5).

The emergence of the coastal regions of northern California is continuing today, as evidenced by the exposures of shallow marine Plio-Pleistocene rocks and elevated Pleistocene marine terraces along the northern coast (Tally, 1980). The vertical movement is probably related to compression caused by the oblique- or strike-slip movement along the north-northwestern trending faults, such as the Maacama Fault zone and the Lake Mountain Fault zone (Herd, 1978).

Geology of Redwood Creek Basin

Redwood Creek basin is underlain by rocks of the Franciscan assemblage (Harden and others, 1982), which is a Mesozoic to early

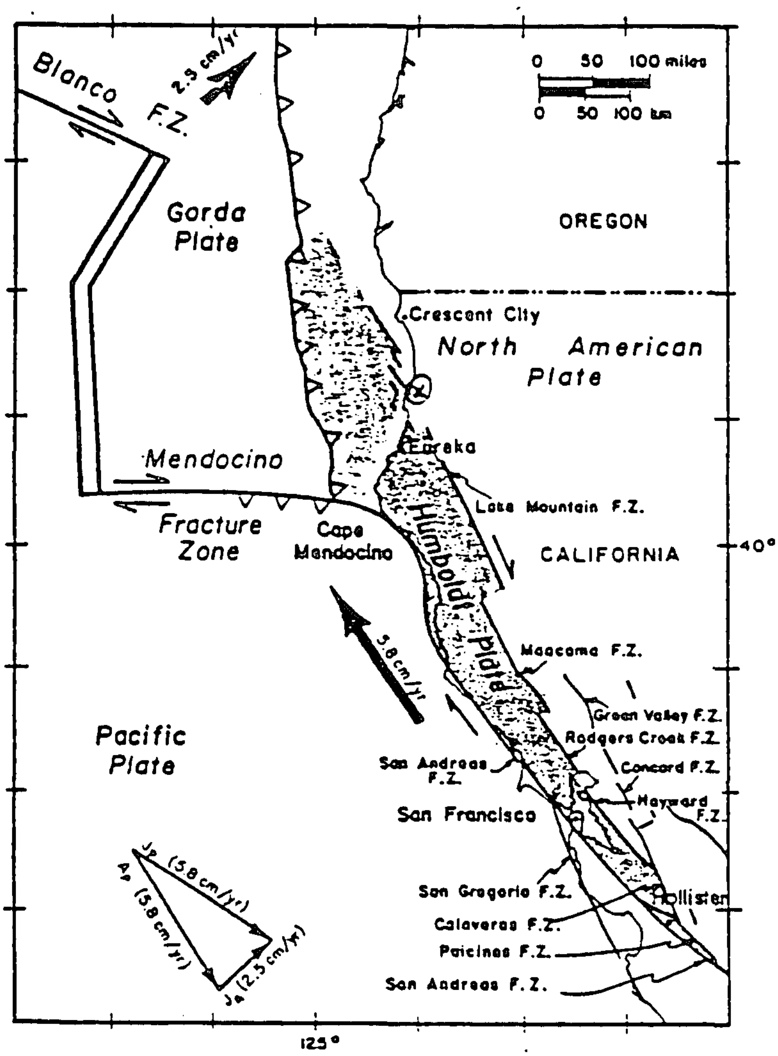


Figure 5. Tectonic setting of Redwood Creek (after Herd, 1978).

Cenozoic accumulation of weakly indurated and pervasively sheared continental margin deposits which are highly susceptible to fluvial erosion and mass wasting (Pitlick, 1978).

The course of Redwood Creek is structurally controlled by the north-northwest-trending Grogan fault, and the elongate geometry of the basin reflects this (Fig. 1). The fault zone is notably straight compared to the other major NNW-trending faults of the region. The straightness of the fault, even in highly dissected areas in the northern portions of its mapped extent, suggests that it is vertical or near-vertical (Hardin and others, 1982).

The Grogan fault separates the Redwood Creek schist on the west from both coherent and incoherent Franciscan sandstone and mudstone units on the east (Fig. 6). The section of Redwood Creek which this study encompasses lies entirely within the Redwood Creek schist. The schist has considerable variation in mineralogy, texture, lithology, and structure, and has been intensely sheared, with complex folding and faulting occurring within it. The most common rock type of the Redwood Creek schist is metamorphosed mudstone, and the typical mineral assemblage is quartz-albite-white mica-chlorite (Harden and others, 1982).

Sediment Sources

The combination of naturally unstable terrain and intensive land use causes the northern California Coast Ranges to have one of the

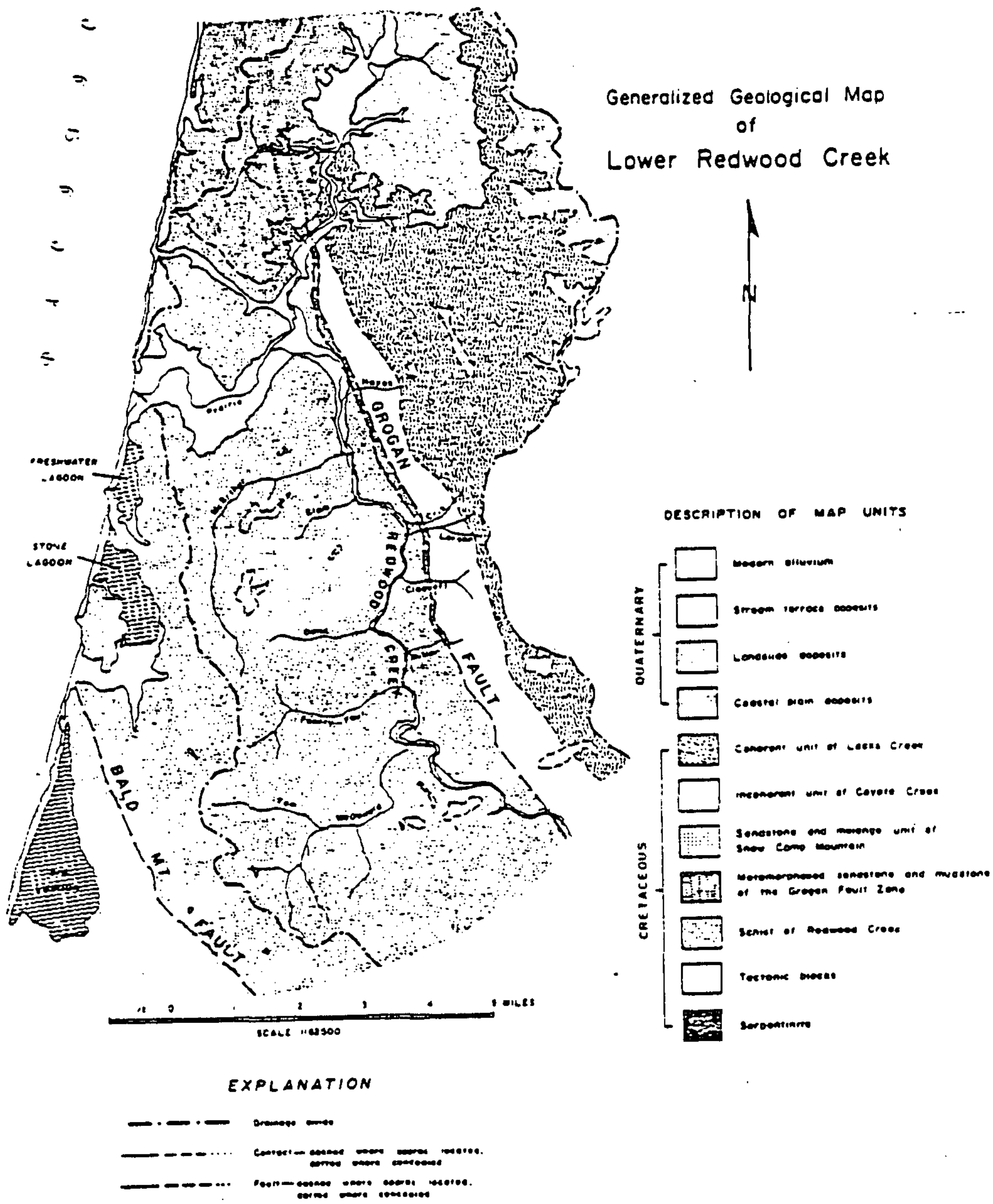


Figure 6. Generalized geologic map of the lower third of Redwood Creek basin (after Harden and others, 1982).

greatest erosion rates in the coterminous United States (Madej and Kelsey, 1981). Due to these high erosion rates and a sequence of intense storms, the channel configuration and behavior of Redwood Creek has changed markedly since the mid 1950's. The most apparent changes along Redwood Creek have been widespread increased channel width, increased channel braiding and a large increase in stream side landsliding (Janda and others, 1975). These changes are characteristic of aggrading stream channels.

In the Redwood Creek basin, the major sediment source areas are stream side landsliding, debris slides and avalanche gullying, earthflows, and stream bank erosion (Table 1). Erosion associated with timber harvesting is also a major source of sediment. Gullying is common on logged areas where skid trails divert water and where road crossings on streams are not maintained. Rainsplash and sheetwash erosion occur on disturbed ground and on compacted road surfaces, transporting fine sediment to stream channels. Fill failures on roads and road washouts are also common (Madej and Kelsey, 1981).

Another major source of sediment to the channel of Redwood Creek in Redwood National Park is channel-stored sediment upstream of the park. The 1964 flood resulted in 1 to 3 m of channel aggradation in upstream reaches. By 1981, 50% of this sediment had been transported to reaches further downstream (Madej and Kelsey, 1981). The most important storage compartments in Redwood Creek are channel sediment,

TABLE 1 - SEDIMENT SOURCE AREAS IN THE REDWOOD CREEK BASIN UPSTREAM OF PRAIRIE CREEK (AFTER MADEJ AND KELSEY, 1981)

Feature	Percent of Basin Area
Debris slides*	1
Debris avalanches*	0.2
Earthflows*	10
Very active earthflows*	2
Unstable streambanks*	3
Main channel stored sediment	0.5
TOTAL	16.7

*from Harden et al. (1978)

point, marginal and mid-channel bars, alluvial terraces, debris jams, overbank deposits and alluvial flats (Kelsey and others, 1981a).

Stream Morphology - General Discussion

The basic morphologic components of many alluvial stream channels are pools and riffles. Pools are topographic lows and riffles are topographic highs. Pools and riffles, for the most part, are formed and maintained at higher, more competent discharges when scour occurs in the pools and accretion takes place on the riffles. At low flow, the water moves quickly over the riffles and slowly through the pools. This has the effect of moving sand size particles off the riffles and depositing them in the pools. However, the lower flows do not have enough power to change the basic morphology of the pool-riffle sequences (Keller, 1971).

Several hypotheses have been proposed to explain the formation of pool and riffle sequences. Yang (1971) proposed that the sequences are formed as a result of the tendency of the stream to minimize the rate of energy expenditure. He argues that energy is dissipated less rapidly over a reach consisting of segments with different energy gradients than over a uniformly sloping reach. Areas of excessive energy loss will erode. This, along with compensatory accretion will disrupt the uniformity of the bed. However, Richards (1982) points out a flaw in this argument: it ignores the fact that the pool-riffle morphology is formed at higher discharges when the energy gradient of the stream is relatively equal throughout the reach.

In an argument similar to Yang's, Yalin (1971) demonstrated theoretically that the undulations of the bed topography form as a result of cross-sectional adjustments which serve to minimize longitudinal velocity variations. Velocity variations are set up by turbulence generated at channel boundaries. Scour enlarges the cross-section where velocity is high, reducing the velocity. Accretion reduces the cross-sectional area, which increases the velocity, and thus, the variations are minimized. The velocity pulsations depend on channel size, and the spacing between the fast or slow zones averages $2\pi w$. According to Richards (1982), the morphology of the pool-riffle sequences agrees with Yalin's theory, since the pool-pool spacing of 5-7 times the mean channel width found by Keller and Melhorn (1973) is within the $2\pi w$ range of velocity pulsation.

Other investigations have demonstrated that minimization of energy loss and velocity variations are not the only cause of pool formation (Keller and Swanson, 1979; Keller and Tally, 1979; Tally, 1980). These investigators suggest that the presence of organic steps in the stream channel may cause a scour hole downstream and a sediment storage site upstream. Large debris accumulations may also cause scouring in and around the debris. Debris-stored sediment may accumulate either upstream or downstream of the organic debris. Lisle and Kelsey (1983) have demonstrated that large roughness elements, including large organic debris, bedrock outcrops, stream side root masses, and in-stream boulders also affect pool formation and depth.

IDENTIFICATION OF POOLS

In order for comparisons to be made between the pool-riffle sequences of different stream channels, it is necessary to have a set criteria for objectively defining the upstream and downstream ends of pools. One such method uses the low-flow water-surface slope, which is steep over riffles and relatively level over pools (Leopold and others, 1964). However, since the water-surface slope increases over pools and decreases over riffles as discharge increases (Langbein and Leopold, 1966), the technique would not be reliable in the analysis of high flow data.

Delineation between pools and riffles has also been made on the basis of sediment size. During low flow, pools may be associated with relatively fine particles, while coarser particles are found on riffles (Leopold and others, 1964). This method is also limited - as discharge increases, pools begin to scour and riffles become zones of accretion (Keller, 1971). The pool fill may disappear, leaving little difference in bed material size between the pools and the riffles.

Wolman (1955) proposed the use of the v^2/d ratio. At low flows, pools are associated with low velocities and high depth, which causes the v^2/d ratio to be small. Riffles are defined as areas with large v^2/d ratios. This method is unreliable for three reasons. It does not take into account the velocity reversal which occurs at high discharges, making pools zones of high velocity (Keller, 1971). Secondly, as Wolman himself pointed out, it is difficult to distinguish the maximum pool v^2/d ratio from the minimum riffle ratio. Third, the method does not take into account the changes in channel width which the stream will make while adjusting to changes in depth and velocity (Wolman, 1955).

To avoid the problems associated with changes in discharge, it is possible to base the identification of pools on the topography of the channel bed relative to the energy gradient of the stream. The undulations in the bed which form at high flow are unlikely to change much as flow drops, thus, such methods encompass the entire spectrum of discharge (Richards, 1976). Three techniques of pool identification based on this idea are analyzed below, using the data obtained during an 18 km survey of the longitudinal profile of lower Redwood Creek.

Method I-Regression Analysis

As suggested by Richards (1976), a regression line was calculated for bed elevations versus distance downchannel. The slope of this line is the energy gradient of the stream. In Redwood Creek, the average slope is 0.002 (Fig. 4). The total longitudinal profile of the lower 18 km of Redwood Creek is shown in Plate 1 and Plate II. The regression line was calculated separately for each of the twelve reaches shown. According to Richards, zones of positive residuals above this line may be considered riffles, and zones of negative residuals below the line correspond to pools. This technique is based on the idea proposed by Leopold and others (1964) that the energy grade line can be used to separate pools and riffles; where the bed profile crosses the line a new bedform is defined, as shown in Figure 7.

The use of this method in Redwood Creek yields a total of 102 pools in the lower 18 km of the channel.

Method II-Regression Analysis in Combination with Water Surface Data

The second technique combines the regression analysis of Richards with the water-surface slope method of Leopold and others (1964). In this method, areas below the regression line are delineated as pools only where the water surface is flat. As long as the water remains level a new bedform is not recognized, even if the profile rises above the regression line. An area in which negative residuals occur more than once in a section with a level water-surface is defined as a "complex pool". This concept of "complex pools" is illustrated in Figures 8 and 9. In Figure 9, pools 4 and 5 are defined as "complex pools". Even though the profile rises above the regression line in these areas, the water surface remains level. Therefore, only one bedform is identified for each area. In Figure 8,

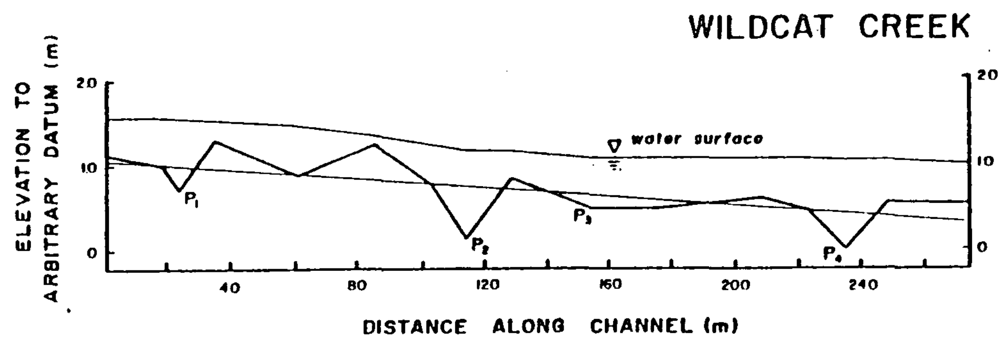


Figure 7. Longitudinal profile of a reach through Wildcat Creek, Indiana (Keller, personal communication). Pools are labeled (P) using Method I - regression analysis.

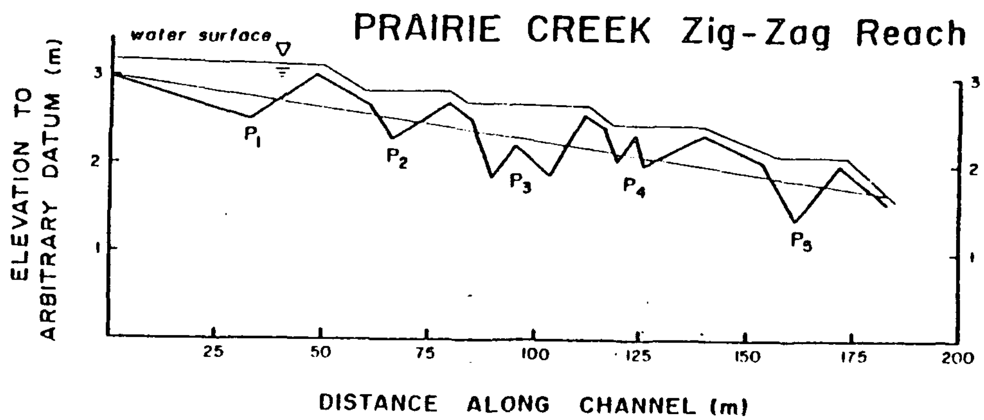


Figure 8. Longitudinal profile of a reach in Prairie Creek, Redwood National Park. Pools are labeled (P) using Method II - regression analysis in combination with water surface data. Pools P_3 and P_4 are "complex pools".

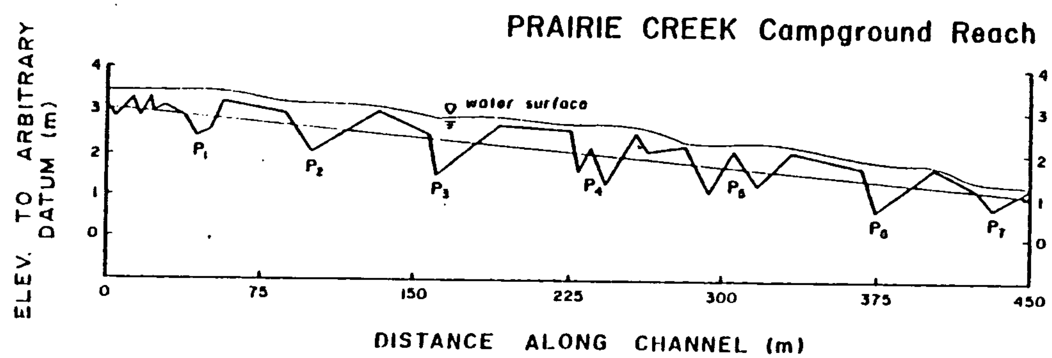


Figure 9. Longitudinal profile of a reach in Prairie Creek, Redwood National Park. Pools are labeled (P), using Method II - regression analysis in combination with water elevation data. Pools P_4 and P_5 are complex pools.

P_3 and P_4 are defined as "complex pools", using this same idea.

A total of 68 pools were defined in the Redwood Creek profile by this technique.

Method III-Average Divergence from the Energy Gradient

In order to further quantify the identification of pools, a third technique was developed as part of this study. In this technique the distance above or below the energy gradient is measured at increments equal to channel width. The mean of these measurements is calculated, and a pool is defined as any part of the profile which is below the energy gradient at a distance exceeding this mean. Fifty-six pools were identified in the 18 km stretch of Redwood Creek using this method.

In order to determine whether the three techniques vary statistically, the distribution of pool-to-pool spacing was determined. Pool to pool spacing is commonly reported in terms of channel width. In Redwood Creek the channel width changes from place to place as a result of bedrock control of meanders, landslides along the hillslopes, and varying degrees of sediment input from timber harvesting activities. Variation in channel width for the lower reach of Redwood Creek is shown in Figure 10, and these values were used to dimensionalize the pool-to-pool spacing.

The average pool-to-pool spacing for Methods I, II, and III are,

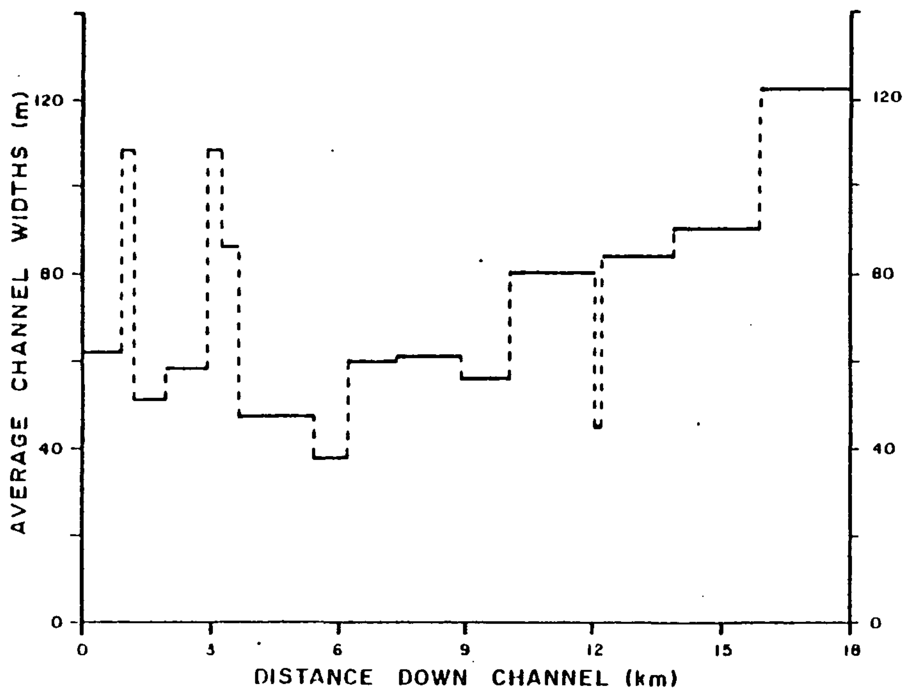


Figure 10. Profile showing average channel width of lower Redwood Creek.

respectively, 2.6, 3.8, and 4.5 channel widths. The frequency diagrams of the pool-to-pool spacing are shown in Figure 11. Kolmogorov-Smirnov paired tests (Siegel, 1956) were performed on this data in order to test the null hypothesis that there is no significant difference in the populations of pool spacing determined by each of the three methods. The results of the tests are shown in Table 2. The tests showed that there is no significant difference between the pool spacing delineated by Methods II and III. On the other hand, there is a significant difference in the pool spacing determined by Method I and Method II, as well as the spacing determined by Method I and Method III.

These results suggest that Method I - the use of the regression analysis alone - may lead to the identification of too many pools and riffles. That is, it may be necessary to define a minimum allowable deviation from the regression line before a new bedform is identified, as was done in Method III.

Methods II and III both seem to be acceptable methods of objectively defining pools from a longitudinal profile. The results obtained through use of these methods are consistent with field observations. Although the best technique of determining pool-riffle sequences is a combination of field observation and numerical analysis of longitudinal profile data, either of these methods may be used when analyzing profile data obtained by other investigators.

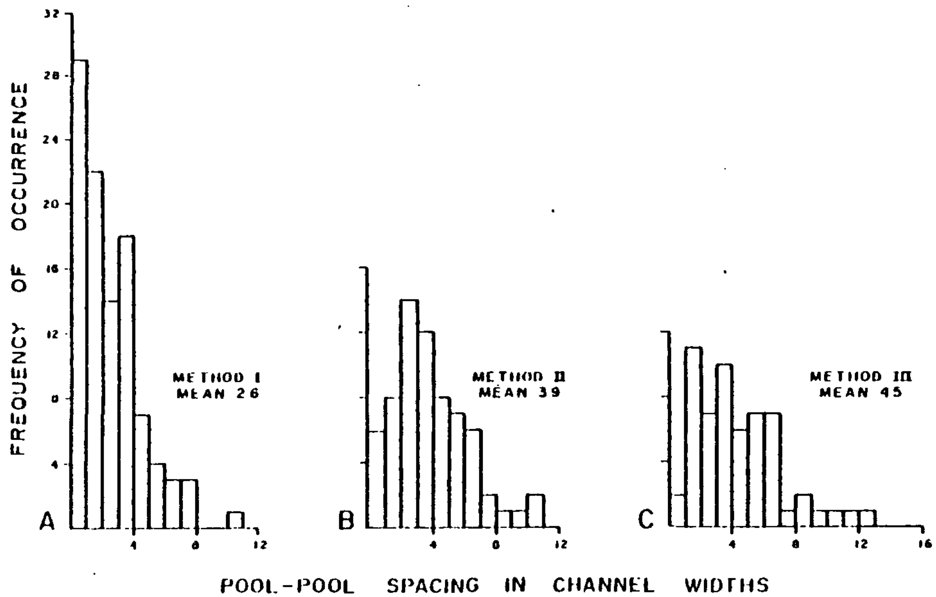


Figure 11. Frequency of occurrence of pool-pool spacing in channel widths; a) pools defined using Method I, b) pools defined using Method II, c) pools defined using Method III.

TABLE 2 - RESULTS OF KOMOGOROV-SMIRNOV PAIRED TESTS ON THE DISTRIBUTION OF POOL SPACING DETERMINED BY METHODS I, II, AND III

Method Tested	N	$\overline{x}$	Dm	Dc	*Ho Decision
Method I	101	2.6	0.296	0.214	R
Method II	67	3.8			
Method I	101	2.6	0.305	0.226	R
Method III	56	4.5			
Method II	67	3.8	0.091	0.246	A
Method III	56	4.5			

N = population size; $\overline{x}$ = mean of the pool-to-pool spacing in channel width; Dm = largest difference in cumulative frequency for a given class; Dc = critical difference in the cumulative frequency for a given class for a significant difference at the 0.05 level.

*Ho (null hypothesis) = there is no significant difference in the pool-to-pool spacing determined by the tested methods: R = rejection of Ho, A = acceptance of Ho.

The pool-to-pool spacing of 3.8 channel width found in Redwood Creek (using Method II) is relatively low. Spacing usually averages 5-7 times the mean channel width in gravel channels (Keller and Melhorn, 1973). This low spacing in Redwood Creek is probably due to recent flooding and disturbance of the basin associated with timber harvesting activities. Disturbance of a system has been found to cause a larger number of pools to form, with a spacing of 3-5 channel width (Keller, 1972). As the system stabilizes, and sediment stored in the channel is moved out of Redwood Creek, a number of the smaller pools may coalesce, causing an increase in the pool-to-pool spacing.

RELATIONSHIP BETWEEN LARGE ROUGHNESS ELEMENTS AND POOL FORMATION

Lisle and Kelsey (1983) have suggested that the thalweg course of a gravel river channel is influenced by the position of large roughness elements (LRE's). LRE's may include bedrock outcrops, large organic debris (LOD), in-stream boulders, sharp bends, stream-side root masses, or any combination thereof. In their study of Jacoby Creek in northwestern California, they found that 96% of the pools and scour holes are associated with LRE's. Their hypothesis is that when a wandering thalweg course encounters a LRE, a stable, large scale system of vortices is generated, causing pool formation by scour at high flow.

During the survey of the longitudinal profile of Redwood Creek, pools were identified in areas where the water appeared significantly deeper than elsewhere and the water surface was level, which corresponds to the technique of pool identification used in Method II. As shown in Figure 12, LRE's were associated with 86% of the pools: bedrock outcrops (38%), large organic debris (34%), combination of large organic debris and bedrock (11%), and instream boulder (3%). The remaining nine pools (14%) are probably due to the oscillation of flow velocities associated with meandering, as described by Richards (1982).

The hypothesis that the population of pool depths, measured from the energy gradient, vary with type of LRE's was tested by using a

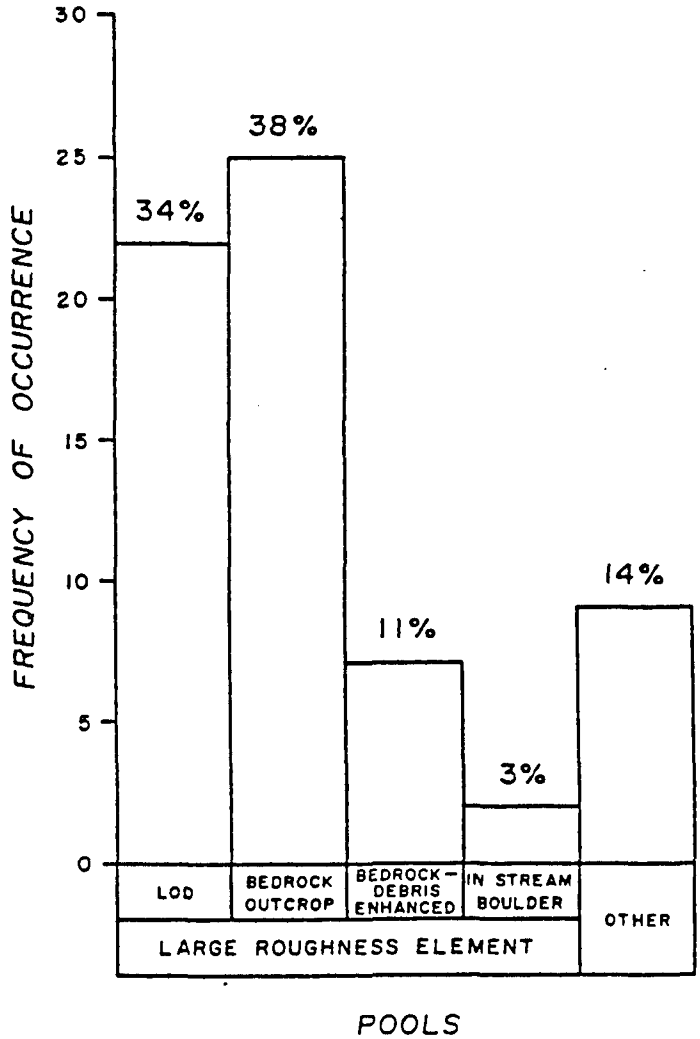


Figure 12. Frequency of occurrence of pools associated with large roughness elements (LRE's) vs. pools of other types.

Kruskal-Wallis test (Siegal, 1956). Pool depths listed by type are shown in Table 3.

Overall analysis of variance rejects the null hypothesis - there is no significant difference - at the 0.05 level (Table 4). Paired tests showed that there is a significant difference in the depth of pools associated with bedrock outcrops and the depth of pools not associated with any type of LRE. The populations of pool depths were also significantly different between the pools associated with a combination of LOD and bedrock outcrops and pools not associated with any type of LRE. However, when pool depths associated with LOD were compared to those not associated with LRE's, no significant difference was found. This may be due to the fact that the majority of the large organic debris is moved during winter high flow. Thus, the pools associated with LOD may not be as stable as those pools associated with other types of large roughness elements. The results of these tests are shown in Table 5. No significant difference was found in the population of pool depths associated with the three types of LRE's tested. The greater depths associated with LRE-type pools strengthen the argument made by Lisle and Kelsey (1983) that pools generated at the sites of LRE's tend to be much more stable.

TABLE 3 - DEPTH OF POOLS* IN REDWOOD CREEK

Class	Pool Depths (m)	N	Mean
Bedrock outcrop	1.7, 1.4, 1.3, 1.15, 1.1, 1.05, 0.9, 0.9, 0.85, 0.8, 0.8, 0.75, 0.7, 0.7, 0.7, 0.7, 0.65, 0.6, 0.6, 0.5, 0.45, 0.45, 0.35, 0.2, 0.15	25	0.77
LOD	2.2, 1.2, 1.1, 0.9, 0.9, 0.8, 0.8, 0.7, 0.7, 0.7, 0.6, 0.6, 0.55, 0.55, 0.45, 0.4, 0.4, 0.3, 0.3, 0.25, 0.2, 0.2	22	0.67
LOD and bedrock outcrop	2.3, 1.8, 1.1, 0.9, 0.6, 0.5, 0.35	7	1.79
In-stream boulder	1.0, 0.5	2	0.76
Other	1.0, 0.75, 0.7, 0.6, 0.4, 0.3, 0.25, 0.25, 0.25, 0.2, 0.2, 0.1	12	0.42

*Pools were identified on the longitudinal profile using Method II. Three of the pools were not identified in the field - their depths (0.25, 0.2, 0.1) are listed in the "other" class.

TABLE 4 - KRUSKAL-WALLIS ONE-WAY ANALYSIS OF VARIANCE TEST FOR DEPTH OF POOLS OF REDWOOD CREEK

Class	Ni	Nt	Ho>chi^2	*Ho Decision
Bedrock outcrop	25			
LOD	22			
LOD and bedrock outcrop	7	68	$p<0.05$	Reject
In-stream boulder	2			
Other	12			

Ni = population size of pool depth for each class; Nt = total population size.

*Ho (null hypothesis) = there is no significant difference in the population of pool depths, arranged by class.

TABLE 5 - KRUSKAL WALLIS PAIRED TESTS ON POOL DEPTHS OF REDWOOD CREEK*

Bedrock Outcrop	Bedrock Outcrop	Bedrock and LOD	LOD
LOD and Bedrock Outcrop	A $p < 0.50$		
LOD	A $p < 0.20$	A $p < 0.20$	
Other	R $p < 0.001$	R $p < 0.01$	A $p < 0.10$

*Null hypothesis -- there is no significant difference in the depths of pools, arranged by class: R=rejection of Ho, A=acceptance of Ho.

RELATIONSHIP BETWEEN POOL DEPTH AND RIFFLE HEIGHT

At low flow, pools are zones of low velocity, and the water moves quickly over the riffles. Thus, one would expect the riffles to erode, with the pools becoming sites of deposition. Yet, these bedforms are remarkably stable over time, as shown by Dury's (1970) resurvey of the Hawkesbury River after 100 years. This is due to the fact that the morphology of the pool-riffle sequences are actually formed at higher, more competent discharges, when velocities are fast through the pools and slower over the riffles (Keller, 1971; Lisle, 1979). Thus, as the pools scour, the materials are deposited on the downstream riffle. As a result, there should be a relationship between the depth of the pool and the height of the downstream riffle. Furthermore, I suggest that the greater the height of the upstream riffle, the higher the energy expenditure as water flows into the downstream pool. Thus, a relationship between the height of the upstream riffle and depth of the downstream pool should also be seen.

To test these ideas, a multivariate analysis was done on the heights of the upstream and downstream riffles and the depths of the intervening pools for four different longitudinal profiles in gravel channels: two reaches of Prairie Creek (Figs. 8 and 9) in Redwood National Park in California (Keller, personal communication) and two reaches of Wildcat Creek (reach #2 is shown in Fig. 7) in Indiana (Keller, personal communication). A regression analysis of this data shows that there is a relationship: $R^2 = .65$. Therefore, approximately 65% of the variability of the depths of pools is explained by the variability of the heights of upstream and downstream riffles. This suggests that there is a rough balance between the erosional processes in the pools and the depositional processes on the riffles.

The test of the hypothesis that the depths of the pools is related to the heights of the riffles is somewhat inconclusive as only 65% of the variability is explained. The remaining variability (35%) may be due in part to frequent occurrence of riffles in areas where the channel is wide. This allows the stream to adjust to deposition by increases in width as well as by increases in the height of the riffles. Thus, an analysis comparing the volume of the pool with the volume of the riffles might show a better relationship. Necessary data to do this is not available for these data sets. The 35% remaining variability may also be related to differences in the size and shape of LRE's associated with the formation of the pools.

A test of the heights of upstream and downstream riffles versus the depths of the intervening pool was also done for the Redwood Creek data alone. No relationship was found. This may be attributed to the fact that the basin has been disturbed by logging activities. Excess sediment has caused the stream to remain in disequilibrium, and thus, the channel forms are not yet adjusted to sediment load.

"COLD POOLS"

Cold pools maintain summer temperatures several degrees lower than the main stream. They were first discovered in Redwood Creek by E. A. Keller in 1981.

There are three necessary factors pursuant to cold pool formation - formation of the pools at high flow, a source of cold water and a barrier which limits mixing between the cold water and the warmer ambient flow. The cold pools of Redwood Creek were found mainly along the outside of bends, where scour had been induced either by bedrock outcrops or large organic debris. Sources of subsurface cold water include springs and seeps, and intragravel flow. Mid- and side-channel bars or large organic debris serve as barriers to mixing between the effluent cold water and the main channel.

During the summers of 1982 and 1983 seven cold pools were found and studied in the lower 20 km of Redwood Creek: Hayes, Elam, Emerald, Footbridge, Jeremiah, Swimmin' Coon, and Tall Trees (Fig. 3). Results of investigation of each cold pool are discussed below.

Hayes Creek Cold Pool

In the summer of 1981, a cold pool was found at the junction of Hayes Creek and Redwood Creek. The pool had apparently formed by scour around a large amount of fallen trees and organic debris which had washed downstream and accumulated at the site during high flow.

As shown in Figure 13, in the summer of 1981 the pool had temperatures as low as 12°C, while the main stream reached 21°C. The pool was cooled primarily by subsurface water (groundwater and intragravel flow) which originated in the Hayes Creek channel. Although the lower portion of Hayes Creek is dry in the summer, its bed serves as a point of concentration for subsurface water. The cold water (11°-12°C) entered the pool through a small trough which was scoured by Hayes Creek during winter flows. Both a mid-channel bar and large organic debris (shown in Figure 13) limited mixing between this cold water and the warmer main stream, allowing a plume of cold water to emerge at the bottom of the pool. Small seeps flowing out of the landslide on the right bank also contributed to this plume (Keller and others, in press).

In order to determine whether the pool remained cold over time, two continuously recording thermographs were placed near the bottom of the pool at the locations shown in Figure 13. Over the same period, from September 22 through September 25, a maximum-minimum thermometer was placed in the main stream of Redwood Creek. As Figure 14 illustrates, the temperatures in the pool never reached those of the main stream, and the location nearest the source had consistently lower temperatures. The temperature differences were greater at mid-day after the sun had heated the main flow, and were

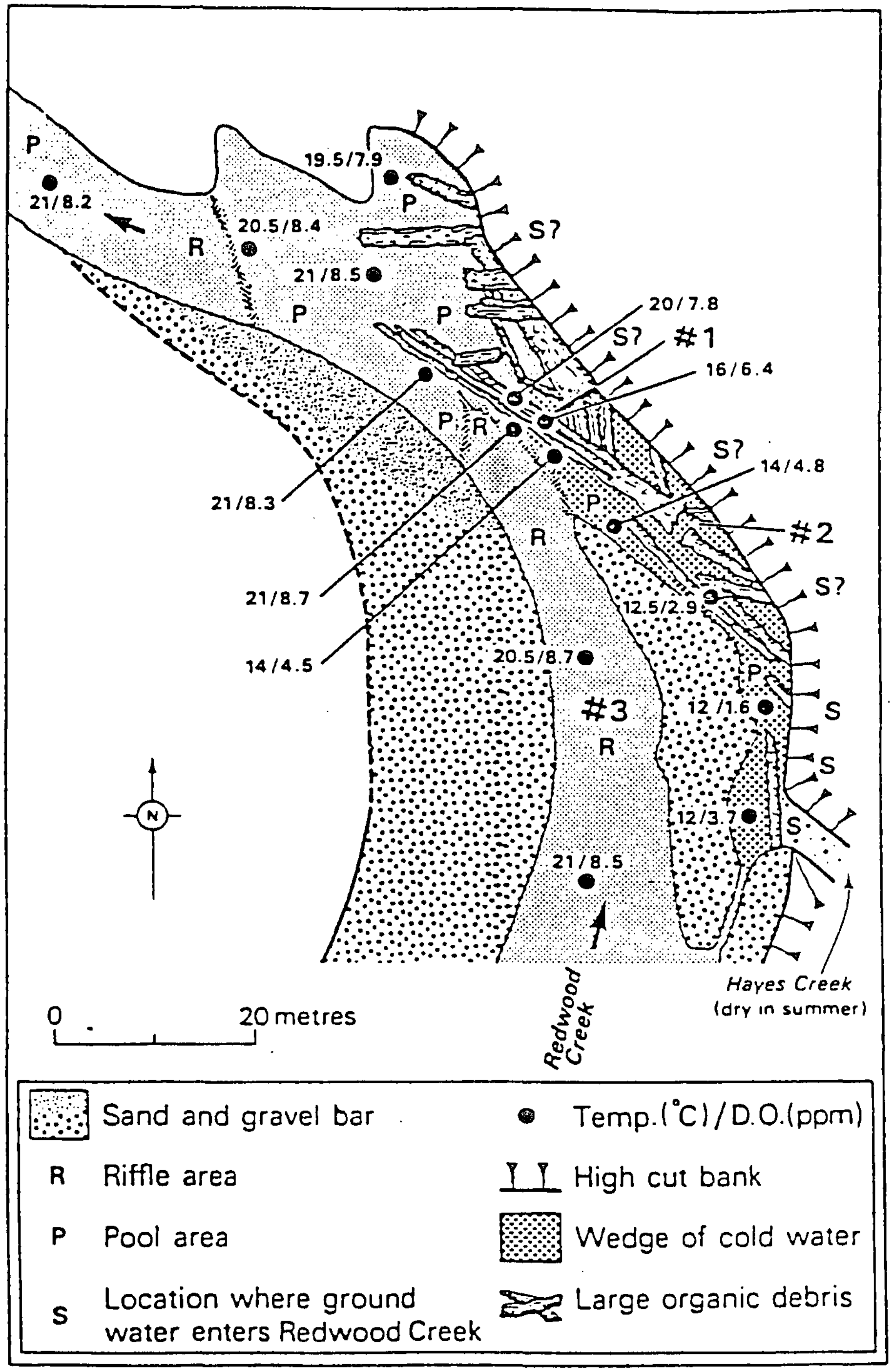


Figure 13. Morphological map and water temperature measurements, Hayes Creek Cold Pool, August, 1981. Location of the pool is shown in Figure 3.

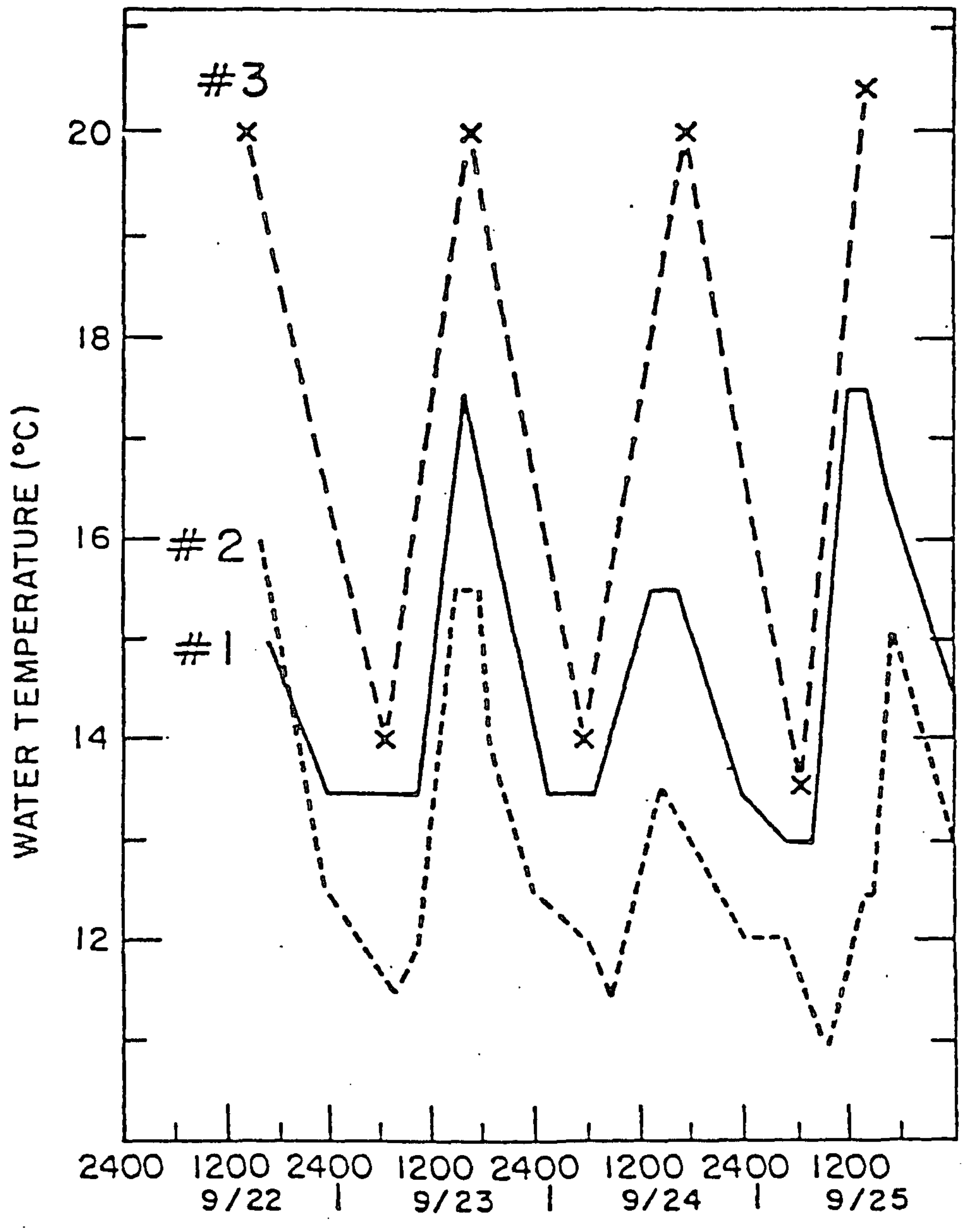


Figure 14. Water temperatures in Hayes Creek Cold Pool, September 22 - September 25, 1981. Temperatures at Stations #1 and #2 were taken with continuously recording thermographs placed in the cold pool. Temperatures at Station #3 were measured with a maximum-minimum thermometer in the mainstream. Locations of the stations are shown in Figure 13. Location of Hayes Creek Cold Pool is shown in Figure 3.

lower at night when the main stream cooled to temperatures close to those found in the pool (Keller and others, in press).

During the winter of 1981-1982, the morphology of the pool significantly changed. The area, depth, and thus volume increased. As shown on Figure 15, the mid-channel gravel bar, which had isolated the effluent cold sub-surface water flowing from Hayes Creek, disappeared. However, the large organic debris, which roughly paralleled the bank, retarded mixing between cold water seeping from the landslide and the water in the mainstream enough that cold spots in the pool emerged as discharge decreased. While this had the effect of changing the locus of the cold pool downstream, as shown in Figures 16, 17, 18, the temperature differences between the pool and the mainstream water were not as great as in 1981, as seen by comparing the thermograph readings in Figure 19 with those in Figure 14. Cross sections and longitudinal profiles are shown in Figures 20-21.

Over the 1982-1983 winter period of high flow, the morphology of the pool remained remarkably stable. The large organic debris shifted very little, and the configuration of the gravel bars remained the same. However, by the summer of 1983 cold spots along the right bank had disappeared (Figure 22). Either the seeps coming from the landslide were relatively inactive (as compared to the summer of 1982), or the higher discharges of the summer of 1983 caused the main stream flow to effectively "drown out" the effects of the colder effluent

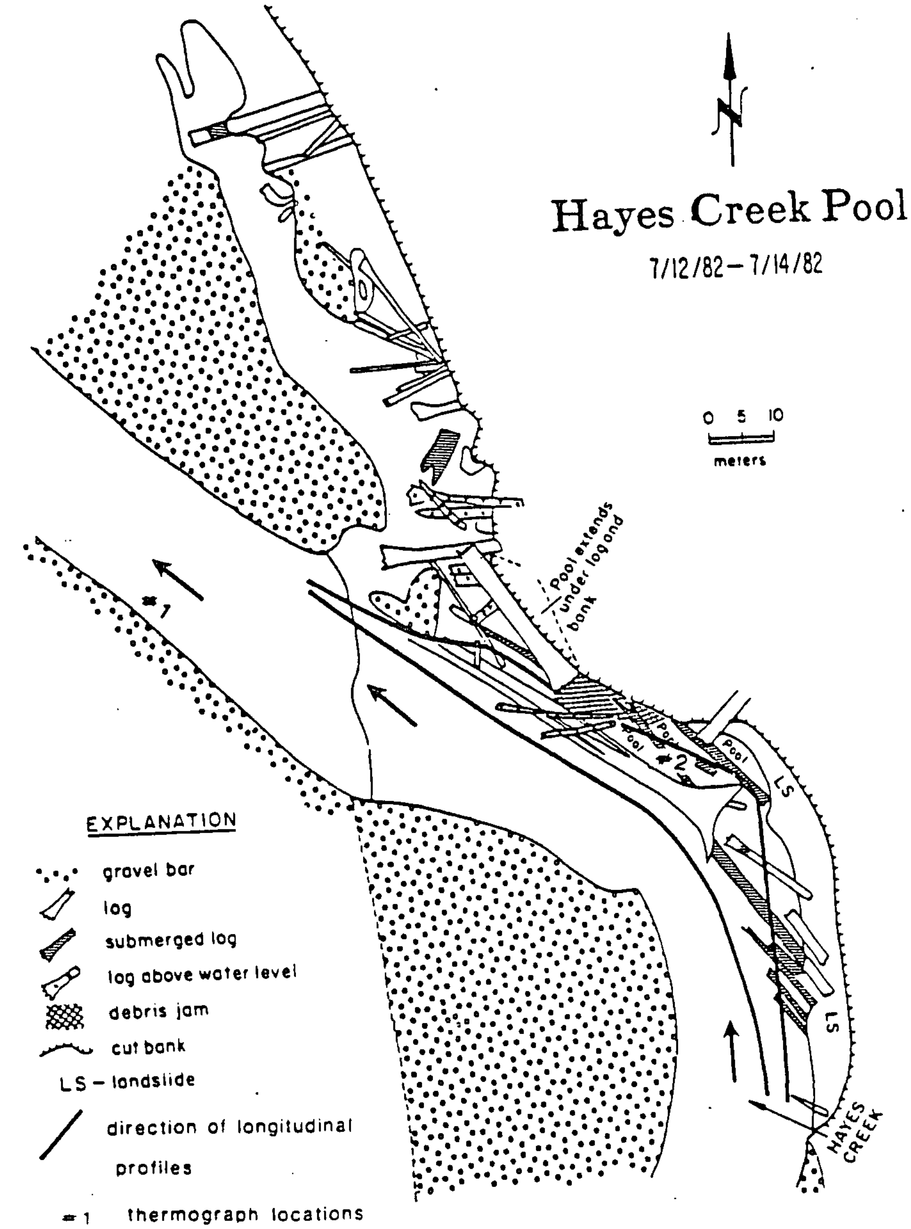


Figure 15. Morphology, Hayes Creek Cold Pool, July 1982. Location of the pool is shown in Figure 3.

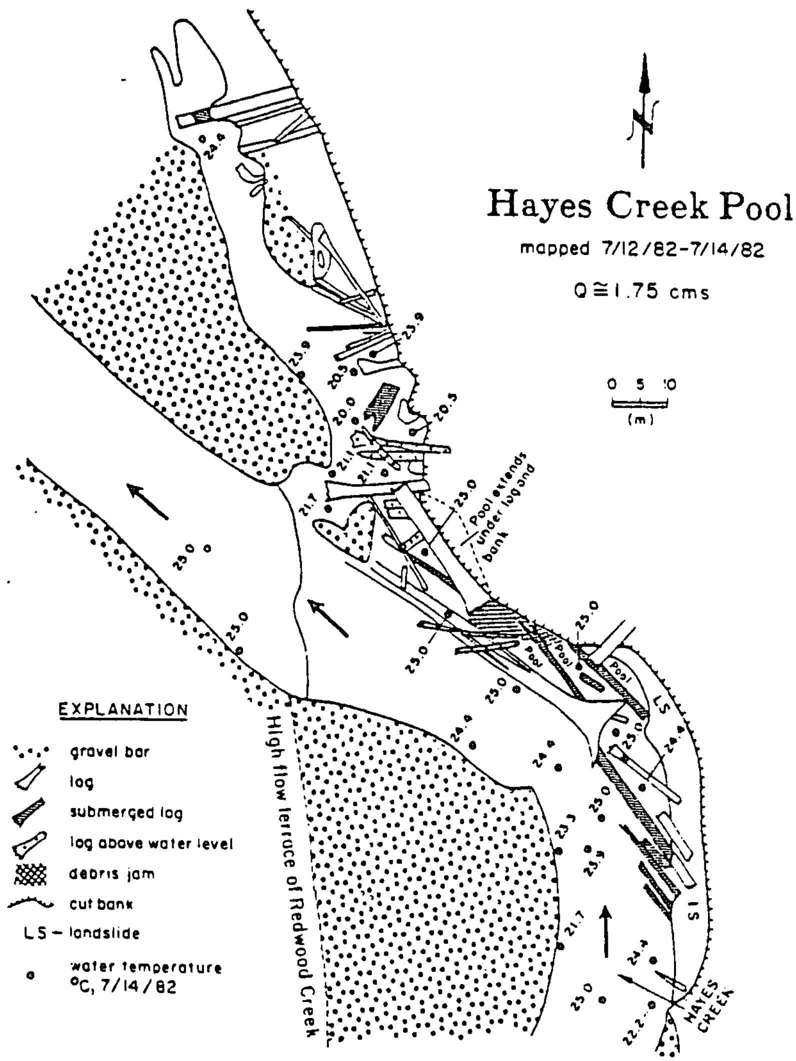


Figure 16. Water temperatures, Hayes Creek Cold Pool, July 14, 1982. Location of pool is shown in Figure 3.

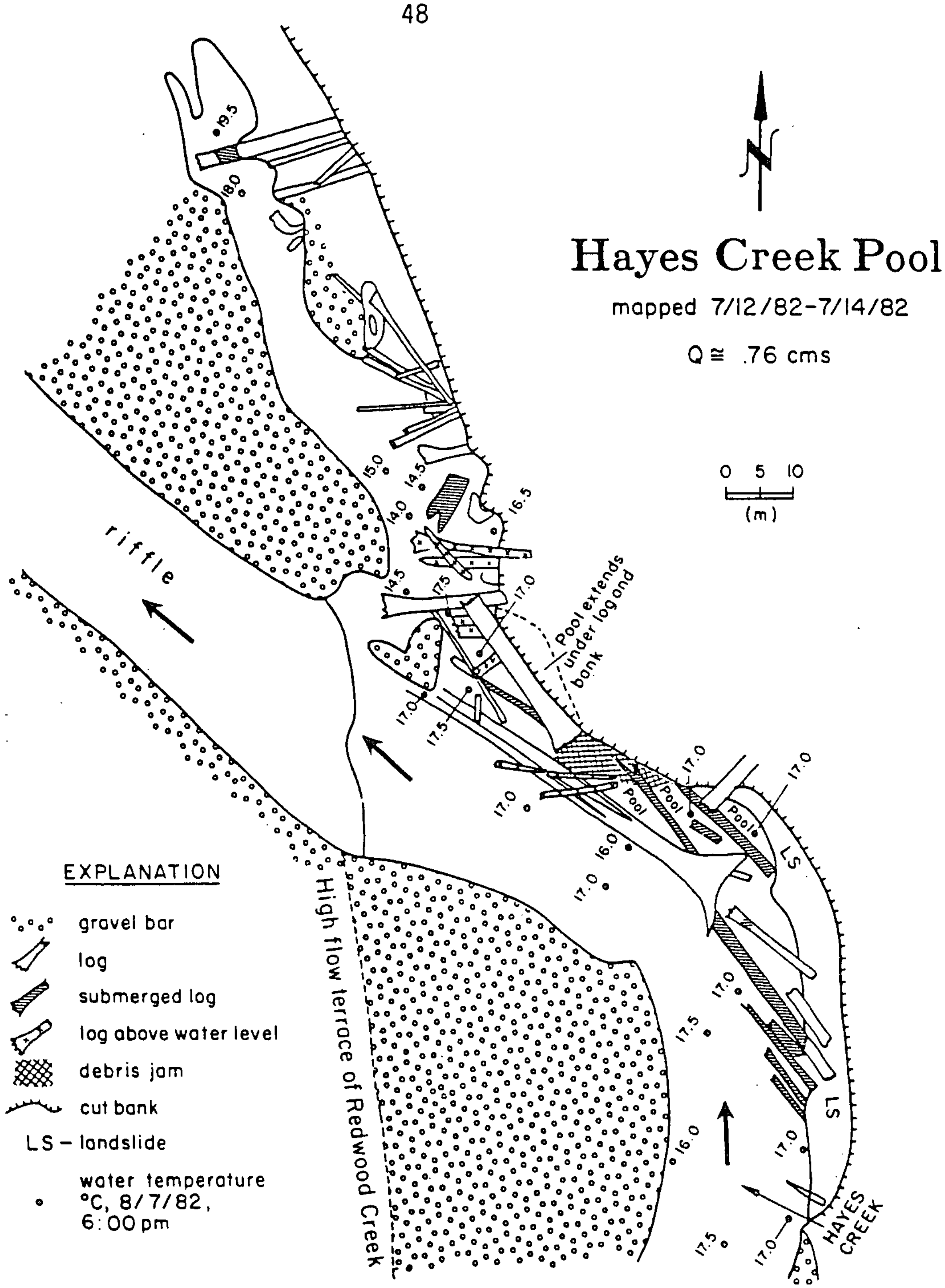


Figure 17. Water temperatures, Hayes Creek Cold Pool, August 7, 1982. Location of pool is shown in Figure 3.

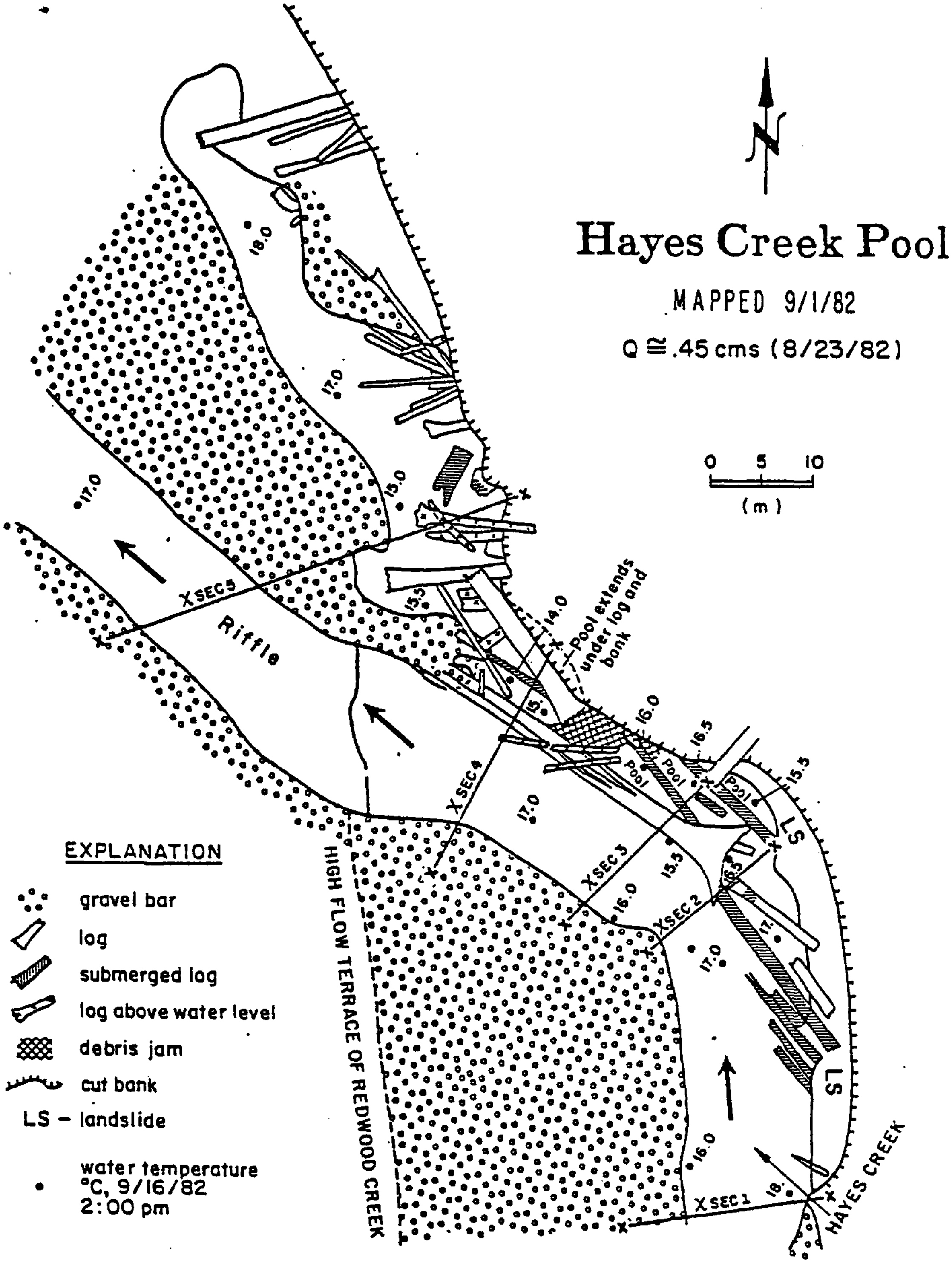


Figure 18. Water temperatures, Hayes Creek Cold Pool, September 16, 1982. Location of pool is shown in Figure 3.

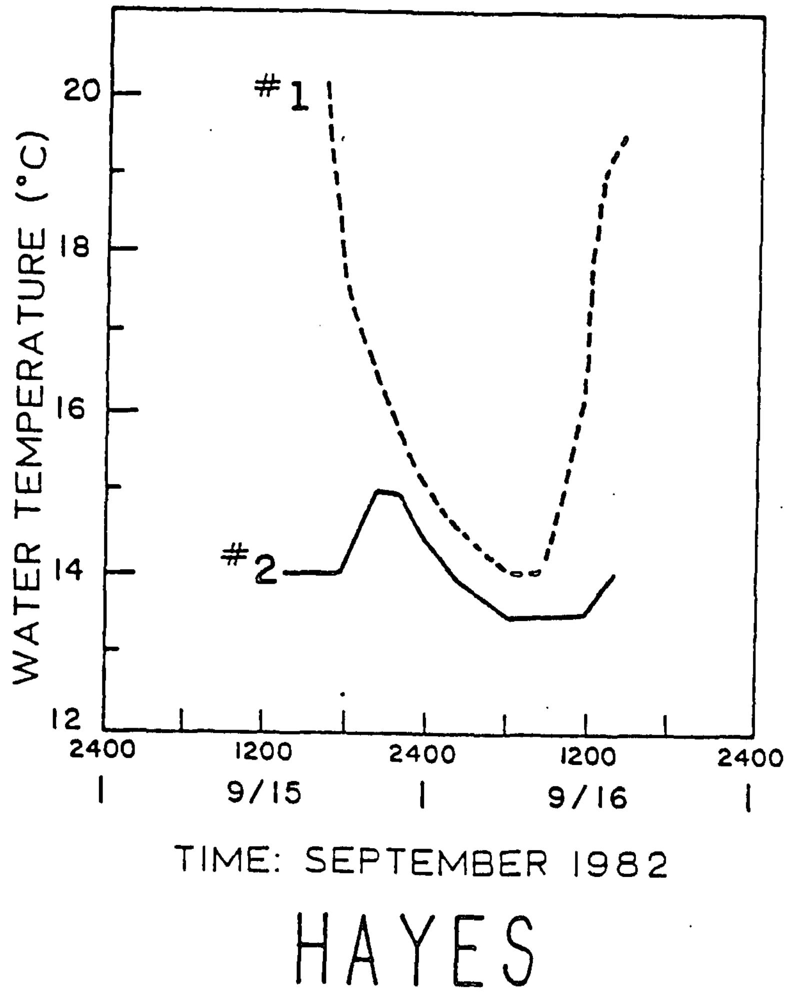


Figure 19. Water temperatures in Hayes Creek Cold Pool, September 15 and 16, 1982. Temperatures were measured with continuously recording thermographs placed in the mainstream (#1) and in the cold pool (#2). Station locations are shown in Figure 15. Location of the pool is shown in Figure 3.

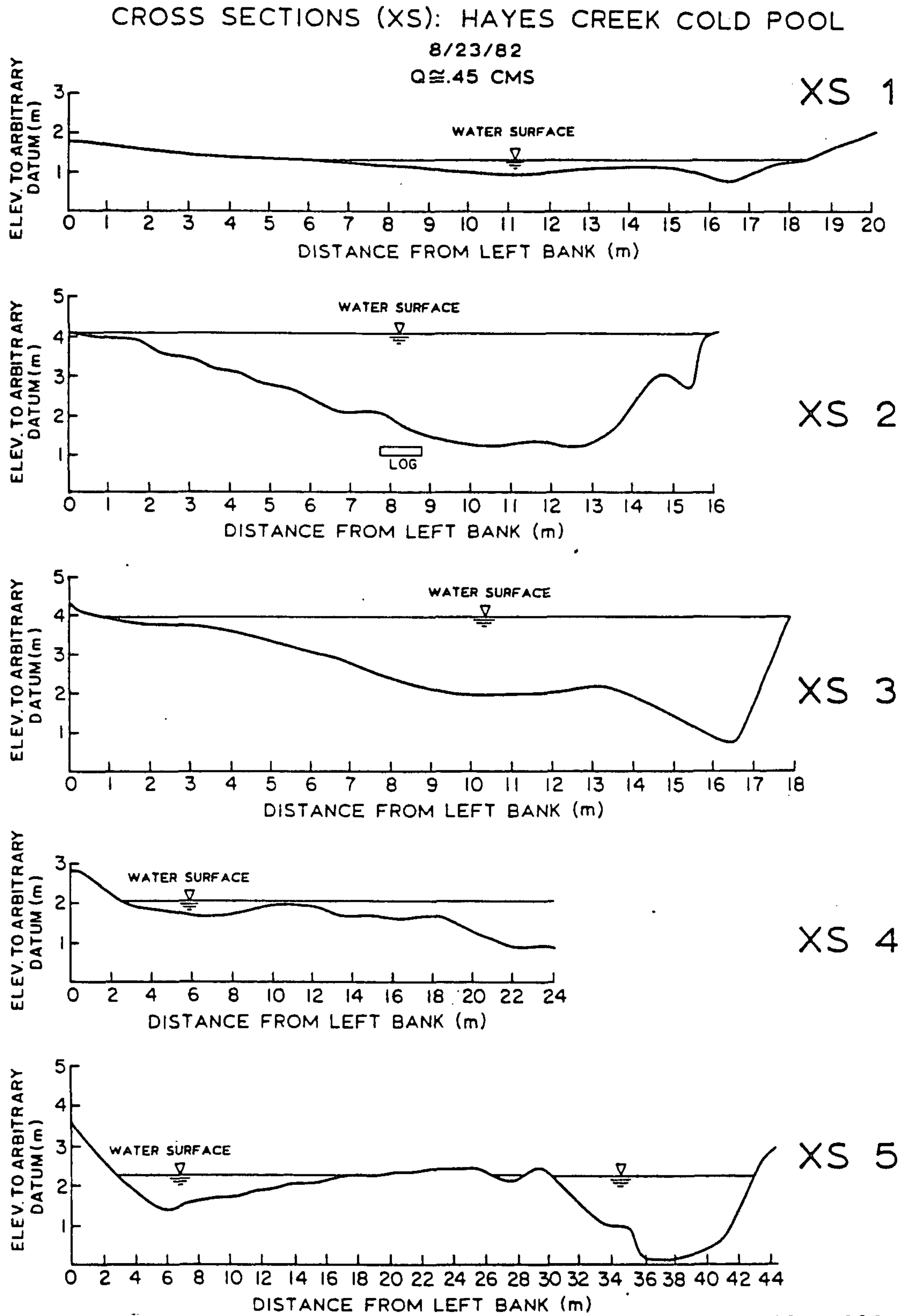


Figure 20. Cross-sections, Hayes Creek Cold Pool, August 23, 1982. Locations of cross-sections are shown in Figure 18.

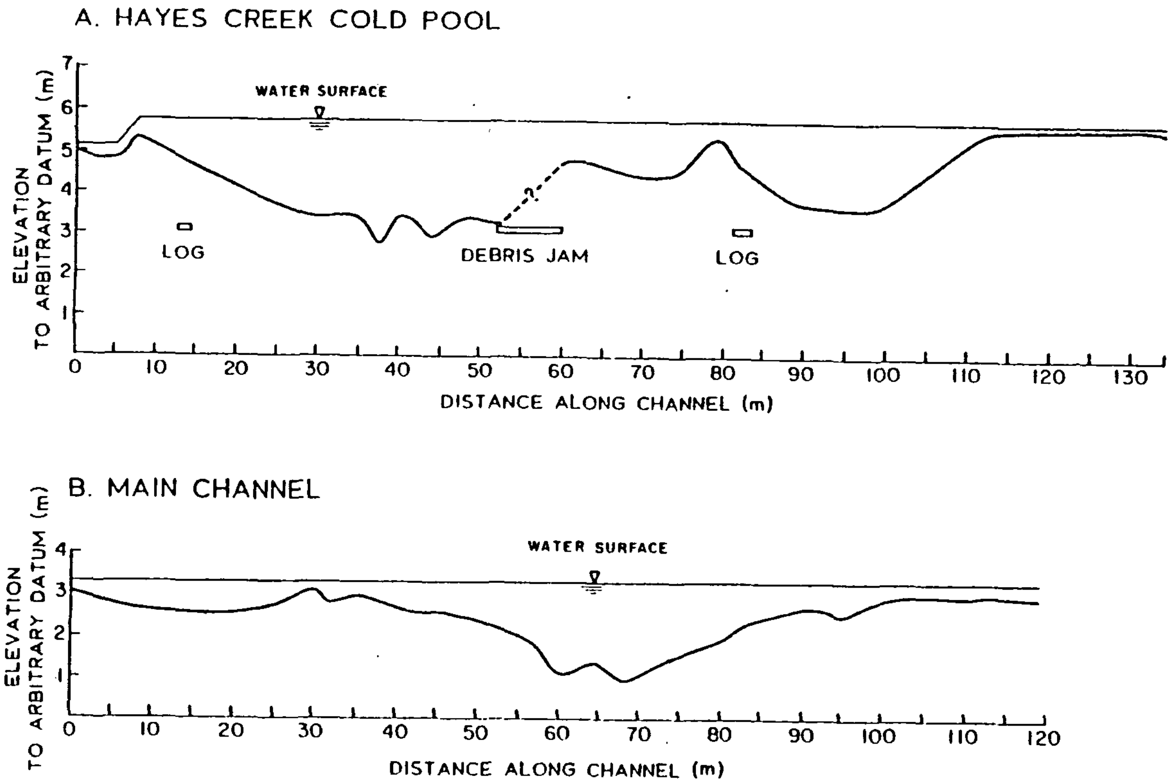


Figure 21. Longitudinal profiles, Hayes Creek Cold Pool and the main channel of Redwood Creek. Profile locations are shown in Figure 15.

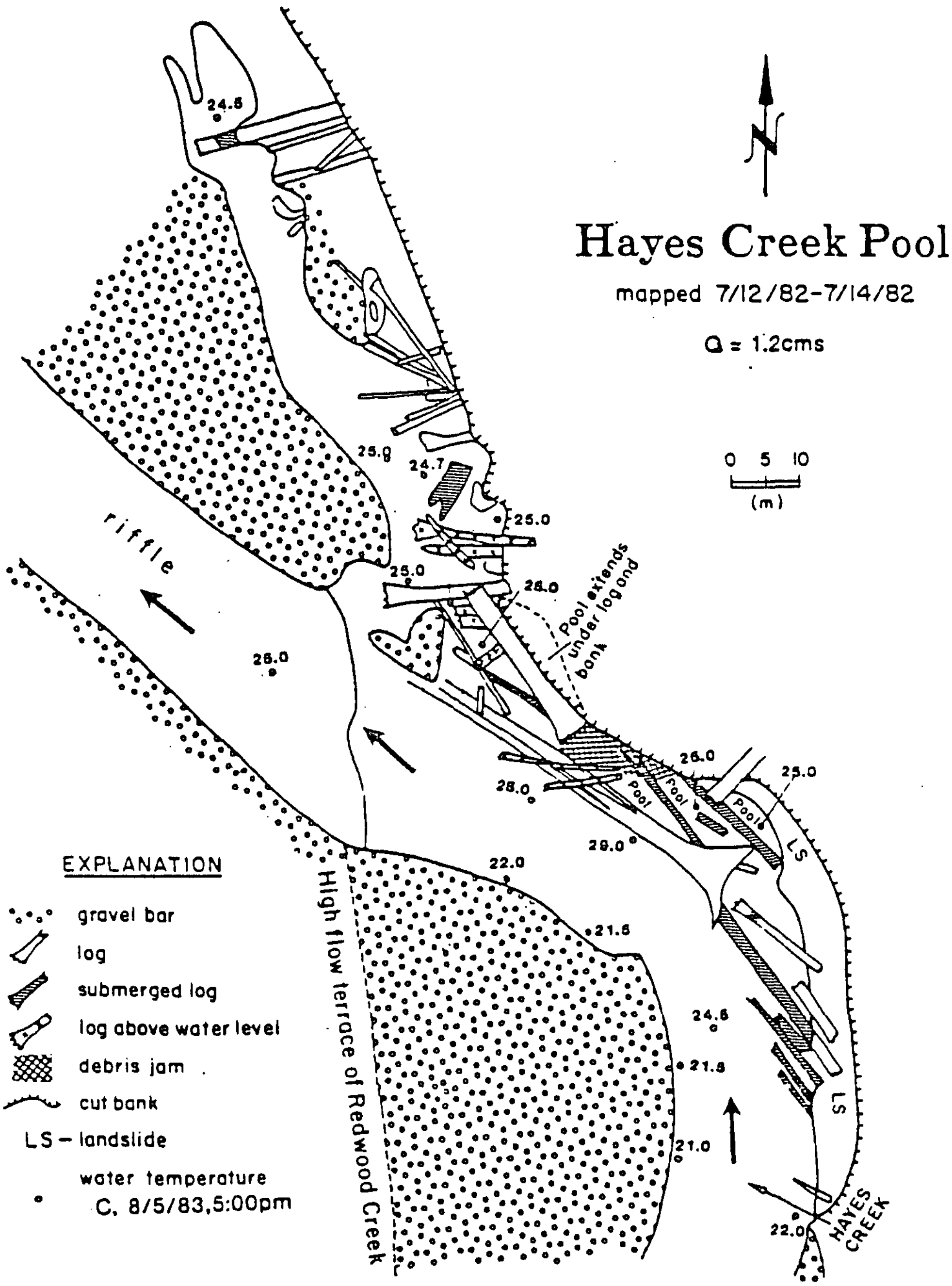


Figure 22. Water temperatures, Hayes Creek Cold Pool, August 5, 1983. Location of the pool is shown in Figure 3.

water.

Cold water was found flowing out of the gravel bar on the left side of the pool, as shown in Figure 22. Apparently, water from Redwood Creek cooled as it flowed subsurficially through the gravel bar. This source was not large enough to cool the whole pool because there was no type of barrier to retard this cold water from mixing with the main stream - one of the three requirements for cold pool formation.

Elam Creek Cold Pool

The cold pool located at the junction of Elam Creek and Redwood Creek (Fig. 3), was first noted in September, 1982. The pool formed by scour along a bedrock outcrop of schist on the outside of a meander bend (Fig. 23). Cross sections and longitudinal profiles through the pools and the main stream are shown in Figures 24 and 25.

In 1982, the pool had temperatures as much as 7°C below ambient (Fig. 23). There were a variety of sources of cold water for the pool: 1) seepage from fractures in the schist outcrop on the NW end of the pool, 2) seepage emerging from a landslide on the left bank, and 3) intra-gravel flow of water from Elam Creek. A side channel gravel bar acted as the barrier to mixing between the cold pool and the mainchannel (Fig. 23). Large organic debris was not present at this site.

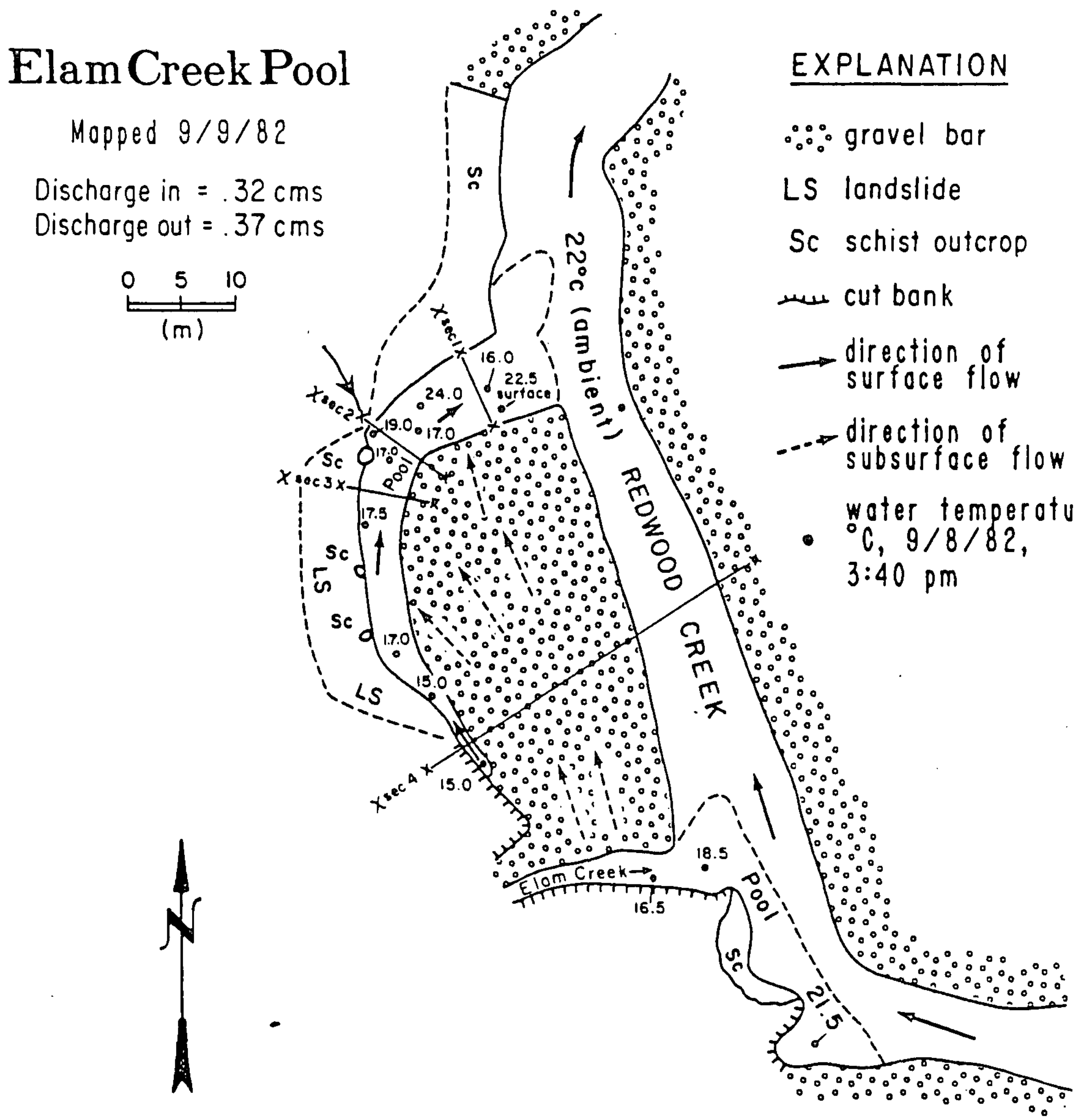


Figure 23. Morphological map and water temperature measurements Elam Creek Cold Pool, September 8, 1982. Location of the map is shown in Figure 3.

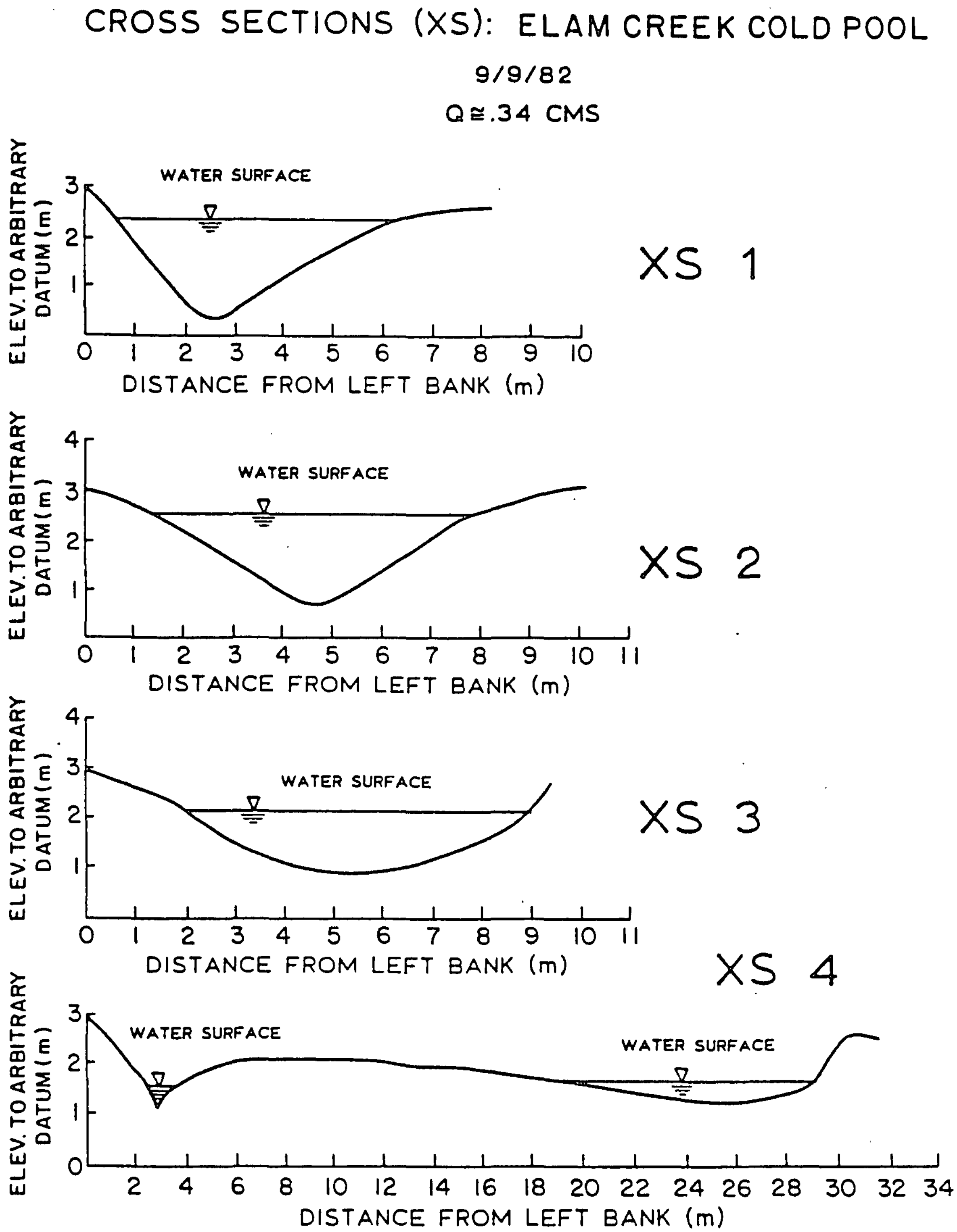


Figure 24. Cross-sections. Elam Creek Cold Pool, September 1982. Locations of cross-sections are shown in Figure 23.

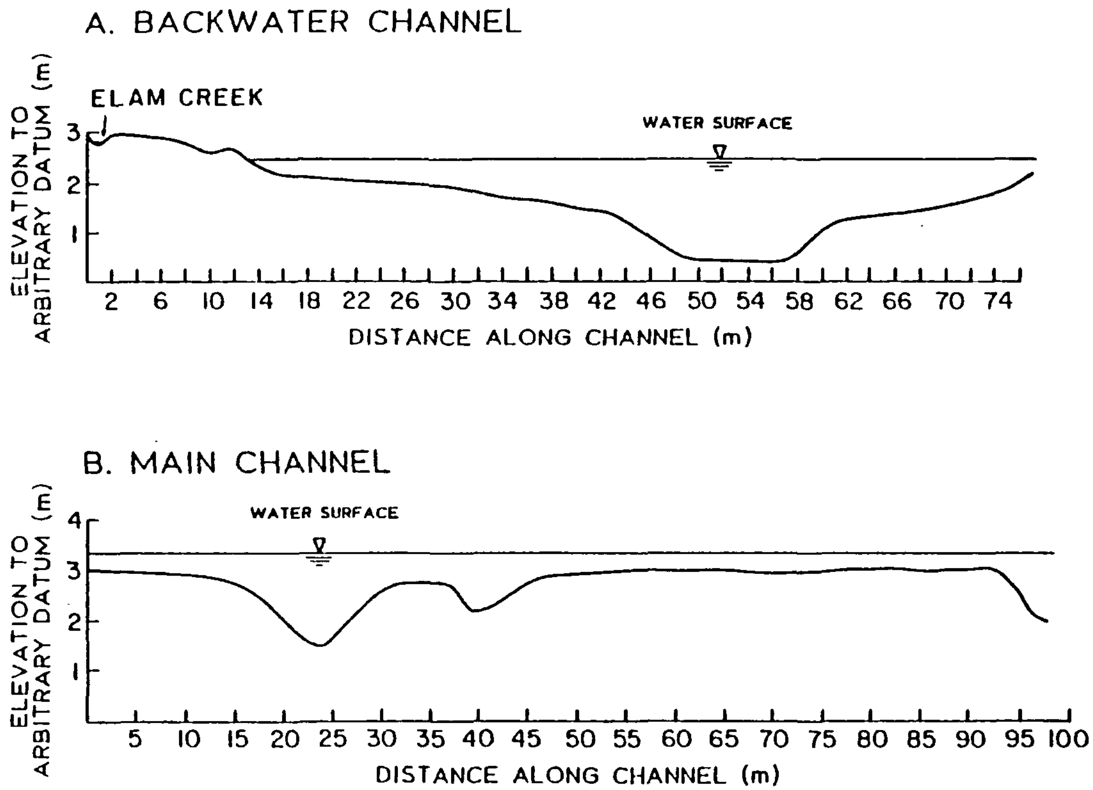


Figure 25. Longitudinal profiles, Elam Creek Cold Pool and the main channel of Redwood Creek. Profile locations are shown in Figure 26.

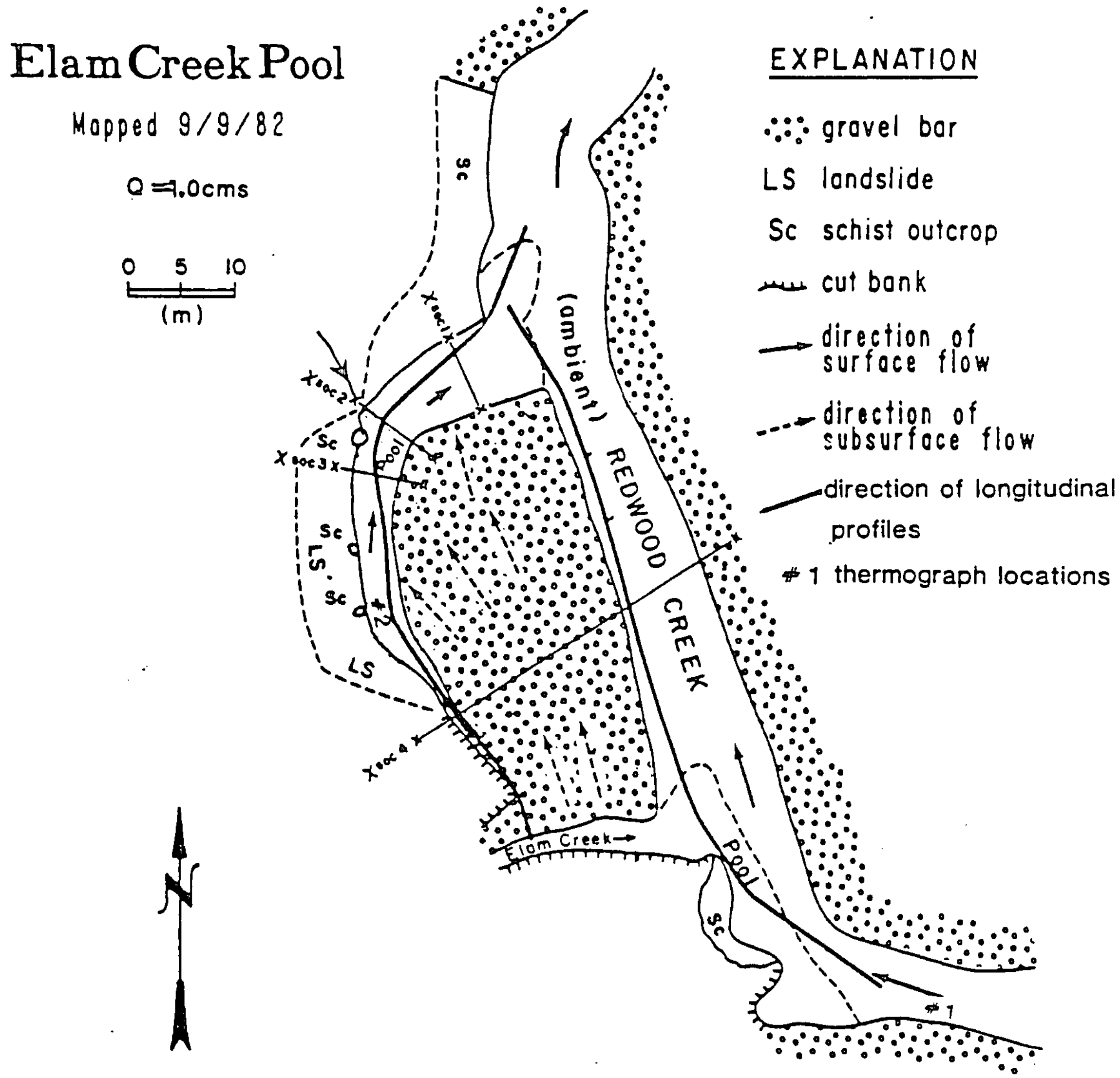


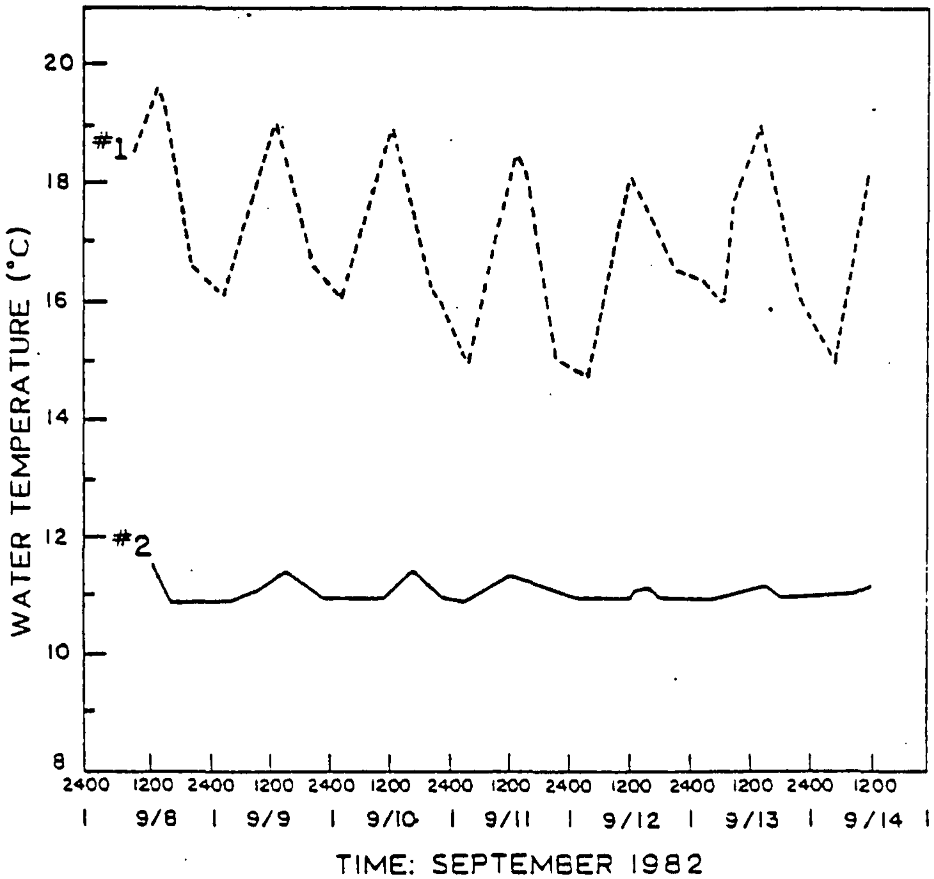
Figure 26. Morphologic map, Elam Creek Cold Pool, September 8, 1982. Direction of the longitudinal profiles (Fig. 25) and thermograph locations (Fig. 27) are shown. Location of the pool is shown in Figure 3.

The thermograph data in Figure 27 shows that the temperature differences between the cold pool and the main stream were consistent over 7 days. It is interesting to note that shading was not a factor in cooling the pool, as both thermographs were placed in direct sunlight.

During the winter of 1982-1983, the only change which occurred in the morphology of the pool was scouring of a small channel from Elam Creek to the cold pool. Water temperature data show that this did not affect the overall temperature differences between the pool and the main stream (Figs. 28, 29 and 30).

Emerald Cold Pools

Two cold pools were found just downstream of the confluence of Emerald with Redwood Creek and upstream from the Tall Trees Grove (Fig. 3). The pools formed as a result of scour around a large debris jam which accumulated against a schist outcrop on the outside of a bend. In 1982, the pool on the left bank was 3.5°C cooler than the main stream, while the small mid-channel pool showed a temperature difference of 2.5°C (Fig. 31). The source of cold water for the larger pool appeared to be a series of seeps emerging from a landslide on the left bank, with the debris jam and a gravel bar acting to retard mixing - similar to the situation at Hayes Creek. As shown in Figures 32 and 33, this pool was remarkably deep - up to



ELAM

Figure 27. Water temperatures in Elam Creek Cold Pool, September 8 - September 14, 1982. Temperatures were measured with continuously recording thermographs placed in the mainstream (#1) and in the pool (#2). Station locations are shown in Figure 26.

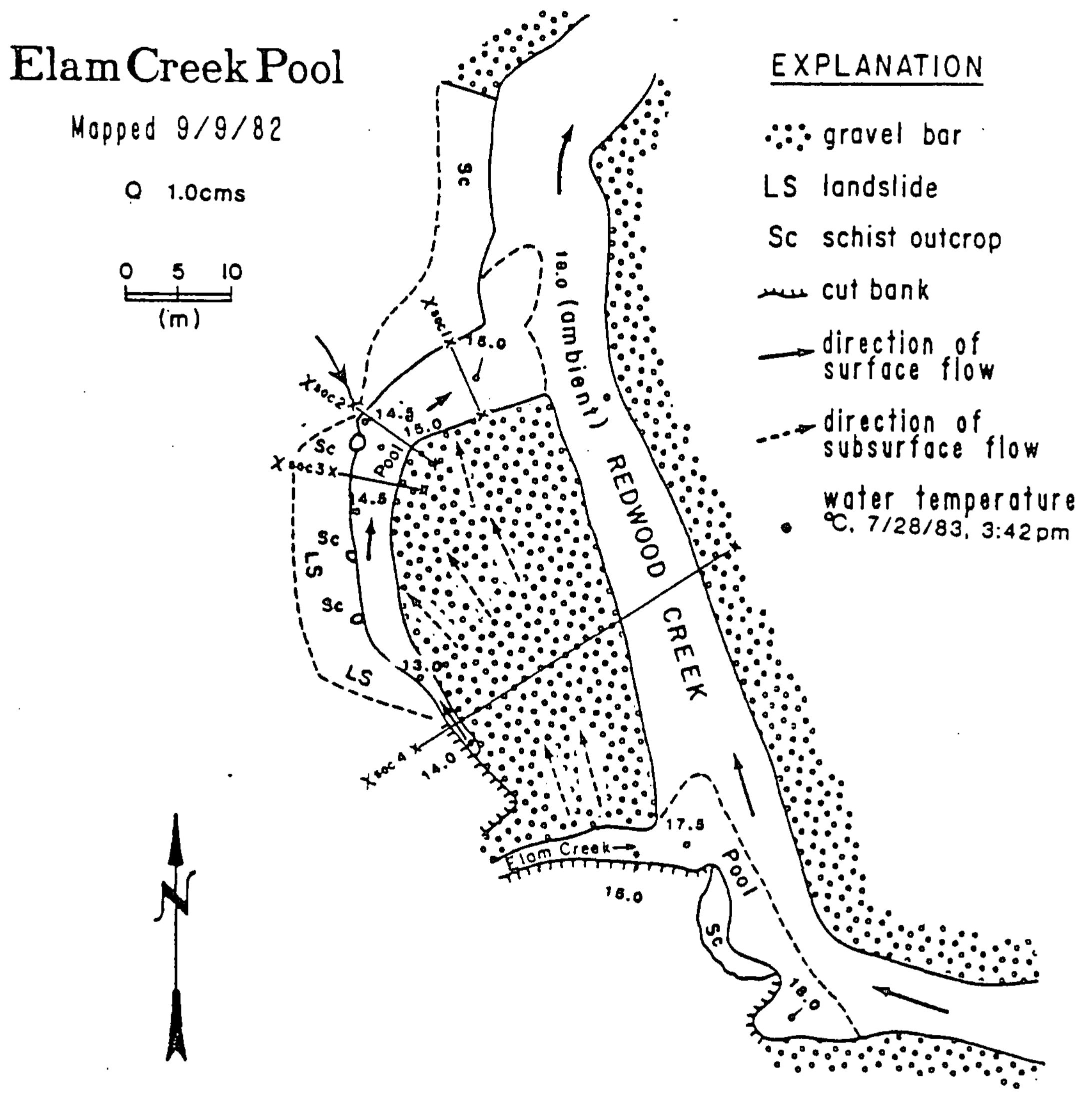


Figure 29. Water temperatures, Elam Creek Cold Pool, July 28, 1983. Location of the pool is shown in Figure 3.

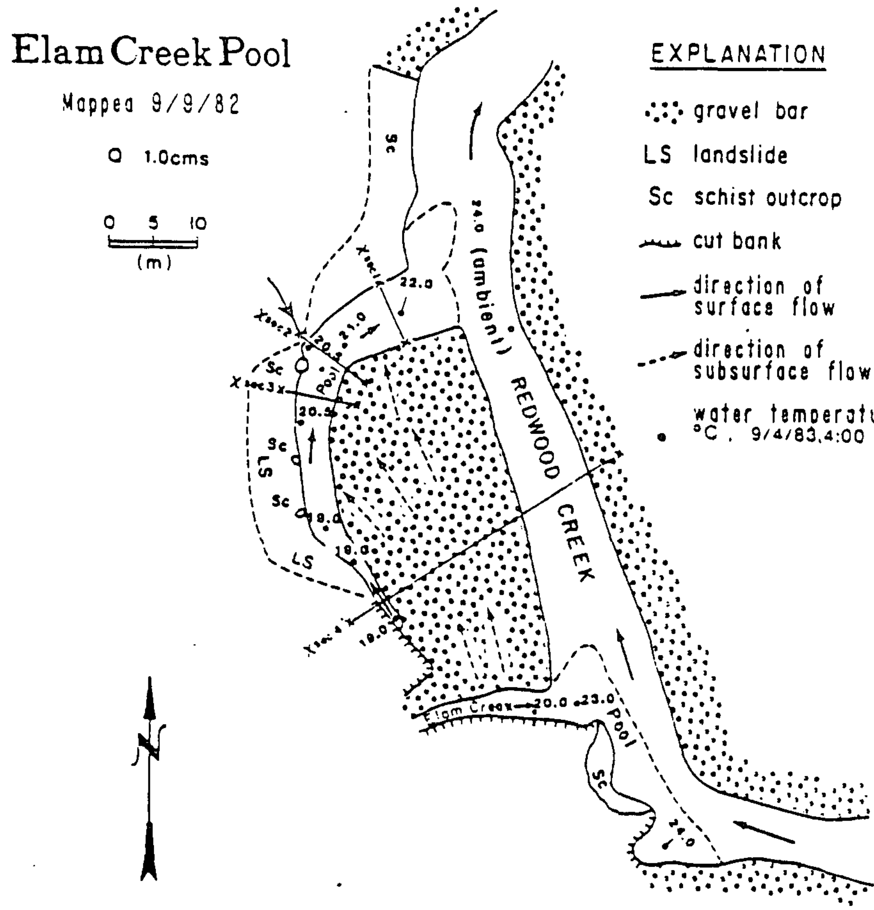


Figure 30. Water temperatures, Elam Creek Cold Pool, September 4, 1983. Location of the pool is shown in Figure 3.

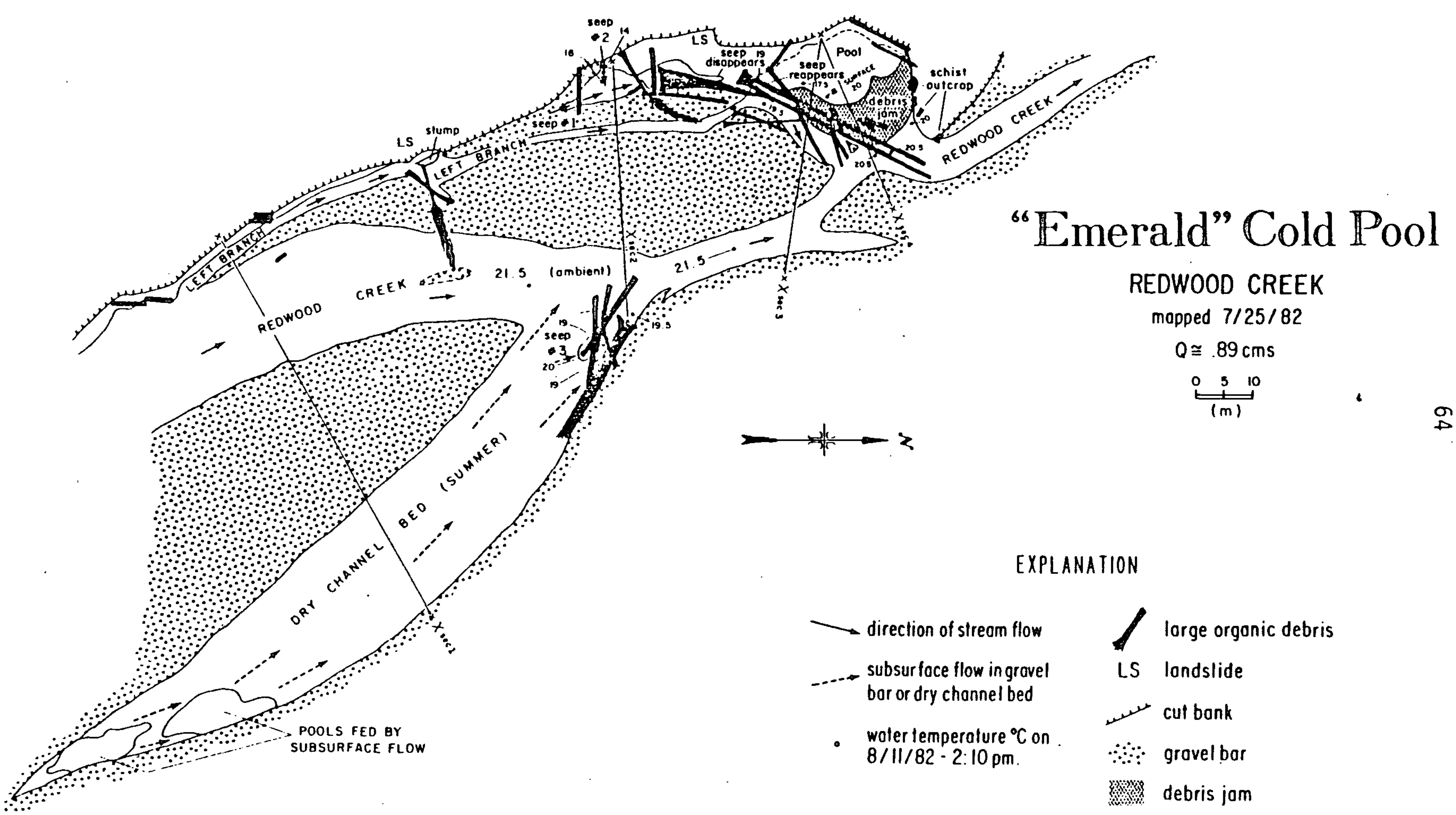


Figure 31. Morphological map and water temperature measurements, Emerald Cold Pool, August 11, 1982. Location of the pool is shown in Figure 3.

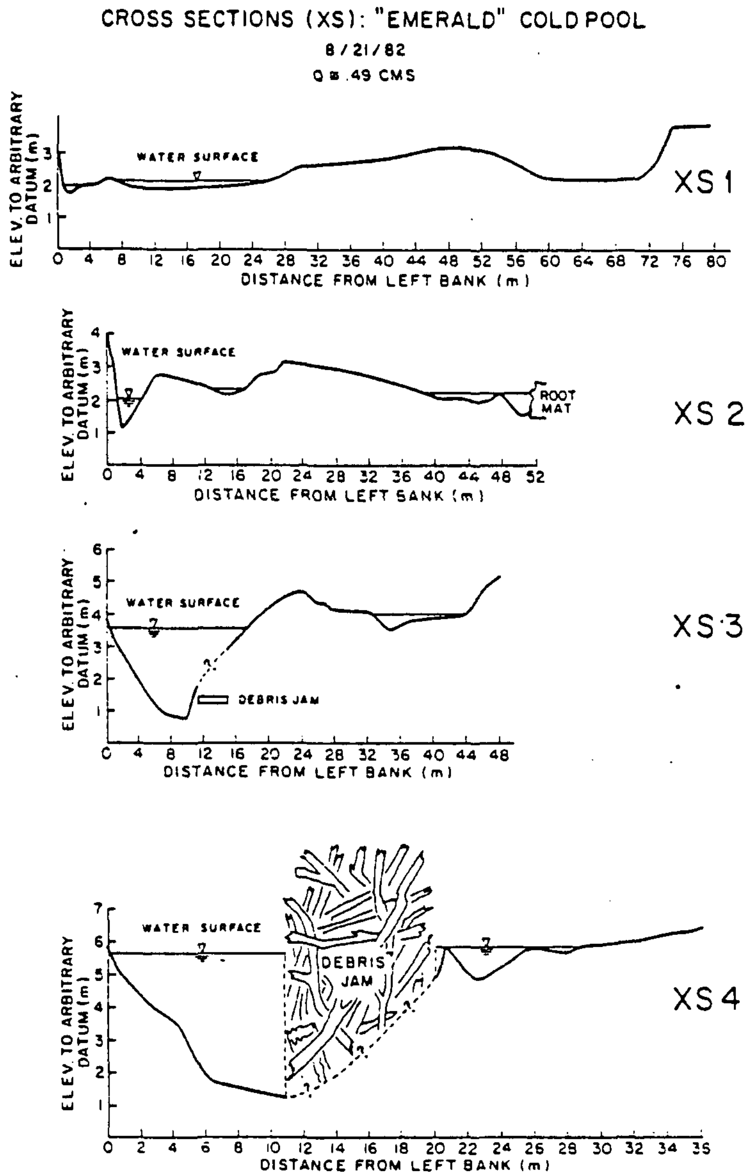


Figure 32. Cross-section, Emerald Cold Pool, August 1982. Locations of cross-sections are illustrated in Figure 31.

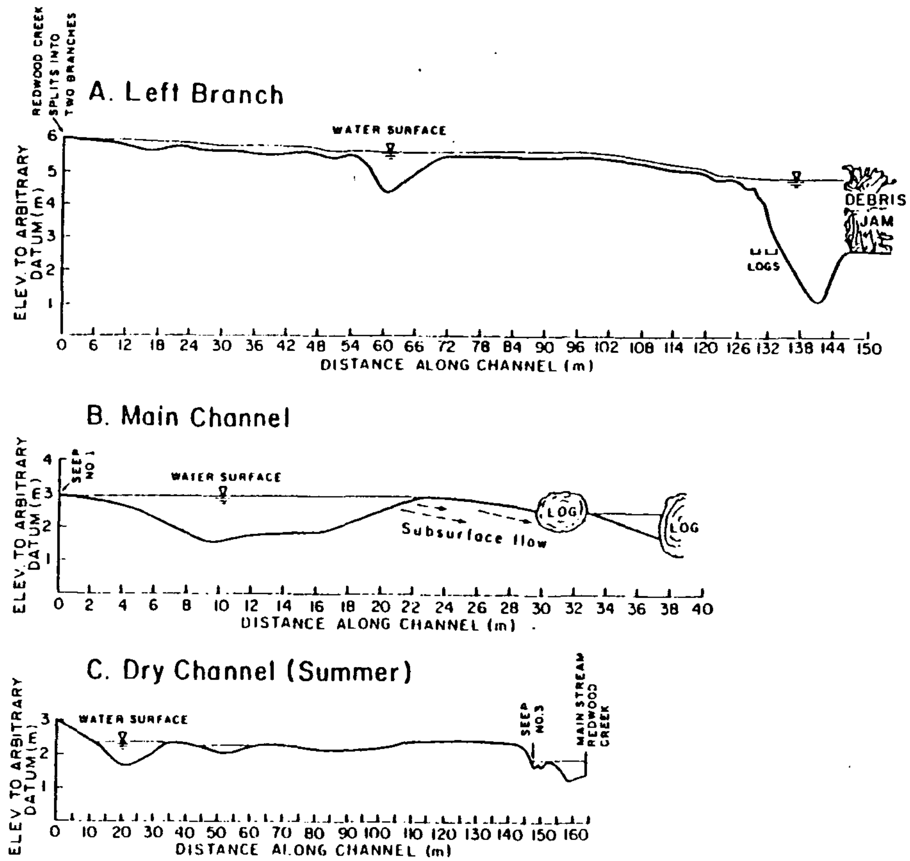


Figure 33. Longitudinal profiles, left branch of Redwood Creek into Emerald Cold Pool; main channel of Redwood Creek; and along the dry (summer) channel into the smaller cold pool, August 1982. Profiles are located in Figure 34.

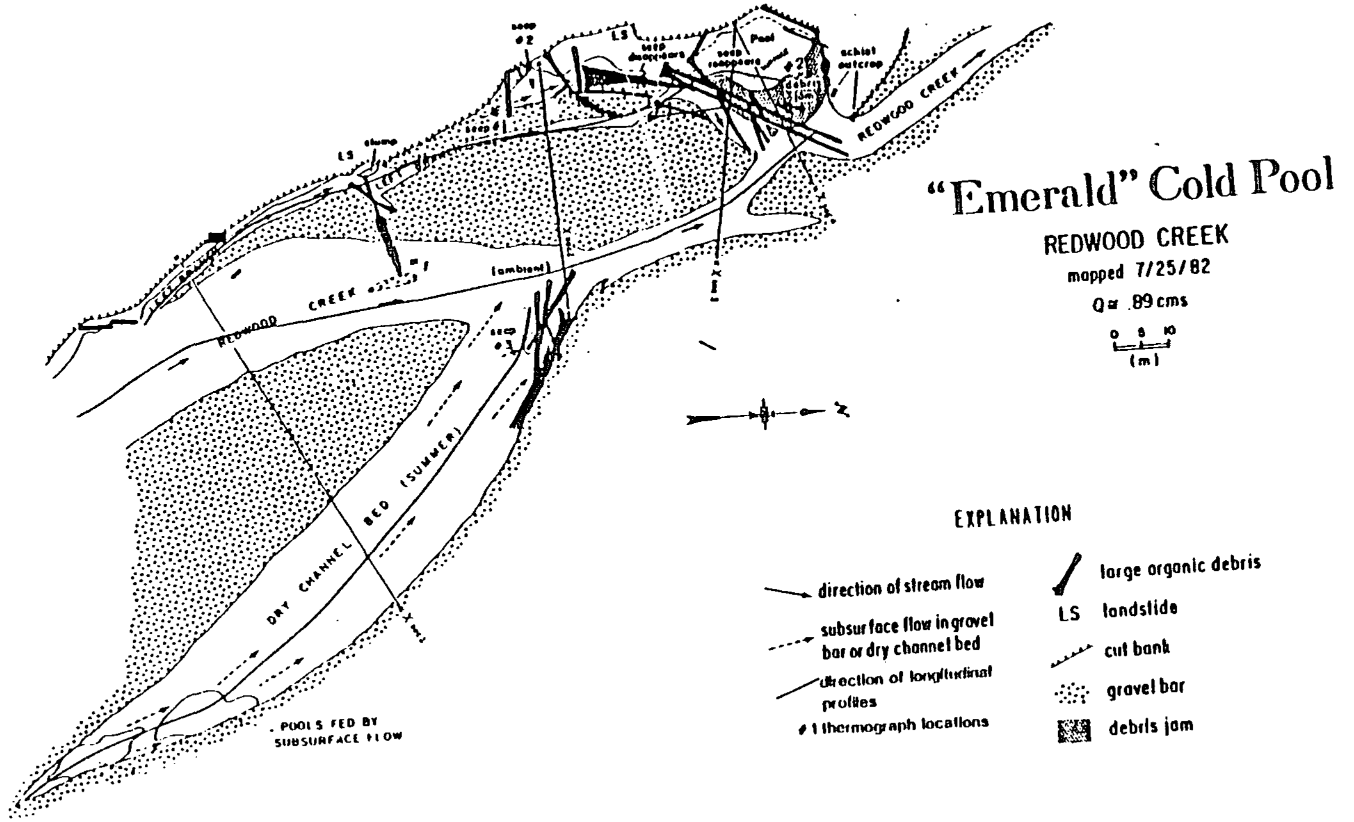


Figure 34. Morphologic map, Emerald Cold Pool, July 25, 1982. Direction of the longitudinal profiles (Fig. 33) and thermograph locations (Fig. 35) are shown. Location of the pool is shown in Figure 3.

5 meters.

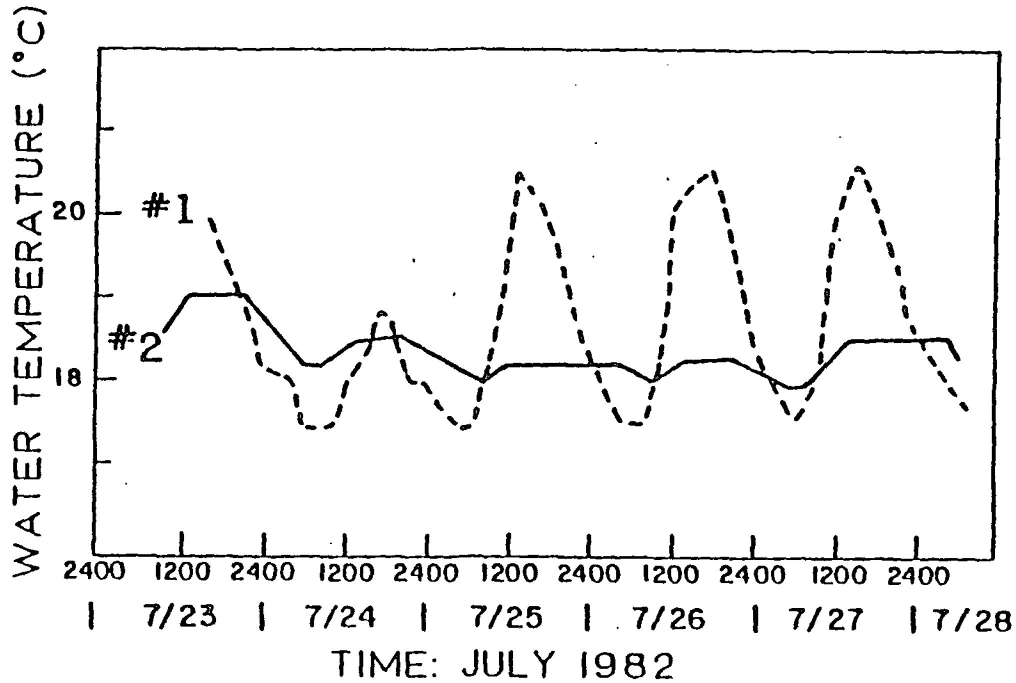
The other smaller pool was cooled by intragravel flow. At some point upstream, the warmer main stream water of Redwood Creek entered the gravel of a dry channel and cooled as it flowed toward the pool (Fig. 31). Large organic debris then slowed this water in mixing with the mainstream.

The thermographs were placed at the bottom of the larger pool and in the main stream. At first glance, it appears as if there is an inconsistency in the data (Fig. 35), since the pool remains warmer than the main stream during the night, with cooler temperatures seen only during the day. I suggest that this is due to insulation of the pool by its covering of floating debris. The shading, combined with the isolation of the pool from the main stream, allowed the pool to remain cooler during the day, while the cover provided an insulating "blanket" against the dropping night temperatures.

As seen in the cross sections in Figure 36, the configuration of the pools changed drastically during the winter of 1982-1983. Conditions favoring scour evidently ceased, as the larger pool almost completely filled with sediment, and the smaller pool disappeared entirely.

Footbridge Cold Pool

The fourth cold pool is located just downstream of McArthur Creek (Fig. 3), where a footbridge is placed across Redwood Creek



"EMERALD"

Figure 35. Water temperatures in Emerald Cold Pool, July 23 - July 28. Temperatures were measured with continuously recording thermographs placed in the mainstream (#1) and in the pool (#2). Station locations are shown in Figure 34.

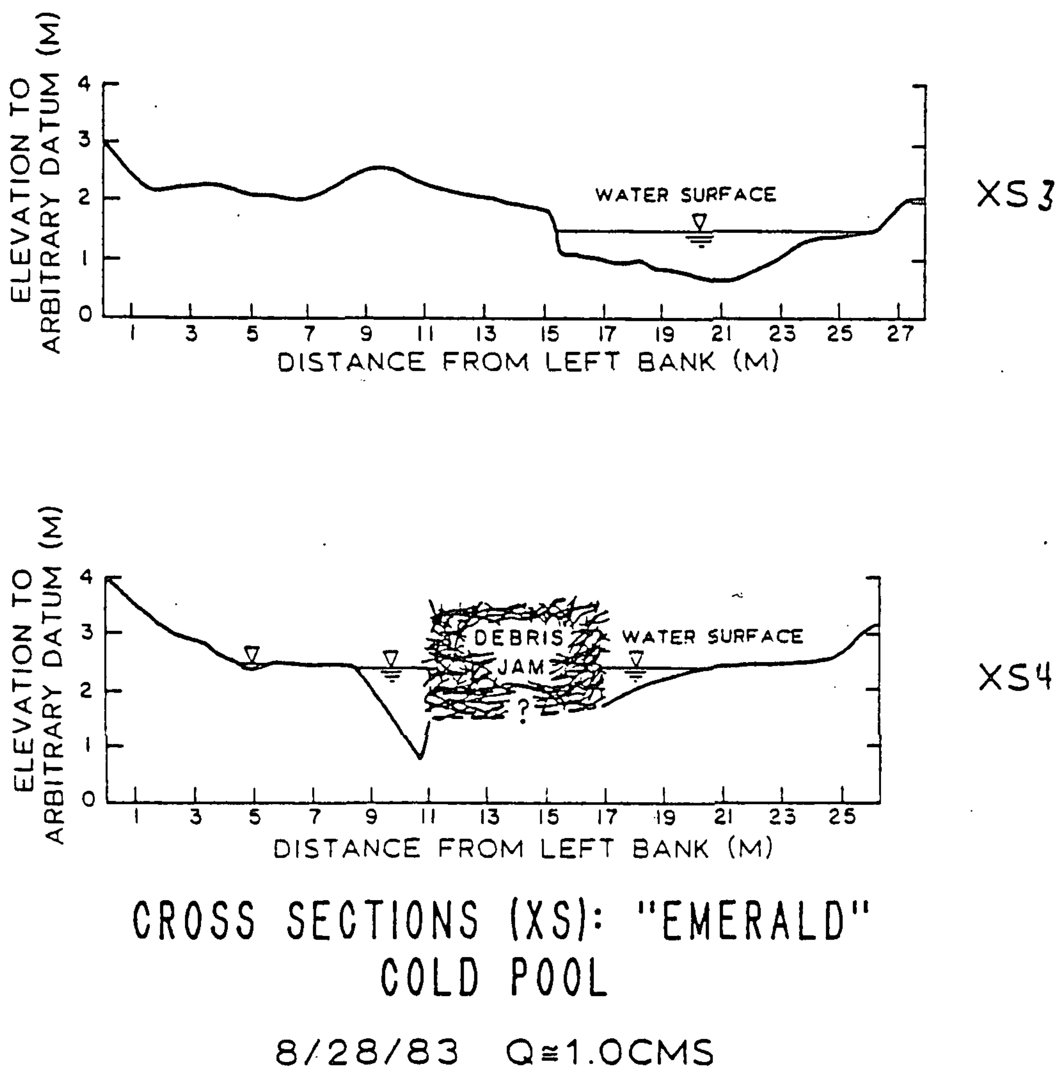


Figure 36. Cross-sections, Emerald Cold Pool, August 1983. Cross-sections correspond to cross-sections 3 and 4 shown in Figures 31 and 32.

during the summer low flows. The pool was apparently formed by scour induced by the schist outcrop on the left bank (Fig. 37).

Although cold water (approximately 3°C cooler than the mainstream) was found seeping out of a large fracture in the bedrock outcrop in August 1982, it only produced a localized cold spot, and did not effect the pool as a whole. However, by July 1983, the configuration of the gravel bar changed enough that the pool was allowed to cool to temperatures as low as 5°C below ambient (Figs. 37-39). Implacement of a large redwood trunk also helped in preventing the cold water from flowing into the main stream. Cross-sections and longitudinal profiles are shown in Figures 40 and 41.

While the coldest part of the pool remained near the fractures at the base of the outcrop, other sources of cold water were discovered: seeps from a landslide along the western edge of the pool, and a seep flowing into its southern end, which is connected by both surface and subsurface flow to McArthur Creek (Fig. 37).

The thermograph data (Fig. 42) showed that the pool remained consistently cooler over time. Although shading was not an influence on the temperature measurements at this pool, its deepness of 2.5 meters may have aided the bottom of the pool in remaining cool.

Jeremiah Cold Pool

Jeremiah Cold Pool, which is named after the bullfrog seen there, is located just downstream from the confluence of Oscar Larson

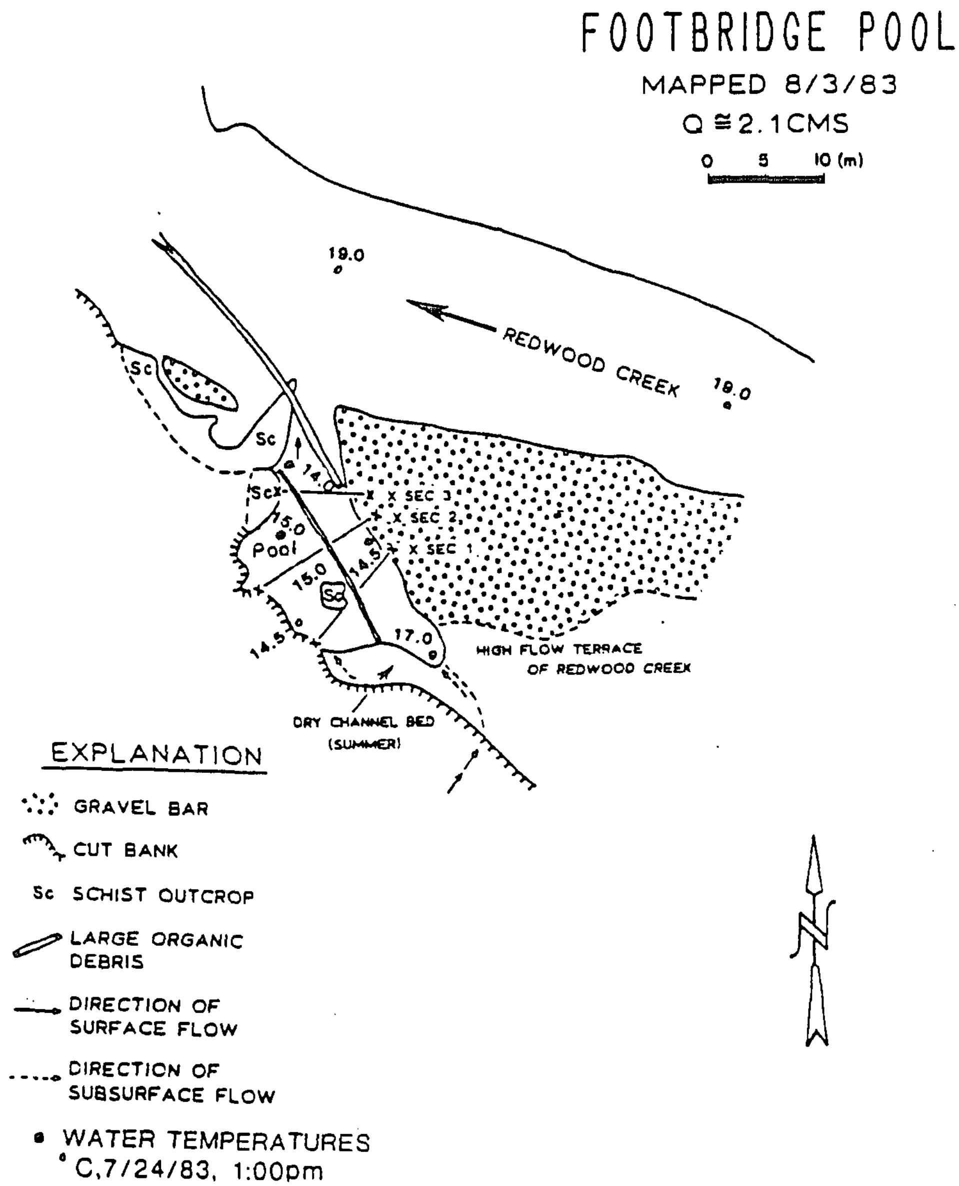


Figure 37. Morphological map and water temperature measurements, Footbridge Cold Pool, July 24, 1983. Location of the pool is shown in Figure 3.

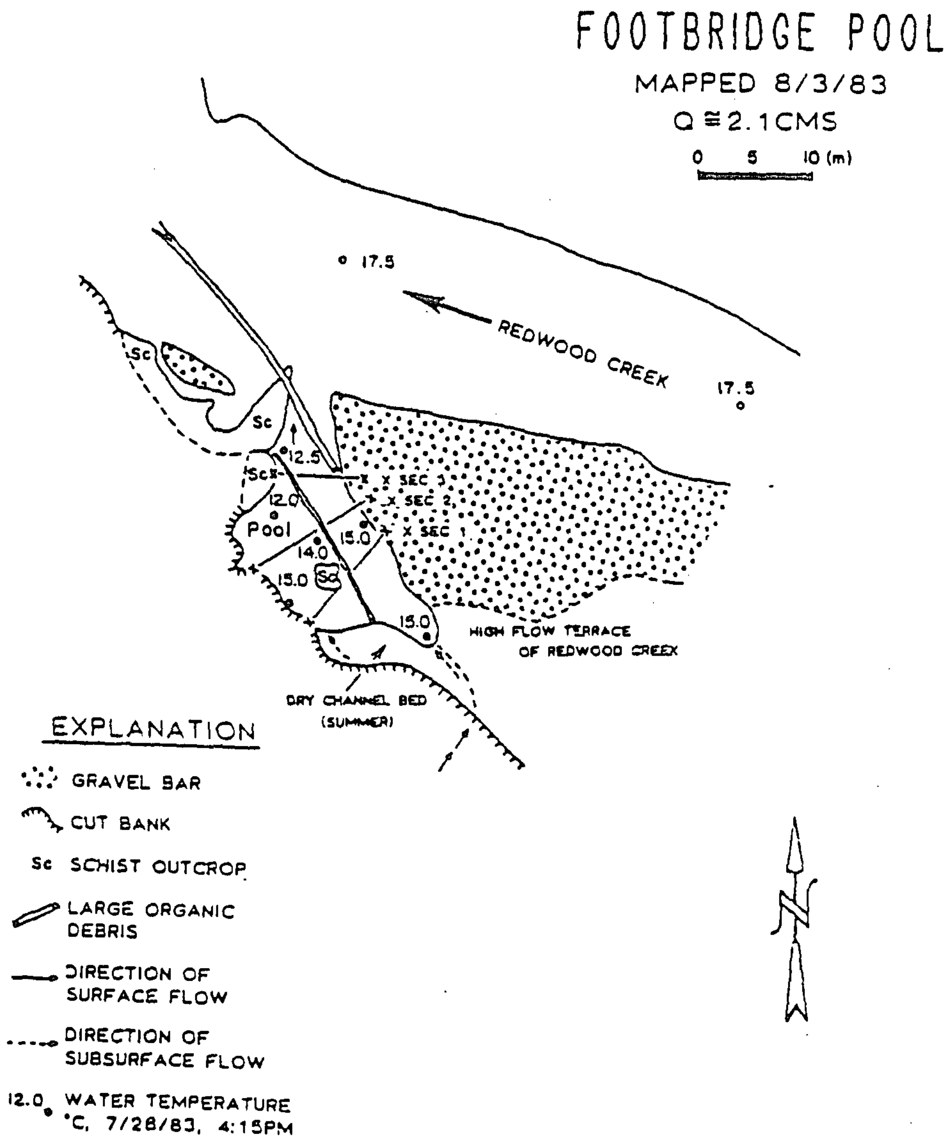


Figure 38. Water temperatures, Footbridge Cold Pool, July 28, 1983. Location of the pool is shown in Figure 3.

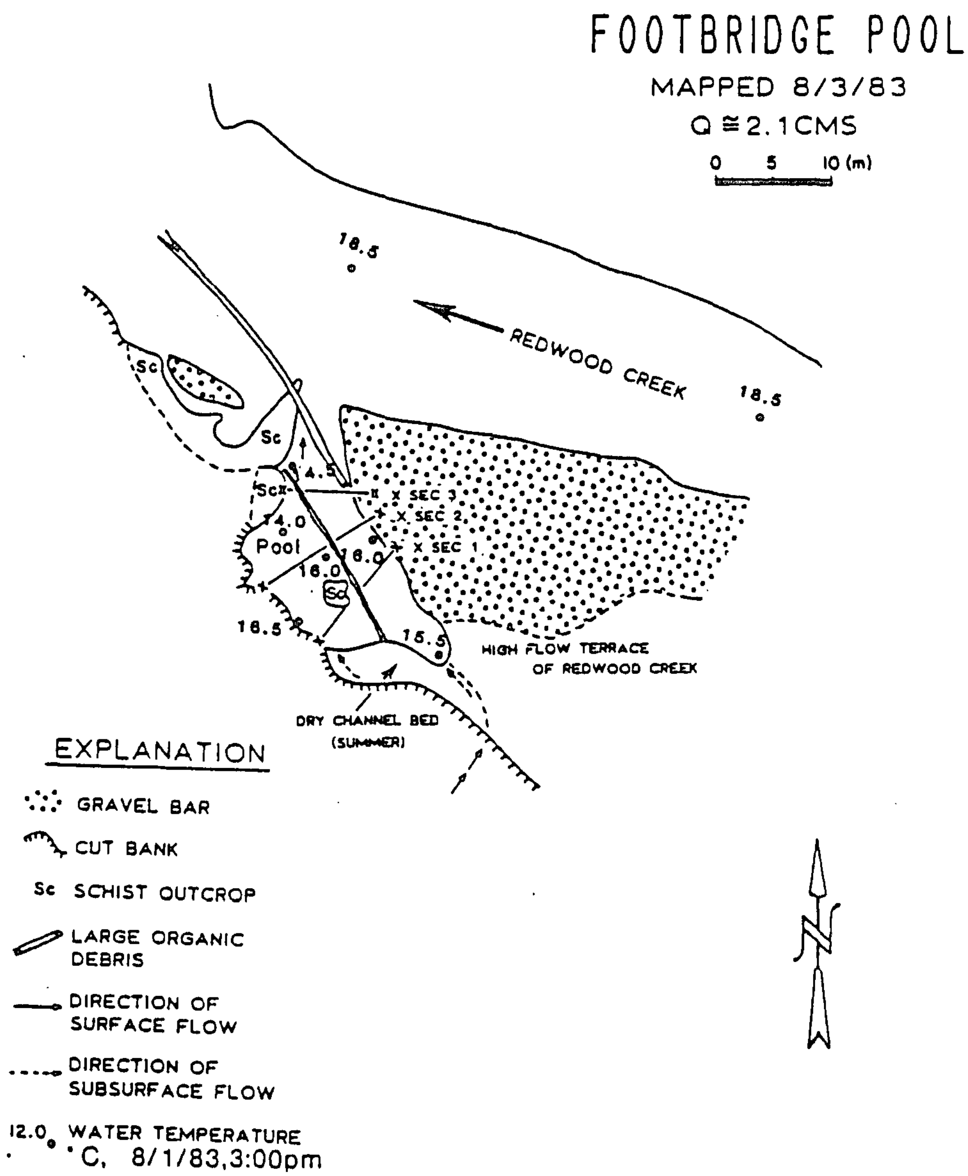


Figure 39. Water temperatures, Footbridge Cold Pool, August 1, 1983. Location of the pool is shown in Figure 3.

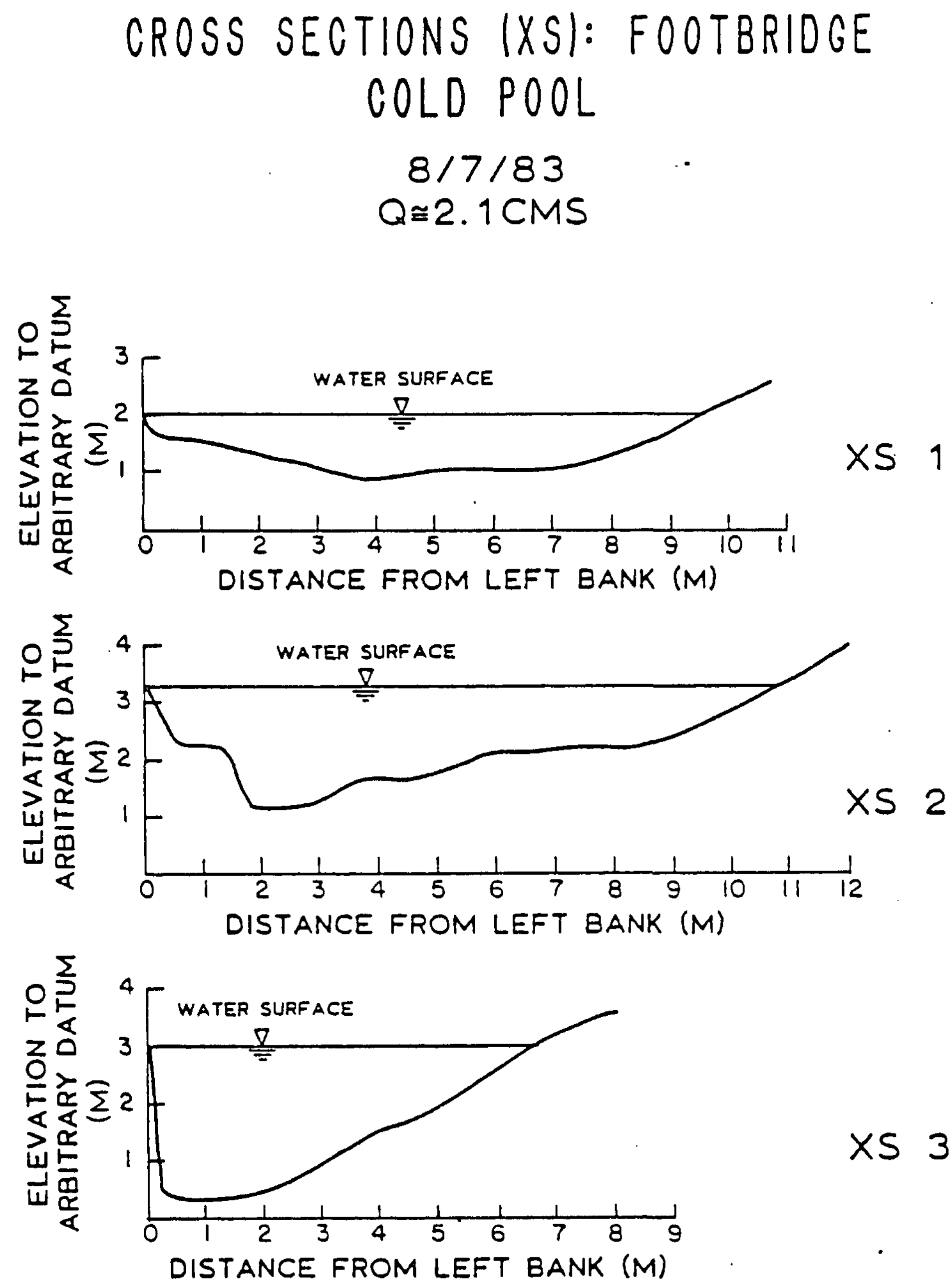


Figure 40. Cross-sections, Footbridge Cold Pool, August 7, 1983. Locations of cross-sections are shown in Figure 37.

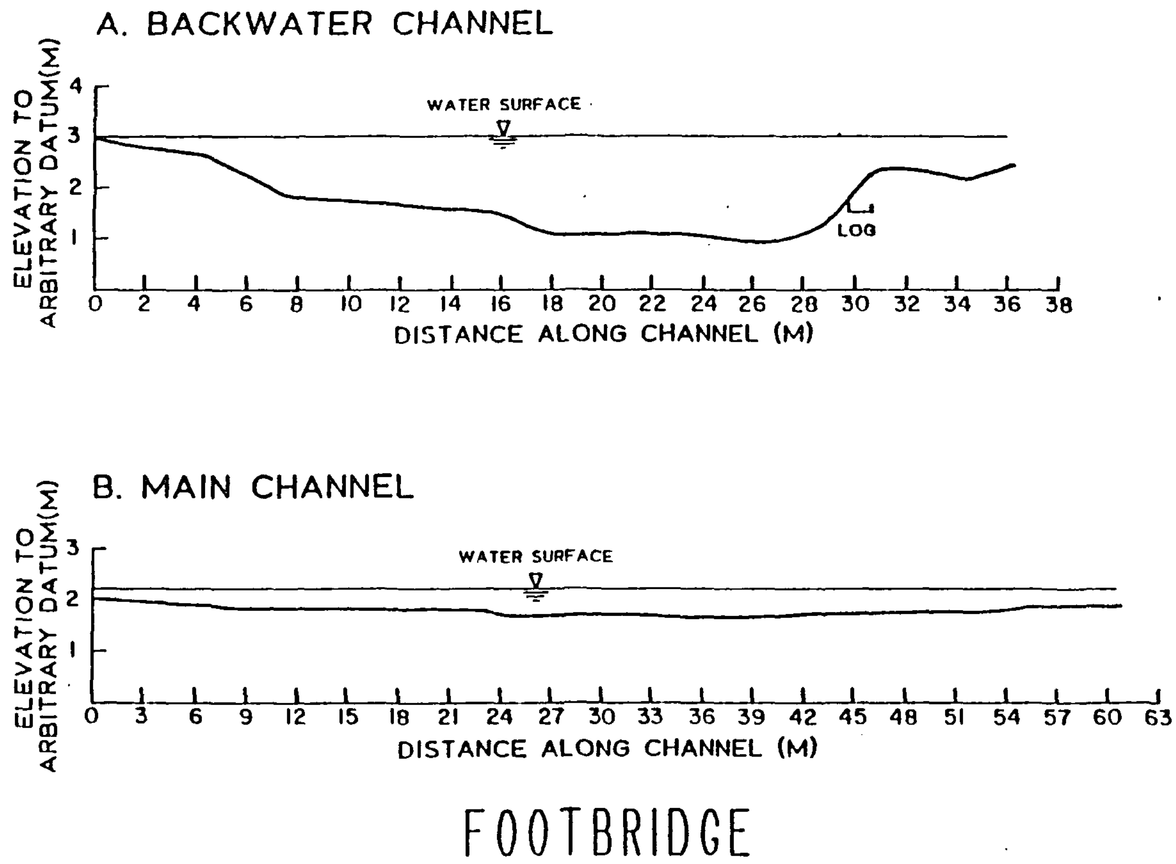
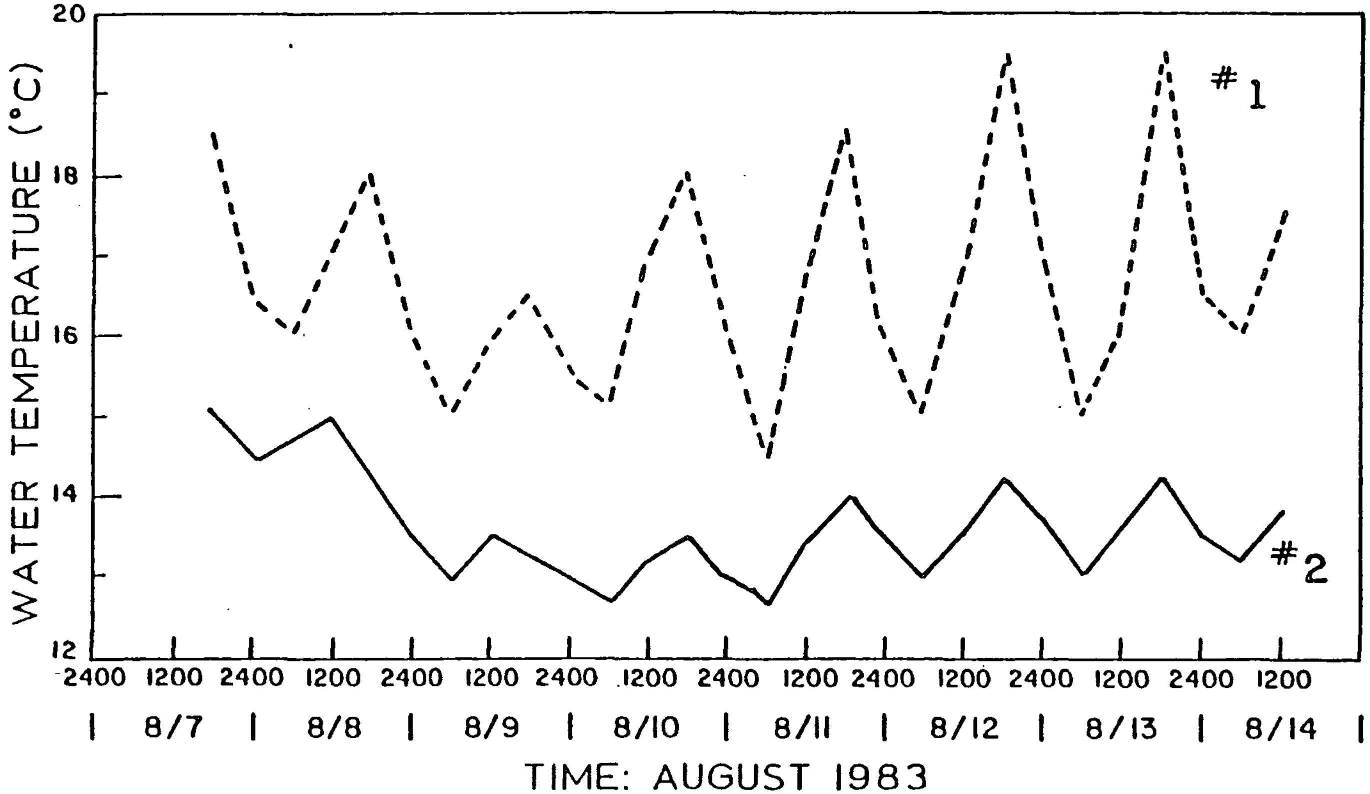


Figure 41. Longitudinal profiles, Footbridge Cold Pool and the main channel of Redwood Creek, August 1983. Profiles are located in Figure 43.



FOOTBRIDGE

Figure 42. Water temperatures in Footbridge Cold Pool, August 7 - August 14, 1983. Temperatures were measured with continuously recording thermographs placed in the mainstream (#1) and in the cold pool (#2). Station locations are shown in Figure 43.

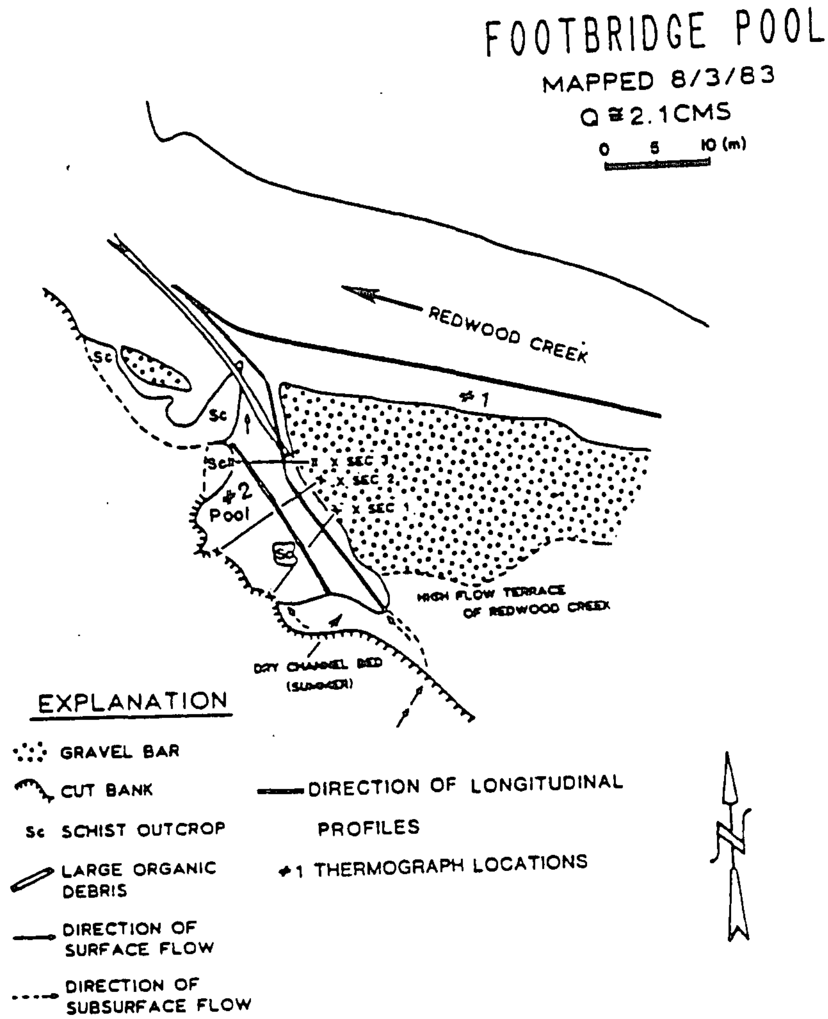


Figure 43. Morphologic map, Footbridge Cold Pool, July 24, 1983. Direction of the longitudinal profiles (Fig. 41) and thermograph locations (Fig. 42) are shown. Location of the pool is shown in Figure 3.

Creek with Redwood Creek (Fig. 3). Similar to most of the other cold pools, it is along the outside of a bend, where both the schist bedrock outcrop and large organic debris induced scour (Fig. 44). Figures 45 and 46 show the cross-sections and longitudinal profiles. Although a cold pool was noted here in August, 1982, it was only approximately 0.5 meters deep. During the winter of 1982-1983 the pool scoured to the 2.5 meter maximum depth seen in July, 1983. This may be due to changes in bedload rates, bar morphology, or a shift of the large organic debris.

The temperature data show that the pool consistently averaged 3°C cooler than the main stream (Figs. 44, 48, 49). There appeared to be three sources of cold groundwater: 1) fractures in the bedrock along the left bank, 2) intragravel seepage from Oscar Larson Creek just upstream, and 3) intragravel seepage from the main stream through the long gravel bar which isolates the pool from the main channel. Intragravel flow is suggested by temperatures along the gravel bar which are 1-2°C cooler than the center of the pool (Fig. 48).

The thermograph data agrees with the temperature readings taken by thermometers, with a consistent 3-4°C difference between the pool and the main stream (Fig. 50). Shading had no influence on the readings.

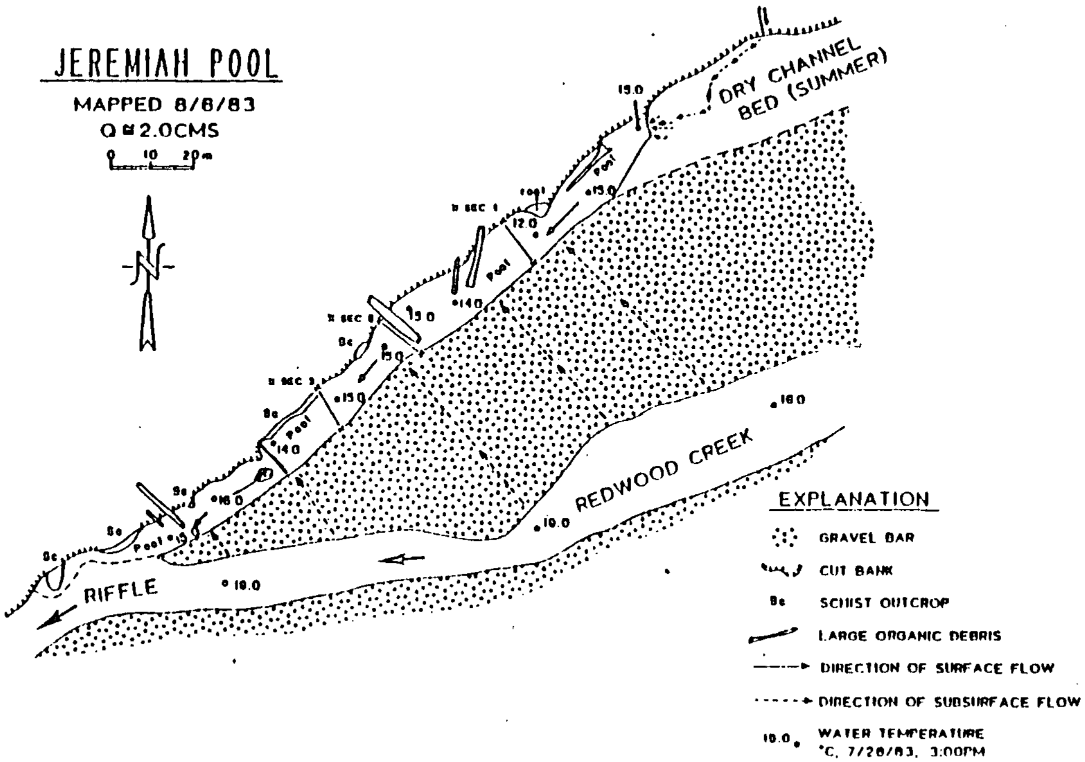


Figure 44. Morphological map and water temperatures, Jeremiah Cold Pool, July 28, 1983. Location of pool is shown in Figure 3.

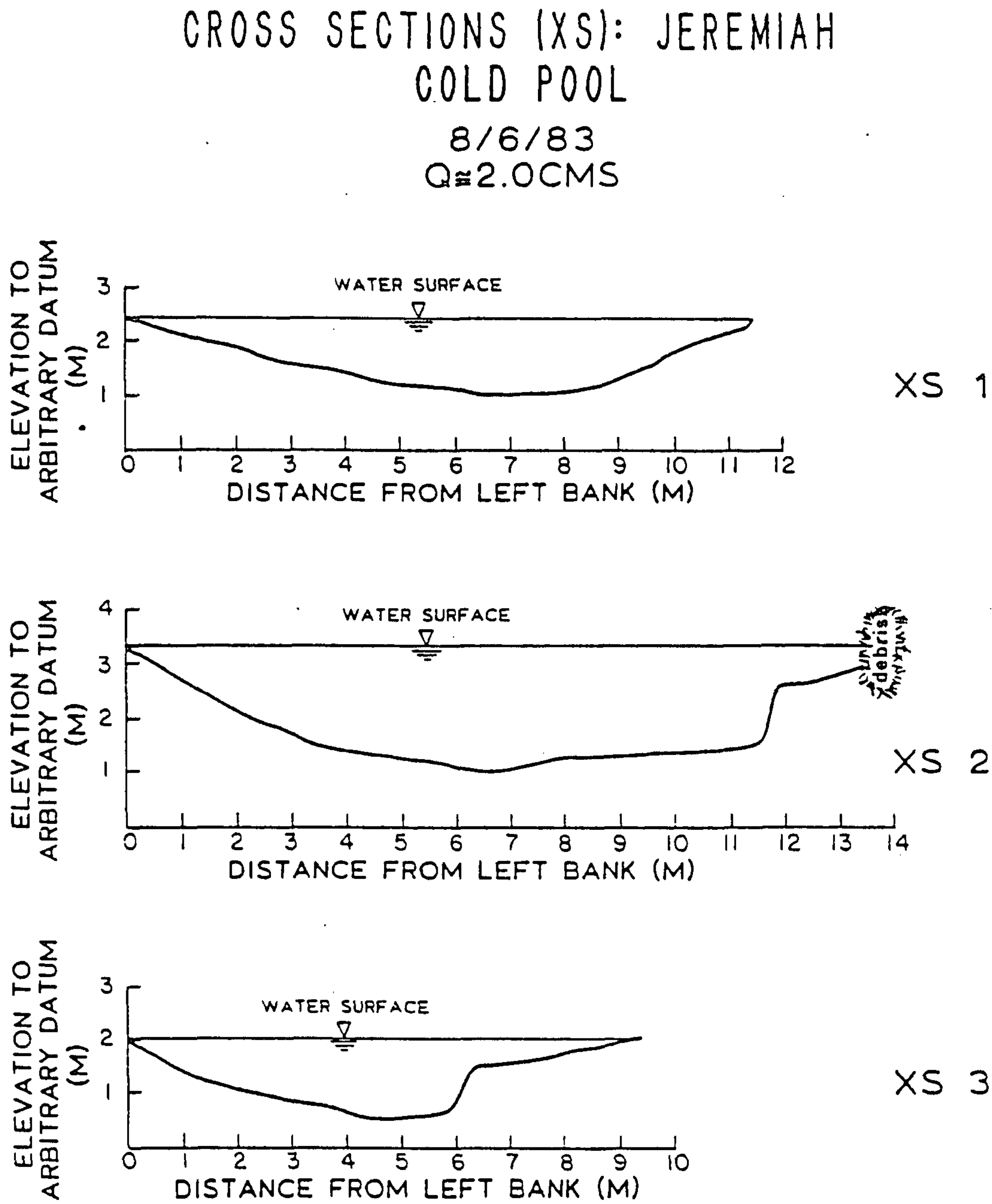
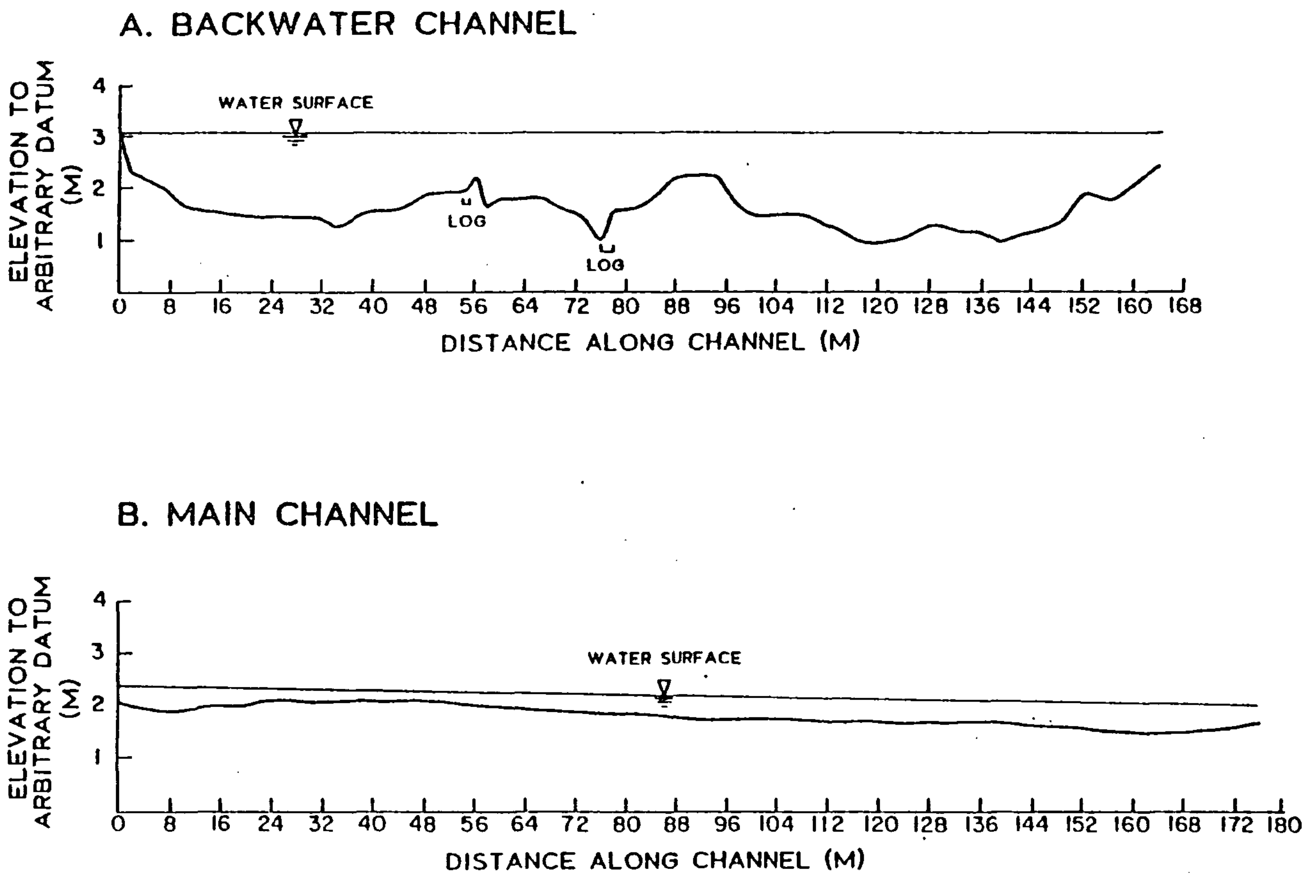


Figure 45. Cross-sections, Jeremiah Cold Pool, August 6, 1983. Locations of cross-sections are shown in Figure 44.



JEREMIAH

Figure 46. Longitudinal profiles, Jeremiah Cold Pool and the main channel of Redwood Creek, August 1983. Profiles are located in Figure 47.

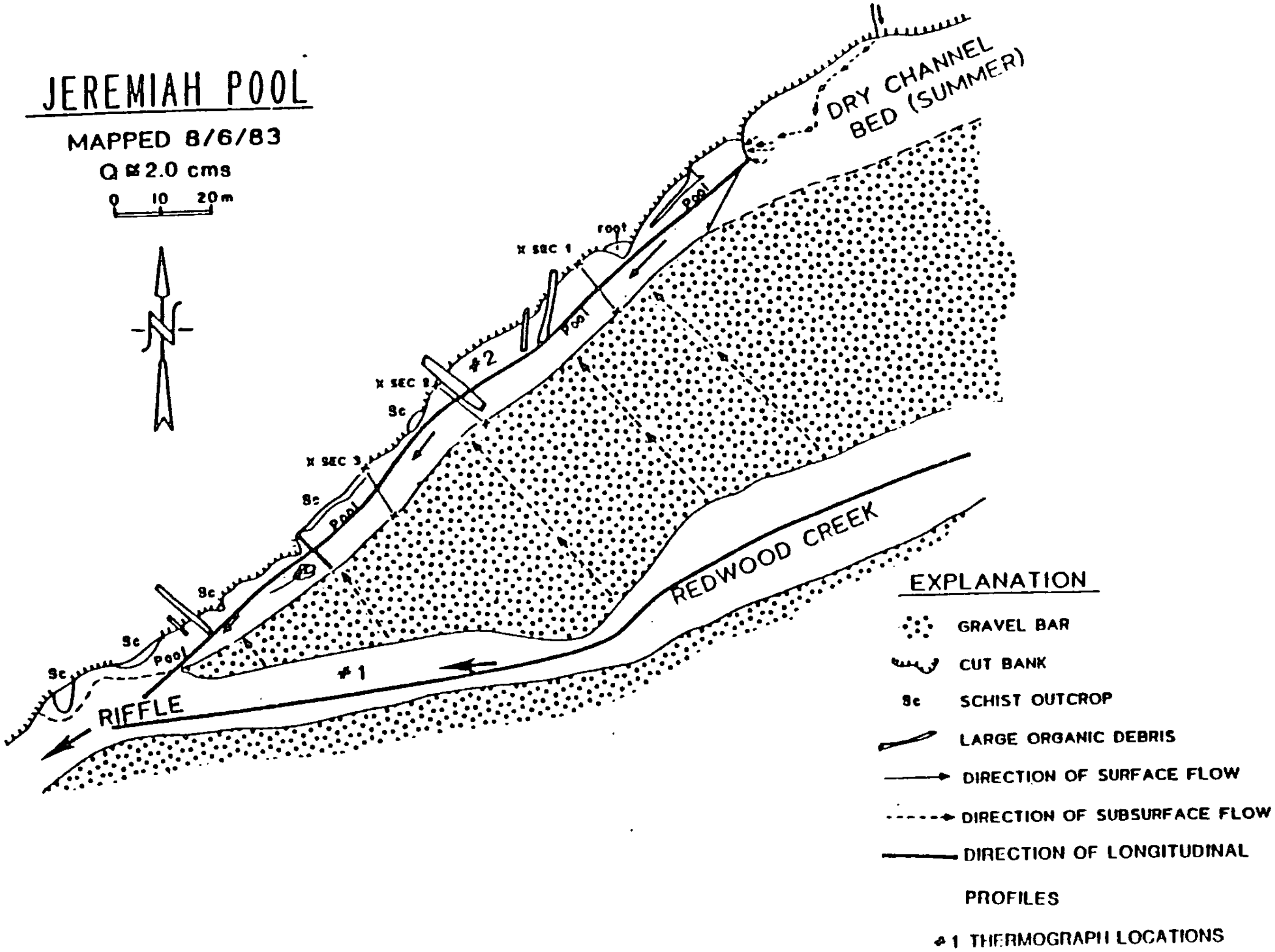


Figure 47. Morphologic map, Jeremiah Cold Pool, August 6, 1983. Direction of the longitudinal profiles (Fig. 46) and thermograph locations (Fig. 50) are shown. Location of the pool is shown in Figure 3.

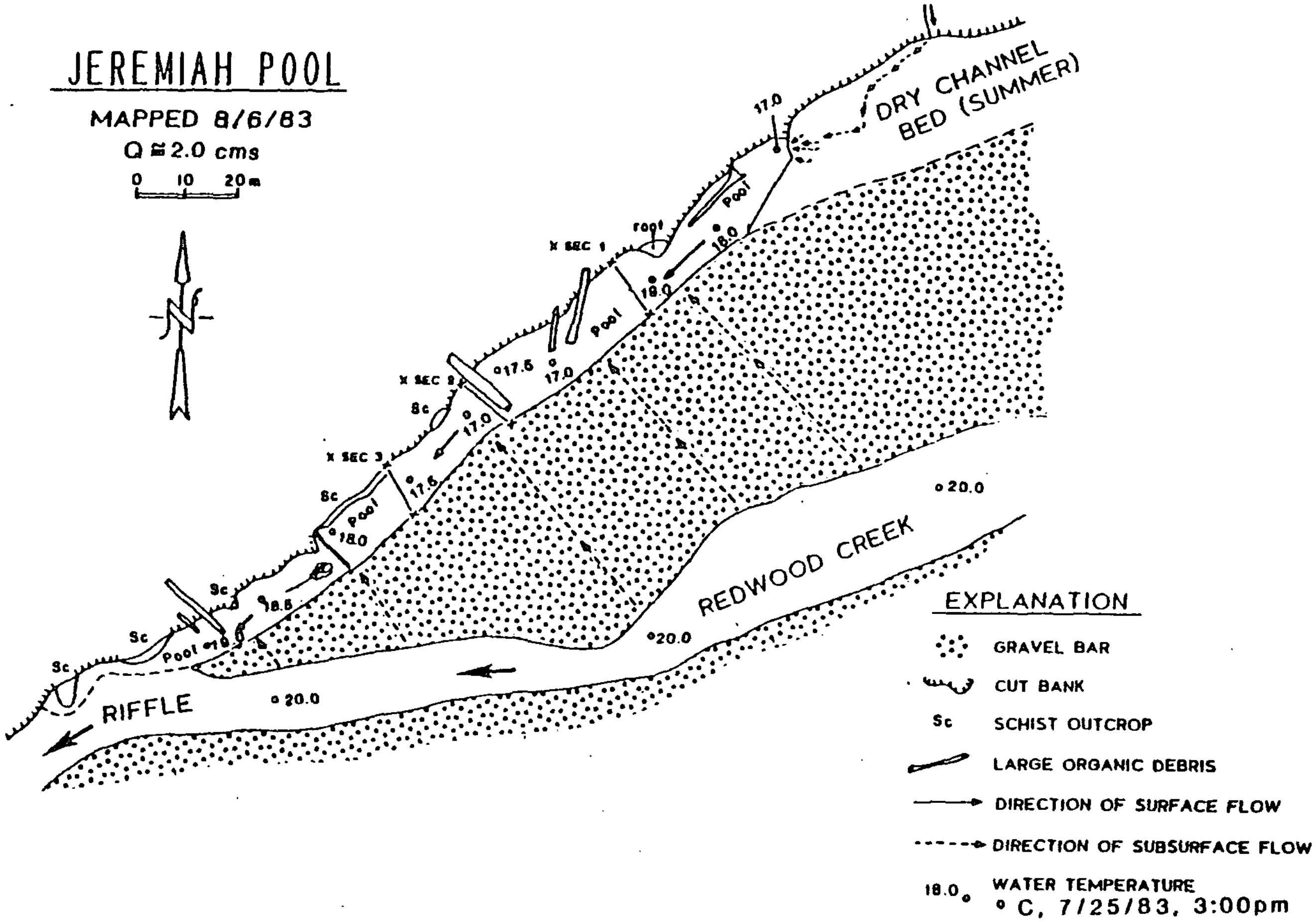


Figure 48. Water temperatures, Jeremiah Cold Pool, July 25, 1983. Location of the pool is shown in Figure 3.

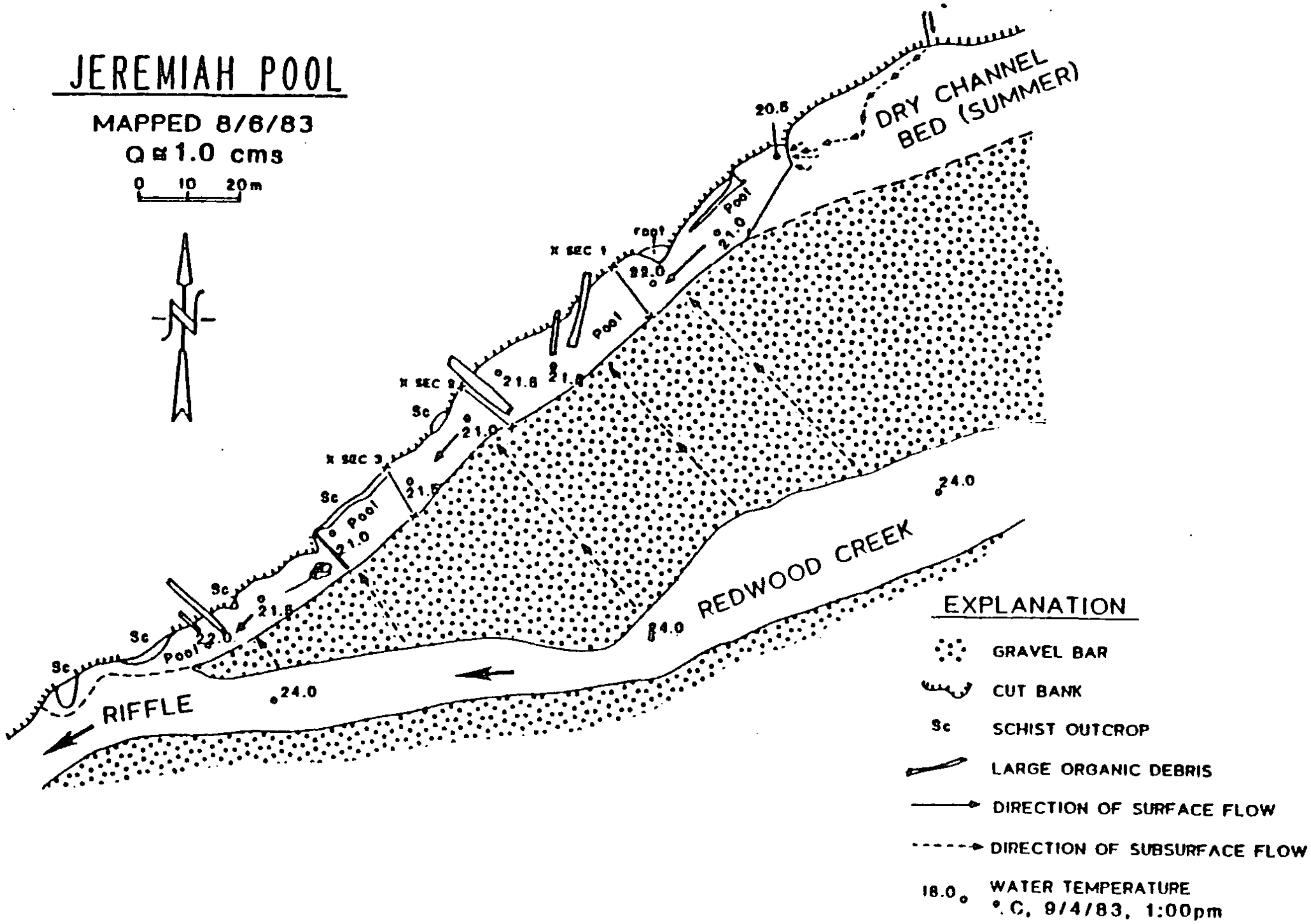
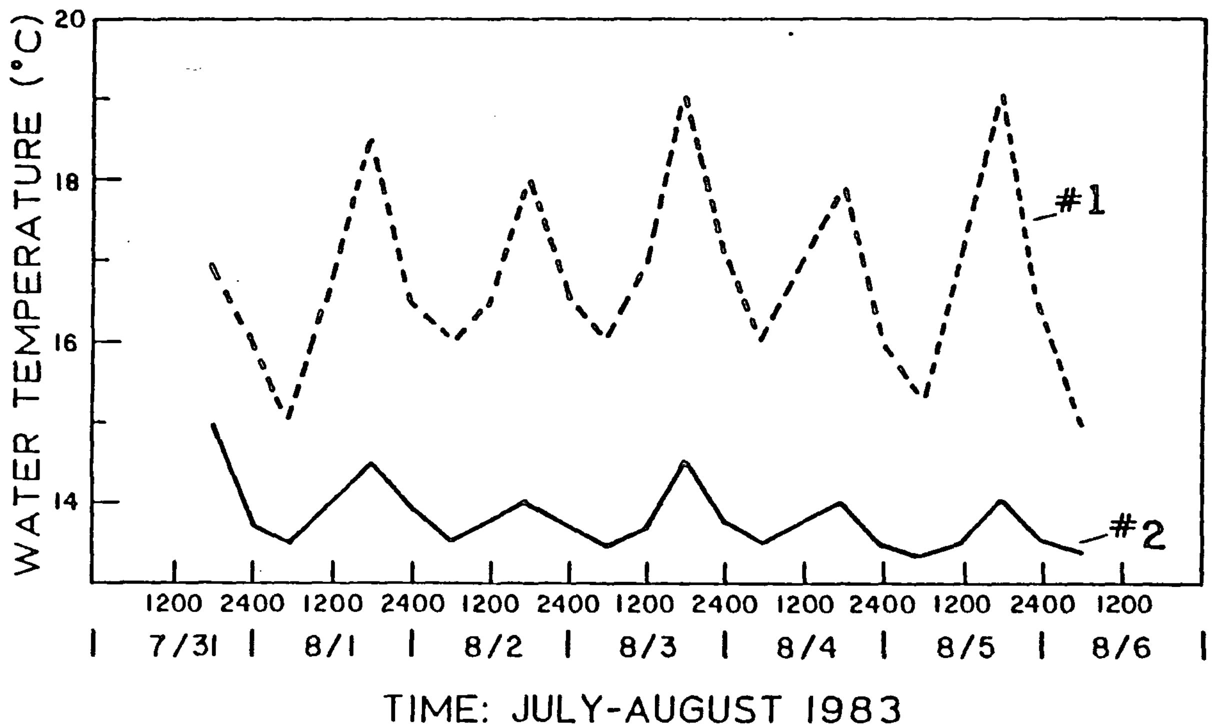


Figure 49. Water temperatures, Jeremiah Cold Pool, September 4, 1983. Location of the pool is shown in Figure 3.



"JEREMIAH"

Figure 50. Water temperatures in Jeremiah Cold Pool, July 31 - August 6, 1983. Temperatures were measured with continuously recording thermographs placed in the mainstream (#1) and in the cold pool (#2). Station locations are shown in Figure 47.

Swimmin' Coon Cold Pool

Swimmin' Coon Cold Pool is located approximately 3 km downstream of the Tall Trees Grove, at the confluence of Tom McDonald Creek and Redwood Creek (Fig. 3). It owes its name to a rascally racoon which attempted to steal our food one night while we were camped at the site. When scared by flying pebbles, boots, and tennis shoes, he jumped in the creek (without our food) and swam away - hence, "Swimmin' Coon".

The cold pool was first discovered in July of 1983. It apparently formed by scour around a large amount of organic debris which fell in the pool as a result of a landslide in the fractured metamorphosed mudstone along the left bank (Fig. 51). Cross-sections and longitudinal profiles are illustrated in Figures 52 and 53.

Pool temperatures in Swimmin' Coon averaged approximately 4°C lower than ambient (Figs. 51, 55, 56). The major source of cold water appeared to be both surface and subsurface flow from Tom McDonald Creek. Other sources included seeps from the landslide and small tributaries along the hillslope. The formation of the tributaries may be partially due to the tractor and cable-yarding associated with the timber harvesting of the area. These practices tend to cause gullies to form on the hillslope, which then act as a source of concentration for both surface and subsurface flow. A long, side-channel gravel bar retarded mixing between the effluent cold water

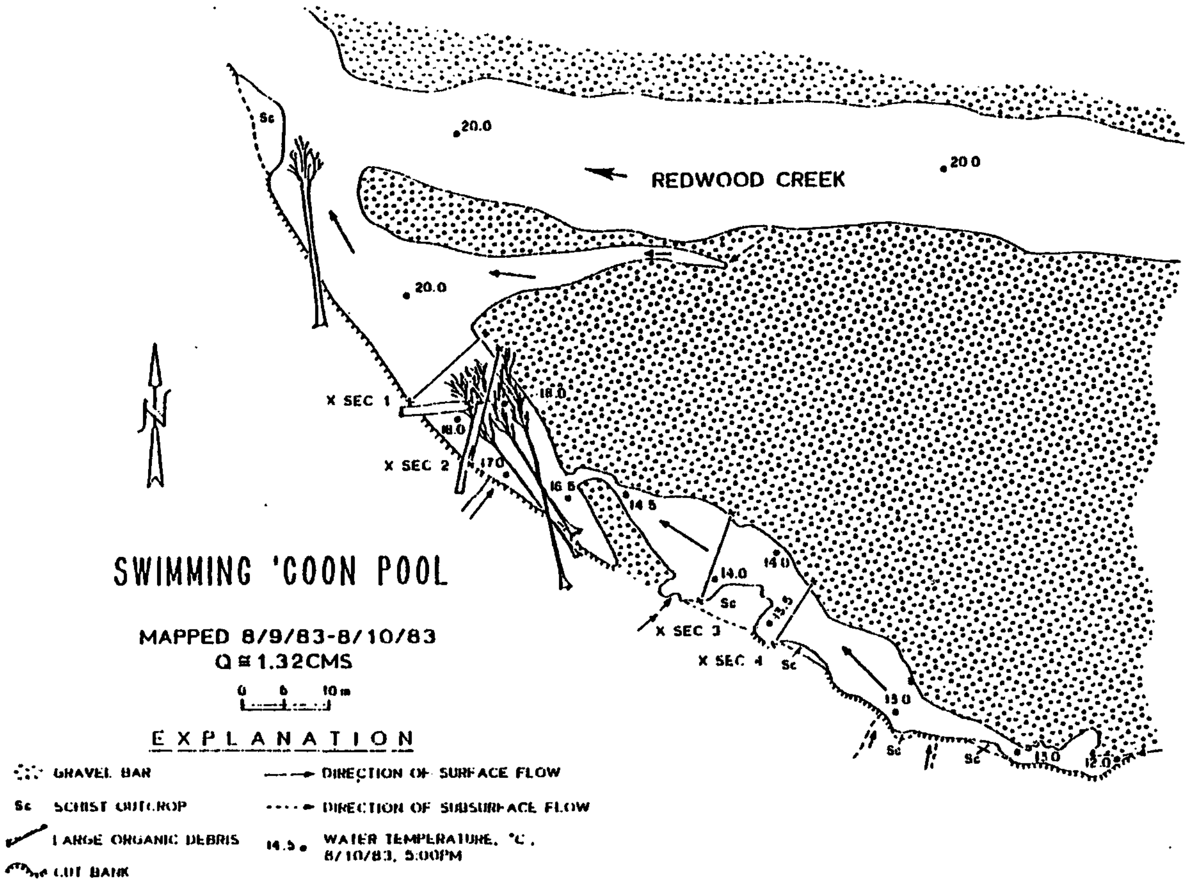


Figure 51. Morphological map and water temperatures, Swimmin' Coon Cold Pool, August 10, 1983. Location of the pool is shown in Figure 3.

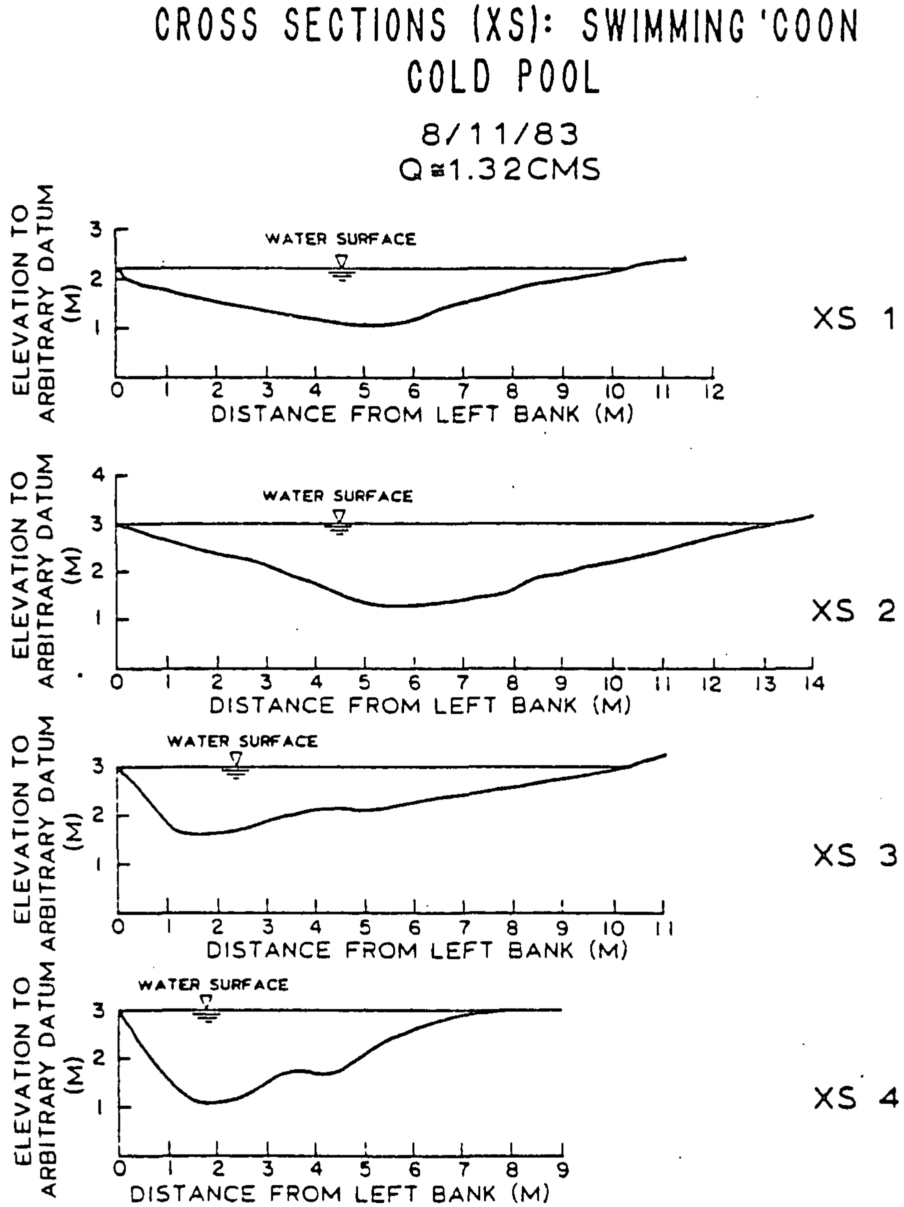


Figure 52. Cross-sections, Swimmin' Coon Cold Pool, August 11, 1983. Locations of cross-sections are shown in Figure 3.

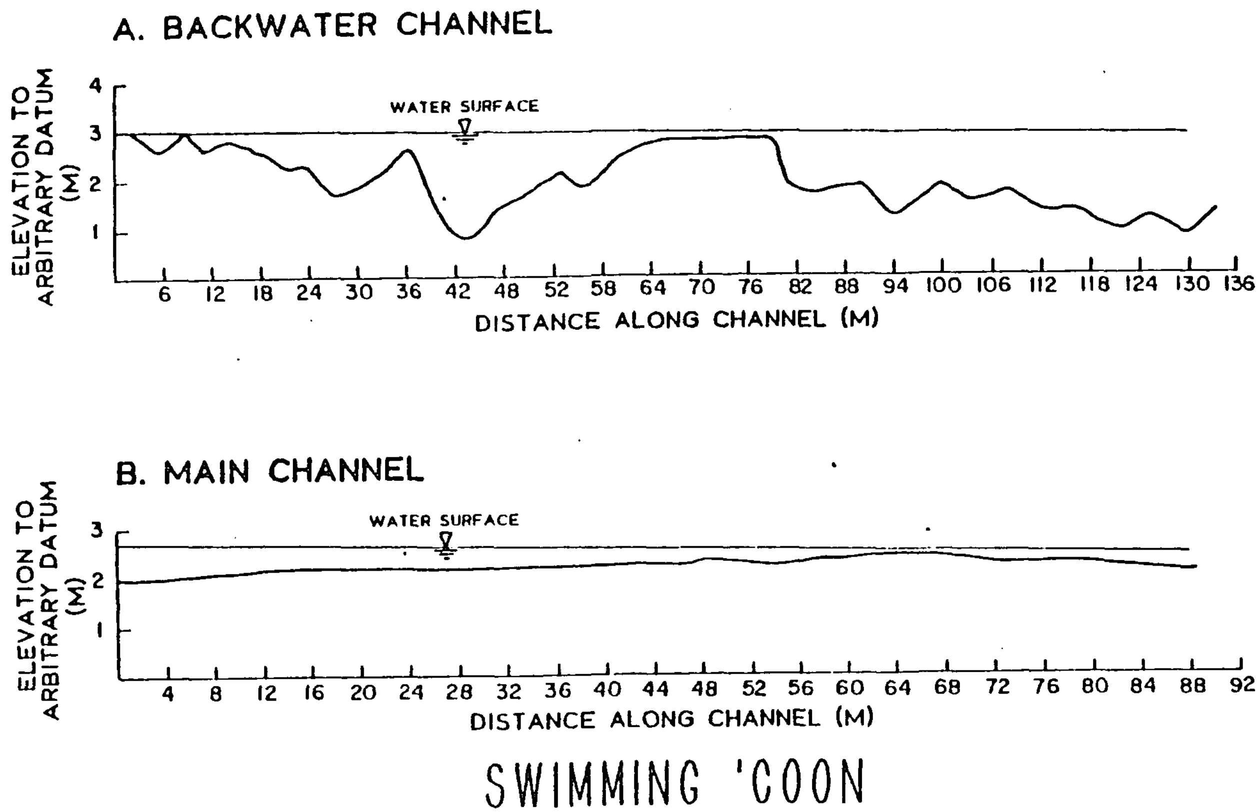


Figure 53. Longitudinal profiles, Swimmin' Coon Cold Pool, and the main channel of Redwood Creek, August 1983. Profiles are located in Figure 54.

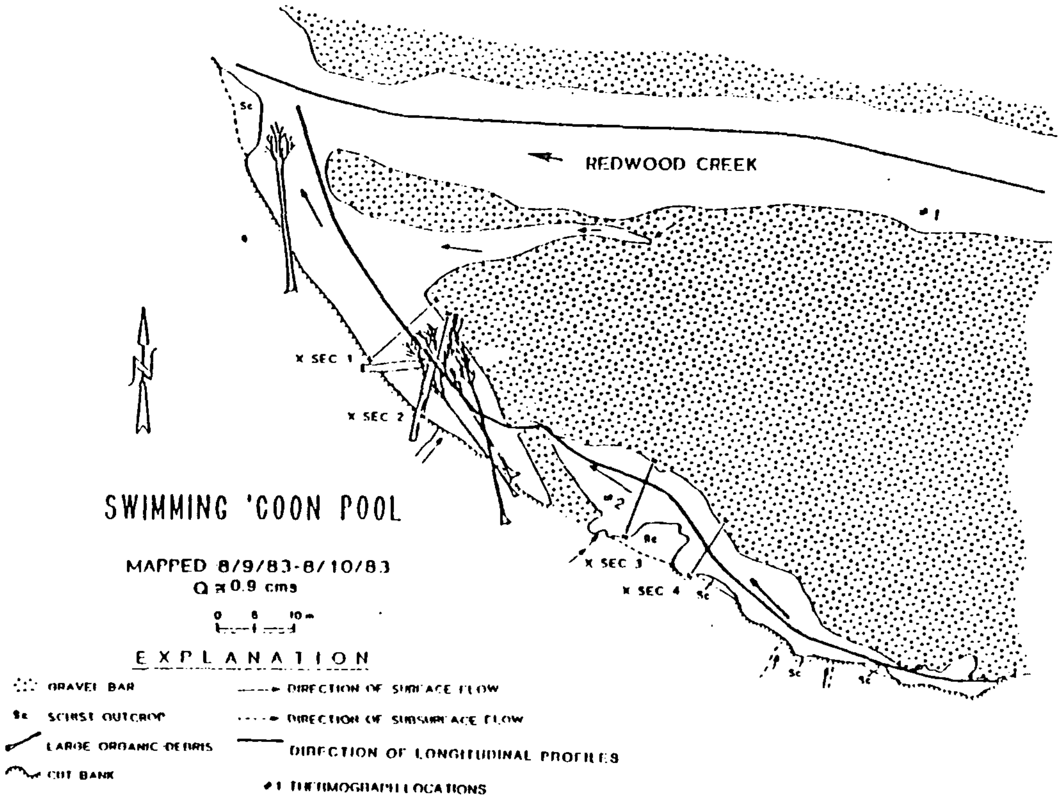


Figure 54. Morphological map, Swimmin' Coon Cold Pool, August 10, 1983. Direction of the longitudinal profiles (Fig. 53) and thermograph locations (Fig. 57) are shown. Location of the pool is shown in Figure 3.

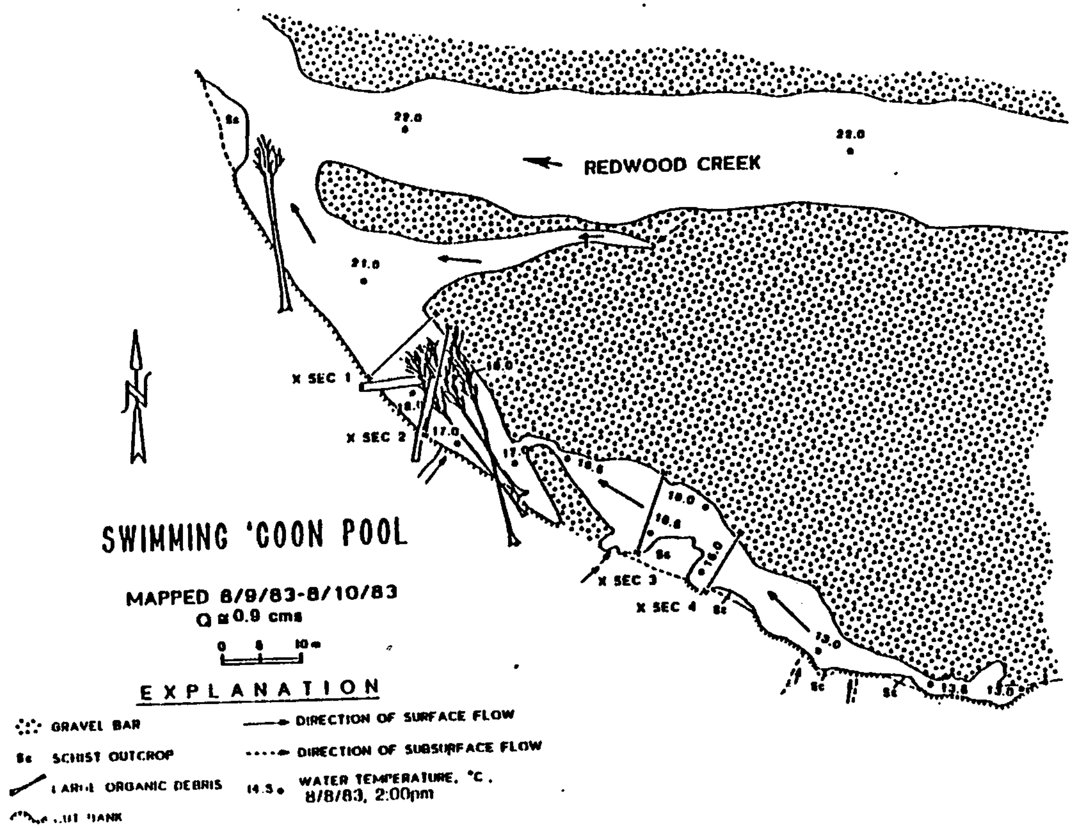


Figure 55. Water temperatures, Swimmin' Coon Cold Pool, August 8, 1983. Location of the pool is shown in Figure 3.

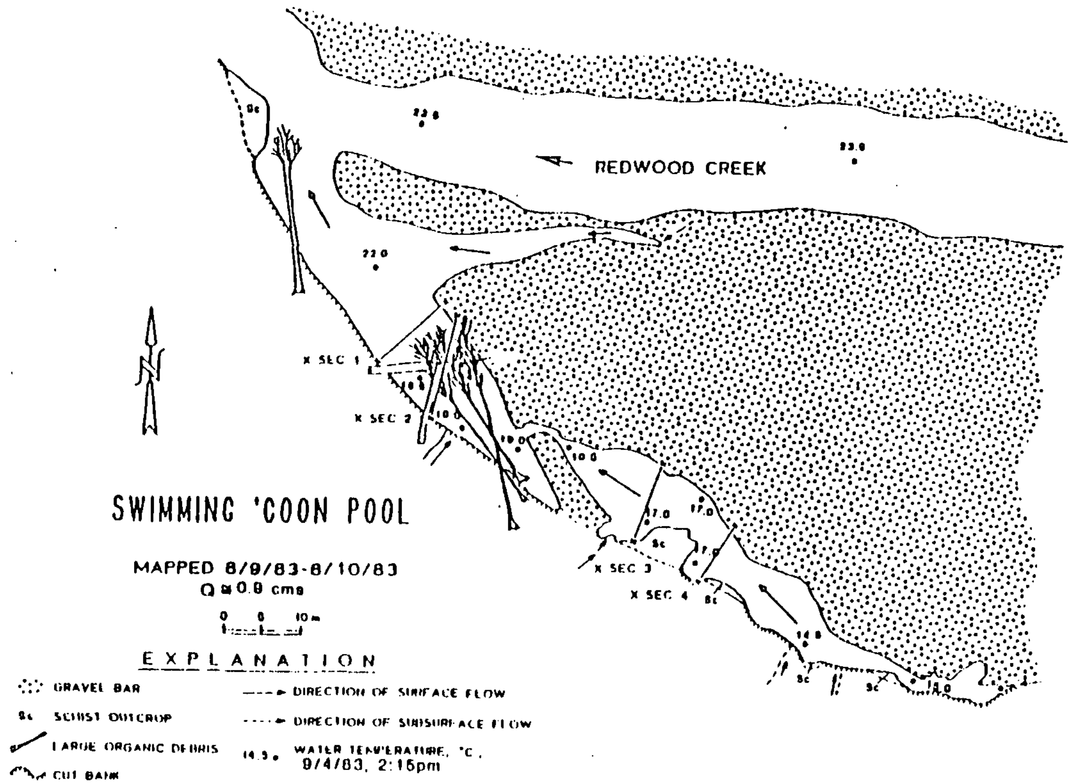


Figure 56. Water temperatures, Swimmin' Coon Cold Pool, September 4, 1983. Location of the pool is shown in Figure 3.

and the main stream.

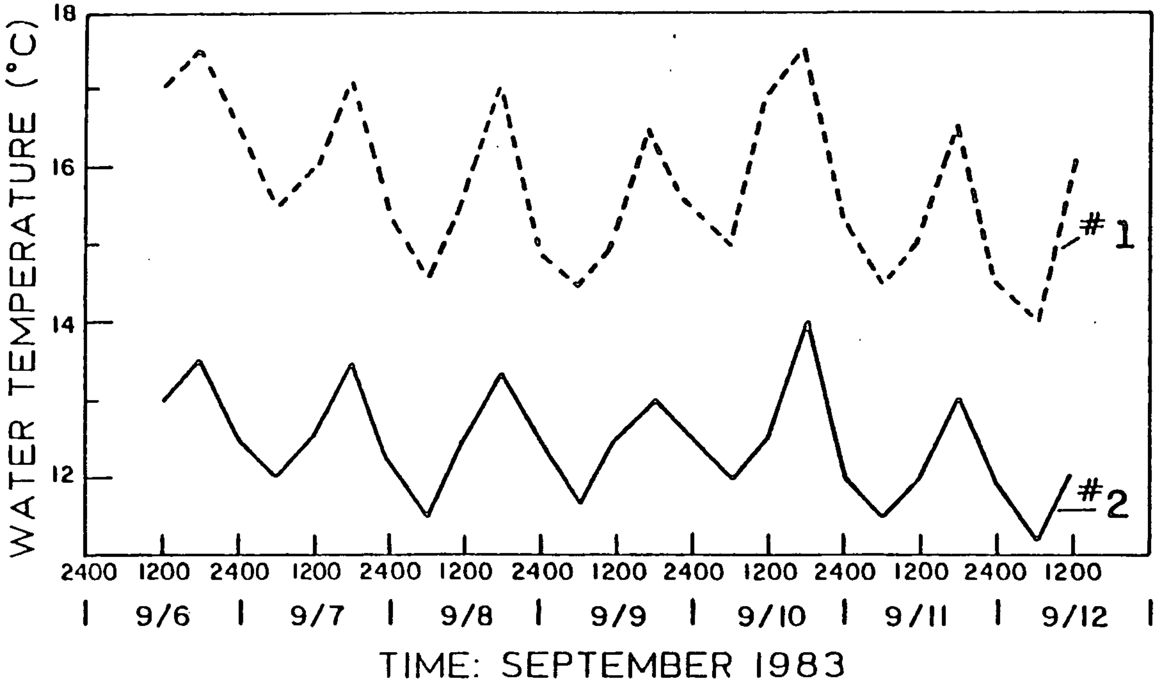
Thermograph data (Fig. 57) show that the pool was consistently cooler from September 6 to September 12. Shading probably played a role in the cooling of the pool, as a large portion of it is covered with branches from the fallen trees, although not as densely as observed at the Emerald Cold Pool.

Tall Trees Cold Pool

The seventh cold pool is located on the Tall Trees Loop Trail between the Tall Trees Grove and Emerald Creek, at the conjunction of Chris Creek and Redwood Creek. It is an example of one of the smaller cold pools. It had a maximum depth of only 0.75 meters and a maximum width of 5 meters (Fig. 58). Approximately five other cold pools of similar size were located within the lower 20 km of Redwood Creek.

The pool was formed as a result of scour along a large schist outcrop. Temperatures in the cold pool averaged 3°C below ambient (Figs. 58, 59). Two sources of effluent cold water were observed: fractures at the base of the bedrock outcrop and subsurface intra-gravel movement of flow from Chris Creek. Relative amounts of flow could not be determined.

The side channel bar acted as a barrier to mixing. Shading did not appear a factor in cooling of the pool.



SWIMMING 'COON

Figure 57. Water temperatures, Swimmin' Coon Cold Pool, September 6 - September 12, 1983. Temperatures were measured with continuously recording thermographs placed in the mainstream (#1) and in the cold pool (#2). Station locations are shown in Figure 54.

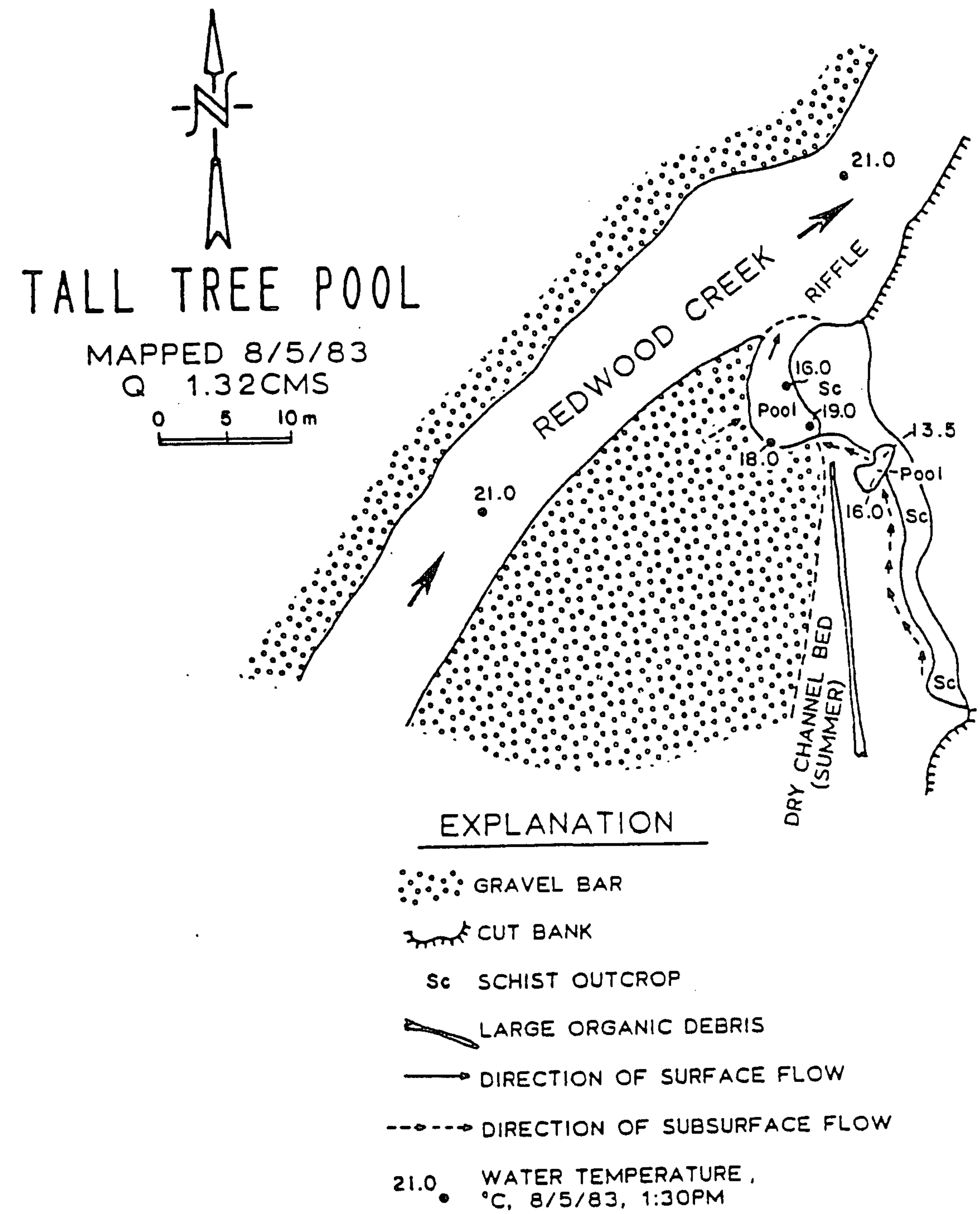


Figure 58. Morphological map and water temperatures, Tall Trees Cold Pool, September 5, 1983. Location of the pool is shown in Figure 3.

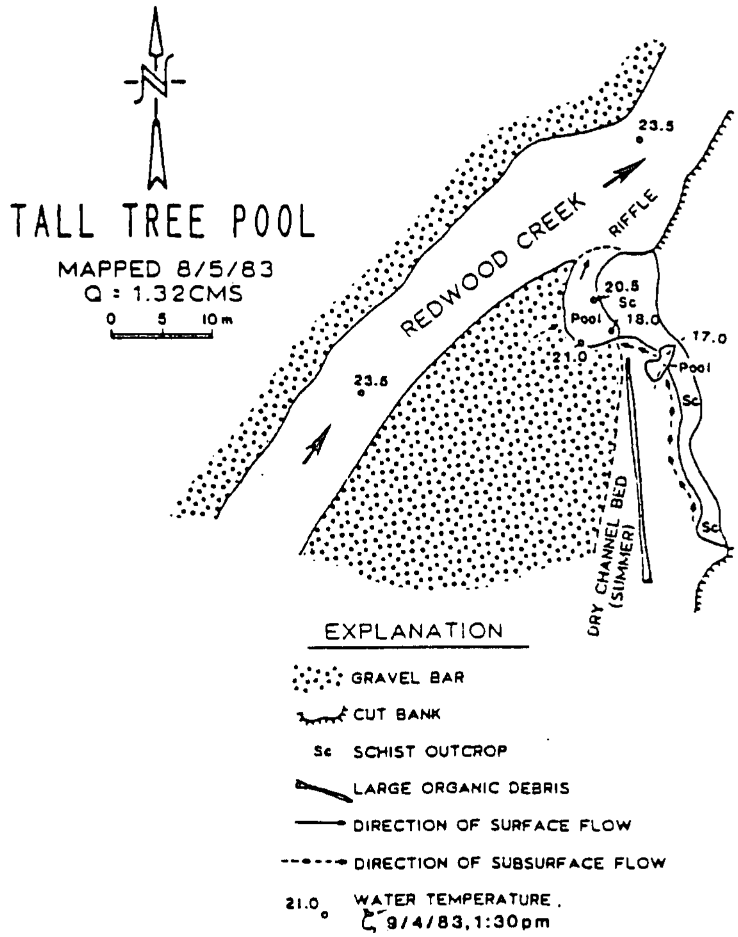


Figure 59. Water temperatures, Tall Trees Cold Pool, September 4, 1983. Location of the pool is shown in Figure 3.

GROUNDWATER CONTRIBUTION TO BASE FLOW

In Redwood Creek, as with most perennial streams, base flow or summer low flow is maintained by groundwater seeps into the channel. These seeps, along with intragravel flow, are the source of cold water for the formation of cold pools. In order to determine how much subsurface flow contributes to the base flow, discharge measurements were taken above and below the cold pools.

Data from the reach through the Hayes Creek Cold Pool, taken during the summers of 1981, 1982, and 1983 (Tables 6 and 7) show (with one exception) that over a distance of about 120 m discharge increased by as much as 22%. An increase of 10% is taken to be greater than potential error of measurement. We were unable to determine how much of the increase was due to effluent intragravel flow versus effluent groundwater flow; however, dissolved oxygen concentration measured in 1981 (Fig. 13) suggest a groundwater source. The data also suggest that as discharge decreases from early to late summer in Redwood Creek, the amount of subsurface water from the Hayes Creek basin entering Redwood Creek also decreases, but the amount of effluent subsurface flow as a percentage of total stream flow increases.

Measurements of discharge above and below the Elam Creek Cold Pool, taken in September of 1982, show an increase of 14%, although much of the increase was probably due to intragravel flow of Elam

TABLE 6 - INCREASE IN DISCHARGE OF REDWOOD CREEK, DUE TO EFFLUENT SUBSURFACE WATER AT THE HAYES CREEK, ELAM CREEK, AND EMERALD CREEK COLD POOLS DURING THE SUMMERS OF 1981 AND 1982

Location of Cold Pool	Date Measures	Upstream Discharge ($m^3 s^{-1}$)	Downstream Discharge ($m^3 s^{-1}$)	Increase ($m^3 s^{-1}$)	Percent Increase	Confidence in the % Increase (1=high;4=low)**
Hayes Creek*	Sept. 4, 1981	0.40	0.49	0.09	22	1
	Aug. 10, 1982	0.69	0.82	0.13	19	1
	July 9, 1982	1.77	1.97	0.20	11	2
Elam Creek	Sept. 9, 1982	0.32	0.37	0.05	14	2
Emerald Creek	Aug. 19, 1982	0.47	0.48	0.01	2	4
	July 24, 1982	0.87	0.91	0.04	5	3

* On August 23, 1982 the discharge upstream and downstream of the Hayes Creek cold pool remained nearly constant at 0.45 $m^3 s^{-1}$.

**Reflects the fact that discharge can only be measured at ± 5-10%. Thus, while the increase in discharge at the Emerald Creek site is in the expected direction, the change is within potential experimental error of measurement.

TABLE 7 - INCREASE IN DISCHARGE OF REDWOOD CREEK, DUE TO EFFLUENT SUBSURFACE WATER AT THE HAYES CREEK, FOOTBRIDGE, JEREMIAH, ELAM CREEK, AND SWIMMIN' COON COLD POOLS DURING THE SUMMER OF 1983

Location of Cold Pool	Date Measures	Upstream Discharge (m^3s^{-1})	Downstream Discharge (m^3s^{-1})	Increase (m^3s^{-1})	Percent Increase	Confidence in the % Increase (1=high;4=low)**
Hayes Creek	Aug. 15, 1983	1.1	1.34	.24	18	1
	Aug. 19, 1983	.95	1.06	.11	10	2
Footbridge Pool	Aug. 1, 1983	2.03	2.23	.2	9	2
	Aug. 19, 1983	1.14	1.24	.1	8	2½
Jeremiah Pool	July 30, 1983	2.0	2.17	.17	8	2½
	Aug. 19, 1983	.95	1.17	.22	19	1
Elam Creek	Aug. 19, 1983	.97	1.16	.19	16	1
Swimmin' Coon	Aug. 11, 1983	1.33	1.39	.06	4	3
	Aug. 19, 1983	.95	1.09	.14	13	2

Creek surface water rather than effluent groundwater (see Fig. 23). Data from August, 1983 show an increase of 16% in discharge through the reach (Table 7). However, since Elam Creek was flowing directly into the cold pool, I was unable to determine what percentage of the increase was due to groundwater flow.

Measurements taken during the summer of 1982 at the Emerald Cold Pool suggest a possible increase in discharge, but the percent change is within the possible error of measurement. Nevertheless, cold groundwater was observed entering the site through small springs along the west bank of Redwood Creek (see Fig. 31), and the flow was evidently enough to maintain, with shading and retardation of mixing by the organic debris, a cold pool environment until the pool was filled in with sediment during the winter of 1982-1983.

Similar increases in discharge were also found at the sites of Footbridge, Jeremiah, and Swimmin' Coon cold pools during the summer of 1983 (Table 7). Temperature measurements at the three sites suggest that subsurface intragravel flow contributes to the cold pool (Figs. 37, 44, 51). I was unable to determine whether this was the main source of cold water or if seeps were the controlling factor. However, temperature data from the Footbridge pool suggest that at this site the seeps from fractures in the bedrock outcrop played a greater role in cooling the pool than did intragravel flow from either Redwood Creek or McArthur Creek.

These discharge data from Redwood Creek suggest that point sources may contribute more to base flow than more general subsurface flow through hillslope soils. Point sources observed included dry channel beds and fractures. This hypothesis is strengthened by data obtained by other authors. Anderson and Burt (1978) found that topographic hollows in the hillslope served as major points of groundwater concentration. Huff and others (1982) found that at distinct seeps and sites where these hollows occurred discharge increased in the stream by as much as 43% (Fig. 60). They suggest that the seeps may be due to concentration of the subsurface drainage along bedding planes which are nearly normal to the channel.

A total of 14 discharge measurements taken in one day in Redwood Creek show that once groundwater enters Redwood Creek, most of it may become influent into the gravels covering the valley floor. Figure 61 shows that discharge remains fairly constant over 18 km even though there are numerous flowing tributaries entering the channel. This is probably attributed to the high amount of aggradation in the lower channel. The increase in effluent flow is taken up by the open spaces between the gravels, causing discharge to drop back to an equilibrium. This same tendency is also suggested by the data collected by Huff and others (1982) with simultaneous measurements over a stream reach. Although discharge increased due to the seeps and hollows, it quickly decreased after each point source of effluent

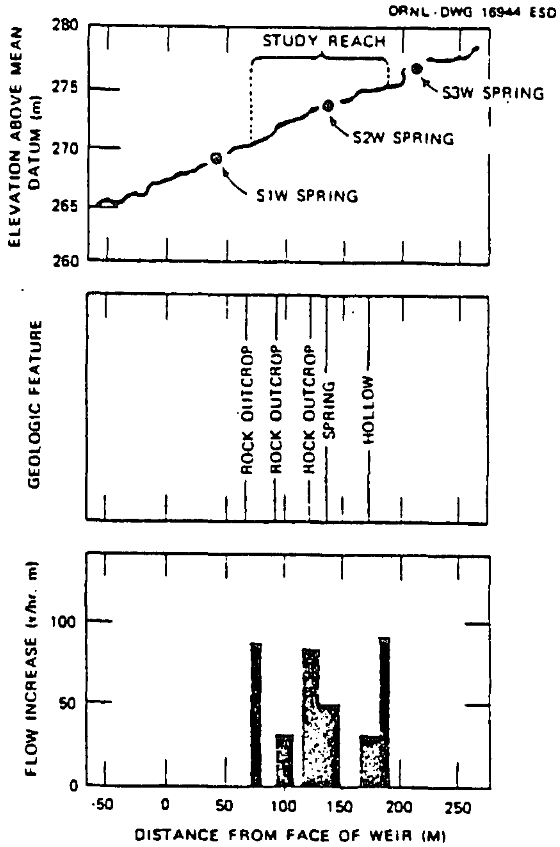


Figure 60. Variability of streamflow increases along a study reach of Walker Branch watershed (after Huff and others, 1982).

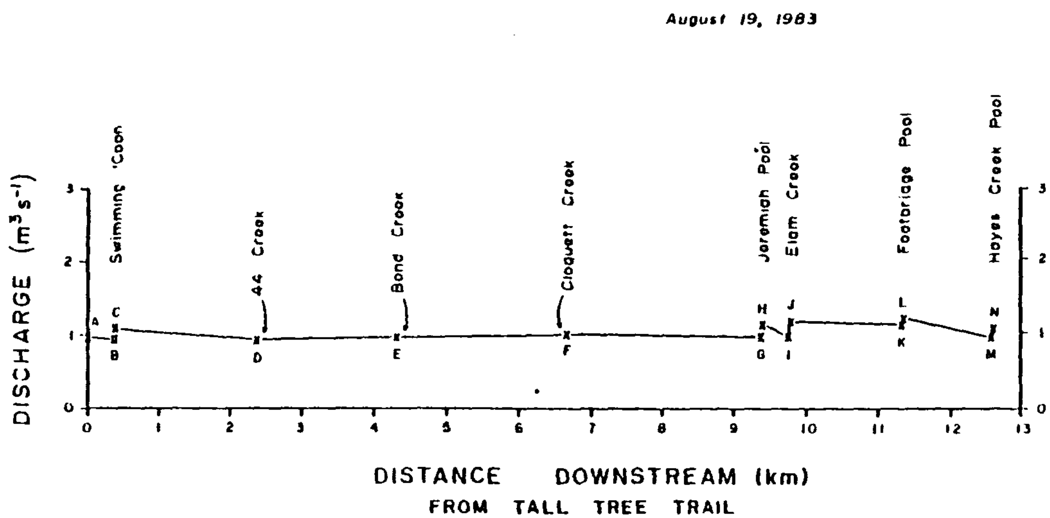


Figure 61. Profile of discharge measurements taken on Redwood Creek, August 19, 1983.

subsurface water (Fig. 60).

SUMMARY AND CONCLUSIONS

Pool and riffle sequences are usually identified in the field, with each investigator using specific criteria for delineating the upstream and downstream ends of bedforms. As a consequence, it becomes difficult to compare data on channel forms and processes. For this reason it is necessary to have set criteria for more objective identification of pools. To this end, two methods were developed as part of this study. The first method utilized both a regression analysis of the bed elevations and the water surface data. Areas below the regression line were defined as pools as long as the water surface remained level. Areas above the regression line are defined as riffles. At locations where the bed profile rose above the regression line, yet the water surface remained level, a "complex pool" was defined. The second technique was developed for cases where water surface data are not known. At increments equal to channel width, the distance above or below the regression line is measured. The mean of these measurements is calculated and bedforms are identified only where the profile rises above (riffles) or below (pools) as much as this amount. It was found that there is no significant difference between the populations of pool to pool spacing data determined by utilizing these two techniques.

The presence of large roughness elements (LRE's) are a major factor in the formation of pools in Redwood Creek - 86% of the identified pools were associated with LRE's such as large organic debris and bedrock outcrops. Pool depths associated with bedrock outcrops and a combination of LOD and bedrock outcrops were found to be significantly different (deeper) than pool depths not associated with any type of LRE. This is attributed to the stability, or retardation, of scour at the sites of the LRE's.

The low pool-pool spacing found in Redwood Creek (3-4 channel width) is probably due to the disturbance of the basin due to recent flooding and timber harvesting activities. As the system stabilizes, the smaller pools may coalesce and the pool-pool spacing might increase to the more typical spacing of 5-7 times the channel width found in most alluvial channels.

A relationship was found between the heights of the upstream and downstream riffles and the depth of the intervening pools in four reaches of alluvial channels: $R^2 = 0.65$. No relationship was found in Redwood Creek. This is more than likely due to the excess sediment deposited in the channel as a result of logging upstream - i.e., the stream is actively aggrading and therefore the regular undulations in bed topography associated with "graded" streams (those which have reached an equilibrium between sediment load and stream power available to carry that load) would not be expected in Redwood Creek.

Seven "cold pools" - those pools which maintain temperatures cooler than the main stream throughout the summer - were identified in the lower third of Redwood Creek. In order for the cold pools to form, there must be a source of effluent cold water. These include seeps, springs, and intragravel flow through bars in the channel. However, not all pools with a source of cool water form cold pools. There must be a barrier of some sort to retard mixing between the cold effluent water and the warmer main stream. In most cases in Redwood Creek it was found that a large gravel bar effectively separated the cold pool from the warmer water. In some cases, large organic debris aided in slowing the mixing.

Discharge data from Redwood Creek show that effluent groundwater from point sources contributes to base flow to a measurable extent. Measurements taken above and below the cold pools show an increase in discharge over the reach. However, it is unclear as to the relative percentages of effluent subsurface flow versus intragravel flow from the main stream. Discharge measurements taken at 14 locations in lower Redwood Creek show that while effluent water (both surface and subsurface) causes a localized increase in discharge, the flow drops back down to a level which remains relatively constant throughout the 18 km study reach.

Discharge data from this and other studies suggest that point sources may be a greater contributing source of groundwater flow to channels than more general subsurface flow through hillslope soils. Point sources include channel beds with no surface flow, bedrock fractures, topographic hollows in the hillside and structural bedding planes.

Further studies utilizing simultaneous measurements of discharge may lead to a better understanding of the extent and processes of groundwater contributions to base flow - an important aspect of fluvial hydrology.