WATER RESOURCES BULLETIN
VOL. 16, NO. 1 AMERICAN WATER RESOURCES ASSOCIATION FEBRUARY 1980

DISSOLVED OXYGEN IN INTRAGRAVEL WATER OF THREE TRIBUTARIES TO REDWOOD CREEK, HUMBOLDT COUNTY, CALIFORNIA[1]

Paul F. Woods[2]

ABSTRACT: As part of a study of Redwood National Park in northwestern California, an investigation was conducted from June to November 1974 on intragravel dissolved oxygen and sediment in three tributaries to Redwood Creek, a major coastal stream that flows through Redwood National Park. Of concern was whether the intragravel environment of streams in logged and unlogged redwood-forested drainage basins was different. The tributary in the unlogged drainage basin had lower percentages of fine streambed sediment than either of the tributaries in logged drainage basins. Concentration and percentage saturation of dissolved oxygen of intragravel water were highest in the stream in the unlogged drainage basin, intermediate in the stream in the patch-cut drainage basin, and lowest in the stream in the clear-cut drainage basin. The differences in intragravel dissolved-oxygen conditions among the three tributaries are attributed chiefly to differences in their interchange of surface and intragravel water. The larger quantities of fine streambed sediment in the two streams in logged basins may have reduced the permeability of the streambeds and hence their capacity to interchange surface and intragravel water. However, differences in the lithology of the three tributary drainage basins examined may contribute to the differences in the percentage of fine sediments observed among the streams, even in the absence of logging.
(KEY TERMS: dissolved oxygen; water quality; California; Redwood National Park; Redwood Creek.)

INTRODUCTION

The economy of the North Coast region of California depends largely upon its forest products and fishery industries. Much of the fishery is composed of anadromous salmonids that use the region's rivers and tributaries for spawning and rearing grounds. The California State Water Resources Control Board (1973) reported that in some instances fishery resources had been damaged by sedimentation of salmonid spawning grounds resulting from increased erosion due to logging and associated road construction in northern California.

Many researchers believe that the deposition of fine sediment over stream gravels may slow the exchange of oxygen between the intragravel water and the overlying stream water causing intragravel dissolved-oxygen concentrations to fall below tolerable limits for salmonids.

Sheridan (1962) and Vaux (1962) found that the DO (dissolved oxygen) concentration in intragravel water is in part dependent on interchange with surface water. Vaux (1962, 1968) studied the interchange process and found it is affected primarily by three streambed characteristics: permeability, thickness of permeable materials, and configuration of the streambed surface. A downwelling of water into the streambed occurs where permeability or the thickness of permeable materials increases in the direction of flow. Decreases in permeability and thickness of permeable materials in the direction of flow result in an upwelling out of the streambed. Upwelling occurs in streambed areas with a concave profile, whereas downwelling occurs in convex profiles. Research has shown that interchange of surface and intragravel water is impeded by a reduction of streambed permeability resulting from increases of fine sediment in the streambed (McNeil and Ahnell, 1964; Cooper, 1965). Reductions in water interchange are cited by Vaux (1962, 1968) as partly responsible for decreases in the DO concentration of intragravel water.

Reductions in interchange and intragravel DO concentration have particular significance to the reproductive success of salmonid fish. Salmonid fish excavate depressions in the streambed where they deposit their eggs. Development of the eggs occurs within the streambed and the alevins (juveniles) migrate to the surface water. The developing eggs and alevins depend on sufficient interchange of water to supply them with DO and remove their metabolic wastes. Coble (1961) found that reduced interchange of water can reduce the survival rate of eggs and alevins. Under laboratory conditions, Shumway, *et al.* (1964), determined that reductions in intragravel DO concentration results in delayed egg hatching, increased egg and alevin mortality, and reduced size of alevins of steelhead trout (*Salmo gairdneri*) and Coho salmon (*Oncorhynchus kisutch*).

This study was designed to determine if two streams in logged drainage basins had higher percentages of fine streambed sediment and lower intragravel DO concentrations than did a stream in a nearby unlogged drainage basin. From June to November 1974, DO concentrations of surface and intragravel water and the percentage of fine streambed sediment were measured in three tributaries of Redwood Creek, a major coastal stream flowing through Redwood National Park (Figure 1). High discharges prevented sampling in the winter.

[1] Paper No. 79034 of the *Water Resources Bulletin*. Discussions are open until October 1, 1980.
[2] Hydrologist, U.S. Geological Survey, Helena, Montana 59601.

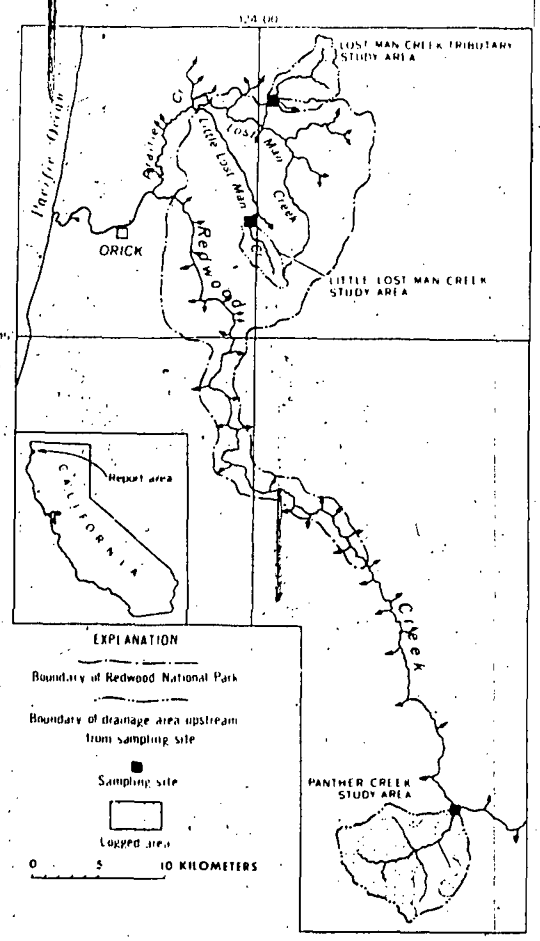

Figure 1. Location of Study Areas.

STUDY AREA

The three streams sampled are in drainage basins representing different degrees of redwood timber harvest, unlogged, clear-cut, and patch-cut (Table 1). The drainage basin upstream from the Little Lost Man Creek sampling site is unlogged. The drainage basin upstream from the Lost Man Creek tributary sampling site had been clear-cut between 1964 and 1969. The upper half of the Panther Creek drainage basin was logged between 1925 and 1940; the lower half has had about 20 percent of its timber harvested since 1963.

The climate is characterized by dry summers and wet winters. At three weather stations near the study areas the reported mean annual rainfall is 180, 153, and 146 mm. Ninety percent of the annual rainfall occurs between October and April (Elford and McDonough, 1964).

Janda, *et al.* (1975), indicated that the soils in the Redwood Creek drainage basin are, in general, shallow stony loams and stony-clay loams. The soils have a high infiltration capacity and good subsurface drainage, but when surface runoff occurs their erosion-hazard rating is moderate to very high. This susceptibility to erosion was attributed to the fact that their surface layers are predominantly loams with little cohesion (Alexander, *et al.*, 1959-62).

It was not possible to select streams of identical lithology. The Little Lost Man Creek drainage basin (unlogged) is underlain by, relatively unmetamorphosed sandstone, siltstone, and conglomerate of the upper Mesozoic Franciscan assemblage that naturally weathers to coarse-grained, well-sorted streambed material. The middle and headwater parts of the tributary to Lost Man Creek (logged) are underlain by Pliocene coastal plain sediments that may naturally yield finer materials than those of Little Lost Man Creek, even in the absence of logging. The Panther Creek drainage basin (patch-cut) is underlain by schists of the Franciscan assemblage that weather to generally clay-rich sediments that may be naturally finer than those of Little Lost Man Creek (Janda, *et al.*, 1975).

METHODS

Spatial variation in the DO concentration of intragravel water was reported by McNeil (1962) and Ringler (1970). To reduce spatial variations and, therefore, the number of samples required to obtain statistically useful results each site was located in a riffle with a linear channel and smooth streambed. Channel gradients in the vicinity of the sites were similar among the three streams. Bedrock outcroppings and blankets of fine sediment were avoided.

At the beginning and end of the study (June 15 and November 22, 1974) the percentage of fine sediment in the streambed was determined at each sampling site. Equipment and procedures used to sample streambed composition were described by McNeil and Ahnell (1964). Streambed material was separated into size classes with seven standard sieves ranging in mesh from 26.67 to 0.104 mm. These mesh sizes were chosen to conform to methods used in previous intragravel research. Wet volumetric displacement was used to determine the contribution by each mesh size to the total streambed core sample. Materials that passed through the finest mesh were settled in a graduated settling cone. Results of streambed sampling were slightly biased because the core sampler excluded materials larger than 152.4 mm. In accordance with previous intragravel research, fine sediment is defined here as that part of the sample passing through a 0.833-mm mesh.

Intragravel water was sampled weekly for DO concentration and temperature from PVC (polyvinyl chloride) plastic standpipes placed in the streambed at the beginning of the study (Figure 2). The standpipes were modifications of those described by Terhune (1958), Gangmark and Bakkala (1958), and Coble (1961). Five standpipes were randomly placed at each sampling site. The perforated part of the standpipe was located 150 to 200 mm into the streambed, a depth at which salmonid fish normally deposit their eggs. A DO meter with a polarographic probe and thermister was used to measure the DO concentration and temperature of surface and intragravel

TABLE 1. Physical Features of the Drainage Areas That Influence Sampling Sites of the Three Streams.

Stream	Degree of Timber Harvest	Area (hm^2)	Main Stream Channel: Length (km)	Main Stream Channel: Slope (percent)	Altitude (m): Maximum	Altitude (m): Sampling Site
Little Lost Man Creek	Unlogged	216	2.225	8.7	594	402
Lost Man Creek Tributary	Clear cut	508	3.383	10.6	457	99
Panther Creek	Patch cut	1,562	4.496	10.5	610	137

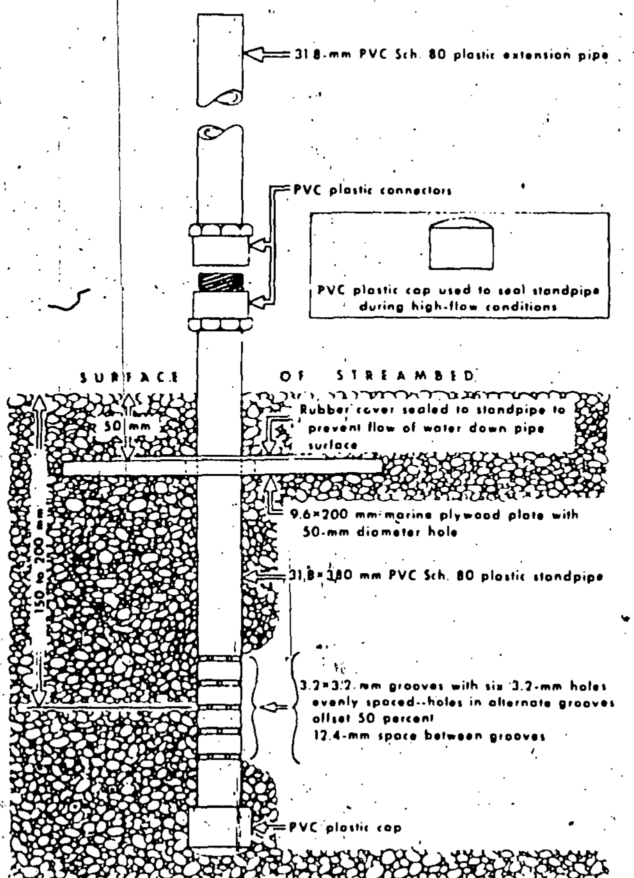

Figure 2. Standpipe, Extension, and Sealing Plate Used to Sample Intragravel Dissolved-Oxygen Concentration.

water. Only a mid-depth sample of surface DO concentration and temperature was taken weekly at each site because water depths did not exceed 460 mm. The DO meter was standardized before and after each sampling trip with the Alsterburg-Azide modification of the Winkler DO analysis (Brown, *et al.*, 1970). Percentage saturation was determined for each DO value to reduce the effects of altitude and water temperature differences among the three sampling sites. For comparisons among the three study streams, interchange of surface and intragravel water was expressed as a percentage using the equation:

$$P = \frac{I}{S} \times 100$$

where:

P = interchange percentage,

I = mean intragravel DO concentration, and

S = surface DO concentration.

Nonparametric statistical analysis was used because the data violated assumptions required for parametric testing. The Kruskal-Wallis test (Sokal and Rohlf, 1969) and a multiple-comparison test (Hollander and Wolfe, 1973) were used to test for and locate significant differences in the data for the three streams.

RESULTS

Streambed material in the Little Lost Man Creek (unlogged) and Panther Creek (patch-cut) sampling-site material ranged from boulders to silt. Small cobbles and finer materials dominated the streambed material in the Lost Man Creek Tributary (clear-cut) sampling site.

The percentage of fine streambed sediment in Little Lost Man Creek in June was significantly less than in either Lost Man Creek Tributary ($p<0.01$) or Panther Creek ($p<0.05$) (Table 2). No significant differences were found between the two streams in logged drainage basins in June. In November the percentage of fine streambed sediment in Little Lost Man Creek was significantly less than in Panther Creek ($p<0.01$).

The percentage of fine streambed sediment in Panther Creek was significantly greater ($p<0.01$) in November than in June. Streamflow eroded an unconsolidated bank upstream, and this resulted in deposition of a layer of sediment throughout the site. A week later the sediment layer had been transported downstream. Movement of sediment bars through the sampling site at Lost Man Creek Tributary also was noted, but the

TABLE 2. Mean Percentage of Streambed Sediment Finer Than 0.833 mm.

Sampling Site	June Composition			November Composition		
	Mean	Standard Error of Mean	Number of Samples	Mean	Standard Error of Mean	Number of Samples
Little Lost Man Creek	15.1	2.0	10	17.5	2.0	10
Lost Man Creek Tributary	24.7	0.5	5	26.2	2.6	5
Panther Creek	23.6	1.4	10	29.8	1.2	10

streambed composition was nearly the same at the November and June samplings.

Throughout the study, DO was at or near saturation in the surface water of the three streams. Surface DO concentrations sampled weekly at Little Lost Man Creek ranged from 9.1 to 11.4 mg/L (mean = 9.9, n = 20, where n is the number of observations); at Lost Man Creek Tributary, from 9.4 to 11.4 mg/L (mean = 10.3 n = 20); and at Panther Creek, from 9.3 to 12.3 mg/L (mean = 10.8, n = 20). Panther Creek had oxygen supersaturation in its surface water 16 of 20 times sampled and Lost Man Creek Tributary, 6 of 20 times sampled. Periphyton, identified as *Zygnema* spp., at times blanketed the sampling site in Panther Creek. Unidentified algae covered the streambed of Lost Man Creek Tributary. The sampling sites in the two logged watersheds were directly exposed to the sun because overstory vegetation had been harvested. When exposed directly to the sun, algae often produce supersaturated levels of DO during daylight hours (Reid, 1961).

In Little Lost Man Creek the weekly mean value (calculated from weekly samplings of five standpipes) for intragravel DO concentration ranged from 9.0 to 11.2 mg/L (overall mean = 9.6, n = 96) (Figure 3), and mean percentage saturation of DO of intragravel water ranged from 87.4 to 97.8 percent (overall mean = 91.7, n = 96) (Figure 4). Both concentration and percentage saturation of DO of intragravel water were lowest during October when the only flow through the sampling site was intragravel.

The weekly mean value for intragravel DO concentration in Panther Creek ranged from 6.7 to 10.2 mg/L (overall mean = 8.4, n = 100) (Figure 3) and the mean percentage saturation of DO of intragravel water ranged from 71.1 to 93.2 percent (overall mean = 80.0, n = 100) (Figure 4). The increase in the DO concentration of intragravel water during late summer was unexpected. Wickett (1958) and McNeil (1962) found that as streamflow declined intragravel DO declined. An explanation for the increase could be that intragravel DO concentration was raised by interchange with supersaturated surface water.

In Lost Man Creek Tributary the weekly mean value of intragravel DO concentration ranged from 3.2 to 7.9 mg/L (overall mean = 6.6, n = 100) (Figure 3), and mean percentage saturation of DO of intragravel water ranged from 28.7 to 76.3 (overall mean = 62.5, n = 100) (Figure 4). Intragravel DO conditions did not vary markedly at this site until the last sampling trip on November 22. At that time, which was after the initial winter storm of October 27, the mean intragravel DO concentration had fallen to 3.2 mg/L, and the mean percentage saturation of DO of intragravel water had fallen to 28.7. A reduction of interchange percentage between surface and intragravel water may have been caused by an increase in suspended-sediment concentration, evidenced by increased turbidity, and movement of fine bedload sediment that were observed on the November 22 sampling trip.

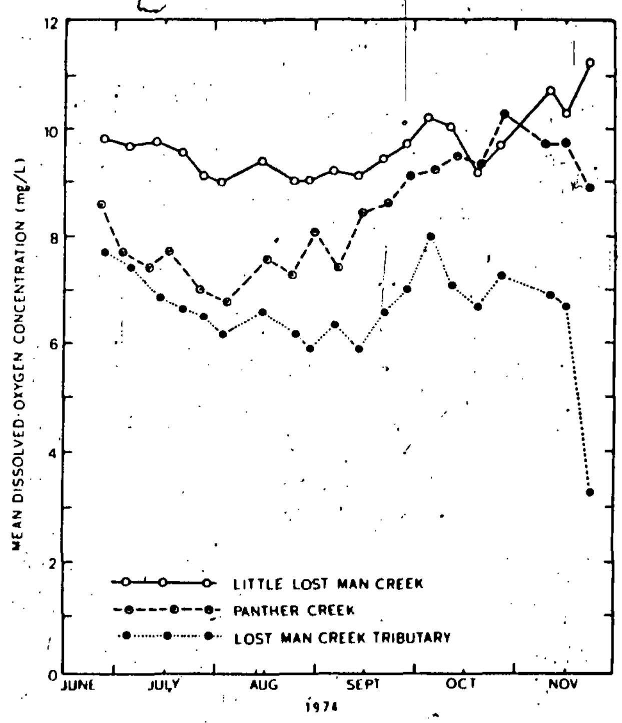

Figure 3. Weekly Mean Values of the Dissolved-Oxygen Concentration of Intragravel Water.

On a weekly basis the interchange percentage in the Little Lost Man Creek sampling site (unlogged) was higher than those in the two streams in the logged drainage basins. The weekly interchange percentage for Little Lost Man Creek ranged from 94.0 to 102.5 (mean = 97.5, n = 20), Lost Man Creek Tributary ranged from 29.0 to 79.0 (mean = 64.1, n = 20), and Panther Creek ranged from 69.0 to 84.5 (mean = 77.4, n = 20).

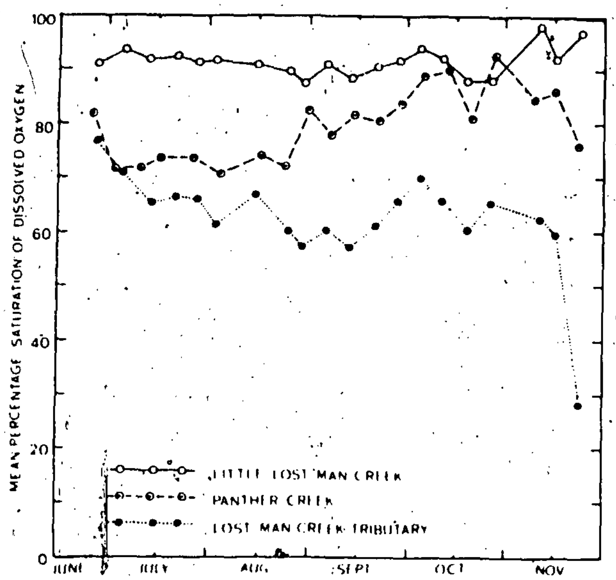

Figure 4. Weekly Mean Values of the Percentage Saturation of Dissolved-Oxygen Concentration of Intragravel Water.

The results of statistical tests used to identify significant differences in intragravel conditions among the three streams are presented in Table 3. The intragravel water in Little Lost Man Creek had, except for one case, significantly more DO and higher percentage saturation of DO than intragravel water of the two streams in logged drainage basins. The interchange percentages in Little Lost Man Creek also were significantly higher than in the logged drainage basins. Panther Creek had significantly higher values for concentration and percentage saturation of DO of intragravel water and interchange percentage than did Lost Man Creek Tributary.

Water in each of the standpipes in Little Lost Man Creek had about the same mean and range of DO concentration during the study (Table 4). In both Lost Man Creek Tributary and Panther Creek, the water in one or more standpipes had a much lower mean and range of DO concentration during the study than did water in the other standpipes. This occurred even though sampling was stratified to reduce the spatial variation of intragravel DO concentration. These results showed that the stratification of intragravel sampling sites by visual characteristics alone of the stream channel was not successful in reducing spatial variability of intragravel DO concentrations.

DISCUSSION

Differences in interchange among the three streams may be responsible for the observed differences in DO concentration and percentage saturation of DO of intragravel water. A major controlling factor on interchange of water is streambed permeability. McNeil and Ahnell (1964) found an inverse relation between streambed permeability and the percentage of streambed material finer than 0.833 mm. The percentages of fine streambed sediment in Lost Man Creek Tributary and Panther Creek were about 1½ times greater than that in Little Lost Man Creek in June. The higher interchange percentage in Little Lost Man Creek suggests a better interchange between surface and intragravel water than existed in Lost Man Creek Tributary or Panther Creek.

Intragravel DO concentrations in the Redwood Creek tributaries were similar to those found by Ringler (1970) in the Alsea Watershed Study in Oregon. In the Alsea study, the mean DO concentration of intragravel water in a stream draining a clear-cut basin was significantly less ($p<0.01$) than that in a stream draining a patch-cut basin where 30 percent of the timber had been harvested and buffer strips were retained along perennial stream channels. Ringler also reported that the mean percentage saturation of intragravel DO was 61.8 in the stream in the clear-cut drainage basin and 76.7 in the stream in the patch-cut drainage basin. In the Alsea study the DO concentration of intragravel water in the stream in the clear-cut drainage basin during logging averaged 4.2 mg/L, while during the same period a stream in a nearby unlogged drainage basin averaged 9.0 mg/L (Hall and Lantz, 1969).

TABLE 3. Comparison of Differences in Intragravel Conditions Among the Three Streams.

Site 1	Site 2	Intragravel Condition, Site 1 vs. Site 2: DO Concentration	Percentage Saturation of DO	Interchange Percentage
Little Lost Man Creek	Lost Man Creek Tributary	1 > 2*	1 > 2*	1 > 2*
Little Lost Man Creek	Panther Creek	1 > 2**	***1	1 > 2*
Panther Creek	Lost Man Creek Tributary	1 > 2*	1 > 2*	1 > 2

*Significantly different at $p<0.01$.
**Significantly different at $p<0.05$.
***Not significantly different at $p<0.05$.

TABLE 4. Dissolved Oxygen Concentration in Individual Standpipes.

Sampling Site	Standpipe Number	DO Concentration (mg/L) Mean	Standard Error of Mean	Maximum	Minimum	Number of Samples
Little Lost Man Creek	1	9.6	0.1	11.2	8.9	20
	2	9.5	0.1	11.2	8.8	20
	3	9.5	0.2	11.2	8.4	20
	4	9.8	0.1	11.2	9.0	18
	5	9.9	0.1	11.2	9.3	18
Lost Man Creek Tributary	1	2.7	0.1	4.2	1.7	20
	2	4.8	0.3	7.8	1.8	20
	3	8.0	0.3	10.0	4.1	20
	4	8.6	0.3	10.3	4.0	20
	5	8.7	0.3	10.7	3.6	20
Panther Creek	1	9.3	0.3	11.5	7.0	20
	2	8.8	0.4	11.4	6.1	20
	3	10.5	0.2	11.8	9.0	20
	4	10.0	0.2	11.5	8.5	20
	5	3.3	0.3	5.0	1.0	20

These intragravel DO measurements were not made during the wintertime incubation of salmonid eggs and alevins, but some speculation is possible regarding the quality of intragravel water that such eggs and alevins might encounter. The mean DO concentrations provide an indication of the relative quality of intragravel water among the three streams, but minimum DO concentrations of intragravel water are more important criteria for assessing the survival of salmonid eggs and alevins.

The U.S. Environmental Protection Agency (National Academy of Sciences, National Academy of Engineering, 1973) has established levels of protection for DO for aquatic organisms based on the premise that any reduction of DO below natural, seasonal levels may reduce the ability of an aquatic organism to meet the demands of its environment. Assuming 10 mg/l as a minimum DO concentration of intragravel water in the winter in an undisturbed stream, such as Little Lost Man Creek, and using the criterion formula suggested (National Academy of Sciences, National Academy of Engineering, 1973, p. 134), a "high level" of protection would be provided salmonid eggs if DO concentrations did not fall below 8.2 mg/L. It is apparent from Figure 3 that mean intragravel DO concentrations in Little Lost Man Creek were moving upward with the approach of winter. This trend would probably continue because the stream water DO would rise as the temperature dropped, providing a better source of DO to the intragravel environment. In Panther Creek the mean intragravel DO peaked in October and moved downward through the remainder of the study. This trend may have been arrested by increasing DO concentrations in the stream as winter approached, so that the intragravel DO did not fall below 8.2 mg/L. Lost Man Creek Tributary was difficult to assess because of the sudden reduction in intragravel DO concentration recorded on the last sampling trip. Before that trip three of the five standpipes would have been expected to contain suitable DO concentrations during the winter. It was not determined whether this reduction in intragravel DO concentration lasted throughout the winter, but such an occurrence would lessen the suitability of this stream as spawning habitat for salmonids. Panther Creek also might have sudden reductions in intragravel DO concentrations, even lethal concentrations, because of the movement of sediment bars observed in that stream.

This study showed that the two streams in the logged drainage basins contained intragravel water with lower DO concentrations than did intragravel water in the stream in the unlogged drainage basin. These differences in intragravel DO concentration are attributed to the greater ability of the stream in the unlogged drainage basin to interchange surface and intragravel water. The stream in the unlogged drainage basin was projected to have higher and more spatially uniform intragravel DO concentrations in the winter and would therefore provide more suitable conditions for the incubation of salmonid eggs and alevins than would the two streams in the logged drainage basins.

Differences in the lithology of the three drainage basins may have contributed to the differences in the percentages of fine sediments observed among the streams; even in the absence of logging.

LITERATURE CITED

Alexander, E., W. Colwell, J. Delapp, E. Cladish, R. Nelson, R. Skoleman, and B. Smith, 1959-62. Humboldt County Soil-Vegetation Survey. U.S. Forest Service, Pacific Southwest Forest and Range Experiment Station, 16 maps, scale 1:31,680.

Brown, Eugene, M. W. Skougstad, and M. J. Fishman, 1970. Methods for Collection and Analysis of Water Samples for Dissolved Minerals and Gases. U.S. Geological Survey Techniques of Water Resources Investigations, Book 5, Chapter A1, 160 pp.

California State Water Resources Control Board, 1973. A Method for Regulating Timber Harvest and Road Construction Activity for Water Quality Protection in Northern California, Volume I.
Coble, D. W., 1961. Influence of Water Exchange and Dissolved Oxygen in Redds on the Survival of Steelhead Trout Embryos. Transactions of the American Fisheries Society 90:469-474.
Cooper, A. C., 1965. The Effect of Transported Stream Sediments on the Survival of Sockeye and Pink Salmon Eggs and Alevins. International Pacific Salmon Commission Bulletin 18, 71 pp.
Elford, R. C. and M. R. McDonough, 1964. The Climate of Humboldt and Del Norte Counties. University of California, Agriculture Extension Service, Eureka, California, 34 pp.
Gangmark, H. A. and R. G. Bakkala, 1958. Plastic Standpipe for Sampling Streambed Environment of Salmon Species. U.S. Fish and Wildlife Service, Special Scientific Report - Fisheries, No. 261, 21 pp.
Hall, J. D. and R. L. Lantz, 1969. The effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. *In:* Symposium on Salmon and Trout in Streams, H. R. MacMillan Lectures in Fisheries, T. G. Northcote, Editor, British Columbia University, Vancouver, British Columbia, pp. 355-375.
Hollander, M. and D. A. Wolfe, 1973. Nonparametric Statistical Methods. John Wiley and Sons, New York, New York, 503 pp.
Janda, R. J., K. M. Nolan, D. R. Harden, and S. M. Colman, 1975. Watershed Conditions in the Drainage Basin of Redwood Creek, Humboldt County, California, as of 1973. U.S. Geological Survey Open-File Report 75-568, 266 pp.
McNeil, W. J., 1962. Variations in the Dissolved Oxygen Content of Intragravel Water in Four Spawning Streams of Southeastern Alaska. U.S. Fish and Wildlife Service, Special Scientific Report – Fisheries, No. 402, 15 pp.
McNeil, W. J. and W. H. Ahnell, 1964. Success of Pink Salmon Spawning Relative to Size of Spawning Bed Materials. U.S. Fish and Wildlife Service, Special Scientific Report – Fisheries, No. 469, 15 pp.
National Academy of Sciences, National Academy of Engineering, 1973 (1974). Water Quality Criteria 1972. U.S. Government Printing Office, Washington, D.C., 594 pp.
Reid, G. K., 1961. Ecology of Inland Waters and Estuaries. Van Nostrand Reinhold Co., New York, New York, 375 pp.
Ringler, N. H., 1970. Effects of Logging of the Spawning Bed Environment in Two Oregon Coastal Streams. Unpublished M.S. Thesis. Oregon State University, Corvallis, Oregon, 96 pp.
Sheridan, W. L., 1962. Waterflow Through a Salmon Spawning Riffle in Southeastern Alaska. U.S. Fish and Wildlife Service, Special Scientific Report – Fisheries, No. 407, 20 pp.
Shumway, D. L., C. E. Warren, and P. Doudoroff, 1964. Influence of Oxygen Concentration and Water Movement on the Growth of Steelhead Trout and Coho Salmon Embryos. Transactions of the American Fisheries Society 93(4):342-356.
Sokal, R. R. and F. J. Rohlf, 1969. Biometry. W. H. Freeman and Co., San Francisco, California, 776 pp.
Terhune, L. D. B., 1958. The Mark VI Groundwater Standpipe for Measuring Seepage Through Salmon Spawning Gravel. Fisheries Research Board of Canada Journal 15(5):1027-1063.
Vaux, W. F., 1962. Interchange of Stream and Intragravel Water in a Salmon Spawning Riffle. U.S. Fish and Wildlife Service, Special Scientific Report – Fisheries, No. 405, 11 pp.
Vaux, W. F., 1968. Intragravel Flow and Interchange of Water in a Streambed. U.S. Fish and Wildlife Service, Fisheries Bulletin 66: 479-489.
Wickett, W. P., 1958. Review of Certain Environmental Factors Affecting the Production of Pink and Chum Salmon. Fisheries Research Board of Canada Journal 15:1103-1126.