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# Fine sediment effects on brook trout eggs in laboratory streams

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## Abstract

This study was designed to determine effects of different fine sediments (0.43–0.85 mm in diameter) on survival of brook trout (*Salvelinus fontinalis*) eggs during early developmental stages under laboratory conditions. Intragravel permeability and dissolved oxygen declined with increasing fine sediment amounts. Survival at each developmental stage generally declined with increasing fine sediment amounts, although not significantly for all stages. Differences in survival to emergence were not significant due to a large amount of variation in survival estimates. Survival of eggs and alevins declined linearly through time for all fine sediment treatments. In general, fry weight declined as the amount of fine sediment increased but fry length changed little. Our results indicate that increased levels of fine sediment may reduce survival of brook trout through early development.

*Keywords:* Eggs; Brook trout; Charr; Laboratory streams; Survival; Sediment

## 1. Introduction

Sediment is defined as fragmental mineral material transported or deposited by water or air (Leopold, 1974) and is believed to be the principal non-point pollutant from forestry (Swift, 1988) and other land use activities. Studies documenting negative effects of fine sediment on salmonid egg and alevin survival have a long history (see reviews in Chapman, 1988 and Everest et al., 1987). Cederholm et al. (1981) reported survivals to emergence of 30% in 10% fine sediment (<0.85 mm diameter) for coho salmon (*Oncorhynchus kisutch*) in a laboratory system. Eighteen-percent survival in redds that had more than 20% fine sediment (<0.85 mm diameter) was reported for coho salmon in Clearwater River, Washington (Tagart, 1976). Similarly emergence of brook trout (*Salvelinus fontinalis*) in Lawrence Creek, Wisconsin, declined when spawning gravels contained 20% sand (2 mm diameter) (Hausle and Coble, 1976). These and other studies show that excessive fine sediment amounts can reduce gravel permeability and dissolved oxygen delivery in redds (Wickett, 1958; Vaux, 1962; McNeil and Ahnell, 1964; Cooper, 1965; Cederholm et al., 1981; Tappel and Bjornn, 1983; Sowden and Power, 1985), smother incubating eggs, and bury alevins (Hall and Lantz, 1969).

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In addition to reducing fry survival, fine sediment may also exert sublethal effects: smaller fry (Koski, 1966; Phillips et al., 1975; Koski, 1981; Tappel and Bjornn, 1983) and delayed emergence by fry that are trapped in gravel interstices (Koski, 1966; Phillips et al., 1975). Exposure to low dissolved oxygen concentrations may cause premature hatching (Alderdice et al., 1958) and poor fry quality at emergence (Mason, 1969). Any reduction in fry size or extension of the incubation period may result in emergent fry that are unable to compete successfully with larger fry that emerged earlier (Mason, 1969).

In the life history of salmonid fishes, survival is generally lowest during the intragravel period (MacKenzie and Moring, 1988). Egg development passes from a green stage (newly fertilized) to an eyed stage, where distinct eyes become visible. After a few weeks (depending on water temperature) eyed eggs hatch to produce sac-fry or alevins, that later swim up and emerge.

Although negative effects of fine sediments on Pacific salmon, *Oncorhynchus* spp., are well known (Chapman, 1988), detailed information about effects on early life stages of brook trout is lacking. Fisheries managers in the southern Appalachians have expressed a need for information concerning how much fine sediment can be tolerated by developing brook trout, at all stages of development (Seehorn, 1987). Brook trout are the only native salmonid species in the southern Appalachians and may be negatively affected during egg and alevin stages in areas with high proportions of fine sediment (Hausle, 1973). Therefore, this study was designed to determine how detrimental fine sediments are to brook trout survival during the intragravel period.

We used an artificial system to test direct effects of fine sediments on brook trout eggs. This system provided an environment in which fine sediment effects could be examined under replicable conditions without many of the confounding effects often associated with field studies. Our objectives were to determine:

1. survival to emergence at six different fine sediment amounts and at varying stages of development;
2. dissolved oxygen concentration and water turnover rate at experimental sediment levels; and
3. fry condition at emergence.

## 2. Methods

Chambers, made from 3.1 mm-thick PVC sheeting welded to form an open box (56 cm wide×122 cm long×30 cm deep, with end walls 25 cm deep), were placed in three "living streams" (Frigid Units, Toledo, OH)[1] equipped with one-third horsepower chiller units (Fig. 1). We drilled 3.1 mm diameter holes spaced every 15 mm in each chamber floor to facilitate intragravel flow and the free exchange of water. A vertical 15 cm-diameter PVC pipe (25 cm long) welded around a 13 cm-diameter hole in the center of the floor accommodated the chiller unit impeller shaft, allowing the chiller unit to be removed for maintenance and preventing stream gravels from entering the impeller shaft. A frame, made from 7.6 cm-diameter PVC pipe drilled with 3.1 mm holes spaced 6 cm apart, raised the chamber above the living stream floor allowing water to move freely under the chamber. Our design was intended to maintain uniform flow and dissolved oxygen.

We obtained washed stream gravel (6.33–24.9 mm diameter) from a local gravel supplier and added it at 15 cm depth to each chamber (Fig. 1). We filled each chamber with well water to 10 cm-depth above the gravel bed (Fig. 1). The artificial system ran for one week prior to the study to stabilize water temperatures and saturate water with oxygen. We used well water, held in a 636-L reservoir, to flush waste materials and to maintain water volume in streams daily.

We loaded 120 two-chambered Whitlock–Vibert (W–V) boxes, lined with 0.4 mm Nitex netting, with washed coarse gravel (6.33–12.49 mm diameter) and one of six fine sediment (0.43–0.84 mm diameter) treatments (0%, 5%, 10%, 15%, 20%, 25% by weight). We selected rough fine sediments less than 0.85 mm in diameter because they have been shown to negatively influence intragravel permeability (McNeil and Ahnell, 1964), reduce salmonid survival (Tagart, 1976; Cederholm et al., 1981; Tappel and Bjornn, 1983; Reiser and White, 1988), and encompass a fine sediment range believed lethal to brook trout. Two-chambered W–V boxes were used because they pro-

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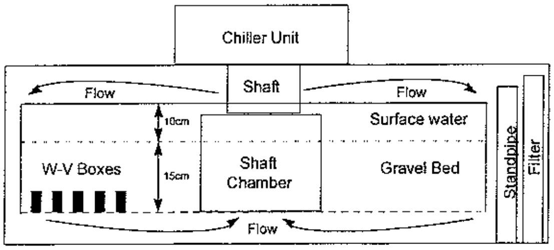

Fig. 1. Cross-section of incubation chamber. Incubation chamber is open at the top; supporting frame is not shown. Whitlock–Vibert (W–V) boxes (only a few are shown) covered the floor of the incubation chamber with approximately 10 cm between boxes. The shaft chamber protected the shaft propeller which drew water up through the shaft chamber and out over the water surface, thereby creating a downward flow through the gravel and W–V boxes. The standpipe maintained the water depth at 25 cm in the incubation chamber and served as an overflow when stream water was turned over.

vided both incubation and emergence chambers. Dry gravel and fine sediment weighing 550±1.1 g were added to the incubation chambers of each W–V box. Nitex netting liners in lower chambers retained fine sediments and eggs, and liners in upper chambers prevented emergent fry from escaping. We sieved fine sediment from washed commercial sand and obtained coarse gravel from a local gravel supplier.

On 4 October 1993, approximately 25 000 freshly fertilized brook trout eggs, Nashua strain (Kincaid, 1981), were obtained from Paint Bank National Fish Hatchery, Craig County, VA. Eggs were held at approximately 8°C during transport until placed in W–V boxes, within 6 h of fertilization. We added 200±5 eggs to the lower chamber of each lined W–V box. Egg densities were selected based on literature describing brook trout fecundity (Vladykov and Legendre, 1940; Robinette, 1978; Gray, 1979; Power, 1980). We randomly assigned W–V boxes among the three streams, for a total of 40 W–V boxes per stream.

We retrieved W–V boxes at six times during our study to estimate survival to specific stages of embryonic development (Table 1). At each retrieval, we removed one box per treatment at random from each stream for a total of 18 boxes per retrieval. During the last retrieval, the remaining one or two boxes per treatment were removed (a total of five boxes per treatment).

We encountered mechanical difficulties with the chiller units early in the study and by day 37 we concluded that temperatures and development rates had diverged among streams. After our third retrieval we chose to use a cumulative degree-day (midpoint temperature value for each 24-h period) schedule to determine later retrieval times (Table 1). Eye-up and hatching were easily determined by examination. When fry had swum up from the lower chamber (incubation chamber) to the upper chamber (emergence chamber) of the W–V box, we considered them

Table 1
Retrieval schedule for laboratory streams

| Retrieval | Day of study | Degree-days | | | Stage of development |
|---|---|---|---|---|---|
| | | Stream 1 | Stream 2 | Stream 3 | |
| 1 | 14 | 96 | 111 | 123 | Green |
| 2 | 28 | 182 | 199 | 236 | Green/Eyed |
| 3 | 37 | 232 | 254 | 289 | Eyed |
| 4 | 64 | | | 480 | Hatched |
| 4 | 76 | | 483 | | Hatched |
| 4 | 83 | 482 | | | Hatched |
| 5 | 114 | | | 749 | >90% Emerged |
| 5 | 120 | | 752 | | >90% Emerged |
| 5 | 128 | 753 | | | >90% Emerged |
| 6 | 123 | | | 809 | Emerged |
| 6 | 128 | | 810 | | Emerged |
| 6 | 136 | 811 | | | Emerged |

At each retrieval, one Whitlock–Vibert box was taken for each of the six fine sediment treatments per incubation chamber. A day schedule was used until retrieval 3 and a degree-day schedule was used after retrieval 3 because stream temperatures and development rates had diverged by retrieval 3.

to be emerged We estimated percent survival from absolute counts of live and dead individuals

Emergent fry were recovered at approximately 750 degree-days (114–136 days, Table 1) Fry condition was determined for individuals recovered at this time because greater than 90% had emerged from the W–V incubation chamber A total of 924 fry were weighed (wet) to the nearest 0 1 mg and measured (wet) to the nearest 1 0 mm total length Developmental index (KD) of Bams (1970) was computed to compare developmental stages of emergent fry:

$$\mathrm{KD} = \frac{10 \times (\text{wet weight (mg)})^{1/3}}{\text{wet fork length (mm)}}.$$

Values of 1 90 or less indicate that emergent fry have resorbed body tissue at the expense of growth, values near 1.96 indicate total yolk absorption, and values greater than 2.0 indicate that high proportions of yolk remain at emergence (Bams, 1970)

We monitored stream conditions throughout our study We calculated mean temperatures for each stream from midpoints of maximum and minimum temperatures recorded during each 24-h period We measured surface water dissolved oxygen (mg/l) daily using a dissolved oxygen meter (Yellow Springs Instrument, Yellow Springs, OH)[1] and measured pH weekly with a hand-held pH meter (Hach, Loveland, CO)[1] Gravel permeability (cm/h) and intragravel dissolved oxygen (mg/l) were measured at the termination of our study using standpipes similar to those described by Pollard (1955); Terhune (1958); Wickett (1958) Lined W–V boxes containing each of the fine sediment treatments, no trout eggs, and a standpipe were used to measure permeability We lowered the water level in a standpipe to create a hydraulic head of known volume and measured the influx of water over time This process was repeated 20 times for each sediment treatment We assumed that each chiller unit provided flow that remained constant during and after our study; therefore, intragravel measures should reflect conditions embryos experienced *Saprolegnia* spp , a common fungus observed at retrieval 1, was treated with 50 ml of Paracide-F[1] in each incubation chamber for approximately 15 min and then flushed with fresh well water Additional treatments given throughout the study (3 per week in each stream) eliminated the spread of the fungus

We sieved fine sediments, recovered at each retrieval, using standard sieves (0.18, 0 43, 0.85, and 6.33 mm) to determine the amount of fine sediment lost or gained during the study We recovered fine sediment retained by the matrix of eggs and *Saprolegnia* spp by washing with water Gravel and fine sediment were dried at 60°C until all water was removed, and then weighed to the nearest 0 1 g

We compared survival of developing brook trout and fry condition among the six fine sediment levels at each retrieval with analysis of variance (ANOVA) and Fisher's least significant difference (LSD) test, which controls for comparison-wise error rates (Ott, 1988) Differences in stream water temperature, pH, and surface dissolved oxygen were tested among streams using one-way ANOVAs and Fisher's LSD where appropriate Linear regression was used to determine if significant relationships existed between fine sediment levels and intragravel permeability and dissolved oxygen Paired *t*-tests were used to detect differences between the starting and ending fine sediment amounts Mean values in text are reported as mean± SD All statistical analyses were performed using the Statistical Analysis System (SAS Institute, 1985) at a significance level of 0.05

## 3. Results

### 3.1. Stream characteristics

Weekly pH ranged from 8.2 to 8.7 Mean stream temperatures were 6.0±1 7°C for stream 1, 6 3±1.8°C for stream 2, and 6.6±2.0°C for stream 3 Stream 3 was significantly warmer than stream 1 ($P<0.05$) Surface water dissolved oxygen ranged from 7.4 to 15.2 mg/l The minimum dissolved oxygen value was recorded in stream 1 after an ice-storm (11 February, day 129) cut-off power (emergency power was supplied within 4 h) Otherwise, the minimum dissolved oxygen level was 7 8 mg/l Surface dissolved oxygen levels did not differ among streams ($P=0.48$)

Intragravel dissolved oxygen was negatively related to percentage of fine sediment ($r^2=0.98$, slope= −0 08, $P<0.0001$), although surface water dissolved oxygen was constant at 10.4±0.2 mg/l in all three streams when measurements were taken Permeability was negatively related to percentage of fine sediment

Table 2
Fine sediment loss (g) for Whitlock–Vibert boxes (retrieval 0 boxes were planted without eggs and retrieved immediately)

| Retrieval | Sediment (%) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | 20 | 25 |
| 0 | 0 | −6.7±1.5 | −6.5±1.5 | −9.0±2.6 | −10.9±1.9 | −12.3±2.6 |
| 1 | 0 | −6.9±2.7 | −6.6±1.0 | −9.2±3.9 | −8.5±1.1 | −12.6±0.5 |
| 2 | 0 | −6.5±1.1 | −7.5±1.5 | −8.7±1.0 | −13.5±2.5 | −10.8±4.3 |
| 3 | 0 | −8.5±0.8 | −6.7±2.8 | −10.6±2.3 | −10.9±3.4 | −9.5±4.4 |
| 4 | 0 | −8.2±1.5 | −8.7±7.6 | −8.7±2.9 | −7.2±5.9 | −7.4±2.6 |
| 5 | 0 | −8.5±4.3 | −7.2±2.8 | −7.9±0.4 | −8.5±1.7 | −9.9±4.0 |
| 6 | 0 | −7.4±2.3 | −4.9±0.9 | −8.7±2.9 | −10.6±1.5 | −8.6±1.1 |

Whitlock–Vibert boxes at the 5%, 10%, 15%, 20% and 25% levels initially contained 27.5, 55.0, 82.5, 110.0, and 137.5 g of fine sediment, respectively. Negative table entries denote losses. Results for retrievals 2 and 4 are similar. No significant differences among retrievals in sediment loss for each sediment treatment (columns) were found (ANOVA, $P>0.05$)

($r^2=0.96$, slope$=-60.6$, $P<0.001$). Estimated permeabilities ranged from 450.0 cm/h at 0% fine sediment to 312.5 cm/h at 25% fine sediment. Permeability and intragravel dissolved oxygen were significantly correlated ($r=0.94$, $P<0.001$)

### 3.2. *Fine sediment mixtures*

Total fine sediment amounts recovered at each retrieval were significantly lower than initial amounts for all treatments except the 0% fine sediment treatment, which also did not gain any sediment (Table 2, $P<0.001$). Of the fine sediment recovered, 19.6–49.3% was broken down into smaller size classes (0.18–0.43 mm and <0.18 mm diameter). To account for all fine sediment, all size classes below 0.85 mm were summed for analysis. Whitlock–Vibert boxes lost similar amounts of fine sediment at all retrievals including boxes retrieved immediately (retrieval 0, Table 2, $P>0.05$). Because time within each stream did not influence fine sediment loss (Table 2), fine sediment loss was probably due to handling when boxes were buried and retrieved

### 3.3. *Brook trout survival*

Survival estimates (Table 3) at all retrievals were based on absolute counts of recovered live and dead eggs, alevins, and emergents. In general, survival from planting to each stage of embryonic development declined with increasing fine sediment amounts but differences were not significant for all retrievals (Table 3, $P>0.05$). At retrieval 1 (day 14) all viable embryos were still in the green stage. By retrieval 2, viable eggs were in one of two distinguishable developmental stages: green (streams 1 and 2) or eyed (stream 3). Non-viable embryos recovered in all three streams were found clumped together by *Saprolegnia* spp. hyphal strands. At retrievals 1 and 2, fine sediment effects were significant (Table 3, $P<0.05$),

Table 3
Survival (%) of brook trout incubated in laboratory streams over time (retrievals) at six fine sediment treatments

| Sediment (%) | Stage of development | | | | | |
|---|---|---|---|---|---|---|
| | Green | Green/eyed | Eyed | Hatched | >90% Emerged | Emerged |
| 0 | 84.8±1.5*z* | 80.2±3.3*z* | 76.8±3.2 | 55.3±7.9*z* | 52.2±17.2 | 45.4±11.2 |
| 5 | 85.1±3.8*z* | 79.7±4.9*z* | 73.5±2.7 | 48.7±3.9*zy* | 48.9±4.3 | 41.6±13.3 |
| 10 | 78.2±3.4*y* | 74.7±2.7*zy* | 71.7±3.2 | 45.0±2.8*yx* | 41.6±18.5 | 35.5±13.7 |
| 15 | 78.6±2.0*y* | 75.2±3.9*zy* | 74.7±2.6 | 40.2±4.3*x* | 42.4±3.6 | 36.4±11.2 |
| 20 | 72.5±4.2*y* | 69.0±4.8*y* | 68.9±3.6 | 40.9±1.5*yx* | 43.4±2.6 | 33.5±4.3 |
| 25 | 72.5±4.8*y* | 72.6±0.4*y* | 66.5±6.9 | 40.6±2.4*x* | 25.7±18.3 | 24.3±4.9 |

Table entries are mean±SD. Differences among sediment treatments were significant for green, eyed, and hatched stages in development (ANOVA, $P<0.05$). Different letters denote significant differences within a column (i.e., each stage of development) (Fisher's LSD, $P<0.05$).

survival at the 0% and 5% fine sediment levels was significantly different from survival at the 20% and 25% fine sediment levels (Table 3, $P<0.05$).

At retrieval 3 *Saprolegnia* spp. still existed in all boxes; however, clumped masses of eggs were not seen, suggesting that Paracide-F treatments had weakened the fungal hyphae and prevented infection of other eggs. Fine sediment did not significantly influence survival at retrieval 3 (Table 3, $P=0.07$). By retrieval 4 (480 degree-days), survival had declined by nearly 25% from the previous retrieval, regardless of fine sediment treatment (Table 3). The effect of fine sediment on survival was significant at retrieval 4 (Table 3, $P=0.005$). Survival to retrieval 4 at 0% fine sediment was significantly different from survival at 10–25% fine sediment (Table 3, $P<0.05$) and differences between 0% and 5% fine sediment were not significant (Table 3, Fisher's LSD, $P>0.05$).

At retrieval 5, greater than 90% of fry had emerged. Dead eggs and alevins at this stage broke apart easily. Survival at the 0% fine sediment treatment was twice that of survival at the 25% fine sediment treatment, but differences were not significant (Table 3, $P=0.26$). Some relatively low survivals at 0%, 10%, and 25% fine sediment in stream 2 resulted in large variances for these sediment treatments (Table 3, Fig. 2). Survival at retrieval 6, full emergence, was not significantly different among fine sediment treatments (Table 3, $P=0.06$), although only about half as many fry survived in 25% fine sediment as did in 0% fine sediment (Table 3). Because 90% of fry had emerged by retrieval 5 and mortality unrelated to fine sediments probably occurred in the 8–9 days between retrievals 5 and 6; we considered retrieval 5 to be the time of emergence.

Through time, survival at the 25% fine sediment treatment (linear regression, $R^2=0.88$, slope$=-0.076$) declined slightly more rapidly than did survival at the 0% fine sediment treatment (linear regression, $R^2=0.78$, slope$=-0.050$) (Fig. 2). A test of the slopes for these two regressions indicated that this difference was not significant ($P>0.05$). Declines in survival over time for all other treatments fell between the 0% and 25% sediment treatments: 5% ($R^2=0.79$, slope$=-0.059$), 10% ($R^2=0.75$, slope$=-0.062$), 15% ($R^2=0.80$, slope$=-0.062$), and 20% ($R^2=0.87$, slope$=-0.055$) (all regressions were significant, $P<0.001$).

Survival values that we calculated may have overestimated actual survival to emergence because some alevins died and disintegrated, and after retrieval 4, a small number ($n=230$) escaped the W–V box, redu-

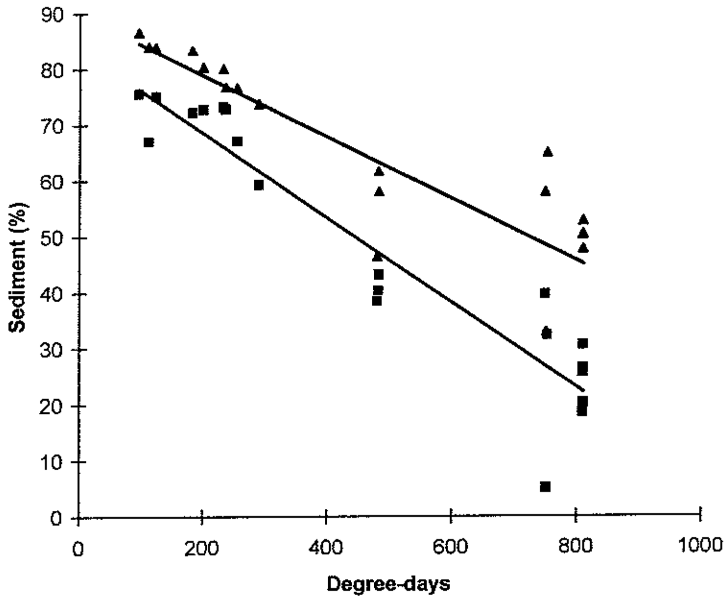

Fig. 2. Survival (%) of brook trout at 0% (triangles, $R^2=0.76$, slope$=-0.05$, $P<0.001$) and 25% (squares, $R^2=0.88$, slope$=-0.08$, $P<0.001$) sediment treatments over the incubation period (degree-days)

cing the total number of recovered individuals. By using an estimate of the total number of eggs deposited (average number retrieved at retrieval 1, $n=201$), numbers of eggs lost were estimated for all retrieved boxes. For retrievals 1, 2, 3, and 6 no significant differences in the total number of eggs lost among fine sediment treatments were found ($P>0.05$). At retrieval 4, egg losses in 25% fine sediment were significantly greater than egg losses in 0% fine sediment ($P<0.05$). At retrieval 5, egg losses among sediment treatments were different ($P<0.01$): fewer eggs were present in the higher sediment treatments (10%, 20%, and 25%) and were significantly different from the 0% sediment treatment ($P<0.05$). Assuming that all eggs and emergents not recovered were dead and did not escape, new survival values were calculated for all fine sediment treatments at retrieval 5. Average survival to emergence was 48.4±17.2, 48.1±8.0, 32.8±17.6, 43.6±2.2, 34.3±1.5, and 18.4±13.8 in 0%, 5%, 10%, 15%, 20%, and 25% fine sediment, respectively, but was not significantly different ($P>0.05$). True survivals of emergent fry probably fall between values reported in Table 3.

### 3.4. *Size and condition of emergent fry*

Emergent fry recovered at retrieval 5 incubated in 0% and 5% fine sediment had significantly higher KD indices than emergent fry in 10%, 20%, and 25% fine sediment (Table 4, $P<0.05$). Significantly heavier fry emerged from boxes with fine sediments less than 15% compared to boxes with at least 20% fine sediment (Table 4, $P<0.05$). Although wet length differed significantly among treatments, no consistent trend could be found among the fine sediment levels (Table 4, $P<0.05$).

Table 4
Size and condition of emergent fry from retrieval 5

| Sediment (%) | Wet weight (mg) | Wet length (mm) | KD |
|---|---|---|---|
| 0 | 62.7±26.6*z* | 19.0±2.1*x* | 2.02±0.23*z* |
| 5 | 60.2±20.7*zy* | 19.2±1.7*x* | 2.00±0.14*zy* |
| 10 | 62.3±14.3*z* | 20.5±1.6*z* | 1.93±0.13*x* |
| 15 | 56.3±18.9*yx* | 19.2±2.1*x* | 1.97±0.17*y* |
| 20 | 53.2±19.8*x* | 19.3±1.9*x* | 1.90±0.16*x* |
| 25 | 55.1±11.9*x* | 19.7±1.5*y* | 1.92±0.13*x* |

Wet weight, wet length, and KD indices were significantly different among fine sediment treatments (ANOVA, $P<0.05$). Different indicate significant differences detected by Fisher's LSD ($P<0.05$). Table entries are mean±SD.

## 4. Discussion

### 4.1. *Brook trout survival*

The artificial system used in this study protected against a variety of factors (e.g., storm events, human disturbance, and predation) that may influence embryonic survival in natural redds. During this study, survival of incubating brook trout decreased as fine sediment amount increased (Table 3). At emergence, survival of fry incubated in 25% fine sediment was about half that of fry incubated without fine sediment. We were unable to determine a specific time period during which embryos are most susceptible to fine sediments. Both permeability and dissolved oxygen were linearly and inversely related to fine sediments; relations were sufficiently strong that we can assume direct influences by fine sediment levels on both permeability and dissolved oxygen for purposes of this discussion.

Differences in survival to emergence were not significant due to large variation of survival estimates. Our design blocked for the confounding effects of differences among three incubation streams; but if survival in one stream deviated systematically from the other two, all variances increased. In fact, at retrieval 5, survival in boxes retrieved from one stream were lower than the other two streams for all treatments (Argent, 1995). The statistical power of the ANOVA for retrieval 5 was only 30%. With the observed variances (Table 3), a sample size of at least seven boxes per treatment would have been necessary to detect a significant difference, at $\alpha=0.05$, among treatment means (Table 3) at retrieval 5 with 70% probability.

Other investigators reported declines similar to ours in survival to emergence of salmonids (Table 5). Hausle (1973) reported brook trout survival to emergence that exceeded 80% when incubated in 0% and 5% sand (<2 mm in diameter) but declined to an average of 27% when sand proportions exceeded 15%; survival was higher in his study because the study began at a more advanced stage in development

Table 5
Salmonid survival to emergence from studies conducted in artificial systems

| Species | Sediment size (mm) | Fine sediment (%) | Starting stage | Mean survival (%) | Source |
|---|---|---|---|---|---|
| Brook trout | <0 85 | 0 | Green | 52 | This study |
| | | 10 | | 42 | |
| | | 20 | | 43 | |
| Brook trout | <2 | 0 | Eyed | 100 | Hausle (1973) |
| | | 10 | | 50 | |
| | | 20 | | 10 | |
| Chinook salmon | <0 84 | 0 | Green | 63 | Reiser and White (1988) |
| | | 10 | | 10 | |
| | | 20 | | 2 | |
| Steelhead trout | <0 84 | 0 | Green | 85 | Reiser and White (1988) |
| | | 10 | | 25 | |
| | | 20 | | 18 | |

(Table 5) The ideal stream bed for incubation should consist of gravel with voids just large enough to contain individual eggs, yet allow adequate percolation of oxygenated water (Iwamoto et al , 1978)

Low levels of intragravel dissolved oxygen and reduced gravel permeability have been implicated in reduced survival of eggs and alevins exposed to elevated levels of fine sediment (Wickett, 1954; Alderdice et al., 1958; Coble, 1961; Silver et al., 1963). Intragravel dissolved oxygen at 25% fine sediment was approximately 1.8 mg/l less than surface water dissolved oxygen, and when surface water dissolved oxygen levels fell to the minimum recorded, 7 2 mg/l (70% saturation, day 128), dissolved oxygen in boxes with 25% fine sediments would be about 5.4 mg/l. Permeability and intragravel dissolved oxygen values that we reported were similar to those for comparable field studies (Tagart, 1976) Mean permeability to 50% emergence ranged from 312 to 4211 cm/h in Hurst Creek, Washington (Tagart, 1976) In the absence of fine sediments, survival to emergence in our study averaged 45% with 11 mg/l intragravel dissolved oxygen and 450 cm/h permeability. Even under ideal hatchery conditions, survival to emergence of Nashua strain brook trout exceeds 90% (Kincaid, 1981) These results suggest that even in the absence of fine sediments, survival can be negatively affected by other factors.

Whitlock–Vibert boxes with 0% fine sediment provided an upper estimate of mortality due to handling: approximately 12% of planted eggs died by retrieval 1. However, this is an overestimate of true handling mortality because 14 d passed between planting and retrieval 1. Reiser and White (1988) reported a handling mortality of 9% for green chinook salmon eggs using similar planting techniques and W–V boxes

Fine sediments present within a redd create conditions conducive to entry and persistence of disease-related organisms (Iwamoto et al., 1978). Non-viable eggs and dead alevins collected throughout our study were infested with the fungus *Saprolegnia* spp. Fungi appeared in all boxes, including those without fine sediment. Treatments with Paracide-F did not eradicate fungi but did slow the rate at which fungi infected other eggs. Fungal infestations like these may increase the susceptibility of viable eggs or alevins to die and disintegrate; however, this contention has not been directly tested.

Greater than 98% of eggs were recovered, either alive or dead, through retrieval 3, but only 81% were recovered at emergence assuming 200 eggs were present initially in each W–V box. Unrecovered fry either disintegrated or they escaped from misshapen mesh liners in W–V boxes. We estimate that about 15% of planted eggs, disintegrated by emergence. Disappearance of brook trout eggs in a similar laboratory study occurred at 2% by 53 d, 24% by 90 d, and 82% by 133 d (Hausle, 1973). In Slovens Creek, New Zealand, brown trout (*Salmo trutta*) eggs disappeared at 0% in 35 d and 9% in 41 d (Hobbs, 1937). In Mill Creek, California, 50% of planted chinook salmon eggs were recovered after 45–58 d (Gangmark and Broad, 1955). We also found that approximately 230 surviving fry were able to escape lined W–V boxes between retrievals 4 and 6 Had these fry been retained in their respective egg boxes, estimated survival to emergence relative to each sediment treatment may have increased by about 2% (5 escaped fry per box/ 200 eggs per box).

### 4.2. Quality of emergents

Due to genetic defects common in hatchery strains, deformed fry were found at all sediment treatments (C. Stevens, Paint Bank Fish Hatchery, Virginia, personal communication) However, an estimate of the frequency with which such anomalies occur was unavailable. Ten emergent fry (0.8% of live fry from retrieval 5) with physical anomalies such as crooked backs, crooked tails, no tails, and two heads were not used to calculate condition indices.

Subtle sublethal effects of fine sediments may alter fry condition (Koski, 1966; Mason, 1969). Emergent fry incubated in 0% and 5% fine sediment at retrieval 5 (Table 4) probably still possessed yolk material as KD indices averaged greater than or equal to 2.0 (Bams, 1970). Fry incubated in 20% and 25% fine sediment had probably completed yolk absorption and may have been resorbing body mass because KD indices averaged less than 1.93 (Bams, 1970). Fry weight generally declined as the proportion of fine sediment increased, and fry length changed little (Table 4). Hausle (1973) found no relation between the percentage of sand and the weight of emerging brook trout fry. Coho salmon fry that emerge from high percentages of sand weigh less than fry from gravels with low percentages, but steelhead fry are of similar weight after emergence from gravels with different percentages of sand (Phillips et al., 1975). No definitive relation was demonstrated between the weight of steelhead fry and the composition of fine sediments in redds (Reiser and White, 1988). Emergent fry incubated in higher proportions of fine sediment ($\geq$10%) in our study had nearly depleted energy reserves at emergence, possibly due to stress at higher sediment levels The alternative hypothesis that fry developed more quickly at higher sediment levels may be rejected because these fry were the same length at emergence as fry incubated with little or no sediment (Table 4).

Future research studies can more fully answer the questions managers have about fine sediments and brook trout in the southern Appalachians. Fewer fine sediment treatments and more replicates (at least seven per treatment based on our power calculation) are needed to demonstrate statistically the reduced survival we observed. Fine sediment sizes below 0.43 mm should also be evaluated, as these size classes accumulate in field settings (Argent, 1995). Further study of sublethal effects beyond the emergence period would provide insights into additional stresses that influence fry recruitment.

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