North American Journal of Fisheries Management 16:167–174, 1996
American Fisheries Society 1996

Evaluation of an Ion Adsorption Method to Estimate Intragravel Flow Velocity in Salmonid Spawning Gravel

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Abstract.—Intragravel water exchange provides oxygenated water, removes metabolic waste, and is an essential factor in salmonid embryo survival. Measurements of intragravel flow velocity have been suggested as an index of gravel quality and also as a useful predictor of fry emergence; however, proposed methods for measuring velocity in gravel are problematic. We evaluate an ion adsorption technique that uses natural streamwater solute chemistry, which therefore does not require introduction of a dye or solute tracer. However, the method requires an access tube for placing an ion exchange resin bag in the substrate. Our studies suggest that the ion adsorption technique is sensitive and reproducible for measuring velocity in free-flowing water but has little utility for measuring velocity in gravel beds. Fine sediment provided a relatively high flux density of adsorbed cations that exchanged readily with the resin, leading to spurious high apparent velocities.

Conditions in the intragravel environment are critical to the incubation of salmonid embryos and alevins. Spawning salmonids excavate redds and bury fertilized eggs in one or more pockets in stream gravel (Burner 1951; Chapman 1988). The eggs incubate in the gravel until hatching. After hatching, alevins remain in the intragravel environment and may move within the substrate before emergence (Phillips and Koski 1969). Gustafson-Marjanen and Dowse (1983) reported that Atlantic salmon *Salmo salar* fed on insect larvae in the substrate before emergence. Fry typically emerge after their yolk sacs are absorbed. Several interrelated intragravel variables including the dissolved oxygen concentration, biochemical oxygen demand (BOD), temperature, interstitial space, and velocity of water flowing through the redd influence successful incubation (Bjornn and Reiser 1991). Literature addressing the intragravel environment of incubating embryos indicates that survival relates positively to both the dissolved oxygen concentration and the velocity of water moving past embryos (Chapman 1988). Oxygen is essential to developing embryos, and flowing water affects oxygen concentration by delivering oxygenated water and removing metabolic wastes (Coble 1961; Cordone and Kelley 1961).

Increased fine sediment in stream gravel can be detrimental to salmonid embryo survival. Increased fine sediment in redds and surrounding gravel decreases porosity and pore size within the gravel matrix and may reduce intragravel water exchange, thereby reducing dissolved oxygen concentrations, increasing concentrations of metabolic wastes, and restricting movement of alevins (Bjornn and Reiser 1991). With reduced intragravel flow, eggs may suffocate because of insufficient aeration and the increased BOD of metabolic wastes. Sediments that impede emergence by blocking pore spaces will also reduce fry survival (Chapman 1988; Bjornn and Reiser 1991). Alevins that are unable to move will perish as their yolk sac is absorbed. Existing literature supports the hypothesis that embryo survival declines as quantities of fine sediment increase (Chapman 1988).

Scientists have attempted to measure intragravel flow (IGF) velocity and have suggested using IGF as an index of gravel quality and as a predictor of emergence success. Both vertical standpipes (Terhune 1958) and horizontal pipes (Hoffman 1986) have been inserted in stream gravel to facilitate sampling of IGF. Orchard (1988) reviewed literature on measurement of IGF and described four techniques: dye tracer, dye dilution, salt dilution, and self heating thermistor methods. According to Orchard, the first three techniques have proven difficult to replicate and interpret. These methods also require introducing a solute into the redd environment, which may be unacceptable for investigating sensitive fish species. The fourth method requires extensive calibration and remains under development. Orchard also described use of a commercial flowmeter. Although the flowmeter method demonstrated excellent reproducibility in the laboratory, both water temperature and substrate size influenced flow measurements.

As an alternative, we proposed introducing an ion exchange resin into the redd environment that would use the natural stream solute chemistry to index flow velocity. Similar resin bags have been

used to index plant-available nutrient quantities in soil (Skogley et al. 1990; Yang et al. 1991). In soil, the adsorption of ions by the resin is a diffusion-controlled process. In stream gravel, the amount of cations adsorbed on exchange resin placed in the redd environment is a function of time, solute concentration, temperature, and a transfer function. The transfer function is some combination of mass flow (i.e., IGF) and diffusion. On the basis of molecular diffusion coefficients, D, of salt in water (10^{-6}·cm^2/s < D < 10^{-4}·cm^2/s) and stream solute concentrations, diffusion becomes an important contributor to solute flux only when mass flow is very low (less than 0.3 cm/h). Initial laboratory experiments with stirred cell reactors suggested that temperature had little effect over the range of 5 to 35°C in a free-water environment. If stream solute chemistry changes little during an experiment (0.5–3 h), the equivalents of adsorbed ions would be strictly a function of IGF velocity in the vicinity of the resin bag and the time that the bag is in the water. With this conceptual model, a linear increase in adsorbed solutes is expected with increasing flow velocity until resin bag geometry or available exchange sites become limiting.

Study Areas

Three streams in southern Idaho were selected for field testing as part of a larger study designed to evaluate temporal changes in sediment intrusion, egg pocket characteristics, and survival to emergence in natural and artificial redds.

The Salmon River site is south of Stanley, Idaho, at 44°03′N, 114°48′W. The selected reach is a steelhead *Oncorhynchus mykiss* spawning ground. The watershed above this site is primarily underlain by Mesozoic granitic rock with lesser Paleozoic marine sediments (Worl et al. 1991) from which the streambed gravels are derived. Total dissolved solids in the sample stream reach were 68 mg/L during the first experiment and 86 mg/L during the second.

The Pine Creek site is tributary to the South Fork Snake River, 43°35′N, 111°16′W, near Swan Valley, Idaho. This reach is a Yellowstone cutthroat trout *Oncorhynchus clarki bouvieri* spawning ground (Thurow and King 1994). Pine Creek drains Mesozoic sandstone, shale, calcareous shale, and limestone (Mitchell and Bennett 1979). Total dissolved solids were 150 mg/L during the first experiment and 197 mg/L during the second.

The Payette River site is north of McCall, Idaho, on the North Fork Payette River, 45°04′N, 116°03′W. This reach is a kokanee *Oncorhynchus nerka* spawning ground. The Payette River at this location drains Mesozoic granitic rock of the Idaho Batholith (Fisher et al. 1983). Total dissolved solids were 30 mg/L during the first experiment and 20 mg/L during the second.

Methods

The resin used was Amberlite IRN-150 (Rohm and Haas Co., Philadelphia, Pennsylvania), a monobed ion exchange resin with a particle size ranging from 16 to 50 mesh (0.3–1 mm in diameter). The resin contains one equivalent of hydrogen for each equivalent of hydroxide and has an exchange capacity of 0.55 meq/mL of wet resin. We constructed spherical bags containing 3 g of dry resin (about 9 mL volume of wet resin) enclosed in 92-mesh polypropylene fabric. The bags were soaked in deionized water (DI) and degassed under a vacuum to remove entrapped air bubbles that occluded flow to the resin surface, then stored in 300-mL wide-mouth jars in DI water until used.

Laboratory experiments.—Laboratory adsorption studies were conducted in two cylindrical flumes with detachable endcaps, one with a radius of 15 cm and one with a radius of 5 cm. Uniform flow velocities as low as 0.01 cm/s could be maintained in the larger flume and up to 3 cm/s in the smaller flume. Flow velocity was controlled with a series of inflow and outflow gate valves with a flowmeter attached at the inlet. We maintained pressure at approximately 0.11 MPa within the flume by observing water level in a standpipe. Bags were freely suspended from the midlength of the flumes to minimize turbulence and high velocity effects arising from water deceleration and acceleration at the inlet and outlet ends. We also compared ion adsorption by freely suspended bags to bags enclosed in stainless steel tea strainers. We abandoned the latter technique because those results were more variable and always lower in adsorbed cations. All results reported are for free bags.

Adsorption studies were run at times ranging from 30 to 180 min and at flow velocities ranging from about 0.01 to 1.9 cm/s. Velocities greater than 1.0 cm/s were analyzed but rejected because of high variability. Samples of outflow water were collected three or four times during experiments to provide information on background solute chemistry. Before extraction, resin bags were placed in 60-cm^3 plastic syringes and covered with 10 mL of 2 M HCl for 10 min. After the 10-min soaking, adsorbed cations were desorbed with a

TABLE 1.—Fractional composition by particle size-class for egg baskets at three sites.

Particle size-class (diameter, in mm) or statistic	Salmon River			Payette River		Pine Creek	
	Low	Natural	High	Natural	High	Natural	High
64–16	0.71	0.65	0.49	0.72	0.53	0.75	0.54
16–6.35	0.24	0.20	0.16	0.16	0.12	0.13	0.10
6.35–2	0.03	0.08	0.18	0.07	0.204	0.06	0.18
2–0.85	0.015	0.03	0.09	0.025	0.073	0.03	0.09
<0.85	0.015	0.04	0.09	0.025	0.073	0.03	0.09
Geometric mean	20.7	17.2	8.0	19.4	9.6	20.1	8.3
N	6	12	12	15	15	15	15

vacuum syringe extractor at an extraction rate of 1 mL/min. This process was repeated two more times with 10 mL of acid, and once with 20 mL of acid for a total extraction volume of 50 mL.

Originally, we extracted each bag twice, but further testing indicated that four extractions were required to remove 95% of the adsorbed cations. Desorbed cations were analyzed by flame emission (Na and K) and flame atomic absorption (Ca and Mg) spectrophotometry. Potassium and Mg were in far lower concentration than other ions in our source water and provided little information for calibration; therefore, they are not discussed in this paper.

Stream experiments.—At each study area, we constructed 30 artificial redds at randomly selected locations by excavating a depression in the substrate gravel with a shovel. Gravel was repeatedly lifted into the current and released, creating a depression (pit) and downstream mound (tailspill). We attempted to mimic the dimensions of natural salmonid redds that were previously measured in the study areas. After excavation, we inserted a basket filled with substrate about one-third of the way up the leading edge of the tailspill to represent the egg pocket. These "egg baskets" were similar to those described by Maret et al. (1994) and were constructed of extruded polyvinyl chloride netting with a mesh diameter of 2.4 mm. We used egg baskets 20 cm tall by 15 cm diameter at the Pine Creek and Payette River sites, and egg baskets 30 cm tall by 15 cm diameter at the Salmon River site. Copper tubes of sufficient diameter to admit the resin bags were placed in the distal (downstream) side of each egg basket during construction and sealed with a rubber stopper.

Substrate composition and particle size distribution of the egg basket and surrounding gravel varied from site to site. We used the percentage of particles smaller than 6.35 mm as an index of fines after Stowell et al. (1983), who used that size as an index of gravel quality. We also report the percentage of particles less than 2 mm and less than 0.85 mm. Embryo survival has been negatively correlated with fine sediments of various sizes, ranging from less than 0.85 to 9.5 mm (Tappel and Bjornn 1983; Chapman 1988; Bjornn and Reiser 1991). Sediment sizes less than 0.85 mm may primarily influence permeability compared to sediments from 0.85 to 9.5 mm that primarily influence interstitial spaces (Kondolf 1988). The target percent fines in egg baskets were based on existing literature describing the "natural" fines in strata containing eggs in steelhead redds (Thurow and King 1991) and kokanee redds (Fraley and Graham 1982). Natural percent fines in cutthroat trout redds were based on freeze-cored samples we collected in Pine Creek in 1991. The size of coarse gravel used in the mixes ranged from 6.35 to 64 mm and was distributed in approximate proportion to natural substrate at each site (Table 1). Gravel used in redd and egg basket construction was gathered locally from each site to match natural angularity and chemistry of the substrate.

We placed additional substrate with the same particle size distribution as the egg basket mixture in and around the egg basket at the Salmon River and Pine Creek sites. This substrate was added to provide a buffer of identical material around the basket. The redd surface was reshaped after the baskets were placed in position.

The IGF velocities were sampled twice in each redd—a day after construction, which was about the time of natural redd construction, and a later date that corresponded with fry emergence. For steelhead at the Salmon River site, the two dates were April 29–30 and June 22–23, 1992; for cutthroat trout at Pine Creek, May 20 and June 9, 1992; and for kokanee at the Payette River, September 17, 1992 and March 30, 1993.

To sample IGF, resin bags were placed in the copper tubes protruding from each egg basket, pushed to the substrate, and held on gravel at the bottom of the tube with a tube with smaller di-

TABLE 2.—Regression equations of total milliequivalents of Na and Ca adsorbed as a function of flume flow velocity (v, cm/s). Equations are of the form: Na or Ca = $b_0 + b_1 v$; MSE is mean squared error of the regression.

Cation	Time (h)	b_0		b_1		r^2	MSE	N
		Value	SE	Value	SE			
Na	0.5	0.0073	0.00061	0.019	0.0014	0.91	4.1 E−6	21
	1	0.0096	0.00080	0.040	0.0021	0.94	9.4 E−6	25
	2	0.019	0.0019	0.123	0.0133	0.77	2.7 E−5	27
	3	0.027	0.0037	0.169	0.0274	0.56	1.1 E−4	30
Ca	0.5	0.005	0.00083	0.0024	0.0019	0.65	7.69 E−6	21
	1	0.0032	0.00049	0.021	0.0013	0.92	3.51 E−6	25
	2	0.037	0.0037	0.053	0.0267	0.13	1.1 E−4	27
	3	0.043	0.0054	0.134	0.0390	0.27	2.2 E−4	30

ameter. The copper tubing was simultaneously withdrawn 2–4 cm to expose the resin to unrestricted intragravel flow. After a predetermined time, the bags were retrieved by attached thread, rinsed for 1 min with DI water, placed in jars, and placed in a cooler to be returned to the laboratory for extraction. The duration of the experiments varied from 2 to 3 h because of differences in solute chemistry of streams, except for the second Payette River experiment which was run for 0.5 h. Extraction and analyses were performed as described for laboratory flume studies.

At each field location, in addition to the bags placed in the gravel, 10 bags were suspended in the free-flowing stream for 30 min, five at relatively rapid flow and five at a lower apparent flow velocity. Six samples of streamwater were collected during the experiment to determine solute chemistry. During the first Pine Creek and Payette River experiments, IGF water was sampled with a vacuum pump through plastic probes installed in the redds to sample water for dissolved oxygen, but there were no differences in cation concentrations between the water column and IGF water, so this practice was abandoned. After bags were recovered from the egg basket access tubes, flow velocity in the water column above each egg basket was determined with a Marsh–McBirney flowmeter. Height of the water column above the gravel surface and height above the bag were also measured as covariates. After the IGF samples were taken, each egg basket was freeze-cored with the tri-tube method of Everest et al. (1980), and the recovered gravel was sieved to obtain a particle size distribution.

Data analysis.—The relation between amount of cation adsorbed and flow velocity for all flume experiments was established by least-squares regression analysis. Prediction equations for IGF velocities are regressions on amount of cation adsorbed. We tested the effect of percent fines on amount of cations adsorbed and IGF velocity by comparing the 95% confidence interval about the mean based on a t-distribution with $n - 1$ degrees of freedom. To test for changes in particle size in egg basket sediment from the first to second field test, an unpaired two-tailed t-test ($P = 0.95$) was used.

Results

Flume Studies

Total milliequivalents of Na and Ca adsorbed on resin bags were significantly ($P < 0.001$) related to flow velocity for each experimental period (Table 2). Variability increased distinctly for experiments of longer duration. Higher velocities, longer residence times, or both resulted in nonlinear adsorption, possibly as the exchange complex approached saturation (Figure 1; Table 2). Nonlinearity and variability were greater for Ca adsorption. We also tested the sum of Na + Ca adsorbed because the proportion of those ions in our source water varied from experiment to experiment, but this did not improve the strength of the regressions. Relations between adsorbed cations and flow velocity were much stronger for Na than Ca for 2- and 3-h experiments (Table 2).

Solute chemistry varied from experiment to experiment as a result of natural chemical variability in the source water. A normalization procedure was applied to see if the strength of the regression equations could be improved if solute concentration differences were accounted for. The normalization procedure used the transform:

$$M_{\text{ads(norm)}} = M_{\text{ads}(i)} \times [M]_{\max}/[M]_{(i)};$$

$M_{\text{ads(norm)}}$ is normalized milliequivalents of Na or Ca adsorbed; $M_{\text{ads}(i)}$ is measured milliequivalents adsorbed for experiment i; $[M]_{\max}$ is the maximum

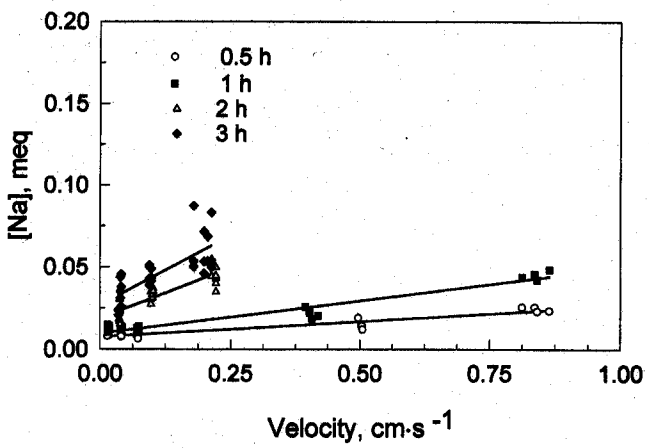

FIGURE 1.—Plot of total milliequivalents of Na adsorbed versus flume water velocity for 0.5-, 1-, 2-, and 3-h experiments. Lines are linear least-squares regressions of milliequivalents adsorbed versus velocity.

solute concentration of Na or Ca; and $[M]_{(i)}$ is mean solute concentration during experiment *i*. The normalization procedure had the greatest influence for 3-h experiments because these experiments had the largest differences in solute chemistry (Table 3). The r^2 for the 3-h Na experiments improved from 0.56 to 0.74 with normalized data. There was little improvement in regressions of adsorbed Ca on velocity with normalization (data not shown).

To use this method for measuring IGF, we were interested in calibration curves of velocity as a function of amount of cations adsorbed. Velocity over the range 0 to 1 cm/s is linearly related to adsorbed Na (Figure 2), and Table 4 displays regression equations of velocity on adsorbed Na. The accuracy of the prediction of velocity declines with 2- and 3-h experiments. Because of the design of the flume experiments, velocities are assumed to be measured without error, so the mean squared error term of these regressions is meaningless. However, given the precision of Na analysis and our ability to achieve replicated values from paired samples, we estimate that we can discriminate velocity differences of 0.2 cm/s over the range 0 to 1 cm/s for 0.5- and 1-h experiments using adsorbed Na.

TABLE 3.—Regression equations of adsorbed Na, normalized to account for differences in dissolved Na concentrations in flume water among experiments, as a function of flume flow velocity (v, cm/s). Equations are of the form: $Na_{norm} = b_0 + b_1 v$; MSE is mean squared error of the regression.

Time	b_0		b_1			
(h)	Value	SE	Value	SE	r^2	MSE
0.5	0.009	0.0008	0.024	0.0018	0.90	7.06 E−6
1	0.004	0.0009	0.050	0.0023	0.95	1.15 E−5
2	0.026	0.0026	0.173	0.018	0.76	5.40 E−5
3	0.031	0.0086	0.581	0.063	0.74	5.60 E−4

Field Studies

For all experiments combined and all gravel mixes, the mean calculated velocity was 590 cm/h with the Na equations from Table 4. Estimated velocities at each site ranged from a low of 36 to a high of 1,040 cm/s, and the 90th percentile velocity for three of the six experiments exceeded 2,000 cm/s. In contrast, bags suspended in free-flowing streamwater at each site adsorbed cations in proportions comparable to those of flume experiments. This suggests that in-gravel placement greatly enhanced cation adsorption. As explained previously, intragravel water solute concentrations were not significantly different from solute concentrations in free-flowing streamwater above the gravel.

We hypothesized that increased percentages of fines in the substrate would decrease pore size and porosity and would therefore reduce IGF velocities. For three of the six experiments, adsorbed Na increased significantly ($P < 0.05$) with increasing percentages of fines in the artificial gravel mixes (Figure 3). The expected trends of decreased cation adsorption with increasing fines were not significant in any of the experiments.

The second sampling at each site was conducted to evaluate the effect of sediment recruitment into the artificial redds during egg incubation. The proportion of particles in the fraction less than 2.00

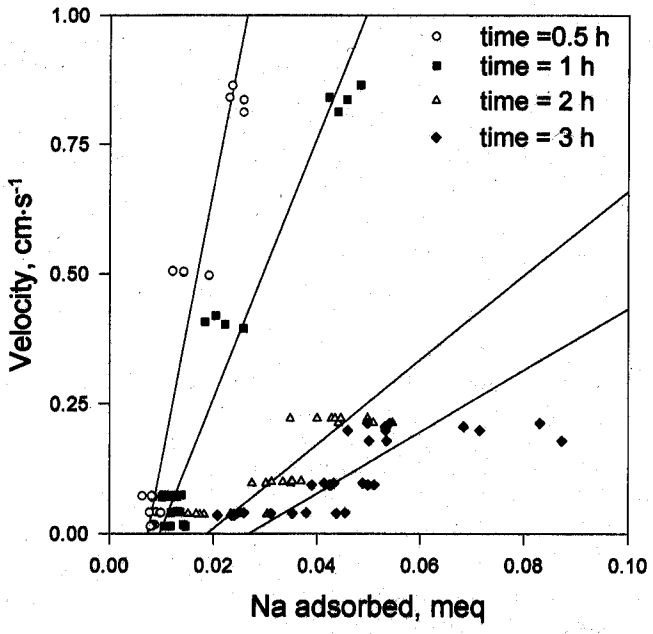

FIGURE 2.—Velocity plotted as a function of Na adsorbed. Data are presented for all experiments for which velocity is less than 1 cm/s. Lines are least-squares regressions of velocity on milliequivalents of Na adsorbed.

mm increased significantly at the Salmon River site; however, this fraction showed net losses at the other two sites. The amount of adsorbed Na decreased significantly from the first to second sampling period at the Pine Creek and Payette River sites and did not change at the Salmon River site (Figure 3).

Discussion

The unexpectedly high calculated IGF velocities are considerably higher than those reported in the literature. Coble (1961) reported apparent IGF velocities as high as 110 cm/h, and Orchard (1988) reported velocities in excess of 150 cm/h. Our high values, coupled with the lack of significant decreases in cation adsorption with increasing percentages of fines, suggest that ion adsorption in the gravel environment was not solely a function of mass flow. Several experiments showed a trend of increasing adsorbed Na with increasing fines (Figure 3). One explanation for this trend is that increasing percentages of fine gravel include larger proportions of silt and clay-sized particles that provide exchangeable cations when directly in contact with the resin bags. This would also explain why the adsorbed Na on all bags placed in the substrate was high, resulting in extremely high calculated IGF velocities. In addition, there were significant decreases in percent fines at the Pine Creek and Payette River sites between the first and second experiments, and this corresponded with lower cation adsorption. This is consistent with the idea that fine sediment contributes adsorbed Na and may mask the effects that fine sediment has in reducing IGF. Withdrawing the copper tubing to the top of the bag during field experiments may have affected the pore size in direct contact with the perimeter of the bag; however, this should not have changed pore geometry in the surrounding gravel matrix and therefore had no effect on IGF velocities.

The resin bag technique for determining IGF velocities appears to have little utility, at least in streams that have fine sediment in the substrate. We tested resin bags enclosed in stainless steel tea strainers during flume experiments, but we found

TABLE 4.—Regression equations of velocity (v, cm/s) on adsorbed milliequivalents of Na for experiments with velocity less than 1 cm/s. Equations are of the form: $v = b_0 + b_1\text{Na}$; MSE is mean squared error of the regression.

Time (h)	b_0		b_1		r^2	MSE
	Value	SE	Value	SE		
0.5	−0.33	0.051	48.1	3.52	0.91	0.0103
1	−0.21	0.028	23.7	1.25	0.94	0.0055
2	−0.09	0.024	6.27	0.677	0.77	0.0014
3	−0.04	0.027	3.50	0.551	0.58	0.0021

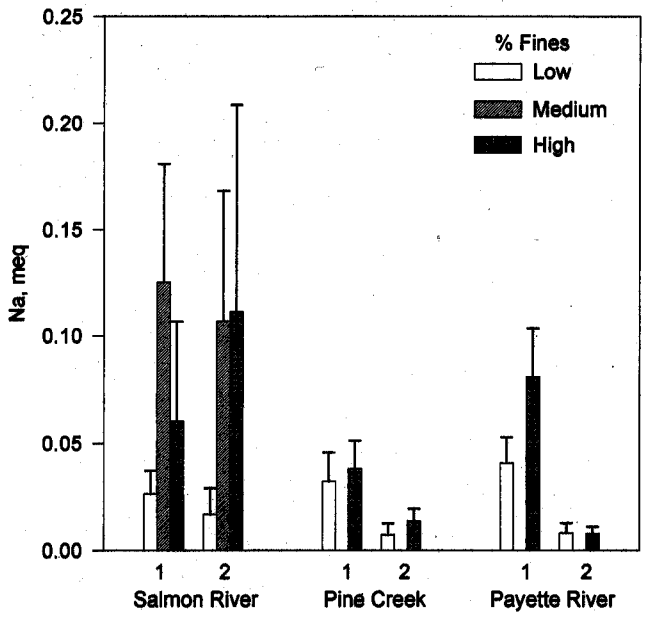

FIGURE 3.—Mean milliequivalents of Na adsorbed by percentage of fines (<6.35 mm) for the first (1) and second (2) experiments at the three field sites. Error bars are half the 95% confidence intervals about the mean.

that enclosing bags always decreased the amount of ion adsorption compared to that of nonenclosed bags. We do not think it is feasible to isolate the resin bags from fine particles in the gravel environment without greatly restricting the movement of water. At low-flow velocities, resin bag adsorption of cations is linearly correlated with flow in free-flowing water; however, current meters would be the preferred method for determining velocity in these situations. The fact that variability in ion adsorption increased with duration of the experiments suggests that as exchange sites on the outer sphere of the bag are saturated, bag geometry and resin particle packing affect flow to inner particles. Experiments of short duration can overcome this to some degree. This problem would be minimized at very low velocities, but diffusion may control rates of adsorption when flow velocity is less than 0.3 cm/h. After comparing results of numerous experiments conducted in laboratory flumes and free-flowing streamwater to intragravel experiments, we believe that the most likely factor confounding the estimation of IGF by ion adsorption is the presence of fine sediment that has a relatively high flux density of adsorbed cations that exchange readily with the resin.

Acknowledgment

The use of trade or firm names in this paper does not imply endorsement by the U.S. Department of Agriculture.

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