Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California

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By EDWARD A. KELLER, TERRENCE D. HOFSTRA, *and* CLARICE MOSES

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U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454-U

CONTENTS

ILLUSTRATIONS

TABLE

SUMMER COLD POOLS IN REDWOOD CREEK NEAR ORICK, CALIFORNIA, AND THEIR RELATION TO ANADROMOUS FISH HABITAT

By EDWARD A. KELLER,[1] TERRENCE D. HOFSTRA,[2] and CLARICE MOSES[1]

ABSTRACT

"Cold pools" in Redwood Creek, Calif., maintain summer water temperatures several degrees Celsius cooler than main-stream temperatures. The cold pools form where cool ground water, or main-stream water cooled by intragravel flow, seeps from the channel and does not rapidly mix with the warmer main-stream water. Mixing may be retarded by large organic debris, which also helps to create the pool by inducing scour during relatively high-flow events, or by midchannel or side-channel gravel bars. Thus, formation and maintenance of cold pools result from a variety of processes operating over a spectrum of flows ranging from winter floods, which scour pools and move large organic debris, to summer low flow, in which effluent subsurface water becomes significant.

Little is known about the hydrologic and fluvial geomorphic implications of effluent-influent subsurface water and streams. During the later summer, however, a larger portion of the base flow in Redwood Creek is probably produced from effluent ground water from point sources, such as the dry channel of Hayes Creek, rather than from more dispersed sources such as small springs that discharge along the valley margin from bedrock aquifers. Measurement of the summer low-flow discharge of Redwood Creek at the site of the Hayes Creek cold pool suggests that main-stream flow may be augmented locally by as much as 22 percent (of the main-stream flow upstream of Hayes Creek) by effluent subsurface flow. Furthermore, as streamflow in Redwood Creek decreases from early to late summer, the amount of subsurface water from the Hayes Creek catchment also decreases, but the amount of effluent subsurface flow as a percentage of the total streamflow increases. A limiting factor to anadromous fish productivity in many northern California streams is the summer pool environment. Cold pools in Redwood Creek, although few in number, provide high-quality summer habitat for juvenile and migratory adult anadromous fish relative to other pools. Formation of new cold pools in areas where cold subsurface water enters the stream would increase summer low-flow habitat for anadromous fish such as salmon and steelhead trout.

INTRODUCTION

Interactions among geologic, hydrologic, and biologic processes in redwood forest areas influence channel form and process on a variety of scales. For example, large organic debris (woody material greater than 10 cm in diameter) in small steep tributary drainage basins of Redwood Creek largely controls local channel morphology (chap. P, this volume); geologic variability, however, tends to significantly control gross morphology of the long profile (Keller and Tally, 1979). On the other hand, in the lower 20 km of Redwood Creek, large organic debris has a lesser influence on channel morphology, while geology significantly influences the characteristic morphology of the valley sides through slope processes that deliver sediment to the main channel.

Large organic debris in the lower reaches of Redwood Creek is generally quite mobile because the stream, during high winter flows, is able to carry downstream even the largest redwood trunks. Occasionally, however, large redwood trunks may accumulate along the bank of Redwood Creek to form a logjam. Such locations tend to influence local scour and fill by inducing a turbulence that produces large pools. These pools in turn provide important aquatic habitat for anadromous fish and other animals such as river otter, beaver, various birds, and other fish. In a few of these pools, the stream environment is further modified by subtle relations between effluent ground water, intragravel flow of stream water, channel morphology, and large organic debris to produce summer pools having water temperatures several degrees Celsius cooler than main-stream temperatures. This paper documents the existence of some cold pools and discusses the processes by which such pools form and their significance to anadromous fish.

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REDWOOD CREEK "COLD POOLS"

Cold pools that maintain summer water temperatures several degrees Celsius cooler than main-stream temperatures, through interaction with ground water that enters the stream or through interaction with intragravel stream water flowing through long gravel bars, were discovered in Redwood Creek near Orick, Calif. (fig. 1), during the summers of 1981 and 1982. Figure 2 shows the cold pool, as it existed in the summer of 1981, located at the junction of Hayes Creek and Redwood Creek approximately 4 km upstream from the town of Orick. Although the lower portion of Hayes Creek is dry in the summer, it contributes subsurface water (ground water and intragravel flow) to the main channel of Redwood Creek. The temperature of the subsurface water is approximately 11 to 12 °C, in marked contrast to the main-stream temperature of Redwood Creek, which, on warm afternoons, may exceed 20 °C. The cold subsurface water collected in a small trough, scoured by Hayes Creek where it joins Redwood Creek during winter flows, and slowly entered into the large downstream pool in Redwood Creek, which has formed or been modified by scour around several large redwood trunks. The cold water apparently was prevented from mixing with the warmer water in the main stem of Redwood Creek by both the organic debris and the midchannel bar shown on figure 2. Thus a plume of cold water lingered in the bottom of the pool, providing temperatures of 12 to 16 °C compared to 21 °C upstream and downstream of the pool. Reid (1961) speculated that cold springwater might produce a cold pool but thought that the cold water would enter the channel in the deep part of the pool rather than migrate there from streambank seeps, as in the Hayes Creek cold pool of Redwood Creek (fig. 1). Of course, other cold pools could form as Reid suggests.

Dissolved oxygen also was measured in the Hayes Creek cold pool. As cold ground water having assumed low dissolved-oxygen content slowly mixes with the warmer more oxygenated water of Redwood Creek, the oxygen concentration in the cold pool increases, as shown on figure 2.

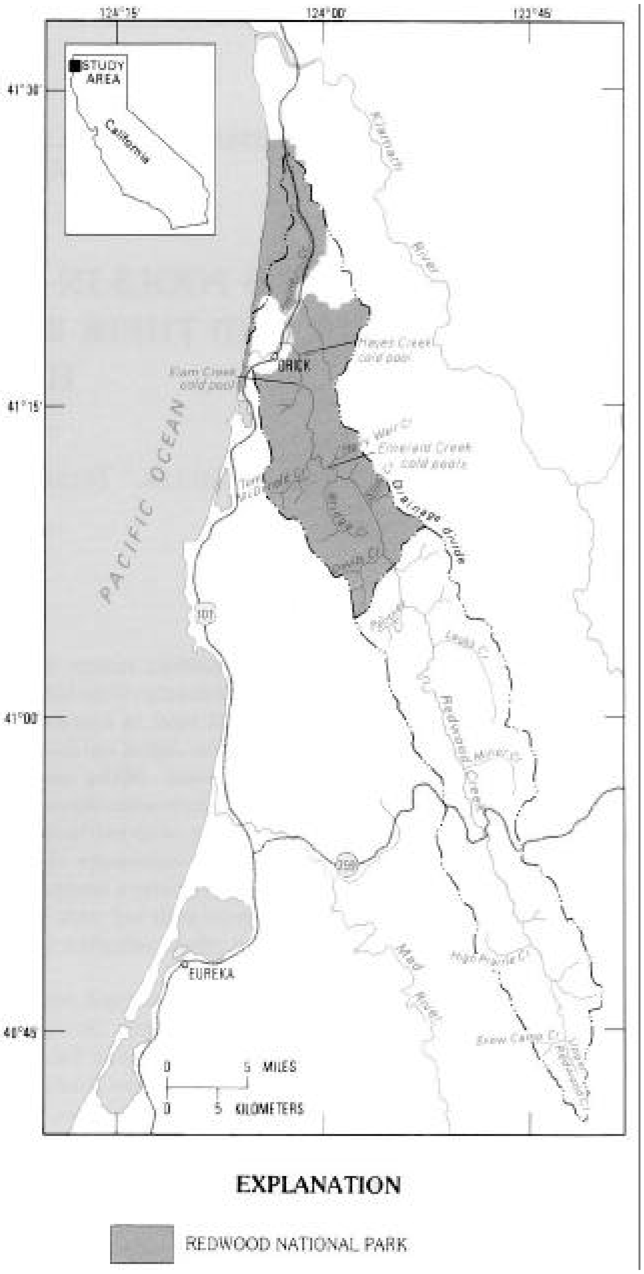

FIGURE 1.—Location of the three cold pools discussed in this paper.

Cold pools apparently persist during the summer low-flow period. Figure 3 shows thermograph data for two locations in the Hayes Creek cold pool (station 1 and 2, fig. 2) and maximum-minimum temperature data for one location in the main stream of Redwood Creek (station 3, fig. 2) from September 22 through September 25, 1981. Data were collected from two continuously recording thermographs placed near the bottom of the cold pool at stations 1 and 2 and from a maximum-minimum thermometer placed in the main stream of Redwood Creek (station 3). At no time during the 4 days was the water in the cold pool as warm as that in the main stream, and the differences in temperature varied

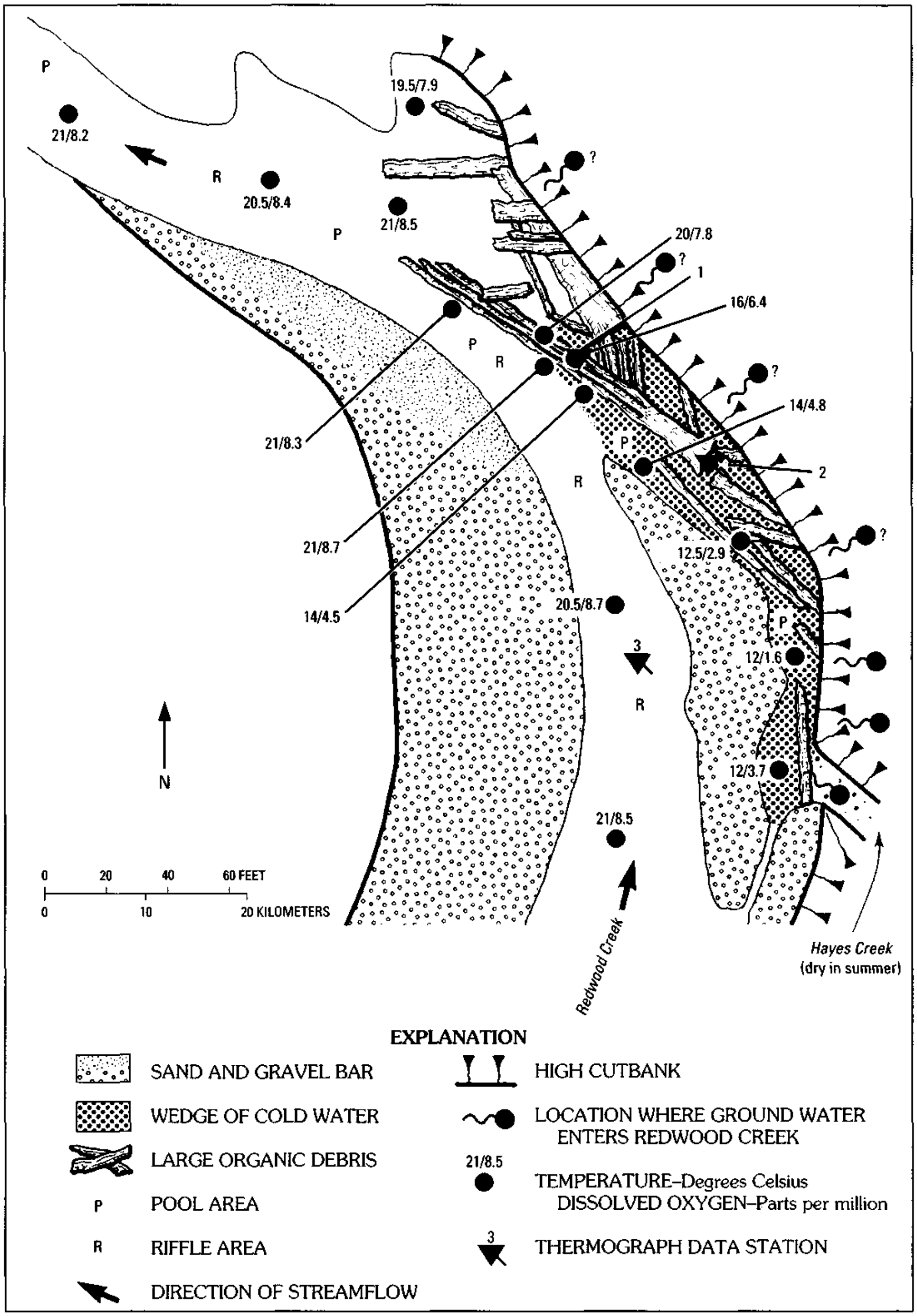

FIGURE 2.—Hayes Creek cold pool in Redwood Creek near Orick, Calif. Data collected on September 1, 1981 (10:30 a.m.-12:30 p.m.). Locations where continuous (station 1 and 2) and maximum-minimum (station 3) temperature data were recorded from September 22, 1981, to September 25, 1981, are indicated. Water depth in the cold pool at station 1 was about 1 m compared to about 0.2 m at station 3.

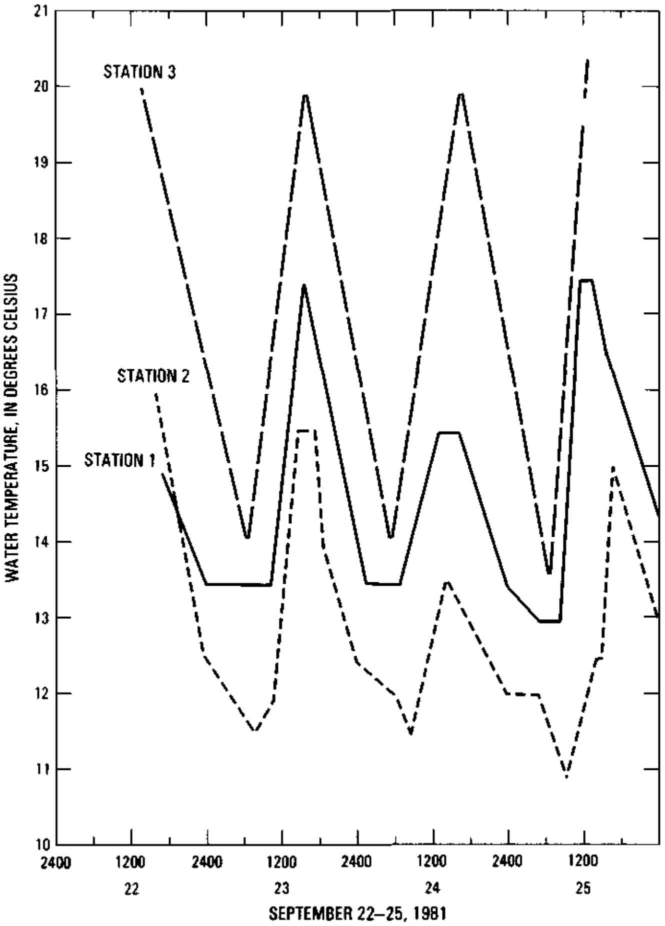

FIGURE 3.—Water temperatures at stations 1-3, Hayes Creek cold pool and main stream of Redwood Creek, September 22-25, 1981. Stations 1 and 2 were sites of continuous temperature recording. Maximum-minimum temperature data are presented for station 3, in the main stream of Redwood Creek. Station locations are shown in figure 2.

systematically with the distance from the source of cold water entering the cold pool. That is, station 2 always had cooler water than station 1, and both stations were always cooler than the main-stream temperatures. During warm afternoons, the temperature differences between the main stream of Redwood Creek and the cold pool were most pronounced, and during the early morning hours the differences were less (fig. 3). The reason for the horizontal portions seen on the graph station 1 is presumably related to a problem associated with the recorder.

Cold pools do not develop at all locations where cold ground water flows into the stream. Conditions favorable in Redwood Creek to the development of a cold pool include a concentrated source of cool ground water and a pool morphology that discourages mixing of the cold and warm water.

In Redwood Creek, large organic debris is apparently important in retarding mixing of the cold and warm water. Just downstream of the mouth of Hayes Creek, large redwood trunks, extending out into the pool and roughly parallel to the flow along with the midchannel gravel bar, trapped cold water and inhibited rapid mixing with the warmer water in Redwood Creek. These events explain the configuration of the plume of cold water shown on figure 2. If there is no barrier to inhibit mixing, cold pools may not develop even in places where inflow of ground water apparently is greater than such inflow at Hayes Creek.

During the winter of 1981-82, the Hayes Creek pool increased in area, depth, and volume. The midchannel gravel bar near the mouth of Hayes Creek, along with the large organic debris that physically isolated the cold effluent ground water, was removed, producing significant changes in the summer low-flow morphology (see figs. 2, 4). The gravel bar no longer isolated the effluent subsurface water, but the large organic debris did help retard complete mixing of the cold subsurface water with the warmer main-stream flow. Water temperature differences, however, were not as great as those observed during the summer of 1981, and a distinct wedge of cool water was not present.

Cold pools also may form during low-flow conditions when relatively warm main-stream water in Redwood Creek infiltrates into long gravel bars, then cools and emerges again downstream. Figure 5 shows two pools that are located approximately 0.4 km downstream of the Emerald Creek[1] confluence with Redwood Creek (not shown) and 2.4 km upstream from the Tall Trees Grove (not shown). The large cold pool on the west bank of the creek formed in a similar way to that of the Hayes Creek cold pool. The small pool on the east bank (at the downstream end of the dry channel) was only 1 °C cooler than the main stream and formed as a result of intragravel flow. Conditions that favored scour of the pools during the 1981-82 winter evidently ceased during the 1982-83 winter as most of the large cold pool on figure 5 filled with sediment, and the small pool completely disappeared.

Figure 6 shows a cold pool located 50 m downstream from the confluence of Elam Creek with Redwood Creek, approximately 5.5 km upstream from Orick. The cool water is from two sources: (1) Elam Creek surface and subsurface water that seeps through the large gravel bar on the west side of Redwood Creek and (2) springs discharging from rock fractures and landslides at the north end of the pool. Streamflow measured on September 9, 1982, indicates an increase in flow of Redwood

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[1] Emerald Creek is shown as Harry Weir Creek on U.S. Geological Survey topographic maps. Locally the names are used interchangeably.

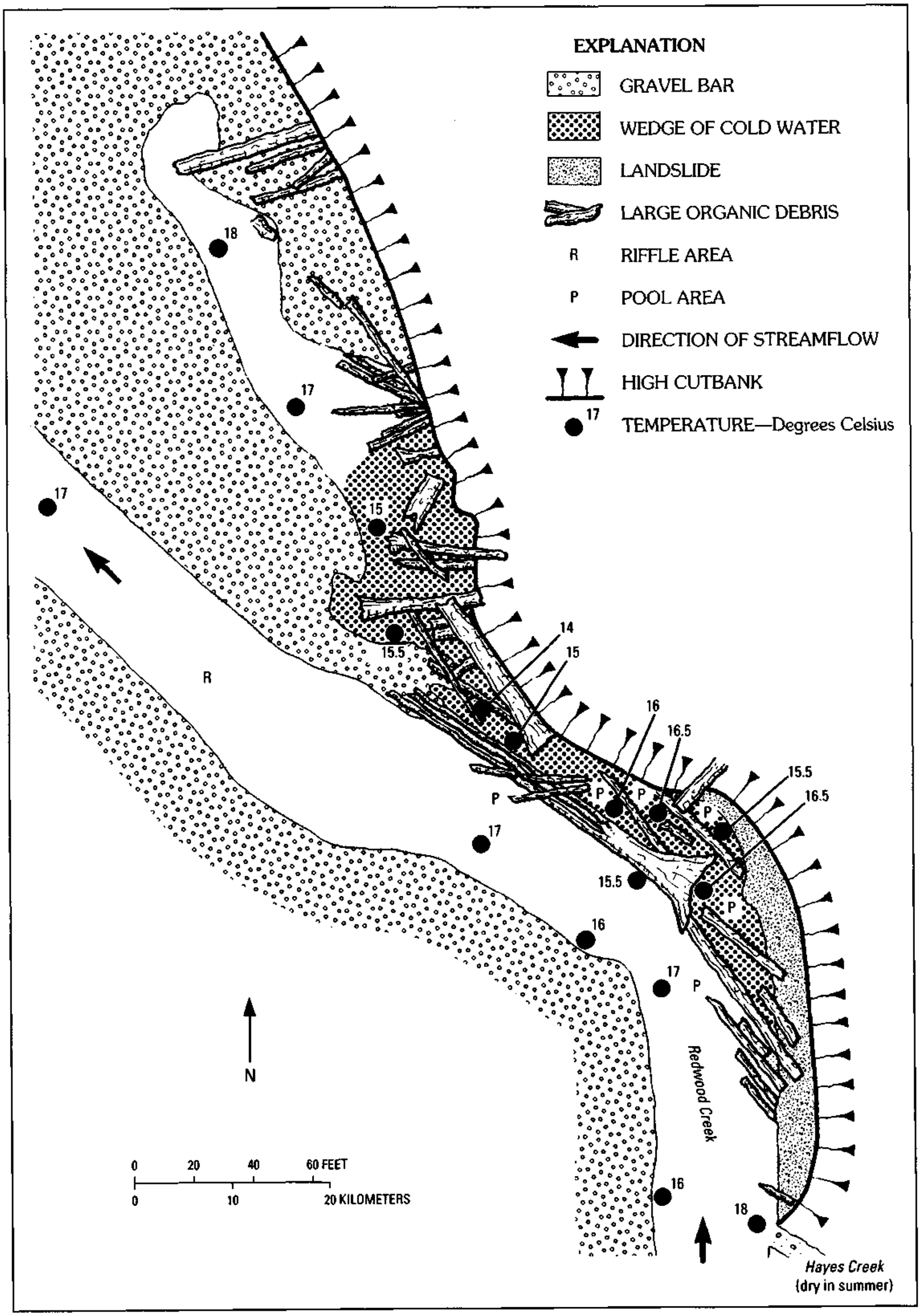

FIGURE 4.—Hayes Creek cold pool in Redwood Creek near Orick, Calif., mapped on September 1, 1982, at a streamflow of about 0.46 m^3/s. Temperature data were collected on September 16, 1982, at 2 p.m.

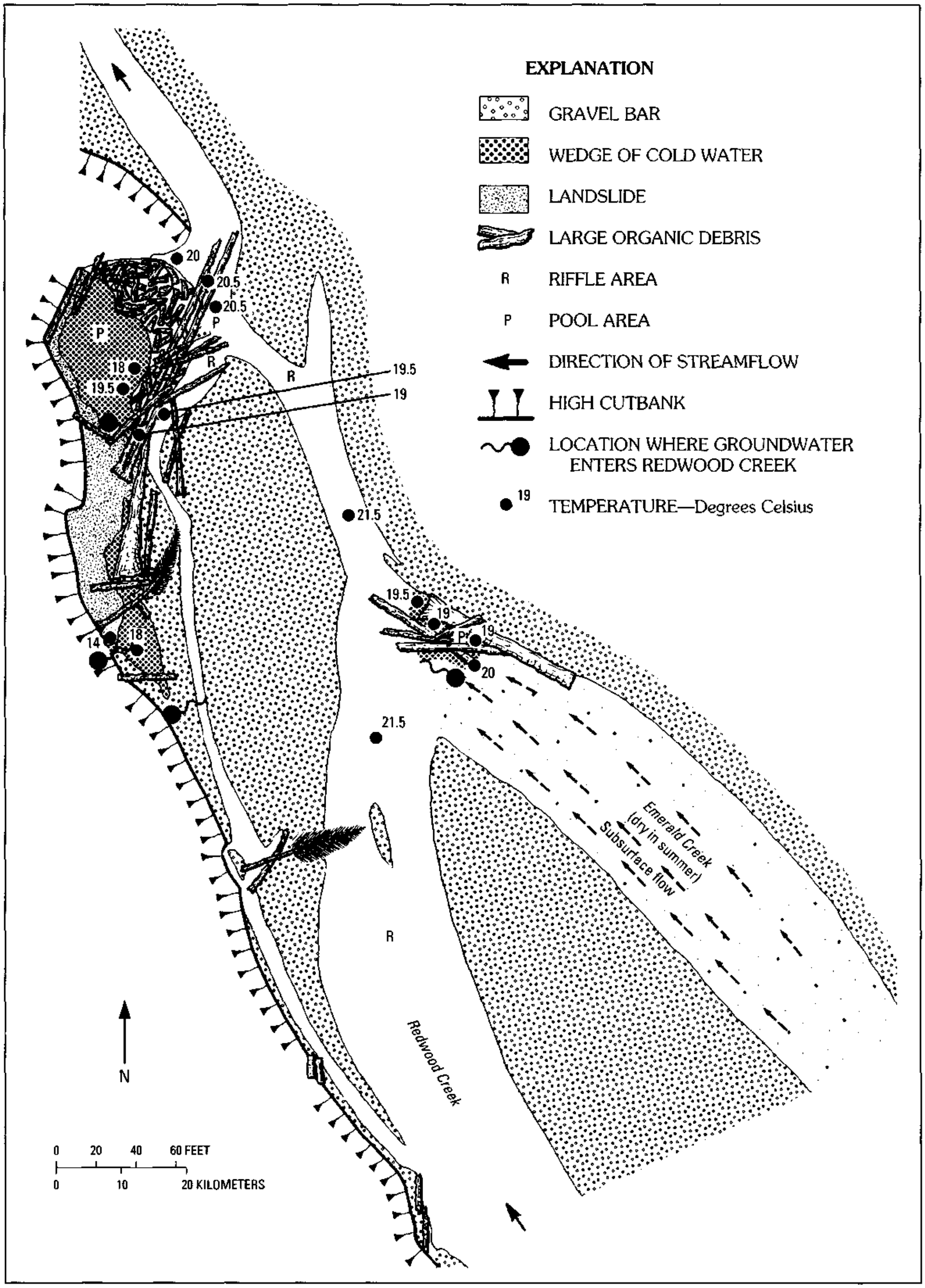

FIGURE 5.—Emerald Creek cold pools in Redwood Creek, mapped July 25, 1982, at a streamflow of 0.89 m^3/s. Temperature data were collected on August 11, 1982, at 2:10 p.m. The small cold pool on the east bank of Redwood Creek is due to cool intragravel water entering a small scour pool (produced at high flow) that is protected during low flow by large organic debris.

TABLE 1.—*Increase in streamflow of Redwood Creek due to effluent subsurface water at the Hayes Creek, Elam Creek, and Emerald Creek cold pools*

Cold pool name	Date measured	Upstream discharge (m^3/s)	Downstream discharge (m^3/s)	Increase (m^3/s)	Percent Increase	Confidence in the percent increase (1=high, 4=low)[1]
Hayes Creek[2] ……………..	Sept. 4, 1981	0.40	0.49	0.09	22	1
Do..………………………..	Aug. 10, 1982	.69	.82	.13	19	1
Do..………………………..	July 9, 1982	1.77	1.97	.20	11	2
Elam Creek………………...	Sept. 9, 1982	.32	.37	.05	14	2
Emerald Creek……………..	Aug. 19, 1982	.47	.48	.01	2	4
Do.......................…………	July 24, 1982	.87	.91	.04	5	3

[1] Reflects the fact that discharge can be measured only at ±5 to 10 percent. 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.

[2] On August 23, 1982, the discharge upstream and downstream of the Hayes Creek cold pool remained nearly constant at 0.45 m^3/s.

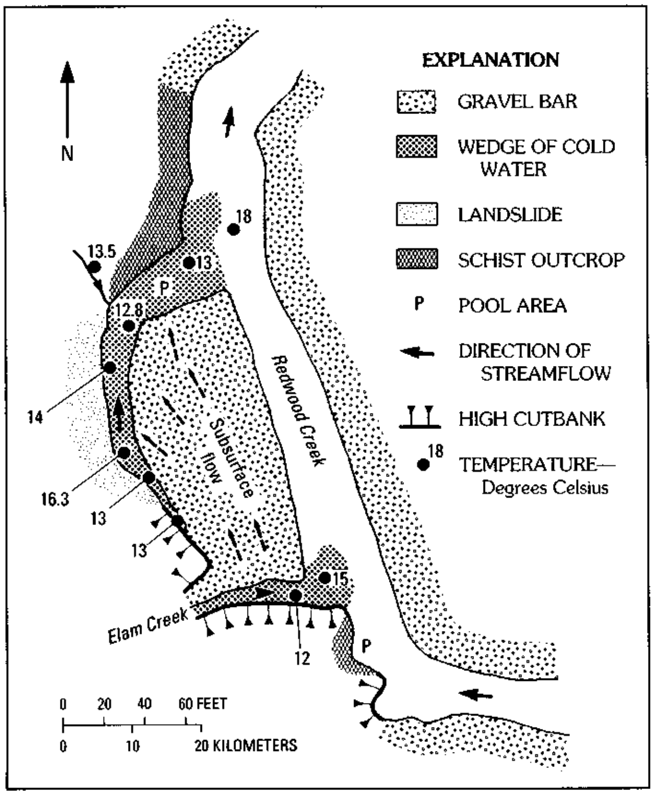

FIGURE 6.—Elam Creek cold pool in Redwood Creek, mapped September 9, 1982, at a discharge of 0.32 m^3/s upstream of the pool and 0.37 m^3/s downstream. Temperature data were collected on September 14, 1982, at 1 p.m.

Creek through the reach from 0.32 m^3/s (upstream) to 0.37 m^3/s (downstream). The relative proportion of cool water flow from the two sources is not known. The most important morphologic features in the formation and maintenance of the Elam Creek cold pool are (1) the scour channel along the west side of Redwood Creek, downstream of Elam Creek (fig. 6) that forms the deep part of the pool, (2) the large gravel bar that probably conveys cool subsurface water from Elam Creek to the pool while isolating the pool from the warmer water of Redwood Creek, and (3) the landslide and bedrock fractures along the west side of the pool, which allow additional cool water inflow to the system. This pool is also significant in its lack of large organic debris, which is present in both the Hayes Creek and Emerald Creek pools (figs. 2, 4, 5). Pools of the three creeks, however, have several features in common: (1) a source of cold water; (2) development of a scour pool, presumably during high flows of Redwood Creek; and (3) a barrier that reduces mixing of the cold water with warmer mainstream flow of Redwood Creek. Thus, as with many features of the fluvial system, the cold pools result from a variety of processes over a spectrum of flows ranging from winter floods to summer low flow.

HYDROLOGY OF COLD POOLS

Basic relations among influent and effluent groundwater flow, intragravel flow of water in the stream channel, and channel form and processes are nearly unexplored with regard to fluvial geomorphology. Observations of a small stream in Alaska by Harrison and Clayton (1970) suggest that both channel morphology and stream competency may be significantly affected by seepage of water into (effluent stream) or out of (influent stream) the channel. In Redwood Creek, as with many perennial streams, the summer flow or base flow is produced where ground water seeps into the channel. What is not known is the nature and extent of the processes that produce the observed base flow.

Measurements of relatively low summer streamflow in Redwood Creek during the summers of 1981 and 1982 (table 1) suggest (with one exception) that, over a distance of about 120 m, streamflow through the Hayes Creek cold pool increased by as much as 22 percent. (An increase of 10 percent is taken to be greater than error of measurement.) We were not able to determine how much of the increase was due to effluent intragravel flow versus effluent ground-water flow. The dissolved-oxygen-content data collected in 1981 (fig. 2), however, suggest a ground-water source. The data also suggest that, as streamflow 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 subsurface water as a percentage of total streamflow increases.

Measurements of streamflow above and below the Elam Creek and Emerald Creek cold pools are also shown on table 1. Streamflow above and below the Elam Creek cold pool in September of 1982 suggests an increase of 14 percent. Much of the increase may be due to intragravel flow of Elam Creek surface water rather than effluent ground water (fig. 6). The data from the Emerald Creek cold pool suggest a possible increase in streamflow, but the percent change is within the possible error of measurement. Nevertheless, cold ground water was observed entering the site by way of small springs along the west bank of Redwood Creek (fig. 5), and the flow was evidently sufficient to maintain, with shading and retardation of mixing by the organic debris, a cold pool environment until the winter of 1982-83 when the pool was filled by deposition of Redwood Creek sediment.

The data from the Hayes Creek and Elam Creek sites and field observations at other sites suggest that a good deal of the base flow of Redwood Creek may be supplied by point sources rather than by seepage from a more general ground-water source. Furthermore, once ground water enters Redwood Creek, most of it must become influent into streambed gravels. If the ground water did not become influent, late summer base flow of Redwood Creek would greatly exceed that observed.

The flow of Redwood Creek is relatively high during and after winter storms when surface flow from tributaries is high. Thus, the significance of subsurface water on the total flow of Redwood Creek during the wet winter months must be much reduced because only a small percentage of the total flow can be expected from subsurface sources. During the higher flows, however, the intragravel flow in the bed of Redwood Creek, especially in riffles, probably is important to anadromous fish (Vaux, 1962).

ANADROMOUS FISH HABITAT AND COLD POOLS

A limiting factor to anadromous fish productivity in many streams of northern California is the summer pool environment (Denton, 1974). Aggradation in Redwood Creek has impacted important nursery areas by decreasing pool volume. Pools also often have water temperatures too warm to maintain a healthy population of young fish. Decline of fish numbers in Redwood Creek is partly a function of availability of habitat, which has been degraded by certain land use practices, particularly timber harvesting, and by floods (National Park Service, 1981). Cold pools in Redwood Creek, although few in number and ephemeral, may in years of below-average summer flow support a disproportionate amount of the young anadromous fish. We observed in 1981 that hundreds of fish occupied the cold pools compared to tens of fish or none at all in adjacent pools having warmer water temperatures. The majority of these fish were smolt sized (greater than 8 cm). Cold pools may represent a refuge where young fish reside when water temperatures would otherwise limit optimum growth and development.

In August 1981, the lower 40 km of Redwood Creek was surveyed by trained swimmers and divers. The survey revealed a spotty distribution of juvenile fish; some deep pools were devoid of fish, while others contained many. The first cold pool was discovered subsequent to and independent of this survey. However, the second cold pool (near Emerald Creek) was located by referring to survey field notes and returning to a location where the number of juvenile fish observed was significantly greater than in other areas.

Both steelhead trout and coho salmon require a period of extended growth in freshwater before entering the ocean. In Redwood Creek, this period is from 2 to 4 years for steelhead trout and 1 full year for coho salmon. Studies of Redwood Creek tributaries (excluding Prairie Creek) have shown an abundance of young-of-the-year (<1 year old) steelhead (Anderson and Brown, 1982; Terrence D. Hofstra, written commun., 1982). Relatively few 1-year-old or older fish are encountered. The more restrictive habitat requirements of these larger fish apparently are not met in severely aggraded streams. In the Redwood Creek watershed, good quality summertime rearing habitat for 1-year-old or older fish exists only in cold pools or in an embayment that sometimes forms at the mouth of Redwood Creek (Hofstra, 1983; James P. Larson, written commun., 1982).

The distribution of young coho salmon is even more restricted (Anderson and Brown, 1982). No coho have been found rearing in the embayment or any of the tributaries (excluding Prairie Creek). Production of coho salmon in Redwood Creek may be closely tied to the cold pools.

It is apparent that, if there were more cold pools, there would be more summer habitat and perhaps greater fish production in Redwood Creek. As more is learned about the nature and extent of cold pools, it is expected that this information may significantly impact management of anadromous fish in streams of the Pacific Northwest. That is, managers may be able to take advantage of locations where cold water enters a stream and use it to enhance anadromous fish habitat. This approach will be particularly important where rearing habitat for juvenile fish is a limiting factor in fish production.

Redwood Creek, as well as other streams and rivers, including the Eel River and Klamath River, also supports a summer or spring run of steelhead trout. Adult, summer steelhead spend the summer in the river and spawn in the fall. These fish are intrinsically valuable, as they have a limited occurrence in California (Jones, 1980). Cold pools in the streams, associated with point-source ground-water effluence and channel morphology, undoubtedly provide refuge for migrating fish and holding sites for those waiting to spawn. In fact, fish migrating in the summer may move upstream from one cold pool to the next, thus avoiding high temperatures that exist during the day over most of the stream.

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