

LIMITING FACTORS FOR TROUT POPULATIONS
IN THE UPPER CLARK FORK RIVER
SUPERFUND SITE, MONTANA

by

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ABSTRACT

Large-scale heavy metal contamination of the upper Clark Fork River from mining deposits has created significant damage to aquatic habitat in the drainage. Trout are present in the system, although with abundances lower than expected. The objectives of this study were to identify critical habitat areas and to identify conditions that continue to limit both native and nonnative trout populations, with the focus of the study on the lingering environmental effects caused by high heavy metal concentrations. A radiotelemetry study, with 256 tagged brown trout *Salmo trutta*, westslope cutthroat trout *Oncorhynchus clarkii lewisi*, and cutthroat/rainbow hybrid trout, was conducted from 2009 to 2011. The radiotelemetry relocation data was used to determine temporal and spatial patterns in movement and survival rates in relation to heavy metals and other environmental factors, and to identify critical habitat areas (e.g., spawning locations and overwintering areas). Brown trout spawning occurred in numerous tributaries throughout the basin and in the upper reaches of the mainstem. Cutthroat trout spawned only in tributaries, and these tributaries were often smaller and more degraded by land use practices than brown trout spawning tributaries. Multistate mark-recapture survival analysis estimated that survival is lowest in the stream segment with the greatest amount of heavy metal contamination; the weekly likelihood of survival was estimated at 0.97 (95% confidence interval 0.97 – 0.98) for brown trout and 0.90 (95% confidence interval 0.84 – 0.97) for cutthroat trout. Additionally, weekly survival estimates for cutthroat trout in tributaries was also low (0.92; 95% confidence interval 0.87 – 0.94), likely because of anthropogenic land use pressures. Very limited movement was observed, except in relation to spawning migrations. Cutthroat trout moved greater distances and at a higher rate than brown trout. The results from this study indicate that the remaining mining contamination continues to reduce trout survival rates throughout the basin and should be removed in order to increase trout densities. Additionally, restoration priority should be placed on tributaries that are negatively affected by land use pressures.

CHAPTER 1

INTRODUCTION

Mining and Aquatic Systems

Mining-related water pollution is one of the most detrimental and persistent effects of anthropogenic activities on aquatic environments (Nelson et al. 1991; Phillips and Lipton 1995; Woody et al. 2010). In the United States alone, over 240,000 km² of land have been or are currently being mined, an area similar in size to the state of Oregon (Luoma et al. 2008). It is estimated that 40% of headwater streams in the western United States are polluted from active and abandoned mining operations and the estimated cost of remediation exceeds \$35 billion dollars (USEPA 2000). Waste materials from mining can cause extensive sedimentation and channel alteration, negatively affecting spawning and other critical habitats (Lewis and Burraychak 1979; Nelson et al. 1991; Phillips and Lipton 1995). The input of large quantities of toxic heavy metals has also had significant, long term detrimental effects on water quality, fish populations, and aquatic food webs over extensive areas (Nelson et al. 1991; Phillips and Lipton 1995). Many of the U.S. Environmental Protection Agency (EPA) designated Superfund sites are former mine sites, including the upper Clark Fork River in southwestern Montana, the largest Superfund site in the United States.

Mining in the Upper Clark Fork River

Mining began in Butte, Montana in 1864, for small placer deposits of gold (Luoma et al. 2008), but later shifted to copper, in response to the increased demand for electrical wiring (Phillips and Lipton 1995). Mining increased dramatically in the 1880s, and by 1955, large open-pit mines had replaced most of the small-scale placer deposit mining operations (Luoma et al. 2008). In 1908, a 100-year flood event deposited an estimated 99.8 billion kg of contaminated mining waste into the Clark Fork River basin (Andrews 1987). Settling ponds were constructed beginning in 1911, near the town of Warm Springs, as a way to collect and settle out contaminated tailings from Silver Bow Creek, the primary headwater tributary that runs through the city of Butte before entering the Clark Fork River. Improvements on the ponds systems continued until 1959, when a liming system was installed as a way to further trap the hazardous cationic metals (Phillips and Lipton 1995).

The deposition of mining waste had negative consequences on the environmental quality of the Clark Fork River. As early as 1891, fish seining surveys near Deer Lodge concluded that the river was too polluted to contain any fish (Phillips and Lipton 1995). In 1950, the state of Montana conducted electrofishing surveys on the river near the town of Garrison and found that there were no fish present in the river (Phillips and Lipton 1995). More comprehensive surveys were completed in 1957 and it was determined that the entire river from Rock Creek, near Missoula, to the headwaters, near Warm Springs, a distance of 160 km, was too polluted to sustain a fishery (Phillips and Lipton 1995). Improvements in wastewater treatment led to a recovery in fish populations in the

mainstem in the 1970s, from Warm Springs to Missoula, with the fish assemblage primarily consisting of nonnative brown trout *Salmo trutta*, although fish kills were still observed into the 1990s (Phillips and Lipton 1995). Fish kills have often occurred in conjunction with summer thunderstorms, when high discharge events cause the settling ponds to overflow and/or mobilization of contaminated soils from the floodplain (Phillips and Lipton 1995; Luoma et al. 2008).

In 1983, the EPA placed the Clark Fork River/Silver Bow Creek area on the Superfund list, a list of hazardous waste sites that pose a particularly significant threat to human and environmental health (Phillips and Lipton 1995). The EPA found that in the upper 60 km of the watershed, Clark Fork River floodplain sediments contained 1000 times greater concentration of copper than tributaries in the basin (Luoma et al. 2008). Since 1990, the state of Montana, through the Natural Resource Damages Program (a division of the Montana Department of Justice), has been receiving monetary settlements from the Atlantic Richland Company, and the money being used for remediation of the area, including removal of contaminated sediments, revegetation of stream banks, construction of berms to reduce flood-related metals contamination, and improvement of the liming facilities at the Warm Springs Ponds (Phillips and Lipton 1995; Luoma et al. 2008).

Restoration efforts that occurred in the 1990s (removing tailings and building berms immediately downstream of the Warm Springs Ponds) have been partially successful. Hornberger et al. (2009) reported that long-term concentrations of copper, the heavy metal that is present at the greatest concentrations relative to toxicity (Phillips and

Lipton 1995) in streamside sediments, the water column, and accumulated in *Hydropsyche* (caddisfly) species had declined more than 50% in remediated areas. However, the liming in the settling ponds may also be creating some unanticipated consequences. For example, liming reduced the amount of cationic metals present in the surface water (copper, cadmium, lead, and mercury), but anionic metal concentrations (arsenic) have increased. As a result, arsenic levels in surface water and in *Hydropsyche* increased 300% from 2002 to 2004 (Hornberger et al. 2009).

Heavy Metal Effects on Fish

Heavy metal contamination affects fish at multiple levels of biological organization (Lipton et al. 1995; Louma et al. 2008). At the individual level, chronic physiological effects of heavy metal exposure include reduced feeding, contamination of food sources, poor food assimilation, and reduced growth at even relatively low concentrations (Nelson et al. 1991; Woodward et al. 1995a; Farag et al. 2000). Behavioral avoidance of contaminated water also occurs at levels well below EPA established acute concentration levels (USEPA 1986; Woodward et al. 1995b; Goldenstein et al. 1999; Svecevicus 2001), causing distinct shifts in distribution (Goldenstein et al. 1999). Fish assemblages can change after mining because of differences in physiological sensitivities and behavioral avoidance thresholds to heavy metals at the species level. For example, in the western United States, nonnative brown trout are less sensitive to heavy metal contamination than cutthroat trout (*Oncorhynchus clarkii*) and rainbow trout (*O. mykiss*) and this variable sensitivity has led to a shift

toward brown trout dominance in mining-contaminated systems (Marr et al. 1995; Hansen et al. 1999).

Currently both native (westslope cutthroat trout *O. clarkii lewisi* and bull trout *Salvelinus confluentus*) and nonnative (brown trout and rainbow trout) trout are present in the upper Clark Fork River, but population estimates suggest that trout density is less than 10% of the expected abundance when compared to uncontaminated reference reaches. Brown trout dominate the salmonid assemblage (Lipton et al. 1995). Trout density is not uniform throughout the river, however, in some reaches trout density is more than half of the density found in reference reaches (reaches 1, 5, 6, and 13) (Figure 1.1), which may indicate that heavy metal contamination may not be the sole limiting factor for trout populations in the upper Clark Fork River. Additionally, some reaches have less than 10% of reference reach density, potentially because of higher heavy metal concentrations (reaches 2 and 4) or other low-quality trout habitat characteristics (reaches 10 and 11). Trout densities in reach 1 have significantly declined since the early 1990's population surveys (J. Lindstrom and B. Liermann, Montana Fish, Wildlife, and Parks, personal communication).

Study Questions

Large-scale remediation (removal of tailings, stream bank stabilization, and revegetation) of the entire upper Clark Fork River, from the Warm Springs Ponds to the confluence with the Blackfoot River began in 2010 and is scheduled to continue until at least 2020 (Clark Fork Coalition 2011). Effective remediation of mining-impacted areas

requires information on the current status of fish populations, location of current and potential critical habitats for spawning and rearing, and the current concentrations of heavy metals and associated effect on fishes (Finger et al. 2007). In conjunction with parallel studies assessing current fish abundance, distribution, and habitat potential of tributaries (Clark Fork Coalition 2011), I sought to identify factors that continue to limit trout populations. Specifically I was interested in determining (1) the location of critical trout habitat (e.g., spawning, over-wintering, and foraging locations); (2) effects of spatial and temporal variation in dissolved copper on trout movement patterns; and (3) spatial and temporal differences in survival rates relative to differences in dissolved copper concentrations. In Chapter 2, the focus is on reach habitat characteristics and trout habitat use, selection, and avoidance of specific reaches. Additionally, in Chapter 2 trout seasonal movement is assessed and the effects of heavy metal contamination on movement and avoidance patterns are determined. In Chapter 3, multistate analysis was used to quantify radio-tagged trout survival and movement rates, in different stream segments and time periods. Recommendations for management and remediation of the upper Clark Fork River (based on all field observations and analytical results) are presented in Chapter 4. I hope to provide managers with an insight to trout critical habitat use, movement patterns, and survival rates so that remediation efforts can be successful in increasing trout populations in the upper Clark Fork River.

Figures

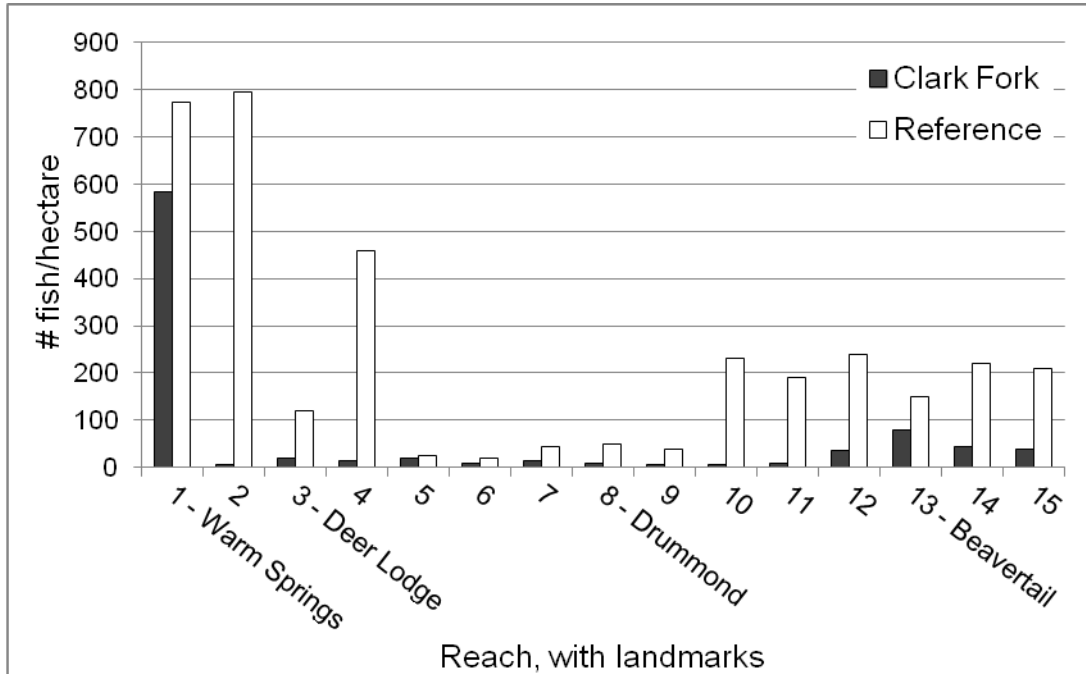


FIGURE 1.1. Mean trout density by reach, for Clark Fork River reaches and reference reaches, visually estimated from Lipton et al. 1995. Reaches were designated based on underlying geology and geomorphologic characteristics (Lipton et al. 1995). Reach 1 is the most upstream reach, just downstream of the Warm Springs Ponds; reach 15 ends near the confluence of the Blackfoot River. Reference reaches used were southwestern Montana streams with similar habitat characteristics but no mining contamination.

Literature Cited

- Andrews, E. D. 1987. Longitudinal dispersion of trace metals in the Clark Fork River, Montana. Pages 179-191 in K. C. Averett and D. M. McKnight, editors. Chemical quality of water and the hydrologic cycle. Lewis Publishers, Chelsea, Michigan
- Clark Fork Coalition. 2011. Aquatic restoration strategy for the upper Clark Fork Basin: elements of an integrated approach. Retrieved from: <http://www.clarkfork.org/programs/restore.html>
- Farag, A. M., M. J. Suedkamp, J. S. Meyer, R. Barrows, and D. F. Woodward. 2000. Distribution of metals during digestion by cutthroat trout fed benthic invertebrates contaminated in the Clark Fork River, Montana and the Coeur d'Alene River, Idaho, U.S.A., and fed artificially contaminated *Artemia*. Journal of Fish Biology 56: 173-190.
- Finger, S. E., S. E. Church, and P. von Guerrard. 2007. Potential for successful ecological remediation, restoration, and monitoring. Chapter F in Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651. S. E. Church, P. von Guerard, and S. E. Finger, eds., 2007, 1,096 p. plus CD-ROM. [In two volumes.]
- Goldenstein, J. N., D. F. Woodward, and A. M. Farag. 1999. Movements of adult Chinook salmon during spawning migration in a metals-contaminated system, Coeur d'Alene River, Idaho. Transactions of the American Fisheries Society 128: 121-129.
- Hansen, J. A., D. F. Woodward, E. E. Little, A. J. DeLonay, and H. L. Bergman. 1999c. Behavioral avoidance: possible mechanisms for explaining abundance and distribution of trout species in a metal-impacted river. Environmental Toxicology and Chemistry 18: 313-317.
- Hornberger, M. I., S. N. Luoma, M. L. Johnson, and M. Holyoak. 2009. Influence of remediation in a mine-impacted river: metal trends over large spatial and temporal scales. Ecological Applications 19: 1522-1535.
- Lewis, M. A. and R. Burraychak. 1979. Impact of copper mining on a desert intermittent stream in central Arizona: a summary. Journal of the Arizona-Nevada Academy of Science 14: 22-29.

- Lipton, J. and 16 coauthors. 1995. Aquatic resources injury assessment report: Upper Clark Fork River basin. State of Montana, Natural Resource Damage Litigation Program, Helena.
- Luoma, S. N., J. N. Moore, A. M. Farag, T. H. Hillman, D. J. Cain, and M. Hornberger. 2008. Mining impacts on fish in the Clark Fork River, Montana: A field ecotoxicology case study. Pages 779-804 in R. T. DiGuilio and D. E. Hinton, editors. The toxicology of Fishes. CRC Press, Boca Raton, Florida.
- Marr, J. C. A., H. L. Bergman, M. Parker, J. Lipton, D. Cacela, W. Erickson, and G. R. Phillips. 1995b. Relative sensitivity of brown and rainbow trout to pulsed exposures of an acutely lethal mixture of metals typical of the Clark Fork River, Montana. Canadian Journal of Fisheries and Aquatic Science 52: 2005-2015.
- Nelson, R. L., M. L. McHenry, and W. S. Platts. 1991. Mining. Pages 425-457 in W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Bethesda, Maryland.
- Phillips, G. and J. Lipton. 1995. Injury to aquatic resources caused by metals in Montana's Clark Fork River basin: historic perspective and overview. Canadian Journal of Fisheries and Aquatic Science 52: 1990-1993.
- Svecevicius, G. 2001. Avoidance response of rainbow trout *Oncorhynchus mykiss* to heavy metal mixtures: A comparison with acute toxicity tests. Bulletin of Environmental Contamination and Toxicology 67: 680-687.
- USEPA (U.S. Environmental Protection Agency). 1986. Quality Criteria for Water (EPA Gold Book). EPA 440/5-86-001. U.S. EPA, Office of Water. 1986.
- USEPA. 2000. Liquid assets: America's water resources at a turning point. EPA-840, Washington, DC.
- Woodward, D. F., A. M. Farag, H. L. Bergman, A. J. DeLonay, E. E. Little, C. E. Smith, and F. T. Barrows. 1995a. Metals-contaminated benthic invertebrates in the Clark Fork River, Montana: effects on age-0 brown trout and rainbow trout. Canadian Journal of Fisheries and Aquatic Science 52: 1994-2004.
- Woodward, D. F., J. A. Hansen, H. L. Bergman, E. E. Little, and A. J. DeLonay. 1995b. Brown trout avoidance of metals in water characteristic of the Clark Fork River, Montana. Canadian Journal of Fisheries and Aquatic Science 52: 2031-2037.
- Woody, C. A., R. M. Hughes, E. J. Wagner, T. P. Quinn, L. H. Roulson, L. M. Martin, and K. Griswold. 2010. The mining law of 1872: change is overdue. Fisheries 35: 321-331.

CHAPTER 2

HABITAT USE, CHARACTERISTICS, AND MOVEMENT PATTERNS OF BROWN
TROUT AND CUTTHROAT TROUT IN THE UPPER CLARK FORK
RIVER SUPERFUND SITE, MONTANA

Introduction

Mining-related water pollution is one of the most detrimental and persistent effects of anthropogenic activities on aquatic environments (Nelson et al. 1991; Phillips and Lipton 1995; Woody et al. 2010), and the estimated cost of remediation is in the billions of dollars (USEPA 2000). Waste materials from mining can cause extensive sedimentation and channel alteration, negatively affecting spawning and other critical habitats (Lewis and Burraychak 1979; Nelson et al. 1991; Phillips and Lipton 1995). The input of large quantities of toxic heavy metals has also had significant, long term detrimental effects on water quality, fish populations, and aquatic food webs over extensive areas (Nelson et al. 1991; Phillips and Lipton 1995). Many of the U.S. Environmental Protection Agency (EPA) designated Superfund sites are former mine sites, including the upper Clark Fork River in southwestern Montana, the largest Superfund site in the United States.

Heavy metal contamination affects fish at multiple levels of biological organization (Lipton et al. 1995; Louma et al. 2008). At the individual level, chronic physiological effects of heavy metal exposure include reduced feeding, contamination of

food sources, poor food assimilation, and reduced growth at even relatively low concentrations (Nelson et al. 1991; Woodward et al. 1995a; Farag et al. 2000). Behavioral avoidance of contaminated water also occurs at levels well below EPA established acute concentration levels (USEPA 1986; Woodward et al. 1995b; Goldenstein et al. 1999; Svecevicius 2001), causing distinct shifts in distribution (Goldenstein et al. 1999). Fish assemblages can change after mining because of differences in physiological sensitivities and behavioral avoidance thresholds to heavy metals at the species level. For example, in the western United States, nonnative brown trout are less sensitive to heavy metal contamination than cutthroat trout (*Oncorhynchus clarkii*) and rainbow trout (*O. mykiss*) and this variable sensitivity has led to a shift toward brown trout dominance in mining-contaminated systems (Marr et al. 1995a and 1995b; Hansen et al. 1999).

Mining contamination may also have significant effects on fluvial trout habitat use during critical periods of their life-cycle, such as spawning and overwintering periods. For example, excessive concentrations of heavy metals may become a chemical barrier, especially during migration to and from spawning areas (Goldenstein et al. 1999). Even when metal concentrations do not completely block fish passage, individuals may be exposed to toxic levels of heavy metals while migrating through areas with higher levels of contamination. This can act as a limiting factor for cutthroat trout because they spawn in spring, when high discharge events are mobilizing heavy metals from the floodplain (Luoma et al. 2008). Overwintering habitat, characterized by areas of ground water influence, is often limited in cold climates (Brown and Mackay 1995), and heavy

metal contamination may reduce access to critical overwinter trout habitat. Identifying critical habitat areas in the upper Clark Fork River and assessing potential avoidance of stream reaches is important for determining remediation priorities.

The deposition of mining waste in the upper Clark Fork River floodplain had negative effects on aquatic life; about 200 km of the river was essentially devoid of fish for many decades because of heavy metal toxicity (Phillips and Lipton 1995). Remediation efforts began in the 1950s with the installation of the Warm Springs settling ponds and continued into the 1990s with improvements to the Butte waste water treatment and small-scale removal of tailings in the uppermost five kilometers of stream (Luoma et al. 2008; Hornberger et al. 2009). Although remediation efforts did help to restore trout to the river, results from extensive surveys conducted in the 1980s and early 1990s suggested that trout densities were $< 10\%$ of uncontaminated reference streams (Lipton et al. 1995). However, very little is known about locations of critical habitats for spawning, rearing, and overwintering, nor of trout movement in relation to heavy metal contamination; such information is key as a template for effective remediation (Finger et al. 2007). Since the initial aquatic damage assessment there has been limited sampling to determine if mining contaminants continue to limit trout populations in the upper Clark Fork River.

The goal of my study was to identify critical habitat areas in the upper Clark Fork River, and to analyze movement and habitat-use patterns and how they changed through space and time. I hypothesized that trout in the upper Clark Fork River avoid areas with high copper concentrations, (e.g., the upper 60 km of river where mining tailing deposits

are still widespread; Luoma et al. 2008), and when contaminant concentrations increased (e.g., during precipitation and high stream discharge events when copper is mobilized into the water column; Luoma et al. 2008). I expected that trout would move farther during high discharge events while seeking refuge from increased heavy metal concentrations and responses would be more pronounced in cutthroat trout than brown trout.

Methods

Study Area

The study was conducted on the upper Clark Fork River, from the confluence of Silver Bow and Warm Springs creeks downriver to the confluence with the Blackfoot River (a distance of 190 km). The mainstem river was divided at major tributary junctions into three stream segments with different geomorphologic characteristics (Figure 2.1): Segment A was a 63-km-long section from near the headwaters of the Clark Fork River at Warm Springs downstream to the Little Blackfoot River confluence; Segment B was 42 km in length and was bounded downstream by the Flint Creek confluence; and Segment C was 84 km in length extending downstream to the Blackfoot River confluence.

Habitat Characteristics

In order to characterize habitat use and selection by trout on a smaller scale, segments were further divided into ten reaches ranging from 8.0 km to 29.5 km long following a similar classification made by Lipton et al. (1995) for the Upper Clark Fork

River based on differences in geologic features and the presence of major tributary junctions (Figure 2.1). Three additional reach boundaries were added; two at tributaries (Racetrack Creek and Harvey Creek) that may have effects on water quality, and one at the city of Deer Lodge because of potential anthropogenic effects on water quality.

Physical habitat characteristics of each reach were measured using a combination of field and map-based methods. Map-based metrics were calculated using existing layers in ArcMap 9.3.1 (ESRI 2009). Reach gradient was measured using digital elevation models (State of Montana, no date) to obtain elevation at the upstream and the downstream point thalweg, using a 100k named streams shapefile. Sinuosity was measured by dividing reach length by the down-valley distance (McMahon et al. 1996). A channel braiding index was obtained by dividing the total length of all stream channels in a reach by the thalweg distance along the primary channel. Mean floodplain width was estimated by measuring the width of the 50-year flood line (FEMA, no date) at 1 km intervals and then calculating the mean for each reach. Pools were ≥ 1.0 m deep and at least one stream-channel-width long (McMahon et al. 1996); depth was measured in the field using a weighted measuring tape. For each reach, pool density and mean pool depth was calculated from the field data. To quantify the extent of mining contamination, I estimated the amount of floodplain mine tailing deposits and exposed bank mine tailings using University of Montana Riparian and Wetland Survey Team data (no date). The area of streamside tailing deposits for each reach was divided by total floodplain area to obtain the percent of floodplain with tailing deposits. Total exposed bank tailing length was

divided by total bank length to estimate the percent of stream bank that contained exposed tailings.

Water Quality

Water quality was assessed for each of the three mainstem segments. Maximum dissolved copper concentration during the study time period was determined from heavy metal concentration data collected eight times per year, at various discharge levels, at three U.S. Geological Survey (USGS) gauge stations on the mainstem near Deer Lodge, Gold Creek, and Clinton (located in segments A, B, and C, respectively). Using USGS dissolved copper and discharge data, I assessed the relationship between copper concentration and discharge for each site separately using simple linear regression. The resulting regressions were used to predict the daily dissolved copper concentration for each segment. Mean dissolved copper concentrations for each segment were determined as the mean value of all the daily estimated dissolved copper concentration during the study period. Dissolved copper was the focus of water quality analysis because it is the metal which continues to be present in the greatest concentrations relative to its toxicity (Phillips and Lipton 1995). Additional synoptic water samples were collected at six sites once during January 2011, and at least monthly during spring and summer 2011. Water samples were fixed in the field with nitric acid and sent to the Montana Tech laboratory (Butte, Montana) for analysis of total recoverable arsenic, cadmium, copper, lead and zinc. Three Hydrolab water quality data loggers (Hach Hydromet, Loveland, Colorado) were also placed in the study area (one in each segment) to continuously measure water temperature from spring until fall during all three field seasons. Because 20° C has been

shown as the temperature where westslope cutthroat trout survival rate decreases significantly (Bear et al. 2007), the mean number of days that each segment exceeded 20°C was determined. The data loggers were removed during the winter to avoid damage, so winter water temperatures could not be recorded. Therefore, to assess potential availability of overwintering habitat, extent of ice cover was noted during field radiotelemetry surveys. ‘Little or no’ ice cover was defined as having surface ice covering less than 20% of the stream channel; ‘moderate’ ice cover was defined as 20-80% of the stream covered in ice, and ‘extensive’ ice cover was defined as having at least 80% ice cover.

Fish Tagging

Habitat use and movement of brown trout and cutthroat trout were assessed using radio tags. Tags were systematically distributed over the entire mainstem at an average of about 1 tag per 0.8 km, following the general distribution patterns of the two study species, although the majority of cutthroat trout caught were tagged in order to obtain a large enough sample size for analysis. Trout were captured by a boat-mounted electrofishing unit in April of 2009, 2010, and 2011. Additional fish were tagged in September 2010 in the mainstem and in two tributaries (Flint Creek, Little Blackfoot River).

Captured trout were anesthetized with tricaine methanesulfonate, identified by species, measured, and weighed. Cutthroat trout were identified as pure westslope cutthroat trout (*O. clarkii lewisi*) or hybridized with rainbow trout (*O. mykiss*) based on visual characteristics (Weigel et al. 2002). Hybrids with predominantly westslope

cutthroat trout characteristics were combined with pure cutthroat trout for analysis.

Anesthetized fish were placed into a V-shaped surgery frame and the tag was inserted into the abdomen using the shielded-needle technique (Ross and Kleiner 1982). Gills were irrigated during surgery with a bulb syringe, and the incision was closed using 2 to 3 sterile surgical staples (size 35W) or absorbing sutures (3.0 gauge), inserted approximately 1 cm apart. Following surgery, fish were placed in a live cage until they regained equilibrium (usually less than ten minutes), and were released near the point of capture.

Radio tags (Lotek Wireless, Newmarket, Ontario) weighing 8.0 g or 10.0 g in air, were implanted in adult trout (282 mm – 570 mm) so that transmitter weight did not exceed the recommended 4% of total fish body weight (Zale et al. 2005). Tags were set to a 12 hours on and 12 hour off schedule and most (67%) were equipped with mortality sensors. Transmitter frequency ranged from 148.500 to 148.560 MHz, and maximum battery life was an estimated 685 to 877 days, depending on transmitter size.

Seasonal Movement

Radio-tagged fish were relocated weekly from April 2009 to December 2011, except during January and February, when survey frequency was reduced to every other week. Fish were primarily relocated from nearby roads using a combination of a car-mounted omni-directional antenna and a directional 3-element Yagi antenna. Areas with limited road access were surveyed by boat. After detection, trout position was located by triangulation and the coordinates of the location were determined with a hand-held global positioning unit. Relocation accuracy, based on trials with dummy tags, was estimated to

be ± 100 m. Location was converted to river kilometer using ArcMap Version 9.3.1 (ESRI 2009). Time and location of mortality for trout without mortality sensor transmitters was estimated when tags were relocated in the same location for several weeks and no movement was detected when disturbed. The majority of these transmitters were recovered from carcasses, land, or relocated in bird nests, and were considered predation mortalities. Radio tags or carcasses found in irrigation ditches were considered entrainment mortalities. All other mortalities were listed as ‘unknown’.

I calculated the weekly movement rate of radio-tagged trout by dividing the total stream distance (in meters) between relocations by the number of weeks since the previous relocation. The resulting rate (m/week) represents the minimum amount of movement by a fish because it does not take into account the additional movement that a fish made between relocations (White and Garrott 1990). Because there was substantial variation in movement rates, data were log-transformed to normalize the data for analysis. Movement rates for each species were compared among seasons using Kruskal-Wallis nonparametric analysis of variance and Dunn’s multiple comparison test with Bonferroni’s confidence interval adjustment (Ramsey and Schafer 2002; Jaeger et al. 2005). Seasonal movement rates were compared by grouping weekly movement rates into four different time periods with varying hydrologic patterns: *spring* started at ice-off (mid-March) and continued to when spring run-off was almost complete (late-June); *summer* was characterized by low flow and high water temperatures and spanned from late-June to mid-September; fall was defined as the time period from mid-September until the river was ice covered (late-December), and *winter* was defined as late-December

until ice-off occurred, in mid-March. High discharge events occurred during spring run-off and from pulses related to summer thunderstorms. Discharge was generally low and stable in the fall and winter except for occasional discharge spikes occurring in fall due during infrequent rain storms.

Habitat Use

Seasonal habitat use and selection was analyzed at the reach scale to determine spatial and temporal changes in distribution. Because radio-tagged fish were not detected every week (estimated detection rate of 0.56/week for brown trout and 0.55/week for cutthroat trout; Chapter 3) and because posttagging survival varied, the number of detections for each individual were unequal, violating an assumption of habitat selection analyses (Rogers and White 2007). Therefore, to minimize bias, a relocation point for each month that a fish was alive was randomly selected for use in habitat analysis (Rogers and White 2007). In addition, because I was interested in seasonal habitat use and selection, we also combined all the years of data by season under the assumption that trout habitat use and selection exhibited similar patterns between years.

I assessed seasonal habitat selection in two ways. First, I compared seasonal relocation frequency distributions for each species to the initial tagging distribution using chi-square tests (Manly et al. 2002), with all tributary relocations combined as a single reach. Next, I calculated selection ratios separately by species and season to identify which reaches were preferred (ratio significantly > 1) or avoided (ratio < 1). Selection ratios were derived by dividing the location frequencies for each season by the expected frequency of relocations based on the initial tagging location; ratios were compared using

90% simultaneous Bonferroni confidence intervals (Manly et al. 2002; Rogers and White 2007).

Spawning Sites and Migration

Spawning sites within tributaries were identified as the uppermost location a fish traveled upstream during the spawning season. The locations classified as ‘spawning sites’ may not be the actual location a fish spawned, rather it is simply the most upstream point it was located and was used for determining spawning migration distances and amount of tributary use. For mainstem spawning, spawning location was determined as furthest location traveled by a fish from its prespawning location or where radio-tagged fish were observed within an area with active spawning redds. For brown trout, prespawning location was the primary location a fish was relocated during the summer; most brown trout remained in one location for the duration of the summer. For cutthroat trout, the prespawning mainstem location was the location where it was tagged. Because cutthroat trout were tagged in the spring after spawning migration may have begun, the total distance of cutthroat trout migration was potentially underestimated. Few cutthroat trout survived overwinter, for those individuals, prespawning location was defined as the overwintering habitat. The total number of fish tagged in the mainstem that were subsequently located in a tributary was recorded each week to assess the timing of spawning activity and tributary use throughout the study period.

To assess spawning migration distances from prespawning to spawning sites, I measured movement in three ways: 1) total distance, 2) mainstem migration, and 3) tributary migration. Total migration distance was defined as the distance from the pre-

spawning to spawning site. Mainstem migration was the total migration distance for mainstem spawning fish and, for tributary spawning fish, that portion of migration in the mainstem. Tributary migration was then calculated as the distance moved upstream to spawning sites. Finally, for each spawning tributary, I identified potential anthropogenic factors that could affect spawning success or migration access. Potential for dewatering during fall or spring spawning periods was evaluated based on the classifications described in MTFWP (2010). Location of potential sources of fish entrainment or passage barriers (low head irrigation dams, irrigation canals) was also recorded during field surveys.

Results

A total of 185 brown trout and 71 cutthroat trout were radio-tagged between April 2009 and April 2011 (Table 2.1). Radio-tagged fish were relocated from April 2009 to December 2011, with a total of 5974 relocations and a mean of 22 relocations per fish. Mean duration a fish was tracked was 24 weeks (95% confidence interval between 21 and 27 weeks), with 26 fish tracked for more than one year and five fish tracked for two or more years.

Physical Habitat Characteristics

The upper reaches of the Clark Fork River (segment A) were characterized by low gradient (2.1 - 2.2 m/km), relatively high sinuosity (sinuosity indices of 1.4 - 1.8), a wide floodplain (484 - 905 m), comparatively high pool density (2.0 - 6.1 pools/km), and shallow pools (1.3 - 1.5 m deep). In contrast, reaches in segment C generally were higher

gradient (2.1 - 3.0 m/km) with more confined floodplains (293 - 566 m), low sinuosity (sinuosity indices of 1.1 - 1.3), and generally few but deeper pools (1.0 - 2.3 pools/km with mean depths of 1.3 - 2.1 m) (Table 2.2). A key difference among segments was in the amount of mine tailings. Segment A (reaches 1-4) had exposed tailings in the floodplain (0.02% - 0.03%) and along stream banks (0.19% - 0.28%), but mine tailings progressively decreased in downstream reaches. No deposits were observed in the lowermost reaches. In winter, ice cover was extensive in segment A during both years but only moderate in segment B; there was little ice cover in segment C.

Water Quality

Dissolved copper concentration was strongly correlated with discharge in all river segments, with substantial increases in copper concentration occurring during high flow events (Figure 2.2). Generally, dissolved copper concentrations decreased progressively downstream (Table 2.3). From 2009 to 2011, the maximum observed dissolved copper value was 45.9 µg/L in segment A, a value over three times the EPA acute effect standard of 13.0 µg/L (USEPA 1986), whereas maximum values in segment B were about half this level, but still above acute levels. In contrast, in Segment C (the segment with the least amount of mining tailings) maximum dissolved copper concentration was below acute levels (11.2 µg/L). At base flows, mean dissolved copper concentrations were below the EPA acute effect standard and generally similar among river segments (3.0 µg/L - 5.0 µg/L).

Dissolved copper was not the only heavy metal that routinely exceeds EPA standards. Mean total recoverable cadmium levels exceeded the chronic effects standard

of 0.25 µg/L (PBS&J 2010) at all synoptic water sampling sites (Figure 2.3).

Additionally, mean total recoverable lead concentrations exceeded chronic standards (3.2 µg/L; PBS&J 2010) at all sites in segments B and C (Figure 2.3). All mean total recoverable metal concentrations were lowest in the upper stream reaches (below the Warm Springs Ponds and Racetrack Bridge), peaked downstream of Deer Lodge, returned to low levels between the Little Blackfoot River and Flint Creek, and then rose again in the lower stream reaches (Figure 2.3). For most of the synoptic water samples, the lowest values were measured during base flow (April 2011) and the highest values were measured during the spring run-off time period (May and June 2011) (Table 2.4). Segment B had the coolest summer temperatures, with a mean of 13 days per year exceeding 20° C, a week less of warm temperatures than in segment C (21 days). Segment A experienced an average of 16 days that exceeded 20° C. For all segments, the overall maximum water temperature was 22° C.

Movement

Radio-tagged brown trout moved relatively little except during two distinct time periods; the fall spawning season (late-September to mid-December) and during spring run-off (April to early-July) (Figure 2.4). Mean weekly movement was greater than 1.0 km for 18% of the survey weeks, and maximum mean weekly movement observed was 3.5 km. Median weekly movement rates varied by season, although they were not significantly different between spring and summer, and summer and fall (Figure 2.5), despite the peaks observed in mean weekly movement during spring and fall. For all seasons, median brown trout movement was < 100 m, the estimated detection distance.

During fall, the median weekly movement for brown trout was 30 m/week, which was over seven times greater than the median weekly movement during winter (4 m/week) (Figure 2.5). Median weekly movement was 16 m/week for spring and 26 m/week in summer.

Cutthroat trout exhibited greater movement than brown trout, especially during spring spawning season (Figure 2.4); mean weekly movement rates were greater than 1.0 km for 40% of the survey weeks, and maximum mean weekly movement was 9.2 km, over two and a half times the maximum value for brown trout. Weekly movement rates for cutthroat trout also varied by season ($P < 0.001$), although the median rate was not significantly different between fall and winter (Figure 2.5). Median weekly movement during spring spawning season was 561 m/week, which was almost 22 times greater than the median weekly movement rate during winter (24 m/week). Summer thunderstorms had little effect on movement rates; median weekly movement during the summer was 146 m/week. Median weekly movement for fall was 46 m/week.

Habitat Use

Brown trout generally showed little evidence of strong selection of specific reaches in the river, with their distribution similar to initial tagging distribution during spring and summer ($P = 0.13$ and 0.06 , respectively). However, distribution shifted significantly during fall and winter ($P < 0.0001$) (Figure 2.6). During fall spawning (late-September to mid-December), 51% of the total brown trout were found in either tributaries or in the uppermost 40 km of river. During winter brown trout were concentrated primarily in tributaries (20%) as well as in a 20 km river section in segment

C reaches 7 and 8 (29%) that were mostly ice-free. Use of reaches 7 and 8 in the winter was about double the use observed during spring and fall. Analysis of reach selection ratios showed little evidence for avoidance by brown trout for specific reaches. There was only moderate avoidance of reach 2 (segment A) in the spring (0.8, SE = 0.05) and reach 5 in the spring and fall (0.9, SE = 0.02) (Figure 2.8). For all seasons, reach 10 (segment C) was the most preferred mainstem reach with selection ratios ranging from 2.1 (SE = 0.25) to 4.1 (SE = 1.08), although the value is likely skewed given the low number of brown trout that were tagged in this reach (n=3). Highest preference by brown trout was for tributaries in the fall (4.0), coincident with spawning, but there was wide variation, and this was not statistically significant (90% CI 0.0 to 8.6).

Cutthroat trout were more likely than brown trout to move from their initial tagging location. Distribution for all seasons was significantly different than the initial tagging distribution ($P < 0.0001$) (Figure 2.7). A higher proportion of cutthroat trout were found in tributaries compared to brown trout, with the percentage of tributary relocations ranging from 19% in the fall to 31% in the summer. In winter, we observed a similar pattern between river kilometers 50 and 70 (reaches 7 and 8) as with brown trout; 47% of cutthroat relocations were in this section, more than twice the percentage during any other time period. Cutthroat trout avoided reaches in segment A (reaches 1, 3, and 4; no cutthroat trout were tagged in reach 2) during all time periods and selection ratios ranged from 0.0 to 0.8 (Figure 2.9); lowest selection ratios were observed during summer and fall/winter time periods. Cutthroat trout also exhibited a strong preference for tributaries,

especially during spawning (spring) and postspawning (summer) periods (3.8, SE = 0.20, and 4.3, SE = 0.45, respectively) (Figure 2.8).

Spawning Sites and Migration

Spawning locations were documented for 50 brown trout and 31 cutthroat trout (Table 2.5). For both species, most spawning occurred in tributaries (brown trout, 72%; cutthroat trout, 100%), with spawning activity documented for 15 different tributaries in the upper Clark Fork drainage (Figure 2.11). Fish that were tagged in tributaries (Flint Creek and Little Blackfoot River) spawned either in the stream they were tagged in or a tributary to that stream. Brown trout spawning occurred in 8 different tributaries, with most (68%) tributary spawning occurring in three larger tributaries located in the upper river (segments A and B; Racetrack Creek, Little Blackfoot River, and Gold Creek), although two large tributaries in the lower river (Flint Creek, Rock Creek) were also important spawning sites. Brown trout spawning was not limited to tributaries; of the 50 observed brown trout spawning locations, 14 (28%) occurred in the mainstem upstream of the Little Blackfoot River.

Five brown trout spawned at least twice during the study; four spawned in consecutive years and one spawned in alternate years. Four of the repeat spawning fish exhibited spawning site fidelity and the fifth repeat spawning fish was observed spawning in the mainstem in 2010 (near the Little Blackfoot River confluences) and in the Little Blackfoot River in 2011.

All cutthroat trout spawning was confined to tributaries, and all spawning was observed in tributaries downstream of Deer Lodge (Figure 2.10). Cutthroat trout

spawning was documented in ten different tributaries. These tributaries were primarily lower order tributaries with more potential barriers than in the larger tributaries where most brown trout spawning occurred (Table 2.5). The most common spawning tributaries for cutthroat trout were two tributaries in the segment C; Bateman Creek and Harvey Creek. There were six spawning fish in each of those streams. Three of the tributaries used by cutthroat trout were also used by brown trout: Little Blackfoot River, Gold Creek, and Rock Creek. There were no observations of repeat spawning by cutthroat trout.

Brown trout and cutthroat trout generally migrated long distances to spawning locations. For both species, the largest mean total spawning migration distances were observed for fish that spawned in the three largest tributaries in the study area; Rock Creek (brown trout = 42.0 km and cutthroat trout = 57.7 km), Flint Creek (brown trout = 30.7 km, no cutthroat observed spawning), and Little Blackfoot River (brown trout = 31.8 km and cutthroat trout = 41.4 km) (Table 2.5). Cutthroat trout that spawned in Harvey Creek also underwent a long total migration (40.2 km). The greatest mean mainstem migration distances occurred for brown trout spawning in the mainstem (23.3 km), and in two lower river tributaries, Rock Creek (24.2 km), and Gold Creek (22.4 km). For cutthroat trout, mean mainstem migration distance was greatest for fish spawning in Harvey Creek (40.0 km), Little Blackfoot River (21.4 km), and Rock Creek (20.5 km). Although spawning fish migrated long distances in the mainstem to reach spawning locations, both brown trout and cutthroat trout spawned near the tributary and mainstem confluence in all tributaries except for in the three largest tributaries (Little Blackfoot

River, Flint Creek, and Rock Creek), Warm Springs Creek (only brown trout), and Spotted Dog Creek (only cutthroat trout) (Table 2.5), where tributary migration distances ranged from 13.8 km to 18.8 km for brown trout and 20.1 km to 37.3 km for cutthroat trout.

Most fish tagged in the mainstem entered tributaries during their respective spawning time periods (Figure 2.10), although each year I observed several brown trout enter tributaries during the summer (July and August). Most cutthroat trout had left spawning tributaries by late-August, although in 2010 one cutthroat trout remained in a tributary until early-November. No cutthroat trout were observed overwintering in tributaries. The largest increase of brown trout from the mainstem into tributaries occurred around October 1st of all years. Most brown trout returned to the mainstem after spawning (by mid-December), although four brown trout overwintered in tributaries in 2009 and three did so in 2010.

Most cutthroat trout and brown trout spawning occurred in tributaries identified as having chronic dewatering (Table 2.5), although this likely has little impact on brown trout spawning because irrigation activity had predominantly stopped by the time fall spawning occurred. In addition to dewatering, I identified potential migration barriers in one of the brown trout spawning tributaries and in five of the tributaries used by cutthroat trout (Table 2.5), including Harvey Creek which has a complete barrier located 0.2 km from the mainstem confluence which greatly reduces the available spawning habitat in a highly used cutthroat trout spawning tributary.

Cutthroat trout experienced a much higher rate of postspawning mortality than brown trout. Sixty-one percent ($n = 19$) of cutthroat trout died within one month of spawning compared to only 16% ($n = 8$) of brown trout. Avian predation may have been an important cause of postspawning mortality as about 50% of recovered tags were found in or under bird nests (osprey, bald eagle, and great blue heron) during the one-month postspawning period. Three cutthroat trout were found entrained in unscreened irrigation ditches postspawning on Cottonwood Creek and Brock Creek.

Discussion

Despite the heavy metal contamination observed in the upper Clark Fork River, there is no evidence that brown trout and cutthroat trout are increasing movement rates to avoid contamination, although cutthroat trout do tend to avoid the upper stream reaches where dissolved copper levels are the highest and the greatest amount of mining tailings still remain. My findings suggest that dissolved copper concentration are related to the degree of mining tailing deposits in the stream banks and floodplain, although copper is not the only heavy metal that may be limiting trout populations in the upper Clark Fork River. Total recoverable cadmium and lead exceeded chronic effect standards in all reaches, with some of the highest heavy metal levels recorded just downstream of Deer Lodge. In segment C, dissolved copper levels are low, and there are no remaining tailings, yet cadmium and lead are still exceeding chronic standards. This may be limiting trout populations in segment C, where densities are currently estimated as the lowest in the study area (B. Liermann, Montana Fish, Wildlife, and Parks, personal

communication). Although these concentration levels may not directly affect survival rates, chronic exposure to heavy metals can cause reduced growth, reduced feeding, and poor food assimilation (Woodward et al. 1995a; Farag et al. 2000).

Although the upper Clark Fork River is still experiencing poor water quality due to mining contamination in some sections, there was no evidence that brown trout avoided reaches with higher dissolved copper concentration. However, I did find evidence that cutthroat trout avoided several reaches in the highly contaminated segment A. This was expected based on laboratory studies that indicate that *Oncorhynchus* species are more likely to avoid heavy metal contamination (Hansen et al. 1999). There is some evidence that the heavy metal contamination in the upper Clark Fork River may be acting as a chemical barrier to migrating cutthroat trout; although cutthroat trout spawned in ten different tributaries throughout the study area, they were not observed in any tributaries upstream of Deer Lodge, where dissolved copper concentrations are the highest, despite there being known populations of resident cutthroat trout in several of the tributaries located near the Warm Springs ponds (Saffel et al. 2011). I observed one cutthroat trout that migrated upstream of Deer Lodge during spring but this fish died near Racetrack Creek before it could reach a spawning tributary. Cutthroat trout are spawning in the spring, when dissolved copper is at its highest concentration and when they may be exposed to toxic levels when attempting to reach headwater tributaries. Although brown trout are migrating during periods of lower dissolved copper concentrations, the elevated levels observed in segment A, where over a quarter of tagged brown trout spawned, may reduce survival of embryos and juvenile fish that hatch and rear in this segment. Juvenile

trout are more susceptible to mortality caused by heavy metal concentrations than adult fish (Woodward et al. 1995a). Little is known about seasonal habitat and rearing of juveniles in the study area and whether their survival is limiting the overall abundance of adult trout in the upper Clark Fork River.

Avoidance of heavy metal contamination during time periods when concentrations increase (primarily spring run-off) was not observed in this study, despite the laboratory and field evidence that has shown trout species exhibiting avoidance (Woodward et al. 1995b; Goldenstein et al. 1999). I expected to observe greater movement rates during periods of increased heavy metals as fish move to avoid contamination. However, the greatest movement occurred during spawning, typical of what has been observed in non-contaminated streams (Ovidio et al. 1998). Despite there being a statistically significant difference between median brown trout movement in fall and winter, these values are < 100 m and are not biologically significant based on our estimated detection precision. There may be some evidence for avoidance when analyzing mean weekly movement patterns; brown trout did exhibit greater mean weekly movement rates during spring (April to June) in both 2010 and 2011. This is the time period when dissolved copper concentrations are highest throughout the basin, but this movement may also be caused by brown trout moving from overwintering habitat into more suitable rearing habitat for the summer or being temporarily displaced by high flow events (Ovidio et al. 1998; Young et al. 2010). Cutthroat trout also exhibited weeks of mean movement greater than 1.0 km during fall (September to November) of 2009 and 2010. There may be small increases in heavy metal concentrations during this time period

because of thunderstorm and rain events that may mobilize tailings into the water column (Luoma et al. 2008), but this fall movement may also be caused by cutthroat trout moving from summer locations into more suitable overwintering habitat (Brown and MacKay 1995). Based on the results of this large-scale project, there is little evidence that trout are increasing movement in relation to heavy metal contamination. These results suggest that movements are primarily driven by seasonal needs for locating spawning and overwintering habitat.

Although I did not observe strong preference or avoidance of specific reaches during most time periods, I did detect strong preference for a specific downstream section during the winter by both species. This section had few relocation points during other seasons, and trout density is low in this section during spring electrofishing, but a large proportion of relocations during the winter occurred here, indicating the presence of critical overwintering habitat. Although copper concentrations are lower in these reaches, trout selection is most likely due to the large number of springs that were observed in segment C during radiotelemetry surveys, which may have led to warmer winter conditions and little ice cover, even during periods of extremely cold weather, which creates ideal overwintering habitat (Brown and MacKay 1995). I did not observe a dense aggregation of radio-tagged fish in overwintering habitat, as is typical in many cold climate streams (Brown and MacKay 1995; Brown 1999), indicating that overwintering habitat is most likely not limited. Brown trout also selected for tributaries during winter and, although cutthroat trout tagged in the mainstem did not overwinter in tributaries,

they did select for tributaries for all time periods, indicating the importance of tributary habitat for this species.

Instead of spawning occurring in a few select tributaries, spawning was observed in a large number of different areas, and there were no concentrated areas of spawning, as have been observed in other fluvial trout populations occurring in large drainages (Magee et al. 1996). Brown trout were more likely to spawn in larger tributaries and upper reaches of the mainstem whereas cutthroat trout spawning locations were mostly located in smaller tributaries. Spawning tributaries were dispersed from the headwaters to downstream at Rock Creek, except that spawning locations for cutthroat trout were not observed upstream of Deer Lodge. This is potentially because of the increased heavy metal contamination in the upper stream reaches, especially during spring. Although both brown and cutthroat trout use a large number of tributaries for spawning, many of these tributaries have significant anthropogenic pressures that can reduce spawning success. Montana Fish, Wildlife, and Parks have classified 9 of the 15 tributaries I documented as spawning locations as 'chronically dewatered'. Additionally, the upper reaches of the mainstem, another key spawning area for brown trout, also carry this classification. Despite many brown trout spawning tributaries having identified dewatering issues, this may be less of a barrier to successful spawning than it is to cutthroat trout because brown trout are primarily using tributaries during fall and winter, when irrigation is no longer taking place, whereas cutthroat trout are attempting to migrate in and out of chronically dewatered tributaries during the height of irrigation season. In addition to dewatering, I identified six spawning tributaries with potential barriers (diversion dams, perched

culverts, and man-made barriers), and five of those were located in cutthroat trout spawning tributaries. Not only do these physical barriers reduce the likelihood that a fish will be able to migrate into spawning tributaries, but they can also affect postspawning survival rates; I observed at least three known mortalities due to cutthroat trout getting trapped in unscreened irrigation ditches.

Results from this study indicate that trout movement and habitat use is not determined solely by heavy metal exposure, rather, there are a variety of factors, both physical and chemical, that may be limiting trout populations in the upper Clark Fork River. I have shown that heavy metal concentrations continue to exceed acute and chronic exposure standards, especially in the upper stream reaches and during high discharge events. By removing the mining tailings still present in the floodplain, heavy metal concentrations will most likely decrease leading to better water quality and more available habitat, especially for native cutthroat trout. Removal of tailing deposits in the stream reach immediately downstream of Warm Springs ponds has shown success in reducing copper in the water column and accumulated in *Hydropsyche* (caddisfly) species, although because restoration was on a small-scale, copper concentrations have begun to increase again (Hornberger et al. 2009), which supports the need for large-scale tailings removal that will eliminate the source of current contamination. Decreased heavy metal concentrations, especially during the spring, may help restore cutthroat trout connectivity with populations in headwater tributaries, increasing spawning success and most likely increasing cutthroat trout populations in the mainstem. Tributary habitat improvement, such as installing screens on irrigation ditches and using more efficient

irrigation systems to reduce dewatering, also has the potential to reduce entrainment and increase passage success, thereby substantially increase trout spawning habitat availability and spawning success, especially for cutthroat trout.

This study has compiled baseline information on trout spawning locations, movement, and habitat use patterns, and will help to provide an understanding of limiting factors for Clark Fork River trout populations in order to guide restoration activities. By understanding how the residual effects of mining contamination and current land use practices are limiting trout populations, managers can better focus remediation efforts to have the greatest impact.

Tables

TABLE 2.1. Number and date of implantation of radio tags into brown trout and cutthroat trout in the upper Clark Fork River, Montana.

Tagging date	Brown trout	Cutthroat trout
April 2009	72	21
April 2010	59	34
September 2010	45	5
April 2011	9	11
<i>Total</i>	<i>185</i>	<i>71</i>

TABLE 2.2. Physical habitat characteristics of the ten study reaches, upper Clark Fork River, Montana.

Segment	Reach	Start point	Length (km)	Gradient (m/km)	Sinuosity index	Braiding Index	Mean floodplain width (m)	Floodplain tailings area (%)	Exposed bank tailings (%)	Pool density (#/km)	Mean pool depth (m)	Ice cover
A	1	Warm Springs Creek	7.8	2.2	1.7	1.0	875	0.03	0.23	6.1	1.3	extensive
A	2	Lost Creek	13.1	2.1	1.8	1.0	905	0.02	0.28	3.7	1.4	
A	3	Racetrack Creek	16.9	2.1	1.7	1.1	782	0.03	0.27	3.1	1.5	
A	4	Deer Lodge	25.6	2.2	1.4	1.1	484	0.02	0.19	2.0	1.3	
B	5	Little Blackfoot River	13.8	3.1	1.2	1.0	187	0.00	0.07	1.5	1.4	moderate
B	6	Gold Creek	28.3	2.6	1.4	1.4	967	0.00	0.12	1.9	1.7	
C	7	Flint Creek	8.0	2.5	1.3	1.3	494	0.00	0.02	1.2	2.1	little
C	8	Tigh Creek	18.8	2.1	1.3	1.0	293	0.00	0.00	1.1	1.3	
C	9	Harvey Creek	29.5	2.6	1.1	1.0	328	0.00	0.00	1.0	1.5	
C	10	Rock Creek	27.8	3.0	1.2	1.4	566	0.00	0.00	2.3	1.9	

TABLE 2.3. Dissolved copper concentrations and water temperatures of mainstem segments, upper Clark Fork River, Montana. Mean and maximum dissolved copper values calculated using regression equations (Figure 2.2).

	Segment		
	A	B	C
Mean estimated dissolved copper ($\mu\text{g/L}$)	6.9	5.6	3.9
Maximum observed dissolved copper ($\mu\text{g/L}$)	45.9	23.3	11.2
Mean days per year $>20^\circ\text{C}$	16	13	21
Maximum temperature ($^\circ\text{C}$)	22.9	22.3	22.2

TABLE 2.4. Synoptic water samples measured for total recoverable heavy metals, in the upper Clark Fork River, Montana. All measurements are displayed as µg/L. Values in italics indicate samples that exceeded the standard for chronic effects; bold values indicate samples that exceeded the standard for acute effects (PBS&J 2010; Montana DEQ 2012).

Location	Date	Arsenic	Cadmium	Copper	Lead	Zinc
Below Warm Springs Ponds <i>reach 1, segment A</i>	1/17/11	7.9	<i>0.6</i>	19.1	1.6	16.4
	4/26/11	3.0	<i>0.5</i>	24.6	0.7	14.2
	5/30/11	25.0	<i>0.5</i>	44.0	2.0	27.3
	6/27/11	22.6	<i>1.2</i>	52.8	2.6	24.5
	7/11/11	15.8	0.1	30.1	0.6	10.2
Racetrack Bridge <i>reach 2, segment A</i>	1/17/11	16.3	<i>0.8</i>	35.2	2.9	22.5
	4/26/11	11.7	<i>0.5</i>	22.0	1.7	20.0
	5/30/11	29.2	<i>0.8</i>	81.5	4.8	47.1
	7/11/11	26.2	<i>0.6</i>	45.1	2.0	20.4
Downstream of Deer Lodge <i>reach 4, segment A</i>	1/17/11	19.5	<i>1.1</i>	118.1	<i>12.8</i>	89.7
	4/26/11	10.6	<i>0.6</i>	42.3	3.6	34.5
	5/30/11	32.5	<i>1.0</i>	136.8	<i>13.3</i>	86.0
	6/27/11	33.1	<i>0.7</i>	84.1	4.5	54.0
	7/11/11	34.6	<i>0.7</i>	107.8	8.8	62.6
Garrison <i>reach 5, segment B</i>	1/17/11	14.2	<i>1.0</i>	88.5	<i>13.3</i>	77.1
	4/26/11	3.3	<i>0.5</i>	28.7	1.8	22.9
	5/30/11	28.4	<i>1.3</i>	111.0	9.7	68.3
	6/27/11	32.9	<i>0.6</i>	96.0	5.1	62.8
	7/11/11	21.0	<i>0.7</i>	<i>70.4</i>	4.7	38.1
Jens Bridge <i>reach 6, segment B</i>	4/26/11	2.3	<i>0.4</i>	17.5	0.3	16.3
	5/30/11	15.3	<i>0.7</i>	75.5	5.8	48.9
	6/27/11	22.4	<i>0.5</i>	<i>71.4</i>	3.1	49.3
	7/11/11	19.7	<i>0.5</i>	<i>63.0</i>	4.0	34.9
Bearmouth <i>reach 9, segment C</i>	4/26/11	3.4	<i>0.4</i>	24.9	2.9	28.2
	5/30/11	25.6	<i>1.8</i>	97.7	<i>11.7</i>	79.6
	6/27/11	24.2	<i>0.6</i>	<i>74.9</i>	4.8	58.8
	7/11/11	23.4	<i>0.9</i>	65.2	4.5	53.6

TABLE 2.5. Spawning migration distances, number of observed spawning locations for all years (N), and tributary land use characteristics (dewatering and presence of barriers), by species.

Tributary	Chronic dewatering	Potential barriers	N	<i>Brown trout</i>			N	<i>Cutthroat trout</i>		
				Mean total migration, km (SE)	Mean mainstem migration, km (SE)	Mean tributary migration, km (SE)		Mean total migration, km (SE)	Mean mainstem migration, km (SE)	Mean tributary migration, km (SE)
Clark Fork River	X		14	23.3 (10.8)	23.3 (10.8)		--			
Rock Creek			3	42.0 (15.4)	24.2 (7.3)	17.8 (9.7)	4	57.7 (10.2)	20.5 (7.2)	37.3 (9.3)
Flint Creek	X		3	30.7 (4.0)	11.9 (5.2)	18.8 (3.3)	--			
Little Blackfoot River	X		9	31.8 (5.8)	18.1 (6.6)	13.8 (2.7)	3	41.4 (31.9)	21.3 (15.5)	20.1 (16.5)
Racetrack Creek	X	X	7	11.0 (7.5)	9.9 (7.6)	1.1 (0.2)	--			
Warm Springs Creek			3	20.2 (5.4)	1.8 (0.1)	18.4 (5.3)	--			
Gold Creek	X		7	27.4 (7.3)	22.4 (7.4)	5.1 (0.5)	3	14.2 (3.5)	7.9 (2.5)	6.4 (3.3)
Lost Creek	X		2	2.6 (7.9)	11.5 (6.4)	9.1 (1.5)	--			
Harvey Creek	X	X	--				6	40.2 (8.4)	40.0 (8.4)	0.2 (0.0)
Cottonwood Creek	X	X	--				1	13.3	3.3	10.0
Spotted Dog Creek	X		--				1	31.2	4.8	26.4
Warm Springs Creek (Garrison)	X		2	8.1 (1.2)	3.6 (3.0)	4.4 (1.8)	--			
Brock Creek		X	--				5	10.2 (4.3)	6.9 (4.9)	3.2 (1.3)
Dunkleberg Creek		X	--				1	12.3	9.6	2.7
Bateman Creek			--				6	8.8 (2.5)	8.1 (2.5)	0.7 (0.2)
O'Neill Creek		X	--				1	9.8	7.7	2.0

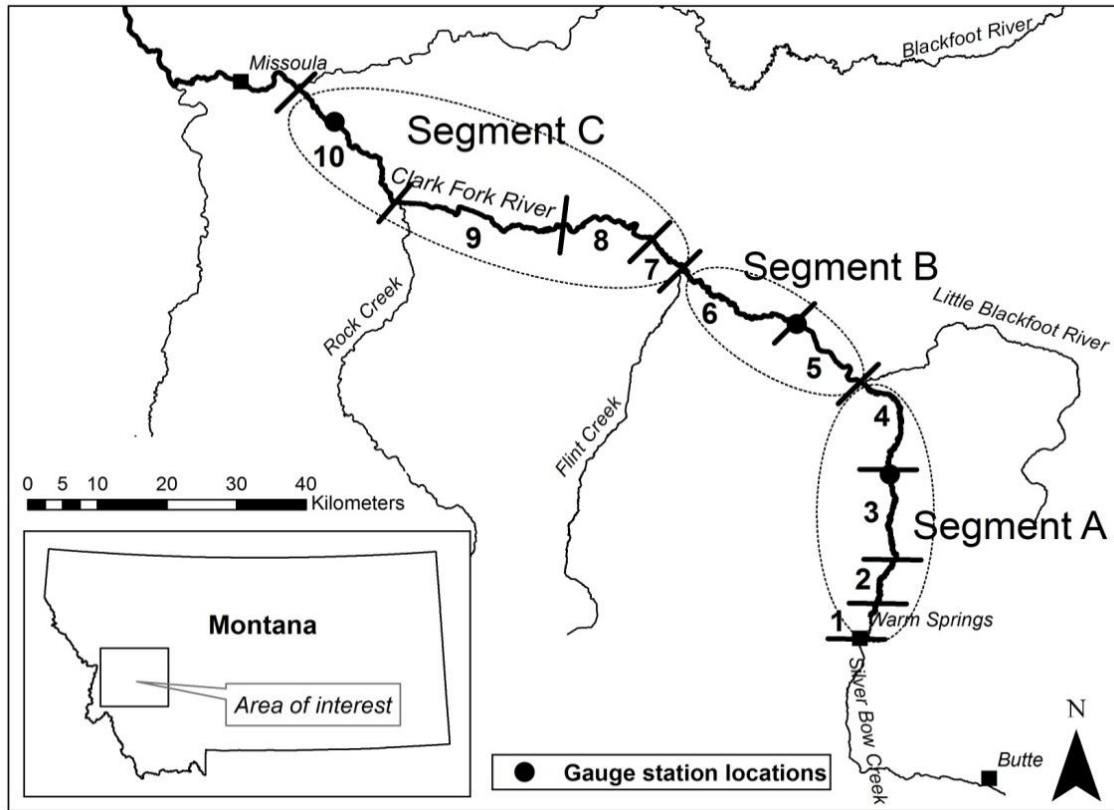
Figures

FIGURE 2.1. Map of upper Clark Fork River study area, with segments, reaches, and major tributaries displayed.

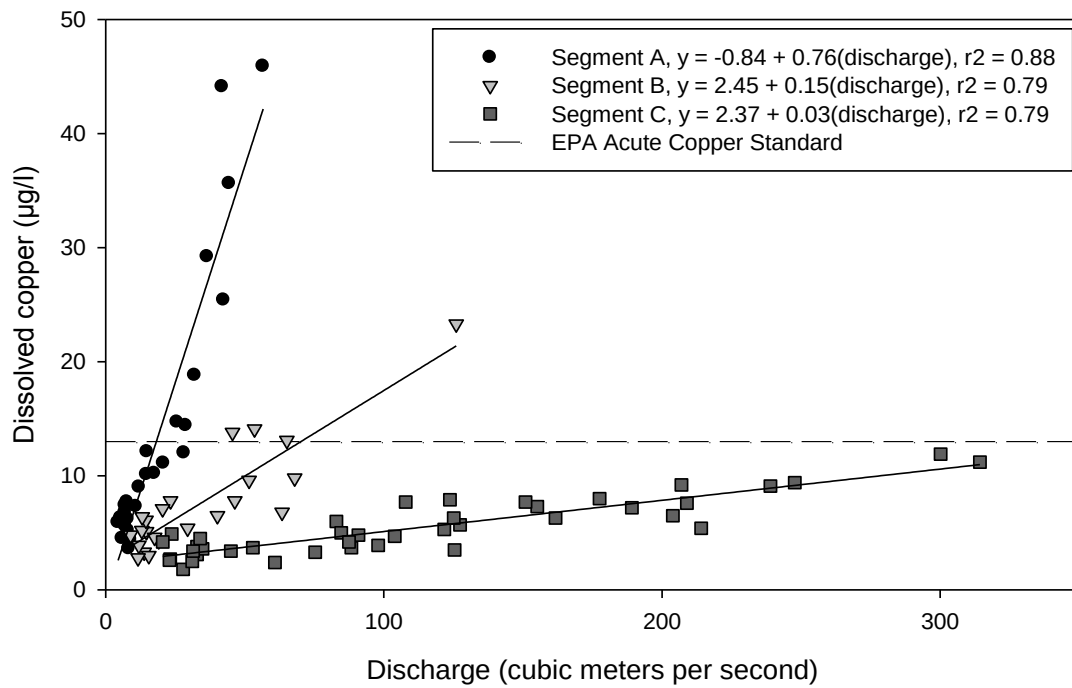


FIGURE 2.2. Dissolved copper concentration in relation to discharge for the three mainstem segments, 2009 to 2011 combined. Regression equations were used to estimate daily concentration. The dashed line is the acute toxicity standard for copper by the EPA (13.0 µg/L at water hardness of 100 mg/L; USEPA 1986).

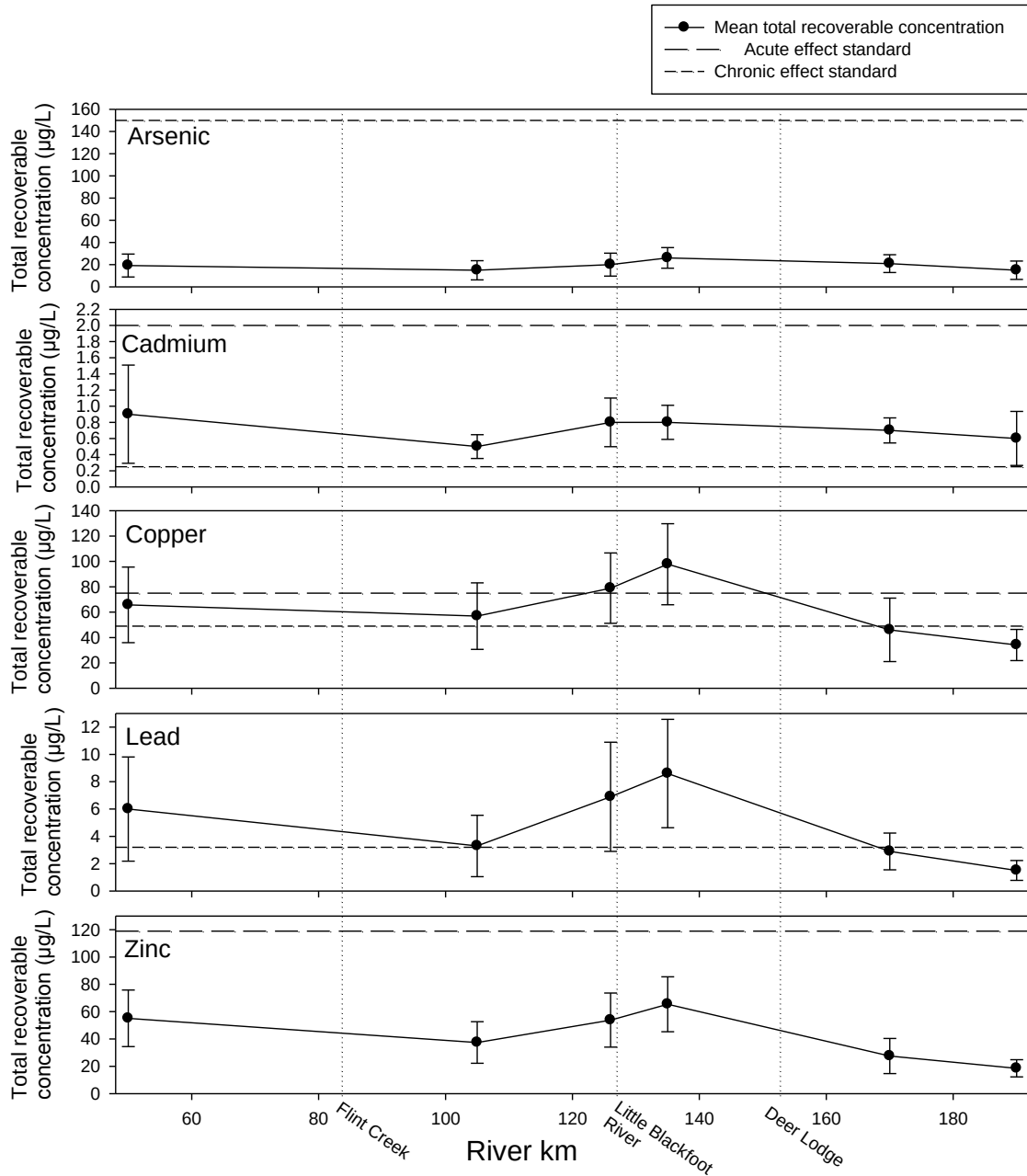


FIGURE 2.3. Mean total recoverable metal concentrations from synoptic water samples (with 95% confidence intervals). River kilometers are measured from the confluence of the Blackfoot River (river km 0) upstream to the Warm Springs Ponds (near river km 190). Acute effect (long dashed line) and chronic effect (short dashed line) standards are displayed for the respective metals, based on a water hardness of 100 mg/L (PBS&J 2010; Montana DEQ 2012). Acute effects standard not shown for arsenic and lead. Acute and chronic standards are the same concentration for zinc. Vertical dotted line indicates stream landmarks.

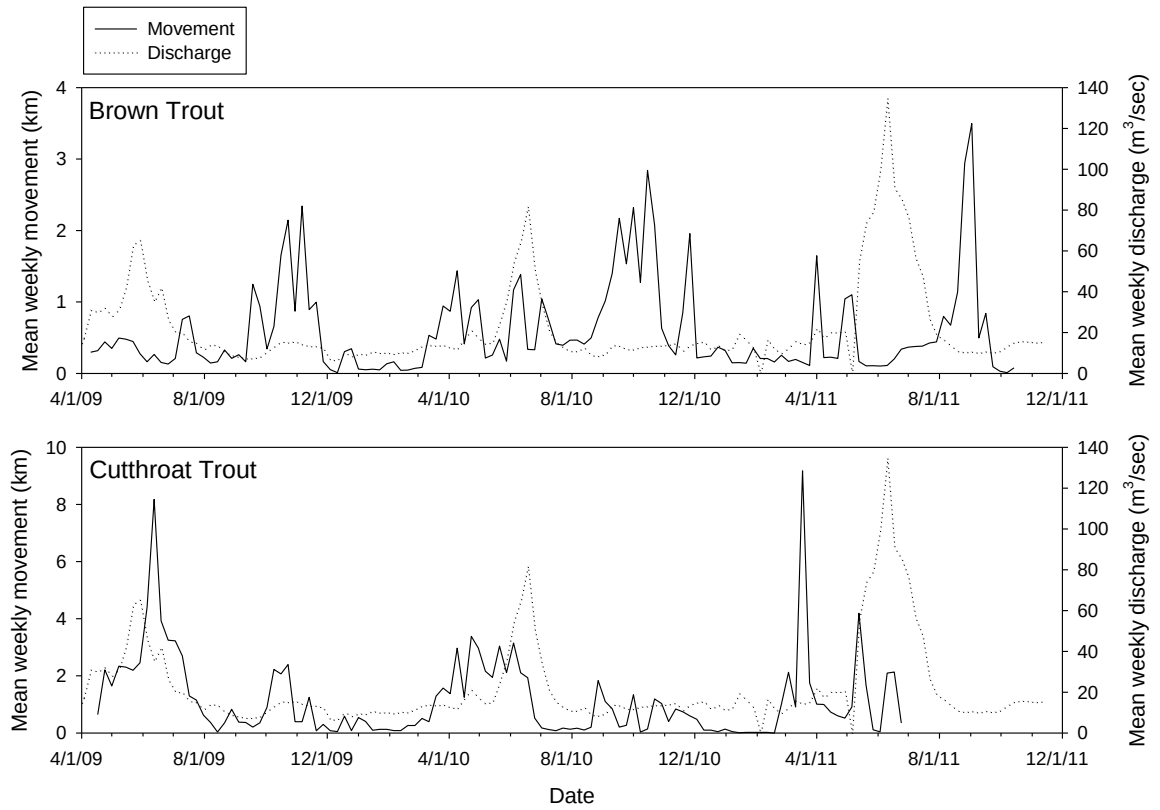


FIGURE 2.4. Summary of mean weekly movement rates (km/week) for brown trout and cutthroat trout in relation to mean weekly discharge.

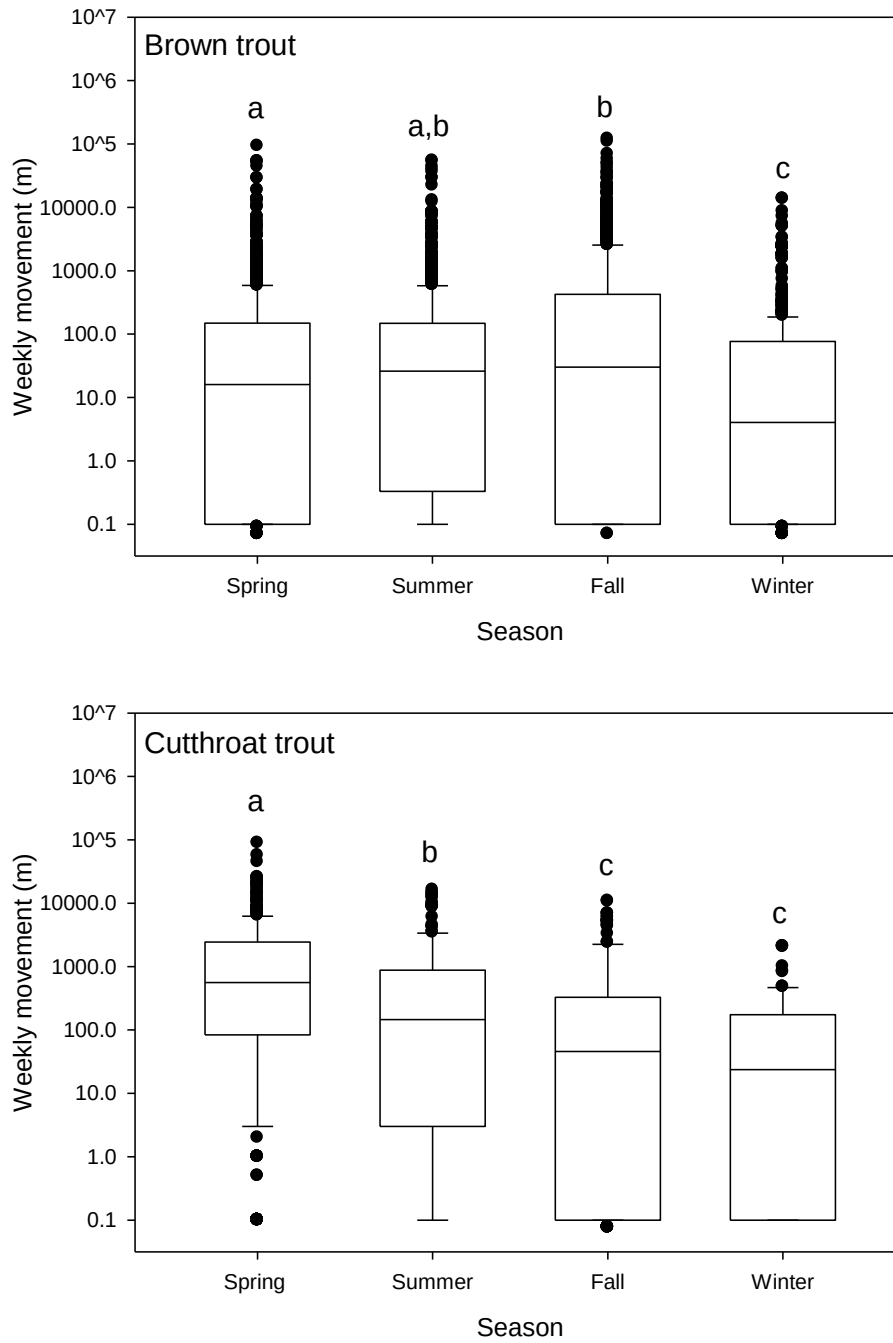


FIGURE 2.5. Median weekly movement of brown trout and cutthroat trout, by season. Letters indicate which seasons had medians that were not statistically different.

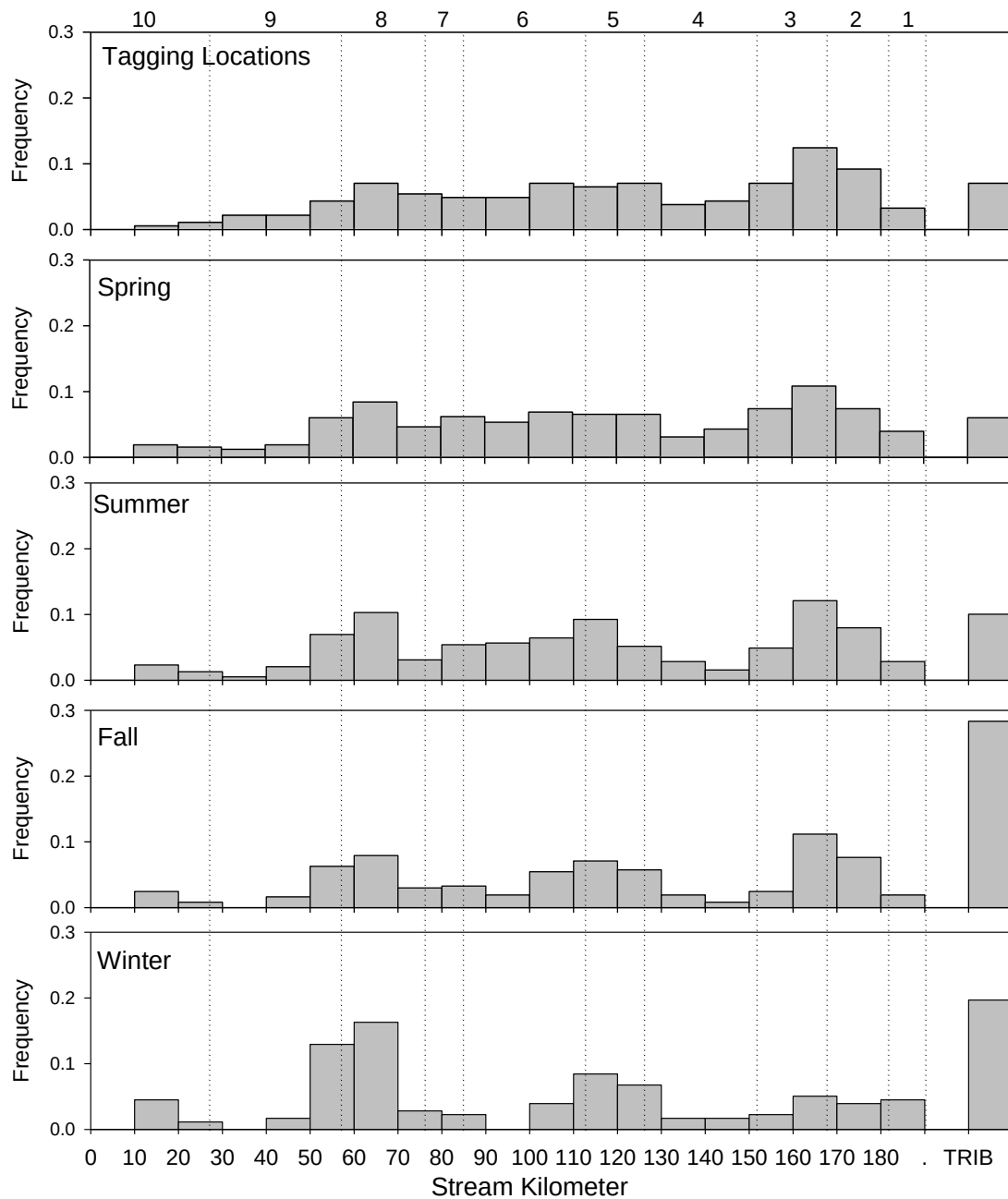


FIGURE 2.6. Initial tagging location and frequency distribution of relocations of radio-tagged brown trout, categorized by season and by 10-kilometer river section. Stream kilometer 0 is the confluence with the Blackfoot River and stream kilometer 180 is near the headwaters. Dotted lines indicate reach breaks and associated reach numbers are listed at top of the figure.

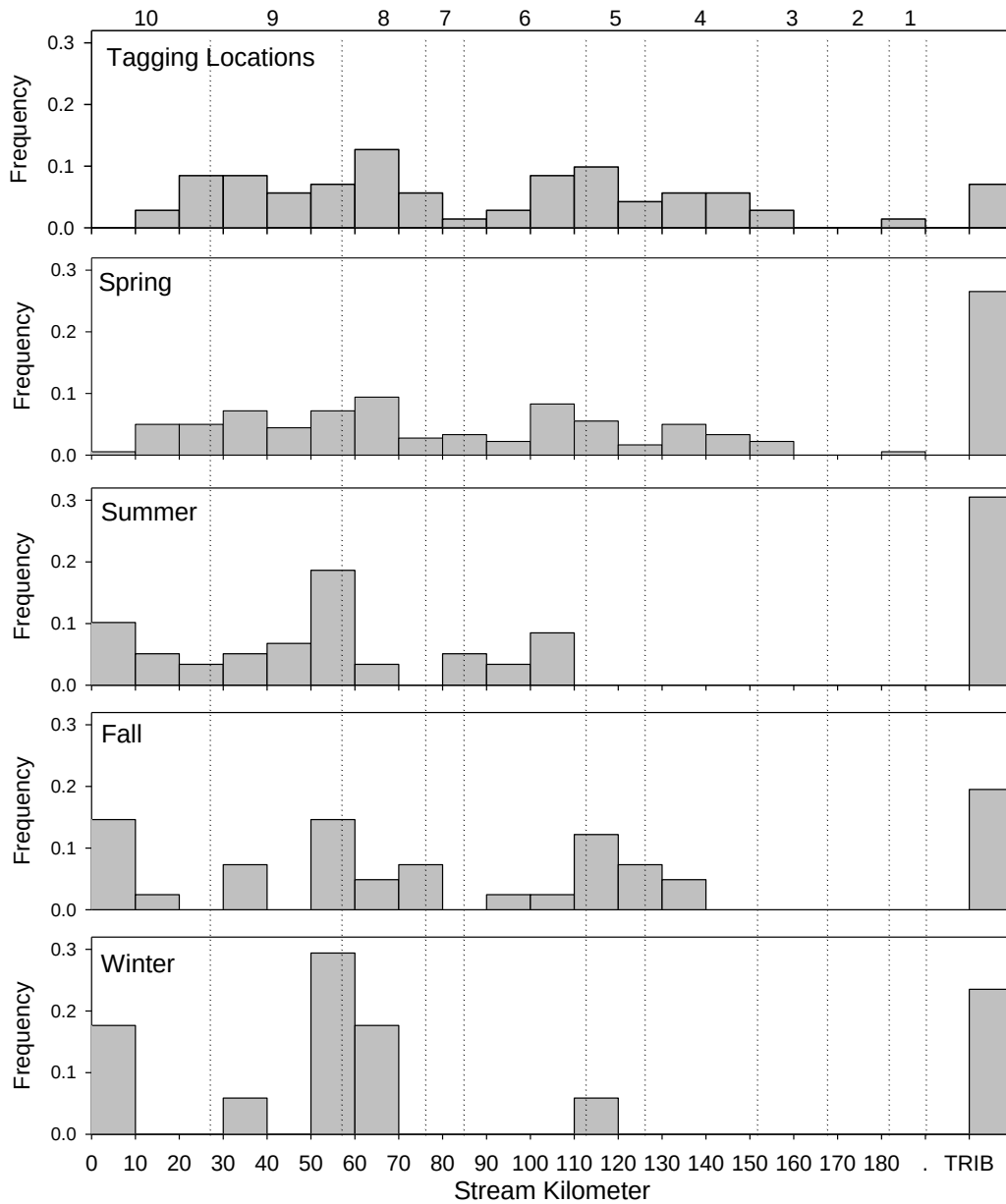


FIGURE 2.7. Initial tagging location and frequency distribution of relocations of radio-tagged cutthroat trout, categorized by season and by 10-kilometer river section. Stream kilometer 0 is the confluence with the Blackfoot River and stream kilometer 180 is near the headwaters. Dotted lines indicate reach breaks and associated reach numbers are listed at top of the figure.

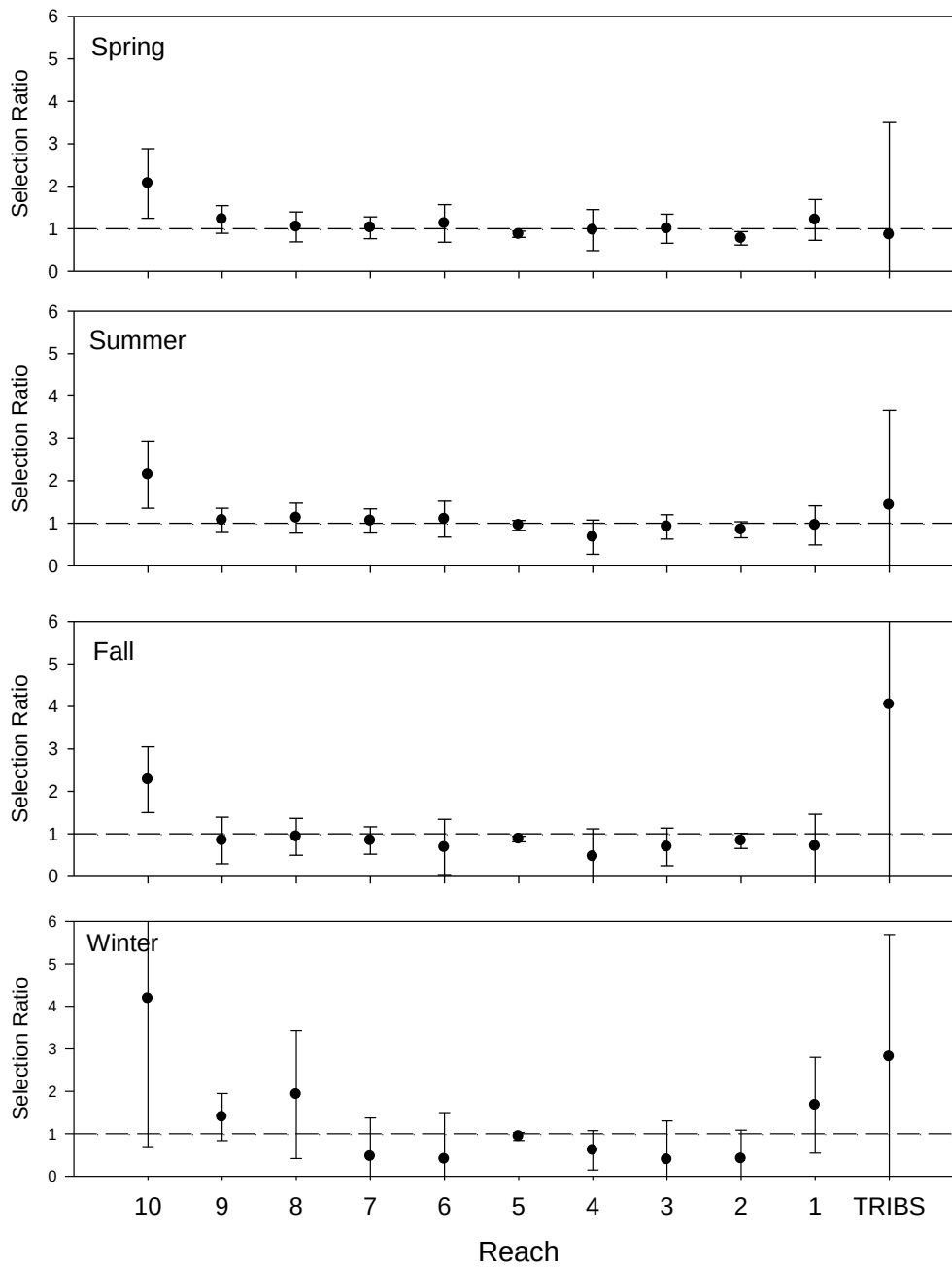


FIGURE 2.8. Seasonal reach selection ratios for brown trout. Dashed line indicates a selection ratio of 1 (no preference); values greater than 1 indicate that a reach is used greater than expected (preference) and less than 1 indicate that a reach is used less than expected (avoidance). Error bars indicate 90% Bonferroni confidence intervals.

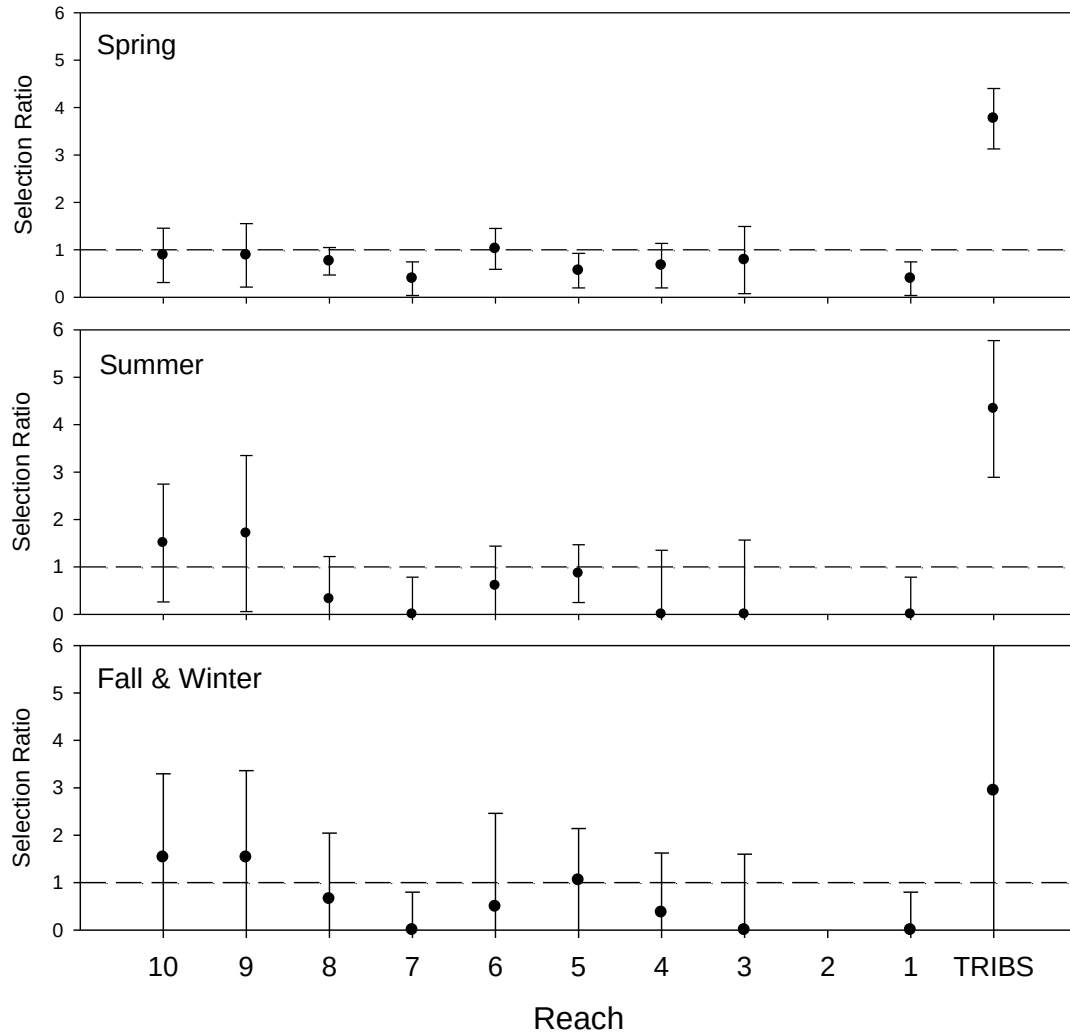


FIGURE 2.9. Seasonal reach selection ratios for cutthroat trout. Dashed line indicates a selection ratio of 1 (no preference); values greater than 1 indicate that a reach is used greater than expected (preference) and less than 1 indicate that a reach is used less than expected (avoidance). Error bars indicate 90% Bonferroni confidence intervals. No cutthroat trout were tagged in reach 2, so selection ratios cannot be calculated.

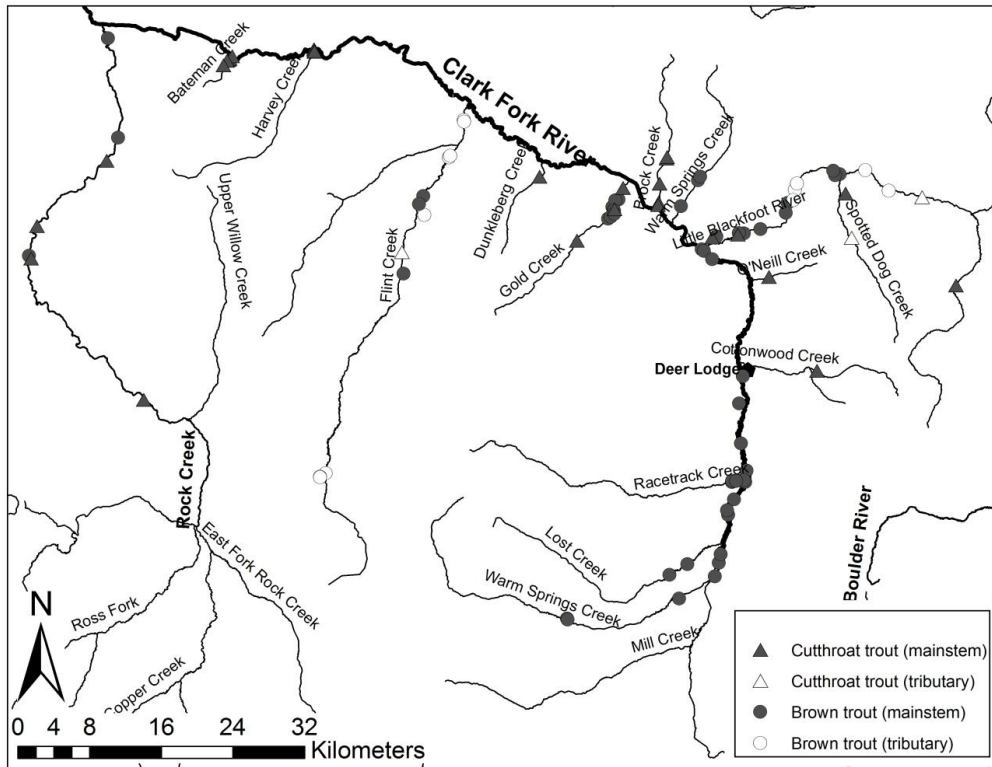


FIGURE 2.10. Observed potential spawning locations in the upper Clark Fork River, Montana, for cutthroat trout and brown trout, based on whether they were tagged in the mainstem or a tributary.

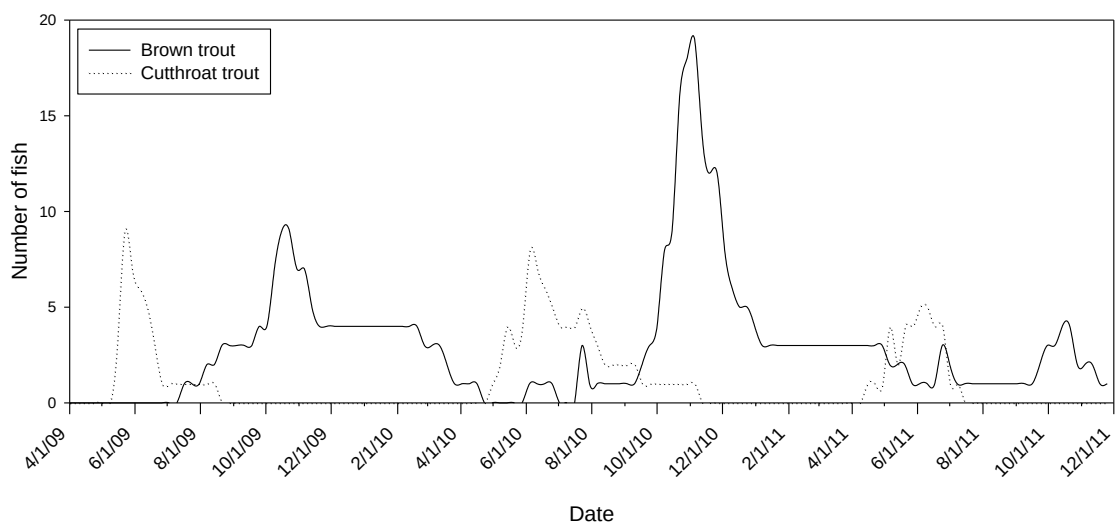


FIGURE 2.11. Number of brown trout and cutthroat trout present in tributaries in the upper Clark Fork River basin, Montana.

Literature Cited

- Bear, E. A., T. E. McMahon, and A. V. Zale. 2007. Comparative thermal requirements of westslope cutthroat trout and rainbow trout: implications for species interactions and development of thermal protection standards. *Transactions of the American Fisheries Society* 136:1113–1121.
- Brown, R. S. and W. C. Mackay. 1995. Fall and winter movements of and habitat use by cutthroat trout in the Ram River, Alberta. *Transactions of the American Fisheries Society* 124:873–885.
- Brown, R. S. 1999. Fall and early winter movements of cutthroat trout, *Oncorhynchus clarki*, in relation to water temperature and ice conditions in Dutch Creek, Alberta. *Environmental Biology of Fishes* 55: 359–368.
- Clark Fork Coalition. 2011. Aquatic restoration strategy for the upper Clark Fork Basin: elements of an integrated approach. Retrieved from: <http://www.clarkfork.org/programs/restore.html>
- De Rito, J. M. 2004. Assessment of reproductive isolation between rainbow trout in the Yellowstone River, Montana. Master's Thesis. Montana State University, Bozeman.
- ESRI (Environmental Systems Resource Institute). 2009. ArcMap 9.3.1. ESRI, Redlands, California.
- Farag, A. M., M. J. Suedkamp, J. S. Meyer, R. Barrows, and D. F. Woodward. 2000. Distribution of metals during digestion by cutthroat trout fed benthic invertebrates contaminated in the Clark Fork River, Montana and the Coeur d'Alene River, Idaho, U.S.A., and fed artificially contaminated *Artemia*. *Journal of Fish Biology* 56: 173–190.
- FEMA (Federal Emergency Management Agency). Upper Clark Fork River floodplain. Shapefile available at <http://nriss.mt.gov>.
- Finger, S. E., S. E. Church, and P. von Guerrard. 2007. Potential for successful ecological remediation, restoration, and monitoring. Chapter F in Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651. S. E. Church, P. von Guerard, and S. E. Finger, eds., 2007, 1,096 p. plus CD-ROM. [In two volumes.]

- Goldenstein, J. N., D. F. Woodward, and A. M. Farag. 1999. Movements of adult Chinook salmon during spawning migration in a metals-contaminated system, Coeur d'Alene River, Idaho. *Transactions of the American Fisheries Society* 128: 121-129.
- Hansen, J. A., D. F. Woodward, E. E. Little, A. J. DeLonay, and H. L. Bergman. 1999. Behavioral avoidance: possible mechanisms for explaining abundance and distribution of trout species in a metal-impacted river. *Environmental Toxicology and Chemistry* 18: 313-317.
- Hornberger, M. I., S. N. Luoma, M. L. Johnson, and M. Holyoak. 2009. Influence of remediation in a mine-impacted river: metal trends over large spatial and temporal scales. *Ecological Applications* 19: 1522-1535.
- Jaeger, M. E., A. V. Zale, T. E. McMahon, and B. J. Schmitz. 2005. Seasonal movements, habitat use, aggregation, exploitation, and entrainment of saugers in the lower Yellowstone River: an empirical assessment of factors affecting population recovery. *North American Journal of Fisheries Management* 25: 1550-1568.
- Lewis, M. A. and R. Burraychak. 1979. Impact of copper mining on a desert intermittent stream in central Arizona: a summary. *Journal of the Arizona-Nevada Academy of Science* 14: 22-29.
- Lipton, J. and 16 coauthors. 1995. Aquatic resources injury assessment report: Upper Clark Fork River basin. State of Montana, Natural Resource Damage Litigation Program, Helena.
- Luoma, S. N., J. N. Moore, A. M. Farag, T. H. Hillman, D. J. Cain, and M. Hornberger. 2008. Mining impacts on fish in the Clark Fork River, Montana: A field ecotoxicology case study. Pages 779-804 *in* R. T. DiGuilio and D. E. Hinton, editors. *The toxicology of Fishes*. CRC Press, Boca Raton, Florida.
- Magee, J. P., T. E. McMahon, and R. F. Thurow. 1996. Spatial variation in spawning habitat of cutthroat trout in a sediment-rich stream basin. *Transactions of the American Fisheries Society* 125: 768-779.
- Manly, B. F. J., L. L. McDonald, D. L. Thomas, T. L. McDonald, and W. P. Erickson. 2002. Resource selection by animals. Kluwer Academic Press, Dordrecht, The Netherlands.

- Marr, J. C. A., H. L. Bergman, J. Lipton, and C. Hogstrand. 1995a. Differences in relative sensitivity of naives and metals-acclimated brown and rainbow trout exposed to metals representative of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2016-2030.
- Marr, J. C. A., H. L. Bergman, M. Parker, J. Lipton, D. Cacela, W. Erickson, and G. R. Phillips. 1995b. Relative sensitivity of brown and rainbow trout to pulsed exposures of an acutely lethal mixture of metals typical of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2005-2015.
- McMahon, T. E., A. V. Zale, and D. J. Orth. 1996. Aquatic habitat measurements. Pages 83-120 in B. R. Murphy and D. W. Willis, editors. *Fisheries techniques, second edition*. American Fisheries Society, Bethesda, Maryland.
- Montana DEQ, Planning Prevention and Assistance Division, Water Quality Planning Bureau, Water Quality Standards Section. 2012. DEQ-7 Montana Numeric Water Quality Standards. Helena, MT: Montana Dept. of Environmental Quality.
- Montana Fish, Wildlife, and Parks. 2001. Dewatered streams. Shapefile available at <http://fwp.mt.gov/doingBusiness/reference/gisData/>.
- Nelson, R. L., M. L. McHenry, and W. S. Platts. 1991. Mining. Pages 425-457 in W. R. Meehan, editor. *Influences of forest and rangeland management on salmonid fishes and their habitats*. American Fisheries Society, Bethesda, Maryland.
- Ovidio, M., E. Baras, D. Goffaux, C. Birtles, and J. C. Philippart. 1998. Environmental unpredictability rules the autumn migration of brown trout (*Salmo trutta* L.) in the Belgian Ardennes. *Hydrobiologia* 371/372:263-274.
- PBS&J. 2010. Interim comprehensive long-term monitoring plan for the Clark Fork River Operable Unit. Missoula, Montana.
- Phillips, G. and J. Lipton. 1995. Injury to aquatic resources caused by metals in Montana's Clark Fork River basin: historic perspective and overview. *Canadian Journal of Fisheries and Aquatic Science* 52: 1990-1993.
- Rogers, K. B. and G. C. White. 2007. Analysis of movement and habitat use from telemetry data. Pages 625-676 in C. S. Guy and M. L. Brown, editors. *Analysis and interpretation of freshwater fisheries data*. American Fisheries Society, Bethesda, Maryland.
- Ramsey, F. L. and D. W. Schafer. 2002. *The statistical sleuth: a course in methods of data analysis*, Second Edition. Brooks/Cole, Cengage Learning, Belmont, California.

- Ross, M. J. and C. F. Kleiner 1982. Shielded-needle technique for surgically implanting radio-frequency transmitters in fish. *Progressive Fish-Culturist* 44: 41-43.
- Saffel, P., B. Liermann, J. Lindstrom, L. Knotek, T. Mostad, and C. Fox. 2011. Prioritization of tributaries in the upper Clark Fork River basin for fishery enhancement. Retrieved from: <http://www.doj.mt.gov/lands/naturalresource/resources/projects/2010tributaryprioritization.pdf>.
- State of Montana. Digital elevation models. Shapefiles available at <http://nris.nt.gov>.
- Svecevicius, G. 2001. Avoidance response of rainbow trout *Oncorhynchus mykiss* to heavy metal mixtures: A comparison with acute toxicity tests. *Bulletin of Environmental Contamination and Toxicology* 67: 680-687.
- University of Montana Riparian and Wetland Survey Team. Upper Clark Fork tailing deposits. Shapefile available at <http://nris.mt.gov>.
- USEPA (U.S. Environmental Protection Agency). 1986. Quality Criteria for Water (EPA Gold Book). EPA 440/5-86-001. U.S. EPA, Office of Water. 1986.
- USEPA. 2000. Liquid assets: America's water resources at a turning point. EPA-840, Washington, DC.
- Weigel, D. E., J. T. Peterson, and P. Spruell. 2002. A model using phenotypic characteristics to detect introgressive hybridization in wild westslope cutthroat trout and rainbow trout. *Transactions of the American Fisheries Society* 131: 389-403.
- White, G. C. and R. A. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, California.
- Woodward, D. F., A. M. Farag, H. L. Bergman, A. J. DeLonay, E. E. Little, C. E. Smith, and F. T. Barrows. 1995a. Metals-contaminated benthic invertebrates in the Clark Fork River, Montana: effects on age-0 brown trout and rainbow trout. *Canadian Journal of Fisheries and Aquatic Science* 52: 1994-2004.
- Woodward, D. F., J. A. Hansen, H. L. Bergman, E. E. Little, and A. J. DeLonay. 1995b. Brown trout avoidance of metals in water characteristic of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2031-2037.
- Woody, C. A., R. M. Hughes, E. J. Wagner, T. P. Quinn, L. H. Roulson, L. M. Martin, and K. Griswold. 2010. The mining law of 1872: change is overdue. *Fisheries* 35: 321-331.

- Young, R. G., J. Wilkinson, J. Hay, and J. W. Hayes. 2010. Movement and mortality of adult brown trout in the Motupiko River, New Zealand: effects of water temperature, flow, and flooding. *Transactions of the American Fisheries Society* 139:137-146.
- Zale, A. V., C. Brooke, and W. C. Fraser. 2005. Effects of surgically implanted transmitter weights on growth and swimming stamina of small adult westslope cutthroat trout. *Transactions of the American Fisheries Society* 134: 653-660.

CHAPTER 3

ESTIMATING SPATIAL AND TEMPORAL SURVIVAL AND MOVEMENT RATES
OF BROWN TROUT AND CUTTHROAT TROUT IN THE UPPER CLARK
FORK RIVER SUPERFUND SITE, MONTANA, USING
MULTISTATE MARK-RECAPTURE ANALYSIS

Introduction

Mining-related water pollution is one of the most detrimental and persistent anthropogenic impacts in aquatic environments (Nelson et al. 1991; Phillips and Lipton 1995; Woody et al. 2010), with the estimated cost of remediation in the billions of dollars (USEPA 2000). Waste materials from mining can cause extensive sedimentation and channel alteration, impacting spawning and other critical habitats (Lewis and Burraychak 1979; Nelson et al. 1991; Phillips and Lipton 1995). The input of large quantities of toxic heavy metals has also had significant, long-term detrimental effects on water quality, fish populations, and aquatic food webs over extensive areas (Nelson et al. 1991; Phillips and Lipton 1995). Many of the U.S. Environmental Protection Agency (EPA) designated Superfund sites are former mine locations, including the upper Clark Fork River in southwestern Montana, the largest Superfund site in the United States, where operation of the Butte copper mines from 1882 to 1959 resulted in deposition of an estimated 99.8 billion kilograms of mining waste in the floodplain, rendering about 200 km of the river essentially devoid of fish for many decades due to heavy metal toxicity (Phillips and Lipton 1995).

Heavy metal contamination affects fish at multiple levels of biological organization (Lipton et al. 1995; Luoma et al. 2008). At the individual level, chronic physiological effects of heavy metal exposure include reduced feeding, contamination of food sources, poor food assimilation, and reduced growth, even at relatively low levels of exposure (Nelson et al. 1991; Woodward et al. 1995; Farag et al. 2000). Behavioral avoidance also occurs at levels well below acceptable concentration levels (Woodward et al. 1995b; Goldenstein et al. 1999; Svecevicus 2001), causing distinct shifts in distribution (Goldenstein et al. 1999). At the population level, fish kills occur when heavy metal concentrations exceed acute toxicity levels and are especially common when heavy metals are mobilized from stream bank and floodplain deposits during peak discharge events (Marr et al. 1995b; Phillips and Lipton 1995; Luoma et al. 2008). Changes in fish assemblages can occur when species have different physiological sensitivities and behavioral avoidance thresholds to heavy metals. For example, in the western United States, nonnative brown trout (*Salmo trutta*) are less sensitive to heavy metal contamination than cutthroat trout (*Oncorhynchus clarkii*) and rainbow trout (*O. mykiss*) and this variable sensitivity has led to a shift toward brown trout dominance in mining-contaminated systems (Hansen et al. 1999c).

Prior to mining, the upper Clark Fork River was home to significant populations of bull trout *Salvelinus confluentus* and westslope cutthroat trout *O. clarkii lewisi* (Luoma et al. 2008). Surveys of the basin in the late 1800s and 1950s found very few or no fish in the river from the headwaters downstream to Rock Creek, near Missoula, Montana, a distance of 160 kilometers (Phillips and Lipton 1995). High concentrations of copper, zinc, lead, cadmium, and arsenic occurred in the river, but copper continues to be the

greatest impairment to aquatic life because it is present at the greatest concentrations relative to toxicity (Phillips and Lipton 1995). Following installation of liming ponds and a waste water treatment plant near the headwaters in Butte, trout populations began to reappear in the river in the 1970s (Phillips and Lipton 1995), primarily comprised of brown trout, with rainbow trout, cutthroat trout, and bull trout rare. Population abundance estimates conducted in the early 1990s revealed that trout densities in impacted reaches were less than 10% of expected trout density compared to non-contaminated reference reaches in nearby rivers, with substantial differences in density among reaches (Lipton et al. 1995). These observations suggest that high mortality and avoidance of some mining-impacted stream segments may still be inhibiting population recovery.

Large-scale, basin-wide remediation of the upper Clark Fork River, including removal of mining tailing deposits, stream bank stabilization, revegetation, and tributary enhancement, is now in the early stages of implementation (Clark Fork Coalition 2011). Population recovery would likely be enhanced if remediation of mining-impacted areas targets those reaches where elevated dissolved copper concentrations continue to limit survival and trigger avoidance responses by trout in the river (Finger et al. 2007). I examined survival and movement of trout in relation to a dissolved copper concentration gradient in the Clark Fork River using a combination of radiotelemetry and multistate mark-recapture modeling. I hypothesized that trout in the upper Clark Fork River experience lower survival rates in areas with greater copper concentrations, specifically, the upper 63 km of the mainstem river where mining tailing deposits are still widespread, and during time periods of increased contamination, such as during spring and summer when precipitation events and high stream discharge mobilizes copper into the water

column (Luoma et al. 2008). Additionally, I predicted that trout would avoid and emigrate from areas with higher copper concentrations, especially during high discharge events, and that these responses would be more pronounced in cutthroat trout than brown trout, due to species-level differences in heavy metal sensitivity (Hansen et al. 1999c).

Methods

Study Area

The study was conducted on the upper Clark Fork River, from the confluence of Silver Bow and Warm Springs creeks, near Warm Springs, Montana, and downriver to the confluence with the Blackfoot River, near Missoula, Montana, a total distance of 190 river kilometers, and all associated tributaries (Figure 3.1). Previous information indicated that dissolved copper concentration, extent of mining contamination, and stream geomorphology differ substantially within the study area. I therefore divided the mainstem river study section into three segments that differed in these characteristics (Figure 3.1): Segment A was a 63-km-long section from near the headwaters of the Clark Fork River at Warm Springs downstream to the Little Blackfoot River confluence; Segment B was 42 km in length and was bounded downstream by the Flint Creek confluence; and Segment C was 84 km in length and extended downstream to the Blackfoot River confluence.

Habitat

To characterize segment differences, I determined floodplain width, percent of mining contamination in the floodplain, and dissolved copper concentration among the

three study segments. Mean floodplain width was calculated by measuring the width of the 50-year flood line (FEMA, no date) at every kilometer, using ArcMap Version 9.3.1 (ESRI 2009), and then calculating the mean for each segment. Sinuosity was measured by taking segment length and dividing by the down-valley distance (McMahon et al. 1996) using a 100k named streams shapefile. The area of streamside tailing deposits for each segment was determined from GIS data (University of Montana Riparian and Wetland Survey Team, no date), and divided by total floodplain area to obtain percentage of contamination. Maximum dissolved copper levels for mainstem segments was determined from heavy metal concentration data collected eight times per year at U.S. Geological Survey (USGS) gauge stations located within each study segment on the mainstem (Figure 3.1). Maximum dissolved copper concentration in tributaries was derived from USGS water samples collected sporadically from 2000 to 2011 from three different major tributaries: Little Blackfoot River, Flint Creek, and Rock Creek. To determine seasonal patterns of dissolved copper concentrations for each mainstem I assessed the relation between copper concentration and discharge for each gauge station separately using simple linear regression, and the resulting regressions were used to predict daily copper concentration within each segment (Figure 3.2).

Radiotelemetry

Survival and movement of brown trout and cutthroat trout were assessed through the monitoring of fish outfitted with radio tags. Tags were systematically distributed in fish over the entire mainstem at an average of about 1 tag per 0.8 river kilometers, following the general distribution patterns of the two study species. Tagged fish were

adult trout ranging in size from 282 mm to 570 mm, and transmitter weight did not exceed the recommended 4% of total fish body weight (Zale et al. 2005). Trout were captured by a boat-mounted electrofisher in April of 2009, 2010, and 2011. Additional fish were tagged in September 2010 in the mainstem and in two tributaries (Flint Creek and Little Blackfoot River) to assess survival and movement in tributaries.

Captured trout were anesthetized with tricaine methanesulfonate, identified by species, measured, and weighed. Cutthroat trout were identified as pure westslope cutthroat trout or hybridized with rainbow trout based on visual characteristics (Weigel et al. 2002). Hybrids with predominantly westslope cutthroat trout characteristics were combined with pure cutthroat trout for analysis. Anesthetized fish were placed into a V-shaped surgery frame and the tag was inserted into the abdomen using the shielded-needle technique (Ross and Kleiner 1982). Gills were irrigated during surgery with a bulb syringe, and the incision was closed using 2 to 3 sterile surgical staples (size 35W) or absorbing sutures (3.0 gauge), inserted approximately 1 cm apart. Radio tags (Lotek Wireless, Newmarket, Ontario) weighed 8.0 gm or 10.0 gm in air, and were set to a 12 hour on/12 hour off schedule. Most tags (67%) were equipped with mortality sensors. Transmitter frequency ranged from 148.500 to 148.560 MHz, and maximum battery life was estimated at 685 to 877 days, depending on transmitter size. Following surgery, fish were placed in a live cage until they regained equilibrium (usually less than ten minutes), and were released near the point of capture.

Radio-tagged fish were relocated weekly from April 2009 to December 2011, except during winter months (January and February) when survey frequency was reduced to every other week. Fish were primarily relocated from nearby roads using a

combination of a car-mounted omni-directional antenna and a directional 3-element Yagi antenna. Areas with limited road access were surveyed by boat. When a fish's radio signal was detected, the trout was located by triangulation, and the coordinates of the location were determined with a hand-held global positioning unit. Relocation accuracy was estimated to be 100 m based on trials with dummy tags. Location was converted to river kilometer using ArcMap Version 9.3.1 (ESRI 2009). Time and location of mortality for those trout lacking mortality sensor transmitters was estimated when tags were relocated in the same location for several weeks and no movement was detected when disturbed.

Survival and Movement Analysis

Multistate mark-recapture analysis of telemetry data was used to estimate trout survival and movement rates among study segments following the approach of Buchanan and Skalski (2010) and Perry et al. (2010). Relocated fish were categorized into one of five 'states' for the analysis: either one of the three mainstem study segments (A, B, or C), a tributary (T), or as a confirmed mortality ('dead state'; D) (Figure 3.3). For each week, transition probabilities were estimated among states based on whether a fish (1) remained alive in its current location; (2) remained alive and moved to another location; or (3) died (Figure 3.3). Encounter histories were created for each fish listing the state occupied each week. Weeks when a fish was not detected were indicated with a '0' in the encounter history and used for analysis to estimate detection probability and error associated with estimates. Data were censored when transmitter batteries likely had failed.

Weekly transition rates between live states (ψ^{rs}) were estimated, where r and s were the states (segment locations) occupied by a fish during week t and $t+1$, respectively. Weekly mortality transition rates (ψ^{rD}) were estimated in a similar fashion, where r indicated the location state in week t and D indicated the dead state in week $t+1$. Weekly survival rate for a fish alive in location r was determined by subtracting the estimated weekly mortality rate (ψ^{rD}) from 1. Annual survival rates for each location state (segment A, B, C, or T) were estimated by calculating the product of weekly survival rates for all weeks of the year, with the standard error of the estimate determined using the delta method (Powell 2007) in Program R (R Core Development Team 2010) and the ‘msm’ package (Jackson 2011).

Estimation of error associated with transition rate estimates in multistate models can be influenced by detection probability, p , and by S , which is the probability that a fish remains in the study area and is relocated during a given week. I held S and p constant over all segments and time periods but allowed estimates of each parameter to be different by species. I expected different p and S values for cutthroat trout due to their greater propensity for movement between relocations, which decreased the probability of weekly detection. For all movement and survival rates, I accounted for the possibility that a fish could leave the study area with its fate undetected by multiplying transition rate estimates by S and calculating new standard errors using the delta method (Powell 2007).

A series of multistate models were developed to assess differences in survival and movement rates among locations and seasons. Seasonal differences in survival and movement were determined by grouping weekly transition rates into four different biologically meaningful seasonal time periods: Spring (late-March to mid-June):

characterized by high discharge and elevated dissolved copper concentrations; Summer (mid-June to mid-September): characterized by low discharge, low copper concentrations, and higher temperatures interspersed with occasional pulses of high copper concentrations during elevated discharges from summer thunderstorms (Luoma et al. 2008); Fall (mid-September to late-December): characterized by low discharge, decreasing temperatures, and low copper concentrations; and Winter (late-December to late-March): characterized by low discharge and presence of ice cover. Models that tested for temporal variation allowed each season to have different transition rates, whereas models without temporal variation had the same transition rates across all seasons. Survival and movement differences among locations were evaluated by comparing models with constant or varying transition rates among segments. Overall, eight different combinations of survival and movement rate models were evaluated (Table 3.2). For all models, survival and movement rates were calculated independently for each species.

Models were run in Program MARK (White and Burnham 1999). Model selection was accomplished using Akaike's information criterion adjusted for sample size (AIC_c; Burnham and Anderson 1998). Model goodness-of-fit was assessed using the median c-hat test in Program MARK. This test is a surrogate for a traditional goodness-of-fit test in models that are not fully time-independent (White and Burnham 1999; Cooch and White 2004), and uses simulations to estimate overdispersion and model fit for the most general model, the one which has the greatest number of parameters, in this case, Model 3, wherein survival and movement rates vary by location and season (Table 3.2).

Mean time of residency and mean posttagging 'life expectancy' of fish occupying different segment locations was estimated using matrix population analysis for stage-

structured population models (Caswell 2001). I considered each of the four different location states (segments A, B, C, and T) as the different ‘life’ stages in the matrix. The estimated movement transition rates and S estimates from the top-ranked model were used to create a transition matrix ($\mathbf{T}$) that contains the weekly likelihood estimates of a fish surviving and remaining in the same segment (e.g., staying in segment A from week t to $t+1$: $S(\psi^{AA})$) or moving to another segment (e.g., $S(\psi^{AB})$):

$$\mathbf{T} = \begin{bmatrix} S(\psi^{AA}) & S(\psi^{BA}) & S(\psi^{CA}) & S(\psi^{TA}) \\ S(\psi^{AB}) & S(\psi^{BB}) & S(\psi^{CB}) & S(\psi^{TB}) \\ S(\psi^{AC}) & S(\psi^{BC}) & S(\psi^{CC}) & S(\psi^{TC}) \\ S(\psi^{AT}) & S(\psi^{BT}) & S(\psi^{CT}) & S(\psi^{TT}) \end{bmatrix}$$

To estimate the mean residency time of fish per segment, by tagging location, I calculated the fundamental matrix ($\mathbf{F}$) of $\mathbf{T}$ by using the equation:

$$\mathbf{F} = (\mathbf{I} - \mathbf{T})^{-1}$$

where $\mathbf{I}$ is an identity matrix with the same dimensions as $\mathbf{T}$ (Caswell 2001: Chapter 5). Mean estimated life expectancy by tagging segment was calculated from $\mathbf{F}$ by summing all mean residency times for each tagging segment (Zipkin et al. 2010). Because I was using parameter estimates to populate $\mathbf{T}$, there is error associated with each value and therefore in the calculation of $\mathbf{F}$. Monte Carlo simulations were run in order to calculate the standard deviation of $\mathbf{F}$. All statistical matrix analysis was completed in Program R (R Development Core Team 2010).

Results

Habitat

Study segments differed substantially in habitat, extent of mining contamination, and dissolved copper concentrations (Table 3.1). Segment A had a wide floodplain with extensive mining tailing deposits (63.3 hectares; 2.3% of floodplain) and high dissolved copper concentrations that regularly exceeded EPA acute standards for dissolved copper (13.0 µg/L; USEPA 1986), especially during high discharge (Figure 3.2). Segment B also had a wide floodplain but contained much less extensive floodplain tailings (15.6 hectares; 0.1% of floodplain) and moderate dissolved copper concentrations that exceeded acute levels only during peak discharge events. Segment C had a relatively narrow floodplain, an absence of floodplain mining tailing deposits, and comparatively low dissolved copper concentrations that did not exceed acute levels. Dissolved copper concentration measured sporadically in the three tributaries tested ranged from 0.0 to 1.7 µg/L.

Radiotelemetry

A total of 185 brown trout and 71 cutthroat trout were radio-tagged between April 2009 and April 2011 (Table 3.3). Radio-tagged fish were relocated from April 2009 to December 2011, which yielded 6,389 total relocations and an average of 35 weekly relocations per individual fish. Twenty-six fish were relocated for more than one year, and five fish were relocated for more than two years.

Model Selection

There was no evidence for overdispersion among the multistate models tested (median $\hat{c}$ = 0.99, 0.97- 1.01 95% C.I.), indicating that our data fits the most general model that we investigated (Model 3). Only models wherein survival transition rates were allowed to vary by segment received weak to strong support (Table 3.2). The most parsimonious model was Model 1 wherein movement and survival rates were allowed to differ by segment but were held constant through time (no seasonal effect). Because of lack of support for other models, parameter estimates from Model 1 were used for analysis. Detection probability was estimated as 0.57 (SE = 0.01) for brown trout and 0.56 (SE = 0.01) for cutthroat trout. Very few radio-tagged fish were unaccounted for, therefore S was estimated by Model 1 to be 0.99 (SE < 0.01) for both species.

Survival

Survival rates varied substantially by species and by location. Lowest weekly survival for both species occurred in segment A, the segment with the highest floodplain copper deposits and dissolved copper concentrations (Table 3.4). In this segment, weekly survival was 0.97 (SE < 0.01) for brown trout and 0.90 (SE = 0.04) for cutthroat trout, yielding estimated annual survival rates of 0.25 (SE = 0.04) and 0.01 (SE = 0.01) for the two species, respectively (Figure 3.4). In contrast, survival for brown trout was much greater in segment C, the mainstem segment with no floodplain mining deposits and relatively low dissolved copper concentrations, with weekly and annual survival estimates of 0.99 (SE < 0.01) and 0.50 (SE = 0.07), respectively. Brown trout in segment B, which had intermediate levels of mining contamination, had intermediate survival

rates (weekly, 0.97; annual, 0.32). Highest survival for cutthroat trout occurred in segment B, with weekly and annual survival estimated at 0.97 (SE = 0.01) and 0.17 (SE = 0.11), respectively. Survival rates for cutthroat trout in tributaries, that had little or no copper contamination, were nearly as low as in most contaminated segment, with weekly and annual survival rates of 0.92 (SE = 0.02) and 0.01 (SE = 0.01), respectively. Tributary survival estimates for brown trout were also low, with weekly and annual survival rates of 0.98 (SE < 0.01) and 0.36 (SE = 0.08), respectively.

Matrix analysis showed that estimated life expectancy was much lower for cutthroat trout than for brown trout (Figure 3.5). Mean life expectancy across all locations was 43.2 to 67.6 weeks for brown trout and only 12.6 to 20.2 weeks for cutthroat trout, with cutthroat trout life expectancy averaging 31% lower than that of brown trout. Life expectancy for cutthroat trout was particularly low in segment A (12.6 weeks) and in tributaries (14.9 weeks), whereas expectancy was 20-60% greater in segments B and C (17.9 and 20.2 weeks). Similar patterns in life expectancy were observed for brown trout, with expectancy highest in segment C (67.6 weeks) and lowest in segment A (43.2 weeks; 35% lower than in segment C).

Movement

Movement among segments was relatively rare, but regardless, the estimated movement probabilities differed by species. For brown trout, the probability of remaining in the same segment between weekly relocations was similar across all sites, ranging from 0.95 (SE = 0.01) to 0.98 (SE < 0.01) per week (Table 3.5). Cutthroat trout exhibited greater movement, averaging 15% lower weekly probability of remaining in the same

location than brown trout; 0.81 (SE = 0.05) to 0.92 (SE = 0.02). For both species, movement away from the home segment was most likely to a neighboring tributary (0.01, brown trout; 0.04-0.09, cutthroat trout). Movement between mainstem segments was rare for both species (≤ 0.01).

Mean tagging location residency times of brown trout derived from matrix analysis ranged from 23.5 (SD = 3.3) to 47.6 (SD = 6.8) weeks, with the longest duration estimated for fish tagged in segment C and other locations averaging about 50% less residency time (Table 3.6). Cutthroat trout residency times in tagging locations were generally lower than for brown trout across all segments, ranging from 5.4 (SD = 1.4) to 13.5 (SD = 1.9) weeks, reflective of their greater movement propensity and lower survival rates (Table 3.6). Regardless of a fish's initial tagging location, individual brown trout spent a mean time of 4.1 (SD = 1.5) to 10.7 (SD = 3.4) weeks in all three of the other locations. Cutthroat trout spent little time in locations other than the segment they were tagged in (0.2 to 5.5 weeks), particularly when movement to segment A occurred; mean residency time for this location was less than one week, regardless of previous location. Tributary residency time was also much lower for cutthroat trout. Cutthroat trout tagged in the mainstem spent about 40% less time in tributaries than brown trout, with mean tributary residency time of 3.9 (SD = 1.0) to 4.7 (SD = 1.3) weeks for cutthroat trout and 5.8 (SD = 1.4) to 8.4 (SD = 2.0) weeks for brown trout.

Discussion

Despite some recovery of trout populations in the upper Clark Fork River over the past 40 years, my results strongly suggest that survival continues to be impaired by high

dissolved copper concentrations. There appeared to be a clear linkage between survival rates and the degree of copper exposure for both brown trout and cutthroat trout.

Although I expected to see a seasonal difference in survival rates based on my field observations, model results indicated that there was no statistical support for seasonal variation. Instead, survival and movement rates were better estimated by location and the variations in dissolved copper concentrations and land use practices in each segment. The lowest survival among mainstem segments was in the segment with the highest dissolved copper concentrations and highest percentage of floodplain mine tailing deposits. In this 63-km-long upstream segment, there were over 63 hectares of floodplain tailings and dissolved copper concentrations frequently exceeded acute concentrations during high discharge events. Accordingly, estimated annual survival for trout inhabiting this segment was the lowest among study segments, averaging only 0.25 for brown trout and 0.01 for cutthroat trout. Moreover, the low residency times of cutthroat trout and lower life expectancy of both species in this segment compared to other mainstem segments, suggest that both cutthroat trout and brown trout may be experiencing negative effects from high dissolved copper levels in this segment.

While field studies have examined trout avoidance of heavy metal contaminated areas (Hansen et al. 1995c; Goldenstein et al. 1999) and laboratory studies have determined mortality rates of trout fry and juveniles when exposed to copper (Marr et al. 1995b; Marr et al. 1998), estimating survival rates of adult trout within a mining contaminated area in the field has not been completed previous to this study. Although dissolved copper concentrations reached acute levels on a regular basis only in segment A, survival rates of brown trout among all mainstem study segments (0.25 - 0.50) were

well below expected. Vincent (1987) reported an annual survival of 0.67 for adult brown trout in the unimpaired Madison River in southwestern Montana. Despite the fact that trout could move to a less-contaminated area with higher estimated survival rates, trout that were tagged in segment A had low mean estimated life expectancies, which may be a result of the effects of long-term exposure to higher dissolved copper concentrations. Chronic exposure to heavy metals, especially copper, can lead to reduced growth, reduced feeding rates, and reduced swimming performance, factors that may be contributing to much lower than expected survival rates in the upper Clark Fork River (Atchison et al. 1987; Marr et al. 1995a; Woodward et al. 1995a; Farag et al. 2000). Other physiological impairments caused by copper that can decrease trout survival include reduction in chemoreceptor function (Hansen et al. 1999b; McIntyre et al. 2008) and inhibition of lateral line development (Linbo et al. 2006), a response which has been demonstrated at dissolved copper concentrations of 2.0 µg/L (Sandahl et al. 2007), a level lower than was observed in all mainstem segments of the upper Clark Fork River. Survival rates and life expectancy estimates were substantially lower for cutthroat trout than brown trout in all segments (Table 3.4; Figure 3.5), supporting previous studies that demonstrated a heightened sensitivity to heavy metal contamination in *Oncorhynchus* species compared to brown trout (Hansen et al. 1999c).

Based on previous studies that determined trout avoidance of heavy metal contamination at dissolved copper concentrations of less than 12.0 µg/L (Woodward et al. 1995b; Goldenstein et al. 1999; Hansen et al. 1999a and 1999c; Svecovicus 2001), we expected trout to avoid and emigrate from segment A at a much higher rate than other mainstem segments with lower dissolved copper levels, especially during periods of high

discharge when dissolved copper increases and exceeds the acute concentration standard. Instead, we observed very limited movement for trout residing in all segments; for both brown trout and cutthroat trout, the greatest movement rates between locations were between the mainstem and tributaries. This may be because most of the studies that analyzed avoidance behaviors were conducted in a laboratory setting with fish naïve to heavy metals, unlike our study fish that were reared in a heavy metal contaminated environment. Additionally, it is likely that the desire to spawn is overriding any olfactory detection of changes in heavy metal concentrations. Cutthroat trout were, on average, six times more likely to move into a tributary than brown trout, and cutthroat trout in segment A were over twice as likely to enter a tributary as those in other mainstem segments. Despite low estimates of weekly movement between segments, matrix analysis determined that brown trout will spend a mean duration of at least four weeks in each segment, regardless of tagging location, indicating that variable dissolved copper concentrations seem to have little effect on brown trout movement. Cutthroat trout are less likely to spend time in all mainstem segments; it is estimated that only cutthroat trout tagged in segment A are likely to spend more than one week there, which could indicate that cutthroat trout tagged in other reaches are avoiding segment A. We did not observe any cutthroat trout moving downstream from segment A into segments B or C. For both species, it is estimated that fish will spend the majority of their life in the segment in which they were tagged, even if tagged in a segment with higher dissolved copper concentrations and floodplain tailings. The lack of movement may be due to acclimation to copper contamination or copper-induced impairment of physiological function, such as olfactory senses, making them less likely to avoid to areas with higher copper

concentrations (Hansen et al. 1999a and 1999b; McIntyre et al. 2008). Fish acclimated to heavy metals may also begin to prefer concentration levels that they have previously been exposed to (Svecevicus 1999).

The clear linkage between survival rate and the degree of copper exposure that I observed for both brown trout and cutthroat trout in the upper Clark Fork River suggests that reduction of dissolved copper concentration could improve survival rates. Removal of tailings deposits in the uppermost seven kilometers in the early 1990's reduced accumulation of copper in aquatic organisms, water column dissolved copper concentrations, and sediment copper levels in segment A (Hornberger et al. 2009). My findings suggest that more extensive removal of tailings deposits in this segment and anticipated decreases in dissolved copper concentration, should improve trout survival rates accordingly. Moreover, improved survival would likely be observed in trout in downstream segments, given that brown trout from all segments were estimated to spend at least four weeks in segment A, which has the highest copper concentrations. Additionally, removal of tailing deposits in segment A would likely further reduce dissolved copper concentrations in downstream segments as tailing deposits mobilized from segment A travel downstream during high discharge (Luoma et al. 2008; Hornberger et al. 2009).

Survival rates of both brown trout and cutthroat trout in tributaries were much lower than expected given the very low dissolved copper concentrations observed therein. Cutthroat trout in tributaries experiences survival rates as low as those observed in segment A; brown trout in tributaries had better survival rates, but were still lower than those in mainstem segment C. High postspawning mortality for westslope cutthroat trout

has been observed in other systems and has been attributed to high predation rates in tributaries (Schmetterling 2001). Tributaries in the upper Clark Fork River have many anthropogenic effects that are limiting trout survival, including unscreened irrigation diversions, dewatering, and migration barriers (Saffel et al. 2011). Indeed, I observed three cutthroat trout die in unscreened irrigation diversions while migrating from tributaries postspawning. Improved fish passage would likely further increase survival and increase population densities of trout. Monitoring trout population response to reductions in dissolved copper levels and improved tributary habitat quality is a needed next step to evaluating the success of future rehabilitation of this severely mining-impacted system and the restoration potential of other mining impacted areas.

The low survival estimates obtained in this analysis raise questions about how trout are able to survive even short periods of time in the mainstem upper Clark Fork River, and especially how juveniles survive to become mature adults. One part of this puzzle may be explained by source-sink dynamics; the mainstem river may act as a population sink while trout are coming from other source habitats, likely tributaries which have no heavy metal contamination. During electrofishing surveys on the mainstem, juvenile trout are rarely observed; instead, the trout caught during these surveys are often from similar size classes (J. Lindstrom and B. Liermann, Montana Fish, Wildlife, and Parks, personal communication). It may be that trout are rearing in tributaries and only entering the mainstem once they become too large for tributaries, at which point their likelihood of survival is reduced. Habitat use data from this study (Chapter 2) may help to identify important spawning and rearing areas, but further

investigation is needed to fully understand the potential source-sink dynamics of the system.

Radiotelemetry is a widely used tool in fisheries, but it has primarily been used to determine movement patterns and habitat use (e.g., Chapter 2; Clapp et al. 1990; Goldenstein et al. 1999). In my study, I was able to use a unique application of multistate modeling to directly estimate survival and movement in the field among areas differing in habitat and water quality using standard radiotelemetry techniques. Multistate modeling can be used to estimate movement rates over different temporal and spatial scales (Buchanan and Skalski 2010; Perry et al. 2010), transition probabilities from one life stage to another (Hadley et al. 2006), or even to measure growth rates from one size class to the next. Using multistate modeling techniques in conjunction with traditional radiotelemetry studies can greatly expand knowledge of fish population dynamics and can help guide population restoration efforts.

Tables

TABLE 3.1. Segment habitat and water quality characteristics of the three mainstem segments (A, B, and C) and tributary segment (T) used for multistate analysis.

	Segments			
	A	B	C	T
Mean floodplain width (m) (S.E.)	704 (43)	686 (115)	410 (31)	--
Sinuosity Index	1.6	1.3	1.2	--
Mine tailings area (hectares)	63.3	15.6	0.0	--
Floodplain mine tailings (%)	2.3	0.1	0.0	--
Max Dissolved Copper ($\mu\text{g/l}$)	45.9	23.3	11.2	1.7

TABLE 3.2. Model selection results for the eight multistate models tested using various combinations of survival and movement rates. ‘Constant’ indicates that the model held transition rate estimates equal for all locations segments (spatial) or seasonal time periods (temporal). ‘Variable’ indicates models that allowed transition rate estimates to vary. ‘Did not converge’ refers to models where maximum likelihood estimates could not be calculated, even using the alternative optimization method in Program MARK (White and Burnham 1999).

Model	<i>Movement rates</i>		<i>Survival rates</i>		AIC _c	Δ AIC _c	AIC _c Weight	Number of parameters
	Spatial	Temporal	Spatial	Temporal				
1	variable	constant	variable	constant	14556.89	0.00	1.00	38
2	constant	constant	variable	constant	14566.89	10.01	0.00	34
3	variable	variable	variable	variable	14575.41	18.52	0.00	134
4	variable	constant	variable	variable	14579.13	22.24	0.00	62
5	constant	constant	variable	constant	14634.61	77.73	0.00	22
6	constant	constant	constant	constant	14639.66	82.78	0.00	16
7	constant	variable	constant	variable	Did not converge			
8	variable	variable	constant	variable	Did not converge			

TABLE 3.3. Number and date of implantation of radio tags into brown trout and cutthroat trout in the upper Clark Fork River, Montana.

Tagging date	Brown trout	Cutthroat trout
April 2009	72	21
April 2010	59	34
September 2010	45	5
April 2011	9	11
<i>Total</i>	<i>185</i>	<i>71</i>

TABLE 3.4. Estimates of weekly survival rates (95% confidence intervals in parentheses) for brown trout and cutthroat trout in the three mainstem segments (A, B, and C) and in tributaries (T) of the upper Clark Fork River, Montana.

Segment	Brown trout	Cutthroat trout
A	0.97 (0.97 – 0.98)	0.90 (0.84 – 0.97)
B	0.98 (0.97 – 0.99)	0.97 (0.94 – 0.99)
C	0.99 (0.98 – 0.99)	0.95 (0.94 – 0.97)
T	0.98 (0.97 – 0.98)	0.92 (0.87 – 0.94)

TABLE 3.5. Estimated probability of weekly movement (SE in parentheses) among segments for brown trout (BR) and cutthroat trout (CT) in the upper Clark Fork River, Montana. Probabilities for remaining in the same location between weeks are shown in bold.

			Location at time t			
			A	B	C	T
Location at time $t+1$	A	BR	0.96 (<0.01)	<0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)
		CT	0.81 (0.05)	0.01 (0.01)	<0.01 (<0.01)	<0.01 (<0.01)
	B	BR	<0.01 (<0.01)	0.96 (0.01)	<0.01 (<0.01)	0.01 (<0.01)
		CT	0.00 (0.00)	0.92 (0.02)	<0.01 (<0.01)	0.01 (0.01)
	C	BR	<0.01 (<0.01)	<0.01 (<0.01)	0.98 (<0.01)	0.01 (<0.01)
		CT	0.00 (0.00)	0.00 (0.00)	0.91 (0.01)	0.06 (0.02)
	T	BR	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.95 (0.01)
		CT	0.09 (0.04)	0.04 (0.04)	0.04 (0.01)	0.84 (0.02)

TABLE 3.6. Estimated mean numbers of weeks spent in each segment (SD in parentheses), by tagging location, for brown trout (BR) and cutthroat trout (CT). Bold values indicate the mean number of weeks spent in the same segment as the fish was tagged.

			Tagging segment			
			A	B	C	T
Mean duration spent per segment (in weeks)	A	BR	29.1 (3.1)	7.0 (1.7)	6.0 (1.7)	9.7 (2.3)
		CT	5.4 (1.4)	0.5 (0.6)	0.2 (0.3)	0.3 (0.4)
	B	BR	4.2 (1.2)	28.6 (3.7)	6.3 (1.9)	8.6 (2.4)
		CT	0.7 (0.5)	13.0 (2.9)	0.9 (0.7)	1.4 (0.9)
	C	BR	4.1 (1.5)	7.3 (2.5)	47.6 (6.8)	10.7 (3.4)
		CT	2.7 (1.1)	3.1 (1.1)	13.5 (1.9)	5.5 (1.5)
	T	BR	5.8 (1.4)	8.4 (2.0)	7.7 (2.0)	23.5 (3.3)
		CT	4.1 (1.4)	4.7 (1.3)	3.9 (1.0)	8.4 (1.3)

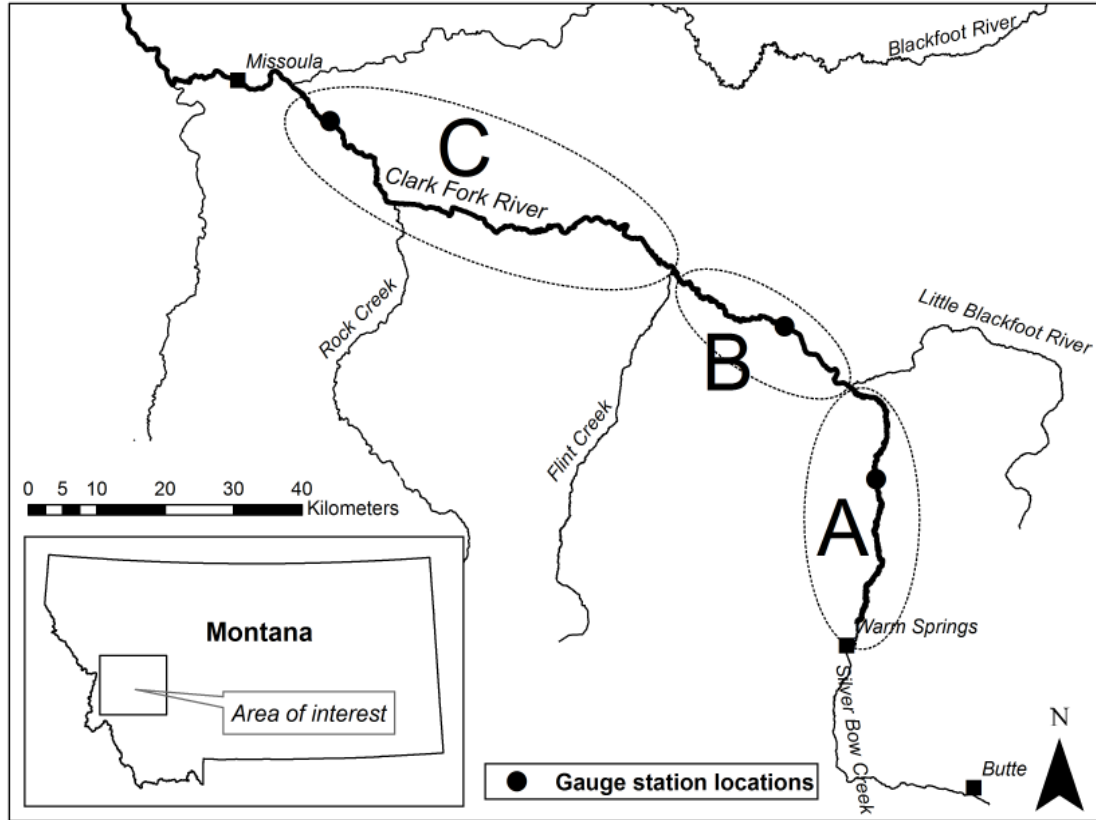
Figures

FIGURE 3.1. Map of the upper Clark Fork River, Montana, showing the location of the three mainstem segments, major tributaries and towns, and locations of three discharge gauge stations where dissolved copper concentrations were measured.

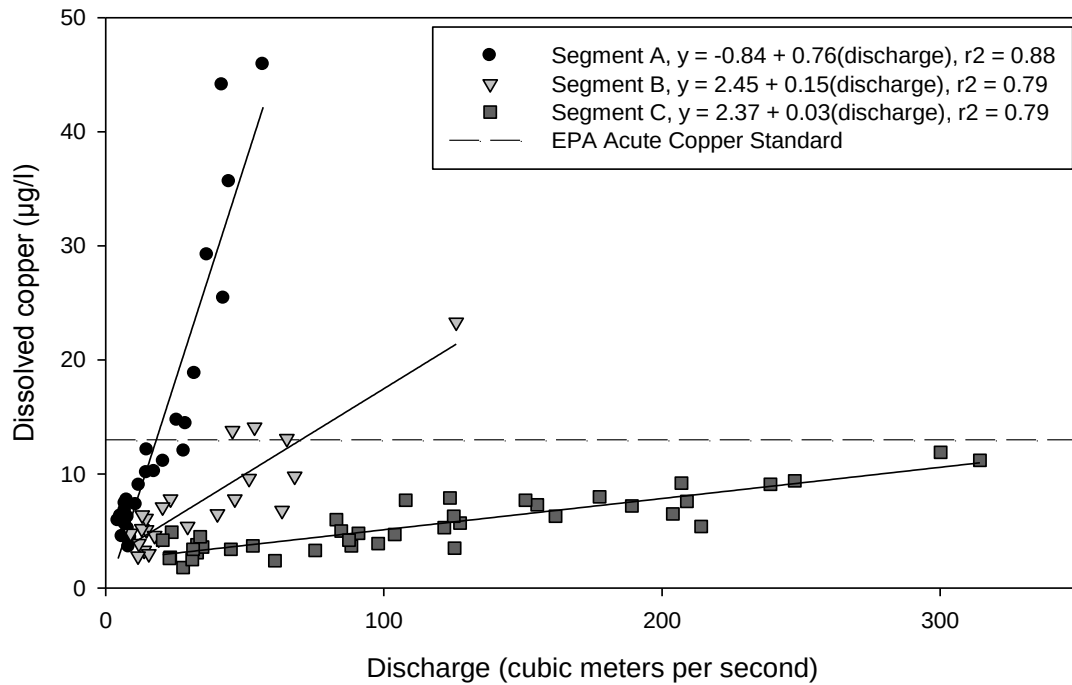


FIGURE 3.2. Linear relationship between dissolved copper concentration and discharge for the three mainstem segments, 2009 to 2011 combined. The reference line is the acute toxicity standard for copper by the EPA (13.0 µg/L at water hardness of 100 mg/L; USEPA 1986).

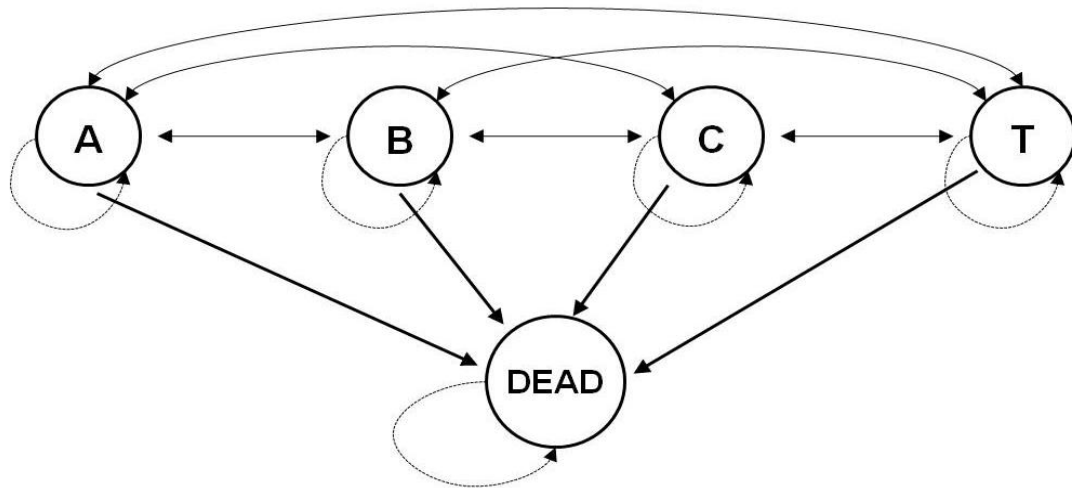


FIGURE 3.3. Multistate model displaying all possible transitions for a tagged fish: (1) stay in current location (light dashed arrows); (2) move to another location; or (3) die (bold arrows).

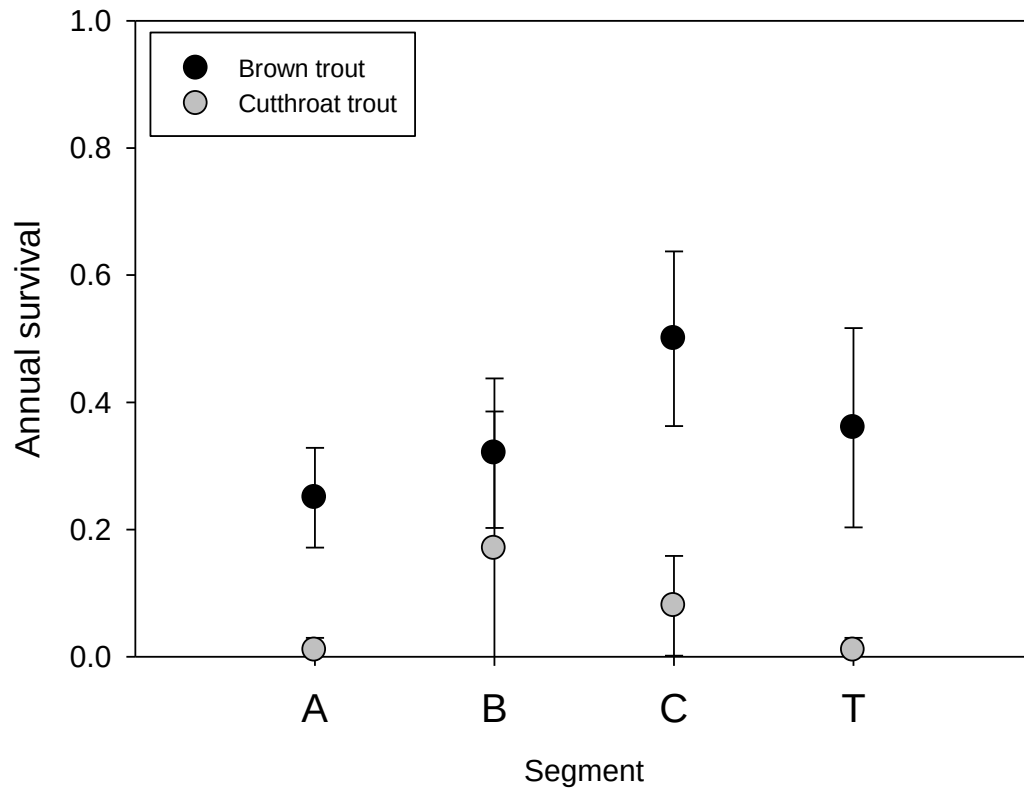


FIGURE 3.4. Estimates of annual survival rates (with 95% confidence intervals) for brown trout and cutthroat trout in the three mainstem segments (A, B, and C) and in tributaries (T) of the upper Clark Fork River, Montana. These annual survival rates are calculated based on the assumption that a radio-tagged fish stays in the same segment for an entire year.

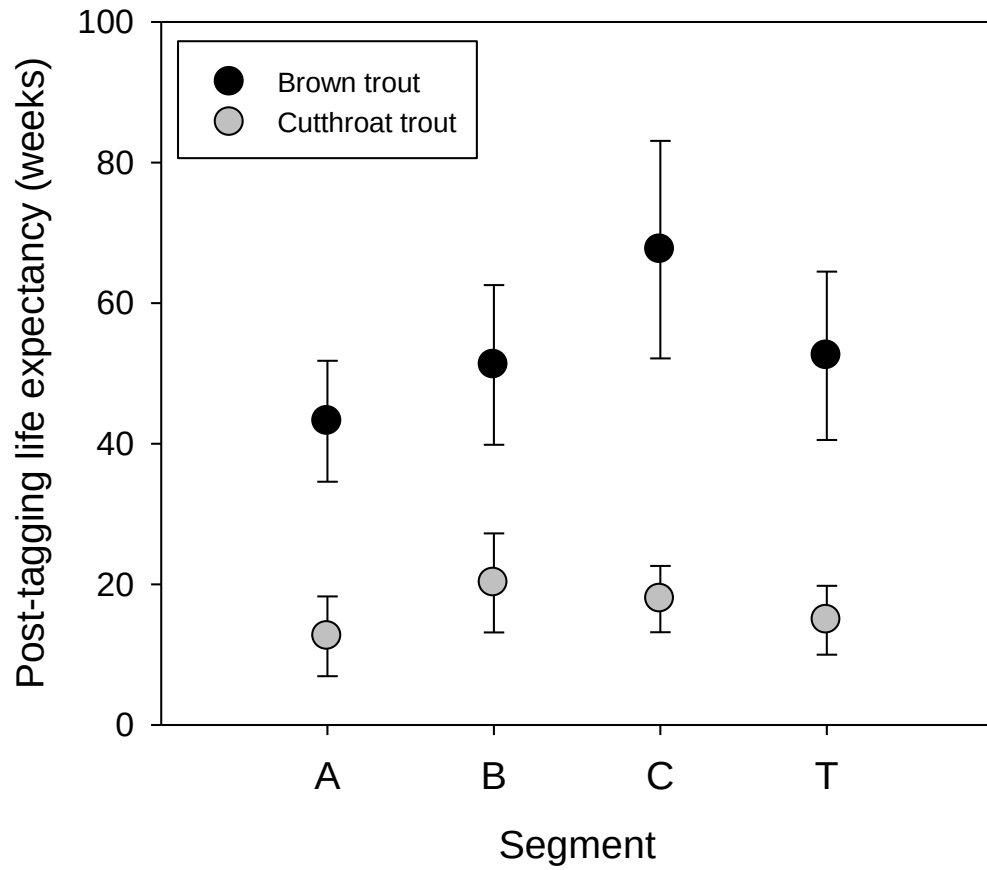


FIGURE 3.5. Mean posttagging life expectancy (95% confidence intervals) of brown trout and cutthroat trout, in the upper Clark Fork River, Montana, by location of tagging; mainstem segments (A, B, and C) or tributary (T).

Literature Cited

- Atchison G. J., M.G. Henry, and M. B. Sandheinrich. 1987. Effects of metals on fish behavior: a review. *Environmental Biology of Fishes* 18: 11-25.
- Buchanan, R. A, and J. R. Skalski. 2010. Using multistate mark-recapture methods to model adult salmonid migration in an industrialized river. *Ecological Modelling* 221: 582–589.
- Burnham, K. P. and D. R. Anderson. 1998. *Model selection and inference: a practical information-theoretic approach*. Springer-Verlag, New York, NY.
- Caswell, H. 2001. *Matrix Population Models: Construction, Analysis and Interpretation*. 2nd edition. Sinauer Associates, Sunderland, MA. 722 p.
- Clapp, D. F., R. D. Clark, and J. S. Diana. 1990. Range, activity, and habitat of large, free-ranging brown trout in a Michigan stream. *Transactions of the American Fisheries Society* 119:1022-1034.
- Clark Fork Coalition. 2011. Aquatic restoration strategy for the upper Clark Fork Basin: elements of an integrated approach. Available: <http://www.clarkfork.org/programs/restore.html> (April 2011).
- Cooch, E., White, G., 2004. Using MARK – A Gentle Introduction. Available: <http://www.phidot.org/software/mark/docs/book/markbook.exe>. (September 2011).
- ESRI (Environmental Systems Resource Institute). 2009. ArcMap 9.3.1. ESRI, Redlands, California.
- Farag, A. M., M. J. Suedkamp, J. S. Meyer, R. Barrows, and D. F. Woodward. 2000. Distribution of metals during digestion by cutthroat trout fed benthic invertebrates contaminated in the Clark Fork River, Montana and the Coeur d’Alene River, Idaho, U.S.A., and fed artificially contaminated *Artemia*. *Journal of Fish Biology* 56: 173–190.
- FEMA (Federal Emergency Management Agency). Upper Clark Fork River floodplain. Available: <http://nris.mt.gov> (November 2009).
- Finger, S. E., S. E. Church, and P. von Guerrard. 2007. Potential for successful ecological remediation, restoration, and monitoring. Chapter F in *Integrated investigations of environmental effects of historical mining in*

- the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651. S. E. Church, P. von Guerard, and S. E. Finger, eds., 2007, 1,096 p. plus CD-ROM. [In two volumes.]
- Goldenstein, J. N., D. F. Woodward, and A. M. Farag. 1999. Movements of adult Chinook salmon during spawning migration in a metals-contaminated system, Coeur d'Alene River, Idaho. *Transactions of the American Fisheries Society* 128: 121-129.
- Hadley, G. L., J. J. Rotella, R. A. Garott, and J. D. Nichols. 2006. Variation in probability of first reproduction of Weddell seals. *Journal of Animal Ecology* 75:1058–1070.
- Hansen, J. A., J. C. A. Marr, J. Lipton, D. Cacela, and H. L. Bergman. 1999a. Differences in neurobehavioral responses of Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*) exposed to copper and cobalt: behavioral avoidance. *Environmental Toxicology and Chemistry* 18: 1972–1978.
- Hansen, J. A., J. D. Rose, R. A. Jenkins, K. G. Gerow, and H. L. Bergman. 1999b. Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*) exposed to copper: neurophysiological and histological effects on the olfactory system. *Environmental Toxicology and Chemistry* 18: 1979–1991.
- Hansen, J. A., D. F. Woodward, E. E. Little, A. J. DeLonay, and H. L. Bergman. 1999c. Behavioral avoidance: possible mechanisms for explaining abundance and distribution of trout species in a metal-impacted river. *Environmental Toxicology and Chemistry* 18: 313-317.
- Hornberger, M. I., S. N. Luoma, M. L. Johnson, and M. Holyoak. 2009. Influence of remediation in a mine-impacted river: metal trends over large spatial and temporal scales. *Ecological Applications* 19: 1522-1535.
- Jackson, C. 2011. Package 'msm'. Available: <http://cran.r-project.org/web/packages/msm/msm.pdf> (May 2012).
- Lewis, M. A. and R. Burroughs. 1979. Impact of copper mining on a desert intermittent stream in central Arizona: a summary. *Journal of the Arizona-Nevada Academy of Science* 14: 22-29.
- Lindo, T. L., C. M. Stehr, J. P. Incardona, and N. L. Scholz. 2006. Dissolved copper triggers cell death in the peripheral mechanosensory system of larval fish. *Environmental Toxicology and Chemistry* 25: 597–603.

- Lipton, J. and 16 coauthors. 1995. Aquatic resources injury assessment report: Upper Clark Fork River basin. State of Montana, Natural Resource Damage Litigation Program, Helena.
- Luoma, S. N., J. N. Moore, A. M. Farag, T. H. Hillman, D. J. Cain, and M. Hornberger. 2008. Mining impacts on fish in the Clark Fork River, Montana: A field ecotoxicology case study. Pages 779-804 in R. T. DiGuilio and D. E. Hinton, editors. *The toxicology of fishes*. CRC Press, Boca Raton, Florida.
- Marr, J. C. A., H. L. Bergman, J. Lipton, and C. Hogstrand. 1995a. Differences in relative sensitivity of naives and metals-acclimated brown and rainbow trout exposed to metals representative of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2016-2030.
- Marr, J. C. A., H. L. Bergman, M. Parker, J. Lipton, D. Cacela, W. Erickson, and G. R. Phillips. 1995b. Relative sensitivity of brown and rainbow trout to pulsed exposures of an acutely lethal mixture of metals typical of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2005-2015.
- Marr, J. C. A., J. A. Hansen, J. S. Meyer, D. Cacela, T. Podrabsky, J. Lipton, and H. L. Bergman. 1998. Toxicity of cobalt and copper to rainbow trout: application of a mechanistic model for predicting survival. *Aquatic Toxicology* 43: 225-238.
- McIntyre, J. K., D. H. Baldwin, J. P. Meador, and N. L. Scholz. 2008. Chemosensory deprivation in juvenile coho salmon exposed to dissolved copper under varying water chemistry conditions. *Environmental Science and Technology* 42: 1352-1358.
- McMahon, T. E., A. V. Zale, and D. J. Orth. 1996. Aquatic habitat measurements. Pages 83-120 in B. R. Murphy and D. W. Willis, editors. *Fisheries techniques, second edition*. American Fisheries Society, Bethesda, Maryland.
- Nelson, R. L., M. L. McHenry, and W. S. Platts. 1991. Mining. Pages 425-457 in W. R. Meehan, editor. *Influences of forest and rangeland management on salmonid fishes and their habitats*. American Fisheries Society, Bethesda, Maryland.
- Perry, R. W., J. R. Skalski, P. L. Brandes, P. T. Sandstrom, A. P. Klimley, A. Ammann, and B. MacFarlane. 2010. Estimating survival and migration route probabilities of juvenile Chinook salmon in the Sacramento-San Joaquin River Delta, North American Journal of Fisheries Management 30: 142-156.
- Phillips, G. and J. Lipton. 1995. Injury to aquatic resources caused by metals in Montana's Clark Fork River basin: historic perspective and overview. *Canadian Journal of Fisheries and Aquatic Science* 52: 1990-1993.

- Powell, L. A. 2007. Approximating variance of demographic parameters using the delta method: a reference for avian biologists. *The Condor* 109: 949–954.
- R Development Core Team. 2010. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available: <http://www.r-project.org> (January 2010).
- Ross, M. J. and C. F. Kleiner 1982. Shielded-needle technique for surgically implanting radio-frequency transmitters in fish. *Progressive Fish-Culturist* 44: 41-43.
- Saffel, P., B. Liermann, J. Lindstrom, L. Knotek, T. Mostad, and C. Fox. 2011. Prioritization of tributaries in the upper Clark Fork River basin for fishery enhancement. Retrieved from: <http://www.doj.mt.gov/lands/naturalresource/resources/projects/2010tributaryprioritization.pdf>.
- Sandahl, J. F., D. H. Baldwin, J. J. Jenkins, and N. L. Scholz. 2007. A sensory system at the interface between urban storm water runoff and salmon survival. *Environmental Science and Technology* 41: 2998-3004.
- Schmetterling, D. A. 2001. Seasonal movements of fluvial westslope cutthroat trout in the Blackfoot River Drainage, Montana. *North American Journal of Fisheries Management* 21: 507-520.
- Svecevicius, G. 1999. Fish avoidance response to heavy metals and their mixtures. *Hydrobiologia* 9: 103-113.
- Svecevicius, G. 2001. Avoidance response of rainbow trout *Oncorhynchus mykiss* to heavy metal mixtures: A comparison with acute toxicity tests. *Bulletin of Environmental Contamination and Toxicology* 67: 680-687.
- University of Montana Riparian and Wetland Survey Team. Upper Clark Fork tailing deposits. Available at <http://nr.is.mt.gov> (November 2009).
- USEPA (U.S. Environmental Protection Agency). 1986. Quality Criteria for Water (EPA Gold Book). EPA 440/5-86-001. U.S. EPA, Office of Water. 1986.
- USEPA. 2000. Liquid assets: America's water resources at a turning point. EPA-840, Washington, DC.
- Vincent, E. R. 1987. Effects of stocking catchable-size hatchery rainbow trout on two wild trout species in the Madison River and O'Dell Creek, Montana. *North American Journal of Fisheries Management* 7: 91-105.

- Weigel, D. E., J. T. Peterson, and P. Spruell. 2002. A model using phenotypic characteristics to detect introgressive hybridization in wild westslope cutthroat trout and rainbow trout. *Transactions of the American Fisheries Society* 131: 389-403.
- White, G.C. and K. P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. *Bird Study* 46 Supplement: 120-138.
- Woodward, D. F., A. M. Farag, H. L. Bergman, A. J. DeLonay, E. E. Little, C. E. Smith, and F. T. Barrows. 1995a. Metals-contaminated benthic invertebrates in the Clark Fork River, Montana: effects on age-0 brown trout and rainbow trout. *Canadian Journal of Fisheries and Aquatic Science* 52: 1994-2004.
- Woodward, D. F., J. A. Hansen, H. L. Bergman, E. E. Little, and A. J. DeLonay. 1995b. Brown trout avoidance of metals in water characteristic of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2031-2037.
- Woody, C. A., R. M. Hughes, E. J. Wagner, T. P. Quinn, L. H. Roulson, L. M. Martin, and K. Griswold. 2010. The mining law of 1872: change is overdue. *Fisheries* 35: 321-331.
- Zale, A. V., C. Brooke, and W. C. Fraser. 2005. Effects of surgically implanted transmitter weights on growth and swimming stamina of small adult westslope cutthroat trout. *Transactions of the American Fisheries Society* 134: 653-660.
- Zipkin, E. F., C. S. Jennelle, and E. G. Cooch. 2010. A primer on the application of Markov chains to the study of wildlife disease dynamics. *Methods in Ecology & Evolution* 1: 192-198.

CHAPTER 4

CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

The primary purpose of this study was to identify factors that continue to limit native and nonnative trout populations in the upper Clark Fork River Superfund Site, in order to help direct remediation efforts. By using radiotelemetry, I was able to provide an understanding of how heavy metals related to mining contamination are affecting trout movement, habitat use, and survival. What I found was that elevated levels of heavy metals are continuing to reduce survival in brown trout and cutthroat trout, and, in cutthroat trout, are resulting in an avoidance of the upper, more highly contaminated stream segments and reducing access to spawning tributaries. However, my results suggest that other non-mining contamination issues are also involved in limiting trout abundance in the upper Clark Fork River, specifically, factors associated with limited passage and poor habitat quality in key spawning tributaries that are further reducing the ability of trout populations to recover to pre-mining densities and distributions.

Through our mark-recapture multistate analysis, I found that survival rates for both species are lowest in the uppermost segment with the highest level of mining contamination (segment A; Chapter 3), and higher survival rates were observed in less contaminated downstream segments. These results paint a clear picture of how to improve trout populations in the upper Clark Fork River: removal of tailings will most likely increase trout survival rates. Although tailing removal is a large and difficult task, the results from the small-scale remediation efforts that occurred in the seven kilometers

downstream of the Warm Springs ponds has been promising, with reductions observed in accumulated copper in *Hydropsyche* (caddisfly), in dissolved copper in the water column, and in sediment copper concentrations in segment A sites (Hornberger et al. 2009). In segments B and C, there was also an observed reduction in water column dissolved copper and sediment copper (Hornberger et al. 2009), which indicate that the effects of remediation in the upper stream segments will likely have impacts in water quality throughout the study area. The removal of tailings and subsequent improvements to water quality would most likely lead to increased trout survival rates in all stream segments.

Removal of tailings in segment A may also help restore trout populations by increasing spawning success. My radiotelemetry results have shown that migrating cutthroat trout have no connectivity to known resident populations located in tributaries in the upper stream reaches, near the Warm Springs Ponds, most likely because heavy metal concentrations are acting as a chemical barrier to migration; cutthroat trout that enter segment A during spring run-off are exposed to toxic levels of dissolved copper that may cause acute physiological effects. By removing tailing deposits in segment A, dissolved copper concentrations would no longer seasonally increase because there would be no remaining contaminated sediments to mobilize into the water column during high discharge events in spring and summer (Luoma et al. 2008), which may lead to increased spawning success for cutthroat trout, especially for trout migrating to segment A tributaries.

Brown trout may also have increased spawning success resulting in increased recruitment and population densities if tailing deposits are removed from segment A.

Brown trout often migrate into upper stream segments to reach spawning tributaries or spawn in the mainstem, which exposes them to increased heavy metal concentrations. One area of concern is the amount of mainstem spawning by brown trout. Over one-quarter of tagged brown trout spawn suspected to have spawned in the mainstem upstream of the Little Blackfoot River, where heavy metal concentrations are highest. During radiotelemetry boat surveys in the fall, I observed areas in segment A with many redds, yet juvenile trout are rarely observed during electrofishing surveys. Although this study did not focus on juvenile trout survival, the lack of juvenile fish in this segment may be due to juvenile fish that are exposed to high levels of heavy metals during critical development stages. Juvenile fish are more sensitive to heavy metals than adults (Marr et al. 1995). In order to fully understand the population effect of higher dissolved copper concentrations in mainstem spawning grounds, further research should be completed to determine where fish are recruiting from and if juvenile survival is also lower in segment A than other less contaminated segments.

Although mining tailings removal may lead to increased spawning success, recruitment, and overall population densities, remediation efforts should also focus on the restoration of spawning tributaries by removing barriers, addressing chronic dewatering issues, and improving on current irrigation systems. For many of the spawning tributaries, especially those used by cutthroat trout, there are barriers to upstream migration. For instance, Harvey Creek, one of the tributaries with the highest number of spawning cutthroat trout observed in it, yet a complete man-made barrier is present 0.2 km from the confluence which greatly reduces the amount of suitable spawning habitat.

This was also the tributary that a bull trout attempted to enter in 2009 and became entrained in an irrigation ditch while trying to bypass the barrier. While this barrier is protecting native populations above the barrier, it is also inhibiting the ability for fluvial trout to return to suitable spawning grounds. In Brock Creek, another tributary with a large amount of cutthroat trout spawning activity, fish were unable to migrate upstream in 2010 because the creek was completely dewatered. In 2011, fish were able to migrate upstream to spawning grounds due to it being an exceptional water year, although several fish became entrained in irrigation ditches while attempting to migrate out of the tributary postspawning. Other issues in tributaries include seasonal construction of irrigation dams and impassable culverts, especially those that pass under Interstate 90. By identifying these tributary issues, both through this study and through the tributary prioritization survey conducted by Montana Fish, Wildlife, and Parks (Saffel et al. 2011), restoration can be focused on areas where trout are facing land use pressures. Remediation of these issues would likely increase spawning success, improve chances of multiple year spawning, and increase juvenile recruitment to the Clark Fork River which will eventually lead to improved trout populations throughout the mainstem.

Reducing tailings and improving water quality may not be the only solution needed for increasing trout densities in the upper Clark Fork River. Despite segment C having the highest estimated survival rates, this segment continually has the lowest population estimates in the mainstem (B. Liermann, Montana Fish, Wildlife, and Parks, personal communication). Suitable habitat seems to be fairly limited in this section; narrow floodplain, limited channel braiding, and low pool density are all characteristic of

reaches in this section (Chapter 2). The habitat is largely affected by loss of floodplain and sinuosity due to the presence of roads and railroad lines, leading to a constrained channel with little variability. As noted, many spawning tributaries throughout the basin receive significant land use pressures that reduce spawning success and this is particularly true in segment C. There were only two brown trout spawning tributaries observed during this study located in this segment (Rock Creek and Flint Creek). While the lack of spawning tributary use in segment C may be because there is not suitable spawning tributaries, connectivity of tributaries to the mainstem is one issue. For example, Cramer Creek, a tributary near Beavertail State Park, has a resident population of brown trout (M. J. Christensen, Bureau of Land Management, personal communication) but fluvial brown trout are unable to enter due to a steep, perched culvert near the interstate. In order to increase trout populations in segment C, restoration efforts could focus on attempting to create more suitable spawning and rearing habitat.

This study provides managers an understanding of what factors continue to limit trout populations in the upper Clark Fork River Superfund Site and how remediation efforts should be focused to maximize restoration potential. The evidence presented here indicates that heavy metals, caused by the presence of mining tailings in the upper stream reaches, is still causing significant damage to trout populations. Removal of these tailings should be first priority and there is evidence that tailing deposit removal will reduce dissolved copper concentrations in all stream segments (Hornberger et al. 2009). Other restoration priority should be placed on restoring spawning tributary connectivity to the mainstem, removal of barriers, and reducing the impact of dewatering and irrigation

practices, in order to help restore trout populations in the mainstem river. Lastly, in order to restore trout populations in segment C, the least contaminated segment, focus should be placed on habitat restoration, including tributary restoration. To gain further understanding of how trout at all life stages are affected by the heavy contamination in the system, research should focus on juvenile habitat use and survival rates, especially considering juvenile trout are more susceptible to the negative effects from heavy metal contamination (Marr et al. 1995).

This study demonstrates how field observations and radiotelemetry can be used to complement our current knowledge of heavy metals in aquatic systems in order to best restore fish populations to pre-mining levels. The remediation of the upper Clark Fork River Superfund Site should be used as an opportunity to attempt to restore trout populations, aquatic health, and angling opportunities to an area that has been severely impacted by anthropogenic factors.

Literature Cited

- Hornberger, M. I., S. N. Luoma, M. L. Johnson, and M. Holyoak. 2009. Influence of remediation in a mine-impacted river: metal trends over large spatial and temporal scales. *Ecological Applications* 19: 1522-1535.
- Luoma, S. N., J. N. Moore, A. M. Farag, T. H. Hillman, D. J. Cain, and M. Hornberger. 2008. Mining impacts on fish in the Clark Fork River, Montana: A field ecotoxicology case study. Pages 779-804 *in* R. T. DiGuilio and D. E. Hinton, editors. *The toxicology of fishes*. CRC Press, Boca Raton, Florida.
- Marr, J. C. A., H. L. Bergman, M. Parker, J. Lipton, D. Cacula, W. Erickson, and G. R. Phillips. 1995. Relative sensitivity of brown and rainbow trout to pulsed exposures of an acutely lethal mixture of metals typical of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2005-2015.
- Saffel, P., B. Liermann, J. Lindstrom, L. Knotek, T. Mostad, and C. Fox. 2011. Prioritization of tributaries in the upper Clark Fork River basin for fishery enhancement. Retrieved from: <http://www.doj.mt.gov/lands/naturalresource/resources/projects/2010tributaryprioritization.pdf>.

REFERENCES CITED

- Andrews, E. D. 1987. Longitudinal dispersion of trace metals in the Clark Fork River, Montana. Pages 179-191 in K. C. Averett and D. M. McKnight, editors. Chemical quality of water and the hydrologic cycle. Lewis Publishers, Chelsea, Michigan
- Atchison G. J., M.G. Henry, and M. B. Sandheinrich. 1987. Effects of metals on fish behavior: a review. *Environmental Biology of Fishes* 18: 11-25.
- Bear, E. A., T. E. McMahon, and A. V. Zale. 2007. Comparative thermal requirements of westslope cutthroat trout and rainbow trout: implications for species interactions and development of thermal protection standards. *Transactions of the American Fisheries Society* 136:1113–1121.
- Brown, R. S. and W. C. Mackay. 1995. Fall and winter movements of and habitat use by cutthroat trout in the Ram River, Alberta. *Transactions of the American Fisheries Society* 124:873-885.
- Brown, R. S. 1999. Fall and early winter movements of cutthroat trout, *Oncorhynchus clarki*, in relation to water temperature and ice conditions in Dutch Creek, Alberta. *Environmental Biology of Fishes* 55: 359–368.
- Buchanan, R. A. and J. R. Skalski. 2010. Using multistate mark-recapture methods to model adult salmonid migration in an industrialized river. *Ecological Modelling* 221: 582–589.
- Burnham, K. P. and D. R. Anderson. 1998. Model selection and inference: a practical information-theoretic approach. Springer-Verlag, New York, NY.
- Caswell, H. 2001. Matrix Population Models: Construction, Analysis and Interpretation. 2nd edition. Sinauer Associates, Sunderland, MA. 722 p.
- Clapp, D. F., R. D. Clark, and J. S. Diana. 1990. Range, activity, and habitat of large, free-ranging brown trout in a Michigan stream. *Transactions of the American Fisheries Society* 119:1022-1034.
- Clark Fork Coalition. 2011. Aquatic restoration strategy for the upper Clark Fork Basin: elements of an integrated approach. Retrieved from: <http://www.clarkfork.org/programs/restore.html>
- Cooch, E., White, G., 2004. Using MARK – A Gentle Introduction. Available: <http://www.phidot.org/software/mark/docs/book/markbook.exe>. (September 2011).

- De Rito, J. M. 2004. Assessment of reproductive isolation between rainbow trout in the Yellowstone River, Montana. Master's Thesis. Montana State University, Bozeman.
- ESRI (Environmental Systems Resource Institute). 2009. ArcMap 9.3.1. ESRI, Redlands, California.
- Farag, A. M., M. J. Suedkamp, J. S. Meyer, R. Barrows, and D. F. Woodward. 2000. Distribution of metals during digestion by cutthroat trout fed benthic invertebrates contaminated in the Clark Fork River, Montana and the Coeur d'Alene River, Idaho, U.S.A., and fed artificially contaminated *Artemia*. *Journal of Fish Biology* 56: 173–190.
- FEMA (Federal Emergency Management Agency). Upper Clark Fork River floodplain. Shapefile available at <http://nriss.mt.gov>.
- Finger, S. E., S. E. Church, and P. von Guerrard. 2007. Potential for successful ecological remediation, restoration, and monitoring. Chapter F in Integrated investigations of environmental effects of historical mining in the Animas River watershed, San Juan County, Colorado: U.S. Geological Survey Professional Paper 1651. S. E. Church, P. von Guerard, and S. E. Finger, eds., 2007, 1,096 p. plus CD-ROM. [In two volumes.]
- Goldenstein, J. N., D. F. Woodward, and A. M. Farag. 1999. Movements of adult Chinook salmon during spawning migration in a metals-contaminated system, Coeur d'Alene River, Idaho. *Transactions of the American Fisheries Society* 128: 121-129.
- Hansen, J. A., J. C. A. Marr, J. Lipton, D. Cacela, and H. L. Bergman. 1999a. Differences in neurobehavioral responses of Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*) exposed to copper and cobalt: behavioral avoidance. *Environmental Toxicology and Chemistry* 18: 1972–1978.
- Hansen, J. A., J. D. Rose, R. A. Jenkins, K. G. Gerow, and H. L. Bergman. 1999b. Chinook salmon (*Oncorhynchus tshawytscha*) and rainbow trout (*Oncorhynchus mykiss*) exposed to copper: neurophysiological and histological effects on the olfactory system. *Environmental Toxicology and Chemistry* 18: 1979–1991.
- Hansen, J. A., D. F. Woodward, E. E. Little, A. J. DeLonay, and H. L. Bergman. 1999c. Behavioral avoidance: possible mechanisms for explaining abundance and distribution of trout species in a metal-impacted river. *Environmental Toxicology and Chemistry* 18: 313-317.

- Hornberger, M. I., S. N. Luoma, M. L. Johnson, and M. Holyoak. 2009. Influence of remediation in a mine-impacted river: metal trends over large spatial and temporal scales. *Ecological Applications* 19: 1522-1535.
- Jaeger, M. E., A. V. Zale, T. E. McMahon, and B. J. Schmitz. 2005. Seasonal movements, habitat use, aggregation, exploitation, and entrainment of saugers in the lower Yellowstone River: an empirical assessment of factors affecting population recovery. *North American Journal of Fisheries Management* 25: 1550-1568.
- Jackson, C. 2011. Package 'msm'. Available: <http://cran.r-project.org/web/packages/msm/msm.pdf> (May 2012).
- Lewis, M. A. and R. Burroughs. 1979. Impact of copper mining on a desert intermittent stream in central Arizona: a summary. *Journal of the Arizona-Nevada Academy of Science* 14: 22-29.
- Lindo, T. L., C. M. Stehr, J. P. Incardona, and N. L. Scholz. 2006. Dissolved copper triggers cell death in the peripheral mechanosensory system of larval fish. *Environmental Toxicology and Chemistry* 25: 597-603.
- Lipton, J. and 16 coauthors. 1995. Aquatic resources injury assessment report: Upper Clark Fork River basin. State of Montana, Natural Resource Damage Litigation Program, Helena.
- Luoma, S. N., J. N. Moore, A. M. Farag, T. H. Hillman, D. J. Cain, and M. Hornberger. 2008. Mining impacts on fish in the Clark Fork River, Montana: A field ecotoxicology case study. Pages 779-804 *in* R. T. DiGuilio and D. E. Hinton, editors. *The toxicology of Fishes*. CRC Press, Boca Raton, Florida.
- Magee, J. P., T. E. McMahon, and R. F. Thurow. 1996. Spatial variation in spawning habitat of cutthroat trout in a sediment-rich stream basin. *Transactions of the American Fisheries Society* 125: 768-779.
- Manly, B. F. J., L. L. McDonald, D. L. Thomas, T. L. McDonald, and W. P. Erickson. 2002. *Resource selection by animals*. Kluwer Academic Press, Dordrecht, The Netherlands.
- Marr, J. C. A., H. L. Bergman, J. Lipton, and C. Hogstrand. 1995a. Differences in relative sensitivity of naïves and metals-acclimated brown and rainbow trout exposed to metals representative of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2016-2030.

- Marr, J. C. A., H. L. Bergman, M. Parker, J. Lipton, D. Cacela, W. Erickson, and G. R. Phillips. 1995b. Relative sensitivity of brown and rainbow trout to pulsed exposures of an acutely lethal mixture of metals typical of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2005-2015.
- Marr, J. C. A., J. A. Hansen, J. S. Meyer, D. Cacela, T. Podrabsky, J. Lipton, and H. L. Bergman. 1998. Toxicity of cobalt and copper to rainbow trout: application of a mechanistic model for predicting survival. *Aquatic Toxicology* 43: 225–238.
- McIntyre, J. K., D. H. Baldwin, J. P. Meador, and N. L. Scholz. 2008. Chemosensory deprivation in juvenile coho salmon exposed to dissolved copper under varying water chemistry conditions. *Environmental Science and Technology* 42: 1352–1358.
- McMahon, T. E., A. V. Zale, and D. J. Orth. 1996. Aquatic habitat measurements. Pages 83-120 in B. R. Murphy and D. W. Willis, editors. *Fisheries techniques, second edition*. American Fisheries Society, Bethesda, Maryland.
- Montana DEQ, Planning Prevention and Assistance Division, Water Quality Planning Bureau, Water Quality Standards Section. 2012. DEQ-7 Montana Numeric Water Quality Standards. Helena, MT: Montana Dept. of Environmental Quality.
- Montana Fish, Wildlife, and Parks. 2001. Dewatered streams. Shapefile available at <http://fwp.mt.gov/doingBusiness/reference/gisData/>.
- Nelson, R. L., M. L. McHenry, and W. S. Platts. 1991. Mining. Pages 425-457 in W. R. Meehan, editor. *Influences of forest and rangeland management on salmonid fishes and their habitats*. American Fisheries Society, Bethesda, Maryland.
- Ovidio, M., E. Baras, D. Goffaux, C. Birtles, and J. C. Philippart. 1998. Environmental unpredictability rules the autumn migration of brown trout (*Salmo trutta* L.) in the Belgian Ardennes. *Hydrobiologia* 371/372:263-274.
- PBS&J. 2010. Interim comprehensive long-term monitoring plan for the Clark Fork River Operable Unit. Missoula, Montana.
- Perry, R. W, J. R. Skalski, P. L. Brandes, P. T. Sandstrom, A. P. Klimley, A. Ammann, and B. MacFarlane. 2010. Estimating survival and migration route probabilities of juvenile Chinook salmon in the Sacramento–San Joaquin River Delta, North American Journal of Fisheries Management 30: 142-156.

- Phillips, G. and J. Lipton. 1995. Injury to aquatic resources caused by metals in Montana's Clark Fork River basin: historic perspective and overview. *Canadian Journal of Fisheries and Aquatic Science* 52: 1990-1993.
- Powell, L. A. 2007. Approximating variance of demographic parameters using the delta method: a reference for avian biologists. *The Condor* 109: 949-954.
- R Development Core Team. 2010. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available: <http://www.r-project.org> (January 2010).
- Ramsey, F. L. and D. W. Schafer. 2002. *The statistical sleuth: a course in methods of data analysis*, Second Edition. Brooks/Cole, Cengage Learning, Belmont, California.
- Rogers, K. B. and G. C. White. 2007. Analysis of movement and habitat use from telemetry data. Pages 625-676 in C. S. Guy and M. L. Brown, editors. *Analysis and interpretation of freshwater fisheries data*. American Fisheries Society, Bethesda, Maryland.
- Ross, M. J. and C. F. Kleiner 1982. Shielded-needle technique for surgically implanting radio-frequency transmitters in fish. *Progressive Fish-Culturist* 44: 41-43.
- Saffel, P., B. Liermann, J. Lindstrom, L. Knotek, T. Mostad, and C. Fox. 2011. Prioritization of tributaries in the upper Clark Fork River basin for fishery enhancement. Retrieved from: <http://www.doj.mt.gov/lands/naturalresource/resources/projects/2010tributaryprioritization.pdf>.
- Sandahl, J. F., D. H. Baldwin, J. J. Jenkins, and N. L. Scholz. 2007. A sensory system at the interface between urban storm water runoff and salmon survival. *Environmental Science and Technology* 41: 2998-3004.
- Schmetterling, D. A. 2001. Seasonal movements of fluvial westslope cutthroat trout in the Blackfoot River Drainage, Montana. *North American Journal of Fisheries Management* 21: 507-520.
- State of Montana. Digital elevation models. Shapefiles available at <http://nris.nt.gov>.
- Svecevicius, G. 1999. Fish avoidance response to heavy metals and their mixtures. *Hydrobiologia* 9: 103-113.
- Svecevicius, G. 2001. Avoidance response of rainbow trout *Oncorhynchus mykiss* to heavy metal mixtures: A comparison with acute toxicity tests. *Bulletin of Environmental Contamination and Toxicology* 67: 680-687.

- University of Montana Riparian and Wetland Survey Team. Upper Clark Fork tailing deposits. Shapefile available at <http://nriss.mt.gov>.
- USEPA (U.S. Environmental Protection Agency). 1986. Quality Criteria for Water (EPA Gold Book). EPA 440/5-86-001. U.S. EPA, Office of Water. 1986.
- USEPA. 2000. Liquid assets: America's water resources at a turning point. EPA-840, Washington, DC.
- Vincent, E. R. 1987. Effects of stocking catchable-size hatchery rainbow trout on two wild trout species in the Madison River and O'Dell Creek, Montana. *North American Journal of Fisheries Management* 7: 91-105.
- Weigel, D. E., J. T. Peterson, and P. Spruell. 2002. A model using phenotypic characteristics to detect introgressive hybridization in wild westslope cutthroat trout and rainbow trout. *Transactions of the American Fisheries Society* 131: 389-403.
- White, G.C. and K. P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. *Bird Study* 46 Supplement: 120-138.
- White, G. C. and R. A. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, California.
- Woodward, D. F., A. M. Farag, H. L. Bergman, A. J. DeLonay, E. E. Little, C. E. Smith, and F. T. Barrows. 1995a. Metals-contaminated benthic invertebrates in the Clark Fork River, Montana: effects on age-0 brown trout and rainbow trout. *Canadian Journal of Fisheries and Aquatic Science* 52: 1994-2004.
- Woodward, D. F., J. A. Hansen, H. L. Bergman, E. E. Little, and A. J. DeLonay. 1995b. Brown trout avoidance of metals in water characteristic of the Clark Fork River, Montana. *Canadian Journal of Fisheries and Aquatic Science* 52: 2031-2037.
- Woody, C. A., R. M. Hughes, E. J. Wagner, T. P. Quinn, L. H. Roulson, L. M. Martin, and K. Griswold. 2010. The mining law of 1872: change is overdue. *Fisheries* 35: 321-331.
- Young, R. G., J. Wilkinson, J. Hay, and J. W. Hayes. 2010. Movement and mortality of adult brown trout in the Motupiko River, New Zealand: effects of water temperature, flow, and flooding. *Transactions of the American Fisheries Society* 139:137-146.

- Zale, A. V., C. Brooke, and W. C. Fraser. 2005. Effects of surgically implanted transmitter weights on growth and swimming stamina of small adult westslope cutthroat trout. *Transactions of the American Fisheries Society* 134: 653-660.
- Zipkin, E. F., C. S. Jennelle, and E. G. Cooch. 2010. A primer on the application of Markov chains to the study of wildlife disease dynamics. *Methods in Ecology & Evolution* 1: 192-198.