AN ABSTRACT FOR THE THESIS OF

Matthew C. Anderson for the degree of Master of Science in Fisheries Science presented on September 18, 2009.
Title: Migratory Behavior and Passage of Redband Trout *(Oncorhynchus mykiss)* in the Donner und Blitzen River, Oregon

Abstract approved:

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Guillermo R. Giannico

Salmonids in arid high-elevation streams find themselves at the fringe of their tolerance range. Under the conditions they endure in such environments, long-distance migratory movements among widely dispersed habitats may be an important mechanism for some fish to persist, and even thrive. The Donner und Blitzen (Blitzen) River redband trout (*Oncorhynchus mykiss gairdneri*) population is known to have a migratory life-history component, but little is known about the timing, spatial patterns, or ecological context of the migration. I tracked trout movements and passage delays at diversion dams with radio telemetry and passive integrated transponder (PIT) tags from March 2007 to November 2008. PIT tag readers established at four locations (river km 1, 35, 48, and 76) recorded large-scale movements of trout. Three of the readers also recorded ladder entry time, ladder ascending time, and total passage time of each trout.

My results indicated the existence of a life-history in which redband trout made long-distance migrations both as sub-adults and as adults. While adult trout migrated for reproductive purposes, movement of immature individuals appeared to be a response to seasonal stream temperature conditions. Trout migration rate was positively correlated with fork length and mean river discharge but was not associated with stream

temperature, tagging method, or the number of dams passed. The upstream-most detection location for radio-tagged adults that reached potential spawning habitat was not different for trout from the lower river versus the middle river ($t(42) = 1.07$, $p = .29$); however, lower river trout reached spawning habitats an average of 20 days later ($t(42) = 3.78$, $p < .001$). Passage times at the dams were not affected by discharge, fork length, or tagging method. At a jump-pool ladder trout were 7.23 times more likely to pass during day than at night ($\chi^2(1, N = 40) = 9.96$, $p = .002$). At a Denil ladder, trout were 25.6% more likely to pass with each degree Celsius increase in stream temperature ($\chi^2(1, N = 22) = 4.39$, $p = .036$). At all three dams, a greater proportion of the total passage time involved trout finding and entering the ladder than ascending the ladder after initial entry. Trout passage times varied significantly between each of the dams.

This study highlights the importance of landscape-scale distribution of habitats and refugia in determining life-history and movement patterns of trout. Migratory behavior was related to both life-stage and environmental conditions. Maintaining connectivity with efficient passage throughout the river is a critical element in managing migratory fish populations like the one in this study. The well-functioning fish ladders were those that provided adequate fish attraction, while those ladders with poor attraction delayed migrating trout for long periods.

Migratory Behavior and Passage of Redband Trout *(Oncorhynchus mykiss)* in the Donner und Blitzen River, Oregon

by
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APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Matthew C. Anderson, Author

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CONTRIBUTION OF AUTHORS

Guillermo R. Giannico and Steve Jacobs assisted with the study design, data analysis, and editing of both manuscripts in the thesis.

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CHAPTER 1

GENERAL INTRODUCTION

Redband trout (*Oncorhynchus mykiss gairdneri*), the inland subspecies of rainbow trout, are distributed from northern British Columbia to northern California and Nevada and from the Cascade Divide into eastern Idaho and Montana (Behnke 1992). Redband trout have adapted to a wide variety of habitats across their range and have developed a diversity of life-history strategies in order to adapt to local conditions. The species is notable for its plasticity and opportunistic approach in finding and exploiting niches (Behnke 1992, Northcote 1997). Some redband are able to complete their life-cycle within a single stream reach, but others make long-distance movements to exploit habitats that optimize growth, survival, and reproduction (Northcote 1997, Meka et al. 2003, Mellina et al. 2005). When such long-distance movement patterns become well-established and involve a large fraction of the population that move at regular periods and return to their natal habitats to spawn, it is considered a migration (Northcote 1997). Redband trout populations can be entirely migratory, partially migratory, or entirely resident (Northcote 1997). Migrations can involve moving into the ocean (anadromous), into lakes (adfluvial), or long distances within streams (fluvial) (Dedual & Jowett 1999, Zimmerman & Reeves 2000, Meka et al. 2003, Mellina et al. 2005).

Diversity in migratory life-histories exhibited by a population of trout can improve the productivity and stability of that population (Rieman & Dunham 2000). Instead of relying on a single stream reach for all ontogenetic life stages, migratory trout transition to habitats specifically suited to a given stage of development and move once those habitats no longer meet their needs. As a result, migratory redband trout often grow larger than residents (Kunkel 1976). Large size can infer advantages for trout in terms of foraging status, mate selection, and increased fecundity (Kunkel 1976). Populations with both migratory and resident trout are likely to be more resilient to stochastic disturbance and temporal variability in habitat conditions that alternately favor one life-history group or another (Rieman & Dunham 2000).

Although migratory behavior has the ability to optimize spatially or temporally heterogeneous habitats, there are also costs and risks associated with migrations. Salmonids that are unable to return to spawning habitat at the correct time may fail to reproduce (Naughton et al. 2005, Caudill et al. 2007). Long-distance migrations are energetically costly (Rand & Hinch 1998a), and transitional habitats may be unproductive or increase the risk of predation. Because of these costs and risks, the time in transit may influence growth and survival rates of stream fishes moving between habitat patches (Schlosser 1995). Risks of migration increase on streams that are used for irrigation. Impoundments for irrigation diversion can delay or prevent fish from migrating between habitats. Additionally, diversion canals can lead downstream migrants into sink habitats, isolated from the main channel.

Human activities have dramatically altered both stream habitat quality and stream connectivity which have led to dramatic declines in redband trout populations. Thurow et al. (2007) summarize the problem of fragmentation of redband trout populations:

> Many systems that support redband trout remain as remnants of what were larger, more complex, diverse, and connected systems… Where watershed disturbances such as construction of dams, irrigation diversions, or other migration barriers result in loss of connectivity, remaining redband trout populations have been progressively isolated into smaller and smaller patches of habitat. Corridors that provide habitat for migration, rearing, and overwintering may be critical…The loss of spatial diversity in population structure and of the full expression of life-history pattern may lead to a loss of productivity and stability important to long term persistence.

Fragmentation of river systems is one of the most serious problems facing redband trout populations, but restoration of connectivity by providing adequate passage is often one of the most cost-effective methods of restoration.

The Donner und Blitzen (Blitzen) River has a migratory population of redband trout that is uniquely abundant in the Great Basin region of the Western United States. In 2000, the U.S. Congress designated parts of the Blitzen River as the nation's first trout reserve and stated that it would be managed "in a manner that conserves the unique population of redband trout native to the Donner und Blitzen River" (Steens Mountain Cooperative Management and Protection Act of 2000). Despite national recognition of the value of Blitzen redband trout, little is known about the spawning migrations, seasonal movement patterns, or life-history diversity of the population.

Redband trout likely first occupied the Malheur Lakes Basin 50,000 years ago and have been largely isolated from Columbia Basin populations since the Voltage lava flows of approximately 18,000 years ago which blocked the Malheur Gap between present day Malheur Lake and Malheur River (Bisson & Bond 1971, Behnke 2007). Although hatchery strains of coastal rainbow trout were historically stocked in the Blitzen River, genetic and meristic evidence suggests that genetic introgression has been limited

(Currens 1990, Phelps et al. 1996, Behnke 2007). Also, there has been little connectivity between redband trout in the Blitzen River and those in the other rivers in the basin, the Silvies River and Silver Creek, based on morphological and genetic evidence (Bisson & Bond 1971, Currens 1990).

A number of historical changes in the Blitzen River have impacted the redband trout population. Although historical data of redband trout abundance is limited, anecdotal accounts indicate that the Blitzen River population, particularly the migratory component, has declined over the last century (Hosford & Pribyl 1983). Extensive channelization of the river and construction of diversion ditches throughout the valley occurred principally between 1910 and 1915. Although some diversion dams were likely constructed during this early period, current diversion structures were constructed in the 1930s by the Civilian Conservation Corps (Hosford & Pribyl 1983). These dams had fish passage provisions, but efficiency of the passage structures was likely poor, based on historical reports of trout attempting passage stacking up below the dams (Hosford & Pribyl 1983). Introduction of carp (*Cyprinus carpio*) to Malheur Lake is thought to be an important factor in the decline of large migratory redband trout and utilization of Malheur Lake (Bowers et al. 1999). The incredibly abundant carp populations may affect the trout population through food-chain interactions and by increasing turbidity in the lake, thereby reducing the ability of the sight-foraging trout to find food (Bowers et al. 1999). Numerous efforts to reduce the carp populations, including chemical treatments, physical barriers, and even dynamite, have had only short-term success.

Despite many natural and human-induced challenges facing the Blitzen River redband trout, there remains a strong population with diverse life-histories. The Malheur Lakes Basin redband trout population has been estimated at over 400,000 trout greater than age 1, accounting for as much as 44% of the Great Basin population (Dambacher et al. 2001). Within the Malheur Lakes Basin, only the Blitzen River population has a migratory life-history expression. Although migratory redband have been documented in other Great Basin rivers, loss of the migratory life-history from these basins may be more common (Bowers et al. 1999, Tinniswood 2007). Migratory movements of redband trout in the Blitzen River have not been extensively studied. A telemetry project conducted by U.S. Fish and Wildlife Service and Oregon Department of Fish and Wildlife in which 17 fish were radio-tagged indicated that there were migratory redband in 2000, but only a small percentage of those fish passed all diversion dams (USFWS unpublished data). Evidence for the persistence of a migratory population was bolstered by a trapping and tagging effort in 1999 and 2000 in which fish were caught in traps at the diversion dams after swimming up through the fish ladders (USFWS unpublished data).

This study was initiated to investigate the movement patterns and life-history of the Blitzen River redband trout and to evaluate fish passage conditions in the river. We collected field data from March 2007 to November 2008, which involved tracking redband trout movement using both radio telemetry and Passive Integrated Transponder (PIT) tags, monitoring stream temperature and stream discharge, and interpreting age and spawning history through scale analysis. The research has resulted in the two manuscripts included in this thesis. Chapter 2, Migratory Behavior of Redband Trout in a High Desert

Basin, focuses on large-scale migratory movements of Blitzen River redband trout. This chapter investigates the effect of seasonal stream temperatures on migrations, factors that influence the upstream spring migration rate, and variation in migration destination and timing based on over-wintering location. In chapter 3, Passage of Redband Trout at Irrigation Diversion Dams on the Donner und Blitzen River, we evaluate passage at three dams. First, we consider potential environmental factors and fish characteristics that may affect passage times. Second, we compare the ladder entry time and the ladder ascending time at each of the dams to determine which stage of passage causes the greater proportion of passage delay. Finally, we compare passage among three dams. Chapter 4 is a general discussion in which we summarize the findings of both aspects of the study, detail management implications, and suggest further research that could be conducted on the subject.

CHAPTER 2

MIGRATORY BEHAVIOR OF REDBAND TROUT IN A HIGH DESERT BASIN

Abstract

Redband trout (*Oncorhynchus mykiss gairdneri*) were tracked between March 2007 and November 2008 in the Donner und Blitzen River. We tested three hypotheses: 1) trout migrations are affected by seasonal stream temperature conditions, 2) trout migration rate is influenced by trout fork length, stream temperature, river discharge, the number of dams passed, or the fish tagging method, and 3) sexually mature trout that reside in different sections of the river prior to migration have different migratory destinations and arrival times. We tagged 74 redband trout with both radio tags and passive integrated transponder (PIT) tags, 544 with PIT tags only, and 3 with radio tags only. Radio tracking involved both mobile and fixed station detections. We established PIT tag readers at four locations (river km 1, 35, 48, and 76) to track large-scale movement patterns and to calculate movement rates. Our results indicated the existence of a life-history in which redband trout made long-distance migrations both as juveniles and as adults. While adult trout migrated for reproductive purposes, the movement of immature individuals appeared to be in response to seasonal stream temperature conditions. Trout migration rate was positively correlated with fork length and mean river discharge but did not differ given stream temperature, tagging method, or the number of dams passed. The upstream-most detection location, for those that reached potential spawning habitat, was similar for lower river and middle river trout; however, fish from the lower river reached spawning habitats an average of 20 days later.

Introduction

Migration in stream fishes is a distinctive type of large-scale movement that is repeated at regular periods during the lifespan of an individual, involves a large fraction of the population, and often implies returning to natal habitats for reproduction (Northcote 1997). Migrations are common in salmonids and are indicative of heterogeneous and spatially separated habitats that allow fish to optimize growth, survival, and reproduction (Northcote 1992, Northcote 1997). Salmonids exhibit a wide variety of migratory behaviors (Brown et al. 1999, Baxter 2002, Meka et al. 2003, Mellina et al. 2005), which are best understood in the context of landscape-scale distribution of habitat patches and refugia from harsh environmental conditions or risk of predation (Schlosser 1995, Gresswell et al. 1997, Fausch et al. 2002). Diversification of migratory life-histories allows a population to exploit various habitats, which may increase both its productivity and resilience under changing conditions (Rieman & Dunham 2000).

Although migrations can provide many benefits to stream salmonids, they are not without risks and costs. Salmonids that are unable to return to their spawning habitats at the correct time may fail to reproduce (Naughton et al. 2005, Caudill et al. 2007). Long-distance migrations are energetically costly (Rand & Hinch 1998b), and transitional habitats may be unproductive or increase the risk of predation. Because of these costs and risks, time in transit may influence growth and survival rates for stream fishes moving between habitat patches (Schlosser 1995). The rate at which fish move upstream has commonly been considered in the context of variation in river discharge and temperature conditions, but the relative importance between the two may vary between streams (Trépanier et al. 1996, Workman et al. 2002, Salinger & Anderson 2006). Stream impoundments, even those with fish passage facilities, can affect migration rates. Most studies on salmonid migration rates have been conducted on anadromous fish in large river systems (Hinch & Rand 1998, Naughton et al. 2005, Caudill et al. 2007), and it is not clear how those studies apply to migratory fish in smaller streams.

Differences in movement patterns have been used to distinguish unique 'ecophenotypic' groups in partial migratory salmonid populations (Meka et al. 2003). In rainbow trout (*Oncorhynchus mykiss*) populations, such groups can be reproductively isolated through spatial, temporal, or behavioral spawning segregation (Zimmerman & Reeves 2000) or reproductively integrated. Most genetic evidence in rainbow trout populations with both anadromous and fresh-water resident individuals suggests that migratory phenotypes within a watershed are genetically distinguishable, but migratory and non-migratory phenotypes within a watershed are more closely related than fish of the same phenotype in adjacent watersheds, which suggests that there is often only partial reproductive isolation between the phenotypes (McCusker et al. 2000, Docker & Heath 2003).

The Donner und Blitzen (Blitzen) River has the largest migratory population of redband trout (*Oncorhynchus mykiss gairdneri*) in the Great Basin region of the Western United States (Bowers et al. 1999, Dambacher et al. 2001). In 2000, congress designated parts of the Blitzen River as the nation's first trout reserve and stated that it would be managed "in a manner that conserves the unique population of redband trout native to the

Donner und Blitzen River" (Steens Mountain Cooperative Management and Protection Act of 2000). Despite national recognition of the value of Blitzen redband trout, little is known about the migrations, seasonal movement patterns, or landscape-scale habitat usage of the population. Although historical data on the abundance of redband trout in the Blitzen River is limited, anecdotal accounts indicate that the population, particularly the migratory component, has declined over the last century (Hosford & Pribyl 1983).

The purpose of this project is to examine the migratory behavior of Blitzen River redband trout to understand the adaptive strategy of migration, to evaluate the factors related to the timing and rate of migration, and to better identify the challenges that face trout with a migratory life-history. The extreme seasonal temperature variability and diversity of habitats in the Blitzen River provides a unique opportunity to study the way that trout use migration to adapt to local conditions. This study explores the landscape-scale movement patterns of redband trout in the Blitzen River by testing the following three hypotheses: 1) trout migrations are affected by seasonal stream temperature conditions, 2) trout migration rate is influenced by trout fork length, stream temperature, river discharge, the number of dams passed, or the fish tagging method, and 3) sexually mature trout that reside in different sections of the river prior to migration have different migratory destinations and arrival times.

Methods

Study Location Description

This study was conducted in the Donner und Blitzen River, which is located in the high desert region of south-eastern Oregon (Figure 2.1). The Blitzen River drains into Malheur Lake and has no further outlet to the ocean. This basin has an area of 2,045 km^2 and a drainage density of 0.33 km/km^2. Its elevation ranges from 1,248 m at Malheur Lake to 2,967 m at the top of the Steens Mountain. The Blitzen River mainstem is 128 kilometers long. The tributaries, most of which drain the west slope of the Steens Mountain, flow through deep, glacially-carved valleys of basalt and andesite bedrock, and have a parallel drainage pattern. Major tributaries included in the study were Indian, Fish, and Bridge Creeks and the Little Blitzen River (Figure 2.1). Mean annual precipitation in the basin ranges from less than 40 cm at lower elevations to over 100 cm at the higher mountain elevations (Taylor 2005). Most precipitation falls as snow during the winter months and most runoff occurs as snow melt during the spring.

For the purposes of this study, we divided the Blitzen River into three sections, lower river, middle river, and upper river, based on general changes in stream morphology. The lower river covers the area from the mouth of the Blitzen River (km 0) to the confluence with Bridge Creek (km 67). This stream section consists of a low-gradient and highly sinuous channel, except where artificially straightened, with predominantly sand and silt bedload. Because there is little gravel in this section, it is not likely that it provides trout spawning habitat. The middle river extends from Bridge Creek up to the Page Springs Weir (km 79). The middle river is characterized by a low-gradient, unconstrained channel with pool-riffle habitat and gravel as the primary substrate type. The upper river, above the Page Spring Weir, is constrained by steep canyon walls and is characterized by boulder-strewn rapids interspersed with pockets of gravel.

The Malheur National Wildlife Refuge (MNWR) has four primary diversion dams on the Blitzen River that are operated during the spring snowmelt period to maintain wetland habitat for breeding waterfowl. Three of those dams (Sodhouse, Busse, and Grain Camp) are located in the lower river segment, and the fourth (Page) is located in the middle river segment (Figure 2.1). Additionally, a meter high concrete gaging station weir (Page Spring Weir) is located at the upstream boundary of the MNWR. Sodhouse, Busse, and Page dams have Denil-style fish ladders and Grain Camp dam has a jump-pool fish ladder. The Page Spring Weir has no passage facility but is low enough to allow some fish passage.

Environmental Conditions

Stream discharge and temperatures were monitored over the course of the study. The U.S. Geological Survey collected river discharge data at 15-minute intervals at the Page Springs Weir gaging station, located immediately upstream of the Malheur National Wildlife Refuge boundary. Water temperature was recorded at 30-minute intervals at 10 locations on the Blitzen River with Onset Hobo® temperature loggers. In 2007, one temperature logger was damaged and one was exposed to air, while in 2008, one temperature logger was exposed to air; therefore, data recorded by these units were not included in any of the analyses. We summarized stream temperatures for both summer and winter conditions. For summer high temperatures, a 7-day moving mean was calculated from the maximum temperature recorded each day. The highest of those 7-day means (7-day max. avg.) was used to characterize the hottest period at each temperature monitoring location. The 7-day max. avg. at each site was compared to both the ultimate upper incipient lethal temperature (UUILT), which is the hottest temperature a fish can tolerate over a prolonged period, and the critical maximum temperature (CMT), the temperature at which a fish looses equilibrium. We used the UUILT of 24.3°C (Bear et al. 2007) and the CMT of 29.1°C (Rodnick et al. 2004) which are both specific to the species *O. mykiss*. Although Great Basin redband trout outperformed coastal rainbow trout at 24°C (Gamperl et al. 2002), a notable increase in oxygen demand for Great Basin redband trout above 24°C (Rodnick et al. 2004) indicates that it is an appropriate temperature threshold for thermal stress. Since the CMT is the same for redband trout as for coastal rainbow trout (Rodnick et al. 2004), it is reasonable to assume that the range of temperatures between 24.3°C and 29.1°C are stressful to redband trout in the Blitzen River.

Fish Tagging and Scale Interpretation

Redband trout were caught in fish traps located at the upstream end of fish ladders at Sodhouse, Busse, and Page dams and by angling in the vicinity of the dams. Traps were set 4 to 7 days a week from late March to early June of 2007 and 2008. Angling with artificial lures was employed approximately 5 hours per week below the dams in April and May of both years in order to increase the number of trout sampled. Additionally, trout were sampled by angling for three days in late March 2008 to catch middle river fish before migrants began moving upstream from the lower river. Each captured trout was measured (fork length to the nearest mm) and weighed (to the nearest g). Scales were taken from a subset of 257 trout. Although fish were not sampled randomly, we attempted to take scales from trout across the range of sizes to fully represent the population. Sexual maturity was assessed for radio-tagged fish based on external characteristics and by examining gonads during the tagging surgery. The sex of the trout was recorded for mature individuals.

We tagged 77 redband trout from 272 mm to 560 mm fork length (FL) with radio tags and 544 trout over 100 mm fork length with passive integrated transponder (PIT) tags (all but 3 radio tagged trout were also PIT tagged). Texas Instrumets® PIT tags, 23 mm in length and 1 g in weight, were inserted into the body cavity of smaller trout (FL < 300 mm) and the dorsal sinus of the larger trout (FL ≥ 300 mm). To be radio tagged, the tag could not exceed 3% of the body weight of the fish. Because we had a limited number of radio tags, we chose not to tag all captured fish early in the season in an attempt to deploy tags throughout the migration season. Trout were radio tagged regardless of condition except in two cases of severe injury. Lotek Wireless® radio tags were implanted in the body cavity following standardized surgical procedures. In 2007, we tagged 36 trout with MCFT-3A (16 g) and 10 trout with MCFT-3FM (11 g) tags. In 2008, we tagged 26 trout with NTC-6-2 (4.5 g) tags, 3 trout with MCFT-3A (16 g), and 2 trout with MCFT-3FM (11 g) tags. Larger tags were used in the first year so the batteries would last throughout the study. Tag weight averaged 1.4% of the body weight of the fish and ranged from 0.5% to 2.5%. All surgeries were conducted on site at the capture location. Trout were anesthetized in an aerated holding tank with approximately 100 mg/l tricane methanesulphonate (MS-222) solution with 120 mg/l of bicarbonate buffer. Anesthesia typically occurred in 2-4 minutes. For the surgery, trout were placed ventral side up in a wet, foam cradle. The gills of the fish were irrigated with anesthetic solution and stream water during the surgery. A 1.5-2.5 cm long incision, just wide enough to accommodate the transmitter, was made on the fish anterior to the pelvic girdle of the fish, offset 2 cm from the mid-ventral line. A cannula shielded with plastic tubing was used to guide the transmitter antenna to the exit location posterior to the pelvic fin (Ross & Kleiner 1982). After placing the transmitter in the body cavity, the incision was closed with 2 to 3 sutures of monofilament absorbable material with a simple interrupted 3-2-1 surgical pattern (Wagner et al. 2000). All surgical equipment was disinfected between uses with Benz-all®. Trout were allowed to recover in a covered tank with cool stream water for at least 15 minutes and until they were fully responsive before being released at the capture location. Trout caught in the traps were released far enough upstream to minimize the risk of having them fall back below the adjacent dams.

Trout scales were interpreted for age and occurrence of prior spawning events. Scales were collected from 257 redband trout. After the scales were cleaned and mounted on gum cards, impressions were made on plastic sheets using a heat press. The scale impressions were viewed on a microfiche reader. Growth annuli and spawning checks were interpreted independently by two readers. The readers had different interpretations of 42 scales, so those were removed from the sample, leaving 215 usable scale samples. We used the scale interpretation to estimate the age distribution, spawning age, and frequency of repeat spawning of the migratory portion of the population.

Seasonal Migrations

We determined the movements of PIT-tagged fish with stationary, swim-through antennae and by scanning recaptured fish with hand-held detectors. PIT tag antennae arrays were installed in April 2007 at Page Dam and in June 2007 at Busse Dam, Grain Camp Dam, and Cato Bridge (Figure 2.1). Some additional detections were made at Grain Camp Dam in April and May 2007 during installation of that array. At each of the three dams, one antenna was located 30 to 50 m downstream of the dam, a second antenna was set in the downstream entrance of the fish ladder, and a third antenna was placed near the upstream exit of the ladder. Each antenna formed a loop. The antennas below the dams spanned the entire river channel (10 to 15 m wide), with the bottom of each antenna following the contours of the channel bed and the top a maximum of 0.7 m above it. During most flows, the detection field filled the entire wetted channel, and at high flows, only the upper portion of the water column was outside the detection field. Antennas at the fish ladders were rigid and rectangular with dimensions that matched those of the ladder. Cato Bridge had two 0.7 m by 7 m semi-rigid rectangular antennas with detection fields that filled most of the channel except the area near each bank. Detection efficiency varied between antennas and through time due to interference of multiple tagged fish entering detection field simultaneously, tag angle within the antenna field, or equipment failures. The antenna read-ranges were checked weekly during the high-flow spring season and monthly the rest of the year. The Busse antenna had periodic power failures in the summer of 2007, and the Grain Camp antenna was damaged from ice formation and was not functioning from November 2007 through February 2008.

Large-scale movement patterns were summarized for trout PIT tagged in the first year of the study and redetected in the second year. Individual movement histories were recreated based on the sequence of movement directions detected by the PIT antennas. Time, location, and direction of these detections were summarized in monthly time-steps for comparison with seasonal changes in temperature and discharge conditions.

Migration Rates

Migration rate was estimated for each of 73 trout that were PIT tagged at Sodhouse, Busse, or Grain Camp dams and subsequently detected at an upstream PIT tag reader. The migration rate was calculated by dividing the distance travelled to the PIT tag reader by the time in transit (km/day). The effects of stream temperature, discharge, fork length, the number of dams passed, and the tagging method were tested with regression analysis. Mean temperature recorded at a single site (Page Dam) during migration period of each trout was used in the analysis because it was not possible to determine the exact location of PIT-tagged trout when they were between tag reading stations. Temperature varied little among the different temperature loggers during the spring migration period. Mean discharge during the migration period of each trout was calculated from Page Springs Weir gaging station data. The number of dams passed was included to evaluate the cumulative effect of passage delays related to dams on the migration route. Trout tagged with both radio tags and PIT tags versus those only tagged with PIT tags were compared using an indicator variable.

Migratory Destination and Timing

Radio-tagged trout were located using Lotek Wireless® SRX 400 receivers, and their positions were recorded with a hand-held GPS unit. Fish tracking was done on foot, from a pick-up truck, from the air with a small plane, and using fixed stations. Tracking intensity was the highest during the spring spawning migration (March to June) with average fish relocations of 1.5 times per week in 2007 and 1.7 times per week in 2008. During summer, fall, and winter, trout were tracked at approximately monthly intervals. Two telemetry fixed-stations were installed in the upper Blitzen River (Figure 2.1) to ensure migrating trout would be detected if long-distance movements took place between scheduled tracking. Fish detection precision ranged from 40 m, when tracking was carried out on foot and triangulation was possible, to 100 m, if done from vehicle. Aerial tracking precision was estimated at about 160 m based on similar aquatic aerial telemetry studies (Roberts & Rahel 2005).

Due to high water and high turbidity during the snowmelt period, it was rarely possible to confirm the spawning location of individual trout. Most radio-tagged fish were confirmed to be sexually mature during the tagging process. Direct spawning observations were limited to tracking radio-tagged trout to spawning aggregations on two occasions and observing a female trout with a telemetry antenna near her redd. Although spawning location could not often be confirmed, most trout were redetected multiple times near the upstream-most site. In characterizing the upstream-most migration sites, we included only trout that migrated more than one km upstream of their tagging location. The time of arrival was the date that a trout was first detected in the vicinity of its upstream-most detection location.

Trout location coordinates from radio telemetry and PIT tag antenna detections were imported into ESRI ArcGIS®. Detection locations were related to a 1:24:000 BLM stream layer rectified to aerial photographs. The coordinates of each of the trout positions were then located along the stream route to determine the relative location from the river mouth in river kilometers (Rkm). The detection locations were joined with the detection records and the fish tagging records in a Microsoft Access database in order to analyze the movements of fish. Individual movement histories were constructed by plotting the position (in Rkm) of all detections of a given trout against the date and time of the detections (Appendix A). Trout were assigned to the lower river or middle river group based on their capture location. The lower river group consisted of fish caught downstream of Grain Camp Dam, and the middle river group consisted of fish caught at Page Dam or in the near vicinity.

Statistical Analyses

Linear regression analysis was used to determine whether or not the migration rate was influenced by trout fork length, temperature, discharge, the number of dams passed (dams), or the tagging method (tag). Preliminary diagnostic scatter plots indicated the need to $\log_e$ transform the response variable, migration rate (Ramsey & Schafer 1997). Following transformation, the model appeared to meet the regression assumptions of normality and equal variance based on a normal QQ-plot and a residual versus fit plot.

A correlation matrix of the covariate parameters was examined for potential multicollinearity. In order to select the best model given the limited sample size, all combinations of models with three parameters or less, including a null model, were evaluated using Bayesian information criterion (BIC) selection process. We used BIC model selection over a step-wise selection approach because the former method may identify numerous potentially adequate models, whereas the latter only selects a single model. BIC was used in favor of Akaike's Information Criterion because the BIC has a larger penalty for inclusion of insignificant coefficients (Ramsey & Schafer 1997). For the top model, the parameters were tested for interactions. All interaction terms were removed because none had *p*-value of 0.05 or less. Cook's distance was calculated to determine if there were outliers that influenced the results. We selected Cook's distance over other statistics because it detects observations that have either large studentized residual, high leverage, or both (Ramsey & Schafer 1997). Based on the low Cook's distance values, no outliers were considered to be influential on the model.

To determine if trout that were caught and radio tagged in either the lower or middle river and that moved at least 1 km upstream migrated to the same upstream reaches (presumably to spawn) and arrived at them simultaneously, two-sample t-tests were used to compare both the location of the upstream-most sites (in Rkm) at which radio-tagged trout were detected and the dates that they were first detected in that vicinity. Trout that did not migrate at least one km and lower river trout that did not move past Rkm 67, where the lowermost potential spawning habitat is, were not included in the analysis.

Results

Environmental Conditions

Summer 7-day max. avg. temperatures in the lower river exceeded 28°C in 2007 and 26°C in 2008, while 7-day max. avg. temperatures in the upper river never exceeded 24.1°C (Table 2.1). The hottest temperatures occurred between July 14th and August 1st in 2007 and between July 7th and August 16th in 2008. Summer water temperatures in the Blitzen River generally warmed from upstream to downstream but cooled notably at Page Springs where the 7-day max never reached the UUILT. The 7-day max. avg. temperatures exceeded UUILT for rainbow trout at all of the lower river temperature loggers in 2007 and at the two temperature loggers that were farthest downstream in 2008 (Figure 2.2). The temperature logger located upstream of Page Springs also recorded 7-day max. avg. temperatures that exceeded the UUILT during both years of the study. None of the loggers recorded 7-day max temperatures that exceeded the CMT. Mean winter temperatures ranged from 0°C to 3°C during December and January (Figure 2.3). In winter, the temperature was slightly warmer in the upper river, and Page Springs appeared to have a mild warming influence.

Fish Tagging and Scale Interpretation

In 2007, a total of 476 trout were trapped and an additional 47 were angled. In 2008, 60 trout were caught in the traps and 35 angled (Table 2.2). Trout ranging in size from 115 to 560 mm in length migrated upstream in the spring of 2007 and 2008 (Figure 2.4). Fish size distribution was bimodal, and according to the scale interpretation, the smaller sized fish consisted primarily of age 1-2 trout while the larger group was primarily age 3-5 trout. Scales indicated that none of the trout had spawned prior to age 3, 51% (26 of 50 scales) of age 4+ trout spawned at age 3, and of 6 age 5+ trout, 3 had spawned once before, 2 had spawned twice before, and one had not previously spawned.

Seasonal Migrations

The large-scale movements observed from PIT tag detections revealed a distinct seasonal movement pattern. Most trout captured first in the lower river segment subsequently migrated upstream. During both years of the study, stream temperatures in the lower river exceeded UUILT, resulting in physiologically stressful to lethal conditions. Of the trout tagged in the lower river, 51% were redetected at least 10 km upstream in 2007 and 60% in 2008, and over the course of the study, 15% were detected at Page Dam. Twenty-four of the trout PIT tagged in 2007 were also detected during 2008, thus providing information about 2-year movement patterns (Figure 2.5). In spring, these trout moved upstream during the high-flow period from March to June. In summer, they remained in the middle or upper river and did not make long-distance movements, as indicated by the lack of detections at the PIT readers. In fall, as water temperatures cooled, they moved back downstream. In 2008, the trout repeated the same migration pattern, moving upstream in the spring and downstream in the fall. This migration pattern is exemplified by the individual movement histories of four trout (Figure 2.6).

Migration Rates

Migration rates ranged from 0.24 km/day to 25.58 km/day and averaged 4.2 km/day. According to the BIC selection criterion, the migration rate was best predicted by trout fork length and mean stream discharge. Table 2.3 shows the BIC scores for the top 12 models and the null model. The top 11 models all include the fish fork length, and discharge was included in the top four models. Given that fork length and discharge were significant in all models in which they occurred and that the model with only these parameters has a better BIC score than the rest, it was chosen as the top model. The parameter estimates and 95% confidence intervals of this model are shown in table 2.4. The model has a multiple R^2 value of 0.45. In this model, each cm increase in trout fork length was associated with an 8.1% (95% CL from 5.5 to 10.5%) increase in median migration rate, while each m^3s^{-1} increase in mean discharge was associated with a 13.8% (95% CL from 5.3% to 23.3%) increase in median migration rate.

Migratory Destination and Timing

Of 74 radio-tagged trout, 16 migrated less than 1 km, 15 migrated between 1 and 10 km, 11 migrated between 10 and 25 km, 19 migrated between 25 and 50 km, and 13 migrated between 50 and 91 km. Of the trout that migrated over 1 km, 36 were tagged in the lower river and 22 were tagged in the middle river. Of the lower river trout, 14 never reached spawning habitats, which only occur in the middle and upper river segments (Figure 2.7). The mean uppermost Rkm did not differ (t = 1.07 ; df = 42 ; p = 0.29) between lower and middle river trout (84.0 ± 10.7 km, lower river trout; 87.1 ± 8.4 km, middle river trout). However, lower river trout arrived at their upstream “destination” significantly (t = 3.78; df = 42; p < 0.001) later in the season (May 26th ± 18.0 days) compared to middle river migrants (May 6th ± 16.3 days). One trout in 2007 and three trout in 2008 migrated into the tributary known as the Little Blitzen River while all other trout remained within the Blitzen River mainstem.

Discussion

Seasonal Migration

Our results show that redband trout made long-distance migrations in the Blitzen River and suggest that such movements may be associated not only with reproduction, as evidence suggests for sexually mature trout (3-5 years old), but also with behavioral thermoregulation in response to seasonal fluctuations in water temperatures. The lower section of the Blitzen River offers suitable redband trout habitat in winter, but its waters reach temperatures that are potentially lethal to salmonids in summer. The growth rates of redband trout are also strongly temperature dependent, with optimal growth occurring in the range of 12-16°C (Bear et al. 2007). Seasonal peaks in water temperatures may be a common factor prompting the migration of both sub-adult (1-2 years old) and adult (3-5 years old) trout towards relatively cooler upper segments of the river.

PIT-tagged trout with a long record of detections revealed a consistent pattern of upstream migration in the spring, as temperatures began to rise, and downstream migration in the fall, as temperatures dropped. Rainbow trout in arid streams have been observed to use thermal refugia in warm stream reaches, but such warm reaches are often associated with low fish densities which indicate that thermal refugia may be limited in such areas (Li et al. 1994, Ebersole et al. 2001). Similarly, summer steelhead in Northern

California streams were observed to make daily movements to nearby thermally stratified pools when ambient temperatures exceeded 23°C (Nielsen et al. 1994). Utilization of small-scale thermal refuge was not evaluated in this study, but it may account for many of the tagged fish that were not detected at upstream PIT antennas. The long-distance emigration of sub-adult trout from the warmer reaches of the lower Blitzen River documented in this study suggest that some trout will make movements on the scale of many kilometers to find appropriate thermal habitat. The movement patterns observed in this study are consistent with the notion that trout underwent large-scale movements to find refuge from stressful temperature conditions or to take advantage of areas with temperatures that maximized growing conditions. Bull trout have also been found to make extensive seasonal movements, likely to avoid stream segments with high temperatures (Swanberg 1997, Baxter 2002).

During the winter, mean daily temperatures remained below 4°C throughout the river for at least 60 days, and ice formed on the surface of much of the lower river. Salmonids that make seasonal migrations typically move to habitats that optimize foraging and growth conditions in the spring and summer and move to habitats with cover, deep pools, and low energetic demands in the winter (Bjorn 1971, Brown & MacKay 1995, Schlosser 1995). However, redband trout in a third-order Idaho stream remained in the same segment in the summer and winter even though winter temperatures ranged from 0.0 to 3.8°C (Muhlfeld et al. 2001). In the Blitzen River, both strategies were used, with some redband trout spending the winter in the middle river while others migrated to the deep pools and slow water of the lower river section.

Movement tracking studies of redband trout in other Great Basin streams have documented spawning migrations (Kunkel 1976, Tinniswood 2007), but a three-stage cycle involving large-scale movements between feeding, winter, and spawning habitats, such as that observed in the Blitzen River population, has not been reported. However, other studies on migratory redband trout in the Great Basin have focused on populations that migrate between a river and a lake (adfluvial), whereas the Blitzen redband trout tracked in this study primarily migrated within the river (fluvial). In the Alagnak River in southwest Alaska, adfluvial rainbow trout remained in the lake until migrating to spawn, while the fluvial migratory fish made long-distances upstream migrations between feeding and winter habitats (Meka et al. 2003). Systems that have habitats with both appropriate thermal conditions and foraging opportunities year-round may support a migratory life-history that only involves large-scale movements between rearing and spawning habitats. The cycle of repeated sub-adult migrations between summer feeding and winter survival habitats before first spawning at age three or four observed in the Blitzen River redband population is likely dependent upon consistent seasonal extreme shifts in temperature and the existence of spatially separated habitat patches with different thermal regimes. This study underscores the importance of local conditions and of spatial and temporal heterogeneity of habitat patch distribution in determining life-history expression of trout populations.

Migration Rates

Redband trout migration rate was highly associated with fork length. This may be partially explained by the fact that both swimming performance (Webb et al. 1984) and energy efficiency (Hinch & Rand 1998) increase with the body length of migrating salmonids. Also, the analysis of spawning checks on the scales indicated that Blitzen redband trout do not reach maturity until age 3+. Because the larger trout (>350 mm) were more likely to be sexually mature, the motivation and seasonal requirements for migratory timing may have been different for this group compared with the smaller sub-adult migrants. Spawning fish are likely to make more directional movements to reach spawning habitats, while immature fish may be more opportunistic in finding transitional rearing habitats, thus moving more slowly up river. Selective pressures, such as mating synchrony, specific seasonal requirements for egg development (de Gaudemar & Beall 1998), and offspring emergence patterns that result in competitive advantages (Einum & Fleming 2000), are likely to influence the motivation of spawners to move upstream within a given period of time.

As well as fork length, mean discharge was positively associated with migration rate as indicated by the top four BIC-ranked regression models. Most of the large-scale upstream movements recorded during this study occurred during the spring snow-melt period, and only downstream movements to winter habitat were detected during low-flow conditions. Similarly, the timing of large-scale movements of rainbow trout in north-central British Columbia was linked to periods of high discharge (Mellina et al. 2005). Elevated discharge often serves as the primary environmental cue for the spawning migrations of trout (Trépanier et al. 1996). During high-flow seasons, fish have access to additional tributary and gravel bar spawning habitats. However, since not all of the migrating redband trout in the Blitzen River were spawners, additional factors were involved in the connection between movement and discharge. Although flow velocity increases with discharge, which raises the energetic cost of migration (Hinch & Rand 1998), deeper water and higher turbidity create cover from mammalian and avian predators during migration (Monnot et al. 2008). We found evidence of 6 radio-tagged trout and 15 PIT-tagged trout killed by predators, so predator avoidance is important in the Blitzen River. Furthermore, high discharge may also be necessary for fish to negotiate barriers or difficult river reaches (Rand & Hinch 1998). The migration rate was significantly influenced by temperature in the models that did not include discharge; however, since temperature and discharge were correlated, it was impossible to separate the effects of the two. Based on both the results of this study and the observations of others (Trépanier et al. 1996), discharge was likely the key factor influencing migration.

Tag type, radio versus PIT, did not affect the migration rate of redband trout in this study. The indicator variable for tag type was included in three of the top twelve regression models but did not have a significant association with migration rate in any of them. Despite many studies that have determined that radio tags did not affect migration rates, behavior, or swimming performance of salmonids (Swanberg & Geist 1997, Jepsen et al. 2003, Matter & Sandford 2003), we felt that it was important to evaluate the tagging method for this particular study. Although it was not possible to compare the performance of radio-tagged trout to untagged fish, PIT tags are much smaller, lighter, and have no external antenna; thus, they were chosen as the control. PIT tags have also been demonstrated to have no effect on growth, survival, or behavior of juvenile salmonids (Brannas et al. 1994, Ombredane et al. 1998). With past validation of radio tagging methods and the fact that there was no difference in migration rates between radio-tagged and PIT-tagged trout in this study, it is reasonable to assume that the types of tags used to track trout did not have a significant effect on the movements observed.

The number of dams that a trout passed on the migration did not influence the rate of migration. This was a surprising result given that long median delays were observed for PIT-tagged trout at Busse and Grain Camp dams (see Chapter 3), and differences in upstream migration rate through open-water segments versus dammed segments was apparent for many of the radio-tagged trout (Appendix A, e.g. tag 15, 50, 56). Although the dams appeared to affect the migration of some individuals, on average there was no difference. Furthermore, passage at individual dams may have been more important to the migration than the number of dams passed since the passage delays among the dams were significantly different (Chapter 3).

Migratory Destination and Timing

The migration of adult trout was clearly associated with the search for suitable spawning substrates, which were absent in the lower section of the river. This conclusion was supported by spawning substrates found in the vicinity of the upstream-most sites where adult trout were detected, direct observations of spawning aggregations, and a radio-tagged female guarding a redd. Given the limited geographic distribution of spawning substrates in the Blitzen River, it may not be surprising that the adult trout that were radio tagged migrated to the same river segments regardless of whether they were in the lower or middle river sections prior to the spawning migration. Lower river trout, which traveled much farther and encountered numerous diversion dams, arrived at their migratory destinations an average of 20 days later in the season. For salmonids, breeding time is highly heritable, and differences between early and late spawners within a given season can limit gene flow between groups (Hendry & Day 2005). Differences in breeding times could suggest that the phenotypic differences between the lower and middle river trout could potentially lead to genetic differences. Different breeding times could result in a competitive disadvantage for the offspring of late spawners, as seen in Atlantic salmon (Einum & Fleming 2000), which could cause early life-history differences between lower river and middle river trout.

The migratory Blitzen River redband trout represent an important life-history that was likely much more prevalent among Great Basin redband trout populations than it is currently. Salmonid populations with multiple life-history strategies are more resilient to changing environmental conditions (Rieman and Dunham 2000), and the conservation of migratory life-history should be a high priority. However, conservation of migratory redband trout provides numerous management challenges. Fish passage problems can adversely affect migratory trout, especially those that move through the lower and middle river multiple times during their life. Passage delays are of concern both for sub-adult trout seeking refuge from high temperatures and for mature spawners for which arriving at spawning habitats at the correct time is critical. Also, since migratory trout utilize habitats in the lower river, water quality, water quantity, and habitat issues should be addressed throughout the river. A riparian restoration strategy that builds on functioning riparian corridors from upstream to downstream will gradually reduce thermal loading, thereby increasing summer rearing habitat. Ensuring minimum flows before diverting water will maximize survival for trout that migrate late or remain in the lower river.

Future research of redband trout in the Blitzen River is needed to expand upon the information gained from this study. This effort was limited to migratory trout caught in the spring that were large enough to tag with a 23mm PIT tag. We did not examine juvenile movement patterns, which would contribute to a full understanding of the life-history of migratory trout. Also, Malheur Lake water level was relatively low during this study, and replication of the study during a period of higher lake levels would be valuable to better understand the importance of the lake to the redband trout population.

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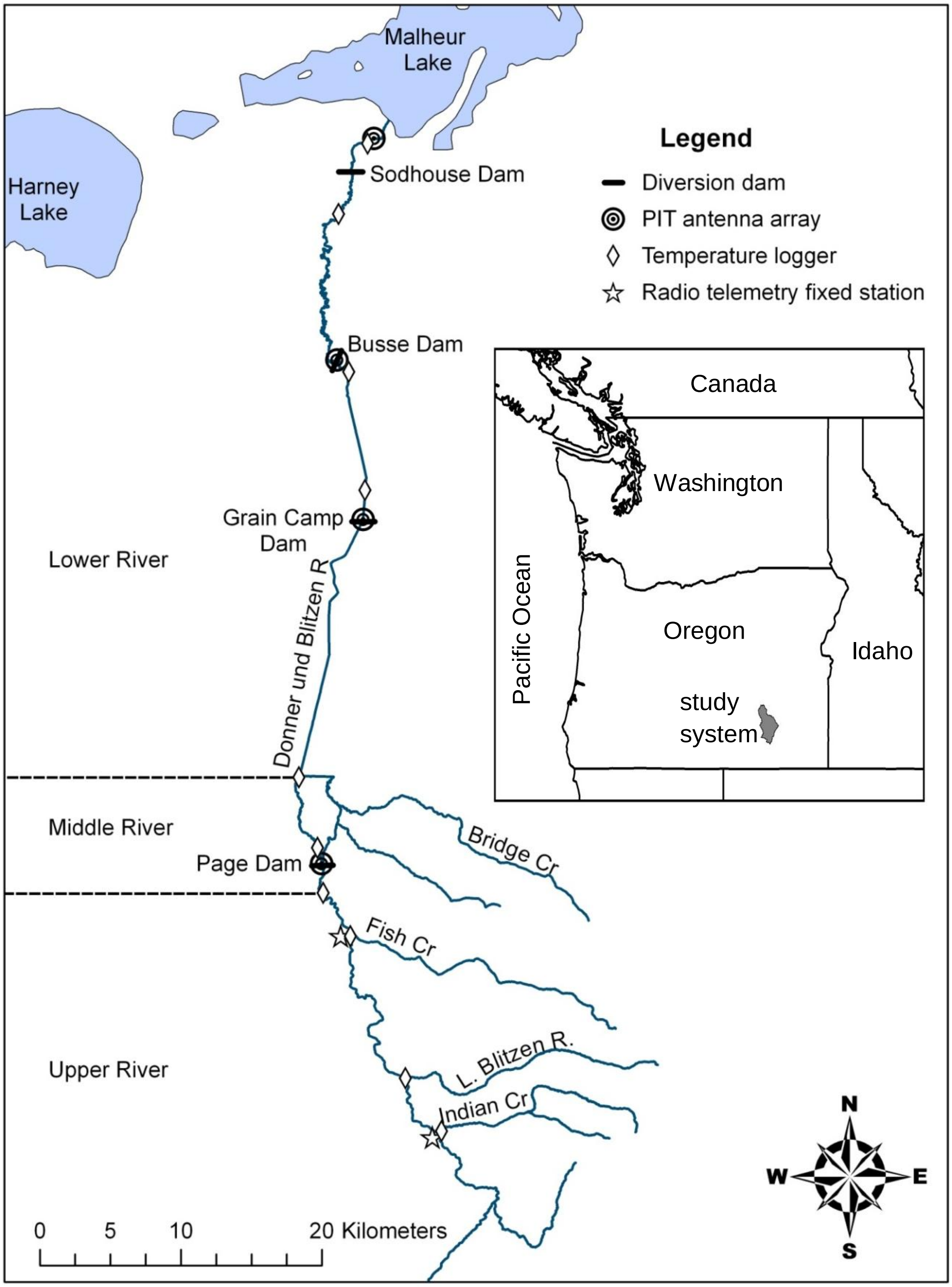

Figure 2.1. Map of the Blitzen River illustrating the locations of diversion dams, PIT tag readers, and radio telemetry fixed stations.

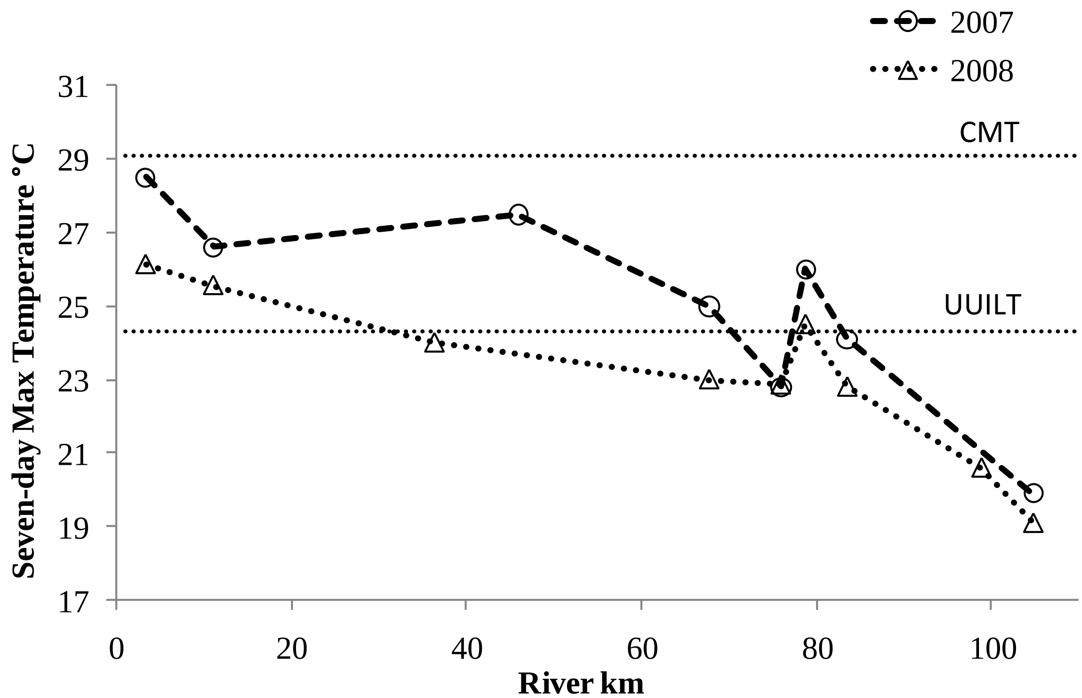

Figure 2.2. Seven-day max. avg. temperatures for the 2007 and 2008 at ten locations in the Blitzen River. The ultimate upper incipient lethal temperature (UUILT) and critical maximum temperature (CMT) for redband trout are shown for context.

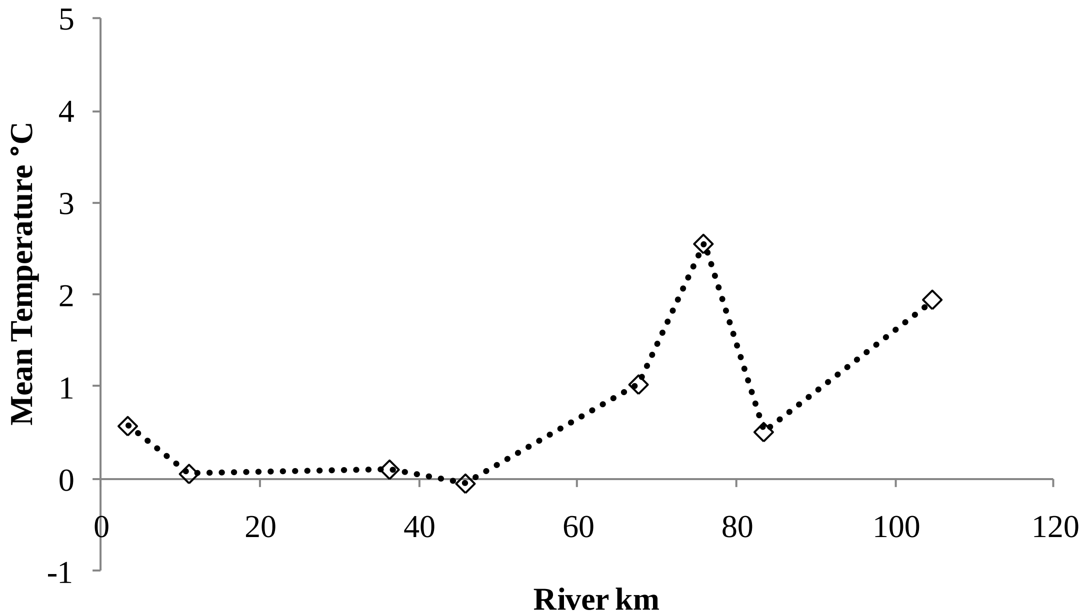

Figure 2.3. Mean temperatures during December 2007 and January 20008 at eight locations in the Blitzen River.

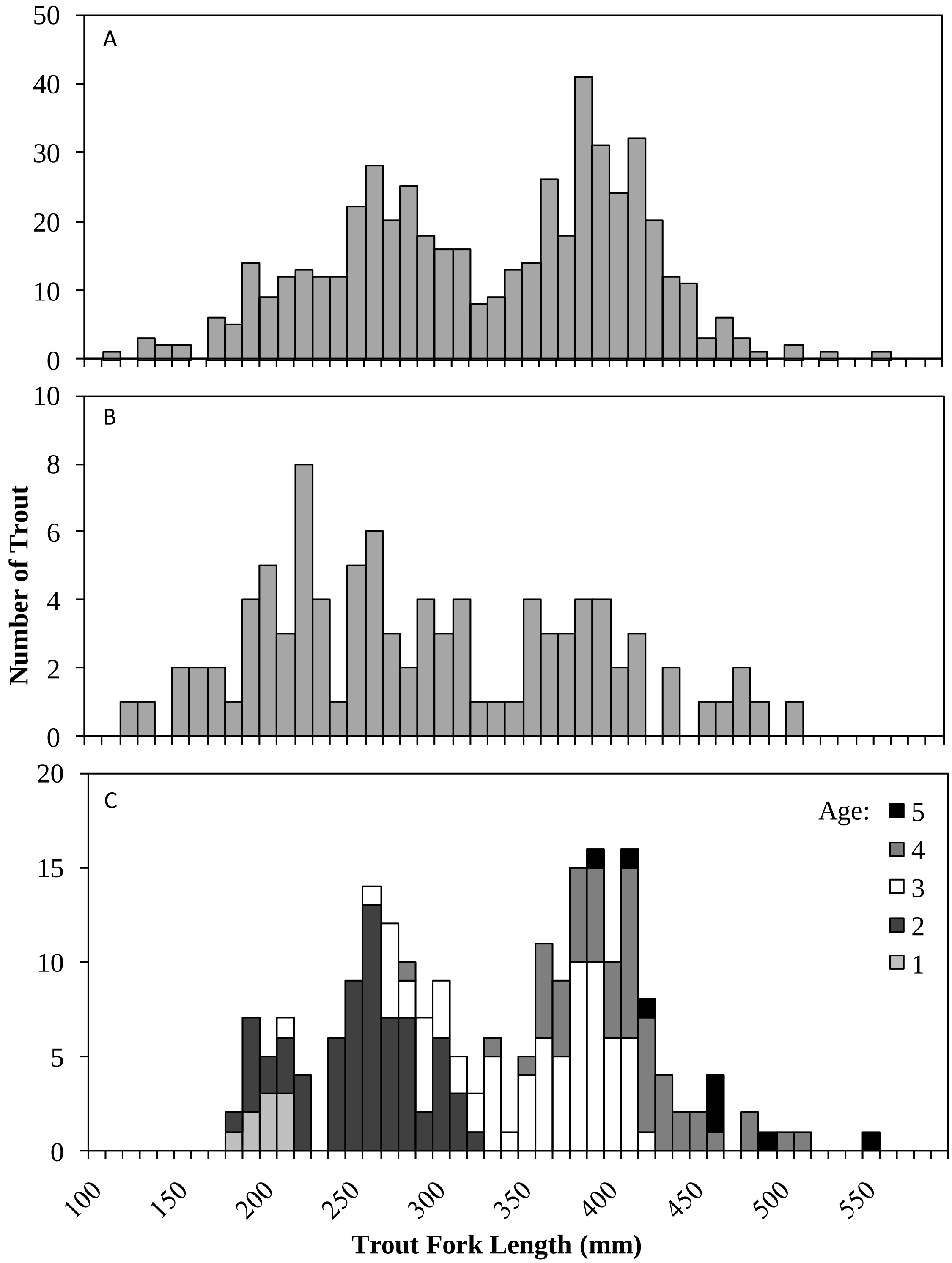

Figure 2.4. Histogram of redband trout lengths for (A) all trout captured in 2007, (B) all trout captured in 2008, and (C) the subset of fish from both years that had ages interpreted from scale samples.

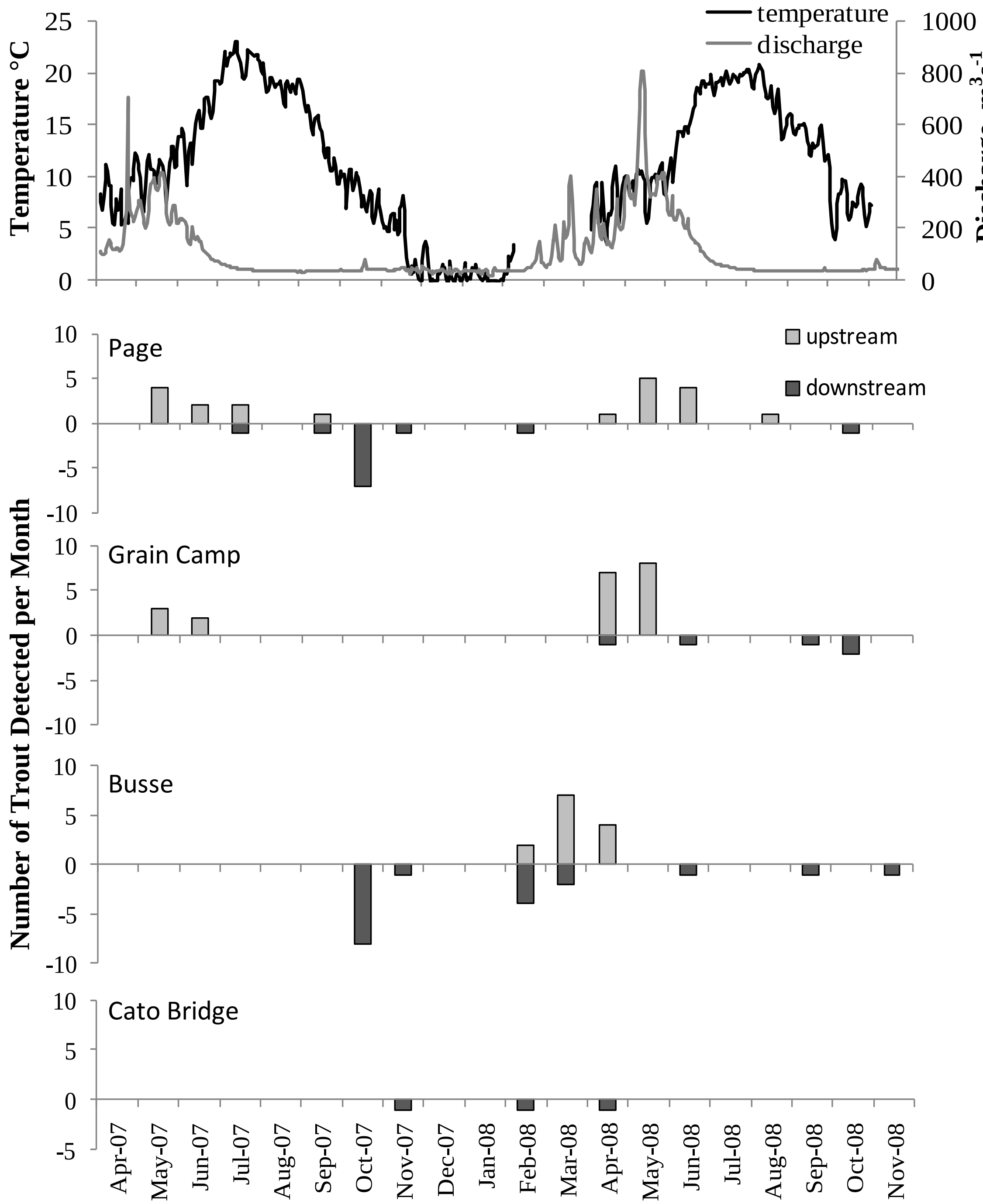

Figure 2.5. Mean daily temperature recorded upstream of Bridge Creek and mean daily discharge at the Page Springs Weir (top panel) compared to directional movements of 24 redband trout tagged in 2007 with detections into 2008 (bottom panel). The vertical axis depicts the number of fish detected at each PIT antenna location each month where negative numbers represent downstream moving trout and positive numbers represent upstream moving trout. The horizontal axis shows a common date for both panels.

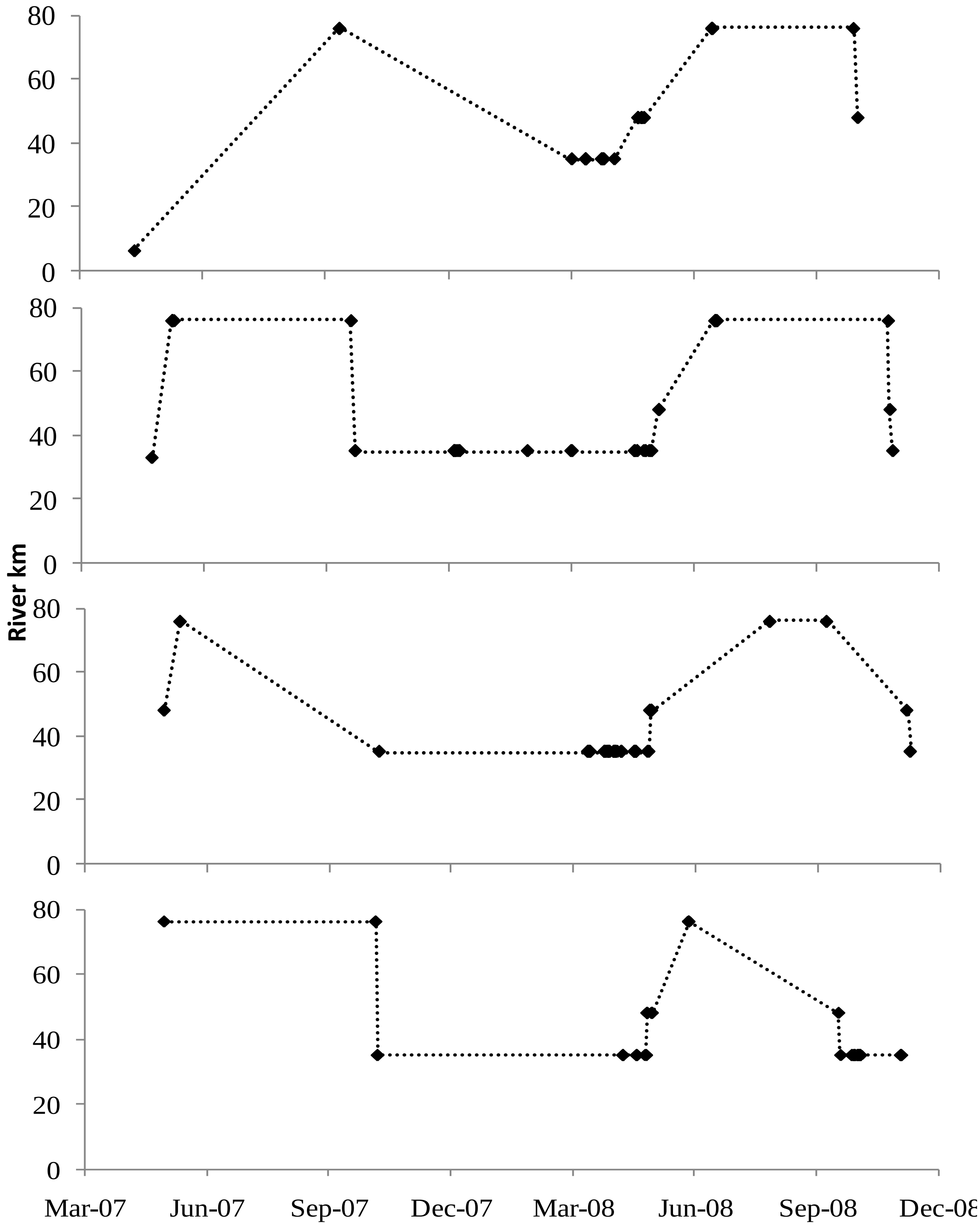

Figure 2.6. Movement patterns of four of the 24 trout that were tracked through 2007 and 2008. Both PIT tag and radio tag detections are shown. The vertical axis indicates the detection location in Rkm, and the horizontal axis indicates the detection time. Dotted lines connect the nodes for clarity but do not indicate known trout locations between successive detections.

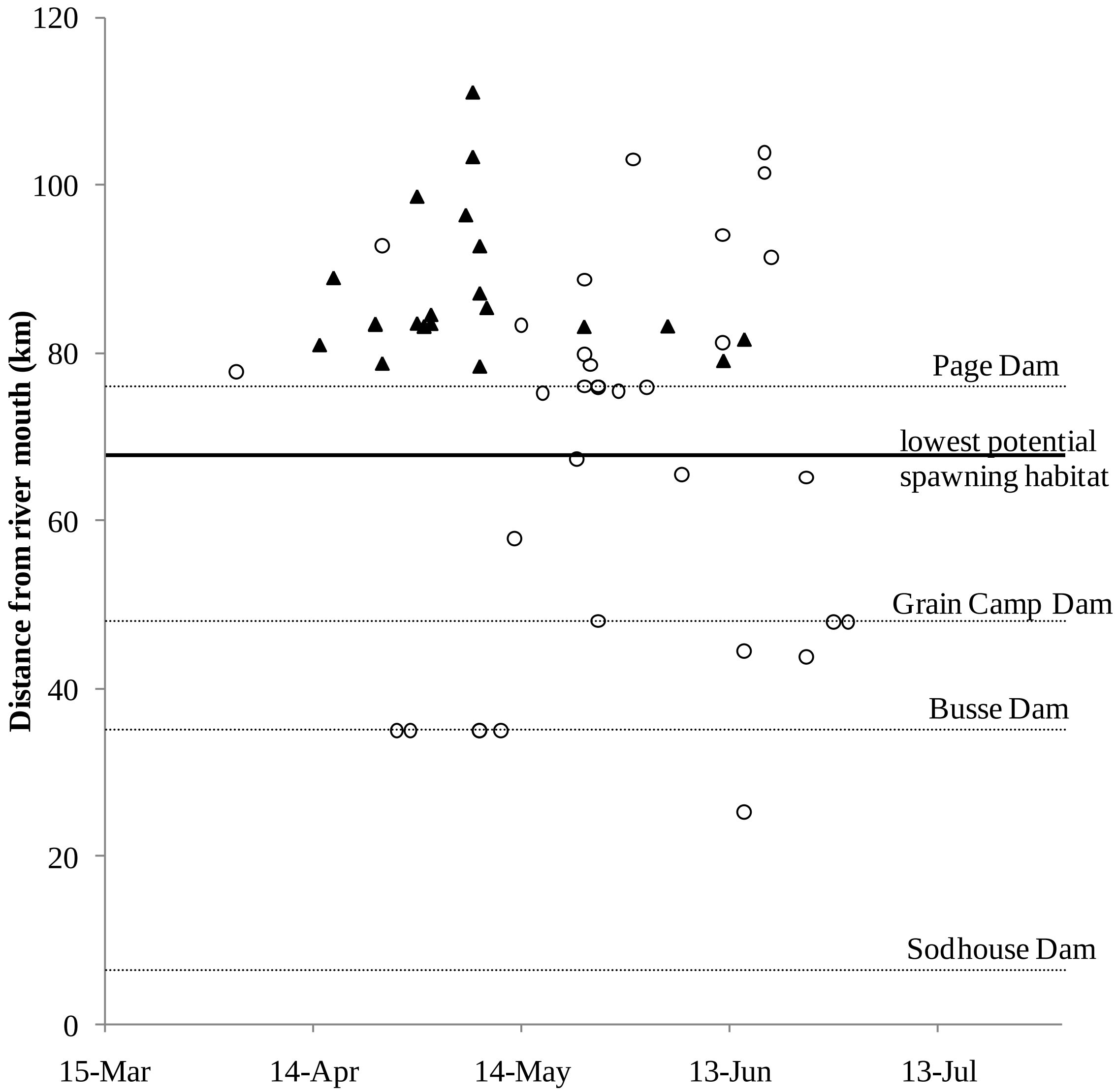

Figure 2.7. Location of the upstream-most site and date of arrival for migratory trout from the middle river (▲) and lower river (○). Dotted lines represent diversion dams on the Blitzen River. Solid line represents boundary between the lower and middle river and the lowest river segment with potential trout spawning habitat.

Table 2.1. Maximum summer seven-day mean of maximum daily temperatures (7-day max. avg.) on the Blitzen River at eight locations in 2007 and nine locations in 2008.

River km		3	11	36	46	68	76	79	84	99	105
Year	**2007**	28.5	26.6	-	27.5	25.0	22.8	26.0	24.1	-	19.9
	2008	26.1	25.6	24.0	-	23.0	22.9	24.5	22.8	20.6	19.1

Table 2.2. Number of trout caught at each location in traps and by angling in 2007 and 2008.

	2007		2008	
Capture Method	**Trap**	**Angling**	**Trap**	**Angling**
Sodhouse Dam	81	2	6	1
Busse Dam	221	12	39	13
Grain Camp Dam	-	29	-	2
Page Dam	164	2	15	5
Other	10	2	0	14
Total	476	47	60	35

Table 2.3. Bayesian Information Criteria scores for the top twelve regression models and the null model explaining variation in trout migration rate.

BIC	**Independent Variables in Model**
195.0	fork length discharge
198.0	fork length discharge tag
199.2	fork length temperature discharge
199.2	fork length discharge dams
199.5	fork length temperature
201.6	fork length
202.1	fork length temperature radio
203.4	fork length temperature dams
205.0	fork length tag
205.6	fork length dams
208.9	fork length dams tag
223.7	discharge dams
229.5	null

Table 2.4. Parameter estimates for the top model of factors influencing the $\log_e$–transformed migration rate of trout.

Parameter	**Estimate**	**Lower 95% CL**	**Upper 95% CL**
intercept	-2.83	-3.85	-1.80
length	0.0078	0.0054	0.010
discharge	0.13	0.052	0.21

CHAPTER 3

PASSAGE DELAYS OF MIGRATING REDBAND TROUT AT DIVERSION DAMS ON THE DONNER UND BLITZEN RIVER, OREGON

Abstract

We evaluated passage delays of migratory redband trout at three diversion dams on the Donner und Blitzen River. Two of the dams, Busse and Page, have Denil fish ladders and the third, Grain Camp, has a jump-pool ladder. Efficiency of the passage facilities at these dams has not previously been examined. We tested three hypotheses related to redband trout passage: 1) trout passage time is influenced by stream temperature, discharge, diel period, fork length, and tagging method, 2) the proportion of total trout passage time accounted for by ladder entry time is greater than that accounted for by ladder ascending time, and 3) trout passage time differs by location among Busse, Grain Camp, and Page dams. An array of passive integrated transponder (PIT) antennas detected tagged trout, first, when they approached each dam, subsequently, when they entered its ladder, and finally, when they reached the upper end of the ladder. Thus data on ladder entry time, ladder ascending time, and total passage time for individual trout were obtained. Survival analysis statistical methods were used because they accommodate both censored data and time-dependent covariates. At a jump-pool ladder (Grain Camp Dam), trout were 7.23 times more likely to pass during day than at night ($\chi^2(1, N = 40) = 9.96$, $p = .002$). At a Denil ladder (Busse Dam), trout were 25.6% more likely to pass with each degree Celsius increase in stream temperature ($\chi^2(1, N = 22) = 4.39$, $p = .036$). Discharge, fork length, nor tagging method was associated with passage at any of the dams. At all three dams, a greater proportion of the total passage time involved ladder entry rather than ladder ascending. Entry time was 14.6 times longer than ascending time at Busse Dam, 23.1 times longer at Grain Camp Dam, and 71.5 times

longer at Page Dam. Trout passage time varied significantly between each of the dams. The expected median passage time was 0.07 days at Page Dam, 1.2 days at Grain Camp Dam, and 9.4 days at Busse Dam. The study indicates that trout delays at diversion dams can be highly variable based on the design of the passage facilities and that adequate attraction to fish ladders is critical in minimizing passage delays.

Introduction

Dams create artificial barriers to fish movement and are one of the key factors leading to the global decline of freshwater fishes (Pringle et al. 2000). Most dam construction has occurred over the past century, and the extent of development has been huge. In 1996, it was estimated that, globally, there were 42,000 large dams (>15m) and 800,000 small dams (<15 m) (Rosenberg et al. 2000). Dams affect freshwater ecosystems by altering habitat, hydrologic flow regimes, sediment and nutrient transport, and aquatic species distributions and interactions (Gregory et al. 2002). Migratory fish species have been particularly disrupted by dams. It is widely accepted that dams have played a major role in the decline or extirpation of hundreds of anadromous salmon stocks in the Pacific Northwest of the United States. Other migratory fishes, both anadromous and potadromous, have also declined dramatically as their ranges have been restricted or spawning habitats made inaccessible by dams (Pringle et al. 2000).

Fragmentation of aquatic habitats reduces the ability of migratory individuals to move between feeding habitats and spawning habitats and can isolate small resident populations above barriers. Those smaller populations are thought to have a higher risk of extinction and a greater reliance on connectivity to other populations, which may also be excluded by an impassable dam (Stacey & Taper 1992). For example, the probability of presence of white-spotted char (*Salvelinus leucomaenis*) in streams above barriers in Hokkaido, Japan decreased with decreasing watershed area and increasing period of isolation (Morita & Yamamoto 2002).

Passage problems can be caused either by barriers that have no fish passage provisions or by those with fish ladders with low passage efficiency (Marmulla & Welcomme 2002). Stream barriers that allow some fish passage but create migratory delays can still cause a number of problems. Sexually mature fish migrating to spawning habitats may be delayed long enough to miss the critical period for spawning timing (Northcote 1997). Migrating fish may be retained in inhospitable habitats resulting in reduced growth and fitness or even mortality. During migratory periods, fish can become crowded below dams leading to elevated resource competition and predation risks. With the adverse effects of poor passage acting disproportionally on the migratory population, the population may tend to shift from a partial-migratory population (with both resident and migratory individuals) towards a strictly resident population (Theriault et al. 2008). The occurrence and consequences of passage delay on migrating salmonids has been evaluated for large hydro-electric dams on the Columbia River, where it has been demonstrated that the duration of delays below dams is associated with reduced spawning success (Keefer et al. 2004, Caudill et al. 2007). Passage efficiency of salmonids at small dams has received much less attention despite the fact that an estimated 95% of the dams in the U.S. fall into this category (Rosenberg et al. 2000, Schmetterling et al. 2002).

Fish passage efficiency is related to fish ladder design and site-specific conditions at the dam (Marmulla & Welcomme 2002). Although fish ladder designs have been extensively tested in controlled settings (Monk et al. 1989), the conditions in real streams can vary considerably from one location to another and over the range of potential river conditions (Marmulla & Welcomme 2002). It is widely held that most standard ladder designs are well-suited to the passage of salmonids (Bunt et al. 1999, Schmetterling et al. 2002). However, fish passage has traditionally been evaluated by fish counts in traps at the top of ladders and by recapturing marked fish above and below dams, but fewer studies have investigated the delay of fish at dams with passage structures (Castro-Santos & Haro 2003).

Populations of redband trout (*Oncorhynchus mykiss gairdneri*) that express both migratory and non-migratory life-history types may be more resistant to environmental variability and more resilient to stochastic disturbances than populations with a single dispersal strategy (Rieman & Dunham 2000, Meka et al. 2003). Migratory redband trout in the Great Basin often grow larger and have higher fecundity than resident redband trout (Kunkel 1976). However, the construction of artificial barriers to movement such as hydro-electric dams, irrigation diversion dams, and weirs has been responsible for reducing or eliminating migratory redband trout from many of the basins within their native range (Behnke 1992, Thurow et al. 1997). In some cases, the redband trout migratory life-history form has become reestablished following improvements in fish passage (Tinniswood 2007).

In the Great Basin, there are few remaining population strongholds of redband trout; most of which are found in areas that have protected habitat and restricted land use (Thurow et al. 2007). The Donner und Blitzen River (Blitzen River), which flows from the Steens Mountain Wilderness Area and through the Malheur National Wildlife Refuge (MNWR), maintains one such stronghold (Dambacher et al. 2001, Thurow et al. 2007). A subpopulation of the Blitzen River redband trout expresses a migratory life-history

(Bowers et al. 1999, Behnke 2007). Although there are numerous diversion dams on the MNWR, all those on the Blitzen River have some provision for fish passage. However, the efficiency of the passage structures has never been quantitatively evaluated, and the impact of the dams on trout migrations is unknown.

This study focused on the passage time of redband trout at three irrigation diversion dams on the Blitzen River. The objectives of the study were to determine the extent of the passage delays at these dams and to evaluate the factors that affected the delay times. In assessing these objectives, the following three hypotheses were tested: 1) trout passage time is influenced by stream temperature, discharge, diel period, fork length, and tagging method, 2) the proportion of total trout passage time accounted for by ladder entry time is greater than that accounted for by ladder ascending time, and 3) trout passage time differs by location among Busse, Grain Camp, and Page dams.

Methods

Study Location Description

We conducted this study on redband trout passage in the Blitzen River Basin, an endorheic system located in the high desert region of south-eastern Oregon, which has Malheur Lake as its inland terminal location (Figure 3.1). This basin has an area of 2,045 km^2 and a drainage density of 0.33 km/km^2. Elevation in the basin ranges from 1,248 m at Malheur Lake to 2,967 m at the top of Steens Mountain. The Blitzen River is 128 km long, and its tributaries, most of which drain the west slope of the Steens Mountain, flow through deep, glacially-carved valleys of basalt and andesite bedrock. Mean annual precipitation ranges from less than 40 cm at lower elevations to over 100 cm at higher elevations in the Steens Mountain (Taylor 2005). Most precipitation falls as snow during winter months, and most runoff occurs as snow melt during spring (Oregon Climate Service, USGS). The Malheur Wildlife Refuge has four primary diversion dams on the Blitzen River mainstem that are operated during spring snowmelt to maintain wetland habitat for breeding waterfowl. From the mouth of the river in an upstream direction the dams are Sodhouse, Busse, Grain Camp and Page (Figure 3.1). Sodhouse, Busse, and Page are equipped with Denil fish ladders, while Grain Camp has a jump-pool fish ladder (Figure 3.2).

Fish Tagging

Redband trout were caught in fish traps located at the upstream end of fish ladders at Sodhouse, Busse, and Page dams and by angling in the vicinity of the dams. Traps were set 4 to 7 days a week from late March to early June of 2007 and 2008. Angling with artificial lures was employed approximately 5 hours per week below the dams in April and May of both years in order to increase the number of trout sampled. Each captured trout was measured (fork length to the nearest mm) and weighed (to the nearest g). Scales were taken from a subset of 257 trout. Although scales were not taken randomly, we attempted to sample trout across the range of sizes to fully represent the population.

We tagged 77 redband trout from 272 mm to 560 mm fork length (FL) with radio tags and 544 trout over 100 mm fork length with passive integrated transponder (PIT) tags (all but 3 radio-tagged trout were also PIT tagged). Texas Instrumets® PIT tags, 23 mm in length and 1 g in weight, were inserted into the body cavity of smaller trout (FL <

300 mm) and the dorsal sinus of the larger trout (FL ≥ 300 mm). For a fish to be selected for radio tagging, the tag could not exceed 3% of the trout's body weight. Because we had a limited number of radio tags, we chose not to tag all captured fish early in the season in an attempt to deploy tags throughout the migration season. Trout were radio tagged regardless of condition except in two cases of severe injury. Lotek Wireless® radio tags were implanted in the body cavity following standardized surgical procedures. In 2007, we tagged 36 trout with MCFT-3A (16 g) and 10 trout with MCFT-3FM (11 g) tags. In 2008, we tagged 26 trout with NTC-6-2 (4.5 g) tags, 3 trout with MCFT-3A (16 g), and 2 trout with MCFT-3FM (11 g) tags. Larger tags were used in the first year so the batteries would last throughout the study. Tag weight averaged 1.4% of the body weight of the fish and ranged from 0.5% to 2.5%.

All surgeries were conducted on site at the capture location. Trout were anesthetized in an aerated holding tank with approximately 100 mg/l tricane methanesulphonate (MS-222) solution with 120 mg/l of bicarbonate buffer. Anesthesia typically occurred in 2-4 minutes. For the surgery, trout were placed ventral side up in a wet, foam cradle. The gills of the fish were irrigated with anesthetic solution and stream water. A 1.5-2.5 cm long incision, just wide enough to accommodate the transmitter, was made on the fish anterior to the pelvic girdle of the fish and offset 2 cm from the mid-ventral line. A cannula shielded with plastic tubing was used to guide the transmitter antenna to the exit location posterior to the pelvic fin (Ross & Kleiner 1982). After placing the transmitter in the body cavity, the incision was closed with 2 to 3 sutures of monofilament absorbable material with a simple interrupted 3-2-1 surgical pattern

(Wagner et al. 2000). All surgical equipment was disinfected between uses with Benz-all®. Trout were allowed to recover in a covered tank with cool stream water for at least 15 minutes and until they were fully responsive before being released at the capture location. Trout caught in the traps were released far enough upstream to minimize risk of falling back below the dam.

Factors that Influence Passage Time

Movements of PIT-tagged redband trout were used to evaluate passage time at diversion dams in the spring of 2008. We placed PIT tag antenna arrays at Busse Dam, Grain Camp, and Page dams. At each of the three dams, three antennas were installed. One antenna was placed 30 to 50 m downstream of the dam, a second antenna was mounted to the downstream entrance of the fish ladder, and a third was put in the upstream exit of the ladder (Figure 3.3). Each antenna formed a loop. The antennas below the dams spanned the entire river channel (10 to 15 m wide), with the bottom of each antenna following the contours of the channel bed and the top a maximum of 0.7 m above it. During most flows, the detection field filled the entire wetted channel, and at high flows, only the upper portion of the water column was outside the detection field. Antennas in the fish ladders were rigid and rectangular with dimensions that matched the dimensions of the ladder. Based on the first trout detection time at each antenna, we calculated total passage time, ladder entry time, and ladder ascending time. Total passage time was the time between the first detection of a fish below the dam and the first detection of that same fish at the ladder exit. Ladder entry time was the time between the first detection below the dam and the first detection at the ladder entrance. Finally, ladder ascending time was the time between the first detection of a fish at the ladder entrance and its first detection at the ladder exit. Additional information about trout that had fall-back events through the dam or backed down the ladder was not considered.

We estimated the antenna efficiency as the percentage of trout with known locations both downstream and upstream of a given antenna that were detected by that antenna. For the efficiency test, known trout locations included tagging location, radio tag detection event, PIT tag detection at another antenna, or recapture location. Trout that were detected at an antenna, but were not independently confirmed to be on either side of that antenna were not included in the test. Table 3.1 lists the estimated efficiency of each of the antennas and the number of trout included in the evaluation.

We collected stream temperature, discharge, and diel period data during trout passage sampling to determine whether or not any of these variables were related to fish passage time at the dams. Stream temperature was collected using Onset Corp. HOBO® temperature loggers. One logger below Page Dam provided temperature data for trout passage at Page Dam and a logger located between Busse and Grain Camp dams provided data for trout passing these two locations. Stream discharge data for trout passing Page Dam was collected at the Page Springs Weir, about 4 km upstream of the Dam (courtesy of U.S. Geological Survey). Discharge data for Grain Camp Dam was available immediately below the dam until May 20, 2008, but after that date the discharge was estimated using discharge recorded 20 km upstream at New Buckaroo Dam. Discharge for trout passing Busse Dam was collected 1 km downstream of Busse Dam (Grain Camp and Busse discharge data courtesy of U.S. Fish and Wildlife Service).

Sunrise and sunset information was acquired from the U.S. Naval Observatory estimated for Burns, OR (http://aa.usno.navy.mil/cgi-bin/aa_rstablew.pl). Passage time was compared with the daily average values of temperature and discharge and the difference between day and night periods (diel period). Trout that passed before sunrise in the morning were assigned average discharge and temperature from the previous day.

The length of each trout captured was also considered as a potential factor that influenced passage time. We assumed that growth during a single migration season was negligible; however, many of the trout that provide passage information during 2008 were captured in 2007. For these trout, a size adjustment was applied to account for growth based on a von Bertalanffy growth curve (Sparre 1989) derived from size and age at time of capture (see appendix B). Age was estimated based on the analysis of 257 scales taken from trout captured during the study. The scales were interpreted by two readers, and 42 scales interpreted differently by the readers were eliminated from the data set, which left 215 scale samples. The parameter estimates for the growth curve were derived using Microsoft Excel Solver® function. Since the growth parameter, K, was low (0.17), the predicted lengths were adequately described by a linear annual increase of 70 mm of growth per year. Although this was only independently confirmed with two recaptured trout, the annual growth of those fish, 69 and 70 mm, was highly consistent with the predicted values.

Fish Ladder Entry Time versus Ascending Time

We used the PIT antenna arrays at Busse, Grain Camp, and Page dams (described above) to compare ladder entry and ascending times of migrating trout that passed the ladder. Due to low detection efficiency in the Busse Dam fish ladder, we compared the minimum entry time to the maximum ascending time, thereby performing a conservative test of the hypothesis, while maximizing data inclusion. Minimum entry time was calculated by subtracting the time of the first detection of a fish below the dam from its first detection at the ladder entrance, or when the ladder entry detection was missing, by substituting its last detection below the dam. Maximum ascending time was calculated by subtracting a fish's ladder entrance time from its ladder exit time, or if the ladder entrance time was missing, the last detection below the dam detection was substituted, and if the ladder exit detection was missing, the first detection of the fish at the next dam upstream was used. Using only trout with exact entry and ascending times, the sample sizes were 3 trout at Busse, 29 trout at Grain Camp, and 23 trout at Page; however, by using minimum entry times and maximum ascending times, the sample sizes increased to 14, 31, and 23, respectively, which allowed Busse Dam to be included in the analysis while having little effect on the estimates of Grain Camp and Page.

Comparison of Passage Times among Dams

Radio telemetry tracking in 2007 and 2008 was used to compare passage delays with the results from the PIT antenna arrays at Busse, Grain Camp, and Page dams (described above). Radio-tagged trout were relocated an average of 1.5 times per week in 2007 and 1.7 times per week in 2008. For each radio-tagged trout that encountered a dam while migrating, we evaluated whether or not the fish passed the dam, and if it did, we calculated the minimum passage delay as the number of days the fish was below the dam after being located within 1 km of the dam. From this information, we determined the percentage of radio-tagged fish that successfully passed and the average minimum passage delay at each dam.

Statistical Analyses

Survival analysis techniques were used to test our hypotheses. Survival analysis data are times until an event has occurred; in this application, the 'event' is passage through a dam, not death. These analytical techniques are used for many applications in the sciences (Allison 1995), but are only recently gaining prominence in the fish passage literature (Castro-Santos & Haro 2003, Keefer et al. 2004, Naughton et al. 2005, Caudill et al. 2007). Survival methods are particularly useful because they allow the inclusion of censored observations, that is, observations for which the time to passage is only partially known. Censoring resulted from failed passage or undetected passage, but trout were considered to be delayed by the structure as long as they continued to be detected downstream of the dam. For example, if a migrating fish was detected multiple times below a dam over a period of time, it did not need to have been recorded passing the dam to provide some information on the duration of delay. Including censored data increases the available information, while reducing bias related to the passage outcome. Survival analysis was conducted with PROC PHreg and PROC Lifereg in SAS v.9.1 (SAS Institute Inc., Cary, N.C.)

The relationship between trout passage time and environmental conditions, fork length, and tagging method was examined independently at each of the three dams using Cox proportional hazards regression model. For each dam, the following model was applied:

$$h_{i(t)} = \lambda_0(t)\exp\,[\beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \beta_4 X_{4i} + \beta_5 X_{5i}];$$

where the passage hazard *h* for individual *i* at time *t* is a function of the unspecified, non-negative baseline hazard function, $\lambda_0(t)$, and the exponentiated linear function of the stream temperature (X_1), discharge (X_2), an indicator variable for diel period (day vs. night) (X_3), an indicator for tagging method (X_4), and fork length (X_5) with β_1,..., β_5 the coefficients of the respective parameters. The proportional hazards model estimates the hazard function, which is the instantaneous rate of passage for the population of fish below a dam given the passage events that have occurred up to that time. The model assumes that the rate of passage differs among fish only as a function of the covariates. The proportional hazards model is well-suited to evaluate time-dependent covariates (Allison 1995). The significance of each parameter is evaluated with a chi-square test. Since the three dams were tested independently, we chose an α-level for significance of 0.016 using the Bonferroni method to correct for multiple comparisons.

For the statistical analysis comparing entry and ascending times of trout at each of the dams, we utilized paired t-test. Based on a graphic evaluation of the distribution of the data, the response times were $\log_e$ transformed to establish homogeneity of the variance. Entry and ascending times were compared at each of the dams. The α-level for significance was set at 0.016 using a Bonferoni adjustment to account for multiple comparisons. The entry and ascending times at each of the dams were displayed using Kaplan-Meyers curves.

To compare trout passage at the three dams, the parametric accelerated failure time (AFT) model was used. The AFT model is a linear model for the logarithm of the event time in which the explanatory variables act directly on time via a scaling factor (Hougaard 1999). In the model, this is accomplished by exponentiation of the explanatory variables. The model is:

$$T_i = \exp\,[\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_3 + \sigma\varepsilon_i];$$

where T is the event time for individual i, which is a function of X_1, an indicator for Busse Dam, X_2, an indicator for Grain Camp Dam, and X_3, an indicator for Page Dam, β_0 is the intercept, β_1, β_2, and β_3 are the coefficients of their respective parameters, σ is a shape parameter, and ε is a standard normally distributed random effect for each individual.

While some of the trout in the study only encountered one of the dams, others encountered multiple dams. In order to compare the passage time at each dam using all observations, it would have been necessary to estimate a variance-covariance matrix to account for the lack of independence of individual fish passing different dams; however, because not all fish passed all the dams, the incomplete repeated measures precluded such estimation. As a result, one passage event for each trout was randomly selected, and data pertaining to the passage of that trout at the other dams were excluded. Goodness-of-fit tests for the distribution of the data were conducted using the likelihood-ratio statistic to compare a series of nested distributions that are special cases of the generalized gamma distribution (Allison 1995). The nested distributions, which include the log-logistic, exponential, Weibull, and log-normal distributions, have fewer parameters than the generalized gamma distribution (Allison 1995).

Results

Factors Influencing Passage Time

In almost all cases, ladder passage times were not associated with environmental conditions. Busse Dam had 22 PIT-tagged trout available for passage, 12 of which were censored; Grain Camp Dam had 40 trout available for passage, 8 of which were censored; and Page Dam had 26 trout available for passage, 4 of which were censored. Trout available for passage at the dams experienced temperatures ranging from 3.5 to 22.7°C and discharge ranging from 0.95 to 22.85 m^3s^{-1}. The results of the Cox proportional hazards regression for each of the dams is shown in Table 3.2. At the jump-pool ladder on Grain Camp Dam, trout were 7.23 times more likely to pass during day than at night ($\chi^2(1, N = 40) = 9.96$, $p = .002$). At the Denil ladder on Busse Dam, trout were 25.6% more likely to pass with each degree Celsius increase in stream temperature ($\chi^2(1, N = 22) = 4.39$, $p = .036$).

Fish Ladder Entry Time versus Ascending Time

The paired t-tests comparing ladder entry and ascending times indicated that most delays were related to trout initially finding and entering the ladders. At all three of the dams, median minimum ladder entry times were significantly greater than median maximum ladder ascending times (Table 3.3). At Busse Dam, median entry time was 14.6 (95% CI: 2.5 to 85.6) times greater than the median ascending time (t (13) = 3.28, p

= .006) at Grain Camp Dam, 23.1 (95% CI: 8.3 to 64.7) times greater (t (30) = 6.28, $p <$ .001) and at Page Dam, 71.5 (95% CI: 25.3 to 204.4) times greater (t (22) = 8.50, $p <$ .001). The differences between entry and ascending times are displayed in Figure 3.4. As apparent from the figure, the long delays at Busse and Grain Camp dams are largely accounted for by the entry phase of the passage process.

Comparison of Passage Time among Dams

The three dams on the Blitzen River had significantly different performance regarding trout passage time. For the AFT model, the log-likelihood goodness-of-fit tests indicated that both the log-normal and Weibull distributions were as well-supported by the data as the generalized gamma distribution (Table 3.4). As a result, we selected the log-normal distribution as the most parsimonious since it required estimation of fewer parameters (Allison 1995). The test failed to reject the null hypothesis that passage time is not influenced by fork length or tagging method (radio tagging versus PIT tagging). On the other hand, there was a significant difference in ladder passage time for trout at each of the three dams (Table 3.5, Figure 3.5). Trout were found to pass Page Dam 295.6 (95% CI: 75.2 to 1,164.5) times faster than Busse Dam and 30.5 (95% CI: 9.7 to 95.6) times faster than Grain Camp Dam. Trout were expected to pass Grain Camp Dam 9.7 (95% CI: 2.7 to 34.1) times faster than Busse Dam (Table 3.5). Based on these results, the null hypothesis that there is no difference in trout passage time among Busse, Grain Camp, and Page dams was rejected.

Differences in fish passage at the three dams were also apparent from radio telemetry data of 14 trout at Busse Dam, 23 trout at Grain Camp Dam, and 17 trout at

Page Dam (Table 3.6). At Busse Dam, 6 of the 14 trout that approached the dam were unable to pass, and those that passed experienced a mean minimum delay of 7.6 days in 2007 and 2008 combined. Out of 23 trout that approached Grain Camp Dam, the 21 that were able to pass experienced a mean minimum delay of 2.9 days. At Page Dam, 16 out of 17 trout that approached the dam were able to pass, and those that passed experienced a mean minimum delay of 0.7 days. Although passage delays from the radio telemetry data are shorter than those calculated from the PIT tags, it was not possible to determine exactly when trout arrived at the dam or exactly when they passed, and therefore, these data likely underestimate the total delays. Consistent with the PIT tag assessment, the radio telemetry assessment of passage delays indicated that the worst passage was at Busse Dam, the next worse at Grain Camp Dam, and the best passage at Page Dam. The radio tags also provided information about the proportion of the trout that were unable to pass the dams at all.

Discussion

Factors Influencing Passage Time

Trout passed the jump-pool ladder at Grain Camp Dam much faster during the daytime than at night, and there was a positive association between passage time and stream temperature at Busse Dam. Otherwise, there was no evidence that stream temperature, discharge, diel period, fork length, or tagging method influenced passage rates. Although redband trout migration rate in the Blitzen River was positively correlated to trout fork length and discharge (see Chapter 2), neither of these factors were associated with passage rate. This indicates that differences in migration rate based on fork length and discharge occurred during travel between the dams, but that the passage times were independent of these variables.

Stream temperature is often considered an important factor controlling the upstream migration of salmonids. In this study, stream temperature had a positive relationship with passage rate at the middle-channel Denil ladder at river km (Rkm) 35 (Busse Dam) but no relationship at the side-of-channel Denil ladder at Rkm 76 (Page Dam) or with passage at the jump-pool ladder at Rkm 48 (Grain Camp Dam). Busse Dam is the farthest downstream of the dams, and migrating trout encountered it earlier in the spring than the other dams and, thus, experienced different temperatures (mean temperature was 9.8°C at Busse and 14.5°C at Page). In the relatively cool early spring temperatures experienced by trout at Busse, temperature may have played an important role in swimming performance. This is consistent with the finding that passage delays of steelhead trout (*O. mykiss*) at hydroelectric dams on the Columbia River had a unimodal relationship with temperature in which the shortest delays corresponded with temperatures that allowed maximum swimming speeds (about 16°C, Salinger & Anderson 2006).

River discharge was found not to significantly affect passage times. At Columbia River dams, slower passage was related to higher flows due to higher water velocity and increased turbulence in the tailrace environment (Keefer et al. 2004, Caudill et al. 2007). At each of the dams in the Blitzen River, the tailrace was highly turbulent, which likely affected passage; however, spill volume and ladder volume were set manually (usually daily), which may have been more important than river discharge. Also, proper function of Denil ladders is highly susceptible to variation in headwater levels (Marmulla & Welcomme 2002), which was not considered in this study.

Time of day had a strong influence on passage time at the jump-pool ladder at Grain Camp Dam, but it had no influence on passage time at either of the Denil ladders. It is possible that trout relied on visual cues to pass the jump-pool ladder but could use other sensory mechanisms to negotiate the Denil ladders. Both Chinook salmon and steelhead in the Columbia River (Naughton et al. 2005, Caudill et al. 2007) and Atlantic salmon in the River Tay, Scotland (Gowans et al. 1999) were found to preferentially pass through fish ladders in the daylight compared to at night.

The fork length of the trout did not affect passage time. This was a surprising finding given the positive relationship between trout length and swimming ability (Webb et al. 1984). Also, since large trout were more likely than small trout to be migrating to spawn (see Chapter 2), they were expected to have a greater motivation to migrate and therefore would make more frequent attempts. This finding supports the conclusion that passage delays were caused by factors other than high velocities that could be overcome by swimming ability.

Fish Ladder Entry Time versus Ascending Time

At all three fish ladders, the median time trout needed to find and enter the ladder opening was longer than the time they took to climb it. This underlines the importance of adequate ladder entrance attraction as part of the overall fish passage structure design and installation plan. The different ladder configurations in this study provide clues about certain design elements of a ladder that are important for successful fish passage. For example, one of the benefits of Denil ladders is that the relatively high water velocity at the entrance of the structure should improve fish attraction (Marmulla & Welcomme 2002). Upstream migrating fish are thought to exhibit positive rheotaxis, moving in or near the point of highest discharge (Bunt 2001, Marmulla & Welcomme 2002). As a result, Marmulla & Welcomme (2002) recommend that the entrance of a fish ladder be located on the bank of a river where current is greatest and as close as possible to the primary outflow of the dam. While this may be the case in large rivers, the results of our study indicate that in smaller rivers it is important to make ladder attraction current as distinguishable as possible from the primary release of the dam. At Busse Dam, where trout experienced the greatest delay in ladder entry, the Denil fish ladder is located in the middle of the channel between two radial gates and therefore, is always adjacent to the dam outflow regardless of which gate is open. The relatively low discharge from the fish ladder is likely to be masked by the turbulent tailrace of the dam. Turbulence and high velocities have been found to distract fish and reduce their chances of entering a passage facility (Barry & Kynard 1986). In the case of the Busse Dam fish ladder, the entrance may be too close to the outflow of the dam. By contrast, Grain Camp Dam, where trout exhibited intermediate entry delays, is typically operated by releasing flow from the radial gate on the bank of the river opposite from the location of the jump-pool fish ladder. This spatial separation seems to effectively isolate the ladder flow from the primary dam outflow. Nevertheless, because water velocities at the entrance of jump-pool ladders are low compared to Denil ladders, trout still seemed to have difficulty in detecting the fish ladder’s flow. The other Denil ladder monitored in this study, at Page

Dam, had the least fish passage delays, and its entrance was also on the river bank opposite from the primary outflow of the dam. Furthermore, it had additional attraction current provided by the downstream fish bypass. The differences in delay times at the dams suggest that fish passage may be improved by having an attraction flow that is distinct from water spilled from the dam.

Comparison of Passage Time among Dams

Redband trout at the Denil ladder at Busse Dam (Rkm 35) had the longest passage delay times of the three dams (median delay of 9.4 days), and this dam was the one primarily responsible for preventing what was deemed to be the upstream spawning migration of mature trout. In contrast, below the jump-pool ladder at Grain Camp Dam (Rkm 48), trout experienced delays that ranged in duration from intermediate in most cases (median delay of 1.2 days), to long for a small proportion of the fish (24% delayed longer than 10 days). Few (9%) of the radio-tagged trout were unable to pass this structure. The recently constructed Denil ladder at Page Dam (Rkm 76) was passed relatively quickly by most fish (median delay of 1.4 hours). The differences among the ladders were more import in determining passage times than either environmental conditions or fish characteristics.

There is evidence to suggest that slow passage has a negative effect on the fitness of redband trout. Delays below dams have been shown to be energetically costly for salmonids (Geist et al. 2000). Based on PIT tag records, trout that experienced long delays in this study would remain below the dams attempting passage for three to four days and then leave for a number of days, possibly to recover in an environment of lower energy compared to that of the tailrace. Slow passage can cause high densities of fish below the dams, which attract predators. Predatory birds were often observed near the dams—Sodhouse and Busse—with middle river Denil ladders, and approximately 5% of radio and PIT tags were recovered near bird nests or mammal dens. Radio-tagged fish that were unable to pass the dams are believed to have failed to spawn since they were unable to reach spawning habitats. Also, long delays for trout migrating to spawn may reduce spawning success or impair the competitive ability of offspring (Einum & Fleming 2000). Immature redband trout in the Blitzen migrate upstream past each of the dams in this study to find summer thermal refuge, and those that are delayed for long periods or that are unable to pass may be exposed to stressful or lethal temperatures (see Chapter 2).

The results of this study highlight the importance of monitoring passage structures in the field in relation to native fish migrations. Fish ladders tested in a laboratory setting may not function as intended when installed in the natural environment. Fish passage facilities should be evaluated for efficiency to ensure that they do not significantly reduce the fitness of migratory fish due to long delays. Automated tag detectors, such as PIT or radio telemetry antennas, provide a cost-effective method for evaluating passage rate. The configuration of the antenna array can be designed to gain information on the various stages of passage and can be used to inform and evaluate modifications to improve passage.

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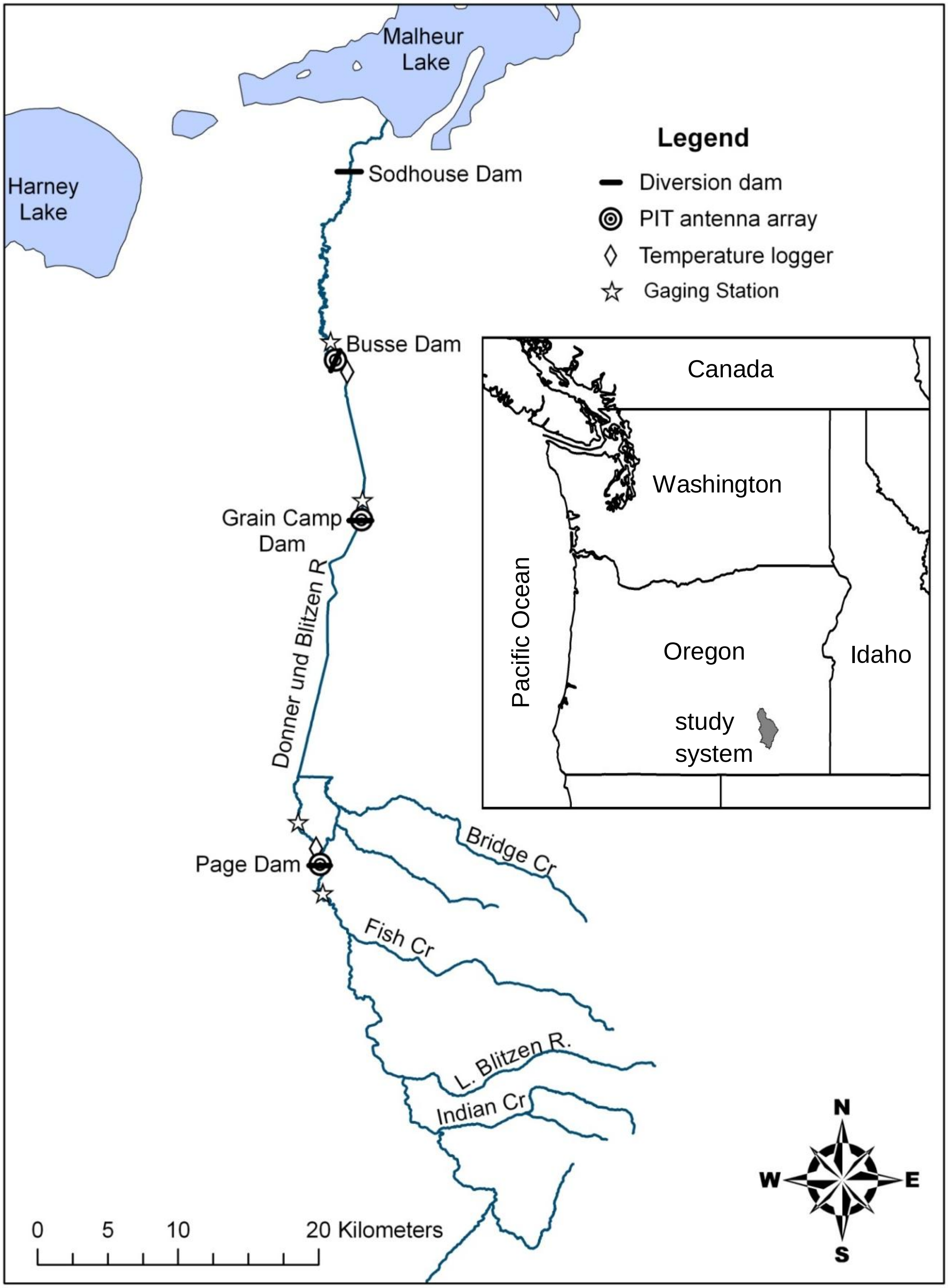

Figure 3.1. Map of the Blitzen River illustrating the location of diversion dams, PIT antenna arrays, temperature loggers, and gaging stations.

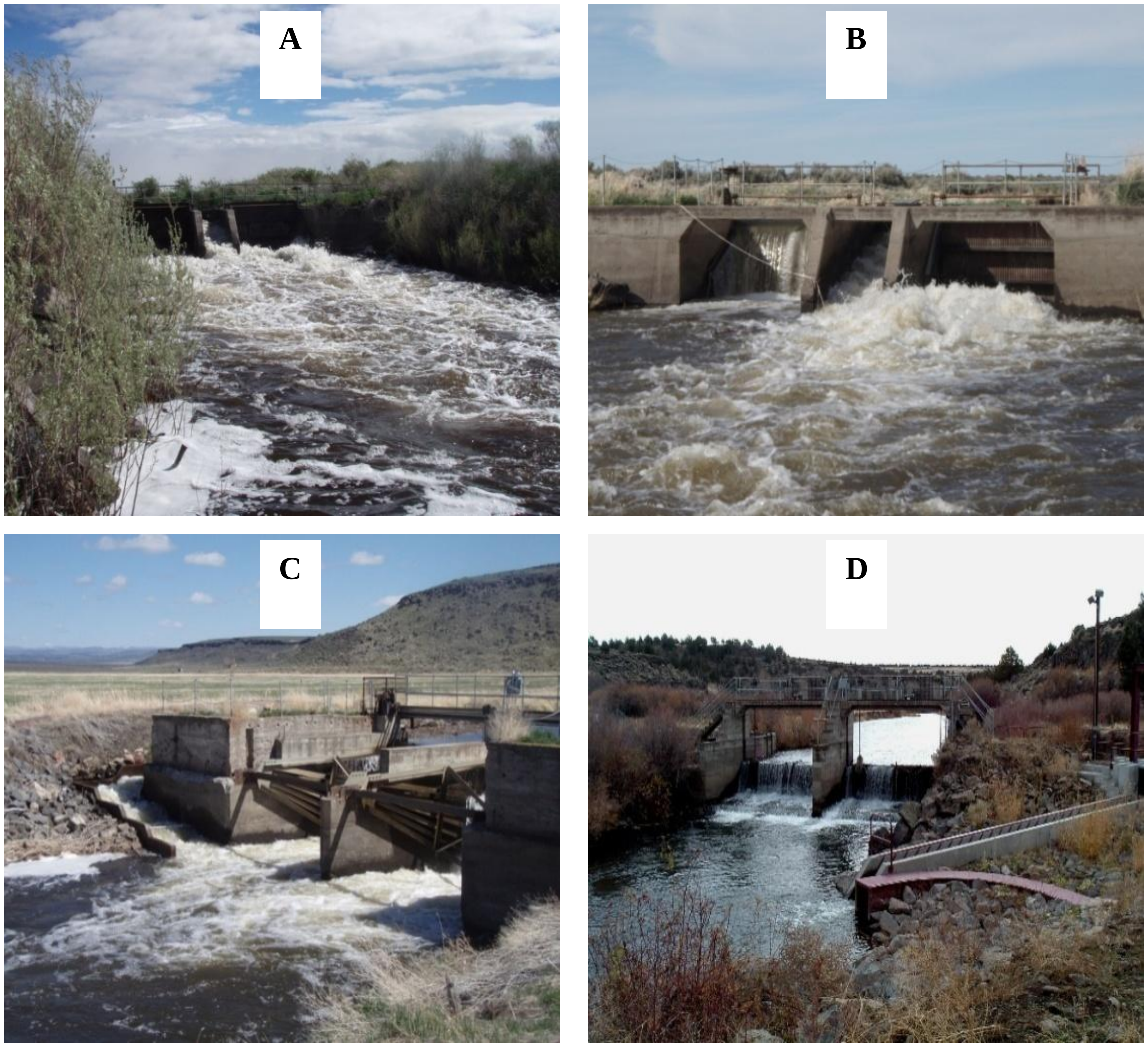

Figure 3.2. Photographs of diversion dams on the Blitzen River: A) Sodhouse Dam, B) Busse Dam, C) Grain Camp Dam, and D) Page Dam.

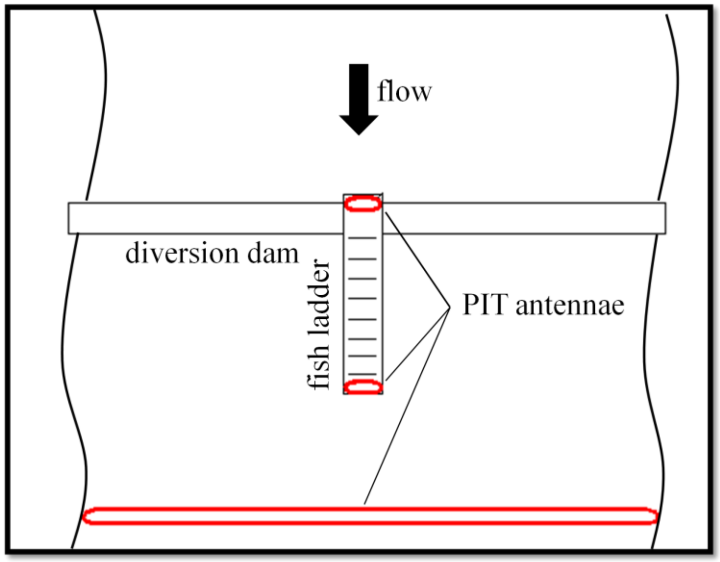

Figure 3.3. Example PIT antenna array at Busse Dam (sketch not to scale).

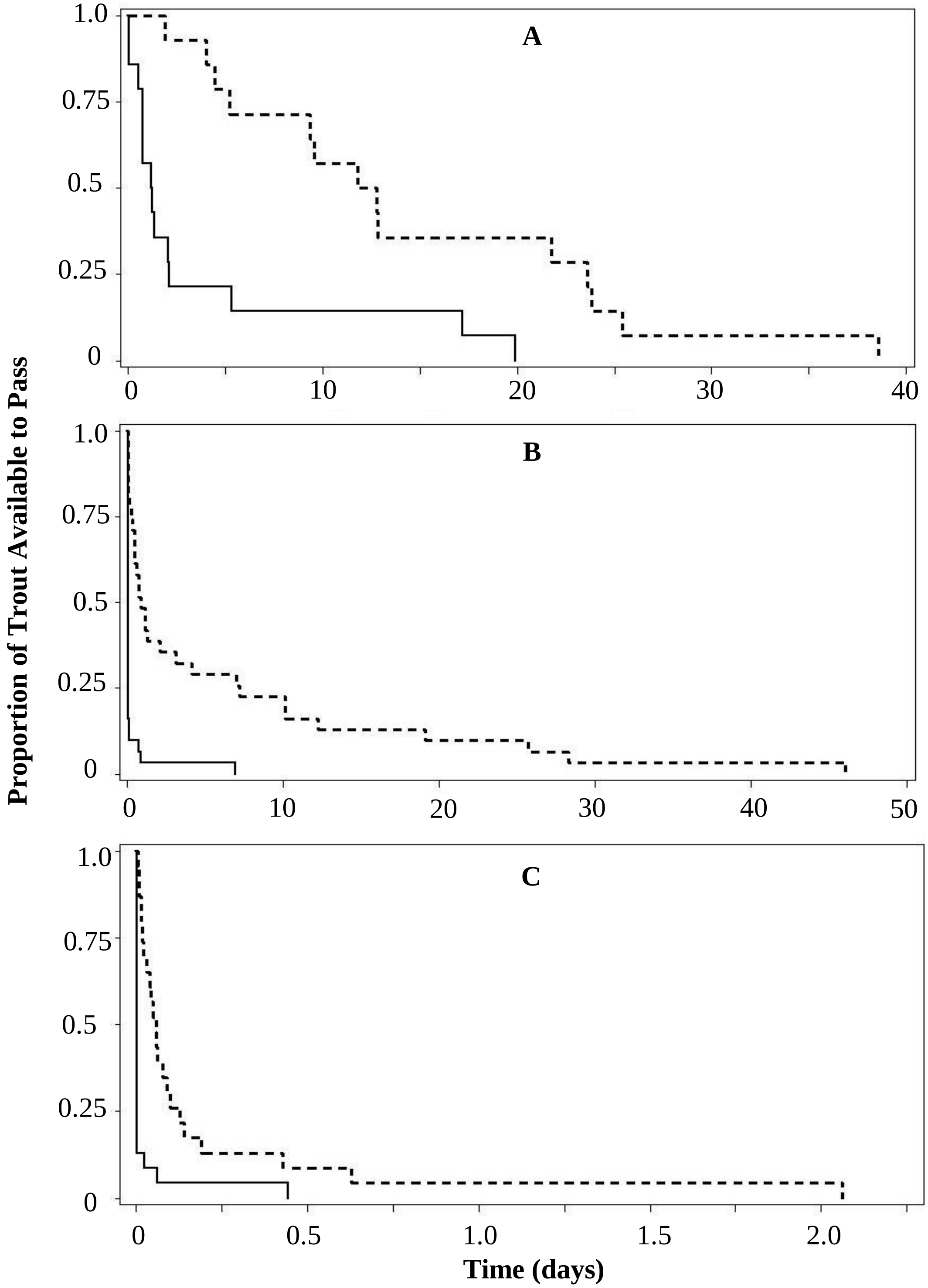

Figure 3.4. Fish ladder entry time (dotted lines) and ascending time (solid lines) at Busse (A), Grain Camp (B), and Page (C) dams. Note the differences in time scale of the horizontal axis in the three panels.

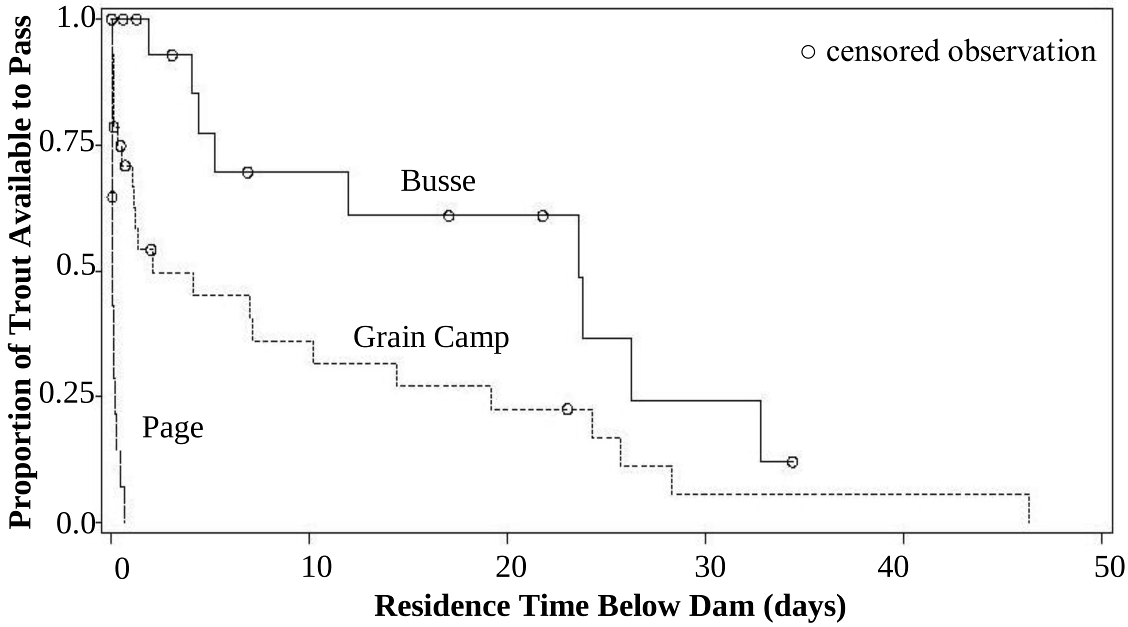

Figure 3.5. Kaplan-Meyers curves illustrate the passage times at the three dams. Trout were considered available to pass as soon as they were detected at the PIT antenna below the dam. The proportion available to pass was the number of trout that had not passed out of the total number that approached the dam. When a trout successfully passed the fish ladder, the proportion of trout available to pass decreased (indicated by a vertical drop of the line in the graph). If a fish was never recorded to successful passage, that individual was censored at its last detection at the downstream antenna and removed from the sample population (represented by the circles in the graph). Censoring resulted from failed passage or undetected passage, but trout were considered to be delayed by the structure as long as they continued to be detected downstream of the dam. Upon a passage event following censoring, the proportion was calculated from a smaller population, thus the vertical drop is greater following censoring of individuals.

Table 3.1. Estimated PIT antenna efficiency at Busse, Grain Camp, and Page dams.

Dam	**Antenna Location**	**Trout that Passed**	**Trout Detected**	**Estimated Efficiency (%)**
Busse	below dam	3	2	66.6
	ladder entrance	16	7	43.8
	ladder exit	15	3	20.0
Grain Camp	below dam	39	31	79.5
	ladder entrance	34	32	94.1
	ladder exit	12	11	91.7
Page	below dam	18	13	72.2
	ladder entrance	18	16	88.9
	ladder exit	11	7	63.6

Table 3.2. Results from Cox proportional hazards model testing for association between environmental factors and passage rate at Busse, Grain Camp and Page Dams.
* Indicates statistical significance.

Location	**Variable**	**Estimate**	**SE**	**Chi-squared**	***p*-value**	**Hazard ratio**
Busse	temperature*	0.23	0.11	4.39	0.036	1.26
	discharge	-0.003	0.006	0.17	0.68	0.99
	diel period	1.00	0.85	1.37	0.24	2.71
	tagging method	--	--	--	--	--
	fork length	0.003	0.008	0.15	0.70	1.00
Grain Camp	temperature	-0.032	0.053	0.37	0.54	0.97
	discharge	0.002	0.002	1.46	0.23	1.00
	diel period *	1.98	0.63	9.97	0.002	7.23
	tagging method	-0.06	0.57	0.01	0.92	0.94
	fork length	0.003	0.003	0.83	0.36	1.00
Page	temperature	-0.18	0.097	3.51	0.061	0.83
	discharge	-0.005	0.003	1.91	0.17	0.99
	diel period	0.16	0.51	0.10	0.75	1.17
	tagging method	0.47	0.58	0.67	0.41	1.60
	fork length	-0.001	0.004	0.04	0.83	1.00

Table 3.3. Ratio of ladder entry to ascending times at Busse, Grain Camp, and Page Dams based on paired T-test. Estimates are back-transformed from the log scale.
* indicates significance after adjusting for multiple comparisons.

Location	**Ratio of Entry to Ascend Time**	**Lower 95% CL**	**Upper 95% CL**	**d.f.**	***t*-statistic**	***p*-value**
Busse*	14.6	2.5	85.6	13	3.28	0.006
Grain Camp*	23.1	8.3	64.7	30	6.28	<0.001
Page*	71.5	25.3	204.4	22	8.50	<0.001

Table 3.4. Results of the log-likelihood goodness-of-fit test for competing distributions of the AFT model of passage times at the dams.

Distribution	**Log-likelihood**	**Chi-sqr**	***p*-value**
generalized gamma	-101.37	-	-
Weibull	-101.41	0.08	0.77
log-normal	**-102.02**	**1.3**	**0.25**
log-logistic	-103.04	3.34	0.067
exponential	-107.55	12.36	0.004

Table 3.5. Results of accelerated failure time model comparing trout passage at Busse, Grain Camp, and Page dams accounting for trout fork length and tagging method. Estimates are back-transformed from the log scale.

Variable	Estimate	Lower 95% CL	Upper 95% CL	Chi-squared	*p*-value
Page vs. Busse	295.6	75.2	1,164.5	61.7	<0.0001
Page vs. Grain Camp	30.5	9.7	95.6	34.2	<0.0001
Grain Camp vs. Busse	9.7	2.7	34.1	12.5	0.0004

Table 3.6. Percentage of trout able to pass and the mean minimum delay (days) at Busse, Grain Camp and Page Dams in 2007 and 2008 based on radio telemetry tracking.

	2007		**2008**		**Total**	
Dam	**Percent Passing (n)**	**Mean Delay**	**Percent Passing (n)**	**Mean Delay**	**Percent Passing (n)**	**Mean Delay**
Busse	50% (12)	5.5	100% (2)	14.0	57% (14)	7.6
Grain Camp	92% (13)	2.9	90% (10)	2.8	91% (23)	2.9
Page	91% (11)	1.1	100% (6)	0.0	94% (17)	0.7

CHAPTER 4

GENERAL CONCLUSIONS AND IMPLICATIONS

There is a highly mobile fraction of the redband trout population in the Blitzen River that utilizes widely dispersed habitats. The trout in this high desert stream system have adapted a unique migratory pattern that involves annual, long-distance migrations to seasonally suitable habitats (Figure 2.5). In the fall, trout move to the lower river and may, when conditions are suitable, also move into Malheur Lake. This lower portion of the watershed provides winter refuge habitat. In summer, because of both natural thermal regimes and water diversion, water temperatures in the lower portion of the watershed approach critical maxima (Figure 2.2), and trout migrate upstream to reaches with cooler temperatures. Additionally, mature fish migrate upstream to access gravel substrates necessary for spawning. Because these habitats are spatially segregated, successful completion of this life-cycle is dependent on connectivity within the river system. Such connectivity is challenged by a series of diversion dams. Trout that make annual migrations may encounter each of these dams many times during their lifespan. Long delays below the dams, such as those observed at Busse and Grain Camp dams (Figure 3.5), can have negative repercussions on trout seeking different habitats and can increase risk of predation. For spawning trout, timing is of paramount importance, and delays can reduce success. Effective conservation of the migratory segment of the population will best be achieved by providing connectivity throughout the river.

For Blitzen redband trout, the rate of upstream spring migration was strongly associated with fork length and mean discharge (Tables 2.3 and 2.4). The positive relationship between trout fork length and migration rate is likely due to both increased swimming ability of larger trout and because large trout are more likely to be migrating to spawn. Both swimming performance and energy efficiency have been demonstrated to increase with body length among salmonids (Webb et al. 1984, Hinch & Rand 1998). Larger trout were more likely to be sexually mature and migrating to spawning habitats, whereas smaller trout were presumably migrating to find thermal refuge. Given the importance of spawning timing on reproductive success (de Gaudemar & Beall 1998, Einum & Fleming 2000), larger trout appear to have been motivated to migrate more quickly than immature trout. The redband trout migration rate in the Blitzen River was also positively related to discharge, a relationship that has been observed in many migratory salmonid populations (Trépanier et al. 1996, Mellina et al. 2005). The factors that encourage fish movement during high discharge, such as favorable spawning conditions (Trépanier et al. 1996), protection from predators (Monnot et al. 2008), and negotiation of difficult river reaches, appeared to be more important than the costs of increased energy expenditure (Hinch & Rand 1998).

Radio telemetry tracking indicated that spawners from the lower and middle sections of the Blitzen River utilized the same spawning habitats but that lower river migrants reached those spawning locations later in the season (Figure 2.7). The mean upper-most stream segment where trout were detected was the same regardless of whether the fish resided in the lower or middle river section prior to migration. Lower river trout reached their upper-most destination an average of 20 days later than middle river trout, suggesting a partial temporal reproductive segregation may exist between the two groups. It is not known whether or not the spawning segregation is caused by fish passage delays, or if there are genetic differences between the two groups of fish.

The diversion dams on the Blitzen River played an important role in upstream migrations of redband trout tracked during this study. The time it took for trout to pass a dam ranged from just a few minutes to over forty days. We were unable to isolate environmental factors or specific fish characteristics that influenced the amount of delay at the dams. However, passage delays among the three different dams evaluated in the study were significantly different. Passage delays were caused primarily by trout having difficulty in finding and entering the ladders.

Stream temperature, discharge, diel period, fork length, nor tagging method influenced the passage time at any of the dams except that trout were seven times more likely to pass the jump-pool ladder during the day than during the night (Tables 3.2 and 3.5). This finding was somewhat surprising because trout fork length and discharge were important in determining the mean upstream migration rate of the trout (Table 2.4). The difference suggests that the factors that created variation in migration rates could be muted or eliminated by passage delays. Large fish, despite greater swimming ability and migratory motivation, experienced the same delays as smaller fish. Similarly, high discharge, which provides a cue for spawning timing and ideal conditions for natural migration, may also create more tailrace turbulence making passage more difficult.

We considered fish passage to be a two-stage process in which the first stage involves fish finding and entering the ladder, and the second stage involves fish ascending the ladder after initial entry, including fall-backs. At all three dams, entry time accounted for the majority of total passage time and ascending time was a smaller proportion of the delay (Figure 3.4). Regardless of the type of ladder, proper placement of the entrance and adequate attraction flow to help guide fish to the ladder are essential for an effective fish passage structure. In this study, entry times were shorter at ladders with entrances distinct from the turbulent tailrace of the dam.

The greatest difference in trout passage times was accounted for by the individual dam being passed. The Denil ladder that had a mid-channel entrance between two radial gates (Busse Dam) had the longest passage delays (Figure 3.5), and most of the delay was accounted for by time for fish to enter the ladder (Figure 3.4.A, Table 3.3). The high turbulence at the ladder entrance created by the layout of this passage structure appeared to be particularly problematic. The second longest passage delays occurred at the jump-pool ladder at Grain Camp Dam (Figure 3.5). At this dam, the ladder entrance was moderately separated from the tailrace, but the volume and velocity of water providing attraction to the ladder were small compared to the dam release. The entrance was also oriented at a 90-degree angle to the primary axis of the channel, which could also be disorienting to a fish attempting to move upstream. Relatively little passage delay was observed at the Denil ladder at Page Dam (Figure 3.5). The entrance to the Page fish ladder is across the channel from the tailrace of the dam, although the entire channel can still be somewhat turbulent. The Page ladder has a greater proportion of flow than the other ladders, and the downstream fish bypass increased the attraction to the entrance of the ladder.

Findings of this study strongly suggest that improvements in fish passage at Busse, Grain Camp, and Sodhouse Dams would benefit migratory redband trout in the Blitzen River. Based on both site location and passage efficiency, we recommend prioritizing dams for passage improvements in the order: 1) Busse, 2) Grain Camp, and 3) Sodhouse. Since migratory trout disperse from upstream natal and summer feeding habitats to downstream winter habitats, passage improvements should be generally be prioritized from upstream to downstream. However, trout at Busse Dam experienced much longer delays than at Grain Camp Dam, so we felt that this was a higher priority for passage improvement. Passage at Sodhouse Dam was not evaluated in this study, but since the design is similar to Busse Dam, conditions are likely similarly poor. Although not evaluated in this study, an additional critical step would include providing adequate screening at diversion points to minimize entrainment of trout in irrigation canals.

Habitat improvements will also benefit the migratory redband trout population. Much of the Blitzen River was straightened and channelized early in the 20th Century (Beckham 1995), and the river has failed to reclaim the natural sinuosity that is apparent from historical aerial photographs. Radio-tagged trout generally spent little time in the straightened channel sections of the river. Reconnecting flood plains and historical channels through dike removal would benefit both the health of the river and the redband trout habitat. Rehabilitation of riparian vegetation has potential to improve many aspects of the habitat of the Blitzen River in the MNWR including moderating stream temperatures, providing cover, and contributing in-stream structure. Since trout are seeking summer temperature refuge in the reach below Page Springs, restoration efforts should focus in that segment first and expand downstream.

Future research on redband trout in the Blitzen River is needed to expand upon the information gained from this study. This study was limited to migratory trout caught in the spring that were large enough to tag with a 23mm PIT tag. We did not examine juvenile movement patterns, which would contribute to an understanding of the full life-history of migratory trout. Furthermore, this study was conducted when Malheur Lake was relatively low, and replication of the study during a period of higher lake levels would be valuable to better understand the importance of the lake to the redband trout population. Finally, the fish passage evaluation should be repeated following future passage improvements to ensure that the dams no longer prevent passage or cause excessive delays. Passage should also be evaluated for other native fish species.

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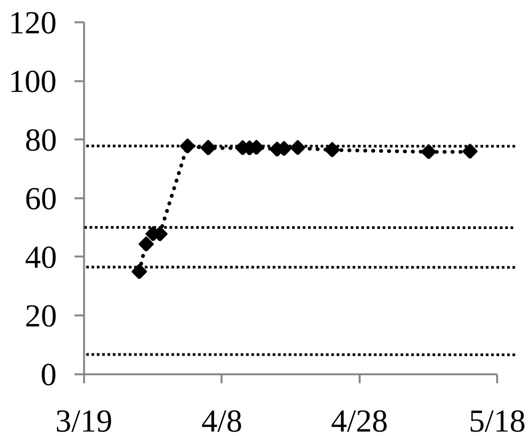
APPENDIX A. INDIVIDUAL MOVEMENT HISTORIES OF RADIO-TAGGED TROUT

Each figure depicts the radio-tag detections of an individual redband trout. The vertical axis is river km from the mouth of the river, and the horizontal axis is the date (MM/DD). The nodes indicate actual tag detection points which are connected by dotted lines for clarity. The horizontal lines depict the location of the four major dams: Sodhouse Dam (km 6), Busse Dam (km 35), Grain Camp Dam (km 48), and Page Dam (km 67). Titles indicate the unique radio tag number and the year the trout was initially tagged (NN-YYYY). Additional annotation has been added where necessary. Trout not illustrated include five tagged in 2007 that showed no movement following radio tagging and seven in 2008 tagged too late in the season to provide sufficient movement information.

10-2007



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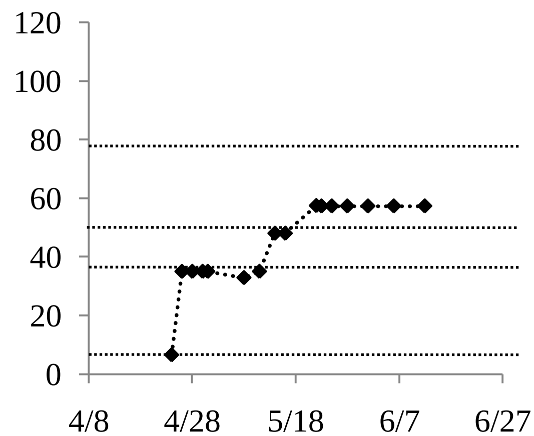

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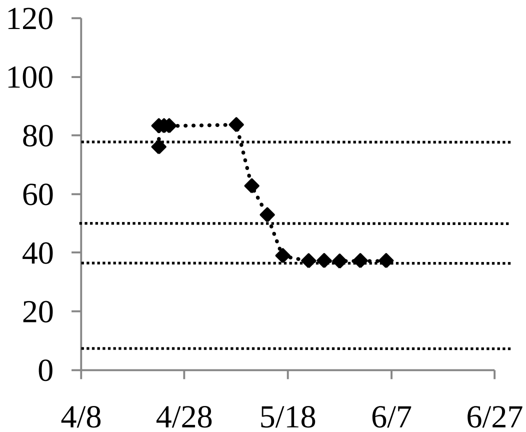

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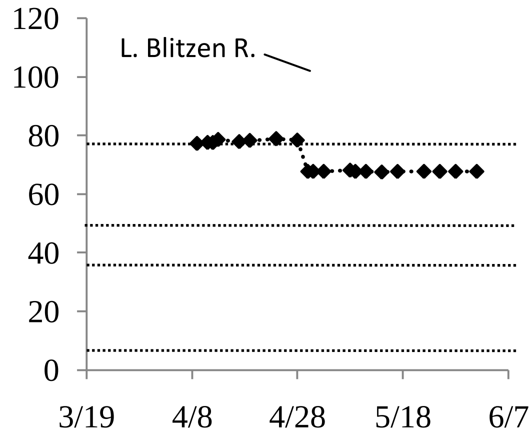

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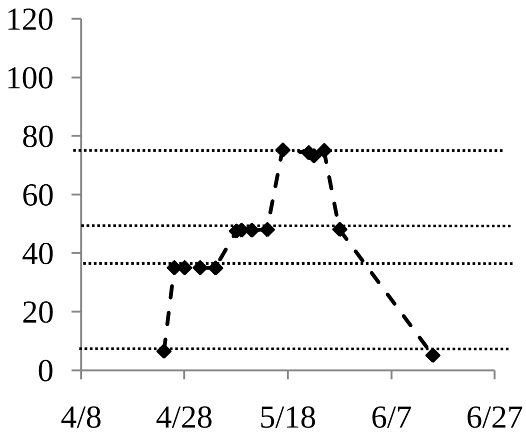

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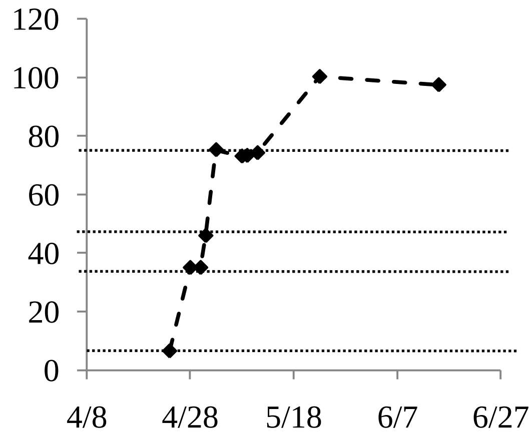

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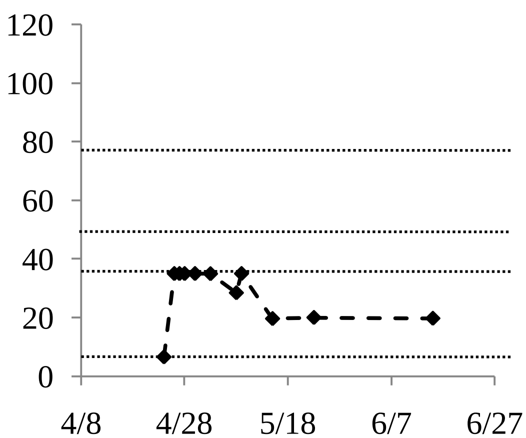

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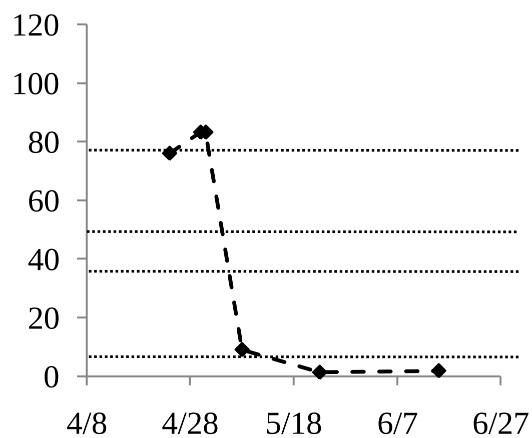

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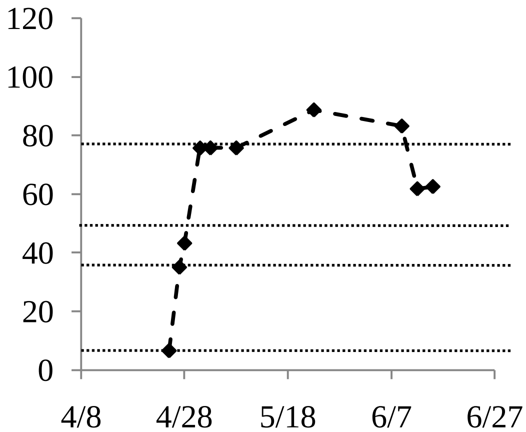

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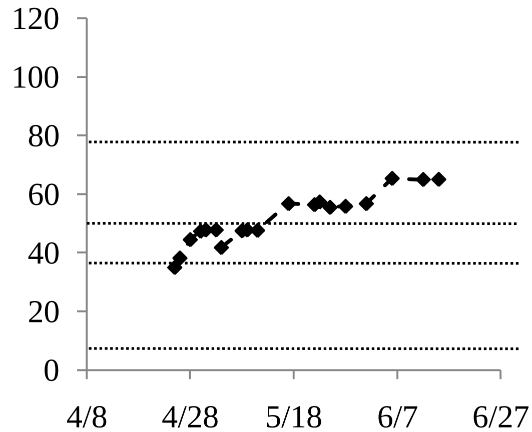

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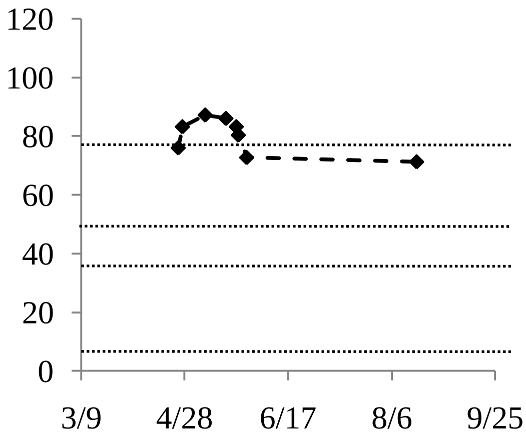

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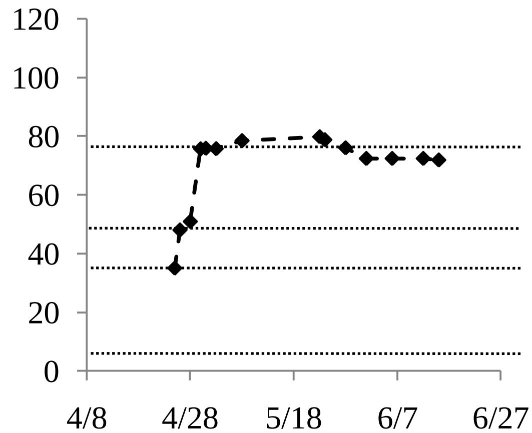

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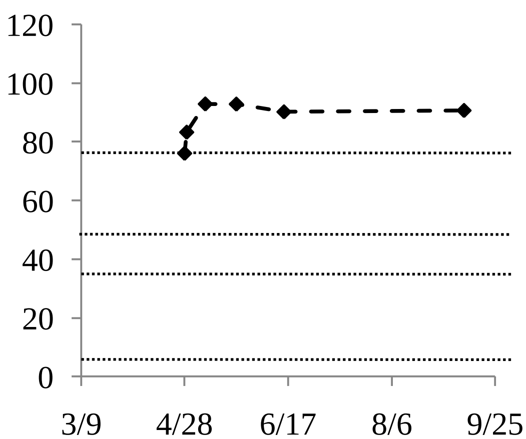

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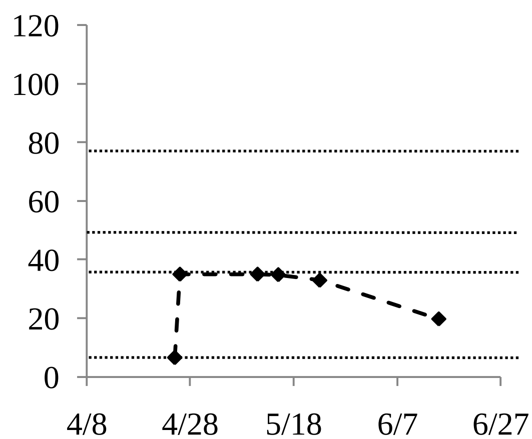

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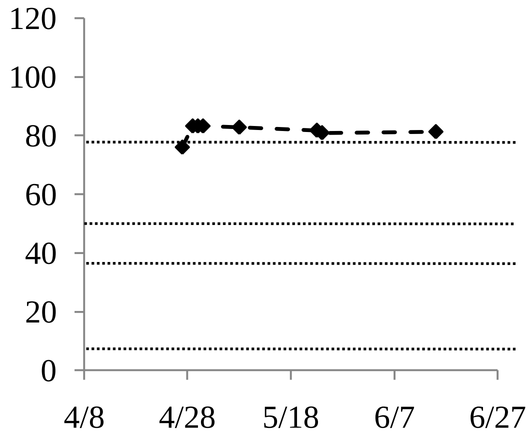

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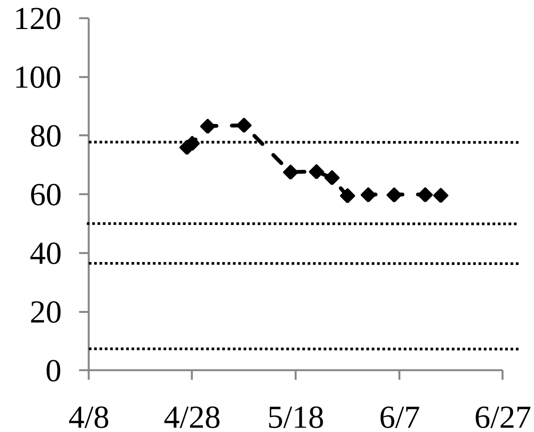

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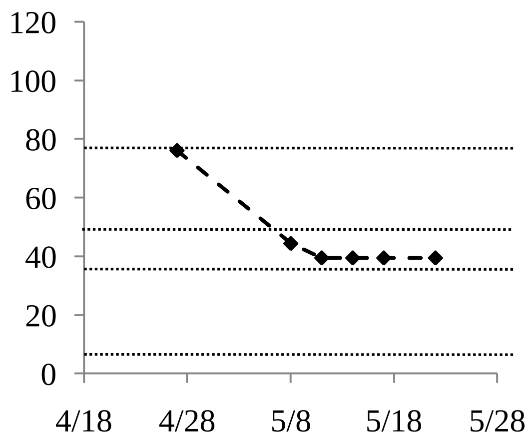

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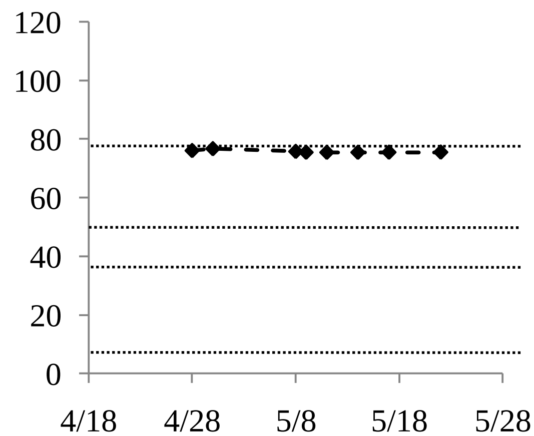

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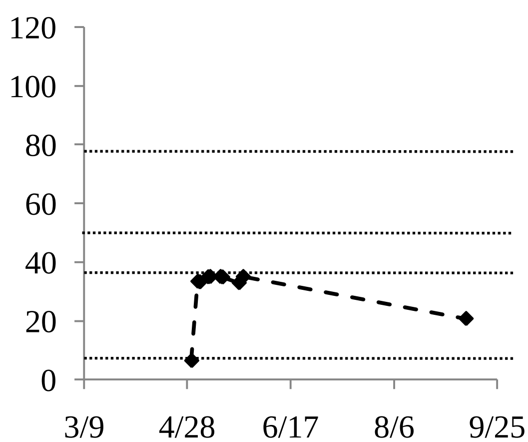
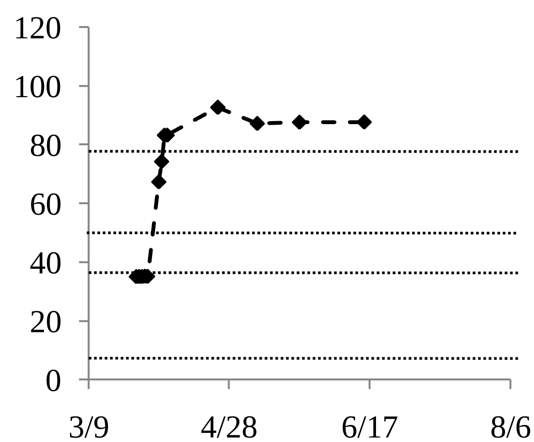


31-2007



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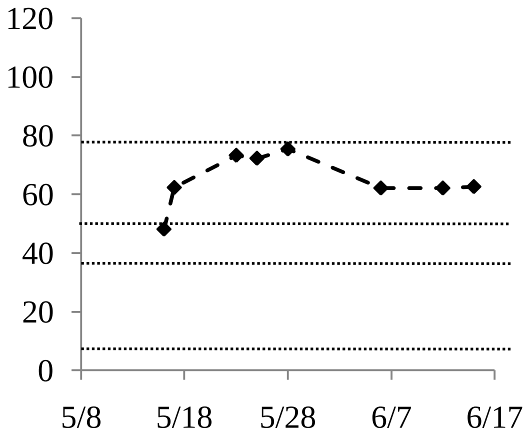

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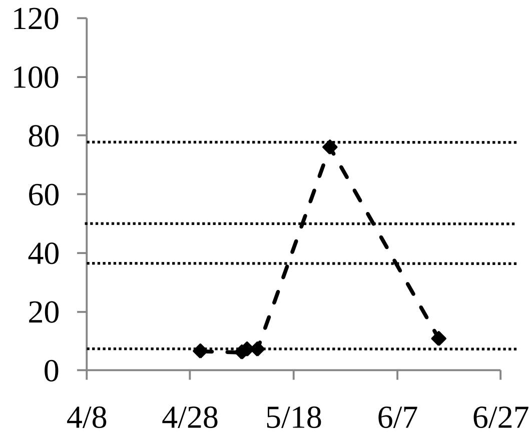

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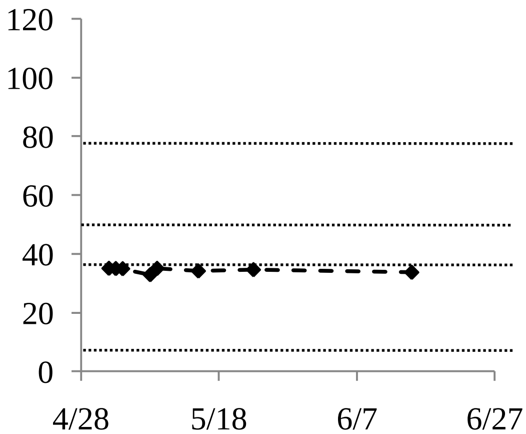

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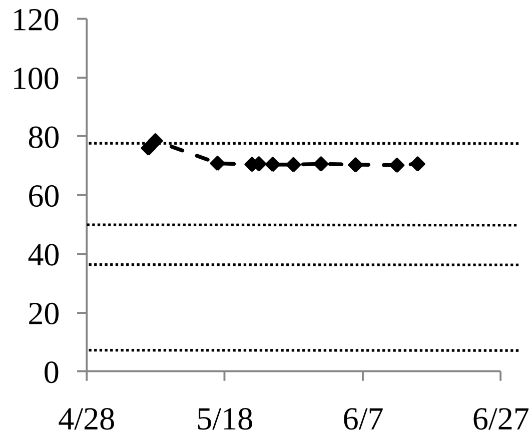
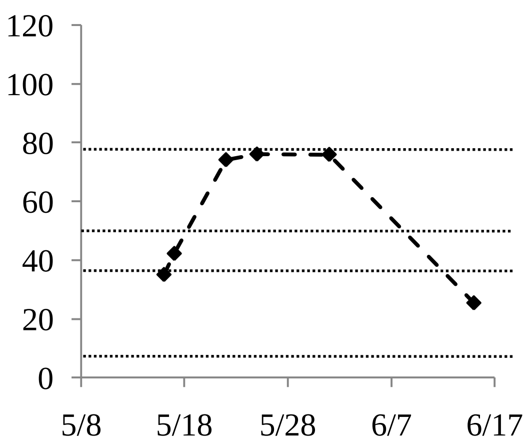


36-2007



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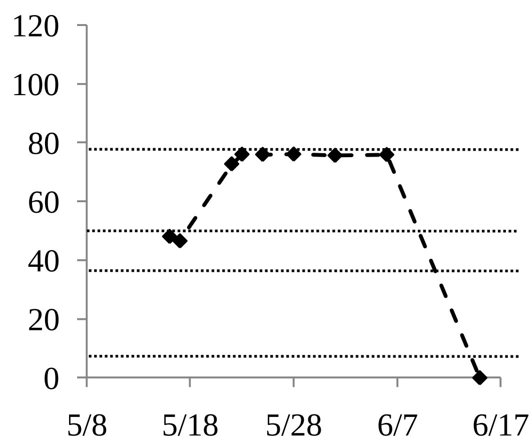

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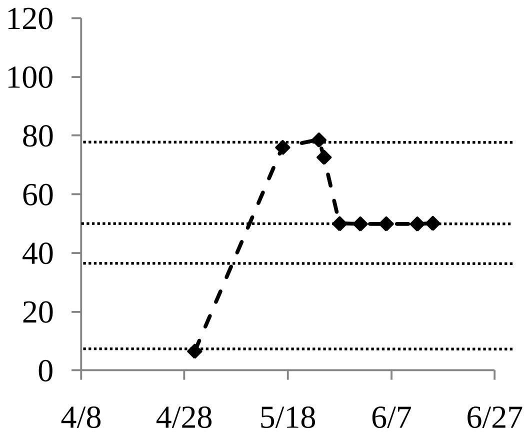

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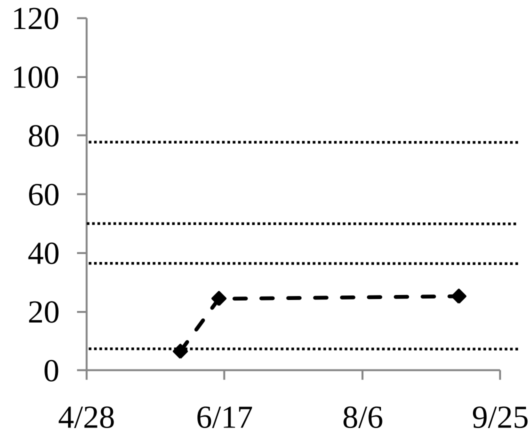

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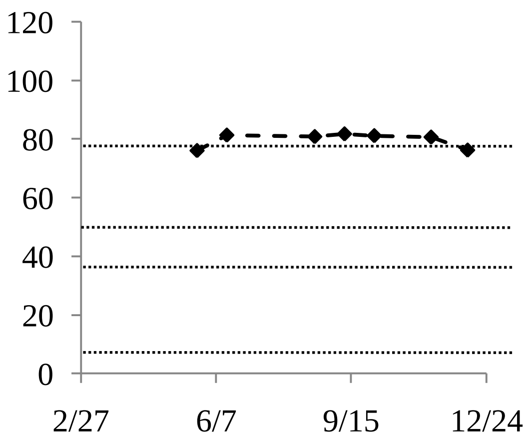

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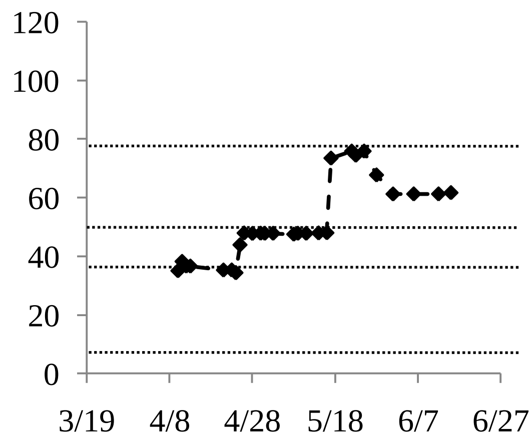

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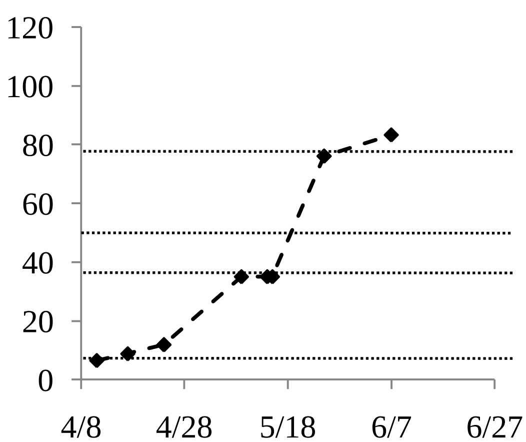

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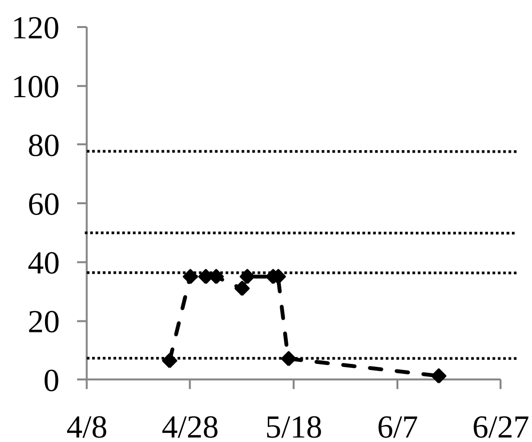

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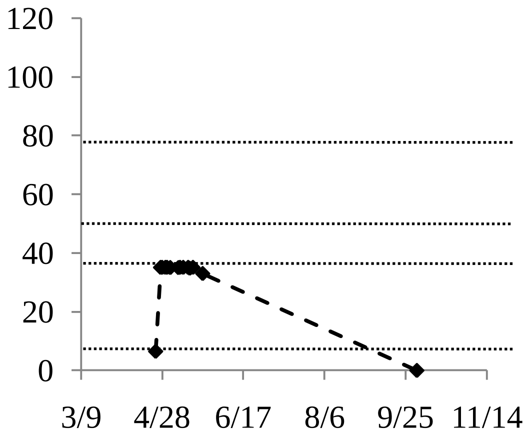

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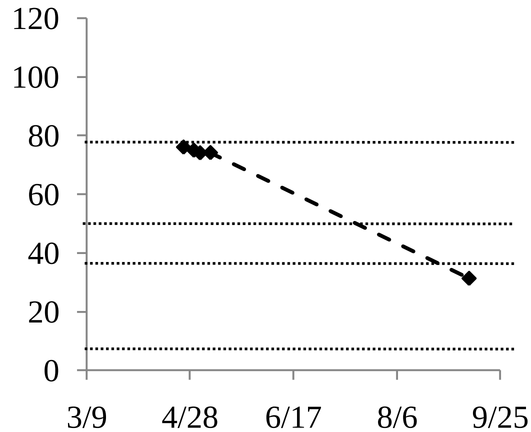

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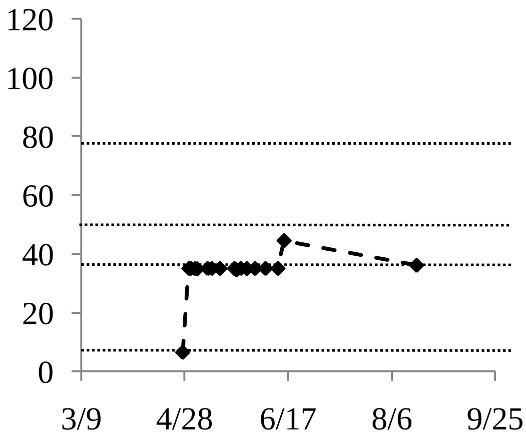

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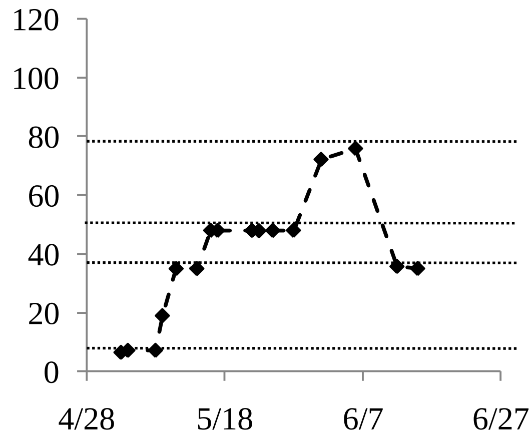

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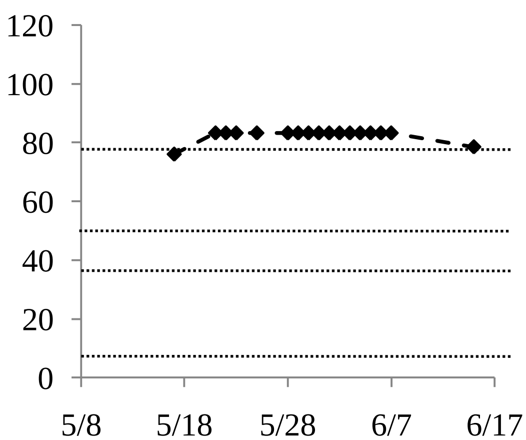

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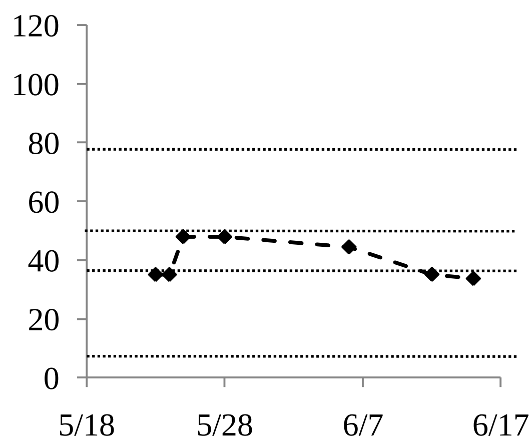

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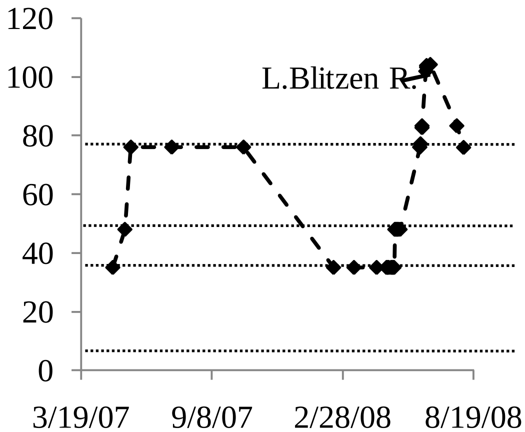

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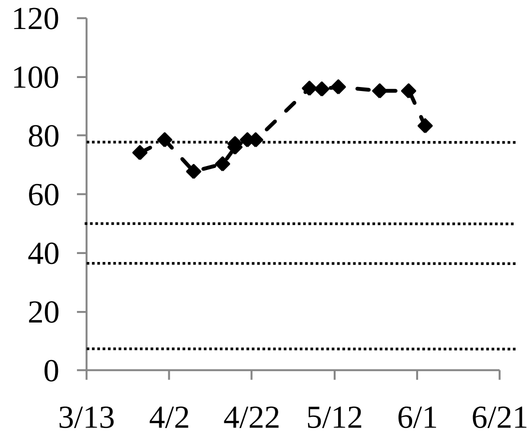

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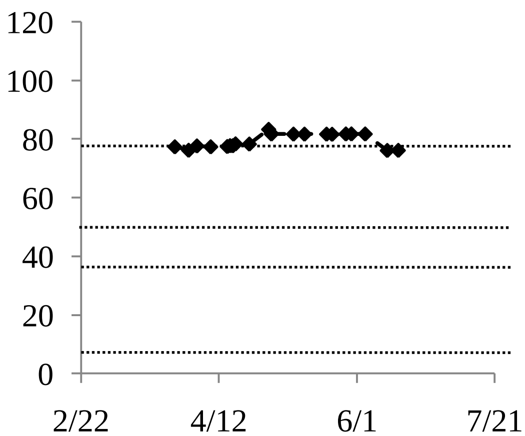

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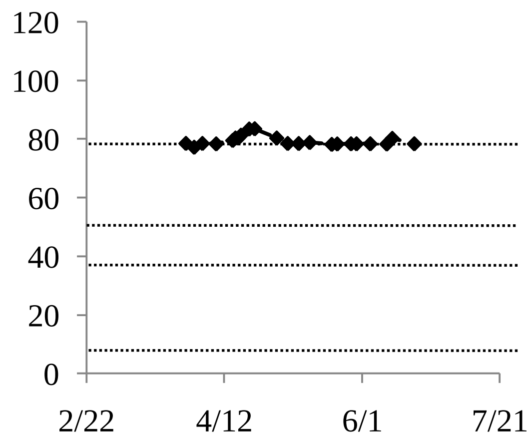

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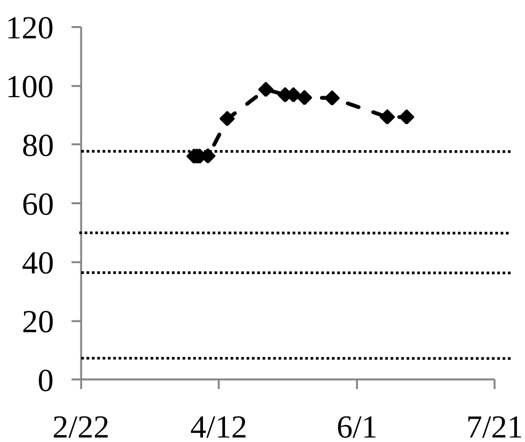

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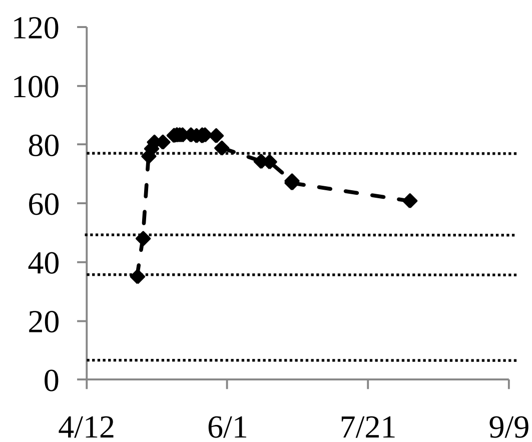

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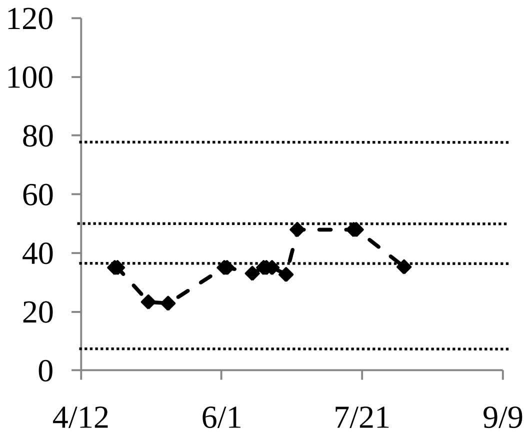

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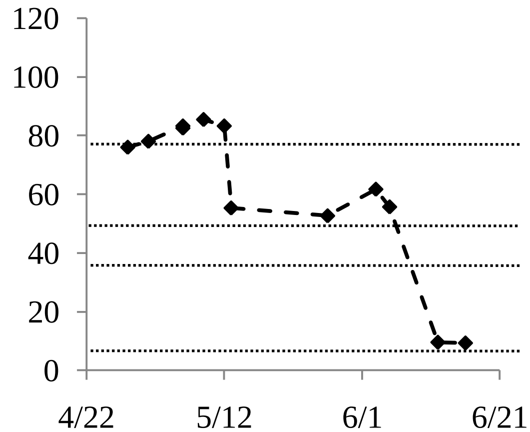

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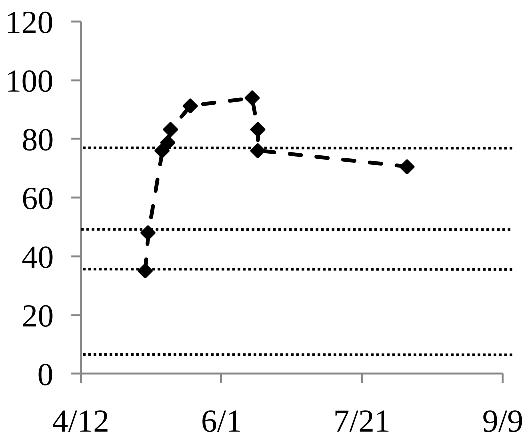

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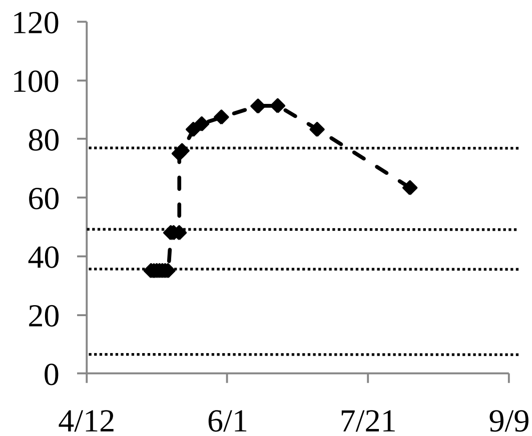

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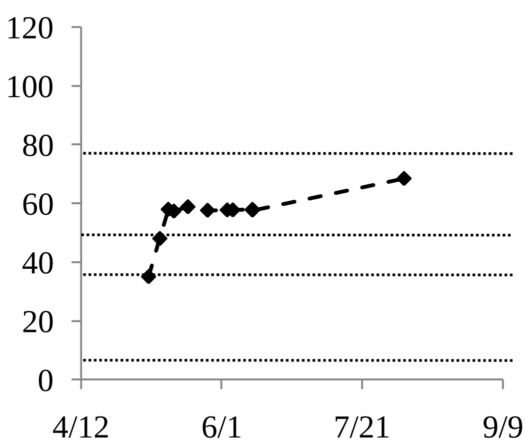

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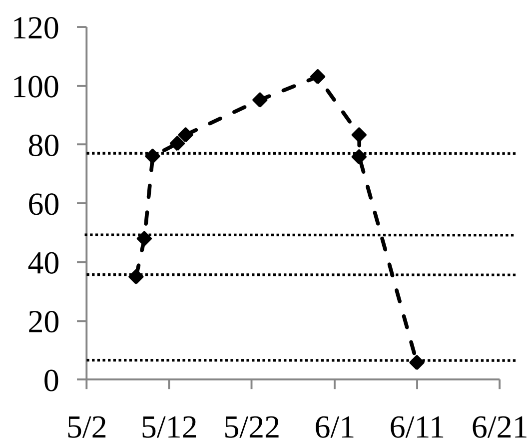

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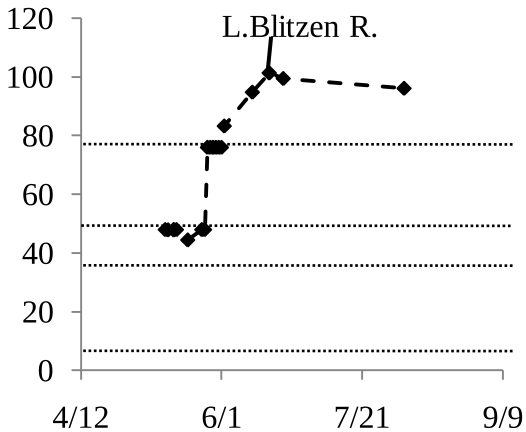

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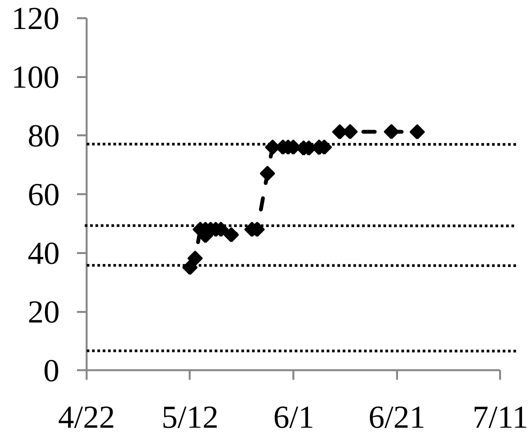

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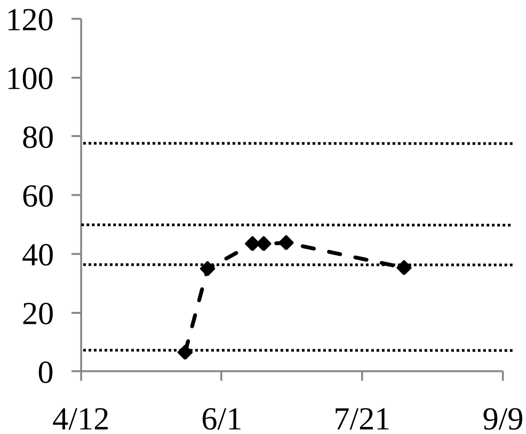

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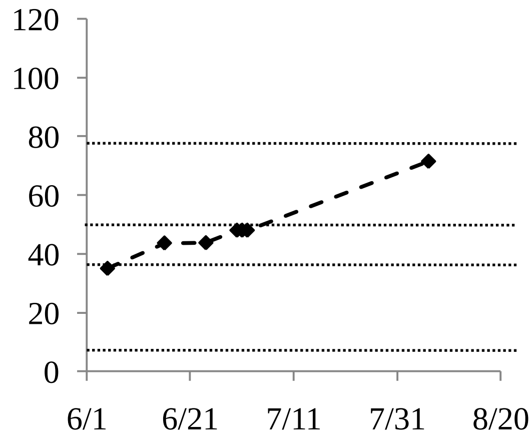

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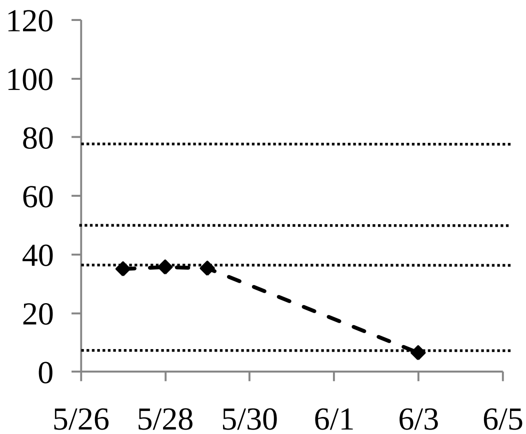

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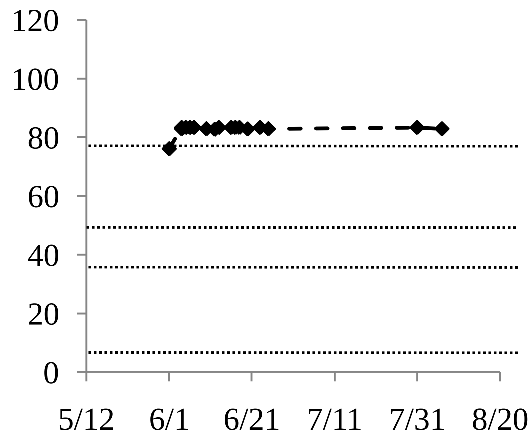

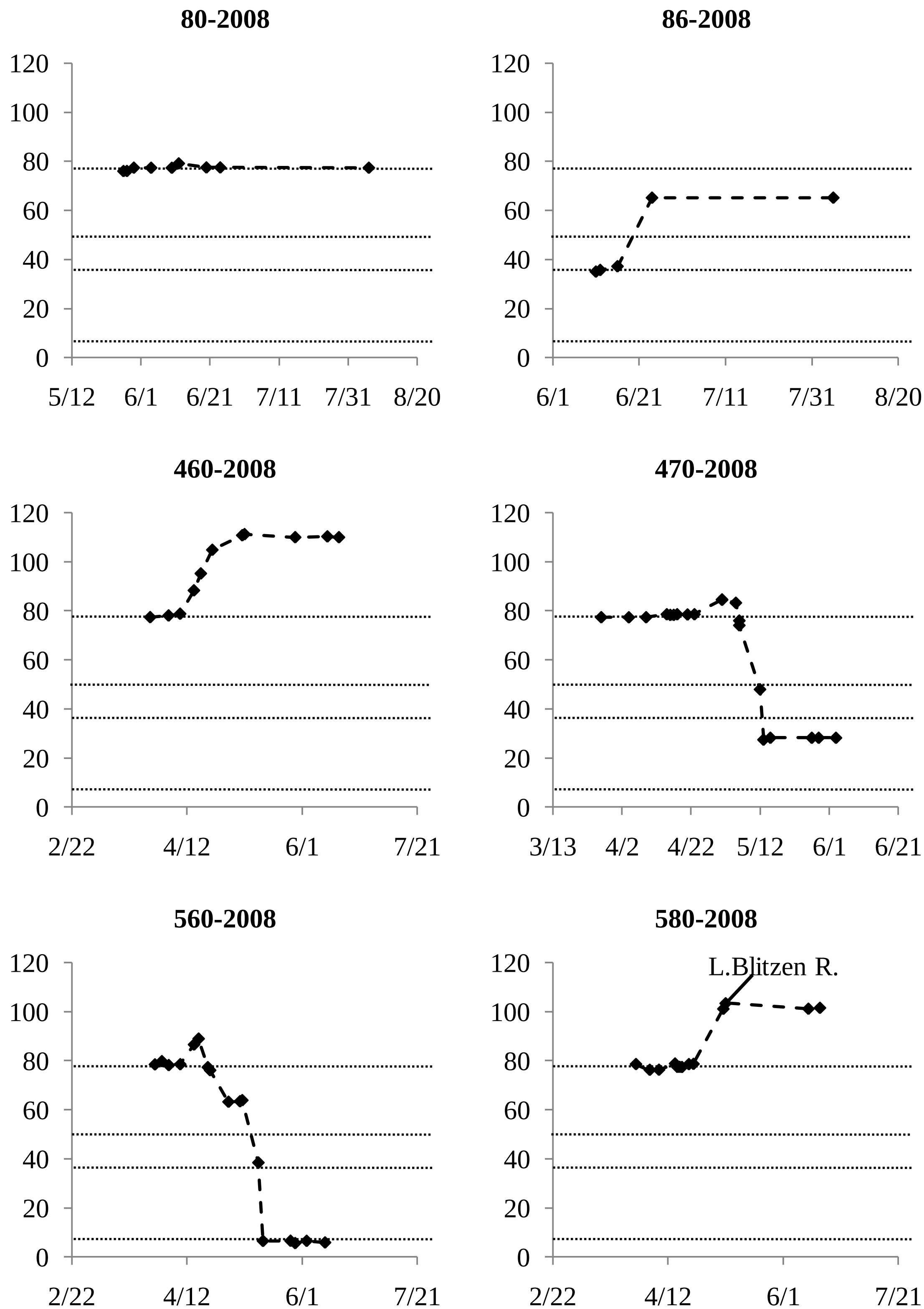
80-2008
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86-2008
120
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6/1
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7/11
7/31
8/20
460-2008
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470-2008
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APPENDIX B. REDBAND TROUT ANNUAL GROWTH ESTIMATES

The sizes of each of 214 trout that had ages determined by scale interpretation were utilized to form a von Bertalanffy growth curve, and the Solver function of Microsoft Excel© was used to derive the parameters for the model,

$$L_t = L_\infty\left[1 - e^{-K(t-t_0)}\right]$$

where L_t is fish length at time, t, L_∞ is the asymptotic length of a fish at maximum age, and K is the curvature parameter. For Blitzen redband trout, L_∞ = 757 mm and growth parameter K = 0.17. Because of the low K-value, we compared the predicted length-at-age estimates to a linear estimate. This estimate explained 99% of the variation in predicted length at age and provided a constant to estimate growth per year.

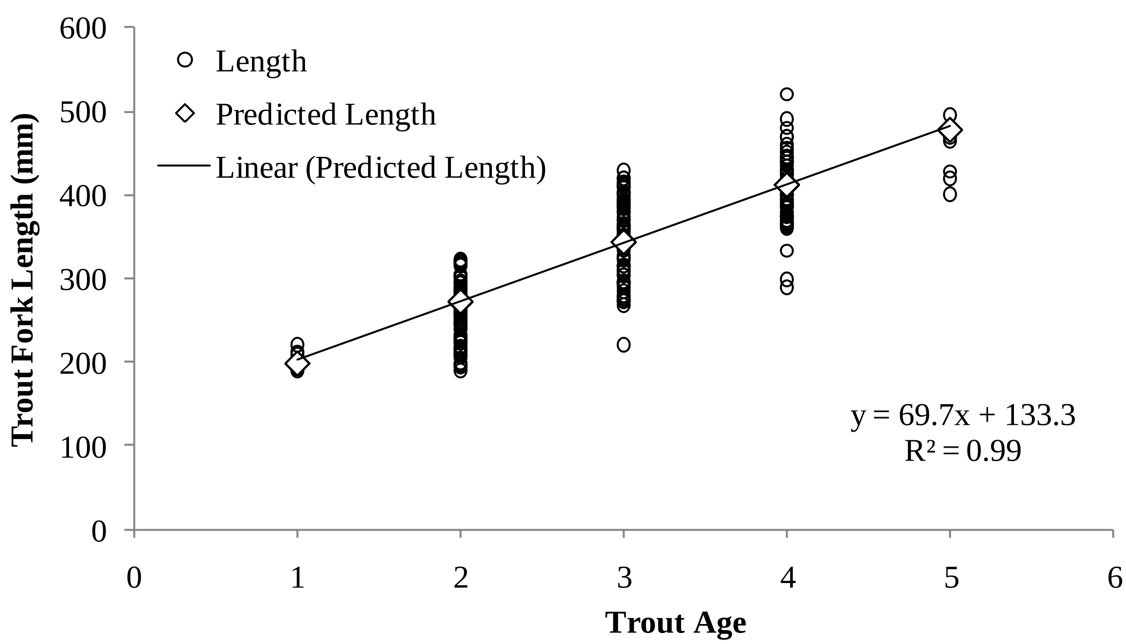

Figure B.1. Redband trout fork length at age estimates. The linear equation describes the mean annual growth rate between age 1 and 5, and the R^2 is the variation in the von Bertalanffy length estimate accounted for by the linear equation.