INTERNATIONAL PACIFIC SALMON
FISHERIES COMMISSION

APPOINTED UNDER A CONVENTION
BETWEEN CANADA AND THE UNITED STATES FOR THE
PROTECTION, PRESERVATION AND EXTENSION OF
THE SOCKEYE AND PINK SALMON FISHERIES
IN THE FRASER RIVER SYSTEM

BULLETIN XVIII

THE EFFECT OF TRANSPORTED STREAM SEDIMENTS ON THE SURVIVAL OF SOCKEYE AND PINK SALMON EGGS AND ALEVIN

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NEW WESTMINSTER, B. C., CANADA, 1965

ABSTRACT

Results are presented of studies made to assess quantitatively the effects of sediment deposition upon and within salmon spawning beds on the survival of salmon eggs and alevin. Methods of determining the size of bed load materials that may be expected on a given portion of a stream bed are presented. Spawning gravel permeability is defined in terms of particle size grading, particle shape and gravel porosity. The velocity of fluid flow through the gravel is quantitatively related to the gravel permeability and the hydraulic gradient. Deposition of sediment either on the gravel surface or within the gravel is shown to reduce gravel permeability with consequent reduction in fluid flow and reduction in rate of survival of salmon eggs and alevin deposited in the gravel. Formulae are developed which relate time and silt size and concentration to the effect on gravel permeability, and examples of the consequent effect on survival of salmon eggs and alevin are presented. The results of the studies show the importance of preventing deposition of sediments on or within a salmon spawning bed.

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THE EFFECT OF TRANSPORTED STREAM SEDIMENTS ON THE SURVIVAL OF SOCKEYE AND PINK SALMON EGGS AND ALEVIN

INTRODUCTION

Fraser River sockeye and pink salmon, in common with other species of Pacific salmon, perpetuate their species by depositing fertilized eggs in redds or nests dug in the gravel beds of the stream selected for spawning. After deposition, the eggs are covered with the gravel by the parent fish and left to incubate. During this incubation period, the survival of the fertile embryos is determined by the environment within the gravel. The quality of this environment is established primarily by the quality and quantity of the water flowing past individual eggs or alevin; it may vary greatly among nests and even between eggs. Silt or stream sediments deposited on salmon spawning beds are generally recognized to be detrimental to the survival of salmon embryos, on the basis of observed effects in rivers where silting has occurred or on the basis of experimental results. However, the observed mortalities during incubation have not been related previously to the quantity of silt deposited. This report presents the results of studies made to assess quantitatively the effects of sediment deposition upon and within salmon spawning beds.

OCCURRENCE OF SUSPENDED SEDIMENT IN RIVERS FREQUENTED BY SALMON

Most of the larger rivers draining the Pacific Coast of the United States and many of their tributaries carry suspended sediment in varying quantities. Data for 12 rivers in California, 12 rivers in Washington and 22 rivers in Oregon as given by Van Winkle (1914) for the period 1906-1912 are summarized in Table 1. In this table, coastal rivers are those which drain the interior parts of each state

TABLE 1—Suspended sediment concentration in ppm in rivers of California, Oregon and Washington in the period 1906-1912.

State	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
A. COASTAL RIVERS												
California	139	225	160	126	120	85	80	53	38	48	59	46
Oregon	27	16	9	8	10	8	20	5	6	3	12	6
Washington	12	7	19	18	14	12	6	4	7	16	28	13
B. INTERIOR RIVERS												
California	137	107	88	96	51	32	44	56	42	47	51	79
Oregon	94	107	58	113	107	194	81	74	62	33	37	13
Washington	6	24	47	41	26	14	16	17	13	14	19	14

out to the Pacific Ocean. The values shown are not mean monthly values, but are means of the data given by Van Winkle separated into the months in which observations were made. Data for the Fraser River at Hope as given by Kidd and Tredcroft (1953) are summarized in TABLE 2. These values also are not monthly

TABLE 2—Suspended sediment concentration in ppm in the Fraser River at Hope.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1950	—	—	—	—	370	503	189	98	—	26	—	28
1951	—	23	—	162	672	187	127	73	45	—	31	—
1952	—	—	15	970	374	200	158	96	57	—	—	—

means, but means of the concentrations measured in each month, and in some instances there is only a single value. The available data are by no means comprehensive for any individual river, but they do serve to show the relative magnitudes of the suspended sediment loads. The data presented in TABLES 1 and 2 summarize 1,675 determinations of suspended sediment concentration. The distribution of the values reported is given in TABLE 3 and FIGURE 1. The most frequently observed concentrations were in the range from 0-10 ppm, the median value was 22 ppm, and 90 per cent of all the concentrations observed were less than 150 ppm. These records show that usually these rivers carried relatively small amounts of suspended sediments.

TABLE 3—Distribution of suspended sediment concentrations in the 1,675 values reported for rivers in California, Oregon, Washington and British Columbia.

Concentration ppm	Percentage of Values Greater Than Stated Concentration
10	63.4
20	52.2
30	43.6
40	36.2
50	31.4
60	27.0
70	23.2
80	20.0
90	17.5
100	15.6
150	9.5
200	6.5
300	3.4
400	2.4
500	1.7
600	1.0
700	0.5
1,000	0.24
1,836	0.0

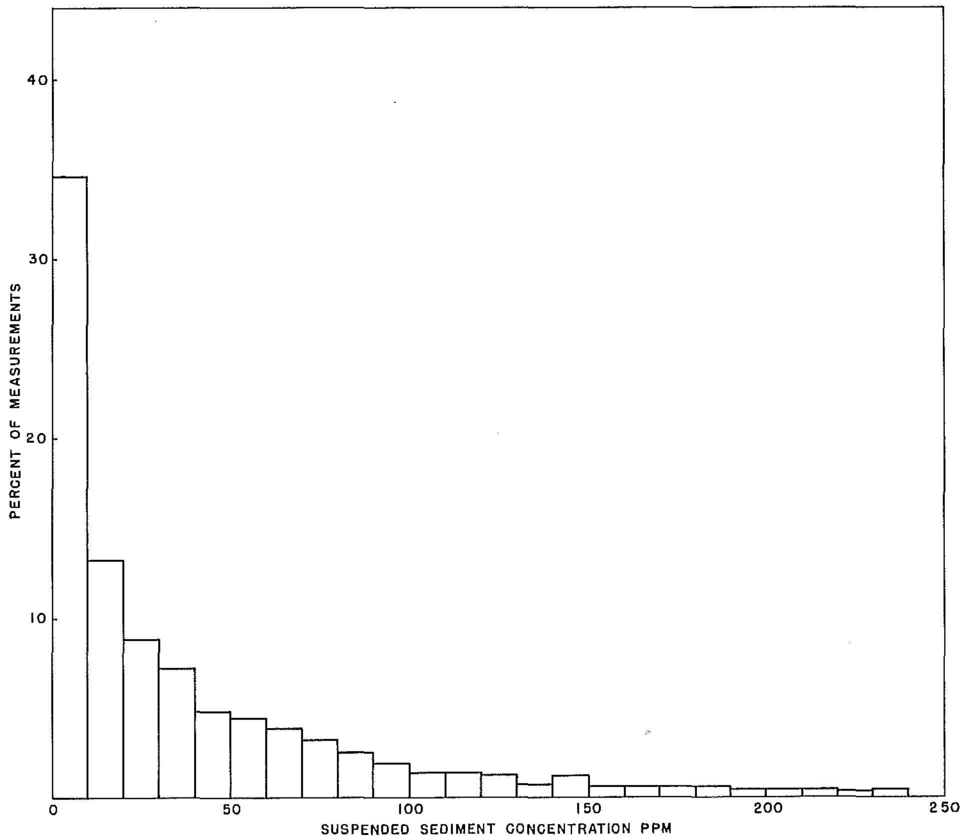


FIGURE 1—Distribution of suspended sediment concentration in 1,675 values reported for rivers in California, Oregon, Washington and British Columbia.

The principal spawning grounds of Fraser River sockeye are located on tributaries which originate in the interior of the province of British Columbia, east of the Coast Range of mountains. The climate of this region is distinctly different from that of the coastal region of the province, resulting in characteristic differences in the annual stream flow patterns of the two regions. FIGURE 2 illustrates the recorded range of stream flows for the Chilko and Adams Rivers, two Fraser River tributaries in the interior zone, which support large populations of sockeye salmon. These rivers have a very stable annual flow pattern with characteristic freshet during May, June or July resulting from snow melt. Also shown on FIGURE 2 are the *(typical)* periods of sockeye migration, spawning, incubation and emergence. Characteristically, all Fraser River sockeye runs spawn during the late summer and fall and the eggs are incubated during the winter months. For purposes of this study it is significant to note that in this interior zone this characteristic results in spawning at a time of declining flows after the freshet and incubation during minimum flows. It is estimated that historically about ninety per cent of all Fraser River sockeye spawned in the interior zone under these characteristic conditions of stream flow. In the many interior zone tributaries of the Fraser River in which salmon spawn, suspended sediment concentrations during the

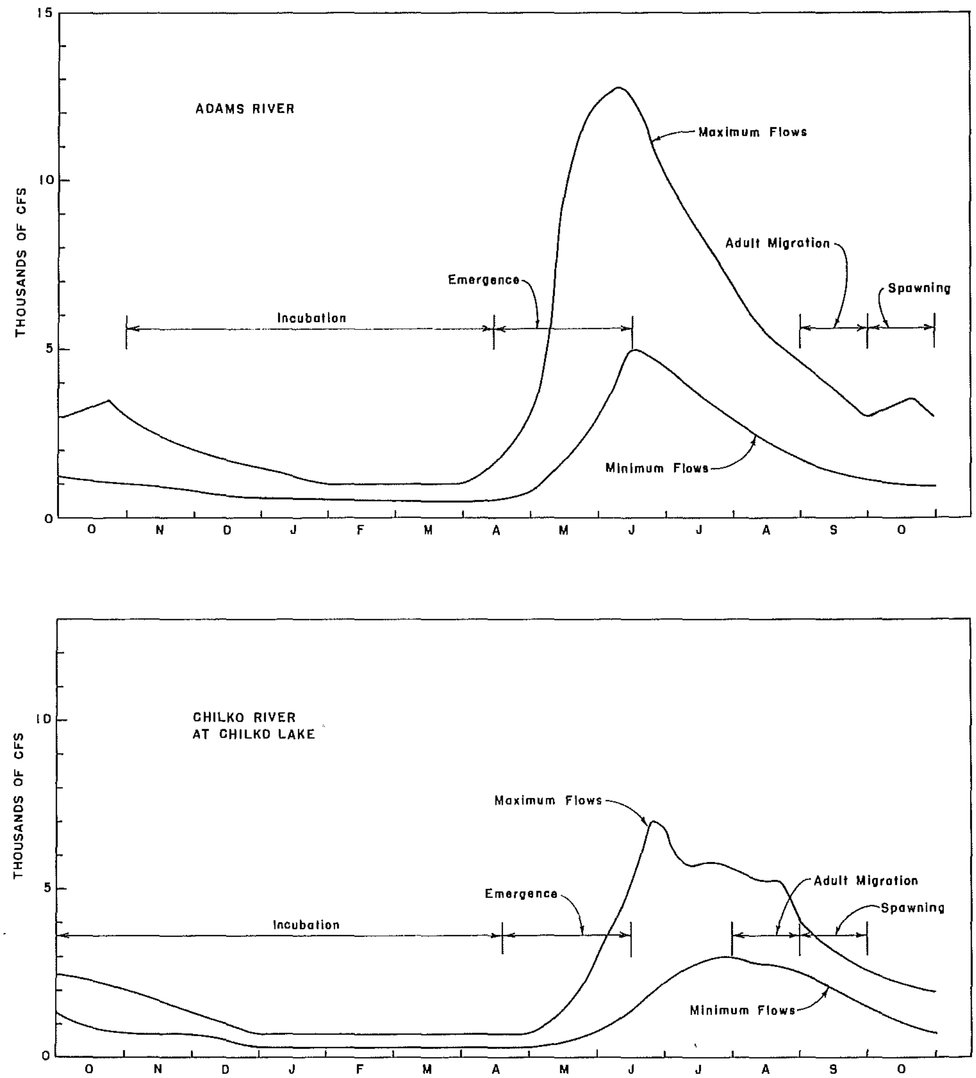
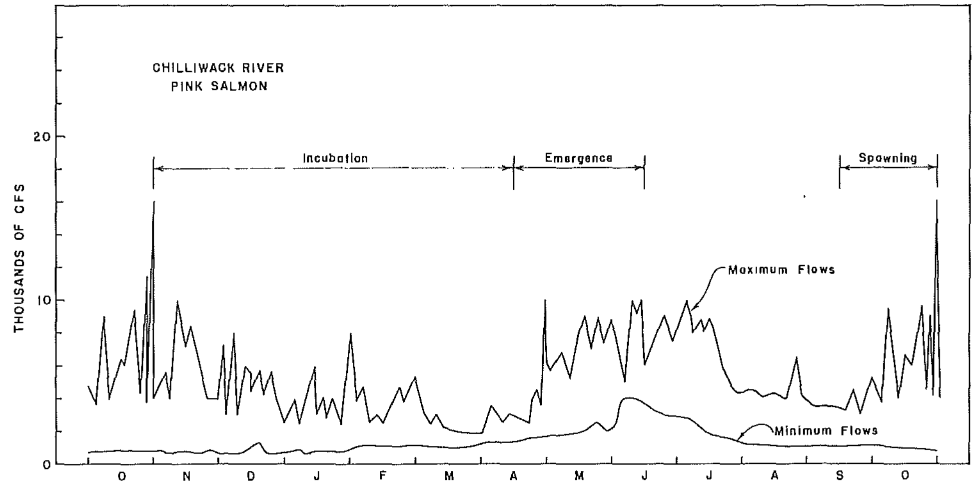


FIGURE 2—Recorded range of stream flow in typical Fraser River sockeye spawning streams in the interior climatic zone.

spawning and incubation period are generally lower than in the Fraser River. In outlet streams of large lakes, such as Adams River, suspended sediment concentrations are very low. In other streams such as Horsefly River, Mitchell River, and the Birkenhead River suspended sediment concentrations at the time of spawning are less than the minimum that can be measured with a Jackson Turbidimeter (approximately 25 turbidity units). The suspended solids concentration in the Horsefly River at the time of spawning during a period of heavy rain and relatively high discharge was found to average 6.21 ppm (Cooper 1956).

In contrast, FIGURE 3 shows the recorded range of flows for a sockeye and a pink salmon spawning stream in the coastal climate zone. The flow pattern



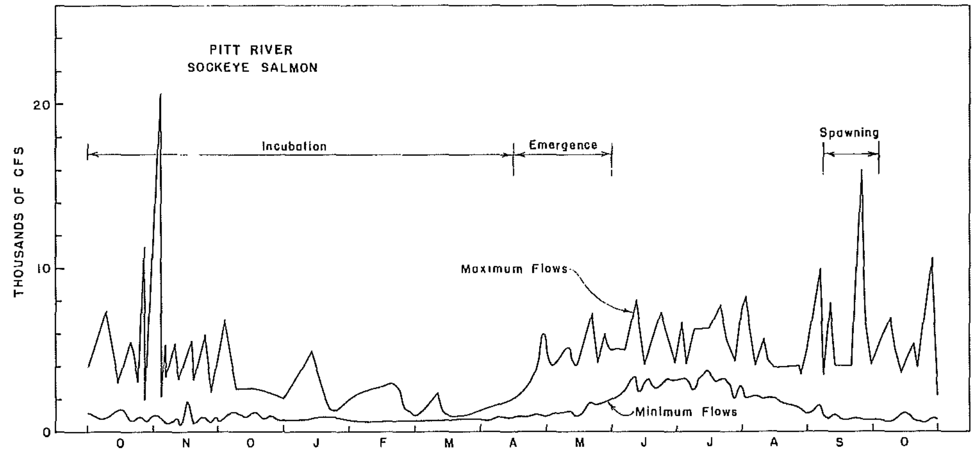


FIGURE 3—Recorded range of stream flows in typical Fraser River sockeye and pink salmon spawning streams in coastal climatic zone.

during the period of spawning and incubation is much less stable due to the prevalence of late fall and winter rainfall. This characteristic of coastal streams can influence the survival of sockeye and other salmon in a number of ways, such as by smothering or erosion of the nests due to shifting of bed load, and smothering of nests due to deposition of suspended sediments. Data shown in FIGURE 4 illustrates the relationship between stream flow pattern and the occurrence of suspended sediments in the Fraser River near its mouth. Because of this characteristic relationship suspended sediments will occur in greater concentration during the spawning and incubation period of sockeye and pink salmon in coastal zone streams than they will in interior zone streams. Furthermore, in the interior zone most of the major sockeye spawning grounds are located downstream from large lakes which serve as settling basins and remove much of the suspended sediments.

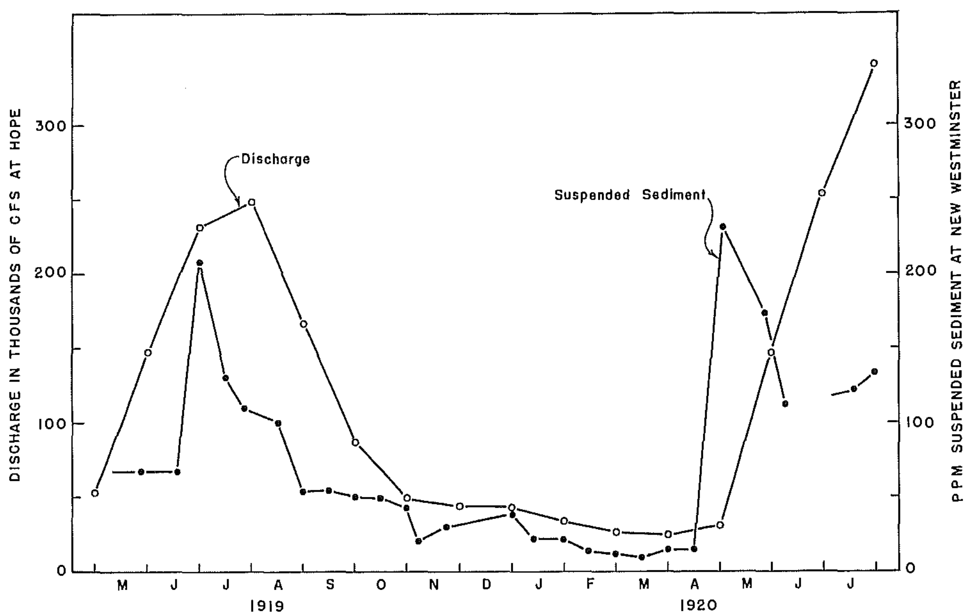


FIGURE 4—Seasonal variation of suspended sediment and discharge in the Fraser River for the period 1919-20 (from Johnston 1921).

In the main Fraser River, the highest concentrations of suspended sediment occur in the period April to August. During the period September to November, when pink salmon spawn in the Fraser River downstream from Hope, the sediment concentrations are at the minimum level of 25 to 30 ppm. This condition continues throughout the winter until at least the end of March, by which time the alevins are beginning to emerge from the gravel.

From the foregoing data, as well as from general observations, it can be stated that in the most stable reproducing areas for sockeye and pink salmon in the Fraser River system, suspended sediment concentrations are minor during the spawning and incubation period. As will be seen in subsequent sections of this report, this condition has a significant bearing on the productivity of these spawning grounds.

The influence of the sediments that are present in these rivers is further minimized by the action of the salmon in digging their nests. This vigorous digging of the stream bed serves to wash the gravel free of fine sediment and when the gravel is replaced over the deposited eggs, it is porous and contains much less of the fine materials which, as will be shown later, have a large influence on flow of water through gravel. In the interior zone, where streams are relatively free of sediments during the winter, there is more opportunity for the gravel in the nests to stay clean than there is in streams in the coastal zone.

STREAM SEDIMENT TRANSPORT

In considering the effect of transported sediments on the stream bed, it is necessary to distinguish between the various kinds of transported sediments. The following definitions describe the categories of materials transported by streams (Lindsay, Kohler and Paulhus 1949).

1. Bed load. Material moving on or near the bed. It may consist of material rolled or slid along the bed in substantially continuous contact with the bed (Contact load), or of material bouncing along the bed or moved by the impact of bouncing particles (Saltation load).

2. Suspended load. Material moving in suspension in the stream. It may consist of particles found in appreciable quantities in the shifting portions of the stream bed (called bed material load) or of particles smaller than those found in appreciable quantities in the shifting portions of the stream bed (called wash load).

In natural streams or rivers the size of the materials in each of these categories will vary along the river, depending on the hydraulic characteristics of the stream. The suspended load of one section of river may become the bed load of another section and vice versa. The quantity of materials transported will vary, depending on the available sources of materials and on the stream discharge. Lindsay *et al.*, review some of the formulae developed to measure the flow of bed materials of specified sizes. In an alluvial stream where the river bed is composed of non-cohesive materials transported and deposited by the river, there is a relationship between the tractive force (τ_o) of the water along the bed and the size of particle that will resist movement by this force. Under conditions of steady, uniform flow, the tractive force is equal to the force causing the water to move, or the component of the weight of the water in the direction of flow, a concept first expressed by du Boys (Equation 1),

$$\tau_o = 10\rho Ds \qquad \ldots\ldots \quad (1);$$

where τ_o = bed tractive force in kg/sq m;

ρ = density of water in gms/cc;

D = depth of water in cm;

s = hydraulic gradient.

From a review of available data, Lane (1952) concluded that the limiting tractive force for fine, non-cohesive materials in canals may be represented by Equation 2,

$$\tau = 0.96d \qquad \ldots\ldots \quad (2);$$

where τ = bed tractive force in kg/sq m;

d = size in cm of particle finer than 25 per cent of the bed material.

Lane suggested that in order to provide a safety margin in the design of canals the tractive force should be limited to the value given by Equation 3, with the same units as above.

$$\tau = 0.766d \quad . \quad . \quad . \quad . \quad . \quad (3).$$

Based on studies made by White (1940), Kalinske (1947) expressed the tractive force that will cause initial movement of a particle (critical tractive force) in terms of the particle size by an equation, which in the gm-cm-sec system becomes Equation 4, with units as above.

$$\tau_c = 1.925d \quad . \quad . \quad . \quad . \quad . \quad (4).$$

Kalinske shows that because of the velocity fluctuation in turbulent flow near the bed of a stream, the tractive force at times may be about three times the mean value. In this case, the mean critical tractive force needed to start movement of the bed need only be about one-third the value given by Equation 4, or a little less than the values given by Equation 3.

The relative stability of the bed materials in a stream can be assessed by comparing the actual bed tractive force obtained from Equation 1 to the limiting tractive force. Such a comparison for a number of sections of the Horsefly River based on data obtained by Cooper (1956), and using Equation 2 for limiting tractive force, is summarized in TABLE 4.

TABLE 4—Representative size of bed surface materials at various points in the Horsefly River and comparison of actual and limiting bed tractive force at these points.

Station	Representative Size in cm 75% finer than	Bed Tractive Force Kg/sq m	
		Actual	Limiting
7A	18.2	1.92	17.5
8A	14.8	2.42	14.2
9A	7.08	1.705	6.8
10A	2.82	0.775	2.7
11A	8.32	0.64	8.0
13A	1.00	0.122	0.96
2A	8.71	0.68	8.35
3A	12.7	0.963	12.2
14A	1.51	0.042	1.45
16A	5.13	0.7	4.93

The field measurements were made at discharges ranging from 772 cfs at station 7A to 1,540 cfs at station 16A. At these discharges the bed materials had a substantial reserve of stability at all stations. The maximum recorded discharge at station 16A is 7,620 cfs, and the corresponding bed tractive force would be about 2 kg/sq m, which is still less than one-half the critical value.

It is not possible to determine theoretically the size of particle that a particular section of river can keep in suspension under the conditions of non-uniform flow prevailing in most rivers. Lindsay *et al.*, review methods of computing the distribution and total transport of particles of various sizes under conditions of uniform flow, but these methods cannot be solved for non-uniform flow conditions.

The materials actually on or in the river bed are of most interest with respect to measurement of the suitability of the bed materials for salmon spawning grounds. Determinations of critical tractive force and bed load transport may be employed to estimate the probable distribution and accumulation on the bed of particles of various sizes that may be added to a river. Sampling of the existing bed materials can provide a measure of the stability of the bed at flood flows and also the maximum transport capability of the river in various reaches. The minimum capability of a section of stream to transport bed materials will occur at minimum water slope and depth, which generally would be at minimum flow. If soil materials discharged to a stream are of a size which is larger than can be transported by the stream as bed load, then such materials will accumulate on the stream bed. If bed materials of transportable size are added to a stream at a rate which exceeds the transport capability of the stream, these materials will also form shifting deposits on the stream bed.

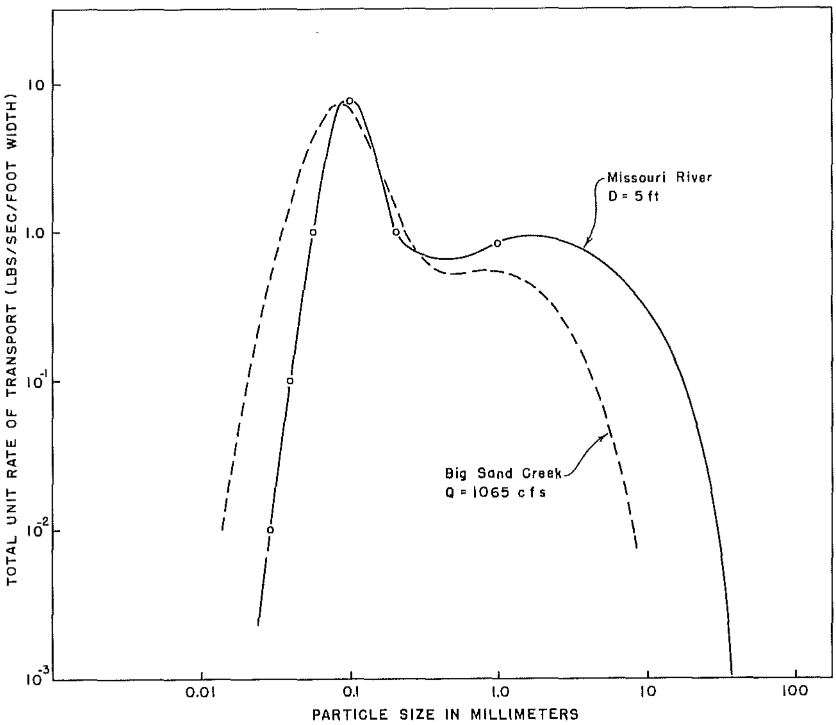


FIGURE 5—Total transport of bed material load for various particle sizes and selected discharges in alluvial sections of the Missouri River and Big Sand Creek (from Einstein 1950).

Lindsay *et al.,* review theoretical and empirical methods of calculating the transport of bed materials along the bed. Einstein (1950) derives a relationship between bed material particle size and total transport along the bed and in suspension. This relationship shows a typical increase in transport (FIGURE 5) as the particle size decreases from 0.3 mm to 0.1 mm.

Einstein attributes this increase to a transition from movement along the bed to movement in suspension. He theorizes that the decrease in transport of bed materials less than 0.1 mm size is the result of small particles coming to rest between larger particles, beyond the influence of turbulence in the laminar sublayer. This view apparently is supported by Lane (1952) who observed that the critical bed tractive force could not be determined from sieve analyses of bed materials because smaller particles were shielded by the larger ones.

Lane (1938) observed that the settling velocity of particles less than 0.1 mm size varied as the square of the diameter, whereas for particles larger than 0.3 mm it varied as the square root of the diameter, with a transition zone from 0.1 to 0.3 mm. Lane concluded that because of this difference in behavior, the energy required to keep particles less than 0.1 mm size in suspension decreases so rapidly with decrease in size that most streams are able to carry without deposition all sediment particles less than 0.1 mm size. However, as shown above, this does not prevent these small particles from entering the laminar sublayer of the stream bed where they may settle out of the water. These observations explain the relative lack of fine particles evident in good spawning gravel (FIGURE 6) and the presence of a small percentage of materials of less than 0.1 mm size in bed surface samples (TABLE 5).

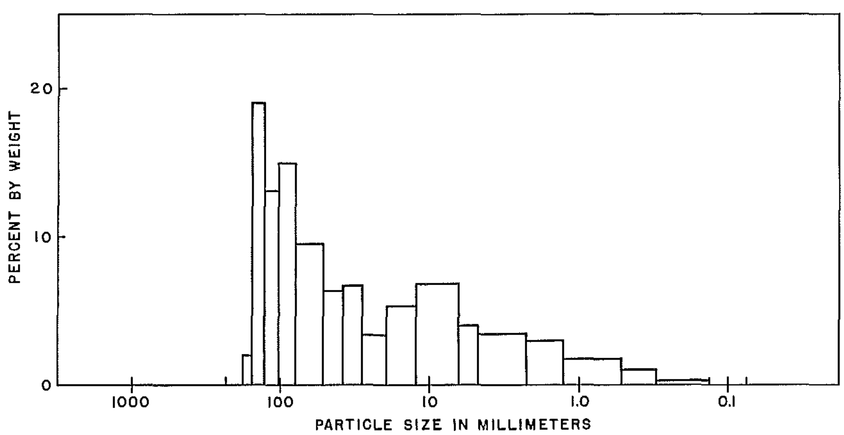


FIGURE 6—Size frequency distribution for Seton Creek spawning gravel.

The effect of the deposition of suspended sediments in the laminar sublayer of salmon spawning bed gravel on the survival of eggs deposited in the gravel will be considered in a subsequent section of this report.

TABLE 5—Occurrence of sediments of less than 74 microns size in bed surface samples from the Horsefly River.

Station	Per cent by weight less than 74 microns	
	Deep Water	Shallow Water
2	0.002	0.027
3	0.0	0.100
7	0.002	0.013
8	0.013	0.002
9	0.0044	0.152
10	0.028	0.127
11	0.085	0.086
16	0.073	0.157

Many empirical and theoretical methods for calculating bed load movement have been deduced by empirical means or from experimental data (Lindsay *et al.*). The method developed by Einstein (1950) takes into consideration the influence of turbulence on bed load movement, and describes the movement of bed materials both along the bed and in suspension. Kalinske (1947) developed a method of computing rate of movement of particles along a stream bed based on the mechanics of turbulent flow. Kalinske's method is used here for illustrative purposes to calculate bed load transport at two sections in the Horsefly River and to calculate the distribution of transport across each section.

Using Kalinske's method, the bed load transport can be related to the tractive force by Equation 5.

$$G = \frac{Uwd}{10}\,\theta\frac{\tau_c}{\tau_o} \qquad \ldots\ldots \quad (5);$$

where G = bed material transport in kg/sec/meter width of stream bed;

U = mean fluid velocity at the particle level in cm/sec;

w = specific weight of bed material particles, taken to be 2.65 in this report;

d = particle diameter or size in cm;

θ = a dimensionless function of $\frac{\tau_c}{\tau_o}$;

τ_c = critical tractive force as given by Equation 4.

By converting units from the relationship given by Kalinske, the mean fluid velocity (U) at the particle level may be expressed by Equation 6.

$$U = 1.92\sqrt{\frac{\tau_o}{\rho}} \qquad \ldots\ldots \quad (6).$$

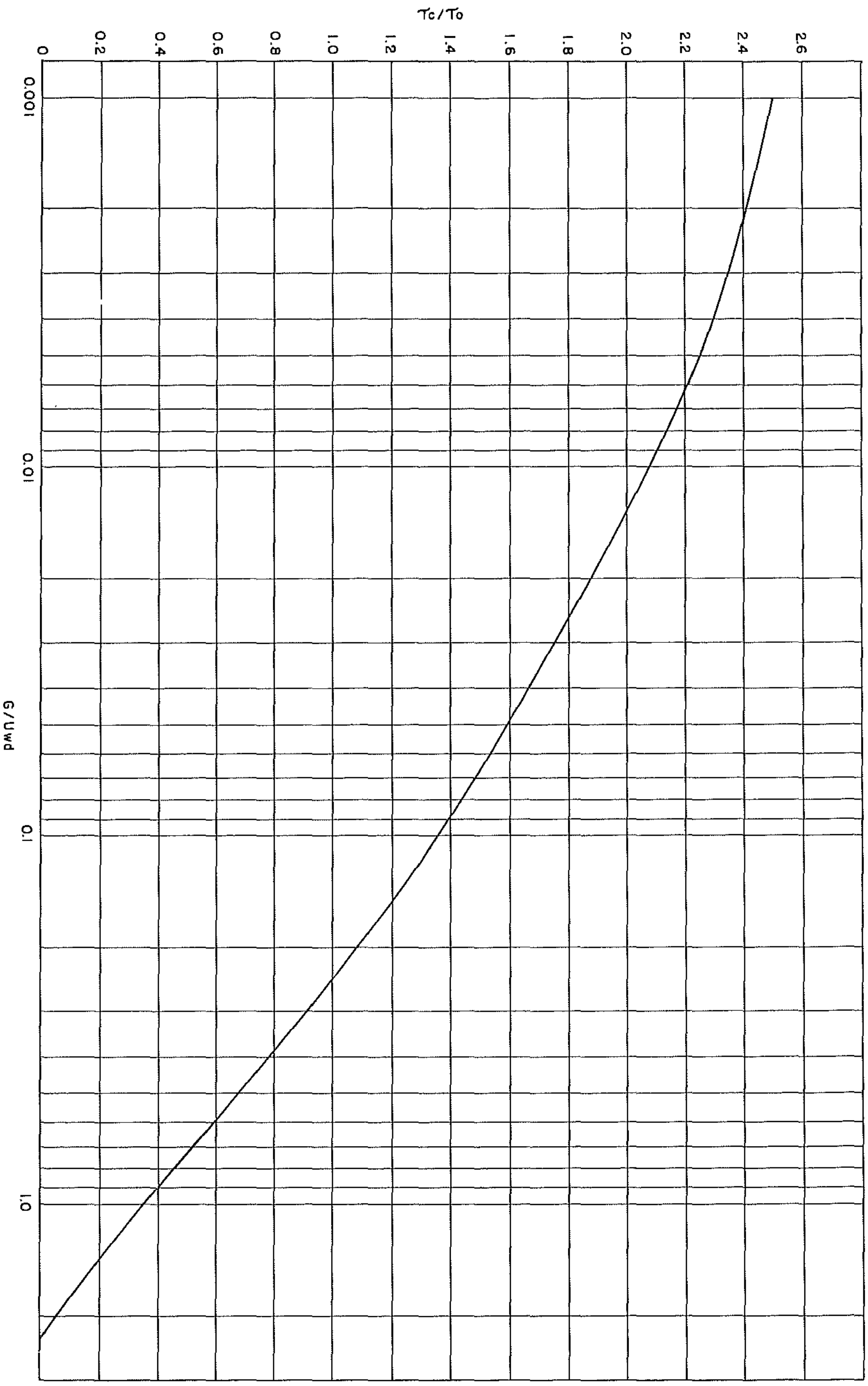


FIGURE 7—Bed load transport function (from Kalinske 1947).

Kalinske compared values of the dimensionless ratios $\frac{G}{Uwd}$ and $\frac{\tau_c}{\tau_o}$ with experimental data from a number of sources and obtained the relationship between them (θ) shown on FIGURE 7. Starting with a given particle size and tractive force (τ_o), the ratio $\frac{\tau_c}{\tau_o}$ can be calculated. Entering FIGURE 7 with this ratio, a value for the ratio $\frac{G}{Uwd}$ can be determined, and by substituting values for U, w and d, the value of G can be calculated.

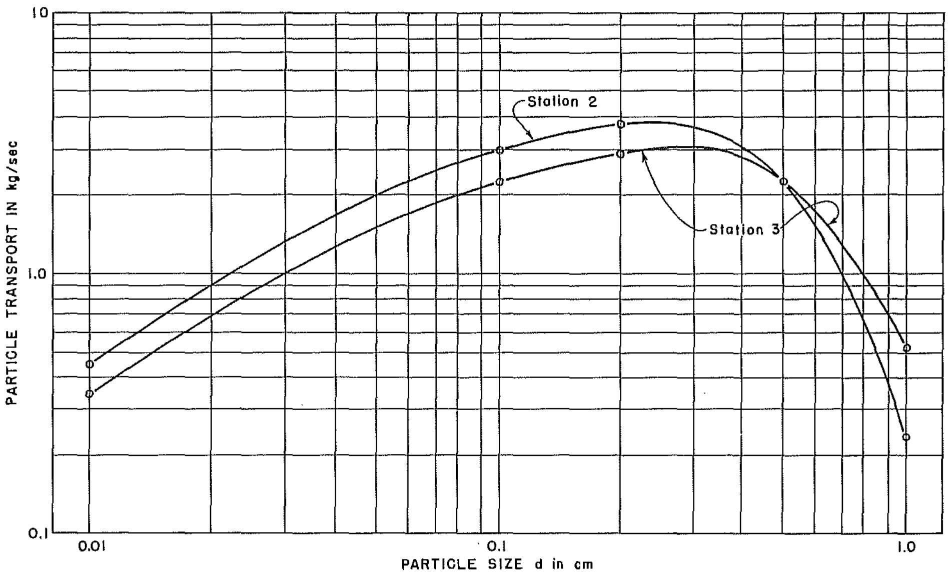


FIGURE 8—Calculated bed load transport at two cross sections of the Horsefly River.

The total transport of bed materials in the range 0.01 cm to 1 cm at two sections of the Horsefly River were calculated by this means, and the results obtained have been plotted in FIGURE 8. It can be seen that between section 2 and section 3 there is a decrease in transport capability for particle sizes less than 0.2 cm, and it could be expected that the difference in transport rate would accumulate on the stream bed at section 3 and for some distance upstream towards section 2. This accumulation would continue so long as the bed materials continued to flow past section 2 or until transport capability changed as a result of a change in cross section or discharge. In order to determine where the materials would be deposited, detailed study of numerous cross sections would be required. Analysis of the transport capability of several particle sizes across section 2 and section 3 of the Horsefly River (FIGURE 9) using the method described above shows that the transport rate would be relatively constant across section 2 because of the uniform depths, and would be largest near midstream at section 3 diminishing to zero on the shallow areas near each bank. At a distance of eight meters from each

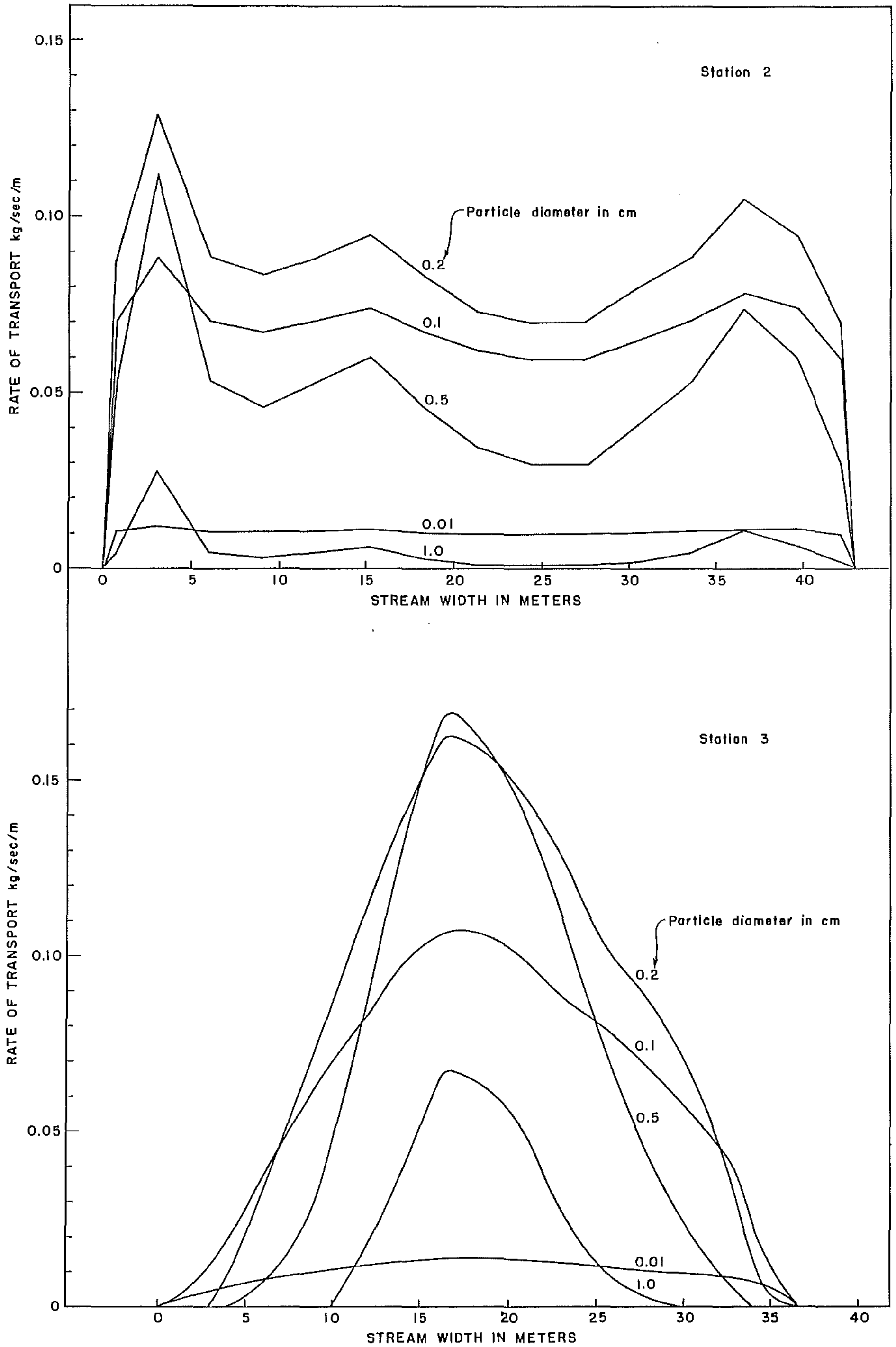


FIGURE 9—Calculated distribution of bed load transport at two sections of the Horsefly River.

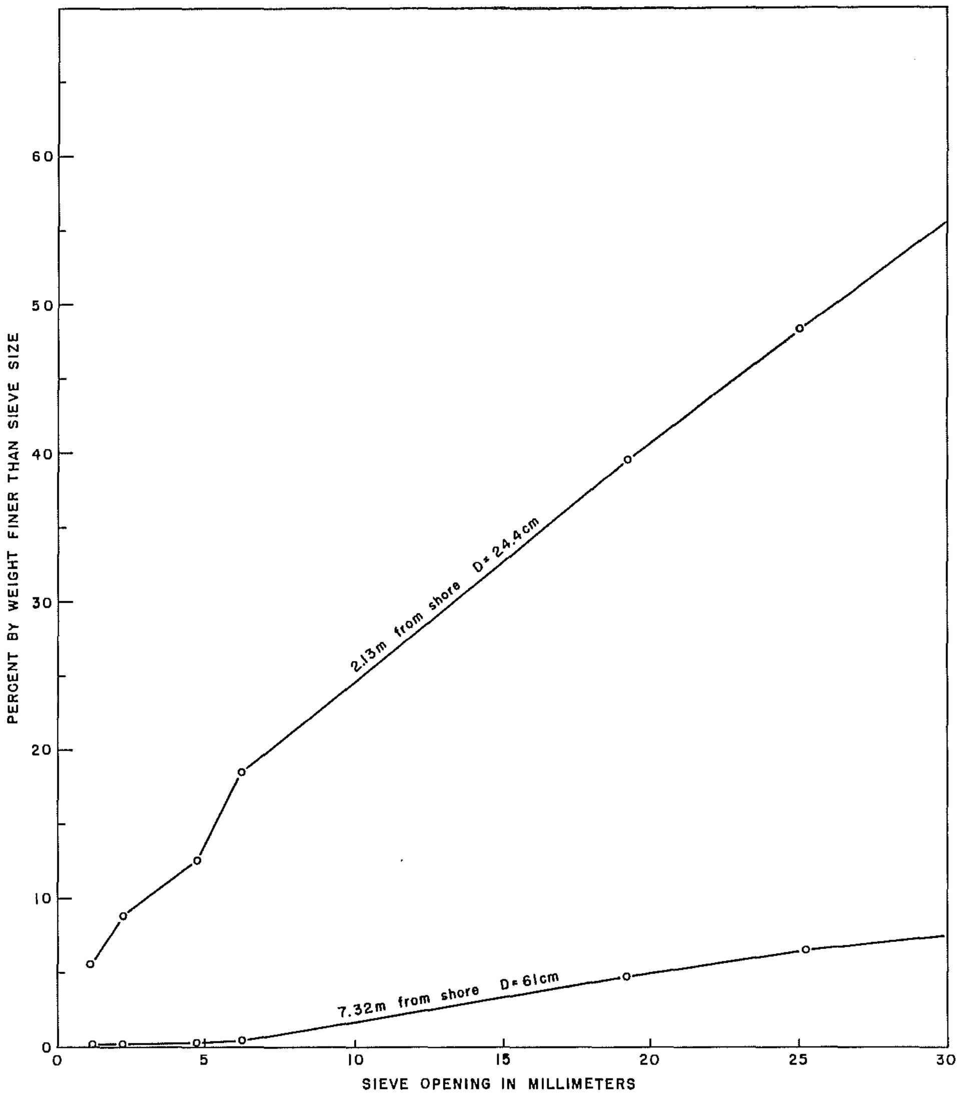


FIGURE 10—Variation in distribution of fine materials at section 3 in spawning grounds of the Horsefly River.

bank at section 3, transport of particles of 1 cm size would be zero, so it could be expected that the greatest accumulation of particles of this size would occur from the shoreline out a distance of eight meters. It would also be expected that the distribution of the materials would not be uniform, but that the percentage of smaller particles present would increase in the direction of shallow water. Analyses of bed material samples obtained at this section (FIGURE 10) show this trend of distribution to be true.

Because stream discharge and the availability of sediments for transport by a stream are seldom steady for long periods, and because of the probable variations in distribution of sediments of various size across a stream section, it would be a formidable task to attempt to estimate the amount of accumulation of various size particles on a particular portion of a stream bed at a particular time, and at best the value estimated would be transitory. It is considered sufficient for the purpose of this study to demonstrate that under certain circumstances the accumulation of bed material will occur.

EFFECT OF SUSPENDED AND DEPOSITED SEDIMENTS ON THE SURVIVAL OF SALMON EGGS AND ALEVIN

The detrimental effects of depositions of fine sediment on the survival of river bottom organisms and salmon eggs and alevin buried in the gravel are well recognized. Cordone and Kelley (1961) have prepared a comprehensive review of a considerable number of investigations all of which demonstrate the harmful effect quite clearly. Smith (1939) and Wendler (1952) report reductions in number of bottom organisms in stream beds as a result of silt deposition. Johnson *et al.*, (1952) report a substantial reduction in survival of steelhead eggs as a result of silt deposited from a slide on the Stillaguamish River. Stuart (1953) and Shaw and Maga (1943) have demonstrated experimentally the reduction in survival of salmon and trout eggs caused by silt deposition. Wickett (1951), Cooper (1956) and Gangmark *et al.*, (1960) have demonstrated mortality to salmon eggs resulting from reduced flow through gravel caused by silt deposition. On the basis of a study of sediment composition in the Horsefly River, Cooper (1956) recommended certain limitations on the quantity and particle size of sediment that should be permitted to be discharged to the river. These recommendations were designed to prevent accumulation of sediments on the stream bed which would reduce the survival of sockeye salmon eggs. However, on the basis of data on the mechanism of flow interchange between the stream and the gravel bed, it was recognized that it might be possible for sediments to enter the interstices of the gravel bed while suspended in the water and then settle out within the gravel. Such depositions would also reduce the survival of any salmon eggs in the gravel. Consequently investigations were conducted to evaluate the effect of suspended sediments on the flow of water through a gravel bed. The results of these investigations are given in following sections of this report.

Seepage Paths Through Gravel Spawning Beds

The distribution and direction of flow paths through the gravel of a stream bed have very significant influences on the survival of salmon eggs deposited in the gravel. Therefore, in order to fully appreciate the effect of suspended and deposited sediments on the survival of salmon eggs, it is desirable to have information on these flow paths. Pyper (MS.) conducted studies in 1956 using dyes as tracers to locate water flow paths through gravel placed in a glass walled flume. These tests were conducted with a typical spawning bed gravel and also with a homogeneous gravel of 8 mm size for four different stream bed configurations. The flow paths through the homogeneous material were found to be more uniform than through the spawning gravel, thereby illustrating the flow paths more clearly,

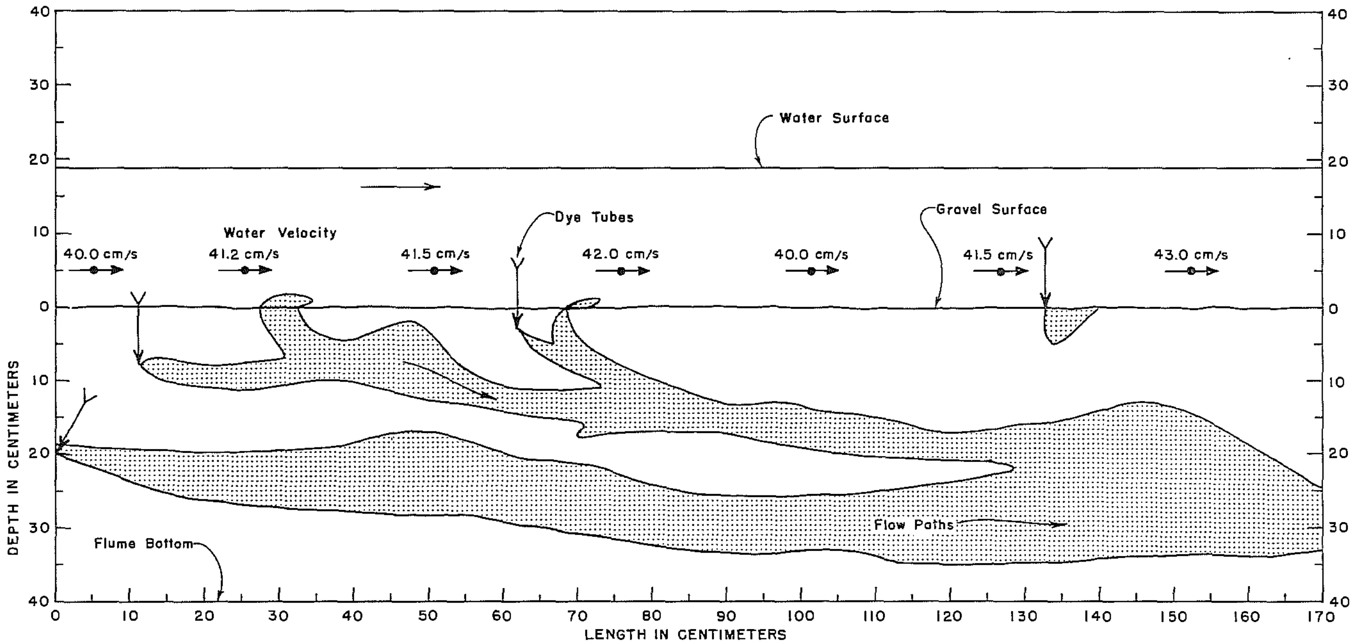


FIGURE 11—Flow paths through homogeneous gravel with level gravel surface.

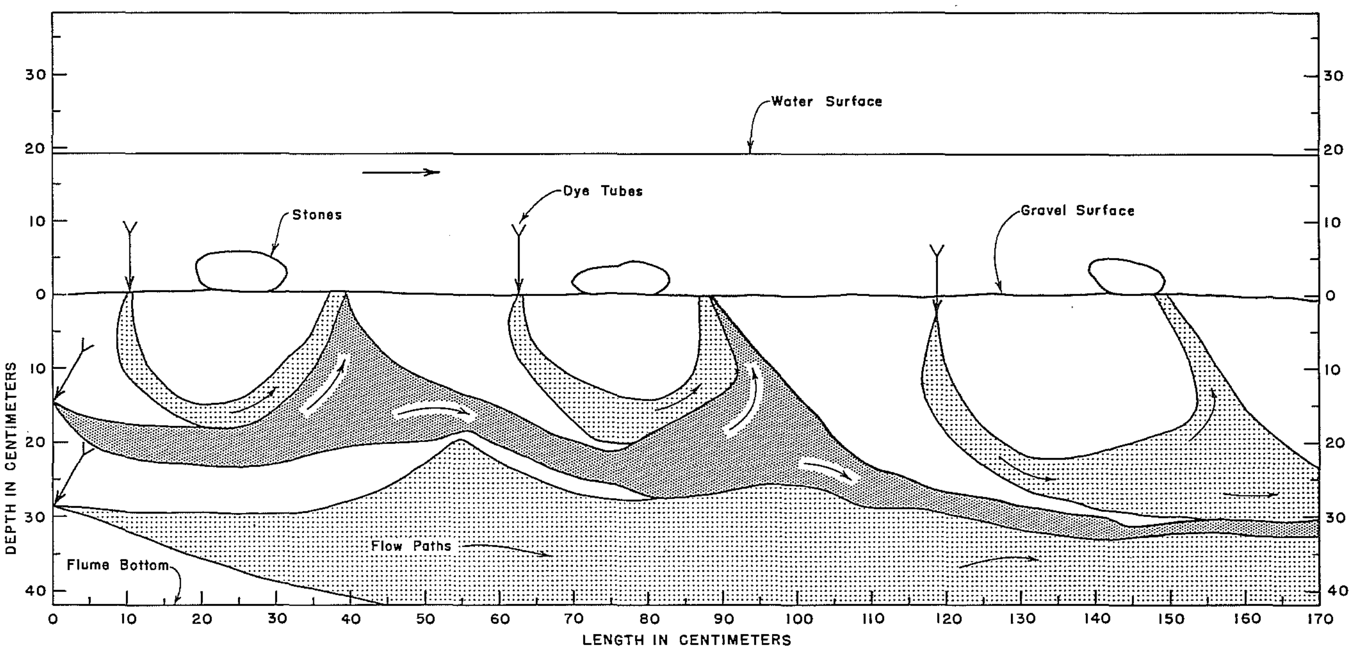


FIGURE 12—Flow paths through homogeneous gravel with level gravel surface with stones protruding above the surface.

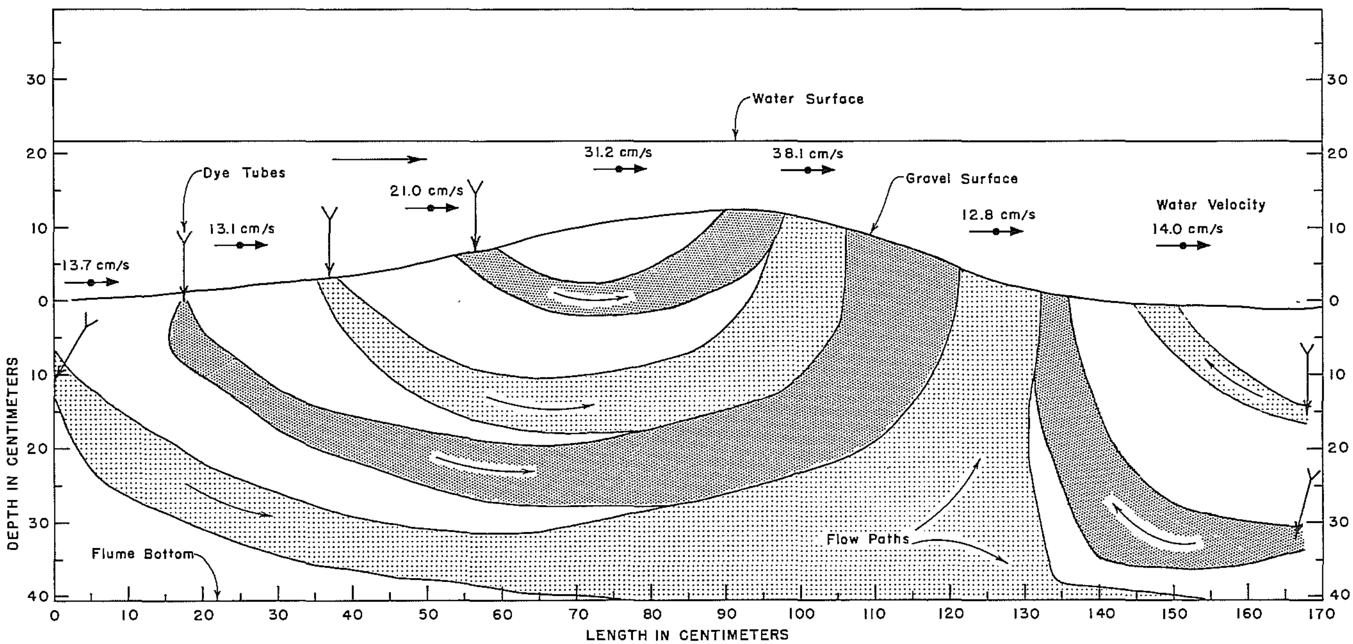


FIGURE 13—Flow paths through homogeneous gravel with a surface similar to a new salmon redd.

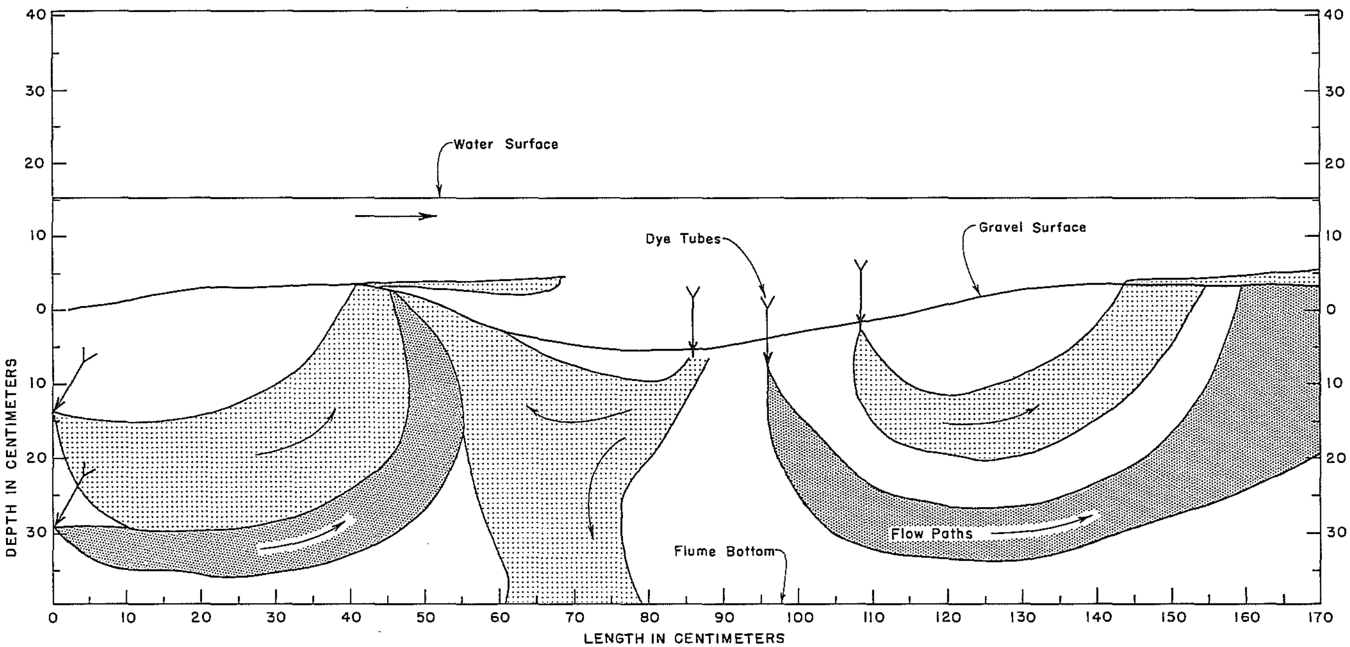


FIGURE 14—Flow paths through homogeneous gravel with a surface similar to a new salmon redd.

although the same general observations would apply to both types of gravel. With a flat, smooth, stream bed, (FIGURE 11) the interchange of water between the stream and the gravel tended to be limited to the upper 15 cm of gravel, although some of the flow penetrated deeper. In addition, the intra-gravel flow at depths greater than 15 cm was generally parallel to the stream surface. This type of flow distribution is not considered to be representative of sockeye and pink salmon spawning grounds, which do not have such flat smooth gravel surfaces. It also would not provide optimum conditions for the survival of salmon eggs which were deposited more than 15 cm deep in gravel since there could be insufficient replenishment of fresh water. Stones placed on the surface of the gravel increased the amount and depth of interchange of fresh water (FIGURE 12). The differences in hydrostatic head upstream and downstream from the stones, created a flow through the gravel beneath the stones which, in the case illustrated, extended to a depth of 30 cm. By forming the surface of the gravel into humps and depressions similar to those made by spawning salmon, even greater intra-gravel circulation was obtained (FIGURES 13 and 14). Under these conditions the surface water exchange penetrated to a depth of 46 cm. It is evident that the surface roughness created by salmon during spawning promotes circulation of fresh water through the redds, thereby improving conditions necessary for good survival of the salmon eggs. It is also evident that sediment deposits on the stream bed surface or within the gravel could reduce the exchange of water between the stream and the gravel.

The Effect of Deposits of Sediment on a Stream Bed on the Flow of Water Through the Gravel Bed

Cooper (1956) performed tests in a permeameter (FIGURE 15) to measure the effect of deposition of various amounts and sizes of sediment on the flow of water through a typical spawning bed gravel. The sieve analysis of this gravel is given in TABLE 6. In conducting these tests it was assumed that in the natural situations

TABLE 6—Sieve analysis of gravel used in permeameter tests.

Opening in Microns	Per Cent Passing
101,600	100
76,200	96.36
57,150	87.28
38,100	68.68
25,400	54.58
19,050	50.04
6,350	28.64
4,760	21.82
2,380	15.67
1,190	9.81
590	5.17
297	1.41
149	0.24
74	0.04

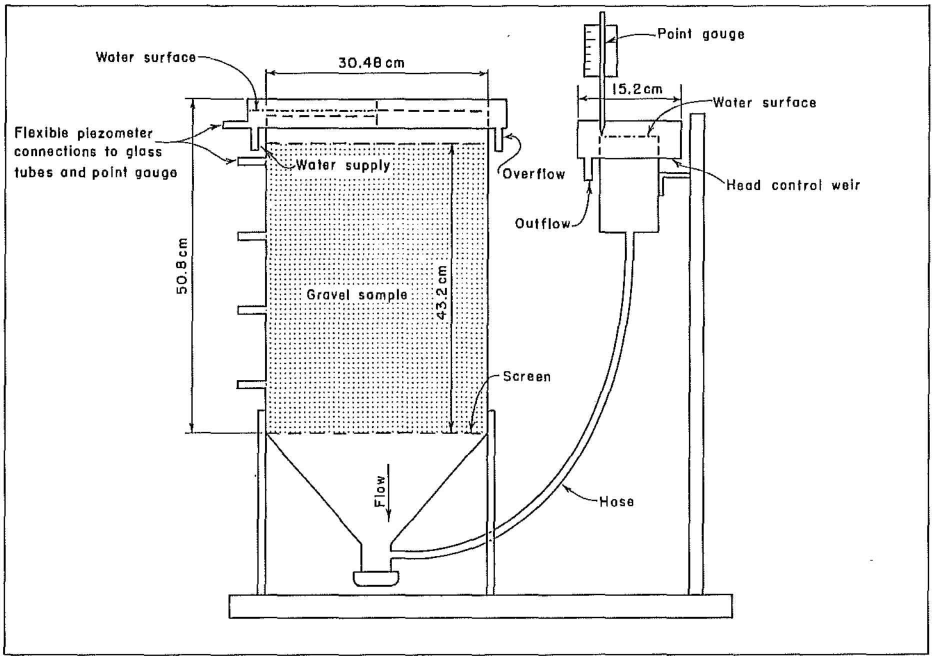


FIGURE 15—Arrangement of permeameter used to measure permeability of gravel and effect of sediment depositions on flow through gravel.

TABLE 7—Relation between rate of flow of water through a gravel bed and the survival of eyed sockeye eggs in the gravel.

Apparent Velocity[a]		Survival
mm/hour	cm/sec	%
1217	.0338	89.3
402	.0112	78.3
195	.00542	68.5
94	.00261	59.0
49	.00136	36.3
34	.000945	26.5
24	.000668	15.6
14	.000389	1.1

[a] Apparent velocity equals discharge divided by total cross section area of voids and solids.

the head difference causing flow through the gravel would remain constant regardless of the deposition of sediments. The initial flow of water through the gravel sample was set the same for each test, and the head difference necessary to establish this rate of flow was maintained constant while sediment was deposited on the surface of the gravel. At the conclusion of each test, the gravel sample was removed in layers and the sediment which had been added was recovered by screening. Tests were conducted with four different sizes of sediment and two initial flow rates. The results for one initial flow rate (FIGURE 16) illustrate the very substantial reductions in flow through the gravel that can result from depositions of sediment on the gravel surface. As will be shown later, this reduction in flow was the result of reduced effective particle size in the gravel bed and consequently reduced permeability. It should be noted that the total weight of the gravel sample was almost

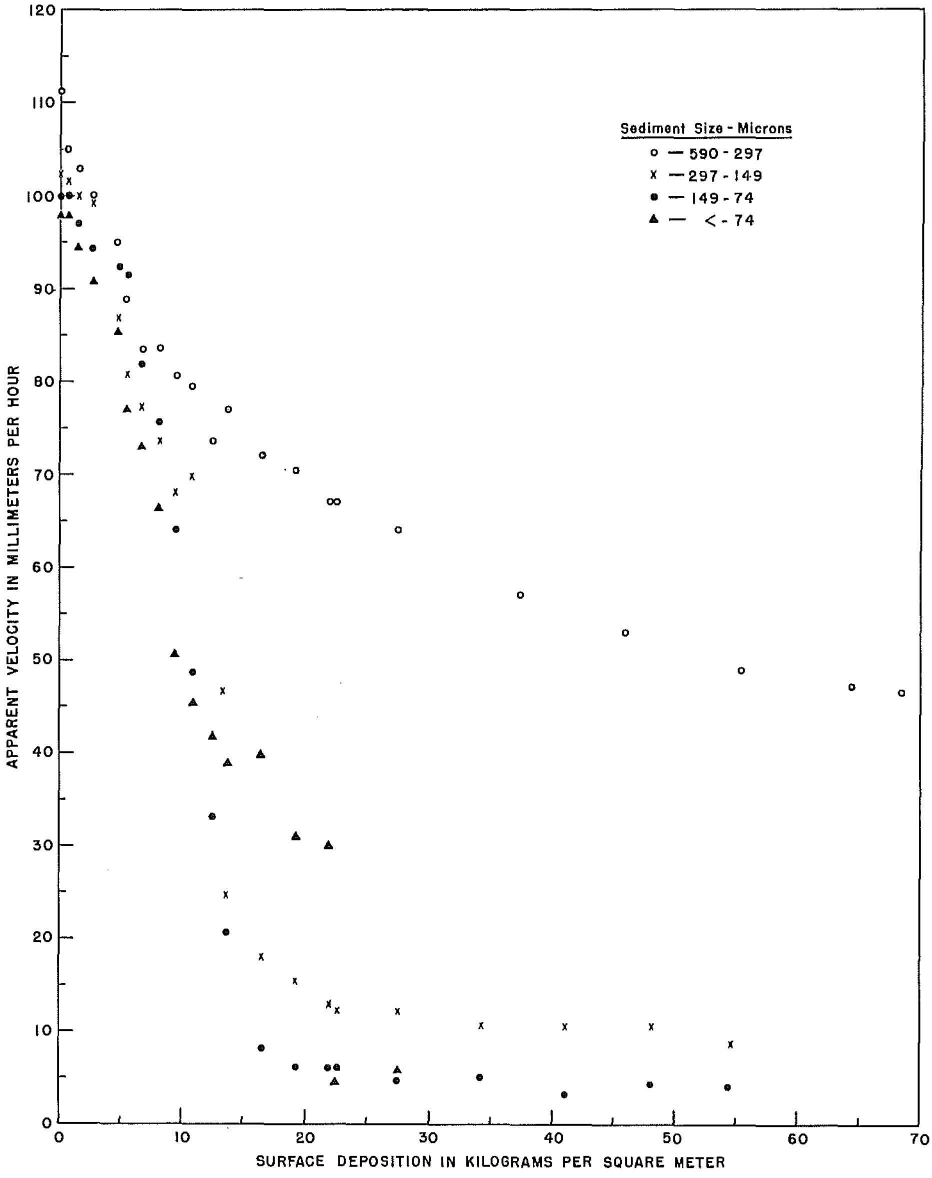


FIGURE 16—Effect of surface deposition of sediment on the flow of water through gravel under constant head in a permeameter.

64 kilograms and that less than 10 per cent of this weight was added as sediment to produce the reduction in permeability. This illustrates the major role of fine materials in establishing the permeability of a gravel, as will be discussed later in more detail.

The Effect of Flow of Water on the Survival of Salmon Eggs and Alevin Buried in Gravel

In an experiment with sockeye salmon eggs (Pyper MS.) a definite relationship was demonstrated between rate of flow of water through the gravel bed and survival from the eyed egg stage to emerged fry (TABLE 7 and FIGURE 17). It was also found that the dissolved oxygen supply must be sufficient to meet the requirements of the eggs and any other organisms or processes present in the gravel. In

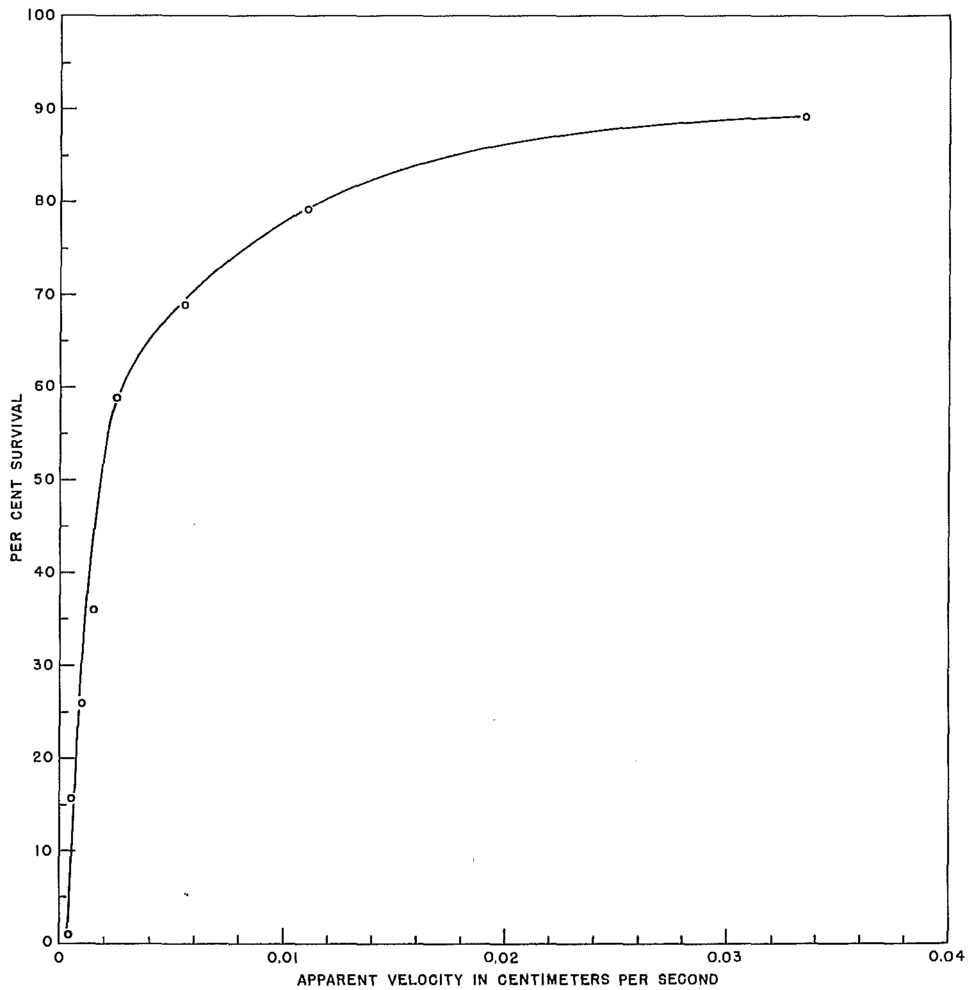


FIGURE 17—Relation between rate of flow of water through a gravel bed and the survival of eyed sockeye eggs in the gravel.

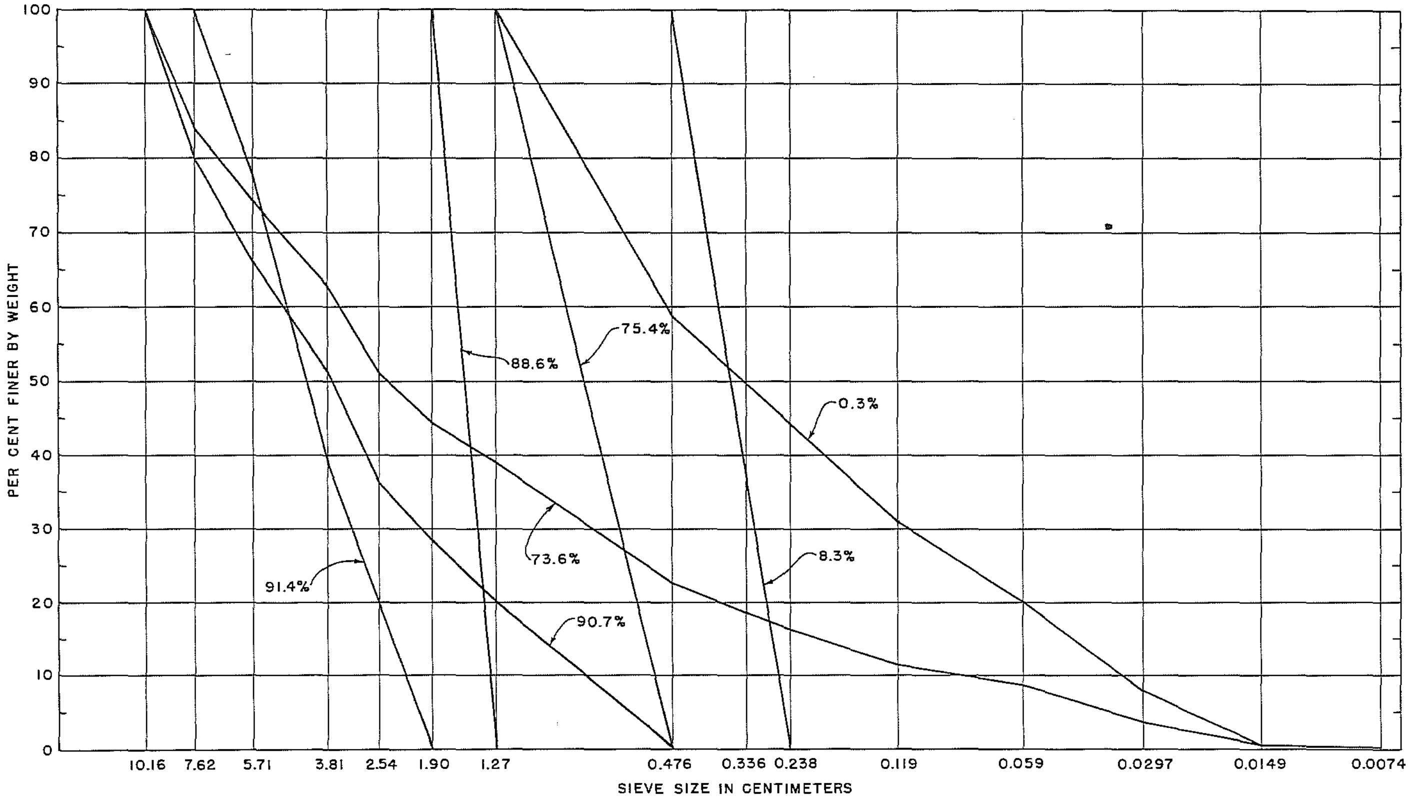


FIGURE 18—Grading curves of seven experimental gravels and survival of sockeye eggs in these gravels at a uniform water velocity of 0.0167 cm/sec.

another series of tests at a constant apparent velocity of 0.0167 cm/sec, it was found that gravel size and grading affected the survival of eggs (FIGURE 18). The porosity of the gravel was not determined in these tests so that the relationship between survival and the permeability and grading of the gravel cannot be determined. The data indicate a relationship between the survival of the eggs and the percentage of gravel finer than 0.336 cm which may be caused by packing of the particles around the eggs or by the transfer of soil pressure to the eggs. These and other data indicate that gravel uniformity is a factor which can affect the survival of eggs, and that very uniform gravels reduce the survival except possibly in coarse gravels (FIGURE 19). These results show that the deposition of sediment which would reduce the flow of water through the gravel, or which would reduce the size of the gravel, would result in reduced survival of salmon eggs in the gravel.

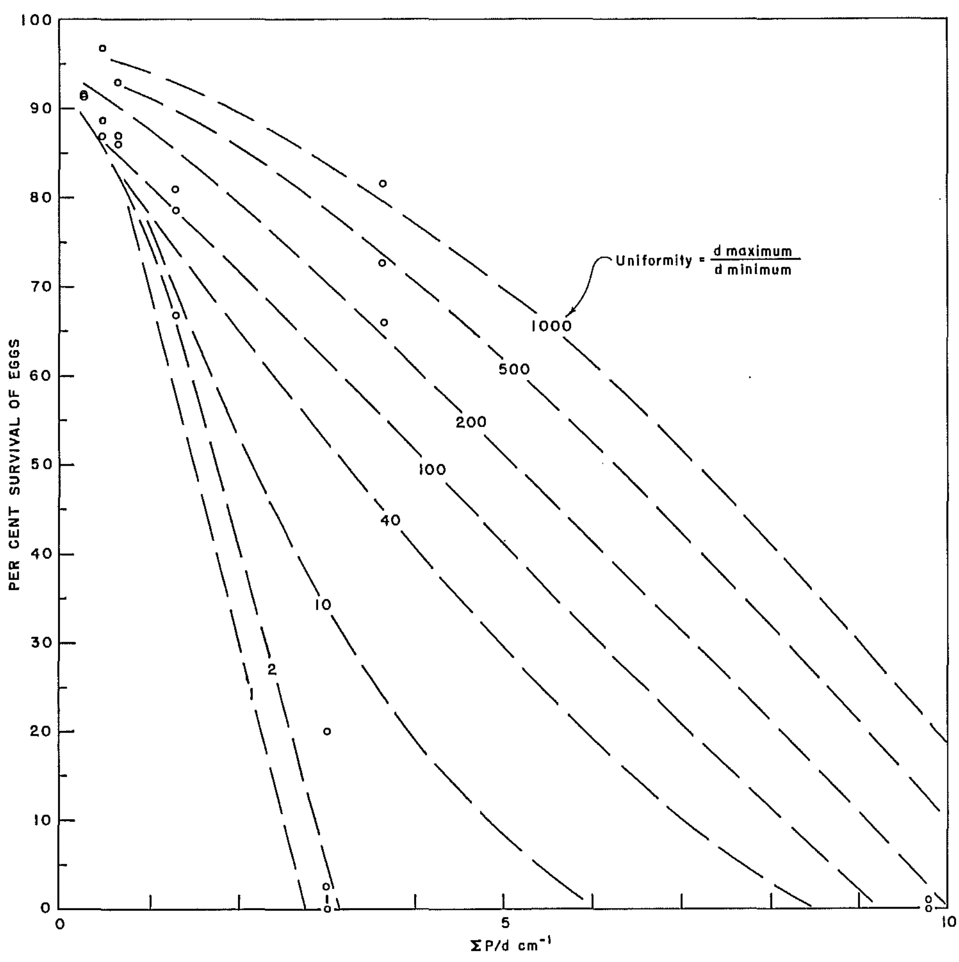


FIGURE 19—The effect of gravel size and uniformity on the survival of sockeye eggs at a flow of 0.0167 cm/sec.

Cooper (1956) conducted experiments with fresh fertilized sockeye eggs to measure the effect of variations in amount of sediment, size of sediment, and time of deposition of sediment on the survival of the eggs to emerged fry. These tests were conducted in a similar manner to the permeameter tests referred to in the preceding section, using an initial apparent velocity of 0.0033 cm/sec and maintaining a constant head throughout the experiment.

It was found that the oxygen consumption of the eggs was relatively constant until hatching commenced but subsequently it increased until the fry emerged from the gravel (FIGURE 20). On the basis of these observations it was concluded that the period during or after hatching of the eggs would be most critical with respect to reductions in the flow of oxygen to the eggs. The survival of eggs subjected to the various experimental conditions was compared to the average apparent velocity of the water flowing through the gravel for the period from the end of hatching to the end of emergence, and it was found that the results were in general agreement with those obtained by Pyper. The observed variations are attributable partly to the difference between starting with the fertilized egg and eyed egg stages, partly to the variable manner in which the deposited sediments reduced flow through the gravel pores, and partly to the variable side effects of the boxes used for the tests. It was concluded that the various sediment regimes lowered the egg survival primarily by reducing the flow through the gravel. In some cases, where large quantities of fine sediments had been deposited, the sediment penetrated 25 cm down the sides of the square box to the level at which the eggs had been buried, and smothered some of the eggs. In general it was found that silts finer than 297 microns mostly remained near or on the surface of the gravel. In one test with a deposition of 56 kg/sq m of 74 to 297 micron size sediment, a penetration of 10 cm into the gravel was observed. At concentrations of 28 and 56 kg/sq m of sediment from 590 to 297 micron size, penetrations of 8 cm into the gravel were observed. As in the permeameter tests previously referred to, it was found that the finer sediments were more effective in reducing flow through the gravel than the coarser sediments.

In the foregoing tests the sediments were added in still water and settled onto the gravel surface. These conditions are not representative of a typical salmon spawning ground, although similar effects might result from the bed load transport of sediments over a spawning ground. However, it will be shown in the following sections of this report that even where turbulence is sufficient to prevent deposition of sediment on the surface of a stream bed, deposition may still occur within the gravel with consequent reduction in permeability.

THE DEPOSITION OF SUSPENDED SEDIMENT WITHIN THE GRAVEL BED OF A STREAM

Factors Affecting Deposition of Suspended Sediment Within Gravel

It has been shown previously that there is an interchange of water between the surface flow in a stream and the flow through the gravel of the stream bed. The magnitude and direction of the flow within the gravel depends on the physical

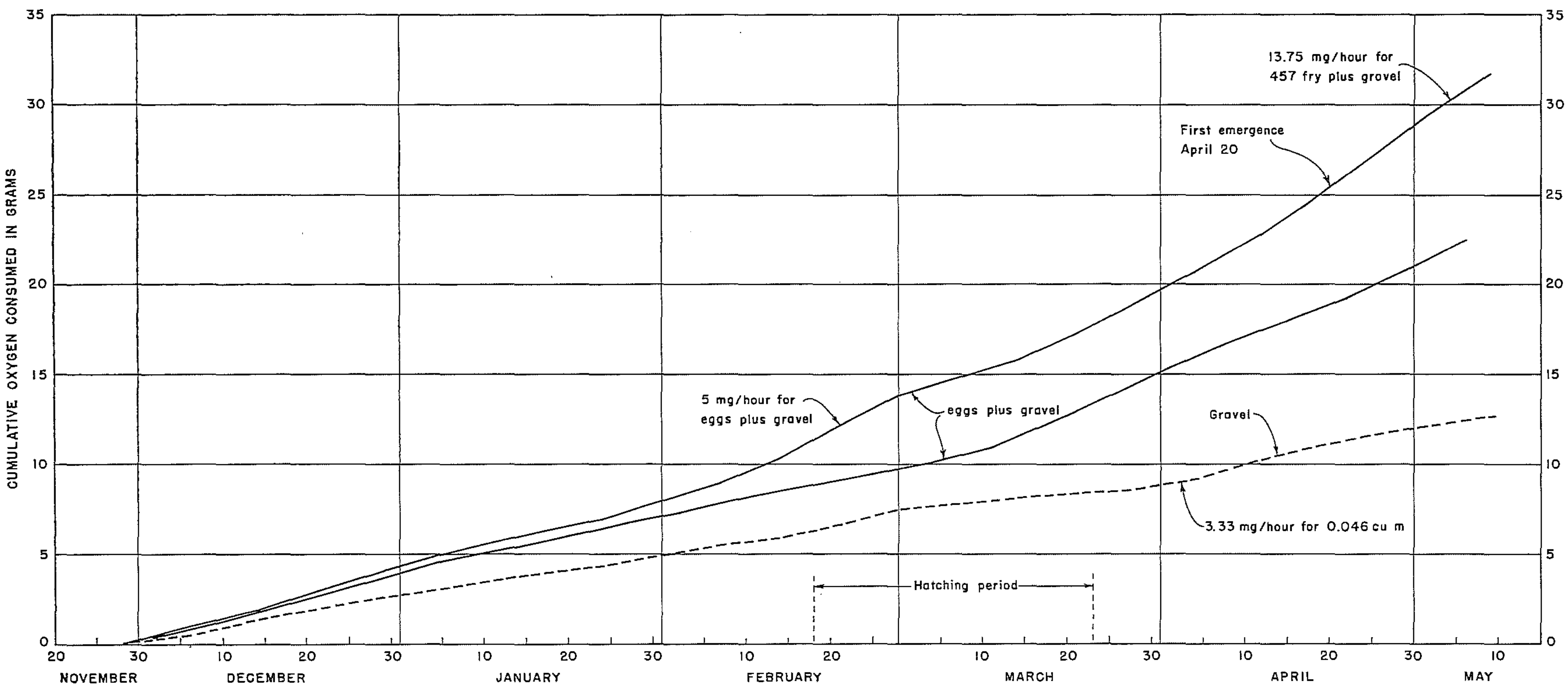


FIGURE 20—Cumulative total dissolved oxygen consumed by eggs and gravel in control tests for experiments.

characteristics of the gravel and the surface configuration of the stream bed. The magnitude of the flow also depends on the physical characteristics of the liquid passing through the gravel. If the relationship of these variables could be expressed mathematically and determined quantitatively, a useful means would be obtained for evaluating the suitability of various stream beds for salmon spawning grounds.

Permeability of Granular Material

The permeability of a gravel or granular media is a major factor which determines the flow of a fluid through the gravel. The other major factor is the head available to create the flow. The fluid viscosity and state of flow are also factors which must be considered.

The simplest expression of the relationship between flow, permeability and head for incompressible fluids flowing through a granular media is Darcy's Law (Equation 7).

$$V = Ks \qquad \text{. . . . . . (7);}$$

where V = apparent velocity in cm/sec;

K = permeability factor in cm/sec.

However, Darcy's Law is a simplification of the more general relationship between the variables affecting flow through granular media, and is applicable only to special conditions of laminar flow and constant temperature.

Hubbert (1956) has stated that the permeability constant so used is a lumped factor which includes not only characteristics of the granular media, but also characteristics of the fluid. Hubbert expressed Darcy's Law in fundamental terms by Equation 8,

$$V = Na^2 \frac{\rho}{\mu} g\, s \qquad \text{. . . . . . (8);}$$

where N is a dimensionless shape factor of the pores of a granular material;

a is a length such as mean particle diameter which characterizes the size scale of the pore structure;

g is the acceleration of gravity in cm/sec/sec;

μ is the absolute viscosity of the fluid in poise.

Hubbert designates the factor Na^2 as permeability since it is a characteristic of the gravel only. Equation 8 would apply to laminar flow of any fluid.

From the general equation for laminar flow in a pipe Fair and Hatch (1933) developed equation 9 for the flow of fluid through sand;

$$V = \frac{s\, g\, \rho}{32\mu} \frac{e^3}{(1-e)^2} \left[\frac{1}{S} \sum \frac{d}{P}\right]^2 \qquad \text{. . (9);}$$

where e = porosity;

S = a shape factor relating surface area of a particle to its volume;

P = fraction of particles by weight of size d.

This equation is identical to Equation 8 except that the factor Na^2 is expressed in terms of particle size and porosity. The shape factor S has a value of 6.0 for spherical particles and Fair and Hatch give the tentative values in TABLE 8 for

TABLE 8—Tentative values of shape factor S.

Shape of Sand	Shape Factor
Spherical	6.0
Rounded	6.1
Worn	6.4
Sharp	7.0
Angular	7.7

other shapes of particles. The particle size (d) used is the geometric mean of the upper and lower sieve sizes for each separation of the sieve analysis, determined by Equation 10,

$$d = \sqrt{d_1 (d_2)} \quad . . . . . . (10).$$

Equation 9 as written applies only to laminar flow, but it can be rewritten to apply to any condition of flow as follows:

$$V^n = \frac{sg}{k} \left(\frac{\mu}{\rho}\right)^{n-2} e^n \beta^{3-n} \quad . . . . (11);$$

where n = an exponent describing the state of flow with value of 1 for laminar flow and 2 for fully turbulent flow;

β = permeability as given by Equation 12.

$$\beta = \left[\frac{e}{1-e}\right] \left[\frac{1}{S \sum \frac{P}{d}}\right] \quad . . . . (12).$$

The permeability β is a characteristic of the gravel and is independent of the flow condition. The product $e^n\beta^{3-n}$ characterizes the gravel and the flow condition and is designated the permeability function ϕ (Equation 13),

$$e^n\beta^{3-n} = \phi \quad . . . . . . (13).$$

In the derivation of Fair and Hatch's formula, the characteristic of the pore in the sand was expressed in terms of the hydraulic radius of the pore. The hydraulic radius was then expressed in terms of the volume-area relationship of the grains of sand. The validity of this method of expressing pore size characteristic may be questioned if the formula is applied to heterogeneous gravels where not all of the surface of any particle is necessarily involved in the perimeter of pores in all directions of fluid flow. However, in tests with gravel described below, consistent relationships were obtained using Equation 11, and it is considered that this equation adequately presents the relationship between the variables.

TABLE 9—Viscosity and density of water.

°C	°F	Viscosity[a] Poise	Density[b] gm/cm^3
0	32.0	0.017921	.99987
1	33.8	.017313	.99993
2	35.6	.016728	.99997
3	37.4	.016191	.99999
4	39.2	.015674	1.00000
5	41.0	.015188	.99999
6	42.8	.014728	.99997
7	44.6	.014284	.99993
8	46.4	.013860	.99988
9	48.2	.013462	.99981
10	50.0	.013077	.99973
11	51.8	.012713	.99963
12	53.6	.012363	.99952
13	55.4	.012028	.99940
14	57.2	.011709	.99927
15	59.0	.011404	.99913
16	60.8	.011111	.99897
17	62.6	.010828	.99880
18	64.4	.010559	.99862
19	66.2	.010299	.99843
20	68.0	.010050	.99823
21	69.8	.009810	.99802
22	71.6	.009579	.99780
23	73.4	.009353	.99756
24	75.2	.009142	.99732

[a] from Hodgman and Holmes (1940).
[b] from Hutchinson (1957).

Values of viscosity and density used in Equation 11 are given in TABLE 9, and values of d in cm may be obtained from TABLE 10 where they are given in microns. Also given in TABLE 10 are the number of gravel particles per kilogram of weight. Comparison of these data (FIGURE 21) with the number of spheres of the same diameter and specific weight shows that the gravel particles are heavier than the spheres.

TABLE 10—Geometric mean particle size of various sieve size separations, and number of particles per kilogram.

SIEVE SIZE RANGE		GEOMETRIC MEAN DIAMETER MICRONS	NUMBER OF PARTICLES PER KILOGRAM
U.S. Sieve Series	Microns		
6"—5"	152,500 — 127,000	139,000	0.2056
5"—4"	127,000 — 101,600	113,500	0.4009
4"—3"	101,600 — 76,200	88,000	0.621
3"—2"	76,200 — 50,800	62,100	2.5733
2"—1½"	50,800 — 38,100	44,000	7.8003
1½"—1"	38,100 — 25,400	31,200	15.259
1"—¾"	25,400 — 19,050	22,000	43.402
¾"—½"	19,050 — 12,700	15,500	123.6
½"—3	12,700 — 6,350	8,950	436.6
3—4	6,350 — 4,760	5,490	3,086.0
4—8	4,760 — 2,380	3,360	10,000.
8—16	2,380 — 1,190	1,685	88,880.
16—30	1,190 — 590	839	1,183,400.
30—50	590 — 297	418	4,854,300.
50—100	297 — 149	207.5	47,619,000.
100—200	149 — 74	106	357,100,000.
	74 — 36	51.6	
	36 — 18	25.5	
	18 — 9	12.75	
	9 — 4	6.0	
	4 — 2	2.83	
	2 — 1	1.41	
	1 — 0.5	0.71	

Note: 1 cm = 10,000 microns.

Permeability Tests

During the initial phase of this investigation, a considerable number of permeability measurements of gravel were obtained under various test conditions. It was found that these tests did not produce consistent results and it was not possible to isolate the factors responsible for the variations. In order to obtain meaurements by which the validity of the theoretical relationship might be checked, two series of permeameter tests were made.

The first series of tests was made in a permeameter which had been used in many earlier tests (FIGURE 15), consisting of a cylinder 30.48 cm in diameter by 50.8 cm long, equipped with means of supplying a flow of water, and piezometers for measuring loss of head. Flow rates were measured volumetrically and heads were measured by point gauge. The wall of the permeameter was coated with pebbles to minimize the effect of the wall on the measurements.

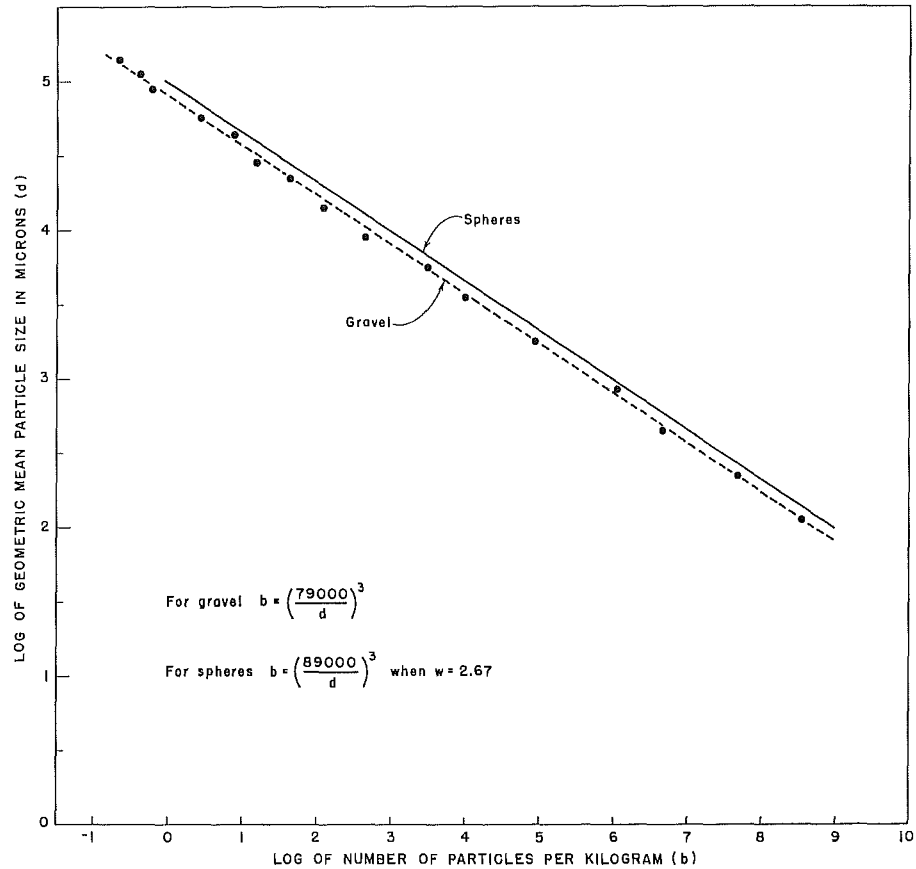


FIGURE 21—Number of particles per kilogram of gravel, sand and silt.

The effect of the permeameter walls on the measurements obtained can be quite significant, as shown by Rose and Rizk (1949). Part of the data presented by them are reproduced in FIGURE 22. This relationship was developed for homogeneous material, and in order to apply it to a heterogeneous material such as gravel, it is necessary to determine a representative particle size. Franzini (1956) concludes that the representative particle size can be determined by computing the average effective particle diameter by the method of Fair and Hatch (1933). On the basis of data presented by Rose and Rizk it was concluded that wall effect of the permeameter was sufficiently small that it could be disregarded.

Five different gravels were used in the permeameter tests to represent the range of gravels normally encountered in sockeye and pink salmon spawning grounds. The experimental gravels were produced from a stock of materials of each sieve size fraction which were obtained from the Coquitlam River. The particle size distributions of the experimental gravels are given in TABLE 11, and the grading curves are shown in FIGURE 23.

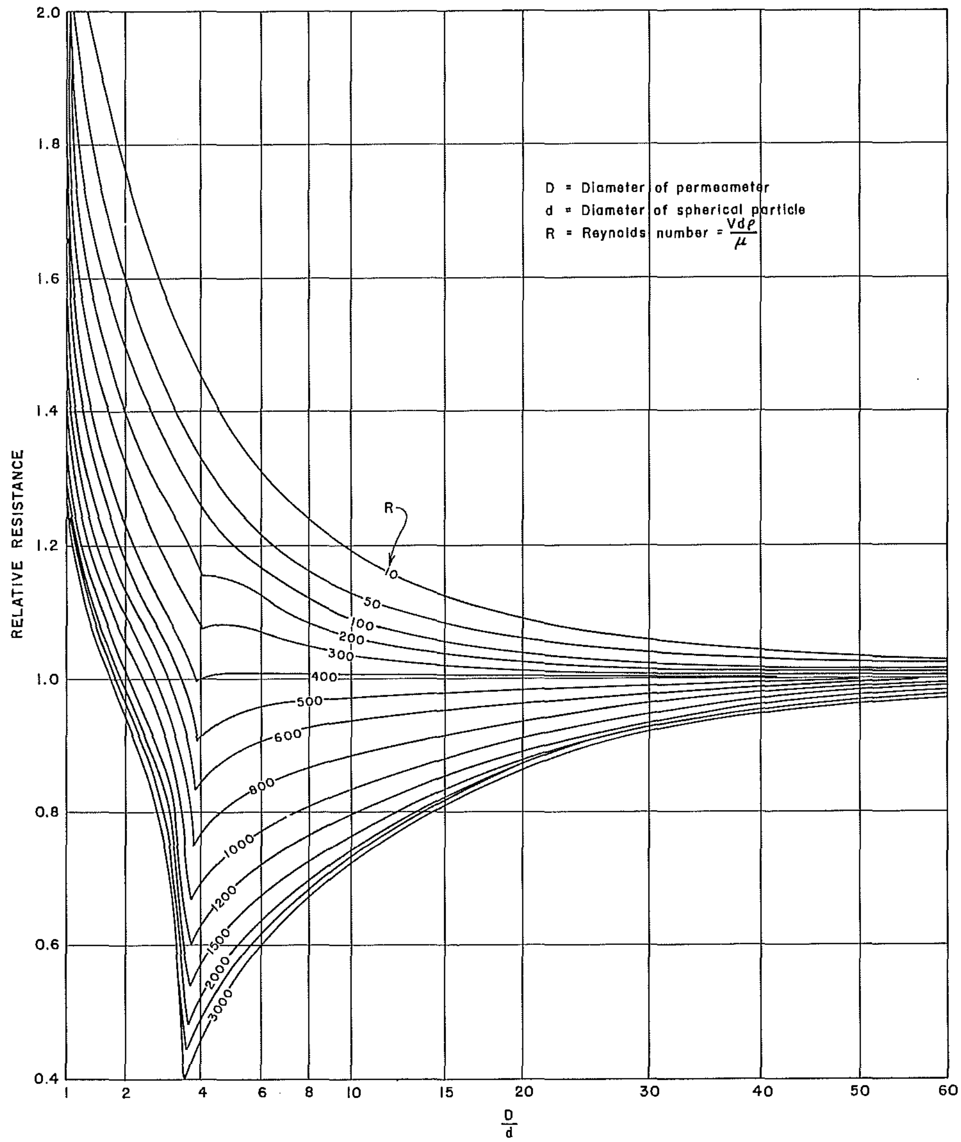


FIGURE 22—Permeameter wall effect on flow resistance of beds of spherical materials (from Rose and Rizk 1949).

Each sample of gravel was tested at a loose compaction first, and then was rodded to greater compaction for a second test. The porosity of each sample was measured in place prior to each permeability measurement. For the tests, a flow of water was passed downward through the samples, and the head loss was measured between the free water surface above the sample and the bottom piezometer. The flows used covered a range of apparent velocities from 0.002 to 0.14 cm/sec, the actual range for an individual test being chosen to provide suitable measureable amounts of head loss. The flows started at a low value, were increased

TABLE 11—Size composition of gravels used in permeameter tests.

SIZE IN MICRONS	PER CENT OF SAMPLE PASSING SIEVE SIZE				
	Gravel 1	Gravel 2	Gravel 3	Gravel 4	Gravel 5
152,500	—	—	—	—	100
127,000	—	—	—	100	74.0
101,600	100	100	100	91.1	52.5
76,200	94.0	83.3	85.7	54.9	41.8
50,800	87.6	67.6	74.2	35.4	23.1
38,100	68.8	58.4	62.9	30.25	17.2
25,400	51.9	46.2	51.45	25.38	11.5
19,050	45.9	39.7	46.3	22.17	9.85
12,700	35.1	31.3	39.4	16.90	7.45
6,350	19.4	20.9	27.6	9.15	4.36
4,760	13.55	18.08	23.9	6.78	3.09
2,380	6.61	10.83	16.95	3.93	1.66
1,190	2.90	5.59	10.74	1.60	0.805
590	1.08	2.00	5.42	0.401	0.202
297	0.705	0.18	1.35	0.087	0.0
149	0.467	0.096	0.445	0.0	0.0
74	0.418	0.0	0.199	0.0	0.0
36	0.1724	—	0.0825	—	—
18	0.0236	—	0.0116	—	—
9	0.00262	—	0.0018	—	—
4	0.00012	—	0.0006	—	—
2	0.0	—	0.0	—	—
1	0.0	—	—	—	—
0.5	0.0	—	—	—	—
$\sum \frac{P}{d}$ cm^{-1}	2.6564	1.8753	3.8384	0.7692	0.4057

$\sum \frac{P}{d}$ is for use in Equations 9 or 12.

to the maximum, and then reduced to a low value. The water used was city domestic supply. No attempt was made to control water temperature, but the range of temperatures observed was quite small. The results of the tests are summarized in FIGURE 24. Flow conditions ranged from laminar in gravel 3 to fully turbulent in gravel 5. Flows in gravels 2 and 4 were in a transitional stage, and in gravel 1 flows went from laminar to a transitional stage. These results will be considered further in conjunction with data obtained from a second series of tests.

The second series of tests was made in a flume which was 30.48 cm wide by 76.2 cm deep with an experimental section 3.048 m long (FIGURE 25). The walls of this flume were also coated to minimize side effect. The ends of the flume were fitted with screens to retain the gravel sample and with chambers for introducing a flow of water. The flume could be tilted so that the hydraulic gradient could be kept parallel to the gravel surface, thus maintaining a constant cross

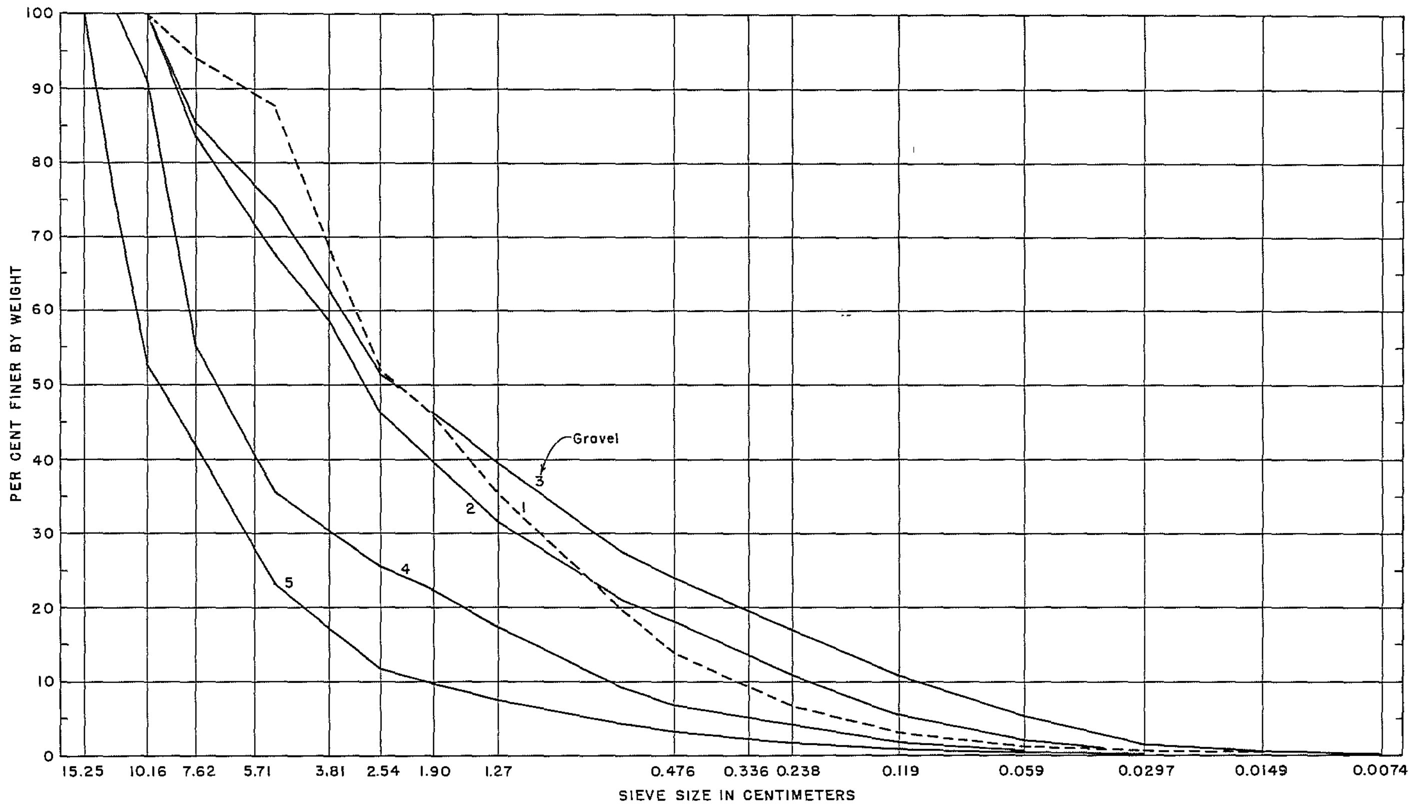


FIGURE 23—Gravel gradings for permeameter tests.

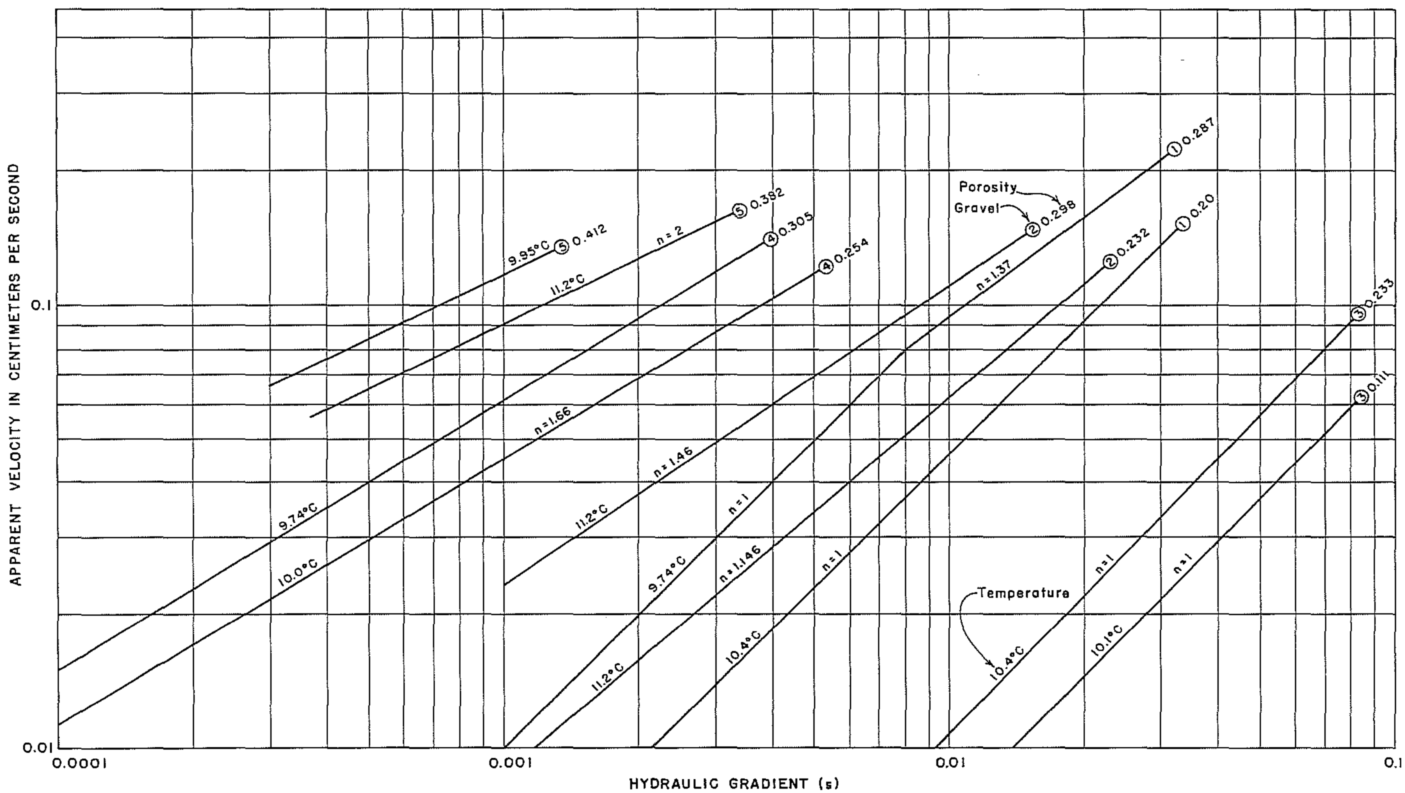


FIGURE 24—Relation between velocity of flow and hydraulic gradient for gravels 1 to 5 tests in a permeameter.

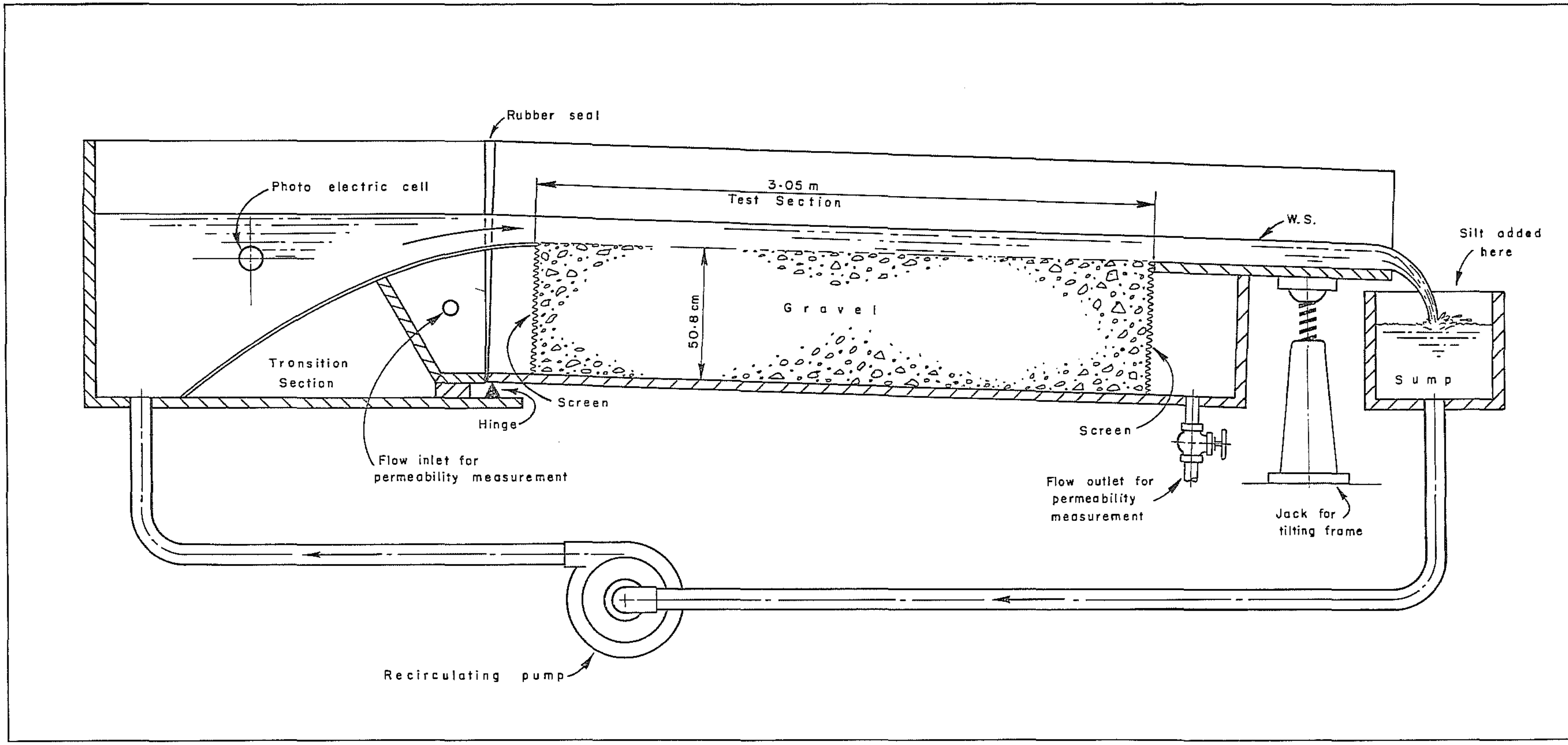


FIGURE 25—Schematic arrangement of test flume.

TABLE 12—Size composition of gravels used in flume tests.

SIZE IN MICRONS	PER CENT OF SAMPLE PASSING SIEVE SIZE				
	Gravel 14	Gravel 15	Gravel 16	Gravel 17	Gravel 18
152,500	100	—	—	—	—
127,000	80	100	100	—	—
101,600	60	81	86	100	100
76,200	40	61	68	79	88
50,800	25	43	52	63.5	75
38,100	17.5	26	37	49.0	63
25,400	13.5	20.5	28	40.0	53.5
19,050	11.0	17.0	22.5	33.0	46.0
12,700	9.0	14.0	18.0	26.5	39.0
6,350	5.0	9.0	12.5	17.5	27.0
4,760	3.8	7.5	10.5	14.5	22.5
2,380	2.0	5.0	7.5	10.0	15.0
1,190	0.5	3.0	5.0	7.0	10.0
590	0.0	1.8	3.0	4.0	6.0
297	—	0.5	1.0	2.0	3.5
149	—	0.0	0.5	1.0	1.5
74	—	—	0.0	0.1	0.2
36	—	—	—	0.01797	0.03594
18	—	—	—	0.00432	0.00864
9	—	—	—	0.00048	0.00096
4	—	—	—	0.00004	0.00008
2	—	—	—	0.0	0.0
1	—	—	—	—	—
0.5	—	—	—	—	—
$\sum \frac{P}{d}$ cm^{-1}	0.39920	1.12301	1.92973	3.0649	4.67385

$\sum \frac{P}{d}$ is for use in Equations 9 or 12.

sectional area of flow. The flume was also arranged so that silt laden water could be passed over the gravel surface to simulate natural stream conditions. Five different gravel types approximately the same as gravels 1 to 5 were used in the various series of tests run (Table 12). Permeability and porosity measurements were made in each gravel prior to circulation of silt laden water over the gravel. City water was used for the permeability measurements at temperatures ranging from 9°C to 22°C. Flows were measured volumetrically. Head loss measurements were taken by point gauge readings to the free water surface within the gravel at two points 2.438 m apart. Similar measurements were also taken after each silt test, but these will be referred to later. The results obtained with the initial permeability measurements expressed in terms of a water temperature of 15.55°C are summarized in Figure 26.

The results from the permeameter and the flume were used in Equation 11 to evaluate the only unknown term k (Figures 27 and 28). It was found that

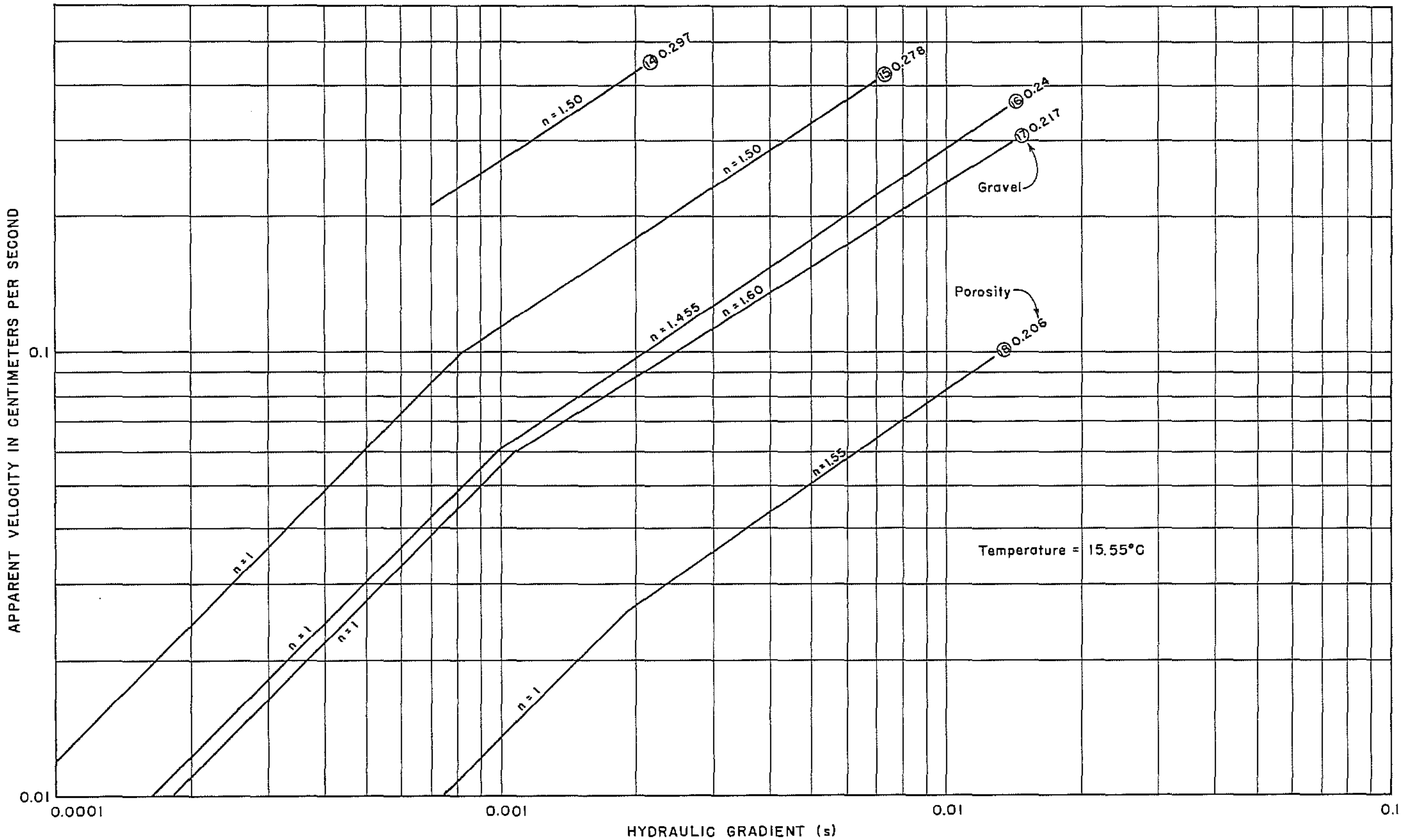


FIGURE 26—Relation between velocity of flow and slope of hydraulic gradient for gravels 14 to 18 in a flume.

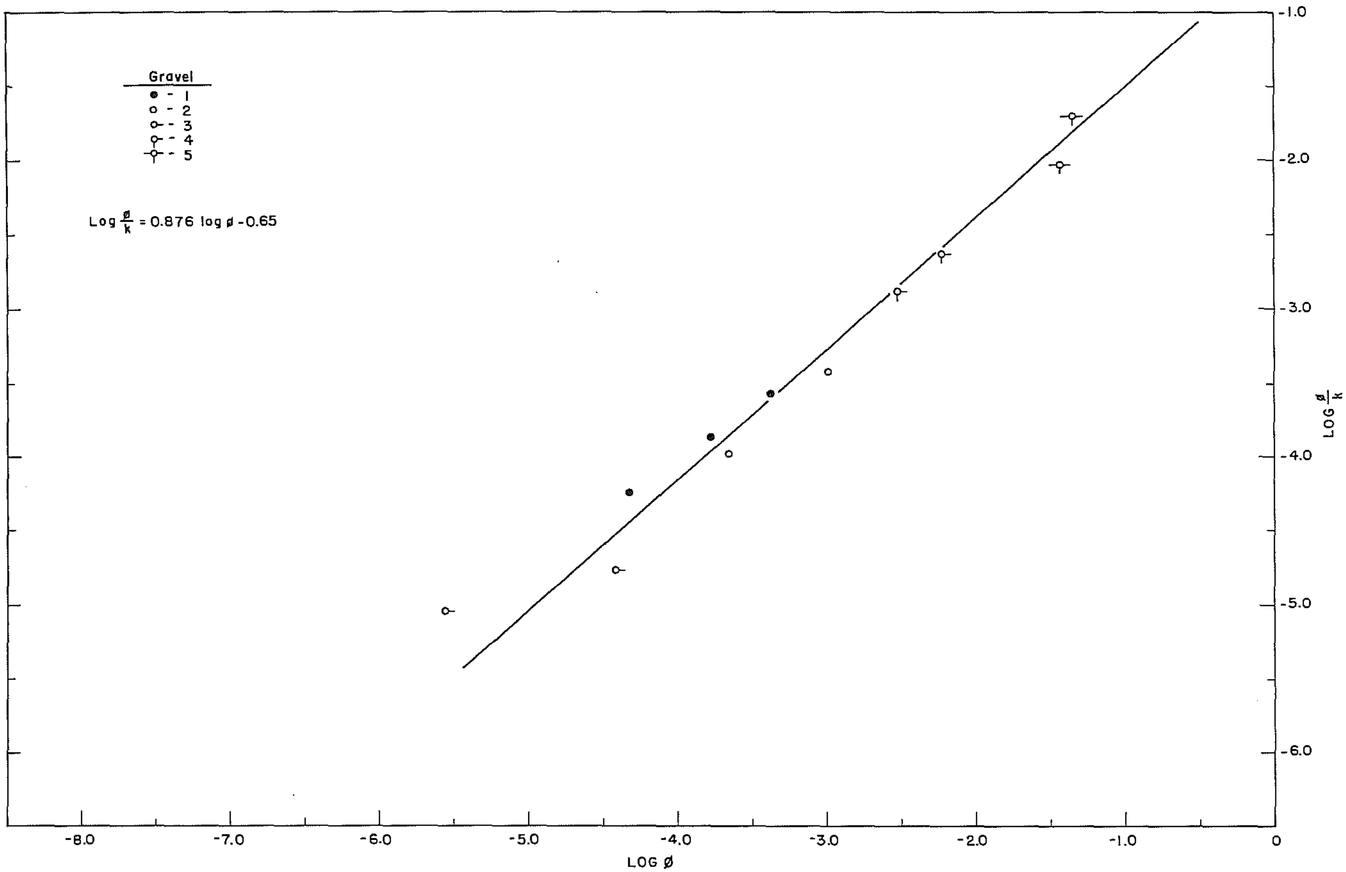


FIGURE 27—Permeability function for gravels 1 to 5 in permeameter vertical flow tests.

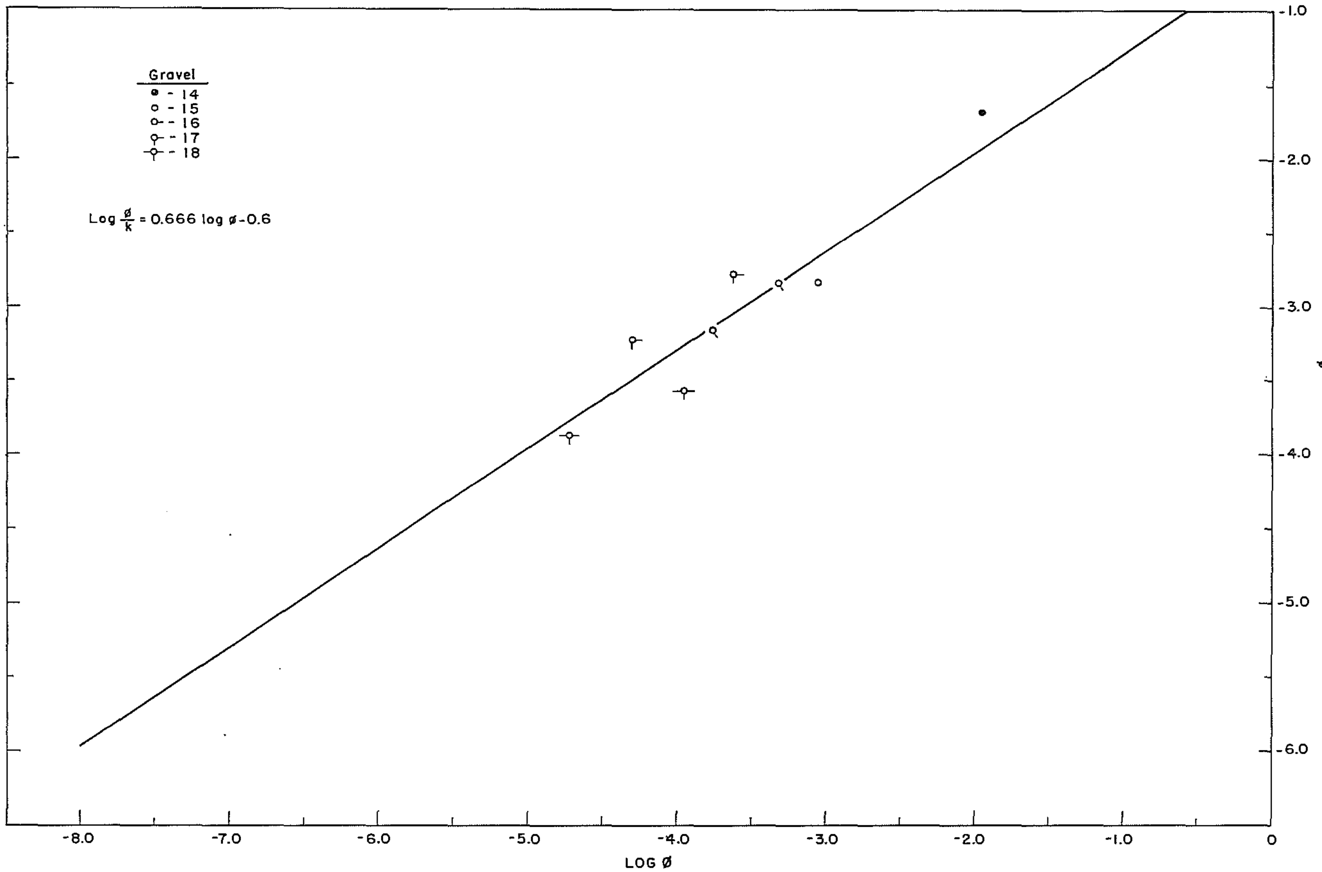
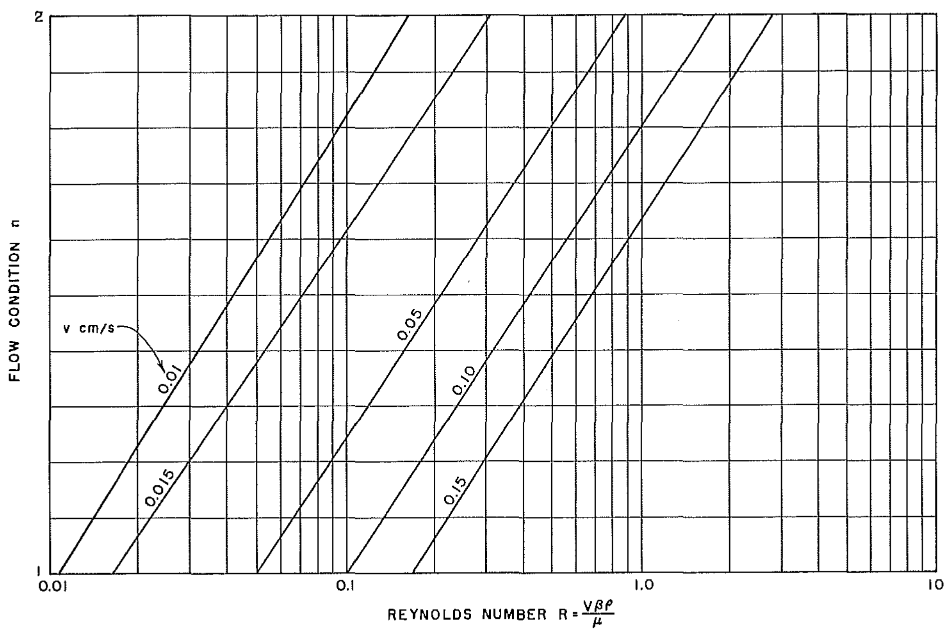


FIGURE 28—Permeability function for gravels 14 to 18 in flume horizontal flow tests.



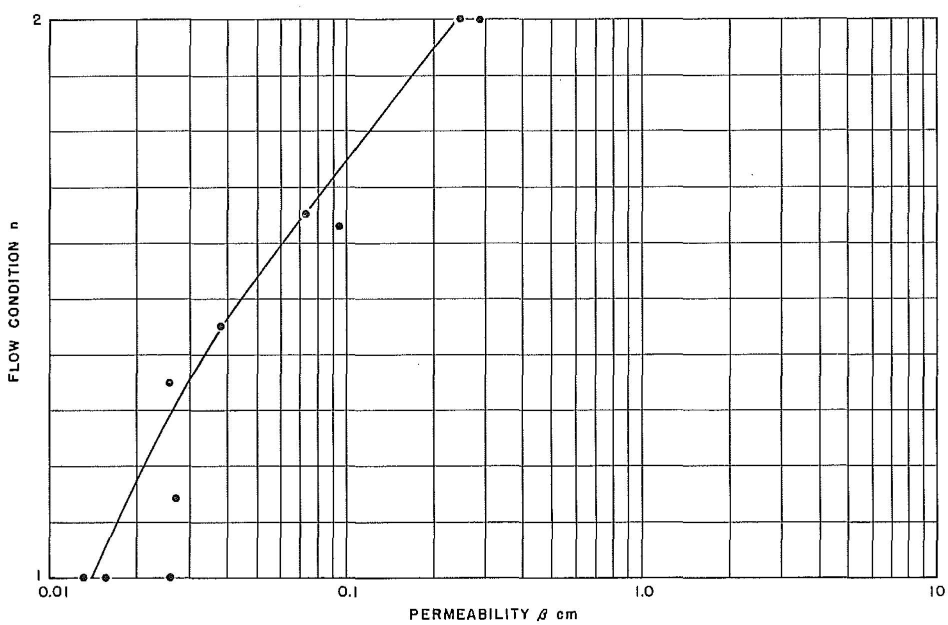


FIGURE 29—Relation between Reynolds number and flow condition, and between permeability and flow condition for vertical flow in a permeameter.

there was a relationship between the permeability function ϕ and the term k for each of the two sets of test conditions, but that the relationship differed for the two test conditions. This difference was caused by the vertical segregation of the gravel which occurred as it was placed in the permeameter or flume. This segregation resulted in variable permeability with depth for the horizontal flow condition so that for a given head differential, the flow horizontally through the gravel varied with depth in accordance with the variation in permeability. Data on the variation in particle size distribution and porosity with depth will be presented in a following section of this report.

In order to determine the value of the permeability function ϕ, it is necessary to determine the value of the exponent n which describes whether the flow condition is laminar, transitional or turbulent. The data obtained from the vertical flow tests in the permeameter indicate that over the range of velocities used in the tests, the condition of flow is determined primarily by the permeability β of the gravel (FIGURE 29). The relationship between Reynolds number and the exponent n, using the permeability β as the characteristic size of the gravel, was also plotted for a series of values of apparent velocity (FIGURE 29). However, in the flume tests with horizontal flow the relationship between the exponent n and Reynolds number was complicated by the non-uniform flow conditions described above. The exponent n for the horizontal flow can be determined best by inspection from the data reported here (FIGURE 26).

TABLE 13—Size composition of gravels used for layer tests of porosity and grading.

SIZE IN MICRONS	PER CENT OF SAMPLE PASSING SIEVE SIZE				
	Gravel A	Gravel B	Gravel C	Gravel D	Gravel E
152,500					100.00
127,000			100.00	100.00	77.20
101,600	100.00	100.00	84.68	82.24	68.82
76,200	79.06	74.40	59.58	55.18	44.82
50,800	69.44	62.89	48.64	37.31	28.92
38,100	66.67	56.07	40.09	26.21	19.38
25,400	55.48	47.77	30.36	18.64	14.24
19,050	46.86	37.78	22.57	15.23	11.49
12,700	39.36	29.87	18.86	12.67	9.20
6,350	25.86	18.77	12.56	7.43	4.93
4,760	20.55	14.96	10.04	5.84	3.75
2,380	12.77	9.84	6.94	3.66	1.86
1,190	7.69	6.54	4.43	2.07	0.47
590	4.47	3.86	2.79	1.54	0.0
297	1.83	1.54	0.38	.17	
149	0.86	0.80	0.12		
74	0.55	0.47			

The possible magnitude of variation in porosity and particle size distribution with depth in the gravel bed used in the flume was assessed by a separate series of analyses. Samples of gravels A to E (TABLE 13) similar to gravels 1 to 5 were placed in a box 30.48 cm square by 50.8 cm deep fitted with an exterior sight glass for measuring water depth. The box was segmented into five sections 10.16 cm deep to facilitate removal of the gravel in layers for sieve analyses. Tests

TABLE 14—Measured porosity and gravel size characteristic and calculated permeability in each of five layers 4 inches thick in a vertical box.

	LAYER					ALL LAYERS
	1 (Top)	2	3	4	5 (Bottom)	
GRAVEL A						
e (loose)	.277	.284	.203	.212	.199	.235
e (compacted)	.279	.176	.187	.136	.154	.186
Σ P/d cm^{-1}	3.9140	5.0013	3.9860	4.4396	4.5860	4.3528
β (loose)	.0161	.01295	.0105	.00995	.0089	
β (compacted)	.0162	.0070	.0095	.00585	.00653	
GRAVEL B						
e (loose)	.354	.214	.179	.180	.420	.269
e (compacted)	.349	.224	.178	.183	.240	.235
Σ P/d cm^{-1}	0.9291	3.9013	5.4446	3.4798	4.6295	3.9271
β (loose)	.0965	.0114	.0066	.01035	.0257	
β (compacted)	.0945	.0121	.00655	.0106	.0112	
GRAVEL C						
e (loose)	.369	.321	.201	.197	.386	.295
e (compacted)	.348	.315	.168	.180	.228	.248
Σ P/d cm^{-1}	1.5172	0.7629	1.7600	1.5750	2.1733	1.5370
β (loose)	.0633	.102	.0244	.0255	.0475	
β (compacted)	.0578	.099	.0188	.0228	.0224	
GRAVEL D						
e (loose)	.375	.291	.298	.224	.390	.316
e (compacted)	.357	.309	.281	.241	.229	.283
Σ P/d cm^{-1}	0.1539	0.2519	0.4099	0.5289	2.3061	0.5816
β (loose)	.641	.268	.171	.0892	.0455	
β (compacted)	.594	.292	.157	.0985	.0212	
GRAVEL E						
e (loose)	.417	.441	.355	.302	.342	.371
e (compacted)	.396	.429	.326	.285	.235	.334
Σ P/d cm^{-1}	0.1262	0.1752	0.2326	0.3534	0.9570	.4058
β (loose)	.93	.74	.388	.201	.089	
β (compacted)	.85	.70	.34	.185	.0528	

were conducted with each gravel in loose and compacted condition. After the porosities were measured in each layer, the layers were removed in succession and analyzed to determine particle size composition (TABLE 14). From this data values of permeability β were calculated for each layer (TABLE 14).

The magnitude of variation in the permeability function ϕ that would result from the observed variations in porosity and particle size gradation is illustrated by the values of ϕ which have been computed for the five layers of gravel A, assuming laminar flow conditions (TABLE 15). The results show that large variations in permeability function can exist within the gravel bed, and that the permeability function in the surface layer may be several times the mean for all layers of the bed.

TABLE 15—Variation of permeability function ϕ with depth in sample of Gravel A.

LAYER	PERMEABILITY FUNCTION ϕ	
	Loose	Compacted
1	7.18	7.30
2	4.76	0.860
3	2.24	1.69
4	2.10	0.465
5	1.57	0.655
Mean	3.57	2.19

n = 1, laminar flow
units are $(cm^2)(10^{-5})$

As mentioned earlier, since it was known that there was an interchange of flow between a stream and the gravel bed of a stream, it appeared logical to expect that suspended sediments carried into the gravel might be deposited in the gravel even though they would not be deposited on the gravel surface. If this occurred, it also could be expected that the permeability of the gravel bed would be reduced. This could be an important consideration in determining the effect of a particular size of suspended sediment on salmon spawning grounds. A series of tests were made to examine this aspect of sediment deposition. As with the permeability measurements previously described, a number of experiments were performed under different conditions as the studies evolved. In the initial studies, data were not obtained on some of the factors pertinent to mathematical analyses. However, all the experiments provided data which show that the gravel in a stream bed can act as a filter in removing suspended sediments from the water flowing through the gravel.

The first four tests were conducted in two identical channels 30.48 cm wide by 60.96 cm deep by 2.13 m long. Each of the channels was filled with typical spawning gravel (TABLE 16) obtained from Weaver Creek. The gravel for test 3

TABLE 16—Size composition of Weaver Creek gravel used in tests 1 to 4.

SIZE IN MICRONS	PER CENT OF SAMPLE PASSING SIEVE SIZE		
	Test 1	Test 2	Test 3 & 4
152,500	—	—	—
127,000	—	—	—
101,600	100	100	100
76,200	89.56	95.13	94.10
50,800	77.95	80.69	88.30
38,100	57.10	59.85	67.70
25,400	44.64	40.28	50.45
19,050	37.84	33.57	44.40
12,700	29.19	25.31	35.88
6,350	17.60	15.15	19.30
4,760	13.45	11.60	13.64
2,380	7.49	6.89	6.83
1,190	3.97	3.91	3.15
590	1.54	1.79	1.31
297	0.61	0.92	0.67
149	0.29	0.57	0.46
74	0.14	0.33	0.37

was washed and used again for test 4. Water was circulated over one of the gravel filled channels by a 100 gpm pump connected between a sump and a head box. The other channel was filled with clean city water and was used for control permeability tests. The sides and bottom of the box were smooth, but in test 2 a series of baffles were placed along the channel to intercept flow paths which might develop along the walls.

Dry silt smaller than 74 microns was added to the circulating water to maintain a desired suspended sediment concentration. This size of sediment was chosen since calculations of bed tractive force indicated that it would not be deposited on the surface of the gravel under the test conditions. The average velocity of the flow of water over the gravel was 41.1 cm/sec. The particle size distribution of the silt used in these four tests was not determined, although a sample obtained from the same source at a later date was analyzed and is recorded as silt 4 in TABLE 17. The determination of the size distribution of particles smaller than the finest sieve size (74 microns in this work) requires the use of hydraulic techniques such as described by the Corps of Engineers (Anonymous 1941) or microscopic measurement as employed for this work. Samples of the three silts used in the other tests reported in this work, consisting of particles less than 74 microns, were measured by means of a binocular microscope with a calibrated eyepiece. The longest and shortest dimensions of individual particles were measured and the geometric mean particle size calculated. The particle size distribution by numbers and the calculated distribution by weight are given in TABLE 17.

TABLE 17—Particle size distribution of silts used for experimental tests.

MICRONS PARTICLE SIZE	PER CENT BY NUMBERS SMALLER THAN SIZE			
	Silt 1	Silt 2	Silt 3	Silt 4
74	100	100	100	100
36	100	94.7	97.9	96.5
18	93.1	87.2	87.3	93.4
9	73.9	69.9	75.3	86.6
4	35.8	50.8	61.3	75.9
2	17.5	34.0	54.5	67.5
1	3.7	8.8	42.5	47.4
½	0	0	31.2	25.9

PARTICLE SIZE MICRONS	CALCULATED PER CENT BY WEIGHT SMALLER THAN SIZE			
	Silt 1	Silt 2	Silt 3	Silt 4
74	100	100	100	100
36	100	18.0	41.3	12.0
18	29.5	4.35	5.7	2.9
9	5.2	0.51	0.75	0.56
4	0.2	0.07	0.15	0.15
2		0.03	0.12	0.12
1				
½				
Weighted mean size, microns	21.4	41.2	40.0	42.9

In the first test a concentration of 200 ppm suspended sediment was maintained, and in tests 2, 3 and 4, a concentration of 2000 ppm. These concentrations were checked at intervals of about 15 minutes by means of a calibrated Jackson Turbidimeter and necessary additions of silt were made to maintain a constant concentration. Turbulence in the sump and head boxes was sufficient to prevent deposition of the silt, and no depositions occurred on the surface of the gravel. Thus the quantities of silt added during the course of an experiment measured the amount of silt retained in the gravel. The calibration of the Jackson Turbidimeter was checked for each concentration used by preparing a suspension of the silt in water. Each channel was fitted with separate inlets and outlets for the flow used in measuring permeability. These openings were closed except during permeability measurements, when the circulating flow of water was shut off.

Two different arrangements were used for measuring permeability. In tests 1 and 2 the flow was passed horizontally through the length of the gravel bed, and the drop in water surface within a fixed length of the gravel bed was measured by means of point gauges. In tests 3 and 4 the gravel was supported on a fine screen in such a manner that the flow of water could be passed vertically through the gravel. In this case, the head loss was measured by point gauge in piezometers above and below the gravel. This arrangement was tried to avoid the effects of horizontal stratification of the gravel but a large proportion of the silt added passed through the gravel to the chamber below the screens, thereby affecting the results obtained. Therefore tests 3 and 4 are reported as a matter of information only.

Test 5 was conducted in the horizontal flume previously described in connection with permeability tests on gravels 14 to 18, using gravel 18 for the test. In this test a photo-electric cell was mounted in the head box to provide more rapid monitoring of the turbidity, and a further check was made on samples by means of a photelometer. Surface water velocity during this test was 61 cm/sec and the sediment concentration was 1000 ppm, using silt 3.

TABLE 18—Water temperatures during tests 1 to 5.

TEST NO.	TEMPERATURE °C	
	Range	Mean
1	19 —25	20.53
2	0 — 6	3.54
3	6.5—13	10.3
4	17.2—20.4	18.4
5	17—24	20.5

Water temperatures were not controlled during these tests and were determined by the temperature of the building in which they were conducted. The range of temperatures for each test are given in TABLE 18. Temperatures during permeability measurements (measured within the gravel) were determined by the temperature of the city water supply. The cumulative amounts of silt added during each experiment are shown in FIGURE 30 and are summarized in TABLE 19. The rates of addition of silt in TABLE 20 were calculated from the slopes of the curves on FIGURE 30. These data show that the rate of accumulation of silt in the gravel decreased with time. The relationship between time, sediment concentration, and relative rate of removal of sediment is shown graphically in FIGURE 31 and can be expressed by Equation 14,

$$\log \frac{r_o - r_t}{r_o} = - \frac{y}{(ct)^x} \quad . \quad . \quad . \quad . \quad . \quad (14);$$

where r_o = initial rate of removal of suspended sediment in gms/min/sq m;

r_t = rate of removal of suspended sediment at time t in gms/min/sq m;

c = suspended sediment concentration in ppm;

t = time in minutes;

x, y = factors related to sediment concentration.

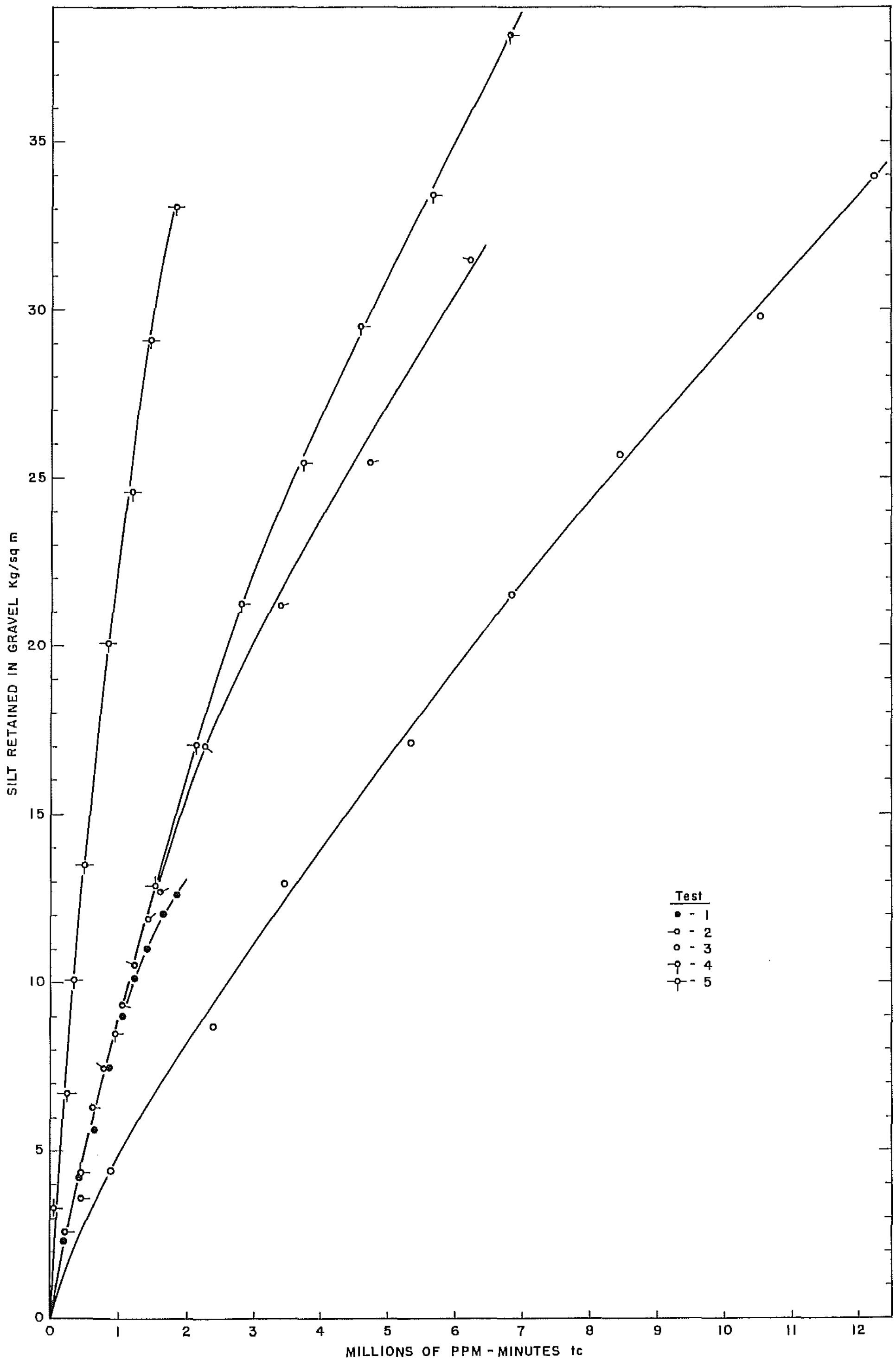


FIGURE 30—Cumulative total retention of silt in tests 1 to 5.

TABLE 19—Summary of results of tests 1 to 5 showing cumulative total silt addition and the rate of silt addition.

TEST 1 c = 200			TEST 2 c = 2000			TEST 3 c = 2000			TEST 4 c = 2000			TEST 5 c = 1000		
t	ΣW	r	t	ΣW	r	t	ΣW	r	t	ΣW	r	t	ΣW	r
0	0	3.0	0	0	26.6	0	0	8.5	0	0	18.9	0	0	40.0
1000	2.30	2.2	100	2.66	20.0	445	4.40	7.5	225	4.26	18.0	87	3.36	35.0
2010	4.19	1.96	205	3.68	15.5	1200	8.61	6.2	480	8.48	16.8	205	6.72	29.5
3025	5.68	1.70	300	6.25	15.0	1920	12.88	5.8	765	12.88	15.2	336	10.01	26.0
4015	7.54	1.40	400	7.53	14.8	2685	17.10	5.2	1065	17.0	13.2	477	13.45	21.5
5025	8.91	1.24	505	9.40	12.8	3420	21.45	5.0	1410	21.2	10.4	842	20.10	16.0
6010	10.1	1.06	605	10.50	12.0	4215	25.7	5.0	1890	25.5	9.4	1158	24.6	14.2
7020	11.0	0.84	705	11.87	11.5	5280	29.8	5.0	2280	29.5	8.8	1494	29.1	13.0
8025	12.0	0.72	805	12.75	11.0	6120	34.0	4.5	2835	33.8	8.0	1829	33.1	12.0
9130	12.8	0.5	1140	17.0	10.0				3430	38.1	7.8			
			1700	21.2	8.0				3975	42.5	7.8			
			2380	25.2	7.0									
			3125	31.5	6.6									

t = minutes, W = kg/sq m, r = gms/min/sq m, c = silt concentration ppm.

TABLE 20—Measurements of permeability function ϕ during tests 1 to 5.

TEST 1 t	TEST 1 ϕ	TEST 2 t	TEST 2 ϕ	TEST 3 t	TEST 3 ϕ	TEST 4 t	TEST 4 ϕ	TEST 5 t	TEST 5 ϕ
0	46.7	0	126	0	12.6	0	—	0	.502
580	53.6	270	70.6	445	17.4	225	53.7	87	.363
2995	17.8	480	63.0	1200	9.9	480	56.0	205	.446
5085	22.2	810	53.6	1920	5.0	765	20.0	336	.316
9130	16.6	1140	50.0	2685	5.0	1065	13.2	477	.263
		1700	40.0	3420	3.55	1410	35.5	842	.372
		2380	15.8	4215	4.0	1890	18.6	1158	.199
		3125	17.8	5280	0.73	2280	11.2	1494	.174
				6120	0.82	2835	22.4	1829	.152
						3435	20.0		
						3975	15.8		

Note—Divide all values of ϕ by 1 million.

The values of y and x in this equation are related to the sediment concentration as shown by FIGURE 32 and FIGURE 33.

Examination of data on the permeability function ϕ obtained during tests 1, 2 and 5 (TABLE 20) shows that for each test the function decreased in proportion to the rate of removal of silt (FIGURE 34). This relationship, in conjunction with Equation 14 can be used to determine the permeability function ϕ at any time. The computed values of permeability function for tests 1, 2 and 5 are compared with the observed values in FIGURE 35.

A further series of tests were run in the same flume as test 5 above to examine the effect of surface velocity, gravel grading, and surface configuration of the gravel on the rate of removal of silt. Each of gravels 14, 15, 16, 17 and 18 were tested with three bed surface conditions, flat, bouldery, and a salmon redd as shown in FIGURES 11, 12 and 14. Successive 2 hour tests were made for each gravel type with surface velocities of 30.5, 61, 91.5 and 122 cm/sec for each bed condition. The permeability of the bed was measured before and after each test and the porosity was measured before and after each change in bed surface condition. The bed was flushed between each change in surface configuration to remove accumulated sediment.

The permeability and porosity data for these tests are given in TABLE 21 and water temperatures are given in TABLE 22. The results of the silt removal measurements are plotted in FIGURE 36.

It is concluded that these data do not demonstrate the effect, if any, of water velocity on the silt removal rate. Most, if not all, of the observed decline in removal rate during each test can be attributed to the relationship described by Equation

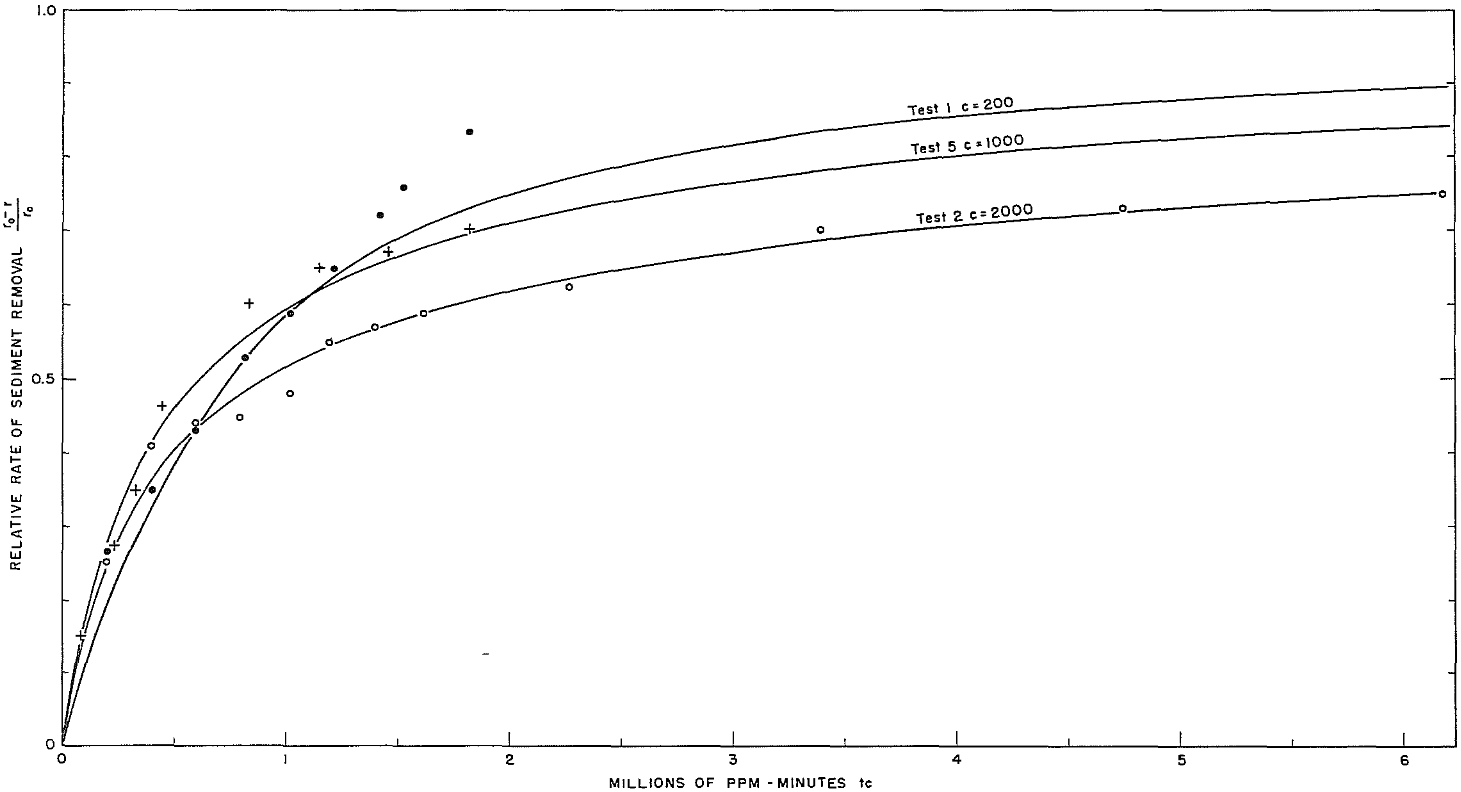


FIGURE 31—Relationship between sediment concentration, time and relative rate of sediment removal.

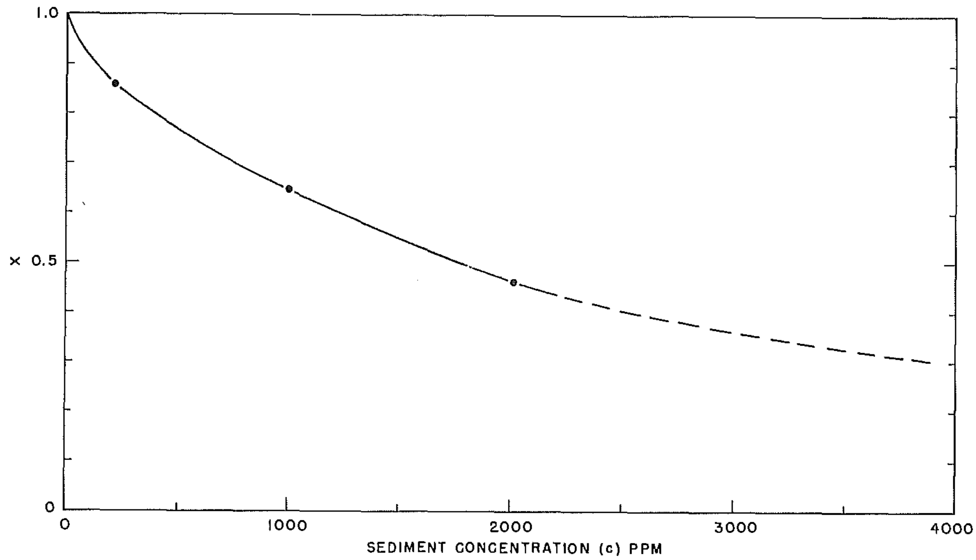


FIGURE 32—Relation between sediment concentration and factor x in Equation 14.

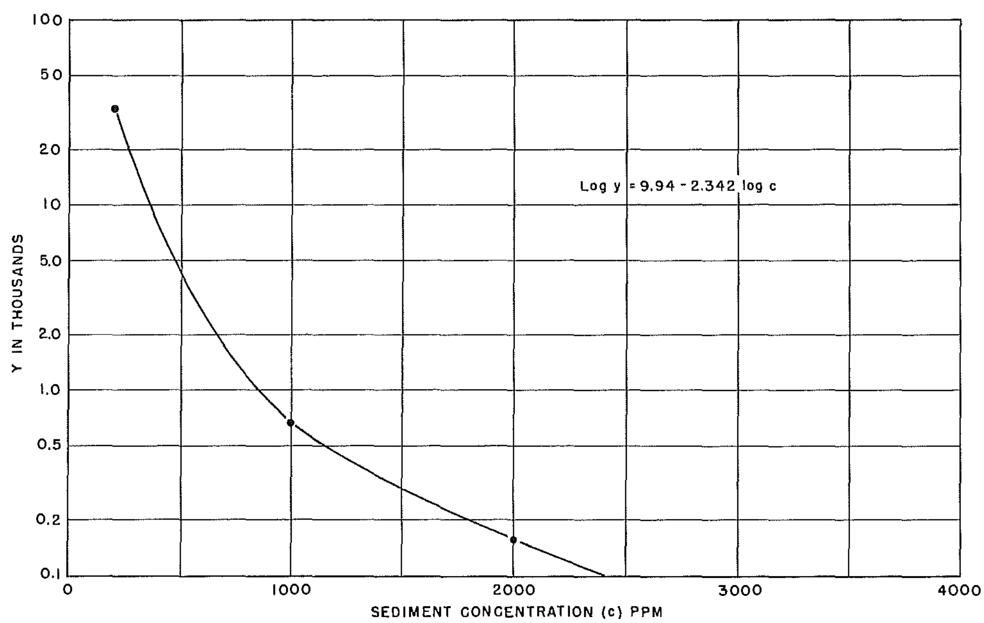


FIGURE 33—Relationship between sediment concentration and factor y in Equation 14.

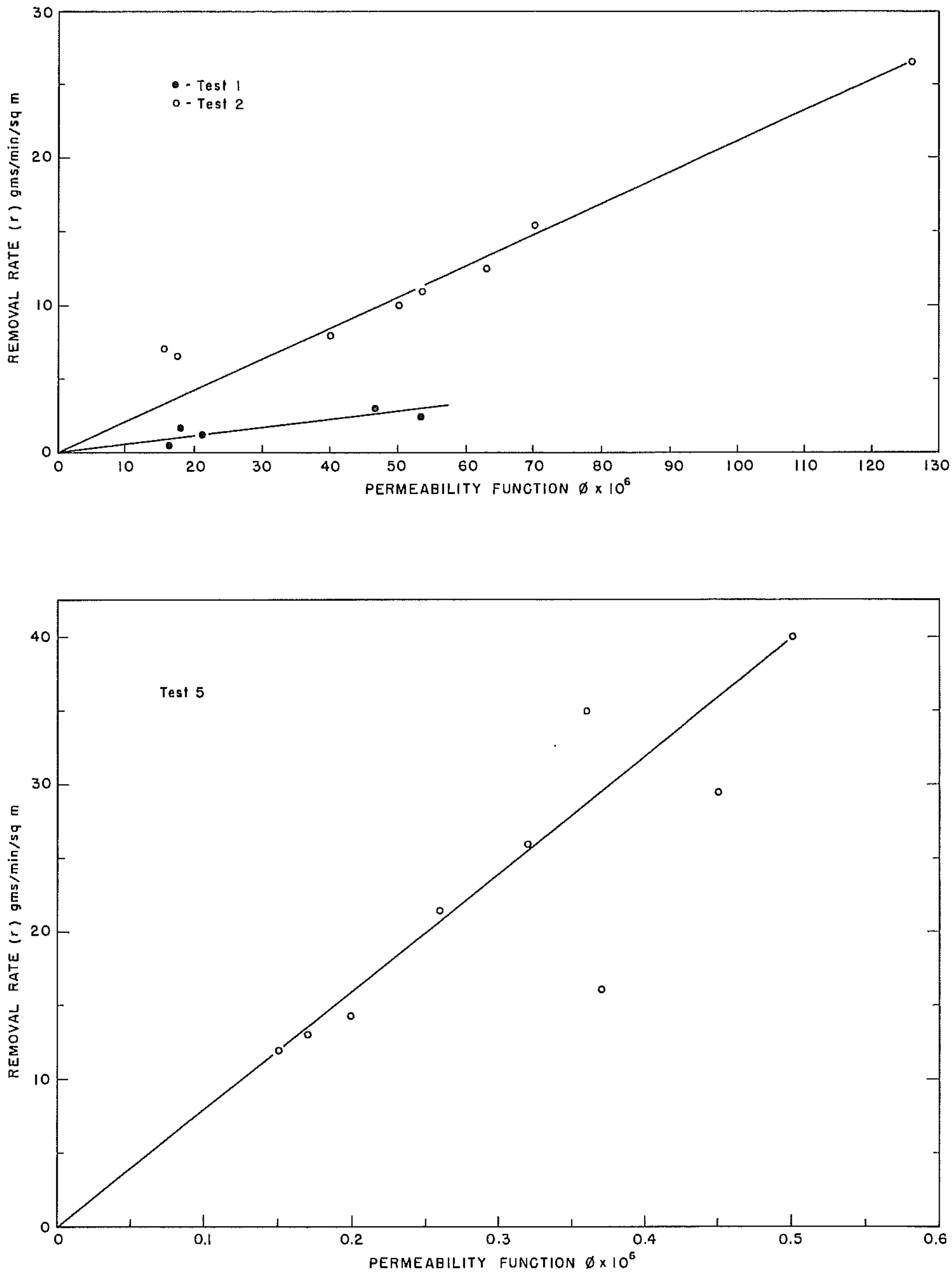


FIGURE 34—Relation between rate of removal of silt and the gravel permeability function ϕ during tests 1, 2 and 5.

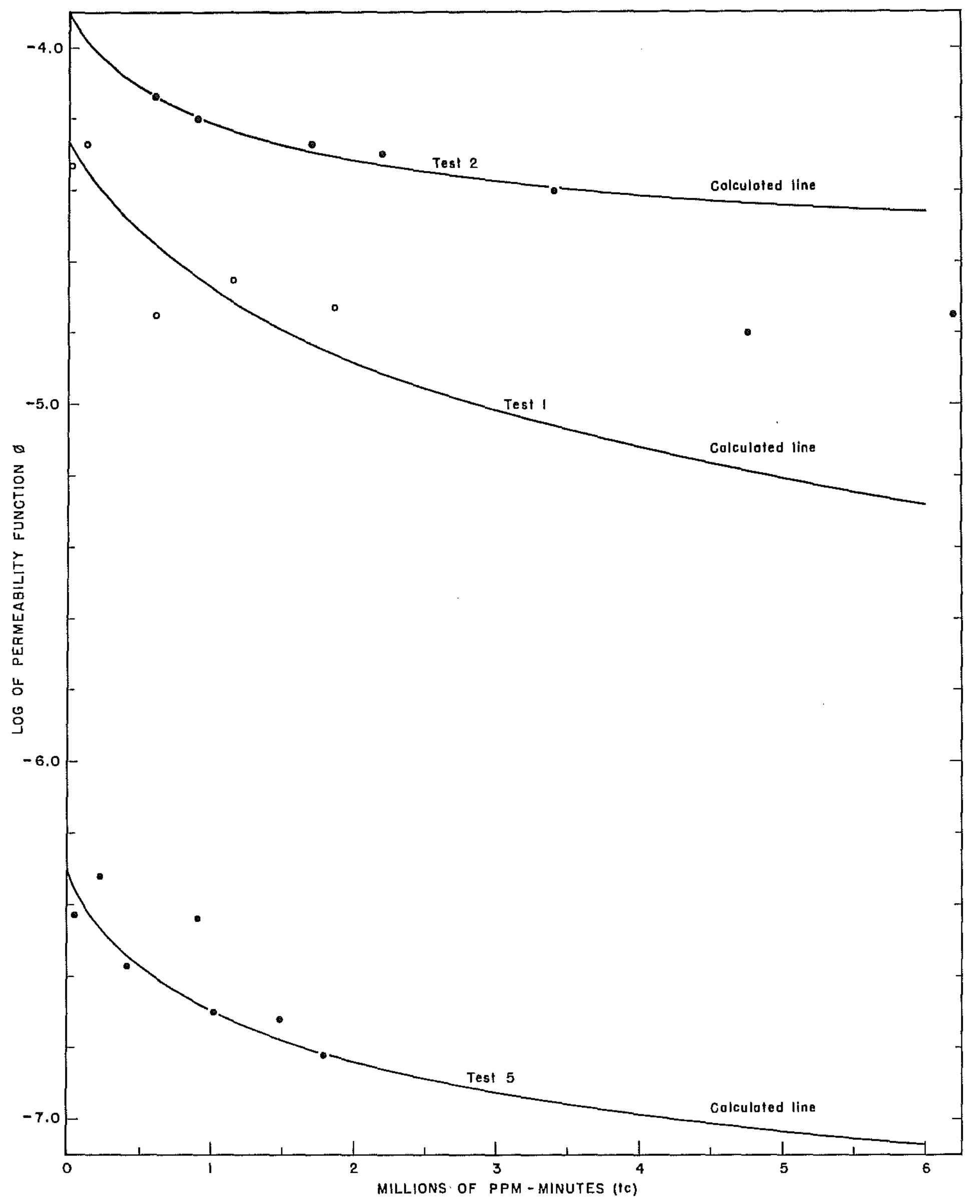


FIGURE 35—Comparison of calculated and observed values of permeability function.

14. It is possible also that part of the decline in removal rate observed toward the end of each test may have been caused by turbulence in the upper layer of gravel picking up some of the silt previously deposited at lower velocities.

The average silt removal rate for each test at velocities of 30.5 cm/sec and 61 cm/sec (TABLE 23) is considered representative of the initial rate for each test, since the reduction in rate during this time interval would not be large. These data

TABLE 21—Summary of porosity and permeability measurements for silt removal tests with gravels 14 to 18.

BED SURFACE	VELOCITY cm/sec	GRAVEL 14			GRAVEL 15			GRAVEL 16			GRAVEL 17			GRAVEL 18		
		e	β	β_c	e	β	β_c	e	β	β_c	e	β	β_c	e	β	β_c
Flat	0	.327	(a)	.20	.278	.075	.0525	.24	.034	.0269	.217	.0217	.0143	.206	.0047	.0091
	30.5					.036			.029			.0174			.00497	
	61					.110			.0245			.0157			.00452	
	91.5					.072			.0235			.0123			.00450	
	122					.074			.0255			.0154			.00454	
Bouldery	0	.329	(a)	.201	.228	.099	.0431	.217	.036	.0236	.187	.0105	.0123	.177	.00519	.0075
	30.5					.096			.029			.0103			.00519	
	61					.094			.034			.0105			.00516	
	91.5					.123			.0225			.009			.0041	
	122					.109			.0368			.0094			.005	
Redd	0	.286	.25	.164	.251	.143	.049	.232	.0262	.0257	.182	.0107	.0119	.162	.00548	.00675
	30.5		.238			.185			.0195			.0126			.0054	
	61		.221			.108			.0203			.0119			.0053	
	91.5		.193			.101			.0151			.0106			.00533	
	122		.214			.081			.011			.01045			.00513	

(a) not measurable.

$\beta_c = \beta$ calculated from sieve analysis and porosity.

TABLE 22—Water temperatures during silt removal tests with gravels 14 to 18.

BED SURFACE	VELOCITY cm/sec	TEMPERATURE °C				
		Gravel 14	Gravel 15	Gravel 16	Gravel 17	Gravel 18
Flat	30.5	21.6	18.3	18.7	17.3	18.7
	61	20.8	19.8	20.0	20.0	20.2
	91.5	21.6	19.8	20.7	20.4	20.2
	122	22.7	21.2	20.9	21.6	21.3
Bouldery	30.5	18.9	20.3	18.7	19.3	18.8
	61	20.4	20.8	20.4	20.3	20.3
	91.5	21.1	21.8	21.2	21.4	20.1
	122	22.3	22.3	21.4	22.1	21.4
Redd	30.5	17.8	20.1	17.8	18.5	19.0
	61	17.8	20.4	18.7	19.2	20.0
	91.5	19.2	21.2	19.8	19.4	20.6
	122	19.7	21.7	20.4	20.6	21.0

Mean temperature at velocities of 30.5 and 61 cm/sec 19.4°C.

TABLE 23—Average rates of silt removal in gm/min/sq m/1000 ppm for tests with gravels 14 to 18 at velocities of 30.5 cm/sec and 61 cm/sec.

SURFACE	SILT 1			SILT 2		
	Gravel 14	Gravel 15	Gravel 16	Gravel 16	Gravel 17	Gravel 18
Flat	11.4	18.4	17.0		79.3	35.4
Bouldery	8.5	13.0		21.9	25.7	31.3
Redd	12.2	10.0		48.3	39.5	45.6

do not indicate any relationship between the initial removal rate and the gravel permeability (FIGURE 37). However, the initial rate apparently is a function of the square of the mean silt size (FIGURE 38). The relationship is about the same for the flat bed and redd shapes, but the removal rates for the bouldery bed shape were less than for the other configurations.

It is concluded that the fall velocity of the sediment particle is the main factor determining the silt removal rate. Since fall velocity is affected by fluid viscosity, the silt removal rates for any water temperature other than those recorded during the tests will vary inversely as the fluid viscosity at the respective water temperatures.

The significance of these findings in terms of the effect of suspended sediment deposition on the flow of water through two types of gravel is illustrated by three examples in TABLE 24. In each case it has been assumed that flow within the

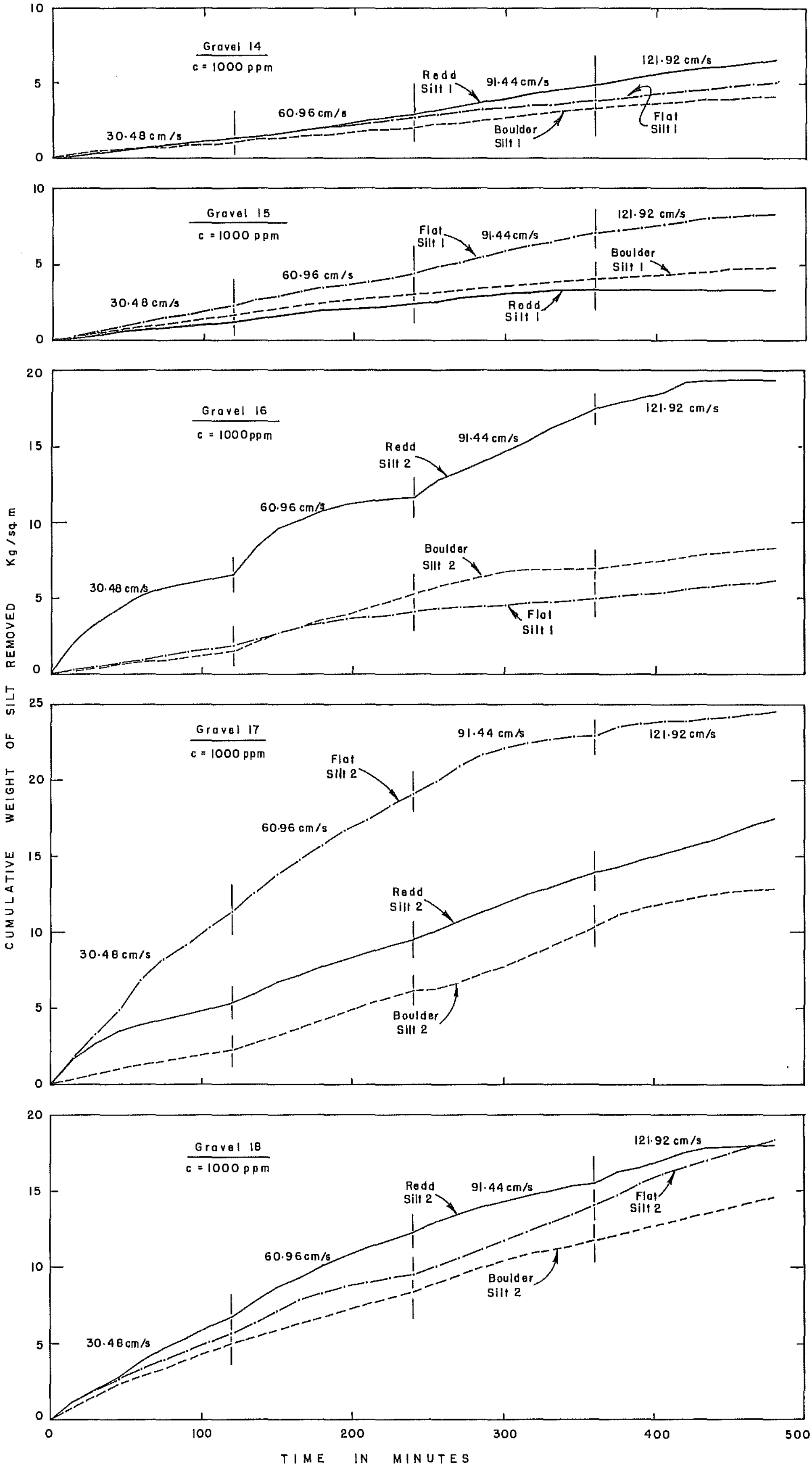


FIGURE 36—Effect of water velocity and gravel surface shape on removal of silt by gravels 14 to 18.

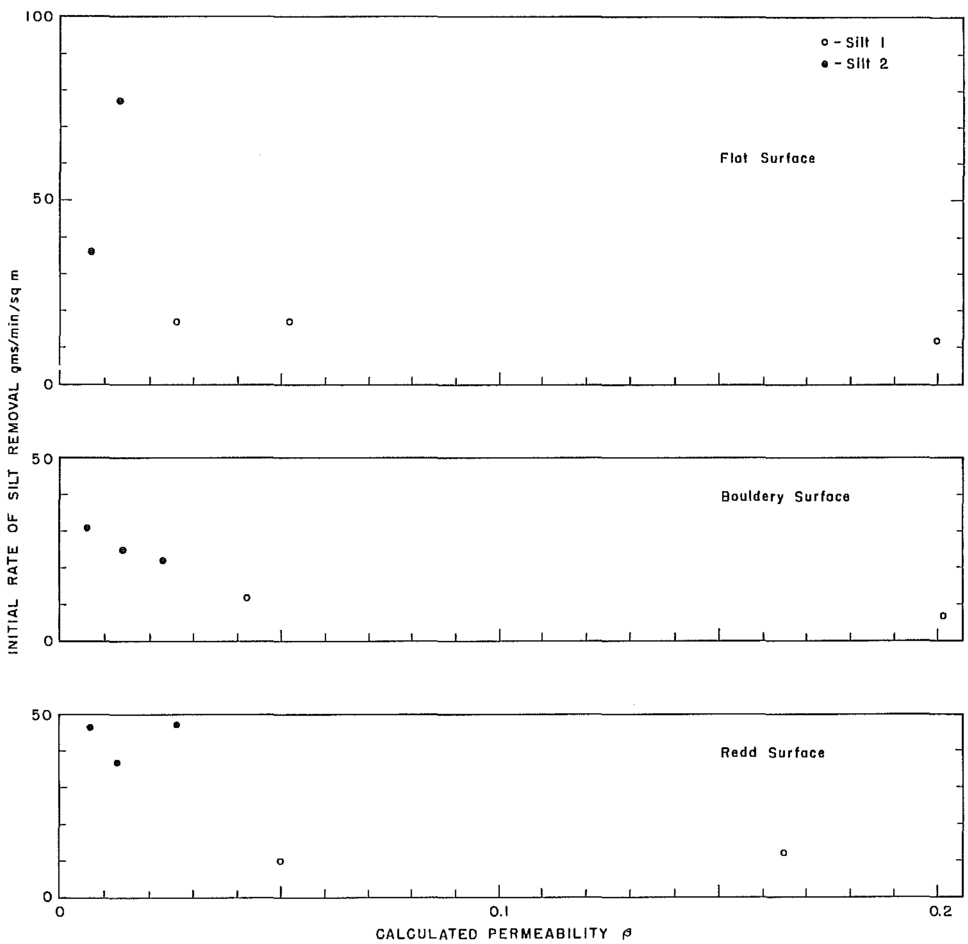


FIGURE 37—Observed initial rates of sediment removal for different surface conditions, gravel permeability and silt size.

gravel would be laminar ($n = 1$) and that silt of 30 micron mean size would be passing over the gravel bed. It has also been assumed that the depth of gravel involved is 50.8 cm as in the tests reported here. There is some indication that the time required for the occurrence of a given change in permeability function is proportional to the gravel depth, but this factor was not specifically investigated. The 250-day time period chosen for illustrative purposes is the approximate period sockeye salmon eggs and alevin are in the gravel. The slope of the hydraulic gradient (s) was arbitrarily chosen to provide a velocity through gravel A which would be representative of the velocity in a spawning bed and the same slope was applied to gravel E. The references for each step in the calculations are given in the table.

Considering first a silt concentration of 200 ppm circulating over gravel A, at the initial velocity through the gravel of 0.0063 cm/sec the survival of eggs

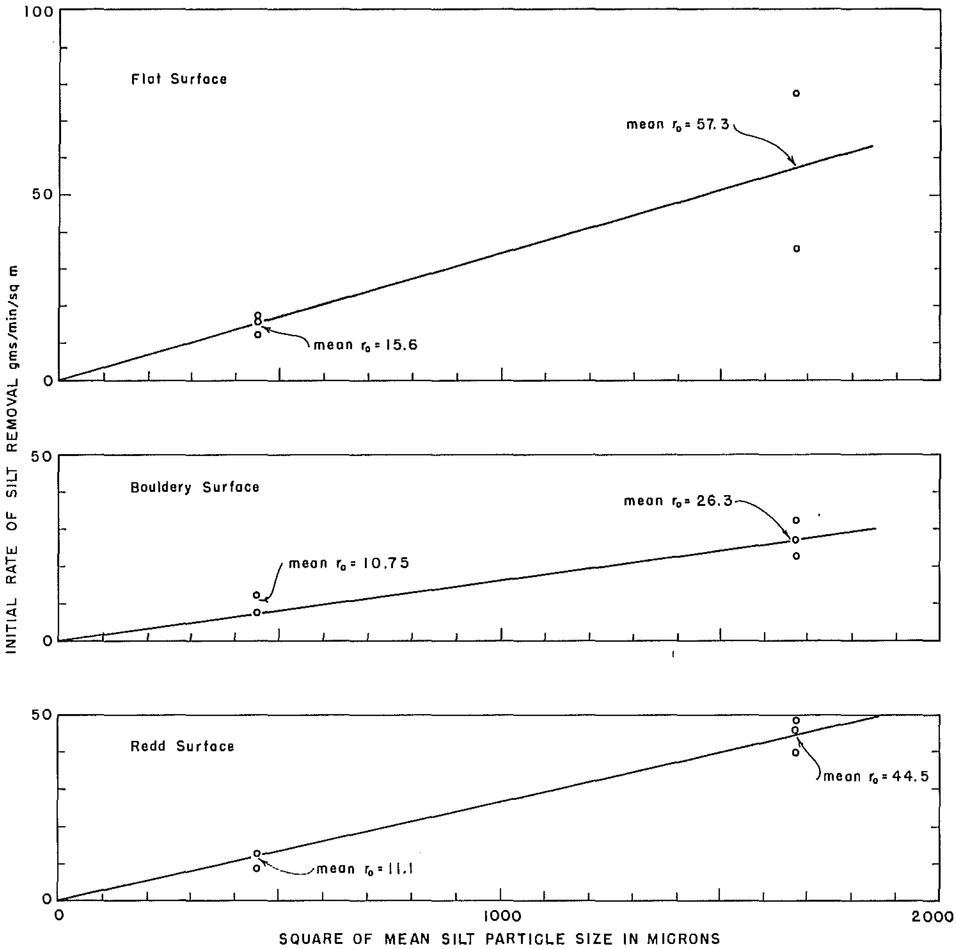


FIGURE 38—Relation between initial rate of silt removal and square of mean silt particle size.

would be 70 per cent (TABLE 7), whereas at the velocity (V_t) of 0.000082 cm/sec after the period of silt deposition, the survival would be zero. In contrast, the effects of a silt concentration of 20 ppm on survival in gravel A would be negligible. The velocity of 0.617 cm/sec through gravel E would be more than adequate to obtain the maximum possible survival of eggs, although it may be too high to provide a normal environment for the eggs and alevin (Brannon 1965). The velocity of 0.0081 cm/sec at the end of the silt deposition would be sufficient to obtain 75 per cent survival of the eggs.

These results illustrate the serious effect of silt deposition on survival of eggs deposited in a typical spawning gravel such as gravel A, and the necessity for maintaining very low suspended sediment concentration in waters flowing over salmon spawning grounds. In coarser gravels such as gravel E, the effect of the silt on survival of the eggs would be very much less because of the higher

TABLE 24—Calculated effect of suspended sediment on the permeability function of two gravels and the velocity through the gravels at 1°C.

	Gravel A	Gravel A	Gravel E	Reference
Σ P/d	4.3528		0.4058	Table 14
e	.186		.334	Table 14
e/1—e	.229		.501	
S	6.1		6.1	Table 8
β	.0086		.202	Equation 12
n	1		1	Assumed
ϕ_o	.00001375		.01365	Equation 13
silt d, microns	30		30	Assumed
r_o, flat bed, 19.4°C	30		30	Figure 38
μ, 19.4°C	.010199		.010199	Table 9
μ, 1°C	.017313		.017313	Table 9
r_o, 1°C	17.6		17.6	Calculated
c	200	20	200	Assumed
t, 250 days	360,000 min.	360,000	360,000	Assumed
x	0.86	0.97	0.86	Figure 32
y	32,000	7,000,000	32,000	Figure 33
$y/(ct)^x$	.0057	1.57	.0057	
$\frac{r_o - r_t}{r_o}$	.987	.0269	.987	Equation 14
r_t/r_o	.013	.9731	.013	
ϕ_t	.0000001785	.00001335	.0001775	
s	.00083	.00083	.00083	Assumed
ϕ_o/k	.0001350	.0001350	.0133	Figure 28
V_o, cm/s	.00632	.00632	.621	Equation 11
$V_t = V_o \left(\frac{\phi_t}{\phi_o}\right)$	.000082	.00614	.0081	

velocities through the more permeable gravel. This illustrates one of the advantages of removal of fine materials from gravel in prepared spawning channels. The coarse gravel combined with suitable sediment settling basin will ensure the maintenance of an adequate flow to eggs buried in gravel. It must be emphasized, however, that the size of gravel used may be governed by other requirements of the salmon embryo during its period in the gravel (see Brannon 1965).

EFFECT OF SUSPENDED SEDIMENT ON UPWELLING FLOW TYPE ARTIFICIAL SPAWNING CHANNELS

The foregoing studies demonstrated the effect of suspended sediment on the flow of water through the gravel of a stream and the resulting detrimental effect on the survival of sockeye salmon eggs. Any artificial spawning channel of the stream type should be provided with water free of suspended sediment if possible.

Since the upwelling flow type of spawning channel may be required for certain applications, additional tests were made to determine the effect of suspended sediments on the flow of water through such gravel beds. These tests were made on a full scale section of such a bed (FIGURE 39). A flow of water was circulated through the bed and silt was added to maintain a constant concentration of 1000 ppm in the water entering the water supply pipes. Observations were made at flows corresponding to apparent velocities of 250, 500 and 1000 mm/hr in the gravel. At the end of each 2 hour test measurements were made of the quantity and size of sediment in the distributor pipes in the gravel, in three layers of the gravel and in the surface water. The sediment used was finer than 200 mesh sieve and was obtained from sediments removed from the hatchery troughs of the Pitt River Field Station on Seven Mile Creek, a tributary of the Upper Pitt River. The approximate particle size distribution of this sediment, based on settling velocities of the particles ranged from 0.032 mm to 0.143 mm (TABLE 25). The gravel used was similar in size distribution to that used in the Seton Creek spawning channel (TABLE 26).

The results of the three tests are partially summarized in TABLE 27. A number of observations may be made from this data.

1. The rate of silt accumulation in the gravel during each test varied in proportion to the flow of water through the gravel.

TABLE 25—Particle size distribution of sediments used and recovered in test at 1000 mm/hr velocity.

Per Cent Finer Than Size Indicated	Sediment as Added mm	Sediment from Distributor Pipes mm	Sediment from Bottom 2.54 cm Layer of Gravel mm	Sediment from Gravel Between Top and Bottom 2.54 cm Layer mm
90	.143	.135	.094	.063
80	.083	.089	.072	.043
70	.067	.079	.063	.035
60	.056	.069	.052	.033
50	.048	.061	.047	.027
40	.043	.051	.040	.025
30	.038	.044	.034	.024
20	.034	.038		.023
0	.032	.034	.026	.021

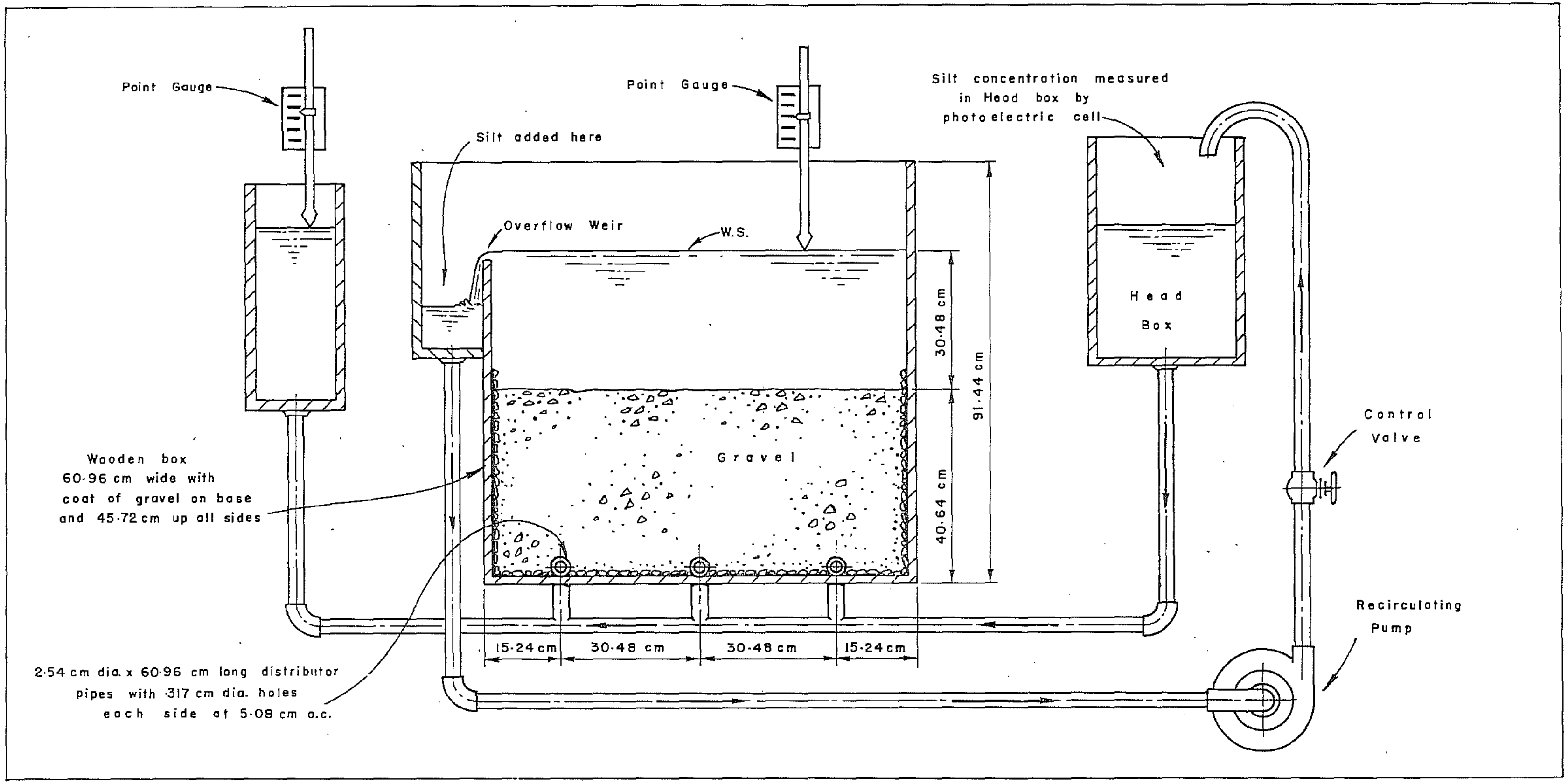


FIGURE 39—Test arrangement for section of upwelling flow spawning channel.

TABLE 26—Size distribution of gravel used in tests of upwelling-type spawning channel.

Size in cm	Per Cent by Weight Passing Sieve
10.16	100
7.62	96.5
5.08	90.0
3.81	84.8
2.54	53.9
1.905	19.7
1.270	2.1
0.635	0
$\Sigma P/d = 0.4173\ cm^{-1}$	

TABLE 27—Summary of results of tests in upwelling flow.

ITEM		TEST 1	TEST 2	TEST 3
Discharge	cc/min	155	77.5	38.7
Apparent Velocity	mm/hr	1000	500	250
Gravel Porosity		0.586	0.582	0.585
β	cm^{-1}	.556	.546	.554
Silt concentration	ppm	1000	1000	1000
Total silt added during 2-hour test	gm	1368	906	547
Total silt recovered from gravel	gm	837	474	337
Rate of silt addition	gm/min/sq m	12.6	7.1	5.05
Silt recovered from				
top 2.54 cm of gravel	gm	5	4	3
central portion of gravel	gm	202	167	130
bottom 2.54 cm of gravel	gm	630	303	204
Per cent in bottom layer		75%	64%	60%
Silt recovered from distributor pipes				
No. 1	gm	179	139	86
No. 2	gm	106	104	46
No. 3	gm	93	58	24
TOTAL	gm	378	301	156
Silt contained in water	gm	135	121	96
Head loss through distributor pipes with no gravel in box	cm	1.525	0.396	0.122
Head loss with gravel in box				
(a) At start of test	cm	1.555	0.396	0.122
(b) At end of test	cm	4.968	1.22	0.214

2. The rates are of the same magnitude as previously observed for flow over a horizontal gravel bed with the same permeability β.

3. The sediment introduced during the two hour test settled mainly in the bottom 2.54 cm layer of the gravel bed. However, if the test had been carried on for a much longer period, the sediment undoubtedly would have been much more widely and evenly distributed.

4. At the flow rates used, there were substantial deposits of silt within the water distribution pipes. These deposits were sufficient to increase substantially the friction loss through the distributor pipes, although this loss is an insignificant part of the total head measured (less than 0.00915 cm). The sediment accumulated along the full length of each distributor pipe, with more at the inlet end than further along each pipe. The largest deposits were in the pipe nearest the incoming supply, and six of the holes at the inlet end of this pipe were covered with sediment so that there would be no flow to the gravel at this point.

5. The coarser fraction of the sediment settled in the distributor pipes. The sediment in the bottom layer of gravel contained more of the finer fraction, and the sediment from the main body of the gravel was still finer. The water leaving the gravel into the tail water basin contained the smallest particles and consisted exclusively of particles of 0.020 mm size. These represent particles whose fall velocity was exceeded by the upwelling velocity.

6. The deposit of sediment within the gravel caused a substantial increase in the head loss through the gravel bed. If this water supply system had been arranged with a constant head, the flow of water through the gravel would have been reduced proportionately. In the test, the flow was maintained constant and the head was allowed to vary. While the arrangement maintained constant flow, it did not assure uniform distribution of flow. As previously noted, some holes in the distributor pipes were plugged. In addition, the heavy deposition of sediment on the bottom layer of gravel would reduce or stop circulation of water to this layer and the layers immediately above. These reductions in flow would reduce the survival of any salmon eggs deposited in the gravel. This reduction could be prevented by provision for removing from the water supply all sediment larger than the size that will be transported through the gravel by the upwelling flow.

The upwelling gravel bed at the Upper Pitt River Experimental Station was provided with settling tanks capable of removing 90 per cent of all particles of the smallest size which occurred in the distributor pipes (0.03 mm). Settling tanks large enough to remove 0.02 mm particles could not be constructed in the limited space available. The upwelling area at this Station was operated at a velocity of 338 mm per hour during the winter of 1963-64 and incubated 2½ million sockeye eggs with a survival from eyed eggs to fry of 75 per cent. The gravel in the bed was examined after the emergence was completed. A small percentage of fine sediment was found in the gravel but it did not affect the velocity of flow through the gravel since this was maintained constant by the arrangement of the water supply. The upwelling velocity of 338 mm per hour corresponds to the settling velocity of particles of 0.014 mm diameter at 0°C. It would be expected therefore that particles between this size and the 0.03 mm size removed in the settling tank would be deposited within the gravel. In actual practice the settling tanks removed particles down to 0.012 mm diameter, although the efficiency for this size would be less than 90 per cent. In addition particles less than 0.03 mm diameter are only a minor portion of the sediments transported by Seven Mile Creek.

In 1964-65 a total of 3½ million eggs were incubated in the upwelling gravel bed with a survival from eyed eggs to fry of 88 per cent.

SUMMARY

Available data on the suspended sediment concentration in streams used by Pacific salmon shows that these streams normally carry relatively small amounts of suspended sediment during the spawning and incubation period of the salmon.

Methods of determining the size of bed load materials that may be expected on a given portion of stream bed are presented. Reference is made to earlier work which shows how such layers of bed material can reduce the survival of salmon eggs by reducing flow of water through the gravel.

The flow of water through a gravel bed is determined by the characteristics of the gravel and the imposed hydraulic gradient. The permeability of gravel is expressed in terms of particle size grading, porosity and particle shape, and a formula is developed relating permeability and flow. It is shown that fine sediment has a large influence on the permeability of gravel.

The effect of a flow of silty water over a gravel bed is measured, and it is shown that deposition of silt occurs within the gravel even though velocities are too high to permit deposition on the gravel surface. This deposition reduced the permeability of the gravel. Formulae are developed which relate time and silt size and concentration to the effect on a given gravel. The results show that the least damaging effect on salmon eggs would occur with a very coarse gravel, and the most severe effect would occur with fine gravel such as found in typical spawning beds. The prevention of deposition of sediment upon or within a spawning bed is shown to be essential to a high survival rate of salmon eggs to emergent fry.

The effect of suspended sediments on an upwelling type of artificial spawning or egg incubation bed is also examined. It is shown that permeability of these beds can be reduced by sediments in the water. This may be prevented by providing settling basins to clarify the incoming water. These basins should be capable of removing all sediments which could settle in the distribution system and also all sediment with a settling velocity less than the apparent upwelling velocity.

SYMBOLS

All units in gm-cm-sec system unless otherwise stated.

a = a length, such as mean particle diameter, which characterizes the size scale of the pore structure (Equation 8).

b = number of gravel particles per kilogram (Figure 21).

c = concentration in ppm.

d = diameter of particle in cm.

e = porosity = $\frac{\text{volume of voids}}{\text{volume of gravel plus voids}}$

g = acceleration of gravity (980 cm/sec/sec).

k = a factor relating permeability function ϕ to velocity and hydraulic gradient (Equation 11).

n = an exponent describing the state of flow ($n = 1$ for laminar flow and $n = 2$ for fully developed turbulent flow).

r_o = initial rate of removal of suspended sediment gm/min/sq m (Equation 14).

r_t = rate of removal of suspended sediment at time t.

s = hydraulic gradient.

t = time in minutes.

w = specific weight of particles.

x = an exponent related to sediment concentration (Equation 14).

y = a factor related to sediment concentration (Equation 14).

D = depth of fluid in cm (Equation 1).

G = bed material transport in kg/sec/meter width (Equation 5).

K = permeability factor (Equation 7).

N = a dimensionless shape factor of the pores of a granular material (Equation 8).

P = fraction of particles by weight of size d.

R = Reynolds number = (velocity) (characteristic dimension) $\frac{\rho}{\mu}$

S = area-volume shape factor of particles (Equation 9, 12).

U = mean fluid velocity at the particle level in cm/sec (Equation 5, 6).

V = apparent velocity in cm/sec = $\frac{\text{discharge}}{\text{area of gravel plus pores}}$

V_o = apparent velocity at time zero.

V_t = apparent velocity at time t.

W = weight of silt added, kg/sq m of gravel surface (Table 19).

β = permeability in cm (Equation 12).

θ = a dimensionless function (Equation 5).

μ = absolute viscosity in poise (Table 9).

ρ = density of fluid gm/cm^3 (Table 9).

τ_o = bed tractive force kg/sq m (Equation 1).

τ_c = critical bed tractive force kg/sq m (Equation 4).

ϕ = permeability function (Equation 13).

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