EVALUATION OF PROCEDURES TO MEASURE INTRAGRAVEL WATER VELOCITY IN STREAMBEDS

R.T. Grost, T.A. Wesche, M.K. Young,
W.A. Hubert and V.R. Hasfurther

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R.T. Grost
T.A. Wesche
Wyoming Water Research Center
University of Wyoming
Laramie, Wyoming

M.K. Young
W.A. Hubert
Wyoming Cooperative Fishery & Wildlife Research Unit
University of Wyoming
Laramie, Wyoming

V.R. Hasfurther
Department of Civil Engineering
University of Wyoming
Laramie, Wyoming

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Abstract.- Four techniques for measuring intragravel water velocity (IWV) in streambeds and salmonid redds were evaluated for accuracy, precision, and reliability for field application by research and management agencies. The Mark VI dye dilution technique (Terhune 1958) was correlated ($P < 0.05$) with IWV but its precision was insufficient to consistently distinguish between IWV'S of 0-50 cm/h. Time-of-travel techniques demonstrated potential for measurement of undisturbed substrate, but were not reliable in field conditions. Calculations with mini-piezometers (Lee and Cherry, 1978) were not correlated with IWV, and the method of Bovee and Cochnauer (1977) was not correlated with IWV estimated by Mark VI dye dilution. Because of measurement imprecision, natural variability within the substrate, and poor understanding of its importance, field measurement of IWV is not recommended for monitoring the incubation environment of salmonid embryos.

Water flowing through streambed gravels is the medium in which salmonid embryos incubate. The velocity of this intragravel water near the embryos has been linked to their survival and condition (Shumway, et al. 1964; Turnpenny and Williams 1980; Sowden and Power 1985). Intragravel water velocity (IWV) is influenced by sediment deposition (Wickett 1954) and dewatering (Reiser and White 1981) therefore, field-measurement of IWV may be useful in assessing the impacts of sedimentation and dewatering on salmonid embryos, and may also be useful in predicting embryo survival under natural conditions.

Yet, IWV is rarely measured in field research. Hansen (1975) suggested that high variability obscured relationships of IWV with other physical and biological parameters. To determine the value of IWV measurements, managers need to know the accuracy and precision of measurement techniques under natural conditions.

Forty years of research has failed to produce a standard method for measurement of IWV, but several techniques have been tried or proposed. The tracer dilution technique was first published by Wickett (1954), then modified into the Mark VI standpipe technique by Terhune (1958). The Mark VI technique remains virtually unchanged, and is probably the most commonly used IWV measurement technique to date (Hansen 1975; Dechant

1979; Reiser, and White, 1981). Terhune (1958) suggested remarkable precision in laboratory tests, but he was not using natural streambed substrates. A dilution technique that used a salt solution was designed by Turnpenny and Williams (1982) and modified by Carling (1986). Measuring time-of-travel of various tracers in water is a common technique for determining surface water velocity and groundwater movement, but it has not been used specifically to measure IWV, and may have application. Techniques used to calculate IWV indirectly include the mini-piezometer (Lee and Cherry 1978) - a plastic tube inserted into the gravel to measure hydraulic head and permeability - and the method of Bovee and Cochnauer (1977) using measurements of permeability and surface water characteristics.

The goal of this project was to identify an accurate, inexpensive, and reliable technique to measure IWV in natural streambeds and salmonid redds. Our objectives were:

1) to evaluate the performance of new and existing IWV measurement techniques under laboratory and field conditions in terms of their accuracy, precision, cost-effectiveness, and applicability, and
2) to recommend standard IWV measurement procedures for use by managers and researchers.

Methods

Existing and potential IWV measurement techniques were examined through an extensive literature review. Four techniques were selected for evaluation: 1) Mark VI standpipe (Terhune 1958; using a solution of 84% Schilling's green food coloring and 16% ethanol), 2) time-of-travel using special standpipes and three tracers (salt solution, Rhodamine WT flourescent dye, and green dye, 3) mini-piezometers (Lee and Cherry 1978), and 4) the method of Bovee and Cochnauer (1977) using surface flow characteristics. The first three techniques were evaluated in open-trough, horizontal-flow permeameters constructed of 13-mm plexiglass to hold a substrate bed measuring 67-cm long, 50-cm wide, and 33-cm deep. A screen of 6.3-mm-mesh hardware cloth and 0.33-mm-mesh polypropylene screen held the substrate in place. Baffles around the inflow and outflow standpipes promoted even flow through the substrate bed, and piezometers installed on the permeameter wall allowed measurement of water level in the substrate. IWV through the gravel bed was calculated as:

(discharge from the tail-pool) / (mean wetted cross-section of the substrate).

Test substrates were obtained from alluvial deposits in the

Laramie River watershed, Laramie, Wyoming, and were sorted and mixed according to percent by weight of 11 particle sizes (Table 1). The five different compositions were designated 0.0, 7.5, 15.0, 22.5, and 30.0 based on the percent of fines they contained, and fines were defined as all particles <3.4-mm. This range of substrate compositions corresponded to embryo survivals from 0 to 100% in our previous work. Two substrates, 0.0 and 15.0, were utilized in the initial evaluation of IWV measurement techniques at various IWV's ranging from 60-400 cm/h. At least three measurements were attempted at a given water velocity for each technique. Measured values were correlated with IWV through the substrate bed, with significance defined at $P < 0.05$.

<u>Dye dilution</u>.- The Mark VI dye dilution technique was comprehensively evaluated in a series of five substrates (Table 1) to test its reported accuracy. Accuracy and precision were evaluated on the basis of dilution rates rather than IWV values derived from Terhune's (1958) calibration charts. The standpipe was driven into the center of each substrate bed and five consecutive measurements made at each of five water velocities (0-100 cm/h). Correlations between mean dilution rates and IWV were computed for each substrate, and considered significant at $P < 0.05$. The Statistical Package for the Social Sciences (SPSS) was used to compute mean dilution rates with 95% confidence intervals (CI), Bartlett's test for homogeneity of variances, two way ANOVA to test for interactive effects between substrate and

IWV, and Scheffe's multiple range test to compare mean dilution rates (Sokal and Rohlf 1981). All tests were performed at $P < 0.05$. The coefficient of variation (CV) was also calculated as an index of precision. The effect of measurement time interval on dilution rate was evaluated in the 0.0 and 30.0 substrates at three IWV's (0, 25, and 100 cm/h). Dilution rates were calculated for 3, 5, and 10 min intervals with three measurements at each IWV and the means were evaluated with a t-test for paired comparisons (Sokal and Rohlf 1981).

Time-of-travel.- From time-of-travel measurements, IWV was calculated using both the leading edge and peak of the tracer concentration as:

(elapsed time between dye introduction and dye recovery) / (distance between standpipes).

Standpipes were constructed of 25-mm inside-diameter steel conduit for introduction and recovery of tracers. A series of 13-mm holes drilled through the lower ends and wrapped with 3.2-mm hardware cloth created a permeable chamber. A valve of 19-mm inside-diameter PVC pipe in the upstream standpipe allowed thorough tracer mixing and precise interval timing. Samples were withdrawn from the downstream standpipe at timed intervals for the green dye and Rhodamine WT measurements, and a conductivity cell was placed in the downstream standpipe during salt solution measurements. The distance between standpipes was 20-30 cm. Time-of-travel measurements with the salt solution were attempted in brown trout (Salmo trutta) redds in Douglas Creek, Medicine Bow National Forest, southeastern Wyoming.

Mini-piezometers.- Mini-piezometers were constructed of 6.3-mm soft polyethylene tubing and wrapped with 0.33-mm-mesh polypropylene screen to enhance permeability relative to the smaller tubing and cloth used by Lee and Cherry (1978). A manometer was used for hydraulic head measurements and permeability measurements were attempted with the falling head test proposed by Lee and Cherry.

Surface characteristics.- The method of Bovee and Cochnauer (1977) using surface water characteristics was evaluated in a concrete flume (91 cm wide and deep by 21.3 m long) and compared with Mark VI dye dilution rates. A riffle was constructed of alluvial substrate and transects positioned at the tail, crest, and head of the riffle. Surface water characteristics were measured before three Mark VI standpipes were driven into the substrate at evenly spaced intervals across each transect. Three dilution rate and permeability (using an electric pump at 50 Hg vacuum) measurements were made from each standpipe at each transect. The series of 27 measurements was repeated at three levels of discharge. For each point and water level, IWV was calculated with this equation:

$$IWV = V_s^2 n^2 K / 2.22 R^{4/3}$$

where: IWV = apparent intragravel water velocity

V_s = mean surface water velocity

n = Manning's roughness coefficient

K = permeability

R = hydraulic radius

IWV was calculated using both an assumed Manning's n of 0.035 (Bovee and Cochnauer 1977) and a Manning's n calculated from hydraulic measurements. These values were compared with both Mark VI dye dilution rates and the IWV values derived from Terhune's (1958) calibration curves.

Results

Review of the literature allowed us to eliminate techniques and tracers that were not suitable for the intraqravel environment or did not meet the guidelines established in our objectives. Acoustic metering devices were not suitable; radioactive tracers were dangerous and regulated; flourocarbon tracers required gas chromatography; and most organic dyes were sorbed or filtered by fine sediments (for a review of water tracers see Davis, et al. 1980). The standpipe of Carlinq and Boole (1986) and the GeoFlo Groundwater Flow Meter (K-V Associates, Inc., Falmouth, Massachusetts) were considered too expensive for routine management applications, and the conductiometric standpipe of Turnpenny and Williams (1982) was not evaluated because of time and funding constraints. The Mark VI dilution technique was selected because of its previous use and reported accuracy (Terhune, 1958), time-of-travel techniques because they measured water directly across an undisturbed cross-section, mini-piezometers because they were inexpensive, and the method of Bovee and Cochnauer (1977) because of its potential for simple field measurements.

Dye dilution

Time interval of the measurement had no effect on mean dilution rate in ten of eleven comparisons. Dilution rates were measured over 5 min intervals in all IWV's less than 100 cm/h, and over intervals of 3 min or less in faster IWV's. Mean dilution rates were correlated with IWV in all substrates (r = 0.93-0.99) with the highest correlations in the 0.0 and 30.0 substrates. Two way ANOVA showed strong interactive effects between IWV and substrate composition on dilution rate, which are exhibited primarily at low IWV'S (Figures 1 and 2). Multiple comparisons of dilution rates were made within each substrate to isolate the effects of substrate from those of IWV (Sokal and Rohlf 1981). Mean dilution rates at IWV's of 0 and 12.5 cm/h were not different in any substrate, and mean dilution rates at IWV's of 12.5 and 25 cm/h were not different in all but one substrate (Table 2). Mean dilution rates at IWV's of 0 and 50 cm/h were not different in the 7.5 substrate, and mean dilution rates at IWV's of 0 and 25 cm/h were not different in the 15.0 substrate. Only between IWV's of 50 and 100 cm/h were dilution rates consistently different. Variability of dilution rates was similar in flume (CV = 20%) and permeameter (CV = 18%) measurements. Mean dilution rates in different standpipes within 25 cm of each other, but under identical discharge conditions, often varied by l00%, and as much as 960%. Problems with Mark VI equipment included: 1) stirrer speed constantly changing, 2) sampling syringe breaking, leaking, and sticking in velocity liner, and 3) turbidity affecting opacity of dye samples.

Time-of-travel

Tracer peaks and leading edges were equally correlated with IWV, but peaks were more reliably measured. Time-of-travel with all three tracers was correlated in the 0.0 substrate (r = 0.98-0.99) but no tracer produced a correlation in the 15.0 substrate. From 33 to 44% of our attempted time-of-travel measurements. in the 15.0 substrate failed to produce a measurable peak. The salt solution was most reliable (least susceptible to failed measurements), easiest for a-single person to use, and produced an objective measure of tracer concentration. However, six of 10 field measurements failed to produce a measureable peak after 20-30 min or were confounded by unstable background conductivities. Rhodamine WT was the least reliable tracer, and was not used in the field. Green dye produced the lowest correlation with IWV, required the fragile Mark VI sampling syringe, and was based on subjective ranking of dye concentrations. In a single field measurement with green dye, it was obscured by natural turbidity within the standpipes.

Mini-piezometers

Calculated IWV values were not correlated with IWV in either the 0.0 or 15.0 substrate. Permeability values from falling head measurements were identical in both substrates and at all IWV's. Hydraulic head measurements were correlated with IWV in the 0.0 but not the 15.0 substrate.

Surface characteristics

Flume discharge at the three water levels ranged from 22 to 139 l/s. Measured characteristics along each transect at each water velocity produced Manning's n values much less than 0.035 (range 0.008 to 0.021). The electric pump at 50 cm Hg vacuum was not powerful enough to measure permeability in all but four cases, so only these four were used to compare Bovee and Cochnauer's (1977) equation with dilution rate and Terhune's (1958) Mark VI IWV values. IWV calculated from Bovee and Cochnauer was not correlated with dye dilution rate or the corresponding IWV derived from Terhune.

Discussion

Since we could not determine the actual IWV at the precise time and point of each measurement, the accuracy of evaluated techniques was based on the average IWV through the substrate bed. Reynolds numbers for each substrate and water velocity ranged from 6 to 182, all within the range where turbulent flow has been observed (Bouwer 1980), so turbulent flow may have confounded relationships based on Darcy's Law, which assumes laminar flow. Non-laminar flow may also cause the erratic interactive effects between substrate composition and IWV on dilution rates.

While the Mark VI dye dilution technique produced mean values correlated with IWV, the precision associated with our measurements was less than reported by Terhune (1958). The CI around mean dilution rates prohibited detection of differences between IWV's of 0, 12.5, 25 and sometimes even 50 cm/h. Thus, the Mark VI was not capable of reliably measuring IWV's below 50 cm/h. Also, we observed that driving the Mark VI standpipe caused fines to settle deeper into the substrate, which created altered conditions at the point of measurement and may have contributed to erratic dilution rates in the 7.5 and 15.0 substrates.

While time-of-travel measurements failed in 60% of our field measurements, the potential for directly measuring IWV in undisturbed substrates and egg pockets makes this technique worthy of further research. Additionally, time-of-travel may be the closest measure of true IWV through the interstitial pores- the velocity that actually contacts embryos. The four IWV's we measured in natural brown trout redds were much higher than the 5-200 cm/h IWV's reported in natural rainbow trout (Salmo gairdneri) redds by Sovden and Power (1985). The reliability of time-of-travel measurements in the uniform 0.0 substrate, but frequent failure in the 15.0 substrate and in field measurements, suggested that failure was due to large particles blocking or diverting intragravel flow between the upstream and downstream standpipes. This might be corrected by the use of multiple recovery points, but we did not evaluated this approach.

Mini-piezometers may allow measurements across an undisturbed cross-section of substrate, but they provide only an indirect estimate of IWV based on the assumptions of Darcy's equation. As these assumptions (ie. uni-directional flow uniformly distributed with depth) are often suspect in the streambed environment, direct measure of IWV should be favored over indirect. We were unable to measure permeability with mini-piezometers, which explains the lack of correlation of calculated values with IWV. Similarly, Sowden (1983) was unable to measure permeability with mini-piezometers in natural salmonid redds. Klassen and Northcote

(1988) used mini-piezometers to measure hydraulic head inside Mark VI standpipes, but did not attempt to calculate IWV.

The method of Bovee and Cochnauer (1977) is another indirect estimate of IWV. While incorporating many surface flow characteristics, it also requires a measurement of permeability. IWV calculated from Bovee and Cochnauer's equation was not correlated with our Mark VI IWV values. However, Reiser and White (1981) reported that Bovee and Cochnauer IWV values (using Manning's $n = 0.035$) were correlated ($P < 0.05$) with Mark VI IWV values in two of three field situations. They also found that Bovee and Cochnauer values were less than Mark VI values by 48 to 88%, while we found Bovee and Cochnauer values greater than Mark VI values by an average of 95%. Our standpipe measurements were taken at shallower substrate depths (8-13 cm) than those of Reiser and White (25 cm), and sample sizes are small in both studies.

Management Implications

The techniques evaluated did not measure IWV with sufficient precision or reliability to assess the impact of IWV on salmonid embryos. The imprecision associated with Mark VI dye dilution measurements made it difficult to distinguish between IWV's in the range of 0-50 cm/h; yet, the IWV'S most often considered critical for successful salmonid incubation are in this range. For instance, the IWV reported for 50% survival was 5 cm/h for rainbow trout (Turnpenny and Williams 1980), 7 cm/h for sockeye salmon, Oncorhynchus nerka (Cooper 1965), and about 50 cm/h for steelhead, Salmo gairdneri (Coble 1961). High variability in Mark VI measurements was also reported by Hansen (1975) within natural brown trout redds.

Chapman and McLeod (1987) pointed out that the salmonid egg pocket is modified by fish and hence different than the surrounding substrate, and suggested that any measurements associated with salmonid embryo survival must be taken directly in the egg pocket. However, the installation of the Mark VI standpipe alters the substrate at the point of measurement, which would destroy the natural egg pocket construction and perhaps also cause unnatural mortality of eggs (Anderson, 1983). Ottaway (1981) reported that natural egg pockets were very difficult to locate, which would make measurements in the egg pocket difficult regardless of technique.

Finally, the effect of IWV on salmonid embryos is not well described. For example, Dechant (1979) found that IWV's ranging from 0.5 to 99.0 cm/h had no effect on survival of chinook salmon (Oncorhynchus tshwaytscha) embryos, while Reiser and White (1981) reported 50% mortality of eyed and green steelhead eggs at 100 and 400 cm/h, respectively. Interactions with dissolved oxygen (Shumway, et al. 1964; Turnpenny and Williams 1980), variable effects on different stages of embryo development, and unreliable measurement techniques all contribute to the poor understanding of the effect of IWV on salmonid embryos. In fact, the effects of IWV on embryonic salmonids may often be overshadowed by post-emergence factors, ie. floods, competition, and predation. Anderson (1983) abandoned intragravel monitoring of brown trout redds, reporting that flood severity and timing in relation to fry emergence was the primary force in limiting abundance of young trout. We conclude that the effect of IWV on salmonid embryos is not currently understood or quantified well enough for IWV to form a basis for management decisions.

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References

Anderson, D.W. 1983. Factors affecting brown trout reproduction in southeastern Minnesota streams. Minnesota Department of Natural Resources, Division of Fish and Game, Completion Report 376.

Bouwer, H. 1978. Groundwater Hydrology. McGraw-Hill Book Company, New York.

Bovee, K.D., and T. Cochnauer. 1977. Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments: fisheries. Cooperative Instream Flow Service Group, Fort Collins, Colorado. FWS/OBS-77/63. Instream Flow Information Paper No. 3.

Carling, P.A., and P. Boole. 1986. An improved conductiometric standpipe technique for measuring interstitial seepage velocities. Hydrobiologia 135:3-8.

Chapman, D.W., and K.P. McLeod. 1987. Development of criteria for sediment in the northern Rockies ecoreqion. U.S. Environmental Protection Agency, Water Division, Seattle, Washington. EPA 910/9-87-162.

Coble, D.W. 1961. Influence of water exchange and dissolved oxygen in redds on survival of steelhead trout embryos. Transactions of the American Fisheries Society 90:469-474.

Cooper, A.C. 1965. The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin. International Pacific Salmon Fisheries Commission Bulletin 18.

Davis, S.N., G.M. Thompson, H.W. Bentley, and G. Stiles. 1980. Ground-water tracers - a short review. Ground Water 18:14-23.

Dechant, T.F. 1979. Relationships between the intragravel environment and egg and alevin mortality in three southern Appalachian trout streams. M.S. Thesis, Western Carolina University.

Hansen, E.A. 1975. Some effects of groundwater on brown trout redds. Transactions of the American Fisheries Society 104:100-110.

Klassen, H.D., and T.G. Northcote. 1988. Use of gabion weirs to improve spawning habitat for pink salmon in a small logged watershed. North American Journal of Fisheries Management

8:36-44.

Lee, D.R., and J.A. Cherry. 1978. A field excersize on groundwater flow using seepage meters and mini-piezometers. Journal of Geological Education 27:6-10.

Ottaway, E.M., P.A. Carling, A. Clarke, and N.A. Reader. 1981. Observations on the structure of brown trout, Salmo trutta Linnaeus, redds. Journal of Fish Biology 19:593-607.

Reiser, D.W., and R.G. White. 1981. Influence of streamflow reductions on salmonid embryo development and fry quality. Idaho Water and Energy Resources Research Institute, University of Idaho. Research Technical Completion Report Project A-058-IDA.

Shumway, D.L., C.E. Warren, and P. Doudoroff. 1964. Influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos. Transactions of the American Fisheries Society 99:342-356.

Sokal, R.R., and F.J. Rohlf. 1981. Biometry. W.H. Freeman and Company, San Francisco, California.

Sowden, T.K. 1983. The influence of groundwater and spawning gravel composition on the reproductive success of rainbow trout in an eastern Lake Erie tributary. M.S. Thesis, University of Waterloo, Ontario, Canada.

Sowden, T.K., and G. Power. 1985. Prediction of rainbow trout embryo survival in relation to groundwater seepage and particle size of spawning substrates. Transactions of the American Fisheries Society 114:804-812.

Terhune, L.D.B. 1958. The. Mark VI groundwater standpipe for measuring seepage through salmon spawning gravel. Journal of the Fisheries Research Board of Canada 15:1027-1063.

Turnpenny, A.W.H., and R. Williams. 1980. Effects of sedimentation on the gravels of an industrial river system. Journal of Fish Biology 17:681-693.

Turnpenny, A.W.H., and R. Williams. 1982. A conductiometric technique for measuring the water velocity in salmonid spawning beds. Water Research 16:1383-1390.

Wickett, W.P. 1954. The oxygen supply to salmon eggs in spawning beds. Journal of the Fisheries Research Board of Canada 11:933-953.

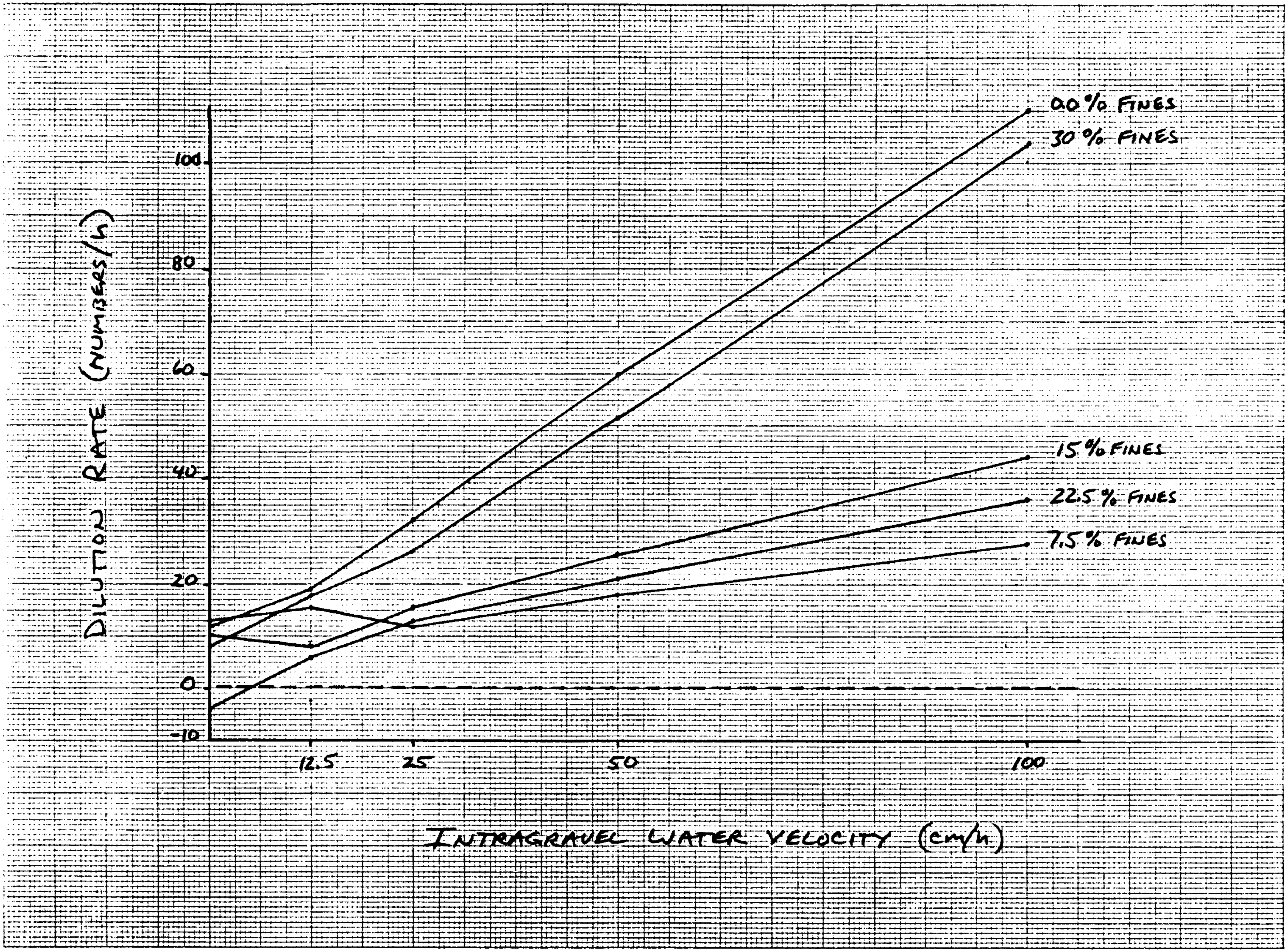
TABLE l.- Percent composition by weight of each particle size (material retained on sieve) of five gravel substrates used in open-trough permeameter experiments. The substrate designations (0.0 - 30.0) refer to the percent by weight of fines, where fines are all particles passing through a 3.4 mm sieve.

sieve size (mm)	Substrate composition (% fines)				
	0.0	7.5	15.0	22.5	30.0
50		2.0	1.8	1.7	1.5
25		28.0	25.7	23.5	21.2
12.5		37.0	34.0	31.0	28.0
9.5		9.8	9.0	8.3	7.5
6.3		9.8	9.0	8.3	7.5
3.4	100.0	5.9	5.4	4.8	4.3
1.7		3.5	7.0	10.5	14.2
0.85		2.0	4.2	6.2	8.2
0.42		1.4	2.7	3.8	5.1
0.21		0.5	1.0	1.5	2.0
0.10		0.1	0.2	0.4	0.5

TABLE 2.- Mean dilution rate (numbers/h) and 95% confidence interval (CI) for Mark VI standpipe measurements in five substrates at five intragravel water velocities (IWV, cm/h). Underlined means are not different at $P < 0.05$.

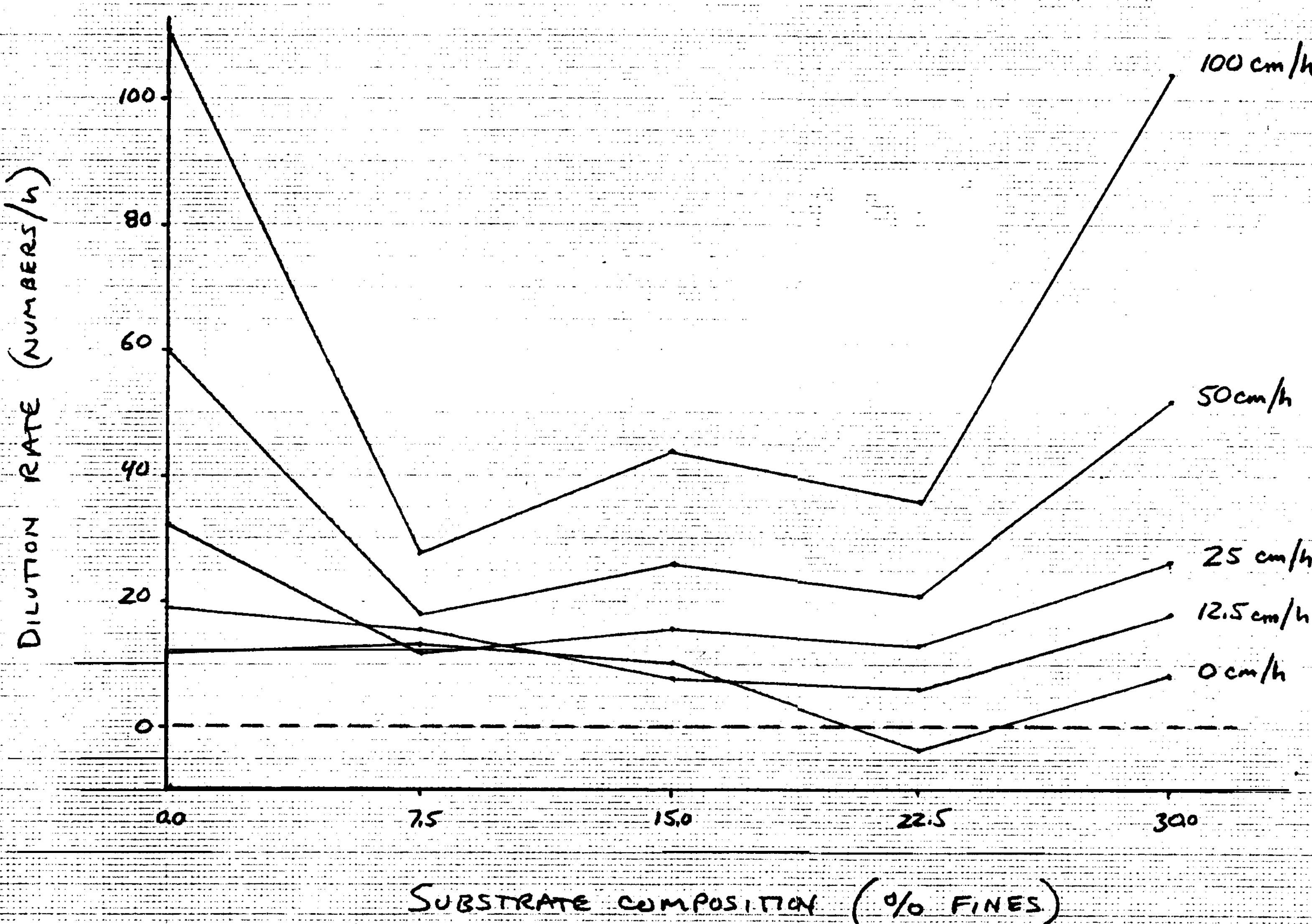
Substrate	Intragravel water velocity				
	0.0	12.5	25.0	50.0	100.0
0.0	12	19	32	60	110
	(12-12)	(16-22)	(24-41)	(51-69)	(99-122)
7.5	13	16	12	18	28
	(10-16)	(12-20)	(12-12)	(18-18)	(23-32)
15.0	10	8	16	26	44
	(8-12)	(3-13)	(12-20)	(24-28)	(41-47)
22.5	-4	6	13	21	36
	(-8-0)	(l-11)	(10-16)	(16-26)	(25-46)
30.0	8	18	26	52	104
	(4-12)	(18-18)	(22-30)	(45-58)	(93-114)

FIGURE l.- Effects of intragravel water velocity (IWV, cm/h) on dilution rate (numbers/h, Terhune 1958) in the five test substrates of 0.0, 7.5, 15.0, 22.5, and 30.0% fines.



DILUTION RATE (NUMBERS/h)
100
80
60
40
20
0
-10
12.5
25
50
100
INTRAGRAVEL WATER VELOCITY (cm/h)
0.0 % FINES
30 % FINES
15 % FINES
22.5 % FINES
7.5 % FINES

FIGURE 2.- Effect of five substrate compositions (% fines) on dilution rate (numbers/h, Terhune 1958) for five intragavel water velocities (0.0, 12.5, 25.0, 50.0, and 100.0 cm/h).



DILUTION RATE (NUMBERS/h)
100
80
60
40
20
0
0.0
7.5
15.0
22.5
30.0
SUBSTRATE COMPOSITION (% FINES)
100 cm/h
50 cm/h
25 cm/h
12.5 cm/h
0 cm/h