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The Intrusion of Fine Sediments into a Stable Gravel Bed

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Beschta, R. L., and W. L. Jackson. 1979. The intrusion of fine sediments into a stable gravel bed. J. Fish. Res. Board Can. 36: 204–210.

A rectangular flume was used to study variables affecting the intrusion of fine sands into a stable gravel streambed. The amount of intrusion by sand (median particle diameter 0.5 mm) was determined under varied conditions of discharge, depth, velocity, flume slope, and rates of sediment transport. During all experimental tests, sand particles were trapped in voids within the upper 10 cm of an initially clean gravel bed (median particle diameter 15 mm), forming a barrier to further intrusion. An analysis of flow variables showed that flow conditions, as indexed by Froude number, significantly (90% confidence level) affected intrusion amounts, possibly by influencing the rate and depth of formation of the sand seal. Intrusion amounts, expressed as a percent of total volume, varied from 2 to 8%. Two replications used a finer grade sand (median particle diameter 0.2 mm) that intruded more and, in one case, completely filled the gravel pore space (25% by volume), further indicating that particle size, and not hydraulic variables, may have a more important influence on the total amount of intrusion.

Key words: sediment transport, intrusion, streambed, substrates, riffles, sedimentation

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Nous nous sommes servi d'une auge rectangulaire pour étudier les variables affectant l'intrusion de sable fin dans le lit de gravier stable d'un cours d'eau. Nous avons déterminé les quantités de sable (diamètre médian des particules 0,5 mm) introduites dans diverses conditions de débit, profondeur, vélocité, pente de l'auge et vitesse de transport des sédiments. Pendant tous les essais, les particules de sable furent emprisonnées dans les espaces des 10 cm supérieurs d'un lit de gravier initialement propre (diamètre médian des particules 15 mm), formant une barrière à l'introduction d'une plus grande quantité de sable. Une analyse des variables du débit démontre que ce dernier, indexé selon le nombre de Froude, affecte de façon significative (limite de confiance à 90%) les quantités introduites, possiblement en agissant sur la vitesse et la profondeur auxquelles la couche scellante se forme. Les quantités introduites, exprimées en pourcentage du volume total, varient de 2 à 8%. Dans deux essais répétés, nous avons utilisé un sable plus fin (diamètre médian des particules 0,2 mm) qui pénétra davantage et qui, dans un cas, remplit complètement les pores du gravier (25% en volume). C'est une indication de plus que la taille des particules peut avoir une plus grande influence que les variables hydrauliques sur le degré d'intrusion.

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In small mountain streams, particle size distributions of bed materials are affected by many interrelated factors. Climate, soils, parent materials, watershed characteristics, and land use activities all interact to produce various combinations of sediment sizes. Particularly important are the bed materials approximately 1 mm in diameter or smaller. These fine sediments can significantly affect fish habitat and other instream biota (Gibbons and Salo 1973; Meehan and Swanston 1977).

Although the evidence is not entirely consistent, research results have generally shown that increased levels of fines have detrimental biological effects (N. H. Ringler unpublished data; Moring and Lantz 1974; Iwamoto et al. 1978). In forest streams of the Pacific Northwest, fine sediments can affect anadromous and resident fish populations after the deposition of eggs. Fine sediments may reduce intergravel circulation of water, which decreases the dissolved oxygen available in the spawning gravels (Vaux 1962). Apparently, relatively small percentage increases in the volume of fine sediments may greatly reduce the permeability of stream gravels (Phillips 1971). In addition, sediments may block the movement of fry from the gravels to the stream (Koski 1972). By eliminating intergravel crevices for juvenile fish and other organisms, fine sedi-

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ments alter habitats and decrease fry survival. Iwamoto et al. (1978) identified several studies noting such effects. Furthermore, many common riffle insects are unable to move upstream on sand substrates (Luedtke and Brusven 1976).

Research has also shown that forest harvesting operations (including road building, yarding, and slash disposal) in steep terrain can increase the amount of sediments entering the stream system. Although watershed responses to land use are highly variable, sediment transport rates typically recover, with time, toward pretreatment levels (Anderson 1972; Brown 1972; Megahan 1974; Swanson and Dyrness 1975). The linkage between this temporary increase in sediment production and changes in streambed composition have not been identified.

Unfortunately, little information is available relating the temporal and spatial variability of percent fines in streambed gravels to hydraulic variables, rates, and mechanisms of sediment transport (i.e. suspended load vs. bedload), as well as sediment characteristics. Although sediment transport mechanisms are complex (Lawson and O'Neill 1975), selected hydraulic and sediment variables may be useful for characterizing these mechanisms and the intrusion or deposition of fines.

This study evaluates factors affecting the intrusion of fine sediments into a stable gravel substrate, thereby improving understanding of the process and possible biological impacts.

Methods

The study was conducted during the summer of 1977 at the Kalama Springs Field Laboratory of the Weyerhaeuser Company, approximately 80 km east of Longview, Washington. A wooden flume, 7.6 × 0.71 m, was constructed so that a range of streamflow and sediment transport conditions could be evaluated. Although a flume does not simulate the exact conditions found in mountain streams, this approach was used because flow conditions and sediment transport variables could be controlled and modified as desired. The flume was hinged at the upstream end and supported by hydraulic jacks so the bottom slope could be adjusted. Several glass windows installed along the sides of the flume allowed observations of both the transport and intrusion of fine sediments.

Water from Kalama Springs was used for each test. A headgate upstream from the flume controlled the discharge of water into an artificial channel that led to the flume. At the immediate upstream edge of the flume, a weir and staff gage enabled us to monitor discharge during each test. Water temperatures remained a constant 7°C throughout the study.

A fertilizer hopper 46 cm wide was mounted at the upstream end of the flume to meter fine sediments into the flowing water. Delivery rates of fine sediments were controlled by a calibrated lever that opened the spreader. After each test, actual rates of sediment delivery or inputs were calculated from the volume of fines that had passed through the spreader.

Clean gravels to a depth of 30.5 cm were placed into the test section of the flume for each test. These gravels, leveled and lightly tamped to provide a uniform gravel surface, averaged 15 mm diam and had a particle size distribution as shown in Fig. 1. The particle density and porosity of these gravels averaged 2.67 g/cm^3 and 35% (by volume). Sand-size sediments, averaging 0.5 mm diam (Fig. 1) and a particle density of 2.26 g/cm^3, were used for most of the intrusion evaluations. Both sands and gravels match those being used by fisheries biologists at the Weyerhaeuser Company to assess survival to emergence ratios of salmonid embryos in artificial redds (J. Fisher, Weyerhaeuser Company, Longview, Wash., personal communication, 1977). The relatively low particle density of the 0.5-mm sands can be attributed to the high occurrence of pyroclastic rock types comprising individual sand grains.

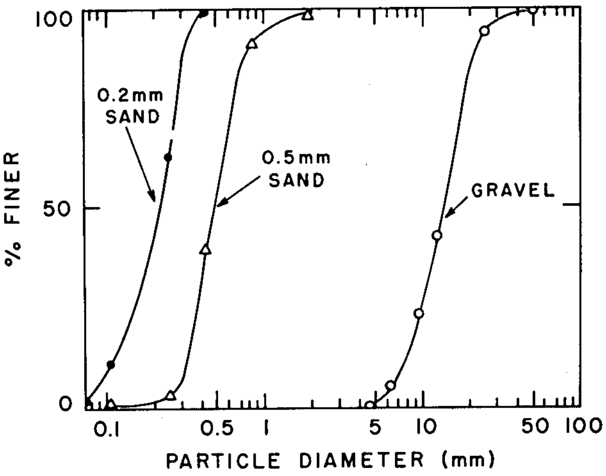

FIG. 1. Size distributions of sands and gravels used to evaluate the intrusion of fine sediments into a gravel-bedded test channel.

During 18 separate runs in the test flume, we evaluated these sediment transport conditions: 1) three discharge rates (≈50, 75, and 90 L/s); 2) three slope conditions (Froude numbers ≈0.6, 1.1, and 1.5); and 3) two (low and high) sediment input rates (≈2500 and 11 500 g/min). These 18 tests (3 × 3 × 2 = 18) were conducted with the 0.5-mm sand. Two additional tests used fine sediments with a particle diameter averaging 0.2 mm (Fig. 1) and a density of 2.53 g/cm^3. A final run for an extended period (i.e. 120 min) was made with the 0.5-mm sand at the low input rate to determine maximum levels of intrusion for a given flow condition. All other tests lasted either 30 or 60 min for the high and low input rates, respectively, because field observations and measurements during individual tests indicated that most of the intrusion occurred within the first 15–20 min of a run.

For a given discharge rate, flume slope was adjusted for evaluating a range of Froude numbers. The dimensionless Froude number (F_r), representing the ratio of inertial to gravitational forces in fluid flow (Streeter and Wylie 1975), is expressed as

$$F_r = \frac{\bar{V}^2}{gy}$$

where $\bar{V}$ = mean velocity, m/s
g = acceleration due to gravity, 9.8 m/s^2
y = depth of flow, m

The Froude number is a useful way to characterize flow conditions. For subcritical flow ($F_r < 1.0$), stream conditions are typified by relatively deep, slow streamflow. At a critical flow ($F_r = 1.0$), the specific energy ($E = \bar{V}^2/2g + y$) is at a minimum. "Standing waves" in a stream indicate critical flow conditions. Supercritical flow ($F_r > 1.0$) is characterized by relatively shallow, rapid streamflow. Because all three conditions occur in mountain streams, this study evaluated a range of Froude numbers.

For each test run, water velocity and depth were measured at 5-cm intervals across the width of the flume near the center of the gravel test section. Velocities were measured using a pygmy current meter. Vertical velocity profiles were also determined for each flow condition. Two small siphon tubes (0.64 mm diam) extracted water and transported sediment from elevations of 1 and 6 cm above the gravels to determine sediment concentrations immediately above the gravel bed.

After each run, cores of the gravel bed were frozen (Walkotten 1973) for estimating the amount of sand that had intruded into the test gravels. This procedure was also intended to provide information about the positioning of intruded sands within the gravel bed. However, during the first several experimental runs, we had a problem — inserting the probe of the freeze-core sampler disturbed the gravels so that sands deposited among the surface gravels moved downward and were redeposited. Wendling (1978) encountered a similar problem when sampling streambed sediments in Alaskan streams. In our situation, the retrieved frozen core usually had sands concentrated within several centimeters of the flume bottom but few, if any, sand particles above that point. Observations through the flume windows confirmed that the sands settled throughout the gravel profile during sampling. Consequently, after the first three tests (no. 1, 4, and 6), we implemented another method of sampling. We buried two containers (12.5 cm diam, 15.0 cm tall, and open at the top) in the gravels before a run, removed them after completing the run, and then determined the dry weight of sands.

Total intrusion for a given run was calculated by dividing the weight of the sands in each container by the weight of the gravels in a column 12.5 cm diam and 15.0 cm high (even though the total depth of gravels was 30.5 cm). These weights were adjusted to account for differences in particle densities between the sands and gravels. Thus, intrusion amounts were expressed as percent by volume of intruded sands in relation to the total volume of sample. The choice of a 15-cm depth was arbitrary, but made the calculated percentages more representative of average fine concentrations in the gravels.

After each run and the retrieval of sampling containers, the gravels were flushed from the flume and clean gravels were inserted into the test reach.

Results and Discussion

The flume windows proved particularly useful for visually observing sediment transport and intrusion processes. At low Froude numbers ($F_r < 0.9$), sands were transported mostly within 1 cm of the gravel bed surface. The transport process consisted mainly of individual grains rolling and sliding along the tops of gravels and other sand particles. At Froude numbers generally greater than 0.9, transport mechanisms shifted so that the suspension and saltation of sand particles became increasingly important. This was further illustrated by the increased average sediment concentrations (mg/L) measured at both 1 and 6 cm above the gravel bed during runs with 0.5-mm sands. Sediment concentrations 6 cm above the gravels typically averaged about one tenth of those measured at 1 cm. Dunes, ripples, or other bed forms were not observed during any of the test runs.

Height (cm)	Froude number		
	$0.5 < F_r < 0.9$	$0.9 < F_r < 1.3$	$1.3 < F_r < 2.6$
1	1700	4800	4500
6	120	370	760

Apparently sediment deposition and intrusion into the gravels involves two principal mechanisms: 1) the transport and deposition of sand particles into the surface voids of the gravel bed, and 2) the settling of the particles into deeper gravel voids. The settling process occurs primarily under the influence of gravitational forces, but seems assisted by turbulent pulses at the gravel surface.

At low Froude numbers ($F_r < 0.9$), the 0.5-mm sands quickly established a sand "seal" within the upper 5 cm of the test gravels as the larger sand particles bridged the openings between adjacent gravel particles and prevented the downward movement of additional sands into the gravels. Once this sand seal had formed and the intergravel space above had filled with fines, the intrusion process stopped. Additional sands were transported past the gravel test section. At higher Froude numbers ($F_r > 0.9$), flow characteristics began to alter this process. Observations indicated that most deposition and intrusion now occurred within the upper 5–10 cm of the gravels. Because of the higher velocities associated with higher Froude numbers, these flows were characterized by greater bed shear and the periodic jiggling of the surface gravels. These turbulent pulses seemed to inhibit the formation of a sand seal near the gravel surface. As a result, the sand seal still formed, but generally deeper within the test gravels. Again the formation of a sand seal in a stable gravel substrate would preclude the additional intrusion of fine sediments into the lower gravels.

Table 1 summarizes measurements for each of the 21 experimental runs. For the first 18 runs (using the 0.5-mm sands), an analysis of variance indicated that flow condition, as indexed by Froude number, significantly (90% confidence level) influenced intrusion amounts. Apparently the main influence of flow conditions was to vary, within a relatively narrow range, the depth and rate of formation of the sand seal. Other flow indicators, such as average bed shear stress, unit stream power, or Reynolds number, did not significantly affect the amount of intrusion, making a physical interpretation of the Froude number relationship difficult.

TABLE 1. Test conditions during the intrusion of fine sediments into a gravel-bedded channel.

Test	Mean particle size (mm)	Test duration (min)	Hydraulic variables				Sediment transport and intrusion variables			
			Discharge (L/s)	Froude number	Velocity (m/s)	Depth (cm)	Input rate (g/min)	c_1[a] (mg/L)	c_6[a] (mg/L)	Total intrusion (% by vol)
1	0.5	60	45.3	0.66	0.75	8.6	1 680	1 010	13	—
2	0.5	60	49.8	1.13	0.92	7.6	2 470	1 430	35	4.6
3	0.5	60	51.0	1.55	1.03	7.0	1 970	1 440	—	6.6
4	0.5	30	44.2	0.89	0.82	7.6	10 000	2 200	72	—
5	0.5	30	53.8	1.08	0.94	8.2	12 850	10 980	260	8.0
6	0.5	30	48.7	2.57	1.20	5.7	8 570	3 770	—	—
7	0.5	60	78.7	0.54	0.84	13.2	1 990	790	70	7.0
8	0.5	60	73.1	1.28	1.09	9.5	2 600	1 500	120	4.5
9	0.5	60	70.2	1.52	1.14	8.7	2 470	1 770	170	6.8
10	0.5	30	73.1	0.53	0.81	12.7	11 860	2 800	200	5.3
11	0.5	30	73.6	1.18	1.06	9.8	11 860	7 210	660	5.8
12	0.5	30	72.2	1.53	1.15	8.9	12 920	7 480	1 200	8.3
13	0.5	60	90.1	0.56	0.88	14.3	2 140	812	70	5.9
14	0.5	60	90.6	1.06	1.10	11.6	3 630	2 450	230	5.0
15	0.5	60	96.3	1.43	1.24	11.1	3 130	1 750	500	7.4
16	0.5	30	91.8	0.66	0.94	13.7	10 830	2 470	280	2.6
17	0.5	30	92.3	0.92	1.05	12.4	11 860	8 970	1 100	5.8
18	0.5	30	92.6	1.52	1.24	10.5	11 860	10 740	1 150	10.4
19	0.2	60	94.0	0.63	0.93	14.1	2 150	970	210	24.9
20	0.2	60	91.5	1.12	1.12	11.5	1 980	860	220	15.3
21	0.5	120	91.8	0.93	1.06	12.2	3 220	1 370	160	6.5

[a] c_1 and c_6 = sediment concentrations 1 and 6 cm, respectively, above gravel surface.

Intrusion amounts by total volume ranged from 2 to 8%.

An increasing Froude number affected intrusion amounts differently at low (Fig. 2) and high (Fig. 3) rates of sediment input. At low sediment input rates, and hence low transport rates across the gravels, intrusion amounts reached a minimum for Froude numbers of approximately 1.0–1.2. However, at high rates of sediment input of the 0.5-mm sand, intrusion amounts generally increased as Froude number increased. These contrasting results further indicated that the intrusion of fines into a stable gravel bed is a complicated and not fully understood process.

Although only 2 of the 21 runs (no. 19 and 20) used 0.2-mm sands, these runs substantially contrasted with those using 0.5-mm sands. The major difference was the absence of a sand seal in the upper gravels. Instead, these finer sands generally moved down through the gravels by gravity and began to fill the test gravels from the bottom up. These observations concur with flume studies conducted by Einstein (1968) where he evaluated the intrusion of silt-size particles into streambed gravels and concluded that silts fill gravels from the bottom upwards.

In comparison to the 0.5-mm sands, more 0.2-mm sands intruded (Fig. 2), further suggesting that particle size is an important variable affecting intrusion into stable gravels. The amount of intrusion by the 0.2-mm sands also substantially decreased as Froude number increased from 0.6 to 1.1. The percentages shown in Fig. 2 are the results of tests that lasted only 1 h. Yet, within that time frame, the 0.2-mm sediments attained intrusion amounts from 15 to 25%. Complete filling of the gravel interstices would be represented by a value of approximately 25% by volume for the 0.2-mm sands.

Although observations indicated that the intrusion and deposition of 0.5-mm sands stabilized before completion of a given run, test no. 21 was implemented to see whether intrusion would continue over a longer period. The measured intrusion of 6.5% for this run was within one percentage unit of that predicted from the curve in Fig. 2. This result seems to substantiate observations that intrusion had essentially stopped by the end of each run.

Particle size distributions for samples obtained during run no. 21 provide an interesting contrast to the transport and intrusion of fine sediment. The particle size distribution of sands from the siphon located 1 cm above the gravels is essentially identical to that of the 0.5-mm sands added at the upstream end of the flume. However, the intruded sands have a mean particle size of <0.3 mm, indicating that the intrusion process into a stable streambed may be selective towards smaller particles (Fig. 4).

Results also illustrate that the mean particle size of sediment in transport 6 cm above the gravels is finer than at 1 cm (Fig. 4). Steep velocity gradients near the gravel surface (Fig. 5) were capable of temporarily

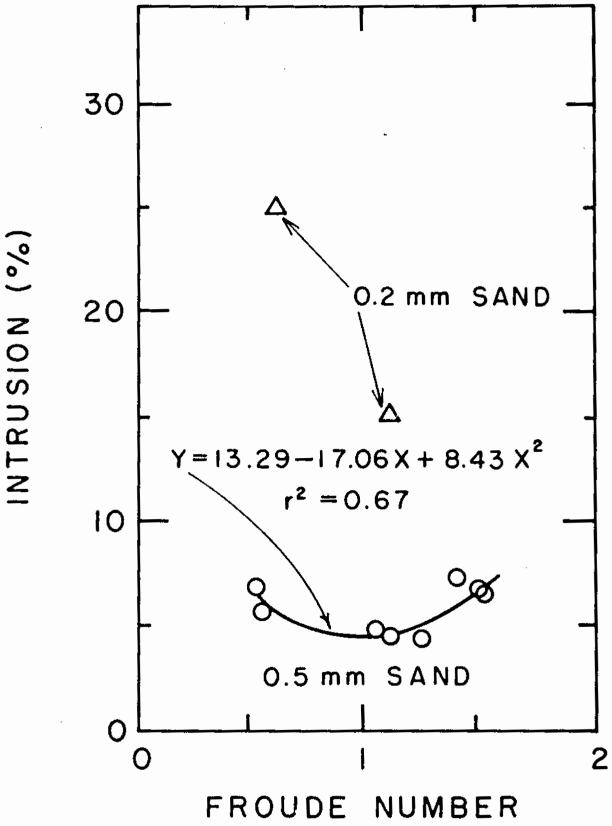

FIG. 2. Total intrusion of sand, percent by volume, in relation to Froude number for low sediment input (≈2500 g/min).

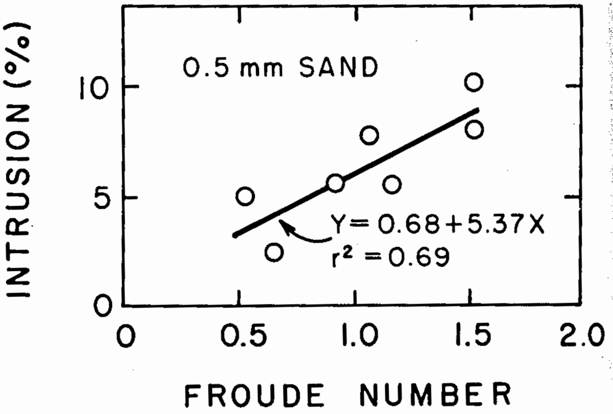

FIG. 3. Total intrusion of sands, percent by volume, in relation to Froude number for high sediment input (≈11 500 g/min).

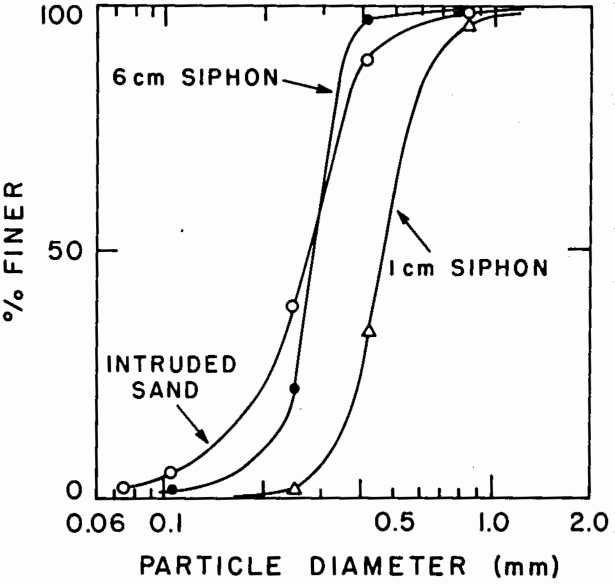

FIG. 4. Size distributions of sands during intrusion test no. 21.

suspending nearly all sand particles at least 1 cm above the bed. At the 6-cm elevation, a reduced velocity gradient and resultant shear stresses (even though average velocities are higher) reduced the transport of larger sediment particles. This is illustrated by the shift in mean particle sizes from 0.5 to 0.3 mm at elevations of 1 and 6 cm, respectively, above the gravels.

An additional experimental run with a flow of approximately 90 L/s and a Froude number exceeding 1.0 was made at the Kalama Springs Field Laboratory; results were not quantified. The 0.5-mm sands intruded until a sand seal formed and the interstices of the gravels had filled with sand. At that point, we stopped adding sand and allowed the flow to clean or flush the fines from the gravels. Observations and photographic evidence showed that fines flushed from the gravels to a depth of about 1 cm. Sands below 1 cm were not entrained by the flowing water, and further flushing did not occur, suggesting stream gravels can be cleansed or flushed only when in motion during high flow events. Without movement of these gravels, apparently no mechanisms are available for flushing. Thus the amount of fines transported during high flow events may have a pronounced effect on the natural quality or composition of gravel substrates in mountain streams. However, McNeil and Ahnell (1964) reported that local fines can be removed from the streambed during spawning.

Flow conditions, sediment transport rates, and sediment particle size all influenced the amount of fines deposited in initially clean gravels. These results indicate the need for improved understanding of the mechanisms of intrusion and the importance of mean particle size in affecting the intrusion of fines. Although several factors were found to influence intrusion, the direct application of these results to natural streams is tenuous. Measurements in small mountain streams must be improved before the ramifications of flume studies

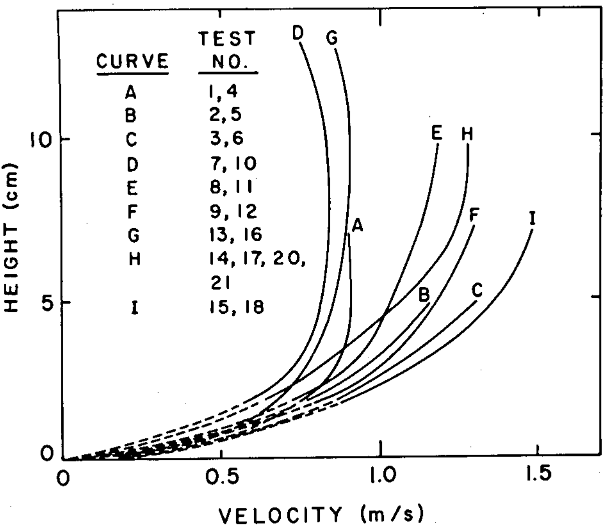

FIG. 5. Velocity profiles measured above gravel test section.

can be fully understood and extrapolated to field situations. For example, flow conditions and transport rates of fine sediments over known spawning gravels must be characterized for a range of high flow conditions. With such information, we may be more able to fully assess the impacts of sedimentation upon the habitats and organisms found in mountain streams.

Even though the quantitative results of this study cannot be directly applied to small streams, the study has several implications concerning land-use activities and stream sedimentation. Fine sediments added when streambed gravels are stable will deposit and intrude into initially clean gravels. If the fine particles are large enough to bridge openings between gravel particles, a seal will form. Then fines will deposit above this seal and fill the upper layers of the gravels. If the fine particles are small enough, they will fill the interstices of the gravels from the bottom up. As long as the gravels remain stable and do not move, adding fines to a stream can only result in the intrusion of fines or perhaps a blanketing of gravel substrates. Biologically, the presence of such conditions will generally have undesirable impacts.

If only intrusion can occur during periods when streambeds are stable, then the question may be posed, How and when are fines flushed in small streams? Apparently, flushing can occur only during periods of relatively high flows that disturb the channel bed and cause bedload transport. Field measurements we have made in Oregon's Coast Range streams indicate that the general transport of bed material (sand size and larger) occurs after discharges exceed ~0.15 $m^3 \cdot s^{-1} \cdot km^{-2}$. Based on a frequency analysis of daily streamflow values, flows exceed this level on an average of about 20 d each year. If the amount of fines is increased during high flow periods as a result of land use activities, stream energy may be used to transport and intrude the additional sediment load instead of flushing fines from the gravels. Thus, additional amounts of fines from accelerated surface or hillslope erosion during high flow events may directly influence gravel quality. Consequently, land managers must continue their efforts to control activities that have a high potential to increase stream sedimentation. Increased amounts of fine sediments must be minimized if the natural quality of a stream system is to be maintained.

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