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GEOMORPHIC AND HYDROLOGIC CONDITIONS FOR COLD POOL FORMATION ON REDWOOD CREEK, CALIFORNIA

REDWOOD NATIONAL PARK

RESEARCH AND DEVELOPMENT

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SEDIMENT BUDGET PROJECT

In 1978, the National Park Service initiated a study project to formulate a sediment budget for the Redwood Creek basin. This investigation documents and quantifies sediment source areas in the watershed, changes in sediment storage in tributary and mainstem stream channels, and sediment transport out of the basin. Results are presented in a series of Technical Reports and Data Releases, and condensed versions will be published in scientific journals.

NOTICE

This document contains information of a preliminary nature, and was prepared primarily on an interim basis. This information may be revised or updated.

GEOMORPHIC AND HYDROLOGIC CONDITIONS FOR COLD POOL FORMATION ON REDWOOD CREEK, CALIFORNIA

by

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Redwood National Park Research and Development
Technical Report 24

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ABSTRACT

Summer cold pools are thermally stratified pools which maintain water temperatures more than 3°C lower than adjacent mainstem water temperatures. These pools provide concentrated areas of cold water and are partially separated from the low flow channel by a gravel bar. During the summer of 1985, four cold pools were studied in the lower 21 kilometers of Redwood Creek, California. These pools were observed in the wide aggraded reaches downstream of the Tall Trees Grove. Although few in number, cold pools on Redwood Creek represent high quality rearing habitat and holding areas for juvenile salmonids and adult summer steelhead (Keller and others, in press).

This study quantifies and describes cold pools from a geomorphic perspective. The objective of this study was to: 1) determine the relationship of temperature structure and mixing to pool morphology; 2) quantify cold water inflow to cold pools; and 3) determine physical factors that affect cold pool formation.

In Redwood Creek, cold pools develop when cold hillslope groundwater, cool tributary flow and/or mainstem intragravel flow enters and is concentrated in the channel. A gravel bar is essential to isolate large volumes of cold water and prevent thermal mixing with the mainstem flow. Since 1981, all cold pools studied on Redwood Creek had gravel bar barriers separating colder pool water from warmer mainstem flow. In contrast, large woody debris created pools in the channel and slightly retarded mixing, but was not effective at isolating large volumes of cold water.

Primary sources of cold water to pools were mainstem intragravel flow and tributary flow. Only trace amounts of inflow could be attributed to hillslope groundwater seepage. Tributary inflow to cold pools was as much as 0.016 m^3/s, and intragravel inflow ranged from 0.008 to 0.020 m^3/s. Baseflow discharges to pools between 0.008 and 0.020 m^3/s sustained cold pools throughout the summer.

Differences between pool bottom and mainstem water temperatures were independent of mean pool depth, maximum pool depth and pool volume and are probably more a function of the quantity, rate and temperature of inflowing water. Pool width-to-length (W/L) ratio is generally related to pool-mainstem temperature differences. The longer and narrower the pool (lower W/L ratio), the cooler the pool.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

Cold pools in Redwood Creek, California occur naturally along the summer low flow channel as side pools separated from mainstem flow by a gravel bar (Fig. 1). Although few in number, these pools provide concentrated areas of cold water and maintain pool temperatures more than 3°C below ambient mainstem temperatures through the summer months. In contrast, most low flow mainstem pools are uniform in temperature and typically exceed 20°C during warm afternoons.

Cold pools provide important juvenile salmonid rearing habitat on lower Redwood Creek. This study attempts to quantify and describe this stream habitat from a geomorphic perspective.

Extensive timber harvesting on unstable hillslopes coupled with several large flood events in the last three decades caused widespread streambed aggradation in Redwood Creek. Recent aggradation of the mainstem has severely affected important juvenile rearing habitat through: 1) filling summer rearing pools, 2) increasing mainstem water temperatures and 3) reducing riparian vegetation and streamside cover (Janda, 1977; Anderson and Brown, 1983). The lack of suitable pool habitat for juvenile fish during summer low flows significantly limits fish production on Redwood Creek (Keller and Hofstra, 1983). Juvenile silver (coho) salmon (<u>Oncorhyncus</u> <u>kisutch</u>) and steelhead trout (<u>Salmo</u> <u>gairdneri</u>) require an extended period of freshwater growth before entering the ocean. This period ranges from one year for coho to as much as four years for steelhead. Summer cold pools on Redwood Creek maintain watertemperatures within or near the preferred temperature range of juvenile salmonids (7-14°C) and provide quality rearing habitat and holding areas for juvenile fish and migrating adult summer steelhead (Keller and others, in press).

My objective in this study was to investigate: 1) physical processes responsible for maintaining thermal stratification in cold pools on Redwood Creek, 2) sources and rates of cold water inflow to pools and 3) physical conditions under which cold pools exist.

To carry out this study, I made detailed morphologic and topographic maps of each cold pool, measured surface and subsurface discharges, and the spatial distribution of water temperatures throughout the pools.

Cold pools on Redwood Creek were studied by Keller and Hofstra in summer 1981 and by Moses in summer 1982 and 1983 (Keller and Hofstra, 1983; Moses, 1984). These studies focused primarily on detailed mapping of pool configuration and monitoring pool bottom temperatures. Moses (1984) qualitatively identified favorable pool morphology and contribution of cold effluent groundwater and intragravel flow as important factors for cold pool formation. However, little research has been done to quantify cold water inflow or examine pool geometry and temperature distribution.

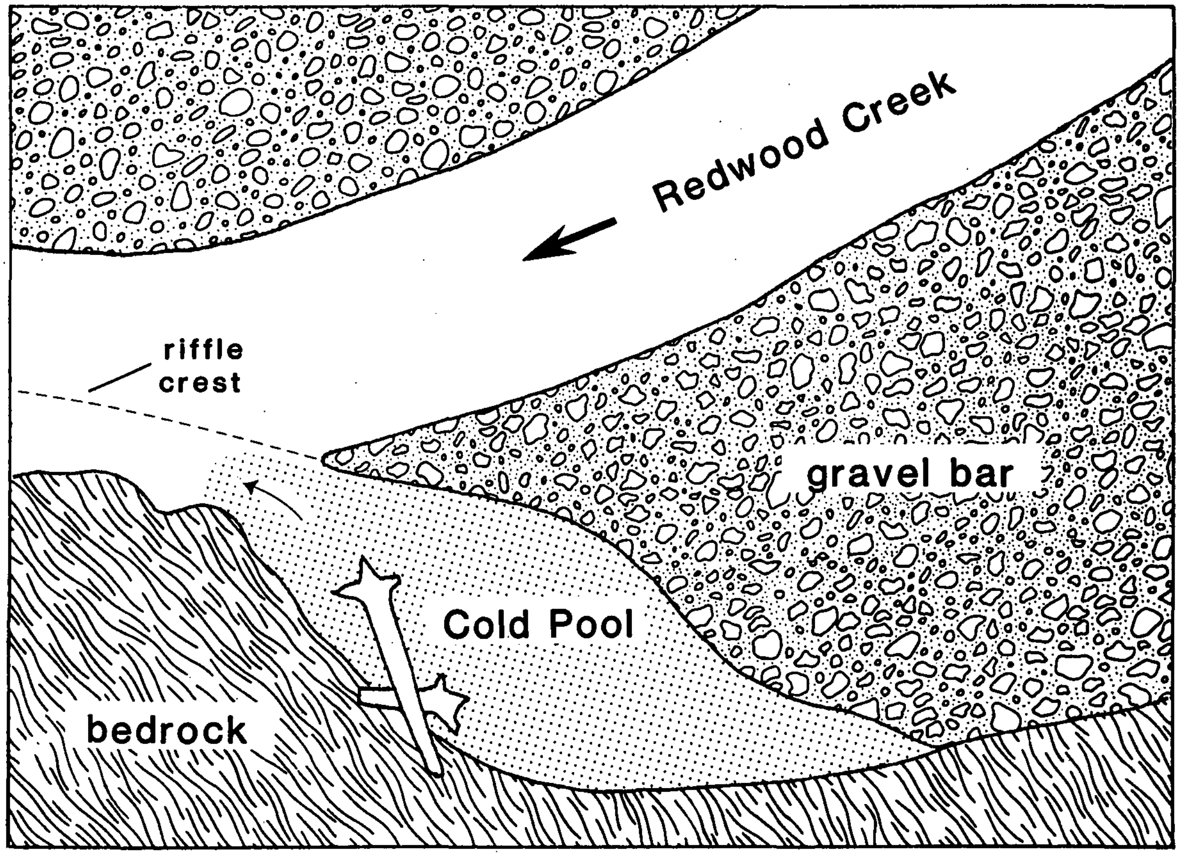


Figure 1. Typical cold pool location and features.

Cold pool features are not limited to the Redwood Creek basin and have been observed on many northern California streams including the Trinity River, South Fork Trinity River (California Dept. of Water Resources, 1976), Mad River (Tom Lisle, U S Forest Service, pers. comm.) and the Middle Fork Eel River (Kubicek, 1977). Cold pools form in a variety of ways including large pool volumes and great depth which inhibit mixing; physical barriers which isolate cold water inflow; or a combination of these factors. Cold pools on Redwood Creek develop when cold effluent groundwater, cool tributary flow or upwelling of intragravel flow enter and are protected from mixing with warmer water by a physical barrier.

II. STUDY AREA

The 720 km^2 Redwood Creek watershed is located in north coastal California 450 kilometers north of San Francisco (Fig. 2). Redwood Creek flows 108 kilometers in a north-northwest direction and empties into the Pacific Ocean near Orick, California. I studied five pools in the lower 21 kilometers of the main channel.

The elongate and linear basin shape reflects structural control by the Grogan Fault, and for much of its length, Redwood Creek flows along the fault trace. Strike-slip movement along the Grogan Fault has brought two distinct rock types of the Mesozoic Franciscan Complex into contact. East of the fault, hillslopes are underlain primarily by unmetamorphosed sandstones and siltstones and minor melange units. Hillslopes to the west of the fault are underlain predominately by a fine grained, well-foliated, quartz-mica schist (Janda, 1975).

Rocks of the Franciscan Complex are closely fractured and pervasively sheared. Weathering has generated noncohesive soils highly susceptible to fluvial erosion and clayey soils which are susceptible to mass failure when wet (Janda, 1977). Melange units on the east side of the basin are characterized by large earthflow complexes.

The basin has a moist, mild climate typical of the northern California Coast Range. Mean annual precipitation is 200 cm. At least 80 percent of the rainfall occurs between October and March during moderately intense, prolonged winter storms. Rainfall in summer months is uncommon. Basin elevations range from sea level to 1615 m (Janda, 1975).

Major floods occurred throughout northern California in 1953, 1955, 1964, 1972 and 1975. Recurrence intervals for these floods range from 10 to 50 years on Redwood Creek (Coghlan, 1984) and peak discharges greater than 1280 m^3/s were recorded on Redwood Creek near Orick during each flood (Harden and others, 1978). Since 1975, peak flood discharges on Redwood Creek near Orick have not exceeded a 7-year recurrence interval (RI).

In the last 30 years, the combination of periodic large flood events, timber harvesting and steep, highly erodible hillslopes has led to accelerated erosion in the basin and major changes in channel morphology (Varnum and Ozaki, 1986). The last major floods, in 1972 and 1975 (RI = 10 and 25-30 years, respectively; Coghlan, 1984), caused significant aggradation in the middle and lower basin. The locus of maximum aggradation (up to 1.2 m) and bank retreat was located about 26 kilometers upstream of the mouth (Nolan and Janda, 1979). A longitudinal profile of lower Redwood Creek surveyed by the U.S. Geological Survey in summer, 1977 showed the streambed downstream of the gorge to be flat and featureless, with poorly defined pool-riffle morphology (Varnum and Ozaki, 1986). By 1983, the longitudinal profile exhibited partial recovery of pool-riffle morphology in degrading reaches upstream of the Tall Trees Grove and minor recovery in aggrading reaches downstream of the Tall Trees Grove. Since 1981, cold pools have been observed primarily in the wide aggraded reaches on lower Redwood Creek around and downstream of the Tall Trees Grove (Fig 3).

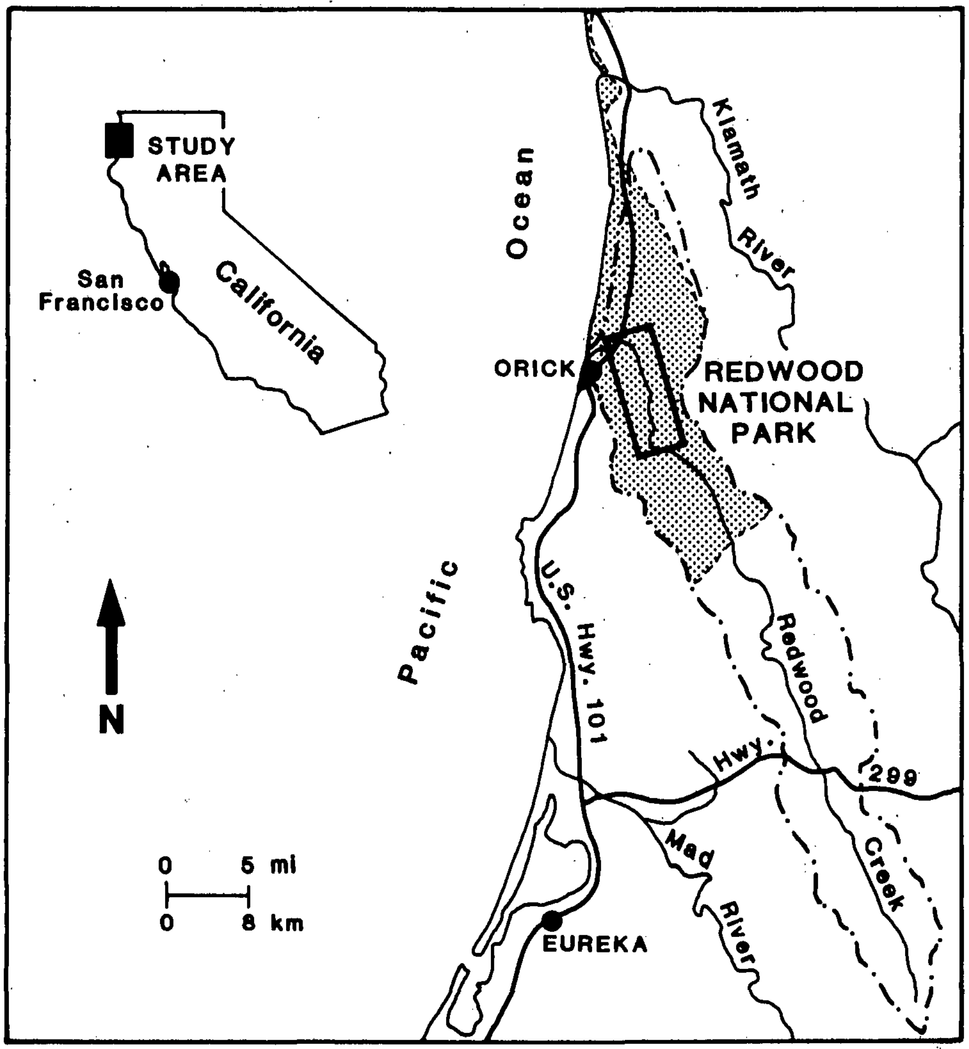


Figure 2. Location of Redwood Creek, California. The shaded area represents Redwood National Park boundaries. The study area is delineated by the rectangular box.

Figure 3. Looking downstream of Elam Creek in a typical aggraded stream reach (downstream of the Tall Trees Grove about 8 km).

III. METHODS

I defined cold pools as low flow mainstem pools in which water temperature was at least 3°C below mainstem water temperatures. During the summer of 1985, I studied five pools in the lower 21 kilometers of Redwood Creek (Fig. 4): Tall Trees Grove Cold Pools A and B, Bond Creek Cold Pool, Elam Creek Cold Pool, and Hayes Creek Pool. The first four of these pools were cold pools in 1985. However, the Hayes Creek pool which developed a cold pool in 1981 (Keller and Hofstra, 1983) did not form a cold pool in 1985.

Detailed topographic and morphologic maps were made of each pool using a plane table and alidade. Pools were mapped at a scale of 1:60 using a 0.5 m contour interval. Cross-sectional and longitudinal streambed profiles were surveyed using a self-leveling level, stadia rod and tape.

I measured temperature distributions along cross sections and longitudinal profiles using a salinity-conductivity-temperature (S-C-T) meter and weighted probe accurate to 0.5°C. Temperatures were measured at 0.15-m depth increments every 0.60 m along cross sections and about every 7.0 m along longitudinal profiles. The temperature probe was suspended in the water column from a rod with a pulley tip to minimize disturbance of the thermocline (Fig. 5).

I used two continuously recording thermographs and a four-channel data logger connected to four temperature probes to monitor mainstem and cold pool water temperatures during the summer. Temperatures were recorded in four of the five pools; however, due to a bad microchip and destruction of temperature probes by beavers, records from the data loggers were unreliable. Continuous temperatures were successfully recorded only in Tall Trees Grove Cold Pool A and Bond Creek Cold Pool.

Figure 6 illustrates potential cold water sources to pools from hillslope groundwater seepage, mainstem intragravel flow, and tributary surface and intragravel flow. I defined water contributed to cold pools from adjacent hillslopes as hillslope groundwater seepage (which includes bank seepage) and water flowing through gravel bars in the stream channel as intragravel flow. Solute transport experiments by Zellweger and others (1986) concluded that surface stream water interchanges extensively with interstitial water in channel gravels over a short time period. In addition, chloride tracers indicated that gravel water was composed primarily of stream flow with only a minor groundwater component.

I used a network of seepage meters to directly measure subsurface inflow into all four cold pools. A seepage meter is an open-bottomed container inserted into the streambed which is connected to a watertight bag. Discharge as low as 0.001 $cm^3/m^2/s$ can be detected by seepage meters (Lee and Cherry, 1978). Seepage inflow is measured as the change in volume in the bag per unit time per area of streambed. A seepage meter consisted of a five-gallon plastic bucket cut to a 15 cm length and connected to a four-liter plastic bag (Fig. 7). Each seepage meter

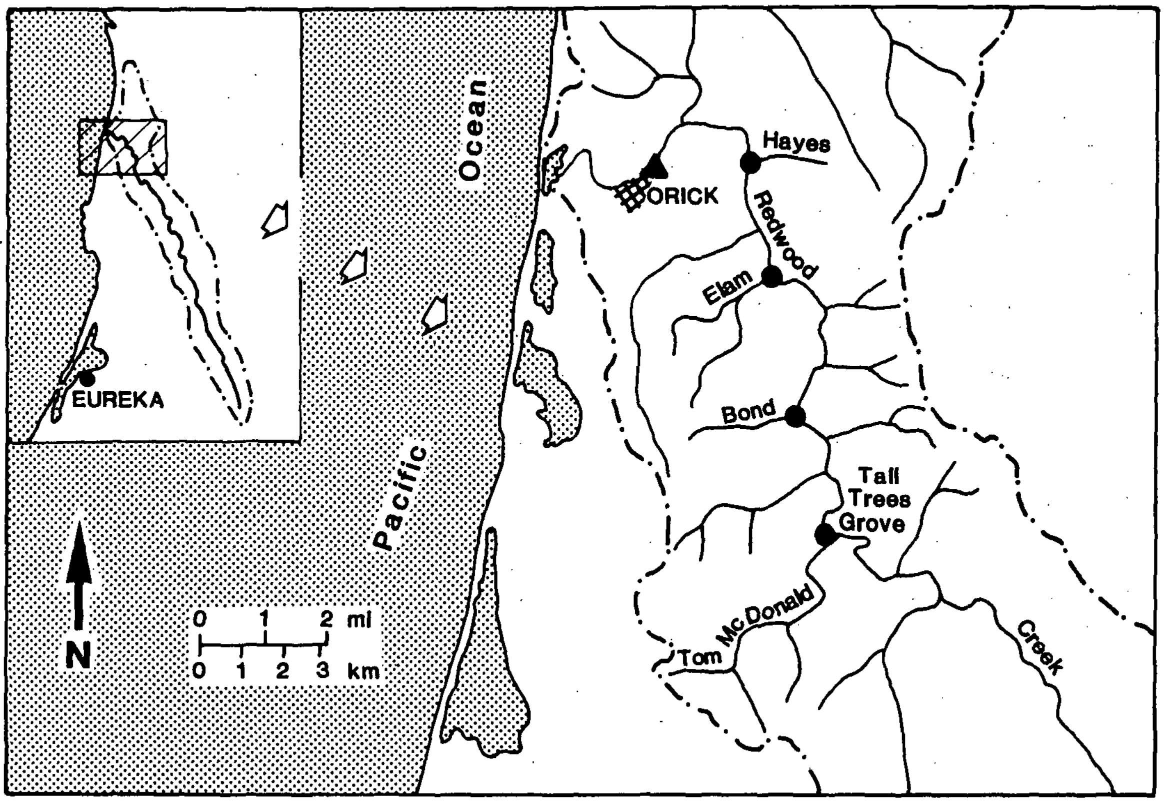


Figure 4. Cold pool study sites in 1985.

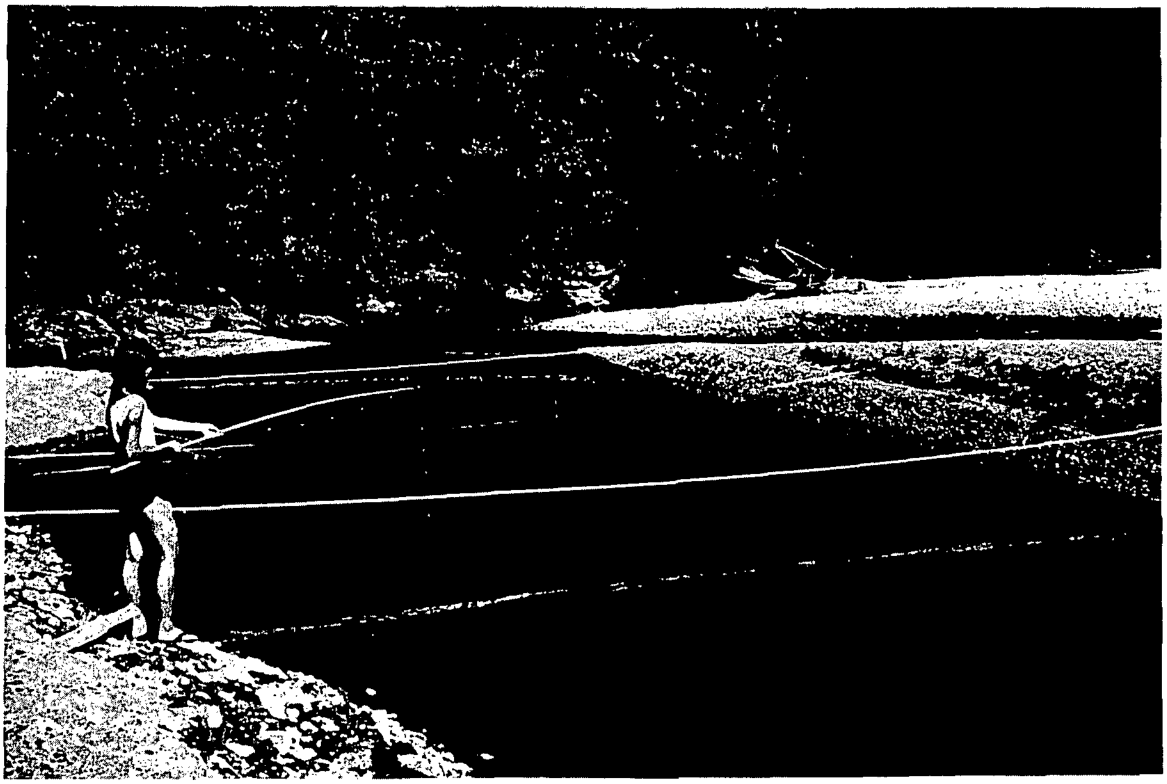


Figure 5. Water temperature profiles were measured with a temperature probe suspended from a fishing rod with a pulley tip.

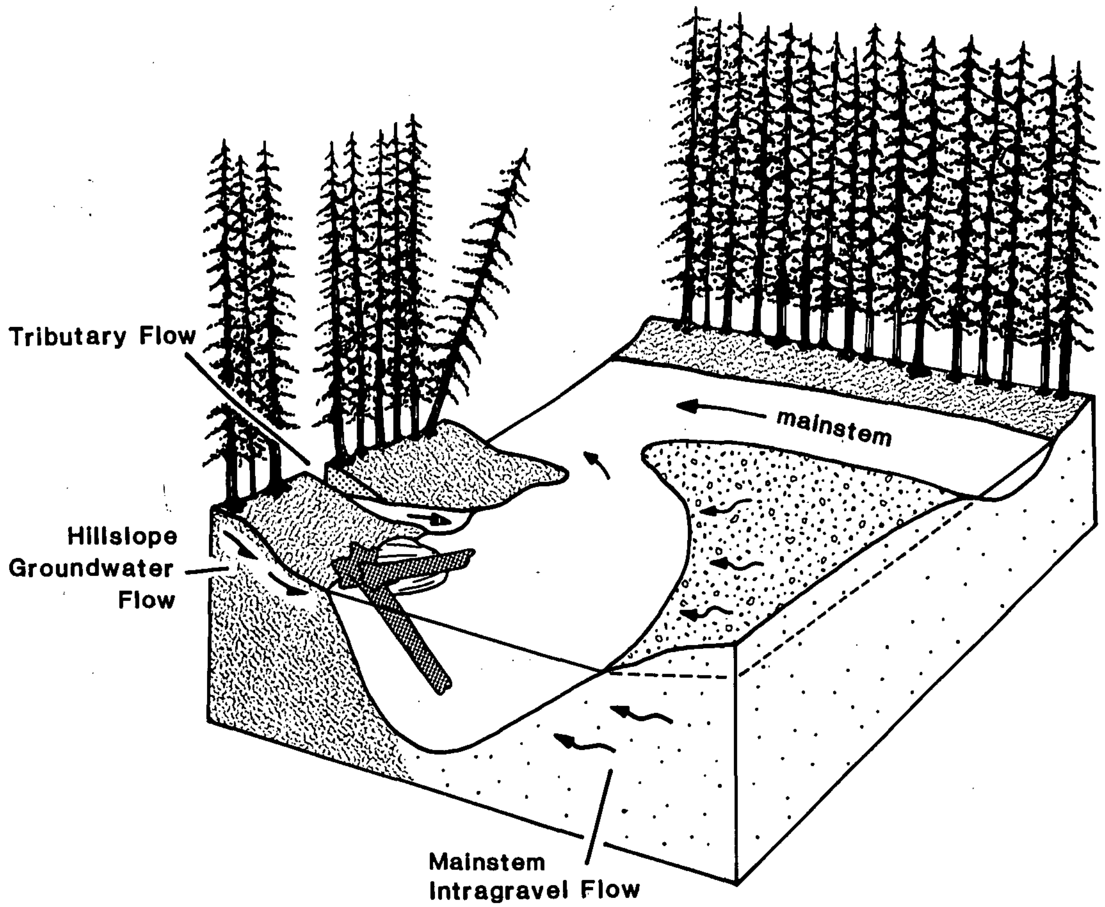


Figure 6. Sources of cold water inflow to cold pools.

Figure 7. Seepage meters measured subsurface seepage into the cold pools. The seepage meter covered 600 cm^2 of streambed and the attached bag holds four liters.

covered 600 cm^2 of streambed. Seepage meters were placed in a network across the pool bottom so that each meter represented about an equal area of streambed. Discharge was determined by timing the filling of the bags and measuring the water volume captured. Duplicate measurements at each meter were made by attaching a new bag to the seepage meter for each measurement. Where possible, temperature was measured at the flow outlet of the meter.

Thiessen polygons were drawn between meter locations to define streambed areas represented by each seepage meter (Shaw, 1983). Polygon areas (a_i) corresponding to seepage meter locations were measured by planimeter and the total subsurface discharge (Q_m) is given by:

$$Q_m = \sum_{i=1}^{n} (q_i * a_i) / A$$

where q_i is the seepage meter discharge in cm^3/s at n total seepage meters and A is the streambed area covered by a meter (600 cm^2).

I measured intragravel flow and hillslope bank seepage (hillslope groundwater) above the pool water surface volumetrically. A 17-cm wide rectangular container was inserted into the gravel bar above the pool water surface (Fig. 8) and inflow was measured as the change in water volume in the container over time. Usually four replicate measurements were taken at each station and the results averaged. Measurements were taken approximately every 1.5 m along gravel bars and flow was computedas discharge per length of streambank. Total seepage (Q_n) into a pool measured with the rectangular trough is given by:

$$Q_n = \sum_{j=1}^{n} (q_j * l_j) /L$$

where q_j is the mean discharge measured at a point at n total locations, L is the length of the container (0.17 m) and l_j is the length of streambank in meters represented by the measurement.

No tests to differentiate water sources were attempted in this study; however, qualitative methods were used to separate hillslope groundwater from intragravel flow. Hillslope groundwater seepage in a small section of Cold Pool A was identified by the lack of diurnal changes in pool bottom temperatures and greater differences in water temperatures (>2°C) compared to surrounding pool bottom temperatures. Mainstem intragravel flow was identified in Cold Pool B and Bond Creek Cold Pool by using dye injected into holes dug into bar surfaces to visualize flow directions within the gravel bars that separated mainstem flow from the pools. Gravel bar thicknesses in excess of one meter above the water table prohibited dye tracing on other pools. Relative elevations of cold pool

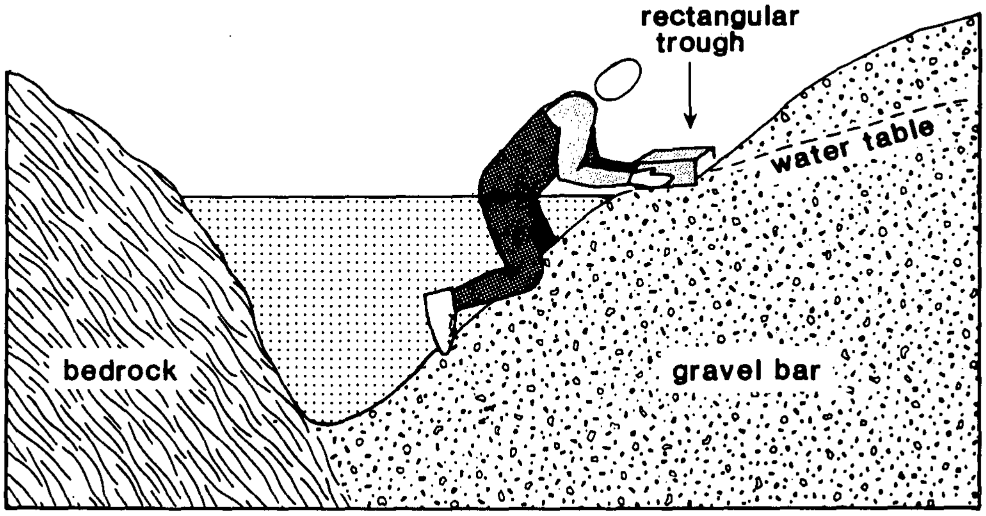


Figure 8. A 17-cm wide rectangular trough was inserted into the gravel bar above the pool surface to measure inflow volumetrically.

and mainstem water were surveyed to determine the local water table gradient. The travel time of dye between holes was measured to estimate intragravel flow rates. However, velocity estimates based on dye travel times were unreasonably large due to poor estimates of porosity, and were not used.

Tributary surface flow and discharge at the outlet of cold pools were measured with a pygmy meter and wading rod. Flows from small tributaries (baseflows of <0.003 m^3/s) were measured volumetrically using the rectangular trough previously described.

IV. RESULTS

Four pools comprised the total cold pool population on the lower 21 kilometers of Redwood Creek during the summer of 1985; these pools represent less than 9 percent of the total pool population. Cold pools were observed around and downstream of the Tall Trees Grove in the aggraded section of the stream.

For each pool, isothermal lines were plotted at 0.5°C intervals for each cross section (Appendix A). Because the temperature intervals lie within the error of the temperature meter, the plots cannot be used to determine absolute temperature values; however, they are useful for describing relative temperature distributions in pools. Minor variations between cross section temperatures within pools reflect measurement at different times of the day. Highest water temperature and greatest difference between mainstem and pool temperature occurred from noon through early evening. Temperature data for each cross section are tabulated in Appendix B.

Table 1 summarizes temperature characteristics of each pool during the months of August and September. During this period, cold pool temperatures were as much as 5.0 to 8.8°C below mainstem temperatures. However, the greatest difference between cold pool and mainstem temperatures occurred in early July, when pool water was 6.0 to 11.0°C colder than the mainstem.

Pool volumes ranged from 68 - 541 m^3 and maximum pool depths ranged from 0.76 - 2.28 m. The percent of the pool volume represented by water temperatures <15.0°C, 15.0 to 19.9°C, and ≥20.0°C is shown for each pool in Figure 9. These classes reflect temperature ranges important to juvenile salmonids. In laboratory studies, water temperatures preferred by juvenile salmonids lie between 7.3 and 14.3°C and upper lethal water temperatures are between 24.1 and 25.8°C for steelhead and coho respectively (Beschta and others, 1987). Except for the Hayes Creek pool, water temperatures of all cold pools were less than 20°C. In contrast, temperatures measured in mainstem pools commonly exceeded 20°C on warm afternoons and were uniform in temperature from top to bottom. Table 2 summarizes volume, surface area, width, length, mean depth, maximum depth, width to length ratios (W/L ratios), and temperature difference between pool bottom and mainstem water for nine cold pools studied since 1981. Data for cold pools prior to 1985 were calculated from pool maps made by Keller and Hofstra (1983) and Moses (1984). Figure 10 shows locations of all cold pools studied on Redwood Creek since 1981.

Mean depth, maximum depth, volume, and W/L ratio are plotted against pool-mainstem temperature difference in Figure 11. Since 1981, multiple observations have been made at three pool locations. Only the most recent data was used to represent these pools in the plots. Some error in pool-mainstem temperature data cannot be avoided since temperatures were measured in different yeasrs, day of the month and time of day.

Table 1. Temperature characteristics of pools studied in 1985.

	WATER TEMPERATURE*				
	Max Pool Surface (°C)	Min Pool Bottom (°C)	Mean Pool (°C)	Mean Mainstem (°C)	Max Temp Diff (°C)
Tall Trees Grove:					
Cold Pool A	18.0	11.5	15.6	20.3	8.8
Cold Pool B	18.8	14.2	17.4	20.3	6.1
Bond Creek Cold Pool	18.6	15.0	18.3	20.0	5.0
Elam Creek Cold Pool	13.0	12.5	13.2	20.0	7.5
Hayes Creek Pool	20.3	18.0	18.3	20.5	2.5

* Temperatures measured in August and September 1985.

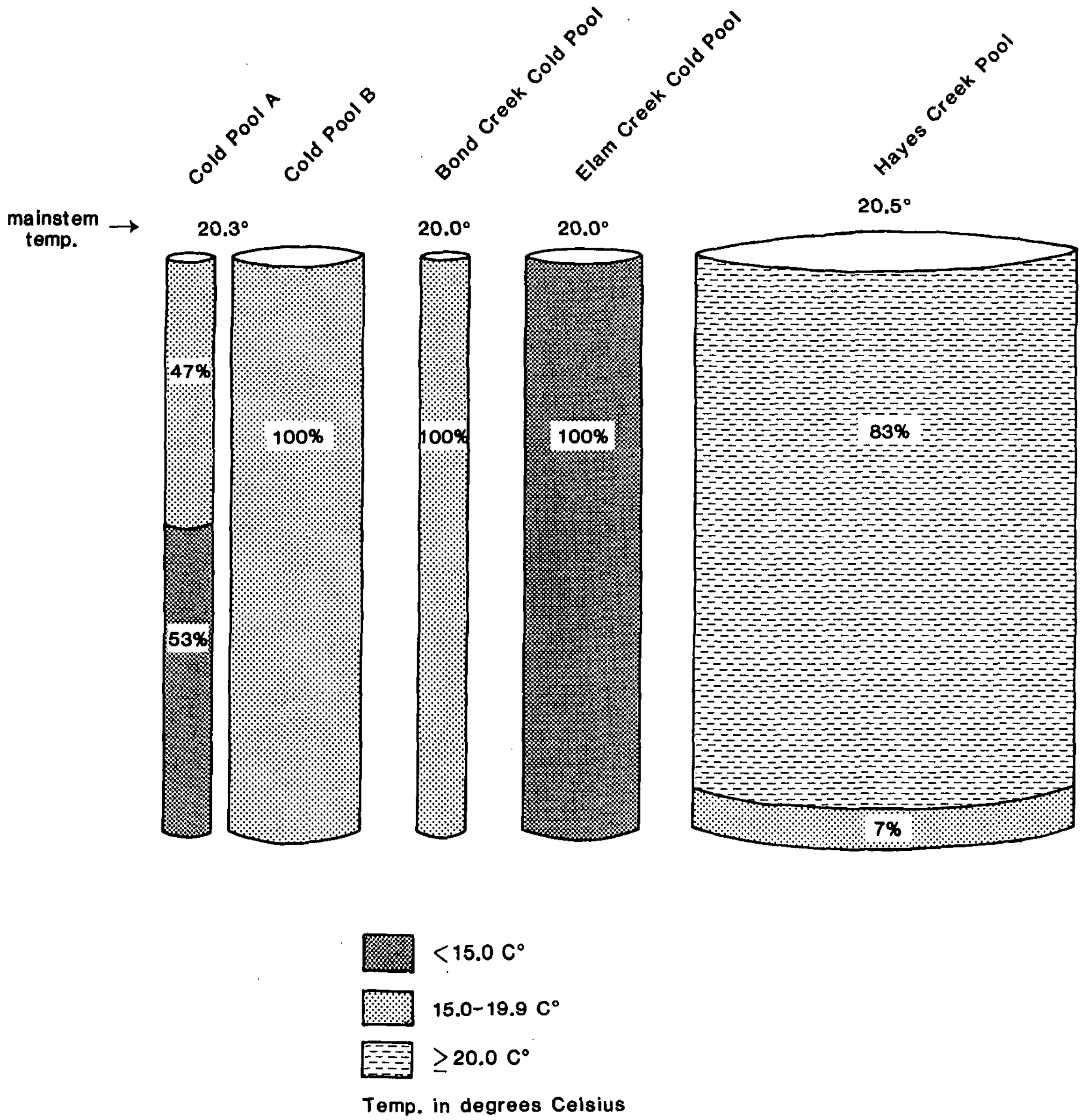


Figure 9. Histogram of the percent volume of different temperature classes in each pool. The size of the cylinders represents relative pool volumes.

Table 2. Physical characteristics of cold pools studied since 1981. Refer to Figure 10 for pool locations.

Cold Pool Name	Date Mapped	Km Dist* (km)	Volume (m^3)	Surface Area (m^2)	Length (m)	Width (m)	Max Depth (m)	Mean Depth (m)	W/L Ratio	Temp Diff. (°C)
1. "Emerald Creek"	1982a	87.00	564	476	31.0	15.4	4.50	1.2	0.50	4.0
Tall Trees Grove:										
2. Cold Pool A	1985	88.75	68	198	34.0	5.8	1.56	0.3	0.17	9.0
	1983a	"	229	356	69.0	5.2	1.88	0.6	0.07	9.0
3. Cold Pool B	1985	88.87	196	464	40.5	11.5	1.83	0.4	0.28	7.0
	1983a	"	186	665	61.0	10.9	1.73	0.3	0.18	5.0
4. Cole Creek[1]	1983a	90.55	51	32	9.8	3.3	0.75	1.6	0.33	5.0
5. Bond Creek	1985	92.80	69	293	28.7	10.2	0.76	0.2	0.36	5.0
6. "Jeremiah"	1983a	95.60	1251	1775	185.0	9.6	2.30	0.7	0.05	3.5
7. Elam Creek	1985	97.30	164	303	49.0	6.2	2.15	0.5	0.13	7.5
	1983a[2]	"	—	—	—	—	—	—	—	5.5
	1982a	"	191	256	58.0	4.4	1.88	0.7	0.08	7.0
8. "Footbridge"	1983a	99.05	183	203	30.0	6.8	2.68	0.9	0.23	5.5
9. Hayes Creek	1981b	100.22	—	404	57.8	7.0	—	—	0.12	9.0

* Kilometer distances are measured from the headwater divide (Madej, 1984).

a Pools mapped by C. Moses (1984).

b Pool mapped by Keller and Hofstra (1983).

1 Moses (1984) named this pool "Tall Trees Pool" and mislocated the pool at the mouth of Chris Creek. The true pool location was at the mouth of Cole Creek.

2 No physical measurements were made in 1983 at this pool. The pool is similar in size and shape to the 1982 Elam Creek Cold Pool (Moses, 1984).

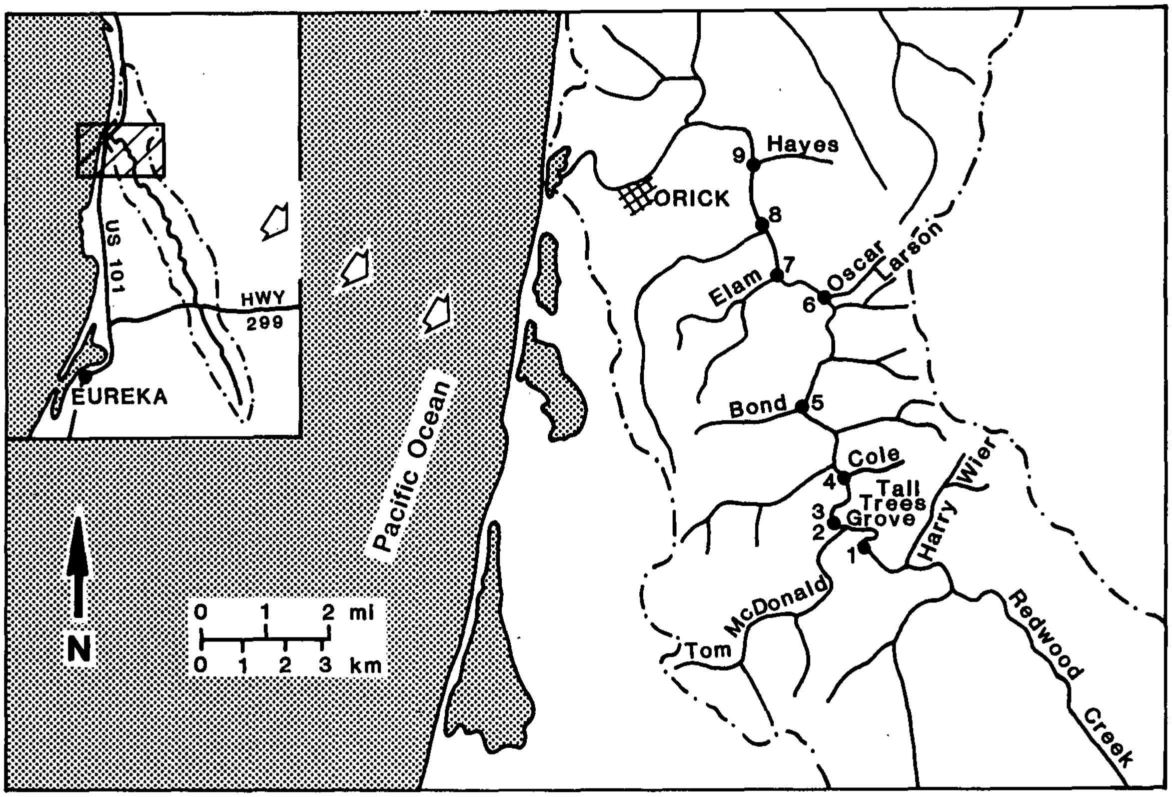


Figure 10. Location of cold pools studied on Redwood Creek since 1981. Numbers refer to cold pool study sites: 1) "Emerald" Cold Pool, 2) Cold Pool A, 3) Cold Pool B, 4) Cole Creek Cold Pool, 5) Bond Creek Cold Pool, 6) "Jeremiah" Cold Pool, 7) Elam Creek Cold Pool, 8) "Footbridge" Cold Pool and 9) Hayes Creek Cold Pool. See Table 2 for data sources.

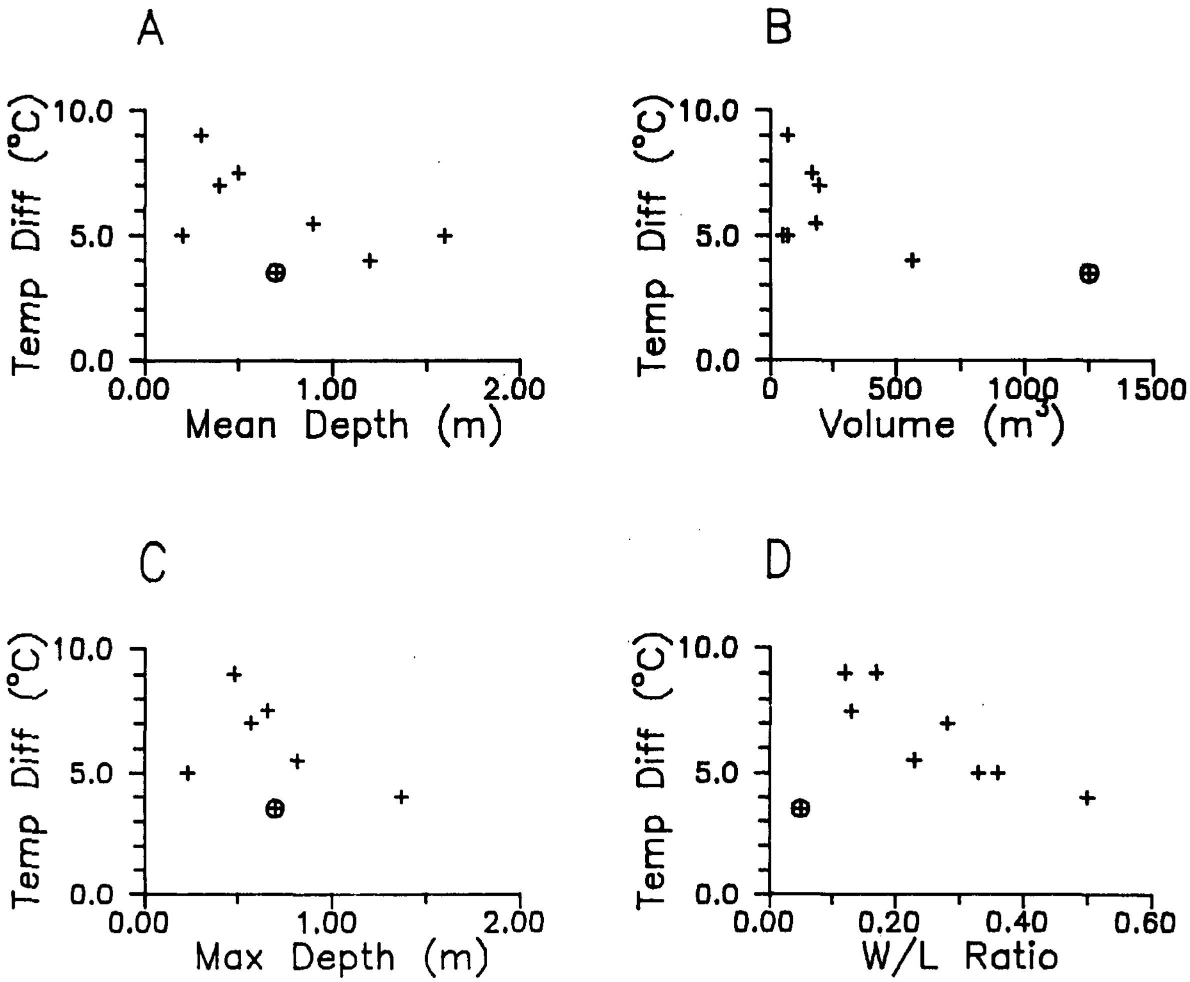


Figure 11. Plot of mean pool depth (A), maximum depth (B), volume (C) and W/L ratio (D) against the temperature difference between mainstem and pool water. The Jeremiah Cold Pool was atypical is size and length and is denoted by a ⊕.

However, this data can be used to determine general relationships between pool-mainstem temperature differences and pool geometry.

These graphs suggest pool-mainstem temperature difference is independent of mean depth (r^2=0.14), maximum depth (r^2=0.06), and volume (r^2=0.28). One cold pool (Jeremiah Cold Pool) was atypical in size and length. However, when this data point is removed from these relationships, no significant change in r^2 occurs. This indicates pool-mainstem temperature difference is probably more a function of the quantity and temperature of inflowing water.

The plot of W/L ratio against temperature difference show a general decrease in temperature difference with increasing W/L ratio. Regression analysis using all W/L data indicates no relationship exists between W/L ratio and temperature difference (r^2=0.06). When data from the Jeremiah pool is removed from the relationship, W/L ratio explains more than 65 percent of the pool-mainstem temperature difference; remaining unexplained variation is probably due to the volume, rate and temperature of cold water inflow. The relationship between W/L ratio and temperature difference may be explained by the fact that longer, narrower pools (lower W/L ratio) have more contact with the streambank and potential cold water inflow. These pools may also have more shading from solar radiation since they are closer to the streambank and riparian vegetation. All cold pools studied since 1981 had W/L ratios less than 0.50 and typically were channel-like in shape.

Multiple regressions using combinations of pool variables could account for at most 61 percent of the variation in temperature difference. The best multi-variate relationship used mean depth, surface area and W/L ratio to predict temperature difference (r^2 = 0.61). However, W/L ratio alone best explains pool-mainstem temperature differences.

Cold water contribution to the pools was complex. Water flowing into the pools ranged in temperature from 11.0 to 21.2°C and was occasionally warmer than the mainstem. Table 3 summarizes total inflow to each cold pool. No inflow measurements were made on the Hayes Creek pool although some cold water inflow was observed. Cold water inflow to pools ranged from 0.008 to 0.020 m^3/s.

Moses (1984) indirectly estimated water inflow to cold pools in 1982 and 1983 by measuring stream discharge in the mainstem above and below cold pools. She estimated her measurement error as 10 percent; hence only discharge differences exceeding that were considered real. Estimated discharges from cold pools ranged from 0.11 to 0.24 m^3/s and were an order of magnitude greater than discharges I determined by directly measuring inflow to pools. The methods used by Moses are not adequate to measure the relatively minute quantities of inflow to cold pools and represent at best a maximum inflow.

Pool maps showing seepage meter locations and corresponding Thiessen polygons and individual water discharge measurements from seepage meters and rectangular troughs are found in Appendix C.

Table 3. Measured values of discharge into cold pools.

	Intragravel Flow Measured with			
	Seepage Meter ($\times 10^{-3}$ m^3/s)	Rectangular Trough ($\times 10^{-3}$ m^3/s)	Tributary Flow ($\times 10^{-3}$ m^3/s)	Total Inflow ($\times 10^{-3}$ m^3/s)
Tall Trees Grove:				
Cold Pool A	6.2	2.0	no	8.2
Cold Pool B	18.1	1.8	no	19.9
Bond Creek Cold Pool	7.1	2.8	6.5*	16.4
Elam Creek Cold Pool	Trace	0.0	16.1	16.1
Hayes Creek Pool		No Measurements**		

* Reflects estimated portion of tributary discharge entering the Bond Creek Cold Pool. Total discharge of Bond Creek was 13.0×10^{-3} m^3/s.

** A large log jam covering the Hayes Creek pool prohibited seepage meter measurements.

Error between successive discharge measurements at individual seepage meters are plotted in Figure 12. Replicate discharge measurements at each seepage meter are plotted against the highest flow measured by that meter. Precise replicate measurements would produce a linear relationship with a slope equal to one and a y-intercept of zero.

Seepage measurements in Tall Trees Grove Cold Pool A were the most precise and measurements of the Bond Creek Cold Pool were the least reliable. Seepage meter measurements at Elam Creek Cold Pool were not used since seepage rates in the pool were too small to be accurately measured by this technique. Replicate measurements that were significantly different (>50 percent difference) than the majority of measurements were not used in water budget calculations.

Sources of variation in seepage meter measurements may be due to measurement error or to natural variations in seepage rates. Measurement error can be caused by not inserting the seepage meter deep enough into the streambed, not positioning the flow outlet of the meter correctly and gaining or losing water while connecting and disconnecting plastic bags. In general, measurement accuracy decreased on pools in which I made seepage measurements alone. To obtain optimum results using seepage meters, two-person teams are necessary.

Some temperature profiles exhibited concentrated cold water areas above the pool bottom. This suggests a higher cold water inflow at depth. However, a plot of seepage rate against water depth above the meter (Fig. 13) shows no relationship and indicates that seepage rate is independent of water depth.

Contour maps of seepage rates in cold pools disclosed that seepage rates vary greatly across the pool bottom, with concentrated points of high seepage rate (Fig. 14). The Elam Creek Cold Pool was not included since seepage rates measured there were less than the accuracy of the meters. Seepage rates varied considerably from pool to pool, with highest rates (> 7.4 cm^3/s) measured in Cold Pool A and B. Bond Creek Cold Pool had maximum seepage rates of 4.8 cm^3/s. In Cold Pool A, highest seepage rates were close to the right bank of the pool on the downstream edge of a large gravel bar. In Cold Pool B, highest rates were near the gravel bar separating the pool from the mainstem. These locations suggest a relatively large contribution of intragravel flow through the downstream face of the gravel bar.

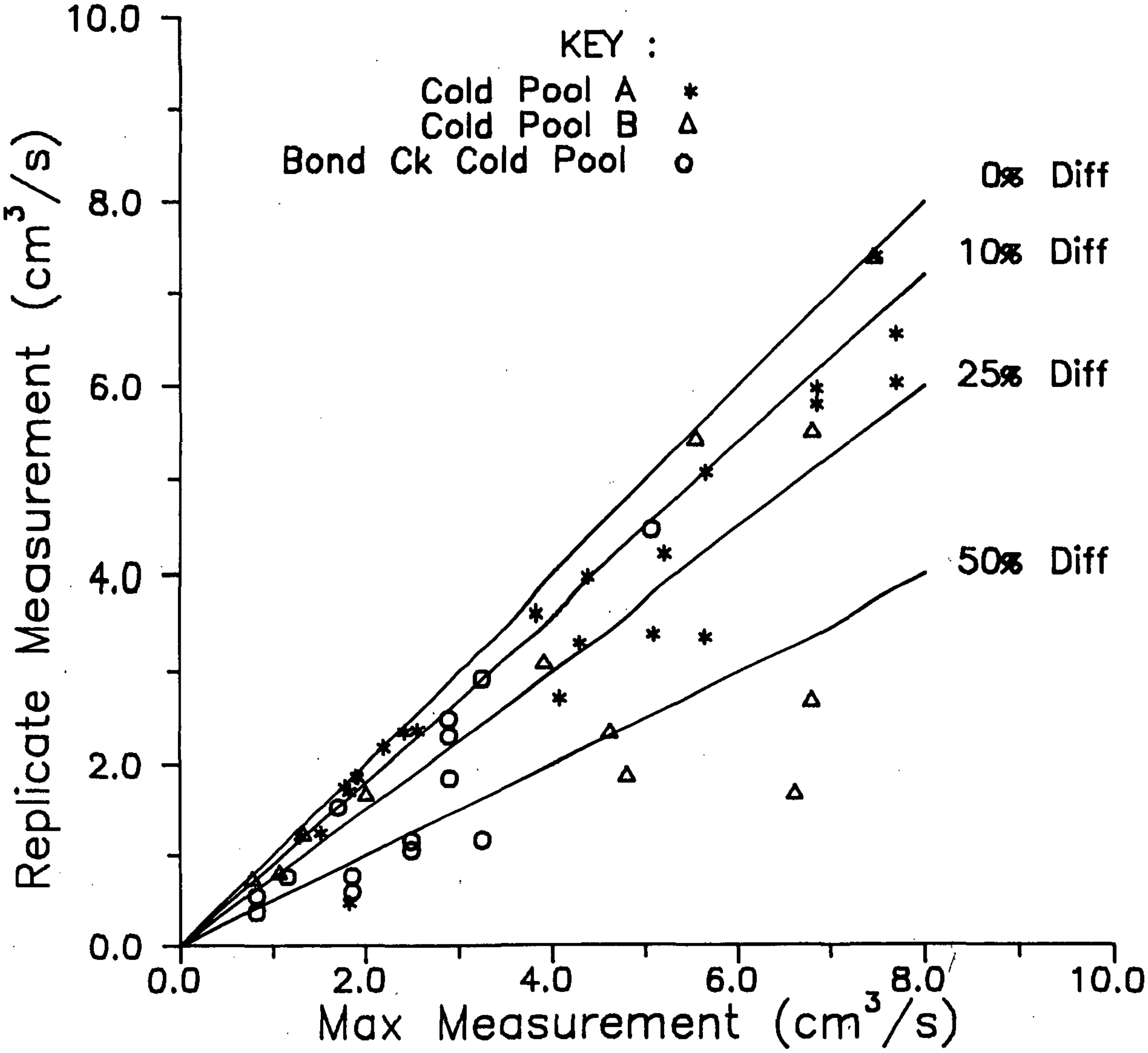


Figure 12. Plot of replicate seepage meter measurements against the highest measured seepage rate at the same meter. The solid lines represent the percent difference between successive measurements.

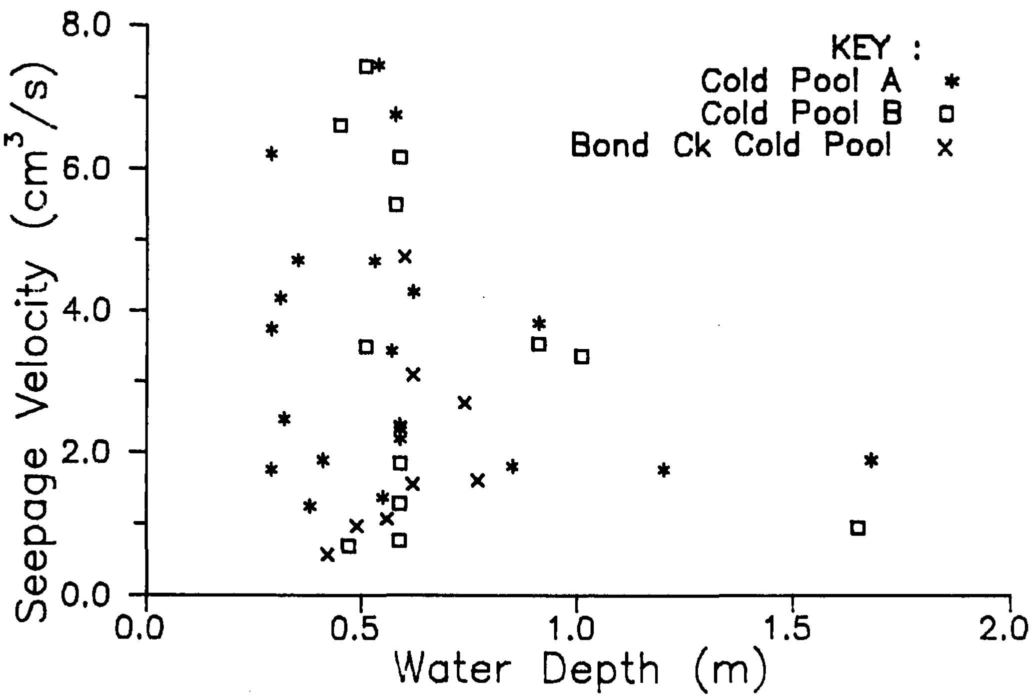
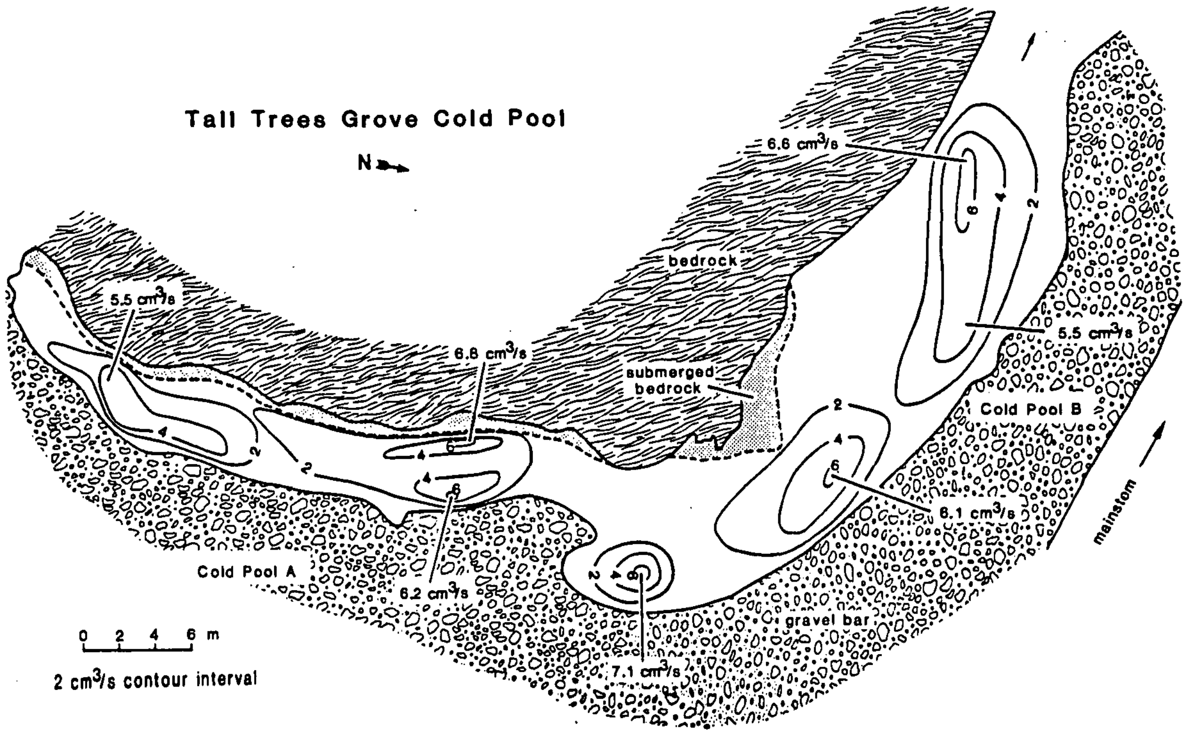


Figure 13. Plot of seepage rate against water depth at seepage meters.



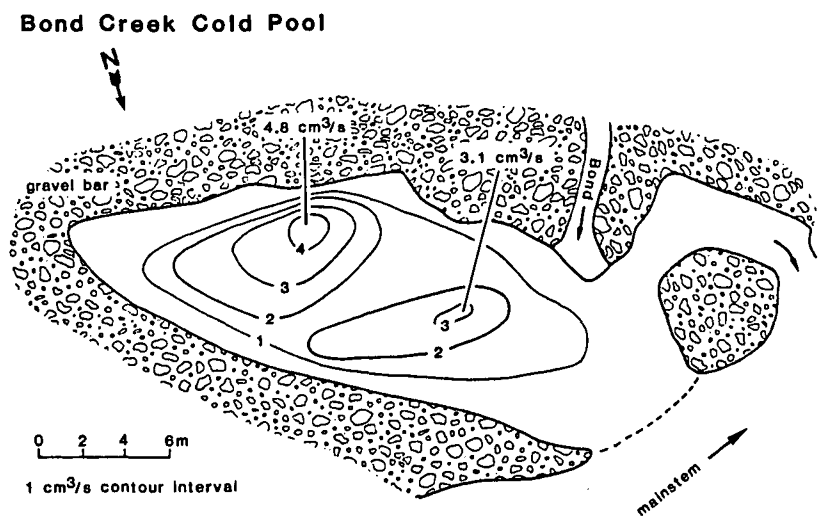


Figure 14. Seepage contour maps of Cold Pool A, Cold Pool B and the Bond Creek Cold Pool.

A. Pool Descriptions

Individual cold pools are described below in downstream order.

Tall Trees Grove Cold Pools

The Tall Trees Grove Cold Pool (88.87 km) comprises two distinct cold pools located 0.25 km downstream of Tom McDonald Creek (Fig. 15) (Kilometer distances are measured from the headwater divide; Madej, 1984). Each pool exhibited distinctly different water temperature distributions. The upstream pool, Cold Pool A, was markedly colder than Cold Pool B (Fig. 16), due to more shading and relatively colder water entering Cold Pool A.

Cold Pool A, while isolated from the mainstem low flow channel by a gravel bar, was connected by a shallow sill to Cold Pool B. Cold Pool B was separated from the mainstem flow by a gravel bar barrier and open to the mainstem low flow channel on the downstream end.

Cold Pool A. Sources of inflow to Cold Pool A were mainstem intragravel flow and hillslope groundwater seepage. Pool temperatures ranged from 11.5 to 19.9°C and averaged 3.6°C lower than mainstem temperatures. Total pool volume was 68 m^3. Fifty three percent of the pool volume was represented by water temperatures <15.0°C, with the remaining pool water between 15.0 and 19.9°C. This cold pool provided large volumes of water within or near the preferred temperature range of juvenile salmonids.

Continuously recording thermographs were placed on the surface and bottom of Cold Pool A and in the mainstem for a two-day period in mid-August, 1985 (Fig. 17). Mainstem and pool surface water thermographs exhibited daily diurnal fluctuations. Water temperatures were warmest in the late afternoon and coolest in the early morning. Diurnal fluctuations on the pool surface generally coincided with mainstem temperature fluctuations. However, pool water was usually more than 2°C lower than mainstem water temperatures. Cold pool temperatures monitored in 1982 and 1983 by Moses (1984) showed similar relationships.

Cold Pool A was the only pool which clearly exhibited hillslope groundwater contribution. The thermograph placed on the pool bottom showed no diurnal fluctuations and recorded a constant temperature of 11.5°C. Bottom temperatures were typically 8.0°C lower than the mainstem during the warmest period of the day. The thermograph was placed in an area of hillslope groundwater seepage; however, seepage rates were too low to affect the overall temperature characteristics of the surrounding pool.

Temperature was used to separate hillslope groundwater seepage from intragravel inflow to the pool. Hillslope groundwater seepage was present in trace amounts and occurred only in a small area at the head of Cold Pool A. Most subsurface inflow temperatures were higher than what one might expect from hillslope groundwater (11-12°C based on regional

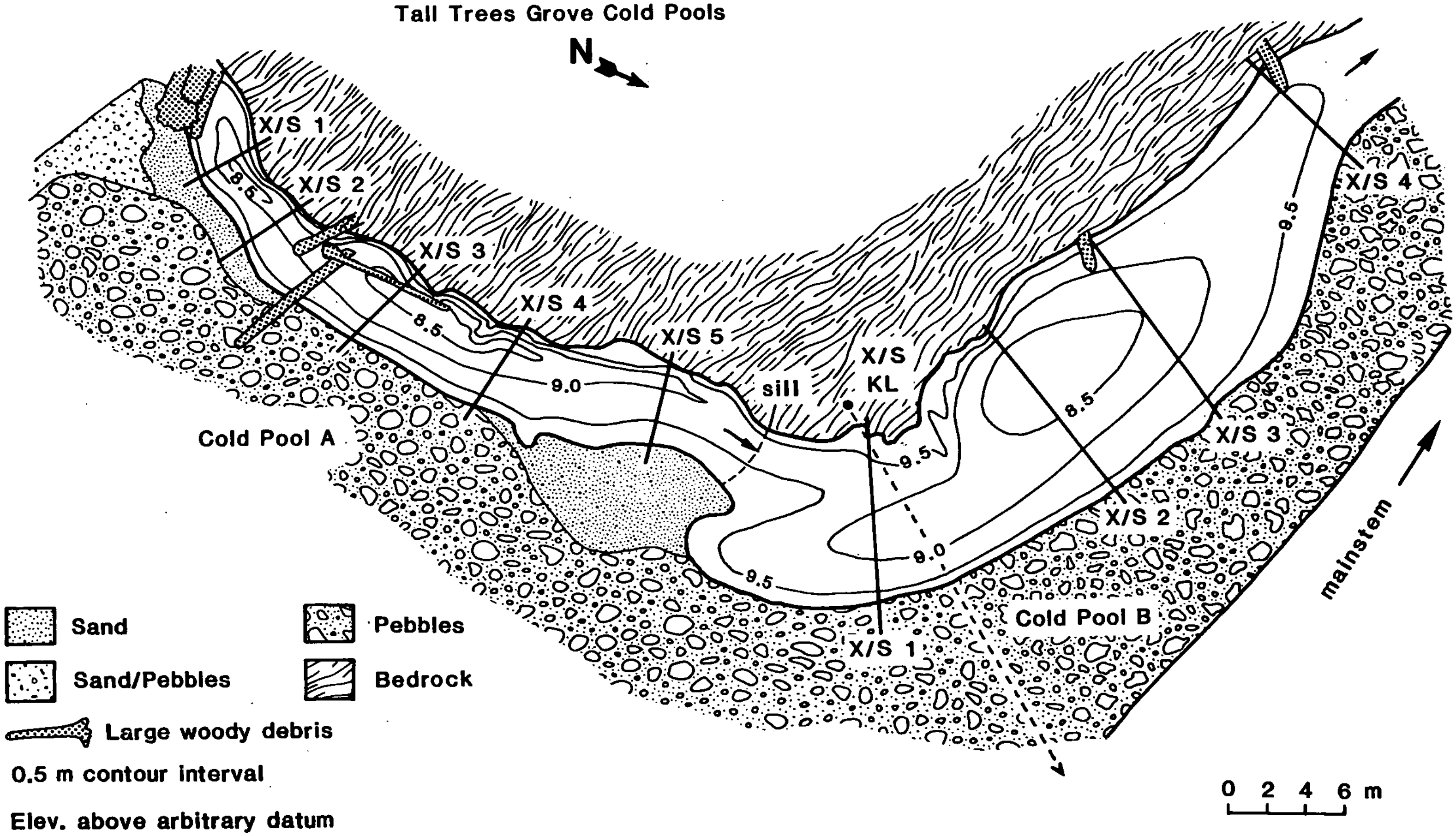
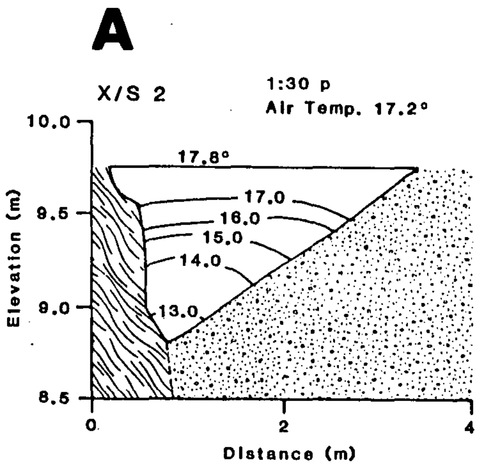


Figure 15. Topographic map of Cold Pool A and B showing cross section locations. The pools were located on the left bank of the channel and a shallow sill separated the cold pools.



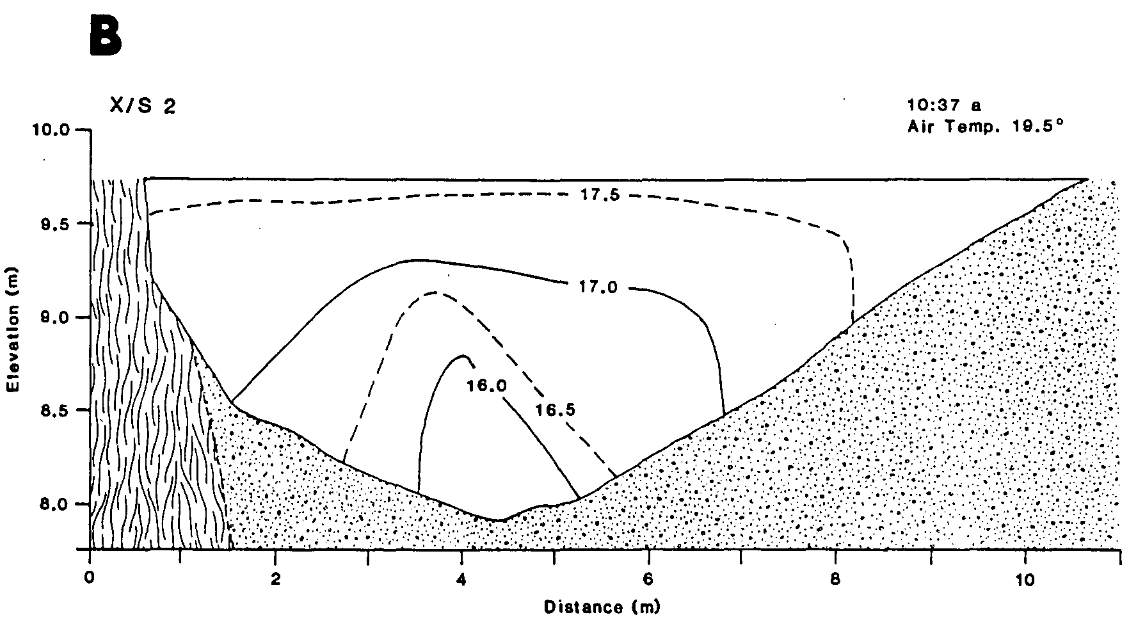


Figure 16. Water in Cold Pool A (A) was much colder than Cold Pool B (B). Refer to Figure 15 for cross section locations.

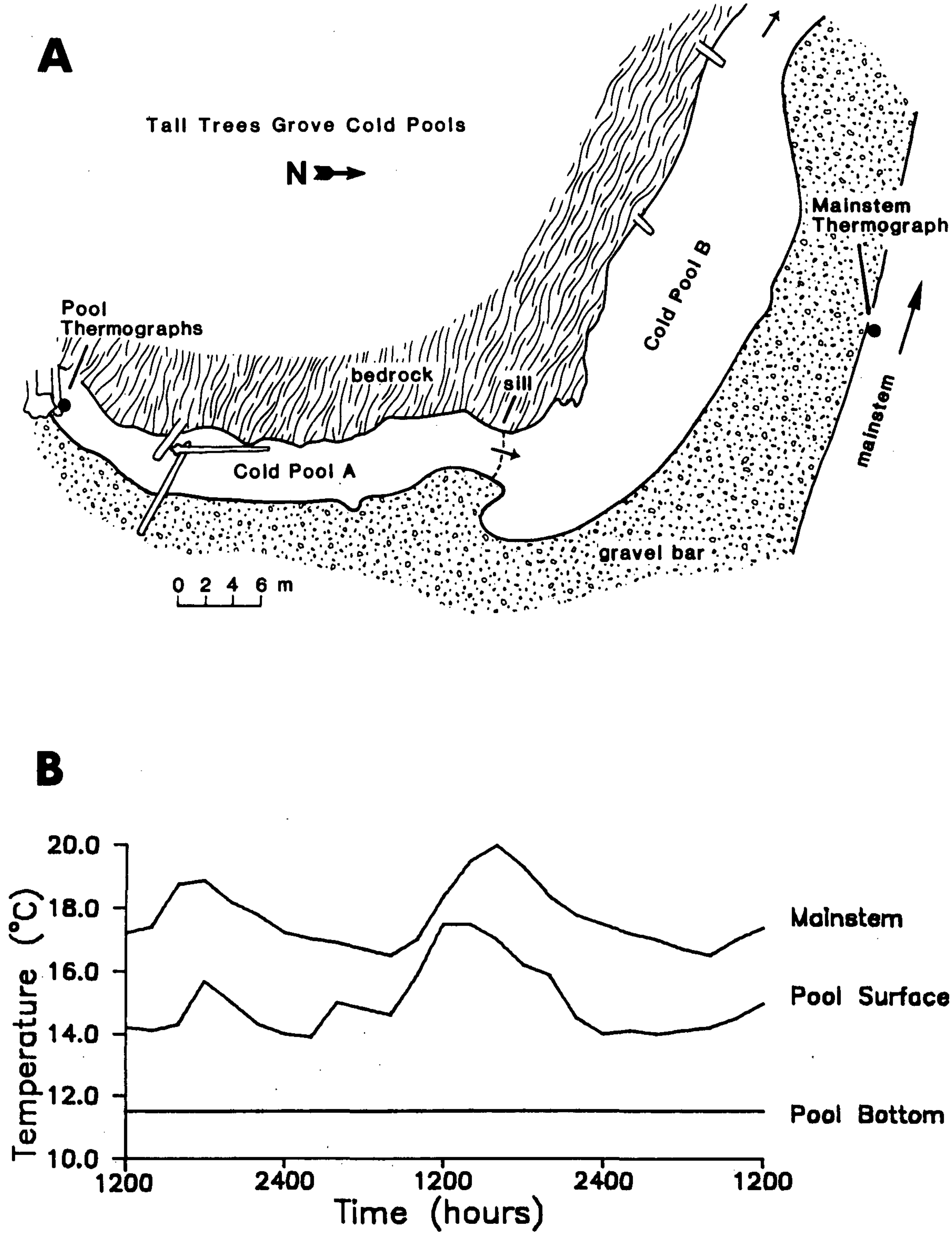


Figure 17. Thermographs were located at the head of Cold Pool A and in the mainstem (A). Water temperatures recorded over a two day period in August in Cold Pool A showed that cold pool water never exceeded mainstem temperatures (B).

models for groundwater temperatures; Todd, 1980) and indicate that mainstem intragravel flow contributed almost 100 percent of the pool inflow. Total pool inflow was determined to be 8.2×10^{-3} m^3/s with intragravel inflow temperatures ranging from 11.5 to 20.0°C.

Cold Pool B. Mainstem intragravel flow and surface flow from Cold Pool A were the only measurable inflows to Cold Pool B. Subsurface seepage accounted for >70 percent of the inflow (19.9×10^{-3} m^3/s) to the pool with the remaining inflow coming from Cold Pool A. Comparison of measured inflow to both pools (0.0281 m^3/s) with measured outflow at the mouth of Cold Pool B (0.0275 m^3/s) showed close agreement, indicating that water budgets for the cold pools yielded good estimates of inflow. Upwelling of intragravel flow was associated with small silt and sand boils on the bottom of Cold Pool B (Fig. 18). Temperature of upwelling water was at least 2.6°C colder than mainstem water and generally increased over the summer from 14.5 to 18.2°C between July and September. A maximum temperature difference of 7.5°C between mainstem water temperatures and silt boils in the cold pool was observed in early July.

Temperature of subsurface inflow to Cold Pool B ranged from 14.2-21.2°C. In some cases, the temperature of intragravel flow entering topographically above the pool surface (Fig. 8) was higher than mainstem temperatures. This may be due to heated gravel bar surfaces warming shallow flow as it traveled through the bars combined with short intragravel travel time of mainstem water to the cold pool. In general, intragravel flow was cooler closer to the hillslope than near the mainstem (Fig. 19).

The volume of Cold Pool B was 196 m^3. All pool water temperatures were between 15.0 and 19.9°C, near the preferred temperature of juvenile salmonids.

Cold pools formed in this location in 1983 (Moses, 1984) and 1984. Pools form in this location as a result of scour around a schist bedrock outcrop and large organic debris on the outside of a prominent meander bend. The pools were located on the downstream edge of a large gravel bar and were associated with a high-flow side channel.

Mainstem channel cross sections around the Tall Trees Grove show that channel shifting is common and as a result pools are ephemeral features which change position from year to year (Varnum and Ozaki, 1986). Cold Pool B is located on the left bank of mainstem Cross Section K-L. Although the low flow channel shifts annually, aerial photographs and cross section records indicate that, generally, in years when the flow is on the right bank a summer pool forms on the left bank of Cross Section K-L (Fig. 20). Moderate flows during the winter of 1986 (Recurrence Interval <5 years), shifted the low flow channel to the left bank and the mainstem flowed through the cold pool location. A small cold pool has persisted through 1987 in the upstream area of Cold Pool A.

Figure 18. Upwelling of intergravel water on the bottom of Cold Pool B formed small silt/sand boils.

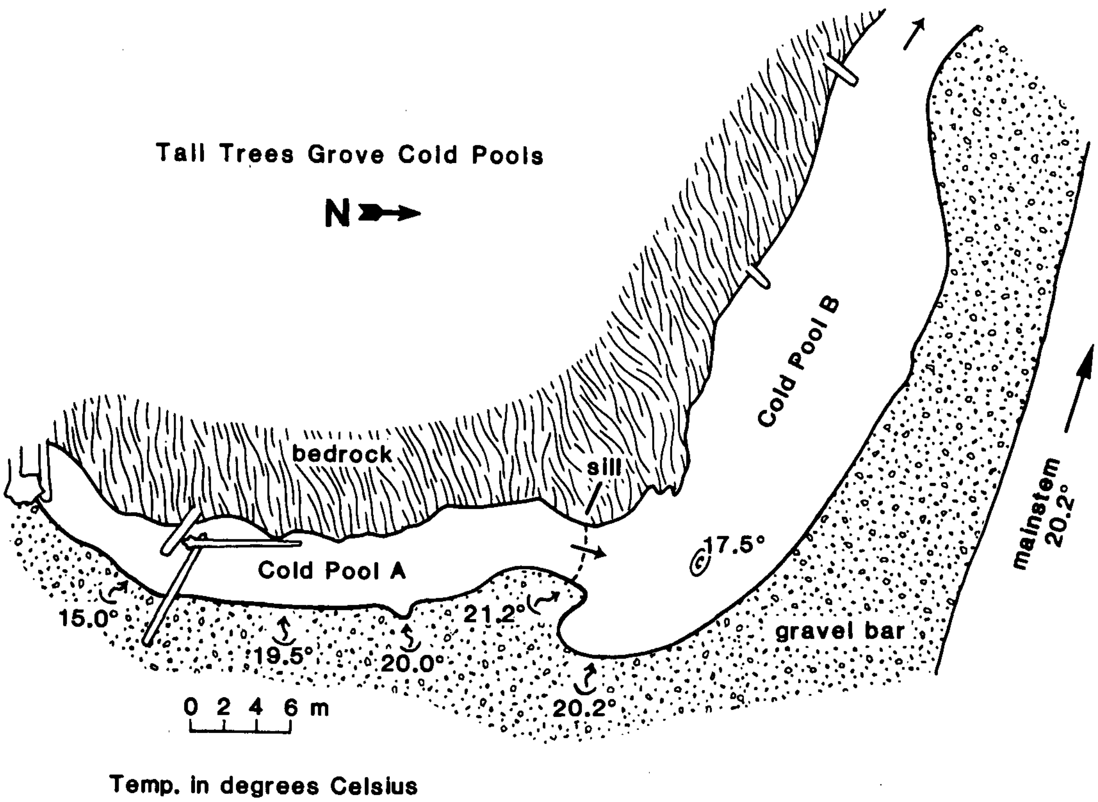


Figure 19. Temperature of near surface intergravel flow increased with distance from the hillslope in the Tall Trees Grove Cold Pools. Temperatures were measured on August 1, 1985.

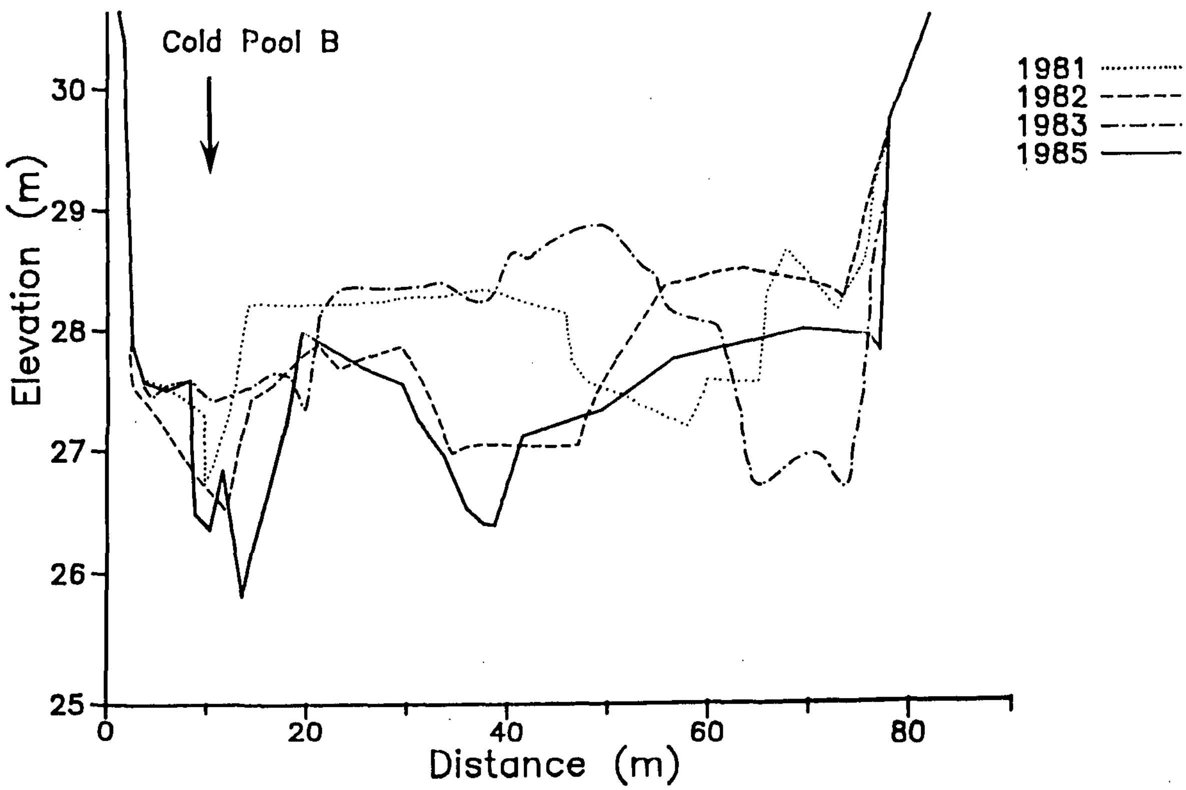


Figure 20. Mainstem Cross Section K-L shows that the channel shifts position annually. The Tall Trees Grove Cold Pools are located adjacent to the left bank. Note that in years when the low flow channel is in the middle or right side of the channel, a pool forms on the left bank (Redwood National Park, unpublished data).

Bond Creek Cold Pool

The Bond Creek Cold Pool was located at the mouth of Bond Creek (92.80 km; Fig. 21). It developed on the downstream end of a large gravel bar and was separated from the mainstem by the bar. Mainstem and tributary flow entered at the downstream end of the pool and a portion of the tributary flow entered the mainstem directly.

The Bond Creek Cold Pool is unusual in that it is less than one meter deep and yet is thermally stratified. Although this was the shallowest of all the cold pools studied (0.76 m max. depth), a 5.0°C temperature difference was observed between the mainstem and pool water. The pool temperature averaged 18.3°C and ranged from 15.0 to 20.0°C. Pool temperatures were stratified with the coldest water at the deepest part of the pool (Fig. 22). Small cold water bulges in temperature profiles indicated subsurface inflow into the cold pool. A small cold water bulge on the left side of the pool probably represented intragravel flow from Bond Creek.

Tributary surface and intragravel flow and mainstem intragravel flow were primary sources of cold water to the pool. The discharge of Bond Creek was 0.013 m^3/s. Approximately 50 percent of the total tributary flow entered the lower end of the pool (6.5×10^{-3} m^3/s); the remainder flowed directly into the mainstem. Measured intragravel flow was estimated to be 9.9×10^{-3} m^3/s and accounted for at least 43 percent of pool inflow. Measured cold water inflow to the pool from subsurface seepage and tributary flow was 0.016 m^3/s. Outflow at the mouth of the pool was 0.043 m^3/s. Mainstem intragravel flow accounted for the difference in discharge between inflow and outflow.

Temperature of inflow to the pool ranged from 14.0 - 19.5°C. The water temperature of Bond Creek was 14.0°C. Pool volume was 69 m^3 and all pool water temperatures lay between 15.0 and 19.9°C. Although water temperatures were not within the preferred temperature range of juvenile salmonids, during periods of high water temperatures this pool would provide a cool water refuge for juvenile fish.

The Bond Creek Cold Pool formed by scour at high flows around a small bedrock outcrop on the outside of a large meander bend. Prior to this study, no cold pool was observed at this location and since 1985 no cold pool has formed here.

Elam Creek Cold Pool

Elam Creek Cold Pool was located below the mouth of Elam Creek (97.30 km) on the downstream end of a large gravel bar (Fig. 23). Elam Creek entered the cold pool at its upstream end and the pool was isolated from the mainstem low flow channel by a gravel bar. At the downstream end of the pool, a submerged gravel bar sill and the cold water density contrast effectively inhibited mixing of warmer mainstem water with pool water Fig. 24).

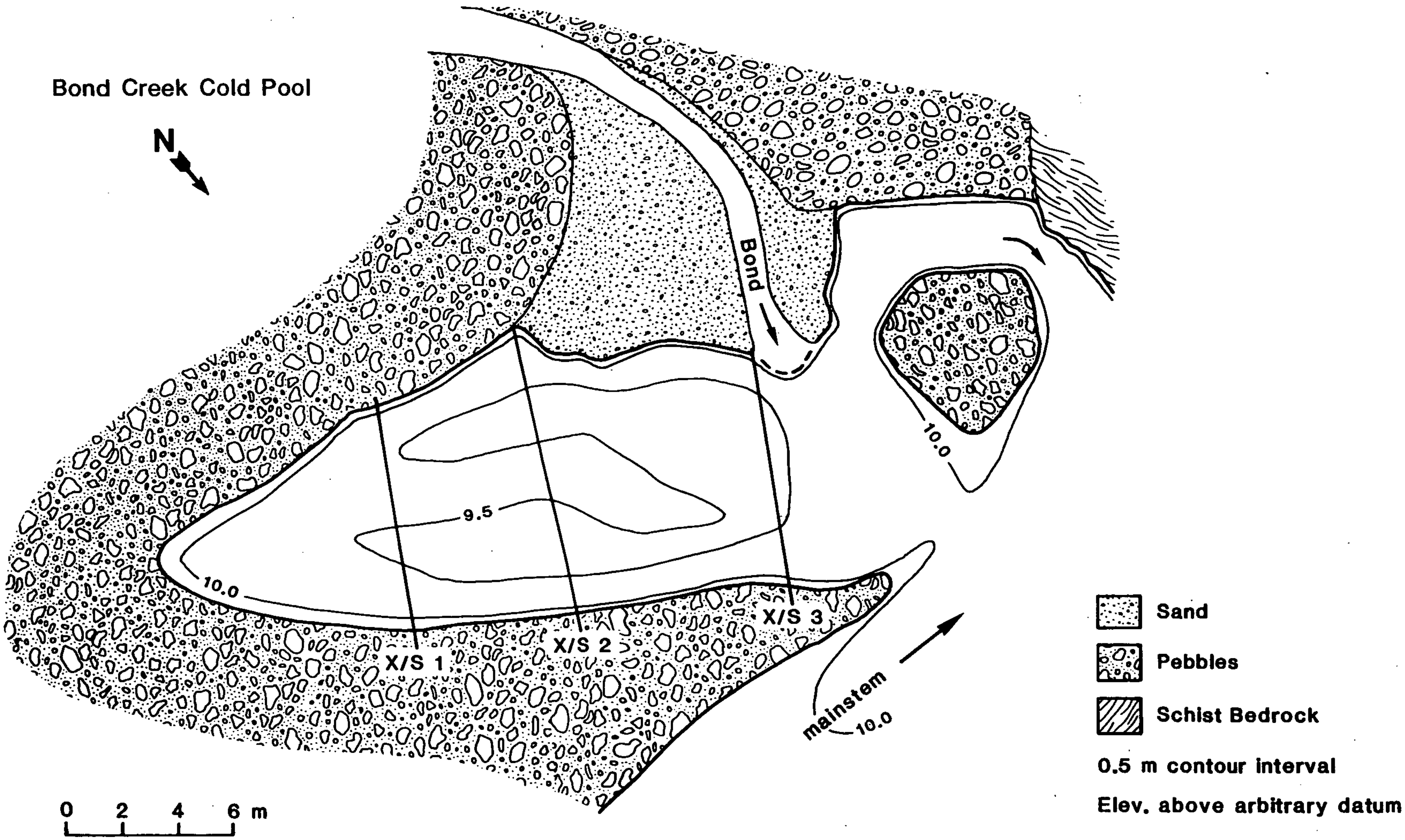


Figure 21. Topographic map of the Bond Creek Cold Pool showing cross section locations. This pool was located on the left side of the channel at the mouth of Bond Creek.

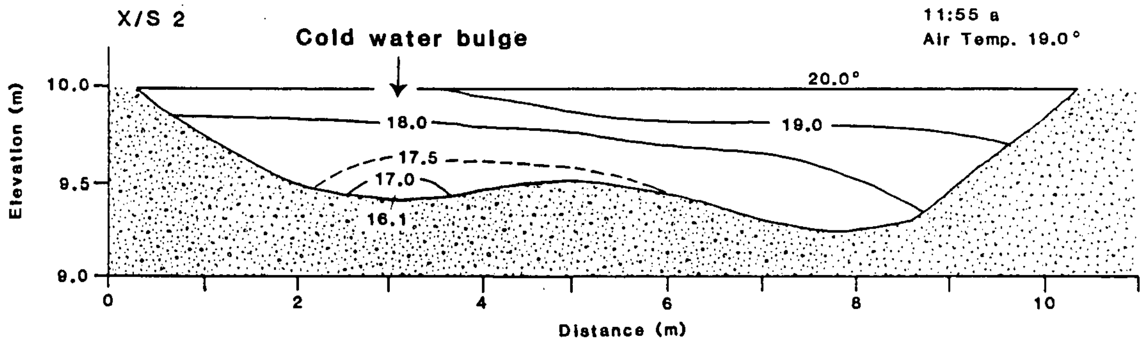


Figure 22. Temperature profile of Cross Section 2 in the Bond Creek Cold Pool shows a small cold water bulge on the left side of the pool.

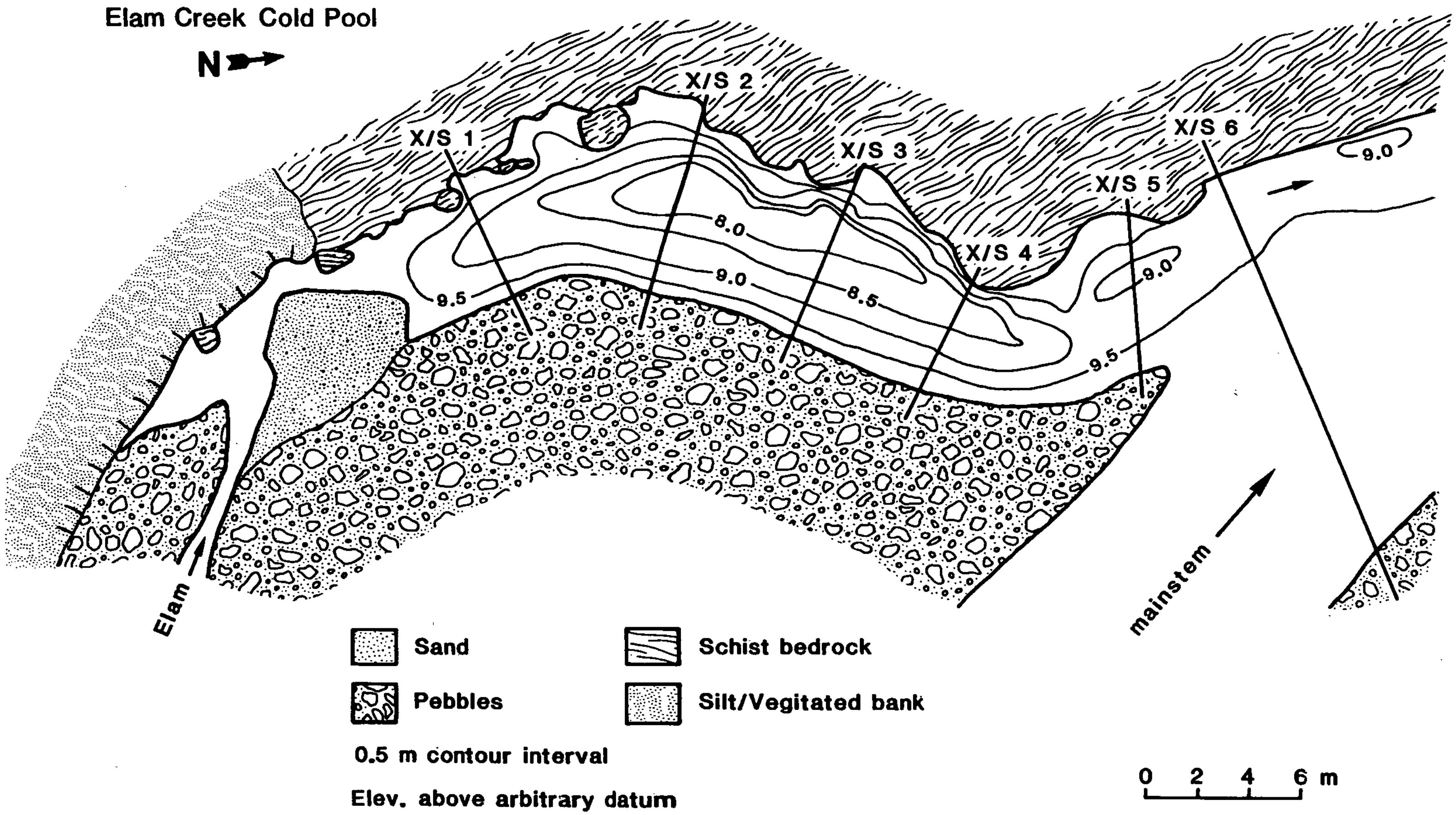


Figure 23. Topographic map of the Elam Creek Cold Pool showing cross section locations. This pool is located on the left side of the channel at the mouth of Elam Creek.

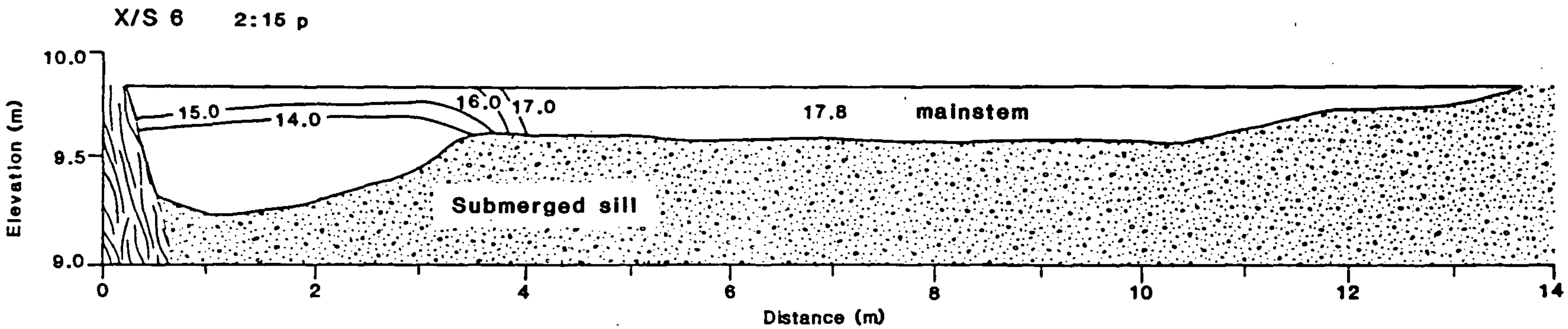


Figure 24. A temperature profile on the downstream end of the Elam Creek Cold Pool (Cross Section 6) shows that the submerged gravel bar sill and colder pool water effectively inhibits mixing of mainstem water with cold pool water.

The pool did not exhibit strong thermal stratification; however, average water temperatures were 4.7°C cooler than mainstem temperatures (Fig. 25) and ranged from 12.5 to 13.0°C. Temperature profiles in Elam Creek pool differed from other cold pools in that temperatures were more uniform and the pool surface much cooler. This was due to large contributions of cold tributary flow from Elam Creek at the head of the pool.

Tributary surface inflow was 0.016 m^3/s and comprised almost 100 percent of the total pool inflow with only trace amounts of subsurface flow. Except for one seepage measurement at the mouth of Elam Creek, measured seepage rates were less than the resolution of the seepage meters. Low velocities prevented measurement of outflow discharge at the mouth of the Elam Creek Cold Pool. Total measured inflow to the pool was 0.016 m3/s.

Water depths in excess of 2.15 m in this pool made it hard to drive seepage meters adequately into the substrate. This may partially account for the low seepage measurements and subsurface seepage rates may be larger than that measured. Regardless, tributary surface flow played a dominant role in maintenance of this cold pool.

Since pool morphology in 1982 was similar to 1985, I assumed that cold water sources were similar. Low pool bottom temperatures (12°C) in 1985 suggest some groundwater inflow; however, the few seepage measurements indicate groundwater seepage rates are probably low. Thermograph measurements in 1982 by Moses (1984) also recorded extremely low pool bottom temperatures (11°-12°C) with little diurnal fluctuation which indicates some groundwater contribution to the Elam Creek Cold Pool.

Pool volume was 164 m^3 and all water in the pool was less than 15.0°C. These temperatures lie in the preferred temperature range of juvenile salmonids and represented favorable water quality.

Pools formed in this channel location as a result of scour during high flows around a bedrock outcrop along the outside of a meander bend. Cold pools developed at the mouth of Elam Creek in 1982 and 1983 (Moses, 1984). During moderate winter flows in 1986, the low flow channel shifted to the left bank and mainstem water flowed through the cold pool location. A gravel bar no longer separates the pool from the mainstem, and since 1985 no cold pool has formed.

<u>Hayes Creek Pool</u>

A cold pool developed at the mouth of Hayes Creek in 1981 (km 100.22; Fig. 26). Since then, a summer pool has formed as a result of scour around a large debris jam at this location; however, no cold pool has developed. In 1985, this pool differed from cold pools in that it was not a quiet side pool separated from the mainstem by a gravel bar (Fig. 27). In contrast, the pool was covered with large woody debris and had mainstem flow through it.

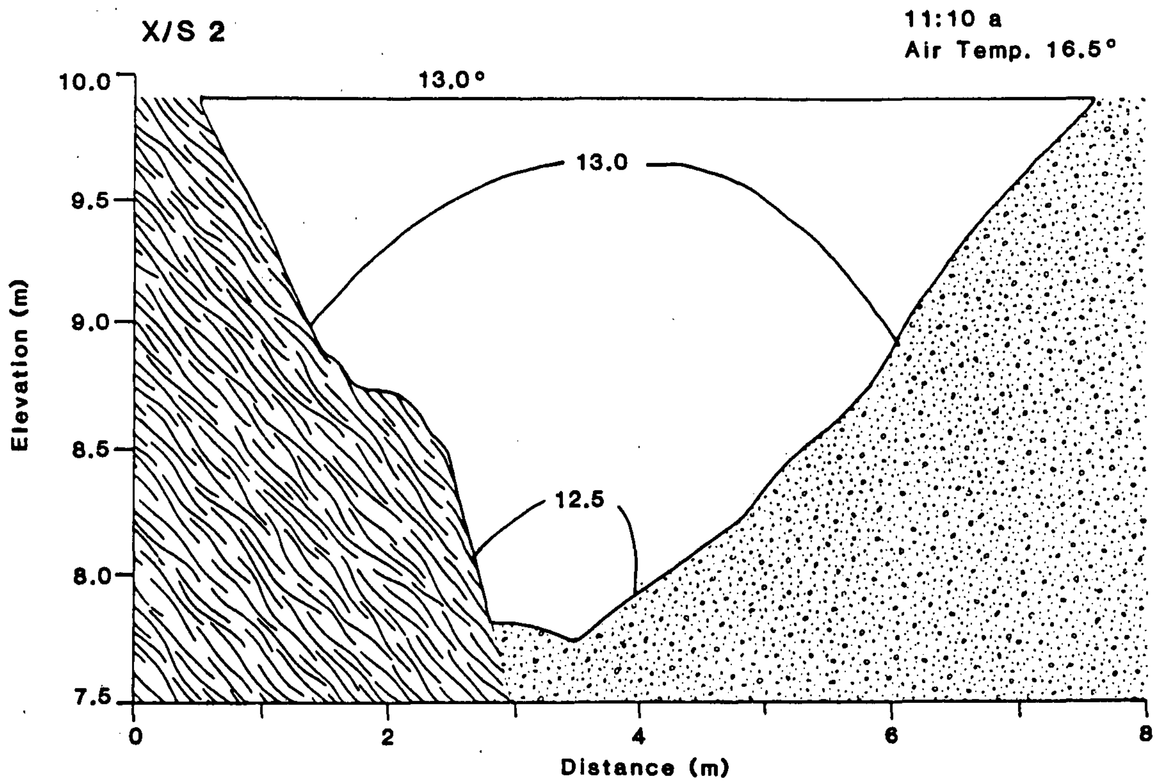


Figure 25. The temperature profile at Cross Section 2 in the Elam Creek Cold Pool shows that pool water was uniform in temperature.

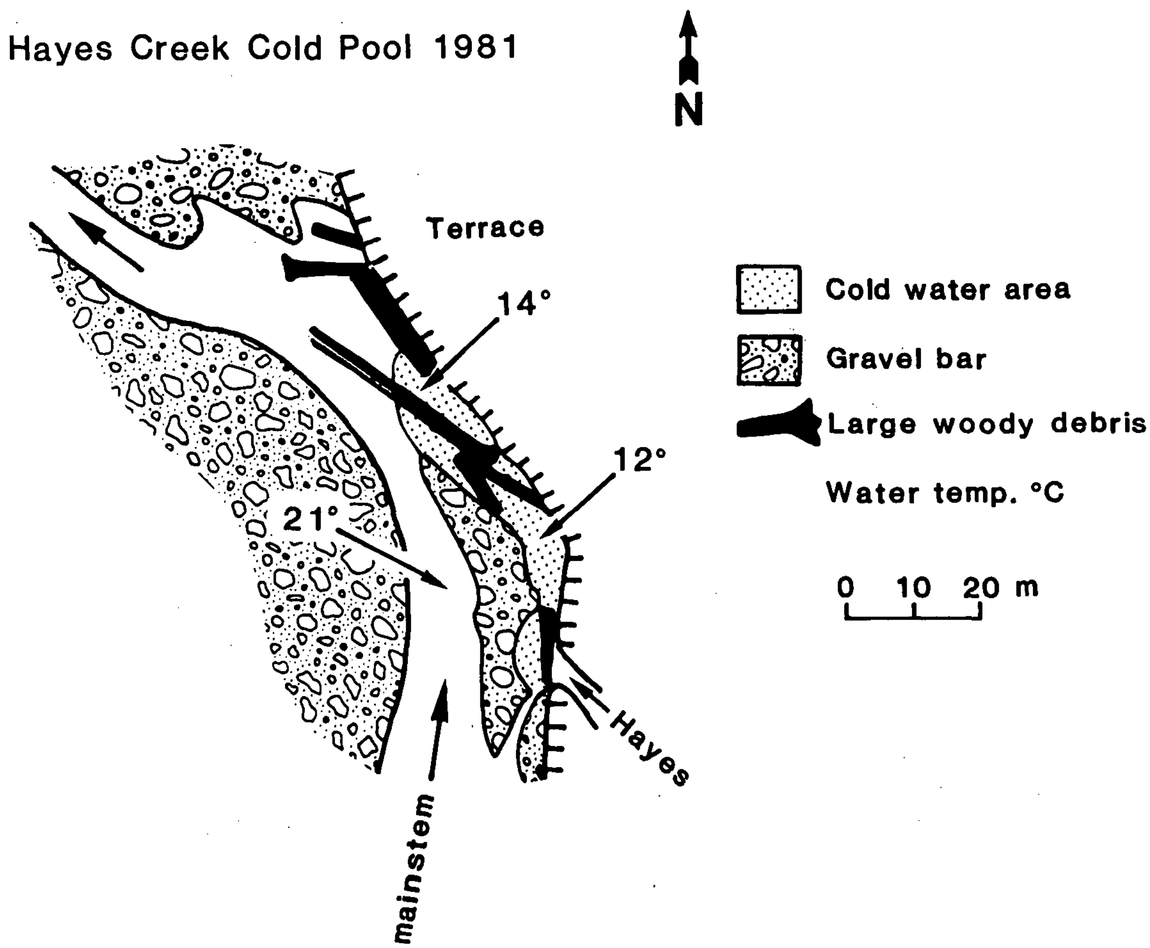


Figure 26. A cold pool developed at the mouth of Hayes Creek only when a gravel bar barrier separated the pool from the mainstem and concentrated cold water inflow (From Keller and Hofstra, 1983).

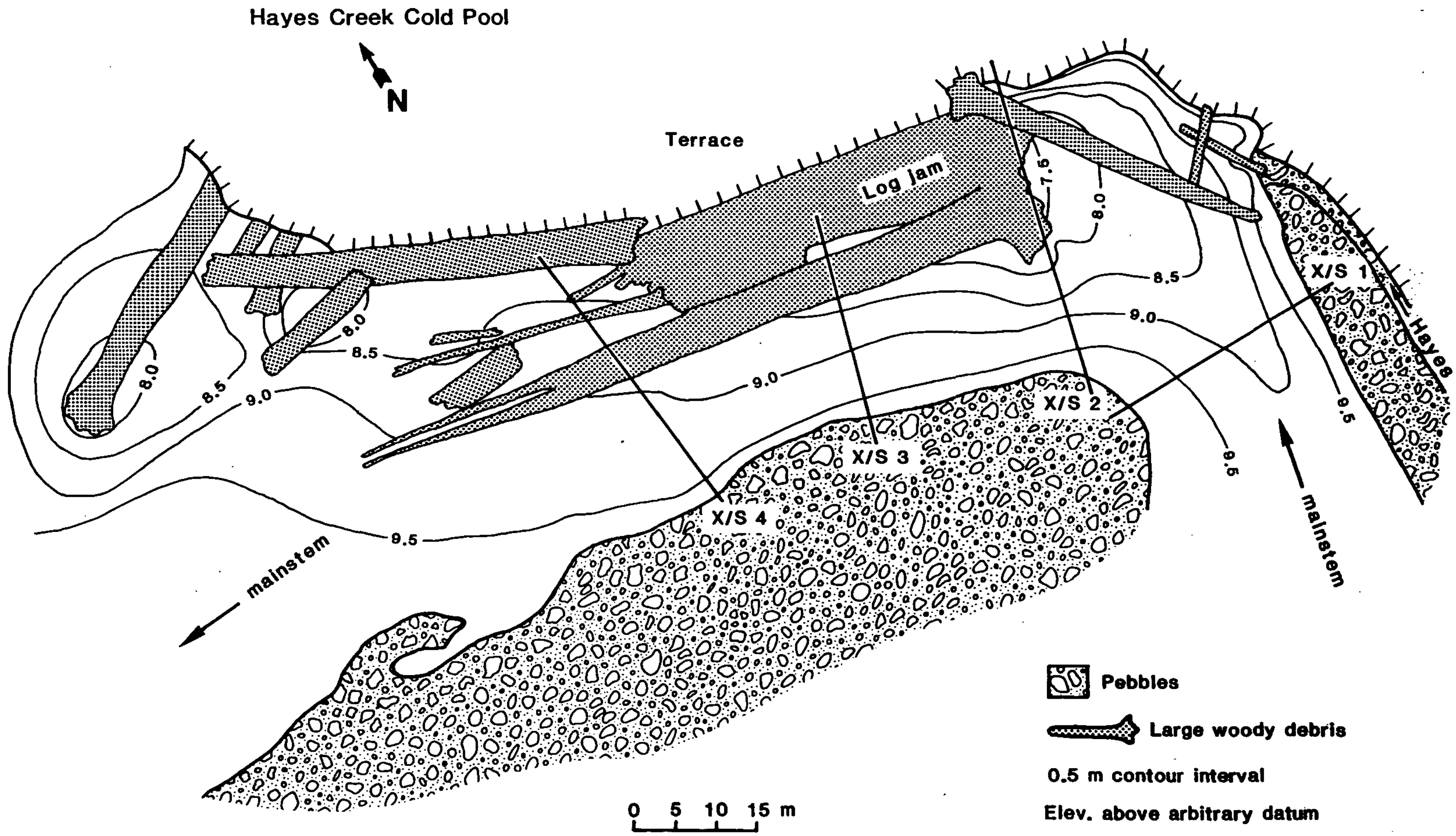


Figure 27. Topographic map of the Hayes Creek summer pool showing cross section locations. The pool was located on the right bank downstream of Hayes Creek.

In the summer of 1981, a cold pool developed in this channel location when a gravel bar isolated the entire Hayes Creek pool from the mainstem and inhibited mixing of warmer mainstem water with pool water. The cold pool was open to mainstem flow on the downstream end. A large cold water area developed when the gravel bar isolated cold intragravel flow from Hayes Creek and bank seepage from the terrace cutbank. The pool bottom was up to 9.0°C cooler than the mainstem (Keller and Hofstra, 1983).

In 1985, a 541 m^3 summer pool formed at the mouth of Hayes Creek, but no gravel bar developed to concentrate cold water. A large root wad at the upstream end of the pool and a dense mat of woody debris inhibited flow through the log structure. Temperature measurements through a window in the log jam showed the pool was thermally stratified under the jam (Fig. 28). Cross section temperature profiles on the upstream end of the log jam showed no thermal stratification since mainstem water thoroughly mixed with pool water. Downstream of the log jam, woody debris slightly inhibited mixing and pool water was somewhat stratified.

Small pockets of cold water were observed near the undercut right bank. This water originated from bank seepage along the terrace cutbank. Temperatures here were up to 6°C cooler than mainstem water. Cool intragravel flow from the Hayes Creek tributary was also observed but not measured. Cold water inflow to the pool was present; however, no cold pool developed.

In contrast to the cold pools, cold water represented only a small fraction of the total pool volume in the Hayes Creek pool. Less than seven percent of the pool volume was represented by water temperatures between 15.0 and 20.0°C. Most of the pool volume was warmer than 19.9°C and pool temperatures typically exceeded 20.0°C during warm afternoons.

The Hayes Creek pool supported a large population of juvenile salmonids, adult summer steelhead and a diversity of other fish species. In this pool fish were observed holding under the woody debris. In contrast, cold pools were relatively devoid of woody debris and only a few juvenile samonids were observed in those pools.

A summer pool formed in this channel location every year since 1980. However, the log jam structure and pool morphology change from year to year as logs shift position or are transported downstream. Channel shifting is also common in this reach. During moderate winter flows (RI = 5 years) in 1986, the low flow channel shifted to the left side of the channel, leaving the Hayes Creek pool isolated from the mainstem low flow channel. A summer pool at the mouth of Hayes Creek no longer exists.

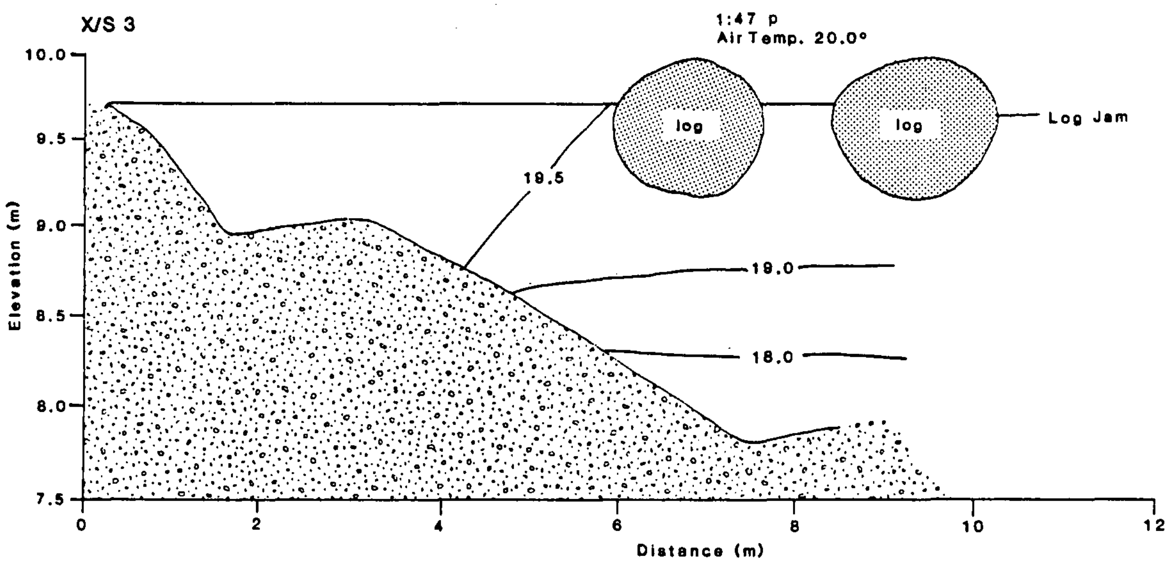


Figure 28. Pool water was stratified under the log jam (Cross Section 3). However, temperature profiles immediately upstream and downstream of the log jam were uniform in temperature.

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V. DISCUSSION AND CONCLUSION

Cold pools are defined as low flow pools which contain concentrated areas of cold water and maintain water temperatures more than 3°C below mainstem temperatures. Moses (1984) walked portions of Redwood Creek from Highway 299 downstream to the mouth and found cold pools only downstream of Harry Wier Creek. On Redwood Creek, cold pools are few in number and develop primarily in the wide (>92 m), low gradient (0.0018 m/m), aggraded reaches around and downstream of the Tall Trees Grove.

Cold pools on Redwood Creek form over a variety of flows. At high winter flows, scour around bedrock outcrops, boulders and/or woody debris creates the pool feature. As mainstem flow drops, cold pools develop when gravel bars emerge and partially separate pool water from mainstem flow. Once separated or isolated they retain cold water while mainstem temperatures become elevated. Cold pools have been observed in early July and probably develop as early as June. Discharge data for Redwood Creek at the Orick gaging station indicate that flows during which cold pools exist ($\leq 2.0\ m^3/s$) are equalled or exceeded 73 percent of the time.

A. Channel Location and Pool Morphology

In Redwood Creek, pools typically form on the outside of meander bends and are often associated with scour around bedrock outcrops and large woody debris. Cold pools typically develop in these locations as side pools separated from the mainstem by a gravel bar barrier and open to the mainstem low flow channel on the downstream end. Since 1981, five out of nine cold pools studied occupied the downstream end of high flow side channels that were partially dry in the summer months.

Pool morphology strongly influences the occurrence and development of thermally stratified pools on Redwood Creek. Without a physical barrier to concentrate and isolate cold water inflow, a large cool water area will not develop. Since 1981, all cold pools were associated with a gravel bar barrier. Temperature profiles show that a bar effectively retarded mixing of the warmer mainstem water with pool water and concentrated cold water.

Moses (1984) identified large woody debris as capable of retarding mixing and forming cold pools. I found woody debris slightly inhibited mixing, but did not effectively isolate large volumes of cold water. The Hayes Creek pool demonstrates that although woody debris and cold water inflow (from bank seepage and tributary intragravel flow) are present, a cold pool develops only when a gravel bar physically separates at least part of the pool from mainstem flow. Although woody debris alone is not effective in concentrating cold water, it does provide shading and cover important to juvenile salmonids.

B. Temperature Structure

With the exception of the Elam Creek pool, cold pools were thermally stratified. Coldest water was associated with the deepest part of the pool and the warmest water was on the pool surface. Pool bottom temperatures were as much as 7°C cooler than near-surface water and up to 11°C lower than summer mainstem temperatures. Temperature differences between mainstem and cold pool water were most pronounced during warm afternoons and least pronounced during the early morning hours. Diurnal water temperature fluctuations reflected changes in solar radiation.

Figure 29 is a plot of cold pool thermoclines. The high rate of cold water inflow at the head of the Elam Creek Cold Pool kept pool temperatures low and uniform from top to bottom. In contrast, Cold Pools A and B were maintained only by subsurface seepage and exhibited well developed thermoclines. Pool temperatures in Cold Pool B were warmer and showed a less dramatic change from top to bottom than Cold Pool A. Temperatures below 0.5 meters were uniform in Cold Pool A and fairly uniform below 0.6 meters in Cold Pool B. Differences between pool thermoclines in the Tall Trees Grove Cold Pools was due partially to more shading and colder water inflow to Cold Pool A than to Cold Pool B. This accounts for the lower surface temperature of Cold Pool A and overall colder water temperatures. Bond Creek Cold Pool was shallow and completely exposed to solar radiation; however, pool bottom temperatures offered cold water up to 4°C lower than the mainstem. Typical mainstem pools were unstratified, uniform in temperature and typically exceeded 20°C in warm afternoons. Thermoclines of the Hayes Creek pool show that in some cases woody debris can slightly inhibit mixing but does not effectively isolate large volumes of cold water.

C. Pool Characteristics Which Affect Temperature Difference

Individual and multiple regression analyses established no relationship between mean pool depth, maximum depth and volume and pool-mainstem temperature difference. Temperature difference between pool and mainstem water was not a function of these variables and was probably more dependent on the amount, rate and temperature of cold water inflow.

W/L ratio is generally related to pool coldness (r^2=0.65); the longer and narrower the pool (lower W/L ratio) the colder the pool water. The longer narrower pools have more contact with the streambank and potential cold water sources. They also have relatively more shading from solar radiation due to a position close to the streambank. Cold pools studied since 1981 had W/L ratios of 0.50 or less and were long, narrow, channel-like features.

D. Cold Water Sources

Cold pools in Redwood Creek are maintained over the summer by cold water inflow. Subsurface inflow of colder water to the pools is defined by

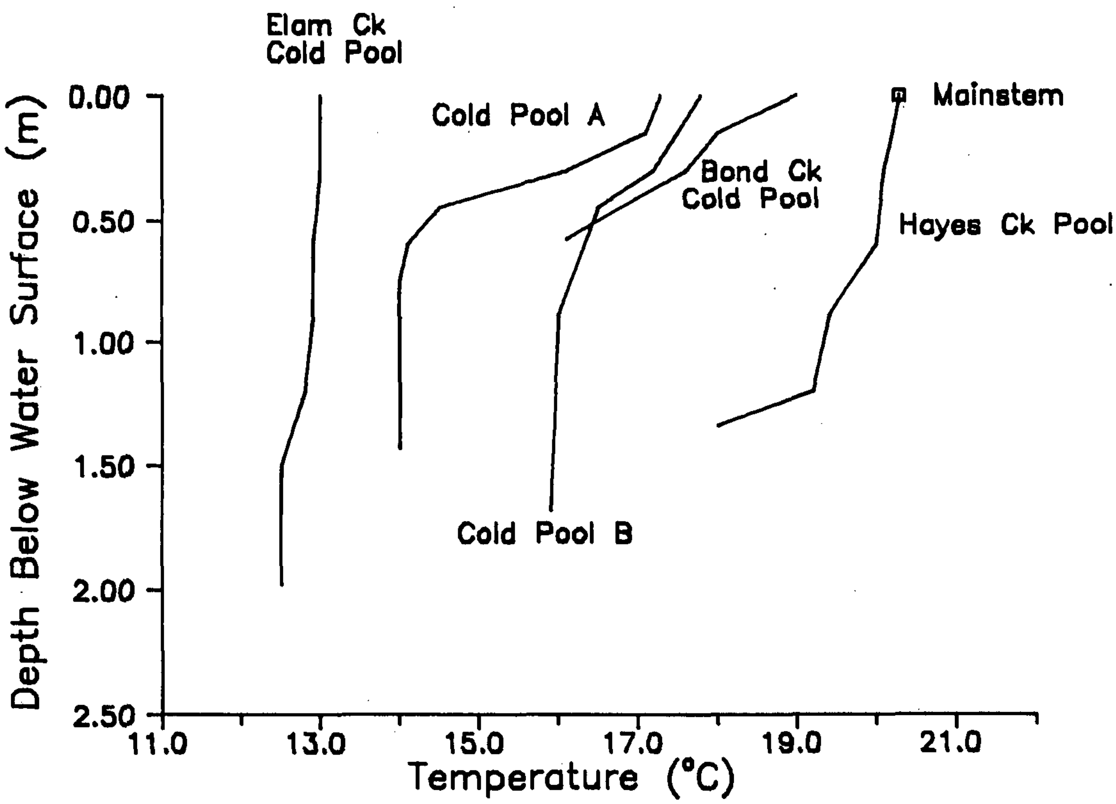

Figure 29. Plot of cold pool thermoclines measured in 1985.

bulges in pool temperature profiles (Fig. 30). In contrast, thermally stratified cold pools on a nearby northcoast stream are more a function of water depth than cold water contribution. These cold pools typically develop in pools which exceed three meters in depth and temperature profiles of these pools exhibit horizontal isotherms with no cold water bulges (Ozaki, unpublished data).

On Redwood Creek, cold pools were maintained by a variety of cold water sources. Hillslope groundwater seepage contributed the coldest water (11 - 12°C) to pools but was only present in trace amounts. Tributary surface and intragravel flow maintained cool temperatures through voluminous inflow of cold water (14 - 15°C). Mainstem intragravel flow was the most prevalent water source and ranged from 13 to 21°C in the pools studied. Pool temperatures were maintained through the summer months by individual water sources or more commonly from a combination of cold water sources. Water entering the pools from these sources was typically 3 to 9°C cooler than mainstem water and increased in temperature a few degrees from July to the end of September. Throughout the summer months, pool water remained significantly cooler than mainstem water and provided large volumes of water within the preferred temperature range of salmonids.

Sources of subsurface inflow to the pools in Redwood Creek were determined qualitatively. Most subsurface inflow to pools appeared to be mainstem intragravel flow. The water surface of cold pools exhibiting subsurface seepage were lower in elevation than the mainstem water surface (~0.15 m). This fact and dye tracing tests indicated that the local water table gradient was from the mainstem low flow channel to the cold pools. In addition, pool bottom temperatures were higher than what might be expected for hillslope groundwater.

Hillslope groundwater seepage appeared to be a minor component of inflow in pools studied. Groundwater inflow was identified in a small area of Cold Pool A by the lack of diurnal fluctuation in pool bottom temperatures and low water temperatures. Water temperatures in the Elam Creek Cold Pool also suggested a minor groundwater component of flow. Thermographs of cold pools studied by Moses (1984) and Keller and Hofstra (1983) showed two pools which exhibited detectable groundwater seepage. Groundwater seepage may have occurred in other cold pools, but either placement of thermographs missed seepage areas or groundwater seepage rates were insufficient to dampen diurnal temperature variations or the overall pool temperature characteristics.

E. Water Budgets

Summer cold pools were sustained by baseflow discharges between 0.008-0.020 m^3/s. In comparison, average low flow discharge on Redwood Creek was 0.810 m^3/s and ranged between 2.010 and 0.368 m^3/s during July and October 1985.

Mass balance calculations indicate that tributary surface inflow and upwelling intragravel flow are the primary sources of cold water which maintained cold pools on Redwood Creek. Cold water inflow to pools from tributaries was as much as 0.016 m^3/s while contribution from mainstem

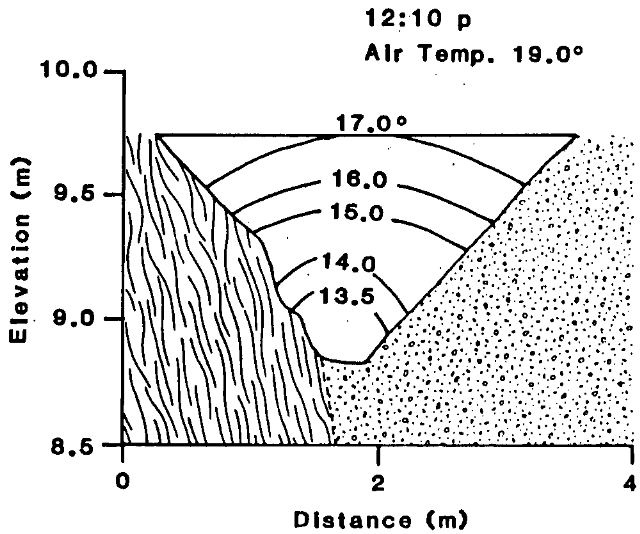

Figure 30. Bulges in temperature profiles indicate cold water contribution to pools. In contrast, cold pools formed by depth alone have horizontal isotherms.

intragravel flow ranged from 0.008 to 0.020 m^3/s. Groundwater was present in trace amounts.

Intragravel flow accounted for almost 100 percent of the cold water inflow in pools not associated with a tributary (Tall Trees Grove Cold Pools). The Bond Creek Cold Pool, located at a tributary mouth, had more than 43 percent of pool inflow from intragravel flow with remaining inflow from tributary flow. The Elam Creek Cold Pool was supported almost 100 percent by cool tributary surface flow with trace amounts of intragravel flow and possibly groundwater seepage.

Assuming that most subsurface inflow in pools was intragravel flow, seepage measurements in this study indicate that intragravel flow rates were up to 0.013 cm^3/s per unit area in the low gradient, aggraded reaches of lower Redwood Creek. Intragravel flow rates varied considerably across pool bottoms with concentrated points of high and low seepage rates. In addition, seepage contour maps indicated relatively higher intragravel flow rates at the downstream end of large gravel bars.

F. Stability of Cold Pools

Cold pools on Redwood Creek are ephemeral features. During years with low peak flows (recurrence interval $\leq$3 years), cold pools are fairly stable morphologic features and reform in the same location. For example, three of the pools studied have persisted in the same channel location from 1982-1985 (Table 4). Moderate flows during the winter of 1986 (recurrence interval ~5 years) caused shifting of the low flow channel and only one cold pool developed in the same channel location. Channel shifting is common in aggraded sections of Redwood Creek and pools in these reaches may form, be destroyed or change locations under even moderate winter flows.

G. Model for Cold Pool Formation

A simple cold pool model can be developed based on this and previous research by Keller and Hofstra (1983) and Moses (1984). A descriptive model for cold pool development on Redwood Creek is:

1. Scour around large roughness elements during high winter flows creates the pool feature.

2. Favorable pool location close to potential cold water sources is important. This may be near the channel edge against the streambank or terrace cutbank, at the base of a landslide or at the mouth of a tributary.

3. Cold water inflow is a critical factor in maintaining pools through the summer months and may originate from: a) tributary surface or intragravel flow, b) hillslope groundwater seepage, c) mainstem intragravel flow or d) probably a combination of these cold water sources.

Table 4. Cold pool locations on lower Redwood Creek since 1981.

	COLD POOLS						
	Tall Trees Grove						
YEAR	Pool A	Pool B	Bond Ck	Elam Ck	Hayes Ck	Other	Total Cold Pools
1981	?	?	?	?	Yes	?	1+
1982	No	No	No	Yes	No	Yes	2
1983	Yes	Yes	No	Yes	No	Yes	5
1984	---	---	No Cold Pool Inventory			---	---
1985	Yes	Yes	Yes	Yes	No		4
1986	---	---	No Cold Pool Inventory			---	---
1987	Yes	No	No	No	No	No	1

4. Formation of a gravel bar to partially separate pool water from mainstem flow and concentrate cold water inflow is crucial to cold pool development.

5. Cold water inflow between 0.008 and 0.020 m^3/s supplies enough cold water to maintain cold pools through the summer months.

H. Fisheries Applications

Cold pools provide cool water refuge for juvenile and adult salmonids when mainstem temperatures become elevated. However, cold water refuge alone does not provide a high quality environment; cover is an important component of juvenile rearing habitat. Cover provides protection from predators and may be in the form of pool depth, undercut banks and/or woody debris.

The Hayes Creek pool illustrates the importance of cover in fish habitat. Although the Hayes Creek pool did not provide a cold water refuge, it was completely covered with large woody debris. During the summer, this pool supported a diverse population of juvenile and adult salmonids as well as other fish species, reptiles, mammals and birds. In contrast, while providing sizable cold water areas, cold pools lacking cover did not support large numbers of fish. The optimum rearing habitat is a combination of large cold water volume and abundant cover.

I. Future Research

Future avenues of research may focus on:

1. Examine the thermodynamics of intragravel flow through gravel bars; specifically determining whether interstitial water cools as it flows through bars and the factors which might affect cooling rates (bar size, length, gradient).

2. Establish field and laboratory techniques to distinguish hillslope groundwater (soil water) from intragravel flow. More accurately identify and quantify cold water contribution to cold pools from different sources.

3. Determine utilization of cold pools by juvenile salmonids and other fish species. Determine at what mainstem temperatures juvenile salmonids will occupy these cold water areas and how they use them.

4. Determine regional distributions of cold pools and develop models for cold pool formation in the different systems.

J. Management Recommendations

Cold pools represent a potentially important management tool for restoring and improving juvenile salmonid rearing habitat in aggraded stream systems. Aggradation of the streambed can severely impact juvenile rearing habitat by: 1) infilling summer rearing pools, 2) increasing water temperatures, and 3) decreasing riparian vegetation and streamside canopy. During extended periods of high mainstem water temperatures, cold pools provide a cold water refuge for juvenile fish. Cold pools or potential sites for these pools should be identified and inventoried in stream systems. After major flood events or changes in channel morphology, cold pool locations need to be reinventoried. By understanding the physical processes responsible for controlling and maintaining thermally stratified pools, cold pools can be created or improved to provide a high quality juvenile rearing habitat and holding area for adult summer steelhead.

Once a suitable summer cold pool site is located a pool can be excavated with heavy equipment and boulder clusters and/or rootwads and logs cabled into the channel. In existing cold pools, addition of cover in the form of rootwads could improve fish habitat. Juvenile salmonids could utilize the cover provided by the woody debris and also be in a cooler water environment and healthier rearing habitat. Boulder clusters and woody debris would also create scour during winter flows and maintain the pool feature. However, in aggraded streams, channel shifting is common and cold pools may form, be destroyed and change locations under moderate flows.

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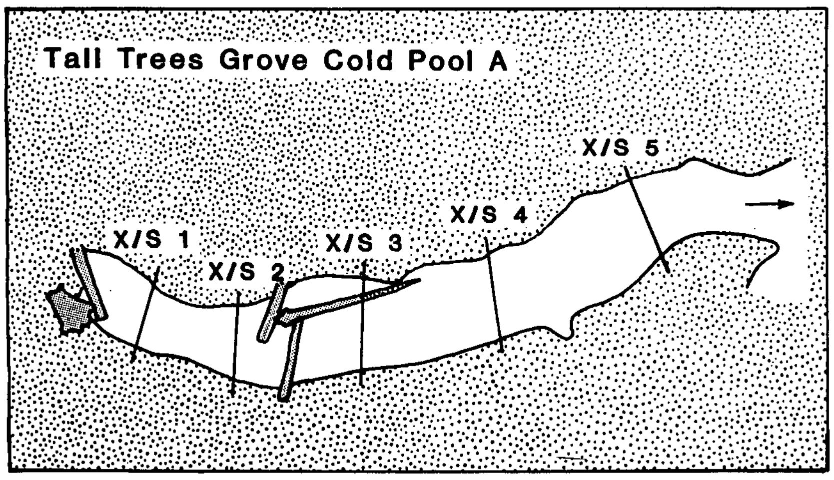
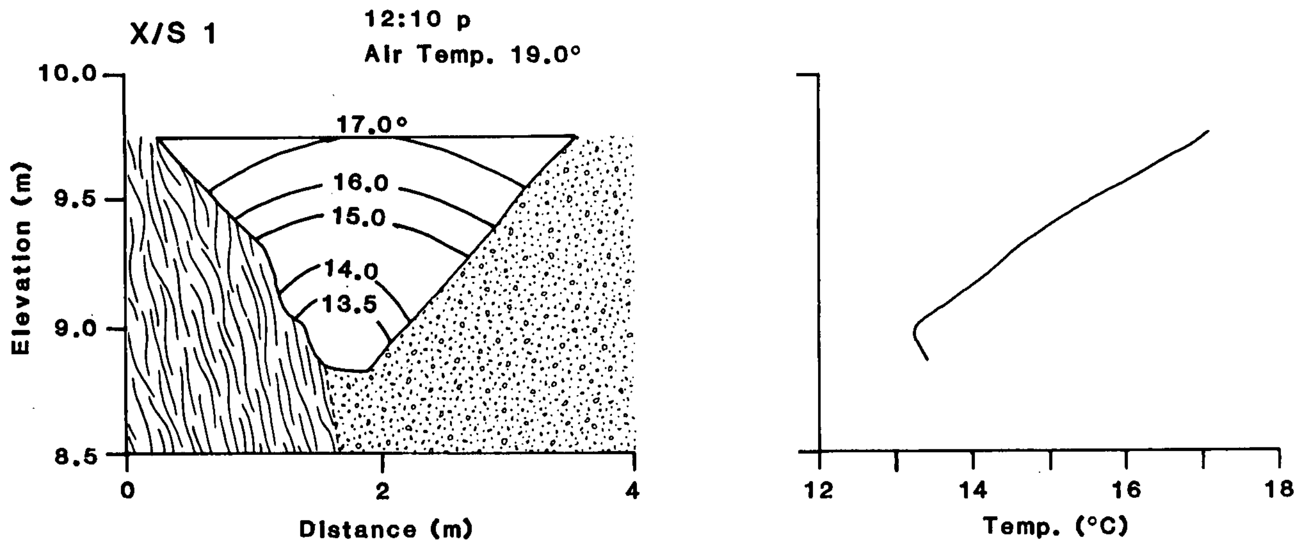
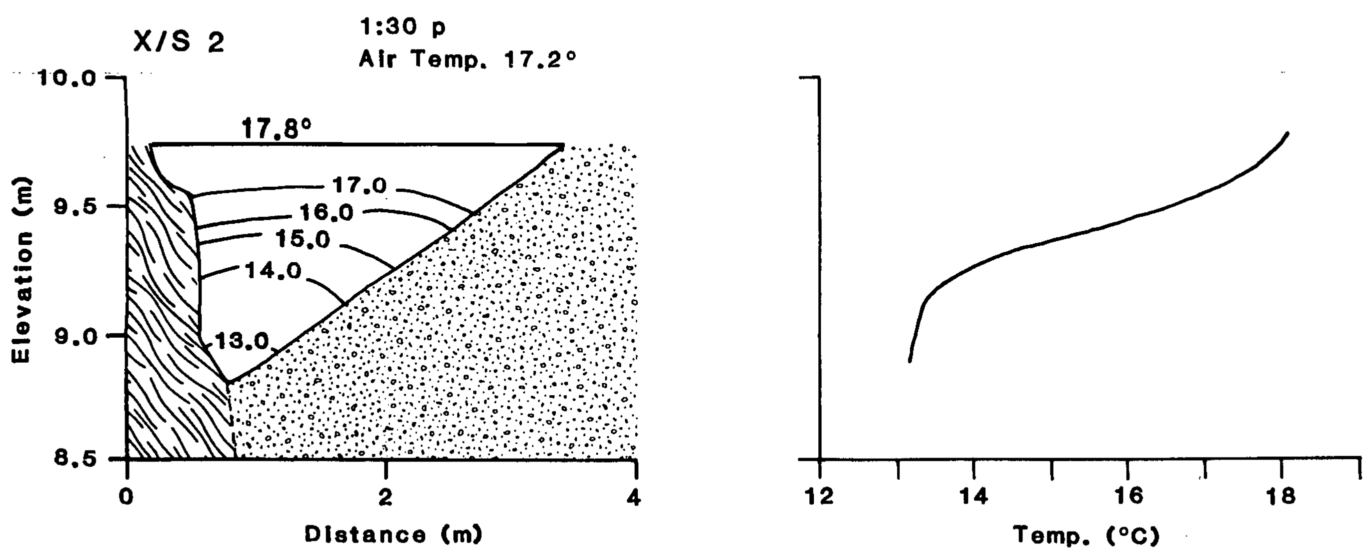
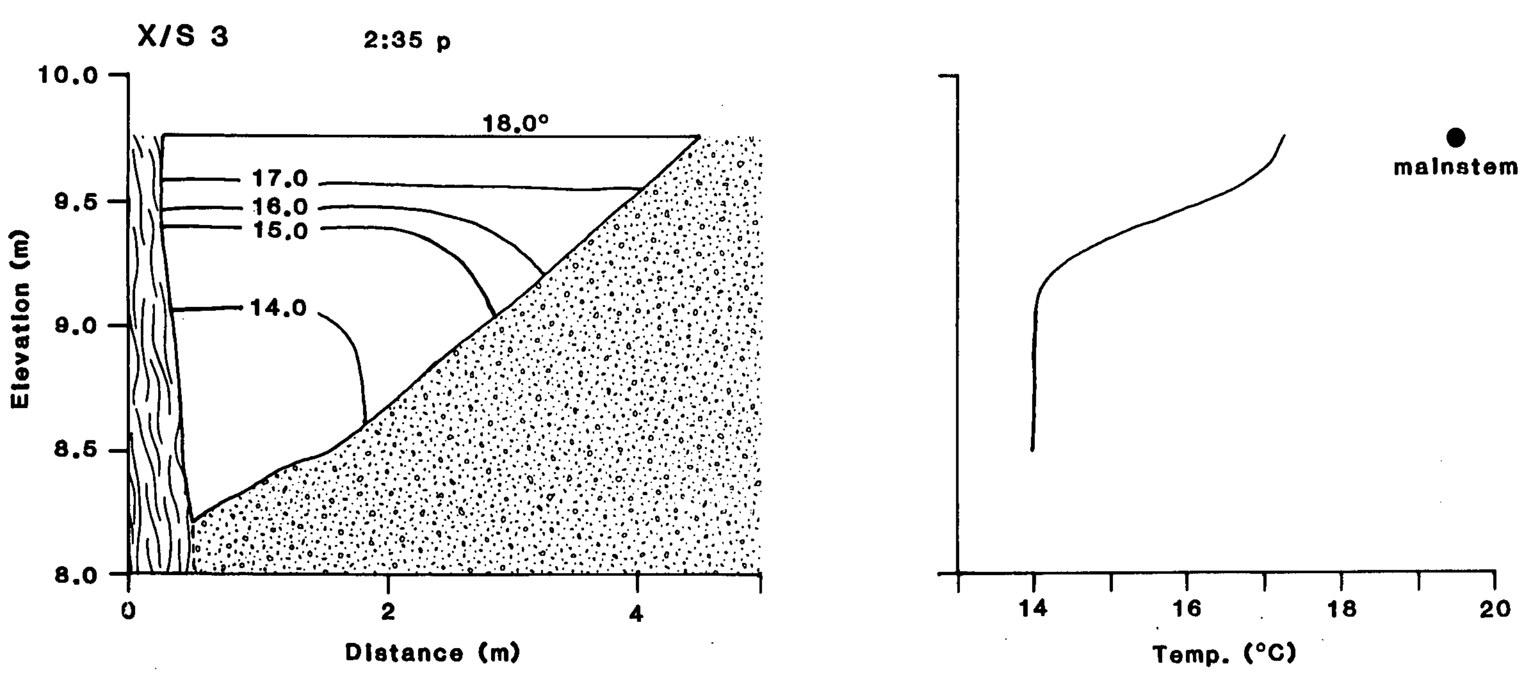

Tall Trees Grove Cold Pool A
X/S 1
X/S 2
X/S 3
X/S 4
X/S 5

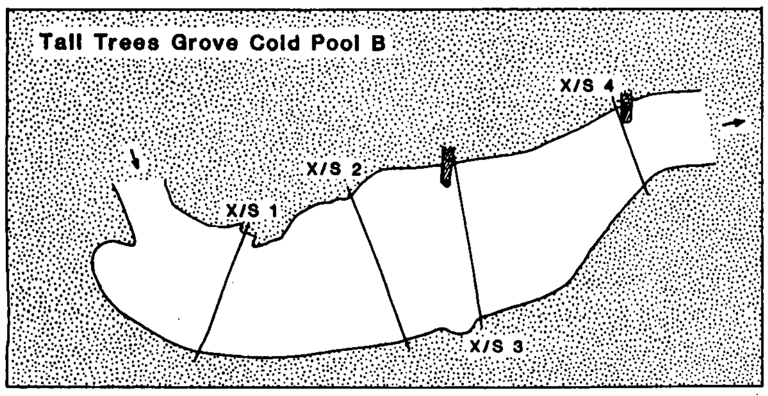

X/S 1
12:10 p
Air Temp. 19.0°
17.0°
16.0
15.0
14.0
13.5
10.0
9.5
9.0
8.5
Elevation (m)
0
2
4
Distance (m)
12
14
16
18
Temp. (°C)


X/S 2
1:30 p
Air Temp. 17.2°
17.8°
17.0
16.0
15.0
14.0
13.0
10.0
9.5
9.0
8.5
Elevation (m)
0
2
4
Distance (m)
12
14
16
18
Temp. (°C)

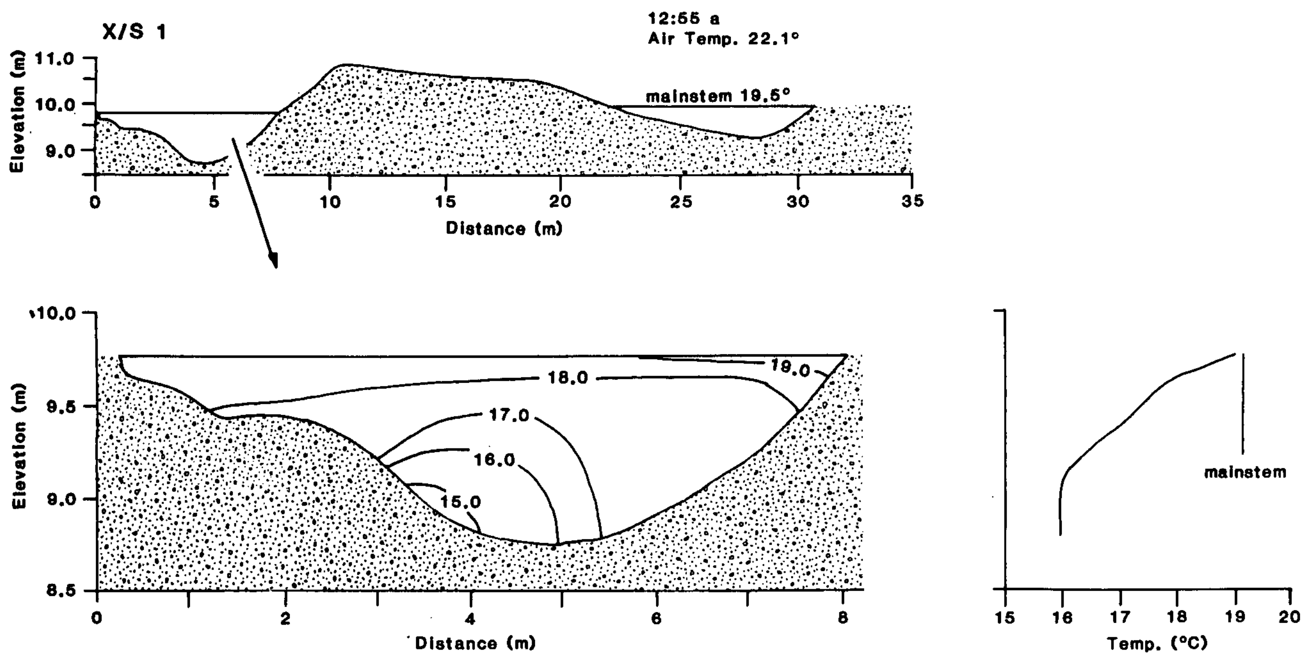

X/S 3
2:35 p
18.0°
17.0
16.0
15.0
14.0
10.0
9.5
9.0
8.5
8.0
Elevation (m)
0
2
4
Distance (m)
14
16
18
20
Temp. (°C)
mainstem

Appendix A

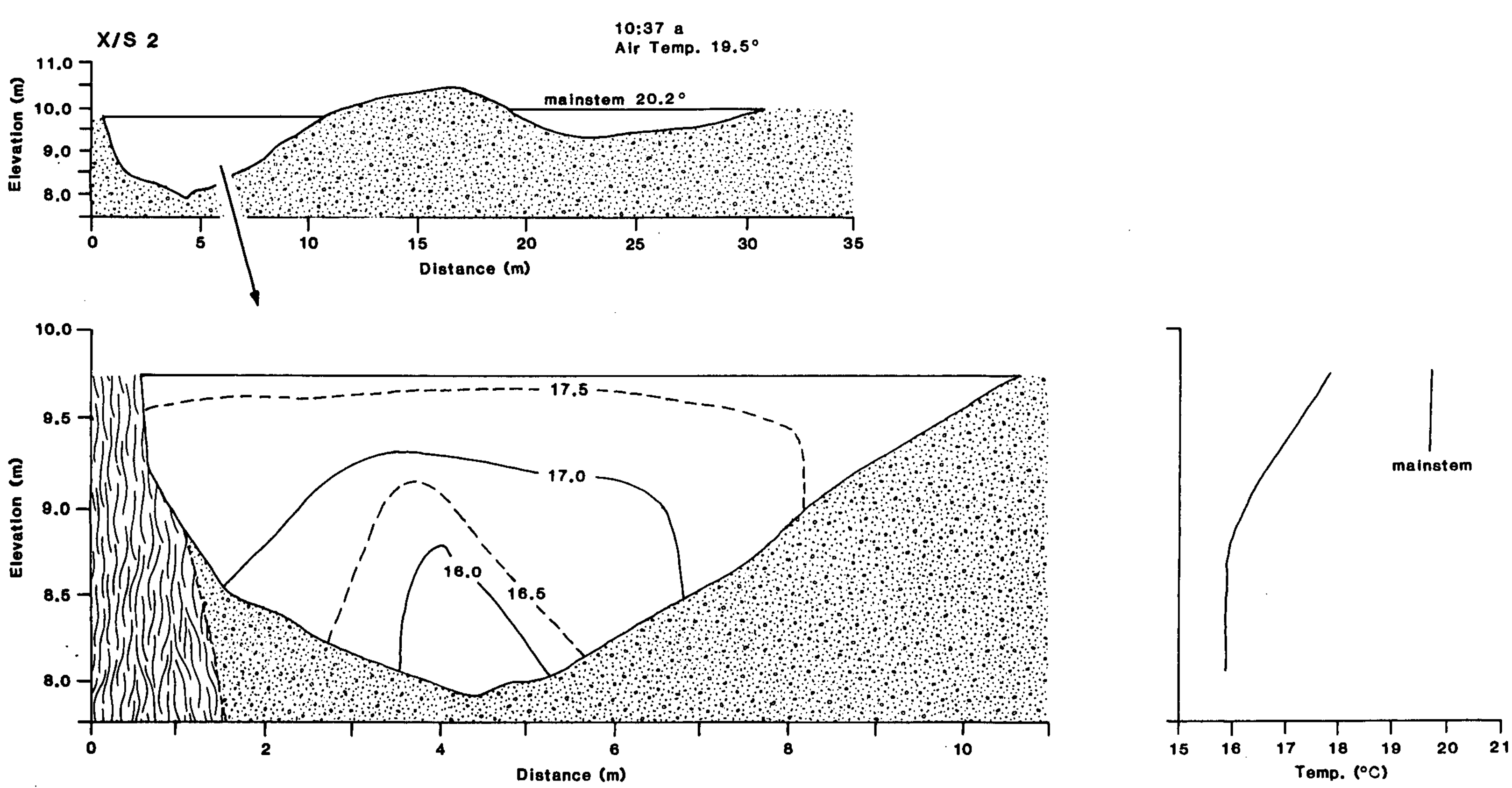
For each pool cross-sectional and longitudinal water temperatures are contoured at 1°C. Corresponding pool thermoclines are plotted adjacent to the cross section (X/S) profiles. Temperatures are recorded in degrees Celsius. Elevation is measured in meters above an arbitrary datum, and distance is measured in meters with 0 m corresponding to the left bank.  represents schist bedrock and  represents a gravel bar.



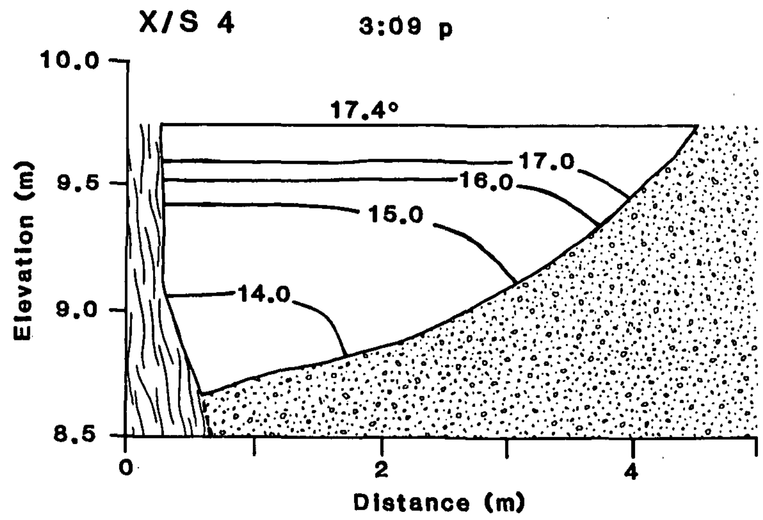
Tall Trees Grove Cold Pool B
X/S 1
X/S 2
X/S 3
X/S 4



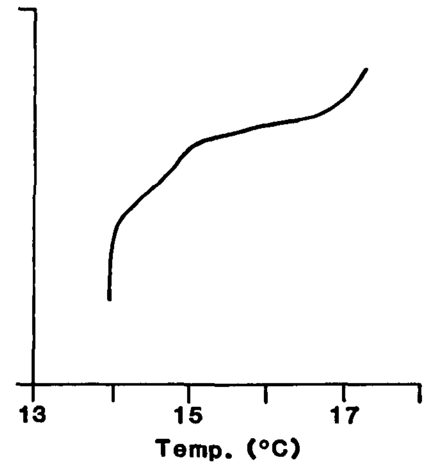
X/S 1
12:55 a
Air Temp. 22.1°
mainstem 19.5°
Elevation (m)
Distance (m)
18.0
19.0
17.0
16.0
15.0
mainstem
Temp. (°C)



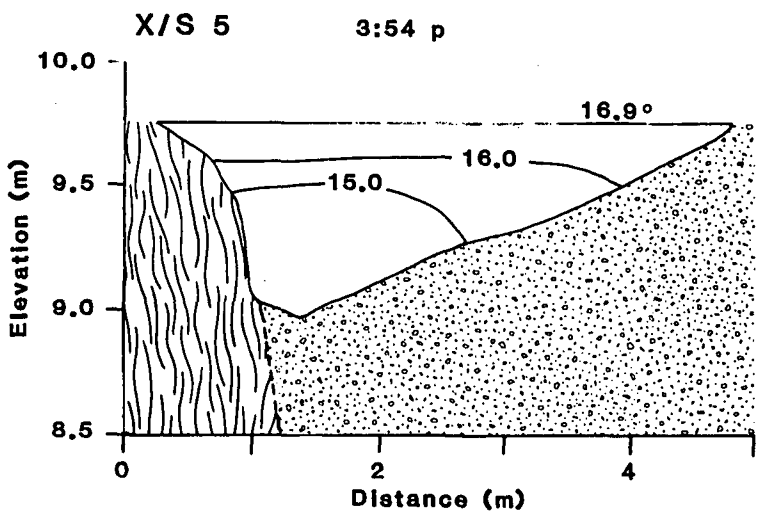
X/S 2
10:37 a
Air Temp. 19.5°
mainstem 20.2°
Elevation (m)
Distance (m)
17.5
17.0
16.0
16.5
mainstem
Temp. (°C)



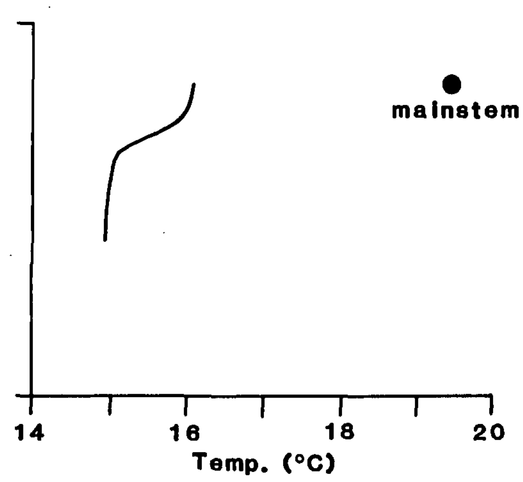
X/S 4
3:09 p
10.0
9.5
9.0
8.5
Elevation (m)
17.4°
17.0
16.0
15.0
14.0
0
2
4
Distance (m)



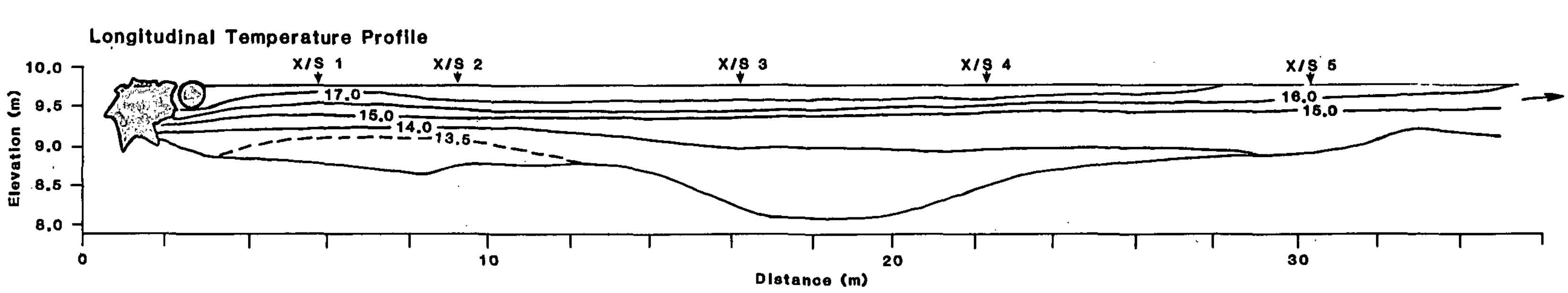
13
15
17
Temp. (°C)



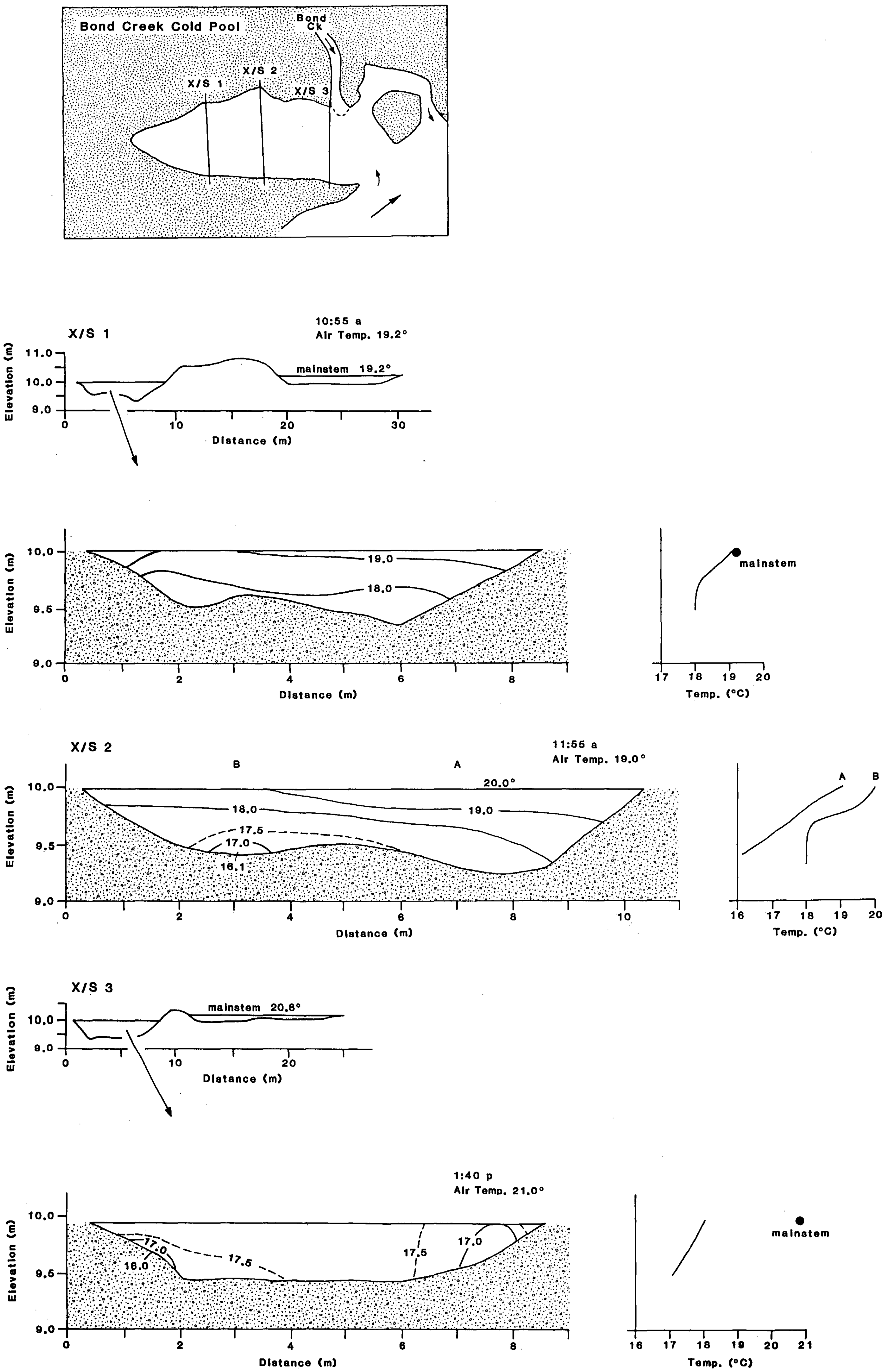
X/S 5
3:54 p
10.0
9.5
9.0
8.5
Elevation (m)
16.9°
16.0
15.0
0
2
4
Distance (m)



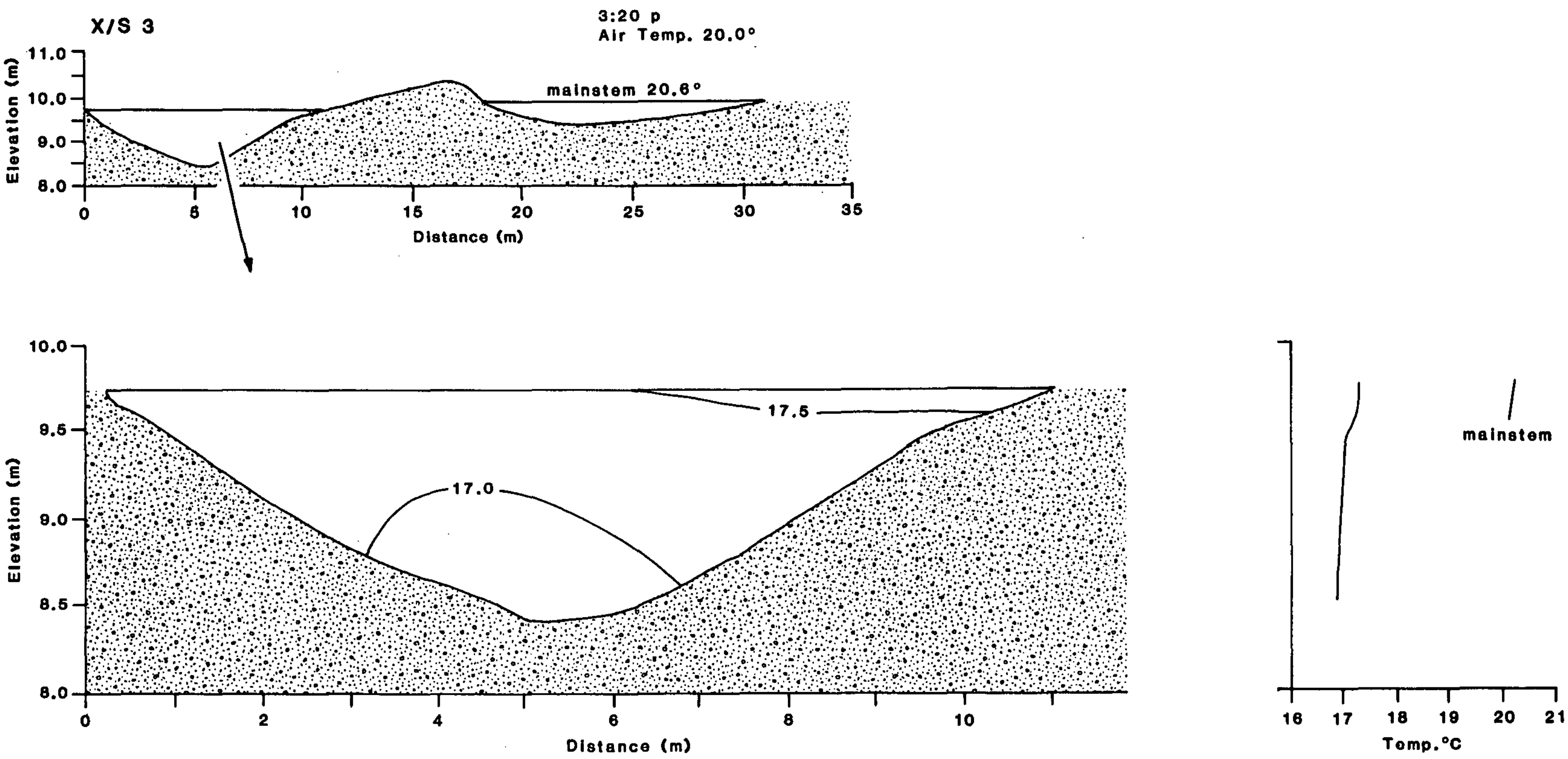
mainstem
14
16
18
20
Temp. (°C)

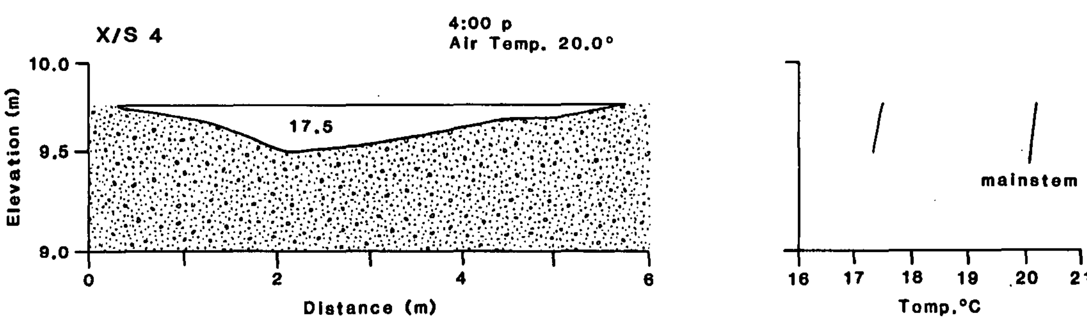


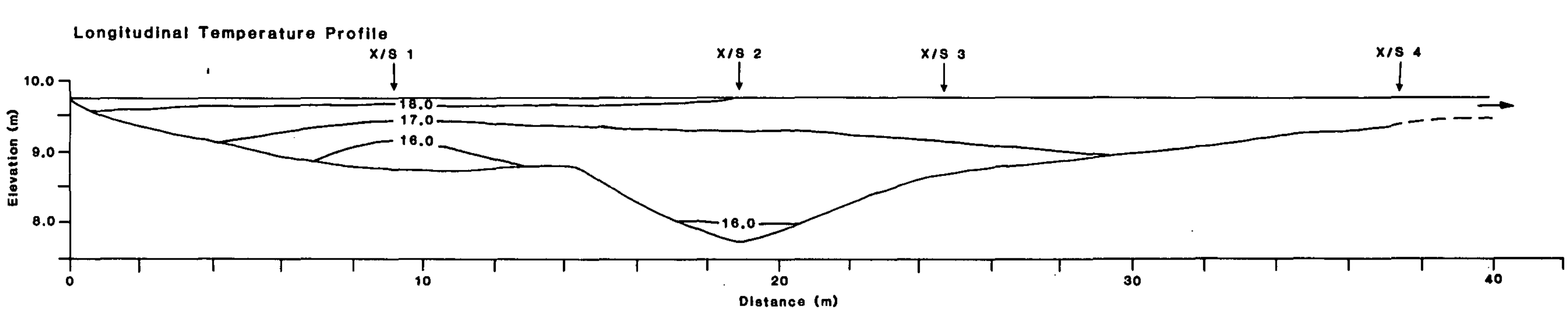
Longitudinal Temperature Profile
X/S 1
X/S 2
X/S 3
X/S 4
X/S 5
10.0
9.5
9.0
8.5
8.0
Elevation (m)
17.0
16.0
15.0
14.0
13.5
0
10
20
30
Distance (m)

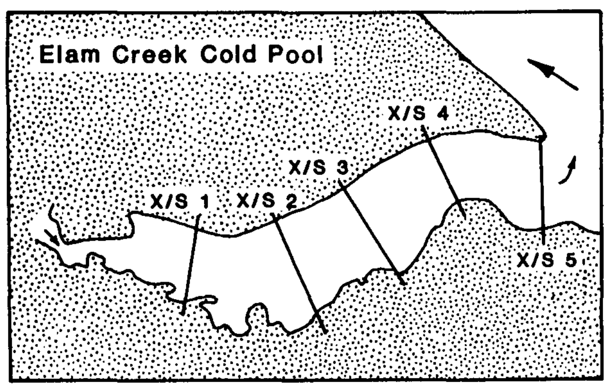


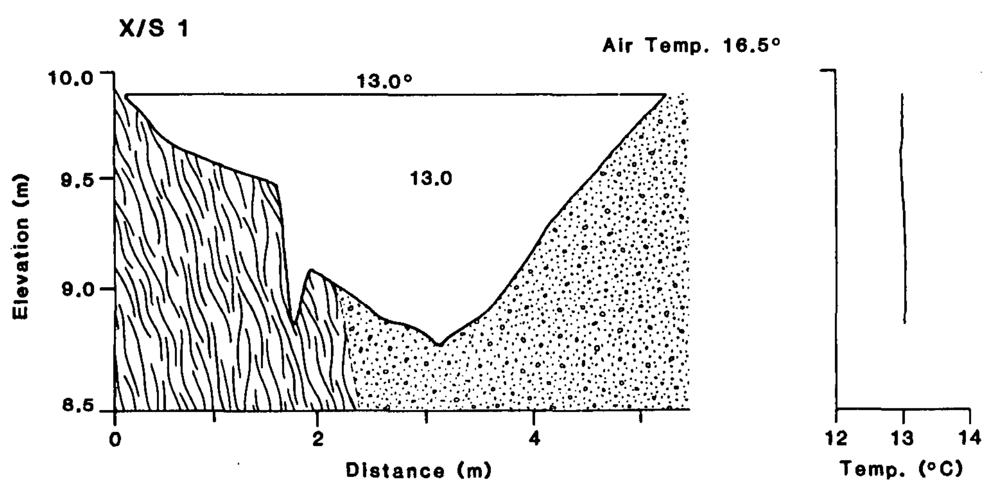
Bond Creek Cold Pool
Bond Ck
X/S 1
X/S 2
X/S 3
X/S 1
10:55 a
Air Temp. 19.2°
mainstem 19.2°
Elevation (m)
Distance (m)
19.0
18.0
mainstem
Temp. (°C)
X/S 2
11:55 a
Air Temp. 19.0°
B
A
20.0°
18.0
19.0
17.5
17.0
16.1
X/S 3
mainstem 20.8°
1:40 p
Air Temp. 21.0°
17.0
16.0
17.5
mainstem

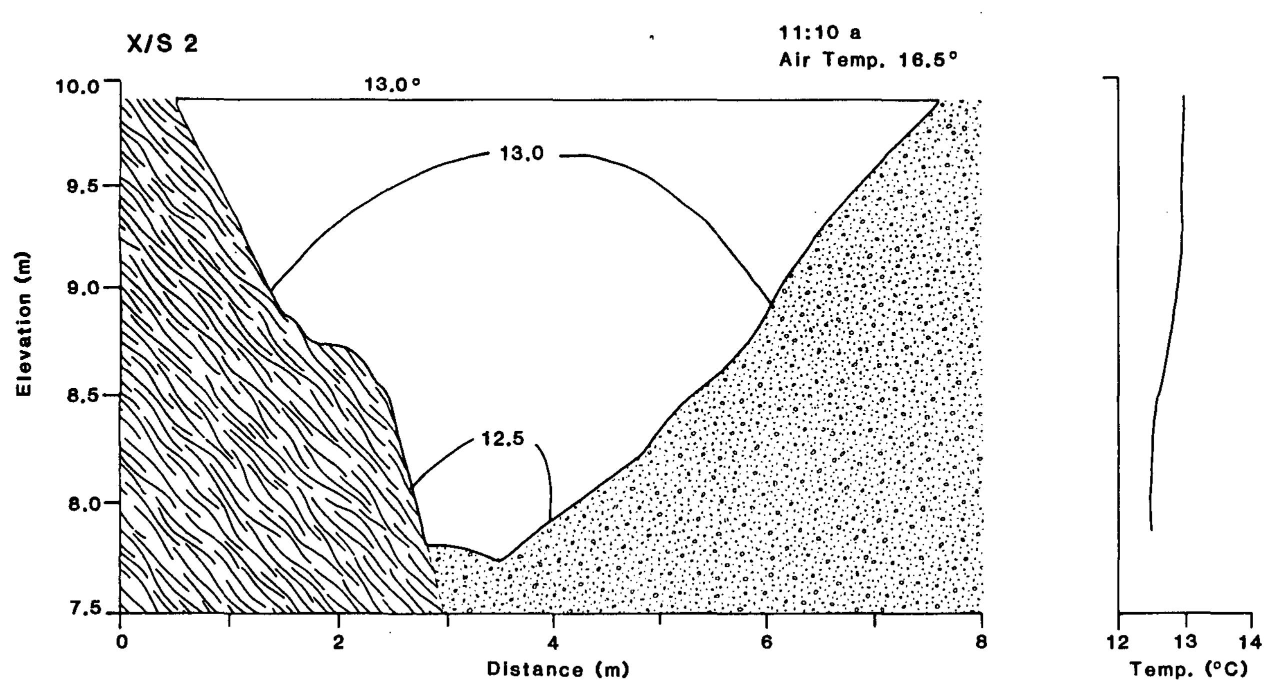

X/S 3
3:20 p
Air Temp. 20.0°
mainstem 20.6°
Elevation (m)
Distance (m)
17.5
17.0
mainstem
Temp.°C

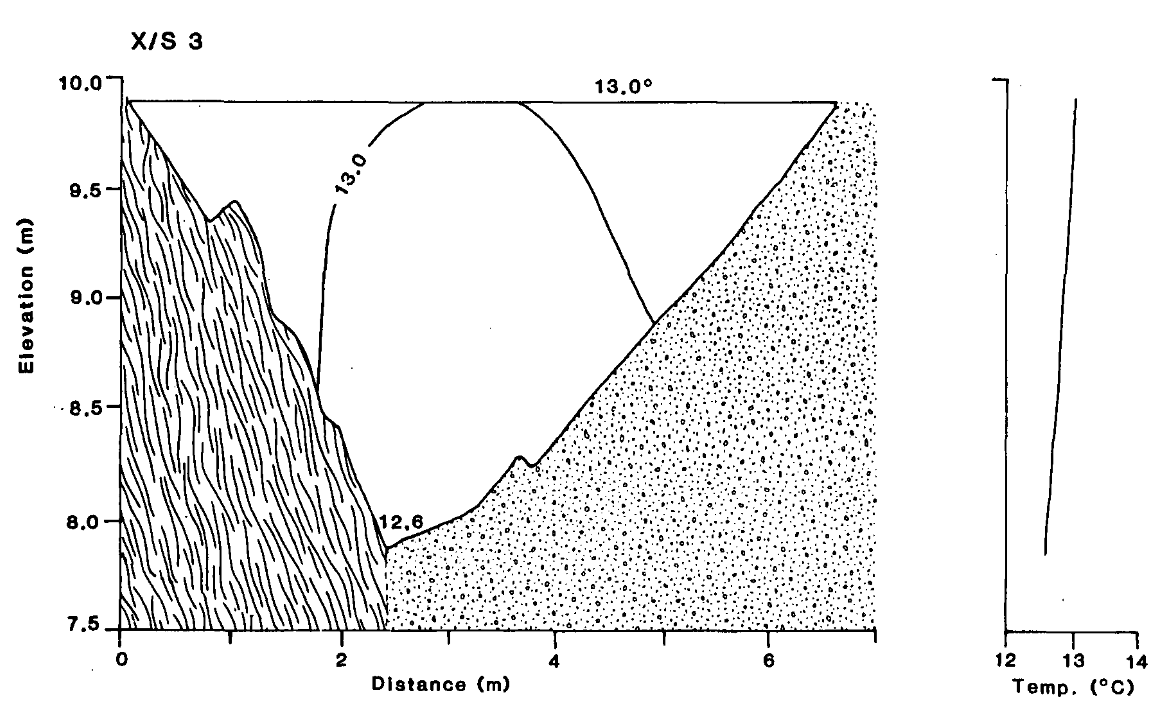

X/S 4
4:00 p
Air Temp. 20.0°
17.5
Elevation (m)
Distance (m)
mainstem
Temp.°C


Longitudinal Temperature Profile
X/S 1
X/S 2
X/S 3
X/S 4
18.0
17.0
16.0
16.0
Elevation (m)
Distance (m)

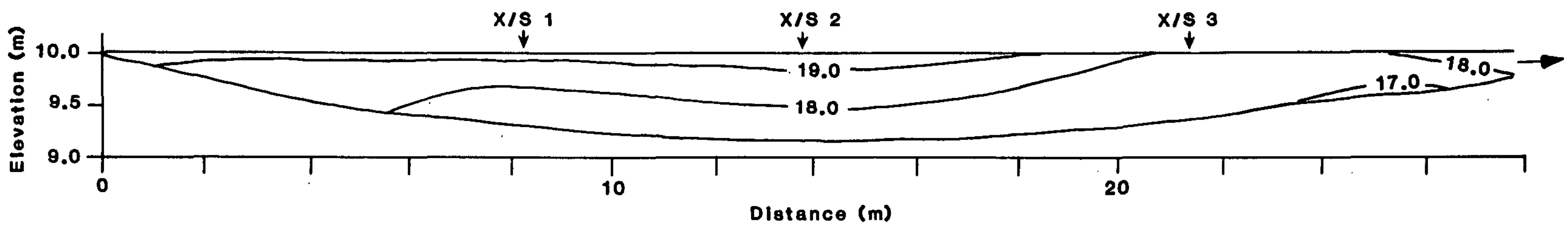

Elam Creek Cold Pool
X/S 1
X/S 2
X/S 3
X/S 4
X/S 5


X/S 1
Air Temp. 16.5°
13.0°
13.0
Elevation (m)
10.0
9.5
9.0
8.5
0
2
4
Distance (m)
12
13
14
Temp. (°C)

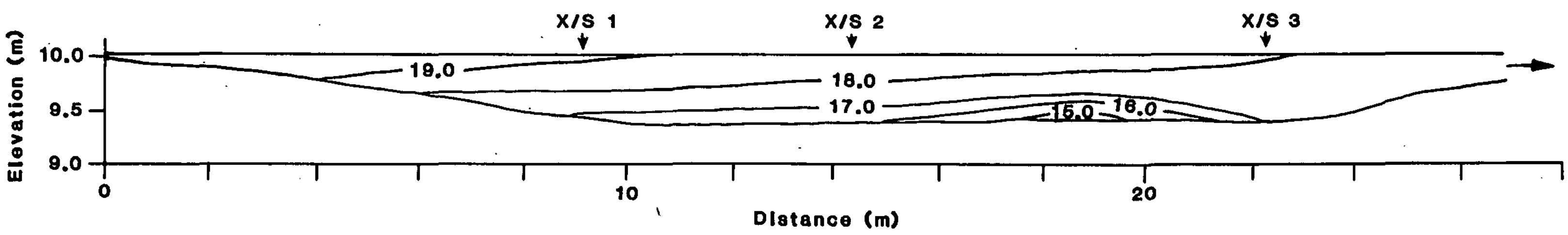

X/S 2
11:10 a
Air Temp. 16.5°
13.0°
13.0
12.5
Elevation (m)
10.0
9.5
9.0
8.5
8.0
7.5
0
2
4
6
8
Distance (m)
12
13
14
Temp. (°C)

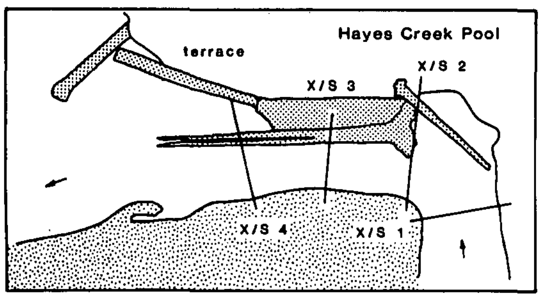

X/S 3
13.0°
13.0
12.6
Elevation (m)
10.0
9.5
9.0
8.5
8.0
7.5
0
2
4
6
Distance (m)
12
13
14
Temp. (°C)

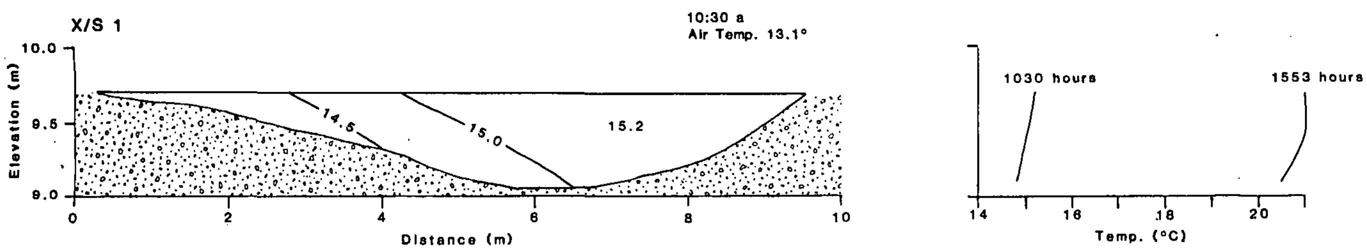
Longitudinal Temperature Profile A

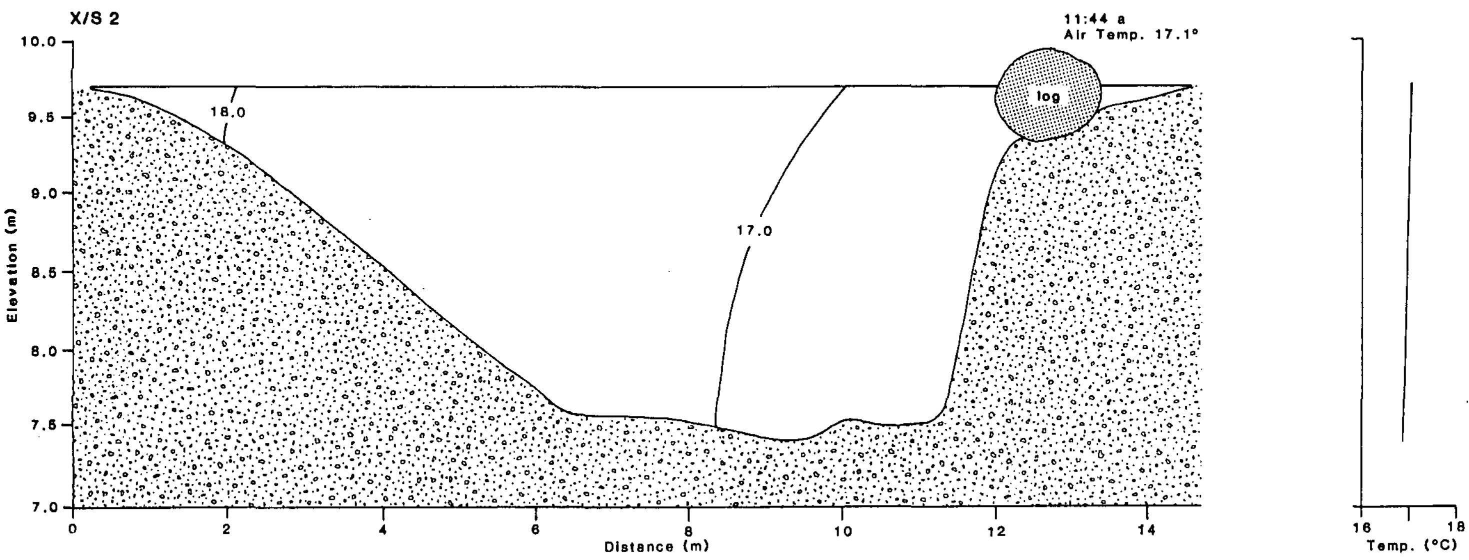


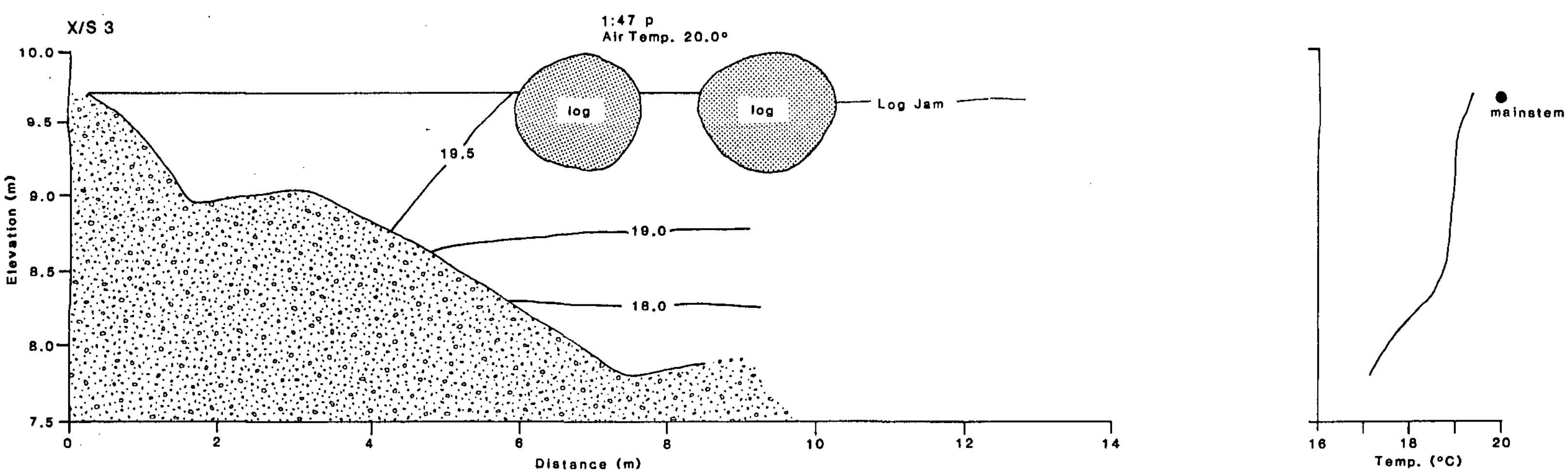
Longitudinal Temperature Profile B

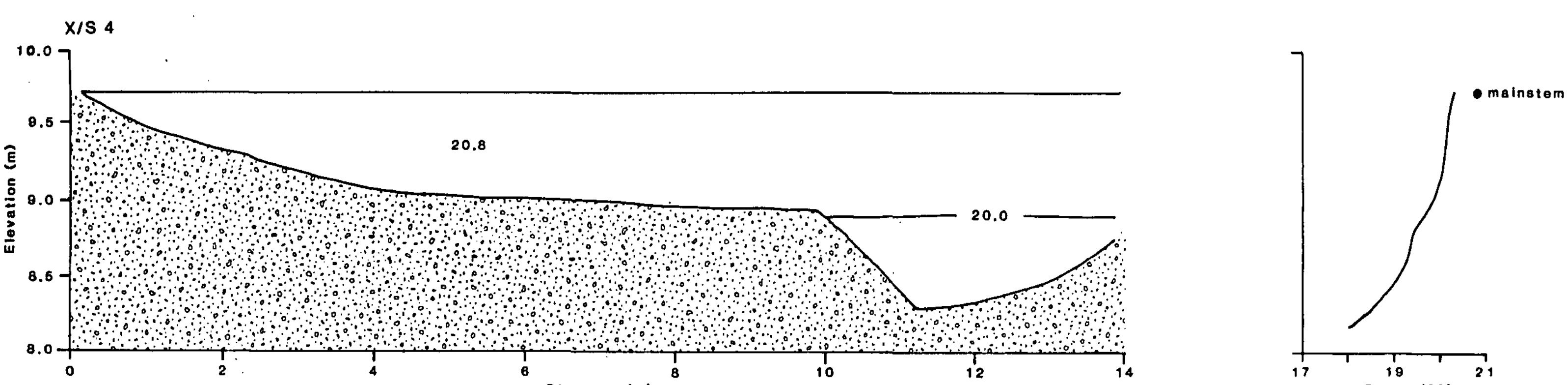



Hayes Creek Pool
terrace
X/S 3
X/S 2
X/S 4
X/S 1

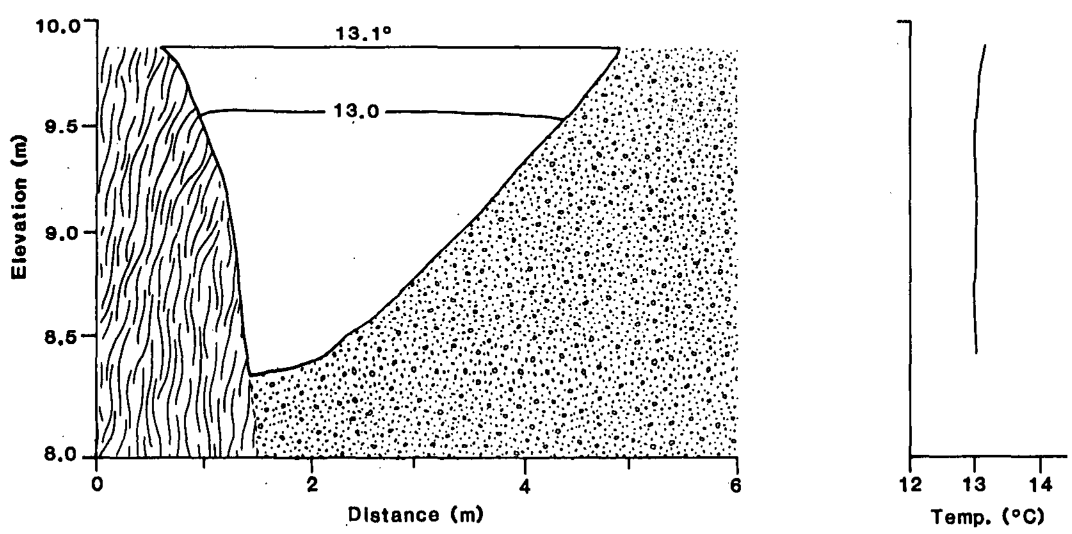

X/S 1
10:30 a
Air Temp. 13.1°
Elevation (m)
Distance (m)
14.5
15.0
15.2
1030 hours
1553 hours
Temp. (°C)


X/S 2
11:44 a
Air Temp. 17.1°
Elevation (m)
Distance (m)
18.0
17.0
log
Temp. (°C)

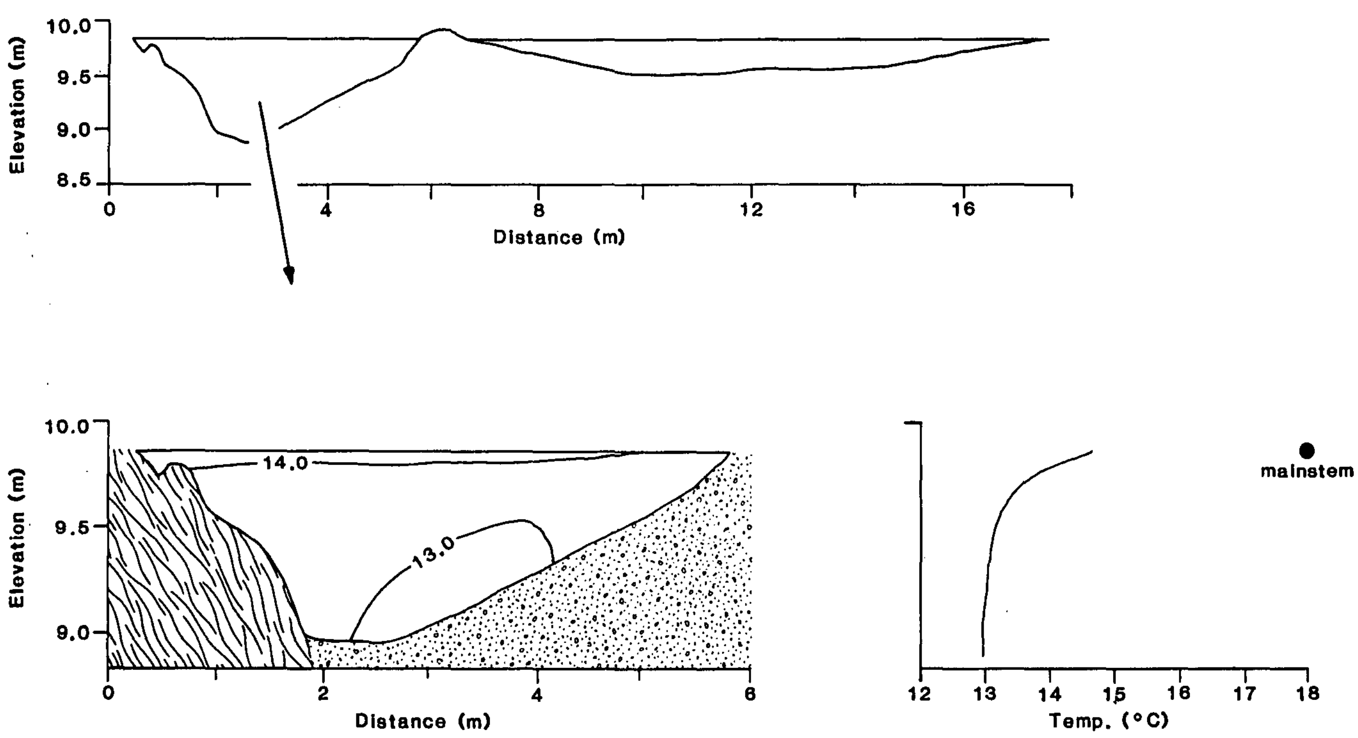

X/S 3
1:47 p
Air Temp. 20.0°
Elevation (m)
Distance (m)
log
log
Log Jam
19.5
19.0
18.0
mainstem
Temp. (°C)


X/S 4
Elevation (m)
Distance (m)
20.8
20.0
mainstem
Temp. (°C)

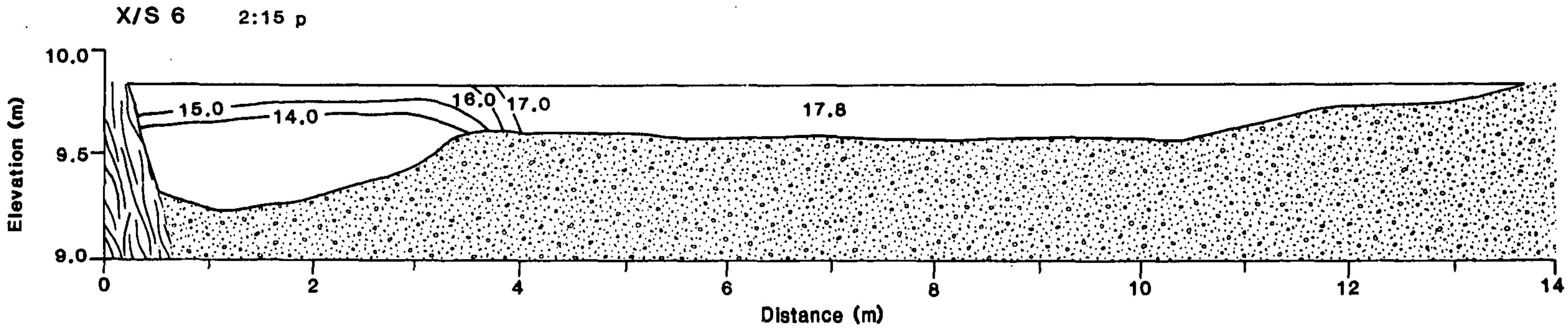
X/S 4



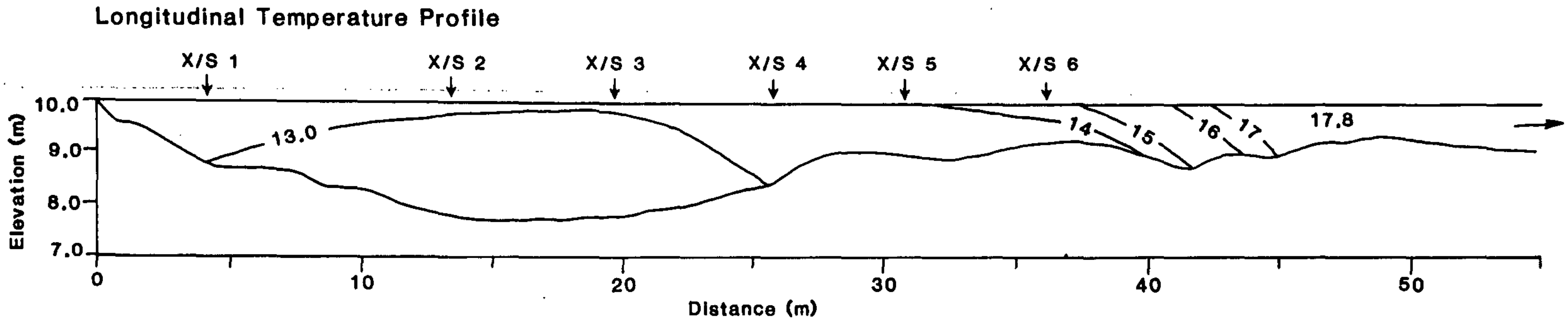
X/S 5



X/S 6 2:15 p



Longitudinal Temperature Profile



Appendix C

Pool maps show seepage meter locations and corresponding Thiessen polygons.

Seepage Meter Data

Discharge (Q_i) at seepage meter i is calculated by:

$$Q_i = (q_i * a_i) / A$$

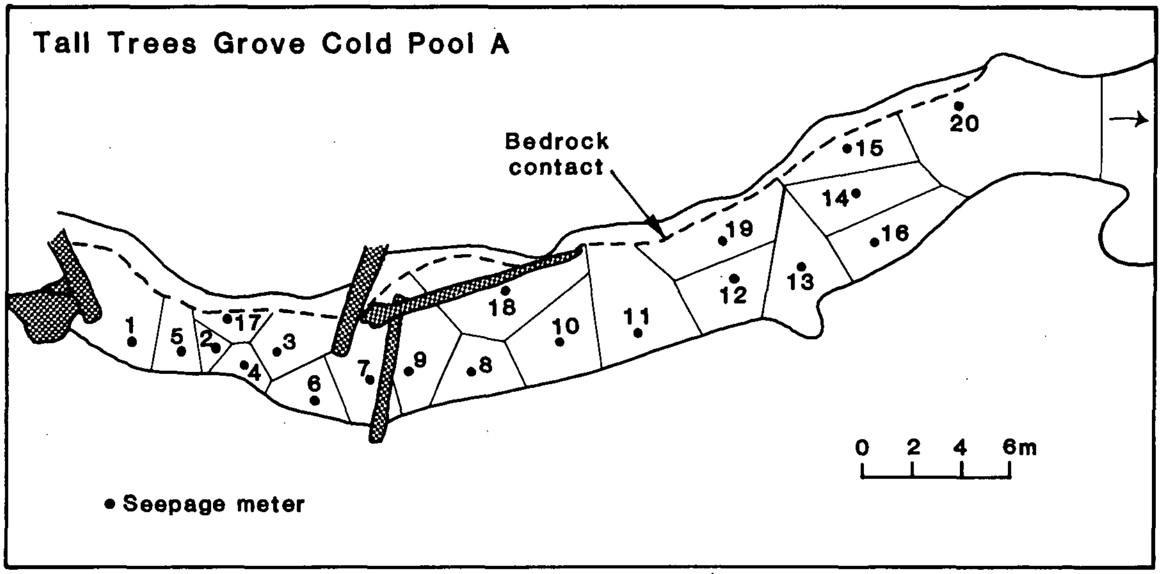
where q_i is the measured seepage rate in cm^3/s, A is the streambed area covered by the seepage meter (600 cm^2) and a_i is the area of the Thiessen polygon in cm^2. Where possible temperature was measured at the flow outlet of the seepage meters and is recorded in degrees Celsius.

Rectangular Trough Data

Distance along the gravel bar face (Bank Dist) is measured in meters with 0.0 m at the upstream edge of the cold pool. Length (L) refers to the length of streambank in centimeters represented by the rectangular trough measurement. Discharge (Q_j) is given by:

$$Q_j = (q_j * l_j) / L$$

where q_j is the discharge measured with the rectangular trough in cm^3/s, L is the length of the container (0.17 m) and l_j is the length of streambank.



SEEPAGE METER MEASUREMENTS

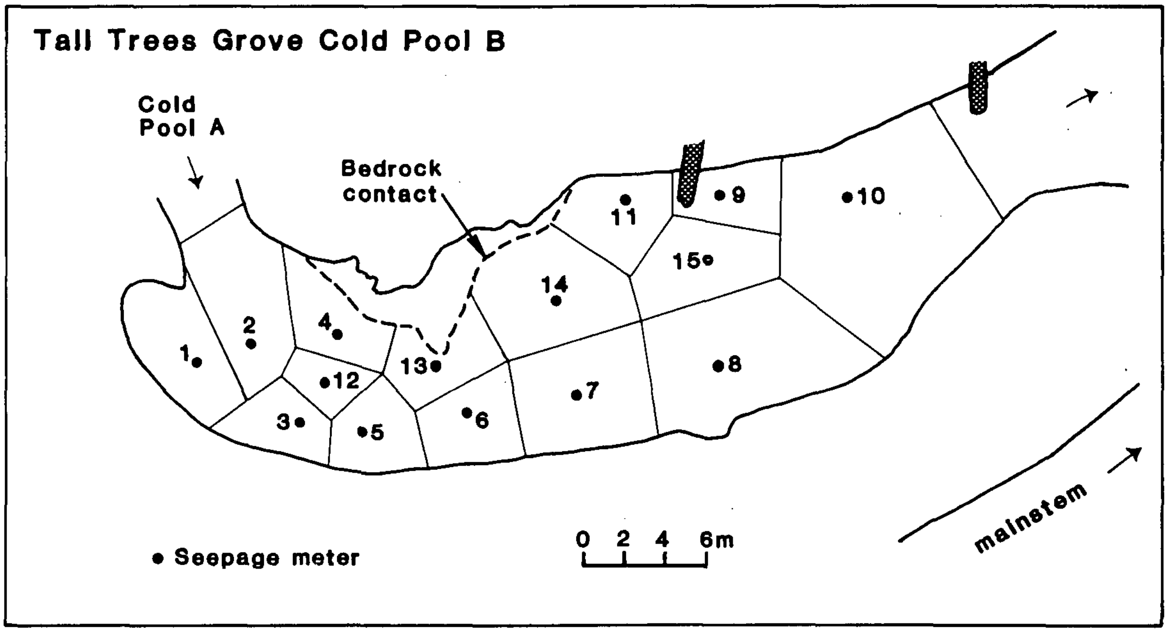
Seepage Meter #	Area cm^2	qi cm^3/s	Qi cm^3/s	Temp °C	Seepage Meter #	Area cm^2	qi cm^3/s	Qi cm^3/s	Temp °C
1	67379	1.20	135	15.8	11	80855	1.87	252	17.1
1	67379	1.29	145	15.8	11	80855	1.90	256	17.1
2	11152	2.18	41	15.1	12	55762	4.08	379	17.2
2	11152	2.20	41	15.1	12	55762	2.78	258	17.2
3	33457	7.41	413	13.8	13	72955	3.83	466	17.3
3	33457	7.49	418	13.8	13	72955	3.64	443	17.3
4	20214	1.70	57	16.4	14	65288	2.35	256	17.0
4	20214	0.46	15	16.4	14	65288	2.42	263	17.0
4	20214	1.82	61	16.4	15	39033	6.03	392	17.4
5	25093	2.37	99	15.8	15	39033	7.70	501	17.4
5	25093	2.56	107	15.8	15	39033	6.56	427	17.2
6	32063	4.38	234	16.9	16	62965	5.97	627	17.3
6	32063	3.96	212	16.9	16	62965	5.80	609	17.3
7	61338	4.20	429	15.8	16	62965	6.85	719	17.3
7	61338	5.20	532	15.8	17	14638	1.77	43	13.5
8	43913	3.40	249	17.0	17	14638	1.75	43	13.5
8	43913	5.07	371	17.0	18	92937	1.86	288	14.1
8	43913	5.65	414	17.0	18	92937	1.91	296	14.1
9	75743	5.09	643	16.0	19	64359	3.33	357	14.0
9	75743	3.43	433	16.0	19	64359	4.30	461	14.0
10	69238	1.51	174	16.0	20	183086	1.80	549	14.9
10	69238	1.23	142	16.0					

TALL TREES GROVE: COLD POOL A

RETANGULAR TROUGH MEASUREMENTS

Bank Dist	Length cm	q_j/L cm^2/s	Q_j cm^3/s
1.5	152	0.04	6
3.0	152	0.07	11
4.6	152	0.30	46
6.1	152	1.47	223
7.6	152	0.89	135
9.1	152	0.93	141
10.7	152	0.21	32
12.2	152	0.22	33
13.7	152	0.22	33
15.2	152	2.41	366
16.8	152	0.96	146
18.3	152	0.76	116
19.8	152	0.61	93
21.3	152	0.04	6
22.9	152	0.04	6
24.4	152	0.02	3
25.9	152	3.89	591
27.4	152	0.05	8
30.5	305	0.15	46

Total Q = 2042 cm^3/s



SEEPAGE METER MEASUREMENTS

Seepage Meter #	Area cm^2	qi cm^3/s	Qi cm^3/s	Temp °C
1	193541	7.40	2387	18.5
1	193541	7.46	2406	18.5
2	269517	0.01*	4	17.8
2	269517	0.03	13	17.8
3	109898	0.74	136	18.4
3	109898	0.77	141	18.4
4	128950	0.10	21	16.1
4	128950	0.11	24	16.1
5	122212	2.36	481	---
5	122212	4.62	941	---
6	148002	6.79	1675	---
6	148002	2.71	668	---
6	148002	5.52	1362	17.2
7	271375	2.00	905	17.2
7	271375	1.68	760	17.2
8	409154	5.53	3771	17.5
8	409154	5.44	3710	17.5
9	113151	0.69	130	17.5
10	596654	6.61	6573	---
10	596654	1.70	1691	---
11	145214	1.32	319	17.0
11	145214	1.23	298	17.0
12	65520	4.80	524	16.0
12	65520	1.89	206	16.0
13	125929	3.91	821	---
13	125929	3.12	655	---
14	252556	0.81	341	16.0
14	252556	1.06	446	16.0
15	198420	0.25	83	16.9
15	198420	0.26	86	16.9

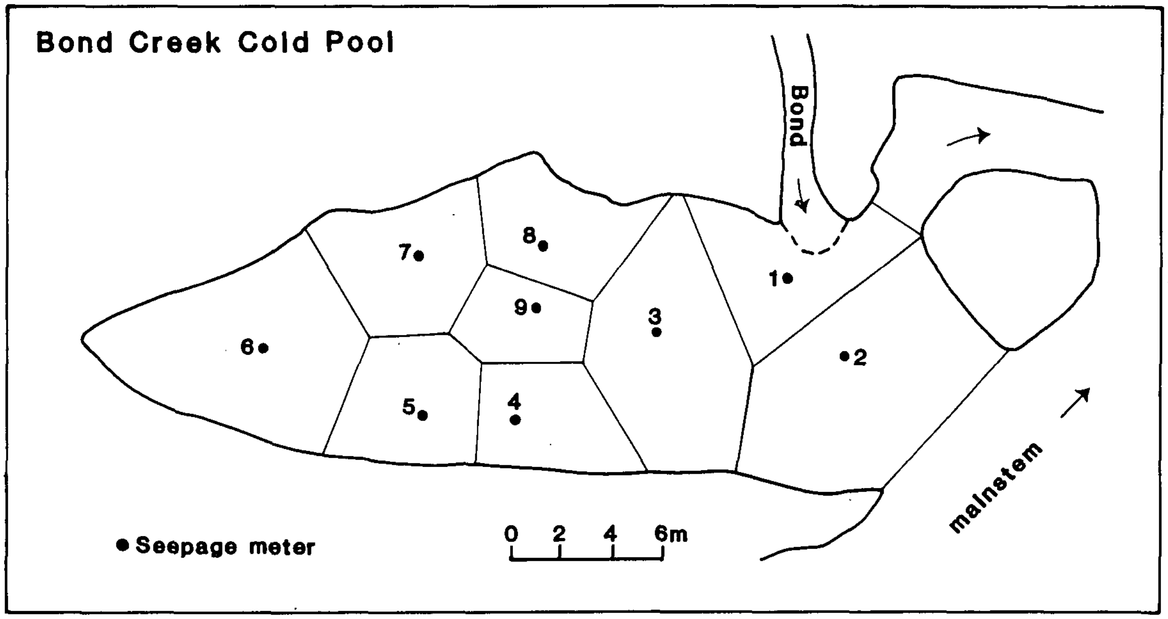
* Measurement less than the accuracy of the seepage meter.

TALL TREES GROVE: COLD POOL B

RECTANGULAR TROUGH MEASUREMENTS

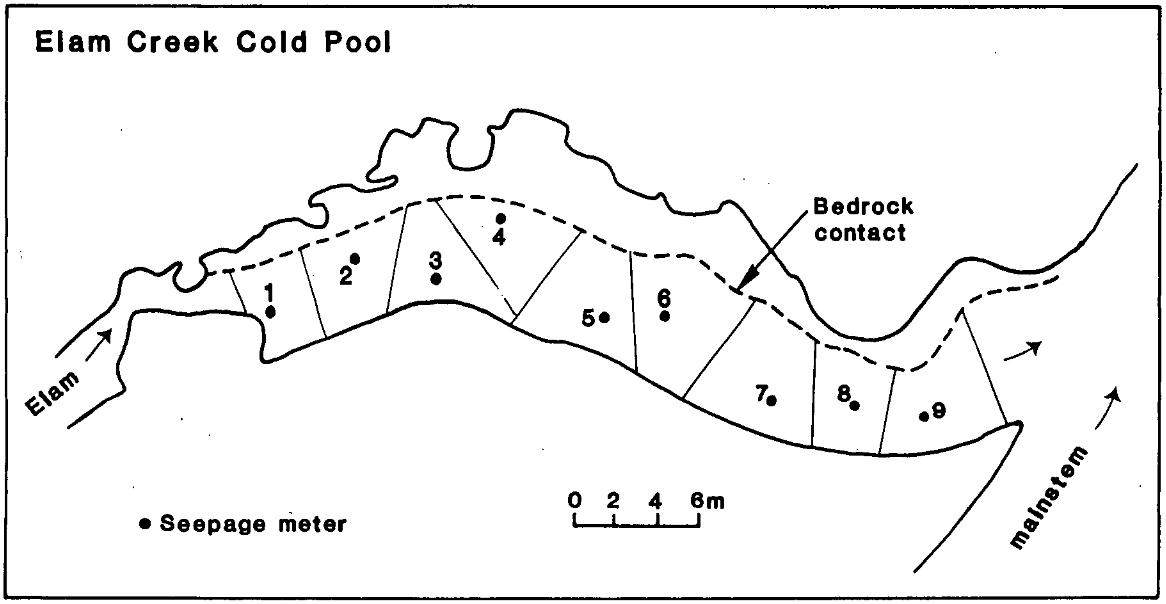
Bank Dist	Length cm	q_j/L cm^2/s	Q_j cm^3/s	Temp °C
0.0	305	1.61	491	18.0
3.0	305	1.96	598	---
6.1	305	0.04	12	---
9.1	305	0.77	235	---
12.2	305	0.37	113	---
15.2	152	0.23	35	---
19.8	61	0.79	48	---
26.5	244	0.92	224	---

Total Q = 1756 cm^3/s



SEEPAGE METER MEASUREMENTS

Seepage Meter #	Area cm^2	qi cm^3/s	Qi cm^3/s
1	182853	0.82	250
1	182853	0.36	110
1	182853	0.54	165
2	403346	0.78	524
2	403346	1.15	773
3	314823	2.93	1537
3	314823	3.25	1705
3	314823	1.16	609
4	145214	2.89	699
4	145214	2.50	605
5	170074	1.70	482
5	170074	1.52	431
6	365242	2.90	1765
6	365242	2.31	1406
6	365242	1.85	1126
7	193773	5.06	1634
7	193773	4.46	1440
8	159851	1.05	280
8	159851	2.49	663
8	159851	1.15	306
9	102928	1.85	317
9	102928	0.59	101
9	102928	0.77	132



SEEPAGE METER MEASUREMENTS

Seepage Meter #	Area cm^2	qi cm^3/s	Qi cm^3/s	Temp °C
1	78956	0.45	59	12.0
1	78956	0.45	59	12.0
2	85647	0.02	3	12.0
3	103714	0.01*	2	12.0
4	113081	0.01*	2	12.5
5	145868	0.06	15	12.9
6	123118	T	0	---
7	147876	T	0	13.2
8	82971	0.01*	1	---
9	131817	T	0	14.0

* Measurement less than the accuracy of the seepage meter.

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