Assessing effects of an overwinter dewatering on the egg-to-fry survival of brown trout in a Montana stream

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ASSESSING EFFECTS OF AN OVERWINTER DEWATERING ON THE EGG-TO-FRY SURVIVAL OF BROWN TROUT IN A MONTANA STREAM

By

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Thesis

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Assessing effects of an overwinter dewatering on the egg-to-fry survival of brown trout in a Montana stream.

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Natural instream flow regimes are necessary for the ecological health of streams, including the maintenance of healthy fish populations. Economic interests such as agriculture, mining, and other industries remove water from streams, which can negatively affect fish populations. Wintertime diversions of water affect autumn-spawning salmonids such as brown trout and bull trout; they occur at the critical egg-to-fry development phase, possibly reducing oxygen flow to the eggs and increasing the rate of sub-gravel freezing. This study was designed to examine the effects of a wintertime industrial water diversion on redd building and egg-to-fry survival of wild brown trout in Warm Springs Creek, Montana.

To measure egg-to-fry survival, I counted fertilized brown trout eggs into mesh-lined baskets and placed these baskets into 6 artificial redds in Warm Springs Creek. While the eggs were developing in the gravel, I measured parameters that are critical to egg development and survival and that could be affected by dewatering. In April, after the hatch, I removed the baskets and tallied the number of live fry, dead fry, live eggs and dead eggs. Survival rate was compared across years and the measured parameters were statistically analyzed to determine whether any of them had a significant impact on survival.

There was no autumn or winter dewatering during the course of this study, so I cannot comment on the effects of a dewatering. Some interesting baseline patterns did emerge. The survival rate for the first two years was similar, 41% and 35%. Survival was significantly lower the third year, measuring only 8%. This may be due to a longer, colder winter the third year. The colder it was within the study redds, the more fish died. Also, the lower the water level, the colder it was within the redds. These patterns indicate that a drawdown or dewatering could increase egg mortality.
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INTRODUCTION

In Montana and other parts of the arid West, diverting water out of streams can cause the drawdown or dewatering of streams, creating environmental challenges for downstream fish populations. Diversions commonly take place in summer months, primarily for crop irrigation. Others are year-round, including the fall and winter months when instream flows are naturally reduced. Industrial and municipal diversions are examples of these year-round uses.

Overwinter drawdowns and dewaterings have particular implications for fish that spawn in the autumn and whose eggs are in the gravel all winter, such as brown trout and bull trout. Water diversions in the late autumn can affect spawning habitat and the placement and number of redds in a stream. Water diversions in the winter reduce water levels at a sensitive time of egg development and growth. This reduction of streamflow may have a critical effect on environmental parameters essential to trout egg development and survival, such as temperature, dissolved oxygen [DO], and metabolic wastes (Bjornn and Reiser 1991, Coble 1961, Curry 1994, Maret et al. 1993, Sowden and Power 1985, Wickett 1954).

Possible environmental impacts affecting egg survival include:

- less habitat available for spawning as sections of creekbed are left too shallow or dry.
- decreased water flow through the gravel, thereby decreasing transport of dissolved oxygen to the eggs and decreasing transport of ammonia, a metabolic waste product, away from the eggs.
- lower water level over the egg pockets, causing egg pocket temperatures to drop below a level critical for survival, and perhaps freeze outright.
- increased anchor ice formation in shallower water, reducing both egg pocket temperature and flow through the gravel.
- complete dewatering of established redds, causing eggs to dessicate and die.
Some of these effects may be mitigated in areas of groundwater upwelling, which can moderate temperatures, provide moisture to developing eggs, and increase flow through the gravel (Hansen 1975, Power et al. 1999, Bjornn and Reiser 1991, Reiser and White 1983, Neitzel and Becker 1985).

In 2003, Montana Resources Incorporated [MRI], a copper and molybdenum mining company, reopened in Butte after being closed for three years (Robbins 2003). In the autumn and winter of 2004-2005, this company diverted water from Warm Springs Creek through the autumn and winter months. This resulted in lowered flow in Warm Springs Creek below the diversion point, with visibly decreased streamflow, stream stage and area available for redd building. These changes in stream stage and streamflow caught the attention of Dennis Workman, contracting biologist with Trout Unlimited and former fisheries biologist with Montana Fish, Wildlife and Parks, who has been studying fish populations at this site since 2002 (D. Workman, personal communication).

This thesis reports results of an independent study commissioned by Dennis Workman and Trout Unlimited to determine the impact of this industrial dewatering on the egg-to-fry survival of Warm Springs Creek’s wild population of brown trout. Brown trout, while not native to Montana, spawn in the wild at this site and are a popular species for the area’s sport fishery (Wills 2006, M. Sweeney personal communication, D. Workman, personal communication). Results of this study were to be used to determine Trout Unlimited’s policy stance on MRI’s overwinter dewatering of Warm Springs Creek.

The objectives of this study were: 1) to evaluate the effect of lowered wintertime water level on selected parameters affecting brown trout egg development and survival, and on the survival rate itself; 2) to provide baseline information on environmental conditions and brown trout egg-to-fry survival for the study site; 3) to develop and assess methods for doing this under wintertime conditions. There was no repeat of MRI’s dewatering during the course of this study, so I cannot make a direct comparison of a “normal” year and a dewatered year. However, interesting patterns emerged from this baseline study that suggest some effects of lowered water level on egg survival. The information on
methods and the data collected will be made available to Trout Unlimited for their information and to facilitate future studies of the area, should there be a repeat of the overwinter industrial (or other) dewatering.

**LITERATURE REVIEW**

**Intragravel dissolved oxygen, intragravel flow and salmonid egg survival**

Many studies cite the primary importance of intragravel dissolved oxygen [IGDO] concentration and rates of intragravel [IG] flow in salmonid egg survival. Concentration of metabolic wastes is also considered to be an important factor in egg survival, and is often linked to intragravel flow and dissolved oxygen [DO] (Rubin and Glimsäter 1996, Kondou et al. 2000). The major source of IGDO is from surface water flowing through the gravel (Bjornn and Reiser 1991). Substratum permeability is linked to the rate of intragravel flow through Darcy’s Law, making a measurement of permeability a useful tool to determine intragravel flow (Coble 1961, Rubin and Glimsäter 1996, Kondou et al. 2000).

These and other studies refer to “permeability” but actually provide equations and calculations for the coefficient of permeability, also known as hydraulic conductivity (K). I adhere to their naming convention and refer to hydraulic conductivity as “permeability” in this section. Maret et al. (1993) and Rubin and Glimsäter (1996) both report a strong correlation between IGDO concentration and brown trout egg survival. Bjornn and Reiser (1991) state that sufficient DO is particularly important at early stages of egg development, between 200-390 temperature units, when the circulatory system is not yet developed and embryos depend entirely on diffusion for satisfying their oxygen requirements.

Rubin and Glimsäter (1996) noted that substratum permeability directly influenced the concentration of ammonia and other metabolic wastes in the egg pocket: higher permeability equaled more flow, which equaled a lower concentration of waste. Surprisingly, their study did not establish a correlation between permeability and IGDO concentration. It did show that IGDO was correlated with the concentration of metabolic wastes. Coble (1961) found that when apparent water velocities are high, DO is usually high; when they are low,
DO is usually low. He also found that, in redds with similar DO levels, embryonic development was better in redds with higher apparent velocities. Kondou et al. (2000) concluded that intragravel water movement is one of the most important determining factors in yamame salmon egg survival, and established a correlation between intragravel flow and both the influx of DO and the removal of metabolic wastes.

Rubin and Glimsäter (1996) reviewed critical and lethal limits of IGDO for salmonid egg development. “Critical” was defined as the level that no longer satisfied the oxygen demand of the developing embryo, and “lethal” as the level that resulted in the death of the embryo. They found critical levels ranging from 0.7-11.9 mg/L and lethal levels ranging from 0.4-8.0 mg/L. They ascribed the range of differences to variables such as egg size/surface area and study methods. Their own study determined that the critical limit for brown trout egg survival was an IGDO concentration of at least 10 mg/L, combined with a substrate permeability of at least 2000 cm/h. They also noted that IGDO levels that were below this critical point but not lethal resulted in delayed emergence and reduced length of fry. This could make the fry more vulnerable to predators and less successful in establishing territory, indirectly affecting survival rate (Rubin and Glimsäter, 1996). Maret et al. (1993) note that the 1989 Water Quality criterion for the state of Idaho was 6.0 mg/L for IGDO and the US EPA standard was 5.0 mg/L (1986). They found an increase in survival rate at IGDO concentrations ≥ 8.0 mg/L. Sowden and Power (1985) found that egg-to-fry survival was negligible at less then 5.0 mg/L IGDO, and a minimum IGDO concentration of 8.0 mg/L was necessary to ensure at least 50% egg-to-fry survival.

**Dewatering and egg survival**

In some situations, salmonid eggs can survive even total dewatering for short periods of time. Bjornn and Reiser (1991) describe a set of conditions that their review found to facilitate egg survival in dewatered conditions: if the dewatering occurred before hatching, if temperatures were kept within a suitable
range (which their review indicates is above freezing for brown trout), if fine sediments do not impede air flow, and if humidity near the redds was maintained near 100%. In a moist environment, the unhatched embryos get the oxygen they need from oxygen in the redds diffusing across the hydrated egg membrane. However, even a 10% drop in humidity can cause total mortality (Bjornn and Reiser, 1991). Becker et al. (1983) and Becker and Neitzel (1985) report similar findings in their studies of salmonid redd dewatering, including improved survival when the dewatering occurs before hatching and when capillary flow from the gravel keeps eggs moist. They report that the less dewatering there is, the better the survival rate of the eggs.

**Ice and egg survival**

Eggs can freeze outright in cold, northern areas. Becker and Neitzel (1985) note the correlation between shallower water and greater variation of intragravel temperature in response to changes in air temperature. “Extremes of freezing or warming that coincide with dewatering can be lethal or detrimental to intergravel development phases” and “freezing [in the cases they compared] caused the highest mortality in streams having the lowest minimum discharge” (Becker and Neitzel 1985, p 39). Also, anchor ice and ice dams can block flow through the gravel and effectively block oxygen exchange and the flushing of metabolic waste (Bjornn and Reiser 1991, Power et al. 1999). Harshbarger and Porter (1979) report a threefold increase in egg mortality at their study sites that corresponded with a period of cold weather and anchor ice formation. Shallower water and slow-moving water form anchor ice and freeze solid more readily than deeper or faster-moving water (Becker and Neitzel 1985).

**Groundwater and brown trout redds**

Groundwater upwellings affect the temperature and chemical composition of stream water (Hansen 1975, Garrett et al. 1998, Malcolm et al. 2002, Malcolm et al. 2003). Groundwater regulates temperature in streams and within the gravel, providing thermal refugia for fish in summer and winter and stable
temperature conditions for developing eggs. In winter, groundwater discharge sites in rivers slow or prevent the formation of anchor ice, keeping pools and entire reaches of streams from freezing (Power et al. 1999, Bjornn and Reiser 1991, W. Woessner, *personal communication*).

Groundwater is typically lower in DO than surface water, although its DO content varies (Malcolm et al. 2003, Hansen 1975, Sowden and Power 1985, Wickett 1954). The longer that groundwater has been in residence in aquifers, isolated from atmospheric oxygen and exposed to reductive geochemical processes, the lower the DO content (Malcolm et al. 2003). However, groundwater influx does not necessarily have a negative impact on egg survival. Hansen (1975) found that there was no significant relationship between the presence of groundwater and low DO levels in naturally occurring redds. There were areas of high groundwater discharge where DO was depleted, but these areas were not selected as redd sites. Other studies cite that egg-to-fry survival actually increases in areas of groundwater discharge (Curry et al. 1995, Garrett et al. 1998, Power et al. 1999). Malcolm et al. (2003) did find increased mortality in areas of groundwater upwelling in a degraded agricultural stream. This is probably because the DO content of the surface water was low and mixing did not mitigate the low DO level of incoming groundwater. Their finding may not apply to streams with higher instream DO levels.

Finally, groundwater flowing close to the egg level can provide a necessary source of moisture for the survival of dewatered redds (Reiser and White 1983, Hobbs 1937, Neitzel and Becker 1985). The maximum effective distance for conducting moisture between groundwater to egg pocket is unknown. Sediment composition affected moisture content in dewatered redds, with the highest moisture levels found in the sediment mixture with the highest percentage of fine particles (Reiser and White 1983).

A high percentage of fines is generally considered to be detrimental to egg survival because it blocks flow to the eggs, smothering them (Carling and McCahon 1987, Grost et al. 1991, Maret et al. 1993). However, Sowden and Power (1985) found that in groundwater-fed streams, the flow of water to the egg
had no significant relationship to substrate composition or permeability. Groundwater discharge, mixed with surface water, became an important vehicle for conveying DO to the developing eggs.

Construction of redds

Like other salmonids, brown trout females dig redds by flexing their tails and loosening the gravel, literally digging pits into the substrate of the stream. Eggs are deposited and fertilized in this pit. Then the female trout continues upstream, moving gravel into the egg pocket to bury her eggs and in the process creating a tailspill, or mound, over these eggs (Grost et al. 1991, Bjornn and Reiser 1991, Maret et al. 1993). The shape and location of the mounded tailspill increases downwelling, or streamflow, through the mounded gravel (Grost et al. 1991, Bjornn and Reiser 1991). Eggs can be found anywhere in the redd, but most eggs are located in the front part of this tailspill, where the increased flow is the greatest (Grost et al. 1991). This increased flow is significant to egg development and survival because it helps bring DO into the gravel and flushes out metabolic wastes (Bjornn and Reiser 1991, Kondou et al. 2000).

The digging process used by the females is generally agreed to clean the gravels of fine sediments (Bjornn and Reiser 1991, Grost et al. 1991, Rubin 1995, Maret et al. 1993). The trout typically dig multiple egg pockets on a single site, working from downstream to upstream; the process of burying one pocket and creating a mound digs the pit for the next pocket. Many researchers and working biologists feel it is important to replicate this process as faithfully as possible when digging artificial redds (Maret et al. 1993, Kondou et al. 2000, D. Workman, personal communication, L. Knotek, personal communication).

The range of egg depth for brown trout tends to be from 3-23 cm (Grost et al. 1991, Rubin 1995), with most of the eggs found towards the middle of this range. Grost et al. (1991) found that the mean depth of egg deposition was 9-12 cm for brown trout in their Wyoming study site; a similar depth was used by Maret et al. (1993) at their Idaho study site, where the spawning trout ranged from 30-45 cm long. Depth of egg burial is linked to the size of the trout, with
larger trout moving more gravel and burying their eggs more deeply in the streambed (Bjornn and Reiser 1991, Grost et al. 1991, Maret et al. 1993).

Kondolf (2000) showed that gravel size in redds is also linked to fish size. The gravel must be small enough for the fish to move. Kondolf (2000) reported that spawning fish can move gravels with a median diameter up to approximately 10% of their body length; he also found that the median gravel size found in salmonid redds was between 10 mm and 50 mm. However, there are often larger particles in the redd, especially in the central egg pocket area. Grost et al. (1991) hypothesize that this larger particle size may serve a key function as egg pocket centers.

**Water depth and velocity at natural brown trout redds**

In their literature review, Bjornn and Reiser (1991) found that preferred water depth and velocity at spawning sites varies according to the size and species of trout. In general, the water was at least deep enough to cover the trout during spawning, and many fish spawned in water deeper than necessary to submerge them. Measurements of depth and velocity are generally taken at the upstream edge of the redd, because this is where conditions are most like the streambed conditions before the redd was constructed (Bjornn and Reiser 1991).

Velocities at the surveyed redd sites ranged from 3 to 152 cm/s, and most were between 20 and 100 cm/s (0.656 to 3.28 ft/s). They found that brown trout preferred water depths of at least 24 cm (0.79 ft) and velocities of 21-64 cm/s (0.69-2.10 ft/s) (Bjornn and Reiser 1991). Witzel and MacCrimmon (1983) found that most (middle 80%) of the brown trout redds in their southwestern Ontario study were in water at least 17 cm (0.56 ft) deep. They measured velocities of 10-80.2 cm/s (0.33-2.63 ft/s) at brown trout redds, with most (middle 80%) of the redds found where velocities measured 28-65 cm/s (0.92-2.13 cm/s).
Using egg baskets to measure egg-to-fry survival

There are several methods of estimating egg-to-fry [ETF] survival rates. Rubin (1995) reviewed several of these methods and determined that using an enclosed ‘box’ or basket to hold a set amount of fertilized eggs was the most effective method for accurately estimating ETF survival. Benefits of this method included knowing the exact number of eggs placed in the redd and having an enclosed area around the egg pocket, thereby eliminating the loss of eggs or fry to movement or predation, which increased the accuracy of survival-to-loss calculations. Rubin (1995) noted that emergence traps, another method of enclosing redds, allowed alevin and fry to escape the study site; often they move through gravel after hatching. Emergence traps also disturbed flow and increased sedimentation within the trap area, with potential negative effects on ETF survival. Harshbarger and Porter (1979) reported significantly higher levels of sedimentation, fungus growth and egg mortality when brown trout eggs were placed in Vibert boxes (which do not contain gravel or other matrix) as compared to eggs placed directly in gravel. They recommend placing eggs within the gravel for optimum survival.

Rubin’s baskets were cylindrical, lined with 1 mm PVC or galvanized aluminum mesh to enclose the eggs and eventual alevin (Rubin 1995). Baskets were filled with layers of gravel and fertilized eggs and capped with mesh before burial in the substrate. Another benefit of the basket design is that it allows for dispersal of the eggs in gravel, replicating a natural spawning environment and preventing the spread of fungi and other pathogens (Rubin 1995, Harshbarger and Porter 1979). Maret et al. (1993) used a similar design in their study, with slightly coarser mesh (3.2 mm), while Coble (1961) used mesh sacks to enclose the study eggs and gravel. Rubin (1995) noted that egg density is recognized as a critical factor in ETF survival and that it was important to avoid crowding the eggs in too tight an area. He found that baskets with an egg density of 100 eggs/308 cm$^3$ did not impair ETF survival rates.
Techniques for measuring intragravel conditions

Standpipes are commonly used to measure flow and draw water samples for chemical analysis (Kondolf 2000, Coble 1961, Maret et al. 1993, Olsen and Townsend 2003, Rubin 1995, Rubin and Glimsäter 1996, Sowden and Power 1985, McNeil 1962). Peristaltic pumps or other hand-held or hand-operated pumps are used to remove water samples for testing (Maret et al. 1993, Olsen and Townsend, 2003, McNeil 1962). Key to any pumping method is to avoid introducing unknown quantities of oxygen into a sample that will be tested for dissolved oxygen. The DO measurement can be converted to percent saturation to facilitate comparison of samples at varying temperatures (Maret et al. 1993).

Dissolved oxygen and temperature are frequently measured in situ using handheld probes such as the YSI 85 or YSI 54A. Water is evacuated from the standpipe and allowed to recharge before samples are taken (Maret et al., 1993, Olsen and Townsend 2003, Rubin 1995). Other chemical parameters such as NH$_3$, NO$_2$, and NO$_3$ are measured in laboratory settings using standard measuring procedures (Maret et al., 1993).

Intragravel flow is typically measured using standpipes (Coble 1961, Kondolf et al. 2000, Kondou et al. 2000). The standpipe method involves drawing the water level down a set amount and measuring the time it takes to recharge to the original level. The rate of water flowing into the pipe can be used to calculate the permeability of the substrate; intragravel flow is a function of hydraulic head and permeability. (Coble 1961, Kondolf et al. 2000, Olsen and Townsend, 2003, Rubin 1995, Rubin and Glimsäter, 1996). Permeability is a function of temperature, and measurements of permeability should be converted to a uniform temperature to ensure comparability of samples (Rubin 1995, Rubin and Glimsäter, 1994).

Groundwater movement in streams is commonly sampled using standpipes or minipiezometers; these are two names for similar instruments that allow measurement of the hydraulic head below the surface of the streambed (W. Woessner, personal communication). Hydraulic head is the total mechanical energy per unit weight of water (Fetter 2001). Water flows from higher to lower...
head. To measure the difference in head between two water bodies, you measure the height of their water column relative to a chosen plane; for example, measuring the water column within a standpipe and within the stream relative to the streambed. In this example, higher head within the standpipe would indicate an area of groundwater upwelling: groundwater flowing into the stream. Higher head within the stream would indicate an area of groundwater downwelling: stream water flowing into the groundwater table. No difference in head would indicate that the water flowing through the gravel was essentially surfacewater (W. Woessner, personal communication, Fetter 2001). Groundwater upwellings, in particular, can impact redd conditions by altering intragravel flow, temperature and DO level (Hansen 1975, Power et al. 1999, Bjornn and Reiser 1991, Reiser and White 1983, Neitzel and Becker 1985).

Calculating time until hatch

Temperature units [TUs], also known as thermal units and degree days, are a standard method of calculating time to hatch for fish eggs (Maret et al. 1993, D. Workman, personal communication). TUs are calculated by adding the difference between the mean daily water temperature and freezing point (0°C, 32°F) over the span of time the eggs are in the gravel. One temperature unit is equal to one Celsius degree above zero for one day. Maret et al. (1993) cites 406-420 TUs as the approximate time for brown trout eggs to hatch under field conditions.

METHODS

Objectives and Study Site Selection

The study was designed to evaluate the effects of lowered water levels in Warm Springs Creek on parameters critical to brown trout egg-to-fry development and survival, and to compare egg-to-fry survival rates across the study seasons. Ultimately, its intent was to determine any impacts of a projected overwinter industrial diversion on brown trout egg-to-fry survival in Warm Springs Creek, Montana, and to provide the organization Trout Unlimited with this
information. Because the research question was specific to Warm Springs Creek, I only collected data from this particular creek. On Warm Springs Creek, the location of the study site was chosen for several reasons:

- It is representative of the area of concern for Trout Unlimited
- It is the same location as Workman’s study site for redd counts and snorkel surveys, which provide years of coordinating data
- It is a very active spawning area for wild brown trout

Site Description

This study was conducted on the lower 0.7 km of Warm Springs Creek, Montana, between the Interstate-90 overpass and the confluence of Warm Springs Creek and Silver Bow Creek, the headwaters of the Clark Fork River (Fig. 1). The nearest town is Warm Springs, Montana, in Deer Lodge County. The latitude and longitude are 46.1919 N, 112.7502 W. The elevation is 1469 m (4819 feet) above sea level. Annual precipitation is 34 cm (13.38 inches). The area’s temperatures (1971-2000) range from average highs around 27°C (80° F) in July and August to average lows near 10.5°C (13° F) in December and January. Low temperatures below -29°C (-20° F) were measured in all three study years (NOAA [updated 2010]).

There are two distinct stretches of the study site with high levels of wild brown trout spawning activity. One area is at the upstream end of the study site. It has been channelized and has relatively large gravels. It fits the description of a Rosgen “B” type stream. The other area is approximately 150 m downstream from the top of the channelized section. This area is more natural, with pools, runs and riffles and with smaller substrate than the upstream site. It fits the description of a Rosgen “C” type stream (see Appendix A for worksheets).

Typical flow (26-year median) through the study site, measured at USGS gage 12323770 (46.1049 N, 112.4706 W), is 30-40 cfs baseflow from September to May (USGS [updated 2010]). Flows during my study years were close to this median data (Figs. 2, 3, 4). The study site ends above the confluence with Silver
Bow creek, where the substrate becomes more armored and where wild trout do not spawn (D. Workman, *personal communication*).

**Field Methods**

This study was conducted between November 2005 and April 2008. This time frame represents three seasons of spawning-to-hatch activity for brown trout in this stream. I selected six locations along the study stretch as artificial redd sites for placing baskets containing brown trout eggs. Three of these sites were located in the channelized upstream portion of the stream; three were located in the more naturalized lower region. This was to determine any effects of human stream modification on egg-to-fry survival rate or other measured parameters.

I obtained the eggs and milt used for the study from wild trout in the study area (Maret et al. 1993, D. Workman, *personal communication*). Washoe Park Hatchery personnel (Montana Fish, Wildlife and Parks, Anaconda, Montana) assisted in collecting and preparing the gametes. The fish used for gamete collection over the course of the study ranged from 26 to 39 cm long, with most being from 30 to 35 cm long (Table 1). The size of spawning trout in Warm Springs Creek is comparable to that of trout in the 1993 study by Maret et al. (D. Workman, *personal communication*).

The fertilized eggs were water-hardened for over an hour using standard hatcheries procedures so that they could be handled without damage (M. Sweeney, *personal communication*). In order to minimize infection from handling, hatchery personnel added iodine to the hardening eggs in study year 2 (Year 2). This was not done in study year 3 (Year 3). No information was available about the iodine treatment in study year 1 (Year 1).

After hardening, I counted the eggs into mesh-lined egg baskets. The egg baskets were a modified version of those used by Maret et al. (1993) and Rubin (1995), using planter baskets made of rubberized wire as the frame. They were lined with 3mm fiberglass mesh and capped with 3 mm galvanized aluminum mesh (Year 1) or fiberglass mesh (Years 2 and 3) to prevent alevin and fry from escaping (Fig. 5). The fiberglass mesh lining was machine-sewn to neatly fit the
basket, using heavy-duty cotton thread and a very tight zig-zag stitch so that eggs or fry could not pass through the seams. The baskets were conical, with a bottom diameter of 8 cm, a top diameter of 22 cm and a height of 16 cm. The total volume was 3032 cm$^3$, more than sufficient for 100 eggs per basket (Rubin 1995).

I dug gravel for the baskets from the substrate of the study site and sieved it to ensure sizes between 10 and 50 mm (Kondolf 2000). I filled each basket with approximately 4-5 cm of the sieved gravel and placed it in a container filled with stream water. The water ensured that the eggs were kept in a moist environment and facilitated the gentle placement of gravel on top of the eggs.

I counted 100 eggs into each basket and wafted more sieved gravel on top of the eggs, which filled the basket to about 2 cm below the top. This design made it easier to attach the cap and would allow for some substrate to wash on top of the sealed mesh basket. I sewed (Year 1) or stapled (Years 2 and 3) mesh caps to the basket lining, using a double fold and closely placed stitches/staples to prevent alevin and fry from passing through. This created a sealed mesh pouch for egg incubation.

Then I dug the assembled egg baskets into the substrate of the stream, in a manner that replicated the natural redd-building processes of brown trout. Egg pockets within each redd were dug from downstream to upstream, and more than one pocket was placed in each redd. I loosened substrate to a depth of about 20 cm below the surface (Maret et al., 1993).

In Years 1 and 2, I placed two egg baskets in each redd, for a total of 1200 eggs (600 in each section). In Year 3, I added an extra basket of 100 eggs to each redd, for a total of 1800 eggs placed. Initially, I planned to remove these additional baskets at regular intervals during the study season to examine the degree of egg development and to conduct a sidebar refrigerator hatch study. I did not remove these baskets and the additional eggs became part of the survival rate tally for each redd.

I placed the baskets so that the rim of each basket was at the level of the substrate and barely visible. This ensured that the central mass of eggs was
placed at a depth of 9-12 cm below the streambed surface, as is typical of brown trout of our study size (Grost et al. 1991, Maret 1993). I used Mark VI metal standpipes to provide a sampling “window” into the intragravel environment at the depth of the egg pockets (Terhune 1958, Coble 1961), Fig. 6. One standpipe was placed in each artificial redd, with its perforations at the egg pocket depth of 9-12 cm.

I placed *in situ* temperature loggers within the gravel at each redd site. In Year 1, I used Thermochron iButton temperature loggers (Dallas Semiconductor, Dallas, Texas, USA), placed in a mesh bag within the standpipe, designed to be removed and replaced at each site visit. Due to heavy data loss from toppled standpipes and malfunctioning loggers, I changed this method. In Years 2 and 3, I used Stowaway Tidbit data loggers (Onset Computer Corporation, Bourne, Massachusetts, USA), placed directly into each egg basket at the same depth as the eggs.

I determined the exact placement for each artificial redd by finding appropriate environmental parameters for brown trout spawning, including stream stage and velocity (Bjornn and Reiser 1991, Maret et al. 1993, D. Workman, personal communication). Placement was facilitated by Workman’s knowledge of natural redd location at this site. I did not place artificial redds on top of existing natural redds, to minimize disturbance to the wild fish population and to Workman’s other studies in the area.

I placed the artificial redds in the same exact locations each study year, with one exception. In Year 2, a natural brown trout redd overlapped the original location of redd #3, so I moved the artificial redd approximately 0.5 m towards the center of the stream. Conditions in this new site were similar to those in the original site. In Year 3, I returned the redd to its original location. Each year, all redd locations were within the parameters of depth and flow for brown trout redds (Bjornn and Reiser, 1991, Witzel and MacCrimmon 1983, Maret et al. 1993). A list of the GPS position of each artificial redd is in Table 2, along with water depth and velocity data measured at the top of each redd each November.
While the eggs were developing in the gravel, I took periodic measurements at each redd site. In Year 1, I visited the site in early December and found the redd sites difficult or impossible to safely access due to extensive shelf ice and deep water. Some standpipes were toppled by the freeze-thaw process. After this, I measured environmental variables starting in late February or early March of each study year, after the river ice had largely melted and the site was safe to access. I used a YSI 85 probe (YSI Incorporated, Yellow Springs, Ohio, USA) to measure intragravel dissolved oxygen (IGDO) intragravel (IG) temperature, instream dissolved oxygen (DO), and instream temperature. I used a top-setting English rod and a Marsh-McBirney portable velocity meter (Marsh-McBirney, Inc., Frederick, Maryland, USA) to measure water column (water depth at redd) and water velocity (velocity) at the head of each redd to find small-scale, site specific conditions (Bjornn and Reiser 1991).

In the second year, I added two measurements: hydraulic head and the rate of inflow to the standpipe at egg pocket depth. Hydraulic head is used to determine groundwater-surfacewater interaction. I compared measurements of hydraulic head in the stream and at egg pocket depth in the gravel to determine whether there were groundwater-surfacewater interactions at any of the redds. Hydraulic head within the gravel was determined by measuring the water column within the standpipe; head in the stream was determined by measuring the water column in the stream, next to the standpipe.

Inflow rate (volume per unit time, or Q) is used to calculate “permeability” or hydraulic conductivity (K) using the relationship determined by Terhune (1958). Many studies have used “permeability” interchangeably with hydraulic conductivity; the latter is the correct hydrogeologic term. My measurements of K are comparable with measurements of permeability in studies by Hansen (1975), Rubin (1995), Rubin and Glimsäter (1996), Kondou (2000), Kondolf (2000) and others. I measured inflow rate at each redd so that I could calculate K values at each redd and determine if this might be a limiting factor in intragravel flow. Knowing flow through the gravel would also allow me to approximate the flow of DO to the eggs and the flushing of ammonia from the eggs, information that
would be difficult to accurately obtain by other means. Accurate measurements of the microclimate at the egg surface would require pinpointing and sampling at the precise interface between egg and water, which is not practicable in field conditions with the equipment I had (V. Watson, personal communication).

To determine the rate of intragravel flow, I measured depth to water using a portable water level indicator (Slope Indicator, Mukilteo, Washington, USA), removed a measured volume of water from each standpipe using a portable peristaltic pump, and clocked the time until the standpipe refilled to its original level. This is standard procedure in hydrogeology (W. Woessner, personal communication). It is also the method used by Terhune (1958), Rubin (1995), and Rubin and Glimsäter (1996) in their studies.

I used Temperature Units [TUs] to approximate the time from egg fertilization to hatch. This matched both the literature and hatchery protocol (Maret et al. 1993, Workman, personal communication). The typical brown trout incubation period, from fertilization to hatch, is 406-420 TUs (Maret et al. 1993). The Maret et al. study (1993) did not specify whether the TU measurement of 406-420 was taken within the gravel or in the stream. The thermal units most accessible for monitoring my site are instream water temperatures from the USGS gage 12323770, located approximately 0.3 km upstream of my study site. There are no water diversions between the gage and my site so conditions are comparable. I used data from this gage (USGS [updated 2010]) to estimate the hatch date for the buried eggs. I also used discharge and water depth readings at the gage to indicate conditions at my site. After the field study, I compared gage data with the intragravel temperature data from the Onset loggers to determine whether the USGS gage was a good predictor of intragravel temperature at my site. If so, it would be a useful indicator of intragravel conditions, including TUs for egg development.

To measure egg-to-fry survival rates, I removed the baskets at or near spring hatching and tallied the number of fry, live eggs, and dead eggs within the baskets. I did not distinguish between live and dead fry in my tally; dead fry were rare and were at the same stage of development as the live fry in the same
basket. I assumed that any dead fry had died during the process of emptying the baskets and clearing out the large gravel. Because there were 100 eggs per basket, the survival rate for each egg basket is the same as the survival tally for that basket. I also logged the total number of fry and eggs found [total found], as I could not account for many of the eggs in each basket. Total found was always less than 100%.

**Data Analysis**

Each redd site contained two egg baskets. Because I expected that fate (survival and total found), would be correlated within redd site, I averaged survival and total found of the two baskets at each redd site within each study year. I expected that environmental variables (instream temperature, intragravel temperature, dissolved oxygen, and intragravel oxygen) would also be correlated within redd site, so I averaged these variables within each study year as well. In addition to the average measurements within study year (mentioned above), I also calculated the average minimum measurements of these variables because survival may be influenced more by extremes, such as long cold periods or the lowest DO levels, than by average values. Thus, in total I have three study years (November – April) with average survival and environmental variables, and average minimum environmental variables, with which to assess: 1) whether survival and total found differ by year or channelization treatment, 2) whether survival and total found are associated with any of the measured environmental variables, and 3) whether these environmental variables themselves differ by year or channelization.

Data for water velocity at each redd was often taken at six-tenths of the total depth (0.6 hereafter), which gives the average water velocity for a water column less than 2.5 feet deep; this is standard hydrologic procedure. My redd site depth measurements were always less than 2.5 feet. Sometimes velocity was taken at eight-tenths of the total depth (0.8 hereafter); sometimes it was taken at both depths. The velocity at 0.8 was an excellent predictor of the velocity at 0.6 ($F_{1, 54} = 156.98$, $R^2= 0.744$, $P <0.001$) so I decided to convert all
0.8 values to 0.6 for analysis. I used the equation of the best fit line for this conversion (Fig. 7).

I used two different methods to measure intragravel temperature: Onset Stowaway Tidbit data loggers buried at egg depth within each egg basket, and YSI 85 probe readings taken at periodic site visits. YSI probe readings provide a temperature reading taken at the exact time as other environmental variables, and are useful for comparison with those variables. The in situ data loggers provide a more complete intragravel temperature record, with hourly temperature measurements at each redd site over the entire field season. I used these data to calculate the number of days where the redds experienced a mean daily temperature at or below 0°C (days mean ≤0) and where the redds experienced a low daily temperature at or below 0°C (days low ≤0). Year 1 was excluded from these calculations because of incomplete and inconsistent data due to problems with the iButton temperature loggers used that year. To find days mean ≤0 and days low ≤0, I averaged temperature readings within each day. The values measured for each logger varied over a range of <0.5 °C. The values were all within the expected error margin for these instruments (Onset User’s Manual 2004). All loggers followed similar temperature patterns, including multi-day stretches, typically in January and February, when the temperature held at a constant low close to 0°C. These stretches also matched times when the USGS gage indicated that the stream was solid ice. I specified that these constant low temperature readings were equal to 0°C and corrected all logger readings accordingly. Then I calculated the number of days where the mean daily temperature was at or below 0°C, and the number of days where the low daily temperature was at or below 0°C.

Survival and total found as influenced by year and channelization

I used Generalized Estimating Equations (GEE) to determine whether survival and total found differed by year and channelization. Generalized Estimating Equations are useful for accounting for correlations in repeated data when one is interested mainly in differences between groups (Quinn and Keough
I used a linear model and specified redd site as the subjects variable, year as the within (repeated) subjects variable (because each redd site was used 3 times), survival and total found as dependent variables, and treatment (channelized vs. natural), year, and their interaction as predictors. In order to look for significant differences in survival and total found between years, I ran the model examining all possible year combinations. Channelization did not interact significantly with either year or survival. Therefore, when I tested for differences in survival between years, I removed the channelization treatment from the model. There was a significant year*channelization interaction with total found. To determine which year channelization may have influenced total found, I used generalized linear models (GLMs) with channelization as a fixed factor and total found as the dependent variable and I did the analysis separately for each of the three years. There were no significant effects of channelization, so I removed the channelization treatment from the model and examined effects of year on total found for all possible year combinations.

**Water depth at redd interacting with year and survival**

Similarly, I used GEE to determine whether water depth at redd differed by year. I specified a linear model with redd site as the subjects variable, study year as the within subjects variable, and water depth at redd as the dependent variable. To determine whether there was a significant effect of water depth at redd on survival, I used a GLM with survival as the dependent variable, redd site as a fixed factor, and water depth at redd as a covariate. I then determined whether there was a significant interaction between water depth at redd and redd site in order to test whether the slopes between water depth at redd and survival were significantly different by redd site. I examined the significance of the covariate to determine whether there was a significant relationship between water depth at redd and survival.
Survival and total found as influenced by dissolved oxygen

To determine the influence of dissolved oxygen and intragravel dissolved oxygen on survival and total found, I again used Generalized Estimating Equations. I then used these explanatory variables within each study year as covariates in the model. I specified redd as the subjects variable, study year as the within subjects (repeated) variable, survival and total found as the dependent variables, study year as a factor, and the average values as covariates. In addition, because of lack of data collection, I decided to leave out Year 1 from the model for this particular analysis. Because this approach yielded a number of significant year*variable interactions, I conducted multiple linear regressions within year to determine whether there was a significant influence of these variables on survival within particular years. I used a forward stepwise procedure (Sergio et al. 2003) with the enter value of 0.10 and removal value of 0.15 because the more traditional enter value of 0.05 may fail to identify important variables (Mickey and Greenland 1989, Hosmer and Lemeshow 2000).

Intragravel temperature summary influencing survival

To determine whether survival was influenced by the number of days where the daily mean intragravel temperature was below 0ºC (days mean ≤0), I used a general linear model with survival as the dependent variable, days mean ≤0 as a covariate, and year as a fixed factor. I tested for the main effects as well as an interaction between year and days mean ≤0, however this interaction was not significant and year was not significant and both were taken out of the model.

Average depth at redd influencing intragravel temperature summary

I used Generalized Estimating Equations to determine the influence of water depth at redd on intragravel temperature (days mean ≤0). These temperature measurements were from the Onset data loggers. I used a general linear model with days mean ≤0 as the dependent variable, average depth at redd as a covariate and year and the interaction with average depth at redd as predictors. There was a significant interaction between year and average depth
at redd on days mean ≤0, indicating that the influence of average depth at redd on the days where the mean temperature was below zero depended on year. I then performed linear regressions with average depth at redd as the independent variable and days mean ≤0 as the dependent variable.

**USGS gage temperatures as a predictor for intragravel redd temperatures**

The USGS website (USGS [updated 2010]) reported gage temperatures as a daily average. I then averaged the temperatures within each month. At my redd sites, temperatures were measured hourly by Onset data loggers. I averaged these readings within each 24-hour day, and then I averaged readings within each month. Year 1 was excluded from this analysis due to lack of data. I conducted an analysis of covariance [ANCOVA] with average redd temp (by month) as the dependent variable, average gage temperature as a covariate, and study year as a fixed factor. I tested first for an interaction between study year and gage temperature, and second without the interaction. Both the interaction term and study year were not significant and were removed from the model.

**Effect of year on water temperature**

I used the calculated monthly average temperatures from USGS gage 12323770 in a general linear model to determine whether temperature differed by year. I specified mean temperature as the dependent variable, and study year and month as fixed factors. Finally, I used pairwise comparisons with Bonferroni corrections to compare differences between years.

**Influence of gage temperature on gage height**

I tested for a relationship between the height of water at the gage and the temperature measured at the gage using a general linear model with average gage temperature as the dependent variable, average gage height as a covariate, and year as a fixed factor. I first tested for a year*gage height interaction. This interaction and the main effects of year were not significant and were removed from the model.
Analyses

I transformed variables using the natural-log transformation, when appropriate, in order to meet the assumptions of normality and homogeneity of variances (Sokal and Rohlf 1995). I used Wald chi-square tests in all GEE models and I report Wald statistics (Wald), degrees of freedom (df), and p-values ($P$) where appropriate. All analyses were conducted in SPSS version 17 (SPSS, Chicago, Illinois, USA).

RESULTS

Year and channelization influencing survival and total found

There was a wide range of values for egg-to-fry survival rate, both within and across the 3 study years. Year 1 had 41% survival; Year 2, 35%, and Year 3, 8% survival. At no time was there 100% survival in any redd; total found ranged from 12.5% to 78.5% across years (Table 3). There were differences in survival rates between redd sites, ranging from 2% to 69%, which were not always consistent by year (Fig. 8). However, channelization did not significantly influence survival (Wald = 0.995, df = 1, $P = 0.38$), and channelization did not significantly interact with year (Wald = 0.38, df = 2, $P = 0.83$). Survival did significantly differ across years (Wald = 28.86, df = 2, $P < 0.001$). Survival in study year 1 and 2 was significantly higher than year 3 (Year 1 and 3, Wald = 23.26, df = 1, $P < 0.001$, Year 2 and 3, Wald = 4.34, df = 1, $P < 0.05$), Fig. 9. This indicates that some factor or combination of factors in Year 3 caused a higher egg mortality rate.

There was a significant interaction between year and channelization on total found (Wald = 6.75, df = 2, $P < 0.05$). Total found in Year 1 was higher than Year 3 (Wald = 3.07, df = 1, $P = 0.08$), though this effect was only marginally significant, and total found in Year 2 was significantly higher than Year 3 (Wald = 51.47, df = 1, $P < 0.001$), Fig. 10.
Effects of year and channelization on velocity and water depth at redd

There was a significant effect of year on water depth at redd (Wald = 7.97, df = 2, \( P < 0.05 \)). Specifically, Year 1 had a significantly lower water depth at redd than both Year 2 (Wald = 7.81, df = 1, \( P < 0.05 \)), and Year 3 (Wald = 4.98, df = 1, \( P < 0.05 \)). There was no significant relationship between water depth at redd and survival (\( F_{1,6} = 0.47, P = 0.52 \)) in this baseline study. There was also no effect of year on velocity (0.6 depth), (Wald = 4.03, df = 2, \( P = 0.13 \)), and there was no significant relationship between velocity and survival (\( F_{1,6} = 0.41, P = 0.55 \)).

Dissolved oxygen as relating to survival and total found

Relating average measurements of dissolved oxygen and intragravel dissolved oxygen to survival, there was a significant study year*intragravel dissolved oxygen interaction (Wald = 9.84, df = 1, \( P < 0.05 \)) indicating that the effects of intragravel dissolved oxygen on survival depended on study year. However, there were no significant variables in the linear regression models for either study year.

Relating to total found, there was a significant study year*dissolved oxygen interaction (Wald = 9.99, df = 1, \( P < 0.05 \)), indicating that the effects of dissolved oxygen on total found also depended on the study year. Again, there were no significant variables in the linear regression models for either year.

Examining the effect of the average minimum values of the variables on survival, there was a significant study year*intragravel dissolved oxygen interaction (Wald = 128.85, df = 1, \( P < 0.001 \)) indicating that the effects of intragravel dissolved oxygen on survival depended on the study year. There were no significant variables in the linear regression model.

Finally, examining the effect of the average minimum values of the variables on total found, both minimum average explanatory variables in the GEE model interacted significantly with study year (IGDO, Wald = 7.21, df = 1, \( P < 0.01 \); DO, Wald = 6.22, df = 1, \( P < 0.05 \)) indicating that the effects of these
variables on total found depended on study year. Again, no variables were significant in the linear regression models.

Intragravel temperature summary as related to survival
The intragravel temperature summary (days mean ≤0) was negatively related to survival. ($F_{1,10} = 5.18, P = 0.046$). This indicates that as the number of days where the mean daily temperature was at or below 0°C increased, survival decreased (Fig. 11); colder weather meant lower survival rates. Days low ≤0, days where the low daily intragravel temperature was at or below 0°C, did not appear in any model and was not significant.

Water depth and velocity influencing intragravel temperature summary
There were no significant relationships across year 2 and 3 between mean ≤0 and low ≤0, and average velocity at redd, or low velocity at redd. The influence of water depth at the redd (average depth at redd) on intragravel temperature (days mean ≤0) was dependent on year ($F_{1,8} = 12.88, P = 0.016$). In Year 2, there was a significant negative relationship between average depth at redd and days mean ≤0 ($t_6 = -4, P = 0.016; $ Fig. 12). In other words, the shallower it was, the colder it was. There were no significant interactions for study year 3.

USGS gage temperatures predict intragravel redd temperatures
Water temperature measured at the USGS gage, averaged by month, is an excellent predictor of intragravel temperature in reds at my study site. There was a highly significant positive relationship between gage temperature and redd site temperature at redd #2 ($F_{1,10} = 4588.02, P < 0.001; $ Fig. 14). This relationship was similar and highly significant for all other redd sites. The $R^2$ values for all of the redd sites varied between 0.996 and 0.998.
Effects of year on water temperature

I found a significant effect of study year and month on water temperature (year: $F_{2, 9} = 4.55, P = 0.04$; month: $F_{6, 9} = 34.6, P < 0.001$). Year 3 was 34.2% colder than Year 2 ($P = 0.05$).

Influence of gage temperature on gage height

There was a significant relationship between average gage height and average gage temperature using linear regression ($F_{1, 10} = 24.06, P = 0.001, R^2 = 0.71$), however, non-linear regression using an exponential-logistic model ($b1/(1+exp(b2+b3*x))$), increased the model fit and $R^2$ value to 0.86. Thus, there was an exponential decline in gage temperature with increasing gage height (Fig. 16).

Groundwater-surfacewater interactions and intragravel flow

There was no indication of groundwater upwelling at any of my redd sites. There were intermittent, slight variations in hydraulic head between the intragravel water and the instream water at some of the redds (Figs. 17, 18, 19). These differences ranged from +/- 0.01-0.23 ft and, with one exception, were not consistent in location or in direction of difference. Redd # 4 consistently showed lower hydraulic head in the gravel than in the stream, with the difference in head ranging from 0.11-0.14 ft. This could indicate an area of groundwater downwelling. Locations that showed higher intragravel head, indicating possible upwelling, did not have any other markers of groundwater mixing with surface water such as lower dissolved oxygen levels or warmer water temperatures (moving towards 45°F/7.2°C, the typical ground water temperature at this latitude (W. Woessner, personal communication)). Instead, intragravel temperature and dissolved oxygen fluctuated with instream temperatures.

There was excellent intragravel flow at my redds. Water flowed into the standpipes as quickly as I was able to evacuate it; so quickly that I was not able to measure the recharge time and calculate exact values for hydraulic conductivity. One exception was redd #5, where there was a measurable
drawdown in both pumping tests. There was no measurement of recovery time to quantify hydraulic conductivity, but conductivity at redd #5 was observably lower than at the other redds. In general, this rate of flow indicates excellent connectivity and high hydraulic conductivity of substrate in the egg basket zone. Under sufficient discharge conditions, this translates to a good flushing flow of the eggs within the gravel.

DISCUSSION

Survival

The survival rate of planted brown trout eggs was much lower in Year 3 then in Years 1 and 2 (Fig. 9). Channelization, water depth at redd and water velocity did not affect survival rate in any study year. The main environmental factor influencing survival was intragravel temperature. Egg survival was positively associated with intragravel temperature in all years (Fig. 11). While it is unclear what factors caused lower egg survival in Year 3, it could be due to temperature. Year 3 was colder than other years, and significantly (34.2%) colder than Year 2 (Fig. 15). The intragravel temperature summary (days mean ≤0 C), which looks exclusively at the extreme cold periods where there was a possibility of eggs freezing, may provide a better assessment of wintertime temperatures that impact egg survival. In this analysis, Year 3 was again colder than Year 1 and 2. Year 3 had 69 days where the mean temperature was below zero, as opposed to 53 in Year 2 and 50 in Year 1 (Fig 20). The iodine treatment of the eggs during hardening may also have had an effect on survival, with added iodine in Year 2 improving survival rate. However, the correlation between intragravel temperature and survival holds across both Years 2 and 3 regardless of iodine treatment, indicating that temperature had a larger impact on survival than iodine treatment.

The iodine treatment may also have affected the total number of eggs recovered (total found) by causing eggs that died to decompose more slowly. The dead eggs in Year 3 were at a more advanced stage of decomposition than in previous years (personal observation). Often they were merely grey blobs.
Total found was also significantly lower in Year 3 than in Years 1 and 2. The significance was marginal between Years 1 and 3, probably due to a larger variability in survival in Year 1 redds.

Dennis Workman’s snorkel counts also showed a large (74-89%) drop in population at all of his sampling sites in 2008, corresponding to my study year 3 (Appendix B). Whatever factor(s) caused a significantly low egg survival rate that year may have also impacted survival of juvenile and adult fish.

Why didn’t water depth at redd and velocity impact survival?

During my study, there was no significant effect of water depth at redd on survival. The hydrographs from my study years (Figs. 2, 3, 4) show that flows for all three years were close to the 26-year median flow. I would not expect water level from a typical flow year to impact survival.

There was also no significant effect of velocity on survival. Again, I would not expect to see adverse effects in a typical flow year, when velocity at the head of the redd is consistently sufficient to drive a flushing flow of water through the redd, circulating DO and metabolic wastes. Other factors could influence survival in full flow years like these.

I would expect to see stream depth and velocity positively correlate with survival in years where there is not enough water in the stream to maintain strong flow through the gravel and adequate moisture to the redds. Reiser and White (1983) found that low water levels in a stream caused even higher egg mortality than a complete dewatering, as low-flow water did not provide sufficient DO or adequately flush metabolic wastes.

Intragravel temperature summary and water depth at redd

Water depth at redd was negatively associated with intragravel temperature in Year 2, indicating that as water depth at redd increased, there was a significant decline in temperature (Fig. 12); this is supported by the findings of other studies, such as Becker and Neitzel (1985) and Bjornn and Reiser (1991). However, there were no significant relationships between these
two variables in Year 3 (Fig. 13). Year 1 was excluded from the study due to lack of temperature data. In Year 3, water depth was only measured in November and April of Year 3; these months typically had higher flow than the rest of the study year. Since the depths were averaged by year for analysis, this may have influenced the results. It is also possible that, over such a narrow temperature range, there is no persistent correlation. The Year 2 analysis agrees with the literature and with practical observation; in winter, without groundwater upwellings, shallower water is colder water.

Water temperature relating to water depth at gage

In the winter, the USGS gage showed an inverse relationship between water depth (gage height) and water temperature; temperatures decreased with increasing depth (Fig. 16). This finding is not in agreement with Bjornn and Reiser (1991) or with practical observation. Examining the USGS gage data for gage height, temperature and discharge, it is clear that freezing temperatures correspond with spikes in gage height and sharp drops in discharge (Figs. 21, 22, 23). Water expands as it freezes. Based on gage data and personal observation, thick shelf ice narrowed the channel and reduced the volume of liquid water in the system. Water that did move through the narrower channel was much deeper and typically full of frazil ice, further expanding the total volume occupied by liquid and frozen water. This resulted in the sharp increases in water depth (gage height). My YSI probe measurements were all taken in warmer weather and warmer water, so they do not show these effects of freezing; they represent a more accurate picture of conditions and correlations where water is flowing freely. There is a consistent connection between lower rate of flow and lower water temperatures in both sets of measurements. This indicates that taking water out of the stream in winter would lower the temperature of the water and thereby the redds, decreasing egg survival.
Water at 0°C – liquid or solid?

0°C represents a phase change for water; water at this temperature can be either liquid or solid. Readings from temperature loggers showed when the intragavel water temperature was at 0°C but could not determine if the water, and therefore the eggs in the water, were frozen. It was not possible to distinguish between the effects of low temperature versus freezing on survival rate. Reiser and White (1983) placed glass vials, filled with water and sealed, within the gravel of their artificial redds. Broken glass in the gravel would indicate that that area had frozen. This could be a useful addition to a future study.

Survival rate and total found less than 100%

It is not unusual to have less than 100% survival in “typical” redd conditions. Maret et al. (1993) found 18-83% survival at their control station in their study of egg-to-fry survival in an Idaho stream. Harshbarger and Porter (1979) found an 11-20% survival rate to hatch of brown trout eggs planted directly in the gravel. It is also common to have less than 100% ‘total found’. Rubin (1995) buried dead brook trout eggs in a stream and found that after 90 days, only 48% were recognizable; after 133 days, none were. He attributed the egg disappearance to scavenging, predation and decomposition. He found that DO and the presence of saprophytes were key to egg disappearance; no eggs disappeared when IGDO was less than 6.0 mg/L and almost all did once IGDO reached 10.0 mg/L and above. Rapid decomposition of dead eggs may cause survival estimates formed by comparing live eggs to dead eggs to run high; this method is common when examining natural redds (Rubin 1995).

Dead eggs in an egg pocket may cause conditions in the pocket to deteriorate, causing further egg mortality. Hobbs (1937) notes that the fungus Saprolegnia, a decomposer infecting dead eggs, can smother live eggs in the vicinity, acting as a secondary cause of loss in egg pockets. He states that this secondary loss varies according to the amount of the original loss; if there are already many dead eggs in a redd, the fungus infecting them is likely to smother a proportionally greater number of other eggs. Maret et al. (1993) note that
decomposition of eggs may deplete oxygen levels in the redd. If the initial egg mortality was caused by low DO levels, this additional depletion would compound the problem.

There were macroinvertebrates in all egg baskets in this study, including large and small mayfly, stonefly, and caddisfly larvae (approximately 3-30mm long), which may have entered when small enough to fit through the mesh or may have been introduced with the gravel. These and other organisms could have eaten live or dead eggs. There were also clusters of dead eggs covered with fungus, similar to that described by Hobbs (1937). Decomposition and scavenging are the most likely causes of “missing” eggs in this study. Eggs that died earlier in the season may have caused the death of more eggs in their basket.

**USGS gage 12323770 as a predictor of redd intragravel temperatures**

The USGS gage was an excellent predictor of redd intragravel temperatures. In future studies, this relationship can be used in well-flushed gravel with no groundwater upwelling, to monitor intragravel temperatures without using data loggers and to determine temperature units and time of hatch. However, I would recommend using loggers in the event of a study during a dewatered year, in case a change in groundwater patterns influences temperature at some or all redd sites. Groundwater flow patterns are not static, and results from this study may not apply to future results (W. Woessner, personal communication, Fetter 2001).

**Conductivity and groundwater flow patterns at my site**

The measured flow through the gravel indicates that the substrate has excellent hydraulic conductivity. As long as there is sufficient oxygenated water in the system, there will be a good flow of DO to the eggs and a flushing of metabolic wastes. The one exception was redd #5. This area was observably high in fine sediment compared to the other redds. Fine sediments have low permeability and probably slowed water movement through this redd site. This
site had an extremely low survival rate in Year 2, when these permeability measurements were taken, which is consistent with the established connection between high levels of fine sediment in a redd and low survival rate (Carling and McCahon 1987, Grost et al. 1991, Maret et al. 1993). It is very possible that this area was not as high in fines in Year 1, when redd #5 had very high survival.

There was no indication of groundwater upwelling at any reds. As Hansen (1975) notes, a difference in head between the gravel and the stream is not enough to determine an area of upwelling; the combination of higher (wintertime) temperature and higher intragravel head is a better indicator. Water flowing within the gravel environment probably had a short subsurface residence time and was close to surface water in temperature and composition. This is supported by my field measurements. However, groundwater patterns and substrate conditions change over time (Hansen 1975, Malcolm et al. 2002, Malcolm et al., 2003, Curry et al. 1994, W. Woessner, personal communication). Groundwater upwellings could mitigate some effects of a wintertime drawdown or dewatering by moderating the water temperature to decrease or prevent anchor ice formation (Power et al. 1999, Bjornn and Reiser 1991), and by providing the high (100%) relative humidity needed to keep eggs alive if totally dewatered (Reiser and White 1983, Neitzel and Becker 1985). A future study should include tests for permeability and groundwater activity.

**YSI meter measurements of IGDO**

IGDO levels measured in this study ranged from 0.89 to 10.54. The lower end of this spectrum is below the minimum levels recommended by many researchers (Rubin and Glimsäter 1996, Maret et al. 1993, Sowden and Power 1985). It is possible that IGDO is truly a limiting factor in egg-to-fry survival in this reach. It is also possible that DO levels truly were this low but that the embryos were able to decrease their oxygen consumption rates and survive in spite of the low DO levels. Silver et al. (1963) found this to be the case unless water temperatures were unusually high, which is not a factor in my study. They report high survival rates with DO concentrations as low as 2.5 mg/L, while
noting that low DO levels result in smaller, weaker fry that may have reduced post-hatch survival in the wild.

A third possibility is that the YSI meter was not always accurate in measuring the DO levels of water within the standpipes. It typically took several minutes to get a reading, cycling up and down over a wide range of measurements; the most difficult readings to get often returned some of the lowest IGDO values. Low values may be difficult to for the probe to measure; or probe difficulties may have resulted in incorrect measurements. There was a consistent pattern of lower DO levels in the gravel than in the stream, and some redds were consistently lower than others (redd #2, redd #5). These redds also had some of the lowest survival rates (Table 3). I believe these relationships were correct, even if the exact DO value was not. The adequate DO levels in the stream, the lack of evidence for groundwater mixing that would lower DO levels, and the excellent flow through the gravel all indicate that IGDO could be higher than was often measured, and may not be a limiting factor in egg-to-fry survival under the study conditions.

Survival during dewatering

There are documented cases of salmonid eggs surviving in dewatered redds. Hardy (1960) excavated dewatered brown trout redds in the Selwyn River of New Zealand and found that, after an estimated 2-5 weeks without water, some eggs near the surface had dehydrated and died, but most were in healthy condition. He notes that the substrate was “damp” at the time of excavation, but does not quantify degree of moisture or speculate on causes of continued moisture. Hobbs (1937) reports a typical survival rate of 83% in redds dewatered for 5 weeks in the Selwyn River; he also notes the dampness of the surrounding substrate and the fact that the groundwater table was 6 in. (15.24 cm) below the eggs. Hobbs did find a lower than average survival rate in areas subject to dewatering. Reiser and White (1983) found that eggs dewatered from 1 to 5 weeks had a survival rate comparable to the fully-watered control group, as long as sediment moisture was at least 4% by weight and sediments neither froze nor
reached a temperature too high for hatching success. In this study, water flow simulating groundwater was maintained 10 cm below the eggs; Reiser and White considered this source of moisture to be essential to the survival of dewatered eggs. Similarly, Becker and Neitzel (1985) found that nearly 100% humidity was required for the survival of dewatered eggs. They also found that temperature extremes or warming and freezing had lethal effects on eggs in dewatered redds.

Alevin and fry are even more sensitive than eggs to the effects of dewatering. They are unable to obtain enough oxygen from diffusion and require oxygenated water to survive (Becker et al. 1983, Becker and Neitzel 1985). Also, extended dewatering would trap alevin in water pockets in the gravel and prevent their emergence (Becker and Neitzel, 1985). Hobbs (1937) considered stranded redds that were not subsequently flooded, allowing alevin to escape, to be a total loss to recruitment.

Sufficient moisture and temperatures that do not permit freezing are essential to embryo survival in dewatered redds. These conditions would not be met in Warm Springs Creek. There were no indications of groundwater upwelling in the study site, to provide necessary moisture to the eggs during a dewatering; and the low wintertime temperatures make freezing of dewatered gravel highly likely, killing eggs and fry (Neitzel and Becker 1985).

**CONCLUSION**

Significant patterns emerged during this study, indicating that lower water levels decrease survival rate. Year two showed that, unless the stream was frozen, shallower water was colder water. Colder water temperatures lowered survival rate across years. This fits a pattern established in other studies: a lower water level or a lower volume of water is more responsive to ambient temperatures; shallow water chills and freezes more quickly in the winter months. This increases the number of days where redd temperatures are at or below 0ºC and increases the possibility of eggs freezing.

There was no industrial dewatering during this study, so there are no specific results concerning dewatering. Results of this study do not indicate how
much water can be removed before survival rate is affected. Since cold temperatures were significantly associated with increased mortality even in full-flow years, decreasing autumn and winter flow in Warm Springs Creek would likely decrease brown trout egg survival.

It is not known how a decrease in egg survival would affect the general brown trout population in Warm Springs Creek. However, the Year 3 population drop of juvenile and adult fish in Workman’s snorkel study (Appendix B) raises the possibility of a common factor that increased mortality in both populations that year. Cold weather is one possible factor; there are many others that were not examined.
GLOSSARY

Alevins: newly-hatched fish; they are nourished by a yolk sac. Also known as sac fry or yolk-sac fry.

Anchor ice: ice that forms on the bottom of a stream.

Armored (substrate): Surface gravel is larger than the gravel beneath the surface, to the extent that it is difficult for the river to move its own sediments in a typical flow year. Median surface gravel size/median substrate gravel size > 1

Channelized (stream): a stream or section of stream that has been artificially straightened or made to flow in a particular course. Stream banks are often reinforced with rip-rap or other material to prevent natural, cyclic changes in flow path.

Discharge: the volumetric flow rate of water; streamflow. Units are commonly m³/s, ft³/s, or acre-feet/day.

Egg depth: the distance between the substrate’s surface and the egg pocket. 9-12 cm in this study.

Egg pocket: the very small portion of the egg stratum in which eggs may be found. There may be more than one pocket in a redd.

Eyed eggs: fertilized fish eggs that have developed to the point where a black dot (the eye of the embryo) is visible.

Frazil ice: ice that forms in the water column of a stream.

Fry: baby fish; often refers to the development stage after alevin, where the yolk sac has been absorbed and the baby fish must find other food sources. This is the stage where they emerge from the gravel.

Milt: seminal fluid of fish – contains sperm.

Redd: the total area excavated by a fish in one contiguous portion of a streambed, where eggs are deposited.

Artificial redd: a redd created by humans, generally for study purposes.

Natural redd: a redd created by wild fish under natural conditions.

Residence time: the amount of time water is groundwater, i.e. below the surface of the earth; the time between recharge (to an aquifer) and discharge. This can vary from hours to millennia.

Salmonid: fish of the family Salmonidae: trout, salmon, whitefish, char. Includes the subfamily Salmoninae, with the genera *Salmo, Oncorhynchus, Salvelinus*, among others.
**Shelf ice**: ice that is attached to the land and projects out into a body of water (ocean, lake, stream).

**Substrate**: the material (cobbles, gravel, sand, clay, etc.) that forms the bed of a stream.

**Temperature Units [TUs]**: a method for determining time to hatch. One temperature unit is equal to one Celsius degree above zero for one day.
REFERENCES


Reiser DW and White RG. 1981. Effects of flow fluctuation and redd dewatering on salmonid embryo development and fry quality. Idaho Cooperative Fishery Research Unit, University of Idaho.


Woessner W. Hydrogeology professor, University of Montana, Missoula MT. Personal communication.

FIGURES AND TABLES
Figure 1: Warm Springs Creek study site – aerial view
Figure 2: Hydrograph of study year 1 (2005-2006). This year and the 26-year median data are graphed; flow in my study year (Nov.-April) is close to this median data.
Figure 3: Hydrograph of study year 2 (2006-2007). This year and the 26-year median data are graphed; flow in my study year (Nov.-April) is close to this median data.
Figure 4: Hydrograph of study year 3 (2007-2008). This year and the 26-year median data are graphed; flow in my study year (Nov.-April) is close to this median data.
Figure 5: Egg baskets and mesh liner
Figure 6: Mark VI standpipe
Figure 7: Conversion of velocity measurement from 0.8 to 0.6. Includes the equation for the best fit line.

\[ y = 0.961x + 0.5578 \]

\[ R^2 = 0.74405 \]
Figure 8: Survival across redd sites; comparing all years.
Figure 9: Average survival of all sites across 3 different study years (2005 – 2008). Survival in study year 1 and 2 was significantly higher than year 3.
Figure 10: Average total eggs and fry found (alive + dead) of all sites across all three study years. Total found was significantly higher in Year 2 compared to Year 3.
Figure 11: Intragravel temperature (data logger measurements) influencing survival across study years. As the number of days where the mean temperature was at or below 0°C increased, survival decreased. Colder weather meant lower survival rates.
Figure 12: Water depth at redd influencing intragravel temperature (data logger measurements): in study year 2, there was a significant negative relationship between average depth at the redd and days where the mean temperature was at or below 0°C; shallower water meant colder redds. There was a similar relationship between average minimum depth at the redd and days where the mean temperature was at or below 0°C; the $R^2$ value for this relationship is 0.884.
Figure 13: Water depth at redd influencing intragravel temperature (data logger measurements): there were no significant relationships between intragravel temperature and water depth in Year 3. This figure shows the relationship between average water depth and temperature. The $R^2$ value for the relationship between low water depth and temperature is even lower: 0.26.
Figure 14: USGS gage 12323770 is an excellent predictor of redd temperatures at my site. This graph shows the relationship with redd #2 temperatures. The relationship was similar and highly significant with all other redd sites, with $R^2$ values from 0.996 to 0.998.
Figure 15: Mean water temperature by study year, measured at USGS gage 12323770. Year 3 was significantly colder than Year 2.
Figure 16: Gage height (water depth) rises as temperature falls at USGS gage 12323770. These measurements cover only the periods of November-April, 2005-2008. Spikes in gage height correspond with periods of freezing temperatures and low discharge; ice may raise gage height.
Figures 17-19: Comparing intragravel and instream head across reds. Head varied only slightly and was typically not consistent in direction. Slight differences (+/- 0.03 in) may be attributed to measurement error. The one exception is redd #4, where there is a consistently higher instream head than intragravel head. This indicates that water is flowing from the stream into the gravel at this point.

**March 24, 2007**

![Bar chart showing water column height for reds on March 24, 2007.](chart)

**Figure 17: March 24, 2007**

**April 9, 2007**

![Bar chart showing water column height for reds on April 9, 2007.](chart)

**Figure 18: April 9, 2007**
Figure 19: April 23, 2007
Figure 20: Water temperature summary across study years. Year 3 had more days at or below 0°C than either Year 1 or 2. These temperatures were from USGS gage 12323770, which is an excellent predictor of redd temperatures.
Figures 21-23: A series of USGS charts plotting gage height, discharge and temperature for my study years. In the winter, temperatures of 0°C correspond to spikes in gage height and drops in discharge.

Figure 21: USGS gage height
Figure 22: USGS discharge
Figure 23: USGS temperature
Table 1: Sizes of brown trout used for gamete collection for all three study years

<table>
<thead>
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<th>Study year</th>
<th>Sex</th>
<th>Length (cm)</th>
<th>Weight (g)</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>Male</td>
<td>37.0</td>
<td>560</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>26.6</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Male</td>
<td>31.2</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>30.8</td>
<td>258</td>
</tr>
<tr>
<td>3</td>
<td>Male</td>
<td>31.2</td>
<td>345</td>
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<td>Male</td>
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<td>420</td>
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<td></td>
<td>Male</td>
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<td></td>
<td>Male</td>
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<tr>
<td></td>
<td>Female</td>
<td>30.2</td>
<td>300</td>
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Table 2: Redd site locations and depth/velocity data for all 3 study years. Redds are numbered from upstream to downstream.

<table>
<thead>
<tr>
<th>Redd #</th>
<th>GPS Coordinates</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<tr>
<td></td>
<td></td>
<td>Water depth to redd (ft)</td>
<td>Velocity @ 0.6 (ft/sec)</td>
<td>Water depth to redd (ft)</td>
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<tr>
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<td>12T362477 Utm5115549</td>
<td>1.0</td>
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<tr>
<td>2</td>
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<tr>
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<td>12T362610 Utm5115578</td>
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<td>0.95</td>
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<td>5</td>
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<td>1.93</td>
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<td>6</td>
<td>12T362597 Utm5115644</td>
<td>1.0</td>
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<td>0.7</td>
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Table 3: Survival rates and total found at reds all study years. Redd site numbers are averages of all baskets within each redd.

<table>
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<tr>
<th>Redd #</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Avg survival</th>
<th>Avg TF</th>
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<tr>
<td></td>
<td>Survival</td>
<td>Total found</td>
<td>Survival</td>
<td>Total found</td>
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<tr>
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<tr>
<td>2</td>
<td>50</td>
<td>65.5</td>
<td>31</td>
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<td>8</td>
</tr>
<tr>
<td>3</td>
<td>24.5</td>
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<td>20.5</td>
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<td>69</td>
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<td>78.5</td>
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<tr>
<td>6</td>
<td>40</td>
<td>48.5</td>
<td>48</td>
<td>48.5</td>
<td>2</td>
</tr>
<tr>
<td>Average</td>
<td>41.33</td>
<td>54.83</td>
<td>35.33</td>
<td>65.0</td>
<td>7.97</td>
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APPENDIX A
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<td><strong>Date:</strong></td>
<td>11-18-07</td>
</tr>
<tr>
<td><strong>Waterbody:</strong></td>
<td>Warm Springs</td>
</tr>
<tr>
<td><strong>Personnel:</strong></td>
<td>N. Shapero</td>
</tr>
<tr>
<td><strong>Bankfull Width (W&lt;sub&gt;bf&lt;/sub&gt;)</strong></td>
<td>7.9 M.</td>
</tr>
<tr>
<td><strong>Mean DEPTH (d&lt;sub&gt;bf&lt;/sub&gt;)</strong></td>
<td>0.63 M.</td>
</tr>
<tr>
<td><strong>Bankf. X-Section Area (A&lt;sub&gt;bf&lt;/sub&gt;)</strong></td>
<td>X Sq. M.</td>
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<tr>
<td><strong>Width/Depth RATIO (W&lt;sub&gt;bf&lt;/sub&gt; / d&lt;sub&gt;bf&lt;/sub&gt;)</strong></td>
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<tr>
<td><strong>Maximum DEPTH (d&lt;sub&gt;max&lt;/sub&gt;)</strong></td>
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</tr>
<tr>
<td><strong>WIDTH of Flood-Probe Area (W&lt;sub&gt;fp&lt;/sub&gt;)</strong></td>
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<tr>
<td><strong>Entrainment Ratio (ER)</strong></td>
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<td><strong>Channel SINUOSITY (K)</strong></td>
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<td><strong>Stream Type</strong></td>
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<tr>
<td><strong>Comments:</strong></td>
<td>It's a &quot;B&quot;-type stream. To determine subcategory, need to do pebble count.</td>
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**CHANNEL CROSS-SECTION (LASER)**

**Date:** 11-18-07  
**Site Visit Code:** US 1044 Interstate

| Distance on tape (Ft) | Distance from Lbfk (Ft) | Fore-Sight | Height (Ft) | CELL WIDTH (Ft) | MEAN CELL DEPTH (Ft) | CELL AREA (sq. Ft) | Notation: *(e.g.: Lbfk, LWE, THWG, RWE, Rbdk) or Comments*
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<tr>
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<tr>
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<td></td>
<td>4.12</td>
<td>0.66</td>
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<tr>
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**TOTAL CROSS-SECTIONAL AREA:**

\[ \text{ft}^2 \]

- **Notations:** Lbfk: Left bankfull, Rbdk: Right bankfull, LWE: Left Water Edge, RWE: Right Water Edge, THWG: Thalweg

- **Bankfull width:** \[17.9\ (0.8) \rightarrow 0.9 + 0.8 = 7.9\]
- **THWG - LbKFL:** \[4.220 - 3.46 = 0.76 \times 2 = 1.52\]
- **May 2005 - 3**

70
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<td>Maximum DEPTH (d_mx)</td>
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<td>Maximum depth of the bankfull channel cross-section, or distance between the bankfull stage and thalweg elevations, in a riffle section</td>
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<td>WIDTH of Flood-Prone Area (W_fp)</td>
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<td>The ratio of flood-prone area WIDTH divided by bankfull channel WIDTH. (W_fp / W_bf) (riffle section)</td>
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<td>The D50 particle size index represents the median diameter of channel materials, as sampled from the channel surface, between the bankfull stage and thalweg elevations.</td>
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<td>Water Surface SLOPE (S)</td>
<td>M/M</td>
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<td>Channel slope = &quot;rise&quot; over &quot;run&quot; for a reach approximately 20-30 bankfull channel widths in length, with the &quot;riffle to riffle&quot; water surface slope representing the gradient at bankfull stage.</td>
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<td>Channel SINUOSITY (K)</td>
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<td>Sinuosity is an index of channel pattern, determined from a ratio of stream length divided by valley length (SL/VA); or estimated from a ratio of valley slope divided by channel slope (VS/S).</td>
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## CHANNEL CROSS-SECTION (LASER)

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**Site Visit Code:** Downstream Natural

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<th>Right Sight (ft.)</th>
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<th>MEAN CELL DEPTH (ft.)</th>
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Notations:  
- **Lbfk**: Left bankfull  
- **RbKf**: Right bankfull  
- **LWE**: Left Water Edge  
- **RWE**: Right Water Edge  
- **THWG**: Thalweg

\[ \text{THWG-BKFL: } 2.45 - 1.655 = 0.795 \times 2 = 1.59 \]

\[ 2.45 - 1.59 = 0.86 \text{- set stake red at this height to find flood plain area, which is } \approx 50 \text{ m} \]

*See back for notes*
Downstream/naturalized section

Floodplain area: Due to thickness of vegetation, laser not reading as far as floodplain, therefore floodplain area was estimated by walking out from both LB & RB and based on visual clues such as standing water and continuous rise in elevation. The entire area between the roads about 25 m on either side of creek was a floodplain area. The total is 50 meters.

Note: Floodplain area is that area which floods for a 50 or 100-yr flood. Here it is 50 m (25 + 25 m)
The Key to the Rosgen Classification of Natural Rivers

SINGLE-THREAD CHANNELS

ENTRENCHED (Ratio < 1.4)

MODERATELY ENTRENCHED (Ratio = 1.4-2.2)

SLIGHTLY ENTRENCHED (Ratio > 2.2)

ENTRENCHED (Ratio < 1.4)

MODERATELY ENTRENCHED (Ratio = 1.4-2.2)

SLIGHTLY ENTRENCHED (Ratio > 2.2)

STREAM TYPE

SLOPE

Channel Material

BEDROCK

BOULDERS

COBBLE

GRAVEL

SAND

SILT/CLAY

KEY to the ROSENG CLASSIFICATION OF NATURAL RIVERS

As a function of the "continuum of physical variables" within stream reaches, values of Entrenchment and Sinuosity ratios can vary by +/- 0.2 units; while values for Width/Depth ratios can vary by +/- 2.0 units.

© Wildland Hydrology 1481 Stevens Lake Road Pagosa Springs, CO 81147 (970) 731-6100 e-mail: wildlandhydrology@pagosa.net
APPENDIX B
Dennis Workman, contracting with Trout Unlimited, has conducted brown trout redd counts on Warm Springs Creek since 2002 and snorkel surveys on Warm Springs Creek since 2004. The following are some of his data and results, excerpted from the Trout Unlimited Warm Springs Creek Fisheries Report for FY 2008, prepared Summer, 2008.

Workman’s Figures 1, 2, and 3 show his snorkel survey results from 2004-2008. Location descriptions follow at the end of this appendix. These descriptions are excerpted from the Trout Unlimited Warm Springs Creek Fisheries Report for FY 2004, prepared Summer, 2004. Workman’s Table 1 (2008) shows November-April streamflow at gauge 12323770 and the number of days where stream flow was less than 20 cfs. According to Workman (2008), Trout Unlimited calls for water augmentation when flows are below 30 cfs; he reports this was not necessary in 2008. His Table 5 (2008) shows redd count data from 2002-2007. The 2008 redd count had not been completed when the 2008 report was written.

Workman’s 2008 snorkel survey, conducted after a heavy spring runoff, showed a large drop in brown trout population in all three of his study locations. This is the same year egg-to-fry survival was significantly low. There may be a link in the environmental factors causing the drop in adult fish population and egg-to-fry survival.

Flow was not low this year, so this was not a factor – see my Figures 2, 3 and 4 and Workman’s Table 1. Workman hypothesized that the decline in fish population could be due to heavy scour from a relatively long spring runoff with higher-than-normal discharge (my figure 4) and, for his Airport Road Section and Section 770, to high copper levels in the water during spring runoff, measured at USGS gage 12323770. Copper is well known to be detrimental to aquatic life (Watson, personal communication, EPA 2007).

I examined water quality data from gage 12323770 from 2003-2008 and found that there is an annual spike in copper and other metals found in Warm
Springs Creek each spring during runoff. The exception was the spring of 2004, where discharge stayed low through the spring (my Table 4, Appendix C). It is likely that, in this former mining/smelting and current Superfund location, riverbank and riverside soils are a contaminant source and are washed into the river in greater amounts at higher discharges. This is supported by the elevated levels of total suspended solids (TSS) that correspond with both high discharge and elevated levels of metals in the water. Since this contaminant spike is an annual event, it is not likely that the spike in 2008 caused the drop in egg-to-fry survival or fish population. It is interesting that there is strong wild brown trout survival in most years in spite of these annual spikes of copper and other metals.

Scour was not a cause of decreased egg-to-fry survival, as eggs were counted before runoff began. It could have impacted fish populations by scouring the channel and reducing the amount of cover available from large woody debris (Workman 2008). It is possible that cold was a factor in both populations.

Workman’s redd count data from 2002-2007 shows a drop in redd numbers in the fall of 2003. Workman notes observing unusually low instream water levels during the 2003 redd count. His stream flow table shows low flow levels in both autumn of 2003 and autumn and winter of 2004, however, Workman reported observing more typical flow levels at the time of spawning in 2004. Redds counted dropped sharply in 2003 but were similar to other years in 2004, indicating that the lower flows in 2004 were timed in a way that did not negatively impact spawning that year.

SNORKEL SURVEY RESULTS
Workman 2008

The total number of brown trout (Salmo trutta) per mile is down significantly from all previous years in all 3 study sections. The total number of brown trout in section 770 is down by 73.6% from 2007 numbers (Figure 1). And the number of brown trout >6 inches total length is down 74.7% from 2007.
Figure 1. A Comparison of total brown trout numbers per mile and the number of brown trout greater than 6 inches total length in 2004 through 2008 in Section 770 of Warm Springs Creek.

![Warm Springs Creek Section 770](image)

*figure from Workman 2008*
In the Airport Road Section, the total number of brown trout is down by 88.5% from 2007 levels and the number of trout >6 inches is down 79.0% from the previous year (Figure 2).

Figure 2. A Comparison of total brown trout numbers per mile and the number of brown trout greater than 6 inches total length in 2004 through 2008 in the Airport Road Section of Warm Springs Creek.

*figure from Workman 2008*
In the Hatchery Section the total per mile is down 84.9% and the number trout >6 inches per mile is down 74.7% from 2007 numbers (Figure 3).

Figure 3. A Comparison of total brown trout numbers per mile and the number of brown trout greater than 6 inches total length in 2004 through 2007 in the Hatchery Section of Warm Springs Creek.

Section 770 held several large mountain whitefish (*Prosopium williamsoni*), and one rainbow trout (*Oncorhynchus mykiss*) was observed in the Hatchery Section but no other species were observed this year.
Table 1. Warm Springs Creek range of mean daily flows in cubic feet per second with number of days when flow was less than 20 cubic feet per second in parenthesis in November through April 2000 through 2008 at gage 770.

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*table from Workman 2008*
REDD COUNT RESULTS
Workman 2008

Table 5. Brown trout redds counted in Warm Springs Creek 2002 through 2007 with a sample of average water depth and velocity at the redd sites.

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table from Workman 2008

In 2008, Workman found that “The number brown trout redds in lower [Warm Springs Creek] continues to hold steady and at this time there is no clear correlation with stream flow (Workman 2008, pg 8).”

SITE DESCRIPTIONS
Workman 2004/2005

MAPLE STREET SECTION /HATCHERY SECTION
Maple Street Bridge is the downstream boundary of this section. It is located in the town of Anaconda several miles upstream from the dewatered reach of Warm Springs Creek. This section runs 1,023 feet upstream to a point directly behind the Washoe Park Trout Hatchery. From the bridge upstream to the hatchery outfall (+ 450 feet), the channel is steep with high water velocity and boulder/cobble streambed. There are no pools or deep runs. The upper half of the section is meandering with good run/riffle development. The channel in the lower half of the section is well shaded by trees and woody vegetation while the upper half is mostly devoid of overhanging vegetation. A few large trees provide some shade to the upper portion of the section.

In 2005 the name and location of this section was changed when high spring runoff opened a major side channel directly behind the Washoe Park Hatchery. The section name was changed from the Maple Street Section to the HATCHERY SECTION. The snorkel count was discontinued on the portion from the Maple Street Bridge to the hatchery outfall and replaced by counting fish in
the new side channel. The total section length changed from 1,023 feet to 1,035 feet (Workman 2005).

AIRPORT ROAD SECTION
Located near the beginning of the dewatered section of Warm Springs Creek, it begins at Anaconda Airport Road Bridge and runs upstream 885 feet to the point where a small stream channel enters the main channel on the left bank. This section has been extensively altered by bulldozers over the years to alleviate flooding due to ice jams. There is very little overhanging woody vegetation although it is well shaded by large cottonwood trees. The channel was mostly straight; stream bed composition was cobble with some gravel and sand. The streambed was very clean with no algae on the rocks. The last alteration was made long enough ago that the stream has developed a thalweg, runs and riffles within the confines of the straightened channel. This section represents the worst trout habitat of the dewatered reach of Warm Springs Creek.

GAGE 770 SECTION
Beginning at the staff gage, this section runs upstream 627 feet to the concrete abutments of an old bridge. Located approximately one mile above the mouth on the Clark Fork River, it is on the lower end of the dewatered reach. It represents the best trout habitat in the dewatered section. It has well developed riparian vegetation that provides ample shade, overhanging cover and undercut banks. Streambed composition was gravel/sand/silt with some algae covering the rocks. There is an exposed pipeline crossing the creek a short distance upstream from the gage, and the start of a new beaver dam immediately downstream of the old bridge above the gage. These obstructions could be passage barriers to fish moving upstream.

REDD COUNTS
Brown trout redds were counted in the lower 0.7 mile of Warm Springs Creek in 2003. ...[In 2003 and 2004, average depth and velocity was measured at the upstream edge of eight redds and the average of the measurements is shown (Workman Table 5).
APPENDIX C
Table 4: Water quality parameters measured at USGS gage 12323770. **Bold** text indicates measurements that exceed the Montana Water Quality (WQ) standard, and the corresponding dates, discharges and total suspended solids (TSS). Spikes in copper (Cu) and other metals correspond with periods of high discharge during spring runoff. Given that this is a former mining and smelting area and is a current Superfund site, it is likely that these contaminants are in the streamside and streambank soils, which are scoured at runoff. This is supported by the elevated TSS levels that correspond with both high discharge and elevated metals in the water.

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E = estimated data.