



Effects of fine sediment accumulation on egg-to-fry survival of cutthroat trout inhabiting a highly sedimented headwater stream
by Andrew Lee Bowersox

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Fish and Wildlife Management
Montana State University
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Abstract:

I investigated fry production of westslope cutthroat trout (*Oncorhynchus clarki lewisi*) in Cache Creek, a highly sedimented headwater, and tested an equation relating gravel composition and emergence success in a natural environment. Emergence success was measured using redd capping and electrofishing methods, and results were compared to emergence success predicted by the equation. I measured redd substrate composition with freeze cores and sediment intrusion with intrusion buckets. Redds contained high fine sediment levels over time (mean % fines <0.85 mm = 17.4% and <6.35 mm = 34.3%) due to rapid sediment intrusion ($>75\%$ of total intrusion occurred within 1 week of bucket installation). The mean freddie index at redds confirmed by a digging female ($F_i = 2.1$) was significantly higher ($P = 0.006$) than at unconfirmed redd sites identified by multiple fish over gravel substrate, or by characteristic pit-tailspill morphology ($F_i = 1.1$). Redd substrate composition by reach was significantly, positively correlated with mean intrusion for fines <0.85 mm ($r^2 = 0.70$, $P = 0.075$). Dissolved oxygen in redds was highly variable though generally low overall (range = 4.0-8.8 mg/L, mean = 7.1 mg/L). Emergence success from capped redds indicated high variability (range 0-41%) though total observed fry production was low during both years (1.5% in 1994, and 5.4% in 1995). Predicted emergence success was also low (12.5%), but higher than observed. The discrepancy may be due to other sources of reduced spawning success in addition to high fine sediment. These additional sources include 1) culverts acting as barriers to upstream migration, 2) direct trampling of spawning areas by livestock, 3) redd dewatering, 4) shallow spawning gravels, and 5) elevated intragravel temperatures. A diversity of redd sites can promote recruitment stability due to high fry survival at a few redds with adequate substrate quality. However, the data presented here suggest that this compensatory mechanism may be overwhelmed in Cache Creek when there is a low number of redds constructed, and when there are other sources of fry mortality in addition to fine sediment intrusion.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 29 January 1998

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ABSTRACT

I investigated fry production of westslope cutthroat trout (*Oncorhynchus clarki lewisi*) in Cache Creek, a highly sedimented headwater, and tested an equation relating gravel composition and emergence success in a natural environment. Emergence success was measured using redd capping and electrofishing methods, and results were compared to emergence success predicted by the equation. I measured redd substrate composition with freeze cores and sediment intrusion with intrusion buckets. Redds contained high fine sediment levels over time (mean % fines <0.85 mm = 17.4% and <6.35 mm = 34.3%) due to rapid sediment intrusion (>75% of total intrusion occurred within 1 week of bucket installation). The mean fredle index at redds confirmed by a digging female ($Fi = 2.1$) was significantly higher ($P = 0.006$) than at unconfirmed redd sites identified by multiple fish over gravel substrate, or by characteristic pit-tailspill morphology ($Fi = 1.1$). Redd substrate composition by reach was significantly, positively correlated with mean intrusion for fines <0.85 mm ($r^2 = 0.70$, $P = 0.075$). Dissolved oxygen in redds was highly variable though generally low overall (range = 4.0-8.8 mg/L, mean = 7.1 mg/L). Emergence success from capped redds indicated high variability (range 0-41%) though total observed fry production was low during both years (1.5% in 1994, and 5.4% in 1995). Predicted emergence success was also low (12.5%), but higher than observed. The discrepancy may be due to other sources of reduced spawning success in addition to high fine sediment. These additional sources include 1) culverts acting as barriers to upstream migration, 2) direct trampling of spawning areas by livestock, 3) redd dewatering, 4) shallow spawning gravels, and 5) elevated intragravel temperatures. A diversity of redd sites can promote recruitment stability due to high fry survival at a few redds with adequate substrate quality. However, the data presented here suggest that this compensatory mechanism may be overwhelmed in Cache Creek when there is a low number of redds constructed, and when there are other sources of fry mortality in addition to fine sediment intrusion.

INTRODUCTION

Decreased survival to emergence of salmonid embryos results when high levels of fine sediment cause a reduction in dissolved oxygen concentration and intragravel water circulation, or physically obstruct emerging fry (Everest et al. 1987; Chapman 1988). Whereas the inverse relationship between fine sediment in spawning areas and survival to emergence is well established, uncertainty in predicting embryo survival outside a controlled laboratory persists. Furthermore, recognition that fine sediment can reduce fry production may not address the question of what factors actually limit a population (Everest et al. 1987). Despite considerable progress, the question remains: under what conditions is fine sediment detrimental to salmonids in a natural environment?

The majority of studies addressing the impact of fine sediment on salmonid survival-to-emergence have been conducted under controlled laboratory conditions. These studies have provided valuable insight on mechanistic responses to physical or biological variables (e.g., Phillips et al. 1975; Beschta and Jackson 1979; Reiser and White 1988). However, extrapolation of these findings to the natural spawning environment has proven debatable

(Chapman 1988). Chapman (1988) expressed the need to better integrate knowledge of spawning gravel, redd structure, and incubation conditions in nature with controlled experiments relating fine sediment to egg-to-fry survival.

Artificial gravel mixtures used to assess emergence success often oversimplify the physical dynamics of fine sediment infiltration that occur in natural redds. In particular, the fine sediment composition may be kept or assumed constant over time. However, trout remove fines from spawning gravel during redd construction (Cordone and Kelly 1961) and fine sediment intrusion accumulates during incubation (Chapman 1988). Accordingly, laboratory modeling that accounts for the strong temporal effect of fine sediment intrusion in natural streams may require that fine sediment be added during the incubation period (Chapman 1988). Such studies would shift their emphasis towards measuring sediment intrusion rates rather than substrate composition at one point in time.

Not only gravel composition, but its structure and surface topography are considerations relevant to study design. The egg pocket frequently contains a few large stones which may provide more interstitial space to developing eggs than the material in the surrounding redd (Chapman 1988). Furthermore, the pit-tail spill morphology

of natural redds may have a major effect on the rate at which cleaned gravels refill with fine sediment over time; the pit acts as a natural settling basin, while the tailspill serves to accelerate water velocity, carrying remaining suspended sediments over the egg pocket (Everest et al. 1987). These effects may operate until scour obliterates redd topography or excessive sedimentation overwhelms the deposition resistant capacity of the redd (Everest et al. 1987).

Monitoring of appropriate incubation conditions also must be incorporated into study designs. Dissolved oxygen is one factor in particular which must be included when assessing sediment-survival relationships. Dissolved oxygen concentration in the egg pocket presumably responds to fine sediment intrusion over time in response to reduced gravel permeability and oxygen consumption of embryos or decaying organic matter. Therefore, dissolved oxygen should be measured at least twice during embryo development, soon after fertilization and near emergence. However, because of the high handling mortality of pre-eyed eggs, many studies employ embryos or alevins developed beyond the eyed-egg stage for planting into artificial redds. In the natural environment, however, pre-eyed eggs may be most susceptible to fine sediment infiltration and low dissolved oxygen as

they lack any circulatory system and are thus dependent on diffusion to meet oxygen requirements (Wickett 1954; Reiser and White 1988; Maret et al. 1993). Consequently, survival estimates derived from planting eyed-eggs or alevins may be biased.

Field testing of sediment-survival relationships is necessary to fully assess and predict the effects of fine sediment on emergence success. One such field approach conducted by Weaver and Fraley (1993) used artificial redds of westslope cutthroat trout (*Oncorhynchus clarki lewisi*) that effectively simulated natural redd structure and pit-tailspill topography containing varying known percentages of fine sediment. They found emergence success to be highly negatively correlated with the percentage of materials less than 6.35 mm ($r^2=0.96$, $p<0.005$). Their approach was useful in being able to assess laboratory derived relationships (Irving and Bjornn 1984) under the dynamic conditions of a natural channel. Their design had three limitations, however. First, eyed eggs were used in their artificial redds. Second, it was assumed that the percentage of fine sediment remained constant during incubation. Third, dissolved oxygen was measured only once (the timing of this measurement was not specified).

Maret et al. (1993) used artificial redds in the field

to measure survival of brown trout (*Salmo trutta*) embryos to hatching in relation to fine sediment and intragravel dissolved oxygen. Percent fines were measured before and after incubation from three sites impacted by agricultural activities containing six redds each and from an unimpacted control site. Intragravel dissolved oxygen concentration was measured on approximately alternate weeks from the time of planting eyed eggs to hatch. This monitoring protocol was advantageous because it incorporated a strong temporal component in relating sediment intrusion to embryo survival. They found that survival was negligible (<10%) at mean intragravel dissolved oxygen concentration less than 6.0 mg/L and that intragravel dissolved oxygen concentration declined linearly with percent fines.

Maret et al. (1993) incorporated three of the basic data requirements needed to adequately test embryo survival in the field in relation to substrate conditions including sediment intrusion, dissolved oxygen, and an estimate of survival. However, by using eyed eggs, survival estimates in relation to dissolved oxygen did not evaluate possible mortality during the pre-eyed stage. Furthermore, survival was estimated based on hatching success rather than successful survival to emergence. Fine sediment intrusion may result in embryo mortality from fry entrapment at

emergence, regardless of dissolved oxygen (Phillips et al. 1975, Everest et al. 1987, Chapman 1988).

Studies by Weaver and Fraley (1993) and Maret et al. (1993) serve to illustrate the difficulty in designing studies which assess the temporal effects of fine sediment on emergence success as it relates to natural spawning conditions. The difficulties associated with assessing temporal variation are further complicated by recognition that spatial variation also influences emergence success in nature. Lisle and Lewis (1992) and Magee et al. (1996) argued that knowledge of spatial variability in redd substrate conditions is necessary to accurately predict emergence success.

Lisle and Lewis (1992) viewed the effects of sediment transport on egg incubation as a hierarchy of processes involving water discharge, sediment transport, changes in gravel conditions, and physiological changes and responses of embryos. They presented a model linking variations in flow and sediment transport to the fraction of fry that survive in a natural channel. With this model, they were able to evaluate the uncertainty and variability of individual processes. They noted that variability is high and uncertainty relatively low in the driving processes (stream flow and sediment transport), but uncertainty is

high in the response processes (temporal and spatial changes in gravel conditions and embryo mortality). Driving processes are measured routinely in the field, while response processes are not. The uncertainty persists because reliable means of measuring response processes in the natural environment have not been developed or have not been related in time and space to measurements of driving processes. Data are needed that will reduce uncertainty while increasing our awareness of spatial variability of sediment intrusion during incubation and its effects on embryo mortality (Lisle and Lewis 1992). In short, the relative lack of published field data describing changes in natural redds itself precludes accurate modeling.

A few studies have attempted to quantify spatial variation in substrate quality in natural redds. Beard and Carline (1991) using a McNeil hollow core sampler (Platts et al. 1983) reported that fredle indices of substrate composition varied from 2.42 to 5.34. Magee et al. (1996), using a McNeil hollow core sampler, reported over five-fold differences in fredle indices (0.5 to 2.7) in 21 cutthroat trout redds from Cache Creek, Montana.

An important consequence of variability in the effects of sediment deposition on incubation success is that it may result in stability of fry recruitment even under conditions

of high sediment loads (Lisle and Lewis 1992; Magee et al. 1996). Magee et al. (1996) calculated emergence success from 252 study redds in Cache Creek using the equation developed by Weaver and Fraley (1993). Based on the equation emergence success was 9.4% overall, but Magee et al. (1996) found little evidence for low recruitment. They speculated that high emergence success at a few redds with high substrate quality compensated for low emergence success at most redds.

I measured actual emergence success from Cache Creek redds having varying redd substrate composition to test this hypothesis. Magee et al. (1996) predicted emergence success using Weaver and Fraley's (1993) equation, however they did not test the accuracy of their prediction with an actual measurement of emergence success in the field. I used two approaches to measure emergence success: 1) at the scale of individual redds and 2) at the scale of individual spawning reaches. The combination of methods relates variability in emergence success between individual redds to variability between individual spawning reaches, thereby reducing uncertainty and strengthening the overall validity of results. Spatial variability in emergence success at the scale of individual redds may be quantified using emergence traps to measure embryo survival (e.g., Phillips and Koski

1969; Fraley et al. 1986). The main advantage of emergence trapping is that you can estimate egg deposition and measure emergence success directly from a redd. A disadvantage is that population level responses to sedimentation are difficult to obtain, unless the majority of redds are trapped. Emergence traps also possess the disadvantage of possible experimental bias. Redd caps may reduce water velocities over redds, thereby increasing sediment deposition or decreasing intragravel water circulation. However, Philips and Koski (1969) reported that their emergence traps had no significant effect on intragravel dissolved oxygen and gravel permeability.

To reduce the potential bias associated with redd capping, a second approach to measuring emergence success uses weirs that enclose stream reaches having different substrate conditions and one or more redds. The main advantage here is that flow conditions over individual redd sites remain undisturbed. A disadvantage is that trapping all emergent fry from within relatively large spawning reaches poses logistical difficulties (such as the need to extrapolate sampled sections to the length of an entire reach), and regardless of substrate variability within a given reach or of how many fish spawned, only a single survival estimate is derived for each reach.

An additional objective of this study was to examine the effects of livestock grazing on emergence success. A major increase in fine sediment input to streams has occurred on western range and forest lands by the cumulative effects of up to a century of livestock grazing (Platts 1991). Livestock actively select riparian habitats causing trampling of stream banks, bank erosion, channel widening, and a lowered water table (Platts 1991; Fleischner 1994; Chaney et al. 1993). Aquatic habitat for trout is reduced because of the loss of overhanging cover, elevated and highly variable water temperatures, destabilized channels, and increased inputs of fine sediment which degrade spawning and rearing areas used by fish (Platts 1991).

Magee et al. (1996) speculated that erosion caused by livestock disturbance may be a primary source of small fines (<0.85 mm) in Cache Creek as cattle were common on stream banks and within the stream channel during egg incubation. In addition, livestock may adversely impact emergence success of trout embryos by trampling redd sites. Few studies have addressed the effects of livestock trampling redd sites during incubation. However, Roberts and White (1992) found that when humans trampled redds containing eyed eggs, survival was reduced significantly for brown trout, rainbow trout (*Oncorhynchus mykiss*), and cutthroat trout.

Livestock impacts were assessed by recording trampling effects at identified redd sites and at sites where suitable spawning gravel was present and by identifying major sites where livestock were known to enter stream channels.

The objectives of my study were to:

1. determine how changes in fine sediment intrusion and dissolved oxygen concentration in natural redds during incubation relate to emergence success among redds in Cache Creek, a highly sedimented stream basin.
2. examine the extent of redd trampling and its potential effects on cutthroat trout emergence success in Cache Creek.
3. test laboratory derived relationships between gravel quality and emergence success under natural conditions.

STUDY AREA

The study was conducted in the Cache Creek sub-basin (area 35-km², elevation 2400 m) of the Taylor Fork drainage of southwestern Montana (Figure 1). The Taylor Fork drainage is a 160-km² catchment to the Gallatin River. Elevation ranges from 3080 m at the headwaters to 2032 m at the confluence with the Gallatin River. The drainage is located 24 km south of Big Sky off Highway 191 in the Gallatin National Forest near Yellowstone National Park.

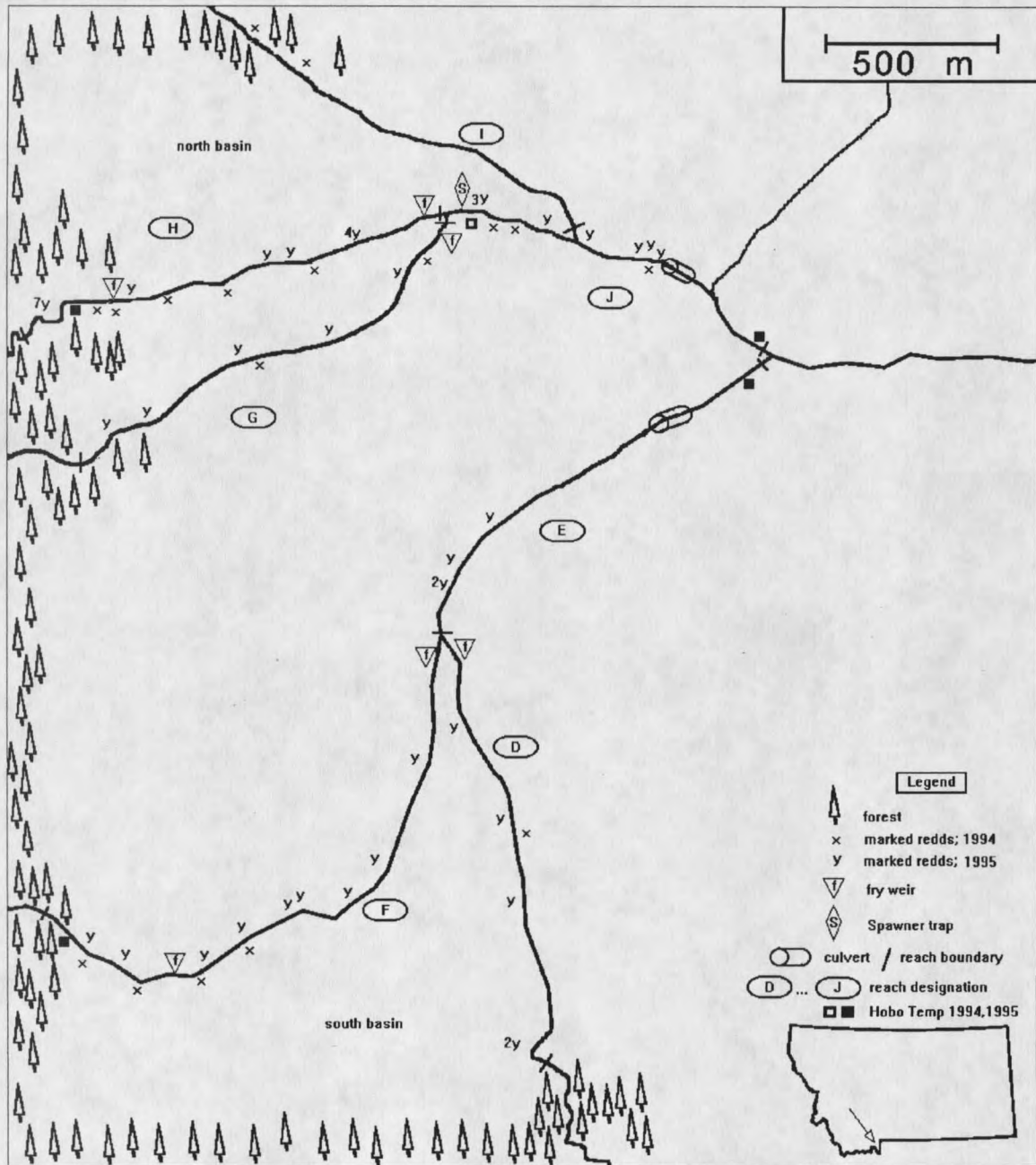


Figure 1. Map of the Cache Creek subbasin showing study reach designations D-J, culverts, redd distributions, weir locations and thermograph sites.

Cache Creek contains the highest density of westslope cutthroat trout reported in the literature (Shepard et al. 1984; Ireland 1993) and is one of only a few remaining populations in the Gallatin River drainage (Liknes 1984; Magee et al. 1996). Cutthroat trout have declined sharply as a result habitat degradation, genetic introgression with introduced salmonids, and over-exploitation (Behnke 1992). Current management priorities include evaluating habitat requirements and sensitivity to disturbance, identification of remaining populations, and enhancing the distribution of pure populations (Young 1995).

The Taylor Fork drainage offers a unique opportunity to study the effects of fine sediment on cutthroat trout emergence due to its naturally unstable geology which produces large quantities of fine sediment <6.35 mm and <0.85 mm (Snyder et al. 1978; Magee et al. 1996). Magee et al. (1996) found that Cache Creek spawning gravels have the highest fine sediment content <0.85 mm reported in the Rocky Mountain region. Quantity of small fines is an indicator of degree of watershed disturbance (Snyder et al. 1978; Magee et al. 1996).

The third-order mainstem of upper Cache Creek meanders through sagebrush meadows with a mean gradient of 0.5% (Ireland 1993). The mainstem drains two second order sub-

basins, the north basin containing three first order perennial headwater tributaries and the south basin containing at least two. All perennial first and second order reaches provide substrate usable for spawning though the proportions vary (3-25%) among reaches (Magee et al. 1996). The third order mainstem contains about 17% usable stream area for spawning (Magee et al. 1996). Magee et al. (1996) counted 252 cutthroat trout redds in Cache Creek during 1992, accounting for 70% of the total spawning within the Taylor Fork basin. Of these, 48 were located in the third order mainstem (Magee et al. 1996). However, high flows may prevent spawning within this reach during some years. Mean gradient among spawning reaches ranges from 0.5 to 3.8% (Magee et al. 1996).

In addition to naturally unstable geology, Cache Creek is also potentially subject to increased sedimentation from land use disturbance (Magee et al. 1996). There are 220 cow-calf animal units that graze an allotment on Cache Creek spawning tributaries during June and July. The predominance of bare, slumping and unstable stream banks, wide downcut channels, and sagebrush encroachment in the area are characteristic of heavily grazed riparian zones (Snyder et al. 1978). Stream bank stability of spawning reaches is less than 50% stable, on average, and no reaches have stream

banks classified as greater than 75% stable (Magee et al. 1996). Areas within the sub-basin have been logged recently with associated road building and culvert installation.

METHODS

Spawning reaches

I compared emergence success and fry production among seven stream reaches in Cache Creek that varied in land use intensity and availability and quality of spawning gravels (Figure 1). Reach delineations were based on the location of tributary junctions. Exceptions included reach E, where the lower limit was delineated by a culvert, and reach J, which included tributary junction I and where the lower limit was also delineated by a culvert.

Spawning migration

Fish were quantified during 1994 (May 18-June 5) using two-way traps to assess the timing and magnitude of spawner migration into first-order spawning tributaries draining the north and south basins (Figure 1). To confirm upstream passage, a weir was installed upstream of the culvert. Fish passage was also estimated by counting the number of fish successfully entering the culvert. Fish were tagged with visual implant tags behind the left eye, adipose clipped, measured, weighed, and identified by sex and spawning condition by the presence of milt or eggs.

Spawning migration in 1995 was monitored by observing the presence of jumping fish at the south basin culvert

(Figure 1). The 10m long culvert measured 80 cm in diameter, with an approximately 40 cm drop to a deep scour pool during high flows. I assumed that movement into the north basin tributaries coincided with the onset of jumping activity at the south basin culvert. Stream stage was measured daily by recording the water surface height from a staff gauge located near the confluence with mainstem Cache Creek.

Redd distribution

Reaches were surveyed for spawning activity daily during hours of available sunlight. Surveys were conducted during the first three weeks of June in 1994 by a single observer alternating between north and south basins; in 1995, (June 21-July 6) two observers split their time equally between basins. Redds were identified by the presence of a digging female and one or more males. Because substrate disturbance by the relatively small spawners is minimal and there is an absence of instream periphyton, the characteristic pit-tailspill morphology of salmonid redds could not be used as a reliable indicator of redd sites in study reaches. Thus, I designated "confirmed" redds only as those where a digging or spawning female was observed. I designated "unconfirmed" redds as those where multiple fish were present over spawning substrate, or a characteristic

pit-tailspill morphology was present. Individual redds were marked by placing numbered stakes on the stream bank and probable egg pocket locations were determined by measuring the distance from the stake and recording a compass heading.

Substrate composition

To test laboratory-derived relationships between gravel quality and emergence success, substrate composition of confirmed and unconfirmed redds was measured with a tri-tube freeze core sampler (Platts et al. 1983). Although I sampled to a depth of 15 cm, only the composition of the upper 10 cm of substrate was analyzed as this represents the typical depth of egg pockets for cutthroat trout redds (Magee et al. 1996). Also, the layer below 10 cm depth was composed primarily of compacted fine silt or clay, which fish cannot use as redd substrate.

To compare potential effects of cleaning and to compare confirmed versus unconfirmed redds, I sampled non-redd spawning substrate and both confirmed and unconfirmed redd sites representing post-spawning and post-emergence gravel conditions. In total, 3 non-redd sites were cored, 7 confirmed redds were cored after spawning, and 17 confirmed redds were cored after emergence. Additionally, 4

unconfirmed redds were cored after spawning and 5 after emergence. Confirmed and unconfirmed redd core sample sites were selected randomly from within a given reach. To estimate frequency of false redds, redd substrate material surrounding post-spawn core sites was searched for the presence of live or dead eggs.

Core samples were oven-dried and weighed after being mechanically shaken through sieve sizes of 50.8, 25.4, 12.4, 9.5, 6.35, 2.36, 0.85, and 0.074 mm. I expressed substrate composition by the percentage of fine sediment smaller than 6.35mm and 0.85 mm, and by a measure of central tendency, the fredle index (F_i), as suggested by Everest et al. (1987), Chapman (1988), and Young et al. (1991).

$$F_i = d_g / S_o;$$

where the sorting coefficient, $S_o = (d_{75}/d_{25})^{1/2}$ (d_{75} and d_{25} being diameters of grains at the 75th and 25th percentiles of cumulative gravel sample weight) and geometric mean particle size, $d_g = (d_{16} * d_{84})^{1/2}$. I excluded particle sizes greater than 50.8 mm to minimize bias from large particle sizes. Particles in this size range are easily lost during core extraction and were inconsistently represented in our samples, but contributed substantially to the total sample weight when present. This procedure of truncating substrate data is consistent with previous studies (Grost et al. 1990;

Thurrow and King 1994; Magee et al. 1996) and, therefore, allows for more appropriate comparisons to other data found in the literature. Statistical comparisons were made using a non-parametric Mann-Whitney-Wilcoxin test.

Fine sediment intrusion

Collapsible intrusion buckets (Lisle and Eads 1991) were used to estimate rates of sediment intrusion during incubation. Buckets were constructed from heavy canvas equipped with 20 cm diameter brass rings sewn into the top opening. Wire handles were secured to grommets along the top rim for ease in removal. For installation, a pit was excavated from an open cylinder placed over spawning-sized gravel substrate. A flattened intrusion bucket was then set in place at the bottom of the pit, 10-15 cm below the substrate surface. Spawning gravel was sieved clean of sediment <6.35mm was then placed over the flattened bucket and the overlying gravel shaped into the pit-tailspill contour of a natural redd.

Intrusion buckets were grouped and distributed among spawning reaches. Fifty buckets were buried in 1994, and 42 in 1995. During 1994, buckets were divided into groups of five with at least one group in each of the five study reaches containing the majority of redds. During 1995

buckets were buried in groups of six with 1-2 groups per reach (Table 1). Reaches had more than one group when the area of available spawning gravel permitted doing so.

Table 1. Number of intrusion buckets buried in spawning reaches.

	Reach	# of buckets
1994	H	10
	J	10
	F	20
	I	5
	D	5
1995	H	12
	G	6
	F	12
	E	6
	D	6

Buckets were installed after the peak in spawning (June 21, 1994; and July 18, 1995). One bucket was removed from the downstream end of each cluster every 1-2 weeks during incubation (June 28-July 29, 1994; July 31-September 25, 1995). By pulling up on the wire handles the buried, flattened buckets would fill with overlying gravel during removal. Contents were emptied thoroughly into a plastic bag. Bucket contents were oven-dried, sieved, and weighed to determine the proportions of fine sediment <6.35mm and <0.85 mm.

Intragravel dissolved oxygen and temperature

Dissolved oxygen and temperature were monitored during incubation in a subsample of confirmed and unconfirmed redds. In 1994, all 17 confirmed redds were monitored among 7 reaches. In 1995, 8 confirmed, and 4 unconfirmed redds were monitored. Seven of the 12 redd sites selected for monitoring in 1995 were located in reach H (Figure 1). Thus, the focus in 1995 was to detect variability in incubation conditions within a particular spawning reach; data from the previous year focused on assessing variability among spawning reaches.

Dissolved oxygen and temperature from both egg pockets and the overlying water column were monitored during incubation (June 27-July 18, 1994; July 6-August 18, 1995). Intragravel water samples were obtained using a 1 cm diameter probe, perforated at the tip, and inserted 7-10 cm into each egg pocket. The open end of the probe tubing was clamped and secured above the stream surface to prevent entry of stream water. A vacuum pump was used to draw a 200 ml sample into a plastic bottle kept partially submerged in the stream to inhibit warming. A volume of water <20 ml was discarded prior to sampling to remove any residual water contained in the tubing (approximately 10 ml) which may not have reflected egg pocket conditions. Due to the small size and depth of Cache Creek redds, care was taken not to draw

too large a volume to ensure that only water from the egg pocket was sampled. Dissolved oxygen was measured using a YSI model 54A meter. Egg pocket temperatures were obtained using a wire thermocouple probe inserted into the egg pocket to a depth of 7-10 cm. Ideally, measurements should be made during the hottest part of the day, when water temperatures are warmest and dissolved oxygen lowest at redd sites. However, because of the time required to take each measurement and walk to each site, both morning and afternoon samples were obtained and pooled. To determine daily temperature fluctuations, Hobo Temp thermistors were installed at one study reach in 1994, and at four reaches in 1995 (Figure 1). Data were recorded at 2 h intervals to determine daily maximum, minimum, and mean temperature.

Egg deposition and emergence success

I estimated fecundity based on the length of digging females to estimate egg deposition at study redds. Female length was measured using a meter stick attached to an extension handle. Females were measured directly over redd sites or against distinct substrate features. A sample of five females was measured against substrate features two different field technicians to determine the error associated with this method. Measurement error between technicians was ± 15 mm. Egg deposition (E) was then

estimated using a length-fecundity relationship based on data obtained from headwater populations of westslope cutthroat trout in Montana, including Cache Creek, where $E = -515.5 + 4.5(FL)$; $r^2 = 0.52$ ($p < 0.001$) (Downs 1997).

Two methods were used to measure emergence success. I used redd cap emergence traps (Phillips and Koski 1969; Fraley et al. 1986) to measure survival from individual redds. Redd caps were installed over all 17 study redds during 1994 and at two confirmed redds in 1995. In addition, during 1995 a pair of superimposed confirmed redds were trapped by installing a fine mesh enclosure around the site. Redd caps were installed near the end of incubation to minimize possible reductions in intragravel water velocity caused by the trap mesh. Hobo-temp thermographs were used to monitor the accumulation of centigrade temperature units to predict the timing of emergence. Redd caps (1 m x 2 m; 2 mm mesh size) sufficiently covered each redd and the surrounding substrate to ensure that fry would not evade capture without extensive lateral migration through streambed gravel. Upon emergence, fry were funneled into a perforated, mesh lined PVC pipe holding reservoir. Traps were checked every other day until emergence and then checked daily.

To assess fry production among reaches having varying

levels of fine sediment, I used a combination of fry weirs and electrofishing. In 1995, I installed 6 weirs prior to emergence (August 10) in 4 reaches (Figure 1). Weirs were monitored daily through October 10, when ice began to form along stream margins and in pools. Single pass electrofishing of reach sections above fry weirs was performed in late September to estimate the number of emergent fry which had not migrated downstream. Fry were counted as they appeared without being netted, as netting efforts would disturb the heavily silted streambed making it difficult to spot other fry. The length of each sampled reach section was measured using a hip chain. Catch rates were presented as number of fry per meter of stream length sampled. These values were then extrapolated to measurements of the entire reach length to estimate total numbers of fry in reaches bounded by fry weirs.

I assessed the effectiveness of current models for predicting emergence success by comparing estimated emergence success to measured emergence success. Estimates of cutthroat trout emergence success in relation to substrate composition were made using the equation of Weaver and Fraley (1993): emergence success (%) = $0.7512(\arcsin\text{-transformed \%material } < 6.35 \text{ mm}) + 39.67$.

Livestock effects

I assessed direct and indirect impacts to spawning sites caused by the presence of livestock in stream channels. I recorded the number of frequently used cattle crossings within spawning tributaries and the number of study redds and intrusion buckets that had been trampled. A cattle crossing was defined as a site along the stream channel with chiseled bare banks on at least one side of the channel, livestock trails leading to the channel from both sides, and the presence of disturbed spawning sized gravel and cobble in the stream bed. The presence of livestock (220 cow/calf pairs) in the study area (from June 30-July 24, 1994; and July 26-September 3, 1995) overlapped the embryo incubation period. Following livestock removal in early September of 1995, I surveyed spawning tributaries containing confirmed redds and counted the number of frequently used cattle crossings within each reach.

Redds were considered trampled when hoof prints were observed on both stream banks and within the streambed on known redd sites. Trampling of intrusion buckets was identified if the bucket was either partially or, in some cases, completely dislodged from the streambed. Trampling effects were distinguished from stream flow scour effects by the angle of the brass rings sewn into bucket openings. The edges of buckets scoured by stream flow were slightly

exposed but remained horizontal with the streambed. Trampled buckets were easily distinguishable because their openings were at a sharp angle to the streambed as a result of being at least partially dislodged. Hoof prints on both stream banks and in the channel at bucket sites further distinguished the effects of trampling from scour.

RESULTS

Spawning migration

Approximately equal numbers of spawners entered north and south basins in 1994 (Table 2). Spring runoff and associated debris transport led to frequent clogging and scour around trap stations, particularly at the south basin weir. Thus, the number of spawners trapped should be considered a subsample of the true total. Of 158 mature fish trapped, 68% were males and 32% females. Mature males averaged 178 mm and 67 g, while mature females averaged 196 mm and 96 g (Table 2).

Table 2. Number, size, and sex composition of cutthroat trout during spawning migration, May 18 to June 5, 1994.

Weir location	N	Sex	#(%)	Mean length (mm)	Mean weight (grams)
North Fork	94	Male	57(61%)	180	71
		Female	37(39%)	196	89
South fork	64	Male	50(78%)	175	62
		Female	14(22%)	198	115
Totals	158	Male	107(68%)	178	67
		Female	51(32%)	196	96

Timing of spawner migration and access to spawning tributaries varied between years. In 1994, peak migration

at the weirs occurred from May 25-June 5 at temperatures >7 °C. Peak migration was about 3 weeks later in 1995 (June 16-24) based on jumping activity at the south fork culvert. Peak jumping coincided with peak flow and initial stages of the falling hydrograph at temperatures >7 °C in both years (Figure 2).

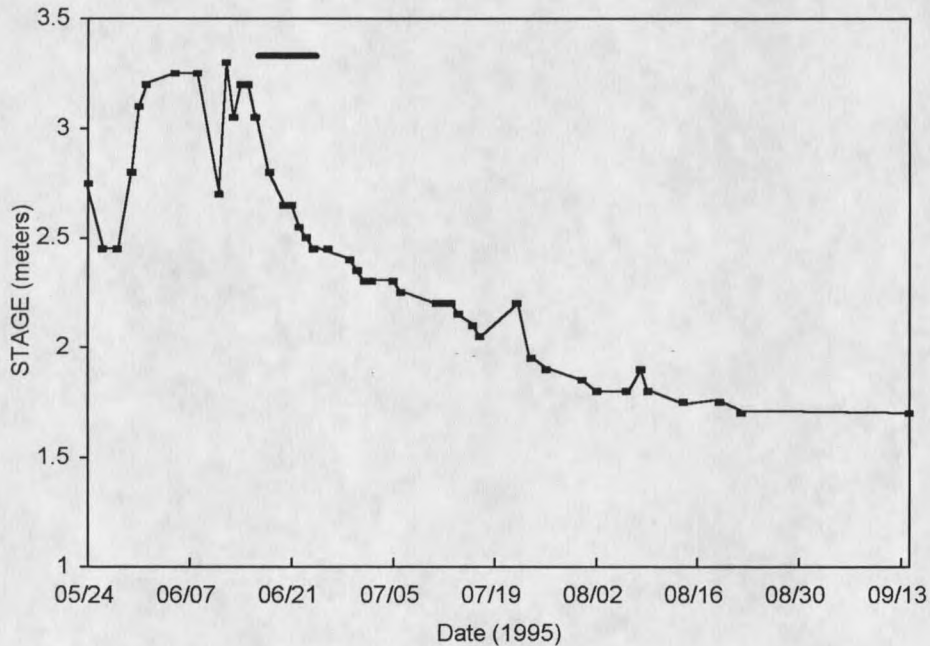


Figure 2. Stream stage measurements recorded in 1995 below the confluence of north and south basin second order tributaries. Horizontal line indicates the period of peak migration.

The south basin culvert was a partial barrier to upstream migration during some years as a result of high flows. Fish were observed entering the culvert in 1994, a comparatively low flow year, and a weir placed upstream verified fish passage. I captured 21 spawners upstream of the culvert between May 25 and May 27. This was a subsample of all fish because severe clogging of trap mesh led to scour around the weir. In 1995, a year with higher flows, at stream temperatures of 9.5-10 °C, I counted 20 (June 16) and 10 (June 19) consecutive failed attempts by spawners to enter the culvert during a 10 minute interval on both days. Fish which jumped but entirely missed the culvert spillway were not included in these counts; therefore, the actual number of failed attempts was higher than reported. The culvert acted as a barrier again in 1996. Two observers independently reported a 5% success rate based on a total of 100 jump attempts by migrating fish. It is unknown whether the 5 fish which successfully overcame the culvert spillway actually traversed the culvert. There is another culvert at the entrance to the north basin, but it is submerged underwater during high flows. It is unknown what effect this culvert has had on spawner access.

Redd Distribution

Only 20 redds were identified in 1994. Most redd

building occurred from June 5-17, soon after peak migration. In 1995, 45 redds were observed. Of these, 31 redds were confirmed by a digging female. The majority of spawning activity occurred after peak migration from June 21-July 6, although I observed spawning as late as July 19. The majority of redds (70%) occurred in reaches H, J, and F, although redd building was observed in all first and second-order tributaries. Redd superimposition was observed at one site, reach G (Figure 1).

Although redd dewatering was not observed during 1994, 12 of 45 (27%) study redds were dewatered during 1995. Flows were higher in 1995, and redds were more likely to be constructed along channel margins. As a result, redds were more susceptible to dewatering as spring flows subsided.

Substrate composition

Redds contained high levels of fines during both years (Table 3). When all samples from confirmed redds from both years were pooled, the mean fredle index (SD) was 2.1 (0.9), mean %fines <0.85 mm was 17.4% (4.4), and mean %fines <6.35 mm was 34.3% (6.2). High variability in substrate composition was also observed, with proportion of fines varying two-fold among cored redds.

Table 3. Mean fredle indices and percent fines <6.35 mm and <0.85 mm from post-spawn and post-emergent core samples (range in parentheses).

Year	Sample redd category	Fredle index	%Fines <6.35mm	%Fines <0.85mm	N
1994	Post-spawn	2.26 (1.4-3.3)	37.1 (28.0-46.2)	15.8 (13.8-17.8)	2
	Post-spawn non-redds	1.84 (0.86-2.5)	38.2 (33.5-45.4)	17.2 (11.8-25.7)	3
	Post-emergent	2.25 (0.85-4.7)	33.6 (22.5-42.4)	18.1 (10.7-25.8)	7
	Post-emergent trampled	1.60	36.6	19.3	1
1995	Post-spawn confirmed	2.07 (1.1-3.7)	29.6 (26.0-31.4)	18.5 (9.7-20.5)	5
	Post-spawn unconfirmed	0.78 (0.14-1.7)	53.5 (47.2-61.3)	39.9 (27.3-55.4)	4
	Post-emergent confirmed	1.91 (0.81-2.9)	36.0 (26.8-45.6)	17.0 (10.8-26.9)	9
	Post-emergent unconfirmed	1.32 (0.51-2.3)	42.9 (35.3-51.8)	22.6 (13.1-33.0)	5

Despite differences in flow conditions between 1994 and 1995, I found no significant between-year differences in substrate characteristics of confirmed redds after spawning ($T = 8$, $P = 1.0$), or after emergence ($T = 61.5$, $P = 0.874$). This allowed data from 1994 and 1995 to be pooled to compare post-spawn and post-emergence substrate composition of

confirmed redds. Again, no significant differences were observed ($T = 83$, $P = 0.973$). Similarly, I found no significant differences between post-spawn and post-emergence unconfirmed redds ($T = 15$, $P = 0.286$). However, when confirmed redds were compared to unconfirmed redds, differences were highly significant after spawning and after emergence ($T = 82.5$, $P = 0.006$).

The number of post-spawn core sites containing eggs versus those with no eggs further suggests that some sites were abandoned after initiating construction, and that core sites containing eggs had higher fredle indices than both non-redd sites or redd sites presumably abandoned. In 1994, for example, the mean fredle index from confirmed post-spawning redd cores was 2.3 ($n = 2$; Table 3). Both cores contained 10 or more ova. Though higher than the mean fredle index of non-redds ($Fi = 1.8$; $n = 3$; Table 3), the difference was not significant ($T = 7$, $P = 0.80$). In contrast, no eggs were found in any of 9 post-spawning cores in 1995, but eggs were found in the surrounding substrate in two cases (22% of the total). Similarly, these had the highest fredle indices of all post-spawn core samples in that year ($Fi = 3.7$; and 2.2).

Fine sediment intrusion

Fine sediment rapidly became entrained into intrusion buckets. In both years, >75% of the total intrusion of fine sediments occurred during the first week of monitoring, with little additional input the remaining 3-4 weeks of sampling (Figure 3).

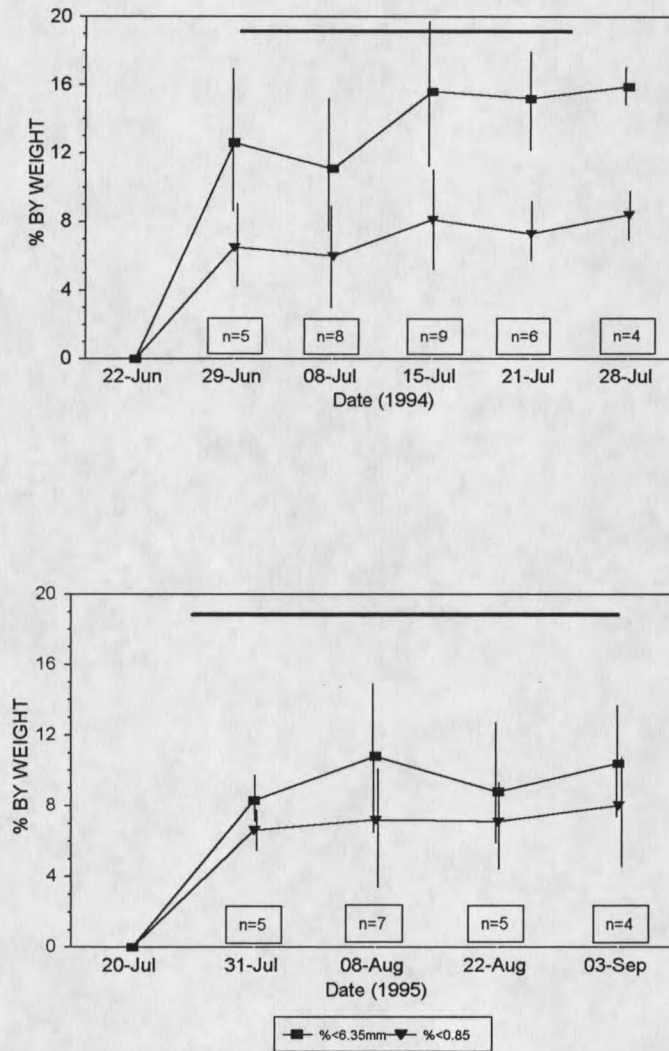


Figure 3. Mean percent fine sediment <6.35 mm and <0.85 mm in intrusion buckets, 1994 and 1995. Starting dates differ due to delayed spawning in 1995 relative to 1994. Presence of livestock indicated by horizontal bars. Error bars indicate ± 1 standard deviation.

Fine sediment <0.85 mm accounted for a large proportion of all fines <6.35 mm. Fines <0.85 mm accounted for 74% of fine sediment by weight in 1995 (n=21, SD = 11%), and 51% in 1994 (n=32, SD = 11%).

Intrusion and percent fines in redds were positively correlated for sediment <0.85 mm (P = 0.075) but not for fines <6.35 mm (P = 0.339) (Figure 4). Reaches F, H, and J tended to have greater sediment intrusion and highest fine sediment content in redds, reaches G, and D were lowest. As mentioned previously, reaches F, H, and J also contained the majority of redds.

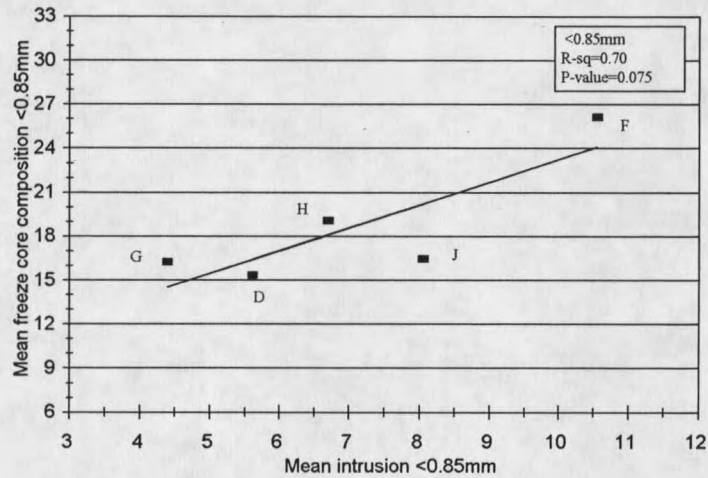
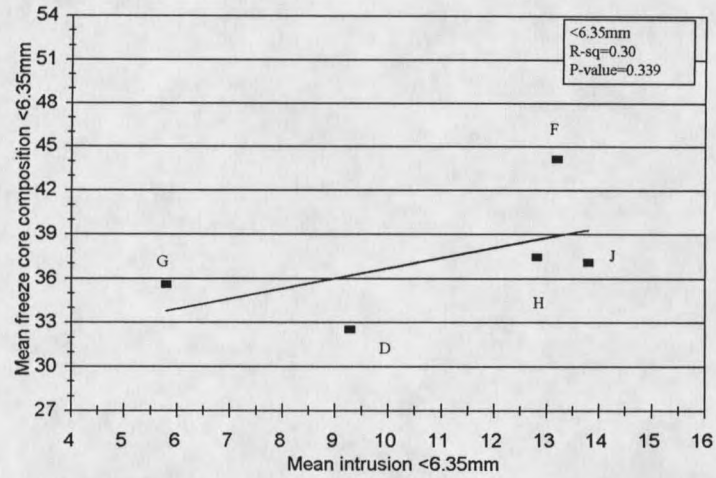


Figure 4. Relation between mean sediment intrusion and post-emergence redd substrate composition in reach D, F, G, H, and J for fines <6.35 mm and <0.85 mm.

Direct comparison of intrusion buckets to redd substrate composition showed mean percent fines <0.85 mm to be close to one-half that observed in actual redds (7.1% versus 17.4%), while mean percent fines <6.35 mm was only about one-third that observed in redds (10-14% versus 34.3%). Two factors account for differences in substrate composition between intrusion buckets and redds. First, spawning females (mean length 196 mm) in Cache Creek may not be effective at removing all fines <6.35 mm during redd building. Second, spawning gravel in Cache Creek is shallow, and cores analyzed to a depth of 10 cm were likely to contain some of the underlying silt/clay substrate. In contrast, substrate used in intrusion buckets was initially cleaned of all fines <6.35 mm to a depth of 10-12 cm. Thus, intrusion bucket gravel substrate was, on average, deeper than the gravel depth available for redd construction.

Intragravel measurements

During incubation, intragravel dissolved oxygen (IGDO) remained lower and more variable than water column dissolved oxygen (WCDO) despite consistently cooler and less variable intragravel temperatures (IGT). When point measurements from all study redds were pooled, dissolved oxygen averaged 0.6 mg/L and temperature 1.0 °C less in redds than in the water column. Overall mean IGDO was 7.1 (SD = 0.75, range =

4.0-8.8 mg/L) and mean WCDO was 7.7 (SD = 0.56), while mean IGT was 8.2 °C (SD = 2.4, range = 4.2-16.4 °C) and WCT was 9.2 °C (SD = 2.8). Among study redds, mean IGDO ranged from 4.4-7.7 mg/L and IGT from 5.6-10.2 °C. In comparison, mean WCDO ranged from 7.1-8.3 mg/L and WCT from 6.5-11.8 °C. Lower and more variable IGDO, despite cooler IGT relative to the water column indicates that other factors not present in the water column influence intragravel conditions. Between year comparisons of mean DO and temperature could not be made as the spatial distribution of sampled redds varied between years. Redd conditions were monitored during daylight hours only; therefore, reported means do not represent 24-h averages.

There was a strong relationship between WCT and IGT ($r^2 = 0.93$, $P = <0.0001$). WCT was also significantly associated with WCDO ($r^2 = 0.63$, $P = <0.0001$). However, IGT accounted for only 30% of the variation in IGDO ($r^2 = 0.30$, $P = <0.0001$) and fredle index was not significantly associated with IGDO at redd sites ($r^2 = 0.044$, $P = 0.47$, $n = 14$). Thus, IGT and substrate composition were not the only factors influencing IGDO.

Thermographs located above the confluence of the third order mainstem (Figure 1) indicated that the south basin was warmer and more variable than the north basin in 1995 (data

was not available for 1994). The South Fork (mean = 8.5°C, SD = 1.5) averaged 1.5°C warmer than the North Fork (mean = 7.0°C, SD = 1.5) during the first three weeks of incubation at these sites (Figure 5). The South Fork WCT ranged 1.9-17.0 °C while the cooler North Fork ranged 4.0-12.6 °C. Means based on thermistor data represent 24-h averages and should not be directly compared to reported daytime mean conditions in redds.

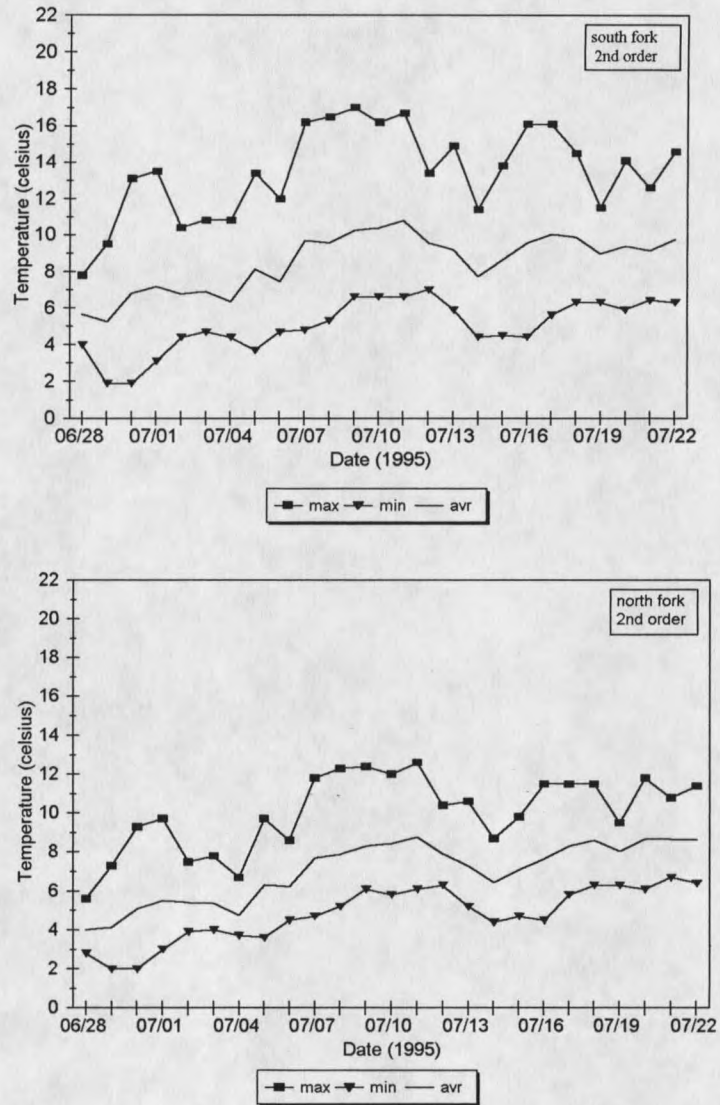


Figure 5. Maximum, minimum, and mean daily water column temperature recorded at South and North Fork second order sites during the first three weeks of incubation during 1995.

A steeper longitudinal gradient was observed in the north basin. The south basin had a mean WCT difference between upstream first and downstream second order thermograph sites of 1.5 °C while in the north basin the difference was 2.8 °C during the first three weeks of incubation.

In 1994, two thermographs located at a north basin site (reach J, Figure 1) recorded no difference between mean IGT and WCT (mean 10 °C, std 1.2) during the last 5 weeks of incubation, though WCT exhibited greater variability (IGT range = 4-19 °C, WCT range = 3-20 °C) (Figure 6). This was the only thermograph site for which intragravel temperature data was available. Intragravel temperatures in the cooler north basin were above 15 °C about 14% of the time (87 out of 634 total measurements), and as high as 19 °C just prior to and during emergence at this site.

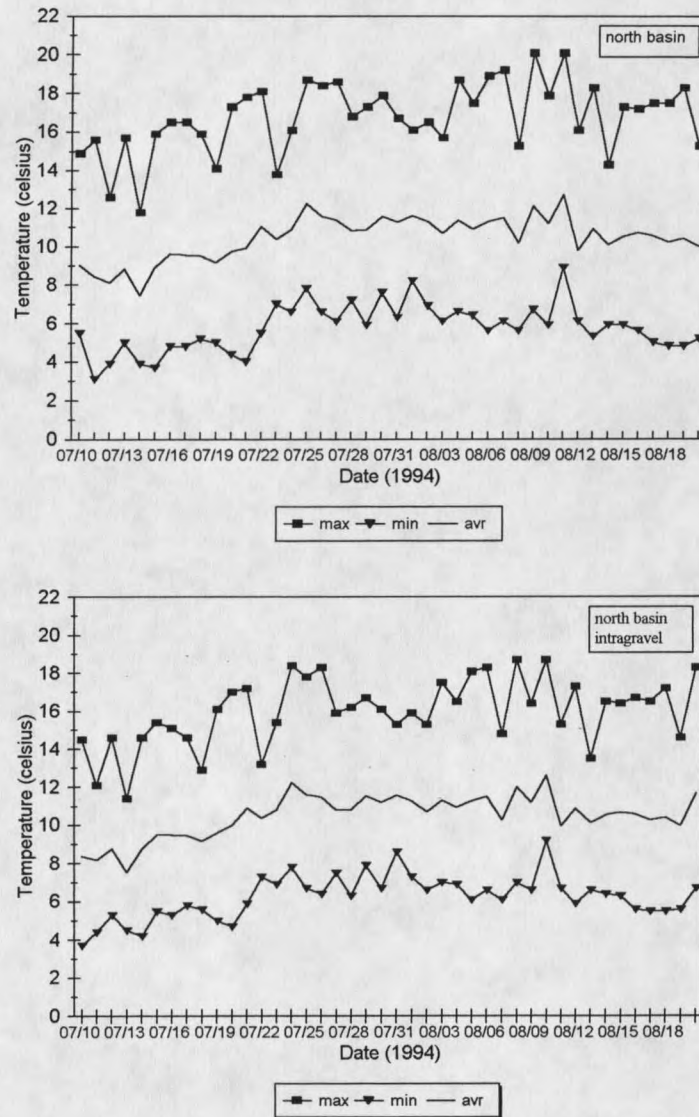


Figure 6. Maximum, minimum, and mean daily water column and intragravel temperature recorded at a north basin site in 1994, upstream of the culvert, reach J.

Egg deposition and fry production

Only 5 of 17 capped redds produced fry in 1994 (Table 5). Emergence began on July 24 and ended on September 3, with peak emergence from August 17-24. Seventy-eight fry were collected, yielding an average of 4.6 fry/redd. Combined total egg deposition from study redds was estimated at 5,352 eggs. Estimated emergence success ranged from 0% to 12.7%, and averaged 1.5% overall (Table 5). Estimated emergence success was much lower than predicted from the Weaver and Fraley (1993) equation. Predicted emergence success ranged from 9.2-18.4%, averaging 12.5% overall (Table 5). Total production among the 17 redds sites was predicted at 670 fry, over 9 times that observed.

Table 4. Percent survival to emergence from redds based on estimated egg deposition and measured emergence success using redd caps. Predicted emergence success (in parentheses) was based on Weaver and Fraley's (1993) emergence success equation.

Redd cap reach location	Female length (mm)	# eggs	# fry trapped (pred.#)	Est. % survival (pred. %)
J*	200	385	0 (49)	0 (12.7) ²
J*	160	205	0 (24)	0 (11.9) ²
J	170	250	11 (27)	4.4 (10.7) ¹
G*	160	205	0 (25)	0 (12.2) ²
G	190	340	0 (41)	0 (12.2) ²
H*	170	250	0 (32)	0 (12.9) ²
H*	190	340	2 (40)	0.59 (11.9) ²
H	210	430	0 (46)	0 (10.6) ¹
H	180	295	0 (35)	0 (11.9) ²
H	200	385	49 (54)	12.7 (14.0) ¹
H	190	340	15 (53)	4.4 (15.6) ¹
F*	360	1105	0 (129)	0 (11.7) ¹
F*	160	205	0 (26)	0 (12.9) ²
F*	140	115	0 (15)	0 (12.9) ²
D	165	228	0 (42)	0 (18.4) ¹
I	150	160	1 (21)	0.63 (13.4) ¹
I	140	115	0 (11)	0 (9.2) ¹
1994	N=17	5352	78 (670)	1.5 (12.5)
G**	230;160	725	93 (88)	12.8 (12.1)
J	260	655	269 (75)	41 (11.4)
H	350	1060	0 (144)	0 (13.6)
1995	N=4	2440	362 (307)	14.8 (12.6)

*, Redds trampled by cattle during egg incubation; **, Two redds superimposed; ¹ A core sample of the actual redd was used to predict survival; ² Predicted survival was based on average substrate composition for that reach.

Peak emergence at capped redds in 1995 occurred from August 20-29. Fry survival estimates combined results from fry trap weirs and electrofishing with redd capping results. Fry weirs trapped 55 fry (Table 5) and electrofishing collected 267 fry (Table 6, Section A) from an estimated 10,251 deposited eggs. Capped redds yielded an additional 362 fry from an estimated 2,440 eggs (Table 4). Combining these estimates, total egg deposition was 12,691 eggs deposited among 27 confirmed redds. Total fry production was estimated at 684 fry, while the equation predicted total production at 1,592 fry, over twice that which was observed (Table 6, Section B).

Table 5. Fry trap weir results including number of redds upstream of traps and estimated egg deposition by reach.

Weir location ¹	# redds ²	# eggs	# fry trapped
Weir (H) downstream	6	3,953	0
Weir (H) upstream	3	1,245	6
Weir (G)	5	1,543	31
Weir (F) downstream	6	2,625	2
Weir (F) upstream	1	205	2
Weir (D)	2	680	14
Totals	23	10,251	55

¹ Downstream and upstream designations refer to a trap's relative location in a reach partitioned by more than one fry trap weir (refer to Figure 1); ² Includes only confirmed redds

Table 6. Section A: estimated fry production among reaches in 1995 based only on electrofishing samples, including distance sampled and reach length, the number of fry observed, and the number of fry per meter of stream length. Section B: total estimated fry production and percent survival among reaches based on electrofishing and fry weirs (from Table 5) combined. The 1995 total combines electrofishing and fry weir results with emergence success from redd capping (from Table 4). Predicted fry production (in parentheses) is based on Weaver and Fraley's (1993) equation.

Section A					Section B	
Sample starting point	Distance sampled/reach Length (m)	#fry obs.	#fry/m	Est.# fry/reach	Est.# fry (pred.# fry)/reach	Est.% survival (pred.% survival)/reach
Weir (H) downstream	350/914	8	0.023	21	21 (470)	0.53 (11.9)
Weir (H) upstream	232/232	5	0.022	5	11 (167)	0.88 (13.4)
Weir (G)	394/464	84	0.21	97	128 (188)	8.3 (12.2)
Weir (F) downstream	720/1095	35	0.049	54	56 (339)	2.1 (12.9)
Weir (F) upstream	135/135	29	0.21	29	31 (26)	15.1 (12.9)
Weir (D)	608/726	51	0.084	61	75 (95)	11.0 (14.0)
Total (1995)				267	684 (1592)	5.4 (12.5) ¹

Although the Weaver and Fraley (1993) equation predicted little variability in percent survival to emergence among reaches (range 12-14%, mean 12.5%), estimated percent survival was highly variable (range 0.53-15.1%, mean 5.4%) (Table 7, Section B). The highest estimated percent survival occurred at reach G (8.3%),

upstream in reach F (15.1%), and at reach D (11.1%).

Although predicted emergence success was more than two-fold higher overall than estimated emergence success, exceptions occurred at two sites: the reach J redd cap (at the confluence of reach I and J, Figure 1) where emergence success was estimated at 41% (predicted at 11.4%), and above the upstream fry trap station at reach F (Figure 1), where estimated survival was 15.1% (predicted at 12.9%). High survival rates characterized some individual redds despite the ubiquitous presence of fines <6.35mm and <0.85 mm, and low overall fry production. For example, in 1995 two capped redd sites (in reach J and reach G) produced 362 fry, accounting for 53% of total estimated fry production in 1995. Though emergence success was extremely low at all capped sites in 1994, one redd accounted for 63% (n = 17) of the total estimated fry production in that year.

Livestock effects

Cattle dispersed throughout the study area following their introduction near the peak of spawning in each year (June 30-July 24, 1994 and July 26-Sept. 3, 1995). The number of cattle crossings in spawning tributaries ranged from 3 in reach G, 4 in reach D, 5 in reach H, and 8 in reach F. Two of the crossings may not be attributable to cattle: one located near the forest edge at upper reach D

was used by wildlife in the spring, and another located below the forest edge in upper reach H is located within 10 meters of a horse corral.

Livestock trampling of redds and intrusion buckets was common during incubation. Seventeen of 50 (34%) intrusion buckets in 1994, and 26 of 48 (54%) in 1995 were either partially or completely dislodged by cattle. Similarly, 8 of 17 (47%) marked redds were trampled by livestock in 1994. All but one redd was trampled within the first week of the grazing season, before barbed wire exclosures were erected to prevent further trampling at additional redd sites. Six of 8 trampled redds were located near cattle crossings. Redd trampling also occurred during 1995. I erected six wire exclosures around redd locations vulnerable to livestock trampling. However, four of the exclosures were breached by livestock prior to fry emergence. In total, 10 of 45 (22%) confirmed redds were trampled.

The highest estimated percent survival in both years occurred at capped redds protected from cattle by exclosures. Of the 8 redds trampled in 1994 only two fry were produced at one redd. In comparison, 4 of 9 redds protected by exclosures produced fry in 1994, though fry numbers remained low (range 1-49 fry). All three capped redds in 1995 were protected by exclosures. Fry were

trapped at two of these sites, producing 93 and 269 fry.

DISCUSSION

Redd distribution

Magee et al. (1996) found spawning gravel availability to be the key factor influencing redd distribution and density in the Taylor Fork watershed, including Cache Creek. My study suggests that access also influences redd distribution in Cache Creek during high flow years. Fish must pass through culverts to access spawning tributaries in both basins. The raised south fork culvert is at least a partial barrier to spawning tributaries. The north fork culvert, submerged during high flows, may also act as a barrier, although no direct evidence as such is presented in this study. However, in 1995, a high flow year, only 27 redds were identified in the north fork and 18 in the south fork, compared to 113 and 100 redds identified in each sub-basin during 1992 (Magee et al. 1996), a comparatively low flow year. The drastically lower redd counts may be caused by culverts acting as barriers to fish movement during some years.

The lack of live eggs observed in freeze core samples or in the surrounding substrate in 1995 may also have contributed to lowered emergence success overall. Redds containing no eggs were observed at 7 of 9 post-spawn sample

sites in 1995. However, in considering the possibility that significant numbers of apparent redds are false, we are still faced with the question of why so many fewer redds were observed in 1995 compared to 1992. Management intended to improve spawning site availability should include culvert removal or replacement in its project plan.

The number of redds identified in 1994 may have been an underestimate of the actual number, as observations were made on alternate days in each basin. However, in 1995 redds were identified every day by two observers, one in each basin.

Fine sediment intrusion and spawning gravel composition

Previous studies have provided evidence that deep intrusion of fine sediment into egg pockets may be prevented by the formation of a sediment seal that bridges gaps in the gravel framework (Beschta and Jackson 1979; Everest et al. 1987; Chapman 1988). Other investigators have noted that silt is perhaps fine enough to penetrate most interstices in many gravel stream beds (Lisle 1989). Whether or not fines intrude deeply depends in part upon the relation between gravel size and the size of sediment in transport, and stream discharge (Lisle 1989). For example, in a study using cans as intrusion buckets, Lisle (1989) found that relatively little fine sediment was deposited in the

streambed because most was carried in the flow above the bed surface. In his study very fine sand, silt, and clay accounted for 80-95% of the total load of 10 storm events but silt and clay accounted for only 10% of the material deposited in gravel cans (Lisle 1989). Lisle (1989) found that suspended sediment could most easily infiltrate the gravel matrix at low discharge, before bed load particles could bridge surface interstices and form a seal.

In contrast, my results indicate that fines <0.85 mm rapidly filled redd substrate interstices within 1-2 weeks after spawning. Fines <0.85 mm accounted for 51%-74% of all fine sediment collected in intrusion buckets. Large quantities of silt and fine sand were present throughout the samples, even on bucket bottoms. It appears that coarser fines (<6.35 mm but >0.85 mm) were prevented from intruding deep into intrusion bucket gravel samples while the finest sediment particles were not prevented from deep intrusion. Similarly, a sediment seal was not observed in redd core samples; spawning gravel interstices were completely filled with silt. Conditions in Cache Creek contrast with the streams in Lisle's (1989) study where most fine sediment remained in suspension above the bed surface. One reason for this may be that Lisle's (1989) streams appeared to be in equilibrium with their sediment loads and were formed

predominantly in alluvium. This contrasts sharply with conditions in Cache Creek which has a sedimentary geology comprised predominantly of fine silt in which livestock grazing has degraded streambanks (Snyder et al. 1978; Magee et al. 1996).

Despite rapid intrusion of fine sediment, the fredle index of confirmed redds was higher than samples from unconfirmed redds. Although I found no significant difference between cores taken about one week after spawning and post-emergent samples, the mean fredle index of confirmed redds (n = 23, mean = 2.1) was significantly higher than unconfirmed redds (n = 9, mean = 1.1). This presents a paradox: how can confirmed redds maintain a higher fredle index than unconfirmed redds under conditions of rapid fine sediment intrusion and no evidence for sediment seal formation? The depth of spawning gravel at confirmed redd sites may have been greater than at unconfirmed sites. Thus, sediment <0.85 mm filled gravel interstices from the bottom up at all sites, but core samples from unconfirmed redd sites were more likely to have penetrated the material which lay below.

In Cache Creek, material underlying spawning gravel reflects the surrounding geology, that of sedimentary soil comprised predominantly of fine silt (Snyder et al. 1978).

Spawning females that initiate redd construction on too shallow gravels may abandon these sites, or egg entrainment in the stream current may occur during spawning. Although my study did not directly assess spawning gravel depth at redd sites, I frequently encountered shallow gravels of approximately 10 cm depth during intrusion bucket installation. Similarly, a bottom layer of sediment containing relatively little gravel was observed in core samples, particularly below 10 cm depth. Although only the upper 10 cm was analyzed, freeze core samples extracted substrate to a depth of 15 cm, the 10-15 cm layer being discarded because gravel sized particles were lacking. It is apparent from these observations that much of the spawning gravel in Cache Creek is shallow.

Intragravel dissolved oxygen and temperature

Overall, mean IGDO remained above the threshold of 5 mg/L considered detrimental to early life stages of salmonid fishes (USEPA 1986). Assessments of the critical threshold for IGDO vary in the literature, however. Shumway et al. (1964) observed decreases in weight of newly hatched fry at DO below 6.6 mg/L in the laboratory. Phillips and Campbell (1961) reported very poor survival of steelhead and coho salmon embryos when IGDO averaged below 7.0 mg/L, while Sowden and Power (1985) and Maret et al. (1993) suggested a

DO concentration of at least 8.0 mg/L to ensure unimpaired emergence success. Based on these criteria, low dissolved oxygen may impair embryo development in Cache Creek where the daytime mean IGDO fell below 8.0 mg/L at all sampled redds (range = 4.4-7.7 mg/L). Of 267 recorded IGDO point measurements 6% were at least 8.0 mg/L, 62% were at least 7.0 mg/L, 40% were less than or equal to 7.0 mg/L, and 9% were 6 mg/L or less.

Considerable evidence has been presented in the literature linking lowered dissolved oxygen concentration to reduced permeability of gravels caused by fine sediments (see Cordone and Kelly 1961, Everest et al. 1987, and Chapman 1988). In a recent study, Maret et al. (1993) reported a weak negative relationship between IGDO and percent fines less than 2 mm ($r^2 = 0.22$, $P = <0.05$, $n = 22$).

I observed no significant relationship between IGDO and fredle index in Cache Creek. This may be because of the shallow nature of Cache Creek spawning gravel. Dissolved oxygen probes were inserted to a depth of 7-10 cm, but the predominantly silt/clay substrate present at that depth may have resulted in water being drawn from the upper 5 cm of gravel, where mixing with the water column may have partially recharged dissolved oxygen concentrations in spite of high fine sediment content.

High temperatures, particularly at downstream redds, may have influenced emergence success as temperatures exceeding 15 °C may impair development of salmonid embryos (Bell 1986). Furthermore, an increase in the minimum critical oxygen level as temperature increases is a reasonable assumption, although a precise relationship has not been established (Chapman 1988). Potential for negative impacts would have been greatest in the warmer south basin which averaged 1.5 °C warmer than the north basin in 1995. This was true even at upstream, first order sites in the south basin, where temperatures averaged only about 1.5°C cooler than at downstream, second order sites. However, two factors served to mitigate high temperature impacts in Cache Creek: 1) there was a larger longitudinal temperature gradient in the cooler north basin than observed in the south basin (2.8°C mean difference), and 2) the buffering effect of the substrate (see Shepherd et al. 1986), which maintained lower and less variable intragravel temperatures relative to the watercolumn.

Egg deposition and fry production

Emergence success was very low overall, though highly variable among Cache Creek redds. The proportion of coarse fine sediment (<6.35 mm) obtained from freeze cores in my study was lower than reported by Magee et al. (1996) using a

McNeil hollow core sampler (mean = 34.3% versus 44.3%), but the percent of small fines (<0.85 mm) was about the same (mean = 17.4% versus 17.9%). Because the Weaver and Fraley (1993) equation predicts survival based on percent fines <6.35 mm, the survival prediction for my study (mean = 12.5%) differed from that of Magee et al. (1996), who predicted embryo survival at 9.4%. Weaver and Fraley (1993) reported mean percent emergence success of 4-39% within a range of fine sediment (<6.35mm; range = 20-50%) comparable to Cache Creek (range = 23-46%) . Magee et al. (1996) speculated that survival in Cache Creek may have been even lower than predicted by the equation because of the high proportion of fines <0.85mm. I found a large discrepancy between predicted (12.5%) and observed (1.5%-5.1%) emergence success. However, several sources of mortality in addition to the high proportion of fines <0.85 mm may contribute to this discrepancy, including redd dewatering, high temperature, and redd trampling by cattle. Nevertheless, sediment/survival relations based on percent fines <0.85 mm may be more appropriate for smaller fish typical of headwater populations.

Livestock effects

The distribution of perennial cattle crossings reflects the ubiquitous presence of livestock among all Cache Creek

spawning tributaries. Cattle crossings often provided suitable spawning sites for resident cutthroat, but trampling after spawning likely prevented the opportunity for augmented emergence success. Instead, I hypothesize that cattle crossings may further increase embryo mortality by inducing spawning females to construct redds at sites most likely to be trampled later on. Livestock were introduced to the basin after peak spawning, and in 1994, 8 out of 17 study redds were trampled by cattle. Of these, six were located near perennial cattle crossings.

Roberts and White (1992) studied the effects of angler wading on trout egg and pre-emergent fry survival in the laboratory. They found that angler wading on redds significantly reduced survival under most conditions, but that negative effects were highly variable. Based on single wading events, mortality was lowest (0-10%) among green eggs and for eggs between the start of the eyed-egg stage and the start of chorion softening, and highest (5-35%) among pre-emergent fry and for eyed eggs between the start of chorion softening and hatching (Roberts and White 1992). Mortality increased sharply under multiple wading treatments, twice-daily wading from egg-fertilization to fry emergence killed 83% of cutthroat trout (Roberts and White 1992). Although livestock effects were not addressed in their study, they

hypothesized that wading by cattle would result in mortality of eggs and pre-emergent fry at least equal to that demonstrated for human wading (Roberts and White 1992).

Livestock trampling of intrusion buckets (34%, 1994; 54%, 1995) and study redds (47%, 1994; 22%, 1995) indicates that trampling was common on Cache Creek spawning redds. Trampling of study redds may have been biased by the presence of DO probes which served to attract cattle (teeth marks were often present on oxygen probes at disturbed sites). However, construction of cattle exclosures at 12 redd sites prevented livestock from trampling areas which would otherwise have been exposed. While 8 of 17 redds were trampled in 1994, the remaining 9 were protected by erecting exclosures. In 1995, the greatest emergence success occurred at redd cap sites G (12.8%) and J (41%), sites protected by cattle exclosures. Together, these sites accounted for 53% (362/684) of the estimated total fry production in that year. Similarly, fry were observed at 5 of 17 capped redds, with one redd producing 63% (49/78) of all trapped fry. Among all 8 trampled redds, one redd produced two fry.

The high percentages of intrusion bucket loss due to trampling indicates that direct physical disturbance to spawning areas is common in Cache Creek. In addition, redds

which are not trampled are likely subjected to intermittent pulses of fine sediment and organic matter from upstream cattle crossings. Although perennial cattle crossings indicate areas of the channel which receive the highest livestock traffic, it should be recognized that these were not the only sites where individual livestock entered stream channels. When livestock enter a channel they deliver a downstream pulse of fine sediment atypical of natural flows during incubation, when base flow conditions would not normally cause entrainment of large quantities of fine sediment. Except during storm events and when livestock are in channels, tributaries in Cache Creek display low turbidity after spring flows subside. However, in view of the rapid intrusion of fines <0.85 mm observed in the week prior to livestock introduction (Figure 3) it is unknown to what extent, if any, sediment pulses influence incubation conditions.

Increased risk of redd dewatering may be an additional side effect of livestock grazing in Cache Creek. Redd dewatering was not observed during 1994, a relatively low spring runoff year, but occurred at 27% of study redds during 1995, a relatively high runoff year. Trout tend to use consistent velocities and depths for redd construction during all flow conditions (Grost et al. 1990; Thurow and

King 1994). Dewatering impacts during high runoff years may be attributable to the history of livestock grazing in Cache Creek. Channel morphology characterized by wide, down-cut, and laid back stream bank soils resulting from grazing create conditions which exacerbate reductions in the wetted surface area of stream channels as base flows are established. These characteristics are readily observable in Cache Creek, particularly where spawning gravel is present, although the degree of disturbance is variable. Thus, redds constructed along channel margins during spring runoff in 1995 were susceptible to dewatering later on. These same channel conditions also influence temperature by exposing the stream surface to solar radiation (Platts 1991). Both redd dewatering and elevated stream temperatures at downstream sites are more likely to occur as a consequence of the history of livestock grazing in Cache Creek.

Is fine sediment limiting recruitment?

Although this study indicates that low emergence success may result in low recruitment during some years, past population surveys from Cache Creek do not support this. For example, in 1992, juvenile and adult densities in pools of Cache Creek were much higher (43.5/100 m²) than reported elsewhere in Idaho and Montana (average 9.2/100 m²

and maximum 26.1/100 m²) (Shepard et al. 1984; Ireland 1993). Lisle and Lewis (1992) suggested that a diversity of redd sites can promote stability in fry recruitment. Such a mechanism could reconcile high observed densities of adults and juveniles in spite of low emergence success at most redd sites. My data suggest that this compensatory mechanism can be overwhelmed in Cache Creek, particularly when there is a reduction in the number of redds constructed and when other sources of fry mortality exist besides fine sediment intrusion. In 1995, when at least one culvert (South Fork), created a partial migration barrier during spring flows, only 45 redds were observed compared to the Magee et al. (1996) redd count of 252 in 1993.

I identified several other factors which may influence fry production: 1) shallow spawning gravels 2) high intragravel water temperature 3) redd dewatering, and 4) direct redd trampling by livestock. Each factor may have a greater or lesser impact in a given year, depending on seasonal conditions such as the magnitude of spring runoff, summer temperatures and precipitation, and livestock management practices. These factors add to potential impacts (such as low DO and fry entrapment) resulting from fine sediment alone. Even if large error margins are assumed, total emergence estimates of 78 fry (1994; 17

redds) and 684 fry (1995; 45 redds) strongly suggest that the Cache Creek population is at risk. The results of this study suggest that a few redds located in areas of minimal substrate disturbance did not sufficiently compensate for low emergence success elsewhere in the Cache Creek basin.

Management recommendations

Perhaps the most expedient way to ensure that emergence success does not drop below a hypothetical minimum threshold is to protect spawning areas during incubation and ensure spawner access by culvert removal or replacement. Keeping cattle away from streams and/or changing the timing of cattle introduction so that it does not coincide with spawning and incubation could accomplish this goal. Successful implementation would reduce trampling effects, reduce fine sediment inputs, minimize temperature variation, and hence increase intragravel dissolved oxygen through the development of riparian vegetation and desirable channel morphology, thereby leading to enhanced reproductive success.

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