AN ABSTRACT OF THE THESIS OF

Shivonne M. Nesbit for the degree of Master of Science in Fisheries Science presented on June 4, 2010.
Title: Population Characteristics and Movement Patterns of Redband Trout (*Oncorhynchus mykiss*) and Mountain Whitefish (*Prosopium williamsoni*) in the Crooked River, Oregon

Abstract approved:

Scott A. Heppell

Over the last decade, the Oregon Department of Fish and Wildlife (ODFW) has documented a precipitous decline in the Crooked River redband trout (*Oncorhynchus mykiss*) population, prompting this study to address potential factors contributing to the decline. There are two main goals to this project: (1) identify potential factors contributing to the reduction of the redband trout population in the Crooked River fishery and (2) provide management recommendations to all of the agencies responsible for managing the Crooked River that might effect a change in the redband trout population trend.

This thesis had three objectives: (1) evaluate the movement patterns of redband trout and mountain whitefish in the Crooked River below Bowman Dam, (2) monitor total dissolved gas levels (TDG) in the Crooked River to evaluate the incidence of supersaturated water and gas bubble disease in redband trout and mountain whitefish and (3) implement a more comprehensive population estimate survey to document both redband trout and mountain whitefish population densities.

Prior to this study, limited data existed on the distribution and movement patterns of redband trout and mountain whitefish in the Crooked River below Bowman Dam. Based on the results from the 2-year telemetry study, redband trout and mountain whitefish population exhibit a resident life history strategy and stay in the

Wild and Scenic Section of the Crooked River below Bowman Dam. Two potential explanations for the observed population decline were plausible: the decline was actually a decline, or the fish moved to other sections of the Crooked River downstream of Bowman Dam. The telemetery study showed that redband trout and mountain whitefish stay within this section of river, thereby providing evidence against the explanation that the observed population decline was a result of movement of fish to other sections of river.

The total dissolved gas study demonstrated that gas saturation levels become elevated enough to cause gas bubble disease in the Crooked River below Bowman Dam. The gas saturation in the Crooked River is equivalent or higher than levels shown to produce gas bubble disease (GBD) in fishes. When flows exceed 600 cfs, the total dissolved gas saturation exceeds the maximum Oregon Department of Environmental Quality mandated level of 110% gas saturation in the Crooked River. Flows in excess of 600cfs are common during spring runoff events below Bowman Dam. From 1989-2009, flows exceeded 600 cfs in 13 of the 21 years and 1000 cfs in 10 of the 21 years. The past population effects of high flows and supersaturated waters on redband trout and mountain whitefish are difficult to quantify, but based on the hydrograph and the saturation curve, the years when gas bubble disease might have been present in fish can be predicted. Given the strong linear relationship between TDG and stream average daily discharge ($r^2 = 0.93$), discharge itself can be used as a predictive tool for assessing TDG levels in the river. Based on the flow data from the USBOR gauging station and the gas saturation curve for the wild and scenic section of the Crooked River generated here, gas bubble disease was probably present in fish in 1993, 1996, 1997, 1998, 1999, and 2004.

The redband trout population density has varied considerably from year to year, with a peak observed in 1994 and the lowest point observed in 2006. A large increase in the number of redband trout per km occurred between 1993 and 1994, indicating that the density of fish can increase substantially in one year. The decline in redband trout density from 1994 to 2006 appears to be more gradual than the increase in density observed from 1993 to 1994. Since 2006, the redband trout population density appears to be increasing based on qualitative patterns.

One interesting finding was that in 2007, the mountain whitefish density was estimated to be 7 times greater than the redband trout population, in 2008 it was estimated to be 4 times greater, but in 2009, the mountain whitefish density was only marginally higher than the redband trout population. In the three years of this study, there appears to be a shift in the relative abundance of redband trout and mountain whitefish directly below Bowman Dam. The reduction in the mountain whitefish population density from 2007 to 2008 was not expected based on angler accounts of the increase in mountain whitefish population densities.

I recommend that ODFW continue to monitor the redband trout and mountain whitefish populations in the Crooked River below Bowman Dam. Annual surveys would allow for a better understanding of changes to the population structure over time. Ideally, enumerating the number of recruits in a year would be a better way to understand survival and population changes, but as recruitment may be a difficult to quantify in the Crooked River perhaps a better effort at sampling age-1 fish would be helpful addition to the annual sampling.

Management recommendations for flow releases from Bowman Dam include pursuing dam modifications to fix the TDG problem. The US Bureau of Reclamation is currently researching dam modifications to reduce the total dissolved gases below Bowman Dam. Until a solution is implemented, TDG monitoring during high flows coupled with fish surveys would better our understanding of how fish in the Crooked River respond to high levels of total dissolved gases.

Population Characteristics and Movement Patterns of Redband Trout (*Oncorhynchus mykiss*) and Mountain Whitefish (*Prosopium williamsoni*) in the Crooked River, Oregon

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

Shivonne M. Nesbit, Author

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Wow, where to begin. This study was truly a collaborative project with contributions from so many people and organizations that I don’t know how to express my gratitude and appreciation to everyone. I would like to list the names of all the people that helped with funding, field work, data collection, lab work, data entry, brainstorming, analysis, and editing but I would fill the pages with names and have no space left for all of the data that we have collected and produced.

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Together we are better!

CONTRIBUTION OF AUTHORS

Scott Heppell, Brett Hodgson, Jason Dunham, Christian Torgersen and Allison Evans assisted with the study design, data analysis and editing of this thesis.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

POPULATION CHARACTERISTICS AND MOVEMENT PATTERNS OF REDBAND TROUT AND MOUNTAIN WHITEFISH IN THE CROOKED RIVER, OREGON

CHAPTER 1

GENERAL INTRODUCTION

Over the last decade, the Oregon Department of Fish and Wildlife (ODFW) has documented a precipitous decline in the Crooked River redband trout (*Oncorhynchus mykiss)* population, prompting this study to address potential factors contributing to the decline. There are two main goals to this project: (1) identify potential factors contributing to the reduction of the redband trout population in the Crooked River fishery and (2) provide management recommendations to all of the agencies responsible for managing the Crooked River that might effect a change in the redband trout population trend.

Historically, the Crooked River supported anadromous summer steelhead (*Oncorhynchus mykiss*), spring Chinook salmon (*Oncorhynchus tshawytscha*) and resident redband trout (Nehlsen 1995). Anadromous fish were extirpated from the Crooked River and resident fish populations were fragmented during the construction of hydroelectric and irrigation dams, specifically the Pelton-Round Butte dam complex at Lake Billy Chinook and Arthur R. Bowman Dam (Bowman Dam) at Prineville Reservoir (Stuart et al. 2007). Beginning in 1989, ODFW started conducting extensive surveys throughout the Crooked River Basin and reported the greatest abundance of redband trout in the 20 river kilometer (rkm) stretch of river below Bowman Dam (Stuart et al. 2007). Stuart et al. (2007) also reported that the majority of the streams and mainstem Crooked River below Bowman Dam are too warm to support healthy redband trout populations. Aside from the ODFW surveys, very little is known about redband trout in the Crooked River Basin. Based on the existing data, the Crooked River below Bowman Dam may be vital to the perseverance of the redband trout population in the Crooked River Basin.

The Crooked River, located in central Oregon, is the largest tributary of the Deschutes River, encompassing a watershed of approximately 14,000 km^2 (Stuart et al. 2007). The two main tributaries of the Crooked River are the North Fork Crooked River which originates in the Ochoco Mountains and the South Fork Crooked River which arises from high desert springs (Stuart et al. 2007). The Crooked River flows into Prineville Reservoir and is discharged through Bowman Dam. Bowman Dam is a 245-foot- high (74.7 m) earth laden impoundment that is impassable to fish (Stuart et al. 2007). The hypolimnetic release of water that supplies cold water to the river, with annual temperatures ranging from 4^0C to 12^0C, is what has created the productive tailrace fishery (Stuart 2007). Flows discharged from Bowman Dam are regulated by the US Bureau of Reclamation (BOR) and operated by the Ochoco Irrigation District (OID). Bowman Dam was constructed and is managed primarily for irrigation purposes, flood control and water storage.

Redband trout, also known as rainbow trout, are native to the Columbia drainage east of the Cascade Mountains (Behnke 1992). Redband trout can display migratory behavior, partial migrations or resident life-histories (Northcote 1997). While redband trout have developed a diversity of life-history strategies throughout their range (Benke 1992), the strategies used by redband trout in the Crooked River have not been documented.

Mountain whitefish (*Prosopium williamsoni*) is the other dominant salmonid species below Bowman Dam. Mountain whitefish are members of the Salmonidae family and the Coregoninae subfamily (Nelson 1994). Mountain whitefish are among the most abundant fish in western North American lakes and rivers (Scott and Crossman 1973) and yet there are very few studies focused on mountain whitefish population characteristics or movement patterns. Population estimate data collected by ODFW indicates that while the redband trout population has declined in abundance the mountain whitefish population is increasing. Prior to this study, ODFW observed mountain whitefish during population enumeration surveys but did not quantify the mountain whitefish population.

Despite the fragmentation of the Crooked River, redband trout and mountain whitefish populations persist below Bowman Dam. The redband trout population estimates have ranged from as many at 13,000 trout per kilometer in 1994 to as low as 600 trout per kilometer in 2006. This study was initiated to investigate the population characteristics and movement patterns of both redband trout and mountain whitefish to better understand what factors are driving population fluctuations. The primary goals of this thesis were to:

GOAL 1: Evaluate the movement patterns of redband trout and mountain whitefish in the Crooked River below Bowman Dam. Chapter 2, Movement Patterns of Redband Trout and Mountain Whitefish in the Crooked River, OR reports the results of a two-year radiotelemetry study.

GOAL 2: Monitor total dissolved gas levels (TDG) in the Crooked River to evaluate the incidence of supersaturated water and gas bubble disease in redband trout and mountain whitefish. ODFW had noted gas bubble disease in fishes below Bowman Dam and one of the hypotheses regarding the redband trout population decline is based on the presence of supersaturated water during spring releases. Chapter 3, Total Dissolved Gases and Gas Bubble Disease in the Crooked River, OR reports the findings of the TDG monitoring conducted on the Crooked River.

GOAL 3: Implement a more comprehensive population estimate survey to document both redband trout and mountain whitefish population abundances. Chapter 4, Population Characteristics of Redband Trout and Mountain Whitefish reports the results of the population survey data and reveals patterns between population structure and environmental variable.

Chapter 5 is a general discussion in which I summarize the findings from all aspects of this study, recommend management actions and suggest further research needs in the Crooked River.

CHAPTER 2. MOVEMENT PATTERNS OF REDBAND TROUT AND MOUNTAIN WHITEFISH IN THE CROOKED RIVER, OREGON

INTRODUCTION

The Crooked River, located in central Oregon, is the largest tributary of the Deschutes River, encompassing a watershed of approximately 14,000 km^2 (Figure 2.1; Stuart et al. 2007). The two main tributaries of the Crooked River are the North Fork Crooked River which originates in the Ochoco Mountains and the South Fork Crooked River which arises from high desert springs (Stuart et al. 2007). The Crooked River flows into Prineville Reservoir and is discharged through Arthur R. Bowman Dam (herein referred to as Bowman Dam). Bowman Dam is a 245-foot-high (74.7 m) earth-laden impoundment constructed in 1961 that is impassable to fish (Stuart et al. 2007) and is managed primarily for irrigation purposes, flood control and water storage. Flows discharged from Bowman Dam are regulated by the US Bureau of Reclamation (USBOR) and operated by the Ochoco Irrigation District (OID). From Bowman Dam, the Crooked River flows approximately 65 river kilometers (rkm) and joins the Deschutes River at Lake Billy Chinook (Stuart et al. 2007). The adjacent land below Bowman Dam is managed by the US Bureau of Land Management (US BLM) and was designated as a part of the federal Wild and Scenic River system in 1988 under the recreational classification (ODFW 1996). An old irrigation diversion, Stearns diversion, is located at rkm 17. Three rkm downstream of Stearns diversion is the primary irrigation diversion, located at rkm 20. We do not know if the fish residing below Bowman Dam migrate below Stearns diversion or the primary irrigation diversion or if either diversion is passable for fish.

The Crooked River “tailrace” fishery, located in the tail water section starting at the outlet of Bowman Dam and continuing several rkm downstream, was created with the dam’s construction. The fishery is extremely popular and has been described as one of the premier redband trout fisheries in Oregon (Shewey 1998). The cold water discharge from Prineville Reservoir has created this productive fishery due to the hypolimnetic release of water; this results in a river with an annual temperature range of just 4^0C to 12^0C (Stuart 2007).

The popularity of the fishery has resulted from the historically abundant redband trout (*Oncorhynchus mykiss*) population, year round angling opportunities, and the high angler success rates. In spite of the popularity of the fishery, population estimate data from the Oregon Department of Fish and Wildlife (ODFW) collected over the last decade indicate that the redband trout population has declined in abundance whereas the mountain whitefish (*Prosopium williamsoni*) population is increasing. The decreasing abundance of redband trout is a source of concern for the Central OR angling community, ODFW, US BLM, USBOR, OID and the Crooked River Watershed Council. These organizations are keenly interested in determining what is causing the observed decline of the fishery.

There is a scarcity of data on the distribution and movement patterns of redband trout and mountain whitefish in the Crooked River below Bowman Dam. To address this lack of knowledge and better understand the changes in apparent redband trout abundance, we performed a two-year radio telemetry study on both species. Our specific objectives with this work were to (1) describe range extent and distribution of fish in the system, (2) characterize migration timing, rearing and spawning locations for both species, and (3) determine if individual fish movement patterns are influenced by species characteristics or environmental conditions.

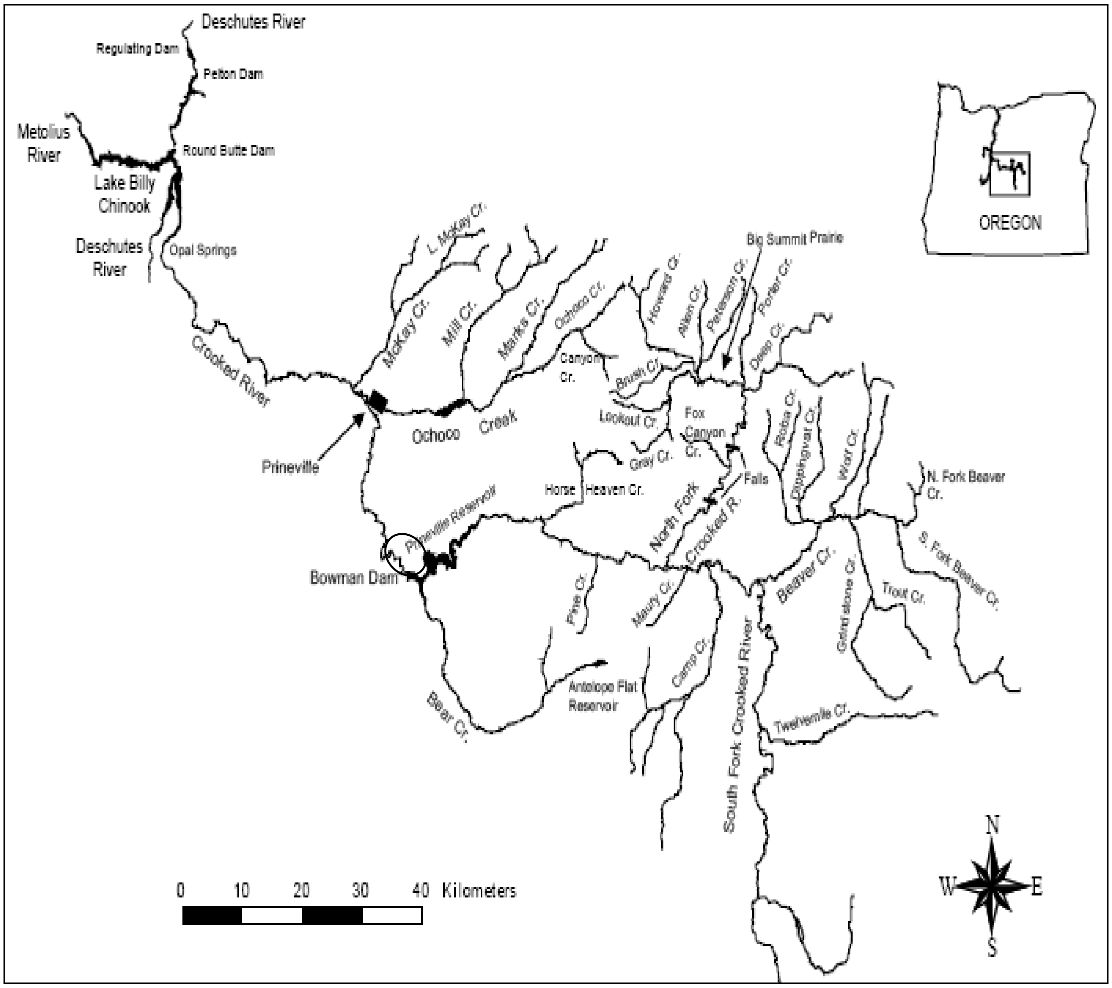

Figure 2.1. The Crooked River basin, which is located in central OR, with the study area below Bowman Dam circled.

METHODS

Methods Capture, Tagging and Tracking

Redband trout and mountain whitefish were captured with hook and line sampling via flyfishing. Angling effort focused on distributing radio tags throughout the thirteen-kilometer section of river from Bowman Dam to the lower end of the wild and scenic section near Castle Rock campground. Fish were implanted with one of two models of high-frequency, digitally encoded transmitters, one of two types of Nano tag, either the NTC-6-2 (300 or 250 day operational life) or the NTC-4-SL (111 day operational life)(Lotek Wireless Inc.). The specific tag model for each fish was chosen based on an attempt to limit implanted transmitters to 2% or less of the total weight for each fish (Winter 1983). Fish were placed in an anesthetic bath with approximately 100mg/L tricane methane sulfonate (MS-222, Argent Laboratories) buffered with 120mg/L sodium bicarbonate buffer (Summerfelt and Smith 1990) standard surgical procedures were used to implant radio tags into the body cavity of each radio tagged fish (Summerfelt and Smith 1990). Total length, weight to the nearest gram, maturity if visible and health of the fish were recorded. To determine age, a minimum of ten scales were removed between the dorsal line and lateral line of each tagged fish.

Radio tagged fish were tracked weekly using hand-held telemetry equipment, including vehicle tracking with a roof mount antenna and foot tracking with a hand-held Yagi antenna. Either a SRX_400 or SRX_400A Lotek Wireless telemetry receiver was used to locate the tagged fish. Each time a radio tagged fish was located through signal triangulation, the position of the fish was recorded in the UTM coordinate system using a hand-held Global Positioning System (GPS). Several times throughout the study, a fixed wing aircraft (when available) was used to track fish that were not detected in the study area. For each fish successfully located, the location details and GPS point for each fish were entered into an access database and imported into a GIS database layer using ArcGIS 9.3 (ESRI). Fish locations were mapped and visually displayed. Each location event was associated with a river distance, measured in meters along the river from Bowman Dam (0 km) to the location of the fish.

Methods of Analysis

Range extent and distribution

Because the focus of this study is to understand both the extent of the Crooked River used by individual fish and where fish concentrate, two methods were used to describe the geographic range for each fish. The linear range was determined for each fish by using the most upstream and downstream location to define maximum movement distance observed. To assess core range, for each fish for which multiple detections existed, the repeat locations were analyzed using percent frequency distributions by river kilometer.

Migration timing, rearing and spawning locations

The Crooked River is a very turbid system. This limits our ability to visually identify redds or conduct spawning ground surveys. Mountain whitefish spawn in the late fall or early winter depending on altitude, latitude and water temperature (Northcote and Ennis 1994). Based on angler accounts, mountain whitefish aggregate in spawning areas from mid-November to early February (ODFW and Central Oregon Flyfishers, personal communication). Over the course of this study, anglers checked mountain whitefish for signs of maturity by manually palpating the abdomen to check for reproductive products, and reported seeing reproductive mature fish from mid-November to late January. This time frame was used to visually display potential mountain whitefish spawning locations.

Stuart et al. (2007) reported observing ripe or spawned redband trout from April to June in the Crooked River. Anglers have reported redband trout spawning as early as February and as late as June (ODFW, personal communication). During the course of this study, anglers documented signs of maturity and locations for mature redband trout. These data was used to map redband trout spawning areas.

Movement patterns, species traits and environmental variables

To explore the relationship between overall movement patterns and individual fish characteristics, and weekly movement patterns related to environmental variables, the data were converted into four different matrices for multivariate analysis (Table 2.1). Multivariate analysis was used to determine whether (1) movement patterns differed among individual fish and (2) movement patterns were related to species characteristics or environmental variables. All multivariate analysis was conducted with PC-ORD version 6.158 beta (McCune, B. & M. J. Medford. 2010).

Table 2.1. Summary of the matrices developed for analysis of movement patterns described below. Numbers in parentheses indicate the number of entries for each of the variables.

Matrix Name	**Rows**	**Columns**						
Total Movement Matrix	Fish Code # (72)	Tag Location	Linear range	Mean location	Median location	Cumulative movement	Absolute movement	
Species Trait Matrix	Fish Code # (72)	Species	Sex	Age	Fork Length (cm)	Weight (g)	Tag Group	
Weekly Movement Matrix (4)*								
Tag group 1	Fish Code # (17)	Weekly distance measure in relation to Bowman dam (m) (33)						
Tag group 2	Fish Code # (8)	Weekly distance measure in relation to Bowman dam (m) (41)						
Tag group 3	Fish Code # (21)	Weekly distance measure in relation to Bowman dam (m)(31)						
Tag group 4	Fish Code # (12)	Weekly distance measure in relation to Bowman dam (m)(13)						
Environmental Matrix (4)								
Tag group 1	Week # (33)	Gauge Height (ft)	CFS min (cfs)	CFS max (cfs)	CFS Avg (cfs)	Temp min (°C)	Temp Max (°C)	Temp Avg (°C)
Tag group 2	Week # (41)							
Tag group 3	Week # (31)							
Tag group 4	Week # (13)							

* Weekly movement matrices were transposed in PC-ORD to align properly with the environmental matrix

Multi-response permutation procedure (MRPP)

Multi-response permutation procedure (MRPP) was used to test the null hypothesis of no differences in movement patterns among groups of fish tagged at different times (4 tag groups) to determine if tag groups could be analyzed together. MRPP is a non-parametric procedure for testing the hypothesis of no difference between two or more groups (Zimmerman et al 1985). MRPP is a useful tool for community data because there are no required assumptions of multivariate normality or variance homogeneity (McCune and Grace 2002). Sorensen distance measures were used for the MRPPs to retain sensitivity for this heterogeneous data set (McCune and Grace 2002).

Total movement matrix & species matrix

For comparisons of total movement patterns among individual fish, a total movement matrix was created using individual fish as the sample units (rows) and measurements of movement as the column variables. The total movement matrix included 72 rows (24 mountain whitefish + 48 redband trout) and 6 columns (movement variables). The movement variables (columns) consisted of tag location, linear range, mean location and median location for each fish, as well as a calculation of absolute movement, which is the absolute difference in distance from the dam between initial tagging and ending recording, and the cumulative distance moved for each individual. The species traits matrix included species, sex, age, fork length (cm), weight (g) and tag group for each fish resulting in a matrix with 72 rows (individual fish) × 6 columns (species traits).

Weekly movement matrix & environmental matrix

The weekly movement data was divided into four smaller matrices for each tag group, consisting of weekly distance measures of each fish. Weekly distance was the distance a fish moved from week to week and was determined by subtracting the current week location for each fish from the previous week’s location and taking the absolute value. The matrix parameters (number of rows and columns) changed for each tag group based on the number of fish detected and the maximum number of weeks that provided the most consistent series of measurements for the greatest number of fish. Therefore the matrix parameters for each of the four tag groups were vastly different. The structures of the weekly movement matrix are as follows: tag group 1 (17 individuals x 32 weekly movements), tag group 2 (8 individuals x 41 weekly movements), tag group 3 (21 individuals x 30 weekly movements), and tag group 4 (12 individuals x 13 weekly movements). The weekly movement matrices were all transposed so the weeks were rows and the distance measures and environmental variables were columns. The environmental matrix consisted of weekly measurements of gauge height (ft) and the minimum, maximum, and average for both flow (cfs) and temperature (°C), as measured from the gauging station at the base of Bowman Dam. The environmental matrix was also divided into four smaller matrices to agree with the weekly movement matrices for each tag group (Table 2.1).

Non-metric multidimensional scaling (NMS)

Non-metric multidimensional scaling (NMS) is an ordination technique that is well suited to non-normal data or data that are on questionable scales (McCune and Grace 2002) and the movement data are non-normally distributed. I first analyzed the structure of individual fish plotted in movement space by performing an NMS ordination on the total movement matrix. NMS was conducted to investigate the ordination of individual fish in movement space to visualize the differences and similarities among movement patterns for individual fish from all tag groups. All NMS ordinations used Sorenson distance measures. For NMS analysis, random starting configurations with 500 maximum iterations were used with 250 runs conducted using real data. Autopilot settings were turned off and two axes, k, were selected based on previously run autopilot trials in NMS in which a 2D solution was recommended. To examine whether the NMS ordination found stronger axes in the data than would be expected by chance, a Monte Carlo randomization test was conducted with 250 runs of randomized data. The randomized runs of data were compared to results of runs from the real data to assess the dimensionality of the solution ordination. Dimensionality is increased when an additional axis improves (reduces) the stress compared to the randomized data ($p \leq 0.05$) (McCune and Grace 2002). Ordinations were plotted as individual fish in movement space and joint plots were used to visualize the relationship between movement variables and ordination scores from the total movement matrix. The proportion of variance represented by each axis was determined by the coefficient of determination (r^2) between the distances in the ordination space and the distances in the original space (McCune and Grace 2002). Pearson and Kendall correlations with each ordination axis were used to measure strength and direction of species and environmental variables (McCune and Grace 2002). To determine whether movement patterns were related to species variables, variables in the species matrix were overlayed on the movement ordination.

To examine the relationship between the weekly movement patterns and the coinciding weekly environmental variables, four NMS ordinations were performed for each tag group. For each NMS ordination, the weekly movement matrices were used as the main matrix and the environmental matrices were used as the second matrix. Ordinations were plotted as individual weeks in fish movement space and joint plots were used to visualize the relationship between weekly movement patterns and environmental variables.

RESULTS

Summary of tagging and tracking

We captured and radio tagged 48 redband trout and 24 mountain whitefish in October 2007, April 2008, October 2008 and March 2009 (Table 2.2). The average total length for tagged whitefish was 34 cm (range 28-43 cm) with an average age of 4 years old (range 3-5). Redband trout had an average total length of 29 cm (range 24-42 cm) and averaged 3 years old (range 2-4 years).

Table 2.2 Date, tag type, and number of fish for both species tagged at each tagging event.

Tag Group	Tag Date	Battery operational life (days)	MWF (n)	RBT (n)
1	October 6-7,12, 2007	300	8	18
2	April 5, 2008	300	8	-
3	October 3-4,11, 2008	250	8	17
4	March 20-21, 2009	111	-	13

The majority of the tagged fish were only detected within the 13 rkm study area. Two fish, one mountain whitefish from tag group 2 and one redband trout from tag group 4, were detected in the Crooked River below the study area at rkm 18. Three additional redband trout from tag group 1 were also detected downstream of the study area, but the tags for those fish were found in a blue heron rookery so the last known location in the river was used for the ending location for subsequent analysis.

For tag group 1 (October 2007) 5 of the 8 whitefish were tracked for the operational life of the battery (300+ days). The 3 remaining whitefish were not detected in any tracking event after the week of (01/24/2008). This week represented the start of a cold weather event that included the coldest river temperatures of the entire study were recorded ($<2^0$C). Of the 18 tagged redband trout in tag group 1, 11 fish were tracked for the operational life of the battery (300+ days). All 11 fish were found only within the study area. Of the 7 fish that were not tracked for the duration of the tag battery life, 1 fish was lost in November 2007 and was removed from the dataset. The remaining 6 redband trout were never detected after the cold weather in January-February 2008. Aerial tracking of the river in February 2008, failed to reveal the location of any of these fish within or below the study area.

Tag group 2 (spring 2008) consisted of 8 mountain whitefish, all of which were tracked for 300+ days. Tag group 3 (fall 2008) consisted of 8 mountain whitefish and 18 redband trout. All of the mountain whitefish were tracked for the operational life of the battery (250+ days). One redband trout was harvested by an angler within a few weeks of tagging and was removed from the dataset. Of the remaining 17 fish, 3 redband trout were not detected in any tracking event after the start of cold weather (January-February 2009). Tag group 4 consisted of 13 redband tagged trout and all 13 were tracked for the duration of the battery life (111 days).

Range and Distribution

The linear range among fish was highly variable (Table 2.3). For mountain whitefish, the average linear range was 3.9 km with minimums ranging from 0.5 km to 1.8 km and maximums ranging from 7.3 km to 9.7 km. The average linear range for redband trout was 3 km, with minimums ranging from 0.2 km to 0.3 km and maximums ranging from 6.7 km to 11.9km.

Table 2.3. Linear range for mountain whitefish and redband trout summarized by tag group.

Tag Group	Mountain whitefish				Redband trout			
	n	Min (m)	Max (m)	Average (m)	n	Min (m)	Max (m)	Average (m)
Tag group 1	8	1800	7300	4400	18	200	11900	3500
Tag Group 2	8	800	9700	3000	-	-	-	-
Tag Group 3	8	500	9500	3000	17	300	8100	2200
Tag Group 4	-	-	-	-	13	300	6700	3300

To assess core range, or if fish concentrated in certain areas, fish locations were summarized by relative frequency of detection by river kilometer. Examining each tag group based on relative frequency showed that fish utilized all sections of the study area at some time during the study (Figures 2.2 and 2.3). Nine of the 24 tagged mountain whitefish were detected within one kilometer of their tagging location for 80% of the time. Over half of the redband trout stayed within one kilometer of their tagging location throughout the study. For the majority of fish in the study, the linear ranges for both mountain whitefish and redband trout spanned from Bowman Dam downstream to the end of the wild and scenic section of river (Figure 2.4), with the exception of the two individuals that left the primary study area.

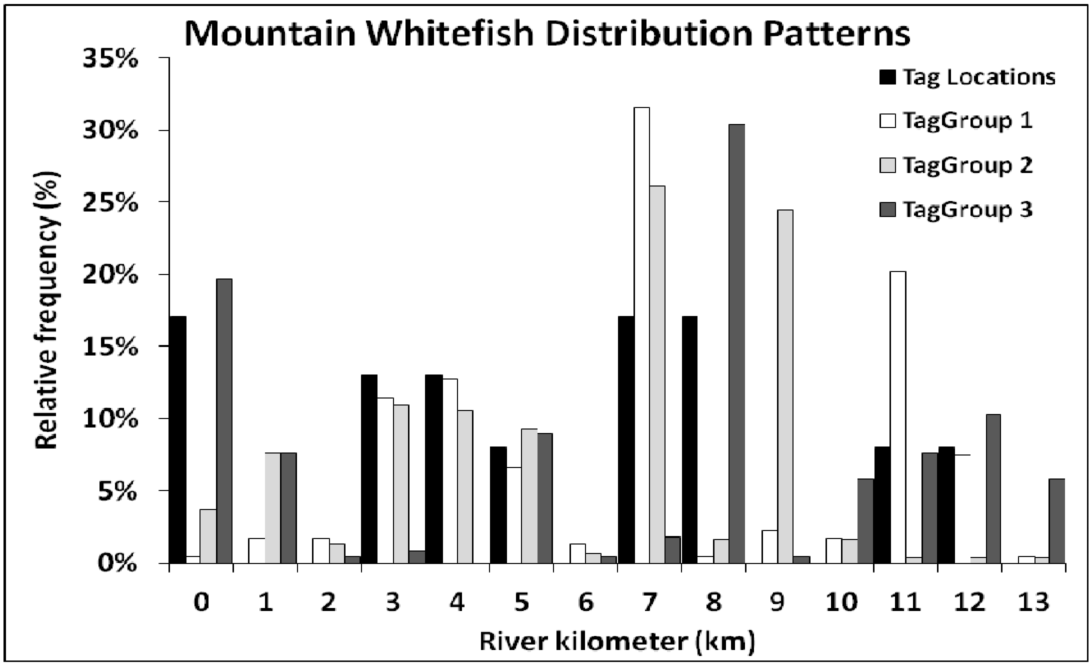

Figure 2.2. Radiotagged mountain whitefish tag locations and detections expressed as a percent frequency of location by river kilometer. Bowman Dam is located at rkm 0 and fish were tagged from Bowman Dam downstream to river kilometer 13.

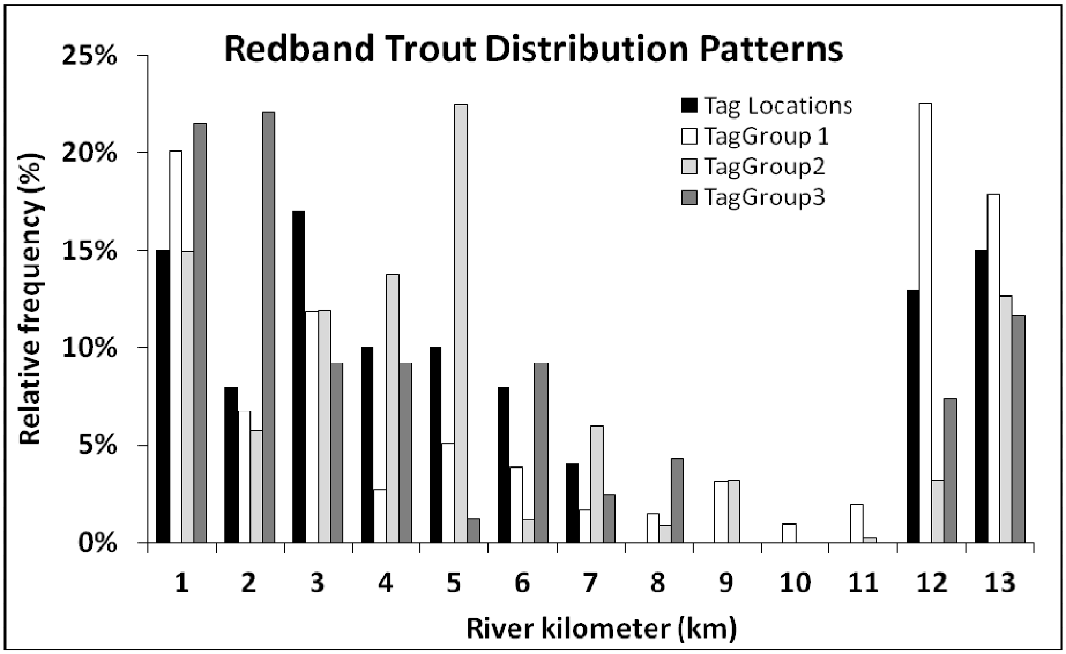

Figure 2.3. Radiotagged redband trout tag locations and detections expressed as a percent frequency of location by river kilometer. Bowman Dam is located at rkm 0 and fish were tagged from Bowman Dam downstream to river kilometer 13.

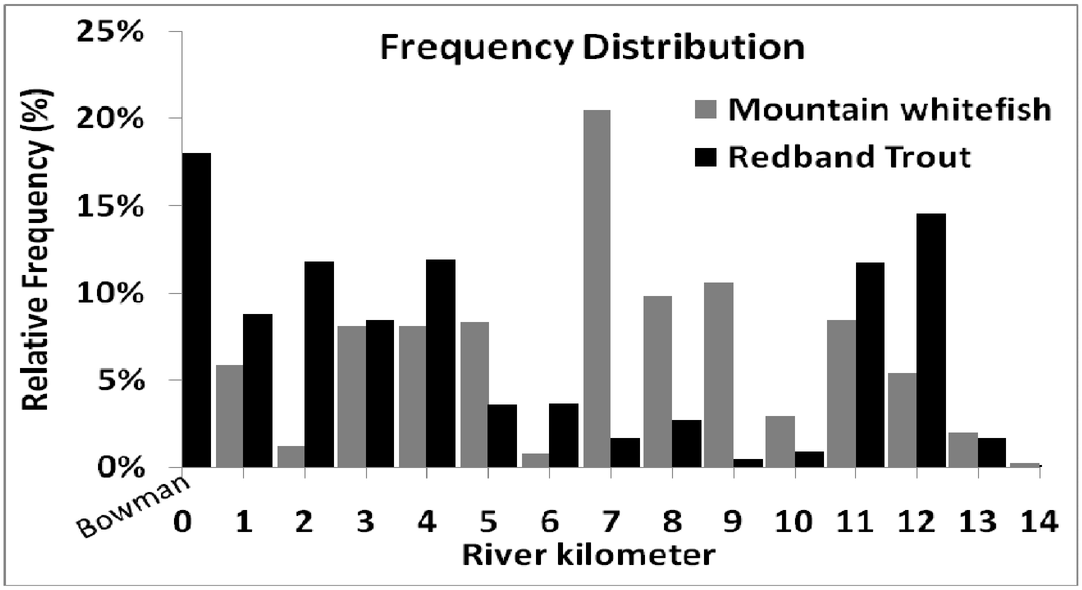

Figure 2.4. Comparison of radio-tagged mountain whitefish and redband trout locations expressed as a percent frequency of location by river kilometer. Bowman Dam is located at rkm 0 and fish were tagged from Bowman Dam downstream to river kilometer 13.

Migration timing, rearing and spawning locations

Anglers reported seeing ripe mountain whitefish from mid-November to late January and ripe redband trout from early April through late June. Anglers also noted that mountain whitefish were captured in shallow riffles when ripe and in pools when no signs of maturity were present (Figure 2.5; COF personnel communications). Based on spawning timing reported by anglers, fish locations were evaluated based on relative frequency of locations categorized by spawning timing versus rearing periods (Figure 2.6). Both species are found throughout the study area during both spawning and rearing period, but mountain whitefish and redband trout fish are found at higher frequencies between river kilometers 1-2 during spawning periods.

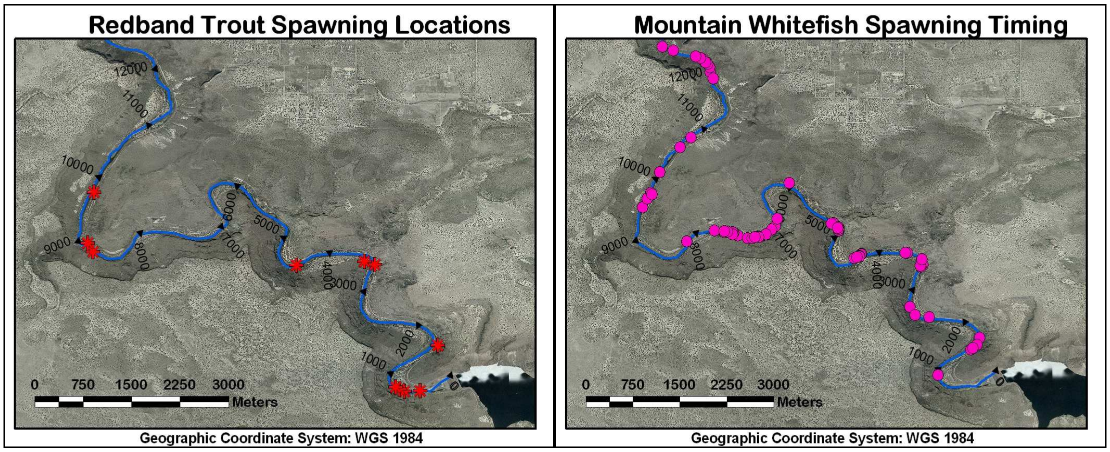

Figure 2.5. Redband trout and mountain whitefish spawning ground locations on the Crooked River below Bowman Dam. Redband trout spawning locations are based on angler reports of where mature fish were captured. Mountain whitefish locations are based on spawning timing reported by anglers.

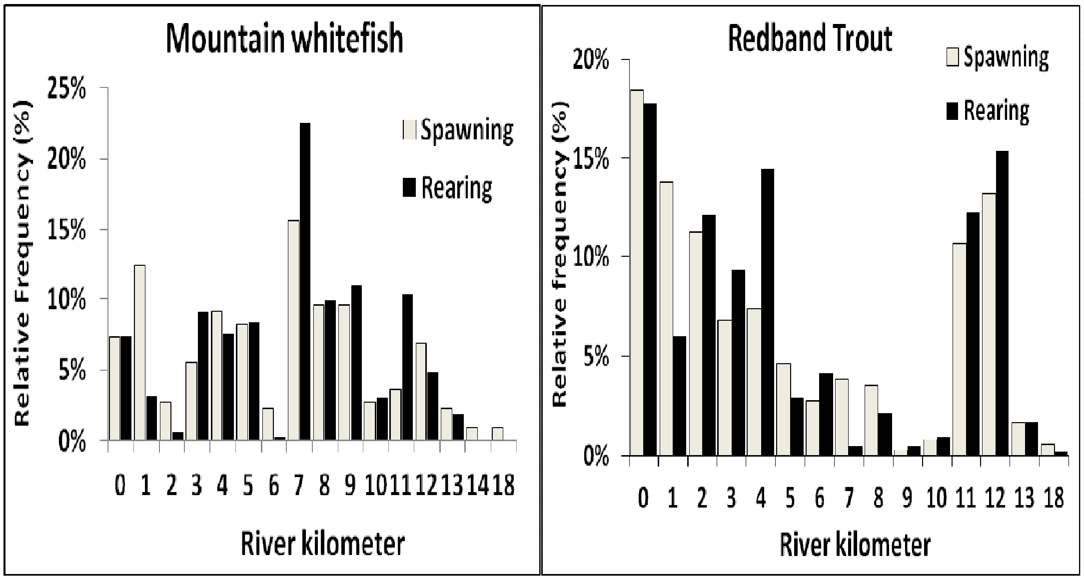

Figure 2.6.Relative frequency of mountain whitefish and redband trout detections by river kilometer categorized by spawning and rearing time-periods.

Movement patterns, species traits and environmental variables

As with range extent, individuals of both species showed a high level of variability in cumulative and weekly movement (Tables 2.4 and 2.5). The total cumulative distance measured for mountain whitefish ranged from as little as 2.4 km to as large as 26.5 km, with an average cumulative movement of 9.7 km. The average weekly minimum movement for mountain whitefish was 300 meters, but ranged from no movement detected in a week to 9.4 km traveled. Redband trout also displayed a high level of variability in cumulative and weekly movement patterns. The total cumulative distance moved by redband trout ranged from less than a kilometer over the course of the study to close 30 km and averaged 6 km. Weekly movements for redband trout varied from no movement detected in a week to 6.8 km travelled. Overall, mountain whitefish had greater cumulative movement than redband trout (one-way ANOVA $p = 0.002$).

Table 2.4. Mountain whitefish cumulative and weekly movement measures, summarized by tag period.

Mountain Whitefish Movement Summary								
			Cumulative Movement			**Weekly Movements**		
Tagging Period	**Number Fish Tagged**	**Number Dates Tracked**	**Average (m)**	**Min (m)**	**Max (m)**	**Average (m)**	**Min (m)**	**Max (m)**
Fall 2007	8	29 (12-40)	10,600	4,251	18,360	443	0	5,289
Spring 2008	8	38 (33-42)	10,163	5,059	17,733	272	0	7,440
Fall 2008	8	28 (25-31)	8,333	2,415	26,582	287	0	9,386
Totals	**24**		**9,699**			**334**		

Table2.5. Redband trout cumulative and weekly movements, summarized by tag period.

Redband Trout Movement Summary								
			Cumulative Movement			**Weekly Movements**		
Tagging Period	**Number Fish Tagged**	**Number Dates Tracked**	**Average (m)**	**Min (m)**	**Max (m)**	**Average (m)**	**Min (m)**	**Max (m)**
Fall 2007	18	23 (4-38)	7,141	616	23,489	308	0	10,070
Fall 2008	17	25 (11-34)	6,081	1,810	28,518	248	0	5,945
Spring 2008	13	12 (7-14)	5,413	1,119	13,238	453	0	5,789
Totals	**48**		**6,212**	**616**	**28,518**	**336**	**0**	**10,070**

MRPP & NMS results total movement matrix

First, an MRPP was performed on the total movement matrix using tag group as the grouping variable. The MRPP indicated that the heterogeneity of the 4 tag groups did not differ more than would be expected by chance (T = -0.3, A = 0.004, *p* = 0.33) so all tag groups were combined and included in the NMS ordination. The ordination of individual fish in movement space resulted in a two-dimensional ordination that explain 95% of the variation between the original and ordination space (stress 7.68, final stability = 0.00000 at 27 iterations). Axis one represented 51% of the variation and axis two represented 44% of the variation in the individual movement data (Figure 2.7). Of the movement variables included in the ordination, absolute movement, cumulative movement and linear range were positively correlated with axis one (r^2= 0.65, 0.65 and 0.59 respectively). Mean location, median location and tag location were highly correlated with axis two (r^2= 0.83, 0.83 and 0.79 respectively). Axis one shows a gradient of fish that moved a lot (left side of the axis) to fish that moved very little (right side of the axis). Axis two shows that fish tagged at the downstream end of the study (upper portion of axis two) had similar movement patterns regardless of species or tag group. The results of the ordination show that fish tagged near the dam showed a lot more variability in movement patterns compared to fish tagged downstream from the dam. The ordination also shows that we do not see differences in movement patterns between redband trout and mountain whitefish. Overlaying the species matrix on the movement ordination did not reveal any strong relationships between movement patterns and size of fish, age of fish, or tag group (Figure 2.8).

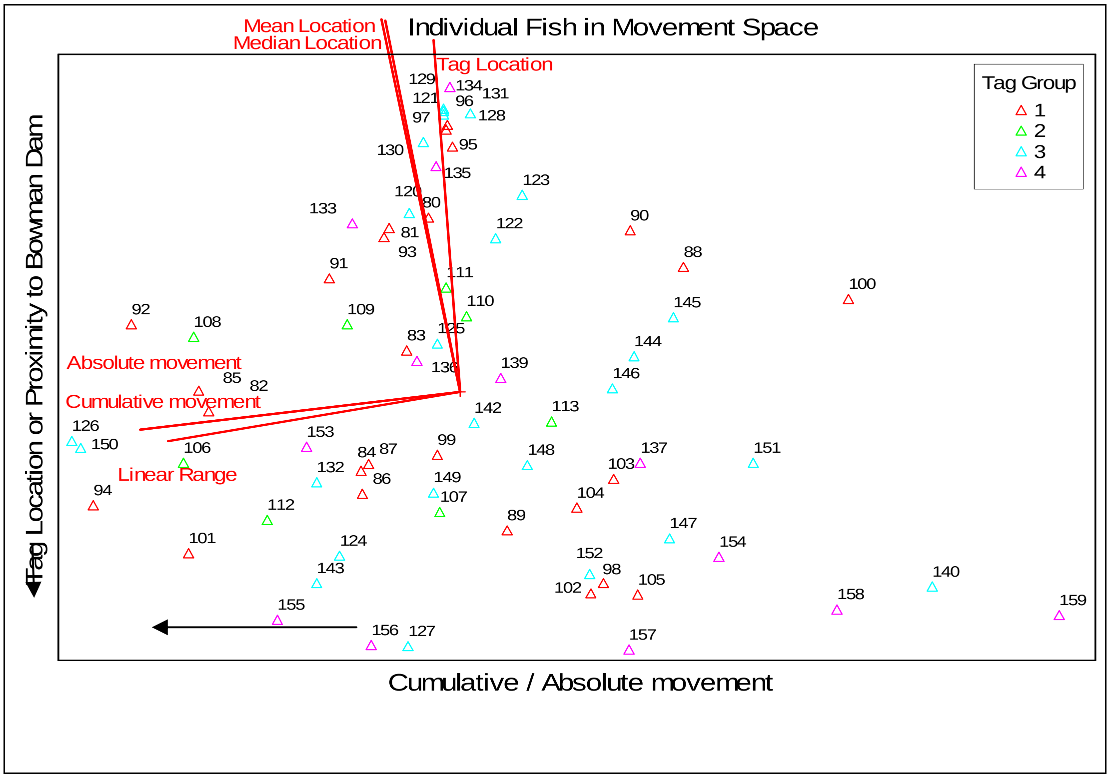

Figure 2.7. NMS ordination results of individual fish in movement space. Each triangle represents an individual fish (numbers identify tag code and colors represent tag groups). Axis one accounts for 51% of the variation in the movement data. The left side of axis one represents fish that moved a lot cumulatively and had large linear ranges. Axis two accounts for 44% of the variation in the movement data. The fish located at the bottom of axis two were tagged near Bowman Dam and fish located at the top of axis 2 were tagged at the downstream end of the study site.

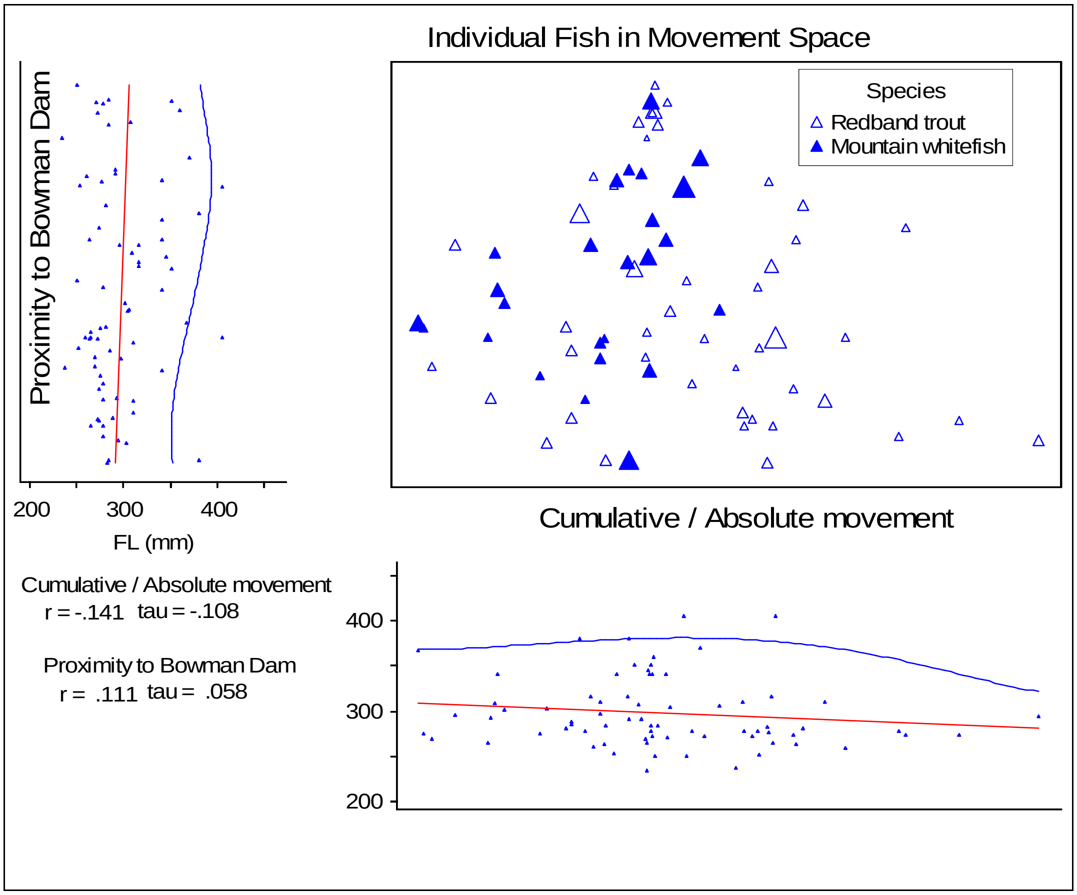

Figure 2.8. Two Scatter plots (upper left and lower right graph) of fork length in relation to both axes from the NMS ordination (upper right) of individual fish in movement space (same ordination as in Figure 2.7). Each point represents the fork length for each fish tagged. Each triangle represents an individual fish identified by species. No strong relationships were evident between movement patterns and fish size (axis one $r^2 = 0.02$, axis 2 $r^2 = 0.01$).

Weekly movement patterns and NMS results:

Four NMS ordinations were conducted on each tag group to determine if any environmental variables correlated to the weekly movement patterns of fish. The NMS ordinations for all four tag groups show that weekly movement patterns for each tag group are related to environmental variables but at different levels of variation (Table 2.6). The NMS ordinations revealed that minimum temperatures are correlated to weekly movement for each tag group. For tag group one, gauge height was also an important variable explaining 28% of the variation within the weekly movement data (Figure 2.9). For the remaining tag groups, minimum and average temperatures are the environmental variables most highly correlated with the weekly movement data (Figure 2.10-2.12).

Table 2.6. NMS 2-D ordination results for the 4 tag groups showing the greatest variance explained for each tag group on axis one and axis two. NMS was used to reveal relationships between weekly movements of individual fish and environmental variables.

Tag Group	Axis 1 r^2	Axis 2 r^2	Strongest correlation axis one	Strongest correlation axis two	Final stress	Final Instability	Number of iterations
1	24%	26%	Gauge height (28%)	Min temp (27%)	23.45	<0.00	92
2	35%	30%	Min temp (54%)	Average temp (5%)	23.44	<0.00	52
3	37%	23%	Min temp (11%)	Average temp (9%)	22.13	<0.00	52
4	21%	12%	Min temp (57%)	Min discharge (11%)	18.13	<0.00	50

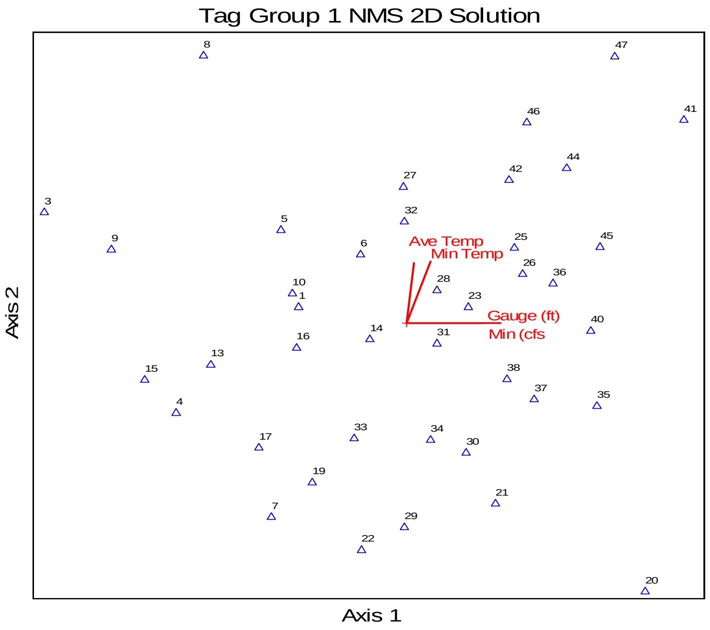

Figure 2.9. NMS ordination of weeks in movement space. Each triangle represents a week (week one is October, 8 2007). Axis one accounts for 24% of variation in the movement data and axis two accounts for 26% variation in the movement data. Gauge height and minimum discharge (cfs) are correlated to axis one (r^2 = 28% and 22% respectively). Minimum temperature and average temperature are correlated to axis two (r^2 = 27% and 24% respectively).

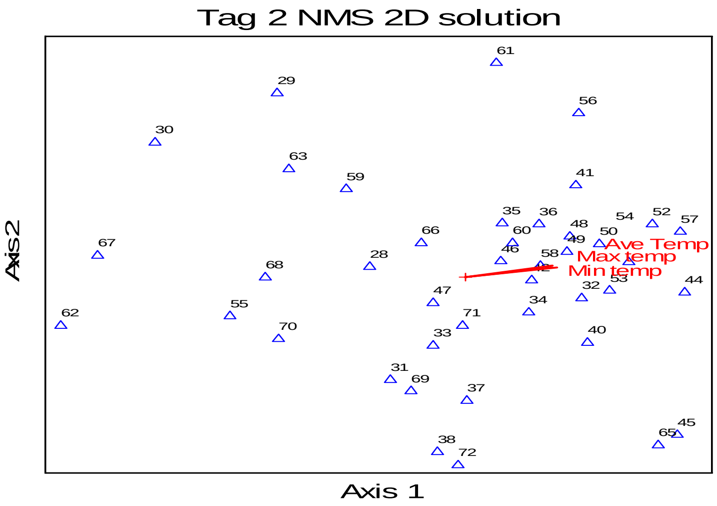

Figure 2.10. NMS ordination for tag group 2 of weeks in movement space. Each triangle represents a week (week one is April 11, 2008). Axis one accounts for 35% of variation in the movement data and axis two accounts for 30% variation in the movement data. Minimum, maximum and average temperature are correlated to axis one (r^2 = 54%, 27% and 27% resprectively). Minimum temperature is weakly correlated to axis two (r^2 = 5%).

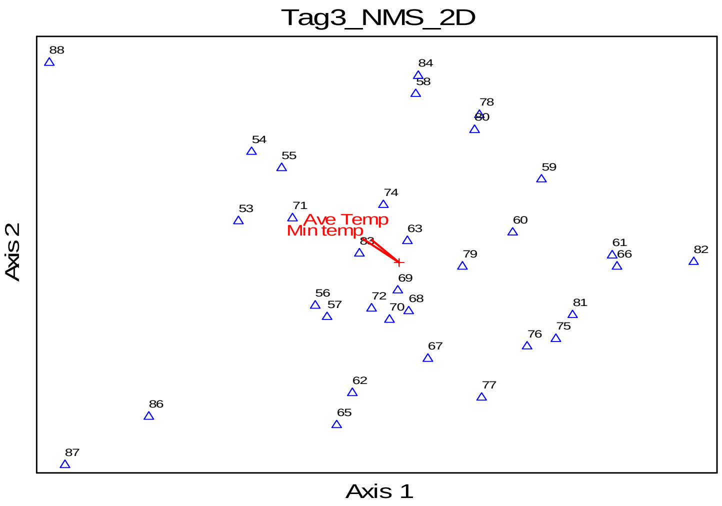

Figure 2.11. NMS ordination for tag group 3 of weeks in movement space. Each triangle represents a week (week one is October, 10 2008). Axis one accounts for 37% of variation in the movement data and axis two accounts for 23% variation in the movement data. Minimum temperature is weakly correlated to axis one (r^2 = 11%). Average temperature is weakly correlated to axis two (r^2 = 9%).

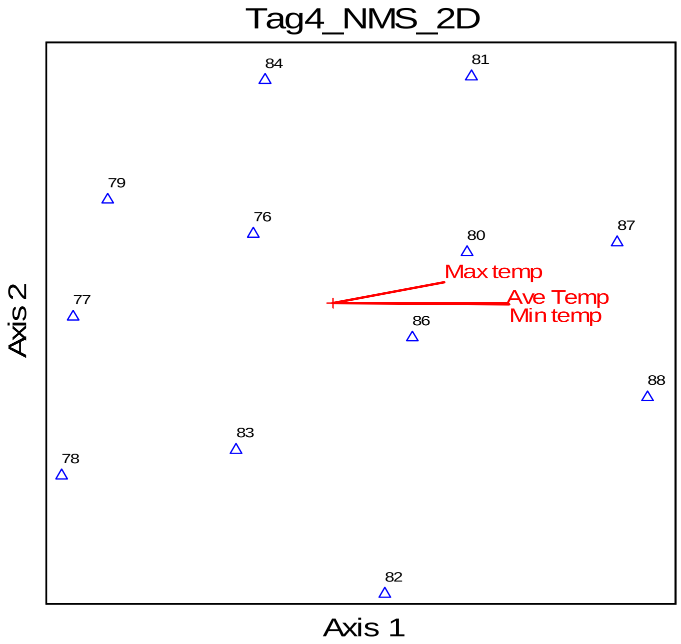

Figure 2.12. NMS ordination for tag group 4 of weeks in movement space. Each triangle represents a week (week one is March 21, 2009). Axis one accounts for 21% of variation in the movement data and axis two accounts for 12% variation in the movement data. Minimum, average and maximum temperatures are correlated to axis one (r^2 = 57%, 56% and 36% respectively).

DISCUSSION

We documented the range, distribution, and movement patterns of redband trout and mountain whitefish in the Crooked River. We found the linear range and movement patterns were variable between individuals for both species. In general, fish that were tagged near the downstream end of the study (rkm 13) moved less than fish that were tagged below Bowman Dam. The range and distribution of tagged fish showed that all parts of the wild and scenic section of the Crooked River below Bowman Dam are important at some time for both mountain whitefish and redband trout, but that there is very little movement downriver out of this section. Although we see differences in distributions for fish of each species, both species occupy most sections of the river throughout the year. Movement patterns were highly variable in terms of weekly movement patterns, cumulative movement, and linear range. We did not see any clear patterns between movements of individual fish and species traits. The analysis of weekly movement patterns and environmental variables showed correlations between weekly movements and water temperatures but much of the variation in the movement data was not explained by environmental variables suggesting other cues for fish movements.

Spawning areas and timing were identified for redband trout and mountain whitefish based on angler information, but were not evident from the telemetry data. The telemetry data did not show directed movements towards spawning areas because many of the fish were tagged near what turned out to be spawning areas, as later identified by anglers. Because the lengthy spawning timing for redband trout coincides with spring releases from Bowman Dam, if was difficult to determine if movement patterns are associated with spawning timing or other environmental variables such as flow and temperature.

Some populations of redband trout complete their life-cycle within a single stream whereas others exhibit large-distance movements that can include migratory behavior, partial migrations or resident life-histories (Northcote 1997). Redband trout are known to have developed a diversity of life-history strategies (Behnke 1992) but based on our research, redband trout in the Crooked River below Bowman Dam appear to be a resident form of the species. It is important to note that the redband trout we radio tagged ranged in age from 2-4 with an average age of 3 years old, so if there is a migratory life history component in the redband trout population, we tagged fish after the age where a migratory life history might be expressed.

Mountain whitefish are among the most abundant species present in many Oregon rivers (Northcote and Ennis 1994) yet there are very few studies related to movement patterns of mountain whitefish. To our knowledge, there is only one other study in Oregon that focused on mountain whitefish movement patterns. Baxter (2002) radiotracked mountain whitefish in the Wenaha River, OR and reported annual home ranges ranging from 0.2km to 190km with an average of 61 km. Baxter (2002) reported mountain whitefish exhibit complex seasonal migrations and numerous life history strategies, and reported that the majority of the tagged fish moved downstream to larger river systems for overwintering and returned the following spring to the location where they were tagged. Although Baxter (2002) documented multiple life history strategies for mountain whitefish, according to our study mountain whitefish have a resident, non-migratory life history in the Crooked River below Bowman Dam. Mountain whitefish stay in the same section of the Crooked River for rearing, spawning and overwintering. Similar to Baxter (2002), we found no correlations between mountain whitefish movements and fish size.

Prior to this study, there was limited data on the distribution and movement patterns of redband trout and mountain whitefish in the Crooked River below Bowman Dam. We questioned if the population decline was truly a decline or if fish were moving to other sections of the Crooked River downstream of Bowman Dam. This study has shown that redband trout and mountain whitefish stay within this section of river. The next step is to examine the river conditions and other factors in the years where the redband trout population showed a marked decline in order to gain a better understanding of what factors may have contribute to the decline. It is important to note that during the telemetry study, river flows did not exceed 2000 cubic feet per second (cfs), which is considered to be a high flow event. Such an event might change the movement dynamics of both species. We conclude that fish stayed within this section of river during low flow events and low spring discharges but how fish respond to high flow events still needs to be examined.

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CHAPTER 3. TOTAL DISSOLVED GAS AND GAS BUBBLE DISEASE IN THE CROOKED RIVER, OREGON

INTRODUCTION

In April 1989, signs of gas bubble disease were observed in over 80% of the redband trout captured during electro fishing surveys conducted by the Oregon Department of Fish and Wildlife (ODFW) in the Crooked River below Bowman Dam. In April of 2006 ODFW again observed signs of gas bubble disease in redband trout and mountain whitefish. Gas bubble disease involves the formation of bubbles within the tissues of an organism that results in visible signs or internal bubbles that result in tissue damage (Gorham 1901). Adult and juvenile salmonids are threatened by gas bubble disease in river systems where gas saturated water is present (Weitkamp and Katz 1980), but the impacts of gas bubble disease on the native fish in the Crooked River are not well understood.

To better understand the frequency of occurrence and extent to which water in the Crooked River becomes supersaturated with gas, and the potential for gas bubble disease to occur in the local fishes, a total dissolved gas (TDG) study was undertaken to address the following objectives:

1. Review the current state of knowledge with regard to gas supersaturation and gas bubble disease for various life stages of redband trout and mountain whitefish
2. Monitor TDG levels downstream of Bowman Dam to better understand the frequency and extent of supersaturated water
3. Create a river-flow saturation curve to predict TDG levels at specific flows

How does water become supersaturated with gases?

The solubility of atmospheric gases in water is determined by water temperature, dissolved solid content of the water, total pressure and the characteristics of the various gases, with the main environmental factors in freshwater systems being temperature and pressure (Colt 1984, Harvey 1975). Henry’s Law states that the mass of a gas dissolved in a liquid at a constant temperature is proportional to the pressure exerted on the solvent (Colt 1984, Harvey 1975). In other words, as the pressure on a given volume of water increases, the capacity of that water to hold dissolved gas also increases (Colt 1984, Harvey 1975). Dissolved gas pressure in water is normally equal to the barometric (atmospheric pressure), but this balance can be altered under natural or anthropogenic situations that cause increased atmospheric pressure, such as the turbulence and head pressure created at dams. Turbulence or agitation of water bodies can result in air bubbles becoming trapped and transported into the water column (Colt 1984, Harvey 1975, Weitkamp and Katz 1980). Air can be entrained in water whenever air and water are in contact at pressures greater than the ambient atmospheric pressure (Harvey 1975), and as water depth and pressure increase, the air bubbles, consisting chiefly of nitrogen, oxygen and argon, become dissolved (Colt 1984, Harvey 1975, Marking 1987).

Gas bubble disease

Gas bubble disease (GBD) is a condition that affects aquatic organisms living in waters that are supersaturated with atmospheric gases (Weitkamp and Katz 1980). Gorham (1901) was the first to describe GBD as a problem resulting from a change in the partial pressure of water and not resulting from a problem with a pathogen. Gorham (1901) provided an accurate, detailed description of GBD as “vesicles of gas invading all the superficial parts of the fish, especially fins, eyeballs, and in loose connective tissue of the orbits, so that the eyes were forced from their sockets; less commonly bubbles formed beneath the lining of the mouth, in the gill arches and beneath the skin, so that scales were raised from the surface”. The effects of GDB on fish can range from mild to fatal depending on the species, life stage, total dissolved gas (TDG) levels, duration of exposure, depth, water temperature and condition of the fish (Ebel et al. 1975, Mesa et al. 2000, Weitkamp and Katz 1980).

Gas bubbles are a precipitate that forms from gases within a liquid. When this happens inside a fish, these gas bubbles accumulate on the surfaces of fish (Marsh and Gorham 1905). When fish are subject to highly supersaturated water (>130% saturation), bubbles collect on the surface of the fish and increase in size and frequency on the surface of the fish (Marsh and Gorham 1905). The gas bubbles in supersaturated water are readily transferred into the bloodstream of fish because osmotic pressures act on both sides of the gill membrane and tend to equalize gas excesses between the water and the bloodstream (Harvey 1975). After 24-48 hours of exposure to water supersaturated >130%, intracellular gas bubbles can produce lesions in the mouth cavity, skin, and fins (Marsh and Gorham 1905). The most common lesions are usually in the gill filaments, where gas bubbles create emboli, blocking the flow of blood through the filaments (Marking 1987, Weitkamp and Katz 1980). Gas bubbles are observed most commonly in caudal fins but bubbles can also develop on the head, opercula, jaws and mouth, usually after the appearance of bubbles on the fins (Weitkamp 1976). “Pop-eye” is also a commonly observed sign of GBD and results from inflammation in the membrane behind or within the eye (Gorham 1901, Weitkamp and Katz 1980). The cause of death from GBD is usually asphyxiation caused by gas bubbles in the heart, gill filaments, or both (Weitkamp and Katz 1980). The gas that causes fatal emboli in the vessels of fishes is almost pure nitrogen (Marsh and Gorham 1905). Mortality can be reduced if the exposure to supersaturation is discontinuous or intermittently compensated for by movement to deeper water (Dawley et al. 1976, Weitkamp 1976). The solubility of gas in water increases with depth resulting in a decrease in the percent saturation of gas with increasing water depth (Weitkamp et al. 2003). For each one-meter increase in water depth, total gas saturation total gas pressure is reduced by 10% (Weitkamp and Katz 1980). As a result, as a fish increases its depth in water, the potential for GBD decreases (Weitkamp et al. 2003).

Water Quality Criteria for Gas Supersaturation

In Oregon, the mandated maximum allowable level for total dissolved gas level is 110%, as established by the U.S. Environmental Protection Agency (USEPA) and the Oregon Department of Environmental Quality (ODEQ) (Shrank 1997). Based on their review of the published literature, the USEPA and ODEQ concluded that gas bubble disease is a factor affecting fisheries in river systems where dams are present (Rulifson and Pine 1976). Ultimately it was concluded that a TDG level of 115% would protect migrating salmonids but that a lower 110% criterion should be adopted to protect shallow living benthos (Rulifson and Pine 1976).

Life stage considerations

There are gaps in the literature related to how gas supersaturation affects varying life stages of fish and different species. It is still unclear what the effects of gas supersaturation are on fish eggs or if GBD affects the fecundity of fishes. Early reports suggested that salmonid eggs are resistant to gas supersaturation and the effects of GBD (Rucker and Kangas 1974, Meekin and Turner 1974). Rucker and Kangas (1974) reported no visible signs of GDB in Chinook salmon eggs held in 128% supersaturated water, as bubbles were not seen adhering to the eggs nor were they seen inside the eggs. Meekin and Turner (1974) found no signs of GBD in Chinook salmon eggs but reported heavy mortality of steelhead eggs. Owsley (1981) reported that in salmonids, nitrogen supersaturation should not exceed 103% for eggs or 105% for parr. To the best of my knowledge there is no mention in the literature on the effects of gas supersaturation on fecundity.

Rucker and Kangas (1974) reported the progression of GBD in Chinook and Coho alevins which included development of gas bubbles in the space between the yolk sac and the perivitelline membrane. Mortality occurred after rupturing of the vitelline membrane due to the increase pressure of gas. Salmon parr have been heavily studied because migration timing of a juvenile salmon occurs at the same time as high flow events in the Columbia River system. Mesa et al. (2000) examined Chinook and steelhead parr and reported that parr exposed to 110% TDG saturation did not usually die, but signs of GBD worsened over time. At 120% TDG saturation, steelhead died more quickly than Chinook parr, and at 130% saturation the signs of gas bubble disease were highly correlated with mortality. Research conducted on the Kootenia River reported mountain whitefish held in shallow cages died within four days when total dissolved gas was above 130% (May 1973).

In the Crooked River, OR, supersaturated water occurs most frequently during high river discharges in April and May, although high flows have also been recorded at other times of the year. In the spring, the redband trout life stages present below Bowman dam include spawning adults, juveniles, incubating eggs, and alevins. The life stages of mountain whitefish include adult and juvenile fish. As gas bubble disease has been observed in both species within the Crooked River system, this study seeks to understand the frequency and extent to which gas supersaturation exceeds the ODEQ standard in this system, and therefore describe the vulnerability of fishes in this system to GBD.

METHODS

Collection of Total Dissolved Gas & River Flow Data:

Total dissolved gas levels were measured beginning in April 2008 at six locations downstream of Bowman Dam, using a dissolved gas meter (Model TBO-DL6, Common Sensing Inc.). TDG data were collected at various river discharge levels from April 18, 2008 to April 21, 2010. Sites sampled were established by the United States Bureau of Reclamation (USBOR) in 2006 (Figure 3.1, Table 3.1). The first TDG monitoring site is located directly downstream of the stilling basin at the base of Bowman Dam. TDG sampling sites 2-5 are located downstream of Bowman Dam and are spread throughout the federally-designated wild and scenic section of the Crooked River. The last TDG site was located directly upstream of the Stearns water diversion located 20 river kilometers (rkm) downstream from Bowman Dam. The 6 sites were established to determine the incidence and extent of saturated water at the stilling basin at various river flows and to examine the dissipation rate of TDG levels as water moves downstream.

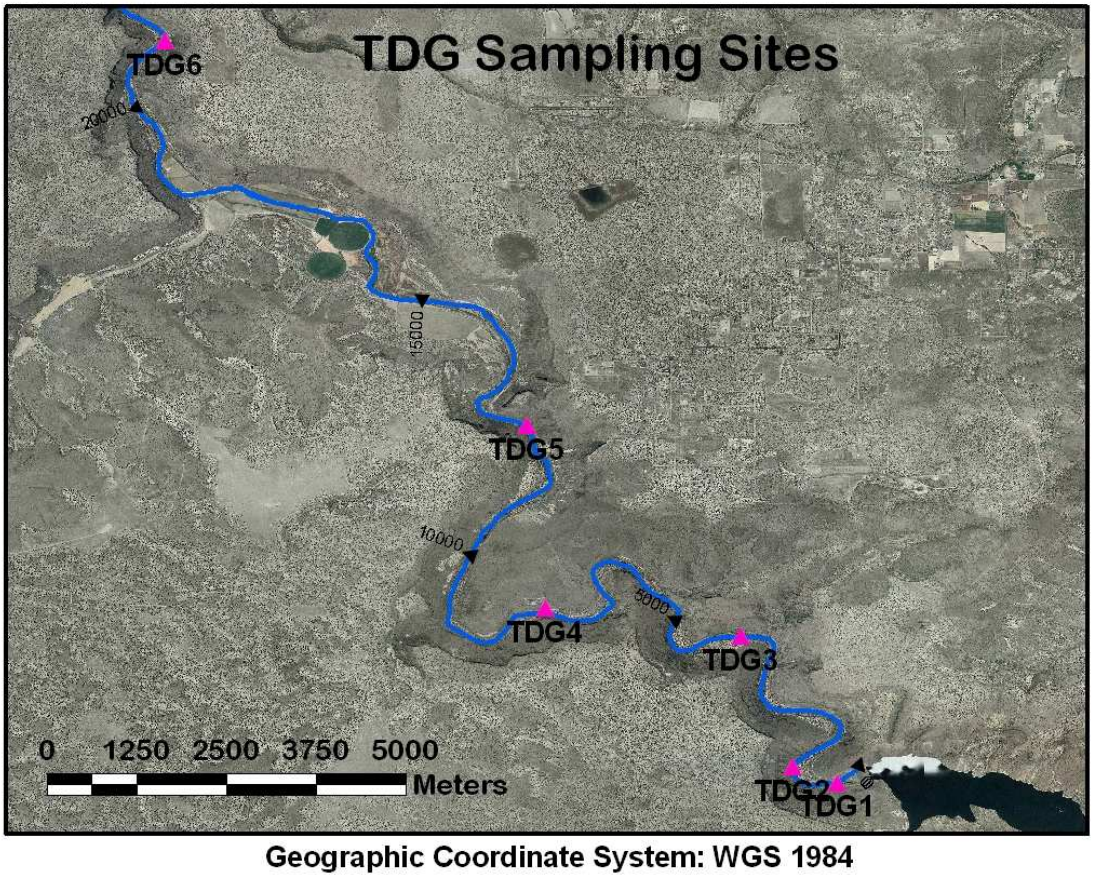

Figure 3.1. The total dissolved gas sampling sites used during the TDG study to monitor the incidence and extent of gas saturation in the water of the Crooked River.

Table 3.1. Name and geographic location of TDG sampling sites on the Crooked River, OR.

SITE NAME	SAMPLING STATION	River km From Bowman Dam	LATITUDE / LONGITUDE
TDG1	At Bowman Dam Stilling Basin	0	44° 06' 62"N, 120° 47' 39"W
TDG2	At USGS Gage below Bowman Dam	1	44° 06' 60"N, 120° 47' 57"W
TDG3	Devil’s Post Pile campsite 4	3.7	44° 07' 71"N, 120° 48' 13"W
TDG4	Lower Palisades campsite 10	7.5	44° 07' 89"N, 120° 49' 71"W
TDG5	Below old Hoffman Diversion Dam Site	12.3	44° 09' 28"N, 120° 49' 72"W
TDG6	At the crest of Stearns Diversion Dam	21	44° 12' 14"N, 120° 52' 30"W

Each sampling site established by USBOR had reasonably uniform velocities to help ensure cross-sectional mixing of water. Ideally, TDG data should be collected at depths greater than five meters in order to ensure measurements occur below the depth at which gas bubbles do not spontaneously form in the water column, a depth termed “the compensation depth”. Fish may attempt to get below the compensation depth to escape the effects of TDG supersaturation. The Crooked River has few pools >5 m depth. When sampling at this depth was not achievable, data were collected from the deepest location accessible from the river bank. Water quality parameters and barometric pressure were collected using a fully calibrated dissolved gas meter (Model TBO-DL6, Common Sensing Inc.). The probe was immersed in the water and allowed to stabilize for 15 minutes at each site before measurements were recorded. The TDG data collected are summarized in Table 3.2.

Table 3.2. Data Collected at each TDG sample site

CATEGORY	PARAMETER
Climate Data	Weather Conditions Barometric Pressure Start/End Time
Water Quality Data	Total Dissolved Gas Pressure (mm Hg) Water Temperature (^{0}C) Total Dissolved Nitrogen + Argon (% Saturation) Total Dissolved Oxygen (% Saturation) Dissolved Oxygen (mg/L) Comp Depth (ft)
Hydromet Flow Data	Average Daily Discharge (cfs) Average Daily Water temperature (^{0}C)

Flow discharge data, for use in the regression analysis with TDG levels, were queried from the USBOR Hydromet Station (PRVO) located at the base of Bowman Dam (http://www.usbr.gov/pn-bin/arcread.pl?station=PRVO).

Analysis

Total dissolved gas levels were regressed against river discharge, and the correlation coefficient (r^2) was used to determine the strength of the linear relationship between discharge (independent variable) and TDG measurements (response variable) (Ramsey and Schafer 2002). Total dissolved gas data were evaluated independently at each location to examine the differences in TDG levels among locations and to determine the dissipation rate of dissolved gases along the length of the sampled area. Finally, flow data from the time period immediately preceding the 1989 and 2006 ODFW fish surveys were compared to the saturation curve established with this current work in order to determine whether the relationship between discharge from Bowman Dam and gas saturation levels can be used to explain the incidence of GBD that ODFW observed during those time periods.

RESULTS

A strong positive relationship exists between river discharge and TDG levels below the Bowman Dam stilling basin ($r^2 = 0.93$, p-value < 0.0001)(Site 1, Figure 3.2). When river flow exceeds 600cfs, the TDG levels surpass the USEPA and ODEQ standard of 110% not only at the stilling basin but as far downstream as TDG site 5 which is 12 rkm downstream from Bowman Dam (Figure 3.3). At site 1, when river flow exceeds 1000 cfs, TDG levels exceed 115% saturation and when flows reach 1200 cfs, the TDG levels exceed 120% saturation. Dissolved gasses dissipate as water moves downstream (Figure 3.3, Figure 3.4) but above 600cfs, TDG saturation remains above 110% as far as site 5. Reduced water release during warmer months results in river TDG values within ODEQ standards acceptable TDG levels (<110%) at the stilling basin, but gas loading in the water column increases towards Stearns diversion. This gas loading below the stilling basin is probably due to higher water temperatures and primary productivity associated with algae and other biological activity in the river.

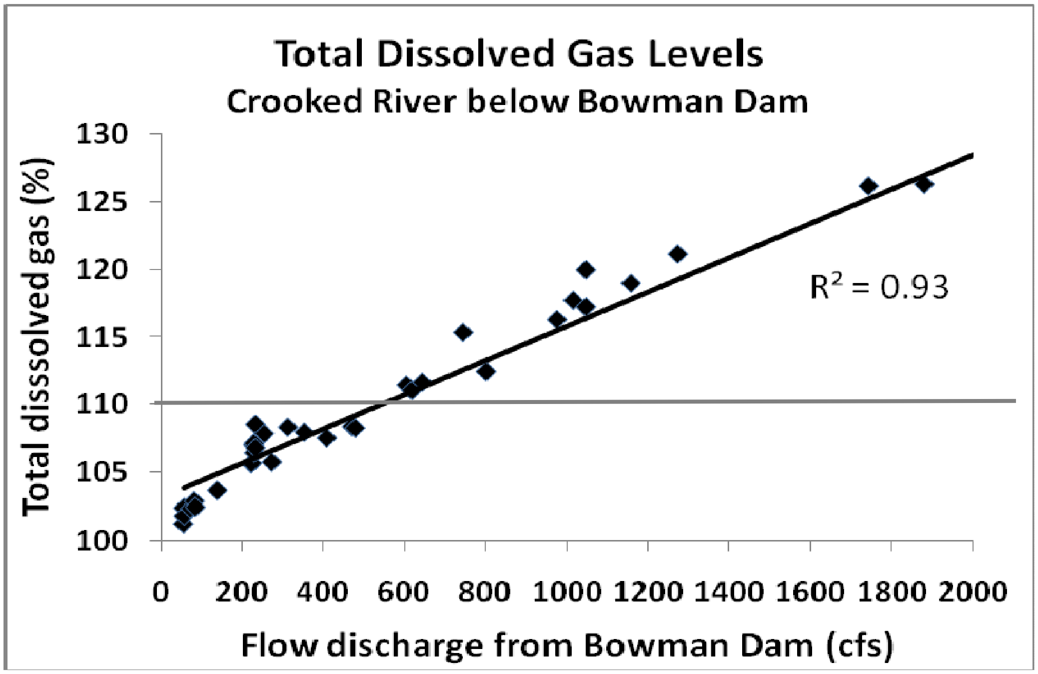

Figure 3.2. Total dissolved gas levels at TDG Site 1 located below Bowman Dam on the Crooked River, OR. The grey line shows the USEPA and ODEQ mandated maximum TDG level of 110%.

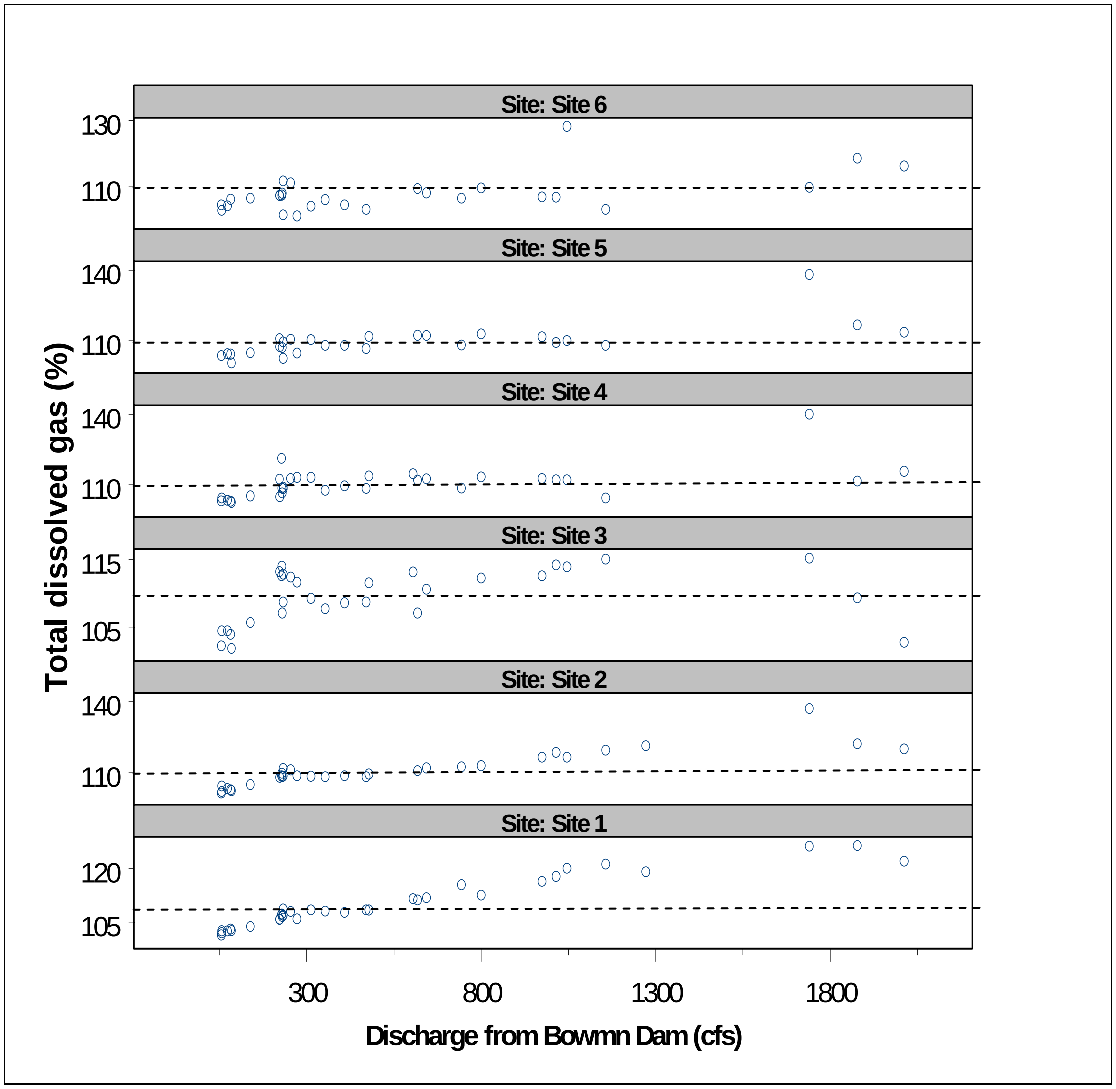

Figure 3.3. TDG sampling results from all 6 sites. The dashed line in each panel, drawn at 110% saturation marks the USEPA and ODEQ mandated maximum TDG level and shows that at high flows (>1700cfs) the TDG levels exceed 110% as far as 20km downstream from Bowman Dam.

Flows in excess of 600cfs are common during spring runoff events below Bowman Dam (Figure 3.4). From 1989-2009, flows exceeded 600 cfs in 13 of the 21 years and 1000 cfs in 10 of the 21 years. The past population-level effects of high flows and supersaturated waters on redband trout and mountain whitefish is difficult to quantify, but based on the hydrograph and the saturation curve, we can predict the years when fish were at risk for gas bubble disease. Given the strong linear relationship between TDG and stream average daily discharge ($r^2 = 0.93$) discharge itself can be used as a predictive tool for assessing TDG levels in the river. Based on the flow data from the USBOR gauging station and the gas saturation curve for the wild and scenic section of the Crooked River generated here, we can predict that gas bubble disease was probably present in fish in 1989, 1993, 1996, 1997, 1998, 1999, 2000, 2004 and 2006.

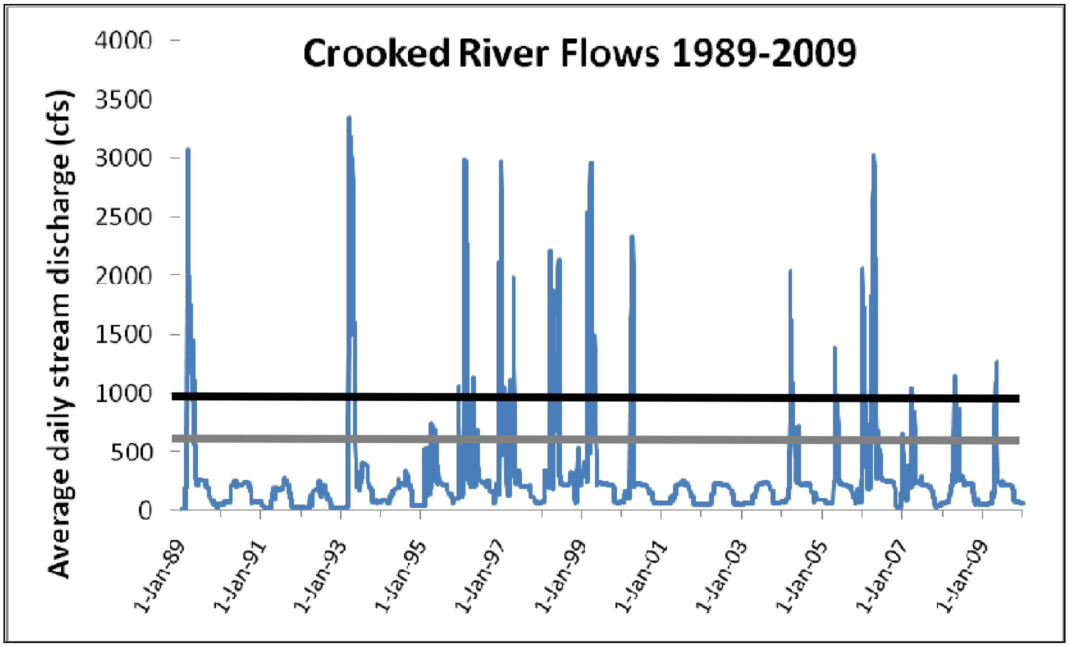

Figure 3.4. Daily average flows from Bowman Dam from 1989-2009. The grey line is drawn at 600cfs. Peaks above this line showing the times during which the TDG levels probably exceeded 110% saturation, indicating the potential for GBD to occur. The black line corresponds to a discharge of 1000cfs showing the years when the TDG levels potentially exceeded 120% saturation.

DISCUSSION

In April 1989, ODFW sampled fish in 8 km of the Crooked River from Bowman Dam downstream to Lower Palisades campground (TDG Site 4). During this sampling event, ODFW estimated that 80-85% of the 560 redband trout captured showed signs of GBD. They also noted signs of GBD in mountain whitefish but did not quantify the frequency of GBD occurrence in mountain whitefish. The average stream discharge was greater than 1000cfs for more than 40 days prior to this sampling event. In April 2006, ODFW captured 38 redband trout and 37 mountain whitefish and noted signs of GBD in 56% of the redband trout and 47% of the mountain whitefish. Prior to the 2006 sampling event, the discharge exceeded 2000cfs for 17 consecutive days. In addition to these GBD events documented by ODFW and correlated with high flow events, based on the TDG saturation curve generated from the current work, gas bubble disease was most likely present in fish not only in 1989 and 2006 but in 1993, 1996, 1997, 1998, 1999, 2000 and 2004 as well.

Trying to predict the population level impacts of gas super-saturation and GBD is difficult for several reasons. It is possible that many fish succumbed to the effects of gas bubble disease prior to the 1989 and 2006 surveys conducted by ODFW. It is also possible that signs of GDB disease were overlooked because diagnosing GBD can be difficult (Mesa et al. 2000). This would result in an incidence of GBD higher than that observed by ODFW. Despite all of the research on GBD, specific methods to describe the severity or development of gas bubbles for individual fish are lacking (Mesa et al. 2000). Another major obstacle to understanding GBD and its effects on fish is that most descriptions of the symptoms and progression of GDB in the literature are based on dead fish (Mesa et al. 2000) and the majority of the GBD research has been conducted in hatchery or laboratory settings. Laboratory studies have been designed primarily to determine acute tolerance to GBD with death being the end point (Nebeker et al. 1976). Application of laboratory results to conditions faced in river systems (Weitkamp and Katz 1980) remains a challenge for fisheries managers, but understanding and documenting gas bubble disease in fishes is a challenging and important endeavor. Gas bubble disease is not a new problem rather it has been recognized as a problem in fishes since the mid- 1600’s (Marking 1987). A century has passed since Gorham (1901) first documented GBD in fishes and even though numerous studies have tried to document the signs and progression of GBD, many questions still remain. GBD research efforts need to address impacts of supersaturated water on all life stages of salmonids, to consider effects on non-salmonid species, to consider the effects on macroinvertebrates, and to investigate the long-term effects of exposure to supersaturated water need to be studied. The water quality criterion for total dissolved gases was set based on very few published studies, and did not extensively evaluate impacts of TDG at various life stages. In addition, the present water quality criterion for gas supersaturation is not adequate for fish that are subjected to chronic exposures to gas-supersaturated water (Colt et al. 1986). More thought needs to be directed towards monitoring TDG supersaturation and of the effects of GBD on fishes in the Crooked River. Dissolved gas supersaturation in excess of federal and state water quality standards commonly occurs below Bowman Dam in the Crooked River and below other dams throughout the state (Ostrand and Gasvoda 2007) leading to the question: why have standards if monitoring and remedial action are not occurring?

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CHAPTER 4. POPULATION CHARACTERISTICS OF REDBAND TROUT AND MOUNTAIN WHITEFISH IN THE CROOKED RIVER, OR

INTRODUCTION

The Crooked River, located in central Oregon, is the largest tributary of the Deschutes River and encompasses a watershed of approximately 14,000 km^2 (Stuart et al. 2007). Just south of Prineville, OR, the Crooked River flows into Prineville Reservoir and is discharged through Arthur R. Bowman Dam (herein referred to as Bowman Dam). Flows discharged from Bowman Dam are regulated by the US Bureau of Reclamation (BOR) and operations are managed by the Ochoco Irrigation District (OID). Bowman Dam was constructed and is managed primarily for irrigation purposes, flood control and water storage. The hypolimnetic discharge of water from Prineville Reservoir has created a productive redband trout tailrace fishery due a constant supply of cold water to the river.

Between 1996 and 2007, the Oregon Department of Fish and Wildlife (ODFW) documented a precipitous decline in redband trout (*Oncorhynchus mykiss*) abundance in the Wild and Scenic section of the Crooked River below Bowman Dam. In addition to redband trout the Crooked River has historically also supported runs of anadromous summer steelhead (*Oncorhynchus mykiss*) and spring Chinook salmon (*Oncorhynchus tshawytscha*) (Nehlsen 1995). Anadromous fish were extirpated from the Crooked River and resident fish populations were fragmented during the construction of the Pelton-Round Butte dam complex (1964), which created Lake Billy Chinook, and Bowman Dam (1961), which created Prineville Reservoir (Stuart et al. 2007). Since 1989, ODFW has conducted extensive surveys throughout the Crooked River basin and reported the greatest abundance of redband trout in the 20 kilometer (km) stretch of river below Bowman Dam (Stuart et al. 2007). Stuart et al. (2007) also reported that the majority of the tributaries and much of the mainstem Crooked River below the first 20 km after Bowman Dam are too warm to support strong redband trout populations. Based on these data, the section of the Crooked

River located below Bowman Dam may be vital to the perseverance of the redband population in the Crooked River basin.

Several hypotheses may explain the decline in redband trout below Bowman Dam, with the leading hypothesis being that interannual variability in river flow conditions are limiting the production and survival of redband trout. This hypothesis is based on the premise that seasonal flow management and variable discharges from Bowman Dam can have both positive and negative impacts on the redband trout population density, and therefore the overall population size. OFDW has conducted population estimate surveys on redband trout in the ~3 km section of river below Bowman Dam (the "index section") since 1989, although these data are not continuous as the survey was not conducted in some years. Population estimates indicate that the redband trout population has declined in abundance whereas the mountain whitefish (*Prosopium williamsoni*) population in the same section of river has increased; however, ODFW has not specifically quantified the increase in mountain whitefish. To better understand the population characteristics of both redband trout and mountain whitefish and to determine if population structure is related to river flows we:

1) Expanded upon ODFW's population estimate surveys to address the following questions: (1) are the redband trout population estimates generated in the index section representative of the Wild and Scenic section and (2) what is the estimated population size for mountain whitefish. To address these questions we had two objectives:

   1.1 Sample a second reach downstream of the index section in order to examine relative abundances for redband trout and mountain whitefish downstream of Bowman Dam.

   1.2 Expand upon ODFW's population surveys to estimate the mountain whitefish population size

2) Evaluated whether the redband trout population structure is related to river flows. We addressed this topic with the following three objectives:

2.1 Determine if the redband trout size structure differs from year to year

2.2 Document how river flow varies from year to year

2.3 Examine if patterns exist between redband trout size structure and river flows

METHODS

1) Population estimates

One of our objectives was to assess whether redband trout population densities were similar downstream of the regularly monitored index section. Therefore, in 2008 and 2009, a second reach, located 3 km downstream of the index section, was also sampled. Because the reports of increases in the mountain whitefish population size, which occurred over the same period as the decline in the redband trout population, were anecdotal, in 2007 we expanded ODFW's redband trout mark-recapture survey to include mark-recapture of mountain whitefish.

Fish were collected in both sections of the river using a drift-boat mounted electroshocker. The index section starts 0.5km below Bowman Dam and was approximately 3.5km in length. The second section, referred to as the lower section, was 2km in length. Over a five day period, fish were collected, marked, examined for previous marks, and biological data were collected, including species and total length. A subsample of fish was weighed. Redband trout and mountain whitefish were marked with a caudal fin punch or a floy tag and released within the same reach from which they were sampled. Due to the large number of mountain whitefish present, sampling whitefish for the entire length of each section was not possible. Whitefish were collected for the first kilometer of each section. Population estimates were generated using the Schnabel mark-and-recapture-estimator (Ricker 1975). From 1996 to 2007, the index section was not sampled equally in each year owing to personnel availability and inconsistencies with regard to boat access. Therefore, to compare my estimates with previous estimates of abundance, population estimates are reported in fish per kilometer.

2) Relationship between redband trout size structure and river flows

Overview of Ordination Analysis

Ordination was used to achieve the objectives of determining if the redband trout population structure is related to river flows. Ordination was chosen because both the redband trout population structure and the variables used to describe flow are multivariate in nature and correlation among population structure variables and among flow variables is likely. These characteristics render commonly used tools, such as multiple regression, inappropriate. First, we will describe the treatment of the population structure data, followed by a description of the flow variable data. We will then describe the ordination techniques used to determine if size structure is related to river flow.

Data Structure for Multivariate Analysis

Size Structure (Main) Matrix

To examine the differences in redband trout size structure from year to year, a size structure matrix was created with individual years (11 years) as the rows and size classes (4) as the columns: 200-249mm, 250-300mm, 300-349mm and 350+mm. The contents of the matrix were the number of fish captured in each size class in each year. The redband trout total length (mm) data were broken into size classes that approximate age-classes determined by scale analysis (Table 4.1). Scale data collected from a subset of fish in 1993, 1998 and 2008 was used to determine the age structure from the length data (DeVries and Frie 1996). Due to inconsistent sampling effort among sampling crews and across years, the use of raw abundance data was inappropriate. Therefore, the size structure matrix was relativized by row totals to examine proportions of fish in each length category captured in a given year rather than absolute abundances of fish. ODFW did not collect fish less than 200mm for several years of the study so the smaller size classes of fish were not included in the matrix.

Table 4.1. Summary of the age data collected in 1993, 1998, 2008 used to estimate length-at-age data for size classes.

Combined Scale Data For Size Structure Matrix Scale Data from 1993, 1998, 2008					
Age	n	Mean (mm)	Min (mm)	Max (mm)	Length Bin
Age 1	118	112	81	160	Not included in analysis
Age 2	211	191	129	274	200-249
Age 3	74	254	181	354	250-300
Age 4	11	308	266	360	300-349
Age 5	2	388	375	400	350+

Environmental Flow (Second) Matrix:

The Bureau of Reclamation operates a Hydromet hydrologic monitoring station at the base of Bowman Dam. The Hydromet station records daily stream flow discharges from Bowman Dam and reports discharge data in cubic feet per second (cfs). The flow matrix was generated by querying discharge data from the BOR Hydromet website (http://www.usbr.gov/pn-bin/arcread.pl?station=PRVO). Daily discharge data from the Hydromet station were summarized by annual and monthly minimum, annual and monthly maximum, and annual and monthly average flows, which resulted in 39 flow variables (12 months X 3 flow variables + annual min, max and average flows). For the cluster analysis (see below), we included flow data starting in 1989 and continuing through 2009, because the four-year-old redband trout sampled in 1993 would have experienced varying flow conditions since 1989. For all additional analyses, the flow matrix consisted of 11 sample units (11 years) to match the size structure matrix. The raw flow data spanned 2.6 orders of magnitude so the flow matrix was log transformed ($\log_{10}(x+1)$) prior to analysis.

An outlier analysis was performed on both matrices using the requirement of a standard deviation less than 2. For the species matrix, 1994 was identified as an outlier. A single outlier can have an effect on the coefficient resulting in strong relationships that are not related to the bulk of the data (McCune and Grace 2002) so the 1994 data were removed from the size structure matrix.

Ordination techniques

We used cluster analysis (Post and Shepard 1967, Wishart 1969) and multivariate ordination using non-metric multidimensional scaling (NMS) (Kruskal 1964, Mather 1976) to evaluate the relationships between redband trout size classes and flow variables from year to year, and to examine any relationships between redband trout size classes and flow variables, using PC-ORD version 6.158 (McCune and Mefford 2010).

Agglomerative hierarchal cluster analyses using Sørensen (Bray-Curtis) distance and flexible beat (β = -0.25) linkage function was applied to arrange the flow years and size structure years into cluster groups. Flexible beta with β = -0.25 is a space-conserving method that avoids distortion and leads to minimal chaining (McCune and Grace 2002).

To determine if a relationship exists between redband trout size structure (main matrix of the ordination) and river flows (second matrix), we performed an ordination of the size structure matrix using Sørensen distance measure (Mather 1976). Ordination is used to identify and describe patterns in multidimensional data that are difficult to graph or visualize. Non-metric multidimensional scaling calculations are based on $n \times n$ distance matrix calculated from the $n \times p$-dimensional data matrix where n is the number of rows and p is the number of columns (McCune and Grace 2002). Random starting configurations were used for the NMS with 250 runs for the real data and a Monte Carlo test was performed using 250 randomized runs of the data to test the significance of the axes identified by the NMS ordination. The final dimensionality was chosen by examining scree plots and selecting the dimensionality which provided the greatest reduction in stress with the fewest number of axes. Sørensen distance measure was used because it retains sensitivity with heterogeneous data sets (McCune and Grace 2002). Correlations between the species size structure ordination and flow matrix ordination were assessed using joint plot overlays. The strength of the relationship between size structure and flow variables were assessed using correlation coefficients.

RESULTS

1) Population estimates

The redband trout population density varied quite substantially from year to year, with a peak of 5000 redband trout estimated in 1994 and a low of 400 estimated in 2006 (Figure 4.1, Table 4.2). A large increase in the number of redband trout per km occurred between 1993 and 1994, indicating that the density of fish can increase substantially in one year. Although population surveys were not conducted from 1996 to 2000, the decline in density from 1994 to 2006 appears to be more gradual than the increase in density observed from 1993 to 1994. This interpretation, however, includes many years with no data and should therefore be treated cautiously. Generally, redband trout population density since 2006 appears to be increasing, but the large error associated with the estimates in 2007 and 2009 make it difficult to determine whether an increase in density is occurring or whether density has just been variable at lower levels in the past 4 years.

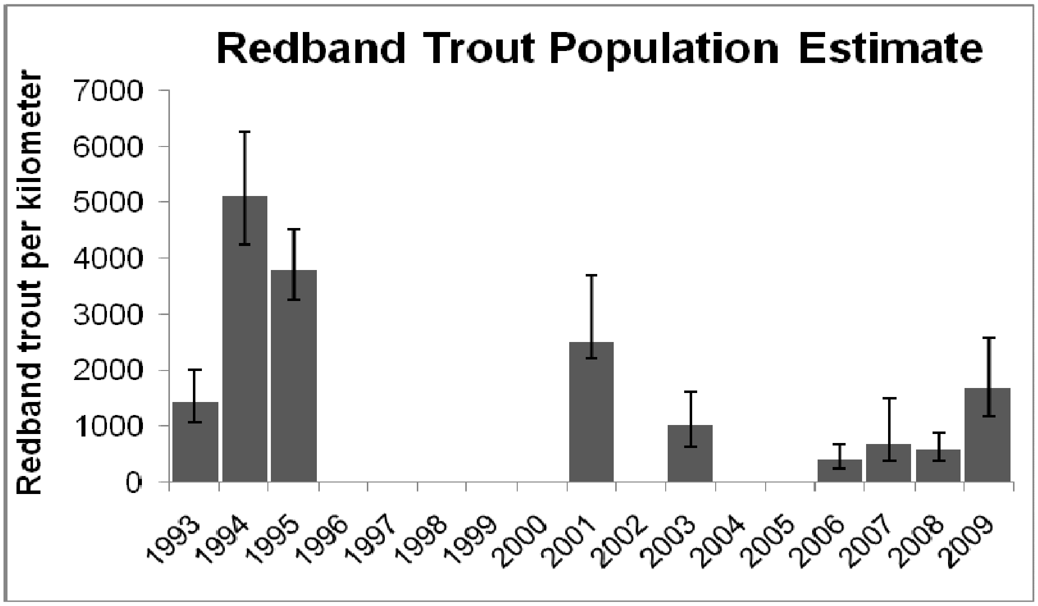

Figure 4.1. Redband trout population estimates generated from mark-recapture surveys conducted by ODFW for the index section of the Crooked River located below Bowman Dam. Error bars represent 95% confidence intervals.

By expanding ODFW’s sampling in 2007 to include whitefish, we observed changes in the density of both redband trout and mountain whitefish. In the index section, the redband trout density was estimated at approximately 600 fish per kilometer in 2007 and 2008, whereas the mountain whitefish density decreased dramatically from more than 4,000 fish per kilometer in 2007 to 2,000 fish per kilometer in 2008 (Figure 4.2, Table 4.2). From 2008 to 2009, the redband trout population density increased threefold, to approximately 1700 fish per kilometer, whereas the mountain whitefish population estimate did not appear to change between 2008 and 2009.

In 2008, the downstream survey section was estimated to hold fewer than 300 redband trout per kilometer, while the mountain whitefish population estimate was 2,000 fish per kilometer. Redband trout densities in the downstream section were similar in 2009. The mountain whitefish density for the downstream section in 2009 was two times higher than the index section. Low recapture rates in 2009 in the downstream section (3 recaptures per species) increased the confidence intervals surrounding the 2009 estimates.

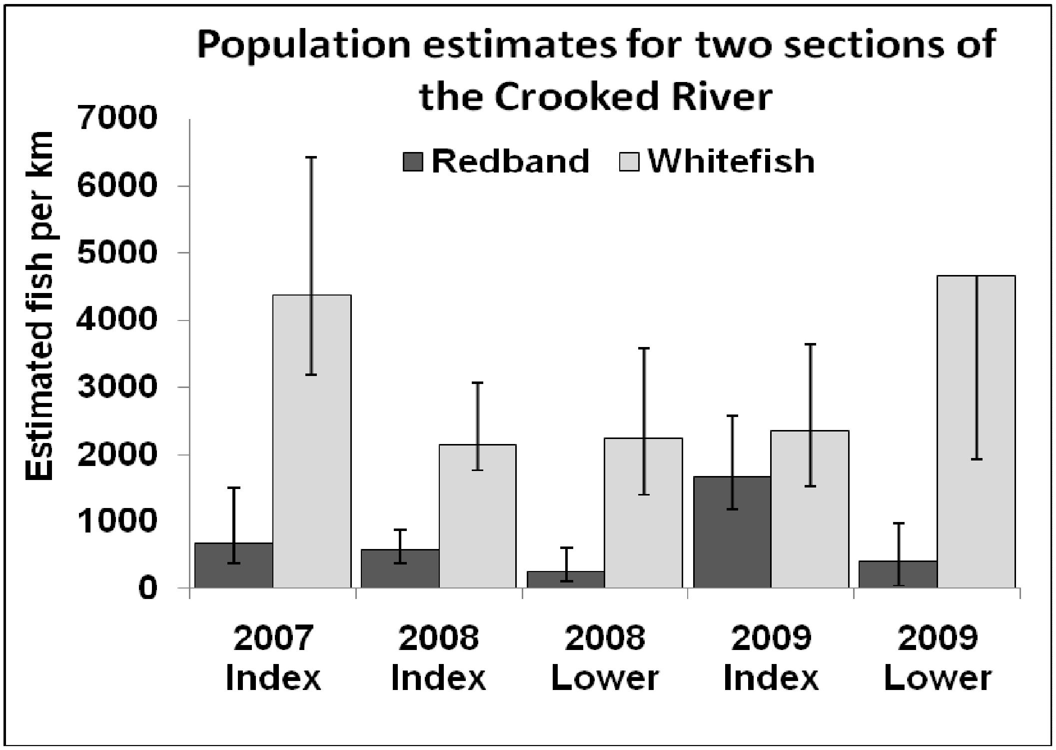

Figure 4.2. Population estimates for redband trout and mountain whitefish in the index and downstream sections of the Crooked River. Error bars respresent 95% confidence intervals.The upper errror bar was not included for the 2009 lower section mountain whitefish estimate because it extends off the graph. The upper point for the error bar for 2009 in the lower section was 26,624.

Table 4.2. Population estimates and 95% confidence intervals of redband trout and mountain whitefish in two sections of the Crooked River below Bowman Dam.

Crooked River Population Estimates per Kilometer				
	Redband Trout		**Mountain Whitefish**	
Index Site	**Estimate**	**95% CI**	**Estimate**	**95% CI**
1993	1422	1059 - 2013		
1994	5111	4255 - 6258		
1995	3788	3263 - 4517		
2001	2493	2220 - 3693		
2003	1003	627 - 1609		
2006	398	230 - 675		
2007	674	381 - 1493	4381	3186 - 6422
2008	574	375 - 877	2133	1763 - 3062
2009	1673	1178 - 2570	2352	1519 - 3628
Lower Site				
2008	257	109 - 606	2242	1398 - 3592
2009	392	38 - 969	4662	1912 - 26624

*2009 Lower Site data estimates for both species were based on 3 recaptures.

2) Size structure, river flows & comparisons

2.1 Does the redband trout size structure vary from year to year?

The redband trout population size varies from year to year but we are also interested in knowing how the size structure varies. The results from the cluster analysis of the size structure matrix showed four groups of years at 75% information remaining and two groups of years at >50% remaining (Figure 4.3). The first group result (at 50% information remaining) are years where the size structure was dominated by the 200-249mm size class (age-2) and include the years 1993, 1994, 1995, 1998, 2006 and 2007 (Figure 4.3, Figure 4.4). Within the top groups in the dendrogram, 1994 joins the cluster at a greater distance than the other years and based on the size frequency data, in 1994 more size 200-249mm were captured as compared to all other years of this study. The years 1993, 2006 and 2007 grouped with 1994, 1995 and 1998 when >50% of the information remained and although these 6 years were similar for the 200-249mm size group these years differed in the proportions of large fish captured. In 1994, 1995 and 1998 the smallest proportions of 350+mm fish were captured. Conversely, in 1996, 1997, 2001, 2003, 2008 and 2009, fewer than 50% of the captured fish were in the 200-249mm length group. These yeas were dominated by larger size classes of fish.

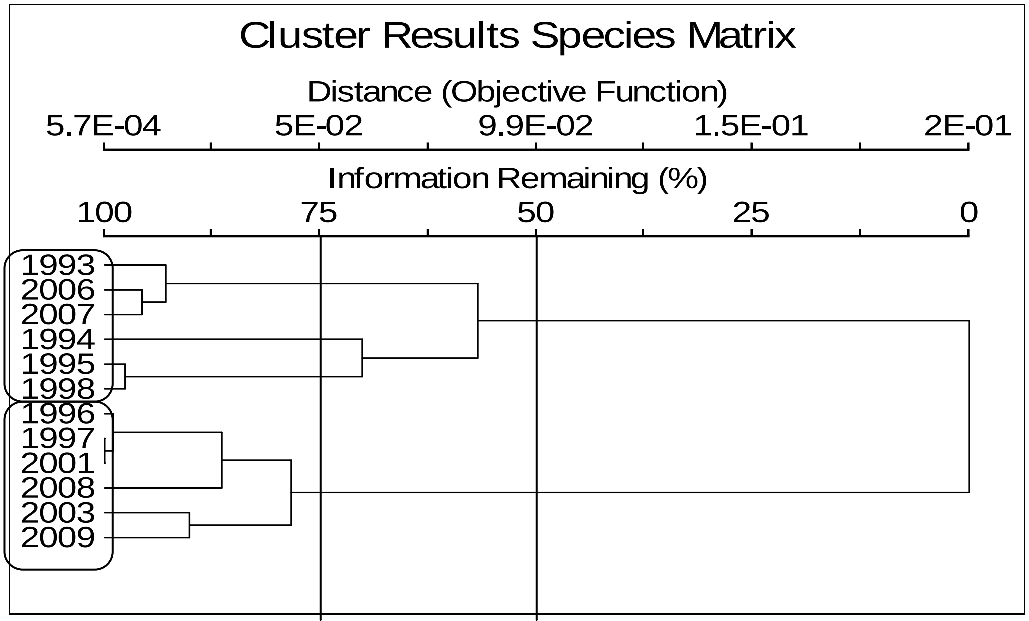

Figure 4.3. Cluster analysis results in years aligning into 4 groups at 75% and 2 groups at 50% information remaining. The length of the brackets indicates the closeness in size structure based on Sorensen distance measure and the percent of information remaining. Distance is measured as Wishart's (1969) objective function which measures the information lost at each step in clustering.

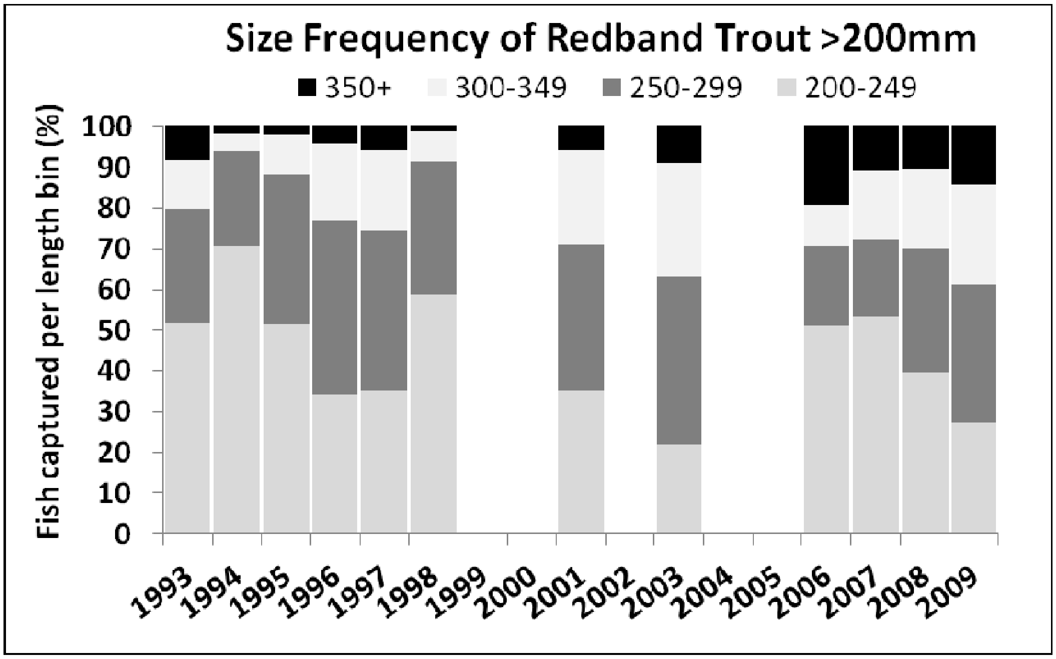

Figure 4.4. Redband trout size frequency expressed as a proportion of the total fish lengths recorded per year. ODFW did not conduct surveys in 1999, 2000, 2002, 2004 or 2005.

The NMS ordination of the size structure matrix resulted in a stable ordination after 63 iterations, yielding a final stress of 6.7124, *p*-value = 0.004 and instability of 0.00000 for a two-dimensional solution (Figure 4.5). A joint plot overlay of the size categories on the NMS ordination of the species matrix reveals that axis one is a gradient of 200-249mm (age-2) on the left to 300-349mm (age-4) fish on the right. Axis one accounts for 83% of the variation in the data. Axis 2 accounts for 16% of the variation in the size structure data and reveals a gradient of large fish (age-5) to medium sized fish (age-3). Together, the first two axes explain 99% variance in the size structure data.

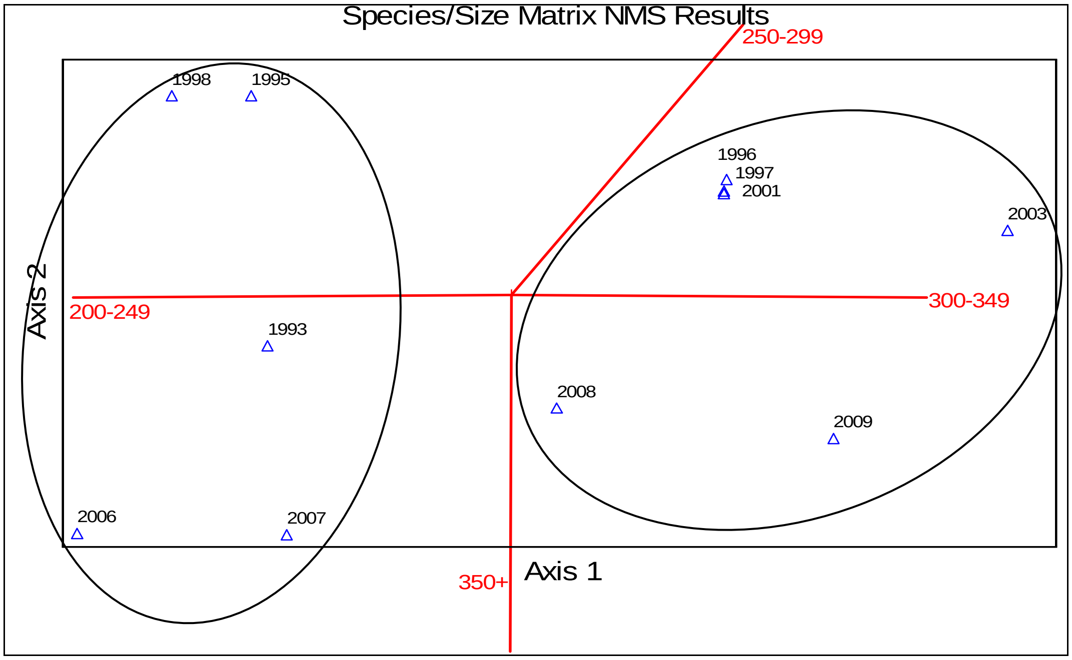

Figure 4.5. The two-dimensional ordination of years in size structure space. Axis one is strongly correlated ($r^2 = 0.83$) with 200-250mm fish on the left and 300-349mm fish on the right. Axis two ($r^2 = 0.16$) is a gradient of large fish (350+mm) to medium sized fish (250-299mm). Size classes are displayed as a joint plot: the angles and length of the radiating lines indicate the directions and strength of the relationship of the size class with the ordination scores. Circles show the group results from the cluster analysis at 50% information remaining (1994 was not included in the ordination).

2.2 Are river discharges from Bowman Dam similar from year to year?

The cluster analysis results for the flow matrix shows that several years cluster together at >70% information remaining (Figure 4.6). The years 1990, 1991, 1992, 1994, 2001, 2002, 2003 are considered to be drought years and are characterized by low annual average discharge and low monthly discharge (Figure 4.7: light grey lines). The drought years join the remaining years at the base of the cluster showing that the drought years are distant from the wet years. The years 1989 and 1993 are characterized by high flows and very low winter flows (Figure 4.7: black lines). The remaining years are characterized by moderate flows in the spring and higher than average flows in the winter.

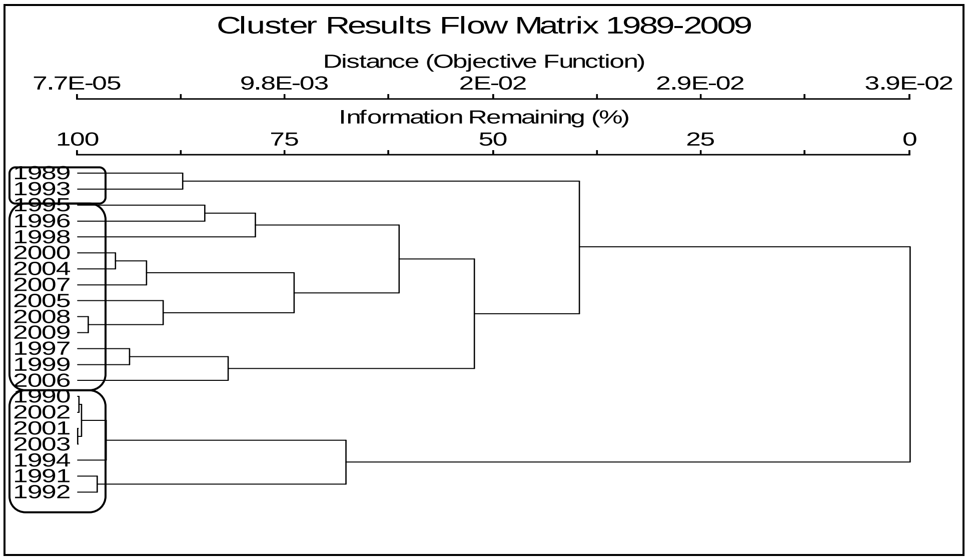

Figure 4.6. Cluster dendrogram showing groups of years based on flow data. The years align into 3 at 50% information remaining. The length of the brackets indicates the closeness in flow variables based on Sorensen distance measure and the percent of information remaining. Distance is measured as Wishart's (1969) objective function which measures the information lost at each step in clustering.

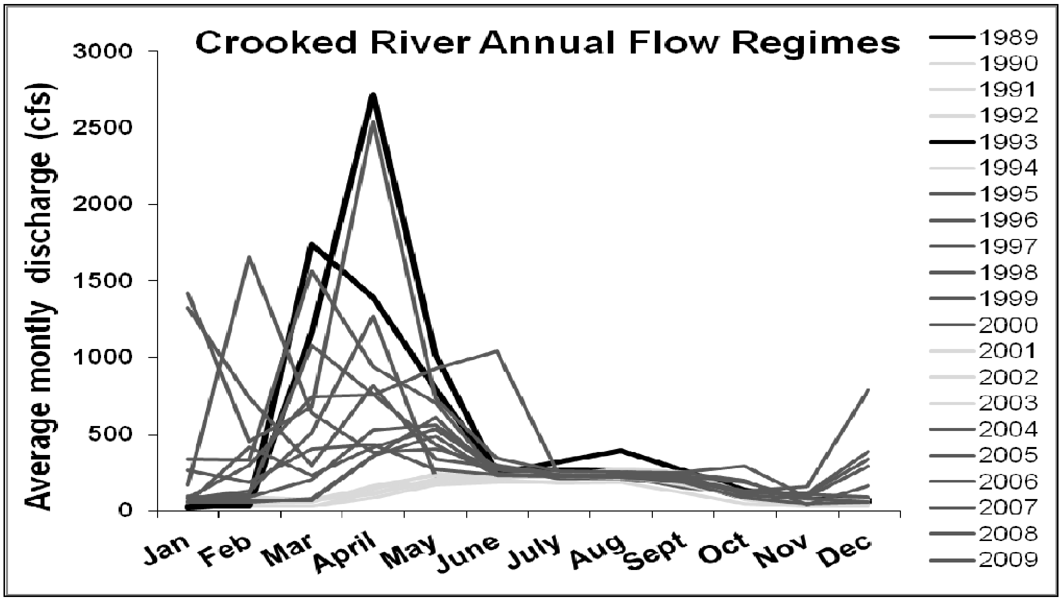

Figure 4.7. Annual flow regimes separated into the 3 groups identified by the cluster analysis at 50% information remaining. The black years: 1989 and 1993 are characterized by high spring flows and low winter flows. The low flow "drought" years are shown in light grey (1990, 1991, 1992, 1994, 2001, 2002, 2003). The remaining years (dark grey) are characterized by moderate flows in the spring and higher than average flows in the winter.

The NMS ordination of the flow matrix resulted in a stable ordination after 32 iterations, yielding a final stress of 8.48, *p*-value = 0.004 and an instability of 0.00000 for a two-dimensional solution (Figure 4.8). Axis one accounts for 77% of the variation in the flow data and reveals a gradient from the low water 'drought' years to high water 'wet' years. Axis two accounts for 18% of the variation in the flow data and represents a gradient from low winter flows (top of axis 2) to high winter flows (bottom of axis 2). Together, the two axes explain 95% of the variance in the data. A joint plot overlay (r^2 cutoff = 0.6) of the flow variables on the flow ordination revealed many correlations between the wet years located on the right side of axis one and spring flow variables.

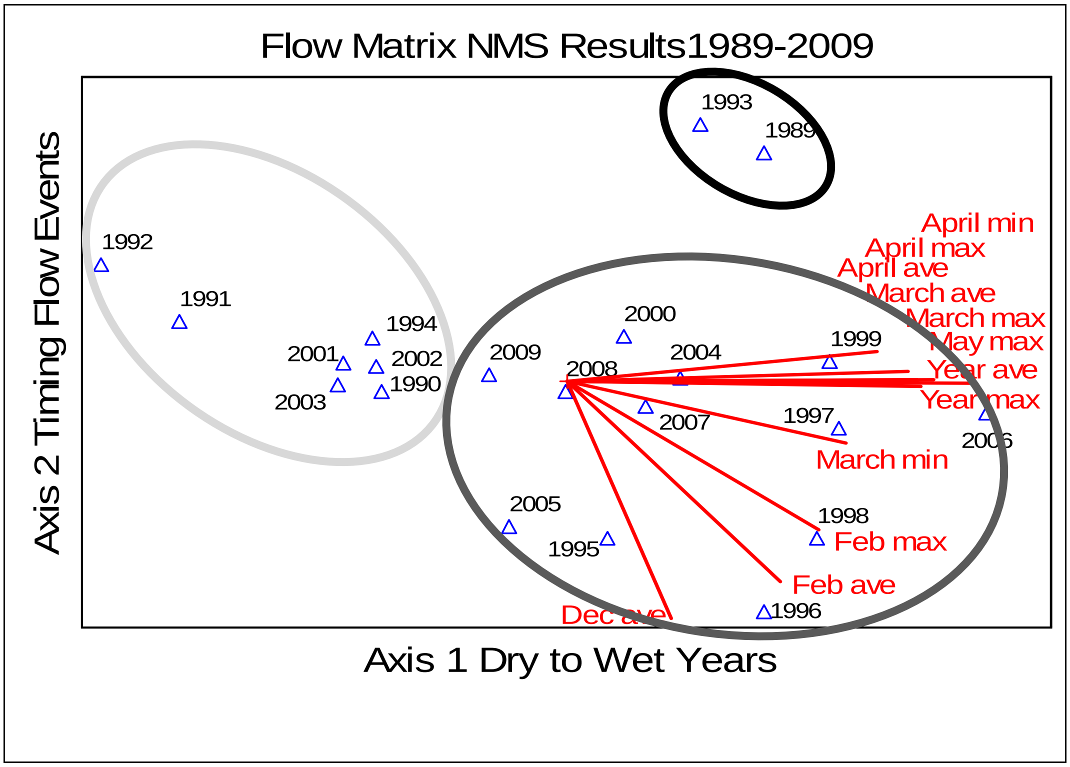

Figure 4.8. Two-dimensional NMS ordination of years in flow space with a joint plot overlay (r^2 cutoff= 0.6) of specific flow variables that contribute to each axis in the NMS ordination. The colored circles show the 3 groups from the cluster analysis.

3.3 Do patterns exist between redband trout size structure and river flows?

A joint plot overlay of the flow matrix onto the ordination of years in size structure space shows that years dominated by 200-249mm fish are also dominated by high March and high April flows (Figure 4.9, Figure 4.10). Likewise, the years dominated by 300-349mm fish are dominated by low March and low April flows. Average and maximum March flows and average April flows are negatively correlated to axis one (r^2 = -0.6, -0.5 and -0.5 respectively). The upper portion of axis two contains the years with high proportions of 250-300mm fish and these years that have the highest flows in November and December (Figure 4.10). The minimum flows in November and December are correlated to axis two (r^2 = 0.6 and 0.5 respectively). The vector representing yearly minimum flow is equally correlated to axis one and axis two (r^2 = 0.4) (Figure 4.11).

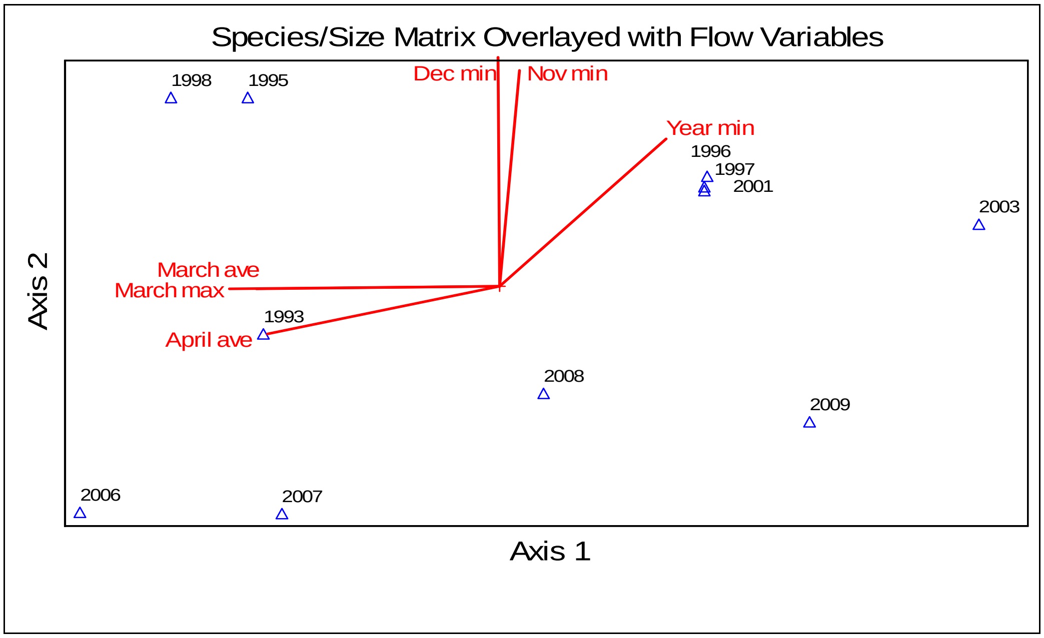

Figure 4.9. Joint plot overlay of the flow variables on the size strucuture ordination (Figure 4.5). The left side of axis one are years with the highest flows recorded in March and April. The top of axis two is years with high flows in December and November.

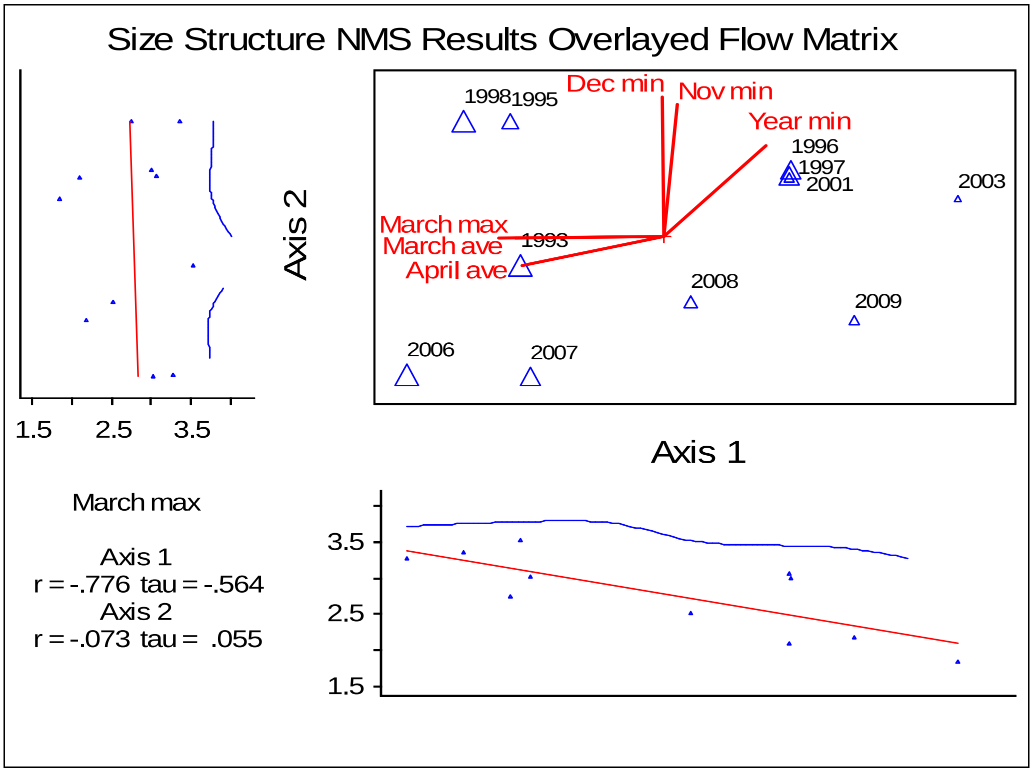

Figure 4.10. Two scatter plots (top left and bottom right graphs) of March maximum flows in relation to both axes from the NMS ordination (graph upper right). Each point in the scatterplots represents a year. Upper right is the 2-D NMS ordination of size structure. March maximum flow is not correlated to axis two (r^2 = 0.005) but is correlated to axis one (r^2 = 0.6).

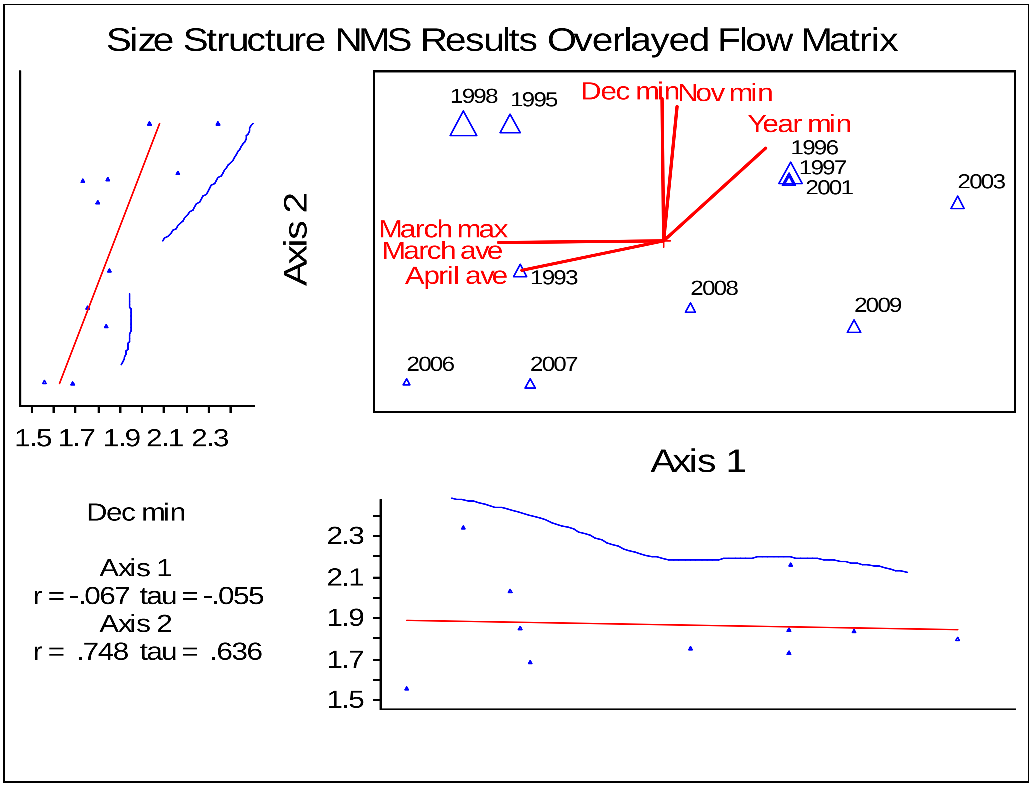

Figure 4.11. Two scatterplots (top left and bottom right graphs) of December minimum flows in relation to both axes from the NMS ordination (graph upper right). Each point in the scatterplots represents a year.. December minimum flow is not correlated to axis one (r^2 = 0.004) but is correlated to axis two (r^2 = 0.6).

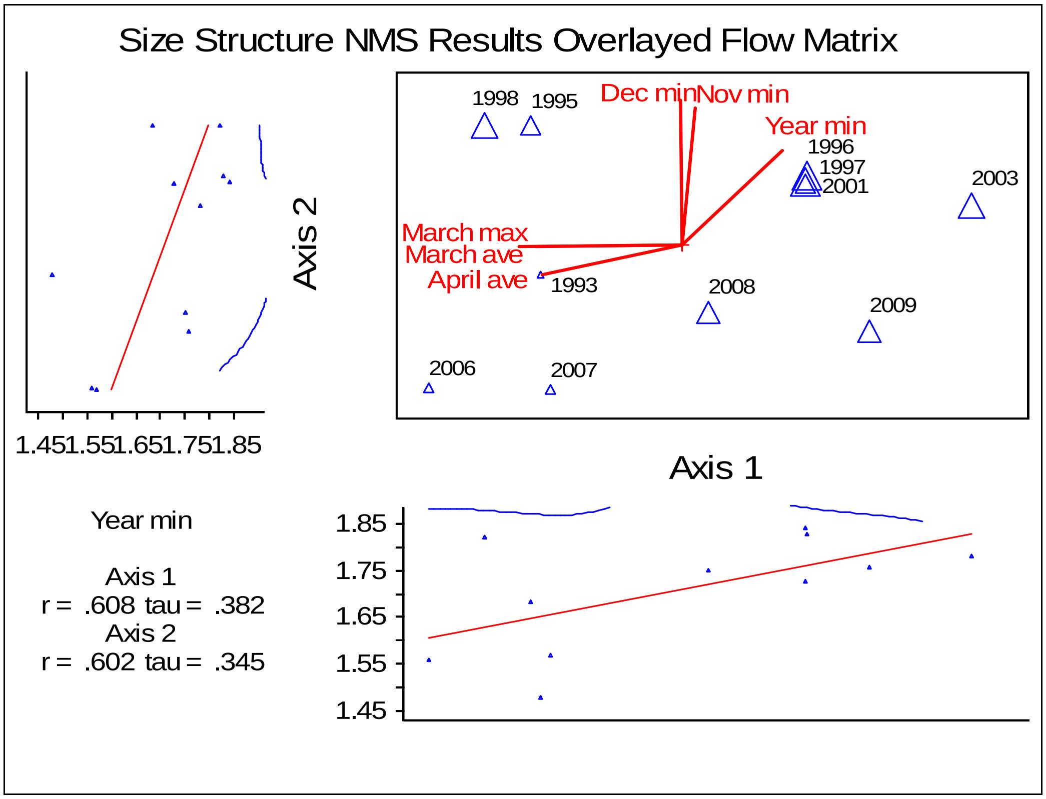

Figure 4.12. Two scatterplots of yearly minimum flows (top left and bottom right graphs) in relation to both axis from the NMS ordination (graph upper right). Each point in the scatterplot represents a year. Symbol size is proportional to the measure of log flow. Upper right is the 2-D NMS ordination of size structure. Yearly minimum flow is equally correlated to axis one and axis two ($r^2 = 0.4$).

DISCUSSION

The redband trout population density varied considerably from year to year, with a peak observed in 1994 and the lowest point observed in 2006. Generally, redband trout population density appears to have been increasing since 2006, but the large error associated with the estimates in 2007 and 2009 make it difficult to determine whether an increase in density is occurring or whether density has just been variable at lower levels in the past 4 years.

The downstream section of the Crooked River below Bowman Dam has lower densities of redband trout and similar or higher densities of mountain whitefish than the index section during the two years that we monitored the downstream section. Based on these data, it would be inappropriate to use the population estimate generated for the index section to predict redband trout densities in other sections of the Crooked River. These results are concordant with ODFW staff and Crooked River angler observations that note that the relative abundance of redband trout seems to decrease in downstream locations.

One interesting finding was that in the index section in 2007, the mountain whitefish density was estimated to be 7 times greater than the redband trout population, in 2008 the mountain whitefish density was estimated to be 4 times greater than the redband trout population, but in 2009, the mountain whitefish density was only marginally higher than the redband trout population. In the three years of this study, there appears to be a shift in the relative abundance of redband trout and mountain whitefish directly below Bowman Dam. The reduction in the mountain whitefish population density in the index section from 2007 to 2008 was not expected based on angler accounts of the increase in mountain whitefish population densities. The winter flows were very low in the Crooked River during the winter of 2007 and 2008 possibly contributing to the reduction in the mountain whitefish density.

Based on comparisons of the NMS ordinations of size structure and flow matrix, patterns exist between redband trout size structure in certain years and specific flow variables. The ordination revealed that younger fish dominated in years with high spring flows. Why might this be? Are high flows flushing out the larger fish? Are the total dissolved gases (Chapter 3) resulting in mortality of the larger fish? The ordination also showed that the largest two size classes dominated either when winter flows were high or when spring flows were low. Do higher winter flows and lower spring flows confer better survival of redband trout and that is why we see higher proportions of larger fish? Or does habitat becomes limiting at low flow levels and only large fish can hold territories?

It is important for ODFW to continue to conduct regular and consistent monitoring of the fish populations below Bowman Dam. Sampling smaller fish (<200mm) would provide a more accurate understanding of the entire population. Ideally, sampling efforts should be expanded to incorporate the number of recruits and/ or age-1 fish each year. If recruitment can be enumerated, and ODFW can continue to conduct annual surveys, cohorts could be tracked through time to understand survival and examine what factors are potentially limiting survival in a given year.

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CHAPTER 5

GENERAL CONCLUSION

This project had two main goals: (1) identify potential factors contributing to the observed reduction of the redband trout population in the Crooked River fishery and (2) provide management recommendations to all of the agencies responsible for managing the Crooked River that might effect a change in the redband trout population trend.

Based on the results from the 2-year telemetry study, redband trout and mountain whitefish population exhibit a resident life history strategy and stay in the Wild and Scenic Section of the Crooked River below Bowman Dam. ODFW conducted extensive surveys in 1989 throughout the Crooked River basin and reported the greatest abundance of redband trout in the 20 river kilometer (rkm) stretch of river below Bowman Dam (Stuart et al. 2007). Stuart et al. (2007) also reported that the majority of the tributary streams and mainstem Crooked River below Bowman Dam are too warm to support healthy redband trout populations. The results of ODFW's surveys and this telemetry study support the need to manage the Crooked River below Bowman Dam to continue to support redband trout populations. Based on the existing data, the Crooked River below Bowman Dam may be vital to the perseverance of the redband population in the Crooked River basin.

Prior to this study, limited data existed on the distribution and movement patterns of redband trout and mountain whitefish in the Crooked River below Bowman Dam. Two potential explanations for the population decline were plausible: one potential explanation is that the population decline was due to mortality, and another possible explanation is that fish were moving to other sections of the Crooked River downstream of Bowman Dam. The telemetery study showed that redband trout and mountain whitefish stay within this section of river, thereby providing evidence against the explanation that the apparent population decline was a result of movement of fish to other sections of river.

The total dissolved gas study demonstrated that gas saturation has the potential to cause gas bubble disease in the Crooked River below Bowman Dam. The gas saturation in the Crooked River is equivalent or higher than levels shown to produce GBD in fishes. When flows exceed 600 cfs, the total dissolved gas saturation exceeds the maximum mandated level of 110% gas saturation in the Crooked River. Flows in excess of 600cfs are common during spring runoff events below Bowman Dam. From 1989-2009, flows exceeded 600 cfs in 13 of the 21 years and 1000 cfs in 10 of the 21 years. The past population-level effects of high flows and supersaturated waters on redband trout and mountain whitefish are difficult to quantify, but based on the hydrograph and the saturation curve, the years when gas bubble disease might have been present in fish can be predicted. Given the strong linear relationship between TDG and stream average daily discharge ($r^2 = 0.93$), discharge itself can be used as a predictive tool for assessing TDG levels in the river. Based on the flow data from the USBOR gauging station and the gas saturation curve for the wild and scenic section of the Crooked River generated here, gas bubble disease was probably present in fish in 1989, 1993, 1996, 1997, 1998, 1999, 2000, 2004 and 2006.

Gas bubble disease is not a new problem; rather it has been recognized as a problem in fishes since the mid- 1600’s (Marking 1987). A century has passed since Gorham (1901) first documented GBD in fishes and even though numerous studies have tried to document the signs and progression of GBD, many questions still remain unanswered. GBD research efforts need to address impacts of supersaturated water on all life stages of salmonids, to consider effects on non-salmonid species, to consider the effects on macroinvertebrates, and to investigate the long-term effects of exposure to supersaturated water need to be studied. More thought needs to be directed towards monitoring TDG supersaturation and towards determining the effects of GBD on fishes in the Crooked River. Dissolved gas supersaturation in excess of federal and state water quality standards commonly occurs below Bowman Dam in the Crooked River and below other dams throughout the state (Ostrand and Gasvoda 2007) leading to the question: why have standards if monitoring and enforcement are not occurring?

The redband trout population density varied considerably from year to year, with a peak observed in 1994 and the lowest point observed in 2006. A large increase in the number of redband trout per km occurred between 1993 and 1994, indicating that the density of fish can increase substantially in one year. The decline in redband trout density from 1994 to 2006 appears to be more gradual than the increase in density observed from 1993 to 1994. Since 2006, the redband trout population density appears to be increasing.

One interesting finding was that in the index section in 2007, the mountain whitefish density was estimated to be 7 times greater than the redband trout population, in 2008 the mountain whitefish density was estimated to be 4 times greater than the redband trout population, but in 2009, the mountain whitefish density was only marginally higher than the redband trout population. In the three years of this study, there appears to be a shift in the relative abundance of redband trout and mountain whitefish directly below Bowman Dam. The reduction in the mountain whitefish population density in the index section from 2007 to 2008 was not expected based on angler accounts of the increase in mountain whitefish population densities. The survey of the lower section revealed that the relative abundance of redband trout was lower relative to the upper section. This suggests that the index reach is not a good indicator of total density of redband trout in other sections of the river.

This result of the telemetry study allowed me to examine the river conditions in the years were the population showed a marked decline to gain a better understanding of what factors contribute to the redband trout decline. We examined how the population is changing not just in terms of abundance but relative to how the size structure varies over time. We investigated whether patterns in size structure across years are evident and determined whether size structure patterns are related to specific flow variables. Our results show that years dominated by 200-249mm (age-2) fish are also dominated by high March and high April flows. Likewise, the years dominated by 300-349mm (age -4) fish are dominated by low March and low April flows. The years with high proportions of 250-300mm (age-3) fish had the highest flows in November and December. Although correlations are evident between the size structure in a given year and specific flow variable, we cannot determine causal mechanisms from this data.

Management recommendations

I recommend that ODFW continue to monitor the redband trout and mountain whitefish populations in the Crooked River below Bowman Dam. Annual surveys would allow for a better understanding of changes to the population structure over time. Ideally, enumerating the number of recruits in a year would be a better way to understand survival and population changes. Recruitment may be a difficult to quantify in the Crooked River so perhaps a better effort at sampling age-1 fish would be helpful addition to the annual sampling.

Management recommendations for flow releases from Bowman Dam include pursuing dam modifications to fix the TDG problem. The US Bureau of Reclamation is currently researching dam modifications to reduce the total dissolved gases below Bowman Dam. Until a solution is implemented, TDG monitoring during high flows coupled with fish surveys would better our understanding of how fish in the Crooked River respond to high levels of total dissolved gases.

Future research ideas

We documented changes in size class structure over the course of the study. An important future step is to consider if the actual biomass of fish in the Crooked River below Bowman Dam had changed. Also, during the population estimate surveys in 2008 and 2009, hundreds of fish were floy tagged and many of the floy tags were recaptured the subsequent summer; therefore, growth rates could also be examined.