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# INTERCHANGE OF STREAM AND INTRAGRAVEL WATER IN A SALMON SPAWNING RIFFLE

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# INTERCHANGE OF STREAM AND INTRAGRAVEL WATER IN A SALMON SPAWNING RIFFLE

by

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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.

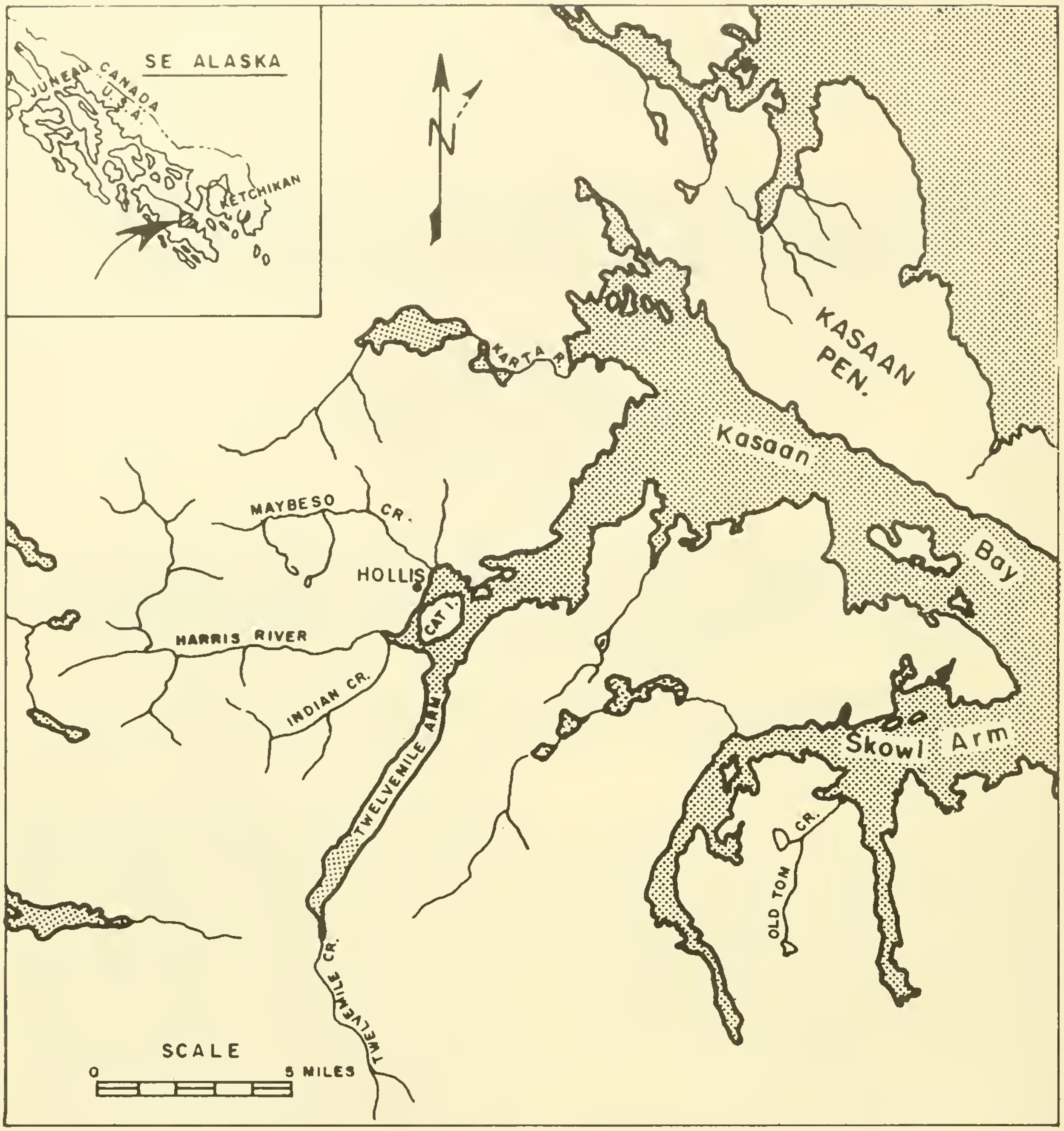

Figure 1.--Location of study streams, Hollis area.

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

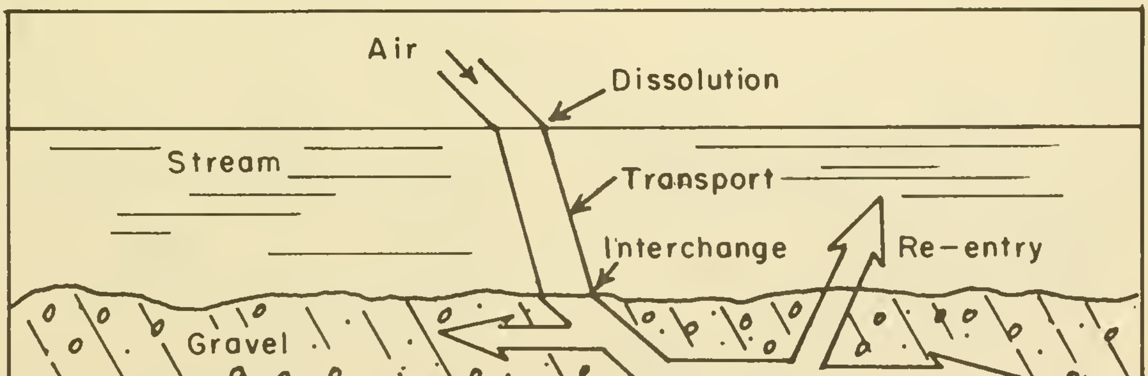

Figure 2.--Oxygen transport through stream to gravel bed.

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.,

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

where V is the average flow velocity, k the gravel permeability and $\triangle$h 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 $\theta$ 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, $\theta$ 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 (Lappie, 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, $\Delta$ L (fig. 3), (intragravel

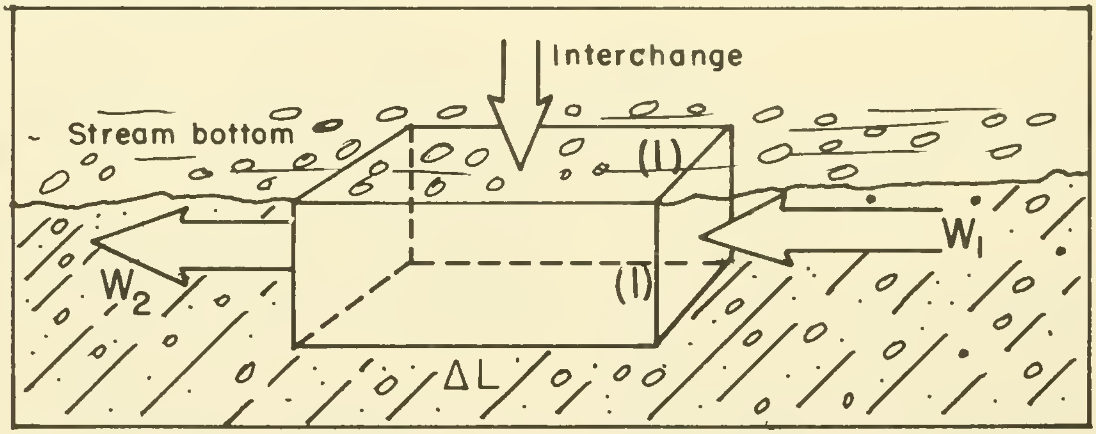

Figure 3.--Interchange and intragravel flow to a channel section.

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, $\Delta W = I \cdot \Delta L$ which may be expressed as first derivative,

$$I = \frac{dW}{dL} \tag{5}$$

Applying this to equation (4),

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

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

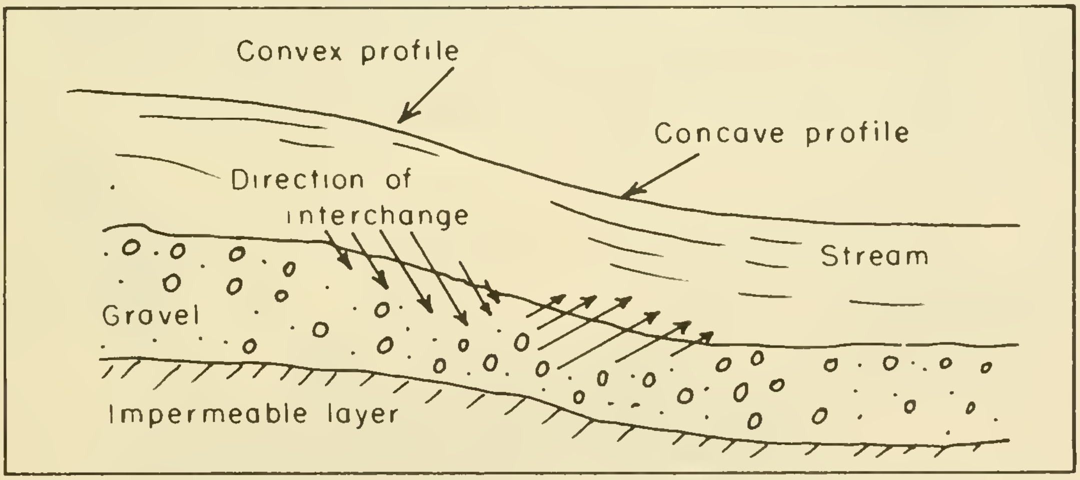

Figure 4.--Longitudinal stream profile showing surface-induced interchange when gravel is underlain with impermeable layer.

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

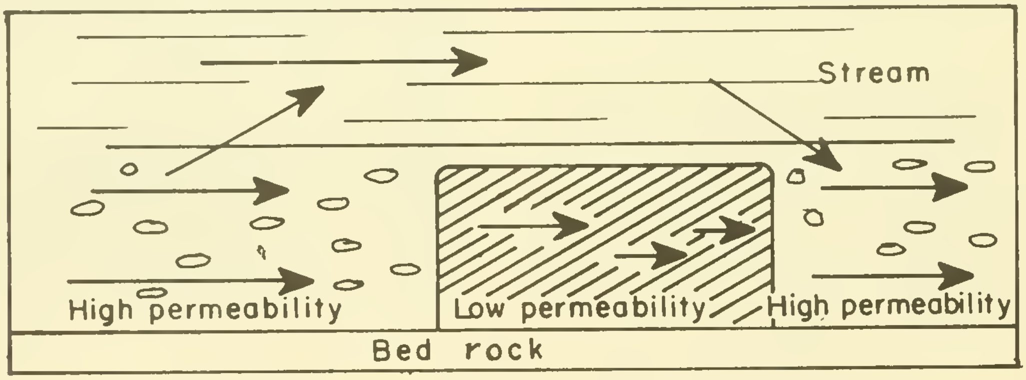

Figure 5.--The influence of varying gravel permeability on interchange.

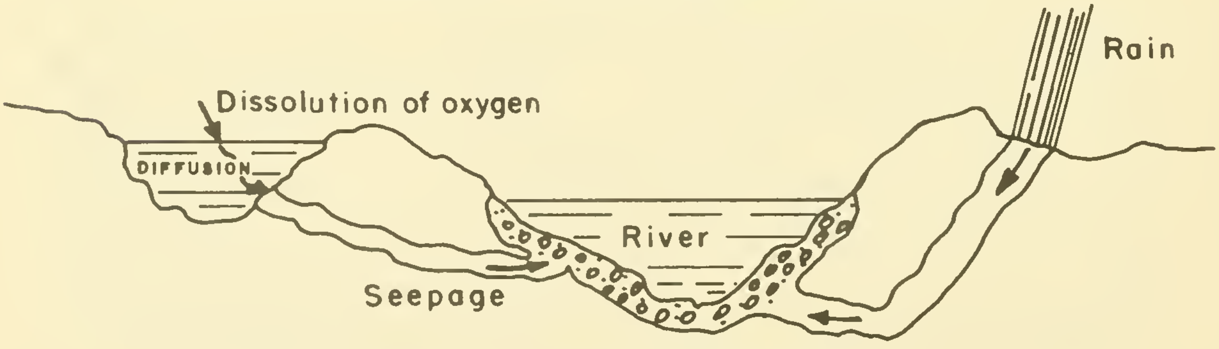

Figure 6.--Ground-water oxygen transport.

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

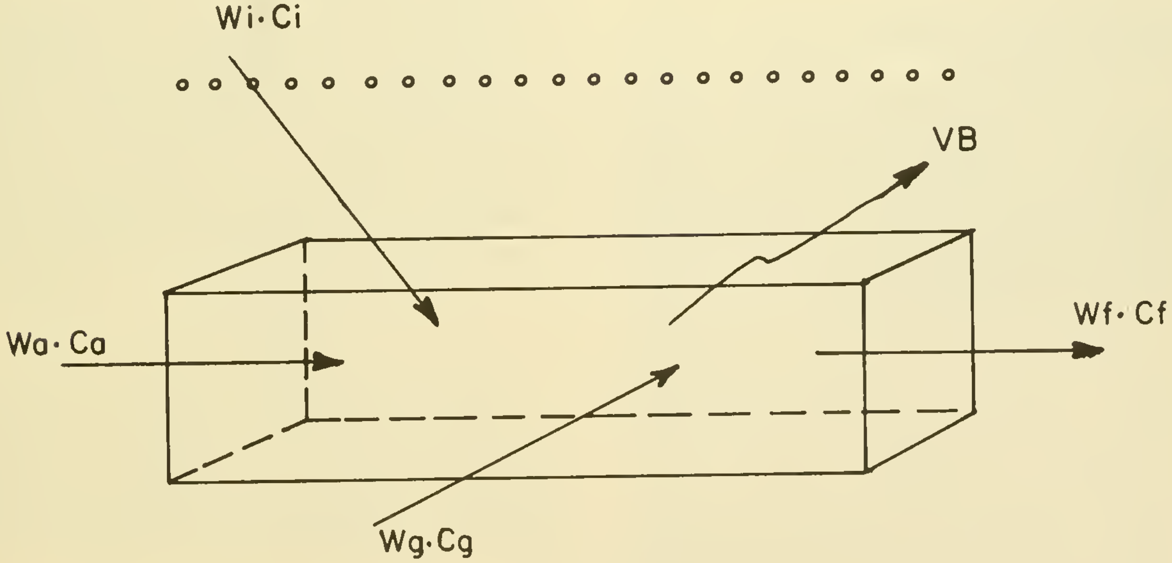

Figure 7.--Intragravel oxygen balance.

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

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