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Substrate Composition and Emergence Success of Fall Chinook Salmon in the Snake River

Abstract

The percentage of fine sediment particles in stream channel substrate is inversely related to emergence success of chinook salmon embryos. We used a previously published method to relate substrate composition at seven fall chinook salmon spawning sites in the Snake River implicitly to emergence success. We used dome suction to sample substrate at four spawning sites in the upper reach of Snake River and three in the lower reach. Mean percent fines < 6.4 mm and < 0.85 mm were less in upper reach samples than in lower reach samples. In laboratory tests, mean emergence success decreased from 47% to 10% as the mixtures of percent fines < 6.4 mm and < 0.85 mm increased in substrate mixtures. A regression equation developed from the laboratory data to predict mean emergence success from mean percent fines < 6.4 mm and < 0.85 mm had an r^2 value of 0.94. Predicted emergence success based on substrate composition in the Snake River ranged from 46% to 48% for sites in the upper reach, and from 29% to 47% for sites in the lower reach. These predictions of emergence success are slightly higher than those reported in the literature for chinook salmon spawning habitat. Based on the combination of field and laboratory findings, we conclude that substrate composition at the seven spawning sites we studied in the Snake River should not limit fall chinook salmon production.

Introduction

During spawning, adult chinook salmon (*Oncorhynchus tshawytscha*) excavate nests in the stream bed referred to as redds. Substrate particle size in combination with certain hydraulic conditions are required to provide an ideal environment for redd construction and the incubation of chinook salmon embryos (Reiser and Bjornn 1979). Snake River fall chinook salmon typically construct redds in relatively homogenous substrate with particle diameters of 2.5 to 15.0 cm, in water depths of 0.2 to 6.5 m, and mean water column velocities of 0.4 to 2.1 m/s (Groves and Chandler 1999).

High concentrations of fine sediments in channel substrates where redds are constructed can reduce the percentage of salmonid embryos that survive to emergence (hereafter, emergence success). The causal mechanisms for reduced emergence success associated with increases in fine sediments were reviewed in detail by Bjornn and Reiser (1991). Excessive fines in the substrate can decrease permeability and water velocity to embryos. Decreased flow through the substrate reduces oxygen availability to embryos and slows

removal of toxic metabolic wastes. Fry can also be entrapped when fine sediments are lodged in substrate interstices (Waters 1995). Emergence success has been quantified in laboratory channels (McCuddin 1977, Tappel and Bjornn 1983) and in the field (Burner 1951, McNeil and Ahnell 1964); each method has its advantages and disadvantages (Chapman 1988).

In general to assess substrate quality, gravel samples are collected within spawning areas (Tappel and Bjornn 1983). Individual samples are shaken through a stack of U.S. standard sieves (mesh size decreases from the top to bottom sieve). The percentage of the material (by weight) that passes through each of the sieves is then calculated to describe the cumulative particle size distribution for each sample. The percentages are then averaged by sieve size for all samples collected at a site to represent spawning gravel quality. Tappel and Bjornn (1983) found that the mean percentages of material that passed through the 9.5 mm and 0.85 mm sieves (i.e., two of the finer sediments) could be used in a second-order regression equation to explain 93% of the observed variability in mean emergence success of chinook salmon fry in the South Fork Salmon River (Figure 1). The findings of Tappel and Bjornn (1983) allowed biologists to relate the percentage of fine sediments

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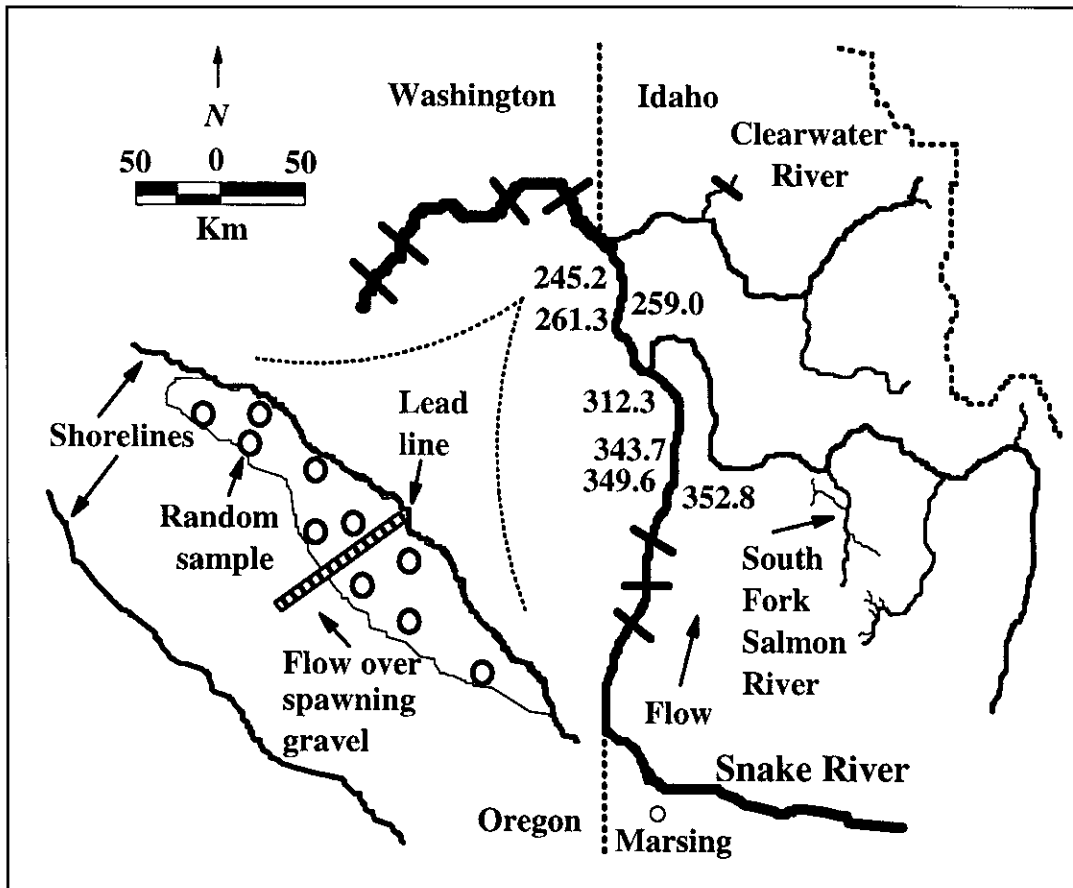


Figure 1. The Snake River where fall chinook salmon spawn including the approximate locations of our seven study sites (shown as the number of kms from the river mouth), the location of the South Fork Salmon River where Tappel and Bjornn (1983) conducted their study, and an inset showing an aerial view of the study site at rkm 245.2 with a marked lead line used to locate random substrate samples.

implicitly to emergence success by using only two particle sizes observed in substrate samples.

Information on substrate composition at fall chinook salmon spawning sites in the Snake River, and on emergence success at these sites, was needed to assess the potential for population recovery. A study on redd capacity indicated that the Snake River could support the 1,250 fall chinook salmon redds needed to meet the population recovery goal (Connor et al. 2001). When estimating redd capacity, however, it was assumed that substrate composition at fall chinook salmon spawning sites would not limit emergence success (Connor et al. 2001).

We use a modification of the method developed by Tappel and Bjornn (1983) to evaluate substrate composition at seven fall chinook salmon

spawning sites in the Snake River. We report the results of laboratory tests on the effect of substrate composition on emergence success of fall chinook salmon embryos, and then use the laboratory findings to predict emergence success from the percentages of two sediment sizes measured in random substrate samples collected at the seven spawning sites.

Study Area

Fall chinook salmon once spawned from Marsing Idaho to the Snake River mouth, but dam construction eliminated much of the historical spawning habitat (Figure 1). For a detailed description of the historical and present distribution of Snake River fall chinook salmon spawners and their habitat, we refer readers to papers by Groves and

Chandler (1999), Dauble and Geist (2000), Connor et al. (2001), and Garcia et al. (2001). The Snake River can be divided into three reaches based on differences in channel morphology and discharge. Between 1986 and 2000, there were 78 documented spawning sites in the upper reach, 11 in the middle reach, and 28 in the lower reach (Garcia et al. 2001). We studied four spawning sites in the upper reach and three in the lower reach. We identified sites by the distance they were located from the mouth of the Snake River (rkm).

Methods

We obtained study site maps including the locations of redds and suitable-sized spawning substrate from Connor et al. (2001). We placed a numbered grid over each site map, and then selected 10 random sampling locations to depths utilized by spawners (Groves and Chandler 1999; Figure 1). In 1994 and 1995, divers identified the sample locations at each of the seven spawning sites in two steps. First, the distance the sample was located from the upstream edge of the gravel was measured along the shoreline. Second, the distance the sample was located offshore was measured by using a lead line marked at 10-m intervals placed perpendicular to the current (Figure 1). Substrate composition at each location was sampled by using a dome suction sampler (Gale and Thompson 1975).

Substrate samples were dried, weighed (g), and shaken through a U.S. standard sieve series (mesh sizes: 75, 50, 25.4, 12.5, 9.4, 6.4, 4.8, 3.4, 2.0, 0.85, 0.5, and 0.25 mm). The percentage of the substrate (by weight) in each sample that passed through each sieve was calculated as the weight

of the material that passed divided by total sample weight. The sample results were used to calculate a mean percentage for each sieve size by spawning site. We selected the mean percentage of the substrate that passed the 6.4 mm and 0.85 mm sieves to relate the percentage of fine sediments to emergence success. We selected these particle sizes instead of 9.5 mm and 0.85 mm used by Tappel and Bjornn (1983) because mixtures of 6.4 mm and 0.85 mm sediments were well represented at the spawning sites and in our laboratory troughs.

We evaluated emergence success in the laboratory in 1996 by using eight substrate mixtures (Table 1) like those found in the seven spawning sites in the upper and lower reaches of the Snake River. Each of 48 wooden troughs (121.9 cm length x 30.5 cm wide x 30.5 cm deep) (Tappel and Bjornn 1983) was filled to a depth of 25 cm with one of the eight mixtures to provide six replicates per mixture. Each substrate mixture was labeled according to its percent fines < 6.4 mm and < 0.85 mm. Substrate mixtures were randomly assigned to each trough.

Eggs from three female and milt from five male fall chinook salmon were brought to our laboratory from Lyons Ferry Hatchery, Washington. To prevent bias resulting from differences in gamete viability, we fertilized the eggs in the form of a 3 X 5 matrix (female 1 with male 1, 2, 3, 4, and 5; female 2 with male 1, 2, 3, 4, and 5; female 3 with male 1, 2, 3, 4, and 5). The fertilized eggs were water hardened and then randomly mixed. We placed 50 fertilized eggs into each of two 25 cm depressions in the substrate, and then gently covered the eggs with ambient substrate

TABLE 1. Mean size composition of substrate mixtures (n=6 replicates per mixture) used in laboratory tests. Each substrate mixture is labeled according to the percent fines < 6.4 mm and < 0.85 mm. For example, 14:4 means that 14% of the mixture was smaller than 6.4 mm and 4% was smaller than 0.85 mm.

Substrate Mixture	Percentage smaller than the given particle size									
	25.4	12.5	9.4	6.4	4.8	3.4	2.0	0.85	0.5	0.25
2:0	82.4	37.1	19.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
9:2	85.8	43.8	25.7	9.0	5.8	4.5	3.3	2.0	1.2	0.4
14:4	96.5	52.6	33.1	13.8	9.8	8.0	6.1	3.8	2.5	0.9
21:9	95.0	54.8	38.5	20.7	17.5	15.5	12.7	8.6	5.3	1.8
24:11	90.3	54.5	38.8	24.2	21.7	19.4	15.9	10.8	6.3	2.1
29:11	98.1	61.9	44.5	29.1	24.1	20.4	16.2	10.7	6.3	2.2
33:15	89.5	58.0	45.6	33.4	31.1	28.0	23.0	15.3	8.4	2.8
34:12	99.8	66.2	49.8	33.6	27.7	23.4	18.4	12.1	7.4	2.4

from the trough. Fungal (*Saprolegnia*) growths in troughs and control trays were treated with formalin.

Chilled, unchlorinated, recycled tap water flowed laterally through the troughs. Flows were regulated by ball valves and determined by gradient differences between the inflow and outflow sources. A 2% gradient was maintained where possible. Apparent velocity (cm/s) was measured weekly based on the volume of water passing through each trough. Dissolved oxygen (mg/L) was measured periodically with a YSI model 57 meter (Yellow Springs Instruments, Yellow Springs, Ohio) in perforated PVC pipe (20 cm long x 1.8 cm diameter) placed in the middle of each egg pocket nearest the outflow (9.78 mg/L = 100% saturation). Water temperatures were recorded hourly with a RTM 2000 meter (Ryan Tempmator, Ryan Instruments, Redmond, Washington). We used ordinary least-squares regression to test the relation between mean percent fines < 0.85 mm, mean apparent velocity, and mean dissolved oxygen concentrations.

We removed and counted fry as they emerged from the substrate in each trough. We calculated emergence success in each trough as the proportion of fry that survived to emergence (n/100) and expressed this proportion as a percentage.

We used the data from our laboratory tests to develop second-order regression equations relating mean percent fines < 6.4 mm ($S_{6.4}$) and < 0.85 mm ($S_{0.85}$) to mean emergence success as described by Tappel and Bjornn (1983). Second-order terms ($S_{6.4}^2$, $S_{0.85}^2$) and a cross-product term ($S_{6.4}S_{0.85}$) were analyzed to account for the curvilinear relation between substrate particle size and emergence success. The best second-order regression model was selected based on r^2 values.

The last step of our analyses was to predict emergence success ($\pm 95\%$ prediction intervals) for embryos at each of the seven spawning sites. We made these predictions by using the mean values of percent fines < 6.4 mm and < 0.85 mm from the substrate samples collected at the sites into the best second-order regression equation.

Results

Mean percent fines < 6.4 mm measured in the substrate samples from the seven spawning sites in the Snake River ranged from 6.7% to 19.8% (Table 2). Mean percent fines < 6.4 mm was low-

TABLE 2. Mean percent fines (\pm SE) calculated from substrate samples collected at known fall chinook spawning sites (rkm) in the upper and lower reaches of the Snake River, Washington, in 1994 and 1995.

	n	< 6.4 mm	< 0.85 mm
Upper Reach			
352.8	10	13.6 \pm 2.06	1.2 \pm 0.25
349.6	10	11.0 \pm 1.17	2.2 \pm 0.34
343.7	10	6.7 \pm 1.23	3.1 \pm 0.25
312.3	10	7.5 \pm 1.26	2.3 \pm 0.50
Lower Reach			
261.3	10	15.3 \pm 0.88	7.9 \pm 0.70
259.0	9	9.7 \pm 2.27	5.0 \pm 1.30
245.2	10	19.8 \pm 3.22	8.5 \pm 1.55

est at rkm 312.3 and highest at rkm 245.1. Mean percent fines < 0.85 mm measured in the substrate samples ranged from 1.2% to 8.5% (Table 2). Spawning sites in the upper reach of the Snake River had consistently lower mean percent fines < 0.85 mm than spawning sites in the lower reach. No significant relationship was found between percent fines < 0.85 mm and 6.4 mm.

Mean apparent velocities ranged from 0.96 cm/s in troughs with the 2:0 substrate mixture to 0.06 cm/s in troughs with the 34:12 substrate mixture. Apparent velocity was significantly negatively correlated with percent fines < 0.85 mm ($r = -0.93$; $P < 0.001$). Mean dissolved oxygen concentrations ranged from 10.0 mg/L in troughs with the 2:0 substrate mixture to 9.7 mg/L in troughs with the 34:15 substrate mixture. The significant correlation between mean dissolved oxygen concentration and percent fines < 0.85 mm was negative and relatively low ($r = -0.71$; $P = 0.048$). Mean water temperature was similar among the troughs and increased seasonally during the experiment (mean, 9.5°C; range, 5.9 to 15.7°C).

Mean emergence success in the laboratory troughs ranged from 7% to 51% (Table 3). Mean emergence success generally decreased as the mean percent fines < 6.4 mm and < 0.85 mm in the substrate mixtures increased (Table 3). The best second-order regression equation relating substrate composition to emergence success was: Emergence success = 46.643 + 1.194 $S_{0.85}$ - 0.111 $S_{6.4}S_{0.85}$ ($r = 0.97$; $P < 0.001$).

Predicted emergence success for embryos at the seven spawning sites in the Snake River was similar among sites, except for the relatively lower

TABLE 3. Mean predicted and observed emergence success (% ± SE, n = 6 replicates per substrate mixture) and 95% confidence limits for fall chinook salmon in laboratory incubation troughs in 1996. Results are presented by substrate mixture according to percent fines <6.4 mm and <0.85 mm. For example, 14:4 means that 14% of the mixture was smaller than 6.4 mm and 4% was smaller than 0.85 mm.

Substrate Mixture	Observed Emergence Success	Predicted Emergence Success		
		Predicted ¹	Lower Limit	Upper Limit
2:0	51 ± 6.1	47	38	55
9:2	45 ± 4.5	47	41	53
14:4	39 ± 4.5	45	40	51
21:9	38 ± 4.1	36	30	43
24:11	34 ± 6.1	31	24	37
29:11	26 ± 6.9	24	20	29
33:15	7 ± 4.1	10	2	17
34:12	16 ± 6.1	16	9	23

¹Emergence success = $46.643 + 1.194 S_{0.85} - 0.111 S_{6.4} S_{0.85}$ ($r = 0.97$; $P < 0.001$).

prediction for embryos at rkm 245.2 (Figure 2). Predicted emergence success of embryos ranged from 29% at rkm 245.2 to 48% at rkm 343.7.

Discussion

These results validate the method developed by Tappel and Bjornn (1983) for implicitly relating substrate composition to emergence success of chinook salmon embryos. The regression equation reported here for predicting emergence success was also similar to the regression equation reported by Tappel and Bjornn (1983). Both equations included the term $S_{0.85}$ and a cross-product term ($S_{9.5} S_{0.85}$ or $S_{6.4} S_{0.85}$), and both equations explained over 90% of the variability in mean emergence success of chinook salmon embryos.

Mean percent fines < 6.4 mm and < 0.85 mm differed among substrate samples collected at fall chinook salmon spawning sites in the upper and lower reaches of the Snake River. Substrate samples collected at spawning sites in the upper reach of the Snake River contained consistently lower mean percent fines < 0.85 mm than sites in the lower reach. A similar, but less distinct pattern was also observed for mean percent fines < 6.4 mm. Overall, the levels of fine sediment in substrate samples from all seven spawning sites in the Snake River were below those known to adversely affect

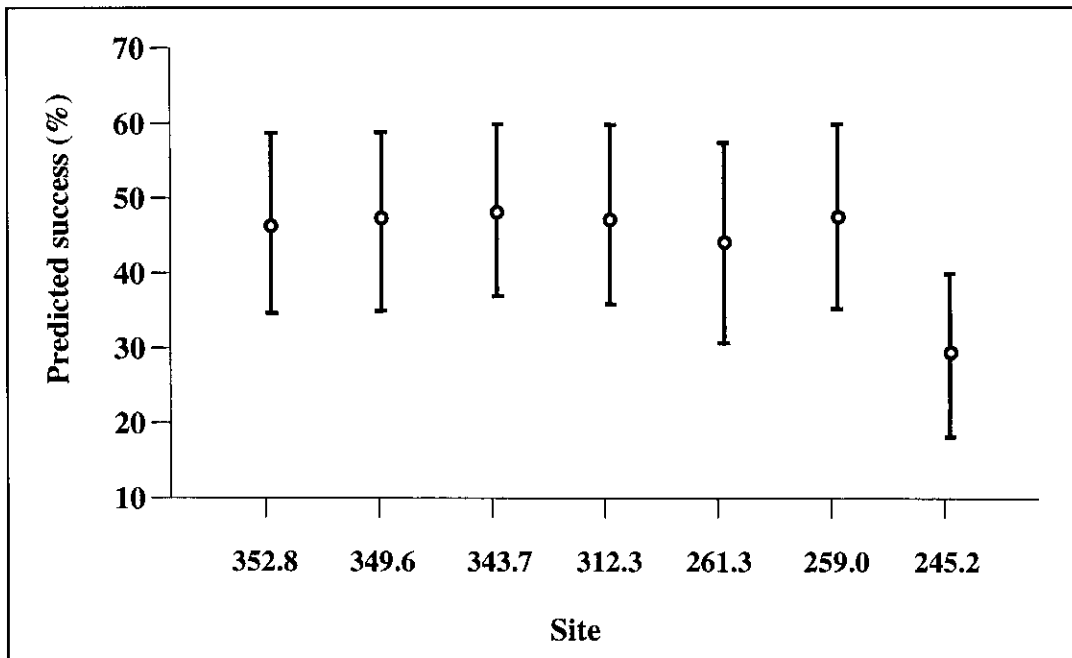


Figure 2. Emergence success (% ± 95% prediction interval) of fall chinook salmon embryos predicted from substrate composition of samples collected at each spawning site. Predictions were made by inputting the values for percent fines < 6.4 mm and < 0.85 mm for each site (Table 2) into the equation: Emergence success = $56.4 + 1.390 S_{0.85} - 0.132 S_{6.4} S_{0.85}$.

chinook salmon embryos (Bjornn 1969, McCuddin 1977, Chapman 1988, Bjornn and Reiser 1991).

Differences in sediment input and channel gradient are the most plausible explanations for differences in mean percent fines < 6.4 mm and < 0.85 mm in the substrate samples collected at spawning sites in the upper and lower reaches of the Snake River. The upper reach begins at Hells Canyon Dam (a sediment trap) (Goldman and Horne 1983), and the river in this reach does not receive sediment input from any large tributaries. Conversely, all of the spawning sites in the lower reach are located downstream of the Imnaha, Salmon, and Grande Ronde rivers. The channel gradient in the upper reach is also higher than in the lower reach (upper reach, 1.4 m/km; lower reach, 0.6 m/km) (Dauble and Geist 2000), which likely results in higher velocities and more efficient transport of fine materials.

Mean emergence success of fall chinook salmon embryos in our laboratory troughs decreased from 62% to 9% as mean percent fines < 6.4 mm and < 0.85 mm increased in the substrate mixtures. Dissolved oxygen concentrations in all troughs were above threshold levels for decreased embryo survival (Reiser and Bjornn 1979), yet the correlation between mean dissolved oxygen concentration and percent fines < 0.85 mm was significant. Also, apparent velocity was significantly correlated with percent fines < 0.85 mm, and apparent velocities measured in the substrate mixtures containing more than 10% fines < 0.85 mm were below safe thresholds for embryos survival (Reiser and Bjornn 1979). We found dead embryos entrapped in the substrate at termination of our experiment, but we could not count them because they were decomposed. We suspect mortality of embryos was largely related to the accumulation of toxic metabolites and embryo entrapment in the substrate.

The second-order regression equation we fit to relate substrate composition to mean emergence

success of fall chinook salmon embryos predicted slightly higher emergence success at upper reach sites (mean, 47%) than at lower reach sites (mean, 40%). This difference was caused by relatively low emergence success predicted for embryos at rkm 245.2 (29%). In his definitive review of chinook salmon life history, Healey (1991) concluded that chinook salmon emergence success was roughly 30% in 13 rivers studied. Embryos in the wild have the advantage of an incubation environment modified by spawners to decrease levels of fine materials and maximize substrate permeability (Burner 1951, McNeil and Ahnell 1964, Chapman et al. 1986, Chapman 1988), whereas embryos in laboratory troughs have the advantage of disease treatment and an environment relatively free of organic sediments (Tappel and Bjornn 1983). Acknowledging the potential for differences in emergence success in the wild and in the laboratory, predicted emergence success of fall chinook salmon embryos at six of the seven spawning sites in the Snake River was high by comparison to the 30% level reported by Healey (1991). Based on the combination of field and laboratory findings, we conclude that substrate composition at the seven spawning sites we studied in the Snake River should not limit fall chinook salmon production.

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