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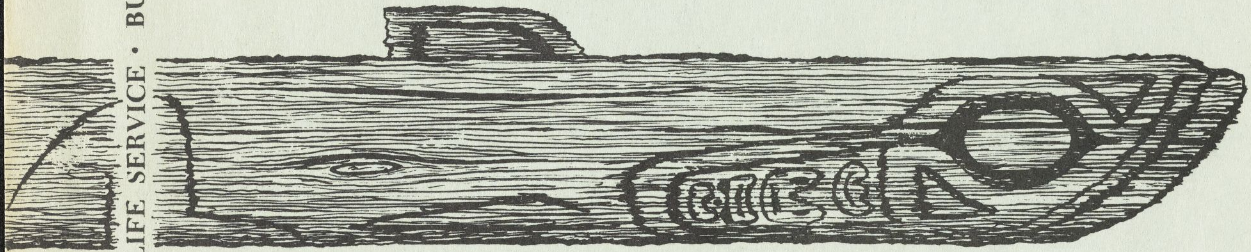

STATUS OF RESEARCH ON THE IMPROVEMENT OF SALMON SPAWNING BEDS IN ALASKA

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STATUS OF RESEARCH ON THE IMPROVEMENT OF SALMON SPAWNING BEDS IN ALASKA[1]

by

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INTRODUCTION

Research on factors limiting production of salmon fry from spawning beds has progressed rapidly in recent years, and a number of environmental attributes that account for a large fraction of the total mortality in spawning beds have been identified. Given an environment free of mechanical disturbances, the growth, development, and survival of a salmon embryo or larva is largely dependent upon physical and chemical characteristics of the surrounding water. Properties of water that affect eggs and larvae include temperature, dissolved oxygen content, velocity, mineral and waste metabolite content, and osmotic pressure.

The first criterion of a productive spawning bed is a high degree of stability, for without stability even the more permeable gravels capable of delivering high quality water to an embryo or larva will often fail to produce significant numbers of fry. Improvements designed to provide increased production of salmon fry from a stable spawning bed can be considered to fall into two general categories. In the first category are improvements designed to protect eggs and larvae from mortality causes related to variations in meteorological conditions (viz, freezing and dehydration). Improvements included in this category may have only a minor influence on the potential number of fry produced per unit area, since no attempt is made to improve the quality of water within the spawning bed. In the second category are improvements designed to increase the potential capacity of a unit area of spawning bed to produce fry by altering the composition of bottom materials or by other physical treatments that would increase interchange between stream

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[1] Paper presented at the Second Governor's Salmon Conference convening at the Hyatt House Hotel, Seattle-Tacoma Airport, January 7-10, 1963.

and intragravel water[2] and to increase circulation of water within the spawning bed. Improvements included in the second category are designed to create conditions favorable for the production of large numbers of fry per unit area by increasing the oxygen delivery rate to eggs and larvae. Ideally, both categories of improvements should be included in endeavors to increase fry production from spawning beds.

ROLE OF IMPROVED SPAWNING AREAS IN ALASKA

Before an expenditure of research effort on problems related to the improvement of spawning grounds can be fully justified, it must be determined that mortality during egg and larval stages commonly limits the abundance of a salmon stock. Particularly with king (Oncorhynchus tshawytscha) and coho salmon (O. kisutch) in Alaska, mortality in the spawning bed may be secondary in importance to mortality in the fresh-water nursery areas and thus may not be limiting. The same argument may pertain to many sockeye salmon (O. nerka) stocks; but with pink (O. gorbuscha) and chum salmon (O. keta), there is good evidence that mortality occurring in the spawning beds influences overall production significantly.

In the shorter streams of coastal British Columbia and Alaska, mortality of pink and chum salmon during spawning, egg incubation, and larval development commonly exceeds 70 percent. By way of example, total fresh-water mortality of pink salmon of the 1961 brood year at Sashin Creek[3] was among the lowest recorded (79 percent); but mortality between time of spawning and fry emergence was at least 74 percent, leaving a relatively minor fraction of total deaths in fresh water to occur outside of the spawning bed. The results of studies in other streams also show that most deaths occur within the spawning bed. Hunter (1959) found mortality of pink and chum salmon during spawning and development to vary between 69 and 94 percent in Hooknose Creek, British Columbia, McNeil (1962) seldom observed a mortality of less than 70 percent but frequently observed mortalities in excess of 90 percent to the preemergent fry stage in three streams near Ketchikan.

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[2] The term "intragravel water" is used to describe water occupying interstitial spaces within the spawning bed,

[3] Sashin Creek is located near Little Port Walter on Baranof Island, Southeastern Alaska.

There is good evidence that fry production is the primary factor limiting the abundance of pink and chum salmon spawning in the shorter coastal streams of British Columbia and Alaska. I have examined the relationship between the number of pink salmon fry produced and adults returning per square meter of spawning ground in Hooknose and Sashin Creeks and find that a highly significant positive correlation exists between these two variables. By pooling data from these two streams, the value of the correlation coefficient, r, is 0.69 (28 degrees of freedom). From this it is concluded that the number of adults produced is dependent to a large degree upon the number of fry going to sea.

It is instructive also to examine the relationship between the potential number of eggs deposited per square meter and the number of fry produced per square meter. The pooled data for Hooknose and Sashin Creek pink salmon stocks give: $r=0.05$ (28 degrees of freedom). This low value of r suggests that mortality in fresh water is highly variable and unpredictable. We must avoid drawing the illogical conclusion, however, that low escapements have the potential of producing large numbers of fry, for it is apparent from inspection of the data that a minimum density of spawners is required to maintain the reproductive potential at a level capable of producing a surplus of adults for harvest. On the other hand, a large escapement of adults does not guarantee good fry production.

Because mortality is highly variable in spawning beds, production of pink and chum salmon will remain highly unstable as long as fry production remains uncontrolled. Although there is an unquestioned need to regulate the fishery to obtain an "optimum density" of adults on the spawning bed, we cannot be assured that such regulation will materially stabilize the catch. Proper regulation would undoubtedly increase the frequency of occurrence of large runs, but we will somehow need to create a greater degree of stability in the number of fry produced before the fishery can be expected to be maintained at a relatively stable level. For this reason we need to consider very carefully the possibilities of improving large areas of spawning ground to help insure a continued high level of output of pink and chum salmon fry.

In 1961, the Fisheries Research Institute, University of Washington, initiated studies on the improvement of natural spawning areas in streams located on Prince of Wales Island about 40 miles west of Ketchikan. The most significant contributions of these studies to date have been the development and evaluation of an improved spawning channel and the initiation of research to determine the feasibility of removing fine sands and silts from otherwise unaltered spawning grounds.

CURRENT RESEARCH ON IMPROVED SPAWNING AREAS

Research by the Fisheries Research Institute on improved spawning areas in Alaska for pink and chum salmon is currently being done in Indian Creek and Harris River. These streams have an intertidal confluence and share a common estuary. The work has been supported by the U.S. Forest Service, the U.S. Bureau of Commercial Fisheries, the Ketchikan Pulp Company, the Alaska Department of Fish and Game, and the Institute of Forest Products.

Indian Creek Improved Spawning Channel

The Indian Creek channel was constructed to test the feasibility of providing a low-flow channel for spawning and fry production in conjunction with a broad flood plain for minimizing velocities during high discharges. Purpose of the flood plain is to maintain stable conditions within the spawning bed during flooding without constructing costly flow-control structures; hence, no means of regulating the naturally occurring discharges have been incorporated into the design. It was recognized, however, that the channel would require periodic maintenance; and the channel has proved to be unstable in years of exceptionally high run-off.

Description of the Natural Stream

The Indian Creek watershed encompasses 8.6 square miles (James, 1956). Average stream gradient in sections utilized for spawning by pink salmon is about 0.5 percent, and the stream is characterized by extreme fluctuations in flow. During the September spawning period, discharge commonly varies between 5 and 300 c.f.s. Average daily discharge during autumn storms approaches 900 c.f.s. some years, and a peak instantaneous discharge of 6,400 c.f.s. was recorded in autumn 1961, soon after completion of the spawning channel. Nevertheless, peak discharges vary between 1,500 and 2,000 c.f.s. most years. The lowest recorded discharge is 4 c.f.s., but between spawning and fry emergence minimum discharges are normally 5 c.f.s. or greater.

Because of scouring during the frequent floods that occur in Indian Creek, bottom materials are relatively coarse and contain much gravel and rubble between 2 and 6 inches in diameter. The bottom materials are fairly permeable and offer generally favorable conditions for eggs and larvae with regard to the oxygen delivery rate. Losses due to flooding and freezing appear to be major factors depressing fry production in Indian Creek.

Mostly pink salmon spawn in Indian Creek, primarily in an intertidal section one-fourth of a mile long beginning at the confluence with Harris River. This was the section selected for constructing the channel. In the 4 years preceding construction of the improved channel, spawning densities in the natural stream varied from about 0.05 to 0.46 female pink salmon per square meter of spawning bed (potential egg deposition varied between 85 and 780 per square meter), and fry production varied between 20 and 80 fry per square meter.

Description of the Improved Channel

Outstanding features of the improved channel are the flood plain and the low-flow spawning channel, which is located in the center of the flood plain. Figure 1 shows a view of the channel shortly after its completion in 1961. A settling pool for intercepting bed-load materials was also constructed at the head of the channel.

The low-flow channel is designed to provide nearly 6 inches of water flowing nearly 1-foot per second at a discharge of 5 c.f.s. Bottom width of the low-flow channel is 15 feet, and the spawning bed is depressed about 18 inches below the flood-plain surface. Total available spawning area is about 1,800 square meters. This represents a 50-percent reduction in the area available for spawning before the channel was constructed. This decrease in area was required to obtain more favorable flows over the spawning bed during periods of low discharge. Gradient of the channel is 0.4 percent, and water spills onto the flood plain at discharges in excess of 150 c.f.s.

The boundaries of the flood plain lie 40 feet on either side of the center line in the upstream 400-foot section and 50 feet on either side of the center line in the lower 800-foot section. An evaluation of the hydraulic characteristics of the channel indicated that the channel would withstand discharge of at least 1,000 c.f.s. without suffering damage from bed-load movement.[4]

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[4] Nece, Ronald E. 1961. Hydraulic design and construction details of salmon spawning channel improvement areas on Indian Creek and Harris River. University of Washington, Fisheries Research Institute, Circular No. 145, 4 p., 5 figs. (Processed).

Figure 1.--Indian Creek channel, looking downstream toward the confluence with Harris River. Discharge was about 20 c.f.s. when this photo was taken.

Performance of the Channel

The Indian Creek channel is now in its second year of operation. Its performance in conjunction with 1961 and 1962 brood year pink salmon will be reviewed briefly. Much of the data given below were obtained from unpublished Fisheries Research Institute project reports or from personal communication with Institute scientists participating in the study.

Pink salmon spawned in the channel throughout September 1961. The average density of pink salmon females spawning was estimated to be 1.46 per square meter, giving a potential egg deposition of nearly 2,500 per square meter. This was nearly three times greater than densities observed in years before the channel was constructed. The improved spawning area was an unqualified success with regard to utilization by adults. It was occupied by adults over a range of discharges between 5 and 1,000 c.f.s. Redd digging in the low-flow channel was observed to occur at discharges between 5 and 150 c.f.s. A small fraction (less than 10 percent) of the females spawned on the flood plain at times when discharges exceeded 150 c.f.s. Also, some damage was caused to the lower 200-foot section of channel by fish undermining unprotected banks of the low-flow channel, nearly doubling its original width. Channel banks further upstream were protected with a layer of rubble and suffered only slight damage during spawning.

After spawning had terminated, stability of the channel was given severe tests during two October floods. The first occurred October 3, 1961, and delivered 2,700 c.f.s. into the channel. This flood filled the settling pool at the head of the channel with bed-load materials and caused damage to the low-flow spawning channel. Before the damage was thoroughly assessed, a flood on October 13 delivered 6,400 c.f.s. into the channel. This was the highest discharge recorded for Indian Creek in the 11 years for which records were available. Much bed load was transported during this exceptional flood and deposited over the spawning bed. The flood caused 12 to 18 inches of gravel to be deposited over the 1,200-foot length of the low-flow spawning channel.

Because of this overburden, it was not possible to obtain satisfactory quantitative estimates of the abundance of surviving eggs or larvae. At the beginning of hatching, in mid-November, it was estimated, however, that 94 percent of the eggs present in the channel at the time of sampling were still alive. In May 1962, just prior to emergence, sizable numbers of live fry were found at depths of 18 to 24 inches in the gravel; but it was estimated that only about 12 percent of them emerged (Bevan, in press).

Materials carried into the settling pool and low-flow channel during October 1961, were removed during reconstruction of the channel in June 1962, and the channel was returned to its basic 1961 configuration. However, bottom materials were not resorted, and baffle boards dislodged in reconstructing the low-flow channel were not replaced in 1962.

Total escapement of pink salmon into Indian Creek in 1962 was about three times greater than in 1961. An estimated 4.40 female pink salmon spawned per square meter in the improved channel, giving a potential egg deposition of nearly 7,500 per square meter. This was far in excess of the spawning density observed in any previous year and at least 1 1/2 times greater than was observed in unmodified spawning areas in Indian Creek or Harris River. The densities of spawners observed in both 1961 and 1962 suggest the possibility that adult females may have been attracted to the channel.

In contrast to 1961, the channel was undamaged by flooding in 1962. Total mortality to hatching was estimated to be 90 percent, and in early December 1962, the population of surviving eggs and larvae was estimated to be 700 per square meter. Observations are being continued by Fisheries Research Institute scientists to evaluate winter mortality and to estimate the number of fry produced in spring 1963.

Harris River Improved Spawning Area

In 1961, an experiment was conducted in an intertidal spawning area of Harris River to evaluate the effect of removal of fine sands and silts on pink salmon fry production. The quality of the spawning bed was improved over a 1,400-square-meter area by hydraulic flushing. Potential egg deposition in the area was estimated to be about 900 per square meter after the fine materials had been removed. It was estimated that 50 percent of these eggs survived to hatch (452 per square meter), but high mortality of larvae reduced the estimated fry yield to less than 1 per square meter.

Samples of bottom materials were collected from the improved area in spring and summer 1962, revealing that fine sands and silts had reentered the area flushed in 1961. There is a possibility that the highly successful hatch in the improved area occurred primarily as a result of removing fine materials from the spawning bed, but that the subsequent high mortality of larvae was partly a result of resilting that may have occurred during autumn 1961 flooding. Although the results of this experiment were inconclusive, they pointed out the need to continue this line of experimentation.

FUTURE RESEARCH

Research on spawning channels and improved spawning areas is still in its infancy. Problems requiring solution will involve much additional basic study of spawning behavior, genetic makeup of stocks, physiology of embryos and larvae, population dynamics of stocks, and physical characteristics of spawning beds. There is also a wide variety of applied research problems growing out of studies to improve spawning areas.

Some Required Basic Research

To be effective an improved spawning area must be attractive to adult spawners, for underutilization of an improved area could render it relatively ineffective. There is a pressing need to understand the factors causing female salmon to select their redd sites, especially where the density of spawners varies over a wide range. There is also a need to study mortality associated with spawning and its relationship to density of spawners, hydraulic characteristics of the stream, and composition of bottom materials.

In some streams spawning occurs over a period of more than 2 months. As a consequence, eggs and larvae of early- and late-spawning adults are subjected to environmental stresses that differ greatly at particular stages of their development. This suggests some interesting questions on how the viability of embryonic and larval salmon might relate to genetic factors. It is likely that many pertinent problems are as yet undefined in this area.

Genetic composition of salmon stocks is of utmost importance where transplantations are attempted. Because of the numerous, unresolved problems involving transplantations (particularly of pink and chum salmon), work on improving spawning grounds should be undertaken initially in streams having adequate spawning stocks.

Physiological stresses affecting embryonic and larval salmon have received more attention in recent years than most other basic problems. One outstanding need in this area is to gain a better understanding of the stresses imposed by a number of interacting environmental factors. For example, it is important to study the effect of oxygen content on metabolic activity, but of far greater importance is an understanding of the effect of oxygen level in conjunction with other factors such as waste metabolites, temperature, flow velocity, and salinity. There is also a need to explore relationships between embryonic growth and viability of larvae and fry.

The dynamics of salmon populations are as yet poorly understood. A number of theoretical models have been proposed, but there is a need to pursue research on questions related to (1) mortality during spawning and egg recruitment to spawning beds, (2) the evaluation of density-dependent and nondensity-dependent mortality factors, and (3) the shape of curves relating potential egg deposition to fry production. Such questions pertain directly to the efficacy of improved spawning areas.

A broad range of basic problems related to a better understanding of siltation and stability of salmon spawning beds requires further investigation. For example, the movement and deposition of suspended and bed-load materials in salmon spawning grounds require much further study. Also, at present we can only crudely approximate the energies developed by turbulent water and the velocities required to cause gravels to shift.

Applied Studies

The type of spawning channel being tested in Indian Creek would appear to be feasible for streams having a less variable runoff than Indian Creek. In fact, for its less than 9 square miles of watershed, Indian Creek possibly has a more variable discharge pattern than most streams in Southeastern Alaska. It is partly for this reason that the Indian Creek study should be continued for a number of years to thoroughly evaluate the stability of this particular channel design and to obtain further information on spawning behavior and survival of eggs, larvae, and fry. Additionally, there is a need to construct spawning channels like the one on Indian Creek on a few streams having less variable runoff. The immediate need for new channels is to obtain a more comprehensive evaluation of the fry production potential of channels of this type and to determine more fully their possible application.

The development of suitable methods of sorting bottom materials to remove fine sands and silts is one of the major applied problems in the area of spawning ground improvement. High priority should be given to the development of mobile equipment for accomplishing this task.

Another area of applied research that should be pursued is the testing of various kinds of improved gravels on intragravel water quality and fry production. There is also a need to continue research on possible applications of baffle boards and other devices for improving interchange between stream and intragravel water.

PLANNED PROGRAMS

Organizations in Alaska presently participating in research on basic or applied problems pertinent to the question of spawning bed improvement include the Fisheries Research Institute, University of Washington; U. S. Bureau of Commercial Fisheries; U. S. Forest Service; Ketchikan Pulp Company; the Alaska Department of Fish and Game; and the Institute of Forest Products. An important feature of the Forest Service's watershed management program is the development of improved spawning areas. The Ketchikan Pulp Company has cooperated very closely with the Forest Service and the Fisheries Research Institute in this endeavor to insure against delay of research programs because of construction difficulties. The Bureau of Commercial Fisheries and the Institute of Forest Products are providing financial support for certain studies undertaken by the Fisheries Research Institute, and scientific personnel of the Auke Bay Biological Laboratory are presently investigating a number of problems which should provide answers to problems important to spawning bed improvements.

The Forest Service plans to expand its program of pilot studies on spawning bed improvement in 1963. Four streams located near Ketchikan have been selected as possible sites for channels like the Indian Creek channel. Present plans call for the construction of one channel in 1963 or 1964. Consideration is also being given to the construction of an improved spawning area in Olsen Bay Creek, Prince William Sound. Evaluation of this area would be made by Bureau of Commercial Fisheries scientists presently studying Olsen Bay Creek.

Current feasibility studies include one by the Forest Service to design mobile equipment for the removal of fine sands and silts from spawning beds and one by the Bureau of Commercial Fisheries to establish a test stream for evaluating the effect of bottom composition on fry production. The Alaska Department of Fish and Game has completed preliminary studies on the utilization by pink salmon of spawning ponds with upwelling water. State biologists plan to continue these studies on a larger scale.

In conclusion, I wish to emphasize that improvements of habitat for spawning and fry production must be thoroughly evaluated to determine their economic feasibility. Furthermore, a maximum benefit will be realized from the pilot studies being undertaken by the Forest Service and the Forest Products Industry in Alaska only if basic and applied research on the many problems pertinent to spawning bed improvement are pursued with vigor.

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INTERTIDAL SPAWNING OF PINK AND CHUM SALMON AT OLSEN BAY, PRINCE WILLIAM SOUND, ALASKA

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AUKE BAY, ALASKA

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INTERTIDAL SPAWNING OF PINK AND CHUM SALMON AT OLSEN BAY, PRINCE WILLIAM SOUND, ALASKA

by

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ABSTRACT

Large numbers of spawning salmon were observed on the Olsen Creek intertidal spawning grounds from 1960 to 1962. Pink salmon spawned as far downstream as the 1-foot tide level, but eggs deposited below the 4-foot level did not survive over winter. Chum salmon spawned slightly below the 6-foot tide level and at higher locations, but none of the eggs deposited below the 6-foot tide level survived. Survival of embryos was generally better at higher elevations of the intertidal zone except at the 8- to 10-foot stratum where mortality was high because of oxygen deprivation. Potential densities calculated for one intertidal riffle were 8,413 pink salmon eggs per square meter plus 5,000 chum salmon eggs per square meter. Actual egg densities of approximately 4,000 pink salmon plus 1,500 chum salmon per square meter were deposited by 3.0 pink salmon females per square meter and 1.3 chum salmon females per square meter. Additional spawning by 1.6 pink salmon females and 0.7 chum salmon female per square meter did not add to the egg population. Presumably, the egg capacity of the riffle had been reached, and superimposition of redds merely resulted in loss of earlier eggs. This interpretation was supported by the fact that observed fry densities in October samples were less than one-tenth of the predicted densities, which were based on the known rate of development of embryos in the riffle. Retention of eggs by females that died before completing spawning was an important mortality factor for a short period after a density of 1.85 adult salmon per square meter was observed.

INTRODUCTION

The importance of intertidal spawning of pink salmon (Oncorhynchus gorbuscha) in Prince William Sound, Alaska, has been documented by Noerenberg[1] for more than 200 streams in that area. Noerenberg reported that each year during the period 1952-61 about 50 percent of the odd-year spawners and about 75 percent of the even-year spawners utilized areas below mean high tide.

Investigations of intertidal spawning by pink salmon began in the early 1950's when Hanavan (1954) reported that pink salmon spawn in large numbers in some intertidal areas of Southeastern Alaska streams and suggested that warm tidewater may modify conditions to enhance survival. Rockwell (1956) noted that intertidal spawning does occur and demonstrated by laboratory experiments that mild sea water was beneficial to survival, growth, and activity of pink and chum salmon larvae. Fry enumeration studies conducted from 1957 through 1959 in certain Prince William Sound streams, including Olsen Creek, were reported by Kirkwood (1962) and by Tait and Kirkwood (1962). Conkle[2] outlined the timing and spatial distribution of the Olsen Bay escapements and indicated that survival rates of eggs and larvae varied with tide level.

A field research station for the study of pink salmon production in the intertidal environment was established by the Bureau of Commercial Fisheries on Olsen Creek, Olsen Bay, Prince William Sound, during the summer of 1960. During the first 2 years, the general features of the intertidal environment were investigated. Streamflows, water temperatures, salinity, and dissolved oxygen patterns were related to tides; the magnitude, timing, and spatial distribution of the adult runs were assessed; and survival of salmon eggs and larvae were measured (Helle, Williamson, and Bailey, in press).

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[1] Wallace A. Noerenberg. 1963. Salmon forecast studies on 1963 runs in Prince William Sound. Informational Leaflet 21, Alaska Department of Fish and Game, 17 p. plus appendix.

[2] Charles Y. Conkle. Temporal and spatial relationships of spawning pink salmon in a Prince William Sound stream. Paper read at the Twelfth Alaskan Science Conference, College, Alaska, 1961. On file Bureau of Commercial Fisheries Biological Laboratory, Auke Bay, Alaska.

This paper is concerned with observations from 1960 to 1962 of pink and chum (O. keta) salmon reproduction in the Olsen Bay intertidal zone. The observations are discussed in two sections. The first, "Utilization of the Intertidal Zone," is concerned with the entire intertidal spawning ground from the 3- to the 12-foot tide level. The major topics of this section are timing, magnitude, and spatial distribution of the escapements; selection of spawning area in relation to tidewater; riffle life; and sex ratios. The second section, "Spawning Efficiency," reports an intensive study of high density spawning on a single riffle in the upper intertidal zone between the 10- and 11-foot tide levels (figs. 1 and 2)

Both species utilized the study riffle in relatively large numbers. Cumulative densities by the end of the spawning period were 4.6 pink salmon females and 2.0 chum salmon females per square meter.

In studies of pink salmon production in fresh-water streams of Southeastern Alaska, McNeil (1962a) did not observe such high densities of spawning salmon but postulated that the egg capacity of a spawning bed is limited by superimposition; that is, when densities of spawners are high, late spawners dislodge previously deposited eggs. Therefore, an investigation of egg deposition in relation to density of spawners was a logical approach to an understanding of factors controlling intertidal salmon production.

At flow discharges of approximately 40 c.f.s., the study riffle had a total area of 1,350 $m.^2$ (14.3 m. X 94.2 m.). Although the actual area available to spawners varied somewhat with volume of flow, this estimate was used for all calculations of egg and adult densities per unit area.

A continuous record of intragravel water temperature at redd depth was obtained from a filled system recording thermograph between July 7 and October 15, 1962, and from a mercury in glass recording thermograph between October 20, 1962, and March 12, 1963. The temperature sensors were buried about 8 inches deep near the center of the stream. The greatest 24-hour fluctuation in intragravel water temperature was 2.2° C., recorded on several occasions with an influx of tidewater. Mean daily temperature was 8° C. on July 7, 1962, rising gradually to the summer maximum of 10° C. on August 14, 1962, and falling gradually to 4° C. by October 5, 1962. Cooling continued,

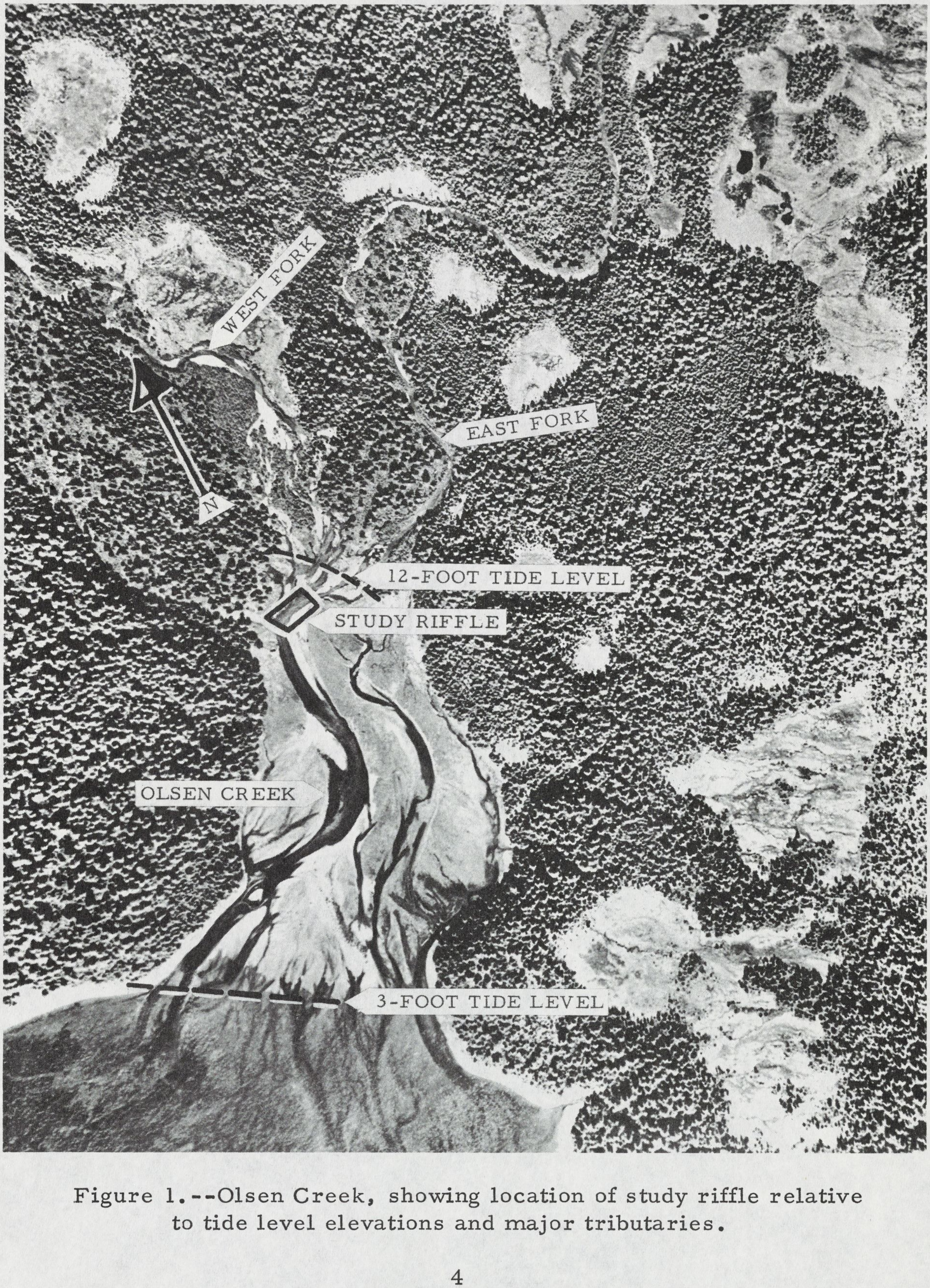

Figure 1.--Olsen Creek, showing location of study riffle relative to tide level elevations and major tributaries.

Figure 2.--Pink salmon spawning on study riffle at Olsen Creek, August 1961.

and the temperature was near 0° C. during December and January. By March 12, 1963, just before fry emergence, it had warmed to 1° C.

Helle et al. (in press) found that salt-water intrusions could be detected at the 10- to 11-foot tide level during 13-foot or higher tides. The maximum salinity recorded at the 11-foot tide level was 9.3 $^{o}/oo$ at the gravel surface during a 14.5-foot tide. Intragravel water samples were generally higher in salinity than gravel surface water samples taken simultaneously. On the basis of calculations from the 1961 tidal reference data (U.S. Department of Commerce, 1961), the riffle at the 10- to 11-foot tide level was inundated by tidewater during approximately 10 percent of the spawning season (July through September).

STUDY AREA AND METHODS

Olsen Creek is located on the eastern side of Prince William Sound. It has two major tributaries, East Fork and West Fork, each of which drains approximately 9 square miles of precipitous rocky terrain, which is covered by coniferous and alder forest and muskeg. The two forks merge at the 11-foot tide level (fig. 1). Annual precipitation amounts to about 100 inches. A rain gage installed near the stream mouth from July 1 to September 30 (the main spawning period) recorded rainfall of 32, 30, and 19 inches in 1960, 1961, and 1962 respectively.

While the low flow discharge of Olsen Creek is about 40 c.f.s., freshets of three to five times this volume occur frequently. Maximum high tides at Olsen Bay are about 15.5 feet. Because of the infrequent and dilute character of salt-water intrusions at the higher levels, I have considered the 12-foot tide level (mean high tide) as the arbitrary dividing line between intertidal and fresh-water habitats.

Four observation towers between 5 and 8 meters high were erected near the riffle to facilitate observation of salmon. Spawning pink and chum salmon were counted every third day. Pink salmon were tallied separately by sex, but chum salmon males and females were not readily distinguishable, and it was assumed the sexes were evenly divided. During the first counts, an attempt was made to count only salmon that were identifiable as spawners by virtue of their actions in relation to a visible redd. Thus, in the early counts not all salmon on the riffle were tallied. After several such counts, it became obvious that this distinction could not be made because of the high density of fish; also, later analysis of the data proved the distinction invalid because the first few counts appeared to show the females depositing more than their potential complement of eggs. During the remainder of the season, all females on the riffle were assumed to be spawners.

To convert the counts made from the towers to an estimate of the actual number of females that spawned on the riffle, it was necessary to obtain a measure of the average number of days the females lived after taking up a position on the riffle (riffle life). Thus, total days of spawning effort observed from the towers could be divided by the average riffle life to estimate the number of females that spawned on the riffle (McNeil, 1962a).

Egg and larval densities, which are expressed as number per square meter of area, were estimated by sampling randomly selected points with a hydraulic egg pump. A circular frame enclosing an 0.2 $m.^2$ area was used to collect the eggs or larve as they were pumped from the streambed. Egg densities were determined every 2 weeks during the 1962 spawning season, except for an interval of 4 weeks between the last two samples of the season.

Plastic hatching boxes of the type described by Gangmark and Broad (1956) were filled with artificially fertilized pink salmon eggs and buried in the gravel near the center of the riffle on July 27, 1962. Egg boxes taken from the riffle at 2-week intervals provided known age eggs that were used to determine rate of development and time to hatching of pink salmon embryos in this riffle.

Dissolved oxygen content of intragravel water was determined by semimicro Winkler analyses of samples drawn from plastic standpipes. The plastic standpipes and collection apparatus were similar to those described by McNeil (1962b).

UTILIZATION OF THE INTERTIDAL ZONE

Timing, Magnitude, and Spatial Distribution of the Escapements

Chum salmon began spawning in Olsen Creek about June 20 and pink salmon about July 4. The last individuals of both species generally disappeared about October 1, although pink salmon far outnumbered chum salmon during the last 2 or 3 weeks each year.

Helle et al. (in press) estimated the 1960 and 1961 salmon escapements at Olsen Creek and described their timing and spatial distribution in the spawning area. The pink salmon escapements totaled 98,574 in 1960 and 135,905 in 1961, 74 percent spawning in the intertidal zone both years. The 1962 escapement comprised 135,459 adults of which 76 percent spawned in the intertidal zone. The even-year runs, 1960 and 1962, were similar in their timing and spatial distribution. Individuals that spawned before August 13 utilized both the intertidal zone and the upstream areas, but later migrants selected redds only in the intertidal zone.

Accurate enumeration of chum salmon was not attempted, but it was estimated that 5,000 to 10,000 adults spawned in Olsen Creek each year and that the escapement of 1962 was substantially greater than the escapements of the previous 2 years. Most of the chum salmon spawned in the intertidal zone.

Selection of Spawning Area in Relation to Tide water

Pink salmon were observed spawning as far downstream as the 1-foot tide level. However, in 1960, 78 percent of the adults counted during intertidal surveys were between the 6- and 12-foot tide levels, and in 1961, 84 percent were above the 8-foot tide level (table 1). Chum salmon were observed spawning at the 6-foot and higher tide levels. Fish were not all spawning when these counts were made. Many were in dense schools, where they congregate before spawning. Therefore, there may be some discrepancy between the actual percent of the total run spawning and the percent given by these counts for the different tide levels.

Table 1.--Distribution of pink salmon adults at five tide levels on the Olsen Bay intertidal spawning grounds expressed as percentage of total counts, 1960-61

Year	Pink salmon adults				
	2- to 4-foot level	4- to 6-foot level	6- to 8-foot level	8- to 10-foot level	10- to 12-foot level
	Percent	Percent	Percent	Percent	Percent
1960	8	14	37	26	15
1961	1	5	10	70	14

A better indication of actual spawning at various tide levels was attained by sampling egg densities at randomly selected points in October at the close of the spawning season. Three tide levels were sampled in 1960 as follows:

3- to 4-foot level	40 samples
7- to 9-foot level	80 samples
10- to 11-foot level	80 samples

In 1962 the entire intertidal zone of the mainstream channel from the 3- to the 11-foot tide level was sampled (321 samples). Confidence intervals at the 90-percent level were caluculated for the mean egg densities (table 2). Pink salmon egg densities of 221 to 706 per square meter at the 3- to 4-foot level were indicative of spawning in that area, but chum salmon egg densities of 1 to 16 per square meter were probably indicative of drift eggs from farther upstream. Successful spawning by chum salmon occurred at the 6-foot and higher levels. Pink salmon egg densities of 1,630 to 5,171 per square meter were indicative of heavy spawning from the 4- to the 11-foot levels. Heavy spawning by chum salmon (1,352 to 1,551 eggs per square meter) occurred between the 8- and 11-foot levels.

Table 2.--Mean numbers of live and dead salmon eggs per square meter in October in Olsen Creek at six tide levels, 1960-62

Tide level	Eggs per square meter					
	1960		1961		1962	
	Pink	Chum	Pink	Chum	Pink	Chum
Feet	Number	Number	Number	Number	Number	Number
3-4	221	16	339	1	706	5
4-6					*2,710	32
6-8					*3,444	267
7-9	*2,295	32	*3,069	251		
8-10					*5,171	1,352
10-11	*1,630	189	*3,612	524	*3,351	1,551

* Indicates means for which the 90-percent confidence interval amounted to less than 20 percent of the value of the mean.

Density of live and dead eggs combined indicated which areas were used as spawning grounds, but densities of live eggs would more accurately reveal the value of such areas in perpetuating the runs.

Accordingly, an attempt was made to separate live from dead eggs in the October collections. Difficulties were encountered because some of the live eggs were in the "tender stage" of development, and even slight mechanical shock resulted in coagulation of the yolk. Unfertilized eggs which were not yet opaque white turned opaque while the samples were being examined. We arbitrarily classified opaque eggs as "dead" and eggs that were clear plus eggs that were in the process of turning opaque as "live."

Average densities of live pink salmon eggs ranged from 79 to 105 per square meter in the 3- to 4-foot tide level and from 1,205 to 2,314 per square meter in the higher tide levels (table 3). Live chum salmon eggs were nearly absent in the lowest tide level examined and were not abundant at the 4- to 6-foot level (19 eggs per square meter). In 1962, which had the best chum salmon escapement of the 3 years studied, there were 228 to 1,211 live chum salmon eggs per square meter in the area between the 6- and 11-foot levels.

Table 3.--Mean numbers of live salmon eggs per square meter in October in Olsen Creek at six tide levels (90-percent confidence intervals), 1960-62

Tide level	Eggs per square meter					
	1960		1961		1962	
	Pink	Chum	Pink	Chum	Pink	Chum
Feet	Number	Number	Number	Number	Number	Number
3-4	105±107	2±1	79±51	0	90±77	0
4-6					1,343±530	19±15
6-8					2,104±770	228±146
7-9	1,898±319	28±40	1,205±310	199±92		
8-10					2,314±540	868±642
10-11	1,469±267	177±104	1,461±332	488±206	2,140±384	1,211±396

Riffle Life

The average riffle life for 21 tagged female pink salmon observed daily in the intertidal spawning grounds was 5.0 days. No female chum salmon were tagged at Olsen Bay, but the average riffle life of tagged chum salmon females at Traitors Cove Field Station in Southeastern Alaska was 6 days.[3]

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[3] Chester R. Mattson and Richard G. Rowland. Chum salmon studies at Traitors Cove Field Station, June 1962 to March 1963. BCF Biological Laboratory, Auke Bay, Alaska, Manuscript Report in preparation.

Sex Ratios

Sex ratios were determined from weir counts and carcass counts in 1960 and 1961 (Helle et al., in press) and from tower counts in 1962. Helle and coworkers found that changes in sex ratio occurred during the season as a result of males appearing somewhat ahead of females. The sex ratios for entire escapements were near 50:50 each year.

SPAWNING EFFICIENCY

Fecundity

Fecundity of pink salmon was determined from counting individual eggs in unspawned females. The average number of eggs per female varied from year to year, but no differences were noted between early and late spawners by Helle et al. (in press). Fecundity of pink salmon was 1,815 eggs per female in 1960 and 2,094 in 1961. In 1962 the average number of eggs per female for 90 specimens was 1,829 (standard error of the mean=33). The regression coefficient calculated for the relation between length and number of eggs per female was 0.308.

Fecundity of chum salmon was not determined for females at Olsen Bay. Mattson examined 158 females from Prince William Sound in 1960 and found a mean egg content of 2,539 eggs per female.[4] Helle (1960) reported mean fecundity of 2,490 eggs per female for nine females from Sheep Bay stream No. 11, which produces a run similar in timing to the Olsen Bay run. A mean fecundity of 2,500 eggs per female was assumed in this paper in calculating potential egg deposition by chum salmon.

Potential Egg Deposition

Potential egg deposition in the study riffle at the 10- to 11-foot tide level was estimated by multiplying the average fecundity by the number of females that had spawned on the riffle. Counts from observation towers and estimates of riffle life of the females indicated that 6,220 pink salmon females and 2,645 chum salmon females spawned

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[4] Chester R. Mattson. Chum Salmon Investigations, Field Activities Report, June-November, 1960. 10 p., unpublished.

on this riffle. The female counts as well as the egg density estimates were converted to densities per square meter for convenience in comparisons. In 1962 seasonal density of spawning effort on the study riffle amounted to 4.6 pink salmon females per square meter and 1.9 chum salmon (table 4). At the conclusion of the spawning season, actual pink salmon egg density determined by pumping was 3,351 eggs per square meter and chum salmon egg density was 1,551 eggs per square meter (table 5), compared with potential densities of 8,413 and 4,750 eggs per square meter respectively (table 6). Estimates were also made periodically throughout the season to follow the pattern of increase in egg density in relation to spawning effort.

Table 4.--Female salmon spawning densities recorded on Olsen Creek study riffle, 1962

Observation period ending	Females per square meter			
	Pink salmon		Chum salmon	
	Total	Cumulative total	Total	Cumulative total
	Number	Number	Number	Number
July 15	0	0	0.5	0.5
August 1	0.9	0.9	0.6	1.1
August 14	1.1	2.0	0.3	1.4
August 29	1.0	3.0	0.4	1.8
October 8	1.6	4.6	0.1	1.9

Table 5.--Pink salmon egg densities determined from pumping in Olsen Creek study riffle, July 14 to October 17, 1962 (90-percent confidence intervals)

Dates	Samples	Eggs per square meter	
		Pink salmon	Chum salmon
	Number	Number	Number
July 14-15	71	265±175	515±295
July 31-August 1	70	1,415±295	870±275
August 13-14	81	3,490±445	1,410±320
August 27-29	81	4,251±464	1,657±349
October 5-17	58	3,351±460	1,551±456

Table 6.--Potential egg densities calculated from fecundities and tower counts of spawners in Olsen Creek study riffle, 1962

Dates	Eggs per square meter			
	Pink salmon		Chum salmon	
	By period	Cumulative total	By period	Cumulative total
July 4-15	73	73	1,250	1,250
July 16-August 1	1,573	1,646	1,500	2,750
August 2-14	2,012	3,658	750	3,500
August 15-29	1,829	5,487	1,000	4,500
August 30-October 8	2,926	8,413	250	4,750

Spawning Bed Capacity

If the salmon had been 100 percent efficient at depositing their eggs in the gravel, observed egg densities should equal potential densities within limits of sampling errors. A straight-line graph depicting potential egg densities plotted against observed egg densities would rise at a 45° or 1:1 slope (fig. 3). In this particular riffle, pink salmon egg densities did approximate such a relation during the first 6 weeks of the pink salmon spawning season. Between July 4 and August 14, 1962, 2.0 females deposited 3,490 eggs per square meter (fig. 3). Within the 90-percent confidence limits of measurement this density was not different from the potential density of 3,658 eggs per square meter (table 6). From August 15 through 29, 1962, egg density increased 661 eggs per square meter to the maximum of 4,251 per square meter. This was accomplished by the spawning effort of 1.0 female per square meter having a potential of 1,829 eggs per square meter. Thus spawning efficiency was only 36 percent during this 2-week period. During the last 5 weeks of the spawning season, August 30 through October 8, 1962, 1.6 females per square meter spawned on the riffle for a potential contribution of 2,926 eggs per square meter. Actual egg density decreased 900 eggs per square meter during this period. Therefore a saturation density of approximately 4,000 pink salmon eggs per square meter was attained as a result of spawning by 3.0 females per square meter, and further spawning did not increase the pink salmon egg population.

Chum salmon egg densities reached their maximum of about 1,500 eggs per square meter in the August 13-14 sampling (table 6). At that time 1.4 females per square meter had spawned, and additional

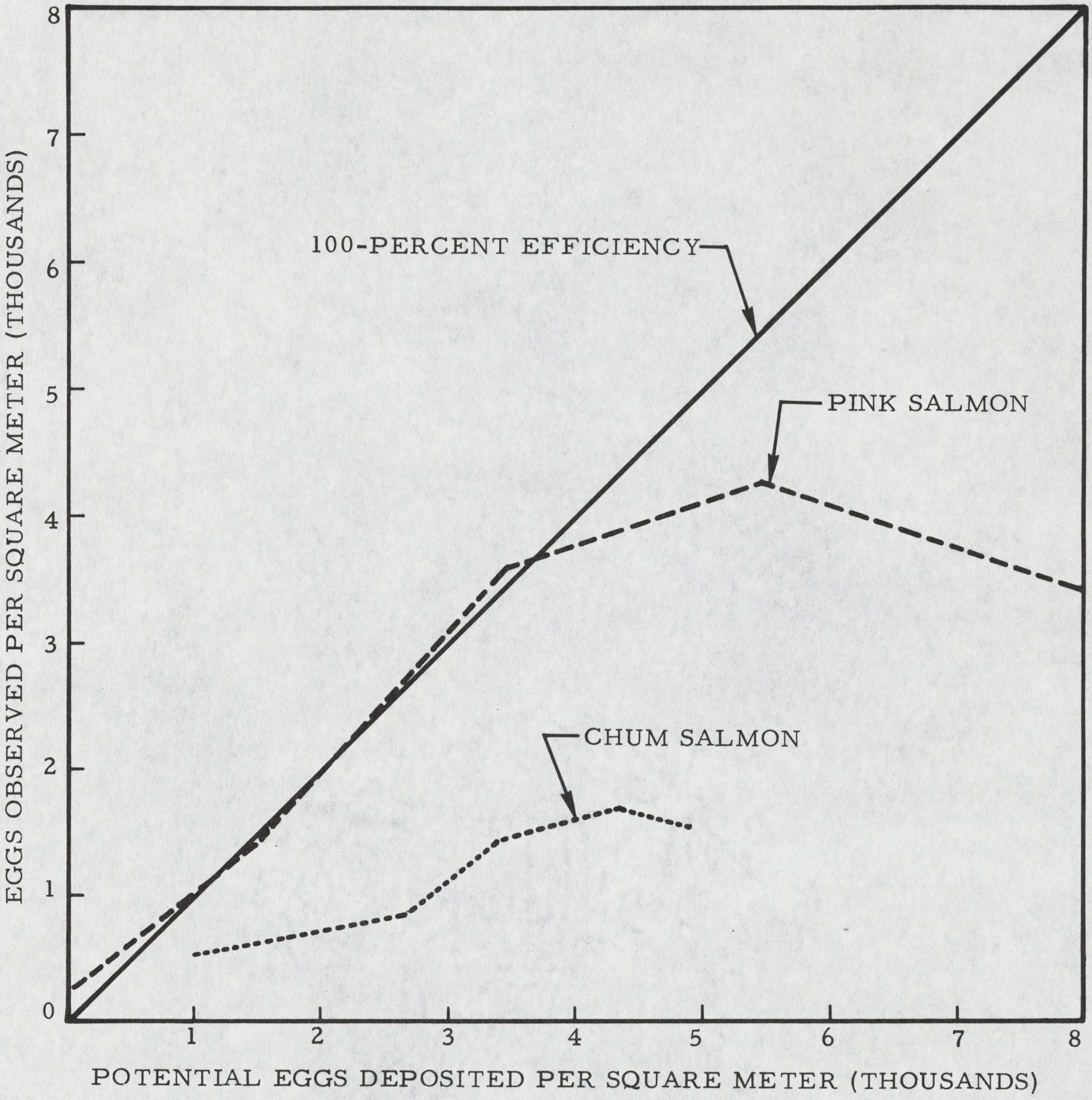

Figure 3.--Efficiency of pink salmon egg deposition in Olsen Creek study riffle, 1962.

spawning by 0.5 female per square meter made no substantial contribution to the egg population. Chum salmon appeared to be less efficient spawners than pink salmon in this situation (fig. 3). Pink salmon egg density in October was 40 percent of potential deposition, and chum salmon egg density was 32 percent of potential. Two explanations are suggested as possible causes for the relatively poor showing of chum salmon eggs in our samples. First, pink salmon spawning in larger numbers and somewhat later in the season than chum salmon may have dug out excessive numbers of chum salmon eggs. Second, chum salmon may have buried their eggs deeper in the gravel so that efficiency of recovery might have been somewhat less for chum salmon eggs than for pink.

Effect of Redd Superimposition on Early Eggs

An indication of the effect of redd superimposition on the first eggs deposited was attained by comparing observed pink salmon fry density in October with an estimate of the potential fry density. Artificially inseminated pink salmon eggs confined in plastic boxes and buried in the study riffle July 27, 1962, had hatched and many had left the boxes by October 19. Therefore, pink salmon eggs deposited in this riffle prior to July 27 were potential yolk sac fry by mid-October, assuming naturally deposited eggs developed at the same rate as the artificially inseminated eggs. Actual egg density based on samples collected with a hydraulic pump was about 1,200 eggs per square meter July 27. An average of 68±58 (90-percent confidence limits) fry per square meter were present in 22 random samples examined October 7 to 17. A 90-percent or greater loss of eggs spawned early and their replacement by eggs of later spawners is implied. It has previously been pointed out that there was a twofold to threefold difference between overall potential egg densities and observed live egg densities at Olsen Creek. Some of the added mortality among early spawned eggs probably resulted from the longer exposure to low oxygen (table 7), but much of the mortality was attributable to effects of redd superimposition.

Interspecific Competition for Gravel Interstices

Pink salmon generally preferred relatively fast water for spawning, but when spawning densities were high they encroached upon the chum salmon redds in relatively slow water. To illustrate this competition for redd areas, egg samples were classified according to the predominant species represented. Samples containing 100 or more eggs of one

Table 7.--Dissolved oxygen content of intragravel water samples from random points sampled in the main stream channel of Olsen Creek, 1962 (95-percent confidence intervals)

Date	Tide level	Dissolved oxygen content
	Feet	Mg/l.
July 9	7	7.0±0.48
July 11	10	7.5±0.40
July 13	13	6.7±0.71
July 28	13	4.9±0.37
August 12	3 to 5	3.1±0.55
August 17	5 to 7	3.0±0.35
August 22	8 to 9	3.6±0.73
August 31	10 to 11	4.8±0.69
September 18	9 to 11	6.1±0.75
September 19	7 to 9	5.7±0.41
September 22	5 to 7	5.5±0.96
September 25	13	8.3±0.49
October 1	3	4.8±0.89

species and less than 100 of the other were tabulated as redds belonging to the majority species. Samples containing 100 or more eggs of both species were tabulated as mixed redds. Samples that contained less than 100 eggs of either species were not classified.

When the first samples were collected, July 14-15, 1962, there were no mixed redds, and there were more chum salmon redds than pink (table 8). The percentage of mixed redds gradually increased to the maximum of 64 percent August 27-29, and few samples could be classified as chum salmon redds after August 1. It is inferred that the high density of pink salmon spawning effort had a somewhat depressing effect on the less numerous chum salmon. Overall efficiency of deposition was almost 50 percent of potential for pink salmon and only 30 percent for chum salmon. The difference probably reflects the effect of high pink salmon spawning density on chum salmon egg deposition at Olsen Creek in 1962.

Table 8.--Classification of salmon redds to species based on occurrence of 100 or more eggs to identify species

Date	Samples		Redds by species		
	Dug	Classified	Pink salmon	Chum salmon	Mixed
	Number	Number	Percent	Percent	Percent
July 14-15	71	20	35	65	0
July 31-August 1	70	56	59	21	20
August 13-14	81	74	41	0	59
August 27-29	81	79	33	3	64
October 5-17	58	57	44	5	51

Flood Losses

The observed poor spawning efficiency of late spawners of both species was probably a result of physical removal of previously spawned eggs when later redds were superimposed. Large numbers of eggs were visible on the stream bottom during the last month of the spawning season. It is presumed that most of the eggs lost were physically removed from the streambed by a combination of spawning activity and stream action. The greatest loss occurred between August 30 and October 8, 1962, when pink salmon egg density decreased 900 eggs per square meter and chum salmon egg density decreased 106 eggs per square meter in the face of potential increases of 2,926 and 250 eggs per square meter respectively. The first heavy rains of the spawning season fell during this period, and the volume of streamflow, which had gradually declined to about 25 c. f. s., suddenly increased in a series of freshets to maximum flow peaks of 200 to 500 c. f. s. Live salmon eggs in all stages of development were deposited on gravel bars by floods, but no quantitative estimate of egg loss due to flooding was made.

Egg Retention

Another source of egg loss--egg retention by pink salmon females that failed to complete the spawning act--was assessed in 1960 and 1961. In 1960, 364 females were opened, and the percentage of eggs voided from each was visually estimated. Helle et al. (in press) reported that the average number of eggs retained amounted to 7 percent of the potential egg content of these fish.

In 1961 Helle and his coworkers examined 373 dead females and counted individually the eggs retained. Egg retention was a relatively minor factor during July and August, amounting to only 3.8 percent for 344 females. The remaining 29 females, examined September 8 and 9, 1961, had retained 41.5 percent of their eggs. Most fish in the 1961 escapement spawned after August 15, resulting in extremely high adult densities. The high incidence of egg retention that followed may have been a result of competition for redds. Hanavan (1954) observed a consistently greater retention of eggs among pink salmon held in crowded spawning pens than in less crowded pens. On August 30, 1961, it was estimated that 41,280 pink salmon plus 517 chum salmon were present on the Olsen Creek intertidal spawning grounds--a density of 1.85 adults per square meter.

No effort was made to assess egg retention in 1962 other than by general observations of female carcasses. Since no evidence of unusual egg retention was noted, it is assumed that it amounted to less than 10 percent. Although the 1962 seasonal spawning density was high, the escapement entered Olsen Creek more or less uniformly throughout the season, and spawning density at any given time was not as excessive as in the latter part of the 1961 season. The peak density of 1.14 adults per square meter on September 1, 1962, comprised 25,851 pink salmon plus 490 chum salmon.

Survival

A rough indication of losses of pink salmon eggs from potential deposition to autumn was obtained by comparing estimates of potential egg densities with actual live egg densities observed in October. Potential pink salmon egg densities for 1960, 1961, and 1962 were calculated from estimates of the number of spawning females, mean fecundities, and the available spawning area. The potential egg densities amounted to 2,518 eggs per square meter in 1960; 4,006 in 1961; and 5,246 in 1962. The actual live egg densities encountered above the 6-foot tide level (table 3) were about one-third to one-half of the estimate of potential density each year.

Survival from live eggs in the fall to live preemergent fry the following spring was determined by hydraulic sampling March 23-29, 1961, and March 10-16, 1963. In 1961 the maximum pink salmon fry density of 786 per square meter was recorded at the 10- to 11-foot tide level,and 377 fry per square meter were found at the 7- to 9-foot tide level (table 9). No survivors were found at the 3- to 4-foot level. Over-winter survival amounted to 54 percent in the 10- to 11-foot level and 20 percent in the 7- to 9-foot level (table 10). In March 1963, pink salmon fry densities of 98 to 678 per square meter and chum salmon densities of 12 to 468 per square meter were similar to densities found in March 1961. There was, however, an unusually high mortality indicated by the 1963 samples at the 8- to 10-foot tide level where only 98 pink salmon fry per square meter and 12 chum salmon fry per square meter were found. The disproportionately high density of dead eggs in this area indicated that an excessive mortality took place before hatching. It was assumed that this mortality was caused by poor oxygen supply (table 7) particularly critical at the 8- to 10-foot tide level because of a comparatively low gradient and low permeability of bottom materials.

Table 9.--Live preemergent salmon fry per square meter at six tide levels in Olsen Creek in March (90-percent confidence limits)

Tide level	Pink salmon		Chum salmon	
	1961	1963	1961	1963
Feet				
3-4	0	0	0	0
4-6		152±64		0
6-8		292±93		20±28
7-9	377±91		19±25	
8-10		98±39		12±13
10-11	786±479	678±128	253±103	468±172

Table 10.--Percent survival from live eggs in fall to preemergent fry in spring

Tide level	Pink salmon		Chum salmon	
	1960-61	1962-63	1960-61	1962-63
Feet				
3-4	0	0	0	0
4-6		11		0
6-8		14		9
7-9	20		68	
8-10		4		1
10-11	54	32	143	39

With the exception of the poor survival in the 8- to 10-foot tide level during winter 1962-63, survival of pink and chum salmon eggs was highest in the upper levels of the intertidal zone and decreased progressively to zero at the 6-foot level for chum salmon and at the 4-foot level for pink salmon. The point estimates of percentage survival were not sufficiently precise to make comparisons between species. Failure to survive at the lower strata cannot be definitely associated with seawater on the basis of presently available information. In this instance, low oxygen was also a factor, but it is of interest to note the percent of time these areas were inundated by the tidewater. In 1961 Helle and coworkers calculated that the 4-foot elevation was covered by tidewater approximately 75 percent of the time; the 6-foot elevation, approximately 55 percent; and the 8-foot elevation, approximately 33 percent.

SUMMARY

Egg deposition, redd superimposition, and embryo survival of pink and chum salmon in an intertidal stream have been studied for 3 years at Olsen Creek, Olsen Bay, Prince William Sound, Alaska. Pink salmon were observed spawning at the 1-foot tide level and higher and chum salmon at the 6-foot level and higher. Live pink salmon eggs were found in October at the 3-foot level and higher and live chum salmon eggs at the 4-foot level and higher. Live egg densities observed in October were about one-third to one-half of estimated potential densities. There was no over-winter survival of pink salmon embryos below the 4-foot level and no over-winter survival of chum salmon below the 6-foot level. The 4-foot level was exposed to tidewater 75 percent of the time and the 6-foot level, 55 percent of the time. Estimates of survival of pink salmon from live eggs in fall to preemergent fry in spring ranged from 4 to 54 percent for the area between the 4- and 11-foot tide levels. Survival was generally better at higher elevations of the intertidal zone, except for a high mortality at the 8- to 10-foot tide level during the winter of 1962-63, which was attributed to poor oxygen supply.

Potential egg densities in an intensively studied riffle at the 10- to 11-foot tide level in 1962 amounted to 8,413 pink salmon eggs and 4,750 chum salmon eggs per square meter. Actual densities of approximately 4,000 pink salmon eggs per square meter plus 1,500 chum salmon eggs per square meter were deposited before the end of August.

At this time 3.0 pink and 1.3 chum salmon females per square meter had spawned. Additional spawning did not increase total egg densities. Eggs that were in excess of the capacity of the streambed were removed by stream action and spawning activity. Chum salmon were less efficient than pink salmon at depositing eggs in the study riffle. The difference in efficiency between species was attributed to interspecific competition for redds, with the more numerous pink salmon overwhelming the chum salmon.

Artificially inseminated pink salmon eggs buried in plastic boxes July 27, 1962, at the 10.5-foot tide level were hatched by October 19. Assuming that naturally deposited eggs developed at the same rate, it was estimated that there was a 90-percent or greater mortality of eggs deposited early in the season. The high mortality was believed to be a result of redd superimposition, although poor oxygen supply was probably also an important factor.

Egg retention by pink salmon females that died before completing spawning was an important factor in reducing actual deposition for a short period during 1961 when a maximum of 1.85 adult salmon per square meter were spawning.

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WATERFLOW THROUGH A SALMON SPAWNING RIFFLE IN SOUTHEASTERN ALASKA

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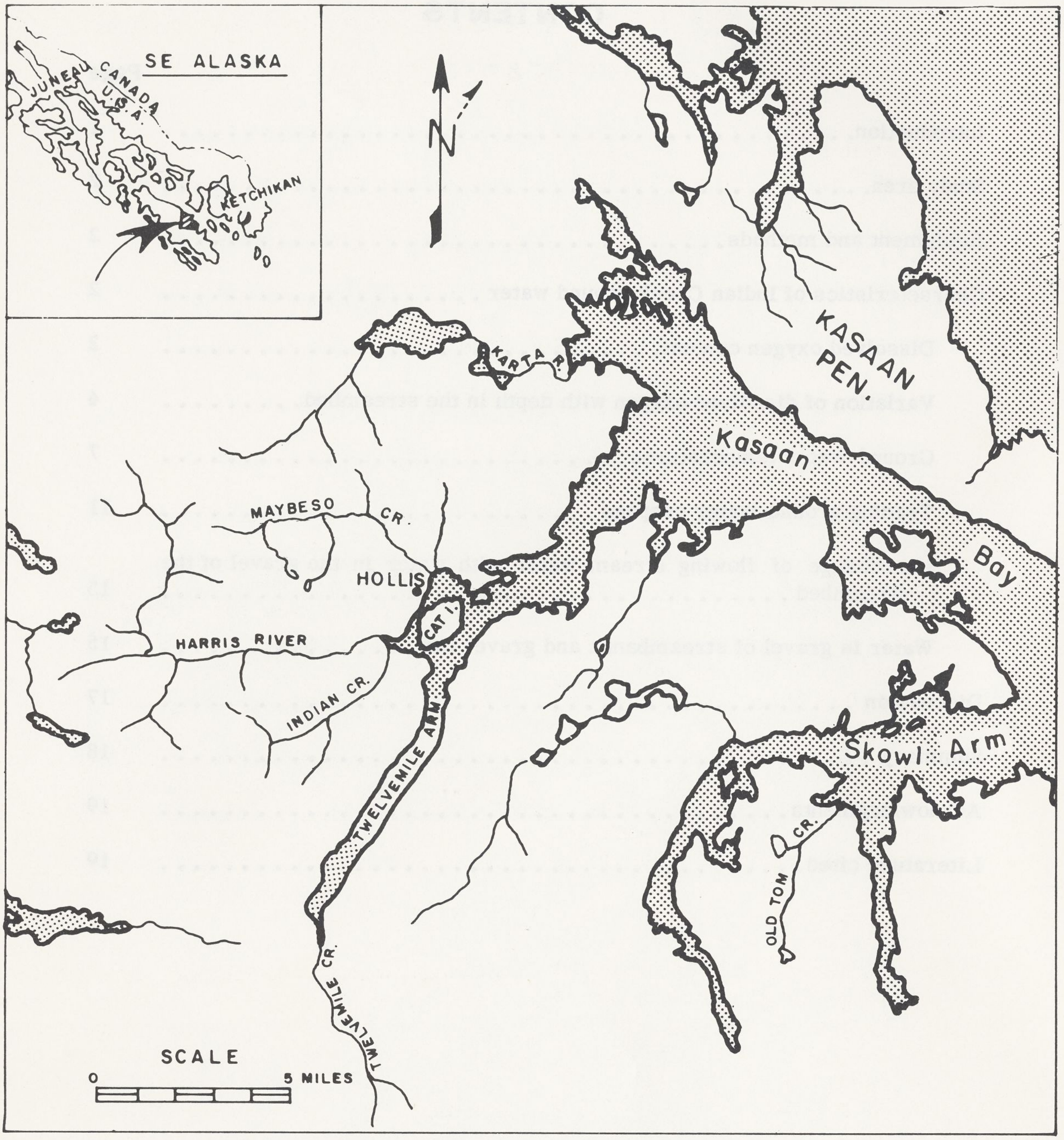

Figure 1.--Location of study streams, Hollis area.

WATERFLOW THROUGH A SALMON SPAWNING RIFFLE IN SOUTHEASTERN ALASKA

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ABSTRACT

The following characteristics were studied in a small salmon stream in Southeastern Alaska from 1956 through 1959: (1) dissolved oxygen content of ground water, (2) variation of dissolved oxygen with depth in streambed, (3) temperature of ground water, (4) extent of ground-water seepage, (5) interchange of flowing stream water and water of streambed gravels, and (6) flow of water in the gravel of streambank and gravel bar.

Ground water was generally low in dissolved oxygen content, and dissolved oxygen levels decreased with depth in streambed. Because of these and other points discussed in this paper, I conclude that the main source of intragravel water of high oxygen content is the flowing stream.

INTRODUCTION

In 1956 the Fisheries Research Institute started a study of the effects of logging on the productivity of pink salmon *(Oncorhynchus gorbuscha)* streams in Alaska, and work has been conducted on four streams in the Hollis area of Kasaan Bay in Southeastern Alaska (fig. 1). The general plan of research was to define normal conditions in the stream before logging, to measure any changes that might accompany logging operations, and to define limits within which environmental changes could occur and yet permit survival of salmon eggs and larvae. The Fisheries Research Institute, in cooperation with the U.S. Forest Service, performed the work under a contract awarded by the Bureau of Commercial Fisheries utilizing Saltonstall-Kennedy funds.

Part of this research involves the mechanics of waterflow within the gravel of a spawning riffle in Indian Creek, one of the study streams. Knowledge of the nature of waterflow through spawning gravels is basic to our study of effects of logging because survival of salmon eggs and larvae depends to a large extent upon water quality (Royce, 1959).

The investigation included: (1) determining dissolved oxygen content of ground water, (2) measuring variation of dissolved oxygen with depth in streambed, (3) measuring ground-water temperatures, (4) determining extent of ground-water seepage, (5) demonstrating the existence of interchange of flowing stream water and water of the streambed gravel, and (6) studying flow characteristics of water in the gravel of streambanks and gravel bars.

The object of this paper is to present and discuss parts of the Indian Creek study.

Note.--William L. Sheridan presently employed with Alaska Department of Fish and Game, Kitoi Bay Research Station, Afognak Island, Alaska.

STUDY AREA

Indian Creek is a small stream with a watershed area of 8.6 square miles. It is confluent at the 12-foot tide level with the larger Harris River, which flows into Twelvemile Arm. Pink salmon spawn only in the lower portion of Indian Creek. Median flood flow of this stream has been recorded as 456 c.f.s. and median flow as 3 c.f.s. (James, 1956). Visual estimates of peak abundance of pink salmon ranged from 100 to 16,000 during the years 1950 through 1958 (peak abundance is that time when the most fish are in the stream).

The valley floor through which Indian Creek flows ascends sharply as it leaves the stream mouth. The sides of the valley are steep in places and heavily wooded, chiefly with Sitka spruce and western hemlock. Although I made no detailed examination of the nature of the valley or of the valley floor, they are probably similar to those of other streams in the area. Zach (1950) reported that many of these watersheds are composed primarily of thin soils over bedrock on steep slopes and waterlogged peat in the muskegs.

There are two major sources of water to Indian Creek--surface runoff during rains and ground-water seepage during periods of drought. Rain-water is charged with dissolved oxygen. On its way to the stream, however, as ground water it is subject to a biochemical oxygen demand imposed by the type of aquifer through which it passes. The entire watershed does not contribute a large amount of ground water as the base flow decreases from approximately 5 c.f.s. 10 days after cessation of rain to 3 c.f.s. 30 days after (James, 1956).

Although most work was done at the 16- to 19-foot tide level, one experiment was done at the 11- to 13-foot tide level.

EQUIPMENT AND METHODS

Dissolved oxygen determinations were made on 25-milliliter portions of water that were withdrawn from plastic standpipes driven to specified depths in banks and streambed. Water samples were fixed and analyzed at once by the Winkler method (for a description of standpipes, method of driving, etc., see McNeil, 1962).

Vertical and horizontal variation of dissolved oxygen content of water within the gravel was determined from Latin square and randomized block designs in standpipe placement.

Water temperatures were measured with a Moeller hand thermometer, a Moeller dial thermometer, and a TRI-R thermistor thermometer. Dial and thermistor thermometers were fitted with 6-foot cables so that the sensitive portions of the bulbs could be inserted into standpipes.

Ground water was detected and traced by means of its difference from stream water in dissolved oxygen content and temperature.

Fluorescein dye was used to chart flow directions of water within the gravel of the streambanks, gravel bars, and streambed and to demonstrate interchange of flowing stream water and water within the gravel. Points of origin and emergence of dye-marked water were located with an engineer's transit.

CHARACTERISTICS OF INDIAN CREEK GROUND WATER

Ground water extends from the water table down to the first impervious stratum. The migratory behavior of ground water in this surface zone is controlled by local topography and gravity flow characteristics; hence, the general trend of flow under the influence of gravity is into lakes and streams. The rate and direction of flow conform primarily to slopes of the land surface and to the form of the first impervious layer below the water table. (A detailed discussion of ground water is given by Todd (1959) and others.)

Dissolved Oxygen Content

The sources of ground water are mainly rain and snow. When rain-water falls upon the ground it is saturated with oxygen at the prevailing temperature, but is subject to a biochemical oxygen demand as it percolates through the ground and after it reaches the water table. The extent of this biochemical oxygen demand depends on temperature and on the quality and quantity of organic matter through which the water must pass.

Despite depletion of its oxygen by organic matter, ground water in certain places contains a relatively large amount of dissolved oxygen, even as it enters a stream or lake beach. Benson (1953) wrote that attempts to locate ground water in Pigeon River, Mich., by chemical methods were futile. This implies that ground water that entered spawning areas of Pigeon River was neither higher nor lower in dissolved oxygen content than any other water he sampled in the stream. Upwelling ground water in lake beaches in Alaska and the Kamchatka Peninsula must contain sufficient dissolved oxygen to support the races of sockeye salmon *(Oncorhynchus nerka)* that successfully spawn on these beaches year after year. Krogius and Krokhin (1948) reported that dissolved oxygen in ground water in sockeye salmon spawning grounds in Lake Dalnee ranged from 1.5 to 13.5 mg./l. but more often from 5 to 6 mg./l. Kurenkov (1957) said that oxygen saturation of spring water in Kamchatka was as high as 90 to 95 percent.

Sampling of Indian Creek ground water was confined to point locations in 1958. In 1959 the same points plus two 4 by 4 Latin squares were used. (Figure 2 shows locations of the installations.)

Sampling points were distributed in the banks and over the gravel bar. Depths of standpipes in relation to a datum plane and each other are shown in figure 3. Water-table heights were determined by measuring distance from top of pipe to surface of water within the pipe.

The two 4 by 4 Latin squares were installed so that the shallowest four standpipes would usually reach the top of the water table (missing data in tables 2 and 8 resulted when standpipes did not reach the water table). Each of the three remaining sets of four pipes was placed 7 inches deeper. Distance from the shallowest four pipes to the deepest four pipes was then 21 inches.

Data from point locations in 1958 and 1959 (table 1) indicate that, in general, ground water that contributed to the Indian Creek riffle was characterized by low dissolved oxygen levels, except in late winter and early spring. At this time of year, when ground-water temperatures are lowest, increase in dissolved oxygen is attributed to decreased biochemical oxygen demand of organic materials in the ground-water aquifer.

Data from the Latin squares (table 2) indicate that during the sampling period dissolved oxygen in ground water was generally low. Oxygen levels in Latin square 1 were

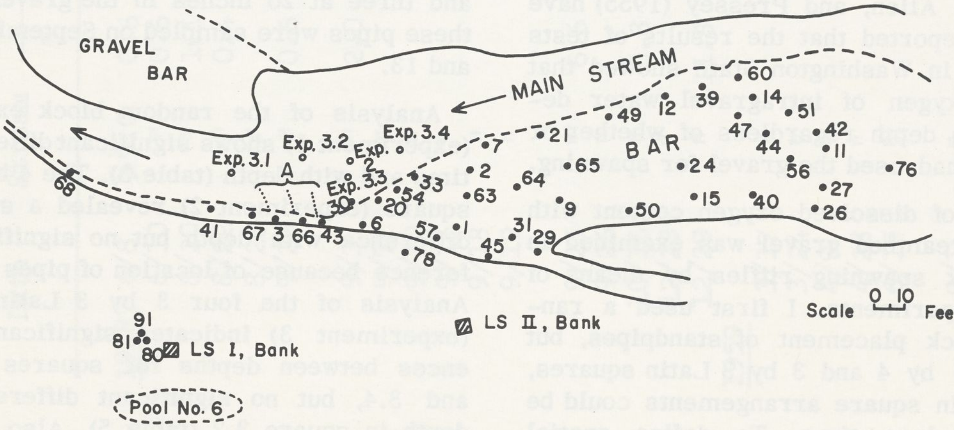

Figure 2.--Indian Creek study area 1 showing location of standpipes, Latin squares, and ground-water extension from bank to stream experiment (A).

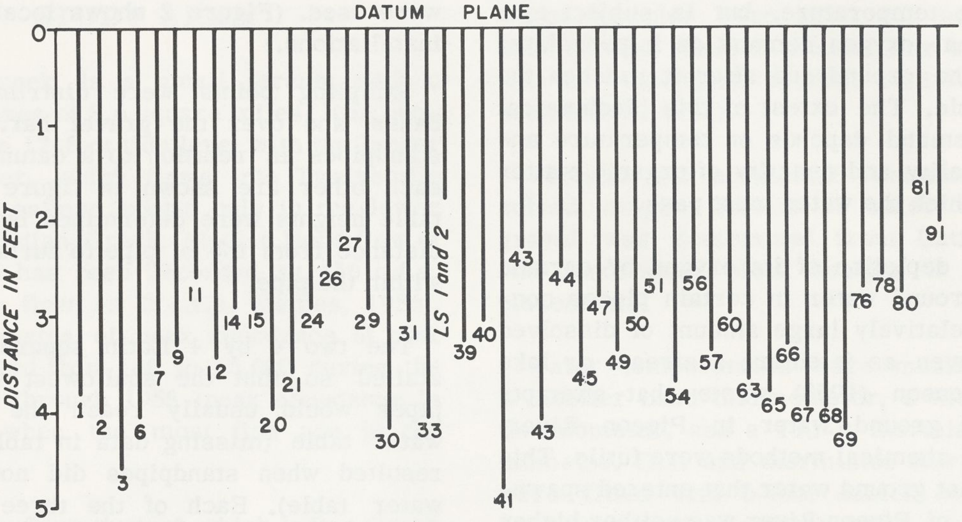

Figure 3.--Distance of bottom of standpipes in gravel bar and bank from established datum plane, Indian Creek, 1958-59.

slightly higher, and more gradation with depth is apparent than in Latin square 2.

Variation of Dissolved Oxygen with Depth in the Streambed

To substantiate results of measurements of dissolved oxygen content of ground water, the variation of dissolved oxygen with depth in the streambed was measured. If the dissolved oxygen content increased with depth or remained the same at different depths, then upwelling ground water could be credited as a source of the water of high oxygen content. If, on the other hand, dissolved oxygen content decreased with depth, a shallower source would be indicated.

Chambers, Allen, and Pressey (1955) have previously reported that the results of tests on streams in Washington State showed that dissolved oxygen of intragravel water decreased with depth regardless of whether or not salmon had used the gravel for spawning.

Variation of dissolved oxygen content with depth in streambed gravel was examined in Indian Creek spawning riffles by means of designed experiments. I first used a randomized block placement of standpipes, but shifted to 4 by 4 and 3 by 3 Latin squares, because Latin square arrangements could be installed in less time. To define spatial variation several installations were made in different places in the riffle (fig. 2).

In experiment 1 (fig. 4), 20 standpipes were used, 5 each of which were randomly placed in study area 3 in a 10- by 10-foot square at depths of 5, 10, 15, and 20 inches in the gravel. In 1958 these pipes were sampled on June 3, 5, 7, and 9, and September 13.

In experiment 2, standpipes were placed in a 4 by 4 Latin square design in study area 1 at depths of 5, 10, 15, and 20 inches in the gravel. These pipes were sampled in 1958 on June 4, 5, 7, and 9.

Experiment 3 was made up of four 3 by 3 Latin squares in the same general area as experiment 2. Within each square there were three pipes at 5 inches, three at 10 inches, and three at 20 inches in the gravel. In 1959 these pipes were sampled on September 4, 10, and 13.

Analysis of the random block experiment (experiment 1) shows significant differences in time and with depth (table 3). The 4 by 4 Latin square (experiment 2) revealed a significant difference with depth but no significant difference because of location of pipes (table 4). Analysis of the four 3 by 3 Latin squares (experiment 3) indicates significant differences between depths for squares 3.1, 3.3, and 3.4, but no significant difference with depth in square 3.2 (table 5). Also indicated is a significant difference because of placement of pipes in square 3.3.

Table 1.--Dissolved oxygen concentration in ground-water standpipes - mg./l. Indian Creek study area 1, 1958-59

	Date	Stream	Standpipe numbers												
			3	6	41	43	45	57	66	67	68	78	80	81	91
1958	6/8	>9.0	0.6	2.2	2.3	1.9	2.9	2.7							
	6/10	"	0.6	2.8	3.2	2.2	3.3	2.8							
	8/20	"	1.1	6.4		3.8		3.9	6.3	8.8	8.6				
	8/22	"	0.4	1.9	4.0	3.7	1.7		3.8	6.0	5.1	0.3	2.2	5.1	
	8/26	"							2.2	3.4	3.1		1.6		
	9/29	"	0.6	1.0	3.4	2.7									
	9/3	"	2.0	1.9	6.8	2.0	2.7	3.7	4.9	3.0	3.7		1.4		
	9/7	"								5.6		5.0	2.2	9.2	
	9/10	"											3.0	6.0	
	9/16	"										2.1	3.6	10.0	
	9/18	"								5.8		0.4	4.3	9.6	
	9/19	"								7.5		1.6	3.3	7.1	3.6
	9/25	"	6.6	7.3			5.7	4.9	8.4	10.1	8.3	1.6		7.0	1.8
	9/26	"					2.9	5.0							
	10/16	"	0.8	3.6		2.6	4.4	4.6	4.9	4.0	4.0		2.7	4.1	2.2
	12/23	"				7.5	12.2		4.4				10.1	11.0	8.2
	12/29	"	11.8			8.0	8.6		2.7				6.9	8.6	6.2
1959															
	3/17	"				7.8							9.8	10.6	
	3/24	"				7.4				8.0		3.9	9.0	9.0	7.4
	4/9	"				10.1						3.0	9.2	9.7	8.8
	4/28	"				4.4						2.9	4.5		4.3
	6/15	"				3.2						3.2	3.4		3.3
	9/1	"											1.8	4.8	4.2
	9/2	"											3.0	3.8	3.4
	9/14	"											3.0	3.6	3.1
	9/15	"											2.6	3.5	2.7
	9/21	"											1.2	1.3	1.3

Table 2.--Dissolved oxygen values (mg./l.) for Latin square ground-water standpipes, Indian Creek, 1959

Sampling dates						By depth (shallowest to deepest)		
Pipe number	9/1	9/2	9/15	9/21	Mean	Pipe number	Mean of 4 dates	Mean of depth
LS1 1	-	4.0	2.2	0.8	2.3	4	2.7	4.1
2	2.2	2.8	2.8	0.8	2.2	7	5.3	
3	4.3	4.2	2.3	-	3.6	10	3.3	
4	-	-	2.5	2.8	2.7	13	4.9	
5	3.9	3.7	2.3	4.8	3.7	3	3.6	3.6
6	1.9	3.2	1.8	0.8	1.9	12	3.7	
7	7.0	6.8	2.2	-	5.3	5	3.3	
8	3.6	4.5	2.8	1.0	3.0	14	3.6	
9	2.8	3.8	2.4	0.9	2.5	2	2.2	2.5
10	3.8	3.9	2.2	-	3.3	8	3.0	
11	2.4	2.2	1.7	0.7	1.8	9	2.5	
12	3.4	3.8	2.6	3.2	3.3	15	2.4	
13	7.0	5.8	2.0	-	4.9	1	2.3	2.0
14	4.2	4.2	2.3	-	3.6	6	1.9	
15	2.6	3.2	2.5	1.4	2.4	11	1.8	
16	-	5.0	2.2	1.8	3.0	16	1.8	
LS2 1	0.8	1.1	0.6	-	0.8	3	2.0	2.1
2	0.9	1.0	1.3	1.0	1.1	8	2.2	
3	-	2.2	1.8	-	2.0	10	1.5	
4	-	2.1	4.3	1.2	2.5	13	2.7	
5	-	1.8	0.9	1.1	1.3	1	0.8	2.0
6	-	1.6	1.0	-	1.3	6	1.3	
7	-	1.3	3.9	1.4	2.2	12	1.0	
8	-	2.0	2.3	-	2.2	15	0.9	
9	3.1	2.0	3.6	1.6	2.6	2	1.1	2.0
10	1.4	1.3	1.9	-	1.5	5	1.3	
11	-	0.7	0.4	1.6	0.9	11	0.9	
12	1.3	0.8	1.0	-	1.0	16	0.7	
13	3.1	2.6	2.3	-	2.7	4	2.5	2.2
14	1.3	1.1	2.6	0.8	1.5	7	2.2	
15	0.7	1.1	1.0	-	0.9	9	2.6	
16	0.6	0.8	1.0	0.5	0.7	14	1.5	

Figure 4.--Randomly placed standpipes at depths of 5, 10, 15, and 20 inches, experiment 1, Indian Creek, 1958.

When the four squares are considered in a factorial analysis (table 6), there are significant differences between depths, between squares, and in interaction. The variance ratio (F) is higher, however, for depths than for the other sources of variation. Statistically significant interactions are due to normal differences found between one point in a streambed and another.

Decrease in dissolved oxygen levels with depth in the streambed is shown in figure 5, where experiments 1, 2, and 3 are combined. Because of this decrease, no deeper source is indicated as contributing to high dissolved oxygen content of intragravel water. This further confirms that the primary source of dissolved oxygen is the stream.

Ground-Water Temperatures

Ground-water temperatures were sampled at the same points and usually at the same time as dissolved oxygen (discussed on page 2). Although not measured consecutively throughout the year, ground-water temperatures at various depths below the water table appeared to be lower than stream temperatures in the summer and higher in the winter (table 7). This agrees with Benson's (1953) findings for the Pigeon River, Mich., and with the ground-water temperature regimen of Cabin Creek in Southeastern Alaska, which was investigated by Institute personnel from 1949 to 1952.

Table 3.--Experiment 1. Dissolved oxygen measurements (in mg./l.) from 20 standpipes placed at random in a 10- by 10-foot square in Indian Creek study area 3, 1958

Pipe number	Depth in inches	Sampling dates					Means
		6/3	6/5	6/7	6/9	9/13	
1	5	8.6	10.0	9.2	9.5	9.6	9.4
2	"	8.4	9.0	8.8	9.7	9.4	9.1
3	"	9.0	8.2	7.9	8.5	9.9	8.7
4	"	8.8	9.3	8.2	9.3	8.9	8.9
5	"	5.6	8.6	7.8	8.8	8.1	7.8
Mean		8.1	9.0	8.4	9.2	9.2	
6	10	7.2	8.6	7.8	9.0	8.3	8.2
7	"	7.8	8.8	8.0	9.0	9.1	8.5
8	"	8.4	8.9	8.7	9.5	10.1	9.1
9	"	8.6	9.4	8.4	9.5	9.1	9.0
10	"	7.1	7.6	6.7	7.7	7.4	7.3
Mean		7.8	8.7	7.9	8.9	8.8	
11	15	7.0	7.9	7.8	8.5	8.6	8.0
12	"	5.9	6.6	5.7	6.6	6.8	6.3
13	"	6.6	6.8	5.9	7.1	6.5	6.6
14	"	5.8	7.9	6.4	7.5	7.7	7.1
15	"	8.3	9.2	8.2	8.9	9.4	8.8
Mean		6.7	7.7	6.8	7.7	7.8	
16	20	6.8	8.1	6.6	7.8	7.6	7.4
17	"	5.4	4.4	4.3	4.8	8.0	5.4
18	"	5.4	6.8	6.5	7.0	6.1	6.4
19	"	7.2	8.0	7.6	8.4	8.8	8.0
20	"	6.1	7.8	6.6	7.4	7.2	7.0
Mean		6.2	7.0	6.3	7.1	7.5	
Grand Mean		7.2	8.1	7.4	8.2	8.3	

Analysis of variance of above data

Source	Sum of squares	Degree of freedom	Mean square	Variance ratio
Time	21.96	4	5.49	5.53*
Depth	61.74	3	20.58	20.75*
Time x depth (Interaction)	0.67	12	0.054	nonsignificant
Error	79.37	80	0.992	

*Significant at 1-percent level.

Table 4.--Experiment 2. Dissolved oxygen measurements (in mg./l.) from 16 standpipes placed in a 4 by 4 Latin square in Indian Creek study area 1, 1958

Pipe number	Depth in inches	Sampling dates 6/4	6/5	6/7	6/9	Means
1	5	7.3	7.8	7.4	7.1	7.4
2	5	8.6	8.8	8.7	9.0	8.8
3	5	9.0	9.0	8.8	8.9	8.9
4	5	6.8	6.6	6.4	6.4	6.6
5	10	8.8	9.1	8.6	9.0	8.9
6	10	6.6	6.5	6.1	6.2	6.4
7	10	5.0	7.0	6.2	6.2	6.1
8	10	6.2	5.4	5.1	5.1	5.5
9	15	5.9	5.4	5.2	4.8	5.3
10	15	6.2	6.4	6.0	5.9	6.1
11	15	6.2	5.8	5.1	5.4	5.6
12	15	6.6	6.0	6.0	5.8	6.1
13	20	5.1	5.4	5.3	5.0	5.2
14	20	5.1	4.4	4.6	4.1	4.6
15	20	5.7	5.6	5.0	4.6	5.2
16	20	6.7	6.7	6.5	6.4	6.1

Analysis of variance of average of four dates above

Source	Sum of squares	Degree of freedom	Mean square	Variance ratio
Columns	8.73	3	2.91	4.69 nonsignificant
Rows	0.45	3	0.15	0.24 nonsignificant
Depths	15.34	3	5.11	8.24*
Error	3.74	6	0.62	

*Significant at the 1-percent level.

Table 5.--Experiment 3. Dissolved oxygen measurements (mg./l.) from four 3 by 3 Latin squares, Indian Creek study area 1, 1958

Latin square	Pipe number	Depth in inches	Sampling dates			Analysis of variance				
			9/4	9/10	9/13	Source	Sum of squares	Degree of freedom	Mean square	Variance ratio
3.1	1	5	10.5	10.4	10.3	Rows	0.81	2	0.405	1.976nonsignificant
	2	5	10.6	10.0	10.4	Col.	1.08	2	0.540	2.634nonsignificant
	3	5	11.3	10.1	9.8	Depths	83.96	2	41.98	204.78 *
	4	10	9.8	10.5	10.4	Error	0.41	2	0.205	
	5	10	10.0	10.0	9.6					
	6	10	10.1	9.9	8.8					
	7	20	3.8	4.0	2.3					
	8	20	8.4	3.6	2.5					
	9	20	1.8	4.6	2.0					
3.2	10	5	10.2	10.8	10.1	Rows	1.18	2	0.590	0.887nonsignificant
	11	5	10.6	11.0	10.3	Col.	4.06	2	2.030	3.053nonsignificant
	12	5	9.4	10.4	10.2	Depths	2.99	2	1.495	2.248nonsignificant
	13	10	10.0	10.5	10.1	Error	1.33	2	0.665	
	14	10	9.6	10.2	9.6					
	15	10	10.2	10.2	4.9					
	16	20	9.3	9.8	9.8					
	17	20	9.9	2.0	9.6					
	18	20	9.7	10.2	10.2					
3.3	19	5	10.4	10.6	10.3	Rows	0.37	2	0.185	18.50nonsignificant
	20	5	-	10.6	10.4	Col.	0.57	2	0.285	28.50 **
	21	5	10.6	10.5	9.4	Depths	21.17	2	10.585	105.85 **
	22	10	10.5	10.5	10.1	Error	0.02	2	0.01	
	23	10	10.4	10.2	7.7					
	24	10	10.1	11.3	7.5					
	25	20	10.3	3.4	7.2					
	26	20	7.4	6.0	7.1					
	27	20	6.6	-	7.8					
3.4	28	5	11.0	-	10.2	Rows	0.04	2	0.020	1.00nonsignificant
	29	5	10.9	-	10.2	Col.	0.00	2	0.000	0.00nonsignificant
	30	5	11.0	10.5	10.2	Depths	1.94	2	0.970	48.50 *
	31	10	10.3	10.4	9.8	Error	0.04	2	0.020	
	32	10	10.6	-	9.8					
	33	10	10.7	10.3	9.1					
	34	20	7.7	10.6	10.6					
	35	20	9.2	9.6	9.7					
	36	20	10.6	8.4	8.9					

*Significant at the 1-percent level.

Table 6.--Analysis of variance of four 3 by 3 Latin squares in Indian Creek study area 1.

Source	Sum of squares	Degree of freedom	Mean square	Variance ratio
Depths	68.75	2	34.37	83.22 *
Squares	21.68	3	7.23	17.51 *
Interaction	40.82	6	6.803	16.47 *
Error	9.91	24	0.413	

*Significant at the 1-percent level.

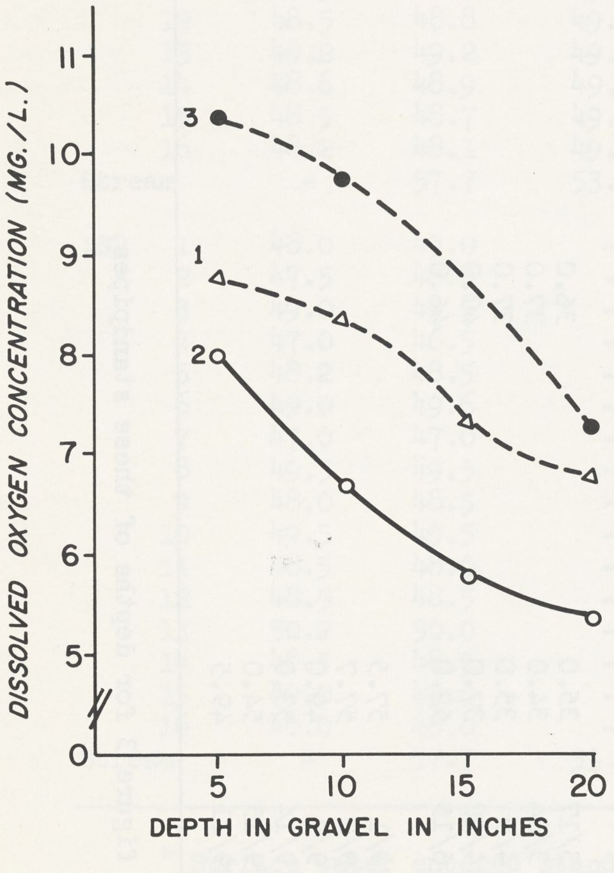

Figure 5.--Decrease in dissolved oxygen with depth in streambed gravel, experiments 1, 2, and 3, Indian Creek, 1958.

Temperature data from the two 4 by 4 Latin squares (table 8) show little variation in ground-water temperatures with time or depth in water table at the time of sampling.

Tracing Ground-Water Seepage

In Indian Creek, riffle ground water flows from the bank into the streambed because of a pressure gradient formed by the slope of the water table (fig. 6). Ground water was traced from the streambank into the streambed by means of dye and through dissolved oxygen and temperature differences. These differences were first determined in 1956 through routine sampling of points throughout the riffle. Figure 7 shows gradual increase in dissolved oxygen content of water 10 inches under the gravel with distance away from the bank.

In 1959 three sampling stations were installed (location shown as A in figure 2) to obtain specific data on oxygen and temperature differences. At the three stations, water within the gravel was sampled at points 1 foot apart extending from the bank 8 feet into the stream. Measurements showed that at the time of sampling (September) both temperature and dissolved oxygen increased (fig. 8) with distance away from the ground-water source until influence of ground-water seepage was no

Table 7.--Ground-water temperatures in degrees Fahrenheit at various depths below the water table, Indian Creek study area 1, 1958-59

Date	Stream	Pipe numbers												
		3	6	41	43	45	57	66	67	68	78	80	81	91
1958														
8/13	57.0	47.0	51.0	53.0	50.0		51.0							
8/17	55.0	47.0	50.0	51.0	50.0	51.0	51.0	50.0	51.0	51.0				
8/20	56.0	50.0	52.0	55.0	52.0	51.0	51.0	53.0	54.0					
8/22	56.0	50.0	48.5		50.5	51.5	53.0	50.5	54.5	52.0	49.0	49.0	50.5	
8/29	57.0	48.0	51.5	49.5	49.0			49.0	50.5	50.5				
9/21									48.0			49.0	49.0	49.0
10/3	42.0		44.5		44.0	44.5	44.5	44.0	44.0	44.0		45.0		46.0
12/23	36.5				39.0	37.5		39.0				36.5		36.0
12/29	35.5				36.5	35.5		37.0				37.0		37.0
1959														
3/17	35.0				36.0							36.0		34.0
3/24	34.0				37.0							33.5		33.5
4/9	35.0				37.0							36.5		37.0
4/28	37.0				40.0							38.5		38.5
6/15	52.0				46.0							48.0		45.0
9/1	57.5											48.2	48.5	48.5
9/2	57.7											48.2	48.0	48.3
9/9	49.0											47.5	48.0	47.5
9/14	53.0											50.0	50.5	50.0
9/15	54.0											49.5	50.0	49.5
9/21	49.5											48.5	49.0	48.0

See figure 3 for depths of these standpipes.

Table 8.--Temperatures in degrees Fahrenheit for Latin square ground-water standpipes, Indian Creek, 1959

Pipe No.		Sampling dates				
	9/1	9/2	9/14	9/15	9/21	Mean
LS1 1	49.0	49.0	49.0	49.0	48.0	48.8
2	49.0	48.6	49.5	49.0	48.0	48.8
3	48.5	48.6	49.5	49.0	-	48.9
4	48.5	-	50.0	49.5	48.0	49.0
5	49.0	49.2	49.0	49.0	48.5	48.9
6	48.5	48.4	49.0	49.0	48.0	48.6
7	49.0	49.2	49.0	49.0	-	49.1
8	48.3	48.1	49.5	49.0	48.0	48.6
9	48.9	48.8	49.0	49.0	48.0	48.7
10	48.5	48.7	49.0	49.0	-	48.8
11	48.5	48.4	49.0	49.0	48.0	48.6
12	48.5	48.8	49.0	49.0	48.0	48.7
13	49.2	49.2	49.0	49.0	-	49.1
14	48.6	48.9	49.0	49.0	-	48.9
15	48.5	48.7	49.0	49.0	48.0	48.6
16	48.2	48.1	49.0	49.0	47.5	48.4
Stream	-	57.7	53.0	54.0	49.5	53.6
LS2 1	48.0	49.0	-	48.0	-	48.3
2	47.5	48.0	-	47.5	47.0	47.5
3	49.0	49.5	-	49.0	-	49.2
4	47.0	46.5	-	50.0*	46.0	47.4
5	48.2	48.5	-	48.0	47.0	47.9
6	49.0	49.6	-	48.5	-	49.0
7	47.0	47.0	-	50.5*	45.5	47.5
8	49.5	49.5	-	49.5	-	49.5
9	48.0	48.5	-	48.0*	46.5	47.8
10	49.5	49.5	-	49.5	-	49.5
11	48.5	48.0	-	47.5	47.0	47.8
12	48.5	48.5	-	48.0	-	48.3
13	50.2	50.0	-	49.5	-	49.9
14	48.5	48.5	-	50.5*	47.0	48.6
15	49.0	49.0	-	48.5	-	48.8
16	48.0	48.0	-	48.0	46.5	47.6
Stream	-	57.7	53.0	54.0	49.5	53.6

* Surface water entered standpipes.

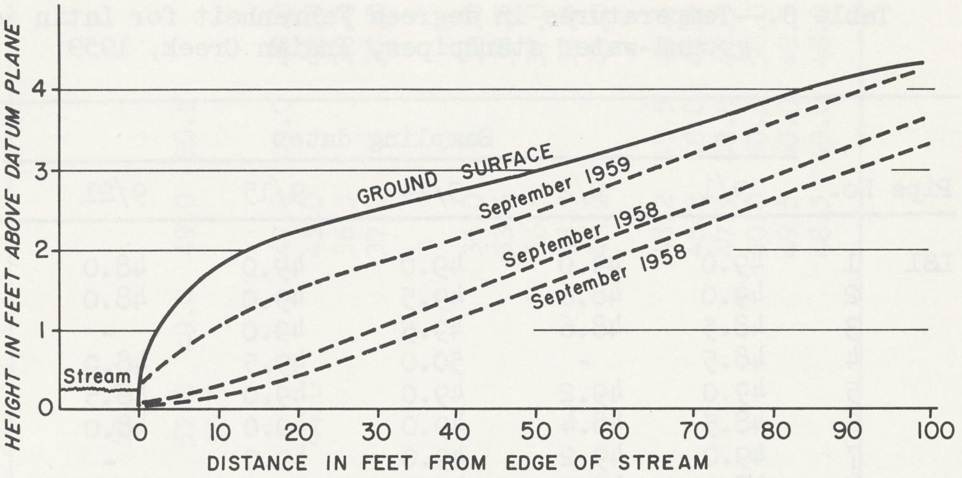

Figure 6.--Water-table gradient for three water-table levels, Indian Creek, study area 1.

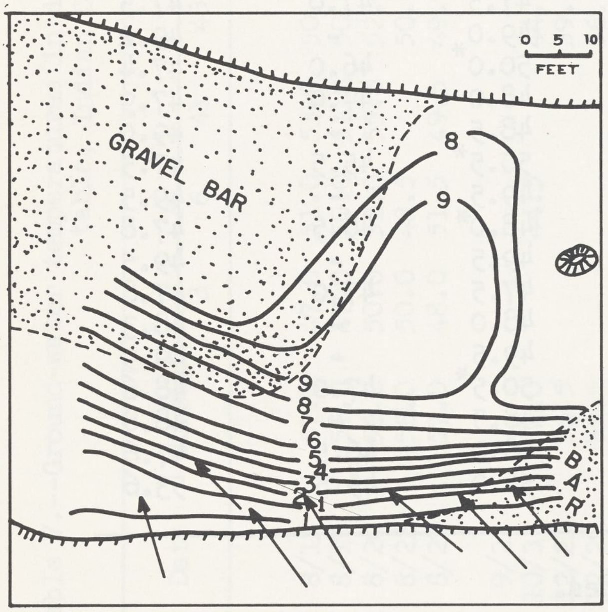

Figure 7.--Indian Creek study area 1 showing mean dissolved oxygen levels at 10 inches in the gravel in contour intervals of 1 mg./1., August 1956. (Arrows indicate direction of ground-water flow.)

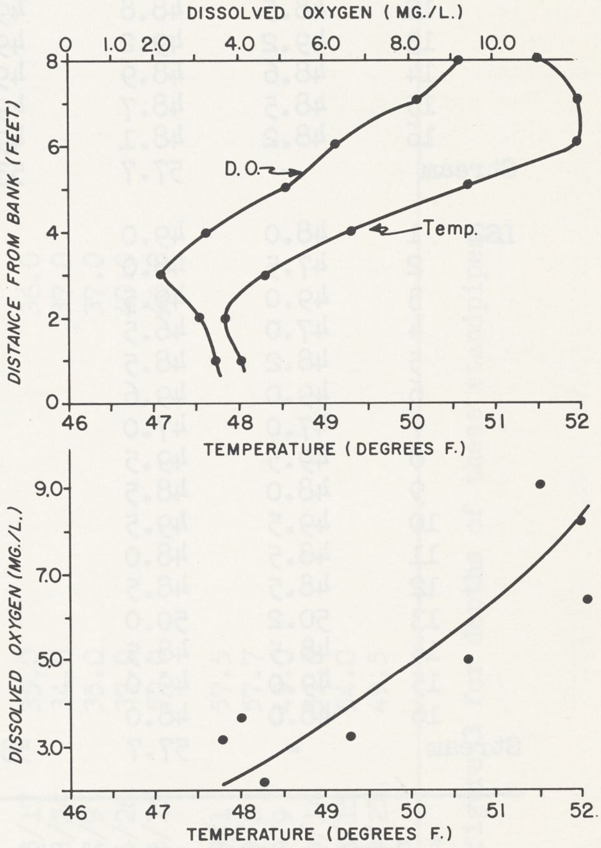

Figure 8.-- Indian Creek study area 1, September 1959. Upper figure shows increase in water temperature and dissolved oxygen with distance away from bank ground-water source at 10 inches in gravel. Lower figure is temperature and dissolved oxygen data from upper figure plotted to show relationship between water temperature and dissolved oxygen.

longer apparent. The trend of increase shown in figure 8 would have been even better defined except for vertical as well as horizontal variation. Vertical gradations of water temperature and dissolved oxygen were well defined near the bank, but were not nearly as pronounced as near the center of the stream (table 9).

Interchange of Flowing Stream Water with Water in the Gravel of the Streambed

Studies of interchange of flowing stream water with water in the gravel of the streambed were started as soon as it became apparent that ground water was usually low in dissolved oxygen content and that dissolved oxygen levels decreased with depth in the streambed. The extent and method of interchange in salmon spawning riffles had not been thoroughly demonstrated.

Wickett (1954) suggested that intragravel water containing a large amount of dissolved oxygen comes from the stream through percolation. Cooper (1959) reported that interchange is greatly increased by placing a few large rocks on the surface of the streambed. Interchange was indicated by the work of Fisheries Research Institute personnel (unpublished) and of Skud (1954) on changing temperatures and salinities in the gravel of intertidal zones through the tidal cycle.

Interchange of water between stream and streambed was first demonstrated in the Indian Creek spawning riffle in 1958. At that time upwelling of intragravel water was shown by inserting fluorescein dye into standpipes placed at various depths in the gravel and mapping the subsequent appearance of dye-marked water at the surface of the streambed. Descent of surface water was demonstrated by marking flowing stream water masses with dye and capturing dye-marked water in standpipes placed at different depths in the gravel downstream from the point of insertion.

The mechanics of interchange in the Indian Creek riffle were qualitatively studied in more detail in 1959; results of this work appear in a report by Vaux and Sheridan (1960).

Water in Gravel of Streambanks and Gravel Bar

Temperatures of water in the gravel of the main stream channel closely approximated temperatures of the flowing stream (except in areas under ground-water influence discussed previously). Because of interchange, dissolved oxygen levels of water in the gravel

Table 9.--Comparison of dissolved oxygen and temperature gradations at two locations in Indian Creek study riffle, September 1959

Depth in gravel	Near the bank (ground-water seepage)		Near center of stream (no ground-water seepage--interchange)	
	Dissolved oxygen	Temperature	Dissolved oxygen	Temperature
Inches	Mg./l.	° F.	Mg./l.	° F.
5	7.0	51.0	10.1	51.0
10	4.4	50.5	9.9	50.8
15	1.4	48.0	-	-
20	0.5	45.5	9.7	51.0

of the main stream channel also usually approximated dissolved oxygen levels of the flowing stream, except in areas under ground-water influence and during low stream levels when interchange was minimized.

On the other hand, within the gravel of the bar, both temperature and dissolved oxygen content of water varied widely depending on stream level. The bar was covered with water on high stream levels (the bar became a part of the main stream channel at a stream gage reading of 2.20 or more) and uncovered on low stream levels (stream gage reading of 1.90 or less). Dissolved oxygen content of water in the gravel of the bar increased with an increase in stream level. This is shown in figure 9. The shapes of the curves representing the increase of dissolved oxygen with stream level at individual standpipes differ because (1) some of the standpipes were located at points where the gravels were more permeable, hence more interchange occurred, (2) some of the curves represent points closer to ground-water outflows, and (3) standpipes were not all at the same depth below the water table.

When stream level was above 2.2 feet and stream water ran over the bar, there was a fairly good relationship between temperature and dissolved oxygen (upper fig. 10).

At a lower stream level sampling points showed a different temperature-dissolved oxygen relationship (lower fig. 10). First, dissolved oxygen levels were generally lower than they were on a higher stream level. Second, although dissolved oxygen and temperature at points 3, 43, 6, and 66 have remained generally low, the water at points which were previously high in dissolved oxygen (64, 29, 9, 2, 20, 30, 67, and 63) shows a marked decrease in dissolved oxygen content, but either remains the same or increases in temperature.

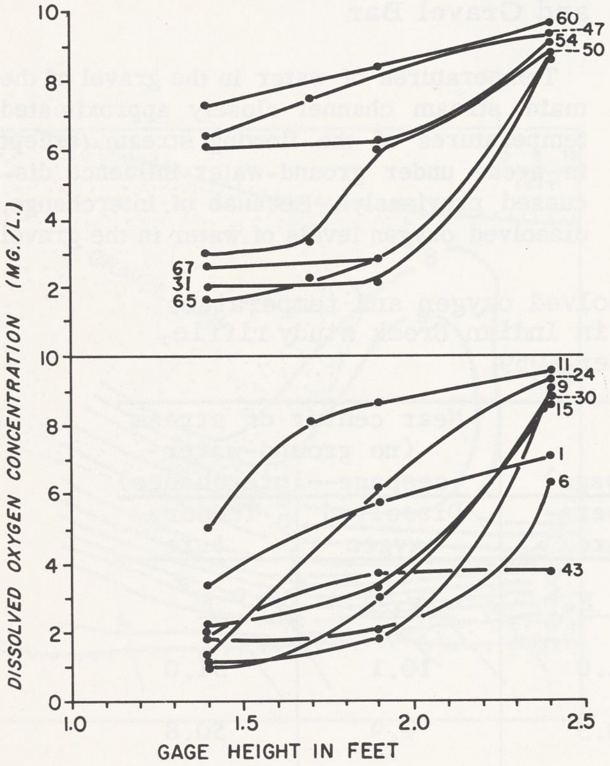

Figure 9.--Increase in dissolved oxygen levels of water in the gravel bar with increase in stream water levels, Indian Creek, August 1958. (Numbers correspond to standpipe locations shown in figure 2. Relative depths of pipes shown in figure 3.)

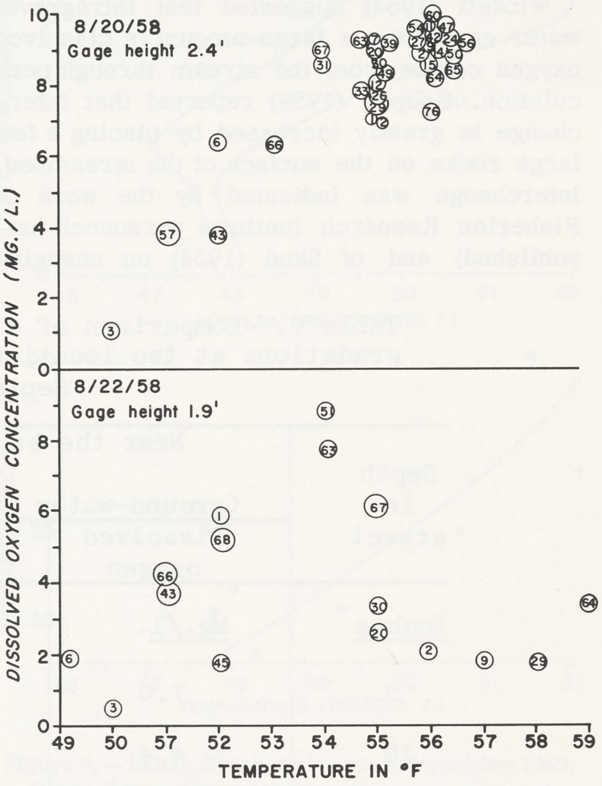

Figure 10.--Dissolved oxygen levels plotted against water temperatures on two different gage heights, Indian Creek, August 1958. (Numbers correspond to standpipe locations shown in figure 2. Relative depths of pipes shown in figure 3.)

I suggest that the reason for a decrease in dissolved oxygen with an increase in temperature (above and beyond decrease due to temperature alone) is that the absence of a layer of water over the bar prevents interchange. Ground-water influence can be ruled out, for the water temperatures are too high to indicate the presence of ground water. Therefore, dissolved oxygen was maintained on a high level as long as surface stream water flowing over the bar permitted interchange to take place. But as soon as the stream level dropped, no interchange occurred, and water flowing through the bar was subject to a continuous oxygen depletion from biochemical oxygen demand.

That such depletion can occur may be indicated indirectly. The range of 27 flow velocity measurements made in the bar in 1956 (by timing the appearance of dye-marked water) was from 2 to 170 feet per day with an average of 37 feet per day. Based on this average velocity and the length of bar, it is possible that high oxygen content water entering the upper end of the bar would be subject to a biochemical oxygen demand for 2 days at a temperature around 55° F. In preliminary studies on the biochemical oxygen demand of Indian Creek gravels, dissolved oxygen content fell from 9.5 to 2.2 mg./1. in 48 hours at an average water temperature of 52.5° F.

DISCUSSION

Ground water in the Indian Creek study riffle was generally low in dissolved oxygen, and dissolved oxygen levels decreased with depth in streambed gravels. Thus, by a process of elimination we can corroborate reports of Royce (1959) and Vaux and Sheridan (1960) that the primary source of high oxygen content intragravel water in salmon streams is the stream itself.

Therefore, if anything interferes with interchange of stream and intragravel water, the amount of dissolved oxygen available to salmon eggs will be decreased, and the rate of flow past embryos will be lowered. Silting of the streambed, by lowering permeability of streambed gravels, can definitely interfere with interchange. An algae cover over the streambed (such as that observed in Indian Creek in September 1957) is another factor that can interfere with interchange.

It is also possible that varying amounts of fine materials in spawning riffle streambeds are responsible for some streams producing more salmon than others. Wickett (1958) found a relationship between permeability of streambed gravels and pink and chum *(Oncorhynchus keta)* salmon fry production in British Columbia streams. If high permeabilities are desirable and a large amount of fines are detrimental to survival of salmon eggs, fines can be removed. This action would increase dissolved oxygen levels and flow rates and enhance survival of salmon embryos.

Low dissolved oxygen levels of Indian Creek ground water during summer and fall months indicate that areas of ground-water effluence may be harmful to salmon eggs. But on the other hand we found that in both Cabin and Indian Creeks ground water was colder than stream water, in summer and warmer in winter. Therefore, as Needham and Jones (1959) point out, ground water may have a tempering effect on stream water and help prevent freezing of streambed gravels. This possibility can easily be investigated, since ground water in salmon spawning riffles can be detected and traced through its distinctive qualities of dissolved oxygen and temperature.

Although ground water has either a harmful or beneficial effect (depending on circumstances) in upstream spawning areas, it is doubtful if it has any direct effect at all in intertidal areas where great numbers of pink salmon spawn in Southeastern Alaska, Prince William Sound, and other regions. Intertidal areas are often underlain by impervious bedrock or a clay layer at relatively shallow depths, and streams meander through extensive tide flats composed mostly of mud. Only main stream channels are kept clean. Since there is no place for ground water to come from, intragravel water in intertidal areas must depend exclusively on interchange for replenishment of dissolved oxygen and on ebb and flow of warmer salt water for protection against freezing.

Because of low ground-water dissolved oxygen, Indian Creek (and probably many other streams in Southeastern Alaska and elsewhere) apparently differs from spawning areas in which the presence of ground water has been reported to affect beneficially spawning of adult salmonids and survival of their eggs and larvae. White (1930), Greeley (1932), Hazzard (1932), and Benson (1953) all stated that the presence of springs and of ground-water seepage determined the location of spawning areas of brook and other species of trout. Benson also said that ground-water seepage affected both sizes and numbers of all age groups of brook and brown trout in the Pigeon River, Mich.

Association of sockeye salmon spawning with ground water has been mentioned by Burgner (1958), and Mathisen (1955) for Bristol Bay, Alaska, and by Krogius (1951), Krokhin and Kurenkov (1954), Krogius and Krokhin (1948), and Kurenkov (1957) for the Kamchatka Peninsula. Royce (1951) found no evidence that lake trout select a lake bottom supplied with spring water for deposition of their eggs.

Results of temperature and dissolved oxygen measurements of water in the gravel bar of the study riffle in Indian Creek furnish indications as to whether or not a gravel bar is a favorable environment for developing salmon eggs. In almost every stream suitable for pink salmon spawning in Southeastern Alaska, there are extensive gravel bars (termed marginal or fringe spawning areas) on which heavy spawning sometimes occurs when stream level and population pressure are high. In Cabin Creek I determined that spawning in a cross section of a riffle increased by 50 percent with a rise in stream level of 1.1 feet (gage height from 0.48 to 1.58 feet). Since salmon eggs and larvae that are developing in marginal spawning areas are subject to fluctuating stream heights and are often exposed to prolonged periods of low air temperatures, their chance for survival would appear to be low. Hunter (1959) reported that in some years spawning in fringe areas showed greater survival ratios than spawning in other areas in Hooknose Creek, British Columbia. He attributed high survival years to relatively constant water levels and absence of persistent freezing temperatures.

Since salmon eggs deposited in certain parts of the marginal spawning area in the Indian Creek study riffle would be subject to intermittent high temperatures and low dissolved oxygen levels, this does not appear to be a favorable environment for survival.

SUMMARY

Part of study conducted by the Fisheries Research Institute on effects of logging in southeastern Alaska salmon spawning streams was an investigation of waterflow through the gravel of a spawning riffle in Indian Creek. This investigation included a determination of (1) dissolved oxygen content and temperature of ground water and the extent of ground-water seepage, (2) variation of dissolved oxygen content of water with depth in the streambed, (3) interchange of flowing stream water and water of the streambed gravel, and (4) flow characteristics of water in the gravel of streambank and gravel bar.

Through tracing flow directions with fluorescein dye and measuring the dissolved oxygen content and temperature of stream and ground water, we found the following:

1. Ground water was low in dissolved oxygen at all times of the year except the winter months when ground-water temperatures were lowest.

2. Ground-water temperatures were lower than stream temperatures during the summer and higher during the winter.

3. Dissolved oxygen content of water within the gravel of the streambed decreased with depth.

4. Ground water flowed from the streambank into the streambed. Its presence was detected by its dissolved oxygen and temperature differences.

5. The major source of water of high oxygen content within the gravels of the riffle was the stream. This was determined by demonstrating large-scale interchange in the main stream and by measuring dissolved oxygen content and temperatures of water in the gravel of a gravel bar with intermittent surface flow.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the foresight of William F. Thompson, who formulated basic concepts of ground-water hydrology and interchange of stream and intragravel water in a salmon stream some years ago. He also wishes to express his appreciation to William F. Royce, Robert L. Burgner, and Ted S. Y. Koo of the Fisheries Research Institute, for helpful suggestions in the preparation of this paper.

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BUREAU OF COMMERCIAL FISHERIES, Donald L. McKernan, *Director*

INTERCHANGE OF STREAM AND INTRAGRAVEL WATER IN A SALMON SPAWNING RIFFLE

by

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Contribution No. 82, College of Fisheries, University of Washington

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INTERCHANGE OF STREAM AND INTRAGRAVEL WATER IN A SALMON SPAWNING RIFFLE

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ABSTRACT

Dissolved oxygen is supplied to intragravel water in a salmon spawning riffle through (1) interchange of water from the stream into streambed gravel, and (2) ground-water flow. The primary variables that control interchange are gradients in the stream profile, permeability of the gravel bed, and dimensions of the bed.

The delivery of dissolved oxygen to intragravel water and the way in which rate of delivery is affected by stream profile, permeability, and dimensions of the bed are explained.

INTRODUCTION

While buried in the gravels of streams for 6 to 9 months, eggs and larvae of the Pacific salmon *(Oncorhynchus)* are subjected to various environmental factors causing mortality, such as floods and freezing (Royce, 1959). Other important factors that affect mortality are dissolved oxygen content and rate of flow of intragravel water[1] that bathes buried salmon eggs and larvae (Wickett, 1958).

Oxygen dissolved in intragravel water is consumed by biological and chemical processes and must be resupplied by diffusion, ground-water flow, or circulation between aerated stream water and water in the gravel. The circulation between stream and intragravel water is called interchange and is either an upward or downward flow.

The Fisheries Research Institute started studies of interchange in 1948 under the direction of Dr. William F. Thompson. These studies were interrupted in 1949 and were not resumed until 1957 when they became part of a project to study effects of logging on productivity of pink salmon *(Oncorhynchus gorbuscha)* in streams of Southeastern Alaska.[2] In 1957 the occurrence of interchange was qualitatively demonstrated in a spawning riffle by injecting dye into the gravel through standpipes and detecting the appearance of dye at the surface of the gravel downstream from the point of injection. In 1958 and 1959 preliminary studies were conducted by the writer in a small flume at the University of Washington Chemical Engineering Laboratory to identify some of the variables that control interchange. During the summer of 1959 studies conducted in a pink salmon spawning riffle in Indian Creek in the Kasaan Bay area of Southeastern Alaska (fig. 1) provided qualitative verification of the dependence of interchange on stream gradient and profile.

The study of interchange is being continued. In addition to field investigations, a quantitative

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[1] The term "intragravel water" refers to water occupying interstices in gravel beds.

[2] Contract with Bureau of Commercial Fisheries, U.S. Fish and Wildlife Service.

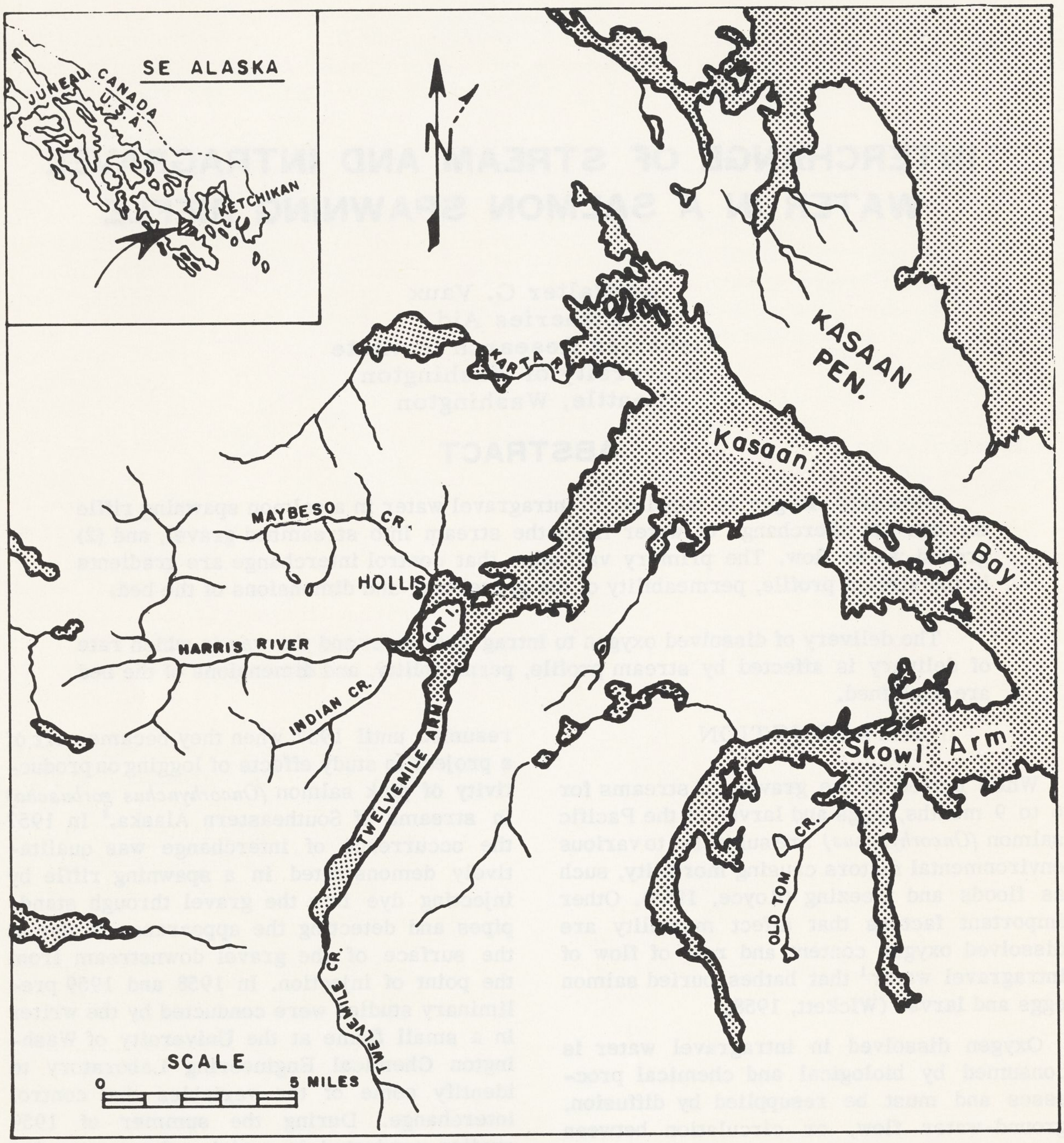

Figure 1.--Location of study streams, Hollis area.

laboratory study of the dependence of interchange upon stream gradient and profile and gravel permeability is being carried on by the writer as a thesis research program at the University of Minnesota Department of Chemical Engineering.

The primary purpose of this paper is to present a theory of interchange. Results of field experiments demonstrating interchange are also described.

THEORY OF INTERCHANGE AND INTRAGRAVEL OXYGEN RESUPPLY

The initial source of oxygen that is dissolved in intragravel water is the atmosphere. The purpose of this discussion is to describe the processes that operate to transport free gaseous oxygen from the atmosphere to intragravel water of salmon spawning riffles.

Transport Processes

Stream-intragravel interchange.--The steps involved in physical transport of free oxygen to intragravel water are:

1. Dissolution of oxygen through air-water interface into stream water.

2. Transport of oxygenated water to the stream bottom.

3. Interchange of oxygenated water from the stream into the porous gravel interior.

These steps are diagrammed in figure 2.

Since this is a series process, the rate at any point will control the entire process.

Rate of oxygen dissolution in standing water is dependent upon temperature, surface area, and difference in partial pressure of oxygen dissolved in water and oxygen in the atmosphere. It is normally a slow process and may be controlling. The dissolution of oxygen in turbulent stream water, however, is a rapid process compared with subsequent steps and is normally not controlling. This is shown by the near-saturation oxygen level in surface water of unpolluted streams.

Dissolved oxygen, present at the stream surface, may be transported to the stream bottom through diffusion or turbulent water current. In the case of standing water, for instance a pool or pond, the water is motionless or in laminar flow. Here the transport of dissolved oxygen is mostly by diffusion, and a downward movement of oxygen is due to differences in oxygen concentration between highly oxygenated surface and poorly oxygenated bottom water.

On the other hand, a stream or river of the kind used by salmon for spawning will usually be in turbulent flow (Russel, 1942), which is characterized by continuous swirling, eddy crosscurrents, and complete mixing. Consequently, oxygenated surface water (saturated with dissolved oxygen) is mechanically carried to all depths of the stream (O'Connor and Dobbins, 1956). Turbulent transport is a rapid process and is not controlling.

For oxygenated water to enter the streambed a force must exist to induce flow across the gravel boundary. Consider a stream flowing over a smooth-surfaced gravel bed of constant permeability and gradient. Turbulent conditions do not exist at the thin water layer adjacent to the stream bottom (McCabe and Smith, 1956), and there is no reason to expect interchange. For interchange to occur there must be inherent factors in the surface water, streambed surface, or streambed interior affecting interchange. The factors that possibly control interchange include (1) stream surface profile, (2) gravel permeability, (3) gravel bed depth, and (4) irregularity of the streambed surface.

If the stream surface profile is not curved, if the gravel bed is of constant permeability

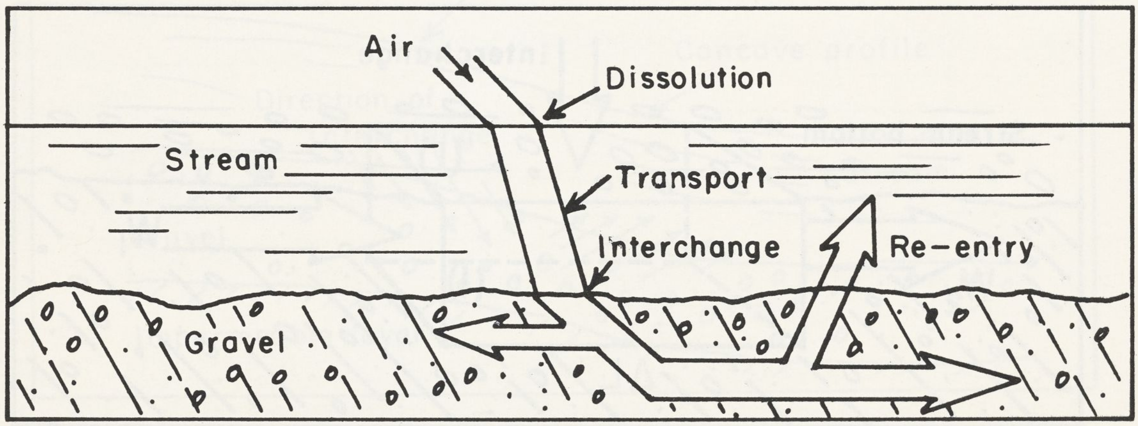

Figure 2.--Oxygen transport through stream to gravel bed.

and depth, and if the stream bottom is smooth, no interchange should occur. If gradient, permeability, or bed depth vary in the direction of intragravel flow, however, interchange should occur. Each of the three variables may cause a change in total intragravel flow independently of the others.

D'Arcy's law of flow related fluid flow velocity in a porous gravel bed to permeability and the energy change within the bed, viz.,

$$V = \frac{-k(\Delta h)}{L} \qquad (1)$$

where V is the average flow velocity, k the gravel permeability and Δh the loss in specific energy through the bed length L (Scheidegger, 1957; King and Brater, 1954). To describe the flow of water within a streambed, the energy change and bed length may be combined, giving,

$$V = -k \sin \theta \qquad (2)$$

where θ is the angle of the energy line, that is, the rate at which energy is lost in the direction of flow (American Society of Civil Engineers, 1949).

In the discussion that follows it will be assumed that the energy line and stream surface profile or hydraulic gradient are approximately equal, that is, they have the same slope and curvature. In extreme cases, for instance hydraulic jump, slopes of the energy line and stream profile differ greatly; however, cases to be considered here are assumed to have nearly uniform flow. Hence, θ will be the slope of the stream surface profile in the direction of intragravel flow. Permeability, defined by equation (1), is the property of gravel permitting fluid flow and is affected by gravel particle size, size distribution, porosity, organic content, and particle shape.

Consider the intragravel channel of unit width and depth, the upper face of which is the gravel surface and the bottom face and sides of which are impermeable boundaries. Axial flow within this channel follows the continuity equation (Lapple, 1951).

$$W = Ap\,V \qquad (3)$$

where W is the mass flow rate (weight of water flowing per unit time), A the channel cross-section area, p the water density, and V the average intragravel velocity. By substitution of equation (2) in (3)

$$W = -k\,Ap \sin \theta \qquad (4)$$

Since the channel cross-section area is assumed to be constant, any increase in mass flow rate must enter the channel by interchange across the gravel surface.

Interchange may be measured by the variable, I, the flow rate of stream water entering the gravel per unit area of gravel surface. The interchange flow into the intragravel channel must equal the change of axial intragravel flow, W. Considering flow along an increment of length, Δ L (fig. 3), (intragravel

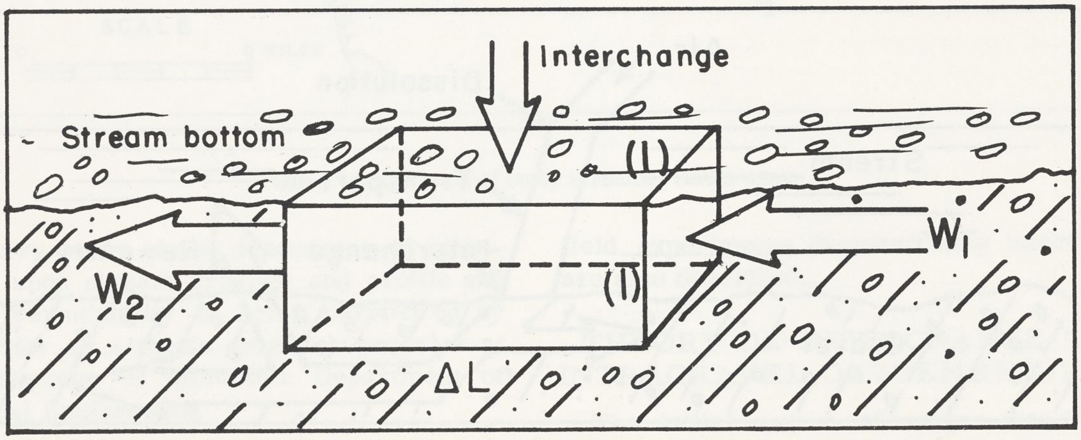

Figure 3.--Interchange and intragravel flow to a channel section.

flow rate in) - (intragravel flow rate out) = I (width of channel x length of channel) or, since the width is assumed to be one unit, $\triangle W = I \cdot \triangle L$ which may be expressed as first derivative,

$$I = \frac{dW}{dL} \qquad (5)$$

Applying this to equation (4),

$$I = -k\,Ap\cos\theta\,\frac{d\theta}{dL} \qquad (6)$$

Since kAp is positive, and for $\theta < \frac{\pi}{2}$, $\cos\theta$ is positive, hence the sign of I and the direction of flow depends upon the sign of $\frac{d\theta}{dL}$. Three cases may be considered:

1. If the stream surface profile is a straight line (not necessarily horizontal), $\frac{d\theta}{dL} = 0$ and there is no interchange.

2. If the surface profile is concave, $\frac{d\theta}{dL}$ is positive, I is negative indicating a flow out of the gravel.

3. If the surface is convex, $\frac{d\theta}{dL}$ is negative, I is positive indicating a flow into the gravel.

In other words, a curved stream surface due to change in profile slope forces an acceleration or deceleration of intragravel flow. A convex surface causes a faster intragravel flow velocity downstream. Since, by definition, the lower boundary is impermeable in this model (fig. 4), water must enter the intragravel channel, by necessity through the gravel surface, to provide the additional mass flow.

Cooper (1959) reported that under constant-gradient smooth-bed surface flow conditions, intragravel flow lines were generally parallel to the bed with some interchange near the surface. He also stated that interchange in the upper 1-foot stratum was greatly increased if large rocks were placed on top of the bed, and that extensive downward interchange could be expected if a hump of gravel was formed by a female salmon digging an egg pocket. In either case--piled rocks or a hump in the stream bed--the water surface is forced to a convex profile and conditions provide a force for downward interchange.

While the curvature of the stream profile induces interchange through controlling intragravel flow velocity, a second effect is the centrifugal pressure due to curved flow. It may be shown, however, that usually the centrifugal effect is negligible.

Varying permeability of streambed gravel is a second cause of interchange. In a stream in which gravel permeability changes, although the stream gradient remains constant and has

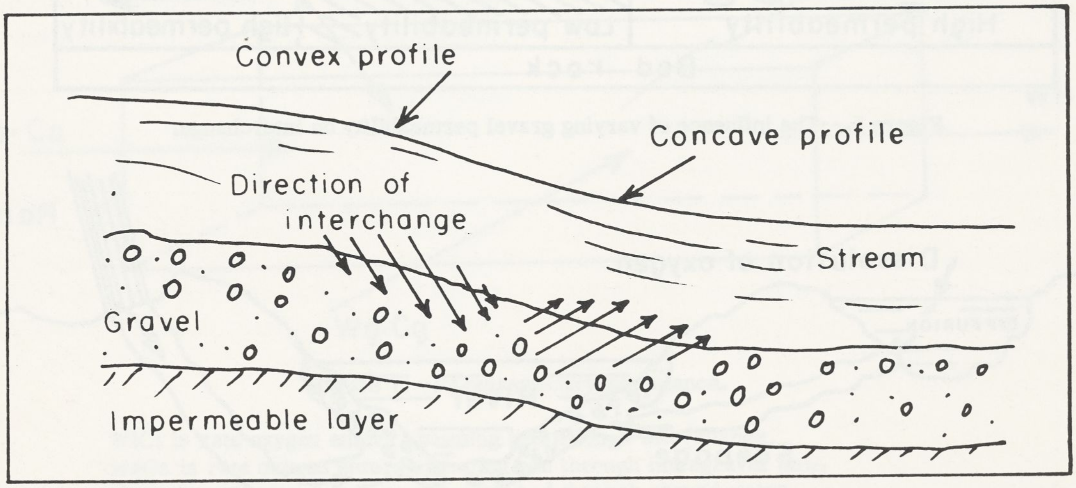

Figure 4.--Longitudinal stream profile showing surface-induced interchange when gravel is underlain with impermeable layer.

a planar gravel surface, the intragravel flow velocity will necessarily increase or decrease. If an area of low gravel permeability occurs between two areas of high permeability, interchange will occur as shown in figure 5.

Looking again at the continuity equation (3), a third cause of interchange is suggested: a change in intragravel flow area or, in effect, gravel bed depth. As gravel depth increases in the direction of flow (assuming constant slope and velocity) the total intragravel flow must proportionately increase, and there will be interchange into the gravel.

A fourth possible source of interchange is the roughness and irregularity of the streambed. It is surmised that the composite effect of surface irregularities and fluid inertia causes a channeling of surface water into the gravel bed.

Since interchange may be either an upwelling, a downdraft, or not present at all, it is a controlling variable in the oxygen transport process from air to gravel interior.

Of final consideration is the actual intragravel flow of water. By D'Arcy's law, intragravel flow velocity depends upon stream gradient and permeability. Since both stream gradient and permeability may vary to restrict or freely permit intragravel flow, they are also controlling variables.

Ground-water oxygen transport.--The mechanisms of ground-water oxygen transport are:

1. Dissolution of atmospheric oxygen in standing surface water (lakes, ponds) or rain.

2. Diffusion of oxygen to lower levels of standing water.

3. Seepage of oxygenated water through soil to the intragravel strata.

This process is shown in figure 6.

Ground-water oxygen transport is subject to controlling variables in each step of the series process. Diffusion of oxygen through

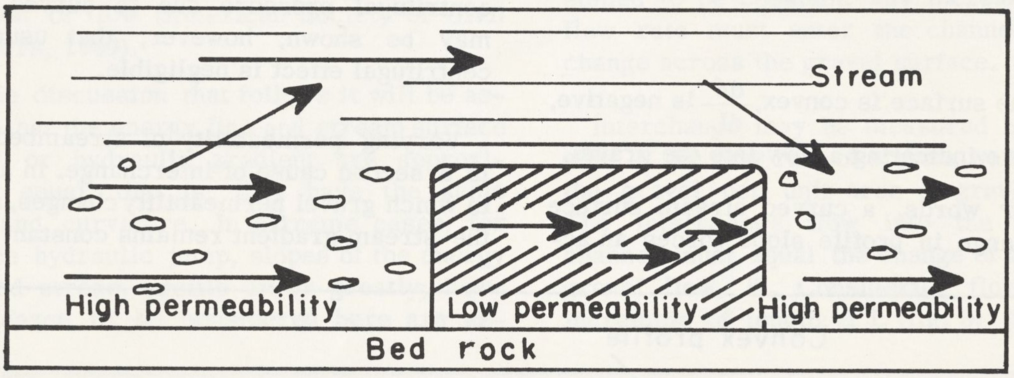

Figure 5.--The influence of varying gravel permeability on interchange.

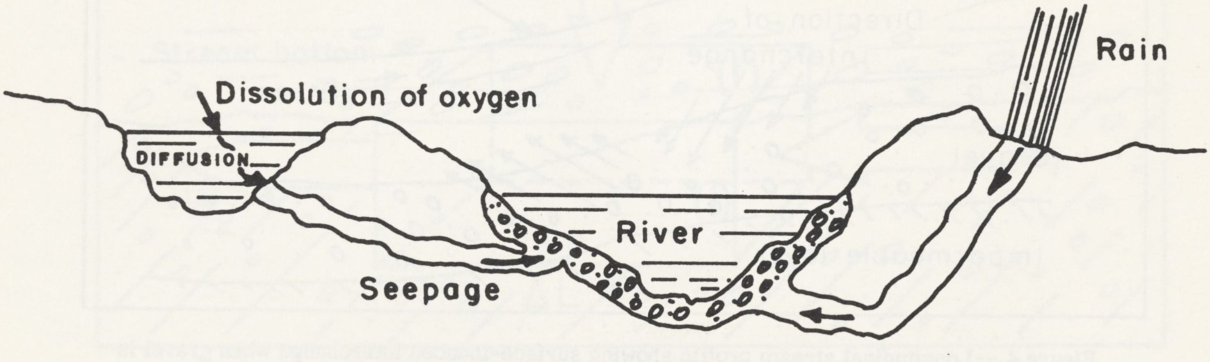

Figure 6.--Ground-water oxygen transport.

standing water is extremely slow; the flow rate of water through soil is restricted through low permeability; and dissolved oxygen in soil water is subject to biochemical oxygen demand.

Intragravel Oxygen Balance

At any instant, a given volume of spawning gravel may be assumed to be in a steady state with regard to supply and removal of dissolved oxygen; that is, dissolved oxygen is supplied and removed at a constant rate. Intragravel dissolved oxygen sources are stream water and ground water having high dissolved oxygen content. Depletion is a result of biochemical oxygen demand and dilution with ground water having low dissolved oxygen content. Periphyton on and near the gravel surface also has an influence on oxygen balance, producing oxygen in the presence of sunlight and consuming oxygen during periods of darkness. Its influence on intragravel dissolved oxygen levels is poorly understood.

Consider the ideal intragravel system pictured in figure 7.

Here interchange (i), ground water (g), and intragravel flow (a) are supplying dissolved oxygen at different concentrations and flow rates. Oxygen is leaving the system through intragravel flow (f), and biochemical oxygen demand (B), (and upwelling if Wi is negative).

A complete oxygen balance over an intragravel volume may be expressed as:

$$WiCi + WaCa + WgCg = WfCf + VB$$

Where W is the volumetric flow rate, $\frac{\text{cm.}^3 \text{ water}}{\text{sec.}}$; C the dissolved oxygen concentration, $\frac{\text{g. oxygen}}{\text{cm.}^3 \text{ water}}$; V the volume of gravel, cm.^{3}; and, B the biochemical oxygen demand, $\frac{\text{g. oxygen}}{\text{cm.}^3 \text{ gravel sec.}}$.

By careful measurements, stream profiles and gravel permeabilities (Pollard, 1955) may

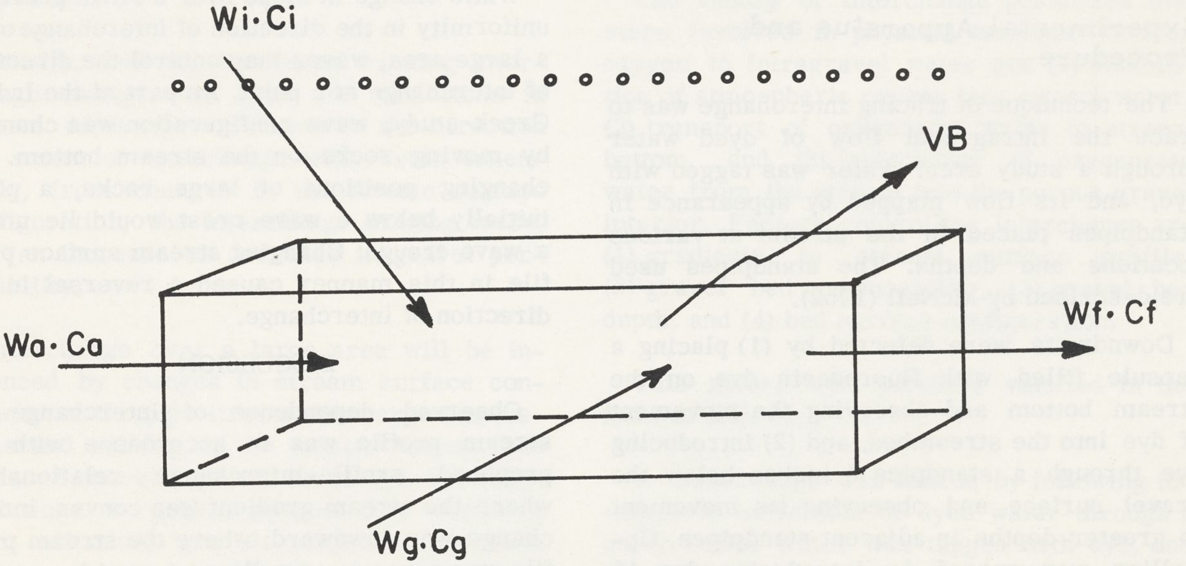

Figure 7.--Intragravel oxygen balance.

WiCi is rate oxygen enters spawning bed through interchange.
WaCa is rate oxygen enters spawning bed through intragravel flow.
WgCg is rate oxygen enters spawning bed through ground water.
WfCf is rate oxygen leaves spawning bed through intragravel flow.
VB is rate oxygen leaves spawning bed through biochemical oxygen demand.

be determined and through such physical studies, the dissolved oxygen supply to intragravel strata may be quantitatively predicted. Qualitatively, intragravel dissolved oxygen levels will be increased by interchange and will be lowered by ground-water dilution and biochemical oxygen demand (Hobbs, 1937).

FIELD VERIFICATION OF THE SLOPE-INTERCHANGE MECHANISM

The occurrence of interchange has been previously reported (Cooper, 1959). In the field of intragravel flow, investigators have described the conditions under which interchange occurs; however, the mechanism of water flow from stream to gravel has not been defined.

From ground-water and intragravel flow studies in Indian Creek in 1957 and 1958, techniques for qualitatively detecting interchange flow were developed. After the theory of interchange was proposed, work was started to verify the proposed slope-interchange mechanism.

Experimental Apparatus and Procedure

The technique of tracing interchange was to trace the intragravel flow of dyed water through a study area. Water was tagged with dye, and its flow mapped by appearance in standpipes placed in the stream at various locations and depths. The standpipes used are described by McNeil (1962).

Downdrafts were detected by (1) placing a capsule filled with fluorescein dye on the stream bottom and observing the movement of dye into the streambed, and (2) introducing dye through a standpipe 6 inches below the gravel surface and observing its movement to greater depths in adjacent standpipes. Upwelling was traced by introducing dye 18 inches below the gravel surface and observing its movement to adjacent pipes nearer the gravel surface and to the gravel surface. For each location where interchange was observed, shape of the stream surface was determined with a transit and stadia rod.

Results

Observations were made in several convex and concave riffles of Indian Creek. In most cases, to provide a point of zero intragravel velocity, a pool bounded one end of each study section. Observed direction of interchange in concave riffles was invariably an upwelling of intragravel water. In convex sections, that is, where the stream gradient increased in the direction of flow, interchange was from stream to gravel (downdraft).

In tracing intragravel flow, it was observed that upwelling occurred in certain sections having constant gradient. Upon examining conditions surrounding these points of upwelling, it was noted that small irregularities in the stream bottom created waves on the water surface. Points of upwelling were directly below troughs of waves.

Influence of waves upon interchange was investigated in more detail by tracing the direction of interchange beneath large waves created by placing large rocks on the streambed. Results showed that upwelling occurred beneath the troughs of waves and downdrafting occurred beneath wave crests.

While change in slope over a riffle provides uniformity in the direction of interchange over a large area, waves may control the direction of interchange at a point. As part of the Indian Creek study, wave configuration was changed by moving rocks on the stream bottom. By changing positions of large rocks, a point initially below a wave crest would lie under a wave trough. Changing stream surface profile in this manner caused a reversal in the direction of interchange.

DISCUSSION

Observed dependence of interchange on stream profile was in accordance with the proposed profile-interchange relationship; where the stream gradient was convex, interchange was downward; where the stream profile was concave, upwelling occurred.

Change in stream gradient over a long distance, for instance 10 feet, provides a unidirectional interchange over a large area. However, the point interchange driving force, inherent in waves, induces a comparable total flow over a smaller area. Beneath the wave are adjacent areas of upward and downward flow which provide a rapid circulation of water over a small area.

It is to be noted that the assumption of equal hydraulic and energy gradients no longer applies. Although there is no apparent basis for predicting the direction of interchange beneath a wave, there is certainly an energy dissipation through the wave. For the general case of equal energy and hydraulic gradients upstream and downstream from a wave there must necessarily be a point of inflection in the energy line and, in turn, adjacent areas of downward and upward interchange.

Another consideration in comparing profile and point interchange is the location of points of interchange in the stream. Assuming constant gravel permeability, interchange due to the axial profile can be expected to be in the same direction across the stream. On the other hand, the occurrence and size of waves vary with velocity of flow. Accordingly, point interchange can be expected to be low in calm water near the stream shore and most extensive at midstream points where turbulence is greatest.

Finally, how do conditions causing interchange change with time and variations in stream discharge? Changes in the direction and extent of interchange will result, essentially, from changes in the stream surface configuration, the interchange driving force, and an increase or decrease in gravel permeability.

Interchange over a large area will be influenced by changes in stream surface configuration through stream discharge fluctuations and shifting of the stream bottom. The extent of interchange will be governed through variations in gravel permeability resulting from siltation, gravel compaction, organic content, and gravel shift.

Point interchange, too, will depend upon stream discharge, in this case, however, through its effect on surface wave configuration. During low stream discharge the water surface is comparatively calm and point interchange will be reduced accordingly. Relative dissolved oxygen levels tend to verify this: McNeil (1962) has shown through extensive intragravel dissolved oxygen sampling that the intragravel dissolved oxygen content increases with stream discharge, and Wickett (1958) has proposed that low oxygen levels of intragravel water are associated with periods of low stream discharge.

SUMMARY

Studies of interchange of stream and intragravel water were conducted in 1957, 1958, and 1959 as part of a project that is supported by the Bureau of Commercial Fisheries to study the effects of logging on pink salmon production. Interchange was first qualitatively demonstrated in a salmon spawning riffle in Indian Creek in Southeastern Alaska. Then, experimental research was carried on at the University of Washington Chemical Engineering Laboratory to determine variables that control interchange and, finally, additional field studies in Indian Creek provided a qualitative verification of dependence of interchange on stream gradient and other factors.

The theory of interchange postulates that steps involved in physical transport of free oxygen to intragravel water are (1) dissolution of atmospheric oxygen into stream water, (2) transport of oxygenated water to stream bottom, and (3) interchange of oxygenated water from the stream into the porous gravel interior. Factors controlling interchange are (1) gradients in stream surface profile, (2) gravel bed permeability, (3) gravel bed depth, and (4) bed surface configuration.

This theory was partially verified in the field as follows:

1. Interchange was traced by following intragravel movement of dyed water through a study riffle. Water was tagged with dye, and its direction of flow mapped by appearance in standpipes placed in the stream at various locations and depths.

2. Downward interchange was detected by (1) placing a capsule filled with fluorescein dye on the stream bottom and observing dye

downdraft, and (2) introducing dye through a standpipe 6 or more inches below the gravel surface and tracing its movement by detection in standpipes at greater depths.

3. Upward interchange from gravel to stream was followed by introducing dye below the gravel surface and tracing its direction of flow through appearances in pipes at lesser depths and at the gravel surface.

Direction of interchange depends on stream surface profile and bed surface configuration:

1. Direction of interchange in that part of a riffle with a concave surface (stream gradient decreases in direction of flow) was upwards--intragravel to stream.

2. Direction of interchange in that part of a riffle with a convex surface (stream gradient increases in direction of flow) was downwards--stream to intragravel.

3. Direction of interchange under the troughs of standing waves created by irregularities in the streambed was upwards; intragravel to stream. Direction of interchange under crests of waves was downwards--stream to intragravel.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the guidance of William L. Sheridan and William J. McNeil in the field studies. He is also indebted to William F. Royce, Robert L. Burgner, and Charles O. Junge, Jr. of the Fisheries Research Institute and to Eugene P. Richey of the Department of Civil Engineering of the University of Washington for helpful suggestions and criticism in the preparation of this paper.

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Fish and Wildlife Service, Clarence F. Pautzke, Commissioner
Bureau of Commercial Fisheries, Donald L. McKernan, Director

VARIATIONS IN THE DISSOLVED OXYGEN CONTENT OF INTRAGRAVEL WATER IN FOUR SPAWNING STREAMS OF SOUTHEASTERN ALASKA

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ABSTRACT

Inexpensive equipment for sampling intragravel water for dissolved oxygen is described. Water samples were withdrawn from plastic standpipes driven into the streambed. Dissolved oxygen values representative of points sampled were obtained from 30-ml. samples of water taken about 24 hours after standpipes were placed.

Fourfold seasonal and yearly changes in dissolved oxygen levels were observed. Spatial differences in dissolved oxygen levels were greatest when discharge was low and temperature was high.

For routine measurement of dissolved oxygen level random sampling was tried and found to be satisfactory.

INTRODUCTION

Pink salmon *(Oncorhynchus gorbuscha)* and chum salmon *(O. keta)* spend only brief periods in fresh water as fry and spawning adults, but their eggs and larvae commonly remain in the streambed 6 to 8 months. During this period mortality is influenced largely by physical conditions, and a decline in quality of the streambed environment may cause considerable mortality.

Mortality of pink and chum salmon is high in fresh water. Neave and Foerster (1955) summarized data obtained over several years on mortality observed in five British Columbia and Southeastern Alaska streams. The stream experiencing the highest mortality had a geometric mean yearly mortality of 99.7 percent, while the stream experiencing the lowest mortality had a geometric mean yearly mortality of 86.8 percent. Because mortality estimates were based on counts of adult females migrating into the streams and of their progeny migrating out of the streams, it was not possible to differentiate among prespawning, egg, larval, and postemergent losses. There is evidence, however, that a considerable portion of fresh-water mortality of pink and chum salmon occurs during embryonic development.

Estimated mortality of chum salmon eggs and larvae ranged from 75 to 95 percent over a 4-year period in a controlled stream (Wickett, 1952). In another experiment (Neave and Wickett, 1955), eyed pink salmon eggs were planted in an artificial spawning channel. Approximately 19 percent were estimated to have died prior to hatching. Mortality up to time of migration was estimated to be 58 percent.

Hunter (1948) excavated natural redds in British Columbia streams during January and found that 86 percent of the chum salmon embryos and 97 percent of the pink salmon embryos were dead. Natural mortality of embryo pink and chum salmon has been observed in three streams in the Hollis area of Southeastern Alaska by the Fisheries Research Institute. Mortality prior to hatching has been observed to exceed 95 percent in certain important spawning areas. A high mortality during early stages of development was observed to occur in 1957 in association with low levels of dissolved oxygen.

Embryonic mortality has been attributed to a number of causes. Wickett (1958) proposed that the most important causes of mortality among eggs and larvae were closely associated with extreme low and high stream discharge. Further, the rate of oxygen supply to eggs was thought to be an important factor limiting survival during certain periods of low stream discharge.

The rate of oxygen supply to embryos has recently received attention by a number of investigators. Wickett (1954) pointed out that the rate of supply is a function of the flow velocity past the embryo, as well as the dissolved oxygen content of the intragravel water. He devised techniques and portable equipment for measuring seepage rate along with dissolved oxygen content. Other workers (Pollard, 1955; Terhune, 1958) have recently refined Wickett's method of measuring seepage rate. Gangmark and Bakkala (1959) also have

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Note.--The author is presently with the Bureau of Commercial Fisheries Biological Laboratory, Auke Bay, Alaska.

described a method for measuring seepage rate with equipment designed for permanent installation in the streambed.

Equipment required for measuring seepage rate is expensive. Furthermore, it is possible that the sampling effort required for statistical precision in measuring seepage rate in a natural stream will limit the application of this equipment.

Compared with measuring seepage rate, measuring dissolved oxygen content of intragravel water is a simple task requiring inexpensive equipment. It is also possible that oxygen content alone will provide a suitable index of quality of intragravel water in terms of survival of salmon embryos.

In view of these considerations, it is surprising that more attention has not been given to the observation of dissolved oxygen content of intragravel water and to the manner in which oxygen levels change with time and differ between sites. Based on samples obtained from nine points, Wickett (1954) made comparisons of oxygen levels among areas having normal gravel, consolidated gravel, and heavy silt deposits. Chambers, Allen, and Pressey (1955) sampled dissolved oxygen content of water seeping through salmon redds by withdrawing 250-ml. water samples from standpipes driven into the streambed. They found much spatial variation. Data on oxygen levels presented by Gangmark and Bakkala (1959) showed temporal changes in dissolved oxygen content of intragravel water to be of considerable magnitude, but their data were not intended to define precise relationships between time and oxygen level.

Observation of the dissolved oxygen content of intragravel water was undertaken by the Fisheries Research Institute in 1956 as a part of a study to evaluate the effects of logging on productivity of pink and chum salmon spawning streams in the Hollis area of Southeastern Alaska. The study was financed by the Bureau of Commercial Fisheries, with Saltonstall-Kennedy Act funds. Figure 1 shows the location of streams where the reported observations were made.

The study of dissolved oxygen content of intragravel water had two broad objectives: (1) to establish whether or not oxygen supply was an important factor associated with mortality in spawning beds and (2) to develop sampling techniques whereby dissolved oxygen level could be measured routinely as an index of environmental quality as it pertains to mortality of salmon embryos. It is the purpose of this paper to describe the methods adopted to obtain samples of intragravel water for the analysis of their dissolved oxygen content and to report observed spatial differences and temporal changes in dissolved oxygen levels.

The author wishes to acknowledge the many helpful suggestions given by William L. Sheridan, who was project leader during the period this study was conducted.

SAMPLING INTRAGRAVEL WATER FOR DISSOLVED OXYGEN CONTENT

It will be shown that dissolved oxygen levels of intragravel water vary greatly in space and with time. The nature of these variations requires that large numbers of oxygen readings be obtained simultaneously if precise estimates of dissolved oxygen levels are desired. It is also essential that water samples be as small as possible to avoid "contamination" of the sample with water from other strata. The sampling requirements therefore dictate to a great extent the design of equipment and the methods employed.

Obtaining Water Samples from Standpipes

Water samples were obtained from standpipes which were open cylinders having 20 holes, three-sixteenths of an inch in diameter, spaced in the lower 3 inches of pipe. A small hand drill was used to make the 3/16-inch holes. Standpipes were constructed of rigid plastic pipe sold under the trade name "Carlon." The inside diameter of the pipe was three-quarters of an inch.

Standpipes were driven into the streambed with a driving rod as illustrated in figure 2. The removable driving rod eliminated the need of having a solid head on each standpipe.

For routine sampling, the pipes were driven to a depth of 10 inches beneath the streambed surface. At this depth intragravel water could enter a standpipe only from 7 to 10 inches beneath the surface of the gravel. It was observed that pink salmon commonly buried their eggs at this depth in Hollis area streams.

After a standpipe was driven into the streambed, turbid water was removed by pumping. Terhune (1958) described a vacuum pump that was efficient for removal of turbidity. Standpipes were left overnight before dissolved oxygen determinations were made, since driving a pipe and clearing it of turbidity disturbed the streambed and may have temporarily facilitated the infiltration of above-gravel water.

A plastic standpipe could be driven into the streambed three to eight times, depending on gravel size and compaction, before damage to its lower edge made it unserviceable. Damaged standpipes were made serviceable

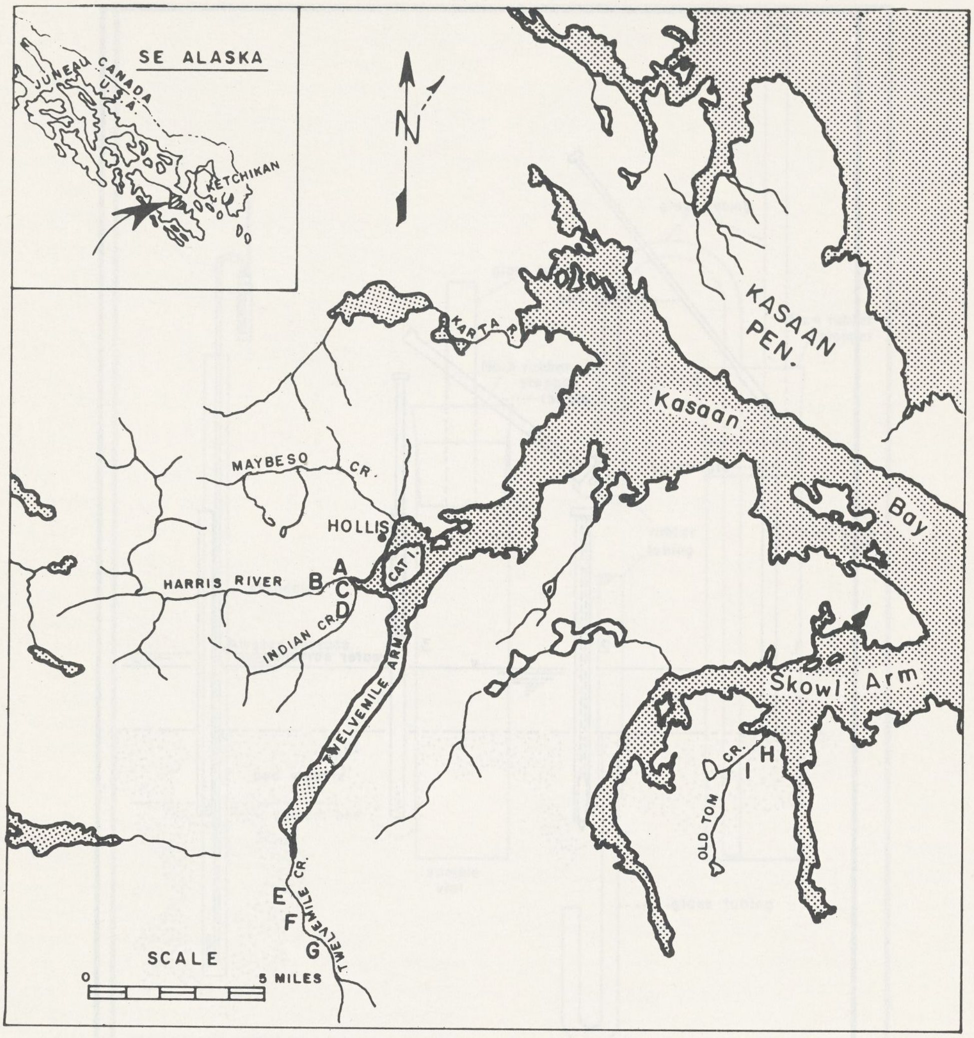

Figure 1.--Location of study streams, Hollis area, where dissolved oxygen levels reported in this paper were observed. Location of study areas is shown by capital letters.

again by removing the lower 3 inches and drilling new holes. Driving rods manufactured from high-quality steel withstood at least 1,000 drives.

Driving rods 36, 33, and 30 inches long were used. Standpipes were initially cut to fit the longest driving rod, and they were subsequently shortened to 33 and 30 inches, respectively, as their lower edges became damaged.

Water samples were sucked from standpipes with an apparatus constructed of tubing and a two-holed, No. 4 rubber stopper, and collected in 8-dram shell vials. Stoppers for the vials were one-holed, No. 3 rubber stoppers with a short piece of 6-mm. glass tubing inserted. Each component of the water sampling apparatus is illustrated in figure 3. Harper (1953) describes similar equipment.

To obtain a sample, the suction apparatus is connected to a vial. The glass tubing through which water enters the vial must extend nearly to the bottom. The suction line is inserted into a standpipe, and water is sucked from near the bottom of the well. About 10 cc. of water is discarded before the sample is collected. The suction line is pinched off before discarding the first 10 cc. of water, preventing the suction line from becoming drained and reducing contact of the water surface with the atmosphere. As the stopper is placed after collecting a sample, a column of water is allowed to rise about halfway up the glass tube in the stopper. Chemicals used to fix the water sample are introduced

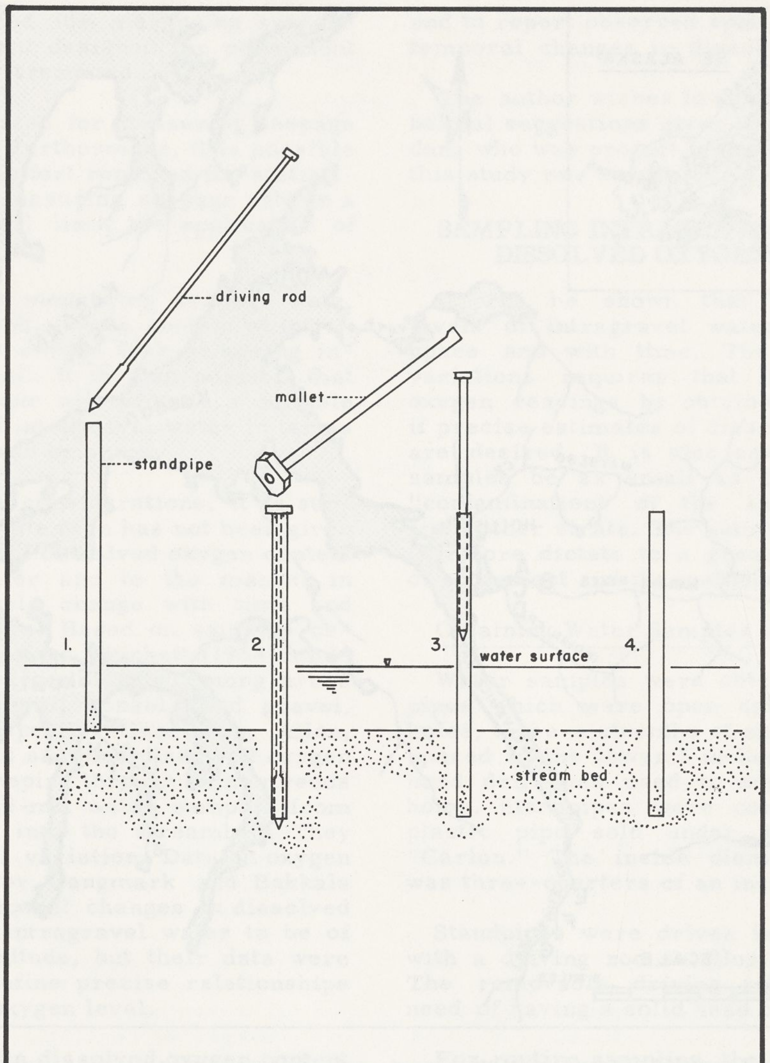

Figure 2.--Method of placing standpipe in streambed for collection of water samples for determination of dissolved oxygen content.

from dropper bottles through this tube. Before the sample is agitated, the column of liquid is forced to the top of the tube by applying pressure to the stopper and is sealed from the atmosphere by closing the opening of the tube with the forefinger.

Analyzing Water Samples

The unmodified Winkler Method was used to analyze water samples for their dissolved oxygen content. The volume of water used for an oxygen determination was only 30 ml., and it was necessary to employ semimicromethods of analysis to obtain precise readings. A 25-ml. aliquant was titrated against 0.0125 N sodium thiosulfate solution delivered from a microburette having 0.02-ml. subdivisions. The 0.0125 N sodium thiosulfate solution was prepared from a stock solution which was periodically standardized against 0.025 N potassium dichromate.

Dissolved oxygen analyses were made in the field near sampling areas. There was very little delay from the time samples were collected to the time they were titrated; thus the possible influence of interfering substances was minimized.

The collection and analysis of water samples from 200 standpipes required about 1 day

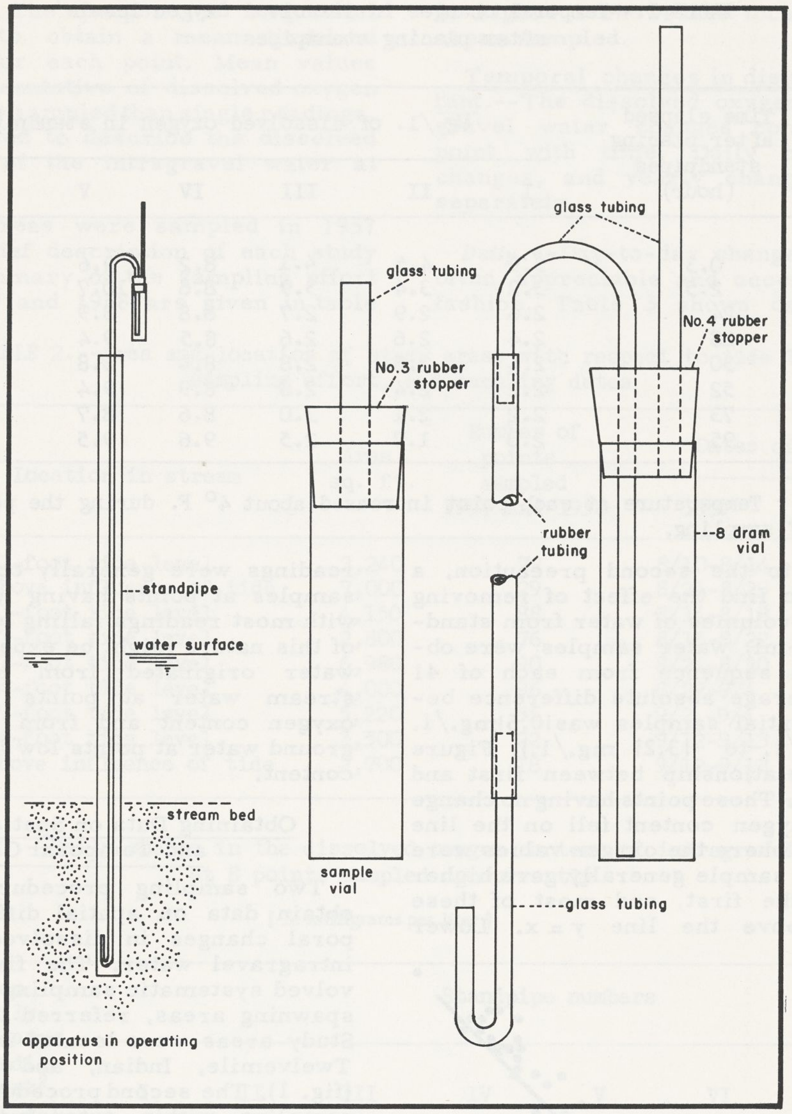

Figure 3.--Apparatus for collecting water samples from standpipes.

for three men. An automatic burette with a three-way stopcock was used for making titrations.

Reliability of Samples

Two precautions are necessary to insure collection of water samples that are representative of points sampled. First, it is essential to leave standpipes in the streambed about 24 hours before sampling to allow conditions within the gravel to stabilize. Second, the withdrawal of large water samples should be avoided to prevent water originating at other levels from entering a standpipe.

With regard to the first precaution, Wickett (1954) reported that points normally having very low dissolved oxygen values required several days after driving a standpipe for their dissolved oxygen levels to return to their normal levels. In the present study, consecutive readings were made at six points over a period of 95 hours after placement of standpipes. At points where oxygen level was relatively low at time of the first determination, oxygen levels declined for at least 24 hours. At points having relatively high oxygen values at time of the first determination, consecutive readings did not show any trend in their variation. Data on oxygen levels are given in table 1. Temperature of intragravel water was not uniform at all points sampled. Temperature increased about 4° F. at each point during the 95-hour sampling period.

TABLE 1.--Temporal changes in dissolved oxygen levels[1] after placing standpipes

Time elapsed after placing standpipes (hour)	Mg./l. of dissolved oxygen in standpipes					
	I	II	III	IV	V	VI
0.3	3.9	4.5	4.1	8.2	9.6	10.0
2.5	3.2	3.4	3.9	8.6	10.7	8.9
24	2.6	2.9	2.7	8.8	8.9	9.3
28	2.4	2.6	2.6	8.5	9.4	8.0
30	2.4	2.8	2.8	8.4	8.8	-
52	2.2	2.4	2.8	8.9	9.4	9.5
73	2.2	2.1	3.0	8.6	8.7	9.4
95	2.0	1.7	2.5	9.6	9.5	9.4

[1] Temperature at each point increased about 4° F. during the period of sampling.

With regard to the second precaution, a test was run to find the effect of removing relatively large volumes of water from standpipes. Two 125-ml. water samples were obtained in rapid sequence from each of 41 points. The average absolute difference between the sequential samples was |0.5| mg./l. (range 0.0 mg./l. to |3.2| mg./l.). Figure 4 shows the relationship between first and second readings. Those points having no change in dissolved oxygen content fell on the line y = x. At points where the oxygen values were high, the second sample generally gave higher readings than the first, and most of these points were above the line y = x. Lower readings were generally obtained for second samples at points having low oxygen values, with most readings falling below y = x. Results of this nature might be expected if intragravel water originated from highly oxygenated stream water at points high in dissolved oxygen content and from poorly oxygenated ground water at points low in dissolved oxygen content.

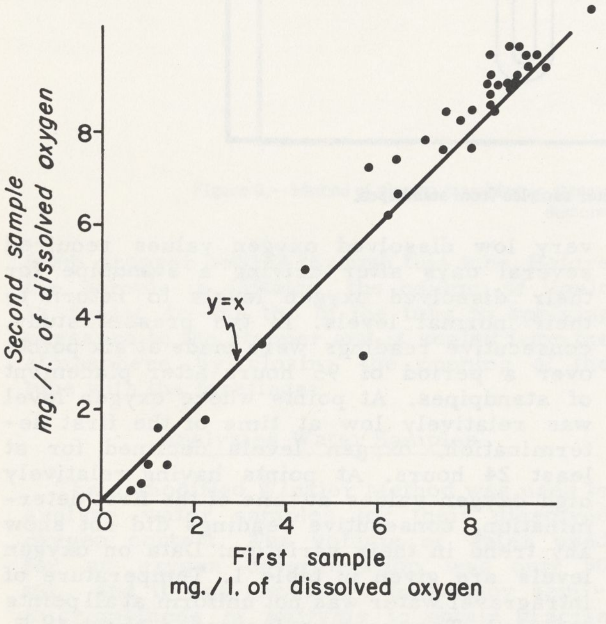

Figure 4.--Relationship between dissolved oxygen content of two 125-ml. water samples withdrawn less than 1 minute apart.

Obtaining Data on Spatial Differences and Temporal Changes

Two sampling procedures were used to obtain data on spatial differences and temporal changes in dissolved oxygen level of intragravel water. The first procedure involved systematic sampling of relatively small spawning areas, referred to as study areas. Study areas were located in Harris River and Twelvemile, Indian, and Old Tom Creeks (fig. 1). The second procedure involved random sampling within extensive spawning areas which were called sampling areas. The sampling areas described in this report were located in Twelvemile Creek.

Systematic Sampling

One purpose of systematic sampling was to obtain detailed information on spatial distribution of intragravel dissolved oxygen levels within a spawning bed. To accomplish this, standpipes were distributed uniformly at 5- to 10-foot intervals over each study area. No attempt was made to stratify pipes with respect to surface water depth or velocity. In several study areas, standpipes were driven into bars that received seepage water from the stream. Efforts were made to confine sampling to periods of low to moderately low stream discharge. During each sampling period an oxygen reading was obtained from every point sampled on two or more consecutive days. The purpose of sequential sampling was to obtain a mean dissolved oxygen value for each point. Mean values are more representative of dissolved oxygen level at the points sampled than single readings, and they are used to describe the dissolved oxygen content of the intragravel water at each point.

Nine study areas were sampled in 1957 and 1958. A brief description of each study area and a summary of the sampling effort in summer 1957 and 1958 are given in table 2. Figure 1 shows the locations of the study areas sampled.

Temporal changes in dissolved oxygen content.--The dissolved oxygen content of intragravel water changes continually at every point with time. Daily changes, seasonal changes, and yearly changes are discussed separately.

Daily.--Day-to-day changes at a point were often appreciable and occurred in a random fashion. Table 3 shows daily oxygen levels

TABLE 2.--Area and location of study areas with respect to tide level, sampling effort, and sampling dates

Study spawning area	Location in stream	Area sq. ft.	Number of points sampled	Dates of sampling	
			1957 and 1958	1957	1958
A	11-foot tide level	3,240	72	8/10-8/14	8/11-8/13
B	Above influence of tide	7,000	29	8/21-8/23	8/12-8/14
C	13-foot tide level	4,150	88	8/14-8/18	8/16-8/19
D	17-foot tide level	2,800	76	8/16-8/22	8/16-8/19
E	11-foot tide level	6,980	90	8/24-8/30	8/22-8/24
F	14-foot tide level	4,000	96	8/27-9/4	8/24-8/30
G	17-foot tide level	5,220	35	9/2 -9/4	8/26-8/30
H	14-foot tide level	3,500	22	9/12-9/13	9/5 -9/7
I	Above influence of tide	2,700	18	9/12-9/13	9/5 -9/7

TABLE 3.--Daily change in the dissolved oxygen content of intragravel water[1] at 8 points sampled concurrently

[In milligrams per liter]

Time after placing standpipe (days)	Mean daily discharge of Indian Creek[2] (c.f.s.)	Standpipe numbers							
		I	II	III	IV	V	VI	VII	VIII
1	7	1.8	1.0	5.4	7.6	9.4	0.6	8.1	9.3
2	6	1.1	0.8	6.8	7.5	9.8	0.9	8.7	10.2
3	6	2.9	0.8	6.5	6.1	10.4	0.8	9.6	10.2
4	6	3.5	1.9	8.6	7.2	10.3	1.6	8.7	9.4
5	85	3.2	0.9	9.5	7.8	9.3	2.2	9.9	9.8
6	60	5.4	1.2	8.2	8.8	11.4	1.0	6.6	10.1
7	51	--	--	--	--	--	--	--	--
8	100	4.3	2.5	8.6	7.0	10.3	0.6	7.9	10.2
9	67	3.9	1.5	9.0	5.2	11.0	1.4	8.3	10.5
Difference between maximum and minimum dissolved oxygen readings		4.3 mg./l.	1.7 mg./l.	4.1 mg./l.	3.6 mg./l.	2.1 mg./l.	1.6 mg./l.	3.3 mg./l.	1.2 mg./l.

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[1] Stream temperatures remained near 52° F. when these observations were made.

[2] Data provided by Northern Experiment Station, U.S. Forest Service, Juneau, Alaska.

observed over a 9-day period at eight points sampled concurrently in study area D. The least difference between minimum and maximum readings was 1.2 mg./l. while the greatest difference was 4.3 mg./l. Oxygen levels increased slightly with discharge at points low in dissolved oxygen. Points high in dissolved oxygen showed little change with increased discharge. Temperature remained near 52° F. during the period of sampling.

Seasonal.--Seasonal changes in dissolved oxygen content of intragravel water were of large magnitude. Samples were obtained from 31 points in study area C during August and November 1957 and during March and August 1958 (table 4). Dissolved oxygen levels were at a very low level during August 1957. They had increased significantly, however, by November 1957, and a second significant increase had occurred by March 1958.

There was only a slight decline in oxygen level during August 1958, which was in sharp contrast to the previous year. Furthermore, the mean dissolved oxygen level of points sampled was significantly higher during August 1958 than during November 1957, despite the fact that water temperatures were approximately 10° F. cooler in November than in August.

Yearly.--Examination of dissolved oxygen levels observed in nine study areas during late August and early September of 1957 and 1958 revealed that a pronounced difference existed between these years (see appendix). Very low dissolved oxygen levels prevailed

TABLE 4.--Seasonal change in dissolved oxygen content of intragravel water (study area C)

Point number	Dissolved oxygen content (mg./l.)			
	Aug. 1957	Nov. 1957	Mar. 1958	Aug. 1958
	Water temp. 60° F.	Water temp. 45° F.	Water temp. 38° F.	Water temp. 55° F.
1	6.0	6.8	10.6	8.6
5	5.3	8.0	10.6	8.1
11	6.7	8.2	12.7	8.7
12	6.6	7.5	11.5	8.6
15	5.7	5.7	11.7	8.1
16	7.4	8.6	12.4	9.6
17	5.2	8.6	12.3	8.8
19	7.6	8.6	10.8	9.0
21	7.4	8.5	11.4	9.3
22	6.3	8.0	10.0	9.6
24	0.0	7.6	8.9	5.7
25	1.8	8.4	11.5	8.1
26	6.0	8.9	12.7	9.4
27	6.1	7.9	11.3	9.1
28	0.0	6.9	9.1	7.6
29	0.6	8.1	12.0	8.9
30	7.0	7.9	12.6	9.3
31	0.0	8.3	10.6	5.9
32	0.4	7.8	11.1	7.0
33	0.2	6.8	11.7	9.0
35	0.0	7.9	7.9	5.1
36	0.0	7.3	10.1	9.4
37	0.0	8.0	11.6	9.1
39	6.1	6.8	8.5	4.8
41	0.2	6.8	11.3	8.5
43	0.0	7.7	9.8	9.5
48	0.0	7.3	10.1	8.3
52	0.0	6.0	6.5	7.2
63	0.9	6.7	4.5	8.0
65	5.7	7.5	9.4	8.0
70	3.4	4.9	9.0	7.9
Mean	3.3	7.6	10.5	8.2

over a considerable portion of each study area during 1957, whereas in 1958 oxygen levels were high by comparison. Figure 5 presents a comparison of mean dissolved oxygen values obtained for each study area in 1957 and in 1958. The mean values shown were obtained from points that were sampled both years (see appendix).

In 1957 sampling was carried out during a period of warm weather, light precipitation, and cloudless days. In 1958 weather conditions were quite different; freshets occurred periodically and most days were overcast. Mean daily discharge of Indian Creek was 20 c.f.s. in August 1957 and 60 c.f.s. in August 1958.

Wickett (1958) has proposed that certain periods of low stream discharge were associated with low oxygen levels of the intragravel water. The data obtained in 1957 supported this contention. The relatively high dissolved oxygen levels observed in 1958 were probably the result of more favorable hydrological conditions.

Spatial differences in dissolved oxygen levels.--Spatial differences in dissolved oxygen content of intragravel water were generally more extreme in 1957 than in 1958. Many points were deficient in dissolved oxygen during the 1957 sampling period, and it was possible to define extensive areas of low (less than 2.5 mg./l.)[1] oxygen levels. These are shown in figures 6 through 11 for study areas A, B, C, D, F, and G. Points sampled both years are indicated in these figures by dots.

In 1958 dissolved oxygen levels exceeded 5.0 mg./l. at most of the points sampled.

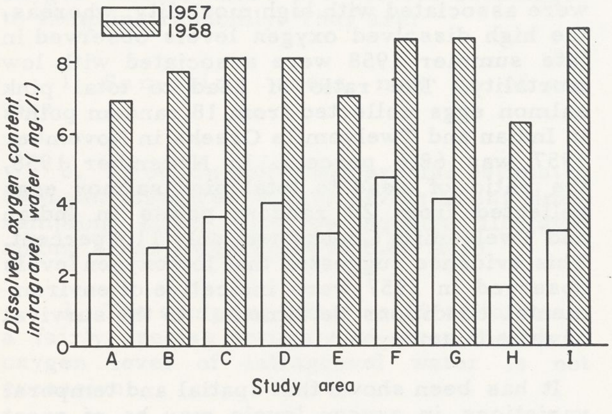

Figure 5.--Mean dissolved oxygen values obtained at study areas in late August and early September of 1957 and 1958.

Relatively few points exhibited low levels of dissolved oxygen. The areas of relatively low and high oxygen values occurring in 1958 are also shown in figures 6 through 11.

A table of dissolved oxygen values observed within each study area appears in the appendix.

Random Sampling

By sampling randomly it was possible to obtain estimates of mean dissolved oxygen level of intragravel water within large spawning areas (sampling areas). Spatial differences in dissolved oxygen levels were detected by sampling two or more areas simultaneously. Temporal changes in dissolved oxygen levels were detected by sampling each sampling area two or more times. Standard statistical techniques were employed to test for significant differences between estimated mean dissolved oxygen values.

Two sampling areas on Twelvemile Creek were sampled concurrently in a random manner during early September and late November, 1958. The lower sampling area, extending from the 12- to 16-foot tide level, incorporated 60,000 square feet of streambed and included most of the intertidal spawning area. The upper sampling area extended upstream from the intertidal zone and incorporated 68,000 square feet of streambed. The heaviest observed spawning intensity above the intertidal zone occurred in this area.

The general sampling procedure employed was to place standpipes at randomly selected points 1 day prior to sampling. One dissolved oxygen reading was obtained from each point, and an attempt was made to obtain all readings for both sampling areas on the same day.

In September 1958, dissolved oxygen readings were obtained from approximately 100 points within each sampling area. In November 1958, it was possible to reduce the sampling effort to 50 points per area, since the variability among readings was considerably less in autumn than in late summer.

Ninety-five percent confidence interval estimates of mean dissolved oxygen content of intragravel water within the two Twelvemile Creek sampling areas are given in table 5. These estimates indicated that:

1. Oxygen levels were significantly higher within both sampling areas during midautumn than during late summer, i.e., there was a change in oxygen levels with time.

2. Dissolved oxygen levels were significantly lower in the upstream sampling area than in the intertidal sampling area

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[1] No physiological significance is attached to a dissolved oxygen content of 2.5 mg./l. This value was selected purely for purposes of illustration.

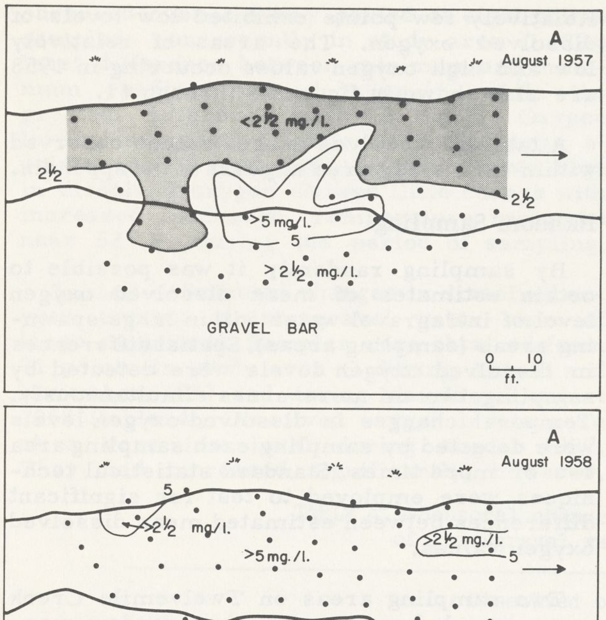

Figure 6.--Dissolved oxygen levels at study area A (11-foot tide level of Harris River). Samples were obtained 7 to 10 inches beneath gravel surface at points shown.

during the early September spawning period, i.e., average oxygen levels differed spatially between two large spawning areas in late summer.

3. There was no significant difference in oxygen levels between the two sampling areas in midautumn.

ROUTINE EVALUATION OF OXYGEN LEVELS

An important objective of the study of dissolved oxygen content of intragravel water is to determine the importance of oxygen level as a factor associated with natural mortality of salmon embryos. Field observations of dissolved oxygen levels and mortality are not intended to define oxygen levels lethal to embryos. Instead, they are designed to establish general relationships between oxygen level and mortality in natural environments. Determination of rates of oxygen supply necessary to sustain embryos is primarily a laboratory problem, and some progress has been reported on the study of the oxygen requirements of embryos (Alderdice, Wickett, and Brett, 1958; Doudoroff, 1957; Silver, 1960; Shumway, 1960).

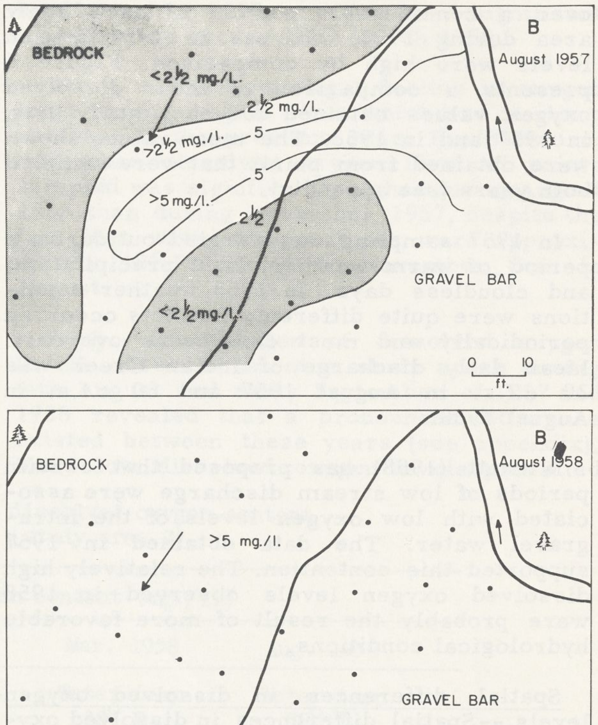

Figure 7.--Dissolved oxygen levels at study area B (upstream Harris River). Samples were obtained 7 to 10 inches beneath gravel surface at points shown.

There was evidence that the low dissolved oxygen levels observed in late summer 1957 were associated with high mortality; whereas, the high dissolved oxygen levels observed in late summer 1958 were associated with low mortality. The ratio of dead to total pink salmon eggs collected from 18 random points in Indian and Twelvemile Creeks in November 1957 was 68.6 percent. In November 1958, the ratio of dead to total pink salmon eggs collected from 20 random points in Indian and Twelvemile Creeks was only 11.4 percent. This evidence suggested that low oxygen levels observed in 1957 were indicative of environmental conditions detrimental to the survival of salmon embryos.

It has been shown that spatial and temporal variations in oxygen levels may be of great magnitude. These variations are apparently influenced by complex environmental factors that are not well understood.

Sampling methods described in this report when used with statistically designed sampling

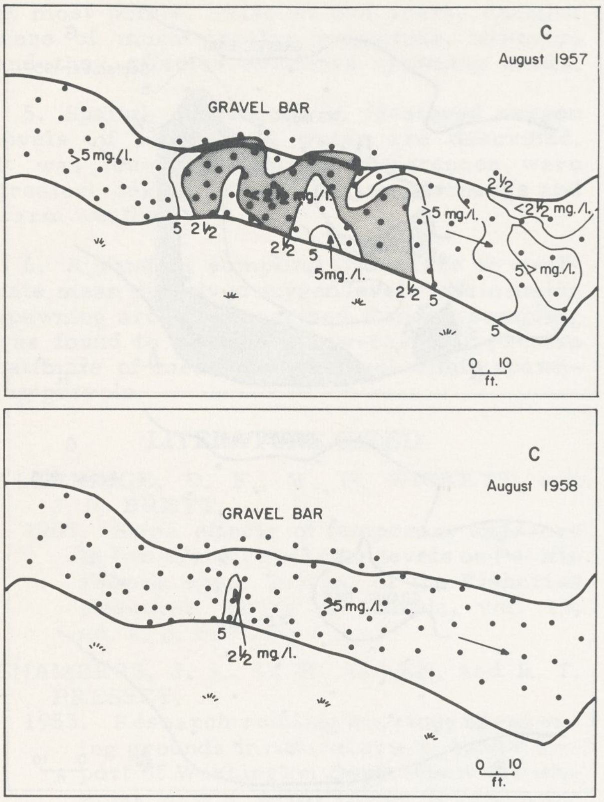

Figure 8.--Dissolved oxygen levels at study area C (13-foot tide level of Indian Creek). Samples were obtained 7 to 10 inches beneath gravel surface at points shown.

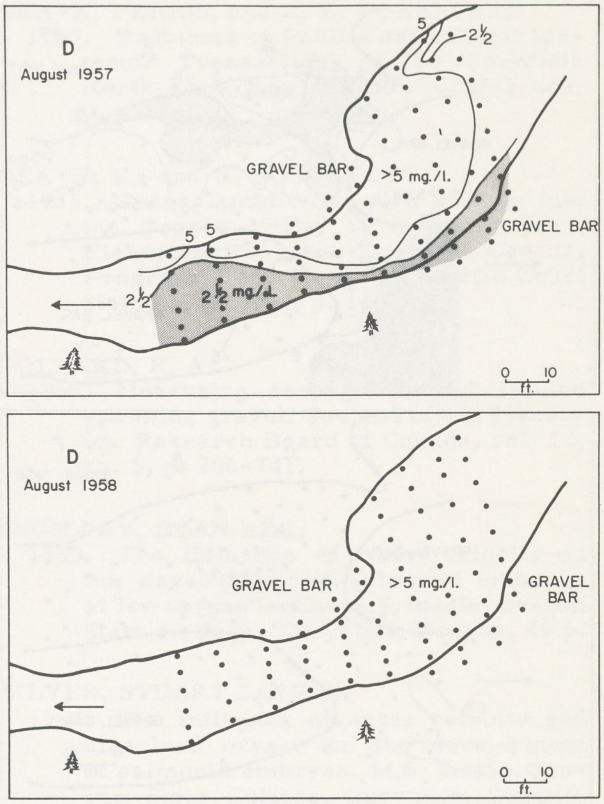

Figure 9.--Dissolved oxygen levels at study area D (17-foot tide level of Indian Creek). Samples were obtained 7 to 10 inches beneath gravel surface at points shown.

schemes are sufficiently precise to detect significant differences in oxygen levels in spawning gravels. For routine evaluation of oxygen levels, there are certain advantages to sampling randomly. They are:

1. Sampling areas may be of any size.

2. To obtain uniformly precise estimates of mean dissolved oxygen levels at any time, sampling effort may be equally allocated among areas, regardless of their size.

3. The sampling effort required to obtain a fairly precise estimate of mean dissolved oxygen level of intragravel water is not excessive.

4. Changes in dissolved oxygen levels with time may be determined by sampling individual areas on two or more occasions.

5. Spatial differences in dissolved oxygen levels may be determined by sampling two or more areas simultaneously.

With regard to points 1 and 2 above, examination of data given in the appendix indicates that temporal and spatial variations are of a similar magnitude in most spawning riffles. It is therefore possible by sampling equal numbers of random points to estimate the mean dissolved oxygen content for a stream or a single riffle with almost equal precision.

With regard to point 3, it has been observed that the greatest variations in dissolved oxygen levels occur in late summer during and after spawning. By sampling 100 random points at this time, the expected 95-percent confidence limits of the mean dissolved oxygen content of intragravel water is approximately ±0.5 mg./1. of the sample mean. At other times, the mean dissolved oxygen level can be estimated with almost equal precision by sampling 50 points.

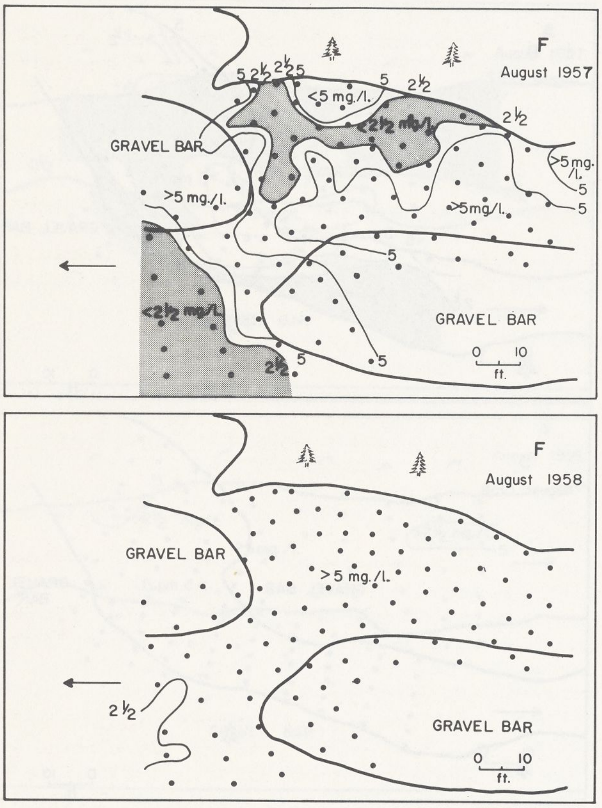

Figure 10.--Dissolved oxygen levels at study area F (14-foot tide level of Twelvemile Creek). Samples were obtained 7 to 10 inches beneath gravel surface at points shown.

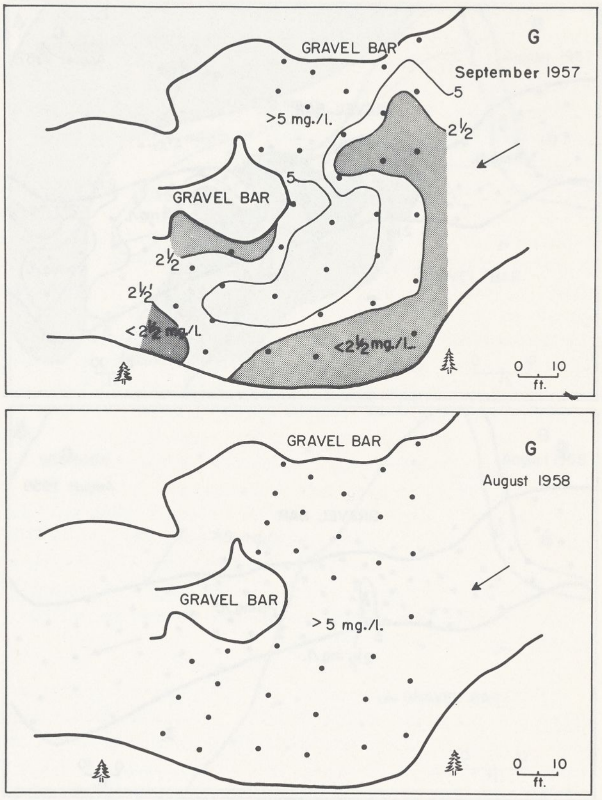

Figure 11.--Dissolved oxygen levels at study area G (17-foot tide level of Twelvemile Creek). Samples were obtained 7 to 10 inches beneath gravel surface at points shown.

TABLE 5.--Estimates of the mean dissolved oxygen levels of intragravel water in Twelvemile Creek

Sampling area	September 1958		November 1958	
	Sample size	95-percent confidence interval estimates of mean	Sample size	95-percent confidence interval estimates of mean
Intertidal	93	6.3 mg./l. $<\mu<$ 7.4 mg./l.	50	8.3 mg./l. $<\mu<$ 9.5 mg./l.
Upstream	100	4.8 mg./l. $<\mu<$ 6.1 mg./l.	50	8.0 mg./l. $<\mu<$ 9.6 mg./l.

SUMMARY

1. Evidence is presented that mortality of pink and chum salmon embryos is high. One factor thought to contribute to high mortality is low streamflow which may be accompanied by a reduction of dissolved oxygen content of intragravel water.

2. Equipment and techniques employed to sample dissolved oxygen content of intragravel water are described. An important component of this equipment is a lightweight, inexpensive plastic standpipe.

3. Two precautions necessary to insure the procurement of reliable water samples are discussed. They are (1) standpipes which should be left in the streambed for 24 hours or longer before sampling and (2) only small water samples (about 30 ml.) which should be removed.

4. Temporal changes in dissolved oxygen content of intragravel water are reported. Observed temporal changes are discussed under three categories--daily, seasonal, and yearly. It was found that dissolved oxygen content of intragravel water fluctuated daily

at most points. Seasonal and yearly changes were of much greater magnitude, however, and they affected extensive spawning areas.

5. Spatial differences in dissolved oxygen levels of intragravel water are described. It was found that spatial differences were greatest during periods of low discharge and warm weather.

6. A random sampling procedure to evaluate mean dissolved oxygen levels within major spawning areas is described. Random sampling was found to provide a low-cost and precise estimate of mean oxygen level within spawning gravels.

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APPENDIX

Dissolved oxygen values* obtained for all study areas in late summer of 1957 and of 1958
(Dissolved oxygen content in mg./l.)

Study area																	
A		B		C		D		E		F		G		H		I	
1957	*1958*	*1957*	*1958*	*1957*	*1958*	*1957*	*1958*	*1957*	*1958*	*1957*	*1958*	*1957*	*1958*	*1957*	*1958*	*1957*	*1958*
3.9	6.3	3.6	8.7	6.0	8.6	0.8	6.2	5.6	4.5	7.1	9.6	5.3	8.8	1.4	9.7	5.6	9.5
5.3	9.9	2.2	8.3	5.5	9.0	3.7	9.7	2.4	5.2	8.8	9.3	6.0	9.0	5.3	2.1	5.9	9.0
2.7	9.6	1.6	7.1	5.3	8.1	6.9	9.4	1.3	8.5	0.5	7.1	2.4	8.4	0.0	3.2	7.2	10.3
0.6	7.1	1.8	8.0	5.9	9.1	5.0	9.7	1.5	6.1	1.8	3.1	1.8	9.5	0.0	5.6	0.7	8.6
0.9	4.9	4.0	9.6	7.3	8.2	3.3	9.8	3.2	9.4	5.7	5.2	1.3	7.3	0.0	7.0	4.5	8.4
0.0	7.2	2.3	9.1	7.3	7.6	2.2	8.4	4.0	1.9	1.8	2.2	2.3	9.4	2.4	3.7	5.2	10.0
0.0	1.7	0.7	7.2	6.7	8.7	1.3	4.7	1.8	1.3	1.4	8.9	6.1	10.5	0.0	0.6	3.6	8.6
4.0	6.5	5.4	7.1	6.6	8.6	0.8	3.3	1.2	5.6	8.5	10.3	0.6	9.9	0.5	9.4	1.8	9.0
3.5	5.2	1.2	9.3	3.5	9.4	0.4	4.0	4.6	4.4	8.0	9.4	1.8	8.7	5.0	9.1	0.2	10.1
3.3	8.3	1.2	4.6	6.3	9.4	5.4	7.7	1.1	8.8	0.8	7.3	5.3	10.0	1.6	2.3	2.5	10.3
0.8	9.1	1.3	7.0	5.7	8.1	6.2	9.0	2.0	8.9	2.0	7.6	6.8	10.6	0.2	8.4	1.0	9.7
1.8	4.0	6.3	8.4	7.4	9.6	6.8	9.3	7.4	8.9	2.6	7.0	4.7	5.8	0.0	9.4	1.8	9.2
0.0	5.9	4.0	8.8	5.2	8.8	6.6	10.0	6.8	8.8	0.0	5.1	0.2	0.7	2.6	9.3	4.8	10.5
0.6	3.5	0.4	9.5	5.4	9.1	0.7	9.4	2.1	1.0	7.9	9.2	8.2	10.8	0.0	4.2	4.0	8.7
2.1	6.8	3.2	5.2	7.6	9.0	8.2	10.4	1.5	0.9	7.8	8.8	5.4	10.7	1.2	9.2	2.1	9.5
3.0	6.3	2.3	5.5	6.0	9.2	1.6	4.8	0.4	0.8	6.1	8.6	0.0	8.2	4.2	6.7	3.0	9.4
1.9	10.0	5.8	2.7	7.4	9.3	1.2	3.8	0.4	3.1	6.5	5.0	4.9	10.3	3.8	6.8	5.3	10.3
1.2	5.5	2.1	7.4	6.3	9.6	1.1	5.9	0.5	3.4	8.0	7.0	8.2	9.9	2.9	1.6	0.1	0.7
0.0	9.1	0.8	9.1	6.6	9.5	6.0	8.0	1.8	3.3	8.2	7.3	8.0	10.2	0.8	5.9		
0.1	8.0	3.5	9.4	0.0	5.7	7.9	8.8	8.4	5.4	2.3	5.0	1.1	3.3	0.3	6.9		
3.7	6.9	5.2	9.2	1.8	8.1	5.7	9.4	5.8	9.0	8.6	10.0	7.0	10.8	1.5	9.5		
3.1	6.1	1.2	4.9	6.0	9.4	8.2	10.0	6.1	8.2	0.2	10.2	7.4	10.5	4.0	7.9		
6.0	7.5	1.6	9.0	6.1	9.1	8.2	9.9	6.4	9.3	0.3	8.1	7.4	10.5				
5.2	6.8	7.0	7.7	0.0	7.6	7.3	10.3	3.3	9.3	7.2	7.8	3.4	10.2				
0.9	8.0	7.0	9.3	0.6	8.9	0.3	2.5	7.2	3.5	8.4	9.3	1.5	7.5				
4.7	6.4	4.8	7.5	7.0	9.3	0.3	9.7	4.5	3.9	8.2	6.3	8.2	9.0				
1.2	6.5	0.2	8.3	0.0	5.9	2.3	9.7	6.6	1.9	7.6	6.7	4.4	10.1				
1.4	5.6	0.2	9.1	0.4	7.0	3.4	9.0	1.8	2.1	9.2	10.5	4.8	10.0				
2.2	5.4	0.0	8.6	0.2	9.0	6.7	5.1	0.6	1.2	0.8	10.0	6.9	10.0				
1.8	4.9			5.8	9.7	7.3	9.4	0.4	2.3	4.8	9.8	4.7	10.2				
7.8	6.7			0.0	5.1	6.3	9.8	1.0	8.2	8.9	10.5	6.3	10.0				
4.5	6.8			0.0	9.4	7.1	10.0	7.4	7.3	2.2	9.0	2.2	7.5				
7.5	9.3			0.0	9.1	7.8	10.1	7.0	8.4	9.0	9.0	3.6	2.4				
0.0	9.6			7.1	9.6	1.6	1.6	8.1	7.3	6.5	7.8	3.7	8.1				
0.0	6.1			6.1	4.8	2.2	7.2	7.8	7.1	8.0	8.0	1.2	5.8				
2.8	7.4			4.7	4.1	6.6	9.5	6.3	9.3	6.2	5.0						
2.8	5.6			0.2	8.5	5.9	7.7	5.2	7.9	5.2	10.7						
3.4	4.7			2.2	9.2	7.1	7.0	7.3	6.6	0.2	7.7						
7.1	8.3			0.0	9.5	7.7	9.6	7.3	6.5	5.1	10.3						
6.3	9.6			0.0	8.2	7.9	9.6	7.8	3.9	0.6	9.4						
1.7	10.8			0.0	7.5	7.6	9.5	4.3	7.3	6.9	9.6						
2.6	9.1			2.7	9.2	0.6	2.4	4.5	6.5	7.0	9.4						
2.1	4.9			3.9	9.6	1.4	8.6	5.5	7.5	6.2	9.9						
0.4	5.4			0.0	8.5	4.8	9.6	5.7	6.5	6.1	8.7						
3.4	6.0			3.4	9.6	5.3	9.5	5.3	8.0	0.4	8.2						
3.2	5.5			6.1	8.7	6.0	8.4	2.5	7.9	0.2	9.3						
2.3	5.2			0.0	7.2	5.7	9.2	7.2	8.6	6.4	9.4						
9.7	6.5			0.0	7.7	6.5	9.3	7.1	7.2	6.1	9.8						
8.0	8.9			0.0	7.3	2.5	8.8	8.1	7.4	5.2	9.8						
6.1	8.3			0.7	7.7	1.0	9.8	5.9	4.9	6.9	10.1						
0.0	5.9			0.0	7.4	0.3	9.6	2.2	7.5	8.0	9.9						
2.0	8.9			0.6	6.9	3.8	9.8	0.0	5.1	6.3	7.2						
0.0	5.3			4.0	6.5	5.1	9.9	0.0	4.9	0.6	5.2						
3.0	6.4			0.2	7.8	5.5	9.0	0.2	8.5	2.9	8.2						
2.2	6.4			0.7	8.0	7.1	8.9	0.0	8.7	1.6	9.2						
2.8	5.4			0.9	8.0	6.9	9.4	0.1	9.4	0.2	9.6						

See footnote at end of table

APPENDIX (continued)

Study area																	
A		B		C		D		E		F		G		H		I	
1957	1958	1957	1958	1957	1958	1957	1958	1957	1958	1957	1958	1957	1958	1957	1958	1957	1958
1.4	7.7			2.9	4.4	0.0	5.1	7.1	9.9	4.2	10.1						
1.0	9.4			5.7	8.0	2.2	9.4	0.2	9.1	6.1	10.4						
0.3	9.6			6.2	9.4	0.0	9.0	6.9	9.3	6.5	10.0						
0.1	8.5			5.6	9.4	2.7	9.2	6.2	8.9	5.1	9.9						
2.3	3.5			3.8	7.0	5.4	9.6	8.0	9.1	7.3	10.4						
3.4	5.7			3.4	7.9	5.0	9.7	0.0	7.1	5.1	10.5						
2.3	5.7			0.1	6.2	6.8	9.6	1.0	9.6	0.0	3.4						
2.8	6.7			5.5	9.5	0.4	3.4	0.0	8.9	6.9	8.0						
1.7	9.0			4.5	7.2	0.1	4.6	0.0	9.6	6.6	9.6						
3.1	8.1			0.0	6.6	5.8	9.4	0.0	8.4	0.6	8.8						
4.0	8.0			0.0	7.3	0.2	5.6	5.9	9.9	2.9	10.2						
0.0	8.3			5.1	8.5	2.6	8.3	4.1	9.5	0.6	9.8						
0.0	9.0			5.0	9.9	1.4	7.9	8.0	9.1	3.2	9.8						
2.9	8.0			0.5	9.4	4.4	6.9	9.2	9.6	6.6	9.8						
4.0	8.2			5.8	9.7	0.0	8.8	3.4	10.0	0.2	10.6						
2.2	8.0			4.8	8.6	0.3	9.8	2.5	9.0	7.6	9.7						
				1.3	6.4	0.6	9.4	0.0	9.0	6.6	10.0						
				1.4	6.9	5.7	9.4	3.4	8.6	7.5	9.2						
				5.1	6.9	2.2	9.7	0.0	9.0	0.7	9.0						
				6.6	7.3	6.2	9.0	2.7	8.4	5.5	10.6						
				5.2	9.8			3.9	8.4	0.9	8.8						
				0.9	9.7			0.0	8.9	7.1	10.6						
				0.8	8.0			2.4	6.6	4.9	9.9						
				5.4	5.6			0.0	9.4	7.5	10.0						
				5.6	8.3			0.0	8.6	8.2	10.1						
				2.2	9.2			7.5	9.6	7.5	9.6						
				6.7	9.4			5.8	8.3	4.6	7.9						
				7.4	9.5			3.9	7.7	6.6	8.9						
				6.7	8.1			0.0	7.4	1.8	10.0						
				6.6	7.8			0.0	5.4	2.3	7.8						
				4.1	8.9			1.2	7.1	4.5	9.8						
				7.7	8.0			0.1	8.9	8.2	9.6						
								9.1	8.4	6.6	9.4						
								0.0	8.8	3.7	9.9						
										4.6	10.2						
										0.0	2.5						
										0.3	6.8						
										4.4	6.8						
										2.6	7.6						
										6.2	6.2						

*These are mean values of two or more sequential samples taken at each point.