MOVEMENT PATTERNS AND MULTI-SCALE FACTORS THAT INFLUENCE EXOTIC BROOK TROUT AND ENDEMIC BONNEVILLE CUTTHROAT TROUT DISTRIBUTION AND ABUNDANCE IN THE MILL CREEK DRAINAGE, UTAH

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Fisheries Biology

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ABSTRACT

Movement Patterns and Multi-scale Factors that Influence Exotic Brook Trout and Endemic Bonneville Cutthroat Trout Distribution and Abundance in the Mill Creek Drainage, Utah

by

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Utah State University, 2008

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Introduced brook trout (*Salvelinus fontinalis*) are implicated as a primary factor leading to the decline in distribution and abundance of native cutthroat trout (*Oncorhynchus clarkii*). However, not all introductions are successful, suggesting local conditions influence the success of invasions. Therefore, I sought to determine the multi-scale factor(s) that influence brook trouts’ invasion success of native Bonneville cutthroat trout (*Oncorhynchus clarkii utah*) habitats in Mill Creek, Utah. I conducted patch occupancy surveys to determine watershed-scale brook trout and cutthroat trout distribution. I also determined the relative abundance of brook trout and cutthroat trout at the reach-scale by conducting three-pass depletion electrofishing surveys at ten index sites throughout the drainage. Upon completion of those surveys, I collected key watershed and reach-scale biotic and abiotic data twice during base-flow conditions. In
addition, to determine watershed-scale population connectivity and the potential for upstream invasion by brook trout, I assessed fish movement using two-way weir traps. At the watershed-scale, stream slope appeared to limit brook trout invasion into some portions of the drainage. Intermittent stream-flows and extreme levels of stream slope (>10%) appeared to limit cutthroat trout distribution. At the reach-scale, regression analyses indicated aquatic invertebrate abundance and low winter water temperatures may have influenced the abundance of brook trout, but my models explained little variation in cutthroat trout abundance overall. I observed high rates (74%) of site fidelity amongst brook trout, and mobile brook trout moved short distances (range=62-589 meters) overall. Cutthroat trout also exhibited high site fidelity (92%), but their movement was more variable, as few individuals moved long distances (up to 12.15 km). These findings will help prioritize cutthroat trout management actions in this watershed, and will be useful in determining why brook trout are successful invaders in some systems, yet remain in low and patchy abundance in others.
DEDICATION

I dedicate this thesis to my wife, Jaynee Nadolski, whose tireless effort and unending patience allowed me to fulfill my academic, professional, and spiritual aspirations. I would also like to thank her for the emotional support she provided during the many periods of academic struggle and hardship.
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unending technical support and guidance, and superb mentorship throughout my program of study. The use of trade or firm names in this paper is for reader information only and does not imply endorsement by the U.S. Geological Survey of any product or service.

Benjamin K. Nadolski
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INTRODUCTION

The worldwide proliferation of nonnative species invasions is well documented and poses one of the greatest threats to the persistence of native fauna (Williamson 1999). In fact, the introduction of nonnative species has been implicated in 49% of all species listings under the Endangered Species Act (Wilcove et al. 1998). For these reasons, the introduction of nonnative species is cited as one of the foremost causes of biotic impoverishment both worldwide (Scott and Helfman 2001), and in the United States. Historically, in an effort to increase species diversity amongst western streams, the United States Fish Commission used the transcontinental railway to transport eastern aquatic species to the west. As a result, one in four fish that occur in streams of 12 western states is nonnative (Schade and Bonar 2005). Despite the well documented impacts to native fish species, nonnative species introductions have continued.

The introductions of nonnative salmonid species, such as brook trout (*Salvelinus fontinalis*), have occurred since the late 1800’s (MacCrimmon and Campbell 1969), and are implicated in the decline, and in some cases, loss of native trout species throughout the intermountain west (Gresswell 1988). The negative impacts of these introductions to native trout species include hybridization (Carmichael et al. 1993; Henderson et al. 2000; Hitt et al. 2003), agonistic behavioral interactions (Wang and White 1994), predation (McGrath and Lewis 2007), habitat use overlap (Gunckel et al. 2002), and diet overlap (Hilderbrand and Kershner 2004). Through interspecific competition, these negative interactions can lead to reduced body condition, growth, and ultimately fitness of native fish populations, including native cutthroat trout (*Oncorhynchus clarkii*).
The cutthroat trout is a salmonid species native to portions of western North America (Trotter 1987), and has the broadest distribution of native western trout species (Behnke 1992). The details of its evolutionary origin are not clearly understood, but fossil records indicate that a divergence of a common ancestor, ancient “Parasalmo,” occurred approximately 2-8 million years ago, and gave rise to ancient forms of cutthroat trout and rainbow trout (Behnke 1988; Smith et al. 2002). Natural dispersal of cutthroat trout followed by geographic isolation events led to the evolutionary divergence of multiple cutthroat trout subspecies. Currently, there are eight putative subspecies of cutthroat trout in western North America (Behnke 1992), including the Bonneville cutthroat trout (*Oncorhynchus clarkii utah*), which is a plesiomorphic sister group to all other native cutthroat trout subspecies (Smith et al. 2002). Extant populations of Bonneville cutthroat trout persist in portions of Utah, Idaho, Wyoming, and Nevada (Gresswell 1988), and have experienced reductions in historically occupied habitats, with populations primarily relegated to headwater tributary streams (Lentsch et al. 1997). Many factors have contributed to this decline, including habitat degradation (Binns and Remmich 1994), disease (de la Hoz Franco and Budy 2004), hybridization (Weigel et al. 2003), and negative interactions with nonnative fish species such as brook trout (Griffith 1988).

The introduction and subsequent invasion of brook trout has occurred throughout western United States (Behnke 1992; Adams et al. 2002; Dunham et al. 2002; Shepard 2004), often in drainages containing native cutthroat trout populations (Tyus and Saunders 2000; Shepard 2004; Meyer et al. 2006). Brook trout are native to portions of
eastern Canada, the Atlantic, Great Lakes and Mississippi River Basins, Minnesota, and northern Georgia (Page and Burr 1991), and have been introduced into 35 out of 50 states to be used for sport fish purposes (Fuller et al. 1999). Negative competitive interactions between brook trout and cutthroat trout are well studied and include diet (Dunham et al. 2000; Hilderbrand and Kershner 2004) and habitat use overlap (Destaso and Rahel 1994; Peterson and Fausch 2003), as well as direct competition through agonistic behavioral interactions (Cunjak and Green 1984; Hutchison and Iwata 1997). These interactions often result in reduced body condition, growth, and fitness of native cutthroat trout populations, and can be so adverse that Behnke (1992), observed a virtual replacement of cutthroat trout by brook trout within Black Hollow Creek, Colorado during a five-year period.

Despite the prolific history of brook trout introductions, not all invasions are successful, suggesting that environmental factors can mediate brook trout invasion success. These environmental factors operate at multiple spatial and temporal scales (Poff 1997), and are important in determining local species assemblages by acting as a species “filter.” According to this concept, species’ pass through a hierarchy (i.e., large-scale to small-scale) of spatially and temporally-nested environmental filters, and as species’ pass through increasingly finer filters, local biotic and abiotic conditions determine a species presence or absence. The declining status of brook trout in its native range (Hudy et al. 2005), and widespread invasion success outside its native range, have resulted in numerous studies of the biotic and abiotic variables that influence brook trout distribution and abundance at multiple hierarchical scales (e.g., filters). Some examples
include geology and geomorphology (Nelson et al. 1992; Kocovsky and Carline 2006), stream slope (Chisholm and Hubert 1986; Adams et al. 2000; Isaak and Hubert 2000), macrohabitat characteristics (Lindstrom and Hubert 2004), water temperature (Shepard 2004; Mullner and Hubert 2005), stream pH (Cleveland et al. 1986; Jordahl and Benson 1987), fine sediment abundance (VanDusen et al. 2005; Hartman and Hakala 2006), invertebrate abundance (VanDusen et al. 2005), and life-history stage (Kennedy et al. 2003). In addition, large scale (i.e., watershed-scale) movement dynamics play an important role in determining the likelihood of successful invasion. Movement behaviors of potamadromous (i.e., migration within flowing freshwaters) brook trout are well studied, and include movements into and out of spawning, over-wintering, and feeding habitats (Northcote 1997; Gowan and Fausch 2002). These behaviors can be influenced by environmental factors including, stream discharge (Chisholm et al. 1987), and frequency of pool habitats (Lindstrom and Hubert 2004). In addition, if suitable habitats are patchily distributed, connectivity amongst those areas through movement is an important mechanism for successful invasion, and in many cases, these movements promote the invasion of native cutthroat trout habitats (Adams et al. 2002; Peterson and Fausch 2003; Benjamin et al. 2007). However, the location, timing, duration, and distance of these movements can vary within and across populations, habitats, and diel periods (Gowan and Fausch 1996), making it important to understand large-scale, population-specific movement dynamics when investigating the factors that influence the success and spatial extent of brook trout invasion.
The goal of my research was to better understand why brook trout are successful invaders in some systems, yet, remain in low, patchy abundance in similar systems. To determine this, I 1) determined the watershed-scale biotic and abiotic factors that influence the distribution of brook trout and cutthroat trout in a northern Utah stream, 2) determined the reach-scale biotic and/or abiotic factors that influence the abundance of brook trout and cutthroat trout, and 3) characterized watershed-scale brook trout and cutthroat trout movement patterns and assessed the effects of movement on brook trout distribution and invasion.
Mill Creek is a tributary to the headwater portions of the Bear River, and is located approximately 2,740 meters above sea level in Summit County, Utah (Figure B.1). The Bear River Basin encompasses portions of Utah, Wyoming, and Idaho before terminating into the Great Salt Lake. The upper portions of Mill Creek has a single channel of low sinuosity and high slope, whereas the lower portion has greater sinuosity and less slope. Mill Creek supports a unique and diverse community of native fish species including Bonneville cutthroat trout, northern leatherside chub (*Lepidomeda copei*), longnose dace (*Rhinichthys cataractae*), speckled dace (*Rhinichthys osculus*), sculpin (*Cottus spp.*), mountain whitefish (*Prosopium williamsoni*), mountain sucker (*Catostomus platyrhynchos*), Utah sucker (*Catostomus ardens*), and redside shiner (*Richardsonius balteatus hydroflox*). The only nonnative fish species in Mill Creek is brook trout. The Utah Division of Wildlife Resources considers the Bonneville cutthroat trout population in Mill Creek a “core conservation population,” thereby warranting increased conservation protection (Lentsch et al. 1997). Mill Creek and its tributaries contain one of the largest remaining genetically pure metapopulations of Bonneville cutthroat trout. In addition, Mill Creek and its tributaries support one of only two extant populations of northern leatherside chub in Utah.

In 2003 and 2004, as part of a large-scale electrofishing survey to document the spatial distribution of northern leatherside chub in Mill Creek and its tributaries, the Utah Division of Wildlife Resources coarsely identified watershed-scale fish species distributions. Those findings suggested that cutthroat trout occupied large portions of the area.
watershed, while brook trout were patchily distributed throughout the watershed and had not invaded some nearby tributary streams, despite no apparent physical or biological barrier(s). In addition, these surveys documented dynamic spatial and temporal differences in fish density at multiple locations, suggesting expansion and contraction of brook trout and cutthroat trout populations throughout the drainage. I used these pilot data to design my study of the watershed and reach-scale factors that influence the distribution and abundance of brook trout and Bonneville cutthroat trout in the Mill Creek drainage.
Watershed-scale assessment

Watershed-scale patch occupancy surveys were conducted to describe large-scale brook trout and cutthroat trout distribution in Mill Creek and its tributaries. Survey methods were based on protocols developed by Peterson et al. (2002), but modified to meet the constraints and objectives of this project. Starting at the upstream extent of known brook trout occupancy (based on pilot study results) in Mill Creek and each of its tributaries, I measured a 50-meter electrofishing study unit. A one-pass electrofishing depletion survey was conducted within that 50-meter study unit. All fish were captured, identified, measured, weighed, and released. Upon completion of that survey, moving in an upstream direction, within another 50-meter study unit separated by a 500-meter stream segment, another one-pass electrofishing depletion survey was completed. This process was repeated until no brook trout or cutthroat trout were detected at three consecutive 50-meter study units, or when the water source was reached, whichever came first. At each study unit, Universal Transverse Mercator (UTM) coordinates were recorded. The lowest 50-meter study unit that contained brook trout represented the upstream extent of brook trout distribution. Likewise, the lowest 50-meter study unit that contained cutthroat trout represented the upstream extent of cutthroat trout distribution.

Watershed-scale stream slope was determined by using stream layers in ArcGIS software to divide Mill Creek and its tributaries into 250-meter stream segments. I then overlaid the stream layers with a 10-meter resolution digital elevation model, and assigned top and bottom elevation values (i.e., meters above mean sea level) to each
stream segment. The difference between the top and bottom elevations was calculated and divided by the distance between the two points (i.e., 250-meters) to determine the percent slope of each stream segment. That process was repeated throughout the watershed to construct a watershed-scale longitudinal profile of stream slope.

Watershed-scale patterns of water chemistry were determined by measuring pH, salinity (ppm), conductivity (μ/cm), turbidity (NTU), and total dissolved solids (TDS; g/L) at multiple locations along the longitudinal gradient of Mill Creek and its tributaries (Figure B.2). All water chemistry measurements were collected using a YSI model 556 MPS multi-meter. Turbidity samples were collected and analyzed using a LaMotte model 2020e turbidimeter following the manufacturers guidelines.

Watershed-scale analysis

The results of patch occupancy surveys were used to determine if stream slope or water chemistry influenced large-scale brook trout and cutthroat trout distribution. I used the results of patch occupancy surveys to determine where brook trout and cutthroat trout occurred, and qualitatively compared that distribution to stream slope and water chemistry measurements.

Reach-scale assessment

Based on spatially explicit patch occupancy surveys, and to represent all habitat types present along the longitudinal stream gradient of Mill Creek and its tributaries, I identified ten permanent 100-meter index sites throughout the watershed that represented the lower, middle, and upper portions of Mill Creek (Mill Creek border, low, middle, and
high), Deadman Creek (Deadman Creek low, middle, and high), and North Fork
(North Fork low, middle, and high; Figure B.3). At each index site, I collected
information describing key biotic and abiotic variables twice during base-flow summer
conditions: once in July and August. Three-pass depletion electrofishing surveys were
performed at each index site in order to understand the relationship of these variables to
brook trout and cutthroat trout abundance.

Nutrient samples were collected using 250-milliliter amber bottles. Immediately
following collection, all samples were placed in coolers containing dry ice. Samples
were analyzed by High Sierra Water Lab in Truckee, California to determine the
concentrations of ammonia, total nitrogen, Kjeldal nitrogen, nitrates, nitrites, dissolved
phosphorous, soluble phosphorous, and total phosphorous. In addition, I measured
stream pH, conductivity, salinity, and turbidity following the protocols described
previously (see watershed-scale assessment).

To determine water temperature profiles at all ten index sites, hourly water
temperature was measured using temperature data loggers. This data was summarized
using yearly minimum, median, mean, and maximum values for each index site. Due to
some incidence of logger loss or malfunction, I obtained temperature profiles for some
index sites by regressing known temperatures of two “nearest neighbor” locations and
applying the regression equation to areas of unknown temperature. For example, the
temperature profiles of the Mill Creek middle and Mill Creek high index sites during
2007 were highly related (n=5,521, $R^2=0.98$), thus allowing me to predict temperature
profiles where data were missing.
Pebble counts were used to characterize substrate composition. Each index site was divided into ten evenly spaced longitudinal stream segments. At one randomly selected location within each stream segment, I collected ten substrate particles across the width of the stream channel using the heel-toe method. Particle size was determined by recording the largest slot that retained the particle using an Albert Scientific field sieve-gravelometer (Bunte and Abt 2001).

Stream discharge was measured by placing a meter tape over the width of the stream channel. Total stream width was recorded at 20 equal distance locations across the stream channel. Stream velocity, depth, and distance from shore were also measured. Velocity measurements were recorded using a Marsh-McBirney Flo-Mate model 2000 electromagnetic flow-meter set at 0.6 of the total stream depth. I calculated stream discharge using methods outlined by Harrelson et al. (1994).

Stream slope was measured using an engineering level. At each index site, a staff gauge was placed at the downstream end of a riffle habitat near the downstream end of the index site, as well as at the downstream end of a riffle habitat near the upstream end of the index site. I estimated stream slope as the difference in elevation at the two staff gauges divided by the total stream distance between staff locations. When necessary, I used turning points to ensure direct line of sight between the laser and the staff gauge.

Aquatic invertebrates were collected both qualitatively and semi-quantitatively to determine species richness and species abundance. For qualitative samples, I used a 25cm x 46cm kick-net with 500-micron mesh to collect a sample from all habitat types...
(e.g., pool, riffle, run, beaver pond), present within each index site. For quantitative samples, I collected two kick-net samples from four riffle habitats within the index site.

As an index of algal abundance, periphyton samples from ten rocks were taken from each index site. Rocks were chosen randomly from ten evenly spaced longitudinal stream segments. Upon collection, rocks were placed on ice and transported to the laboratory. Two subsamples of the scrubbate were collected and filtered through a glass fiber filter to determine concentrations of chlorophyll $a$. After filtration, I froze all filters until they were processed using protocols outlined in Clesceri et al. (1989).

Brook trout and cutthroat trout abundance was estimated using standard 3-pass depletion techniques (Krebbs 1999). Stream distance of all 100-meter electrofishing survey locations was measured using a drag tape. A block net was placed at the lower and upper ends of each index site and electrofishing surveys were completed using battery powered backpack electrofishing units. Electrofishing settings varied depending upon levels of conductivity within the stream. In general, I set the pulse at J (70 Hz), the frequency at 4 (4 ms), and the voltage at 300 V. Electrofishing commenced with a crew ranging from 3-6 people. Three electrofishing passes were conducted and all the fish encountered were removed and placed into live cages. I identified all fish to species, weighed them to the nearest gram, and measured them to the nearest millimeter total length. Before release, I anesthetized all brook trout and cutthroat trout that measured $\geq$ 150 millimeters total length with a non-lethal dose of tricaine methanesulfonate (MS-222) and inserted an external anchor tag posterior to the dorsal fin. In addition, a 23-millimeter half-duplex radio frequency identification (RFID) transponder tag was
surgically implanted into the ventral region slightly posterior to the pectoral fin. Upon completion of the survey, I measured wetted stream width at ten randomly selected locations along the longitudinal gradient of the index site to determine average stream width.

Reach-scale data analyses

To standardize fish abundance across index sites, all estimates were converted from linear abundance (i.e., number of fish per kilometer of stream) to aerial abundance (i.e., number of fish per hectare of stream) using average stream width values. To determine the variable(s) that influenced the magnitude of brook trout and cutthroat trout abundance at the reach-scale, I plotted each biotic and abiotic variable as continuous explanatory variables versus the log-transformed brook trout and cutthroat trout abundance estimates for each index site as the response variable. I used linear and quadratic regression models to determine the relationship between each explanatory variable and brook trout and cutthroat trout abundance estimates. Regression analyses were generated using the REG procedure in SAS/STAT software, Release 9.1.3 of the SAS System for Windows. P-values were assessed with significance determined a priori at $a=.05$, and I evaluated goodness of fit, homogeneity of variance, and influence.

Movement

To determine the extent of large-scale brook trout and cutthroat trout movement, and to identify the primary pathways of fish movement throughout the watershed, in-stream, two-way weir traps were deployed at two locations in Mill Creek, one location in
Deadman Creek, and one location in North Fork (Figure B.4). All traps were checked
daily from June through September, 2007. I identified all captured fish to species,
weighed them to the nearest gram, and measured them to the nearest millimeter total
length. If a marked fish was captured (e.g., from index site sampling), the unique tag
identification was recorded. In addition, for all fish captured I recorded the direction of
movement (i.e., upstream or downstream) and the date of capture. All unmarked trout ≥
150 millimeters total length were anesthetized with a non-lethal dose of tricaine
methanesulfonate (MS-222), and internal and external tags were surgically administered.
In addition, during September, 2007, I “spotshocked” portions of Mill Creek, North Fork,
and Deadman Creek to supplement the movement data collected from index site and
weir-trap sampling. All marked fish were identified to species, measured to the nearest
millimeter total length, and weighed to the nearest gram. In addition, the date of capture
and unique tag identification were recorded. Finally, the location of each capture was
recorded using Universal Transverse Mercator (UTM) coordinates.

**Movement model**

A multi-strata mark/recapture model in Program MARK was used to estimate
capture, survival, and movement probabilities for brook trout and cutthroat trout. Four
main areas (i.e., strata) of brook trout and cutthroat trout occupancy throughout the
drainage were identified (Figure B.5). I assigned each stratum a unique identification
code (A, B, C, or D), then divided all six encounter occasions into six categories as
follows: 1) index sites sampled during July, 2006, 2) index sites sampled during August,
2006, 3) two-way weir traps sampled from June through September, 2007, 4) index sites
sampled during July, 2007, 5) index sites sampled during August, 2007, and 6) study streams spot electrofished during September, 2007. The individual encounter histories of all marked fish were used to determine which stratum each fish occupied during each encounter occasion. I expressed the encounter history of each fish as a contiguous series of locations (strata A-D) for each encounter occasion (1-6), and assigned a “0” to fish that were not observed in any strata for that particular encounter occasion. For example, a fish with encounter history “AA0BCD” was originally captured in stratum A during index site sampling in July of 2006, was recaptured in stratum A during index site sampling during August of 2006, was not seen in any strata during weir trap sampling from June through September of 2007, was recaptured in stratum B during index site sampling during July of 2007, was recaptured in stratum C during index site sampling in August of 2007, and was captured in stratum D during spot electrofishing surveys in September of 2007. All encounter histories were compiled into an input file (Table A.1), and I estimated the probability of capture (p), the probability of survival (Φ), and the probability of transition (i.e., movement; ψ) among all strata for brook trout and cutthroat trout. I started by estimating the best model (i.e., global model) for all three probability estimates (p, Φ, and ψ) by varying recapture, survival, and transition structure. Next, I calculated subsequent iterations with one probability structure varying at one time, while the remaining two probability structures remained constant. This was repeated for all combinations of all three probability estimates. I then used corrected Akaike’s Information Criteria (AICc) to choose the most parsimonious top model of capture, survival, and transition probabilities.
RESULTS

Watershed-scale assessment

Despite the apparent lack of physical or biological barriers to fish movement, brook trout were patchily distributed throughout portions of the Mill Creek drainage and had not invaded some nearby tributary streams. More specifically, brook trout invaded and were established in approximately 24.68 of 30.92 km (80%) of Mill Creek, and were only sparsely distributed throughout an additional 4.69 km (15%) of Mill Creek. In addition, brook trout had invaded and were established in approximately 4.54 of 6.19 km (73%) of Deadman Creek, but had not invaded Carter Creek, Christmas Tree Creek, McKenzie Creek, the unnamed tributary near the headwater portions of Mill Creek, and the unnamed tributary adjacent to McKenzie Creek. In total, brook trout occupied approximately 33.91 of 71.12 total km (48%) of the Mill Creek drainage. Conversely, cutthroat trout were widely distributed throughout the drainage and occupied large portions of Mill Creek, Carter Creek, Christmas Tree Creek, Deadman Creek, McKenzie Creek, North Fork, and the unnamed tributary adjacent to McKenzie Creek. In total, cutthroat trout occupied approximately 55.52 of 71.12 total km (78%) of the Mill Creek drainage.

Based on watershed-scale stream slope profiles, patch occupancy surveys, and index-site abundance estimates, brook trout were established in areas with low to moderate stream slopes. More specifically, mean stream slope of all areas where brook trout were established was 0.019%, and ranged from 0.002% to 0.046% in Mill Creek, and 0.013% to 0.060% in Deadman Creek (Table A.2). In both streams, brook trout


establishment ended at a point of precipitous increase in stream slope (Figure 1). Conversely, cutthroat trout were established in areas that ranged from low to high stream slope. More specifically, stream slope in areas where cutthroat trout were established averaged 0.035%, and ranged from 0.005 to 0.101% (Table A.2).

In general, conductivity, pH, and TDS measurements were lower in North Fork and McKenzie Creek than in Mill Creek, Deadman Creek, and Carter Creek, while turbidity and salinity measurements varied widely across sample sites and sample streams (Table A.3). Brook trout occupied some areas with higher levels of conductivity, pH, and TDS (i.e., portions of Mill Creek and Deadman Creek), and were generally absent in areas of low conductivity, TDS, and pH (i.e., North Fork and McKenzie Creek). Cutthroat trout were widely distributed throughout all sampled tributaries and occupied stream reaches that varied in turbidity, conductivity, salinity, pH, and TDS.

Overall, the density of brook trout ranged from 23 (North Fork low July, 2006) to 6084 (Deadman Creek middle August, 2007) individuals per hectare, and varied across sample periods and years (Figures 2, B.6, and B.7). Brook trout were detected at eight index sites, and in general, population abundance was lowest in North Fork, highest in Deadman Creek, and intermediate in Mill Creek. Overall, the density of cutthroat trout ranged from 59 (Deadman Creek low July, 2007) to 1870 (Mill Creek middle August, 2007) individuals per hectare, and varied within index sites and across sample periods and years (Figures 2, B.6, and B.7). Cutthroat trout were detected at all ten index sites and, in general, abundance was lowest in North Fork, highest in Mill Creek, and intermediate in Deadman Creek. Overall, cutthroat trout were more abundant than brook
trout in Mill Creek and North Fork, and brook trout were more abundant than cutthroat trout in Deadman Creek.

Nutrient concentrations, water temperature, substrate, discharge, stream slope, and aquatic invertebrate abundance and diversity varied widely within and across all index sites and study streams (Tables 1, and A.4-A.10). Nutrient concentrations were generally higher in 2007 than in 2006, and differences across sites remained similar across years (Table A.4). Water temperatures were generally cooler in 2006 than in 2007, and were highest in Deadman Creek, lowest in North Fork, and intermediate in Mill Creek (Table A.5). In addition, median water temperature distribution was skewed towards cooler temperatures (Figure 3). In general, substrate size was greatest in North Fork, smallest in Deadman Creek, and intermediate in Mill Creek. Percent fines ranged from zero to 74, with the lowest values from the Mill Creek high index site and the highest values from the Deadman Creek low index site (Table A.6). Stream discharge measurements varied widely across index sites, sample periods, and sample years, but were generally highest in Mill Creek, lowest in Deadman Creek, and intermediate in North Fork (Table A.7). Stream slope varied across index sites and study streams, and was highest in North Fork, lowest in Deadman Creek, and intermediate in Mill Creek (Table A.8). Total invertebrate abundance was generally highest in Mill Creek, lowest in Deadman Creek, and intermediate in North Fork, and species diversity was highest in Deadman Creek, lowest in Mill Creek, and intermediate in North Fork (Table A.9). For watershed-scale water chemistry results, conductivity and pH values measured in Mill
Creek and Deadman Creek were similar, but were generally higher than those measured in North Fork (Table A.10).

Median temperature, dissolved phosphorous, minimum temperature, D16, and conductivity were significantly related to brook trout abundance based on a linear model, and total invertebrate abundance, percent fines, and mean temperature were significantly related to brook trout abundance based on a quadratic model (Table 2; Figure 4). I observed no other significant relationships among the remaining explanatory variables and brook trout abundance.

Maximum temperature, nitrate-nitrite, chlorophyll \( a \) abundance, D84, D90, D64, and D50 were significantly related to cutthroat trout abundance based on a linear model (Table 3; Figure 5). In addition, soluble reactive phosphorous was significantly related to cutthroat trout abundance based on a quadratic model. I observed no other significant relationships among the remaining explanatory variables and cutthroat trout abundance. However, due to low \( r^2 \), none of the explanatory variables measured appeared to explain a meaningful portion of the variation in cutthroat trout abundance.
Figure 1. Longitudinal stream profile of percent stream slope (solid line) of Mill Creek and Deadman Creek (y-axes), with the location and number of brook trout per hectare (bars) at each index site positioned along the longitudinal stream profile (x-axes). Dashed vertical lines indicate the approximate upstream extent of brook trout establishment based on patch occupancy surveys.
Figure 2. Mean brook trout and cutthroat trout abundance at all ten index sites during 2006 and 2007. Error bars represent 95% confidence intervals.
Table 1. Mean (SD) values of all biotic and abiotic variables measured at all ten index sites in Mill Creek, Deadman Creek, and North Fork during July and August, 2006 and 2007.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mill Creek</th>
<th>Deadman Creek</th>
<th>North Fork</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity</td>
<td>253.19 (38.96)</td>
<td>355.58 (93.65)</td>
<td>40.51 (12.53)</td>
</tr>
<tr>
<td>pH</td>
<td>8.21 (0.41)</td>
<td>8.11 (0.43)</td>
<td>7.56 (0.32)</td>
</tr>
<tr>
<td>Turbidity</td>
<td>0.96 (0.47)</td>
<td>1.68 (0.88)</td>
<td>1.66 (0.63)</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>-0.12 (0.18)</td>
<td>-0.03 (0.33)</td>
<td>-0.33 (0.23)</td>
</tr>
<tr>
<td>Median Temperature</td>
<td>0.24 (0.18)</td>
<td>0.5 (0.36)</td>
<td>0.03 (0.13)</td>
</tr>
<tr>
<td>Mean Temperature</td>
<td>2.67 (0.54)</td>
<td>3.11 (0.32)</td>
<td>1.87 (0.01)</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>20.03 (3.39)</td>
<td>18.85 (3.19)</td>
<td>17.94 (1.47)</td>
</tr>
<tr>
<td>Discharge</td>
<td>0.17 (0.19)</td>
<td>0 (0)</td>
<td>0.01 (0)</td>
</tr>
<tr>
<td>Soluble Reactive Phosphorous</td>
<td>2 (0.76)</td>
<td>1 (0)</td>
<td>2.67 (2.66)</td>
</tr>
<tr>
<td>Dissolved Phosphorous</td>
<td>7.75 (1.49)</td>
<td>8.67 (2.73)</td>
<td>7.33 (1.97)</td>
</tr>
<tr>
<td>Total Phosphorous</td>
<td>13.75 (3.73)</td>
<td>12.17 (3.54)</td>
<td>11.17 (3.25)</td>
</tr>
<tr>
<td>Nitrate-Nitrite</td>
<td>112.25 (109.57)</td>
<td>5.33 (3.08)</td>
<td>47.17 (47.13)</td>
</tr>
<tr>
<td>Total Keljdal Nitrogen</td>
<td>216.75 (43.27)</td>
<td>189.83 (69.43)</td>
<td>118.5 (15.76)</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>329 (112.74)</td>
<td>195.17 (69.57)</td>
<td>165.67 (36.26)</td>
</tr>
<tr>
<td>Ammonia</td>
<td>5.25 (3.77)</td>
<td>2.17 (0.41)</td>
<td>17 (34.8)</td>
</tr>
<tr>
<td>Chlorophyll a Abundance</td>
<td>3.33 (1.61)</td>
<td>36.4 (73.15)</td>
<td>1.36 (1.41)</td>
</tr>
<tr>
<td>Hill Eveness</td>
<td>0.56 (0.09)</td>
<td>0.58 (0.13)</td>
<td>0.6 (0.1)</td>
</tr>
<tr>
<td>Number OUT</td>
<td>27.13 (6.13)</td>
<td>38.17 (8.28)</td>
<td>30.83 (3.82)</td>
</tr>
<tr>
<td>Shannon Diversity</td>
<td>2.19 (0.22)</td>
<td>2.49 (0.53)</td>
<td>2.46 (0.27)</td>
</tr>
<tr>
<td>Simpson Diversity</td>
<td>0.19 (0.05)</td>
<td>0.16 (0.15)</td>
<td>0.14 (0.06)</td>
</tr>
<tr>
<td>EPT Abundance</td>
<td>361.88 (42.66)</td>
<td>185.33 (143.23)</td>
<td>337.5 (75.88)</td>
</tr>
<tr>
<td>Total Invertebrate Abundance</td>
<td>482.25 (51.64)</td>
<td>434.83 (76.21)</td>
<td>455.17 (54.35)</td>
</tr>
<tr>
<td>D16</td>
<td>37.44 (14.12)</td>
<td>4 (0)</td>
<td>38.5 (12.75)</td>
</tr>
<tr>
<td>D50</td>
<td>76.94 (30.38)</td>
<td>12.75 (9.1)</td>
<td>77.67 (21.91)</td>
</tr>
<tr>
<td>D64</td>
<td>98.06 (37.08)</td>
<td>20.75 (14.01)</td>
<td>104.17 (30.52)</td>
</tr>
<tr>
<td>D84</td>
<td>149.81 (50.13)</td>
<td>52.92 (22.88)</td>
<td>171 (35.06)</td>
</tr>
<tr>
<td>D90</td>
<td>183.56 (60.06)</td>
<td>78.5 (27.7)</td>
<td>220.17 (35.72)</td>
</tr>
<tr>
<td>Percent Fines</td>
<td>3.44 (3.44)</td>
<td>47.5 (23.88)</td>
<td>2.58 (2.27)</td>
</tr>
<tr>
<td>Percent Slope</td>
<td>0.03 (0.02)</td>
<td>0.02 (0.02)</td>
<td>0.06 (0.01)</td>
</tr>
</tbody>
</table>
Figure 3. Median (open circles) and mean (dark circles) annual water temperatures at all index sites during 2006 and 2007. Bars represent minimum and maximum annual water temperatures.
Table 2. Outputs of all linear models and all significant quadratic models for brook trout. All models are ranked in descending order of $r^2$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>P-value</th>
<th>$r^2$</th>
<th>Parameter Estimate</th>
<th>SE</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Invertebrate Abundance</td>
<td>*0.003</td>
<td>0.737</td>
<td>0.000</td>
<td>0.000</td>
<td>Quadratic</td>
</tr>
<tr>
<td>Median Temperature</td>
<td>*0.001</td>
<td>0.664</td>
<td>2.239</td>
<td>0.504</td>
<td>Linear</td>
</tr>
<tr>
<td>Percent Fines</td>
<td>*0.000</td>
<td>0.520</td>
<td>-0.001</td>
<td>0.000</td>
<td>Quadratic</td>
</tr>
<tr>
<td>Mean Temperature</td>
<td>*0.029</td>
<td>0.463</td>
<td>-1.510</td>
<td>0.581</td>
<td>Quadratic</td>
</tr>
<tr>
<td>Dissolved Phosphorous</td>
<td>*0.038</td>
<td>0.395</td>
<td>0.205</td>
<td>0.084</td>
<td>Linear</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>*0.044</td>
<td>0.346</td>
<td>1.767</td>
<td>0.768</td>
<td>Linear</td>
</tr>
<tr>
<td>D16</td>
<td>*0.012</td>
<td>0.276</td>
<td>-0.017</td>
<td>0.006</td>
<td>Linear</td>
</tr>
<tr>
<td>Conductivity</td>
<td>*0.033</td>
<td>0.207</td>
<td>1.598</td>
<td>0.396</td>
<td>Linear</td>
</tr>
<tr>
<td>Simpson's Diversity</td>
<td>0.074</td>
<td>0.312</td>
<td>3.636</td>
<td>1.801</td>
<td>Linear</td>
</tr>
<tr>
<td>Hill Evenness</td>
<td>0.077</td>
<td>0.308</td>
<td>-3.361</td>
<td>1.680</td>
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<tr>
<td>Maximum Temperature</td>
<td>0.092</td>
<td>0.260</td>
<td>5.115</td>
<td>1.600</td>
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<tr>
<td>D50</td>
<td>0.054</td>
<td>0.173</td>
<td>-0.069</td>
<td>0.003</td>
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<tr>
<td>Shannon's Diversity</td>
<td>0.219</td>
<td>0.163</td>
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<td>Linear</td>
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<tr>
<td>D64</td>
<td>0.070</td>
<td>0.154</td>
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<tr>
<td>D84</td>
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<td>0.124</td>
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<td>Total Invertebrate Abundance</td>
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<td>0.117</td>
<td>-0.004</td>
<td>0.004</td>
<td>Linear</td>
</tr>
<tr>
<td>D90</td>
<td>0.131</td>
<td>0.110</td>
<td>-0.003</td>
<td>0.002</td>
<td>Linear</td>
</tr>
<tr>
<td>Soluble Reactive Phosphorous</td>
<td>0.372</td>
<td>0.089</td>
<td>-0.325</td>
<td>0.347</td>
<td>Linear</td>
</tr>
<tr>
<td>Percent Slope</td>
<td>0.523</td>
<td>0.086</td>
<td>15.426</td>
<td>22.485</td>
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<tr>
<td>Percent Fines</td>
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<td>0.062</td>
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<td>0.007</td>
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<td>Mean Temperature</td>
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<td>Turbidity</td>
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<td>0.213</td>
<td>0.202</td>
<td>Linear</td>
</tr>
<tr>
<td>Total Phosphorous</td>
<td>0.248</td>
<td>0.050</td>
<td>0.077</td>
<td>0.062</td>
<td>Linear</td>
</tr>
<tr>
<td>Discharge</td>
<td>0.594</td>
<td>0.019</td>
<td>-0.815</td>
<td>1.496</td>
<td>Linear</td>
</tr>
<tr>
<td>EPT Abundance</td>
<td>0.811</td>
<td>0.007</td>
<td>0.000</td>
<td>0.002</td>
<td>Linear</td>
</tr>
<tr>
<td>Number OTU</td>
<td>0.813</td>
<td>0.007</td>
<td>0.006</td>
<td>0.026</td>
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<tr>
<td>Chlorophyl $a$</td>
<td>0.744</td>
<td>0.005</td>
<td>0.015</td>
<td>0.046</td>
<td>Linear</td>
</tr>
<tr>
<td>pH</td>
<td>0.801</td>
<td>0.003</td>
<td>0.095</td>
<td>0.371</td>
<td>Linear</td>
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<tr>
<td>Nitrate-Nitrite</td>
<td>0.896</td>
<td>0.002</td>
<td>0.000</td>
<td>0.003</td>
<td>Linear</td>
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<tr>
<td>Total Keljadial Nitrogen</td>
<td>0.920</td>
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<td>0.000</td>
<td>0.004</td>
<td>Linear</td>
</tr>
<tr>
<td>NH4_N</td>
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<td>0.001</td>
<td>-0.007</td>
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</tr>
<tr>
<td>Total Nitrogen</td>
<td>0.974</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002</td>
<td>Linear</td>
</tr>
</tbody>
</table>

* significant (p<.05)
Figure 4. Log-transformed brook trout abundance (y-axes) plotted against conductivity (A; µ/cm), dissolved phosphorous (B; ppb), D16 (C), minimum yearly water temperature (D; °C), median yearly water temperature (E; °C), mean yearly water temperature (F; °C), aquatic invertebrate abundance (G; m²), and percent fine substrate material (H) on the x-axes.
Table 3. Outputs of all linear and all significant quadratic models for cutthroat trout. All models are ranked in descending order of $r^2$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>P-value</th>
<th>$r^2$</th>
<th>Parameter Estimate</th>
<th>SE</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soluble Reactive Phosphorous</td>
<td>*0.030</td>
<td>0.289</td>
<td>-0.052</td>
<td>0.022</td>
<td>Quadratic</td>
</tr>
<tr>
<td>Maximum Temperature</td>
<td>*0.044</td>
<td>0.260</td>
<td>-0.056</td>
<td>0.025</td>
<td>Linear</td>
</tr>
<tr>
<td>Nitrate-Nitrite</td>
<td>*0.025</td>
<td>0.248</td>
<td>0.002</td>
<td>0.001</td>
<td>Linear</td>
</tr>
<tr>
<td>Chlorophyl a</td>
<td>*0.005</td>
<td>0.203</td>
<td>0.048</td>
<td>0.016</td>
<td>Linear</td>
</tr>
<tr>
<td>D84</td>
<td>*0.007</td>
<td>0.187</td>
<td>0.003</td>
<td>0.001</td>
<td>Linear</td>
</tr>
<tr>
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<td>*0.007</td>
<td>0.184</td>
<td>0.002</td>
<td>0.001</td>
<td>Linear</td>
</tr>
<tr>
<td>D64</td>
<td>*0.022</td>
<td>0.137</td>
<td>0.003</td>
<td>0.001</td>
<td>Linear</td>
</tr>
<tr>
<td>D50</td>
<td>*0.040</td>
<td>0.112</td>
<td>0.003</td>
<td>0.002</td>
<td>Linear</td>
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<tr>
<td>Median Temperature</td>
<td>0.067</td>
<td>0.220</td>
<td>0.554</td>
<td>0.279</td>
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</tr>
<tr>
<td>Total Phosphorous</td>
<td>0.081</td>
<td>0.160</td>
<td>0.044</td>
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<td>Linear</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>0.133</td>
<td>0.121</td>
<td>0.001</td>
<td>0.001</td>
<td>Linear</td>
</tr>
<tr>
<td>Minimum Temperature</td>
<td>0.215</td>
<td>0.108</td>
<td>0.425</td>
<td>0.327</td>
<td>Linear</td>
</tr>
<tr>
<td>Percent Fines</td>
<td>0.071</td>
<td>0.088</td>
<td>-0.004</td>
<td>0.002</td>
<td>Linear</td>
</tr>
<tr>
<td>Percent Slope</td>
<td>0.414</td>
<td>0.085</td>
<td>4.563</td>
<td>5.301</td>
<td>Linear</td>
</tr>
<tr>
<td>pH</td>
<td>0.148</td>
<td>0.057</td>
<td>0.181</td>
<td>0.122</td>
<td>Linear</td>
</tr>
<tr>
<td>Soluble Reactive Phosphorous</td>
<td>0.326</td>
<td>0.054</td>
<td>0.056</td>
<td>0.056</td>
<td>Linear</td>
</tr>
<tr>
<td>Hill Evenness</td>
<td>0.516</td>
<td>0.048</td>
<td>-1.647</td>
<td>2.437</td>
<td>Linear</td>
</tr>
<tr>
<td>Simpson's Diversity</td>
<td>0.376</td>
<td>0.046</td>
<td>0.633</td>
<td>0.696</td>
<td>Linear</td>
</tr>
<tr>
<td>EPT Abundance</td>
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<td>0.041</td>
<td>0.000</td>
<td>0.001</td>
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</tr>
<tr>
<td>Mean Temperature</td>
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<td>0.034</td>
<td>-0.100</td>
<td>0.142</td>
<td>Linear</td>
</tr>
<tr>
<td>D16</td>
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<td>0.003</td>
<td>0.003</td>
<td>Linear</td>
</tr>
<tr>
<td>Total Invertebrate Abundance</td>
<td>0.462</td>
<td>0.032</td>
<td>0.001</td>
<td>0.001</td>
<td>Linear</td>
</tr>
<tr>
<td>Shannon's Diversity</td>
<td>0.475</td>
<td>0.031</td>
<td>-0.126</td>
<td>0.172</td>
<td>Linear</td>
</tr>
<tr>
<td>Dissolved Phosphorous</td>
<td>0.502</td>
<td>0.026</td>
<td>0.031</td>
<td>0.044</td>
<td>Linear</td>
</tr>
<tr>
<td>Number OTU</td>
<td>0.614</td>
<td>0.015</td>
<td>0.004</td>
<td>0.008</td>
<td>Linear</td>
</tr>
<tr>
<td>Turbidity</td>
<td>0.693</td>
<td>0.004</td>
<td>-0.033</td>
<td>0.082</td>
<td>Linear</td>
</tr>
<tr>
<td>Total Keljdal Nitrogen</td>
<td>0.786</td>
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<td>0.000</td>
<td>0.001</td>
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</tr>
<tr>
<td>Discharge</td>
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<td>0.075</td>
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<td>NH4_N</td>
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<td>0.005</td>
<td>Linear</td>
</tr>
<tr>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>Linear</td>
</tr>
</tbody>
</table>

* significant (p<.05)
Figure 5. Log-transformed cutthroat trout abundance (y-axes) plotted against nitrates-nitrites (A; ppb), soluble reactive phosphorous (B; ppb), Chlorophyl a abundance (C; ug/cm²), D50 (D), D64 (E), D84 (F), D90 (G), and maximum yearly water temperature (H; °C) on the x-axes.
**Movement model**

In total, I marked 86 brook trout and 291 cutthroat trout. Recapture rates were relatively high: of those marked fish, 23 brook trout and 90 cutthroat trout were recaptured. For all recaptured brook trout, 17 were recaptured once, five were recaptured twice, and one was recaptured four times. All but six of those fish were recaptured at their initial capture location. Of those brook trout that were recaptured outside of their initial capture location, all were recaptured within the same stratum, and each of those fish moved from 62-589 meters (mean = 247 meters). For all recaptured cutthroat trout, 69 were recaptured once, 18 were recaptured twice, and three were recaptured three times. All but seven of those fish were recaptured at their initial capture location. Of those cutthroat trout that were recaptured outside of their initial capture location, five were recaptured within the same stratum, and each of those fish moved from 152-991 meters (mean = 508 meters).

I analyzed seven mark/recapture model combinations (Table 4). Based on $\Delta AIC_c$ values, the most parsimonious top model included capture and survival probability that varied by group with a constant transition probability structure [i.e., $s(g) \, p(g) \, \psi(.)$]. The top-ranking model provided plausible estimates of survival and capture probability for both brook trout and cutthroat trout, and accounted for 66% of the Akaike weights. The next three models accounted for 13%, 10%, and 10% of the Akaike weights, respectively. Transition probability could not be estimated for brook trout with any model, as no brook trout transitioned amongst strata. Estimates of cutthroat trout transition probability were very low in all four top-ranking models, as only two out of 291 cutthroat trout
transitioned amongst strata. Of the two cutthroat trout that moved amongst strata, one was initially captured in stratum A during index site sampling in July, 2006 and was recaptured in stratum C during spot electrofishing in September, 2007, for a total downstream movement of approximately 12.15 km. The other cutthroat trout was initially captured in stratum C during index site sampling in July, 2006, and was recaptured in stratum D during index site sampling in July, 2007, for a total downstream movement of approximately 6.37 km. The top ranking model did not plausibly estimate brook trout or cutthroat trout survival for most strata. Capture probability was higher for cutthroat trout than for brook trout in all four strata.

Table 4. Rankings of seven multi-strata mark/recapture models of survival (Φ), capture (p), and transition (ψ) probabilities for brook trout and cutthroat trout in the Mill Creek watershed based on program MARK output and AIC selection criteria, where AICc= corrected Akaike’s information criterion, NP = number of parameters, (g) = grouped parameters, and (.) = constant parameters.

<table>
<thead>
<tr>
<th>Model</th>
<th>AICc</th>
<th>ΔAICc</th>
<th>AICc weight</th>
<th>Model likelihood</th>
<th>NP</th>
<th>Deviance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ(g), p(g), ψ(.)</td>
<td>870.20</td>
<td>0</td>
<td>0.659</td>
<td>1</td>
<td>24</td>
<td>290</td>
</tr>
<tr>
<td>Φ(.), p(g), ψ(.)</td>
<td>873.41</td>
<td>3.21</td>
<td>0.132</td>
<td>0.2005</td>
<td>22</td>
<td>297</td>
</tr>
<tr>
<td>Φ(.), p(.), ψ(.)</td>
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<td>3.68</td>
<td>0.105</td>
<td>0.1591</td>
<td>20</td>
<td>302</td>
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<tr>
<td>Φ(g), p(.), ψ(.)</td>
<td>873.89</td>
<td>3.69</td>
<td>0.104</td>
<td>0.1583</td>
<td>22</td>
<td>298</td>
</tr>
<tr>
<td>Φ(g), p(.), ψ(g)</td>
<td>886.75</td>
<td>16.56</td>
<td>0.000</td>
<td>0.0003</td>
<td>28</td>
<td>297</td>
</tr>
<tr>
<td>Global (no group effects)</td>
<td>887.28</td>
<td>17.08</td>
<td>0.000</td>
<td>0.0002</td>
<td>32</td>
<td>289</td>
</tr>
<tr>
<td>Φ(.), p(g), ψ(g)</td>
<td>898.38</td>
<td>28.18</td>
<td>0</td>
<td>0</td>
<td>35</td>
<td>293</td>
</tr>
</tbody>
</table>
DISCUSSION

Based on watershed and reach-scale surveys, brook trout distribution and establishment appeared to be limited by precipitous increases in stream slope in both Mill Creek and Deadman Creek. In Mill Creek, brook trout abundance increased in an upstream direction, but the upstream extent of brook trout establishment then terminated abruptly upstream of the Mill Creek middle index site. Within that same area, stream slope increased from approximately 0.027% to 0.046%. In addition, patch occupancy surveys suggest that brook trout were abundant just upstream of the Mill Creek middle index site, but were sparsely distributed near the Mill Creek high index site. With one exception (see Deadman Creek below), at the lower reaches of all tributaries, stream slopes exceeded those of most areas of brook trout establishment in this drainage.

A similar pattern persisted in Deadman Creek, where again, brook trout establishment ended at a point of a precipitous increase in stream slope. Therefore, the pattern of brook trout distribution and establishment observed here suggests that steep stream slopes in the upper reaches of Mill Creek and its tributary confluences may limit additional brook trout invasion and establishment.

Species segregation along a streams longitudinal gradient is not unique to this watershed (Rieman et al. 2006), and many studies have investigated the potential effect of stream slope on salmonid distribution (Chrisholm and Hubert 1986; Fausch 1989; Hilderbrand 1998; Isaak and Hubert 2000; Hicks and Hall 2003). Findings by Hilderbrand (1998) and Fausch (1989), for example, suggest that brook trout perform better in lower slope (< 3%) stream reaches, and struggle to establish populations in
streams that exceed 4-7%. Additional studies suggest that higher slope stream reaches limit brook trout abundance (Chisholm and Hubert 1986; Kozel and Hubert 1989; Bozek and Hubert 1992), potentially limiting successful establishment in some areas. These findings are consistent with this study, as areas of brook trout establishment in the Mill Creek watershed ranged from 0.02% to 6% in stream slope, but averaged only 2%.

Fausch (1989) hypothesized that brook trout are weaker swimmers compared to other salmonids, making it difficult for brook trout to ascend steep stream slopes (but see Adams et al. 2000). In addition, other habitat variables that are associated with steep stream slope (e.g., low water temperature) may pose demographic challenges to brook trout by limiting spawning, recruitment, and survival (Fausch 1989), and thus the potential for successful establishment in some areas.

Based on Utah Division of Wildlife Resources stocking records, brook trout were first introduced into this system in 1948, with eight additional stocking events that occurred between 1949 and 1966. The precise locations of these introductions are not known, but given the absence of public property near the lower portions of the watershed and poor vehicle access in the upper portions of Mill Creek, most fish were probably stocked at the road crossing near the Mill Creek middle index site. Despite the close proximity of those introductions to the confluences of North Fork and McKenzie Creek, as well as the upper portions of Mill Creek, brook trout have not become established in those areas. During patch occupancy surveys, only three brook trout were captured upstream of the apparent stream slope barrier in Mill Creek, and all were large adults (172-226) in good condition (mean Fulton’s K=1.25; Anderson and Newman 1996).
These findings suggest brook trout can ascend steep slopes in this watershed, and are consistent with the findings of Adams et al. (2000) who observed brook trout ascending stream slopes as steep as 22%. However, the ability of few brook trout to ascend the apparent stream slope barrier does not indicate successful invasion of those areas.

Given the length of time since brook trout were initially introduced into this system, the close proximity of those introductions to the upper portions of Mill Creek and its tributaries, and the paucity of brook trout above the apparent stream slope barrier, it appears local conditions in the upper portions of this watershed have limited successful establishment, and therefore successful invasion of those areas. While stream gradient appears to be the factor that limits the upstream distribution of brook trout in this system, smaller-scale factors that are associated with steep stream gradient may be more influential in determining brook trout distribution and establishment in this watershed. Given the large size (i.e., absence of sub-adult fish) and good condition of the few fish captured above the apparent stream slope barrier, it appears that brook trout experience poor spawning and/or recruitment success in the upper portions of Mill Creek, thereby limiting successful invasion of those areas by brook trout. Therefore, factors that are known to be influential in the early life-history of salmonids, such as water temperature and groundwater discharge (see below), may limit brook trout invasion in this system.

While stream slope, or environmental attributes associated with steep stream slope, appeared to influence watershed-scale brook trout distribution, additional factors appeared to influence brook trout abundance at the reach-scale, and therefore successful establishment in some areas. Based on model relationships, invertebrate abundance
appeared to be influential in determining brook trout abundance; a quadratic model was positively related to brook trout abundance and had the highest explanatory power of all models. However, two data points were highly influential in determining the curvilinear relationship, and both of those data points were from the Deadman Creek middle index site, where brook trout were the most abundant and aquatic invertebrates were the least abundant. While upon first examination, this relationship may make little biological sense, it is possible that invertebrate abundance in the Deadman Creek middle index site was low because brook trout abundance was high, as there were more fish present to consume invertebrate taxa and reduce invertebrate abundance (Bechara et al. 1993; Flecker and Townsend 1994; Huryn 1996). In addition, the Deadman Creek low and high index sites, which are located just upstream and downstream of the middle index site, contained among the highest densities of aquatic invertebrates, and brook trout abundance was markedly lower at both index sites compared to the middle index site, further suggesting that brook trout reduced the abundance of aquatic invertebrates in the middle index site. Finally, the data from all other index sites (i.e., excluding Deadman Creek middle) best represented a positive linear relationship between brook trout abundance and aquatic invertebrate abundance, suggesting that indeed, invertebrate abundance may influence brook trout abundance in this watershed.

Despite the potentially confounding effects of other factors, a positive relationship between invertebrate abundance and trout biomass has also been observed in other systems (Murphy et al. 1981; Bowlby and Roff 1986; Jowett 1992; VanDusen et al. 2005). In fact, Bowlby and Roff (1986) and Jowett (1992) modeled the effects of
multiple biotic and abiotic variables simultaneously, and both studies concluded that invertebrate abundance is among the most important factors influencing the biomass of stream-dwelling salmonids, further suggesting that invertebrate abundance may influence brook trout abundance in this watershed. However, while invertebrate abundance may influence brook trout abundance in this watershed, this factor alone cannot fully explain why brook trout were so abundant in the Deadman Creek middle index site compared to other areas in the watershed.

Of the remaining variables evaluated, the abundance of fine substrate material (i.e., percent fines) appeared to positively influence brook trout abundance as well. However, it appears that again, two data points were highly influential. Both influential data points were from the Deadman Creek low index site where the substrate was composed of a much higher percentage of fine material relative to the other index sites, and brook trout were detected only twice during this study and at very low abundance both times. When those data points were excluded from the analysis, the linear model was highly significant (p-value=<0.001) with reasonable model fit (r²=0.579). Nevertheless, in this watershed the abundance of fine substrate material was positively related to brook trout abundance, regardless of the model.

This relationship may not make biological sense, as increased fine substrate material is often associated with low trout biomass. Some studies suggest that abundance of fine substrate material negatively affects salmonid reproduction by reducing the rate of intergravel flow, thereby reducing the levels of dissolved oxygen delivered to developing embryos (Waters 1995). Hall (1986) and Tagart (1984) both report an inverse
relationship between survival of salmonid eggs and abundance of percent fines, observing minimal survival when the percent of fine substrate material was greater than 10% and 20%, respectively. Percentage of fine substrate material in Deadman Creek exceeded 30% during all sample periods. In fact, in the Deadman Creek middle index site where brook trout were the most abundant, the percent of fine substrate material far exceeded detrimental levels during all sample periods (mean = 41%, range = 34-47%).

In addition to the detrimental effects of fine sediment abundance on early life stages of salmonids, excess levels can also negatively affect aquatic invertebrate communities, the primary forage for stream-dwelling salmonids. More specifically, by altering substrate composition, excess fine substrate material can decrease aquatic invertebrate standing stock and alter invertebrate community structure (see Lenat et al. 1979). These findings suggest that fine substrate material may not influence brook trout abundance at the reach-scale in this watershed.

Of the remaining explanatory variables evaluated, minimum, mean, and median annual water temperatures were related to brook trout abundance. In this watershed, the distribution of water temperature is skewed towards cooler temperatures, as cold winter periods are prolonged and warm summer periods are protracted. These data suggest that cold winter water temperatures may negatively influence brook trout abundance. The effects of winter stream conditions on salmonid habitat selection and movement have been firmly established (Chrisholm et al. 1987; Lindstrom and Hubert 2004), and in addition, some authors have linked (Reiser and Wesche 1979; Wood 2008) or postulated a link (Harshbarger and Porter 1979; Wiley et al. 1993) between low early life-history
survival rates of fall spawning salmonids (e.g., brook trout), and cold winter water
temperature. Those studies suggest that eggs that are deposited in the fall rather than
spring or summer are exposed to harsh winter conditions (e.g., anchor and frazile ice)
shortly after deposition. In the Mill Creek study area, it appears that water temperatures
were below freezing for extended periods during the winter at most index sites, excluding
the Deadman Creek middle index site during 2006. These data suggest that warm winter
water temperatures in the Deadman Creek middle index site may positively influence
early life-stage survival of brook trout.

The stream channel at the Deadman Creek middle index site was narrow and
deeply incised, and riparian vegetative cover was dense relative to channel width. These
conditions may have facilitated snow-bridging during winter months, thereby insulating
the stream channel and recently deposited brook trout eggs from harsh winter conditions
(Chisholm et al. 1987). Conversely, at North Fork and some areas of Mill Creek, the
stream channel was shallow and wide, and riparian vegetation was less dense in relation
to its channel width, leaving those stream channels exposed to harsh winter conditions.
The formation of anchor ice occurred in some areas of Mill Creek as early as mid-
November, while in Deadman Creek anchor ice was comparatively absent. While winter
stream conditions were not a focus of this study, field observations suggest that anchor
ice did not form in all areas of this drainage, perhaps a result of groundwater discharge
(Prowse 1994). In the midst of harsh winter conditions, brook trout as well as other fall-
spawning salmonids can spawn successfully in areas of groundwater upwelling (Webster
and Eiriksdottir 1976; Curry and Noakes 1995; Baxter and Hauer 2000). However, like
other stream systems (e.g., Baxter and Hauer 2000), these areas of upwelling may be patchily distributed throughout the Mill Creek watershed, a factor that may explain, in part, the patchy distribution and abundance of brook trout throughout this system.

Cutthroat trout were widely distributed throughout the watershed making it difficult to elucidate the factors that limit their watershed-scale distribution and reach-scale abundance, if any. All significant models explained little variation in cutthroat trout abundance, making it difficult to determine with a high degree of confidence, the variables that influence cutthroat trout abundance at the reach-scale. Given the high abundance of cutthroat trout in this watershed compared to other streams within its historical range, this result is not surprising, as Mill Creek and its tributaries likely represent high quality, suitable habitats for Bonneville cutthroat trout.

However, it does appear that extreme levels of stream slope (>10%) may limit cutthroat trout distribution in this system, and in some cases, upstream cutthroat trout distribution was limited only when tributaries became intermittent. Other research suggests that Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*) rarely occur in stream reaches that exceed 10% (Kruse et al. 1997), however; Lohantant cutthroat trout (*Oncorhynchus clarkii henshawi*) can occupy stream reaches as steep as 26% (Dunham et al. 1999). Stream slope tolerance is not well studied for Bonneville cutthroat trout, but based on research of other closely related subspecies, it is possible that cutthroat trout distribution in this watershed could transcend stream slopes that exceed 10%, given adequate in-stream flows.
Despite the patchy abundance and limited distribution of brook trout in this watershed, movement dynamics can facilitate their continued upstream invasion by providing source populations from areas with suitable spawning and rearing habitats (Peterson and Fausch 2003; Peterson et al. 2004; Benjamin et al. 2007). In this study, I evaluated population-level movement dynamics to determine if areas of core brook trout occupancy were connected through movement. My results suggest that few brook trout move long distances in this watershed, as no brook trout were observed moving from one stratum to another. In addition, a relatively high percentage (74%) of brook trout were recaptured at their initial capture location, indicating high site fidelity. Finally, of the brook trout that were captured outside their initial capture location, but within the same stratum as their initial capture location, all had moved relatively short distances (mean=247 meters).

Salmonid movement, and in particular brook trout movement is well studied, but divisive contradictions exist amongst researchers (Gowan et al. 1994; Gowan and Fausch 1996). Gowan et al. (1994) reviewed the extensive literature that studied salmonid movement and concluded that most stream-dwelling salmonids are sedentary, later coining the term, “restricted movement paradigm”. These findings were consistent with the restricted movements of fish first described by Gerking (1959). However, subsequent research by Gowan and Fausch (1996) urged a reconsideration of this paradigm, suggesting that sampling bias is responsible for the observed patterns of restricted movement amongst many studies. To date, refuting studies report that brook trout are largely sedentary (i.e., typical movement <1.61-river kilometers; Shetter 1968), or highly
mobile (Riley et al. 1992). However, it may be misleading to describe a population as entirely sedentary or entirely mobile. Some studies suggest that seasonal variations in movement amongst stream dwelling salmonids exists, and populations contain primarily sedentary individuals, with few individuals moving over long distances (Hilderbrand and Kershner 2000). While these contradictions have not been resolved, movement patterns across populations appears variable, and are likely influenced by both environmental factors and life-history characteristics (Lindstrom and Hubert 2004; Diana et al. 2004; Colyer et al. 2005), suggesting that movement is dependant upon local conditions. When compared to other studies, movement of brook trout in this watershed was primarily, if not entirely restricted, as no individuals were observed moving over long distances (i.e., >1.61-river kilometers). While sampling bias may have played a role in these findings (see Gowan and Fausch 1996), the high rate of site fidelity and short distance of movement amongst recaptured brook trout in this study is compelling evidence that brook trout movement was restricted.

In contrast, cutthroat trout movement was more variable, as two individuals were observed moving amongst strata and both fish moved considerably long distances (12.15 km and 6.37 km). However, based on transition probabilities attained from my top mark/recapture model, the overall probability of cutthroat trout movement amongst all strata remained low. The five cutthroat trout captured outside of their initial capture location, but within the same stratum, moved longer distances on average (508 meters) than brook trout (247 meters). However, I recaptured 92% of cutthroat trout at their initial capture location, indicating relatively high site fidelity by many individuals within
this population (but see Budy et al. 2007). Overall, it appears that cutthroat trout in this watershed moved more often and over longer distances than brook trout; however, the spatial-scale of cutthroat trout movement in this watershed remains minimal compared to similar systems (Hilderbrand and Kershner 2000; Colyer et al. 2005).

Financial and logistic restraints precluded the evaluation of all explanatory variables for all sample periods. As a result, my dataset contained missing observations for some explanatory variables, making more rigorous statistical testing (e.g., multiple regression and model selection techniques) impossible. Nevertheless, I provide evidence of the factors that influence brook trout and cutthroat trout distribution and abundance at multiple spatial scales. Additional research should further investigate the affects of low winter water temperature on brook trout egg and fry survival in this watershed, given fine-scale heterogeneity in habitats. Finally, the temporal-scale of this movement study, from late-spring to early-fall, may not have adequately assessed spawning migrations. Despite these limitations, I observed a relatively high rate of sight fidelity by both species, and movement patterns did not appear to facilitate additional upstream invasion by brook trout, nor limit watershed-scale cutthroat trout movement.

The results of this study will aid in prioritizing management actions for cutthroat trout in this watershed. More specifically, continued upstream invasion by brook trout does not pose an immediate threat to cutthroat trout in the headwater portions of Mill Creek or Deadman Creek, as local conditions appear to limit brook trout invasion of those areas. Based on those findings, the use of artificial barriers to prevent additional upstream brook trout invasion is not necessary in this watershed. In addition, I observed
some cutthroat trout moving long distances in this watershed, therefore; the use of artificial barriers could impede watershed-scale cutthroat trout movement and hinder their natural dispersal and migration patterns (Peterson et al. 2008). Finally, if resource managers decide to eradicate brook trout from this system, my species distribution and establishment data will help identify and prioritize areas where those projects should occur.

In conclusion, the results from this study suggest that stream slope, or smaller-scale factors associated with stream slope, limits the upstream distribution of brook trout at the watershed-scale, and aquatic invertebrate abundance and low winter water temperatures influence the magnitude of brook trout abundance at the reach-scale. Within this watershed, brook trout movement appeared minimal overall, as I observed relatively high site fidelity and no movement across strata. I could not explain the variation in cutthroat trout abundance at the reach-scale based on the explanatory variables I measured, but given the high abundance of cutthroat trout in this watershed relative to other historically occupied habitats, this system likely represents high quality habitat for cutthroat trout. In addition, while small-scale cutthroat trout movement was more variable than that of brook trout, few individuals within the population moved long distances. These results provide resource managers with critical demographic data and information describing the invasion potential of a ubiquitous and often aggressive nonnative species. Mill Creek contains one of the largest remaining genetically pure metapopulations of Bonneville cutthroat trout. Protection of this metapopulation is
critical for the future persistence of this subspecies, and the results of this study aid in prioritizing cutthroat trout management actions in this watershed.
REFERENCES


Fausch, K.D. 1989. Do gradient and temperature affect distributions of, and interaction between, brook charr (Salvelinus fontinalis) and other resident salmonids in streams? Physiology and Ecology Japan Special Volume 1: 303-332.


APPENDICES
APPENDIX A
Table A.1. Input file for multi-strata mark-recapture model in Program MARK, including unique fish ID and capture history (stratas A-D) for each recaptured cutthroat trout (1 0) and brook trout (0 1).

/* 087C518D */  AA0A00  1  0 ;
/* 087C518A */  A00000  1  0 ;
/* 087C518E */  A00000  1  0 ;
/* 087C518F */  A00000  1  0 ;
/* 087C5191 */  AA0000  1  0 ;
/* 087C5192 */  A00000  1  0 ;
/* 087C5193 */  AA0000  1  0 ;
/* 087C5190 */  AA0000  1  0 ;
/* 087C5195 */  AA0000  1  0 ;
/* 087C518C */  AA0A00  1  0 ;
/* 087C5108 */  0A0AA0  1  0 ;
/* 087C5107 */  0A0A00  1  0 ;
/* 0876472A */  00AA00  1  0 ;
/* 08764723 */  000AA0  1  0 ;
/* 08764724 */  000A00  1  0 ;
/* 0876472B */  000AA0  1  0 ;
/* 087643F8 */  0000A0  1  0 ;
/* 087643F7 */  0000A0  1  0 ;
/* 087643F9 */  0000A0  1  0 ;
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/* 087C511F */  0C0000  1  0 ;
/* 08764726 */  000C00  1  0 ;
/* 08764728 */  000CC0  1  0 ;
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/* 087C5185 */  A00A00  1  0 ;
/* 087C517F */  A00000  1  0 ;
/* 087C5182 */  A0000C  1  0 ;
/* 087C5184 */  A00000  1  0 ;
/* 087C516C */  A00000  1  0 ;
/* 087C516D */  A00000  1  0 ;
/* 087C5181 */  A00A00  1  0 ;
/* 087C5197 */  A00000  1  0 ;
/* 087C5187 */  A00000  1  0 ;
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/* 087C511A */  0A0000  1  0 ;
/* 0876471F */  000A00  1  0 ;
/* 08764729 */  000A00  1  0 ;
/* 08764722 */  00AA00  1  0 ;
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/* 087C5142 */  CC0000  1  0 ;
/* 087C513D */  CC0000  1  0 ;
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/* 0876471C */ 000D00 0 1 ;
/* 087643D0 */ 000D00 0 1 ;
/* 087643D4 */ 000D00 0 1 ;
/* 08764734 */ 00D000 0 1 ;
/* 08764732 */ 00D000 0 1 ;
/* 08764730 */ 00D000 0 1 ;
/* 0876472E */ 00D000 1 0 ;
/* 0876472F */ 00D000 1 0 ;
/* 0876472D */ 00D000 1 0 ;
/* 087643A1 */ 00C000 1 0 ;
/* 08764733 */ 00C000 1 0 ;
/* 0876472C */ 00C00C 1 0 ;
/* 0876471D */ 00C000 1 0 ;
/* 087643BE */ 00C000 1 0 ;
/* 0876472F */ 00C000 1 0 ;
/* 08763948 */ 00C00C 0 1 ;
/* 087643C1 */ 00C000 1 0 ;
/* 08763946 */ 00C000 1 0 ;
/* 08763943 */ 00C00C 0 1 ;
/* 08763952 */ 00C000 0 1 ;
/* 0876392B */ 00C000 0 1 ;
/* 087643C2 */ 00C000 1 0 ;
/* 0876392E */ 00C000 1 0 ;
/* 087643C3 */ 00D000 1 0 ;
/* 08764731 */ 00D000 0 1 ;
/* 087643A2 */ 00C000 1 0 ;
/* 08764735 */ 00C000 1 0 ;
/* 08764720 */ 00C000 1 0 ;
/* 087643BC */ 00C000 1 0 ;
/* 0876394A */ 00C000 1 0 ;
/* 08763930 */ 00C000 1 0 ;
/* 08763930 */ 00C00C 1 0 ;
/* 0876393B */ 00C00C 0 1 ;
/* 0876396B */ 00C000 0 1 ;
/* 08764731 */ 00D000 0 1 ;
/* 08763946 */ 00D000 0 1 ;
/* 0876393C */ 00D000 0 1 ;
/* 0876395B */ 00D000 1 0 ;
Table A.2. Minimum, mean, median, and maximum percent slope values at all stream reaches that contained brook trout (BKT) and Bonneville cutthroat trout (BCT) during patch occupancy sampling.

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>Minimum % Slope</th>
<th>Mean % Slope</th>
<th>Median % Slope</th>
<th>Maximum % Slope</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deadman Creek</td>
<td>0.013</td>
<td>0.028</td>
<td>0.027</td>
<td>0.060</td>
<td>BKT</td>
</tr>
<tr>
<td>Mill Creek</td>
<td>0.002</td>
<td>0.017</td>
<td>0.016</td>
<td>0.046</td>
<td>BKT</td>
</tr>
<tr>
<td>Carter Creek</td>
<td>0.029</td>
<td>0.051</td>
<td>0.047</td>
<td>0.092</td>
<td>BCT</td>
</tr>
<tr>
<td>Christmas Tree Creek</td>
<td>0.022</td>
<td>0.039</td>
<td>0.034</td>
<td>0.089</td>
<td>BCT</td>
</tr>
<tr>
<td>Deadman Creek</td>
<td>0.013</td>
<td>0.030</td>
<td>0.027</td>
<td>0.064</td>
<td>BCT</td>
</tr>
<tr>
<td>McKenzie Creek</td>
<td>0.025</td>
<td>0.047</td>
<td>0.049</td>
<td>0.083</td>
<td>BCT</td>
</tr>
<tr>
<td>Mill Creek</td>
<td>0.023</td>
<td>0.023</td>
<td>0.018</td>
<td>0.060</td>
<td>BCT</td>
</tr>
<tr>
<td>North Fork</td>
<td>0.005</td>
<td>0.054</td>
<td>0.056</td>
<td>0.101</td>
<td>BCT</td>
</tr>
<tr>
<td>Unnamed Tributary 1</td>
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<td>0.057</td>
<td>0.048</td>
<td>0.099</td>
<td>BCT</td>
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</table>
Table A3. Water chemistry measurements collected along the longitudinal gradient of Mill Creek, North Fork, Deadman Creek, McKenzie Creek, and Carter Creek.

<table>
<thead>
<tr>
<th>Stream Location</th>
<th>Turbidity</th>
<th>Conductivity (ms/cm3)</th>
<th>Conductivity (ms/cm)</th>
<th>Salinity</th>
<th>pH</th>
<th>TDS</th>
</tr>
</thead>
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<td>Mill Creek High</td>
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<td>279</td>
<td>209</td>
<td>0.13</td>
<td>8.6</td>
<td>181</td>
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<tr>
<td>Mill Creek Middle</td>
<td>1.55</td>
<td>308</td>
<td>235</td>
<td>0.15</td>
<td>7.51</td>
<td>200</td>
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<td>1.19</td>
<td>286</td>
<td>274</td>
<td>0.14</td>
<td>8.72</td>
<td>0.186</td>
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<tr>
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<td>0.99</td>
<td>33</td>
<td>24</td>
<td>0.01</td>
<td>7.51</td>
<td>0.021</td>
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<td>60</td>
<td>48</td>
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<td>7.89</td>
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<td>2.53</td>
<td>60</td>
<td>60</td>
<td>40</td>
<td>6.84</td>
<td>0.035</td>
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<tr>
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<td>427</td>
<td>344</td>
<td>0.21</td>
<td>8.52</td>
<td>0.277</td>
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<td>350</td>
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<td>0.275</td>
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<td>226</td>
<td>0.1</td>
<td>7.96</td>
<td>0.058</td>
</tr>
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<td>68</td>
<td>54</td>
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<td>8.18</td>
<td>0.034</td>
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<td>7.73</td>
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</tr>
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<td>325</td>
<td>278</td>
<td>0.16</td>
<td>7.81</td>
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<td>280</td>
<td>0.16</td>
<td>7.83</td>
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</table>
Table A4. Nutrient concentrations collected at all ten index sites during August, 2006 and 2007, measured in parts per billion.

<table>
<thead>
<tr>
<th>Index Site</th>
<th>Year</th>
<th>Ammonia</th>
<th>Nitrates-Nitrites</th>
<th>Soluble Reactive Phosphorous</th>
<th>Dissolved Phosphorous</th>
<th>Total Phosphorous</th>
<th>Total Keljdal Nitrogen</th>
<th>Total Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deadman Creek High 2006</td>
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<td>8</td>
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<td>7</td>
<td>8</td>
<td>192</td>
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<td>1</td>
<td>1</td>
<td>7</td>
<td>11</td>
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<td>182</td>
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</tr>
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<td>7</td>
<td>10</td>
<td>71</td>
<td>77</td>
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<td>17</td>
<td>211</td>
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<td>9</td>
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<td>3</td>
<td>7</td>
<td>14</td>
<td>233</td>
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<td>345</td>
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<td>121</td>
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</tr>
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</table>
Table A.5. Minimum, mean, median, and maximum yearly water temperatures collected at all ten index sites during 2006 and 2007.

<table>
<thead>
<tr>
<th>Index Site</th>
<th>Year</th>
<th>Min. Temp.</th>
<th>Mean Temp.</th>
<th>Median Temp.</th>
<th>Max. Temp</th>
</tr>
</thead>
<tbody>
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<td>Deadman High</td>
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</tr>
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<td>3.61</td>
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<td>18.65</td>
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<td>2.07</td>
<td>0.43</td>
<td>15.86</td>
</tr>
<tr>
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<td>0.07</td>
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<td>0.34</td>
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* Measurements not collected
Table A.6. Substrate characteristics collected at all ten index sites during 2006 and 2007.

<table>
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<th>Sample period</th>
<th>Percent Fines</th>
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<th>D50</th>
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</tr>
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Table A.7. Stream discharge measurements collected at all ten index sites during 2006 and 2007.

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<th>Discharge (m3/s)</th>
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</tr>
<tr>
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<td>August</td>
<td>*</td>
<td></td>
</tr>
<tr>
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<td></td>
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<tr>
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<tr>
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* Measurement not collected
Table A.8. Percent stream slope values measured at all ten index sites.

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Table A9. Number of organizational taxonomic units, Shannon’s diversity index, Simpson’s diversity index, and Hill evenness calculated from all qualitative and semi-quantitative invertebrate samples at all ten index sites during 2006.

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<th>Sampling Period</th>
<th>Organizational Taxonomic Units</th>
<th>Shannon's Diversity Index</th>
<th>Simpson's Diversity Index</th>
<th>Hill Evenness</th>
<th>Total Invert. Abundance</th>
<th>EPT Taxa Abundance</th>
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Table A.10. Conductivity, pH, and turbidity measurements at all ten index sites during 2006 and 2007.

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<th>Conductivity (μ/cm)</th>
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<th>Turbidity (NTU)</th>
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Figure B.1. Map of the Mill Creek watershed located in northern Utah.
Figure B.2. Map of the Mill Creek watershed, with watershed-scale water chemistry sampling locations marked by shaded circles.
Figure B.3. Map of the Mill Creek watershed with the locations of ten permanent index sites marked by shaded circles.
Figure B.4. Map of the Mill Creek watershed with two-way weir trap locations marked by shaded circles.
Figure B.5. Map of the Mill Creek watershed with the locations of four mark/recapture stratum marked by ovals. Letters within each stratum indicate the unique stratum identification.
Figure B.6. Brook trout and cutthroat trout abundance (number of fish per hectare) at all ten index sites during July and August, 2006. Error bars represent 95% confidence intervals.
Figure B.7. Brook trout and cutthroat trout abundance (number of fish per hectare) at all ten index sites during July and August, 2007. Error bars represent 95% confidence intervals.