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Title: EFFECTS OF IMBEDDED PERFORATED PIPES ON PERMEABILITY OF GRAVELLY STREAMBEDS

Abstract approved: Redacted for Privacy
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Perforated pipes were buried in the gravel bed of a laboratory stream, extending upstream from a simulated riffle in order to study their effect upon mixing and interchange of stream water and intragravel water. In the absence of such pipes the drop of energy gradient of the stream was concentrated locally at the riffle whereas the perforated pipes caused the local drop of hydraulic gradient to occur over an extensive portion of the gravel bed due to the direct connection of the pipes with the flow downstream of the riffle. The resulting increase in interchange of stream and intragravel water would be directly beneficial to fish eggs and hatched fry in the gravel pore space by permitting a greater supply of dissolved oxygen to reach them and thus reducing the risk of suffocation.

A significant difference in the permeabilities of gravel beds with

and without imbedded perforated pipes was found after the same amount of fine sediment was applied to each bed. The much higher final permeability of the gravel streambed containing imbedded pipes suggests that perforated pipes might be of considerable use in reducing silt deposition in spawning gravels and thus minimizing exit-route blockage and environmental stresses for the hatched fry.

Effects of Imbedded Perforated Pipes on Permeability of Gravelly Streambeds

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INTRODUCTION

Statement of the Problem

The fate of eggs deposited by spawning fish at some depth in the gravel bed of a stream depends in part upon the amount of dissolved oxygen in the intragravel water and the availability of an unblocked exit route out of the gravel to the surface. These conditions are directly influenced by the amount of fine sediment in the pore space of the gravel. Silt in the gravel bed provides a physical barrier to the movement of hatched fry. It also prevents stream water from moving into and flowing through the gravel. This prevents renewal, in the pore water, of the oxygen supply upon which the eggs depend for life. Many eggs thus suffocate in the gravel.

Spawning fish apparently seek instinctively to minimize the risk of egg loss. Successful redds, or "nests," of salmon are frequently found just upstream of a riffle where the local hydraulic gradient is comparatively large and provides a strong intragravel flow of water. The preparation of the redd by a spawning fish tends to flush out much silt from the gravel pores. The final shape of the redd after eggs have been placed and fertilized is also conducive to intragravel flow through the cleaned pores. The term "intragravel" refers to interstitial spaces within the streambed.

River development by man, particularly in the form of dams constructed across main stems of river systems, has had a generally adverse effect upon anadromous fish. Many former spawning reaches of rivers are now inundated by reservoirs. High dams lacking fish passage facilities permanently bar fish from many headwater areas. Mortality incidence among upstream and downstream migrants is greater than before due to river pollution, unfavorable temperature, nitrogen, and oxygen levels in streams, and fish passage losses at low and medium-head dams.

To compensate for the harmful effects of man, fishery agencies have done much to artificially sustain and maintain fish runs. Besides the more common hatchery programs, efforts have been made to enhance natural stream and spawning conditions in rivers. Even artificial spawning channels have been developed in an effort to boost fish stocks under controlled environmental conditions.

In artificial spawning channels and in improved natural streams a potential for gravel siltation still remains. Control measures vary from use of such large equipment as the U.S. Forest Service's "riffle sifter" and the traveling sluice gate proposed for an irrigation canal by the U.S. Bureau of Reclamation to use of much simpler means such as portable pumps and fire hoses. Reduction of silt from upstream sources, while the most logical-appearing control measure, has not proven adequate even in instances where water was withdrawn from reservoirs a short distance upstream of a spawning channel. The need for a simple, economical means of minimizing siltation of spawning gravel remains. It is the intent of this research to investigate one approach to simple, inexpensive silt control.

Objective of This Study

The objective of this study is to determine the effectiveness of imbedded perforated pipes in reducing siltation of the gravel streambed and for increasing intragravel flow.

The pipes would be installed parallel to each other and to the direction of streamflow. They would be buried at some adequate depth in the gravel bed and their downstream ends would terminate at the lower end of a riffle. It is hypothesized that an increased amount of the stream water will enter the gravel bed over these pipes because of locally increased energy gradients through the gravel in the vicinity of the perforated pipes, since the energy grade line near the pipe would more nearly correspond to that downstream of the riffle than without such pipes present. It is further hypothesized that the increased flow and correspondingly higher velocity of intragravel water will reduce the degree of silt deposition in the gravel bed. The increased flow and reduced siltation would both be quite beneficial to the egg and fry stages of fish life by increasing the dissolved oxygen level and reducing the environmental stress and physical clogging of the gravel caused by finer sediment. Therefore, it is the purpose of this study to determine how the perforated pipes affect the permeability of the gravel and the productivity of a spawning bed.

LITERATURE REVIEW

Effect of Oxygen Content on Survival of Fish Eggs

In the spawning process, the female fish uses her tail to excavate a redd or "nest" in the gravel of the stream before depositing her eggs. The eggs are then placed in the redd and covered with from 3 to 15 inches of gravel, a typical depth for salmon eggs being 10 inches (Terhune, 1958). Thereafter, the eggs receive the oxygen they require to sustain life from the water which moves through the pore space of the gravel streambed.

Therefore, the amount of dissolved oxygen present in the subsurface gravel pores of the spawning bed is very critical to the survival of the egg and fry. This has been substantiated by actual field measurements relating low dissolved oxygen content to high egg mortality (Wickett, 1954). The critical level of dissolved oxygen ranges from approximately one part per million (ppm) in early fish egg development stages to 7 ppm near the time of hatching (Alderice *et al.*, 1958). The critical level is defined as that amount of dissolved oxygen below which the eggs will receive less oxygen than they need for normal development.

The oxygen content of the water is the essential factor to the survival of the fish embryo. Usually, dissolved oxygen concentrations and flow velocities are closely related in the streambed; when one is high the other may be expected to be high. However, situations may occur where oxygen levels are low while velocities are high because of the flow pattern in the gravel or because of large amounts of organic matter or large numbers of embryos in the gravel. In two redds receiving waters flowing at different velocities but containing the same concentration of dissolved oxygen, a higher survival may be expected in the area with higher velocity and flow exchange rate (Coble, 1960).

Flow Interchange and Intragravel Dissolved Oxygen

Because of the gravel cover over the eggs, intragravel flow of water becomes extremely important in order to maintain the minimum dissolved oxygen for survival of the eggs.

Wickett (1954) concluded that the amount of oxygen supplied to the eggs was dependent upon the amount of flow over them and the dissolved oxygen content of the water. Vaux (1962) stated that percolation of groundwater into the streambed gravels is one of the means by which the dissolved oxygen transfer rate might be increased. However, this source of supply was shown by Sheridan (1962) to be relatively unimportant. Sheridan instead showed experimentally that the most important source of oxygen for the eggs is water from the streamflow above the gravel bed. Therefore, flow interchange has a direct effect on the intragravel dissolved oxygen content. Also, siltation plays an important role in this fish egg mortality problem since the rate of oxygen interchange may be reduced due to clogging of the void space in the gravel bed.

Flow Interchange Process

The pattern of flow of water through the streambed depends on the nature of the gravel surface. If the bed is smooth and on an even gradient, flow lines through the gravel will generally by parallel to the bed and there will be only minor interchange between the stream and the bed near their interface. If a few large rocks are placed on top of this bed (simulating the gravel hump of a redd), the flow remains parallel to the surface and extends to the same depth of the bed but interchange at the surface is greatly increased (Cooper, 1959).

Cooper (1959) investigated the flow pattern for oxygenated water to enter the streambed and found that a net driving force must exist to induce flow across the gravel boundary. For a stream flowing over a smooth-surfaced gravel bed of constant permeability and constant bed slope, turbulent conditions do not extend through the thin laminar water layer adjacent to the stream bottom and, therefore, interchange is kept to a minimum (McCabe and Smith, 1956).

Vaux (1962) showed that interchange between the stream and intragravel water occurred when certain hydraulic requirements of the stream and streambed were satisfied. The factors influencing this interchange include: (1) stream surface profile, (2) gravel permeability, (3) gravel bed depth, and (4) irregularity of the streambed surface. Vaux formulated models which showed that the direction of interchange depends on the curvature of the gravel surface profile. Where the profile was concave, water upwelled; where it was convex, a down-flow occurred. In the absence of bed curvature, there was no significant interchange, provided that the permeability and depth of the gravel bed did not vary. These relations were verified by Vaux with field and laboratory experiments. Figure 1 illustrates the direction of flow interchange with change in the curvature of the natural stream bottom.

Vaux (1967) has also shown that if the permeability of the bed varies this will have a significant influence upon intragravel flow. For example, if the gravel bed has varying permeability in the direction of channel flow the interchange process might be as represented in Figure 2.

Siltation and Its Effects on Permeability

Sediment in rivers can be shown to be detrimental to the survival of fish eggs in redds. Egg mortality may result from lack of oxygen, either by suffocation due to coating of the eggs or by

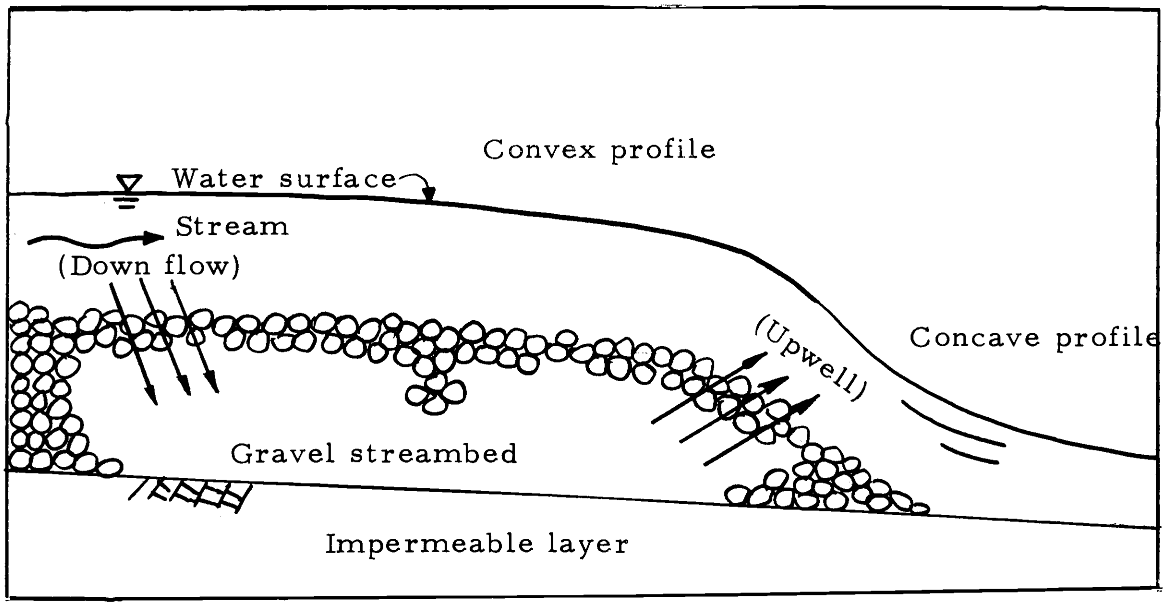


Figure 1. Relationship of flow interchange to curvature of the stream bottom (after Vaux, 1962). Arrows indicate direction of interchange.

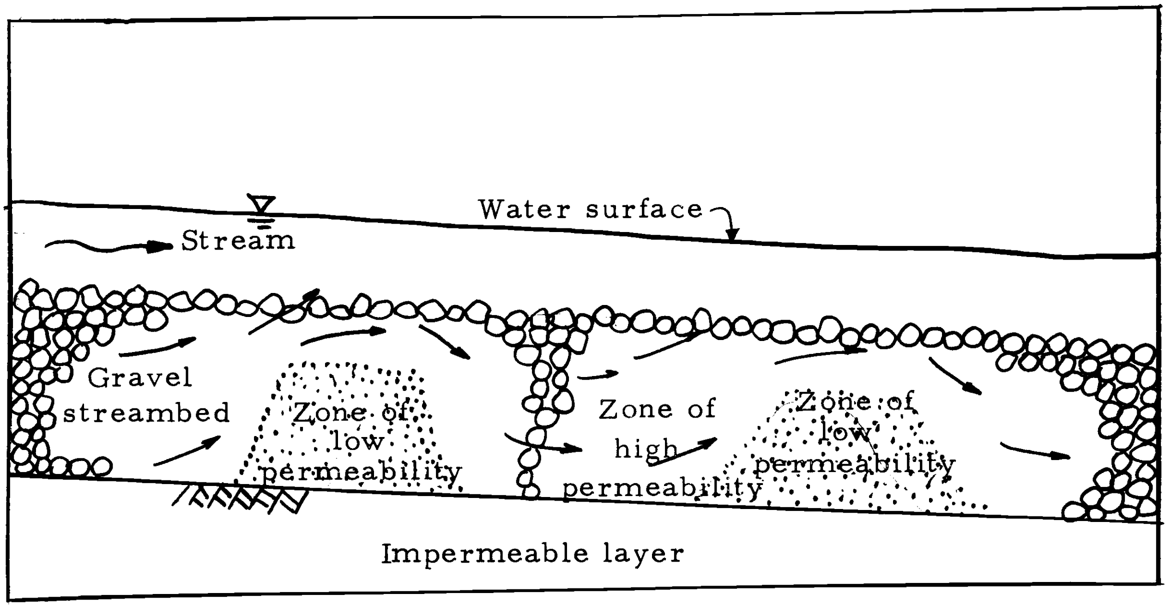


Figure 2. Effect of non-uniform streambed permeability upon flow interchange (after Vaux, 1967). Arrows indicate direction of interchange.

suffocation due to reduction in the supply of oxygen-bearing water. Sediment deposition on the surface of a gravel streambed reduces the flow of water into the bed. The finer sediments, of less than 0.3 millimeter (mm) size, have been found to be more effective in reducing flow than coarser materials, as might be expected (Cooper, 1959).

Siltation, therefore, is regarded as one of the major hinderances to adequate interchange of fresh water and the attainment of satisfactory dissolved oxygen levels in a gravel streambed. Watershed practices greatly influence channel siltation. For example, when a watershed is logged fine sediments may enter the stream in large quantities and settle in the gravel pores of the streambed.

Studies by McNeil and Ahnell (1964) at six different streams in the Pacific Northwest showed that the silt content of the gravel streambeds may be appreciable, varying from 7.4% (Indian Creek) to 17.4% (Harris River), based upon averages of several samples. All the data were obtained during the low flow period (August to October) when the streamflow was quite clear and silt-free. In their study, silt was defined as particles passing through a 0.833 mm sieve.

In spawning gravels that contain a considerable amount of silt, stream water which may have a large concentration of dissolved oxygen is hindered or prevented from entering and mixing with or displacing water in the gravel pore space. This prevents renewal of the oxygen supply which the eggs depend upon for life. Thus, many eggs suffocate in the gravel. These findings have been experimentally verified in the laboratory by adding fine sediment to good spawning gravel and observing the mortality of the fish eggs caused by increasing amounts of sediment (Hall, 1967).

Pollard (1955) found that in the immediate vicinity of a salmon redd the low apparent velocity of intragravel water and the low concentration of dissolved oxygen in the groundwater were significant detrimental factors to fish egg survival. This apparent velocity is given by Darcy's Law, which relates fluid flow velocity in a porous media to the permeability and energy gradient within the media.

Darcy's Law may be expressed as

$$V = K \frac{\Delta H}{L} = KI \qquad (1)$$

where

V = apparent velocity

K = permeability coefficient

ΔH = change in energy head

L = flow distance over which the energy head changes

$I = \frac{\Delta H}{L}$ energy gradient (or hydraulic gradient, if velocity change in flow direction is negligible)

Here, the apparent velocity is seen to be dependent, in part, upon the permeability of the gravel.

Silt in the gravel bed is considered to be one of the major factors causing permeability reduction. When silt particles are being deposited, such as during a period of turbid runoff, intragravel permeability decreases with time. This is illustrated by McNeil's data (McNeil, 1964), from which a curve has been prepared in Figure 25 showing the inverse relationship between the coefficient of permeability and the percentage by volume of silt (passing through an 0.833 mm sieve) present in the streambed.

Einstein (1968) found that the fine particles which are carried from upstream and settle out of suspension into a gravel bed have a tendency to filter slowly down through the pores of the gravel. Such "fines" may leave a slight dusting on top of the individual gravel particles, but never appear to clog any of the passages. The silt which does not deposit on the top of any gravel slowly settles down to the bottom of the gravel bed and gradually builds up a deposit there, filling the pores from the bottom up while leaving the upper layers of gravel relatively clean. In other words, intragravel permeability was found to decrease with depth into the gravel. This also implies that the flow interchange in the gravelly bed is higher toward the upper surface than at the bottom of the bed.

Field Measurement of Intragravel Seepage

The direct measurement of gravel permeability involves forcing water through the gravel under a hydraulic gradient and measuring the head loss across a known length of flow path through the material.

The permeability of stream gravel is often measured by means of a permeameter of either the tank or trough type (Pollard, 1955). These permeameters consist of a vertical cylindrical tank and a horizontal rectangular trough, respectively, and are generally used in the laboratory. However, in transferring gravel from the natural stream to the laboratory permeameter, the material will be disturbed and the degree of compaction will be changed. Hence the measured gravel permeability is no longer that of the streambed. Therefore, some type of field measurement for the gravel permeability is preferred.

The permeability of a granular streambed can be measured indirectly in the field by pumping a liquid out of (or into) a hole or "well" made in the bed by driving a vertical standpipe. If the geometry of the well and the dimensions of the bed are simple, then the rate of pumping required to remove or add water to the bed at a steady rate under a known head will allow the permeability of the granular material to be calculated. Several researchers have developed or modified standpipes to accomplish this (Wickett, 1954; Pollard, 1955; Terhune, 1957, 1958; Gangmark and Bakkala, 1958).

The evaluation of permeability by use of a standpipe has been developed by Terhune (1958) and is summarized in the following paragraph.

If the depth, D (Figure 3A), to the impermeable stratum below the gravel is large compared with the dimensions of the perforated standpipe, "a simple analysis of the analogous problem of a spherical sink will show the dependence of the inflow rate upon permeability, for laminar inflow in a gravel of uniform permeability, K." In Figure 3B, the apparent velocity of inward flow at a distance, r, from the center of the sink is V, the radius of the sink is r_o, and the velocity at the periphery of the sink is V_o. Let the hydraulic head in the sink be lowered by h, and let the head drop be dh across a spherical shell of radius r, and thickness dr. Then, from continuity:

$$V = V_o \frac{r_o^2}{r^2} \tag{2}$$

and from the definition of permeability:

$$\frac{dh}{dr} = I = \frac{V}{K} \tag{3}$$

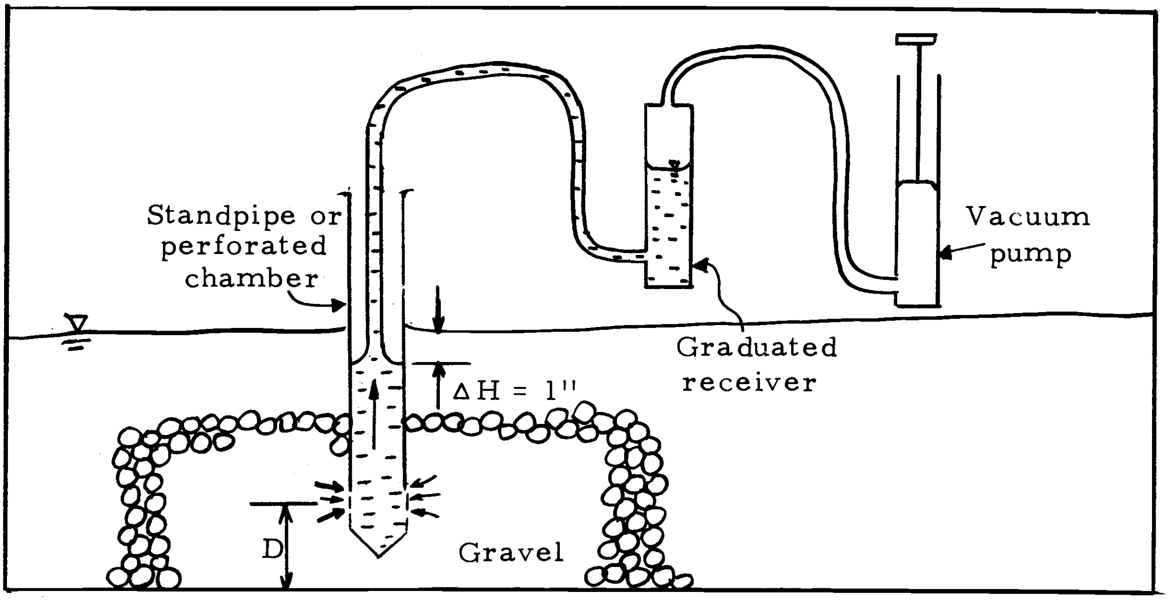
so that:

$$dh = \frac{V_o r_o^2}{Kr^2} dr \tag{4}$$

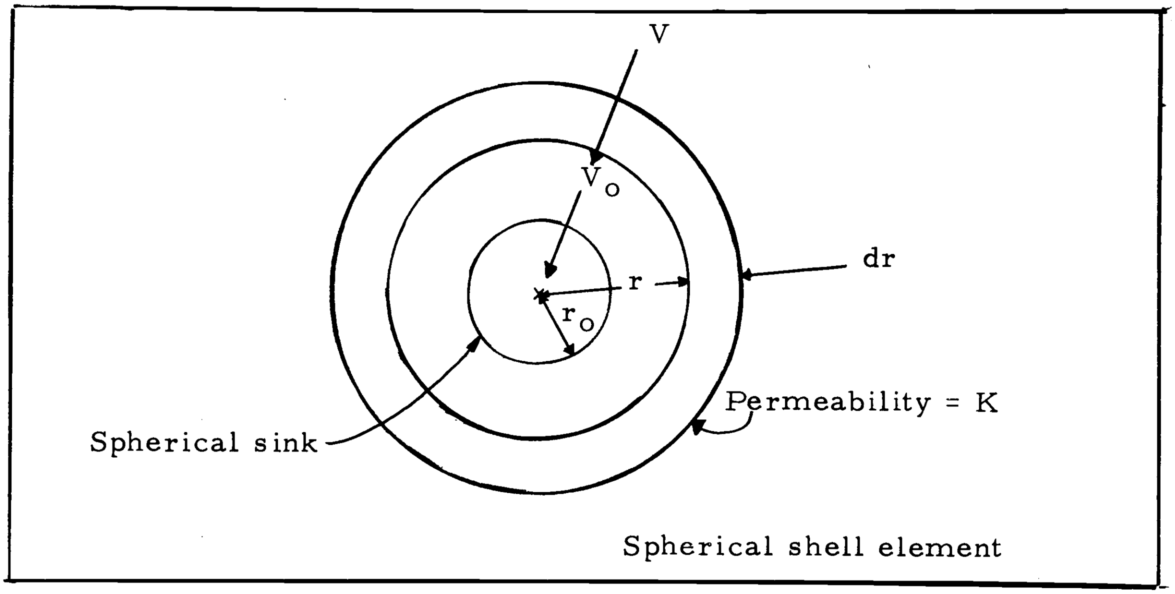
integrating, the total head drop is:

$$\Delta h = \frac{V_o r_o^2}{K} \int_{r_o}^{\infty} \frac{dr}{r^2} = \frac{V_o r_o^2}{K} [\frac{-1}{r}]_{r_o}^{\infty} = \frac{V_o r_o}{K} \tag{5}$$

from which the rate of inflow is:



A. Schematic diagram of the apparatus used for measurement of permeability.



B. Diagram for the analysis of the spherical sink problem.

Figure 3. Permeability measurement by means of a standpipe (after Terhune, 1958).

$$V_o = \frac{\Delta h}{r_o} K \qquad (6)$$

Thus, for a fixed value of Δh and for fixed dimensions of the perforated standpipe, the rate of flow into the chamber is dependent only upon the permeability and a convenient means is available for its field determination.

Size of Fine Sediments and of Bed Material

According to Sherard (1963), deposition of fine sediment in a typical river channel depends on both the size of fine particles which are carried from upstream and the size of bed material. Moreover, a certain size of fine material would settle better in a portion of the channel with certain sizes of bed material than in another location along the same channel where the bed material differs in size. Therefore, in design of an artificial spawning channel and selection of bed material, knowledge of the suspended load of the stream undoubtedly plays an important role.

The siltation problem of a spawning bed is somewhat analogous to the situation in which filter criteria are used for earth dam design. For instance, in designing any earth dam, as water from the reservoir seeps through the pores of an earth dam, seepage forces are exerted on the soil particles in the direction of the flow (Sherard, 1963). Where the water discharges from fine material into coarse material, however, it is theoretically possible for the finer soil particles to be washed into the void spaces of the coarser material. Therefore, in designing any barrier structure, it is generally accepted as good practice to require that the relative gradation of adjacent soil zones meet established "filter criteria" to prevent any possibility of appreciable migration of soil particles. For a spawning bed, on the other hand, it is hoped that fine particles will pass through the coarser material with little or no trapping. Hence, to experiment with the siltation of spawning gravel, a certain size of fine particles could be selected in order to be washed into and through the gravel bed to simulate the natural siltation phenomenon. The criteria in selecting this fine material for such an experiment would be the opposite from those described here as the "filter criteria" for an earth dam filter:

1. The 15% size of the filter (i. e., the particle size which is coarser than the finest 15% of the soil, also identified as D_{15}) should be at least five times as large as the D_{15} size of the soil being protected by the filter.

2. The D_{15} size of the filter should not be larger than five times the D_{85} size of the protected soil.

3. The gradation curve of the filter should have roughly the same shape as the gradation curve of the protected soil.

In Einstein's experiments on gravel siltation (1968), the D_{15} size of the gravel used was more than five times as large as the D_{15}

size of the fine sediment particles used (criterion 1 above was satisfied). However, the D_{15} size of the gravel was found to be more than five times the D_{85} size of the sediment particles (the second criterion above for an effective filter was not met). Consequently, the size of the fine particles was found to be suitable for successful penetration of the upper gravel. Apparently, filling of the voids of the gravel bed only occurred when the silt could penetrate no deeper because of reaching the bottom of the gravel bed. From this study one may conclude that if fine material does not completely satisfy the "filter criteria" it can move freely through the gravel as long as vacant voids are available for such motion. Therefore, one may also expect that some device to carry intragravel silt away from the base of the streambed, as used in the experiments described in this thesis, should be successful in minimizing gravel siltation.

Gravel Requirements for Spawning

Bed material in spawning areas must consist of gravel of such size that fish can excavate redds in which their eggs can be deposited, fertilized, and hatched (Rantz, 1964). The preferred areas are either in riffles or at the downstream end of pools, where velocities are fairly rapid. The force of the current assists the salmon in moving the gravel; the larger the gravel, the faster the current required. If, however, the current is too fast, the eggs will be washed downstream.

Immediately after the eggs are deposited and fertilized, the salmon moves some gravel into the redds to cover the eggs. Thereafter, a continuous circulation of water through the gravel and over the eggs is required to insure successful hatching. The gravel must be large enough to provide the interstices needed for this circulation.

Ranges of gravel size have been measured in different spawning areas by some investigators (McNeil, 1964; Rantz, 1964). Spawning channels operated by the Canadian Department of Fisheries have used gravels ranging in size from 1/4 - 4 inches nominal diameter (Department of Fisheries of Canada, 1960; MacKinnon et al., 1961). Typically, less than 5-10% by weight of the gravel is in the 1/2 - 3/4 inch range, whereas the 3/4 - 1 inch and 1 - 2 inch ranges each contain 40% of the mixture and 20% is in the 2 - 4 inch range. Bed cleaning has been required in many instances to rehabilitate the gravel after siltation (Klingeman, 1968).

The Washington Department of Fisheries also uses gravel of 1/2 - 4 inch size in its spawning channels, with some rock up to 6 inches in size. The Department's fisheries engineers feel that it is essential to keep out the "fines" of less than 1/2 inch size (Klingeman, 1968).

In designing spawning beds for fall Chinook salmon in western Oregon, Klingeman (1968) recommended that most of the gravel have a particle size of 1/2 - 4 inches and that special care be taken to exclude any smaller material. However, particles of 4 - 8 inch size were also recommended in order to give greater bed stability during floods, with about 10% by weight in this coarser range. Pollard (1955) used gravel ranging from no. 200 sieve (0.074 mm) to 3/8 inch, with D_{10} approximately at 2.7 mm in a laboratory study of salmon spawning bed. Gravel size ranged between 1 mm and 10 mm in Terhune's studies (1958). The gravel gradation curve and size limits reported by MacKinnon et al.(1961) are shown in Figure 4. The gravel size used in their study ranged from 1/4 to 1-1/2 inches, with depth of bed varying from 12 to 18 inches.

Flow Conditions for Spawning

Desirable flow velocities for spawning fish vary with fish species. The five species of Pacific salmon generally spawn in flows with velocities of 1 - 2-1/2 feet per second (fps) and depths of 1 - 2 feet (Department of Fisheries of Canada, 1960; MacKinnon et al., 1961). Lucas (1960) reported the average velocity at normal flow to be 1.5 fps in Robertson Creek spawning channel. Nece (1962) reported that the minimum flow to satisfy the biological requirements of Pink salmon is one having a velocity of 1 fps and a water depth of 4 inches. The criteria for favorable spawning conditions for Chinook salmon used in Rantz's (1964) study were: a depth of water equal to 10 inches and a bottom velocity (measured 0.3 foot above streambed) equal to

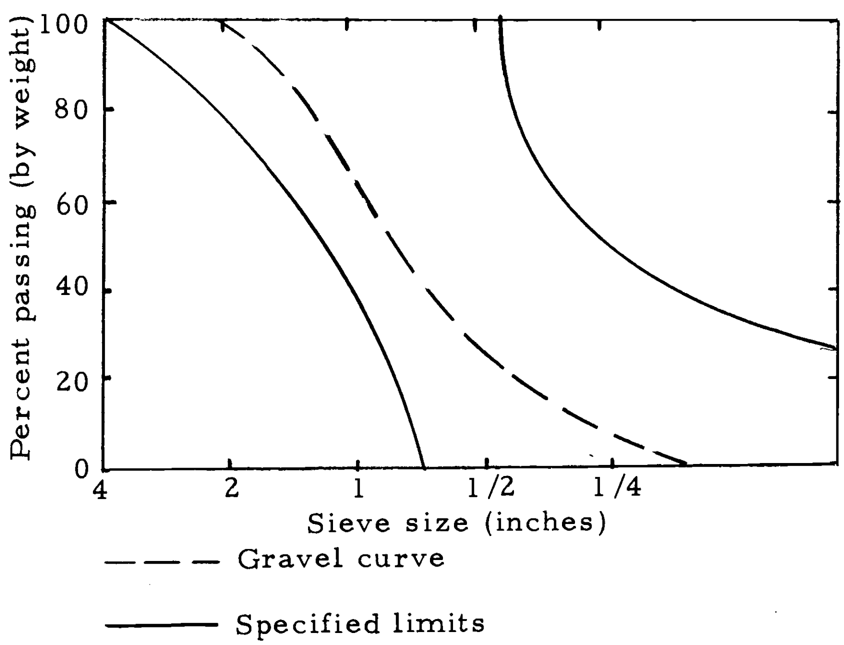


Figure 4. Gradation curves for spawning gravel in Jones Creek (from MacKinnon et al., 1961).

1 - 3 fps. The criteria used by Rantz were not developed specifically for conditions in the streams studied, but are a composite of criteria derived from studies of various streams by the California Department of Fish and Game (Westgate, 1958) and by other Pacific Coast conservation agencies.

Holding pools spaced along spawning channels have been used to simulate the pool-riffle sequence of natural streams and thus provide a resting area for spawning fish. Because of the deceleration and acceleration of flow as it crosses each pool zone, local energy losses occur which must be considered for design of the channel slope, along with the energy gradient over the spawning gravel. To allow for head losses across each pool, Wood (1966) indicates that a drop in head equal to the channel velocity head may be assumed.

EXPERIMENTAL THEORY

Flow Interchange for Laboratory Streambed Near Riffle

Consider a laboratory model of a river channel that is bedded with gravel in such a way that the profile of the gravel surface would cause flow curvature. Suppose also that sampling stations are selected in three locations along the channel such that the influence on permeability of changes of flow interchange due to the gravel surface profile may be detected. Such a situation is shown in Figure 5 and is developed in the laboratory for the research discussed here. The system starts with a deep pool at the upstream end, as shown in Figure 5 and transitions into a gravel bar near station 1. The gravel bed has a level surface near station 2. Near station 3 the gravel bed terminates at a rigid wire mesh installed to simulate the downstream end of the riffle caused by the gravel bar. Station 3, located nearest to the gravel-holding structure, is expected to have a higher value of permeability than for stations 1 or 2. This is because of the influence of bed curvature on flow interchange (shown by Vaux) and since changes in curvature of the stream bottom are most pronounced at this location. Station 1, however, should have a higher permeability than at station 2 since the stream bottom at station 1 has a convex profile whereas at station 2 the stream bottom is flat.

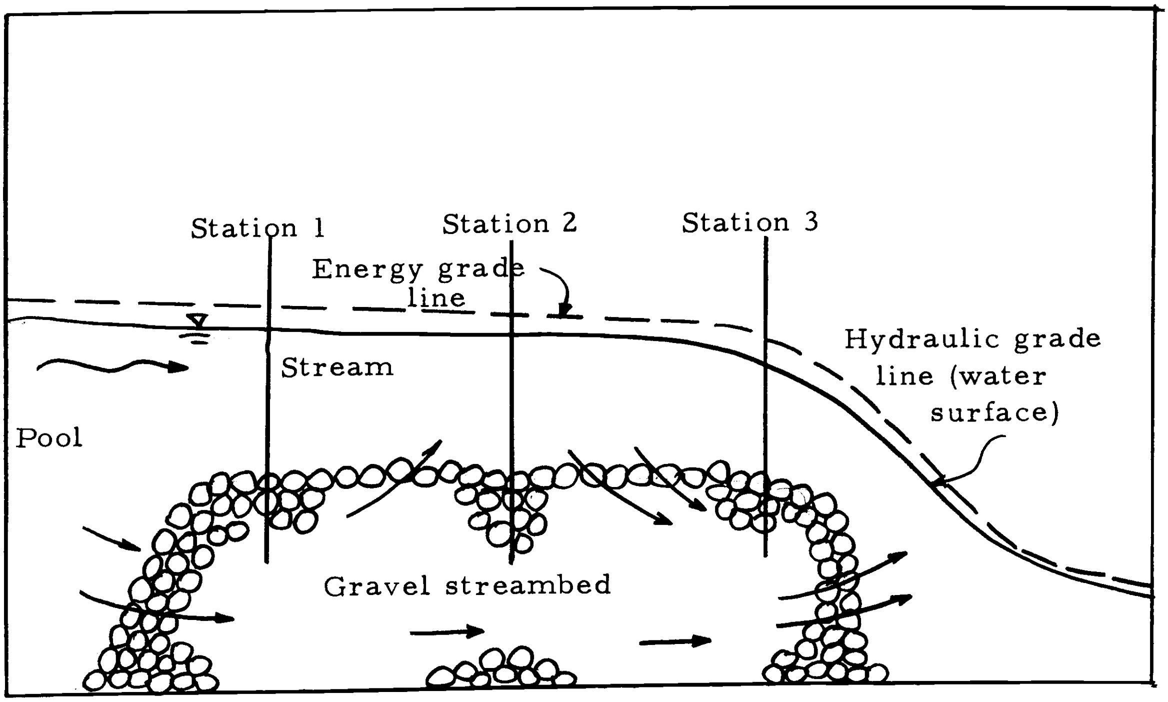


Figure 5. Probable flow interchange pattern for gravel streambed causing bottom curvature.

The gravel bed of Figure 5 could be modified by placing perforated pipes longitudinally along the bottom of the gravel from the downstream end of the riffle almost to the upstream end of the gravel bed. With such a modification, one could expect that the flow over the gravel would be altered because of the possibility for greater seepage into the gravel. This is because of the shorter length of porous media flow and larger hydraulic gradient for seepage water entering the gravel near station 1 or 2 with the perforated pipes in place than with no pipes imbedded in the gravel. In the case where perforated pipes are present, permeabilities at the stations should be considerably higher than with no pipes.

Energy Gradients Near a Riffle

Theoretically, no flow interchange should occur within the gravel bed unless: (a) the stream surface profile is curved; (b) the gravel bed is of varying permeability; or (c) the stream bottom is rough in surface texture. Also, there can be no seepage flow even if a permeable material is saturated as long as there is no energy gradient across the fluid in the material. If water is to flow through the gravel, then the energy level upstream must exceed that downstream at the same elevation of the bed. The energy head drop, or head loss, per unit length in the direction of flow is the slope of the energy grade line. Since velocities in the bed are small, velocity heads will likewise be quite small and for all practical purposes one may replace the energy grade line by the hydraulic or piezometric grade line with little loss of accuracy.

The flow pattern along the channel over a silty gravel bed in a zone such as that near station 2 of Figure 5 tends to be longitudinal with little intragravel exchange. This occurs due to the low intragravel permeability caused by siltation. The hydraulic gradient (I_1) in this case is equal to the slope of the stream surface (S)

$$I_1 \cong S \cong \frac{\Delta H_1}{\Delta L_1} \qquad (7)$$

where $\frac{\Delta H_1}{\Delta L_1}$ is the energy or piezometric head drop per unit length in the direction of the flow, which is longitudinally along the channel in this particular case. Figure 6 also illustrates this relation.

As the flow approaches station 3, convergence and acceleration take place. The curvature of the flow provides a larger hydraulic gradient across the gravel bed than near station 2 and flow interchange is much greater. The hydraulic gradient continues to increase past station 3 until the flow reaches the riffle zone (characterized by white water in many streams). Below the riffle, pools of deeper water and low hydraulic gradient are common. An appreciable drop of water surface elevation usually occurs across a riffle and provides the large hydraulic gradients in such areas.

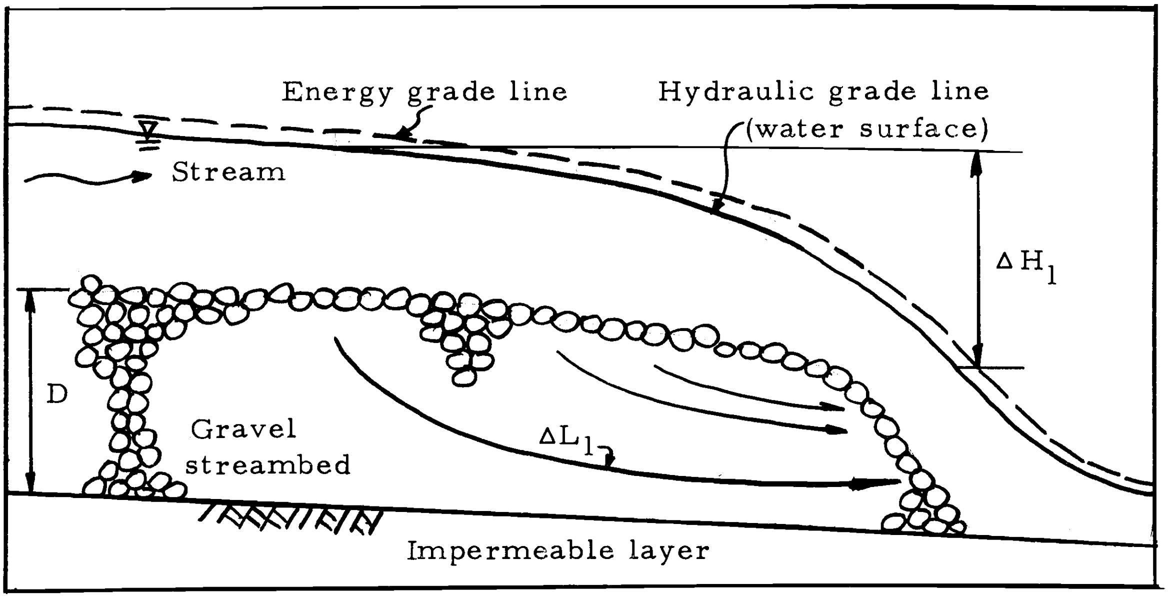


Figure 6. Longitudinal view of a "natural" gravel spawning bed and its hydraulic grade line.

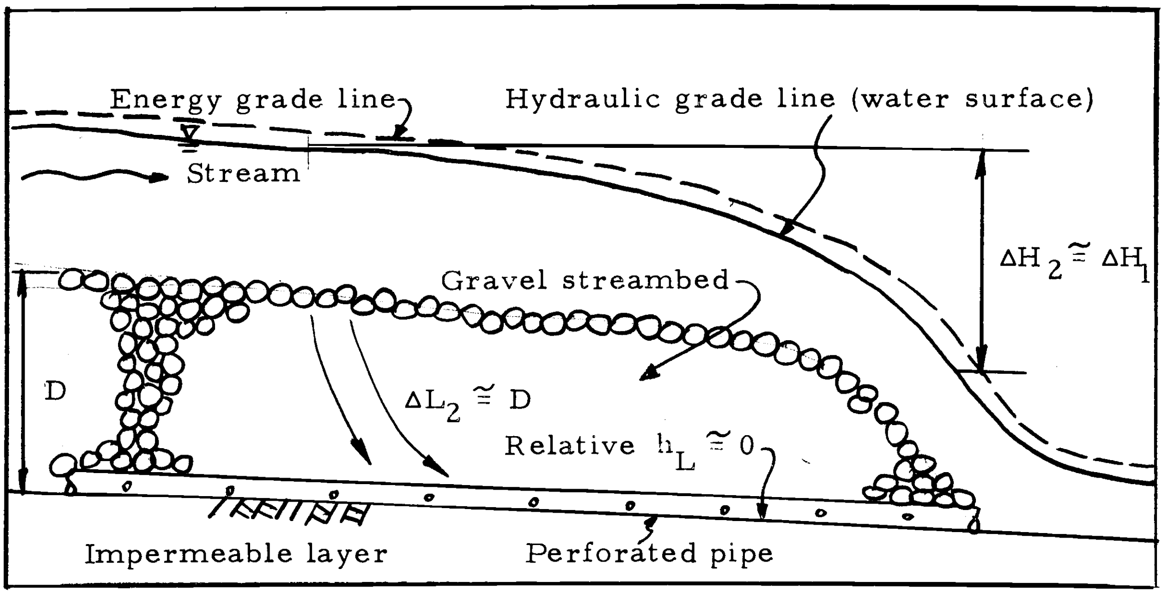


Figure 7. Longitudinal view of a gravel spawning bed with imbedded perforated pipe and its hydraulic grade line.

Effect of Imbedded Perforated Pipes

With the presence of the imbedded perforated pipes, the flow pattern will change. Infiltration into the gravel bed could be expected to be greater and to occur over a greater portion of the bed. The energy grade line is again very close to the hydraulic grade line or water surface. The hydraulic gradient is

$$I_2 = \frac{\Delta H_2}{\Delta L_2} \qquad (8)$$

where $\frac{\Delta H_2}{\Delta L_2}$ is again the piezometric head drop per unit length in the direction of the flow. But in this case, the seepage flow is more nearly vertical from the gravel surface to the imbedded perforated pipes. Head losses within the pipes are assumed to be much less than for intragravel flow. Differences in the flow paths for the ingragravel water in the absence or presence of perforated pipes are illustrated in Figures 6 and 7.

With ΔL_2 much less than ΔL_1, close to the riffle, and with ΔH_1 approximately equal to ΔH_2, a comparison of equations 7 and 8 shows that I_2 is much greater than I_1. Furthermore, from Darcy's Law ($V = KI$), with I_2 much greater than I_1, the intragravel flow is greater in the case with imbedded perforated pipes than for the case where pipes are not installed, provided the permeability is the same in both cases. If, on the other hand, the permeability is not the same, the presence of perforated pipes will allow the gravel bed to drop to a lower permeability condition and still maintain an intragravel flow similar to that in the case where perforated pipes are not installed.

Application of Darcy's Law

Permeability, as defined by Darcy's Law in an earlier section of this thesis, is the property of a porous media relating the fluid properties and the particle size, size distribution, shape, and porosity of the media. Permeability is discussed below the respect to the two types of experimental gravel beds studied, one without and the other with imbedded perforated pipes.

Without Perforated Pipes

Siltation of the gravel is not likely to be uniform with depth, as shown by Einstein (1968); voids deeper in the bed should have a relatively greater silt content. Therefore, permeability is likely to decrease with depth. This means that seepage flows should be greatest in the upper portion of the bed. Also, the intragravel flow may only travel short longitudinal distances before reappearing at the bed surface (see Figure 2 and Figure 6). Some intragravel flow should occur deeper in the bed because of the existence of an hydraulic gradient, in spite of the lower permeability. The amount of such flow would be comparatively small except near the riffle. In this particular case where no perforated pipes are present, the flow in the lower portion of the gravel bed would be limited by the greater number of voids filled by silt.

The intragravel flow along some distance L of the gravel bed may be calculated by Darcy's Law as follows:

$$V = K \frac{\Delta H}{\Delta L} \tag{9}$$

$$Q = AV = AK \frac{\Delta H}{\Delta L} \tag{10}$$

$$\cong AK \frac{\Delta H}{L} \tag{11}$$

Now

$$A = DW \tag{12}$$

therefore

$$Q_1 = \frac{\Delta H}{L} DWK \tag{13}$$

where, in the above equations,

V = apparent velocity (L/T)

W = width of the spawning bed channel (L)

A = cross sectional area of the spawning bed (L^2)

D = depth of the gravel (L)

L = average path length of the intragravel flow (L)

ΔH = drop in the water surface (L)

Q = discharge (L^3/T)

h_L = head loss (L)

$\frac{dh}{dL}$ = hydraulic gradient (L/L)

K = average permeability coefficient over the depth of the gravel bed $(\frac{L^3/T}{L^2})$

With Perforated Pipes

If perforated pipes are buried in the gravel bed, the flow path will instead consist of a distance D downward through the gravel and an additional distance along the pipe from the point of intragravel flow to the downstream end of the pipe. Since the head loss along the pipe is much less than the head loss through the gravel, the intragravel flow may be expressed by Darcy's Law as follows:

$$Q_2 = AK\frac{\Delta H}{\Delta L} \cong AK\frac{\Delta H}{D} \qquad (14)$$

$$A = LW \qquad (15)$$

$$Q_2 = LWK\frac{\Delta H}{D} \qquad (16)$$

Furthermore, comparing equations 13 and 16, one may write

$$\frac{Q_1}{Q_2} = \frac{(\Delta H/L)DWK}{(\Delta H/D)LWK} = \frac{D^2}{L^2} \qquad (17)$$

or

$$Q_2 = (\frac{L}{D})^2 Q_1 \qquad (18)$$

If it is assumed that the longitudinal distance L of intragravel flow when no pipes are present is greater than the depth D of buried pipes which may be installed in the streambed, it can be seen from equation 18 that the presence of buried pipes can materially increase the amount of intragravel flow.

A large hydraulic gradient should be created across the gravel layer by surface water carried to the perforated pipes from the upstream bed. Therefore, a significant intragravel flow may be induced due to the presence of this energy gradient. By doing so, the silt in the voids may also be "flushed" or washed into the pipes and carried downstream. This should promote a high permeability value in the intragravel area.

If the entire riffle is considered, then L becomes the longitudinal length of the riffle whereas D remains the burial depth of the pipe. Again, if head losses in the pipe are minor compared to intragravel losses of water reaching the pipe, the L/D ratio in equation 18 will be much greater than unity and the intragravel flow for a bed with perforated pipes should also be much greater than that for the unmodified bed.

From equation 18, it is understood that even at two identical-size spawning beds, the intragravel flow at the bed with imbedded perforated pipes should be considerably greater than the intragravel flow in the bed with no pipes installed. This, in turn, implies that the gravel bed with imbedded perforated pipes and with higher intragravel flow will also have higher oxygen interchange. Thus the mortality of fish eggs may be reduced by means of perforated pipes.

Permeability Variations Due to Siltation

As the silt and other fine material is carried into the river channel, a portion will tend to settle into the gravel bed and fill the void space between the gravel particles. The intragravel flow and bed permeability will therefore decrease as this void space becomes filled. The presence of the imbedded perforated pipes, however, should change this behavior by reducing the extent to which the pores become filled, due to the higher hydraulic gradient and velocity expected, as discussed earlier.

Theoretically, if silt is continually being brought into the channel, the intragravel permeability of the streambed would have an inverse relationship with time. However, it is hypothesized that although the intragravel permeability for the bed with imbedded perforated pipes may decrease, it will tend to retain a relatively higher value than for the bed where perforated pipes are absent. In both cases, the intragravel permeability would arrive at a relatively constant value as a steady state condition is reached after a long period of time. This idea is expressed in Figure 8.

Silt or organic detritus already present in the streambed,

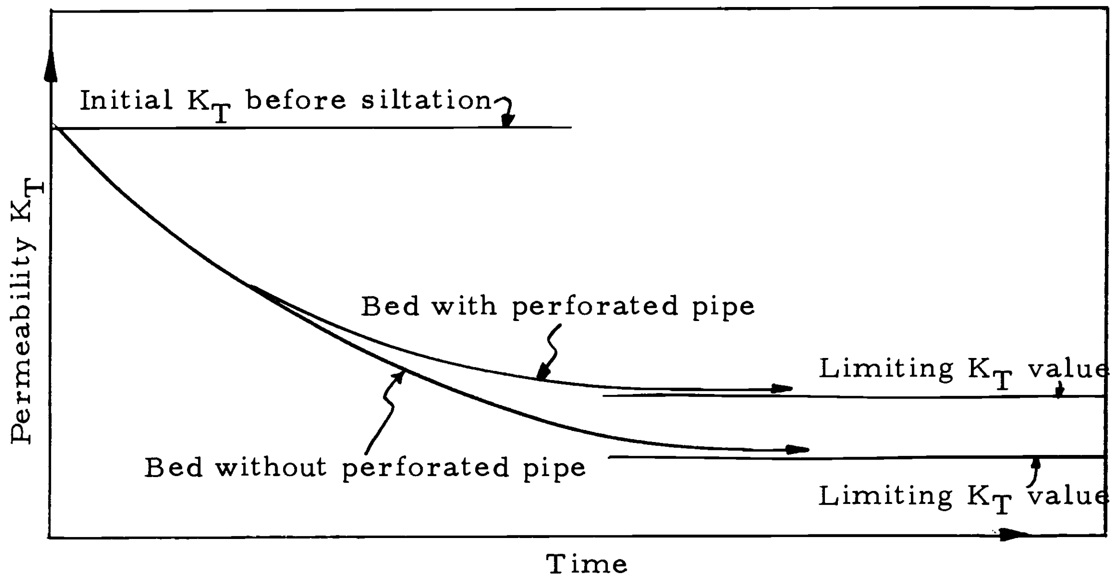


Figure 8. Hypothesized time-variation of intragravel permeability for silt steadily applied to gravel streambed.

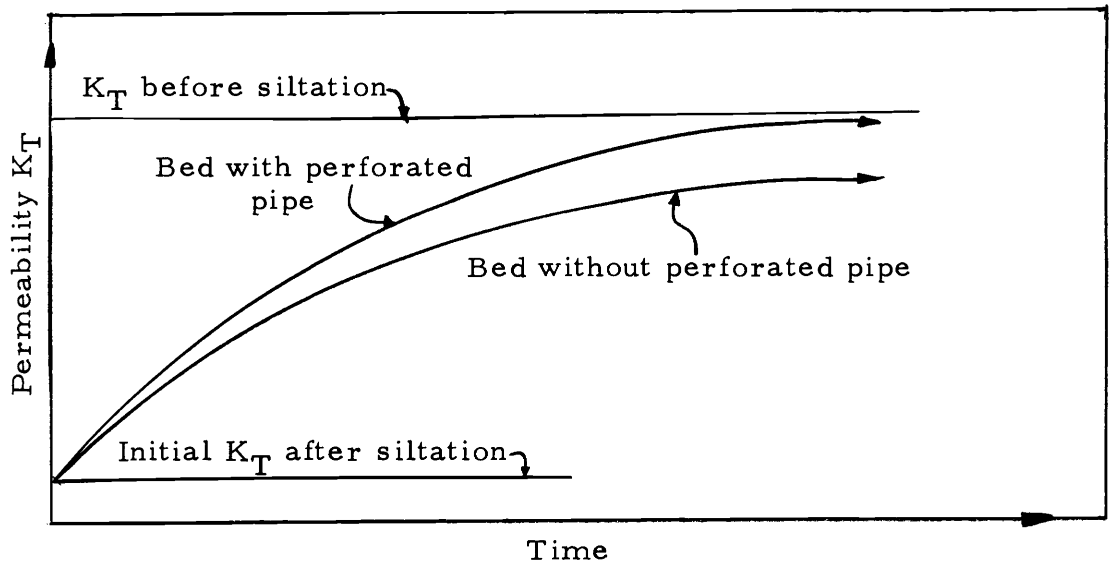


Figure 9. Hypothesized time-variation of intragravel permeability for silt removed from gravel streambed.

however, may be removed by spawning fish or by storm runoff. During the silt removal process, permeability would be expected to increase with time in both cases. In this situation, assuming that both the bed with the buried perforated pipes and the bed without any begin at the same initial permeability value, the gravel permeability for the case with imbedded pipes should attain a relatively higher final value than for the case where perforated pipes are absent, as shown in Figure 9. This is because the intragravel flow path in the former case could be expected to be shorter, the hydraulic gradient larger, and the seepage velocity greater, which would facilitate a greater degree of silt removal. If, instead, it is assumed that the bed with perforated pipes has a larger initial permeability than for the bed without pipes, the final permeability differences would be even greater than for the bed with buried pipes. This latter assumption appears to be more nearly typical of a real situation.

The supply of oxygenated water that would reach buried fish eggs is directly dependent on gravel permeability, as already stated. Therefore, with a given river gradient, the intragravel permeability will indirectly reflect the relative dissolved oxygen level in the gravel bed. Consequently, it is reasonable to expect that buried perforated pipes would have a beneficial effect upon intragravel dissolved oxygen levels.

EXPERIMENTAL FACILITIES AND PROCEDURES

In this study a 28-foot laboratory channel was used to simulate a river channel. A selected size of river gravel was placed in the channel to simulate the natural spawning gravel bed.

Laboratory Stream

General Features

A 28-foot long wooden channel (referred to as "wood channel" throughout the text) was used to simulate the river channel. The channel was 3 feet wide and was made with cedar planks 1-1/2 inches thick.

The channel was calked with rubber sealant to prevent leaks. A quantity of pea gravel (nominally 3/8 - 3/4 inch in size) was placed along a portion of the wooden channel to simulate the spawning bed. The gravel bed was laid with dimensions of 14 feet long by 2.8 feet wide by 1 foot deep.

Down the center of the gravel bed, an 18-foot long by 1-foot high plank was installed parallel to the channel as a dividing wall. By doing so, two separate beds resulted.

Two perforated pipes of 2-inch diameter and 16-feet in total length were laid parallel to each other on one side of the dividing wall. The pipe diameter was selected on the basis of commercial availability and size of the wood channel. These pipes were placed 5 inches apart, center to center. They were installed before gravel was added, such that the pipes lay flat at the bottom of the bed and the slope of the pipes was the same as for the wood channel floor. The perforated pipes used were 8 feet in section length with four rows of 3/8-inch holes, those in each row spaced 3 inches apart along the full length of the pipe. The holes in adjacent rows were staggered so as to give 1-1/2 inch spacing. The pipes were installed such that all the holes were facing upward. The laboratory stream is shown in Figure 10.

Having two gravel beds running parallel, one with perforated pipes installed and one without, two separate sets of data may be obtained in one single experimental trial. Thus the different results put forth by the two beds may be used to indicate the effectiveness of the perforated pipes that were installed.

An outer concrete channel approximately 32 feet long by 5 feet wide by 4-1/2 feet deep (referred to as "main channel" throughout the text) was also used as part of the facilities for this study. This channel has a rectangular shape with end walls as well as side walls. The wood channel was supported horizontally 27 inches above the floor of the main channel by several wooden horses and jacks. The main channel served as a catch basin. A 6-inch closable drain was located at the downstream end of the main channel to permit occasional drainage. A 12-inch tall cylinder was fitted above the drain such that

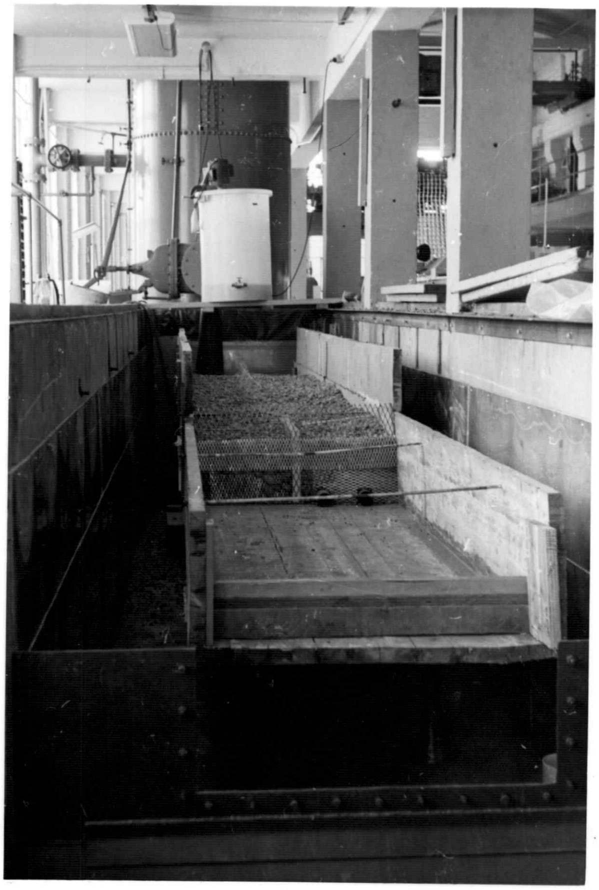


Figure 10. Laboratory model of the stream channel.

any sand or small gravel would be caught and retained in the main channel without flushing down to the reservoir or clogging up the system. Normally, the flow from the channel would pass over a weir plate into a weighing tank for discharge measurement. A sketch of the two channels is given in Figure 11.

A 2-inch thick marine plywood board was installed as a partition at the upstream end of the main channel. The board was cut in a "U" shape such that a portion of the wood channel could be inserted in it and obtain support. The resulting head tank dimensions were 4-1/2 feet by 5 feet by 4-1/2 feet. Its purpose was to serve as a supply storage and mixing tank for the system. Curved aluminum baffles were built at the mouth of the wood channel to attempt to obtain an evenly distributed flow from the head tank (Figure 12).

Water Supply

Since the model was located about 20 feet above the laboratory reservoir, an 18-inch propeller pump was used to provide water to the experimental channel. The water was pumped through 8-inch and 6-inch pipes to a 20-foot tall water tank and then to the head reservoir by means of a 12-inch fitting (partially shown in Figure 13). In doing so, a relatively constant head was maintained throughout the experiment. By adjusting the valve, high flows or low flows could also be maintained in a consistent manner.

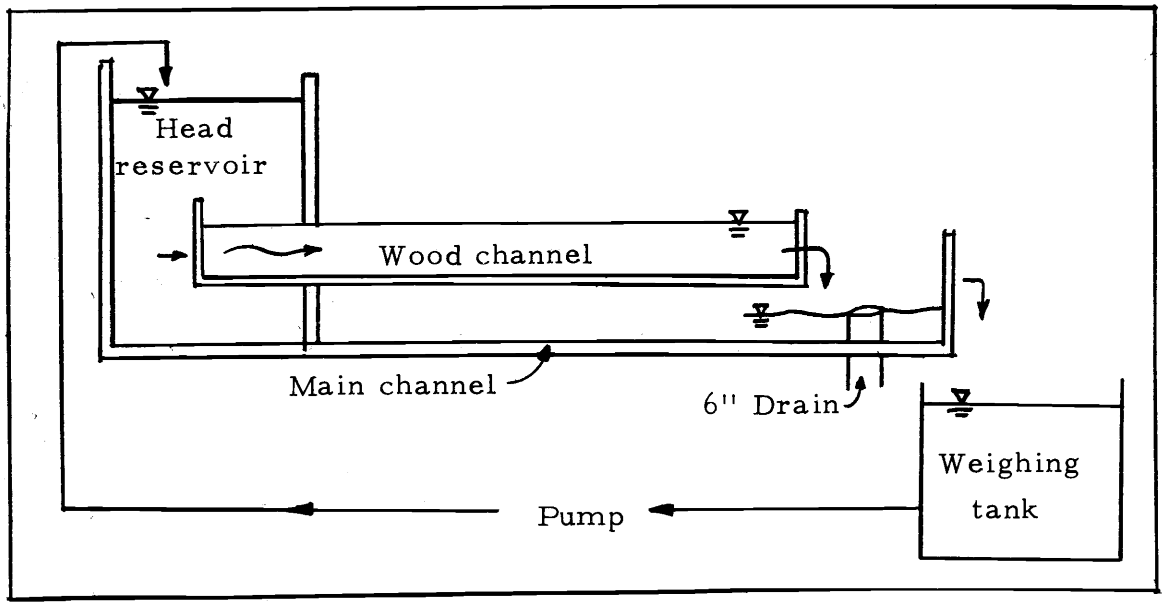


Figure 11. Flow diagram of the experimental system.

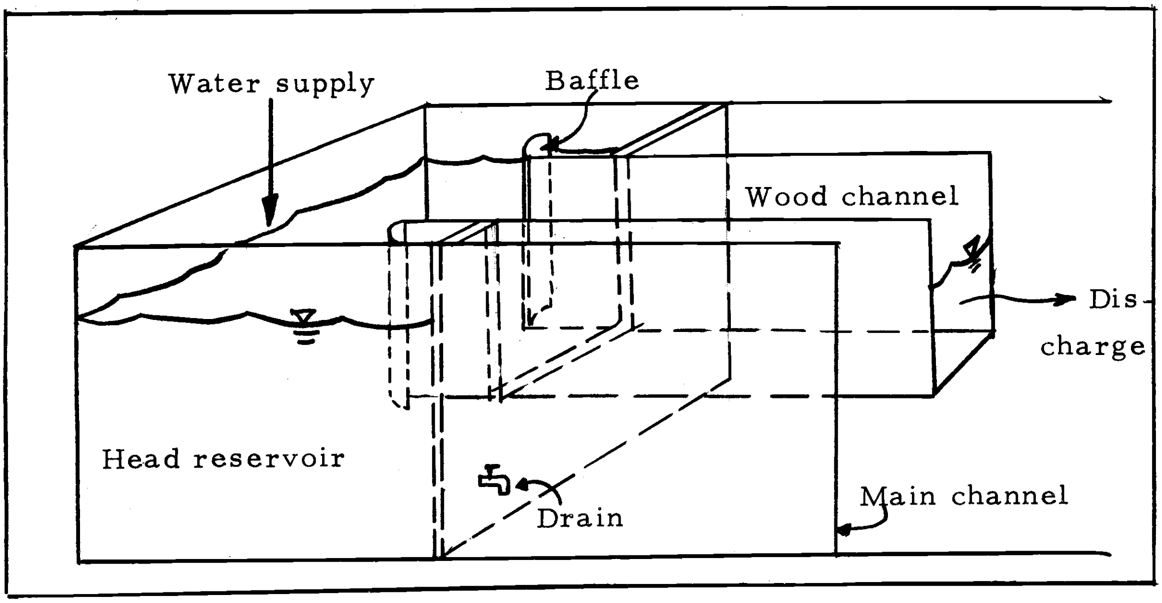


Figure 12. The head reservoir of the experimental system.

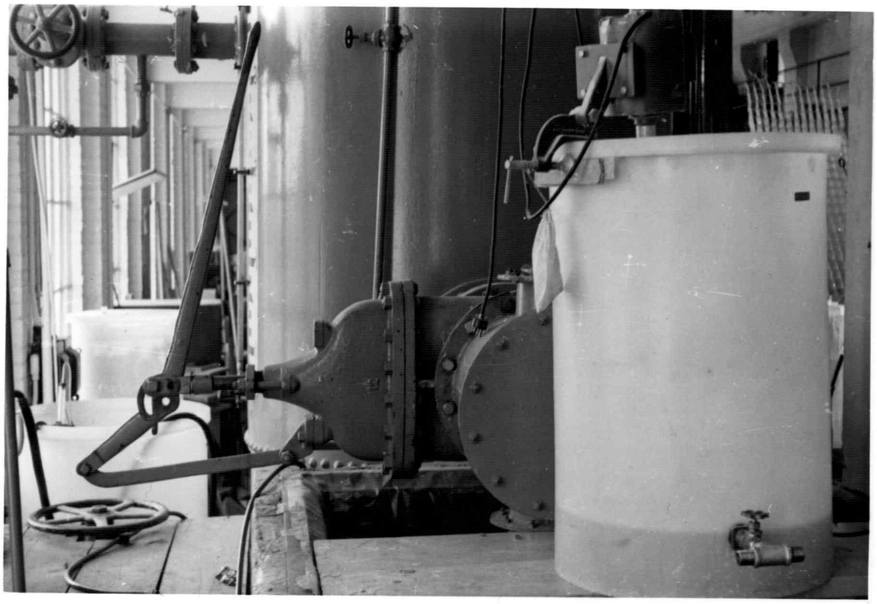


Figure 13. Water supply system.

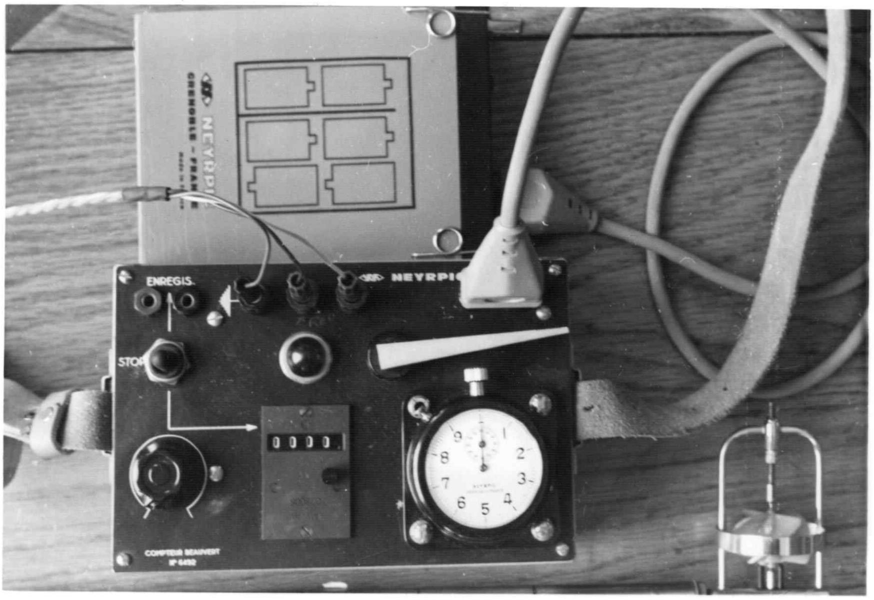


Figure 14. Beauvert midget current meter.

Streambed Gravel and Siltation Material

In this study the writer tried to simulate a natural spawning bed and to study the flow conditions within the gravel bed which are critical to the mortality of fish eggs. Since salmon eggs are typically placed and covered with from 3 to 15 inches of gravel, 12 inches of gravel depth was arbitrarily selected.

The gravel chosen for the experiment to simulate the spawning bed is described as "pea gravel" and has a nominal commercial size range of 3/8 to 3/4 inch. The actual particle size distribution is discussed in a later section and shown in Table 1 and Figure 19. The gravel was initially well graded and clean. Therefore, no dirt or fines were present in the bed when the experiment was started.

The writer selected the pea gravel based on the typical gravel sizes observed in natural spawning beds, but excluding the largest of of these gravels due to limitations in the size of the laboratory stream. In this study, the composition of the pea gravel is not necessarily the same as used in any other studies of a similar type. Even in a natural spawning bed in a stream it is not uncommon for the gravel composition to be different from one location to another. Different composition of bed material will certainly have its uniqueness in its response to different flow and silt conditions. Different siltation patterns are likely and will undoubtedly complicate the evaluation of results.

However, the fundamental thesis of the experiments--that buried perforated pipes can improve intragravel water quality--should not be in jeopardy.

The material selected for streambed siltation studies consisted of very fine concrete sand and white sand. Characteristics of its particle size distribution are given in connection with discussion in a later section and are shown in Table 1, as already noted.

The quantity of fine material applied to the gravel streambed was determined so as to conform with observations for natural stream siltation by McNeil and Ahnell, as reported in the literature review. Hence, the weight of fine sediment in the total weight of bed material was adjusted to be about 8-17% by application of a sufficient amount of fines in the suspension slurry.

Hydraulic Conditions for Channel

Streamflows ranging from 0.97 to 1.66 cubic feet per second (cfs) were used in this study. The discharge was limited both by the size and freeboard of the wood channel and by the operating capacity of the supply pump. Discharges are called "low flow rate" and "high flow rate" in later sections of this report to distinguish at which end of the range of streamflows the tests were run.

The average flow depths over the gravel bed ranged from 2 to 3 inches and were limited as noted above by the freeboard remaining after 12 inches of gravel had been placed in the wood channel. The velocities varied from 1.4 to 2.0 fps at the water surface, depending upon the flow rate. The depths and velocities were selected based upon assumed desirable spawning conditions as reported in the literature review.

Measurement Equipment and Procedures

Discharge Measurement and Average Velocity

The channel flow discharged into a weighing tank for measurement of the flow rate, as shown in Figure 11. The total weight of the water collected over a time period was recorded. By applying the water's specific weight at the ambient temperature, the discharge (Q), in cfs, was then calculated. Furthermore, by measuring the cross-sectional area of flow (A), in square feet, at different points over the gravel in the wood channel and using the continuity equation:

$$Q = AV \tag{19}$$

the average flow velocity over the gravel (V), in fps, could be calculated.

Actual Velocity Measurement

Beauvert Midget Current Meter. This French meter, manufactured by Neyrpic, Inc., was used throughout the study to measure water flow velocity. The important features of this current meter are its size and its operating principles. The propeller is 1-1/2 inch in diameter and has four pales. Therefore, because of its small size, it is particularly recommended for use when the flow velocity is low and the wetted cross-section small. The operating range of velocities is 0.4 inch per second to 40 inches per second. The current meter is operated with a frictionless signal mechanism. It has two fixed electrodes, arranged in such a way that rotation of the propeller periodically varies the electrical capacitance of the intermediate liquid medium, without any mechanical contact. The number of propeller turns is counted by a separate electronic unit that detects the capacitance variations. Figure 14 shows the current meter, the data recorder, and accessories.

Paper Dots Method. In order to check the measurements made by the Midget current meter at low velocities, paper dots were used. The time required by the paper dots to travel a known distance was recorded. By this, small velocities up to one tenth of a foot per second could be verified:

$$V = \frac{L}{T} \tag{20}$$

V = velocity of the paper dots flowing on top of the water (assume to be approximately equal to the average velocity of the flow)

L = known distance between two stations at the channel

T = time required by the paper dots to travel the distance L.

Standpipes

The standpipes which have been utilized in this study are basically lengths of pipe perforated at one end. When such a pipe is placed vertically in a streambed, subsurface water flows through its lower end. The top of the pipe, extending above the surface of the stream, provides access to the intragravel water. The standpipes used in this study (see Figure 15) were 26 inches in length and made from aluminum pipe having an inside diameter of 1-3/8 inches. Forty eight 1/8-inch diameter holes evenly spaced at the lower end of the pipe allow water to flow into or through the standpipe. Vertical grooves 1/16-inch wide by 1/16-inch deep in the outside of the pipe extend between the holes to reduce hole blocking by pebbles.

Permeability Measurement

Suction Assembly. The suction gear shown in Figure 16 is essentially that described by Pollard (1955) and Terhune (1957). Terhune's description follows: The suction tip is of 5/16-inch (outside diameter) copper tubing and has three thin centering lugs near its lower end. A heavy-walled rubber tube with an inner diameter of 1/4 inch connects the suction tip to the brass fitting (1/4-inch inside diameter) at the top of the 500 milliliter (ml) plastic cylinder,

Figure 15. Standpipe.

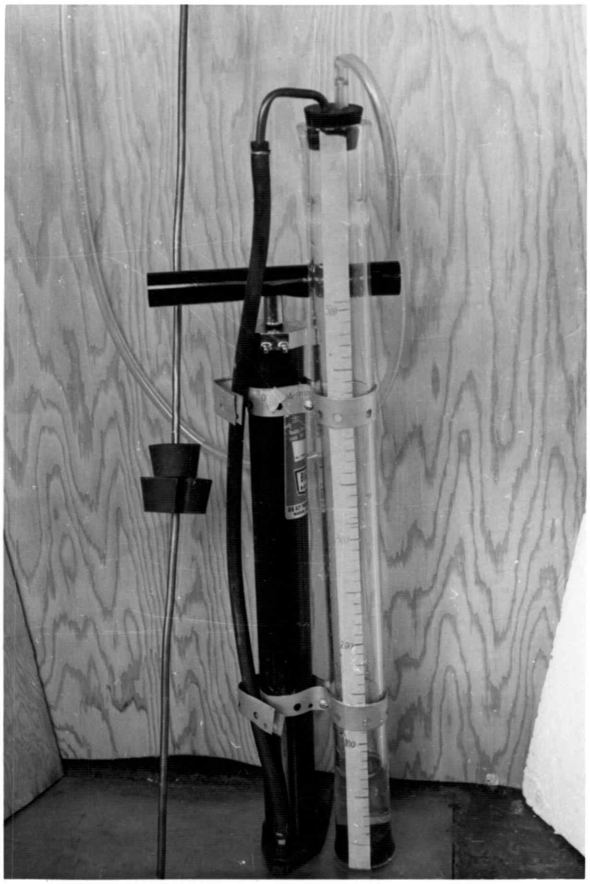


Figure 16. Permeability pump.

graduated in 10 ml, which is attached to the side of the pump. A rubber stopper closes the lower end of the cylinder, making it easy to empty. A smaller rubber tube leads from a ball valve at the top of the cylinder to the pump. The pump is a tire pump with a reversed piston. The pump should be capable of attaining and holding a good vacuum. The metal piston type used here will readily give a vacuum of about 27 inches of mercury. A sliding marker on the 5/16-inch copper tubing holds the tip at any desired depth by resting on top of the standpipe. Two 3-inch strips of thin flat spring steel bolted together at the ends with the copper tubing between them serve adequately. They should hold the tubing firmly yet slide on it smoothly. A 1 inch spacer completes the suction gear. This is a 1-inch of 1-1/4-inch pipe open at one side.

Measurement of Permeability. Terhune (1957) describes the permeability measurement as follows: Two men are required, one to pump while the other manipulates the suction tip and stopwatch. Place the 1-inch spacer on top of the standpipe. Introduce the copper suction tube into the standpipe so that its tip is slightly above the water level while the sliding marker rests across the top of the spacer. Start pumping. Slowly and carefully slide the suction tip downward until it touches the water surface. This point is indicated by a "slurping" sound. The first "slurp" should be used as the surface indication. Stop pumping. Remove the spacer and lower the suction tube till the marker rests on top of the standpipe without allowing the marker to move on the tube. Empty the water receiver.

Pinch off the rubber tube and by several quick pump strokes obtain a full vacuum. Continue pumping furiously. Simultaneously release the rubber tube and start the stopwatch. Before the receiver overflows, simultaneously stop the watch and raise the suction tip out of the water. Stop pumping. Record the volume of water collected and time interval. Measure and record the temperature. Calculate the inflow in ml/sec and read the permeability at the observed temperature from the calibration curve.

The principle involved here is that the rate of inflow to the standpipe at a fixed (1 inch) head is a measure of the permeability of the gravel. One inch was chosen as large enough to be obtainable with sufficient accuracy but not large enough to cause the fines to be washed from the gravel. By starting with a full vacuum the suction tip quickly lowers the water level inside the pipe by 1 inch and then by alternately sucking air and water maintains that level. Removing the tip from the water at the end of the timed interval allows water in the tubing to reach the receiver but prevents residual vacuum in the receiver from withdrawing more water from the standpipe.

Unless a sucking sound is heard throughout the timed interval the pump is not removing water fast enough to maintain the 1 inch head.

In this case it can only be said that the permeability is higher than the value indicated by the pumping rate. Slightly different results may be obtained with different suction gear because of the difference in time needed to remove the first inch (25 ml) of water. If, however, the pump is a good one and the 1/4-inch inner diameter of the tubing and fittings is maintained the time to remove this 25 ml will be only about 1/4 second and any error in this may be neglected.

The laboratory measurement of permeability is illustrated in Figure 17.

Thermometer

Permeability varies inversely with the kinematic viscosity of the water, which in turn is a function of temperature of the water. Therefore, temperature of the water was recorded. A standard laboratory thermometer was used to accomplish this. It is noted here that the temperature fluctuation during the experimental tests was quite minor, so that corrections to the permeabilities were considered negligible and therefore not made.

Sand Slurry Feeding Unit

Fine sand was mixed with water as a slurry in a 50 gallon plastic barrel. The resulting suspension was applied to the system in the latter part of the experiment in order to create a siltation problem

Figure 17. Measuring permeability
at the laboratory model.

such as often occurs in the natural stream. The slurry was then fed into the channel from a manifold made of a section of perforated tube, such that approximately equal amounts of silt would be evenly distributed at the upper end of the two different beds. A diagram of this apparatus is shown in Figure 18.

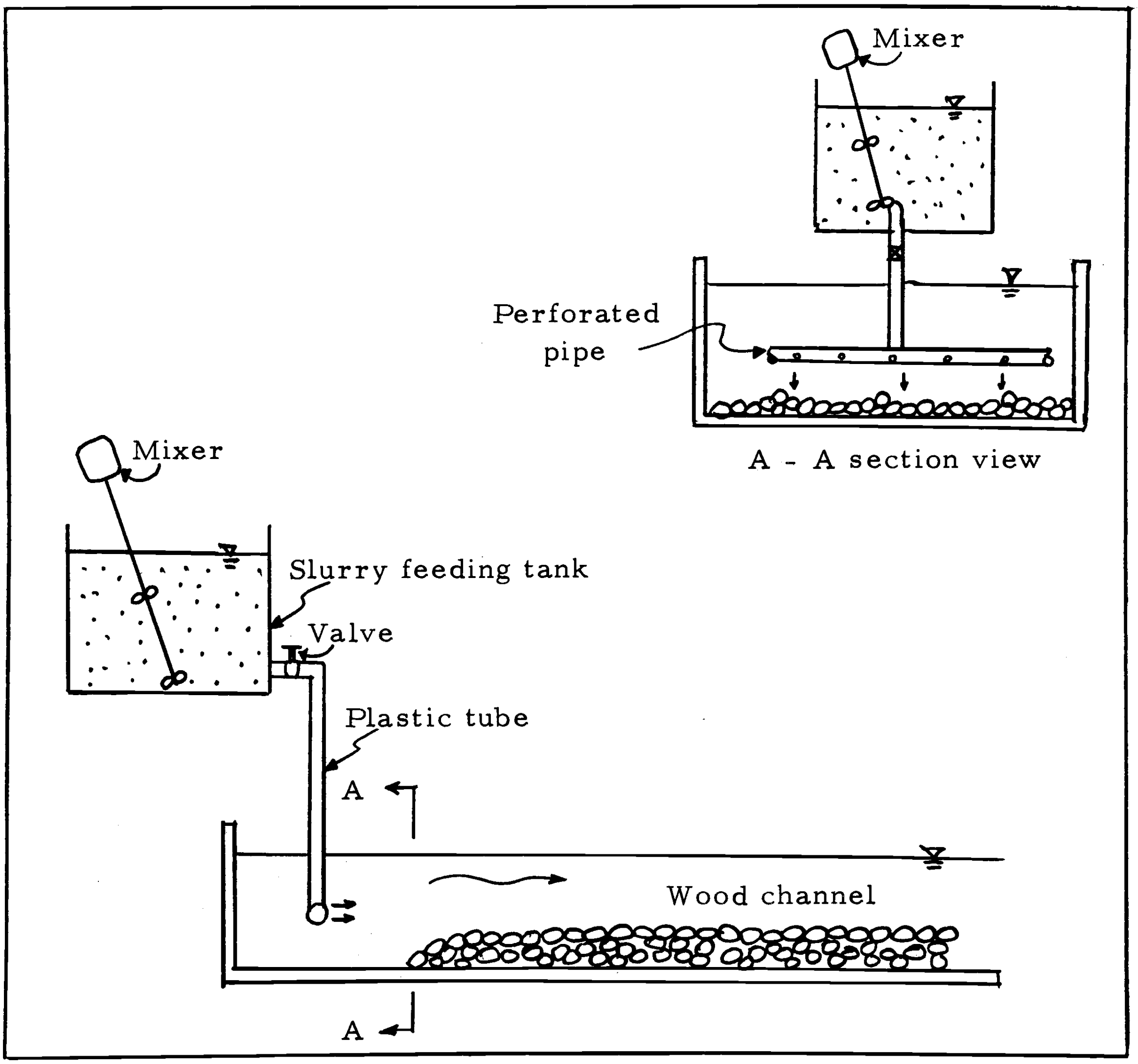


Figure 18. Sand slurry feeding system.

EXPERIMENTAL RESULTS AND DISCUSSION

Tests Performed

The experiments on streambed permeability involved the following variables: location along the gravel bed (three stations); presence of buried perforated pipes (no pipes; pipes); siltation condition (before siltation; after siltation); streamflow after siltation (low flow; high flow). The three stations were located along the gravel bed near the upstream edge, in the central portion of the bed, and the downstream edge, as shown on Figure 5. The bed was divided down the center so that buried pipes were present in half of the bed only, as shown in Figure 10. Bed permeabilities were measured with both low and high flows before sand was added to the bed. The sand was then added under low-flow conditions. After siltation, the permeability was remeasured. Additional permeability measurements were made after the flow over the silted bed had been increased to a high-flow condition.

Size Gradations for Bed and Fine Sand

The particle size distribution of the streambed gravel ("pea gravel") nominally falls within the range of 3/8-inch to 3/4-inch. The measured particle size distribution, based upon sieve analysis, is given in Table 1. It can be seen that approximately 75% of the bed

Table 1. Grain size distribution of the gravel, concrete sand, and white sand used in the tests.

Sieve size*	Weight retained (lb)	Percent retained	Percent finer
	Gravel		
3/4" (18.85 mm)	0.50	1.90	98.10
3/8" (9.52)	19.75	74.79	23.31
# 3 (6.35)	4.90	18.56	4.75
# 4 (4.76)	1.10	4.16	0.59
# 8 (2.38)	0.10	0.38	0.21
#16 (1.19)	0.05	0.18	0.03
pan	0.01	0.03	--
	26.41	100.00	
	Concrete Sand		
# 8 (2.38 mm)	0.05	0.50	99.50
#16 (1.19)	2.76	27.00	72.50
#30 (0.590)	1.15	11.30	61.20
#40 (0.420)	2.52	24.68	36.52
#50 (0.297)	1.27	12.50	24.02
#80 (0.177)	2.10	20.59	3.43
#100 (0.149)	0.20	1.96	1.47
pan	0.15	1.47	--
	10.20	100.00	
	White Sand		
#30 (0.590 mm)	0.01	0.12	99.88
#40 (0.420)	1.80	22.96	76.92
#50 (0.297)	2.84	36.24	40.68
#80 (0.177)	2.89	36.87	3.81
#100 (0.149)	0.15	1.91	1.90
#200 (0.074)	0.14	1.78	0.12
pan	0.01	0.12	--
	7.84	100.00	

*Sieve numbers are for U.S. standard series.

material actually fell within that range and that practically all of the bed material was coarser than about 2 mm.

The two types of fine materials used to cause siltation of the streambed are commercially designated as "concrete sand" and "white sand". Their grain size distributions are given in Table 1. As shown by the data, the concrete sand is considerably coarser than the white sand (e.g., 40% of the concrete sand is coarser than 0.59 mm, whereas almost all of the white sand is smaller than 0.59 mm).

The particle size distributions of the gravel and fine sands are shown in Figure 19. Again, it is evident that the concrete sand is coarser than the white sand, whereas both are much finer than the pea gravel used for the streambed. Hence, they would appear initially to be suitable for simulating streambed siltation.

Additional measures of the grain size distribution are shown in Table 2. Also, ratios between sizes for the gravel and for each of the fine materials are given for use in checking the filter criteria of Sherard (discussed in the literature review).

In order to select the appropriate particle size of fine material which would not penetrate through layers of coarser particles, Sherard suggests the D_{15} of the bed material should be at least five times the D_{15} of the fine particles and the D_{15} of the bed material should not be more than five times the D_{85} of the fine particles.

The concrete sand which was first used in these experiments has

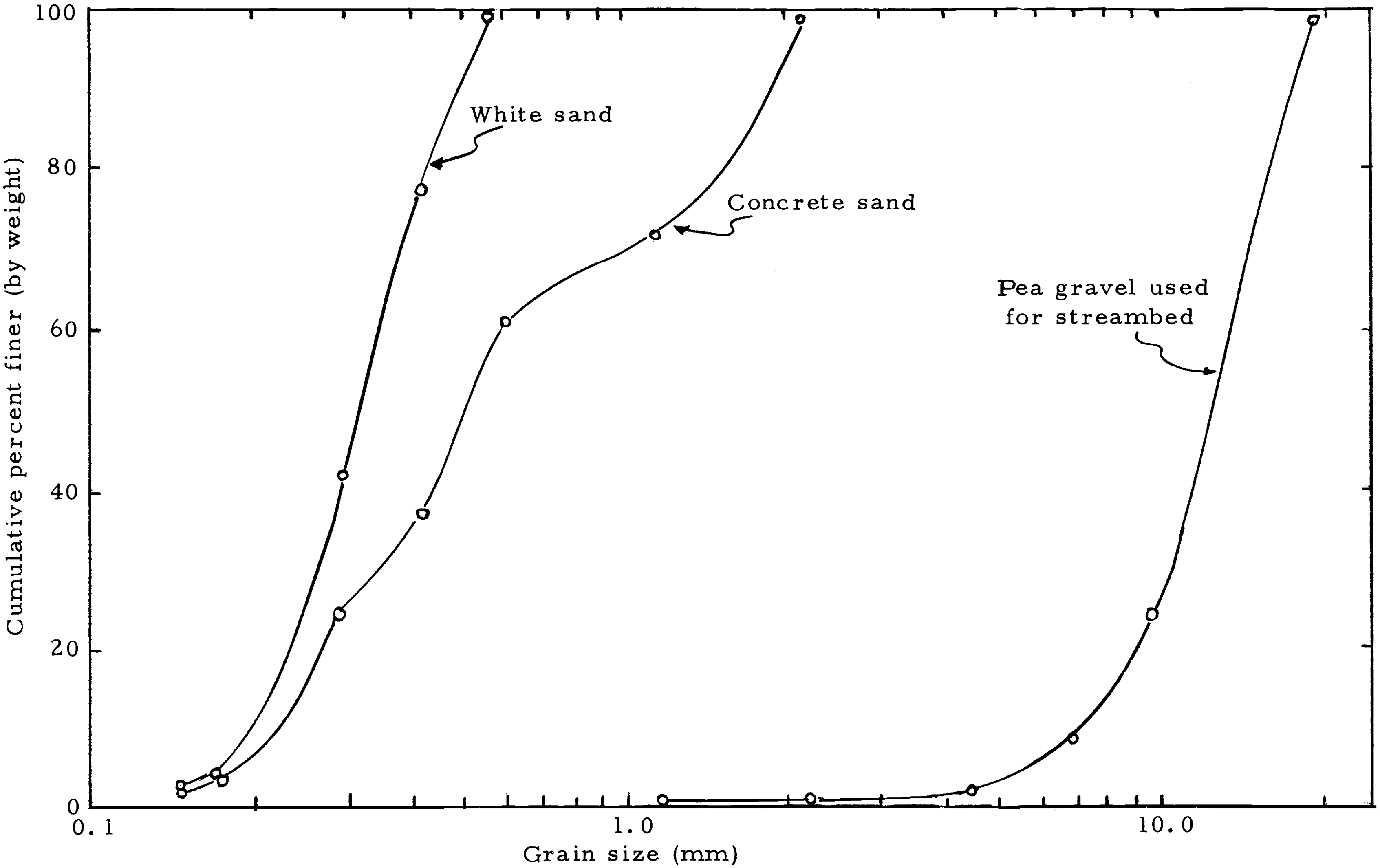


Figure 19. Grain size distribution for gravel and fine sands.

Table 2. Comparison of size distribution for the bed and fine sediments.

Representative size	Equivalent particle diameter (mm)		
	Gravel	Concrete sand	White sand
D_{10}	7.4	0.21	0.19
D_{15}	8.4	0.23	0.21
D_{50}	12.8	0.52	0.32
D_{85}	17.5	1.80	0.45

Ratios[1]:

Concrete sand

$$\frac{D_{15}G}{D_{15}S} = \frac{8.4}{0.25} = 36.5 > 5.0$$

$$\frac{D_{15}G}{D_{85}S} = \frac{8.4}{1.8} = 4.6 < 5.0$$

White sand

$$\frac{D_{15}G}{D_{15}WS} = \frac{8.4}{0.21} = 40.0 > 5.0$$

$$\frac{D_{15}G}{D_{85}WS} = \frac{8.4}{0.45} = 18.2 > 5.0$$

[1]The symbols G, S, and WS stand for gravel, concrete sand, and white sand, respectively.

a D_{15} of 0.23 mm and D_{85} of 1.8 mm. The ratios of these figures with the D_{15} of the bed material used show that it would satisfy the filter criteria (Table 2). In fact, most of the concrete sand was actually found to be deposited on the surface or within only the top thin layer (approximately 1 inch) of the gravel bed, thus leaving the rest of the gravel bed undisturbed. This occurred regardless of the presence of buried perforated pipes. Hence use of this concrete sand was abandoned and a finer sand was instead used after removal of the concrete sand.

The white sand, with a D_{15} equal to 0.21 mm and a D_{85} equal to 0.45 mm, was then applied to the same gravel bed. The ratios between these sizes and the D_{15} size for the gravel show that the second filter criteria cited was violated, that is to say, the D_{15} size of the bed material is more than five times the D_{85} size of the white sand (Table 2). This characteristic enabled the white sand to successfully penetrate into this gravel bed, as shown by the experiments.

Porosity of Streambed

Calculated Porosity for Clean Bed

Porosity, be definition, is the ratio of the volume of interstices of a material (volume occupied by water, in this case) to the volume of its mass (volume occupied by water plus gravel). Since the porosity reflects the availability of space among gravel particles (intragravel voids), it is therefore one of the major factors affecting the intragravel permeability. Porosity may be given by:

$$\text{Porosity} = \frac{\text{Volume of water}}{\text{Volume of water} + \text{Volume of gravel}} \quad (21)$$

Porosity may be measured by either a filling method or a draining method. The draining method was used in this experiment. It involves adding water to a container with a known volume which is packed with the particles being measured. The volume of water necessary to fill the container and thus all of the voids within the gravel is then determined. The ratio of the volume of water added and the total volume of the container then gives the porosity of the gravel tested. Substituting measurement values obtained from a representative sample of the streambed:

$$\text{Porosity} = \frac{0.086\ \text{ft}^3}{0.086\ \text{ft}^3 + 0.248\ \text{ft}^3} = 0.257$$

Prediction of Permeability from Porosity

Pollard (1955) has developed a relationship between porosity and premeability for a certain range of the gravel sizes which is shown in Figure 20. The use of the filling or draining method to measure porosity is shown to cause a slight difference in the value of porosity and its relationship to permeability.

With a porosity value of 0.257, as obtained and shown

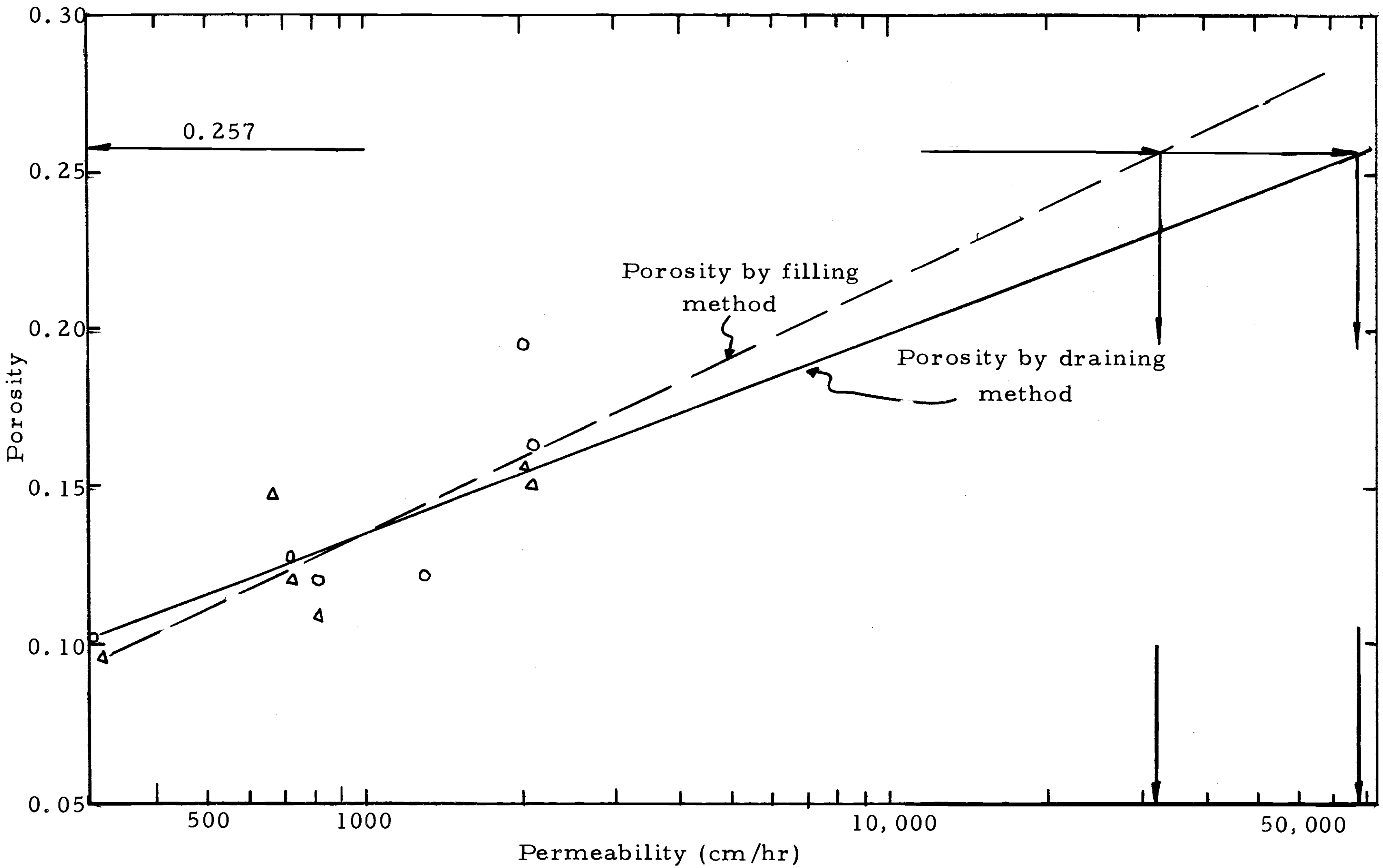


Figure 20. Prediction of permeability from porosity based on Pollard's data.

previously, use of Figure 20 gives a range of permeability value from 31,000 cm/hour to 74,000 cm/hour, according to Pollard's curves. The experimental results given later in this chapter show that the measured intragravel permeability did actually fall within this permeability range. No porosity was measured for the streambed after fine sand had mixed with the gravel. However, the intragravel permeabilities measured after the fine materials were applied would not be expected to fall into this range since the porosity value must decrease due to the presence of the fine particles in the previously unoccupied voids.

Analysis of Observed Permeabilities

Three intragravel permeability measurement stations were established on each of the gravel beds (that with and that without imbedded perforated pipes). The stations were located 2 feet, 8 feet, and 14 feet from the upstream end of the gravel bed (Figure 21). Station 1 for the bed without pipes was side-by-side with station 1 for the bed with imbedded pipes, as was true for stations 2 and 3. A total of six measuring stations were thus established for the system. Standpipes were inserted into the gravel bed at these six stations, penetrating to the bottom of the bed.

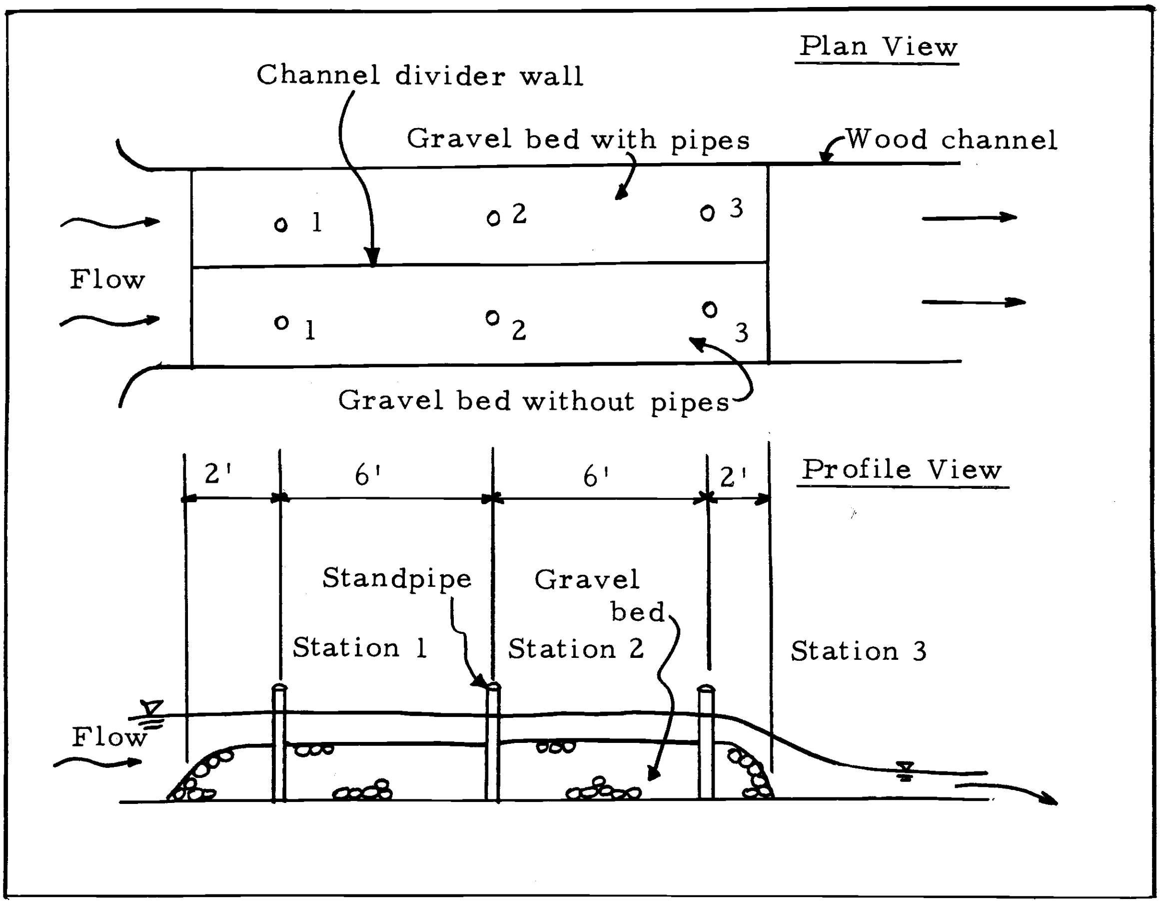


Figure 21. Location of the permeability measurement stations.

Data

Measurements of permeability as a function of the parameters described earlier were made at the six stations during the experiments. The data are summarized in Table 3.

Analysis of Data

Due to the limited size of the laboratory model, only a 12-inch depth of gravel was used. Any shallower gravel depth was not considered desirable in simulating at full scale a natural spawning area. Similarly, because of the limited freeboard remaining in the model after the gravel bed was placed, only a shallow water depth could be maintained. The significance of findings in the study, however, should remain unchanged in spite of these testing restrictions.

The flow depths over the gravel were typically 0.2 to 0.33 feet, except for the shallower accelerating flow near station 3. With the limitation on the water depth over the gravel bed, the flow discharge was adjusted so that the velocity developed over the gravel bed would fall within the range of a typical spawning velocity, typically between 1.5 fps and 2 fps. In this study, the flow velocity over the gravel bed ranged from 1.3 to 2.6 fps.

The city water supply was used in this study. Therefore, generally constant water temperatures were experienced. A

Table 3. Observed permeabilities, sand quantities, and related hydraulic data.

Gravel depth (ft)	Water depth (ft)	Velocity (ft/sec)	Water temp. (°C)	Applied sand (lb)	Permeabilities (cm/hr) with pipes	Permeabilities (cm/hr) without pipes
			Station 1			
1.0	0.25	1.4	19	0	52,000	55,000
	0.25	1.5	18	0	54,000	52,000
	0.22	1.3	17.6	400	40,000	2,000
	0.23	1.4	18	400	40,000	2,500
	0.33	1.7	19	0	70,000	50,000
	0.34	1.6	19	0	65,000	50,000
	0.31	1.7	18	400	50,000	3,000
	0.32	1.8	18	400	48,000	2,900
			Station 2			
1.0	0.21	1.5	19	0	70,000	70,000
	0.20	1.4	18	0	65,000	70,000
	0.18	1.6	17.6	400	40,000	1,300
	0.19	1.5	18	400	40,000	1,500
	0.27	2.0	19	0	68,000	68,000
	0.26	2.1	19	0	70,000	68,000
	0.25	1.9	18	400	42,000	1,800
	0.25	2.0	18	400	41,000	1,700
			Station 3			
1.0	0.08	1.9	19	0	70,000	70,000
	0.08	1.9	18	0	68,000	65,000
	0.10	1.8	18	400	40,000	28,000
	0.11	1.9	18	400	38,000	25,000
	0.15	2.3	19	0	70,000	68,000
	0.15	2.4	19	0	65,000	60,000
	0.18	2.4	18	400	45,000	30,000
	0.18	2.6	18	400	48,000	32,000

fluctuation from 17.6 to 19°C was considered insignificant in affecting the water viscosity and, hence, the intragravel permeability values. For this reason, no viscosity correction to the permeability values was attempted in this experiment.

After the concrete sand had been found unsatisfactory in achieving the goals of this study, both by Sherard's theory and by actual application to the laboratory model, the gravel bed was cleaned. This was done by removing the top, silted portion of the bed material and replacing it with clean gravel. In the process of cleaning the bed, some small amount of concrete sand undoubtedly settled into the undisturbed portion of the bed. However, care was taken to keep the presence of the concrete sand to minimum. White sand in slurry was then gradually applied to the gravel bed until a significant drop in intragravel permeability was noted by frequent check. This occurred after 400 pounds of white sand had been applied. No official intragravel permeability measurements were made during the course of the white sand application. Nor was any attempt made to apply more sand after 400 pounds of white sand were added, since the anticipated results of this study were already indicated by the relative flows and permeabilities for the two beds.

Before any fine sand was added to the system, intragravel permeability was measured under low and high flow conditions for the two beds. As expected, no significant difference in permeability was noted between the two beds, since the beds were considered to be clean and free of any fine particles within the gravel voids and hence identical in character; the presence of the imbedded perforated pipes did not have any effect on the high intragravel permeability. Slightly smaller intragravel permeability values were noted at station 1 for both beds than at the other stations. This may have been due to the presence of some concrete sand which still remained in the gravel after the system was carefully cleaned. The initial bed permeabilities are shown in Figure 22 for low flow and high flow conditions.

After 400 pounds of white sand were applied to the system, a significant drop in intragravel permeability was noted over the streambed. This phenomenon was especially emphasized in the bed with no perforated pipes. For the bed with buried pipes, a definite drop was also noted, even though not as pronounced as in the bed with no pipes. Permeability variations along each stream channel were also noted. Final permeabilities are shown in Figure 22. Trends with time at each station can be seen in Figure 23.

Due to the nearness of measuring station 3 to the riffle area, the permeability there after fine material had settled into the bed was found to be much higher than at the upstream and middle stations. This observation shows that the high intragravel flows experienced near the riffle due to flow curvature are important in minimizing siltation of the gravel bed there. Numerous field observations by others support this.

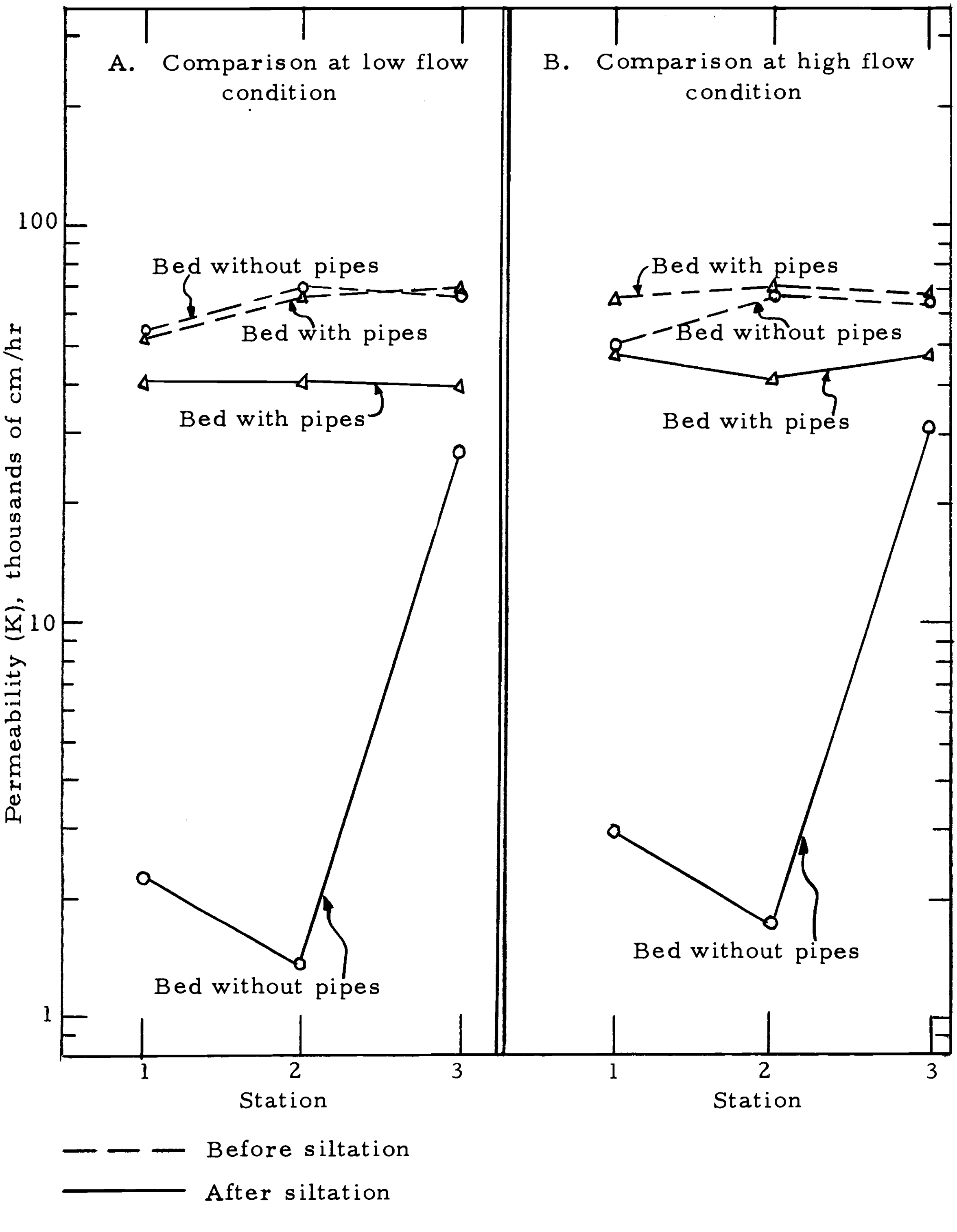


Figure 22. Observed permeabilities of gravel beds.

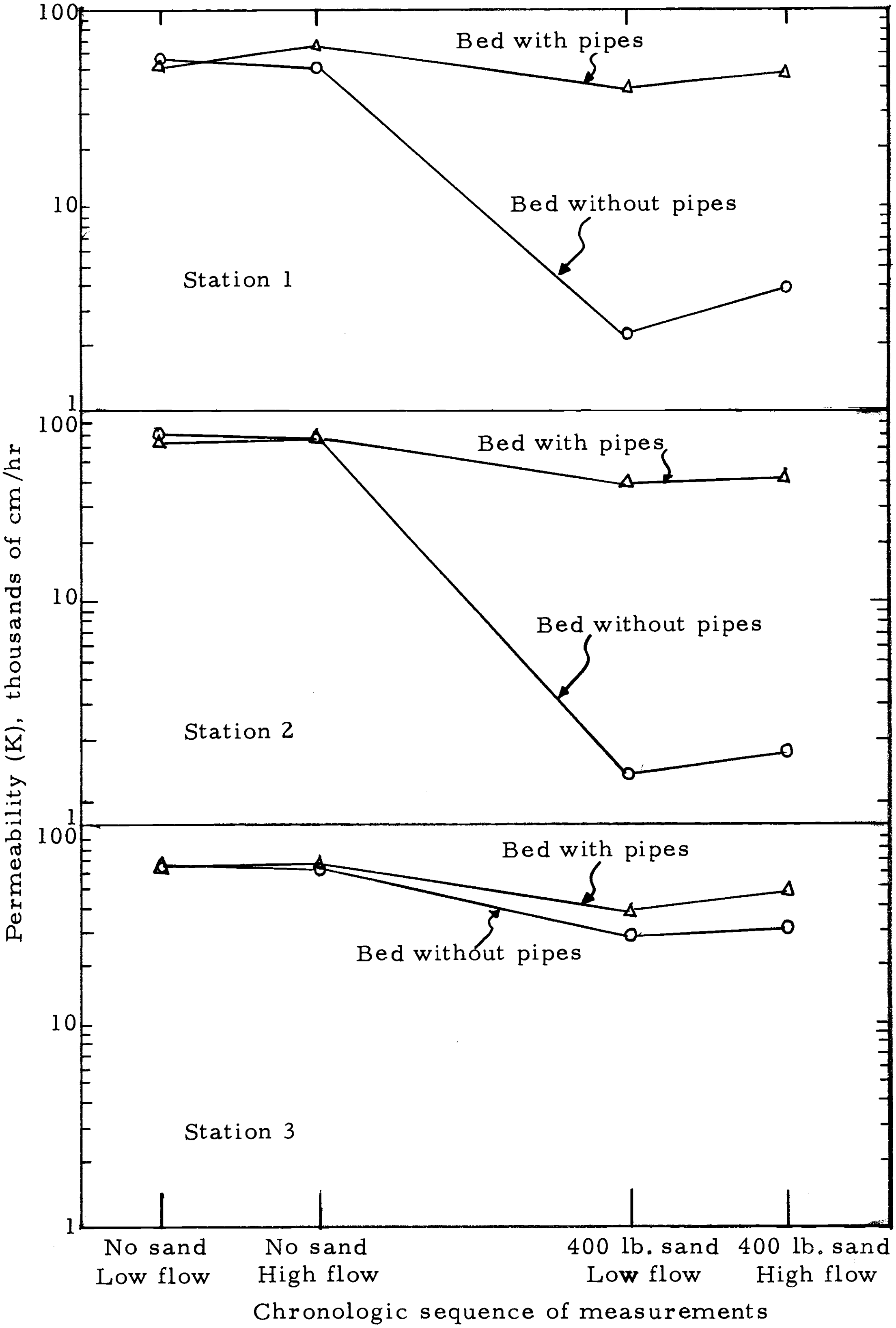


Figure 23. Changes in permeability of gravel beds at measurement stations.

A slight but definite increase in the intragravel permeability values was noted when post-siltation flows were increased. This may be due to some flushing of fine material inside the gravel bed. However, this conclusion cannot be fully verified since the same effect was also noted before the white sand was applied, when only a small residual amount of concrete sand was in the bed.

Analysis of Permeability Measurement Reliability

In measuring the intragravel permeability, a custom-made permeability pump was built to match that described by Terhune. Little difficulty was noted in measuring permeability when the suction pump was used. Different inflow rates from the gravel bed into the standpipes would result if pumping rates were varied; however, after practice for a period of time, a uniform and consistent rhythm was developed by the pump operator and thereafter repeatable and consistent measurements were produced.

Since the assembly of the pump closely followed the described specifications and since the standpipes used were a standard type, it was assumed that the calibration curve provided by Terhune (1958) for conversion of pump rate to permeability was also applicable in this study. Therefore, no other calibration of this measuring device was made. The calibration curve is shown in Figure 24.

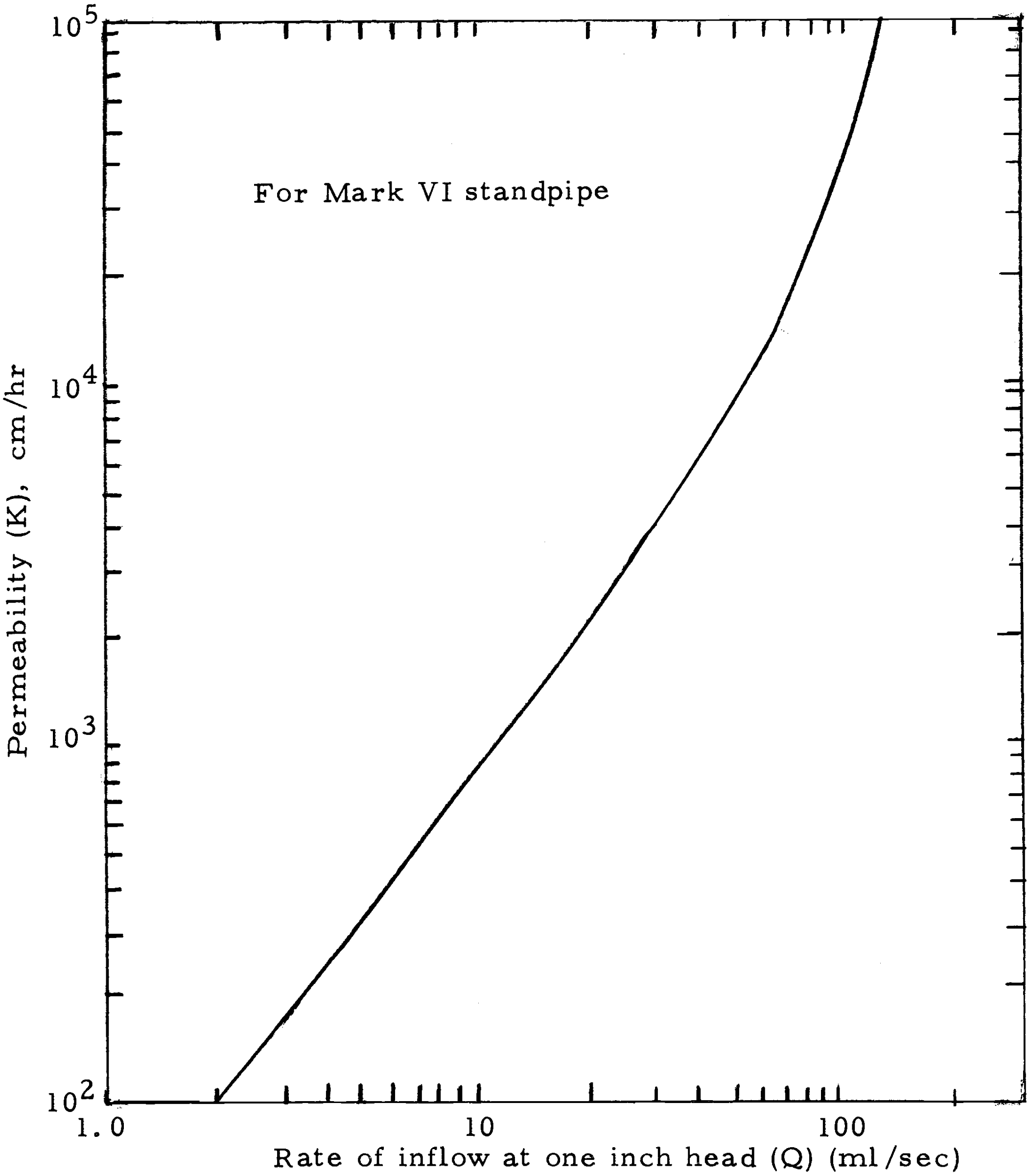


Figure 24. Permeability calibration curve for Mark VI standpipe.

In interpolating Terhune's permeability calibration curve, an accurate permeability value may be difficult to obtain for high inflow rates due to the steep shape of the curve. A slight difference in inflow rate due to imprecise measurement, especially between 95 ml/sec and 120 ml/sec would introduce a considerable difference in permeability value. Differences in logarithmically interpolating the curve could easily result in a 2,000 cm/hr difference in permeability value. However, even if the permeabilities measured in this study were a few percent off the actual value, the essential results of this study would be unchanged, since the magnitude of change in comparable permeability values was large enough to reflect the significance of the application of the imbedded perforated pipes in the gravelly bed. The purpose of this particular study was thus accomplished.

Relation of Permeability to Size Distribution of Bed

McNeil (1964) correlated the coefficient of permeability with the percentage of bottom materials in a natural stream that pass through a 0.833 mm sieve. This correlation is given in Table 4. The data were plotted and the inverse relationship between these two parameters can be noted in Figure 25. It is apparent from Figure 25 that permeability is high where bed materials contain less than 5% by volume of sand and silt passing through the 0.833 mm sieve. Low

Table 4. Coefficient of permeability as a function of the percentage of bottom materials passing through a 0.833 mm sieve from McNeil (1964).

Percentage of material	Permeability (cm/hr)
4.5	30,600
5.0	24,060
5.5	31,140
5.6	17,280
5.6	18,780
6.1	16,200
6.2	19,920
6.3	17,280
8.1	10,920
9.3	10,800
9.7	9,780
10.1	11,700
10.3	10,620
10.9	3,480
12.2	7,860
12.7	2,580
12.7	5,940
14.7	1,740
15.6	1,440

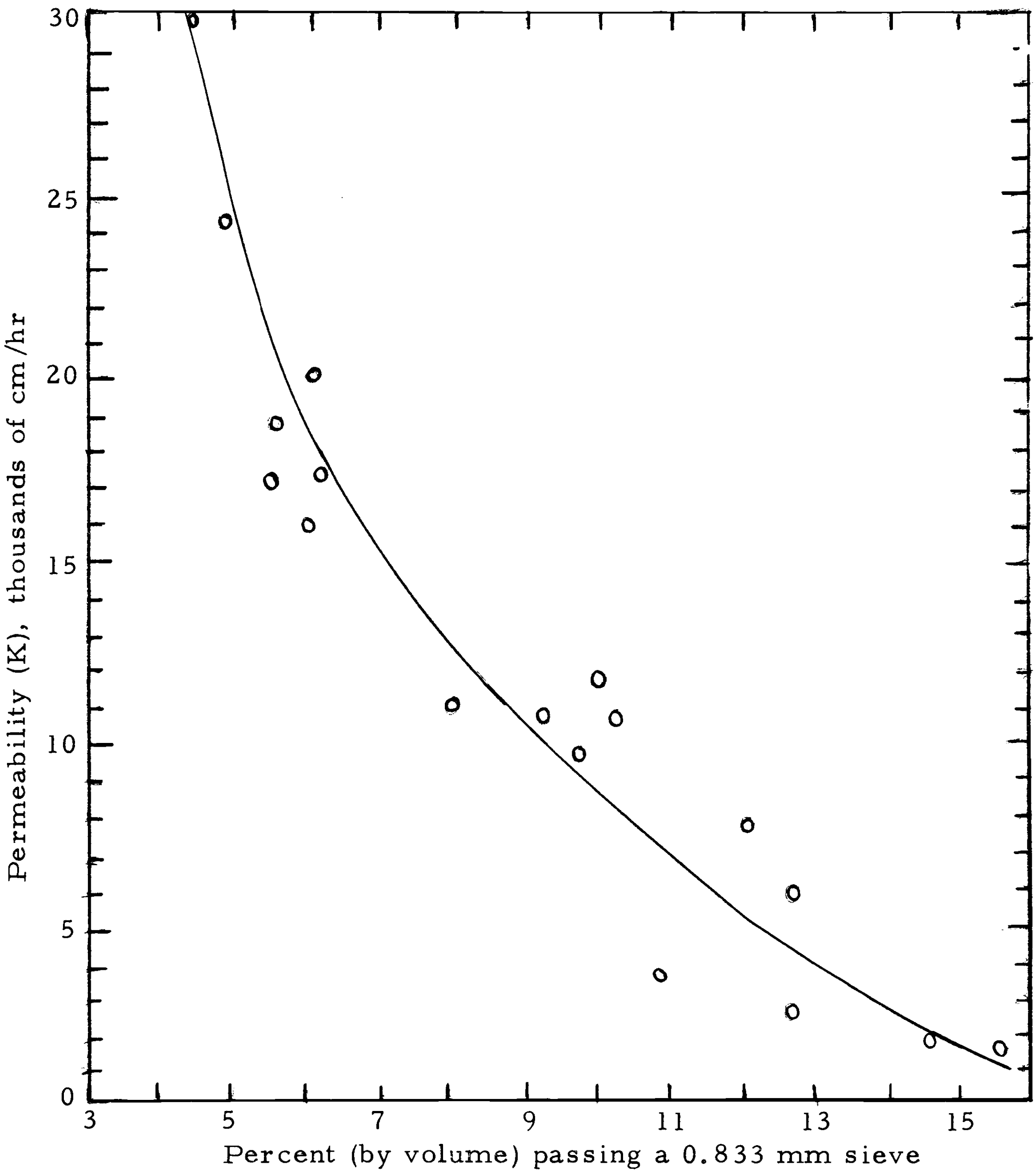


Figure 25. Relationship observed between coefficient of permeability and the fraction of the total volume of stream bottom materials passing through an 0.833 mm sieve (after McNeil, 1964).

permeability occurs where bed materials contain more than 15% by volume of sand and silt passing through the 0.833 mm sieve. At the low range of percentage values for the bed materials that pass through this sieve, a slight difference in the percentage value would result in a considerable difference in permeability value. On the other hand, as the amount of fine sediment increases and one reaches a high range of percentage values, a slight difference in the percentage value would result in a comparatively insignificant difference in permeability value.

The percentage, by volume, of a bottom sample passing through the 0.833 mm sieve in this experiment, after 400 pounds of white sand had been applied to the gravel bed, is calculated as shown below:

Volume of the pea gravel used:

$$V_G = 14' \times 2.8' \times 1' = 39.2 \text{ cubic feet}$$

Volume of the 400 lb of sand added:

$$V_S = 400 \text{ lb}/80 \text{ lb per cubic foot} = 5.0 \text{ cubic feet}$$

Total volume of the material in the system:

$$V_T = V_G + V_S = 44.2 \text{ cubic feet}$$

Since the material passing the 0.833 mm sieve is all white sand (see Table 1):

Percent by volume passing 0.833 mm sieve =

$$\frac{5}{39.2} \times 100\% = 12.6\%$$

With the calculated 12.6% by volume that passes a 0.833 mm sieve, Figure 25 gives an approximate permeability value of 4,260 cm/hr. Comparing this with the estimated value from McNeil's field observations, the average intragravel permeabilties measured in this experiment after streambed siltation were found to be of similar magnitude (Table 3: 1,700 - 3,000 cm/hr).

The gradation curve for the bed material in this experiment is compared with those for Pollard's and Terhune's studies as shown in Figure 26. The permeability values for each bed material used are also given for reference. As shown by the figure, the three curves were generally similar; the bed material used in this study, however, is coarser than the bed material used in the other two studies. The relationship between the size of the bed material used and the intragravel permeability value is shown to be approximately in direct proportion. However, it is not a linear relationship.

As discussed earlier, intragravel permeability is severely affected by the presence of the fine particles. Their presence might be approximately indicated by the D_{10} particle size for the bed. Since a greater similarity is found for the D_{10} size between this and Terhune's study than between the same two sizes in Pollard's and Terhune's studies, closer permeability values could be expected, and in fact, were found between Terhune's and this study than between Pollard's and Terhune's work.

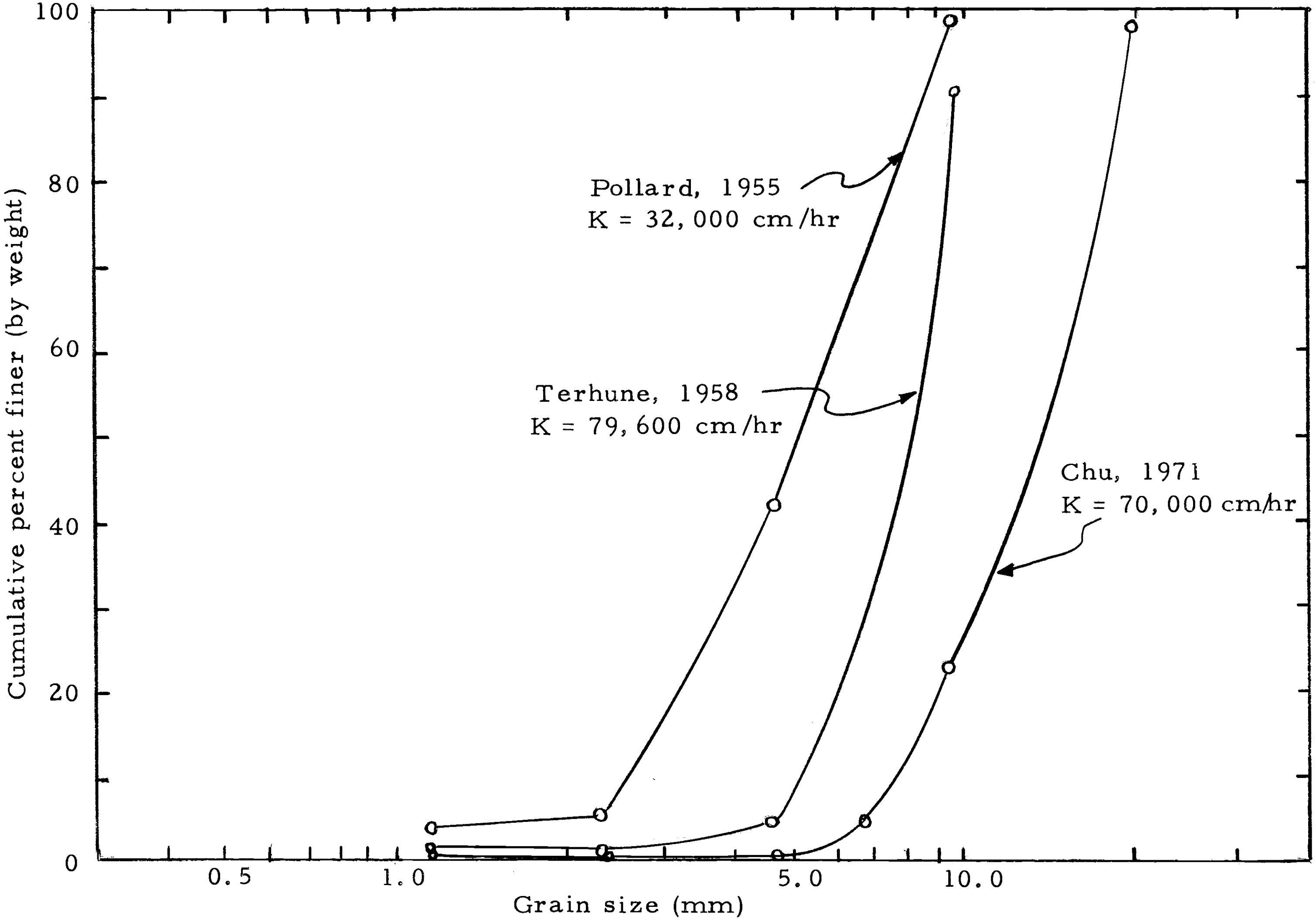


Figure 26. Gradation curves for streambed gravels in this and other studies.

Influence of Perforated Pipes on Streambed Permeability, Siltation, and Flow Interchange

As shown in Figures 22 and 23, the intragravel permeabilities for the two different beds were very similar at the initial conditions, that is, before any fine material was applied to the gravel beds. After a considerable amount of white sand was added to the system, a significantly larger drop in permeability value was illustrated for the bed without perforated pipes than for the bed with pipes.

By using permeability measurements at station 2 as a typical example, permeability values decrease from an average of 68,250 cm/hr to 40,750 cm/hr in the case where perforated pipes were present; in other words, the initial value was reduced by 40.3%. In the case where perforated pipes were not present, permeability values decrease from an average of 69,000 cm/hr to 1,575 cm/hr, a 97.9% reduction.

Stations 1 and 3 were located at the two ends of the gravel beds (see Figure 21). The intragravel permeabilities at these two stations did not drop to as low a value as at station 2, located midway along the gravel bed. This variation can be explained by the fact that the flow interchange at station 2 is not likely to be as high as at stations 1 and 3, due to the influence of flow curvature, as discussed in the literature review. This variation, however, was not so pronounced for the bed

bed with perforated pipes as for the bed without pipes.

During the process of applying fine sand to the system, the fine particles were seen to "wash" into the gravel and disappear. Subsequent permeability measurements revealed that the fine particles were washed down to the bottom of the gravel bed and filled the voids there, causing reduced permeability even though the gravel surface was not choked with sand. It is assumed that the filling occurred in the manner observed by Einstein and described earlier. In the case where perforated pipes were used, while the sand slurry was being applied to the flow a quantity of fine particles were found to discharge out through the perforated pipes and deposit in a pool downstream of the gravel bar. This observation both concurs with the Einstein contention that fine particles reach the empty voids deep within a gravel bed and demonstrates the effectiveness of the perforated pipes.

Once the laboratory gravel bed silted up with white sand it was considered nearly impossible to recover the bed to its original unsilted condition without complete disturbance of the gravel. The gravel bed was considered to be heavily silted after 400 lb of white sand were applied. Because of the stated limitation, only one set of data concerning silt quantities was obtained. Several sets of permeability observations for different silt quantities would have given a more complete description of the siltation process and its effect on permeability and flow interchange. Nevertheless, it can be seen that the presence of the imbedded perforated pipes helped retain the permeability of the streambed to a significant degree.

At stations 1 and 3, relatively large changes of water surface level and large hydraulic gradients were present. These presumably caused a higher flow interchange inside the gravel bed than near station 2. Therefore, the permeability was slightly higher near the ends of the bed than in the middle. This is particularly obvious at the channel where no perforated pipes had been installed.

Expected Influence of Perforated Pipes on Dissolved Oxygen

Some influences may be drawn from these experiments regarding the likely influence of perforated pipes upon intragravel dissolved oxygen levels.

Although the study was conducted in the laboratory only, attempts were made to reproduce the "environmental conditions" experienced at a natural spawning bed, so that the experimental data may have their highest probable value. A field study of the same nature should also be carried out in order to justify these experimental analyses. Especially when organic sediments are present, a true dissolved oxygen deficit may then be measured directly rather than relying on the permeability measurement as an indirect measure of the probable dissolved oxygen deficit. However, it is understood that the permeability of the gravel, the ability with which water can pass through it, may be used as an index of streambed dissolved oxygen--the higher the permeability the greater the supply of oxygenated water that can reach the fish eggs. The presence of the perforated pipes in the bed can thus be expected to be beneficial to the intragravel dissolved oxygen content.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made from the experimental study:

1. The buried perforated pipes were capable of removing and carrying the fine sediments from the bed at times when such material was being added to the flow upstream. Hence, such pipes were effective in reducing streambed siltation and encouraging flushing of the tested fine material from the gravel bed.
2. In the streambed where no perforated pipes were installed, the intragravel permeability decreased when the amount of fine sand increased; the reduction in permeability was 97.9% at station 2 for the amount of fine sand applied. In the bed with imbedded perforated pipes, only a 40.3% reduction of the intragravel permeability took place under identical siltation conditions.
3. Permeability was found to vary along the length of the laboratory streambed. This probably was due to permeability being a function of the hydraulic gradient, and the hydraulic gradient in turn being a function of the shape of the streambed. Since greater change in gravel bed shape was found at stations 1 and 3, higher flow interchange resulted

there together with higher permeabilities.

4. "Successful" siltation for a limited size range of fine material was accomplished in this study by having the right size of fine sediment come in contact with the stream-bed gravel.

The following recommendations are made:

1. In this experiment, permeability was measured only before and after 400 pounds of fine sand were applied. Therefore, further study of the effect on permeability at different degrees of siltation would also be recommended.
2. The fine sand used in this study was entirely composed of uniformly graded inorganic particles. In the actual stream, foreign matter, organic as well as inorganic, of any type or size would be likely to cause siltation. Dissolved oxygen deficiencies may be due to the low flow interchange rate as well as to the decomposition of the organic debris. This would justify field verification of the laboratory study.
3. Since this entire study was conducted in the laboratory, a field experimental study is recommended to justify the practicality and applicability of this study.

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