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Bibliography on Percent Fines in Stream Substrate as a Measure of Watershed Condition and Health

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Summary

A bibliography of the key literature addressing the effects of fine sediment in gravel substrate as a measure watershed health was compiled (see attached). The focus of the initial literature review was on the deleterious effects of fine sediment on either salmonid spawning success or macroinvertebrate production. From this initial bibliography, seven papers that focused on these issues were selected for review by Campbell Timber Company and are included in this annotated bibliography. Table 1 summarizes the major findings of the annotated bibliography.

Researchers have used two strategies to determine acceptable levels of fine sediment in spawning gravels: (1) determine the relationship between percent fine sediment and survival of eggs to emergence and set percent fines criteria based on a desired emergence success, or (2) use values for percent fines measured in undisturbed watersheds as targets. Cederholm et al. (1981), and McHenry et al. (1994) developed relationships between incubation success and percent fines in natural conditions. Chapman (1988) argues that these studies are flawed by the inherent difficulties in conducting field experiments on survival to emergence. Survival rates of artificially placed eggs can be extremely low or variable due to handling stress and other environmental variables, including scour and stream temperatures. Estimating survival by placing fry emergence traps over natural redds reduces handling stress, but is still affected by other environmental variables and the error in determining the number of eggs spawned by the female. Further, Chapman (1988) notes that field experiments typically are unable to determine accurately the environmental conditions (e.g., percent fines or dissolved oxygen) in the redd egg pocket.

Cederholm et al. (1981) attempted to reduce variability from environmental factors by conducting experiments in the laboratory. Chapman (1988) notes that laboratory experiments typically result in a better relationship between percent fines and incubation success than field studies, but may not be applicable to natural streams. In reviewing literature relating percent fines to emergence success, Tappel and Bjornn (1983) concluded that percent fines is an inadequate measure of substrate because it does not take into account the total size range of spawning substrate particle sizes that affect embryo survival. They found that by examining the percent composition of two particle sizes (9.5 mm and 0.85 mm) they could accurately represent the total distribution of substrate sizes. Further, they found that the percent composition of particles less than 9.5 mm and 0.85 mm was well correlated with steelhead and Chinook salmon incubation success in laboratory experiments. Chapman (1988) concluded that the principle flaw in Tappel and Bjornn (1983), and other laboratory experiments, is their inability to accurately simulate the egg pocket environment. It is clear that increases in fine sediment reduce incubation success, but these papers do not provide a clear indication of the survival response to be expected from a particular level of fine sediment under natural conditions. Kondolf (2000) notes that relationships between incubation success and percent fines from the literature are further complicated by the lack of a consistent definition of fine sediment, and by temporal and spatial variability in percent fines. For example, substrate composition measured prior to spawning is not likely to reflect redd conditions after the female "cleans" the substrate during spawning.

Measuring percent fines has been used as an indirect measure of permeability within the substrate. Permeability is affected by fine sediment, and also by larger substrate, therefore it is difficult to develop a consistent relationship between percent fines and incubation success relying on one size class of substrate to estimate permeability. In addition, bulk sampling with a 6" McNeil sampler may overestimate the amount of fines in substrate by not collecting enough substrate to determine the true size composition (Church et al. 1987), and simply sampling the upper 6" of the substrate often does not penetrate the armor

layer, and may be inadequate to characterize the substrate. One possible solution is to measure the permeability of the substrate directly, using methods proposed by Barnard and McBain (1994). Permeability measurements provide a more direct measure of the substrate factors that affect incubation conditions and provide a monitoring method that can be implemented more cost effectively than bulk sampling. Egg-to-emergence survival based on gravel permeability can be predicted based on a relationship developed from studies by Tagart (1976) on coho salmon, and McCuddin (1977) on Chinook salmon.

Peterson et al. (1992) concluded that setting targets based on predictions of survival to emergence would be arbitrary. Rather than basing a target on a desired survival to emergence, their approach was to set target conditions based on values observed in streams draining unmanaged forests. Based on their review they chose a target condition of 11% fines, because it appeared to represent the level around which a majority of the sites they examined in Washington clustered. It appears that Peterson et al. (1992) intended this value to be a standard to compare with other streams in Washington, and not as a regulatory target for the West Coast. Burns (1970) has data on percent fines in undisturbed watersheds for northern California. However, as Kondolf (2000) noted, temporal variability in substrate composition exists, and it is not clear that conditions that existed in the 1960's would exist today, even in the absence of land management. In addition, the results of McHenry et al. (1994) illustrate that percent fines within a tributary, and even within one riffle can vary significantly. Setting a single standard based on percent fines is arbitrary. Percent fines within a basin vary significantly due to hydraulic conditions, channel morphology, and basin geology. Therefore the objectives and sampling design of studies addressing percent fines need to be carefully developed. Site selection to characterize spawning habitat suitability in a basin, for example, may require entirely different criteria than site selection to monitor specific land management activities, or trends in percent fine sediment over time.

Table 1. Summary of results of references reviewed in this annotated bibliography

Source	Location	Watershed or Site Description	Size Criteria Used (mm)	Percent in substrate	Observed Effects	Methods Used	Notes
McCuddin (1977)	N/A	N/A	< 6.4	0	Approximately 89% egg-to-emergence survival of Chinook	Laboratory	Not annotated.
				16	Approximately 75% egg-to-emergence survival of Chinook		
				28	Approximately 65% egg-to-emergence survival of Chinook		
Burns (1970)	Bummer Lake Creek, Ca	Unlogged	< 0.8	10.2	N/A	6 inch McNiel sampler, collected in riffles during summer and fall to a depth of 6 inches.	Annotated
	South Fork Yager Creek, Ca	Unlogged		16.4 to 22.1			
	Godwood Creek, Ca	Unlogged		17.3 to 17.7			
	North Fork Caspar Creek, Ca	Logged 100 years prior to sampling		17.5 to 23.2			
	Little North Fork Noyo, Ca	Second growth, pre-road construction		20.0			
	South Fork Caspar Creek, Ca	Second growth, pre-road construction		20.6			
Cederholm et al. (1981)	Stequaleho Creek, Wa	Upstream of landslides	< 0.85	8.0	76% egg-to-emergence survival of cutthroat trout	6 in McNeil sampler, and egg baskets.	Annotated
		Downstream of landslides		10.9	78.3% egg-to-emergence survival of cutthroat trout		
	East Fork Miller Creek, Wa	Upstream of landslides		16.1	57.2% egg-to-emergence survival of coho salmon		
		Downstream of landslides		23.7	24.7% egg-to-emergence survival of coho salmon		
	Tributaries to the Clearwater River, Wa	N/A		<20	31.9% egg-to-emergence survival of coho salmon		
		N/A		>20	17.1% egg-to-emergence survival of coho salmon		
Tappel and Bjornn (1983)	South Fork Salmon River, Idaho	Not stated	< 0.85 and < 9.5	11.7% < 0.85 30% < 9.5	59% egg-to-emergence survival of steelhead	Laboratory	Annotated. Figure 1 demonstrates relationship between particle size and survival.
					82% egg-to-emergence survival Chinook		
				12.9% < 0.85 55% < 9.5	30% egg-to-emergence survival of steelhead		
					78% egg-to-emergence survival of Chinook		

Source	Location	Watershed or Site Description	Size Criteria Used (mm)	Percent in substrate	Observed Effects	Methods Used	Notes
				19.5% (50% < 9.5 mm)	10% egg-to-emergence survival of steelhead		
					6% egg-to-emergence survival of Chinook		
McHenry et al. 1994	Five North Olympic Peninsula watersheds, Wa	Most portions of the watersheds were disturbed	< 0.85 mm	10%	13% maximum steelhead and coho survival to eyed stage observed	Egg baskets placed in artificial redds of known substrate composition.	Annotated
NMFS 1997	PALCO ownership	Properly Functioning Conditions matrix target	< 0.85 mm	11-16%	N/A	N/A	Not annotated, but included for comparison. Based on research described in Peterson et al. (1992), Chapman (1988), and Burns 1970 data from S. Fork Yager.
Klein 1999	Main-stem Prairie Creek above Browns Creek, Ca	Nearly pristine watershed	< 2 mm	1.7 to 6.7%	N/A	McNeil sampler (diameter not stated) in potential spawning riffles collected during winter to a depth of 30 cm.	Not annotated, but included for comparison.
Reiser and White 1988	N/A	N/A	< 0.84 mm	0%	Approximately 98% survival of eyed steelhead eggs	Laboratory	Not annotated, but included for comparison.
				10%	Approximately 60% survival of eyed steelhead eggs		
				20%	Approximately 58% survival of eyed steelhead eggs		

Annotated Bibliography

Burns, J. W. 1970. Spawning bed sedimentation studies in Northern California streams. California Fish and Game 56: 253-270.

In the late 1960's, Fish and Game attempted to determine the affect of logging on spawning bed substrate composition in northern California streams. Burns (1970) monitored the size composition of spawning beds for three years in seven sections in six coastal streams (Table 2) before and after logging activities. The predominately loamy soils in all of these drainages were moderately erodable. Three of the stream sections were not disturbed (Godwood Creek, upstream section of South Fork Yager Creek, and North Fork Casper Creek), and served as controls. Study sections from 1,119 to 3,110 meters in length were delineated in each stream (two study sections, one control and one subject to logging, were delineated in South Fork Yager Creek).

Logging treatments varied by study reach, and are described in Table 2. Substrate samples were collected in the summer or fall in each study section in 1966, 1967, and 1968 (before, during, and after logging activities). About 20 samples were collected from each study section during each visit. Burns used a McNeil-type 6-inch diameter stainless steel cylinder to collect substrate from potential spawning riffles. Substrate was collected to a depth of 6 inches, and separated into four size classes, the smallest being <0.833mm (fines). The percentage of each size class was determined for each sample, and averaged for the study reach.

The percent of fines in the substrate less than 0.8 mm increased in all reaches during the study, perhaps due to high magnitude storm events in 1969. The percent fines in Godwood and North Fork Casper Creeks (control reaches) changed by less than 1% during the study, while the control reach in South Fork Yager increased by 5.7%. Percent fines in the treatment reach changed only slightly in Bummer Lake Creek, despite the use of a bulldozer in the stream. Percent fines in the logged section of South Fork Yager Creek did not increase significantly more than in the control reach. In the Little North Fork of Noyo River, percent fines increased significantly (13.3%) over pre-disturbance levels. In the South Fork Casper Creek, fines increased significantly immediately following road construction, dropped to pre-disturbance levels within a year, and then increased to 8.8% over pre-disturbance levels over the following two years. Burns attributed most of the increases in fines in all treatment reaches to road construction in close proximity to streams.

Burns notes that sampling during the low flow summer period may not reflect conditions during incubation. Burns also notes that none of the treatments were logged extensively, operations were limited to one season, and small fractions of the basin were logged. He also suggests that streams respond differently to similar disturbances, due to inherent geomorphic conditions.

Table 2. Summary of Burns (1970) results.

Stream	Treatment	Pre-Treatment Condition	Pre-Treatment % fines (<0.8mm)	Post-treatment % fines (<0.8mm)
Godwood Creek	Control	Undisturbed; old growth redwood	17.3	17.7
South Fork Yager Upstream section	Control	Undisturbed; old growth redwood and Douglas fir	16.4	22.1
South Fork Yager Downstream section	Selectively cut in 1968 to 305m from stream. No stream crossings, and no equipment stream. Some new road construction.	Undisturbed; old growth redwood and Douglas fir	16.4	23.6
North Fork Casper Creek	Control	100 years post-logging; second growth redwood-Douglas fir	18.4	23.2
Bummer Lake Creek	Clear cut in 1968 in alternate blocks over 272 acres. No stream crossings. Bulldozer operated in the channel.	Undisturbed; old growth redwood and Douglas fir	10.2	13.3
Little North Fork Noyo	30% of timber cut from 1,338 acres in 1966. Bulldozer worked in and near stream.	Periodic road construction and selective logging; second growth redwood	20.0	33.3
South Fork Casper Creek	In 1967 timber was removed for road construction, and materials were side-cast into stream. Bulldozer operated in stream.	100 years post-logging; second growth redwood	20.6	27.1

Cederholm, C. J., L. M. Reid, and E. O. Salo. 1981. Cumulative effects of logging road sediment on salmonid populations in the Clearwater River, Jefferson County, Washington. Pages 38-74 *in* Salmon-spawning gravel: A renewable resource in the Pacific Northwest? Report No. 39. State of Washington Water Research Center, Washington State University, Pullman, and the University of Washington, Seattle.

Cederholm et al. (1981) studied the production of fine sediment from logging roads, increases in the portion of fine sediment in spawning gravels downstream from logging roads, and the effect of fine sediment on survival to emergence of coho salmon and cutthroat trout in the Clearwater River, Washington. They concluded that logging roads increased fine sediment (<0.85 mm) in streams, and that elevated levels of fine sediment lowered survival to emergence of coho and cutthroat. They suggest that fine-sediment inputs from logging roads in conjunction with over-fishing jeopardize the sustainability of coho salmon in the Clearwater River.

Egg-to-emergence survival
Cutthroat survival to emergence was measured in the Stequaleho Creek using eggs planted both downstream (treatment) and upstream (control) of a series of landslides due to logging road failures. No significant difference between the affected and unaffected groups was detected (Table 3). A similar experiment in the East Fork Miller Creek demonstrated a noticeable lowering of survival to hatching and to the button-up stage of coho salmon fry development downstream of the treatment reach.

Survival of coho salmon in 19 natural redds was measured during two spawning seasons. Over 72 gravel samples were collected in, and adjacent to, the study redds. No significant relationship was found between fine sediment (<0.85mm) and survival to emergence for levels of fines less than 20%. However, when fines exceeded 20% the range of survival rates was reduced, and was significantly affected by further increases in fines.

Survival to emergence of coho salmon was measured in the laboratory with varying gravel compositions (3.5 to 21.0% fines). A significant inverse relationship was found between percent fines and survival to emergence. When the portion of fines is greater than 10%, each 1% increase in percent fines corresponded to a 2% decrease in survival to emergence.

Logging Roads
Substrate composition was measured using a hand-coring device (15.2 cm diameter). Fines were considered to be particles <0.85 mm diameter. Over 900 samples were collected in potential spawning riffles. The mean percentage of fines was 10.9% (range of 3.1–22.0%). In undisturbed portions of the basin fines averaged 10% (no range given). A significant positive relationship (r^2=0.62) was found between road area in the basin and percent fines in downstream spawning gravels. The authors concluded that when road area exceeded 2.5% of the basin area, fine sediments begin to accumulate in downstream spawning gravels. In general, they concluded that logging roads are a significant source of fine sediment in spawning gravels.

Table 3. Survival to emergence and substrate composition in the Clearwater River. Based on Cederholm et al. (1981).

Group	% Fines (<0.85mm)	Mean survival to emergence	Species and notes
Stequaleho Creek			Cutthroat trout
Downstream of landslides	10.9	78.3	
Upstream of landslides	8.0	76.0	
East Fork Miller Creek			Coho salmon
Downstream of landslides	23.7	24.7	
Upstream of landslides	16.1	57.2	
Various tributaries	<20%	31.9	Coho salmon
	>20%	17.7	

Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society 117: 1-21.

Chapman (1988) critically reviewed literature addressing the effects of fine sediment on salmonid incubation success. The paper presents a review of literature describing spawning behavior, redd development and structure of redds, and effects of fine sediment on embryo survival. In particular, he reviewed information on the structure and characteristics of the egg pocket. In general, he concludes that the unique structure of egg pockets is ignored in all laboratory and most field studies addressing the effects of fine sediment.

The behavior of spawning pairs influence's redd characteristics. For example, fines and organic matter are removed by the female during the redd building process. In areas where many pairs spawn annually, the bed may remain coarse, and thus maintain higher quality spawning habitat. The structure of the redd influences incubation success as well. For example, the shape of the redd draws surface water deeper into the substrate than does a gravel bed with a relatively flat surface. After construction of the redd, intrusion of fines into the gravel is common. Sediment that infiltrates the egg pocket forms a silt "crust", which can lower the survival of fry to emergence. The depth of infiltration is higher for smaller particle sizes, but in general intrusion occurs within the top 10 cm of the substrate. Froude numbers, which represent the ratio on inertial to gravitational forces in fluid flow, characterize the flow conditions that influence the infiltration of fines (Beschta and Jackson 1979).

The configuration of the egg pocket, and the placement of eggs by the female appear to lead to optimal physical conditions for egg incubation and alevin emergence. The mean diameter of particles within the egg pocket is typically higher than in surrounding substrate. Consequently permeability is also typically higher in the egg pocket than in the surrounding substrate. Construction of artificial egg pockets can increase permeability, but may still be lower than in a natural egg pocket. The fredle index (Lotspeich and Everest 1981), which incorporates elements that integrate gravel permeability and pore size, is also typically higher in the egg pocket than in surrounding substrate.

The large body of literature devoted to the intragravel ecology of incubating embryos has failed to provide an accurate analog for the unique environment within the egg pocket. However, it has been demonstrated that direct mortality, delayed mortality, and size at emergence are all correlated with dissolved oxygen, permeability, apparent velocity, gravel size, and proportion of fine particles.

According to Chapman, researchers correlating survival to permeability, fredle index, and proportion of fines have failed to conduct experiments in gravel mixtures that simulate the egg pocket. Researchers typically fail to use particles that reflect the size composition of natural substrate, and often ignore larger particle sizes typically found in the egg pocket. Tappel and Bjornn (1983) for example, ignored particles larger than 25.4 mm, distancing their results from real conditions in the egg pocket. Laboratory gravel mixtures do not get packed by natural substrate shifts, and do not experience intrusion of fine sediment during incubation. Researchers also typically do not bury embryos as deep in laboratory gravels as is observed in natural conditions, and use a variety of stages of egg development. Chapman concluded that results of laboratory studies are unlikely to apply to field conditions, where the structure of an egg-pocket, behavior of females during spawning, and other environmental conditions alter embryo survival. Therefore the quantitative relationships between percent fines and survival developed in the lab would not likely apply to the field.

Field studies that attempt to document survival related to fine sediment typically sample the redd periphery, and fail to make measurements within the egg pocket. Chapman argues that conditions within the egg pocket are substantially different than in surrounding substrate, and therefore survival models based on gravel size from "natural" substrate may not be reliable. This discrepancy between the conditions surrounding egg-pockets, and conditions within the egg pocket may explain the wide variety in survival rates for the same percent of fine sediment reported in the literature. In addition, other environmental conditions, including groundwater influence, affect intragravel flow, and hence survival. There is also error associated with estimating the number of eggs deposited in natural redds.

Chapman concludes that the variety of gravel mixtures, egg burial depths, stages of embryonic development, and lack of measurements from within egg pockets limits the utility of past research to a general understanding of the deleterious effects of fine sediment on incubation success. He argues that evaluations have, "produced results that are quantitatively inconsistent among and usually within fish species… One cannot, with the existing information on survival of embryos and alevins in the redds of large salmonids, predict survival quantitatively and with known accuracy on the basis of physical factors measured in field or laboratory studies." He also doubted the claim Tappel and Bjornn (1983) made that the change in survival observed with increasing fines in the laboratory would apply to field conditions. Chapman suggests that future research continue to collect Fredle index, permeability, percentage of fines (<0.85 and <9.5 mm), and dissolved oxygen concentrations. However, he believes future research must focus on the conditions within the egg pocket, and laboratory studies need to simulate this environment. For field experiments future research should determine accurate female egg deposition rates, and develop a more thorough understanding of the relationship between egg-pocket conditions and surrounding substrate within the redd.

References cited in review of Chapman (1988)

Beschta, R. L., and W. L. Jackson. 1979. The intrusion of fine sediments into a stable gravel bed. Journal of the Fisheries Research Board of Canada 36: 204-210.

Lotspeich, F. B., and F. H. Everest. 1981. A new method for reporting and interpreting textural composition of spawning gravel. Research Note PNW-369. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Kondolf, G. M. 2000. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society 129: 262-281.

Kondolf reviewed literature on salmonid spawning gravels and made recommendations for assessing spawning gravel quality. The size of natural substrate is extremely diverse in most streams, such that substrate composition data are usually log-transformed. He maintained that while a single statistic cannot fully represent the attributes of gravel size distribution, there is a need to establish methods to assure comparability among studies. Selecting a single statistic is further complicated by the need to assess gravel quality for salmonid redd construction, incubation, and emergence. Kondolf concludes that there is a single statistic appropriate for assessing gravel quality at each of these life-stages; D50 for redd construction, percent fines <1 mm for incubation, and percent fines between 1–10 mm for emergence.

Substrate requirements for spawning are based on the ability of a female salmon to move the substrate during redd construction. Females can typically move substrate up to 10% of their body size. The D_{50} (median particle size) is good descriptor of the size of the coarse sediment that might prevent the female from constructing a redd, and can accurately be interpreted from a pebble count. Kondolf and Wolman (1993) offer an excellent review of the substrate preferences (expressed as D_{50}) for redd construction.

Successful incubation requires high permeability to facilitate the flow of oxygen to eggs and the removal of metabolic waste. Permeability is reduced by the percent of the substrate with a diameter less than about 1 mm, and has been correlated with incubation success. McNeil and Ahnell (1964) first correlated incubation success with percent fines, and selected 0.83 mm as their cutoff between fine and coarse sediment (based on their available sieve screens). Subsequent researchers have chosen values for fines near 0.83 mm, following McNeil and Ahnell, though there is no biological or geomorphologic reason for selecting this size. Kondolf notes that there is nothing wrong with 0.83 mm as a definition of fines, but focusing on one size class ignores the range of substrate sizes affecting incubation. Since the percentage of particles less than 1 mm is a function of the total substrate composition, the value will be dependant on the portion of particles of larger size classes. Tappel and Bjornn (1983) improved on the relationship between survival to emergence and percent fines by considering fine sediment in two size categories (<0.83 and <9.5 mm). However, Tappel and Bjornn ignored particles greater than 25 mm, which makes it difficult to compare their results to the results of other researchers.

Kondolf suggests that bulk sampling is the most accurate method for determining percent fines, noting that Young et al. (1991) found that bulk core samples most frequently approximated the true substrate composition. However, Church et al. (1987) reviewed required sample sizes and determined that in a typical river a sample of more than 200 kg is required to get a truly representative sample of substrate composition.

The relationship between fine sediment and incubation and emergence success is highly variable (Table 4). Kondolf elected to focus on the percent fines corresponding to 50% survival, because he considers 50% survival to emergence to be indicative of a productive redd. However, he notes than even in natural redds in undisturbed streams survival can be considerably less than 50%. Kondolf also notes that comparing the results of different researchers is further complicated by the wide variety of definitions used for fine sediment. He cites several studies with definitions for percent fines ranging from 0.83 mm to 9.5 mm. He notes that gravel quality criteria have been inconsistent in the literature, and thus, "defining precise thresholds for fine sediment content is probably not justified." However, Kondolf suggested comparing results of fine sediment sampling to a standard of 12–14%, based on the work of McNeil and Ahnell

(1964). He also suggests that the approach of comparing results with values from other streams (presumably undisturbed streams) is useful.

Shirazi and Seim (1981) attempted to develop the geometric mean diameter (d_g) as a "unifying substrate statistic", but Kondolf notes it improved very little over percent fines as a statistic. Kondolf also noted several disadvantages to the Fredle index as a unifying substrate statistic.

Substrate composition can change substantially from year to year, complicating the ability to apply composition values collected at one time to conditions during the time of spawning, incubation, or emergence. Further, because spawning females "clean" the substrate, there is a reduced percentage of fines in the gravels prior to egg deposition. Kondolf suggests that a downward adjustment of the value of percent fines be used to account for cleaning of gravels during spawning, and includes a figure showing percent fines in a redd prior to and after cleaning. He also notes that fine sediment can also increase during incubation by infiltration. Kondolf recommends that consideration be given to changes in the substrate composition before and during the egg incubation period.

Table 4. Levels of percent fine sediment corresponding to 50% emergence of coho salmon and steelhead. Based on Kondolf (2000).

Source	Size Criterion (mm)	% fines	Species
Cederholm and Salo (1979)	0.83	7.5,17	Coho Salmon
Koski (1966)	0.83	21	
Phillips et al. (1975)	3.35	36	
Tagart (1984)	0.83	11	
Bjornn (1969)	6.35	25	Steelhead
Tappel and Bjornn (1983)	6.35	39	
McCuddin (1977)	6.35	27	
Phillips et al. (1975)	3.35	25	

References cited in review of Kondolf (2000)

Bjornn, T. C. 1969. Embryo survival and emergence studies. Salmon and Steelhead Investigation Completion Report, Job 5 Project F-49-R-7. Idaho Department of Fish and Game, Boise.

Cederholm, C. J., and E. O. Salo. 1979. The effects of logging road landslide siltation on the salmon and trout spawning gravels of Stequaleho Creek and the Clearwater River basin, Jefferson County, Washington, 1972-1978. Final Report--Part III, FRI-UW-7915. Fisheries Research Institute, College of Fisheries, University of Washington, Seattle.

Church, M. A., D. G. McLean, and J. F. Wolcott. 1987. River bed gravels: sampling and analysis. Pages 43-88 in C. R. Thorne, J. C. Bathurst and R. D. Hey, editor. Sediment transport in gravel-bed rivers. John Wiley and Sons, New York.

McCuddin, M. E. 1977. Survival of salmon and trout embryos and fry in gravel-sand mixtures. Master's thesis. University of Idaho, Moscow.

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Koski, K. V. 1966. The survival of coho salmon (Oncorhynchus kisutch) from egg deposition to emergence in three Oregon coastal streams. Master's thesis. Oregon State University, Corvallis.

Phillips, R. W., R. L. Lantz, E. W. Claire, and J. R. Moring. 1975. Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. Transactions of the American Fisheries Society 104: 461-466.

Shirazi, M. A., and W. K. Seim. 1981. Stream system evaluation with emphasis on spawning habitat for salmonids. Water Resources Research 17: 592-594.

Tappel, P. D., and T. C. Bjornn. 1983. A new method of relating size of spawning gravel to salmonid embryo survival. North American Journal of Fisheries Management 3: 123-135.

Tagart, J. V. 1984. Coho salmon survival from egg deposition to emergence. Pages 173-181 in J. M. Walton and D. B. Houston, editor. Proceedings of the Olympic wild fish conference. Peninsula College, Port Angeles, Washington.

Young, M. K., W. A. Hubert, and T. A. Wesche. 1991. Biases associated with four stream substrate samplers. Canadian Journal of Fisheries and Aquatic Sciences 48: 1882-1886.

McHenry, M. L., D. C. Morrill, and E. Currence. 1994. Spawning gravel quality, watershed characteristics and early life history survival of coho salmon and steelhead in five north Olympic Peninsula streams. Prepared by Lower Elwha S'Klallam Tribe, Port Angeles, Washington and Makah Tribe, Neah Bay, Washington.

McHenry et al. (1994) measured the substrate composition in spawning gravels in five watersheds on the Olympic Peninsula in Washington State. All of the watersheds had a history of land management, and none could be considered undisturbed. Results were compared to natural and anthropogenic basin characteristics to explain sedimentation processes. The authors also measured egg-to-alevin survival rates of coho salmon and steelhead.

Ten to twenty-two sample sites, consisting of known or potential spawning areas, were selected within each watershed. At each site 5 to 10 bulk samples were collected using a McNeil coring device (150 mm diameter; 254 mm depth). All samples (564 total) were collected during low flows from May to October of 1991 and 1992 in a total of 38 tributaries. In 1992 a sub-sample of sites were revisited during the winter. Samples were dried, and sieved into seven size categories, and particles less than 0.85 mm were considered fines.

Percent fines at all sites ranged from 0.39% to 26.79%, and averaged 9%. The authors found that variability in particle size distribution among sites was highly significant. They found that the coefficient of variation (CV) among sites was higher for smaller particle sizes, averaging 41.2% for fines <0.85 mm at all sites. No differences were detected between summer and winter sampling.

The results of correlation analysis showed the composition of fine sediment was generally not related to land management variables. In one basin there was a strong inverse relationship between fine sediment and management activities, while in two other basins, increases in fine sediment were related to both channel gradient and watershed relief. The composition of fine sediment was related to stream morphology, watershed size, length of first and second order channels, road density, and vegetation age-class. Percent fines exceeded 17% in seventeen of 38 tributaries, and was less than 11% in one tributary. The authors observed that in tributaries with high stream power fines were low (4.8% in the Clallam River) despite a history of logging and road building, whereas in low gradient reaches with similar sediment inputs, percent fines were substantially higher.

Egg survival to alevin stage was measured by placing coho or steelhead eggs in baskets, which were then placed in artificial redds. Survival to alevin stage in artificial redds was generally low, and ranged from 0 to 58%. No relationship was detected between percent fines and survival to alevin stage, except that survival became extremely low when fines exceeded 13%.

Peterson, N. P., A. Hendry, and T. P. Quinn. 1992. Assessment of cumulative effects on salmonid habitat: some suggested parameters and target conditions. Timber/Fish/Wildlife Report No. TFW-F3-92-001. Prepared by Center for Streamside Studies, University of Washington, Seattle for the Washington Department of Natural Resources and Cooperative Monitoring Evaluation and Research Committee, Olympia.

Peterson et al. (1992) attempted to describe parameters that could be used to assess the cumulative impacts of forest management on anadromous salmonids. For each parameter, a target condition and method for measuring the parameter was suggested. Parameters for stream temperature, large woody debris, pools frequency, substrate composition, gravel stability, and substrate interstitial space were reviewed. For the purposes of this annotated bibliography, we focus on their discussion of substrate composition.

Based on a review of the literature, the authors assumed that salmonid survival to emergence decreases as the portion of small particles in the substrate increases. They concluded that percent fines (<0.85 mm) is an appropriate parameter for monitoring stream condition. They suggest that percent fines be monitored using a McNeil cylinder in potential spawning riffles prior to the spawning season. Citing several studies, they concluded that setting targets based on survival to emergence results would be arbitrary. Rather than basing a target on a desired survival to emergence, their approach was to set target conditions based on values observed in streams draining unmanaged forests. They believe that percent of fines in managed watersheds should approximate those in streams draining unmanaged forests. No "poor" condition targets were set, but rather the targets suggested were intended to be a standard to compare against. The values they cited as representing those in unmanaged forests are shown in Table 5. Based on their review a target condition of 11% fines was selected, because levels in Washington sites clustered around this value. They believed that it should only be applied in streams with moderate gradients (<3%), and 5 to 30 meters in channel width.

The authors note that no two streams are alike, and that a "one size fits all" approach may be inappropriate. Basin geology, and other site-specific variables can have a significant effect on percent fines, and the authors did not suggest their target be applied universally. For example, the levels of fines in some unmanaged coastal Oregon streams are considerably higher than 11%. They recommend that fine sediment target conditions be based on natural levels observed in undisturbed sites with similar characteristics to the basin of concern. They recognized that streams have substantial variability, and recommended that the most appropriate management response is to thoroughly investigate possible reasons for fine sediment concentrations greater than 11%.

Table 5. Levels of fines in the substrate of unmanaged streams. Based on Peterson et al. (1982).

Source	Fine sediment criterion (mm)	% fines	Location, and notes
Edington (1984)	<0.833	6.3–13.6	Southeast Alaska
Koski (1966)	<0.833	22.7–28.4	Coastal Oregon
Sheridan et al. (1984)	<0.83	9.65±5.19	Southeast Alaska
Cederholm (1991)	<0.85	11.38–14.50	Main and South Fork Hoh River, Wa
Cederholm and Reid (1987)	<0.85	6.37	Olympic National Park, Wa
Hatten (1991)	<0.85	6.6–14.5	Hoh River Tributaries, Wa
Tripp and Poulin (1986)	<0.85	4.3–5.6	Queen Charlotte Islands
Adams and Beschta (1980)	<1	10.6–29.4	Oregon Coast Range
Scrivener and Brownlee (1989)	<1.19	<8	Carnation Creek, British Columbia, Canada
	<2.38	<15	
Ringler and Hall (1988)	<3.33	45.2	Coastal Oregon
Koski (1984)	<4.0	6.7–18.4	Southeast Alaska

References cited in Table 5:

Adams, J. N., and R. L. Beschta. 1980. Gravel bed composition in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 37: 1514-1521.

Cederholm, C. J., and L. M. Reid. 1987. Impacts of forest management on coho salmon (Oncorhynchus kisutch) populations of the Clearwater River, Washington: a project summary. Pages 373-398 in E. O. Salo and T. E. Cundy, editor. Streamside management: forestry and fishery interactions. College of Forest Resources, University of Washington.

Koski, K. V. 1966. The survival of coho salmon (Oncorhynchus kisutch) from egg deposition to emergence in three Oregon coastal streams. Master's thesis. Oregon State University, Corvallis.

Koski, K. V. 1984. A stream ecosystem in an old-growth forest in southeast Alaska. Part I. Description and characteristics of Porcupine Creek, Etolin Island. Pages 47-56 in W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley, editor. Fish and wildlife relationships in old-growth forests. American Institute of Fishery Research Biologists, Juneau, Alaska.

Ringler, N. H., and J. D. Hall. 1988. Vertical distribution of sediment and organic debris in coho salmon (Oncorhynchus kisutch) redds in three small Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 45: 742-747.

Scrivener, J. C., and M. J. Brownlee. 1989. Effects of forest harvesting on spawning gravel and incubation survival of chum (Oncorhynchus keta) and coho salmon (O. kisutch) in Carnation Creek, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46: 681-696.

Sheridan, W. L., M. P. Perensovich, T. Faris, and K. V. Koski. 1984. Sediment content of streambed gravels in some pink salmon spawning streams in Alaska. Pages 153-166 in W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley, editor. Fish and wildlife relationships in old-growth forests. American Institute of Fishery Research Biologists, Juneau, Alaska.

Tripp, D. B., and V. A. Poulin. 1986. The effects of logging and mass wasting on salmonid spawning habitat in streams on the Queen Charlotte Islands. Land Management Report No. 50. British Columbia Ministry of Forests and Lands, Victoria, British Columbia.

Tappel, P. D., and T. C. Bjornn. 1983. A new method of relating size of spawning gravel to salmonid embryo survival. North American Journal of Fisheries Management 3: 123-135.

Tappel and Bjornn (1983) reviewed literature relating spawning substrate to incubation success and concluded that "percent fines" and "geometric mean" are both inadequate measures of substrate, because neither took into account the total size range of spawning substrate particles sizes that affect salmon embryo survival. In this paper the authors examined distributions of spawning gravels, proposed a method to describe sediment size composition, applied the method, and conducted laboratory tests of steelhead and Chinook embryo survival. In general, they found that the percent composition of particles of 9.5 mm and 0.85 mm represent the total range of substrate sizes, and that these same particle sizes were well correlated with steelhead and Chinook salmon embryo survival.

Describing Substrate Composition

Sediment sizes from 100 samples collected in the South Fork Salmon River in Idaho were plotted on log-probability paper. Particle size distributions were close to log-normal, and had r^2 values averaging 0.95 (range 0.62–1.00). By removing particles larger than 25.4 mm the samples were consistently linear, and had r^2 values averaging 0.97. Because the size composition is consistently linear, the authors were able to develop a regression equation to describe gravel size composition (for particles below 25.4 mm). The regression equation developed was:

$$\text{PERCENT} = C + K * \text{Log}_e\text{SIZE}$$

where

PERCENT=inverse probability transformation of percentage of substrate smaller than a given sieve size,
C=intercept of regression line,
K=coefficient of variable Log_eSIZE,
SIZE=sieve size in millimeters

Tappel and Bjornn demonstrated that gravel samples with the same percentage of fines (0.85 mm for example), or geometric mean, could have very different gravel size compositions. Therefore samples with the same percent fines or geometric means could have different particle size distributions.

Because the relationship is linear, lines passing through data points for two of the sieve sizes can be used to approximate the relationship. Using an analysis of residuals for particles of 9.5 mm and 0.85 mm the size composition of gravel samples (less than 25.4 mm) can be determined. However, this consistently overestimated the amount of material smaller than 0.25 mm (which is usually only a very small fraction of the total substrate).

Application

Tappel and Bjornn concluded that survival of salmon should be related to particles of 9.5 mm and 0.85 mm, since doing so would implicitly relate survival to the entire range of material less than 25.4 mm. The advantage is that this eliminates the need to define exactly which particle sizes are detrimental to salmonids, as long as particles larger than 25.4 mm that are not detrimental to survival (an assumption supported by the literature).

Laboratory tests were conducted to on embryo survival of steelhead and Chinook salmon in a variety of gravel mixtures intended to be similar to those found in streams. Survival ranged from 6 to 99%, and was inversely related to the amount of fine material in the substrate. Survival was found to be correlated with the percentage of substrate smaller than 9.5 mm, and percentage of substrate smaller than 0.85 mm. Simply relying on percent fines based only on substrate smaller than 0.85 mm was a poor indicator of survival. For example, at 10% fines (<0.85 mm) survival varied from 20 to 80%, as the amount of fines smaller than 9.5 mm varied. A second order equation was developed relating survival to gravel size composition:

Steelhead survival=$94.7-0.116S_{9.5}S_{0.85}+0.007S^2_{9.5}$ $r^2=0.90$

Chinook survival=$93.4-0.171S_{9.5}S_{0.85}+3.87S_{9.5}$ $r^2=0.93$

The authors warn that though these equations were accurate when applied to laboratory data, they may not be when applied to natural field conditions. Other variables, such as the cleaning action of female salmon and steelhead during spawning will affect the size distribution of substrate. However, they conclude that the equations are particularly useful for determining relative change in survival to be expected from changes in particle size distribution.

When embryo survival was related to a single particle size, 1.7 mm diameter particles provided the strongest relationship, and 4.76 mm diameter particles provided the strongest relationship for Chinook. Particles between 1.70 and 4.76 mm were more harmful to Chinook than to steelhead embryos. No significant relationship was found between emergent fry size and amount of fine material, though steelhead fry emerging from gravels with a high percentage of fine material were generally smaller than fry emerging from gravels with low percentage of fine material. In gravels with a high percentage of fine material steelhead and Chinook fry tended to emerge before yolk sac absorption was complete, whereas in gravels with a low percentage of fines this was not observed. There was little variation of the size of emergent Chinook salmon fry, though steelhead fry emerging from substrate with low percent fines did appear slightly larger than those emerging from substrate with high percentage of fines. When geometric mean gravel size exceeded 10 mm, survival rates of steelhead and Chinook salmon were both about 90%. Survival rates declined with decreasing geometric mean size.

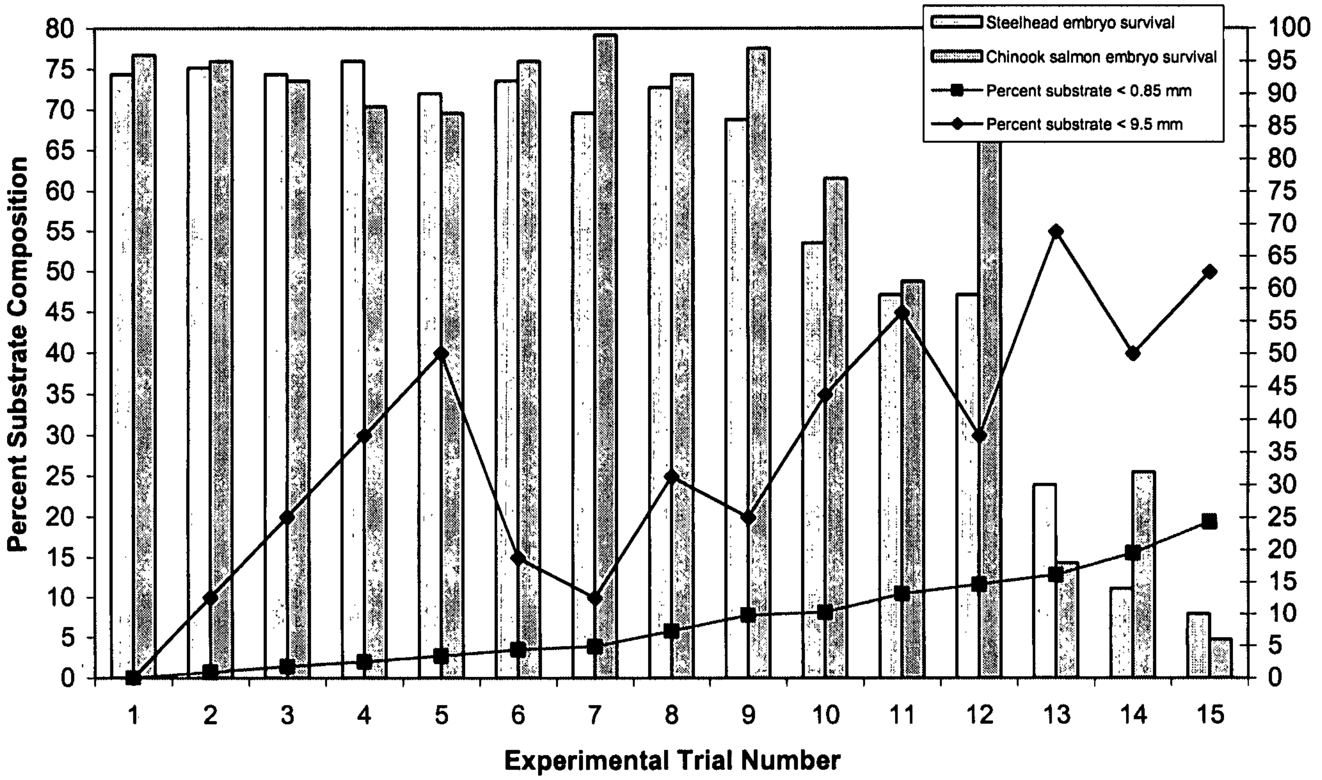

Figure 1. Embryo survival of steelhead and Chinook salmon in experimental trials of varying compositions of substrate (<0.85mm and <9.5 mm). Based on data from Tappel and Bjornn (1983).

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