HABITAT SUITABILITY AND AVAILABILITY FOR RAINBOW TROUT

ONCORHYNCHUS MYKISS IN THE CANYON RESERVOIR TAILRACE

AND EVALUATION OF SIDE SCAN SONAR FOR HABITAT

MAPPING IN A SEMI-WADABLE RIVER

by

Greg A. Cummings, B.S.

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Committee Members:

Thom Hardy, Chair

Tim Bonner

Adam Kaeser

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DEDICATION

This thesis is dedicated to the memory of

Milburn Cummings

(1928 – 2014)

He helped me catch some of my first fish and I had the immense honor of witnessing him catch some of his last. We all owe deep appreciation to those who introduce youth to the outdoors.

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individuals have tremendous passion for a special resource and have turned that into meaningful action.

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ABSTRACT

Rainbow Trout *Oncorhynchus Mykiss* are typically stocked in tailraces across the
southeastern United States to mitigate fish habitat and assemblage alterations caused by
large impoundments. Hypolimnetic discharges from Canyon Reservoir have created
conditions suitable for a coldwater tailrace fishery and trout have been stocked there
since 1966. Changes in habitat availability for adult Rainbow Trout with discharge rate
were examined to provide flow and habitat improvement recommendations for the
Canyon Reservoir tailrace. Physical habitat modeling incorporated habitat suitability
information for trout coupled with hydraulic modeling to assess habitat quality and
quantity at various flow rates. Habitat mapping included traditional surveying, remote
sensing, bathymetric mapping, and side scan sonar. Side scan sonar was evaluated for
efficiency and applicability to river systems similar to the tailrace. Results indicate that
summer water temperature is likely the primary limiting factor for adult trout survival
and could impose limitations on physical habitat during critical summer months.
Modified flow rates and habitat improvement could cause a potential increase in adult
trout abundance and assist put-grow-and-take strategies in the upper portion of the
tailrace. Side scan sonar provided efficient mapping of non-wadable sections of the study
area. Challenges related to water level, access, navigability, positional accuracy, and
post-processing were overcome. Trial runs, training, map accuracy assessments, and
technological development will improve the effectiveness of this technique.

I. HABITAT SUITABILITY AND AVAILABILITY FOR RAINBOW TROUT *ONCORHYNCHUS MYKISS* IN THE CANYON RESERVOIR TAILRACE

INTRODUCTION

Since the 1930s, agencies like the U.S. Army Corps of Engineers (USACE) and the Tennessee Valley Authority (TVA) have constructed high dams with low level discharges, creating coldwater fisheries where none existed, especially in the southeastern U.S. (Axon 1975). Impoundments of rivers can alter downstream ecosystems physically and biologically through changes in flow regime, turbidity, sediment loading, thermal regime, and water chemistry that can alter or interrupt the life cycles of macroinvertebrates and fish (Cheslak and Carpenter 1990). Depending on the goals of a particular fishery these changes can help or hinder the success of stocking programs, regulation, and management.

A tailrace/tailwater fishery is one located immediately downstream of a hydraulic structure such as a natural or man-made dam. The extent of a tailrace fishery can be influenced by stocking strategy or environmental factors such as temperature. The Canyon Reservoir tailrace extends 22.2 km below Canyon Reservoir Dam. This distance was set because a bridge crossing provided an easily recognizable regulation boundary, although the extent to which oversummer survival for trout may occur was thought to be further upstream (Magnelia 2004). Coldwater tailwater fisheries typically require stocking of salmonids and can maintain high standing stocks with fishing effort several times higher than the upstream reservoir (Cheslak and Carpenter 1990). Rainbow Trout (*Oncorhynchus mykiss*) are typically stocked due to their lower unit cost of production,

ability for fast growth, adaptability, suitability for put-and-take fisheries, and high recreational value (Pawson 1987, 1991).

Southern tailwater trout fisheries are popular with anglers and require extensive stocking, making them an important component of fisheries management in southern states (Swink 1983). High angler exploitation rates and a multitude of factors limiting growth and survival require intensive management and research (Fry and Hanson 1968; Aggus et al. 1977; Wiley and Dufek 1980; Klein 2003; Bettoli 2004). Eleven states in the southeastern U.S. have a total of 54 tailraces with current or proposed trout stockings, encompassing over 147 thousand square km of watershed and over 952 km of managed rivers (Caudill 2007). An estimated 4.9 million trout are stocked annually in the Southeast, with Arkansas (1.9 million), Tennessee (1.3 million), and Missouri (760,000) stocking the highest amounts (Caudill 2007). The resources put into these fisheries illustrate their cultural and recreational significance.

The stocking of catchable Rainbow Trout in southern tailraces typically has a high benefit/cost ratio. A five-year study on the Lower Mountain Fork River below Broken Bow Dam in Oklahoma reported increasing returns of license sales offsetting the cost of trout stockings, with a benefit/cost ratio of 16:1 (Harper 1994). A Texas Parks and Wildlife Department (TPWD) study on the Brazos River below Possum Kingdom Reservoir estimated a benefit/cost ratio of 28:1 for trout stocking (Forshage 1976). The success was attributed to the novelty of trout fishing in Texas, the publicizing of stocking dates, and the willingness of anglers to pay more to fish for trout than native fishes. Overall estimated benefit/cost of trout tailwaters in the Southeast is $7.41 for every dollar spent stocking (Caudill 2007).

The Canyon Reservoir tailrace has high socioeconomic value as well. It was rated among the 100 Best Trout Streams in the U.S. by Trout Unlimited (Ross 2005) and 50 Best Tailwaters to Fly Fish (Gunn and Gunn 2013). Trout stocking and leasing of two access sites from December 2004 to February 2005 generated $4.75 of economic value for every dollar spent by TPWD (Bradle et al. 2006). During this 3-month period state revenue from sales tax and fishing license sales exceeded $21,000.00 (Bradle et al. 2006). In 2010, tourists spent over $12 million on water-oriented recreation (including fishing) in unincorporated portions of Comal County (Walker and Scheuren 2012). A 2012 study focused on fishing trips of non-local members of the Guadalupe Chapter of Trout Unlimited (GRTU) and their respective parties. It estimated $1.9 million in total direct expenditures, with $1.4 million of that in Comal County (Leitz 2013).

Historically, the Canyon Reservoir tailrace trout fishery was managed under a put-and-take strategy. Documentation of oversummer survival in the early-1990's led to a portion of the fishery being regulated under a put-grow-and-take management strategy in 1997 (Magnelia 2004). This special regulation zone extended from 6.3 km to 22.2 km below Canyon Reservoir Dam (Special regulation zone two, Figure 1.1), and allowed only one trout over 457 mm in length to be harvested per day (Magnelia 2007). Management actions in this portion of the fishery included supplemental stockings of Rainbow Trout fingerlings, a water temperature monitoring program, trout angler lease access areas, and electrofishing surveys to document survival (Magnelia 2004). In addition to the harvest restriction in 2003, a flow agreement between GRTU and the Guadalupe-Blanco River Authority (GBRA) was put in place to keep summer water temperatures in the special regulation zone below 21.1°C to reduce temperature-induced

stress and mortality (Magnelia 2007). In 2014, a second special regulation zone was established (Special regulation zone one, Figure 1.1) that extends from 731.5 m below the outflow from Canyon Reservoir to the upstream boundary of the other special regulation zone (6.3 km downstream from the outflow). This zone has a slot length limit in which trout under 305 mm and one exceeding 457 mm in length can be harvested, with a 5 fish daily bag limit. This regulation was put in place after the field collection phase for the current study and is meant to limit harvest on adult trout in the most thermally suitable portion of the tailrace. This section offers the best opportunity to establish a put-grow-and-take trout fishery and increasing residency time is key to achieving this.

In 1997 an extensive temperature monitoring program was initiated by TPWD to investigate the temperature regime throughout the Canyon Reservoir tailrace. Water temperatures in the tailrace are directly related to discharges from Canyon Reservoir (Groeger and Tietjen 1998; Magnelia 2004; Groeger and Bass 2005). Temperature monitoring stations are mapped in Figure 1.2. Temperature exceedance data were compiled by TPWD and summarized in Table 1.4. Mean water temperature at the Canyon Reservoir outflow typically reaches its maximum in October and is usually caused by thermal destratification in the reservoir (Magnelia 2004). From the outflow of the dam to 3.75 km (bottom of section 2), temperatures rarely exceed 21.1°C, the temperature at which trout become stressed. At 6.3 km, temperatures exceed 21.1°C 16 percent of the time but do not reach lethal temperatures (25°C). At the midpoint of section 3 (11.9 km) temperatures exceed 21.1°C 32 percent of the time and exceed lethal limits by nine percent. Beyond this point, temperatures exceed 21.1°C a majority of the time and reach lethal limits frequently.

The flow agreement between GRTU and GBRA made effective in 2003 was meant to keep temperatures below 21.1°C beyond 6.3 km downstream of Canyon Reservoir dam. The agreement goes into effect in years when Canyon Reservoir exceeds 277.06 meters above mean sea level (m/msl) (909.0 ft/msl, conservation pool) and guarantees flows between 3.96 and 5.66 cms from May 1 to September 30. The reservoir has rarely exceeded 277.06 m/msl in recent years due to reduced inflows, evaporation, pumping from the reservoir, and releases for environmental flows, municipal contracts, and senior water rights downstream (GBRA 2015). The flow agreement has gone into effect six of the twelve years since it was established (Figure 1.3). As a result of drought and periodic absence of prescribed flows, average flows in the Canyon Reservoir tailrace have been reduced (Figure 1.4). The flow agreement expires in December 2018. Considering variable water supply for the area, projected increases in population, and multiple interests in Canyon Reservoir water it is possible terms will have to be renegotiated.

According to documented oversummer survival and temperature monitoring, a put-grow-and-take trout fishery can be maintained to 6.3 km downstream of the dam, which is the upstream boundary of special regulation zone two (Magnelia 2004). Even in years when the flow agreement does not go into effect this upper portion of the tailrace normally provides adequate water temperature for trout survival. With the establishment of special regulation zone one, adult trout will be protected from overharvest. Habitat improvement in this area could maximize adult trout abundance.

A limitation of the flow agreement is its reliance on Canyon Reservoir achieving conservation pool. This is an understandable requirement regarding GBRA's authority

over the conservation storage of the reservoir and the intent to avoid conflicts during

drought. However, this is the time when guaranteed flows are most beneficial. The

intermittent nature of prescribed releases prevents the establishment of a put-grow-and-

take fishery in a large portion of special regulation zone two.

Temperatures in the downstream portion of special regulation zone two still

exceed the tolerance limits for trout during times the flow agreement is in place. With

protective regulations, prescribed releases, and extensive stocking in this section, trout

sampling catch rates declined throughout the summer (Magnelia 2007). Data analysis

has revealed above optimal temperatures as far upstream as 11.9 km (section three) for 90

days in 2010 during prescribed releases (TPWD, unpublished data). With the current

flow agreement consistent oversummer survival should not be expected beyond 11.9 km.

Several researchers have investigated other possible limiting factors to growth and

survival of trout in the Canyon Reservoir tailrace. In 2006, a food availability study

analyzed macroinvertebrate distribution and composition of trout diet. The study found

trout diets were not optimal compared to available taxa but this alone probably did not

limit growth and survival (Sullivan and Grubh, 2011). In 2009, a radio telemetry study

was initiated to assess movement and habitat selection of stocked adult Rainbow Trout

(Magnelia and Cummings 2015, unpublished). The primary objective was to document

movement of individuals stocked in the special regulation area upstream beyond the

upper regulation boundary where they were subject to harvest, or downstream where

summer water temperature routinely exceeded an optimal level of 21.1°C. This study

concluded stocked trout had median dispersal distances from stocking sites of less than

0.05 km, most (75%) of individuals dispersed downstream from stocking sites, few

(<1%) trout moved upstream out of the special regulation zone, dispersal from stocking sites was significantly greater ($P<0.05$) when flows were higher, and pool mesohabitat was selected over riffles and runs (S. Magnelia, TPWD, unpublished data). Findings suggested trout stocked near the lower thermal boundary of the tailrace, especially when discharges are high, might move downstream during the winter into areas where water temperature reached lethal levels during the summer (Magnelia and Cummings, unpublished). It also suggested avian predation was a major source of mortality, which has been found in other salmonid populations (Modde et al. 1996; Hodgens et al. 2004; Harris et al. 2008, Kennedy and Greek 2008).

In addition to avian predators, there are several species of piscivorous fish in the Canyon Reservoir tailrace that are potential predators of Rainbow Trout (Terre and Magnelia 1996). These include Striped Bass, which have been known to impact other trout fisheries (Deppert 1979; Bettoli 2000). Avian and fish predation on trout might be reduced through installation of instream structures that provide additional cover.

The Canyon Reservoir tailrace attracts a variety of recreational users, which presents several challenges for managing habitat specifically for Rainbow Trout. For example, Large woody debris (LWD) is removed by outfitters and the river authority to provide safe passage for recreational tubers and other paddlecraft. Large woody debris that provides instream cover for trout can include fallen trees, standing timber, stumps, large branches, brushpiles, or root wads. Homeowners along the river also remove woody debris for aesthetic purposes, leaving many sections of the river devoid of cover. There were few pieces of LWD (30 pieces/km; 80% was less than 5m in length and had a diameter less than 55 cm) observed in a 2006 TPWD habitat survey (author's

unpublished data). Large woody debris provides cover from predation, substrate

stability, habitat complexity, and withstands normal flows (Flebbe and Dolloff 1995,

Fischenich and Morrow 1999). Instream cover such as LWD or boulders provide

energetically favorable feeding positions for trout. LWD can modify stream

geomorphology, contributing to pool formation and increasing abundance of salmonids

(Sullivan et al. 1987; Urabe and Nakano 1998). An assessment of all instream cover in

the tailrace could further inform managers on deficiencies and identify areas for

improvement.

Beyond instream cover, other habitat impairments may impact the Canyon

Reservoir tailrace trout fishery. Canyon Reservoir topped the emergency spillway in

2002, forming the Canyon Gorge when approximately 800,000 acre/feet of water

dislodged over 481,000 cubic meters of limestone bedrock before joining the Guadalupe

River 1.9 km downstream (Ibes 2008, Lamb and Fonstad 2010). This event also removed

trees, reducing shading and overhead cover. Other areas on the tailrace experience

erosion from heavy foot traffic or cattle grazing. Grazing can increase river width,

decrease water depth, bank stability, and cover, and degrade pool quality (Keller and

Burnham 1982). Some homeowners replace riparian vegetation, trees, and root wads

with concrete bulkhead, which can increase runoff, alter watershed hydrology, decrease

ground water storage and eventually impact habitat and fish communities (Sain 2006).

Connecting habitat suitability to these processes could lead to habitat improvement

projects.

Results of the telemetry study gave fisheries managers impetus to further study

Canyon Reservoir tailrace habitat in more detail, providing the basis for an evaluation of

habitat suitability and availability. The purpose of the study was to evaluate Rainbow Trout habitat as it relates to discharge and current flow agreements. A primary objective of the study was to provide fisheries managers with recommendations for flow. This information can be used to modify the GRTU/GBRA flow agreement set to expire in 2018. A secondary objective was to provide general habitat improvement recommendations to fisheries managers, which can be used to plan, implement, and assess habitat improvement projects in the future.

To accomplish study objectives, a Physical Habitat Simulation System (PHABSIM) approach was taken based on the Instream Flow Incremental Methodology (IFIM) established by Bovee (1982). This method is used for evaluating the effect of flow manipulation on riverine habitats through problem identification, scoping, implementation, and problem resolution (Bovee et al. 1998). The PHABSIM system relates physical habitat to the life stage of a species through grid cells with a defined area characterized by microhabitat parameters such as depth, velocity, substrate, and cover (Bovee 1982). The area of these cells is weighted by a suitability index based on the species' relative preference of habitat parameters and summed to estimate habitat availability.

The following steps were taken to evaluate physical habitat responses in the tailrace to Canyon Reservoir discharge. Spatial locations of known radio tracking relocations for adult trout from the 2009-2010 radio tracking study were used to modify literature-sourced habitat suitability criteria (HSC) for adult trout and test the resulting habitat model. Side scan sonar accompanied traditional surveying to map habitat. Side scan sonar, a relatively new and inexpensive technique, allowed rapid identification of

submerged habitat in areas too deep for traditional surveying. Habitat mapping was

coupled with hydraulic modeling to assess changes in habitat quality and quantity with

chosen discharge rates. Habitat availability at each discharge was quantified to determine

1) if habitat was limiting trout survival, 2) minimum recommended flows, and 3) if the

GRTU/GBRA flow agreement was adequate for maintaining adult Rainbow Trout

habitat. Areas of low suitability provided potential habitat improvement sites for adult

Rainbow Trout. The tailrace habitat study evaluated conditions for spawning, juvenile,

and adult Rainbow Trout. However, adult trout were the primary concern for fisheries

managers. Findings and recommendations focus on adult trout habitat and flow

requirements, and a final recommendation report will follow the study.

STUDY AREA

In 1964, the USACE impounded the Guadalupe River to create Canyon Reservoir in Comal County, Texas. The reservoir is located near the boundary of the Edwards Plateau ecoregion and the area is characterized by rocky hills and limestone canyons (Ibes 2008). Hypolimnetic releases altered the warmwater fish assemblage downstream of the dam, creating a temperature regime suitable for a coldwater fishery (Edwards 1978). To fill the niche created by the impoundment, Rainbow Trout (*Oncorhynchus mykiss*) were stocked in 1966 (White 1968). Since 1974, TPWD has stocked trout (primarily Rainbow Trout) each winter annually. Currently, TPWD stocks the tailrace with 15,000 to 20,000 trout per year, with an average length of 204 to 254 mm (Magnelia 2004). GRTU stocks 8 to 12 thousand trout per year, averaging 356 mm in length.

The study area spans 16.7 km below the outflow of Canyon Reservoir, approximately the furthest downstream trout were found with radio telemetry (Figure 1.1). This section of the tailrace experiences variable discharge, with periodic high flow events (Figure 1.5). The median discharge rate for the tailrace between 1997 and 2014 was approximately 3.96 cms. A TPWD habitat survey from the dam outflow to 17.1 km downstream in 2006, using the basinwide visual estimation technique (BVET), (Roghair and Nuchols 2005) found 75% pools and 13% riffles with bedrock the dominant substrate (61%), (author's unpublished data). Three study sections were chosen for habitat analysis.

Study section one was located between the outflow of Canyon Reservoir and Horseshoe Falls (~ 2.4 km). The area was composed of 58% pool, 22% glide, 13% riffle, and 7% run. Two stocking sites from the telemetry study were located here, with 83 trout

relocations. Located just below the dam, it was the coldest portion of the tailrace, and had the most consistent water temperatures below 21.1°C (Magnelia 2004). It included a potential location for habitat improvement where erosion occurred due to topping of the Canyon Reservoir emergency spillway in 2002 (Appendix II).

Study section two was located between Horseshoe Falls and the Canyon Corner residential area (~1.9 km). It was composed of 81% pool, 11% riffle, and 7% run. One stocking site and 51 trout relocations were contained in this section. During most years it remained cool enough for year-round trout survival, depending on spring outflows from Canyon Reservoir (Magnelia 2004).

Study section three was located between the Little Ponderosa residential area and a riffle near Lazy L&L Campground (~2.2 km). The area was composed of 83% pool, 11% riffle, 3% run, and 2% glide. A stocking site and 43 trout relocations were associated with this section. Depending on summer air temperatures and reservoir discharge, this portion of the tailrace has experienced water temperatures above the tolerance level (>21.1°C) for trout (Magnelia 2004). This section included a possible site for habitat improvement along a GRTU lease access site (Appendix II).

METHODS

Habitat suitability criteria

  Previous to the current thesis research, TPWD conducted a telemetry study in 2009 and 2010 investigating Rainbow Trout movement and habitat selection (Magnelia and Cummings, unpublished). Relocations from the telemetry study were used to modify habitat suitability curves (HSC) and test the habitat model for adult Rainbow Trout. Authors were able to estimate the position of stationary radio transmitters within a mean of 1.54 m (SD = 1.17) of the actual location (Magnelia and Cummings, unpublished). Microhabitat data collected in the telemetry study relevant to HSC construction included current velocity (m/s), depth (m), and dominant substrate. Velocity, depth, and substrate values used for HSC were taken at the estimated fish location.

  Information for habitat suitability criteria (HSC) were derived from various literature sources (Table 1.2). HSC for each life stage investigated were collected for salmonids (mainly Rainbow Trout) and graphed on habitat suitability curves. HSC derived from habitat data collected during the telemetry study were compared to the literature using the HSC Development Tool. Frequency analysis utilized the Sturges equation (1926) for frequency bin widths and a 90 percent tolerance limit. Envelope curves summarized final HSC for depth, velocity, and substrate. Envelope curves are commonly used in developing suitability curves for habitat modeling (Laliberte et al. 2013). They synthesize literature findings (Category One) and field data (Category Two) by creating a single curve that summarizes available habitat usage information.

Habitat Mapping and Modeling

Three representative study sections were chosen for habitat mapping and modeling. Study sections were selected based on density of trout telemetry relocations, association with the special regulation zones, known water temperature regime, stocking locations, access, landowner permission, and avoidance of dense recreational activity. Each section was approximately 2 km long, which is about 50 times the mean river width (40m). This length is considered sufficient to provide adequate representation of river characteristics (Simonson et al. 1994).

Habitat mapping utilized several methods to collect topography, substrate, water surface elevations (WSE), and instream cover for each study section. Instream cover included objects within the river channel that provided refuge from velocities or predators such as boulders, LWD, and undercut banks. Structural features such as ledges, humps, and channels were not delineated. Substrate was categorized on a modified Wentworth scale and converted to grain size values for hydraulic modeling (Table 1.3). Traditional or direct-measurement surveying documented topography, WSE, visible instream cover, and substrate in accessible areas of the tailrace. Known benchmarks for elevation were inventoried and convenient reference benchmarks were created along the tailrace and fully documented. Within channel topographic data were collected to bank full channel elevations by a two person team. One operated the survey level and one was equipped with a depth rod and Trimble GPS unit. Using a systematic irregular method, boundaries, special features, and breaks in topography were documented. This method was adopted to optimize field data collection by focusing effort in irregular areas to capture complexity and minimizing effort in regular areas. Systematic sampling may miss

breaklines in topography or over sample uniform areas when utilizing a computational

mesh. Point data for Latitude (X), Longitude (Y), topography (Z), and dominant

substrate were recorded in Trimble® data dictionaries. Instream cover polygons were

also delineated and recorded in the field.

Bathymetric data in deep pools was obtained from a jet-powered aluminum boat

or a small aluminum boat powered by a trolling motor. A Garmin® GPSmap 535s sonar

unit was used to record depth. The track feature on the unit captured GPS position and

depth reading at 1-second intervals. A systematic irregular method was used to capture

the heterogeneity of each study section. A Trimble GPS was used in sync to improve

positional accuracy. Garmin track data and Trimble point shapefiles were joined using

the TIME fields for both units using methods described by Winkelaar (2010). All

topographic data were compiled to create a single bathymetric layer for the entire study

section.

Two water surface elevation surveys were completed. The first was conducted

January 30-31, 2012 at a discharge of 2.5 to 2.6 cubic meters per second (cms). The

second was conducted July 22-23, 2013 at 1.9 cms. WSE was collected at the upstream

and downstream boundaries of each study section and at each transition from one

mesohabitat to another. A temporary staff gauge was placed upstream of each field

sampling site and periodically checked for changes in discharge.

Side scan sonar habitat mapping was conducted as described by Kaeser and Litts

(2010). Side scan sonar was employed to map sections of the tailrace too deep to conduct

traditional surveying. A Humminbird® 1198c side scan sonar system was employed to

obtain sub-surface instream cover and substrate data from portions of each study section

that allowed access and boat operation. An external GPS antenna was located just above a bow mounted transducer. A downstream, mid-channel position was maintained at roughly 8 km/h. If multiple passes were required, they were evenly spaced across the channel to ensure full coverage.

Post processing of side scan data was performed according to Kaeser and Litts (2010). Overlapping side scan images were saved with the track file and mosaicked together using ArcGIS and IrfanView, a graphics software viewer. Output was saved as JPEG (.jpg) images georeferenced to UTM Zone 14, North American Datum 1983 (NAD83). Riverbank and substrate boundaries were digitized in ArcView 9.3. Sonar imagery was segmented into areas of similar image texture and tone, and areas were assigned a substrate classification by visual interpretation. Additional classes were designated for areas of poor resolution and sonar shadow. Substrate values were converted to roughness (grain size, m) for input into a hydraulic model. Delineation of LWD was conducted as described in Kaeser and Litts (2008). Data collected during field ground-truthing of substrate classes were used to edit or modify the final substrate map layer.

Geographic Information Systems (GIS) were relied upon to compile, overlay, and analyze spatial data. All point and polygon data from surveying were inputted into ArcView 9.3 projects to be edited and converted for use in other analysis software. Substrate polygons in the map were defined using a variety of techniques including: utilization of previous habitat data, conventional surveying, side scan interpretation, and aerial photography. Imported LIDAR (Light Detection and Ranging) data supplemented

topography surveys. Habitat suitability output was converted to Triangular Irregular Networks (TINs) using the 3D Analyst extension.

Hydraulic modeling utilized the Multi-Dimensional Surface Water Modeling System (MDSWMS), (McDonald et al. 2001), an application developed by the U.S. Geological Survey to build, edit, and visualize computational hydraulic models for surface water. Study sections were divided into subsections to increase the computational capability of the program and reduce errors. The output of these subsections was reconnected for further analysis. Topography, roughness, WSE, and discharge were used to calibrate the model. Viscosity, roughness coefficient, and stage parameters were extrapolated through regression to model depth and velocity at relevant discharge rates. Modeled simulations were outputted as 2-dimensional grids of point features with depth and velocity as attributes.

The discharges modeled were selected based on flow agreements and permits (GRTU 2015), model construction, and number of trout relocations represented for the Canyon Reservoir tailrace. The GRTU/GBRA flow agreement prescribes flows from 3.96 cms to 6.80 cms. The Federal Energy Regulatory Commission (FERC) minimum flow requirement for Canyon Reservoir is 2.55 cms with 2.83 cms and 3.40 cms required outside of drought periods. The Texas Commission on Environmental Quality (TCEQ) minimum flows are a "pass-through" requirement based on water permits for GBRA, ranging from 3.06 cms to 4.64 cms. Some modeled flows assisted in constructing the model by keeping increments small enough to detect habitat responses to small changes in discharge. Discharge rates which represented relatively high number of trout relocations were chosen to test model accuracy.

Depth, velocity, channel index (substrate), and mesohabitat (previously collected) were imported into a Visual Basic module called the TwoD Habitat Program. This module was created by Dr. Thom Hardy and used in the Hardy Phase II report for the Klamath River (Hardy et al. 2006). Parameters were evaluated based on imported habitat suitability criteria (HSC) for spawning, juvenile, and adult Rainbow Trout. The output spreadsheets included latitude, longitude, weighted usable area (WUA), suitability for depth, velocity, substrate, and their combination. Data were imported into ArcView and converted to TIN models representing suitability for each life stage at each designated discharge rate. Combined suitability (Cbsi) was derived from the geometric mean of depth, velocity, and substrate suitability.

$$Cbsi = (Dsi * Vsi * Ssi)^{1/3}$$

Where Dsi = depth suitability, Vsi = velocity suitability, and Ssi = substrate suitability. WUA was calculated using Cbsi to determine proportion of usable area per grid cell ($\sim 0.25 m^2$) and summing the cells within the wetted channel.

Habitat Analysis

Distance to cover analysis determined whether instream cover should be used in Cbsi calculation. Trout relocations were placed in ArcView with delineations of cover collected in habitat surveys. Cover included LWD, boulders, or undercut banks. Distance was measured with the ArcView distance tool and recorded. Distances were categorized by 1.5 m increments and plotted in a frequency histogram.

The model output for adult Rainbow Trout was tested through overlay analysis of trout relocations and habitat suitability data. Relocations were grouped according to the

discharge rate at which they were collected and overlaid onto respective Cbsi contours. Combined suitability was recorded for relocations within study sections. The highest Cbsi within a one meter radius of the trout location was used to account for GPS (Trimble GeoXT) and triangulation error. Selections of areas representing Cbsi were quantified using The Manly Preference Index (1972) similar to Guensch (1999). This tested whether or not trout were selecting what the model represented as optimal habitat.

WUA output for each subsection was compiled for each study section and overall study area. WUA (m^2) was calculated for spawning, juvenile, and adult trout for each modeled discharge. Cbsi values were divided into poor (0.0 to 0.5), fair (0.5 to 0.75), and good (0.75 to 1.0) habitat quality. The corresponding cell WUA values were summed to quantify areas of sub-optimal and optimal habitat for each discharge. Optimal habitat for each life stage was then normalized according to the stream area at each discharge.

Mean daily flow rates (cfs) of the Canyon Reservoir tailrace were obtained from the U.S. Geological Survey (USGS) 08167500 gauging station at Sattler, TX. Data spanned from 1997 to 2014 and were converted to cms. The hydrograph of the tailrace was produced and a comparison of median annual discharge to median discharge during drought years was graphed for analysis. Annual and monthly flow exceedance levels (80%, 50%, and 20%) were calculated using flow duration analysis. This was accomplished by ordering daily flow rates, computing the total number of time step intervals, and calculating the percent of time each discharge was equaled or exceeded. Exceedance levels were used as reference for relevant flow rates in habitat curves.

A model of theoretical restoration was created in MD_SWMS to illustrate how habitat manipulation may improve suitability values (Appendix II). The model

represented the area in Section 1 where water and debris from the Canyon Gorge entered the main river channel.   Topography and substrate inputs were manipulated to reflect channelization and addition of velocity breaks. River channel depth was modified to resemble the upstream portion of the river and gradually decreases downstream toward a low water dam. Eight one-meter high boulders were placed along the channel to simulate velocity breaks. Substrate input was modified to reflect exposing bedrock with channelization and increased boulder habitat on river edges. Overhead cover could not be modeled. Area (m^2) of optimal habitat throughout the flow regime was compared to the original model.

RESULTS

Habitat Suitability Criteria

Radio-tracked adult Rainbow Trout provided specific habitat association data for the Canyon Reservoir tailrace. Adult trout were found in depths ranging from 0.4 to 3.2 meters, with most observations occurring between 1 and 2 meters (Figure 1.6). Velocities ranged from 0.03 to 1.05 m/s, with observations tapering off at 0.23 m/s. Most adult trout were located over bedrock substrate. None were found over substrates composed of vegetation or large woody debris.

Habitat suitability criteria for adult trout were developed from associated habitat data (Figure 1.7). Optimal suitability for depth ranges from 0.99 m to 1.84 m. Optimal suitability for velocity ranges from 0.08 to 0.22 m/s and decreases at higher rates. Adult trout HSC for substrate includes organic matter (0.01), clay/silt (0.18), sand (0.05), small gravel (0.18), large gravel (0.08), cobble (0.16), boulder (0.04), bedrock (1.00), vegetation (0.00), and LWD (0.00). Clay and silt substrate HSC were combined to ease comparison to literature sources. Mid-range values are included in the graph to allow comparison to other studies that used mixed categories. Final envelope curves for adult trout incorporated both radio telemetry findings and literature (Figures 1.8, 1.9).

Habitat Analysis

Distance between adult telemetry locations and mapped cover is shown in Figure 1.10. Trout were found between 2 and 54 meters from cover. Although a declining trend exists, many trout were found 10 to 30 meters away from cover, suggesting other factors

determined location. Based on the weak cover association, cover was not included in the modeling of adult habitat.

Manly's Index of Preference tested the effectiveness of using the combined suitability (depth, velocity, substrate) to delineate optimal habitat for adult trout. Five discharge levels (1.13 cms, 1.70 cms, 2.27 cms, 2.83 cms, and 3.40 cms) were evaluated based on the highest number of trout relocations (Figure 1.11). Four of the five discharges evaluated had all trout locations located within areas associated with combined suitability values from 0.9 to 1.0. One discharge (1.13 cms) had locations divided between combined suitability's of 0.8 to 0.9 and 0.9 to 1.0. These results show that the vast majority of observed radio-tracked trout were found in areas associated with high modeled habitat suitability and the developed envelope HSC for adult trout were applicable to the Canyon Reservoir tailrace.

Total optimal habitats for spawning, juvenile, and adult trout were compared to determine if any particular life stage appears limiting to the fishery (Figure 1.12). Optimal habitat, normalized by percentage of study area, was relatively high throughout all modeled discharges for juveniles and adults compared to spawning trout. Adult trout optimal habitat contributed 71% to 82% of study area with a peak at 6.80 cms. Total optimal habitat for spawning peaked at nine percent of study area. Optimal habitat for each life stage declined at higher discharge rates as stream area outpaced optimal habitat.

Weighted usable area for adult trout was scaled to percent of maximum WUA (Figure 1.13). Adult trout WUA ranged from 163,000 m^2 to 237,000 m^2 and peaked at 16.43 cms. Adult WUA and percent maximum show a relatively high rate of decline at discharges less than 3.96 cms (50% exceedance) compared to higher discharge rates.

Weighted usable area for adult trout was partitioned qualitatively using combined suitability values (poor = 0.00 – 0.50, fair = 0.50 – 0.75, good = 0.75 – 1.00). "Good" (optimal) adult habitat dominated in all sections (Figure 1.14). "Fair" and "poor" habitats were consistently low contributors to habitat quality. Overall adult habitat quality is primarily composed of "good" habitat, which ranges from 146,000 m^2 to 227,000 m^2, peaking at 13.31 cms (Figure 1.15). Section one contains the most optimal habitat, followed by section three (Figure 1.16). Optimal habitat declines in all sections at discharge rates less than 9.63 cms, but declines at a higher rate for section one less than 3.96 cms (50% exceedance).

These figures are summarized in Table 1.5, which organizes available adult trout habitat according to modeled discharge rate. Discharges between 3.40 cms and 6.80 cms represent median summer flows between 1997 and 2014. These also roughly represent the prescribed flows from the GRTU/GBRA flow agreement (3.96 cms to 6.80 cms). Optimal habitat in this section ranges from 196,000 m^2 (79% of study area) to 216,000 m^2 (82% of study area). For the critical summer months of July, August, and September the flow agreement prescribes flows of 5.66 cms. This discharge rate provides 211,000 m^2 of optimal habitat (81% of study area). Discharges between 1.70 cms and 2.27 cms represent median summer flow during drought years (2010 – 2014). These are years with low inflow to Canyon Reservoir and low outflow due to decreased water availability and lack of prescribed flows. These discharges provide 175,000 m^2 (75% of study area) to 184,000 m^2 (78% of study area) of optimal habitat. The lowest discharge modeled was 0.57 cms, which provides 146,000 m2 of optimal habitat (71% of study area).

Modeled habitat improvement in the Canyon Gorge area (Appendix II) resulted in moderate increases in habitat availability. Optimal habitat for adult trout was improved between 0.57 and 3.96 cms discharge rates. Discharges greater than 3.96 cms resulted in optimal habitat being virtually identical to the original model.

DISCUSSION

Habitat Suitability Criteria

Adult habitat suitability curves for the Canyon Reservoir tailrace generally conformed to those found in the literature. However, adults in the study area were found in lower velocities than most referenced studies. Flows during the radio telemetry study were relatively low and could explain some of this difference. During the radio telemetry study, trout were selecting pool mesohabitat (Magnelia, unpublished data), which is characterized by slower velocities.

The apparent high suitability associated with bedrock was unique to the Canyon Reservoir tailrace when compared to other published HSC on substrate use. The suitability index for substrates of most referenced studies declined at bedrock. The high suitability of bedrock on the tailrace could have been due to its high availability (61%). If the telemetry substrate data were adjusted to account for availability, then the resulting preference curve may show a lower suitability than the 1.0 value initially assigned. However, in some situations bedrock may be preferred habitat by trout. Quinn and Kwak (2000) found rainbow trout selected bedrock at low flows, and snorkeling surveys revealed trout using bedrock crevices as velocity refugia at high flows. This suggests bedrock formations that provide velocity refuge or overhead cover (overhangs) could simulate instream cover that is attractive to trout. We chose to drop the suitability of bedrock to 0.75 to account for the high utilization of bedrock by trout in the tailrace and

low suitability referenced in the literature. The final envelope curve for substrate

incorporated this adjustment into habitat modeling for adult trout.

It is difficult to compare the results of PHABSIM studies. Stream size and system

characteristics make each river unique. Weighted usable area (WUA), a common metric

associated with the IFIM, is not standard or transferable because it is derived from a

range of HSC and a selectable array of variables (Mathur et al. 1985; Payne 2003).

Varying reach sizes and methods to present WUA (WUA per unit length of river, %

maximum WUA, weighted variables, etc.) further complicate matters. So the findings

from the Canyon Reservoir tailrace study are relevant, but direct comparisons to other

studies are not available.

Trends of WUA in other studies can reveal aspects of flow/habitat relationships.

On the Lower Spokane River, % maximum WUA increased from 65% at 9.91 cms to

100% at 48.14 cms, then declined at higher flows (Post 2012). Peaking of WUA

followed by a decline at higher flows was similar to what the Canyon Reservoir tailrace

experienced, presumably due to unsuitable velocities associated with higher discharge.

Habitat Mapping and Modeling

Habitat modeling for the Canyon Reservoir tailrace revealed several issues for

trout spawning. The greatest limiting factor to spawning is the large amount of bedrock

in the tailrace. Each spawning phase of salmonids require different gravel requirements

for redd construction, incubation, and emergence (Kondolf 2000). Periodic high flow

events during spring and temperature regime could be other restraints on spawning. The

low amount of optimal spawning habitat available indicates the tailrace is spawning limited.

Modeling shows optimal habitat for juvenile trout is abundant in the Canyon Reservoir tailrace. Juvenile trout habitat would need to be a consideration if there were adequate reproduction in the tailrace or if juvenile (fingerling) stockings were to continue. After temperature-induced mortality of fingerlings in areas > 6.3 km from the outflow of Canyon Reservoir from 1996 to 2000 and 2005 it was recommended to cease future fingerling stockings (Magnelia 2007).

Spawning and juvenile trout life stages do not compose a manageable portion of the Canyon Reservoir tailrace fishery. As a result, these life stages are not relevant to flow recommendations or potential habitat improvement. More information for these life stages is available in Appendix III. Further discussion will focus on adult trout and associated habitat and flow requirements.

Modeling shows habitat is primarily suitable for adult Rainbow Trout in the study area. Since the model indicates sufficient habitat quantity and quality for adult Rainbow Trout at all modeled flows, habitat is not likely the primary factor limiting survival although some improvements can be made. These improvements would include potential habitat improvement in areas of low suitability and/or prescribed flows to maintain adequate habitat and temperature for adult trout.

Modeling has identified some areas of the tailrace that were unsuitable for adult trout, especially at low flows (Figures 1.17 – 1.19, Appendix I). Study section one contained three sites: a riffle area just below the Canyon Reservoir outflow, a shallow run approximately 1.3 km below the outflow, and the area below the Canyon Gorge. Study

section two included a riffle/run area below Horseshoe Falls and study section three included the area along a GRTU lease access site. Insufficient depth (<0.2 m) was the main factor that gave these sites low combined suitability at low flows (<2.27 cms).

Water depth can be a limiting factor in salmonid populations and increasing depth (pool habitat) has been a goal of many habitat improvement projects (Roni et al. 2006). Pools offer preferred habitat, velocity refuge, and sufficient water depth during low flows and their frequency, surface area, and volume can be an indicator of channel condition (Buffington et al. 2002). Predation risk from wading/diving predators has been shown to decrease with deeper water, especially for larger fish (Harvey and Stewart 1991; Harvey et al. 2005). Pools also offer thermal refugia during times of water temperature stress (Matthews and Berg 1997; Ebersole et al. 2001; Baird and Krueger 2003).

Instream cover was not modeled because trout from the radio tracking study did not have a strong association with mapped instream cover. This could have occurred due to a combination of factors. First, some instream cover could have been in unsuitable depths or substrates. Second, trout behavior could be a response to a lack of instream cover. Salmonids utilize deeper water positions in areas devoid of cover (Bugert et al. 1991). Third, low flows could reduce the need for trout to seek velocity shelters. Trout in an Ozark tailwater river utilized deep microhabitats distant from the streambank and randomly utilized cover at low flows, while at high flows they moved toward streambanks and utilized velocity refugia (Quinn and Kwak 2000). The telemetry study found trout were selecting pool mesohabitat (Magnelia, unpublished data). These factors suggest trout in the Canyon Reservoir tailrace may be seeking refuge in deeper water in part due to a deficiency of instream cover.

The importance of instream cover to trout is well documented. The addition of cover has been shown to decrease trout predation (Sullivan et al. 1987; Tabor and Wurtsbaugh 1991). Instream cover in the form of LWD has been shown to increase trout density (Flebbe and Dolloff 1995; Neumann and Wildman 2002). Many fishes use instream cover for velocity refuge, maximizing energy by reducing swimming costs (Webb 2006). Instream cover can enhance foraging for drift-feeding salmonids, by providing energy-efficient feeding stations (Hughes and Dill 1990). Installation of instream structures such as weirs, deflectors, cover structures, and boulders have the potential to increase pool area, cover, depth, and protection from predators (Whiteway et al. 2010). A parameter representing instream cover could be added to the tailrace habitat model to refine suitability and availability information.

Habitat Improvement Recommendations

Before habitat improvement is decided upon and implemented on the Canyon Reservoir tailrace, proper assessment, planning, and preparation must take place. Cause and severity of impairments must be assessed and an understanding of stream functions is required for successful habitat improvement (Harman et al. 2012). Rosgen (2010) promotes the four "C's" of river assessment: cause (of instability, impairment), consequence (of instability), correction (to prevent instability), and communication (to those who can help correct the problem). One approach to begin assessment and select appropriate mitigation is to define the classification of the tailrace based on geomorphic characterization, stream type, stream condition, and direct measurement of stream processes (Rosgen 1994). Failure of many habitat improvement projects has been due to

inadequate assessment of river conditions and impairments, ignorance of large-scale processes that affect localized projects, and lack of proper monitoring (Roni et al. 2008).

Successful fish habitat enhancement projects on rivers have incorporated stream processes and functionality, while performing holistic improvements to address habitat impairments. Integrated instream and riparian habitat improvement commonly applied to small streams can be applied to large tailwater rivers (Quinn and Kwak 2000). Reconnecting isolated habitat, addition of instream structures, riparian rehabilitation, and sediment reduction have proven to be effective ways to improve habitat and increase fish abundance (Roni et al. 2008). A meta-analysis of instream structure restoration projects showed that 73% of projects resulted in increased salmonid densities and 87% increased salmonid biomass, with streams over 8 m in width experiencing a larger mean density increase (Whiteway et al. 2010). Investigators found Rainbow Trout had larger increases in density and biomass than other salmonids, and restoration projects were more beneficial to larger fish. These results suggest that habitat improvement can provide potential benefits to the Canyon Reservoir tailrace, with proper assessment and techniques.

If habitat improvement for adult trout on the Canyon Reservoir tailrace were implemented, several actions could be taken at designated sites. The addition of instream cover structures such as boulders, submerged shelters, or half log cover could enhance cover for adult trout (Rosgen 1996). Structures such as single wing deflectors, double wing deflectors, channel constrictors, cross-vanes, j-hook vanes, or "W" weirs could increase depth by scouring, narrowing channels, holding back water, decreasing width/depth ratio, increasing sediment transport, or stream grade control (Rosgen 1996).

The amount of exposed bedrock on the tailrace may reduce options for modifying depth. However, boulder weir placement has been shown to increase pool area and abundance of trout on bedrock and incised river channels (Roni 2006). Native riparian vegetation could be planted on eroded or denuded streambanks. This type of habitat regulates stream temperatures, provides bank stability, provides nutrients to the system, provides macroinvertebrate habitat, and overhead cover for fish (Moring et al. 1985). Riparian vegetation can influence trout standing crop and carrying capacity (Wesche 1987). Bank placed materials (boulders, root wads, logs) along with native materials (root wads, vegetation, trees) could stabilize streambanks, provide shading, and increase overhead cover (Rosgen 1996). These projects would be most effective in areas of the tailrace where optimal temperatures are consistent. Consultation with stream restoration experts, landowners, outfitters, GBRA, USACE, WORD and TPWD is strongly recommended.

Two potential habitat improvement sites are located where the Canyon Gorge area enters the main river channel and along a GRTU lease access site (Appendix II). These areas have low combined suitability at low flows (<2.27 cms). Modeled habitat improvement at the Canyon Gorge site simulated the effects of some techniques mentioned above. Increased suitability for flows up to 3.96 suggests that habitat could be improved in this location, especially for low flows. The model serves only as a preliminary example and can be manipulated further to test additional changes. For example, the single boulders could be expanded to larger boulder clusters and the river could be narrowed. Theoretically, this could increase flow and depth through the area, while providing velocity breaks.

The GRTU lease access area on the Canyon Reservoir tailrace could benefit from habitat improvement. Cattle grazing, foot traffic, and high flow events have potentially caused erosion issues on the steep north bank. Coordination with landowners could result in a grazing exclosure (Keller and Burnham 1982) that may prevent future erosion (Contor and Platts 1991). Water could be pumped from the river for cattle. Grazing management seeks to protect the native riparian species that maintain stable streambanks and depends on stream type and season (Rosgen 1996). If an exclosure was put in place, streambank stabilization and riparian vegetation plantings could protect the north bank.

There are several factors that pose challenges to habitat improvement on the tailrace. First, the tailrace experiences high discharge events that can damage habitat structures (Ibes 2008; Earl et al. 2003). Habitat improvement would need to be secured and protected from high velocities. If damage were to occur, immediate repairs would be necessary and location/design reassessed. Second, the tailrace has multiple recreation uses and restoration projects should not interfere with tubing, kayaking, canoeing, rafting, swimming, etc. Habitat structures could be placed sufficiently below the water surface not to impede navigation. Structures that do reach above the water surface could be placed in locations where navigation around/through is possible. Third, there is extensive privately owned land adjacent to the river. Coordination, permission, and input from landowners concerning access and restoration efforts will be key to make them a part of solutions.

Flow Recommendations

Several flow recommendations can be made regarding past and current research on the Canyon Reservoir tailrace. Based on this study, a discharge rate of 3.96 cms could be considered a minimum discharge rate to maintain habitat quantity for adult trout outside of drought periods. A discharge rate of 3.96 cms provides 90 percent of maximum WUA and optimal habitat spans 80 percent of the study area. The minimum daily release for May (1st through 15th) according to the GRTU/GBRA flow agreement coincides with the 3.96 cms value. Since the model indicates adequate habitat at the lowest modeled flow of 0.57 cms, this rate could be considered a critical minimum flow rate when prescribed flows are not achievable (during drought).

Target flows to maximize habitat on the Canyon Reservoir tailrace would be greater than 3.96 cms. To maximize WUA, a discharge rate of 16.43 cms would be needed. WUA includes combined suitability values of 0.01 to 1.0. The inclusion of 'poor' and 'fair' habitat may not be a priority for fisheries managers in determining prescribed flows. Therefore, optimal habitat may be the best metric to maximize habitat quality and quantity. To maximize optimal habitat, a discharge rate of 13.31 cms would be required. Discharges greater than 13.31 cms cause optimal habitat to decline due to an increase in unsuitable velocities associated with high discharge.

The concern for flow rates on the tailrace centers on critical summer months (July through September) when ambient temperature is the greatest. According to the model, median summer flow rates provide optimal habitat for 79% to 82% of study area. Median summer flow rates during drought years provide optimal habitat for about 76% of

study area. Initially, this seems adequate for maintaining trout habitat (and possibly survival) through critical summer months. The GRTU/GBRA flow agreement assigns a minimum daily release of 5.66 cms to the critical summer months of July, August, and September. This would mean over 211,000 m^2 of optimal habitat (81.20% of study area). According to the model, this would be adequate to maintain habitat. However, water temperature is not included in the habitat model. One would expect habitat availability to decline as water temperatures exceed optimal levels in summer months.

Water temperature during the summer is likely the main limiting factor for trout survival on the Canyon Reservoir tailrace. Summer water temperatures have been shown to cause extensive mortality in the tailrace (Magnelia 2004, 2007). Physical habitat availability is likely reduced because of summer water temperatures. A renewed flow agreement should continue to focus on maximizing optimal temperatures for adult trout during critical summer months. A habitat component can be added to the agreement since prescribed flows assist in maintaining optimal habitat during potential low flow periods. Discharge might be lowered in winter, spring, and early summer. This stored water could be released during the critical summer months of July, August, and September when ambient temperature is the greatest. The feasibility of maintaining optimal summer temperatures throughout the entirety of special regulation zone two is unlikely. Therefore, the intentions of the flow agreement, stockings, and regulations beyond 17.1 km (3rd Crossing) could be modified to focus on the upstream portion of the tailrace from the outflow of Canyon Reservoir to 6.3 km.

Variable weather patterns and water use pose challenges to habitat and flow management on the Canyon Reservoir tailrace. There is consensus that the severity and

duration of drought and high water periods will increase as a result of regional and global climate change, impacting recreational fisheries and river flows (Kaufman and Allen 2008). Coldwater salmonid populations particularly are likely to be impacted. Increased diversion of water resources will decrease trout movement and the ability to find coldwater refuge, especially in the interior West of the U.S. (Kinsella et al. 2008). Reduced groundwater outflows and associated increases in temperature are likely to impact river, lake, and coastal ecosystems in the future (Meisner et al. 1988; Twilley et al. 2001). According to the Texas Water Development Board (TWDB) the population of the South Central Texas region is projected to increase by 75 percent by the year 2060, with a 150 percent increase in water demand (TWDB 2012). Temperatures in Texas are likely to rise and precipitation trends are difficult to predict, but drought frequency and severity are likely to increase (Nielsen-Gammon 2011). Trout populations within regulated systems and subtropical climates such as South Central Texas are increasingly susceptible to drought. Fisheries management on the tailrace will have to adapt to changes in regional climate and water use.

Future Research

Further examination of factors affecting trout on the Canyon Reservoir tailrace can lead to future enhancement of the fishery. Increased monitoring of summer water temperature in the area between 6.3 and 17.1 km (upstream portion of Trout Zone 2) can indicate just how far downstream optimal temperatures exist with and without the current flow agreement. Recommendations from the radio tracking study suggest using methods developed by Wehrly et al. (2007) to evaluate exposure time limits (Magnelia and

Cummings 2015). Summer water temperatures above and below habitat improvement

sites can be monitored before and after habitat improvement. Several studies suggest

water temperature in streams can be modified with habitat manipulation (Hetrick et al.

1998; Runge and Peterson 2008; Cross et al. 2013; Pierce et al. 2014).

Refinement of the Canyon Reservoir tailrace habitat model should be done before

a final recommendation report is made. Inclusion of summer water temperature regime

would give a more realistic output of available habitat during critical summer months.

Also, a parameter representing instream cover could be assessed as another indicator of

habitat suitability. Model adjustment would not require additional habitat mapping or

hydraulic modeling. A general representation of summer water temperature regime based

on historic monitoring data would have to be created. The suitability output from the

TwoD Habitat Program is already in spreadsheet form and could be spatially joined with

layers representing temperature and instream cover suitability. Inclusions would be

represented by the following equations:

$$(Dsi*Vsi*Ssi*Tsi)^{1/4} \quad \text{and/or} \quad (Dsi*Vsi*Ssi*Tsi*Csi*)^{1/5}$$

The first equation would evaluate depth, velocity, substrate, and temperature suitability.

The second equation would incorporate these parameters and instream cover suitability.

Habitat availability and possible deficiencies could be assessed more thoroughly with

these additions, potentially modifying recommended habitat improvement and flows.

If habitat improvement is decided as a way to mitigate habitat limitations on the

Canyon Reservoir tailrace, proper assessment before and after would be a worthy

research direction. The results of many restoration projects go unmonitored and

unreported (Quinn and Kwak 2000; Rosenfeld 2003; Whiteway et al. 2010). Assessment

could include trout density, biomass, instream cover association, width/depth ratio, pool volume and area, temperature, canopy cover, riparian recovery, angling effort, macroinvertebrate abundance, or other metrics. This type of monitoring can give fisheries managers the data to evaluate the success or failure of habitat improvement actions and guide future management decisions for the tailrace.

Table 1.1: Modeled flows for the Canyon Reservoir tailrace study (2010 – 2015) and criteria for selection. Flow agreements/permits/licenses for each flow are denoted by an "X". Fish locations refer to radio-tracked positions of adult Rainbow Trout found during the telemetry survey. Model parameters denote discharges added to improve model construction.

Flow Rate (cms)	Flow Agreements/Permits			# Fish Locations	Model Parameters
	FERC	TCEQ	GBRA/GRTU		
0.57				0	Minimum
1.13				24	Model Improvement
1.70				67	
2.27				36	Model Improvement
2.83	X	X		109	
3.40	X	X		21	
3.96		X	X	0	Model Improvement
4.53		X	X	0	Model Improvement
5.10			X	7	
5.66			X	0	Model Improvement
6.80			X	8	
7.36				4	
9.63				4	Model Improvement
11.33				49	
13.31				10	
16.43				15	
22.66				6	Maximum

Table 1.2: Literature sources for habitat suitability criteria (HSC) used for adult Rainbow Trout in the Canyon Reservoir tailrace study (2010 – 2015).

Source	Curve Type	Category	Data Analysis	Data Collection	Location
Lambert et al. (1987)	Suitability	2	FA	SN/OB	California
Cochnauer & Elms-Cockrum (1986)*	Probability-of-use; IDFG	2	FA	U	Idaho
Bovee (1978)	Probability-of-Use	2	FA	U	Oregon/Washington
Baltz & Moyle (1981)	Suitability	2	FA	SN/OB	California
Moyle & Baltz (1985)	Suitability	2	FA	SN	California
Raleigh et al. (1984)	Suitability	2	FA/RO	SN/U	California/Utah
Cochnauer & Elms-Cockrum (1986)**	Probability-of-use; IDFG	2	FA	U	Idaho
LeClerc (1995)	Utilization	2	FA	TM	St. Lawrence R.
Hill & Hauser (1985)	Suitability	2	U	U	Tennessee
USFS (1985)	GAWS (Suitability)	2	FA	U	U.S. Western
Suchanek et al. (1984)	Utilization	2	FA	U	Susitna R., Alaska
USBR (2006)	Suitability	2	FA	U	San Juan R. (South Platte)
YCWA (2012)	Suitability	2	PJ	SN/OB	California (Yuba R).
TRPA (2004)	Suitability	2	FA	SN/OB/RD	Klamath R. (Bypass Reach)
TRPA (1991)	Suitability	2	FA	SN/OB	Klamath R. (Buck/Grizzly Creeks)
PacifiCorp (2004)	Suitability	1	PJ	LT	Washington (Lewis R.)
SCE (2007)	Suitability	1	FA	LT/OB	California (Bolsillo, Rock Creeks)
PCWA (2008)	Suitability (Envelope)	1	FA	LT	California (American R.)
Hoffman et al. (2002)	Suitability	2	FA	SN/SCUBA	Montana (Kootenai R.)
SCE (2004)	Suitability	1	FA	LT/SN/OB	California (Big Creek ALP)
NHC (2004)	Suitability	1	FA	LT	Washington (Spokane R.)

SN = Snorkeling, OB = Bankside Observation, U = Unknown, TM = Radio Telemetry, RD = Redd Measurement, LT = Literature, NT = Net/Seine, EL = Electrofishing

*Trout 20.4 – 30.5 cm

**Trout > 30.5 cm

Table 1.3: Substrate categories for habitat suitability analysis on the Canyon Reservoir tailrace (2010 – 2015). Grain size used for roughness values in hydraulic modeling.

Substrate Class	Label	Acronym	Size (mm)	Grain Size (m)	Definition
Organic Matter	1	Om		0.0001	Dead leaves, twigs, etc.
Clay	2	Cl	<2	0.00025	>75% of area composed of particles <2 mm diameter
Silt	3	Si	<2	0.0005	>75% of area composed of particles <2 mm diameter
Sand	4	Sa	2-Jan	0.0015	>75% of area composed of particles ≤2 mm diameter, grainy
Small Gravel	5	Sg	16-Mar	0.0095	Sand to thumbnail size, >75% of area composed of small rocks
Large Gravel	6	Lg	17 - 64	0.0405	Thumbnail to fist size, >75% of area composed of large rocks
Cobble	7	Co	65 - 256	0.1605	Fist to Head size, >75% of area composed of cobble
Boulder	8	Bo	>256	0.384	Larger than head size, disregard underlying substrate
Bedrock	9	Br	Emergent Submerged <102	0.229 0.051 0.07	Solid Rock, >75% of area composed of solid rock
Vegetation	10	Veg	103 - 999 >1000	0.23 1.2	>75% of area composed of vegetation
Large Woody Debris	11	LWD		0.23	>75% of area composed of large woody debris

Table 1.4: Statistical summary of TPWD temperature monitoring data for the Canyon Reservoir tailrace (1997 – 2014). Sites indicate where temperature loggers were deployed for varying durations in the Canyon Reservoir tailrace. Temperatures over 21.1°C are stressful to trout. Temperatures over 25°C are lethal.

Site	Distance Downstream (km)	Minimum Temp (°C)	Maximum Temp (°C)	% Time Over 21.1°C	% Time Over 25.0°C
Dam	0.8	11.12	18.70	<1.00*	<1.00**
Canyon Corner	3.8	12.68	20.34	<1.00*	<1.00**
Whitewater	6.3	12.68	24.90	16.01	<1.00***
Rio Guadalupe Resort	8.7	14.41	25.37	47.49	1.53
Ponderosa	11.9	15.99	26.44	32.27	9.17
Rocky Beach	14.8	14.90	28.36	62.40	29.10
Third Crossing	17.1	14.40	35.98	73.86	33.73
Second Crossing	22.2	14.88	30.26	63.78	21.94

*Maximum summer temperatures exceeded 21.1°C for years: 1992, 1997, 1998, 1999, 2000, 2002, 2007, 2009, and 2012
**Maximum summer temperatures exceeded 25.0°C for years: 2002, 2007
***Maximum summer temperature exceeded 25.0°C for years: 2000, 2002, 2004, 2007, 2009, 2011, and 2012

Table 1.5: Adult trout habitat/flow statistics for the Canyon Reservoir tailrace (2010-2015). Exceedance values represent discharge from 1997 to 2014 at the Sattler USGS gauge.

Discharge (cms)	Exceedance	WUA (m^2)	% Max WUA	Optimal Habitat (m^2)	% of study area
0.57	100%	162592.14	68.69	146263.71	70.65
1.13	99%	175245.75	74.04	160744.81	72.82
1.70**	80%	189118.49	79.90	175113.86	75.47
2.27**	73%	197099.81	83.27	184435.85	77.75
2.83	67%	203389.15	85.93	190607.12	78.43
3.40*	56%	208369.82	88.03	195968.02	79.43
3.96*	50%	212550.08	89.80	200953.29	80.34
4.53*	48%	215880.52	91.21	205179.50	80.99
5.10*	45%	218463.67	92.30	208537.49	81.17
5.66*	41%	220418.65	93.12	211098.12	81.20
6.80*	34%	224216.41	94.73	215940.97	81.56
7.36	32%	226023.31	95.49	217902.30	81.43
9.63	26%	231216.71	97.69	223475.81	81.24
11.33	23%	233588.33	98.69	225733.90	80.93
13.31	20%	235614.07	99.54	227398.31	80.50
16.43	17%	236693.42	100.00	227288.59	79.37
22.66	13%	233232.61	98.54	220755.68	75.43

*Median summer flows from 1997 to 2014
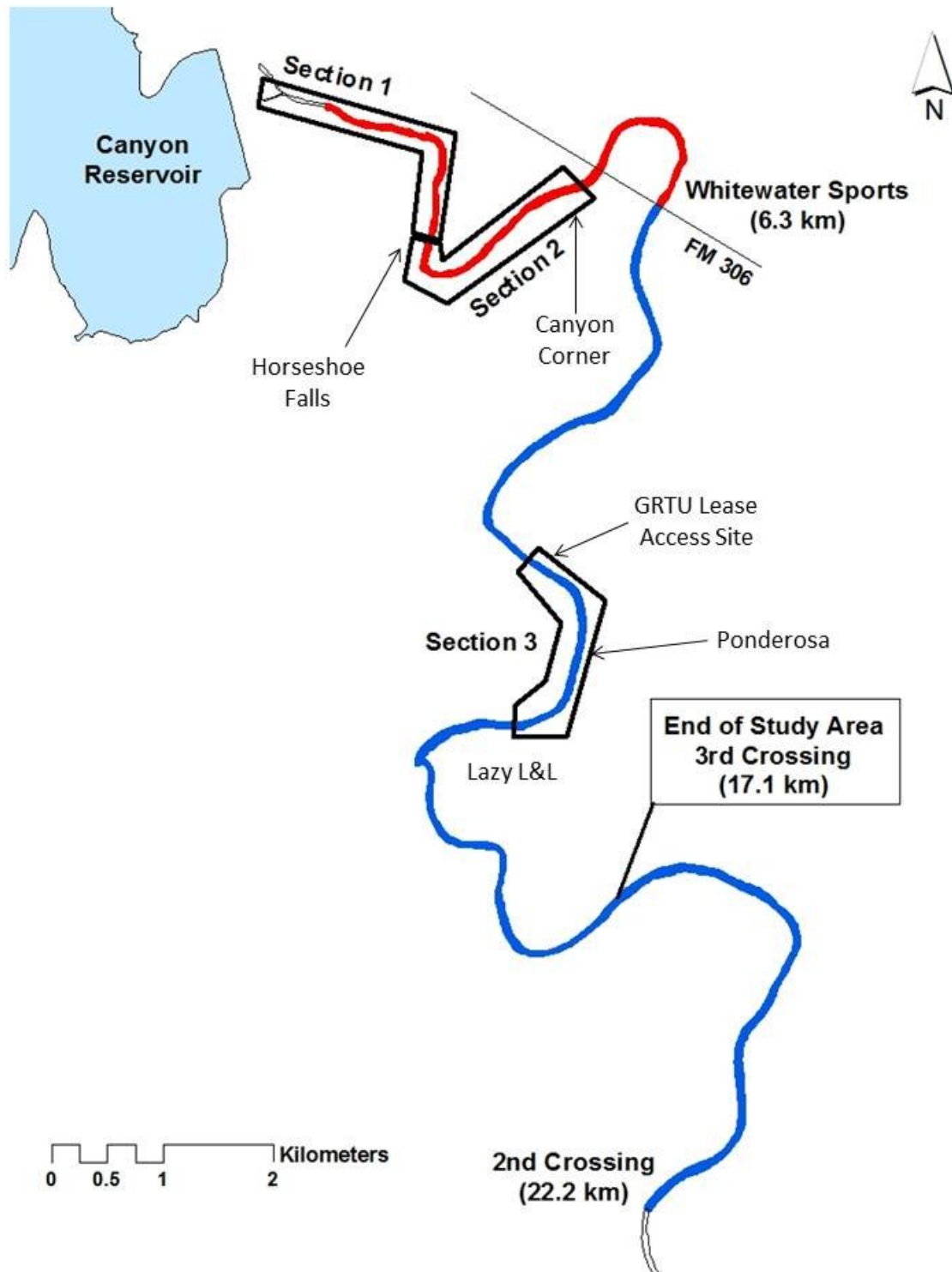**Median summer flows from 2010 to 2014 (Drought)

Figure 1.1: Study area (2010-2015) and special regulation zones on the Canyon Reservoir tailrace. Study sections are outlined by black boxes. Special regulation zone one is highlighted in red and special regulation zone two is highlighted in blue.
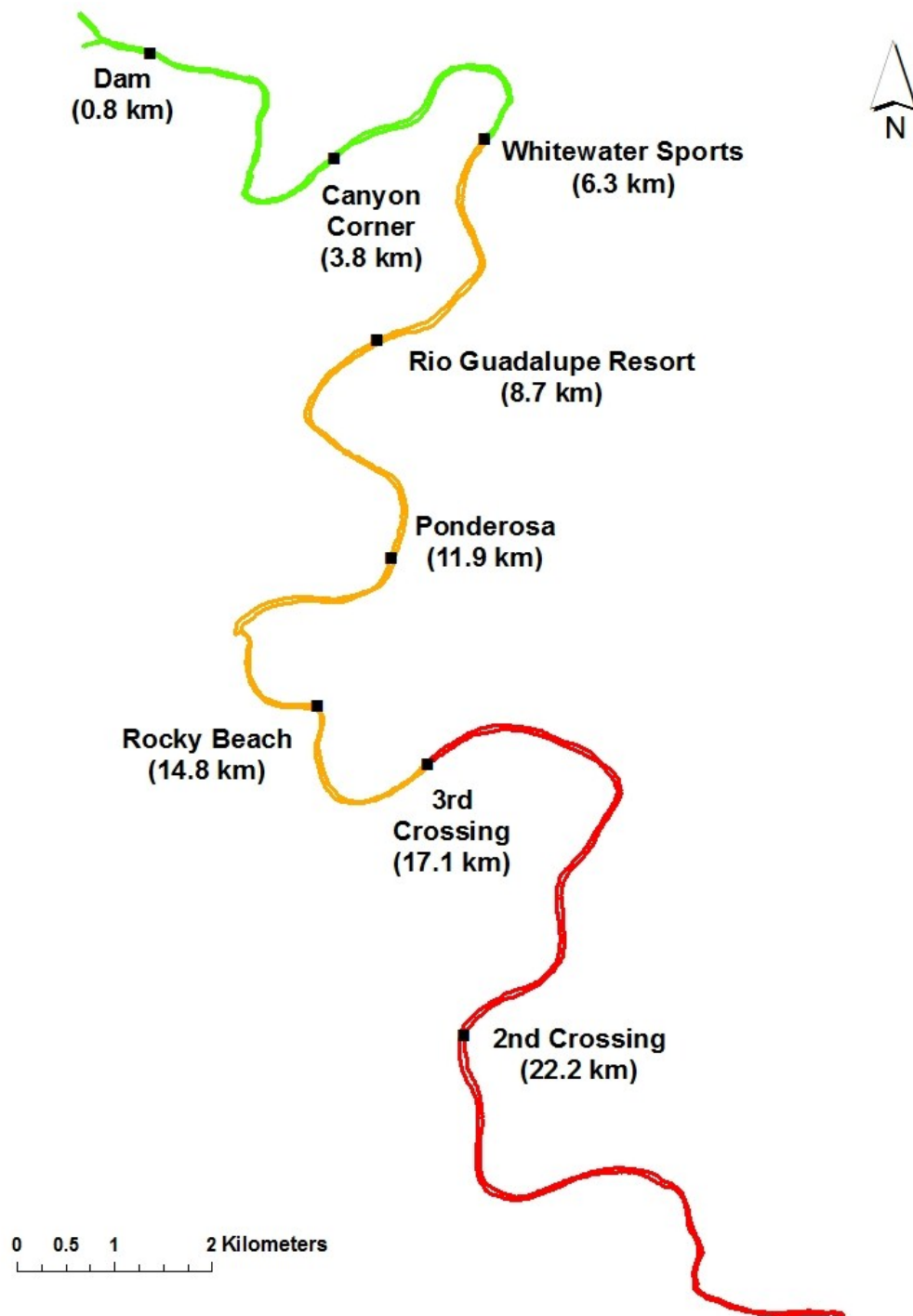
Figure 1.2: Water temperature monitoring station locations on the Canyon Reservoir tailrace (1997-2014). Sections of the tailrace have been highlighted to illustrate general trends of summer water temperature exceedance. Green = optimal temperatures rarely exceeded, orange = optimal temperatures sometimes exceeded, red = optimal temperatures frequently exceeded.
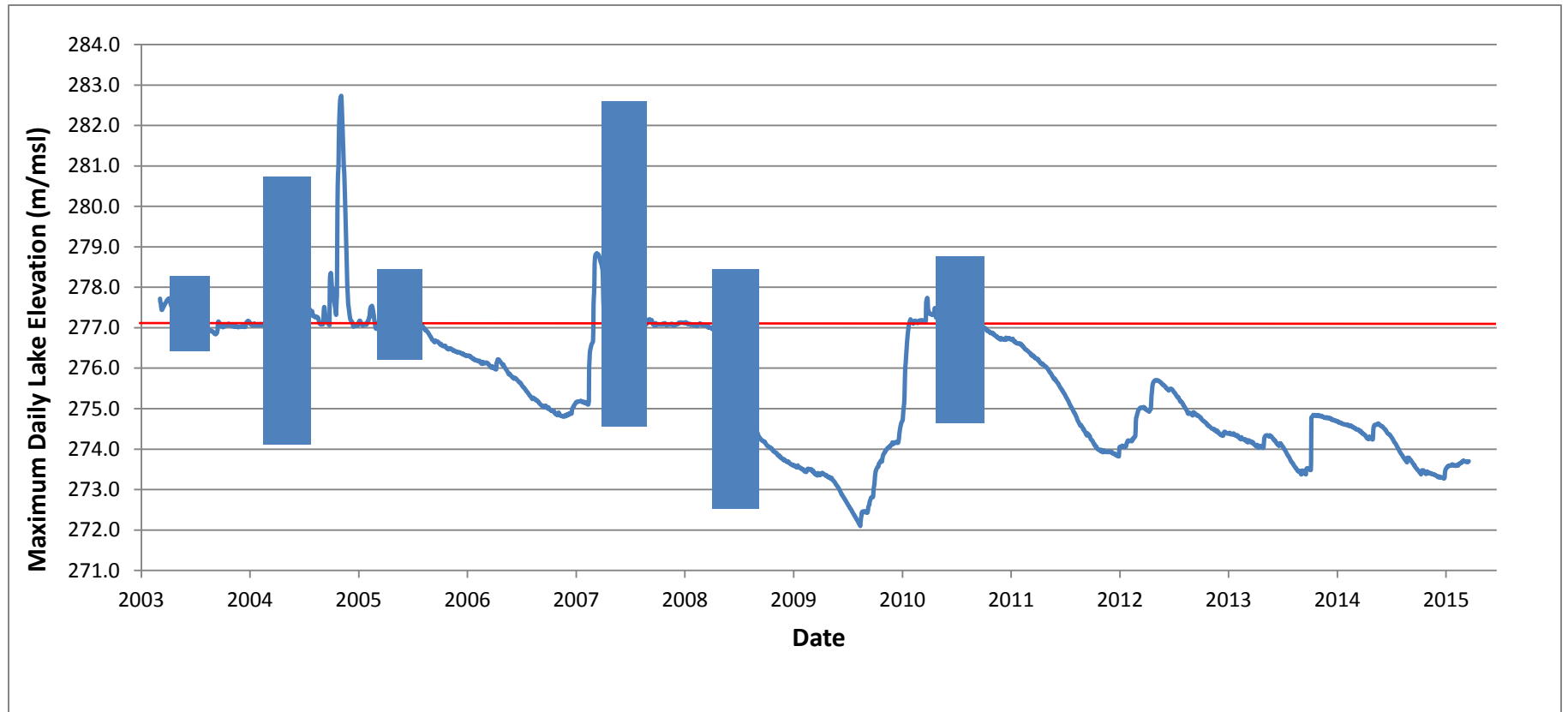
Figure 1.3: Canyon Reservoir maximum daily elevation (2003 – 2015) and periods when the GRTU/GBRA flow agreement has initiated prescribed flows. Red line depicts conservation pool (277.06 m/msl). Blue areas delineate times at which the flow agreement was potentially influencing discharge.
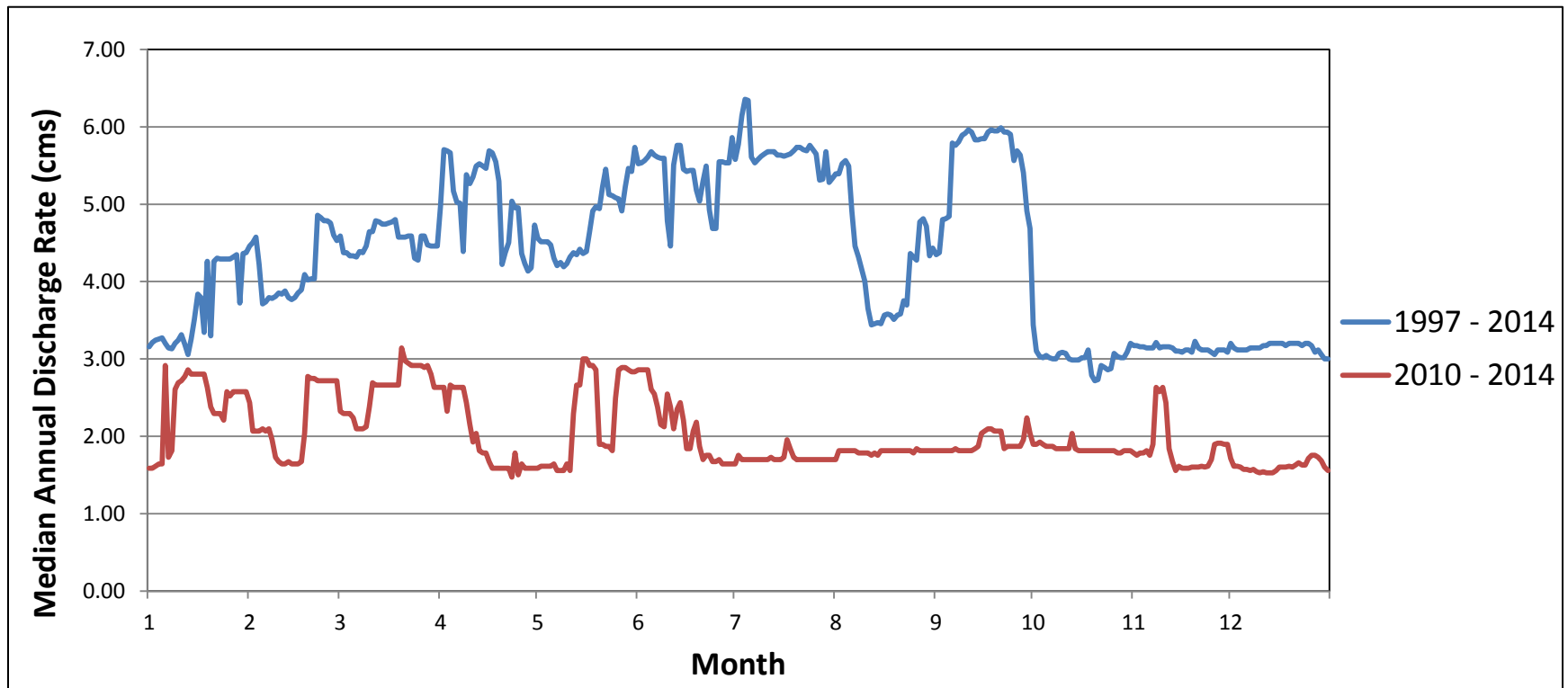
Figure 1.4: Comparison of median annual discharge rates (1997 – 2014) to median discharge rates during drought years (2010 – 2014) below Canyon Reservoir Dam.
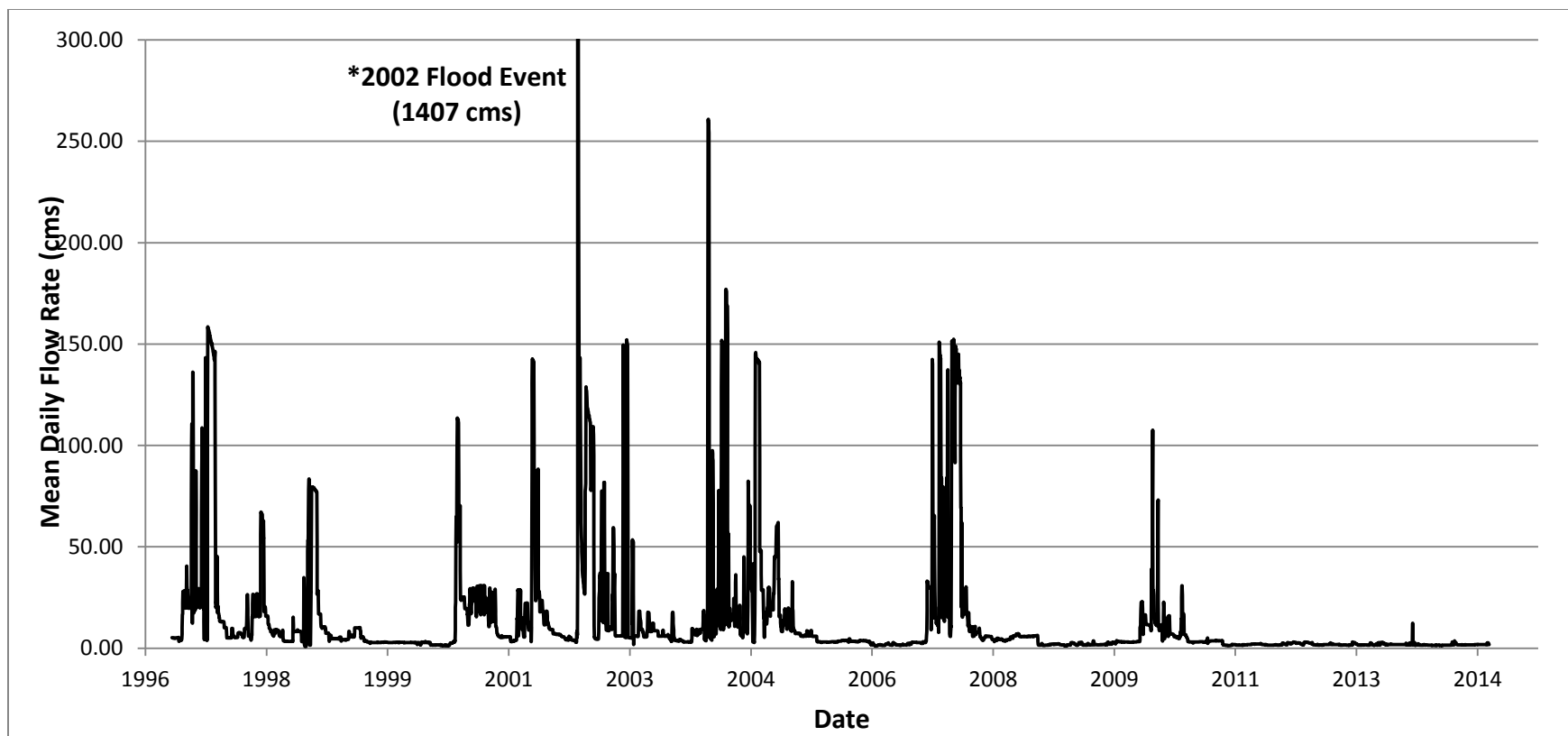
Figure 1.5: Hydrograph of Guadalupe River at USGS Sattler gauge (1997 – 2014) below Canyon Reservoir Dam.
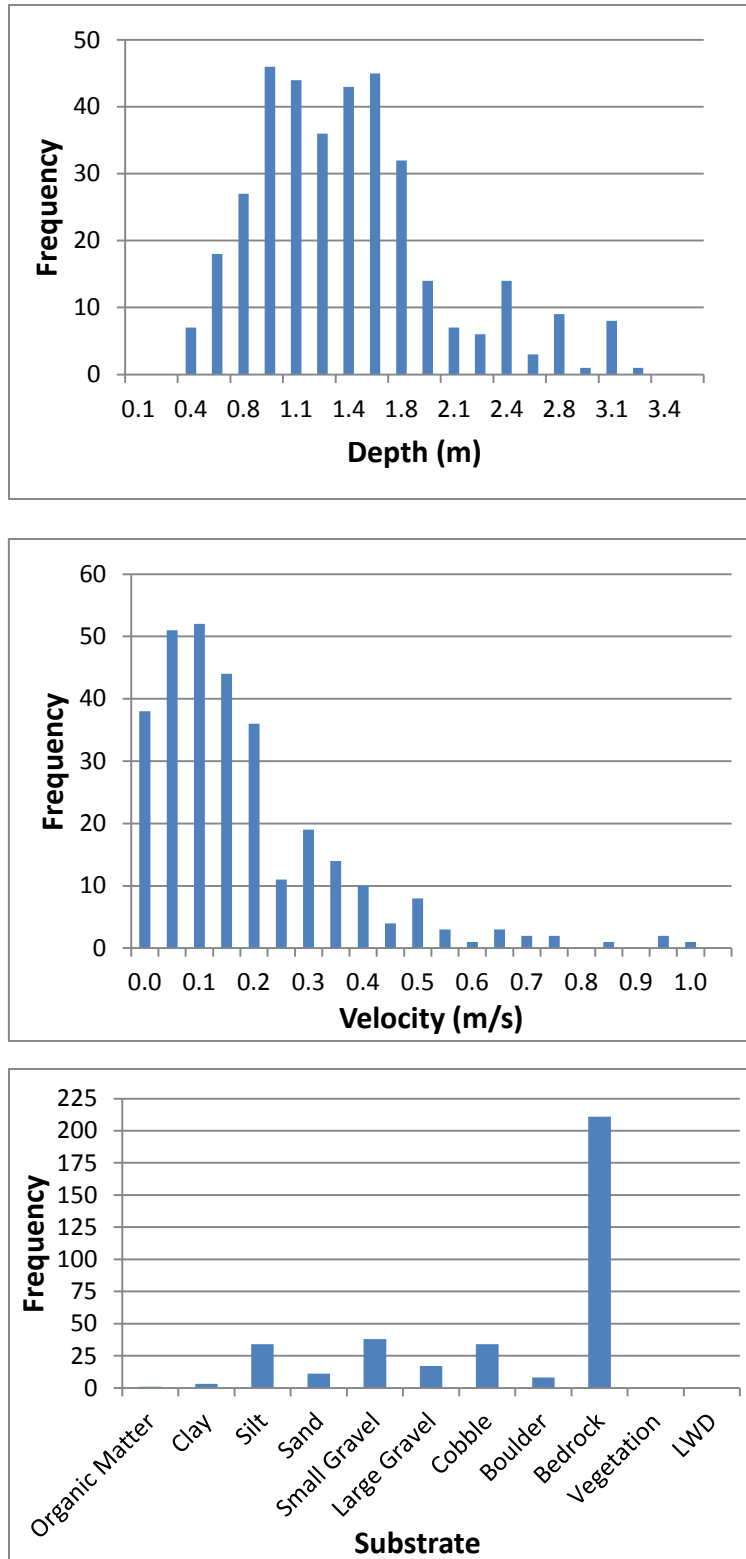
Figure 1.6: Frequency of observations for depth, velocity, and substrate for adult Rainbow Trout radio telemetry relocations in the Canyon Reservoir tailrace (2009-2010).
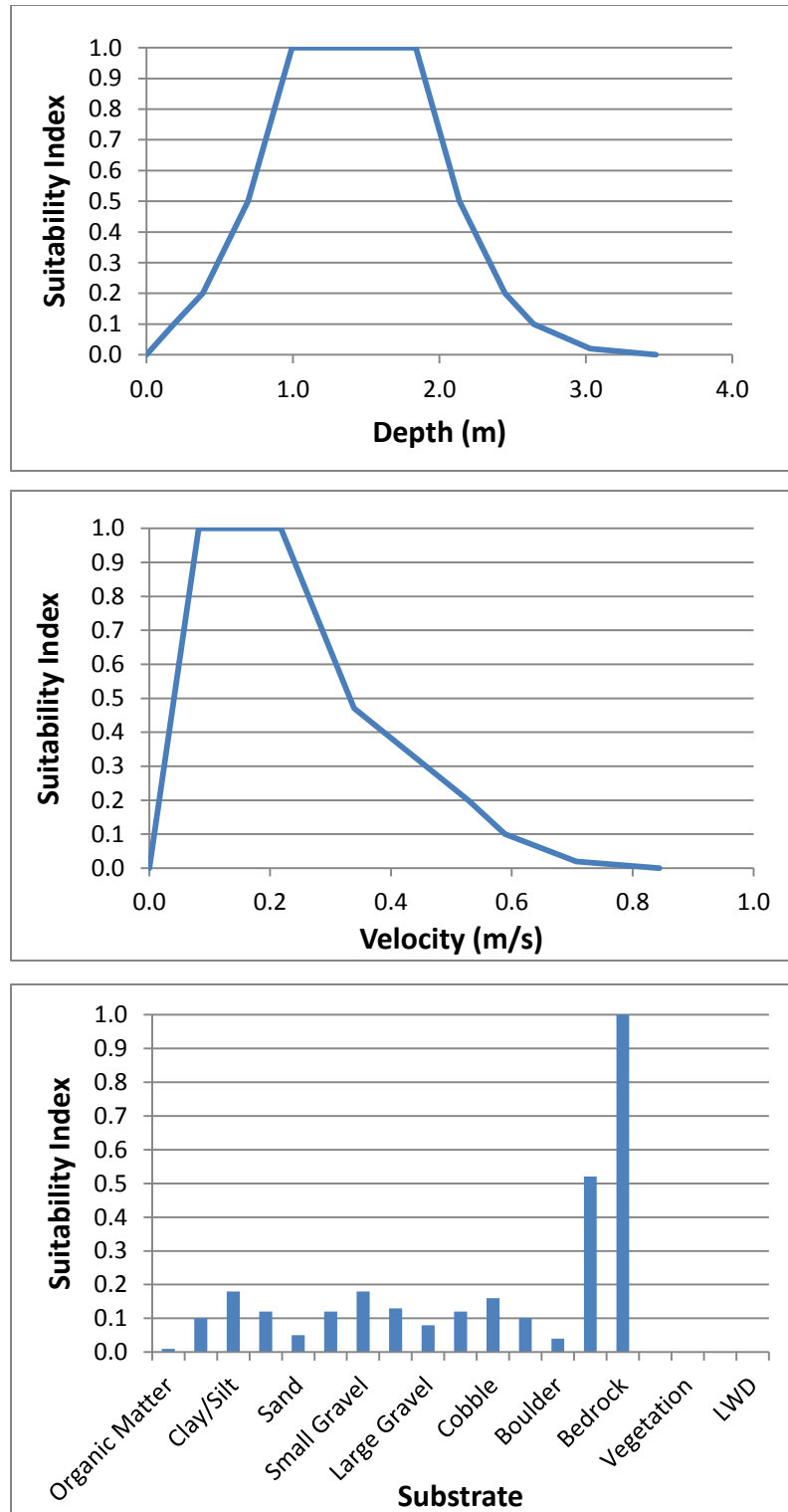
Figure 1.7: Habitat suitability curves for adult Rainbow Trout in the Canyon Reservoir tailrace depicting depth, velocity, and substrate (2009-2010). Substrate is represented by columns.
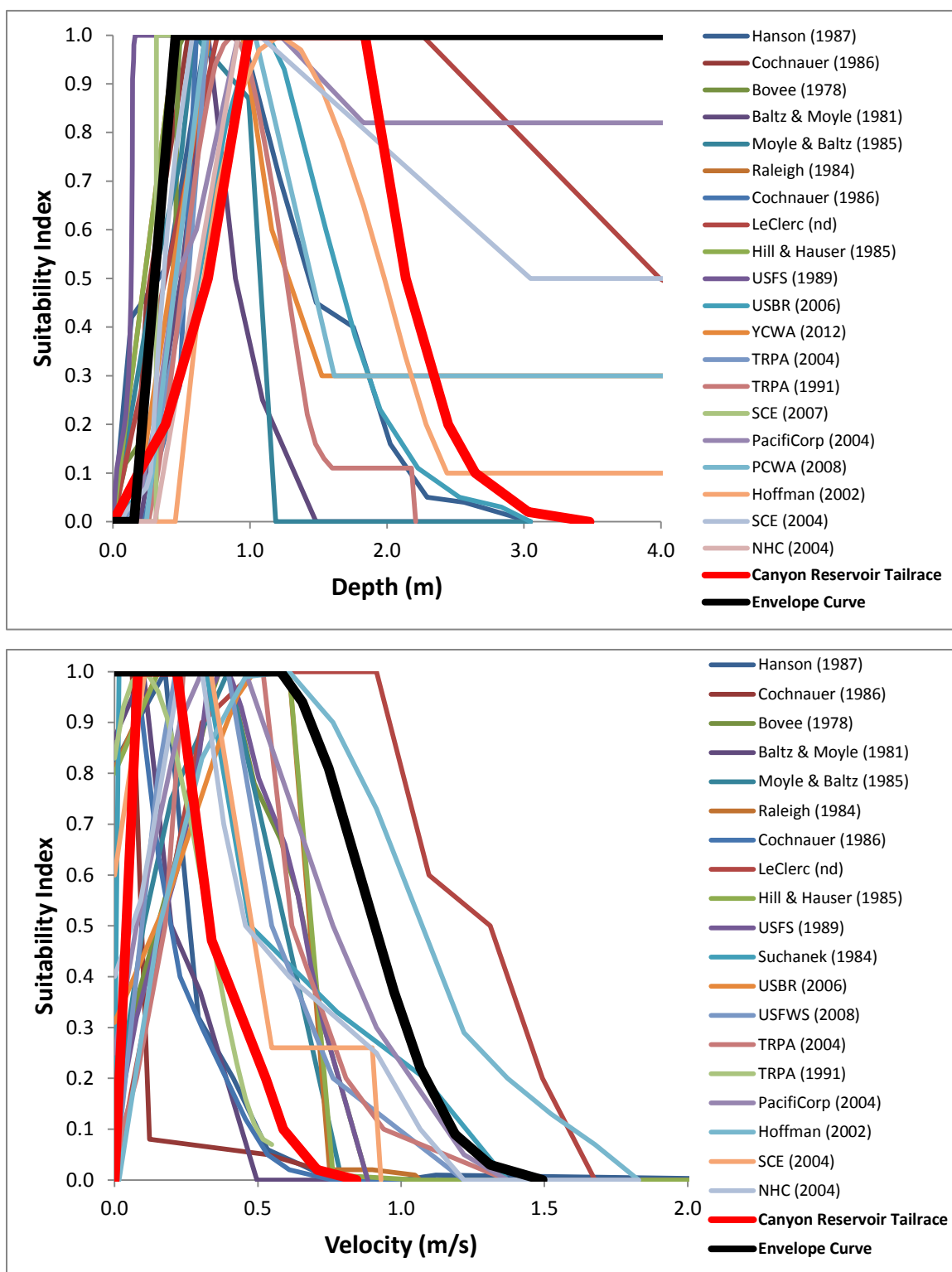
Figure 1.8: Comparison of adult Rainbow Trout HSC (depth and velocity) for the
Canyon Reservoir tailrace (2009-2010) to literature sources. Canyon Reservoir tailrace
HSC are depicted by red lines and envelope curves are depicted by black lines.
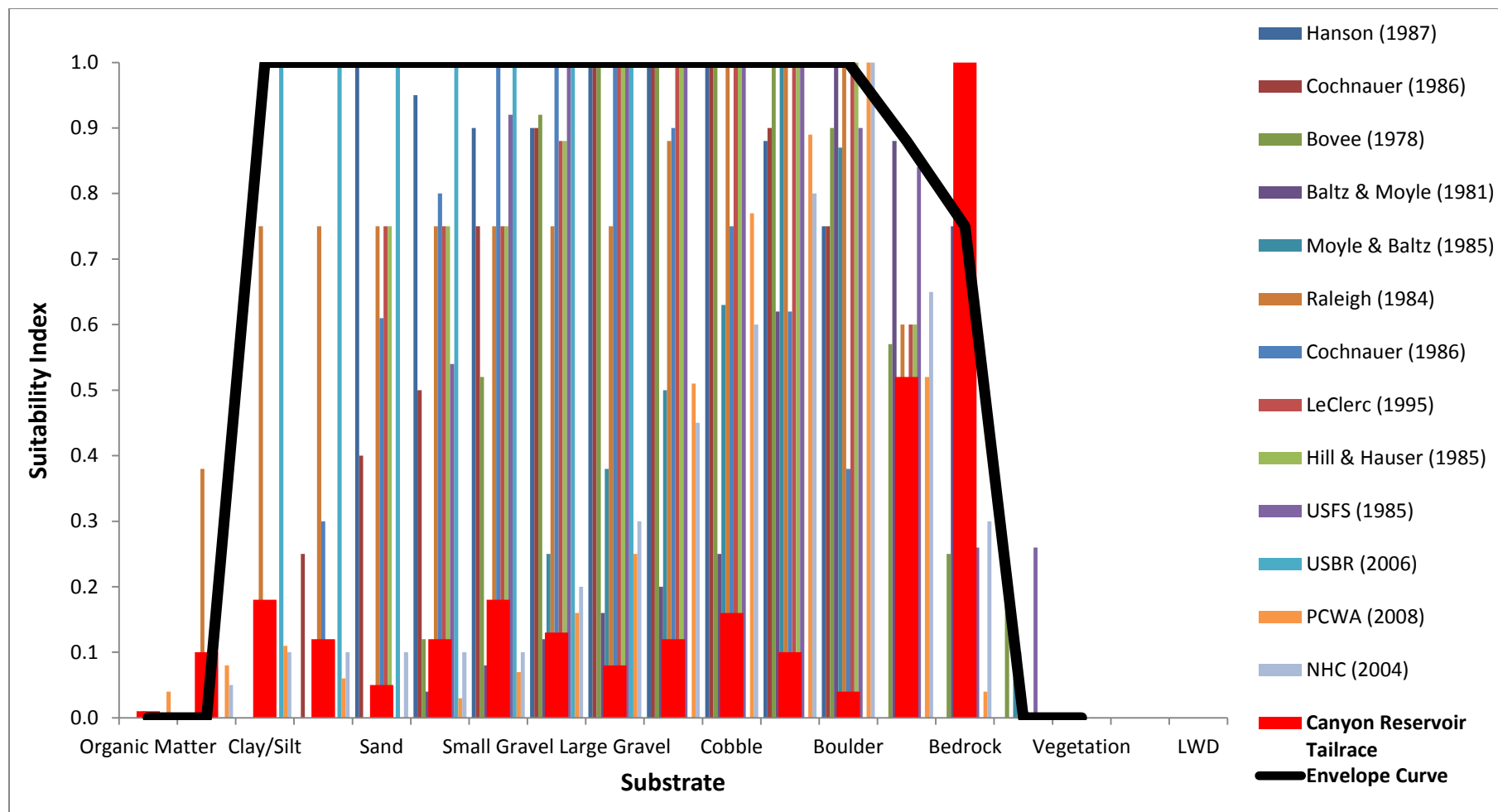
Figure 1.9: Comparison of adult Rainbow Trout HSC (substrate) for the Canyon Reservoir tailrace (2009-2010) to literature sources. Canyon Reservoir tailrace HSC is depicted by red columns and the envelope curve is depicted by a black line.
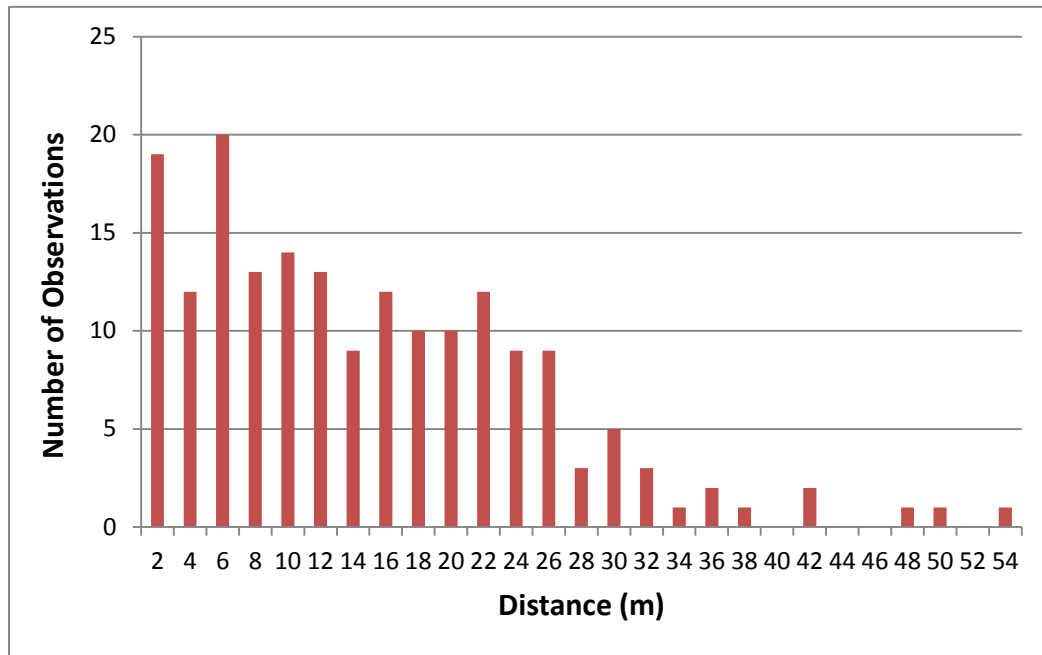
Figure 1.10: Frequency histogram showing distance to cover for adult Rainbow Trout radio telemetry locations (2009-2010) on the Canyon Reservoir tailrace.
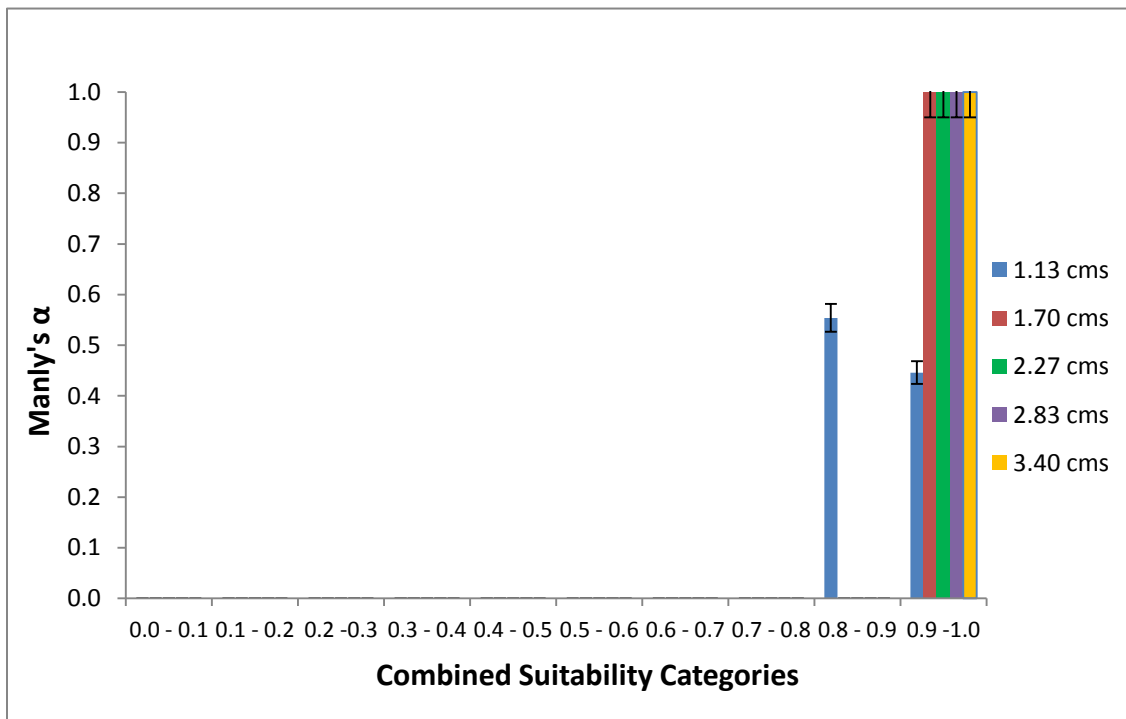
Figure 1.11:   Manly's Index of Preference **(α)** for combined suitability associated with trout telemetry locations (2009-2010) at various discharge rates on the Canyon Reservoir tailrace. Combined suitability includes depth, velocity, and substrate.
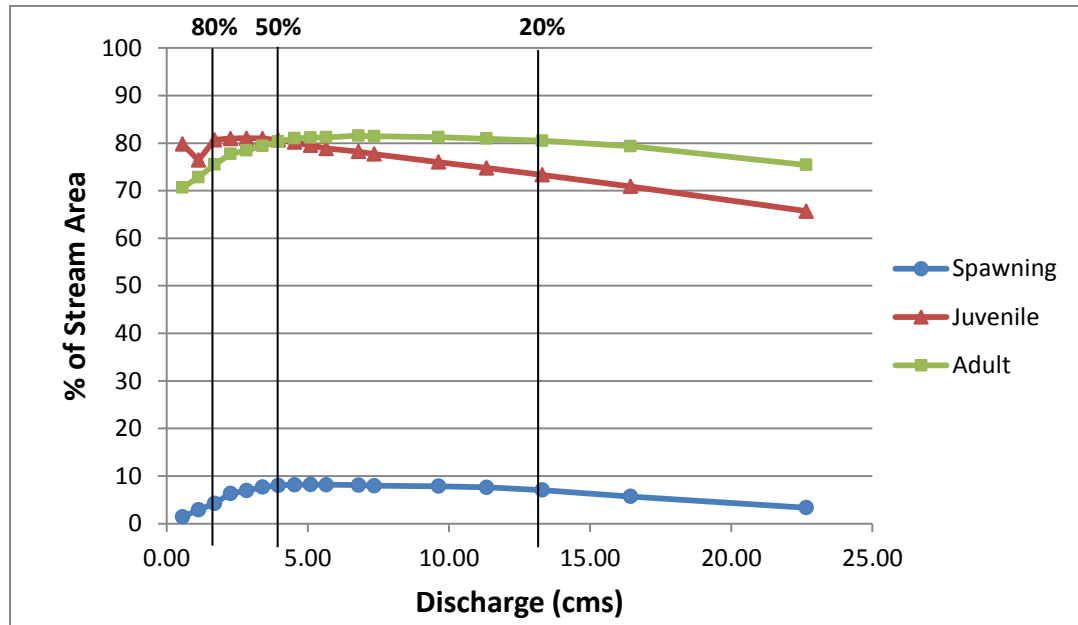
Figure 1.12: Total optimal habitat for spawning, juvenile, and adult Rainbow Trout on the Canyon Reservoir tailrace (2010-2015). Optimal habitat is normalized by percentage of study area at each discharge rate. Vertical lines represent annual flow exceedance
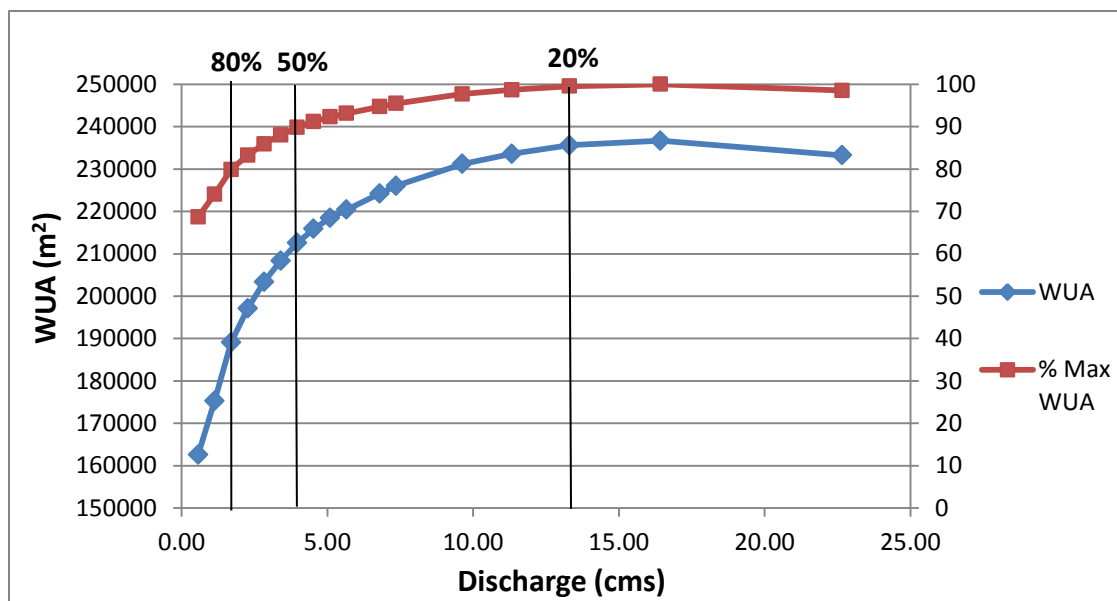
levels.

Figure 1.13: Total weighted usable area (WUA) for adult Rainbow Trout on the Canyon Reservoir tailrace (2010-2015). Total area (m^2) is located on the left axis and percent maximum WUA is located on the right axis. Vertical lines represent annual flow exceedance levels.
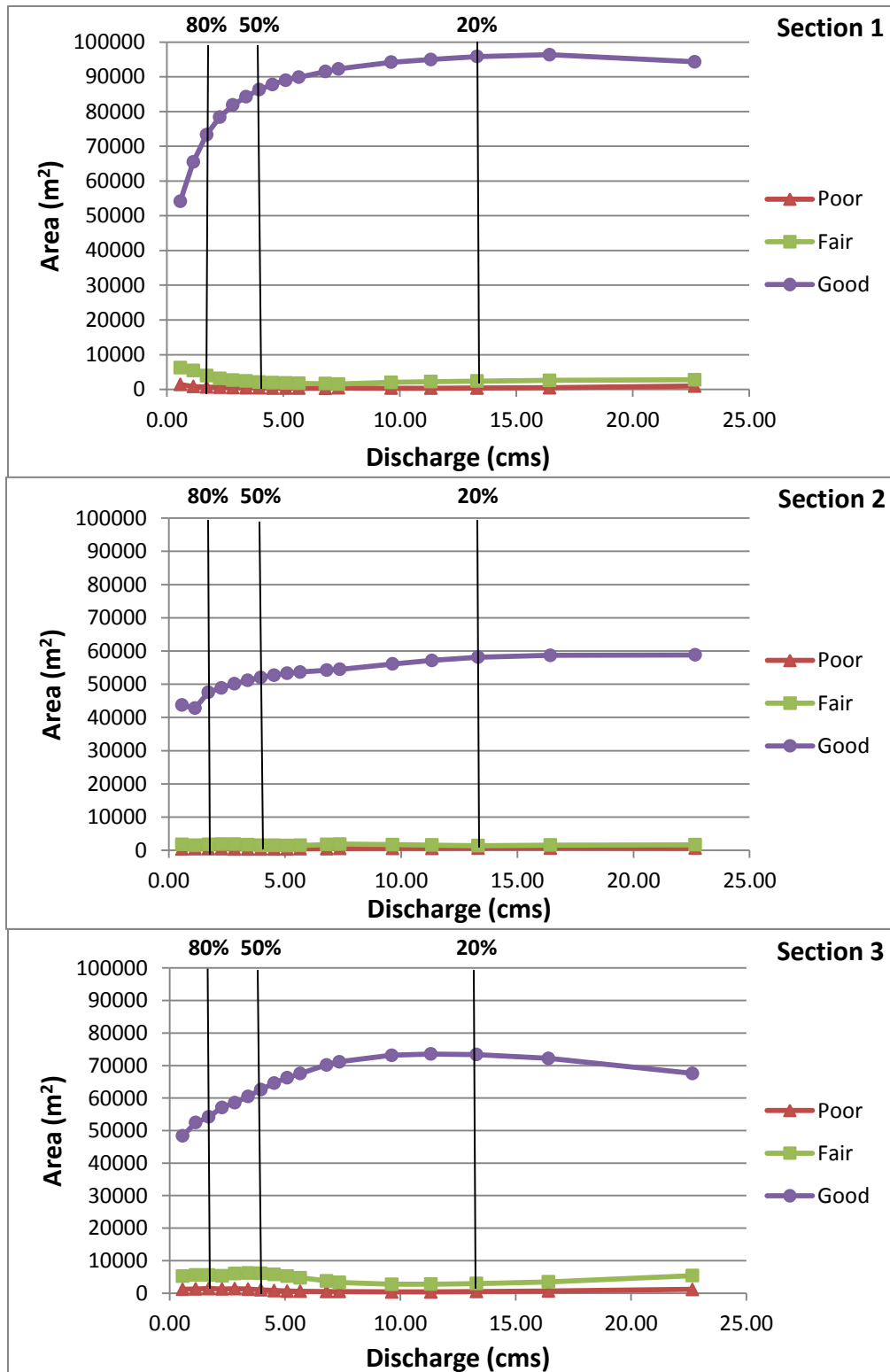
Figure 1.14: Adult Rainbow Trout habitat quality for each study section on the Canyon Reservoir tailrace (2010-2015). Vertical lines represent annual flow exceedance levels.
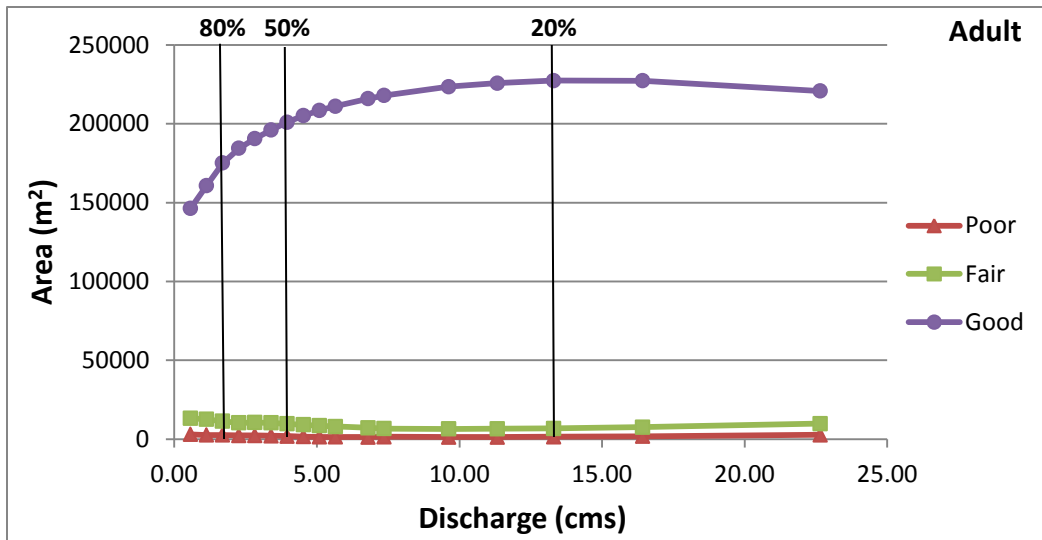
Figure 1.15: Overall habitat quality for adult Rainbow Trout on the Canyon Reservoir tailrace (2010-2015). Vertical lines represent annual flow exceedance levels.
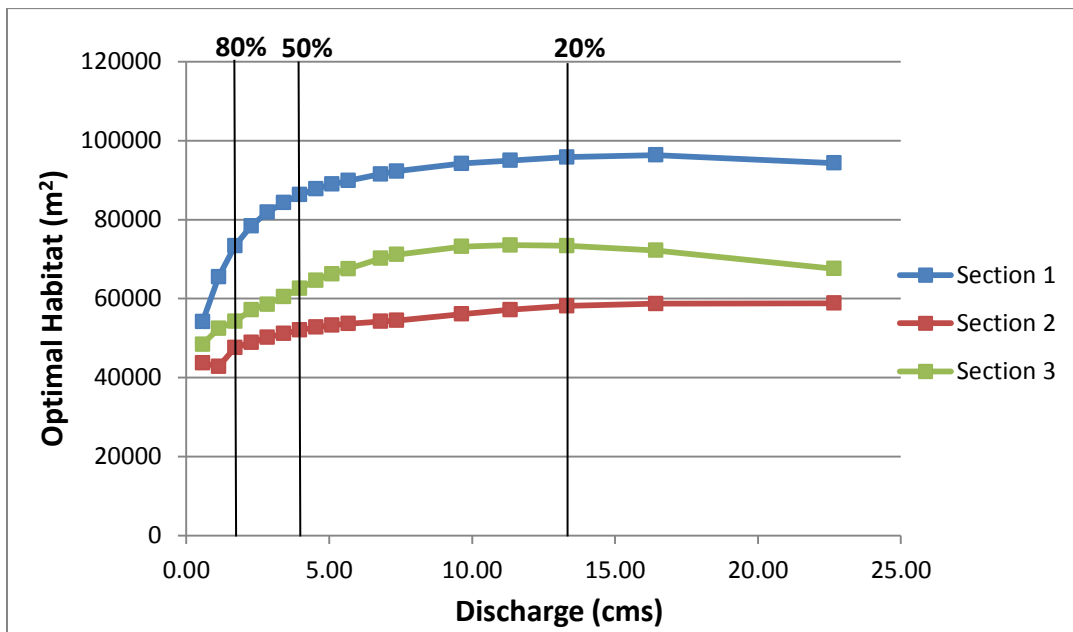
Figure 1.16: Optimal habitat for adult Rainbow Trout for each study section on the Canyon Reservoir tailrace (2010-2015). Vertical lines represent annual flow exceedance levels.
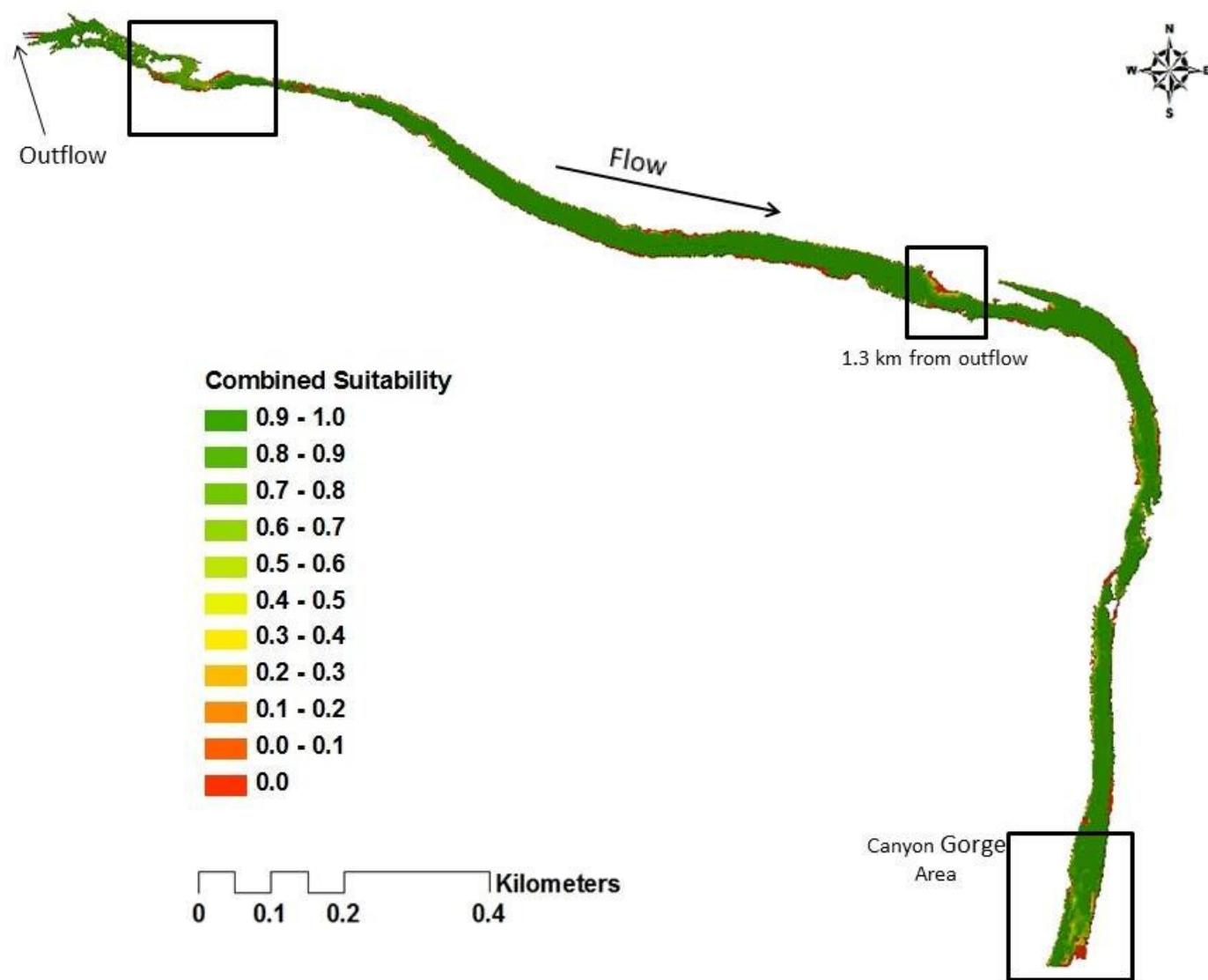
Figure 1.17: Combined suitability map for section one of the Canyon Reservoir tailrace study area (2010-2015). Modeled suitability represents a discharge rate of 1.70 cms. Black boxes indicate areas of low suitability for adult trout. White areas within the river channel indicate dewatered areas.
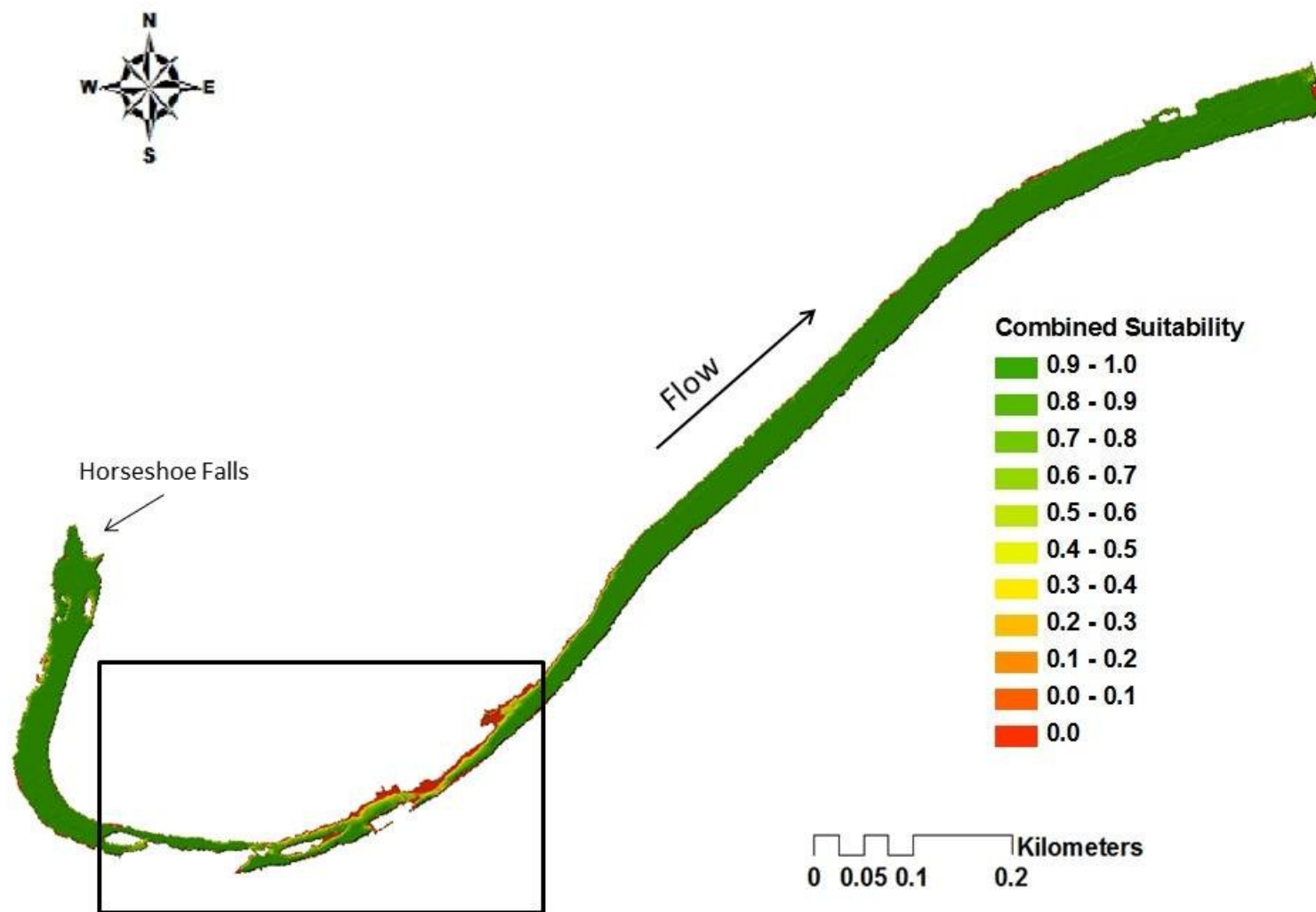
Figure 1.18: Combined suitability map for section two of the Canyon Reservoir tailrace study area (2010-2015). Modeled suitability represents a discharge rate of 1.70 cms. Black box indicates area of low suitability for adult trout. White areas within the river channel indicate dewatered areas.
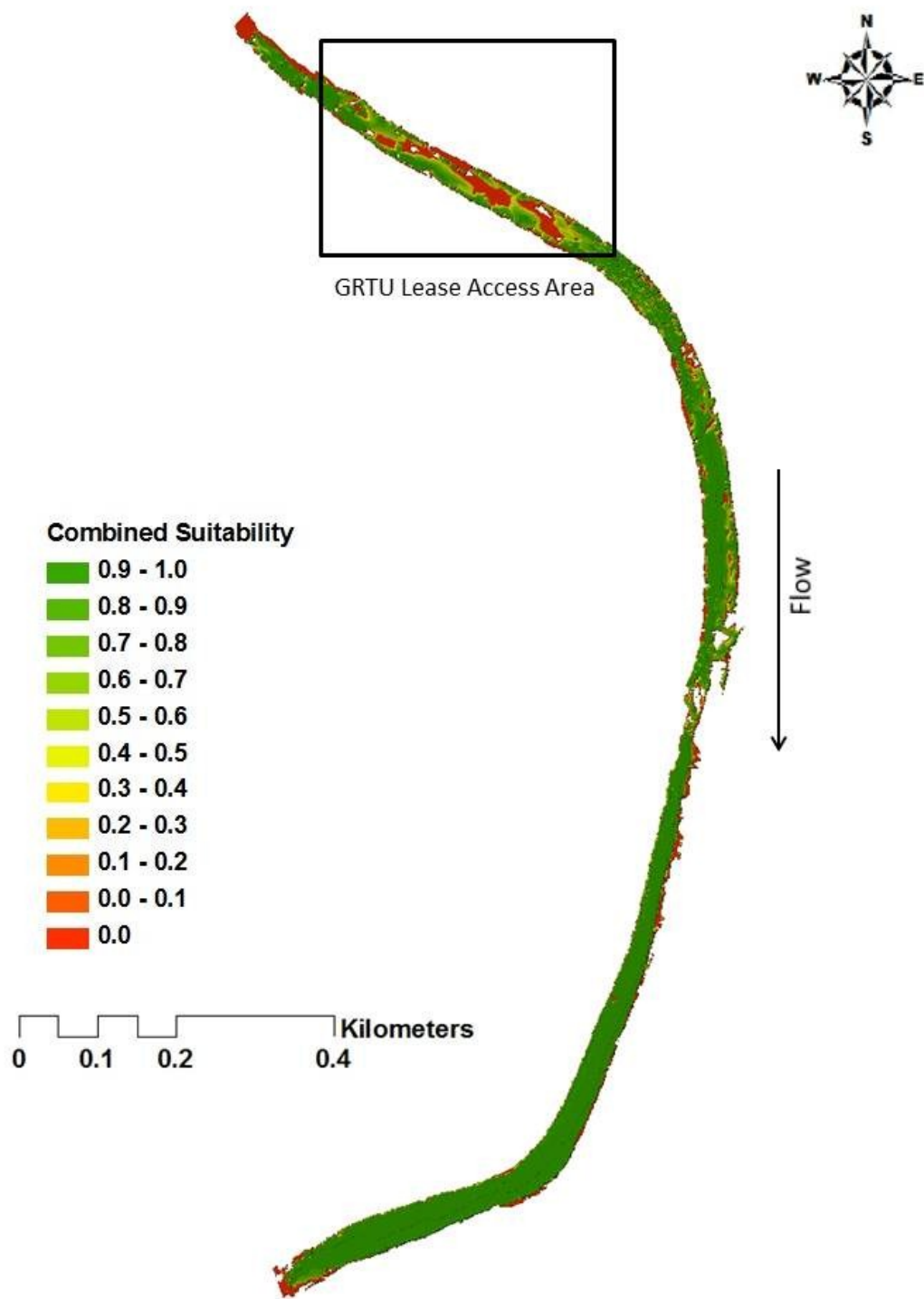
Figure 1.19: Combined suitability map for section three of the Canyon Reservoir tailrace study area (2010-2015). Modeled suitability represents a discharge rate of 1.70 cms. Black box indicates area of low suitability for adult trout. White areas within the river channel indicate dewatered areas.

LITERATURE CITED

Aggus, L.R., D.I. Morais, and R.F. Baker. 1977. Evaluation of the trout fishery in the tailwater of Bull Shoals Reservoir, Arkansas, 1971-73. Proceedings of the Annual Conference Southeastern Association of Game and Fish Agencies 31: 565-575.

Axon, J.R. 1975. Review of coldwater fish management in tailwaters. Proceedings of The Annual Conference Southeastern Association of Game and Fish Commissioners 28: 351-355.

Baltz, D.M. and P.B. Moyle. 1981. Segregation by species and size class of the rainbow trout (*Salmo gairdneri*), and Sacramento sucker (*Catostomidae occidentalis*), in three California streams. Environmental Biology of Fishes, Vol. 10 No. ½ pp 101-110, 1984.

Baird, O.E. and C.C. Krueger. 2003. Behavioral thermoregulation of brook and rainbow trout: comparison of summer habitat use in an Adirondack river, New York. Transactions of the American Fisheries Society 132: 1194-1206.

Beecher, H. and B. Caldwell. 2013. Instream flow study guidelines: technical and habitat suitability issues including fish preference curves. Washington Department of Fish and Wildlife. Olympia, Washington. 79 pp.

Bettoli, P.W. 2000. Potential impacts of striped bass on the trout fishery in the Norris Dam tailwater. Fisheries Report 00-31. Tennessee Wildlife Resources Agency, Nashville. 42 pp.

Bettoli, P.W. 2004. Survey of the trout fishery in the Caney Fork River. Fisheries Report 04-10. Tennessee Wildlife Resources Agency, Nashville. 26 pp.

Bovee, K.D. 1978. Probability-of-use criteria for family salmonidae. Instream Flow Information Paper No. 4. FWS/OBS-78/07. Cooperative Instream Flow Group; Western Energy and Land Use Team, Fort Collins, Colorado.

Bovee, K.D. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12. U.S.D.I. Fish and Wildlife Service, Office of Biological Services. FWS/OBS-82/26, 248 pp.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream habitat analysis using the instream flow incremental methodology. Information and Technology Report USGS/BRD/ITR-1998-0004. Fort Collins, CO: U.S. Geological Survey-BRD. 130 pp.

Bradle, T.A., S.J. Magnelia, J.B. Taylor. 2006. Trout angler utilization, attitudes, opinions and economic impact at the Canyon Reservoir tailrace. Texas Parks and Wildlife Department. Austin, TX. 48 pp.

Buffington, J.M., T.E. Lisle, R.D. Woodsmith, and S. Hilton. 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18: 507-531.

Bugert, R.M., T.C. Bjornn, and W.R. Meehan. 1991. Summer habitat use by young salmonids and their responses to cover and predators in a small southeast Alaska stream. Transactions of the American Fisheries Society 120: 474-485.

Caldwell, B., J. Pacheco, H. Beecher, T. Hegy, and R. Vadas. 2004. Chehalis River Basin WRIAs 22 and 23 fish habitat analysis using the instream flow incremental methodology: open file technical report. Washington State Department of Ecology and Department of Fish and Wildlife. Olympia, Washington. 103 pp.

Caldwell, B., J. Shed, H. Beecher. 1999b. East Fork Lewis River fish habitat analysis using the instream flow incremental methodology: open file technical report. Publication # 99-152 Washington State Department of Ecology. Olympia, Washington.

Caudill, J. 2007. The economic impacts of trout stocking on tailwaters in the Southeast Aquatic Resources Partnership (SARP). 23 pp.

Cheslak, E. and J. Carpenter. 1990. Compilation report on the effects of reservoir releases on downstream ecosystems. U.S. Department of the Interior, Bureau of Reclamation. REC-ERC-90-1.

Cochnauer, T. and T. Elms-Cockrum. 1986. Probability-of-use curves for selected Idaho fish species. Project F-71-R-10, Job No. 1-a, Idaho Department of Fish and Game. Boise, Idaho.

Contor, C.R. and W.S. Platts. 1991. Assessment of COWFISH for predicting trout populations in grazed watersheds of the Intermountain West. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. General Technical Report INT-278.

Corning, R.V. and G. Elliot. 1987. An evaluaton of IFIM curves developed for the Swanson River rainbow trout populations. Draft report for the U.S. Fish and Wildlife Service, Alaska Invest Filed Office. Anchorage, Alaska. 24 pp.

Cross, B.K., M.A. Bozek, and M.G. Mitro. 2013. Influences of riparian vegetation on trout stream temperatures in central Wisconsin. North American Journal of Fisheries Management, 33:4, 682-692.

Deppert, D.L. and J.B. Mense. 1979. Effect of striped bass predation on an Oklahoma trout fishery. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 33: 384-392.

Earl, R.A., R.D. Benke, and K. Knaupp. 2003. Analysis of the July 2002 flood at the Canyon Dam spillway, Guadalupe River, south-central Texas. Papers and Proceedings of Applied Geography Conferences: 371-379.

Ebersole, J.L., W.J. Liss, and C.S. Frissell. 2001. Relationship between stream temperature refugia and rainbow trout *Onchorhynchus mykiss* abundance in arid-land streams in the northwestern United States. Ecology of Freshwater Fish 10: 1-10.

Edwards, R.J. 1978. The effect of hypolimnion reservoir releases on fish distribution and species diversity. Transactions of the American Fisheries Society 107:1, 71-77.

Flebbe, P.A., and C.A. Dolloff. 1995. Trout use of woody debris and habitat in Appalachian wilderness streams of North Carolina. North American Journal of Fisheries Management 15: 579-590.

Fischenich, J.C. and J.V. Morrow, Jr. 1999. Streambank habitat enhancement with large woody debris. EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-13), U.S. Army Engineer Research and Development Center, Vicksburge, MS.

Forshage, A. 1976. Cost/benefit analysis of a catchable rainbow trout fishery in Texas. Proceedings of the Annual Conference Southeastern Association of Game and Fish Agencies 29: 293-300.

Fry, J.P. and W.D. Hanson. 1968. Lake Taneycomo: A cold-water reservoir in Missouri. Transactions of the American Fisheries Society 97: 138-145.

Groeger, A.W. and T.E. Tietjen. 1998. Hydrological and thermal regime in a subtropical reservoir. International Review of Hydrobiology Special Issue 83: 83-92.

Groeger, A.W. and D.A. Bass. 2005. Empirical predictions of water temperatures in a subtropical reservoir. Archiv für Hydrobiologie 162(2): 267-285.

Guadalupe-Blanco River Authority (GBRA). 2015. GBRA website. http://www.gbra.org/canyon/default.aspx. Accessed 2015 April 18.

Guadalupe River Chapter of Trout Unlimited (GRTU). 2015. GRTU website. http://www.grtu.org/wp-content/uploads/2015/05/grtuminimumflow.pdf. Accessed 2015 April 18.

Guensch, G.R., T.B. Hardy, and R.C. Addley. 2001. Validation of an individual-based, mechanistic habitat selection model for drift-feeding salmonids. Canadian Journal of Fisheries and Aquatic Science 58(3): 446-457.

Gunn, T. and W. Gunn. 2013. 50 best tailwaters to fly fish. Stonefly Press. 253 pp.

Hampton, H. 1988. Development of habitat preference criteria for anadromous salmonids of the Trinity River. U.S. Department of Interior, Fish and Wildlife Service, Division of Ecological Services. Sacramento, California. 93 pp.

Hardy, T.B., R.C. Addley, E. Saraeva. 2006. Evaluation of instream flow needs in the lower Klamath River. Phase II Final Report, prepared for U.S. Department of the Interior. Prepared by Institute for Natural Systems Engineering and Utah Water Research Laboratory. Utah State University. Logan, Utah. 229 pp.

Harman, W., R. Starr, M. Carter, K. Tweedy, M. Clemmons, K. Suggs, and C. Miller. 2012. A function-based framework for stream assessment and restoration projects. US Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC EPA 843-K-12-006.

Harper, J.L. 1994. Evaluation of a year-round put-and-take rainbow trout fishery in the Mountain Fork River. Oklahoma Department of Wildlife Conservation, Federal Aid in Sport Fish Restoration Project F-37-R, Job 18. 25 pp.

Harris, C.M, J.R. Calladine, C.V. Wernham, and K.J. Park. 2008. Impacts of piscivorous birds on salmonid populations and game fisheries in Scotland: a review. Wildlife Biology 14:4, 395-411.

Harvey, B.C. and A.J. Stewart. 1991. Fish size and habitat depth relationships in headwater streams. Oecologia 87:3, 336-342.

Harvey, B.C., J.L. White, and R.J. Nakamoto. 2005. Habitat-specific biomass, survival, and growth of rainbow trout (*Oncorhynchus mykiss*) during summer in a small coastal stream. Canadian Journal of Fisheries and Aquatic Sciences 62: 650-658.

Hetrick, N.J., M.A. Brusven, W.R. Meehan, and T.C. Bjornn. 1998. Changes in solar input, water temperature, periphyton accumulation, and allochthonous input and storage after canoy removal along two small salmon streams in southeast Alaska. Transactions of the American Fisheries Society, 127:6, 859-875.

Hill, D.M and G.E. Hauser. 1985. Effects of proposed water supply withdrawals on fish habitat in the Piney River. TVA Office of Natural Resources and Economic Development. Norris, Tennessee.

Hodgens, L.S., S.C. Blumenshine, and J.C. Bednarz. 2004. Great blue heron predation on stocked rainbow trout in an Arkansas tailwater fishery. North American Journal of Fisheries Management 24:1, 63-75.

Hoffman, G., D. Skaar, S. Dalbey, J. DeShazer, L. Garrow, T. Ostrowski, J. Dunnigan, and B. Marotz. 2002. Instream flows incremental methodology for Kootenai River. Project No. 1994-00500. BPA report DOE/BP-00006294-2. 86 pp.

Hughes, N.F. and L.M. Dill. 1990. Position choice by drift-feeding salmonids: model and test for Arctic Grayling (*Thymallus arcticus*) in subarctic mountain streams, interior Alaska. Canadian Journal of Fisheries and Aquatic Sciences 47(10): 2039-2048.

Ibes, D.C. 2008. Post-disaster parks: prospects, problems, and prescriptions. Texas State University. San Marcos, TX. 132 pp.

Jowett, I.G. and J. Richardson. 2008. Habitat use by New Zealand fish and habitat suitability models. NIWA Science and Technology Series No. 55. 148 pp.

Kaeser, A.J. and T.L. Litts. 2008. An assessment of deadhead logs and large woody debris using side scan sonar and field surveys in streams of southwest Georgia. Fisheries 33(12): 589-597.

Kaeser, A.J. and T.L. Litts, 2010. A novel technique for mapping habitat in navigable streams using low-cost side scan sonar. Fisheries 35(4): 163-174.

Kaufman, G. and M.S. Allen. 2008. Potential impacts of global climate change on warmwater fisheries of the USA. Department of Marine Sciences, University of Georgia, Athens, Georgia. 38 pp.

Keller, C.R. and K.P. Burnham. 1982. Riparian fencing, grazing, and trout habitat preference on Summit Creek, Idaho. North American Journal of Fisheries Management 2: 53-59.

Kennedy, G.J.A. and J.E. Greek. 2008. Predation from cormorants, *Phalacrocorax carbo* (L.), on the salmonid populations of an Irish river. Aquaculture Research 19:2, 159-170.

Kinsella, S., T. Spencer, and B. Farling. 2008. The impacts of global warming on trout in the interior west. Natural Resource Defense Council. 34 pp.

Klein, L. 2003. Investigation of the trout fishery in the Chattahoochee River below Buford Dam. Georgia Department of Natural Resources, Wildlife Resources Division. Social Circle, GA. 57 pp.

Kondolf, G.M. 2000. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society, 129: 1, 262-281.

Laliberte, J.J., J.R. Post, and J.S. Rosenfeld. 2013. Hydraulic geometry and longitudinal patterns of habitat quantity and quality for rainbow trout (*Oncorhynchus mykiss*). River Research and Applications. Published online May 2013.

Lamb, M.P. and M.A. Fonstad. 2010. Rapid formation of a modern bedrock canyon by a single flood event. Nature Geoscience, June 2010.

Lambert, T.R., F.D. Hanson, and J.E. Morhardt. 1987. Development of habitat suitability criteria for trout in the Kings River Basin, California. Pacific Gas and Electric Company, California. Report 009.4-87.10.

LeClerc, M., A. Boudreault, J.A. Bechara, and G. Corfa. 1995. Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology. Transactions of the American Fisheries Society 124(5): 645-662.

Leitz, J. 2013. 2012 Survey of the Guadalupe River Trout Unlimited members. Texas Parks and Wildlife Department (unpublished). Austin, TX. 6 pp.

Magnelia, S.J. 2004. Summary of 1987-2001 data from the Canyon Reservoir Tailrace with implications for establishment of a put-grow-and-take rainbow trout fishery. Texas Parks and Wildlife Department, Management Data Series No. 215. Austin, TX. 47 pp.

Magnelia, S.J. 2007. Survival of rainbow trout fingerlings stocked into the special regulation zone of the Canyon Reservoir Tailrace. Texas Parks and Wildlife Department Management Data Series No. 247. Austin, TX. 27 pp.

Magnelia, S. J. and G.A. Cummings. 2015. Persistence, movement, and habitat use of stocked rainbow trout in a Texas tailrace fishery. Texas Parks and Wildlife Department (unpublished manuscript). San Marcos, TX. 58 pp.

Manly, B.F.J., P. Miller, L.M. Cook. 1972. Analysis of a selective predation experiment. America Nature 106: 719-736.

Mathur, D., W.H. Bason, E.J. Purdy Jr., and C.A. Silver. 1985. A critique of the instream flow incremental methodology. Canadian Journal of Fisheries and Aquatic Sciences 42: 825-831.

Matthews, K.R. and N.H. Berg. 1997. Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. Journal of Fish Biology 50: 50-67.

McDonald, R. R., Bennett, J. P., and Nelson, J. M. 2001. The USGS multi-dimensional surface water modeling system. Proceedings of the 7th U.S. Interagency Sedimentation Conference, Reno, Nevada.

Meisner, J.D., J.S. Rosenfeld, and H.A. Regier. 1988. The role of groundwater in the impact of climate warming on stream salmonines. Fisheries 13:3, 2-8.

Modde, T., A.F. Wasowicz, and D.K. Hepworth. 1996. Cormorant and grebe predation on rainbow trout stocked in a southern Utah reservoir. North American Journal of Fisheries Management, 16:2, 388-394.

Moring, J.R., G.C. Garman, and D.M. Mullen. 1985. The value of riparian zones for protecting aquatic systems: general concerns and recent studies in Maine. U.S. Forest Service General Technical Report RM-20: 315-319.

Moyle, P.B. and D.M. Baltz. 1985. Microhabitat use by an assemblage of California stream fishes: developing criteria for instream flow determinations. Transactions of the American Fisheries Society 114: 695-704.

Northwest Hydraulic Consultants (NHC). 2004. Instream flow and fish habitat assessment. FERC Project No. 2545, Avista Corporation. Report prepared by NHC and Hardin-Davis, Inc. Corvallis, Oregon. 98 pp.

Neumann, R.M. and T.L. Wildman. 2002. Relationships between trout habitat use and woody debris in two southern New England streams. Ecology of Freshwater Fish 11: 240-250.

Nielsen-Gammon, J.W. 2011. The changing climate of Texas. Schmandt and others, eds. The Impact of Global Warming on Texas, Second Edition: University of Texas Press. 33 pp.

PacifiCorp & Cowlitz PUD. 2004. Swift bypass reach instream flow study (AQU 2). PacifiCorp & Cowlitz PUD. Lewis River Hydroelectric Project. FERC Project Nos. 935, 2071, 2111, 2213. Portland, Oregon.

Pawson, M.G. and C.E. Purdom. 1987. Relative catchability and performance of three strains of rainbow trout, *Salmo gairdneri* Richardson, in a small fishery. Aquaculture and Fisheries Management 18: 173-186.

Pawson, M.G. 1991. Comparison of the performance of brown trout, *Salmo trutta L.*, and rainbow trout, *Oncorhynchus mykiss* (Walbaum), in a put-and-take fishery. Aquaculture and Fisheries Management 22: 247-257.

Payne, T.R. 2003. The concept of weighted usable area as relative suitability index. IFIM Users Workshop. Fort Collins, Colorado. 14 pp.

Pierce, R., C. Podner, L. Marczak, and L. Jones. 2014. Instream habitat restoration and stream temperature reduction in a whirling disease-positive spring creek in the Blackfoot River Basin, Montana. Transactions of the American Fisheries Society, 143:5, 1188-1198.

Placer County Water Agency (PCWA). 2008. Juvenile and adult rainbow trout habitat
   suitability criteria. Report prepared by PCWA Middle Fork American River
   Project. FERC Project No. 2079. 16 pp.

Post, R. 2012. Spokane river minimum instream flow recommendations. Washington
   State Department of Ecology, Washington State Department of Fish and Wildlife.
   11 pp.

Quinn, J.W. and T.J. Kwak. 2000. Use of rehabilitated habitat by brown trout and
   rainbow trout in an Ozark tailwater river. North American Journal of Fisheries
   Management 20(3): 737-751.

R2 Resource Consultants (R2RC), Inc. 2008. Proposed habitat suitability criteria (HSC)
   curves for application in habitat – flow modeling for the Sultan River instream
   flow study – RSP 3. Draft report prepared by R2RC for Public Utility District
   No. 1 of Snohomish County and City of Everett. 60 pp.

Raleigh, R.F., T. Hickman, R.C. Solomon, and P.C. Nelson. 1984. Habitat suitability
   information: rainbow trout. U.S. Fish and Wildlife Service FWS/OBS-82/10.60.
   64 pp.

Rempel, L.L., K. Healy, and F.J.A. Lewis. 2012. Lower Fraser River juvenile fish
   habitat suitability criteria. Canadian Technical Report of Fisheries and Aquatic
   Sciences 2991: ix. 73 pp.

Roghair, C.N., and D.R. Nuchols. 2005. Guide to stream habitat characterization using
   the BVET methodology in the George Washington-Jefferson National Forest,
   Virginia. Center for Aquatic Technology Transfer. 24 pp.

Roni, P., T. Bennett, S. Morley, G.R. Pess, K. Hanson, D. Van Slyke and P. Olmstead.
   2006. Rehabilitation of bedrock stream channels: the effects of boulder weir
   placement on aquatic habitat and biota. River Research and Applications 22:
   967-980.

Roni, P., K. Hanson, and T. Beechie. 2008. Global review of the physical and
   biological effectiveness of stream habitat rehabilitation techniques. North
   American Journal of Fisheries Management 28: 856-890.

Rosenfeld, J. 2003. Assessing the habitat requirements of stream fishes: an overview
   and evaluation of different approaches. Transactions of the American Fisheries
   Society 132(5): 953-968.

Rosgen, D.L. 1994. A classification of natural rivers. Elsevier Science B.V.
   Amsterdam. Catena 22: 169-199.

Rosgen, D.L. 1996. Applied rive morphology. Wildland Hydrology Books. Lakewood, Colorado.

Rosgen, D.L. 2010. Applied fluvial geomorphology. Wildland Hydrology Books. Pagosa Springs, Colorado.

Ross, John. 2005. Trout Unlimited's Guide to America's 100 Best Trout Streams, Updated and Revised. The Lyons Press. 384 pp.

Runge, J.P., J.T. Peterson, and C.R. Martin. 2008. Survival and dispersal of hatchery-raised rainbow trout in a river basin undergoing urbanization. North American Journal of Fisheries Management, 28: 745-757.

Sain, R.L. 2006. Characterizing how fish communities and physical habitat structure are affected by urbanization in an East Tennessee watershed. University of Tennessee, Knoxville. 112 pp.

Sando, S.K. 1981. The spawning and rearing habitats of rainbow trout and brown trout in two rivers in Montana. Montana State University. Bozeman, Montana. 55 pp.

Simonson, T.D., J. Lyons, and P.D. Kanehl. 1994. Quantifying fish habitat in streams: transect spacing, sample size, and a proposed framework. North American Journal of Fisheries Management 14: 607-615.

Sitka Electric Department. 2005. Revised draft habitat suitability curves and coho salmon and steelhead trout. Draft report prepared for Blue Lake Hydroelectric Project, FERC No. 2230. Sawmill Creek, Alaska. 28 pp.

Southern California Edison (SCE). 2004. CAWG 3 – instream flow studies: PHABSIM technical study report. Report prepared for Combined Aquatics Working Group by SCE. Big Creek, California. 739 pp.

Southern California Edison (SCE). 2007. CAWG 3 – instream flow studies: stranding report.Report prepared for Combined Aquatics Working Group by SCE. Big Creek, California. 98 pp.

Stillwater Sciences. 2012. Lower Tuolumne River instream flow studies: pulse flow study report. Final. Prepared by Stillwater Sciences, Berkeley, California for Turlock Irrigation District and Modesto Irrigation District, California.

Sturges, H. A. 1926. The choice of a class interval. Journal of the American Statistical Association 21:65-66.

Suchanek, P.M., R.L. Sundet, and M.N. Wenger. 1984. Resident fish habitat studies. Part 6 in D.C. Schmidt, S.S. Hale, D.L. Crawford, and P.M. Suchanek, eds. ADF&G, Susitna Hydro Aquatic Studies, Report 2: resident and juvenile anadromous fish investigations (May-October 1983).

Sullivan, K., T.E. Lisle, C.A. Dolloff, G.E. Grant, and L.M. Reid. 1987. Stream channels: the link between forests and fishes, 39-97. Streamside management: forestry and fishery interactions. University of Washington, Seattle.

Sullivan, M. and A. Grubh. 2011. Winter diet composition of introduced rainbow trout and macroinvertebrate assemblages in the Guadalupe River, Texas. Texas State University, San Marcos. 28 pp.

Swink, W.D. 1983. Survey of stocking policies for tailwater trout fisheries in the southern United States. The Progressive Fish-Culturist, 45:2, 67-71.

Tabor, R.A. and W.A. Wurtsbaugh. 1991. Predation risk and the importance of cover for juvenile rainbow trout in lentic systems. Transactions of the American Fisheries Society 120: 6, 728-738.

Terre, D.R. and S.J. Magnelia. 1996. Survey report for the Guadalupe River in Kendall and Comal counties, Texas, 1995. Texas Parks and Wildlife Department, Federal Aid in Sport Fish Restoration Project F-30-R, Job No. 21, Austin. 54 pp.

Texas Commission on Environmental Quality (TCEQ). 2014. Texas Surface Water Quality Standards, Rule Project No. 2012-001-307-OW, page 88.

Texas Water Development Board (TWDB). 2012. Water for Texas 2012 state water plan. 314 pp.

Thomas R. Payne & Associates. 1991. Instream flow study for Mild Ranch, Bucks, and Grizzly Creeks, Bucks Creek Project (FERC 619). Prepared for Pacific Gas and Electric Company Technical and Ecological Services, San Ramon, California.

Thomas R. Payne & Associates. 2004. Klamath hydroelectric project (FERC No. 2082) habitat suitability criteria. Report prepared for PacifiCorp by Thomas R. Payne & Associates. Portland, Oregon. 114 p.

Thurow, R.F. and J.G. King. 1994. Attributes of Yellowstone cutthroat trout redds in a tributary of the Snake River, Idaho. Transactions of the American Fisheries Society, 123: 1, 37-50.

Twilley, R.R., E.J. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D.J. Reed, J.B. Rose, E.H. Siemann, R.G. Wetzel, and R.J. Zimmerman. 2001. Confronting climate change in the Gulf Coast region: prospects for sustaining our ecological heritage. Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, DC.

Urabe, H. and S. Nakano. 1998. Contribution of woody debris to trout habitat modification in small streams in secondary deciduous forest, northern Japan. Ecological Research 13: 335-345.

U.S. Bureau of Reclamation. 2006. Final environmental impact statement: Navajo Reservoir operations. U.S. Department of the Interior, Bureau of Reclamation, Upper Colorado Region-Western Colorado Area Office. Grand Junction – Durango, Colorado.

U.S. Fish and Wildlife Service. 2008. Flow-habitat relationships for juvenile spring/fall-run Chinook salmon and steelhead/rainbow trout rearing in the Yuba River. U.S. Fish and Wildlife Service, Sacramento, California.

U.S. Fish and Wildlife Service. 2010. Flow-habitat relationships for spring and fall-run Chinook salmon and steelhead/rainbow trout spawning in the Yuba River. U.S. Fish and Wildlife Service, Sacramento, California.

U.S. Forest Service. 1985. Fisheries habitat survey handbook. Ogden, UT: U.S. Forest Service, Region 4. FSH 2609.23. 400 pp.

Walker, J. and P. Scheuren. 2012. A report of the economic impact of water recreation tourism in unincorporated parts of Comal County, TX. Water-Oriented Recreation District of Comal County (WORD). Canyon Lake, TX. 16 pp.

Webb, P.W. 2006. Use of fine-scale current refuges by fishes in a temperate warm-water stream. Canadian Journal of Zoology 84: 1071-1078.

Wehrly, K.E., L. Wang, and M. Mitro. 2007. Field-based estimates of thermal tolerance limits for trout: incorporating exposure time and temperature fluctuation. Transactions of the American Fisheries Society 136: 365-374.

Wesche, T.A., C.M. Goertler, and C.B. Frye. 1987. Contribution of riparian vegetation to trout cover in small streams. North American Journal of Fisheries Management 7(1): 151-153.

White, R.L. 1968. Evaluation of catchable rainbow trout fishery. Texas Parks and Wildlife Department, Federal Aid in Sport Fish Restoration Project F-2-R-15, Job E-9, Austin. 24 pp.

Whiteway, S.L., P.M. Biron, A. Zimmermann, O. Venter, and J.W.A. Grant. 2010. Do in-stream restoration structures enhance salmonid abundance? A meta-analysis. Canadian Journal of Fisheries and Aquatic Sciences 67: 831-841.

Wiley, R.W. and D.J. Dufek. 1980. Standing crop of trout in the Fontenelle tailwater of the Green River. Transactions of the American Fisheries Society 109: 168-175.

Winkelaar, M. 2010. Data collection and analysis of a bathymetric model of Pineview Reservoir, Utah. Utah State University, Logan. 25 pp.

Yuba County Water Agency (YCWA). 2012. Fish behavior and hydraulics near Narrows 2 Powerhouse. Report prepared by YCWA Yuba River Development Project. FERC Project No. 2246. 114 pp.

II. EVALUATION OF SIDE SCAN SONAR FOR HABITAT MAPPING IN A SEMI-WADABLE RIVER

INTRODUCTION

Low-cost, recreational-grade side scan sonar (SSS) systems are a relatively new and inexpensive technology used for habitat mapping in riverine habitats. Large, navigable rivers or turbid systems pose challenges for traditional habitat surveying techniques, and SSS technology provides a rapid, flexible method of collecting large-scale habitat data (Kaeser and Litts 2010). Side scan sonar has been used in rivers to map large woody debris (LWD), (Kaeser and Litts 2008), investigate sedimentation issues (Singer et al. 2008), identify fish species (Hale et al. 2003; McCarty 2014; Flowers and Hightower 2015), and recover abandoned fishing gear (Kappenman and Parker 2007). With further development, this technology could provide the bulk of spatial habitat data to fisheries research and management on rivers.

Side scan sonar is a form of remote sensing that generates underwater imagery using acoustic pulses (Fish and Carr 1990). These pulses are sent out by the transducer and reflected back by underwater objects. Timing and amplitude of the sonar signals are recorded and processed, creating a continuous 2-dimensional image of the bottom of a waterbody and any objects that were insonified. Traditional SSS systems have seen limited use in inland aquatic systems presumably due to expense, expertise and specialized software required to operate, and reliance on towed transducers. Recent releases of low-cost, recreational-grade SSS have allowed investigators to map shallow, rocky streams and rivers on a large scale (Kaeser and Litts 2010; Kaeser et al. 2012).

Side scan sonar was used in the Rainbow Trout habitat availability study of the Canyon Reservoir tailrace to map substrate and instream cover. Instream cover refers to objects within the wetted river channel that can provide velocity or predator refuge such as LWD or boulders. Side scan sonar was employed in conjunction with traditional habitat survey techniques, mainly in areas of the river too deep or swift to wade.

The purpose of this study was to evaluate the efficiency and applicability of side scan sonar for habitat mapping in river systems similar to the Canyon Reservoir tailrace. Objectives include assessing the ease of use, equipment preparation, time requirements, post processing, image quality, and accuracy of SSS. This information can provide recommendations to researchers or fisheries managers for purchasing, planning, and implementing SSS surveys on riverine environments. Assessing the capabilities and limitations of the technology is an important step in the development of new applications of low-cost, SSS instream habitat mapping.

STUDY AREA

The study area of the Canyon Reservoir tailrace spanned 16.7 km below the outflow of Canyon Reservoir. Some sections of the tailrace can be waded and some are too deep to wade. Paddlecraft can make it through the tailrace with several portages. While continuous navigation is possible in some sections, motorized watercraft cannot navigate the entire tailrace due to low-water dams and other obstructions. Side scan surveys were performed in accessible areas of the tailrace using aluminum jon boats powered either by trolling motor or jet drive outboard.

Discharge on the tailrace is variable with periodic high flow events. Median discharge on the Canyon Reservoir tailrace is approximately 3.96 cms. For the duration of this study the median discharge rate was 1.81 cms (Figure 2.1). The high flow events that occurred at the beginning and end of the study period were accompanied by debris and stained water. During high discharge events some sections of the tailrace become turbulent with boulder obstacles and Class III rapids.

A TPWD habitat survey from the Canyon Reservoir Dam outflow to 17.1 km downstream in 2006, using the basinwide visual estimation technique (BVET), (Roghair and Nuchols 2005) found 75% pools and 13% riffles (author's unpublished data). Mean thalweg depth was 102 cm and mean river width was approximately 40 m. Dominant substrates were bedrock (61%), boulder (14%), large gravel (11%), and cobble (7%).

METHODS

Side Scan Sonar Setup

The SSS used in this study was a Humminbird® 1198c side imaging system

(Johnson Outdoors Marine Electronics, Inc.). The control head was mounted on a

plywood platform and the transducer was mounted on a modified trolling motor bracket

equipped with a wooden pole. The transducer was mounted at the bottom of the pole and

the magnetic external GPS antenna was mounted to a metal plate at the top. Coordinate

data for waypoints and track points were provided by a Garmin® GPSmap 535s unit. The

setup allowed transferability between watercraft with no permanent attachment or wiring

to boat hulls. The transducer was bow-mounted as suggested by Kaeser and Litts (2010)

to avoid turbulence caused by prop wash, and deployed 4 to 6 inches underwater to avoid

disruption caused by it rising above the surface. The trolling motor mount allowed for

secure deployment of the transducer and could easily be raised to remove debris, avoid

obstacles, or travel between sites. All SSS data collection was conducted in a

downstream direction.

Side scan sonar settings were adjusted to provide the clearest imagery given the

water conditions, river width, and depth. The Humminbird 1198c offers two operating

frequencies for SSS (455 kHz and 800 kHz); 455 kHz was used for this study to allow

imaging in deeper water and maximize bottom coverage. Sub-slant range correction was

not applied to sonar images displayed on the control head. Range was estimated or tested

to capture imagery from bank to bank, while minimizing unidentifiable areas located

beyond the streambanks. Increasing range decreases resolution (Fish and Carr 1990).

For portions of river over 100 meters wide or if a depth-to-range ratio of 10-20% could

not be maintained, several passes were taken. To improve image quality, sensitivity and contrast were either set to 10/13 or 8/12 respectively.

Field Trials

Before the data collection phase began, field trials were conducted with various watercraft and equipment configurations. All trial runs took place in study section three. Initial tests involved a five-meter long Cataraft rowed with two side-mounted oars. Final tests utilized a three-meter long john boat powered by a trolling motor and a four and a half-meter long aluminum boat with a 35 hp outboard motor jet drive. Equipment setup, boat control, speed, snapshot timing, data transfer, and maintaining good image quality were all practiced and evaluated. Pros and cons of each vessel were noted and the usefulness of each in the tailrace was considered.

Sonar data were processed, and habitat maps produced in sonar surveyed areas of the river by A. Kaeser using methods described in Kaeser and Litts (2008, 2010). Resolution, snapshot timing, boat control, and SSS settings were modified and improved over time with feedback from collaborators. Final imagery was georeferenced using track points and mosaicked together. Substrate and woody debris polygons were delineated and returned.

Habitat Mapping

Side scan sonar surveys collected raw image data that were later interpreted and digitized to produce maps for substrate and instream cover. Bow-mounted transducers were paired with one of two outboard motor-powered boats. A downstream, mid-channel

position was maintained with speed between 8 and 10 km/h. Drifting, swaying, or tipping of the boat was avoided to maintain image quality. Overlapping side scan images were saved along with the track file for post processing. Multiple passes were taken around islands, side channels, and wide areas of the river. Areas not mapped by sonar were surveyed using conventional survey techniques.

Side scan sonar images were processed according to Kaeser and Litts (2010). Images were transformed into sonar image maps (SIMs) using ArcGIS software and IrfanView, a graphics software viewer, which automatically crops and connects snapshots in a series based on matching attributes. Raw image mosaics were saved as JPEG (.jpg) images and georeferenced in ArcGIS by accompanying track points. These points were saved as shapefiles and processed through custom algorithms in Avenue script, creating a control point network for image transformation. Control points linked raster points to known map coordinates and were rectified to transform raw mosaics into SIMs. SIM files were saved as JPEG (.jpg) images georeferenced to UTM Zone 14, North American Datum 1983 (NAD83).

Habitat maps were produced from interpretation of the imagery. Aerial photography and nearby or overlapping data collected by conventional means assisted with interpreting substrate composition. A minimum map unit (MMU) of 314 m^2, an area equal to a circle with a 10 m radius, was established. A modified substrate classification was created to simplify interpretation (Table 2.1). Small and large gravel were combined into "gravel". Bedrock was separated into "bedrock outcrop coarse" and "bedrock outcrop smooth". Additional "no data", "unsure", and "sonar shadow" categories were added to delineate areas with poor resolution or interpretation issues.

These areas were located in the field and assigned the appropriate class, or surrounding substrate was used as a surrogate. River bank and substrate boundaries were digitized in ArcView 9.2. Since slant range correction was not performed, substrate boundaries that intercepted the water column were properly interpreted as extending to the center of the image. Large woody debris mapping was conducted as described in Kaeser and Litts (2008). Large woody debris was first denoted with points then delineated with polygons after field verification. All imagery were interpreted at one time for consistency.

Habitat data from conventional and SSS were compiled in ArcView 9.3. Areas of overlap, previous habitat studies, aerial photography, and ground truthing were used to create a final coverage of substrate and instream cover polygons.

Accuracy Assessment

Random reference points for substrate delineated from both conventional field collection and SSS were ground truthed. Three-hundred points were randomly selected for all study sections using Hawth's Tools in ArcView 9.3. Of these points, 170 were selected from conventional surveying and 130 were selected from SSS based on area. Number of points selected per substrate class was also based on area. A buffer of 2 m from substrate boundaries was used to contain reference points sufficiently inside of polygons to reduce effects of GPS error (4 m between adjacent polygons). Surveys were performed by a two-person team on kayaks using a Trimble GeoXT handheld GPS to navigate to each random sampling point. Snorkeling, wading, poling, and benthic sampling were used to classify substrate at each position. Substrate class was recorded and later compared to original classification.

Instream cover surveys took place in conjunction with substrate surveys. One-hundred random cover polygons were selected across all study sections. Selections were weighted toward areas of the map produced via sonar interpretation since that was the focus of evaluation. Crews navigated to reference sites and confirmed whether or not cover was present, type of cover, and condition. Poling, wading, and snorkeling were used to verify instream cover. These data were compared to original classifications.

RESULTS

Habitat Mapping

Side scan sonar provided a large portion of substrate information. Overall, 3.53 river kilometers were surveyed with this method, composing 54 percent of river distance within study sections. A total of 136 substrate polygons were delineated from side imaging, with 79 of them defined and 57 undefined. Area for defined polygons ranged from 5 m^2 to 29948 m^2. Figure 2.2 illustrates the contribution of SSS collected data to the study area. For study section one (Figure 2.3) SSS provided 69 percent of river length, 54 percent of study section two (Figure 2.4), and 38 percent of study section three (Figure 2.5). Twelve substrate categories were mapped including eight defined and four undefined classes. Of the defined categories, "bedrock coarse" and "bedrock smooth" were combined into a general "bedrock" category. "Rip rap" was converted to "boulder". "Gravel" was eventually divided into "small gravel" and "large gravel" with ground truthing. "Mixed Rocky" areas were also ground truthed and placed into traditional substrate categories. Percentage of area mapped with SSS for each defined class was: gravel (44%), bedrock (24%), sand (7%), boulder (5%), silt (2%), cobble (2%), and mixed rocky (1%) for a total of 85% coverage. Issues with substrate interpretation resulted in several categories of unclassified substrate (Table 2.2). Overall, this resulted in 16 percent of the area delineated by SSS being unclassified and requiring field inspection.

Instream cover delineated by SSS accounted for 40 percent of mapped cover overall. Forty-two percent of mapped instream cover in sections one and two, and 31 percent of study section three were provided by SSS. Conventional field surveys

inventoried LWD, boulder, and undercut bank, while SSS output was almost exclusively LWD.

Accuracy Assessment

Accuracy was assessed for conventional, SSS, and overall substrate data collection. Error matrices allowed comparison of each method and provided producer's and user's accuracy assessments. Producer's accuracy describes the probability that initial classifications are correct, and user's accuracy describes the probability that mapped data is correct in the field (Kaeser and Litts 2010).

Overall substrate accuracy was 83% (conventional = 86%, SSS = 78%, Tables 2.3 and 2.4). User's accuracy for both methods combined ranged from 27% (sand) to 91% (cobble, Table 2.3). Producer's accuracy for both methods combined ranged from 0% (organic matter, LWD) to 100% (boulder). Conventional surveying user's accuracy ranged from 69% (silt) to 94% (cobble), while producer's accuracy ranged from 0% (organic matter) to 100% (boulder, bedrock). Side scan sonar user's accuracy ranged from 33% (sand) to 100% (silt), while producer's accuracy ranged from 0% (organic matter, LWD) to 100% (large gravel, boulder). Side scan substrate maps did not delineate small gravel, large gravel, or vegetation so these were not available for comparison.

Overall accuracy of identifying instream cover was 73 percent. Conventional methodology was 83 percent accurate, with 20 reference sites out of 24 being classified correctly. SSS was 70 percent accurate, with 53 out of 76 reference sites classified correctly. Of the 23 objects misidentified by SSS to be instream cover, 20 of these were

either absent of any object or the object did not meet the criteria (Height = 1.5 X adult

trout body height).

DISCUSSION

Field Trials

Several findings from the trial phase of SSS collection guided our approach.

First, the five-meter long Cataraft did not suit our needs. Since it was powered by oars, it

was difficult to maintain the recommended eight to ten km/h speed for SSS collection.

The raft also experienced drift, sway, and yaw that affected SSS output. Exhaustion from

rowing was also a factor due to extra weight for personnel and equipment and periodic

navigation upstream against current. The boats powered by motors proved to be much

better at maintaining course and speed. The smaller boat could be used in areas with

limited access and the larger jet drive could be used where ramps or suitable shoreline

allowed trailering. The larger boat had more room and was more stable, while the

smaller boat had limited weight capacity and required stable footing. The smaller boat

could be portaged around some obstructions.

Second, we found using an audible timer to take snapshots on the SSS unit

performed better than using the screen transition or a second hand on a watch to ensure

that consecutive images with a small portion of overlap were collected. Missing a

snapshot or too much overlap among consecutive images hinders post-processing.

Performing trial runs before data collection provided the time increment to set based on

travel speed and screen scrolling speed.

Third, weather and water conditions can affect results. Windy or wavy conditions

can cause the bow to bounce and either distort imagery or cause disruption in data

collection if the transducer comes out of the water (Appendix III). Debris in the water

column can cause problems with resolution and floating debris can get caught on the

transducer itself and disrupt data collection. This is why it is suggested to avoid SSS collection during first high water events of the wet season or rising water in general.

Habitat Mapping

Overall, SSS was very helpful with the completion of this project. The ability to run watercraft down a river and collect detailed, georeferenced habitat information that can be saved, viewed, processed, and analyzed offsite was invaluable. Since conventional surveying combined topography collection, was done at varying pace, and was typically done in areas not surveyed by SSS, there is no direct comparison available for time requirements. However, it is apparent SSS enabled faster data collection for substrate and instream cover. SSS has been shown to be faster than traditional, transect-based techniques on rivers at an estimated 11 min/km (Kaeser and Litts 2010). SSS also prevented the need for extensive scuba diving, benthic sampling, poling, or other subsurface surveying to capture habitat data that can't be seen from the water surface. While there are many benefits to this technology, there are still challenges and limitations with the equipment and techniques.

Originally, side scan sonar surveying was to span the entire 22.2 km tailrace. Outside of mapping substrate and instream cover within study sections this survey was to provide GRTU and TPWD an inventory of habitat and possible sites for restoration efforts. Due to several factors this was not accomplished. First, during the timeframe of this study the area had experienced drought conditions. Flows were reduced and depth/access in some areas decreased. Optimal conditions for side scan sonar are on the receding side of high flow events (Kaeser and Litts 2010). This ensures the most

scanning coverage and safe passage over shallow or rocky areas. The few high flow

events that occurred at the beginning and end of the study period were accompanied by

flooding, debris in the river, and flows which were not optimal for SSS mapping.

Another barrier to a full survey is the intermittent navigability of the tailrace.

Four low-water dams, several rapids, shallow/rocky shoals, and a waterfall are located in

this area of the river. These prevent passage of most motorized watercraft and require

portaging or finding additional access points. Other studies have utilized kayaks

(McCarty 2014) and canoes (Wensink 2005), which may be helpful in scanning the

tailrace in the future. While there were a few additional areas within study sections that

could have been surveyed with SSS, they were short in length and not worth the

equipment setup and post-processing effort. These were surveyed by traditional means.

A third barrier to SSS surveying on the river dealt with general logistics. The

high number of private landowners along the river sometimes makes gaining access a

challenge, although most residents encountered were supportive and accommodating.

The areas of dense recreational use in summer were avoided. Summer was the time of

year most available for field work and this conflicted with tubing, kayaking, and

swimming in certain sections. Finally, time constraints and scope of the study were

additional reasons a full survey was not possible.

This scenario should provide instruction to others considering SSS surveys on

rivers with similar conditions. Extensive planning, pre-surveying, testing, and ground-

truthing should be part of proposed work plans. Coordination with controlling

authorities, partners, and landowners should be done early with periodic updates. Scope

and estimated time of completion should allow for a realistic range of river conditions and challenges.

Bathymetric data to supplement topography surveys was to be collected using the Humminbird 1198c. Using the track feature, GPS coordinates along with a depth reading would be taken at one second intervals. After initial attempts, it was discovered that in shallow water (<0.5 m) the unit gave erratic depth readings. There was no way to distinguish invalid depths from true ones so this task was accomplished with the Garmin GPSmap 535s. With the Garmin unit, water too shallow for accurate measurement would cause the depth indicator to flash and depth would not be recorded for those track points. These could easily be deleted from processing and only true depth readings would remain.

Post Processing

Post processing was performed according to techniques similar to Kaeser and Litts (2010). Field collection techniques and resulting image quality were greatly improved over the duration of this study. Imagery was converted to polygon shapefiles compatible with ArcGIS software. Although, most of the processed data returned were useful for habitat analysis and modeling, some portions of imagery were not discernable (Table 2.2). The largest data gap included portions of imagery that were out of range but still within the river channel (Appendix III). This occurs when the range setting does not capture the river bank to bank. This can be improved by adjusting the range setting and restarting a scan. If range is adjusted during scanning, the image pattern is disrupted. The next phenomenon that caused problems with imagery was sonar shadow. Sonar

shadow occurs when the signal hits an object in the water column and doesn't record data behind it (Appendix III). This is largely unavoidable unless several passes/angles are taken to capture the shaded area. Most of the time, surrounding substrate can provide clues for what is being hidden. Other categories that needed further evaluation included unsure rocky, mixed rocky, or unsure. These could be due to poor resolution caused by inexperienced field crew or they can be areas of complex, heterogeneous substrate that were not easily classified. Using other habitat data or follow-up surveys to classify these areas improved the final output.

Similar portions of unclassified data should be expected with SSS studies. In a survey of 27 kilometers of Ichawaynochaway Creek, Georgia unsure areas composed seven percent of total map area (Kaeser and Litts 2010). A study investigating Black Bass habitat on the Upper Flint River, Georgia also documented missing data for seven percent of mapped areas (Goclowski et al. 2012). A benthic mapping study on the Lower Flint River documented unsure (10%), no data (4%), and sonar shadow (2%), totaling 16 percent of mapped area (Kaeser et al. 2012).

Although it has been shown that SSS can quicken and enhance data collection in the field, there can be substantial investments of time, expertise, and software for post processing. Sediment trend analysis on the Buffalo River in the 1990s utilized a Klein 590 Sonar System, which output analog paper side-scan records and required rubber-sheeting to georeferenced images using ArcMap, Adobe Photoshop, and Vidar TruInfo (Singer et al. 2006). This method was tedious, time consuming and sometimes resulted in misplacement of features. In July 2005, it was eliminated with the use of digital side scan (Klein 3000) which used SonarPro to obtain digital data and SonarWeb software to

mosaic and georeference imagery (Singer et al. 2008). A U.S. Geoglogical Survey (USGS) study on the Little Colorado River utilized a Klein 500 kHz SSS tow fish and processed images via the USGS Mini Image Processing system (MIPS), which converts raw data into geo-referenced images (Anima et al. 2007). These images were converted to TIFF format and classified by reflectance value in Adobe Photoshop. This process was time consuming and researchers recommended a separate team of experienced processors to handle post processing (Anima et al. 2007). Kaeser and Litts (2008) reported image preparation time at 63 min/km using the mosaicked snapshot method similar to this study. This was improved to 10 min/km with the incorporation of custom ArcGIS 9.2 software and IrfanView (Kaeser and Litts 2010). Further improvement to 3 min/km was made with updated tools that utilize ArcGIS 9 or 10 (Kaeser et al. 2012). Other processes follow image preparation including georeferencing, substrate digitization, substrate classification, and LWD digitization which vary in additional time requirements (Kaeser and Litts 2010). While processes have been considerably streamlined over the last decade, the software and expertise required for post processing of SSS data may be a drawback for some compared to conventional methods.

Another option to ease field collection and post processing is utilizing the recording method available on SSS units. This method is being used by researchers and agencies to collect habitat data but published accounts are sparse. This is one reason it was not used in the current study. SSS recordings have been used to assess littoral habitat changes with water level fluctuation on 11 reservoirs in the Brazos River basin in Texas (Daugherty et al. 2015). Humminbird 1198c units were employed to record swaths of submerged habitat parallel and perpendicular to shore at designated sampling sites.

Recording files were transformed to georeferenced mosaics with ArcGIS 9.3 and DrDepth Sea Bottom Mapping Software (v. 5.0.1). Another software option for post processing recordings is SonarTRX (Leraand Engineering, Inc.). This software supports recordings from Humminbird side imaging units, Lowrance StructureScan, and Garmin SideVu (SonarTRX 2015). The benefits of the recording method include elimination of timed snapshots during fieldwork and reduced post processing time devoted to connecting individual snapshots. A downside to the recording method is distorted imagery due to navigation around obstacles and sharp turns.

Accuracy Assessment

Ground truthing was imperative to create accurate substrate maps. The process revealed some inconsistencies with substrate delineation and assisted with deciphering output from traditional surveying and SSS. Accuracy for substrate and instream cover delineation was assessed for conventional, SSS, and overall data collection.

For conventional surveying, the most problematic substrate to classify was silt (69% user's accuracy). Silt was found with sand, organic matter, and gravel, either mixed or as a deposited layer on top. This required a subjective decision for what substrate actually composed the majority of that mapping unit and what roughness value should be applied for modeling. Inaccuracies for other substrates could be related to varying experience levels and training for the three field personnel designated for substrate mapping. There was a moderately high flow event that occurred between substrate data collection and ground truthing. This could have slightly altered substrate composition, resulting in decreased accuracy. Positional error associated with GPS could

be another source of inaccuracy, although an attempt was made to keep reference points well within substrate polygons.

Ground truthed substrates delineated by SSS included silt, sand, gravel, cobble, boulder, and bedrock. Small and large gravel substrates were combined into a general gravel category since it is difficult to distinguish the subtle size difference, especially if they are mixed. Side scan sonar mapped a higher percentage of gravel than previous habitat surveys, which could be due to the avoidance of shallow bedrock areas for boat work or layering of gravel on top of bedrock. The substrate category that had the lowest user's accuracy was sand (33%). Of 15 reference points classified as sand, only 5 were correct. Eight of these points were confirmed as silt and one was confirmed as small gravel. The resolution of the SSS unit makes interpretation of fine sediment difficult (Kaeser and Litts 2010), and this most likely explains the low accuracy for this category. Low user's accuracy of Cobble (50%) and boulder (57%) were probably functions of low sample size with 2 and 7 reference sites checked. The lowest producer's accuracies were organic matter (0%) and LWD (0%). These substrate classes are not typically delineated using SSS and involve subjective field classification to parse out mixing. The low producer's accuracy for silt (24%) was primarily caused by confusion with sand due to resolution. The misclassification of silt as gravel and bedrock was probably due to a silt layer on top of these substrates. In side imaging, a silt/sand layer may show the shape and texture of underlying substrate but it may be thick enough to be classified as silt or sand for roughness values used in hydraulic modeling. A similar situation was documented in the Flint River where reference sites classified as sand through imagery, were revealed to be a fine layer covering other substrates (Kaeser et al. 2012). The low

producer's accuracy of cobble (33%) was due to confusion with gravel, but a low number of reference points (3) probably exaggerated this issue.

The overall accuracy of the SSS portion of this study (78%) is representative of other side imaging studies. Kaeser and Litts (2010) had an overall accuracy of 77% for Ichawaynochaway Creek. User's accuracy for interpreting SSS imagery ranged from 61% to 90% for that study, while producer's accuracy ranged from 69% to 83%. Authors attributed misclassifications to confusion between boulder types, fine sediment types, and limerock sizes. Interpretation was complicated by excessively detailed substrate types, transition zones, image compression in the center of images, and particles below the transverse resolution (63.5 mm) of the Humminbird unit (Kaeser and Litts 2010). Transverse resolution (target separation) refers to the ability to distinguish between objects parallel to survey path (Fish and Carr 1990). Due to resolution limitations, sand and small gravel had similar textures in imagery, but when observed at a larger scale sand exhibited dunes or ripples (Kaeser and Litts 2010). Accuracy was improved when similar methods were used on the Flint River where overall accuracy was 84%, producer's accuracy ranged from 77% to 96%, and user's accuracy ranged from 72% to 100% (Kaeser et al. 2012). Authors attributed improvement to enhanced ability to identify coarse-textured substrate and because substrate patches had more defined edges in this portion of the river. They attributed most misclassifications to interpretation of fine substrates.

Accuracy for instream cover varied between conventional and SSS methods. Conventional surveying had 83% accuracy due to two reference sites classed as LWD but nothing found during ground truthing and two sites that were classified as LWD but

verified as boulder. The absence of LWD could have been due to positional error, objects being moved by high flow, or removal by landowners or river authorities. Boulders misclassified as LWD could have been caused by stumps or branches protruding to the water surface out from a hidden boulder complex. It is also possible field crew selected the wrong cover type in Trimble data dictionaries. For SSS, three reference sites were classed as LWD but verified as boulder. This could be due to resolution issues or signal readings on the edge of boulder/bedrock resembling branches or logs. Twenty reference sites were classed as LWD but either nothing was found or the woody debris present did not fit the criteria to be considered cover for adult trout. For the sites where nothing was found, the same reasons given to conventional surveying apply. Sites with woody debris present but not of a sufficient size could be explained by several factors. The criteria for an object to provide sufficient cover for trout is protection from velocity, predators, or both and a height that is 1.5 times the body height of an adult trout. Object height in side imaging is difficult to measure, although sonar shadow can give an indication to height. Also, the angle of side imaging may not fully capture the complexity of the object. Those delineating LWD from SSS were possibly marking any type of woody debris they identified, and were unaware of criteria. Large woody debris can be readily identified by SSS, especially large logs and complexes, but size and orientation can affect accuracy necessitating ground truthing (Kaeser and Litts 2008).

Limitations of Side Scan Sonar

Shallow water can be a limitation with SSS. For this study, the minimum depth SSS was effective was about 0.5 m. This applied to side scan imaging as well as depth

collection. The angle of the signal and recommended depth-to-range ratio mean a narrow swath of imagery can be collected in shallow water. For depth, inaccurate readings were recorded at 0.5 m and below. Rocky terrain, obstructions, and flow brought risk of damage to transducer and watercraft at water depths less than 0.3 m. Other studies have had similar results. Evaluations of a River Surveyor acoustic Doppler profiler (ADP) system in several streams in Ohio revealed a minimum effective depth of 0.6 m (Wensink 2005). Below this depth, the investigator experienced "blanking" in which velocity and bathymetry data were invalid. A study measuring stream channel habitat on the Green River near Vernal, Utah utilized a Raytheon Marine model V850 sonar (Flug et al. 1998). Authors reported accuracy problems at depths under 0.8 m, but managed to acquire some useful data at depths to 0.6 m.

Resolution issues can inhibit interpretation of imagery and decrease accuracy. Increasing sonar range decreases transverse resolution, affecting the ability to discriminate far-field objects (Kaeser et al. 2012). This means multiple passes might be required to maintain resolution in shallow water or wide rivers. Substrate sizes below the transverse resolution of SSS units usually require ground truthing. Visual cues developed during pre-survey trials to build demonstration data sets can also be useful in classifying fine substrates. Data gaps such as sonar shadow, data out of range, and interference can be mitigated with additional surveying. Training for inexperienced users in field collection, unit operation, and image interpretation must take place to ensure data quality.

Positional accuracy is required for georeferencing imagery. Some SSS models may not have sufficient GPS capabilities to ensure the horizontal accuracy required for post processing especially in canopy situations. The stated GPS accuracy of the

Humminbird 1198c is +/- 4.5 meters 95% of the time, and +/- 3.0 meters 95% of the time

with the Wide Area Augmentation System (WAAS), (Humminbird 2011). Handheld

GPS devices such as WAAS-enabled Garmin or Trimble units can be connected to SSS

systems to improve this. Map accuracy assessments can be employed to evaluate

positional accuracy as well as dimensional accuracy of transformed imagery (Kaeser and

Litts 2010).

Cost, time, software, expertise, and training for post processing of SSS imagery

could be a limitation for some researchers. Although cost and time are saved upfront

with field collection, post processing involves multiple steps that require specific

software and skills that could be costly to obtain. It is recommended that users seek

training to identify substrate patterns, quality control be performed by experienced map

makers, and SSS projects include accuracy assessments (Kaeser et al. 2012).

Demonstration data sets, training, georeferencing, and map accuracy assessments all

increase post processing time. These issues will likely improve as software becomes

available at lower cost and made more user friendly.

Side scan sonar is limited to where it can be used. River conditions and

characteristics for this study posed several challenges to the operation of SSS, although

some areas were well suited for this technology. Small, wadable streams would not be

suited for SSS since these systems are boat mounted and traditional surveying could

sufficiently map these environments. For river systems, recreational grade SSS is best

for continuous, deep, low gradient stream systems with minimal sinuosity and flow

regimes that allow safe operation at high flows to maximize habitat imaging within the

bankfull channel (Kaeser and Litts 2010). Rivers with numerous low water dams,

waterfalls, rapids, obstructions, thick or matted vegetation or standing timber may pose problems for operation and interpretation of SSS. Rivers with low flow conditions or large expanses of shallow water (<0.5 m) could also limit use of SSS. High flow conditions, especially in systems where rocks, boulders, rapids, or debris are present could pose safety issues and risk of damage to transducer or watercraft.

Benefits of Side Scan Sonar

The upfront benefit to using recreational grade SSS is expense. These systems typically cost around $2,000, which is much cheaper than salt water grade systems that utilize tow fish. Side scan sonar is much less expensive than other remote sensing methods such as bathymetric LIDAR, radar, aerial photography, or hyperspectral imagery and isn't as limited by canopy cover (Kaeser and Litts 2010). Additional accessories and equipment may need to be purchased to make the system fully functional and compliant with scientific standards. Research and development has led to cost-effective techniques to collect and geoprocess sonar data in large-scale riverine environments (Kaeser and Litts 2010).

Side scan sonar reduces field collection time and effort compared to other methods. Sonar habitat mapping is quicker than traditional, transect-based methods and has similar accuracy (Kaeser and Litts 2010). For the Canyon Reservoir tailrace, SSS enabled faster data collection of substrate and instream cover than would have been obtained by other means. It also provided a more detailed, high resolution visual reference to use for interpretation and habitat inventory. For deeper areas, SSS was faster, safer, and more efficient than scuba diving, poling, or other benthic sampling

techniques. It enabled more accurate habitat mapping in water depths that would be passed over using visual estimation techniques.

The flexibility of recreational grade SSS makes it a useful tool for a variety of habitats and purposes. The system can be mounted on a variety of watercraft and used in lakes, ponds, small streams, and large rivers. The acoustic technology allows for use in deep or turbid stream systems, where traditional survey methods are difficult to conduct (Kaeser and Litts 2010). Side scan sonar can collect riverine data spanning substrate, instream cover, sedimentation, habitat availability/association, river morphology, fish density, and limited fish identification.

Recommendations for Side Scan Sonar Surveying

Trial runs are recommended before any data acquisition for side imaging of rivers. Equipment setup, unit settings, operation, watercraft type/ability, river conditions, access, flow, speed, and general logistics can be assessed and modifications can take place before the data collection phase. Issues with resolution such as interference, depth-to-range ratio, image interpretation, and data gaps can be dealt with to ensure image quality. Demonstration data sets can begin to be formed at this point to assist with future image interpretation. If snapshots are to be used, timing method can be practiced. Area capable of being surveyed and appropriate time of completion can be estimated. Trial runs can also allow users to practice data transfer, storage, and post processing.

Training on all aspects of SSS data collection, interpretation, and processing can be invaluable, especially to novices. Those with more experience or training can collect higher quality imagery and classify habitat more accurately, reducing the need for

additional surveys due to poor image resolution. Oversight and verification by experienced personnel are useful, but training can decrease the reliance on external assistance that can extend completion time. Training is provided through universities, federal and state agencies, manufacturers of SSS technology, and professional fisheries organizations such as the American Fisheries Society. Training is also available through online sources and manuals such as those provided by the U.S. Fish and Wildlife Service below.

http://www.fws.gov/panamacity/sonarhabitatmapping.html

Map accuracy assessments should be done to assess the quality of data acquisition and interpretation. Assessment of positional, dimensional, and classification accuracy will allow correction of map data and quantify the precision of spatial data. Substrate and instream cover assessments should follow classification as soon as possible to reduce effects of sediment transport or changes in river morphology after high flow events (Kaeser et al. 2012). Reference points should be sufficient to ensure a good sample size and assigned randomly within substrate polygons.

Recommendations to recreational grade side scan manufacturers could include upgrades to make control units more user-friendly and adaptable for scientific applications. Audible timers could be added to head units to assist with spacing of snapshots. Improved GPS accuracy could reduce the need for additional units to be synched with surveys. Depth collection could be more accurate and avoid recording false depths. Adding post processing capabilities to proprietary software that comes with SSS units would streamline geoprocessing. The ability to mosaic and georeference output from accompanying systems would reduce the need for multiple software programs and

data conversions. The AutoChart-Live feature from Humminbird's ONIX side imaging system is an example of this type of software integration. Further development to reduce distortion in recordings may make data collection and processing easier. These improvements may increase cost. However, a single SSS system with scientific instrumentation could make this method more efficient and still be competitively priced.

Table 2.1: Substrate classification for side scan sonar on the Canyon Reservoir tailrace (2010-2015).

Substrate Class	Definition
Organic Matter	Dead leaves, twigs, etc.
Silt	>75% of area composed of particles <2 mm diameter, slippery, does not hold form when rolled
Sand	>75% of area composed of particles $\leq$2 mm diameter, grainy
Gravel	Sand to fist size, >25% of area composed of gravel
Cobble	Fist to Head size, >25% of area composed of cobble
Boulder	Larger than head size, any area greater than MMU with boulders, regardless of underlying substrate
Bedrock Outcrop Smooth	Solid Rock, >25% of area composed of solid rock, Smooth surface
Bedrock Outcrop Coarse	Solid Rock, >25% of area composed of solid rock, Rough/broken surface
Mixed Rocky	Area composed of 2 or more substrate classes (at least 1 being rocky) arranged such that no homogeneous portion is $\geq$ MMU
Unsure	An area of the sonar map difficult to classify due to reduced image resolution
Sonar shadow	An area of the sonar map within range that was not imaged because the sonar signal was blocked by reflective objects
No data	An area of the sonar map beyond sonar range but within the boundaries of the river channel
Vegetation	>75% of area composed of vegetation, species to be groundtruthed and recorded
Large Woody Debris	>75% of area composed of large woody debris

MMU = Minimum Mapping Unit

Table 2.2: Data gaps in substrate mapping due to resolution/interpretation of side scan imagery of the Canyon Reservoir tailrace (2010-2015).

Data Gaps	Area (m^2)	Percent
No data (out of range)	10345	7.93
Sonar shadow	8088	6.20
Unsure rocky	921	0.71
Mixed rocky	817	0.63
Unsure	337	0.26
Total:	**20507**	**15.72**
Total Area delineated:	**130455**	

Table 2.3: Standard error matrix and associated statistics for substrate accuracy on the Canyon Reservoir tailrace (2010-2015). Side scan sonar and conventional surveying methods included. Substrate categories on the left side are initial classifications and categories at the top are confirmed substrates. Shaded cells indicate correct classifications.

Classified Data	Reference Site Data										Row Total	User's Accuracy
	Si	Sa	Sg	Lg	Co	Bo	Br	Veg	Om	LWD		
Si	13			2					2		17	76%
Sa	8	5	1				1				15	27%
Sg			10	2							12	83%
Lg	1		2	19	1						23	83%
Co				1	32		1	1			35	91%
Bo		2		1	1	23		1	1		29	79%
Br	3		2	4			75				84	89%
Veg					1			8	1		10	80%
Gravel	4		28*	36*	2		1			4	75	85%
Column Total	30	6	43	65	37	23	78	10	4	4	300	
Producer's Accuracy	43%	67%	88%	85%	86%	100%	96%	80%	0%	0%	Overall Accuracy 83%	

Si = silt, Sa = sand, Sg = small gravel, Lg = Large gravel, Co = cobble, Bo = boulder, Br = bedrock, Veg = vegetation, Om = organic matter
*Reference site confirmations of small and large gravel were considered correct for SSS gravel classification.

Table 2.4: Standard error matrices comparing conventional versus side scan sonar substrate delineation on the Canyon Reservoir tailrace (2010-2015). Shaded cells indicate correct classifications.

Classified Data	Conventional Surveying Reference Site Data								Row Total	User's Accuracy
	Si	Sg	Lg	Co	Bo	Br	Veg	Om		
Si	9		2					2	13	69%
Sg		10	2						12	83%
Lg	1	2	19	1					23	83%
Co			1	31			1		33	94%
Bo			1	1	19		1		22	86%
Br	2	1	4			50			57	88%
Veg	1			1			8		10	80%
Column Total	13	13	29	34	19	50	10	2	170	
Producer's Accuracy	69%	77%	66%	91%	100%	100%	80%	0%	Overall Accuracy 86%	

Classified Data	Side Scan Sonar Reference Site Data									Row Total	User's Accuracy
	Si	Sa	Sg	Lg	Co	Bo	Br	Om	LWD		
Si	4									4	100%
Sa	8	5	1				1			15	33%
Gravel	4		28	36	2		1		4	75	85%
Co					1		1			2	50%
Bo		2				4		1		7	57%
Br	1		1				24	1		27	89%
Column Total	17	7	30	36	3	4	27	2	4	130	
Producer's Accuracy	24%	71%	93%	100%	33%	100%	89%	0%	0%	Overall Accuracy 78%	

Si = silt, Sa = sand, Sg = small gravel, Lg = Large gravel, Co = cobble, Bo = boulder, Br = bedrock, Veg = vegetation, Om = organic matter
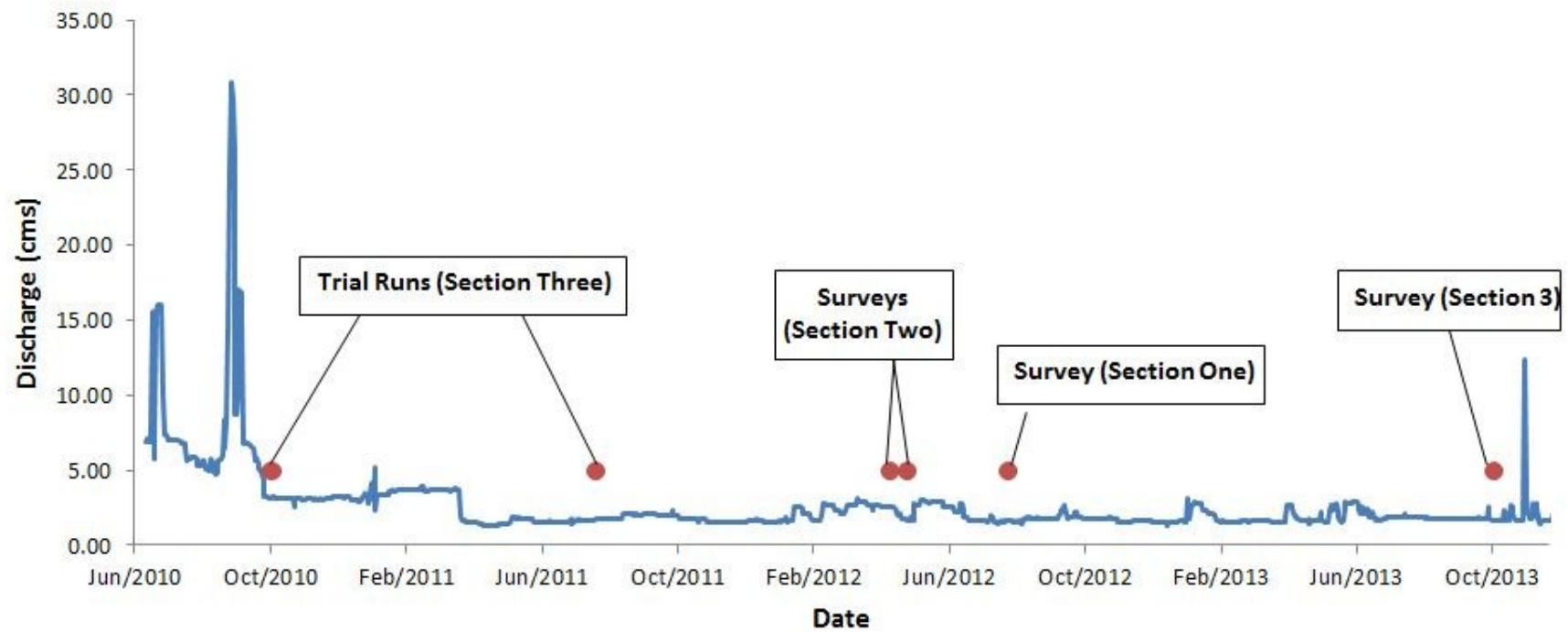
Figure 2.1: Hydrograph of the Canyon Reservoir tailrace and side scan sonar surveys completed during the study period (2010-2013). Hydrograph is for Guadalupe River at USGS Sattler gauge (June 2010-October 2013). Survey dates are depicted by red circles and discharge is depicted by blue line.
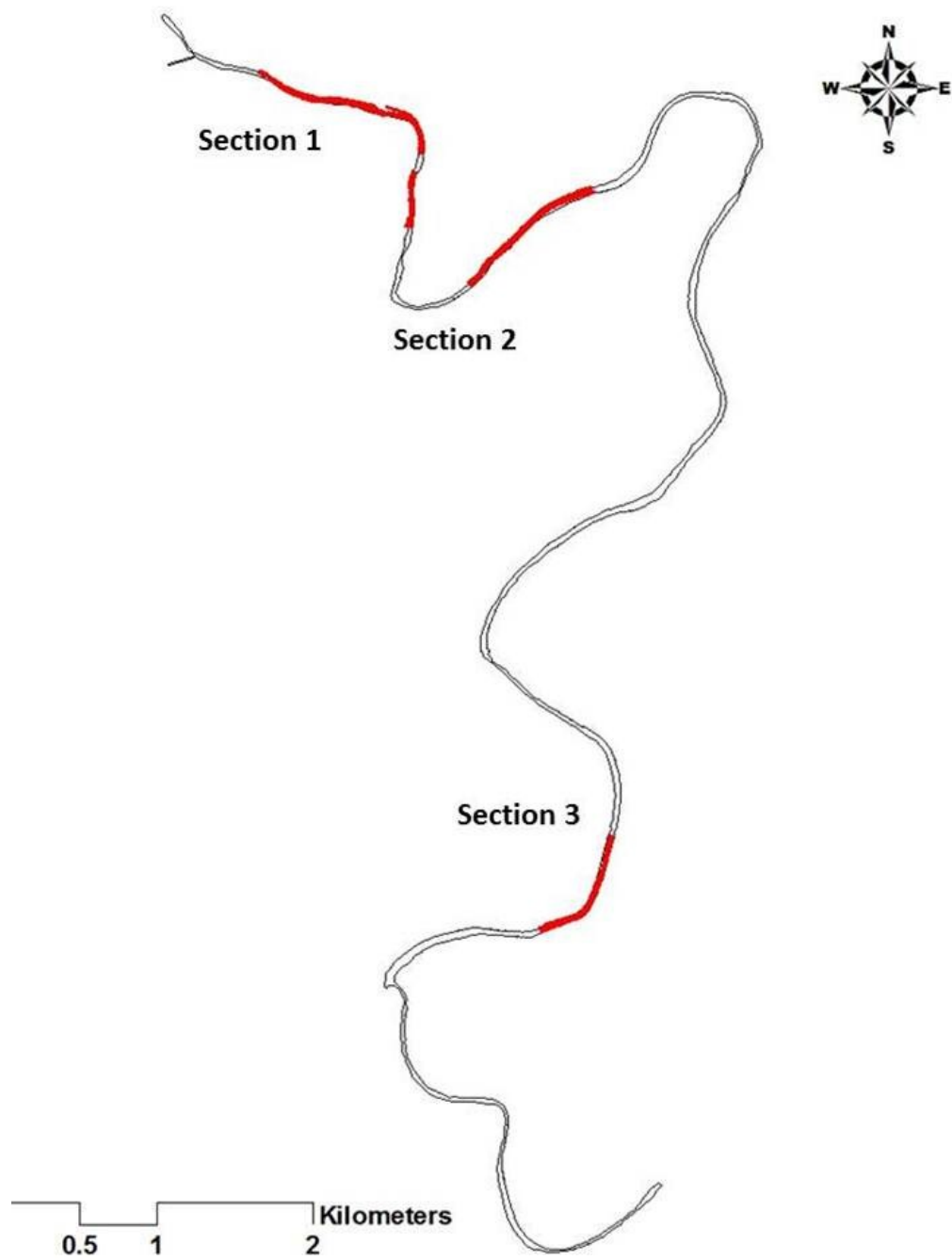
Figure 2.2: Study sections and side scan sonar survey areas on the Canyon Reservoir tailrace (2010-2015). Red areas indicate where side scan sonar surveys were performed.
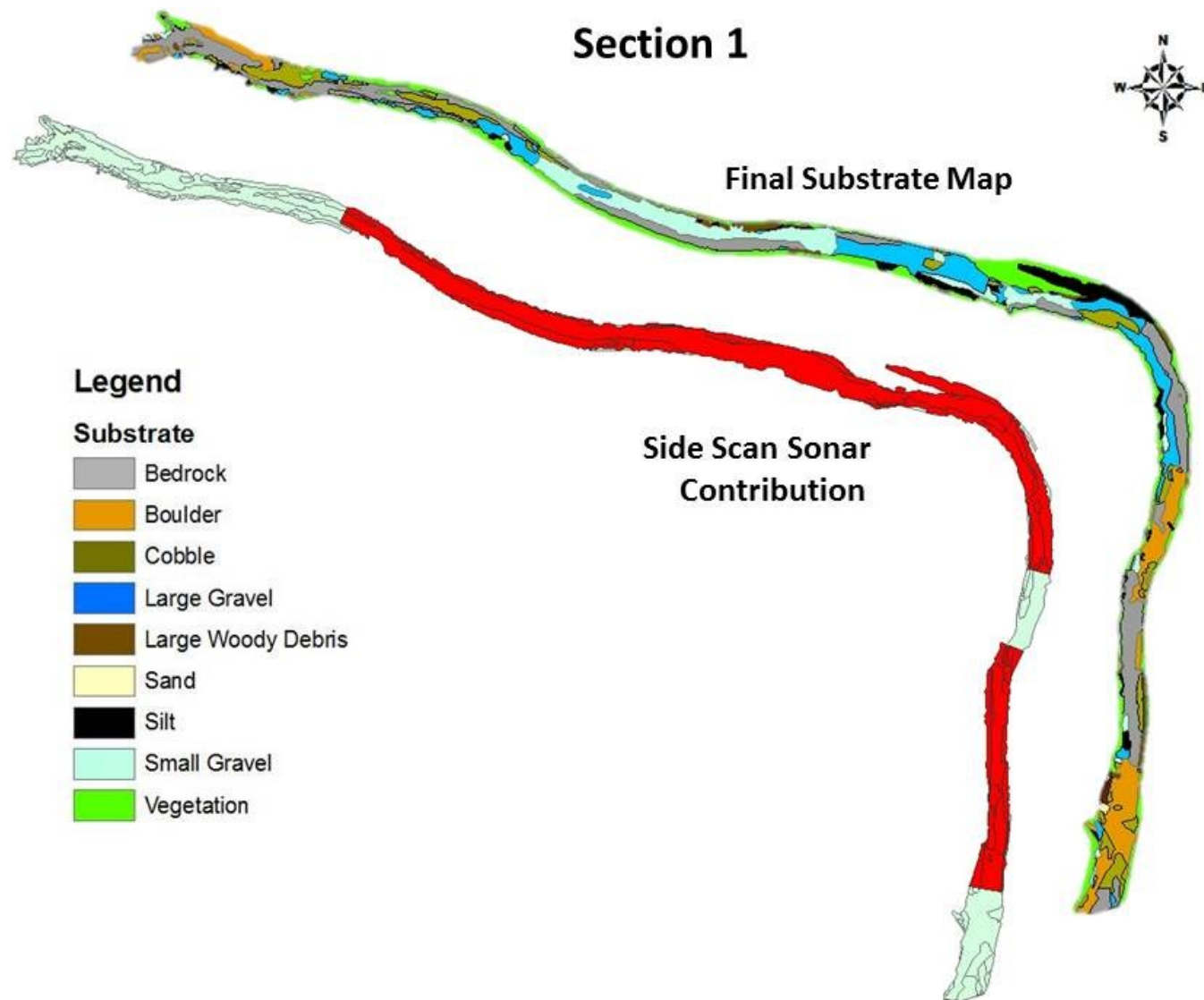
Figure 2.3: Final substrate map for study section one of the Canyon Reservoir tailrace and portion contributed by side scan sonar (2010-2015). Red areas delineate side scan sonar survey areas
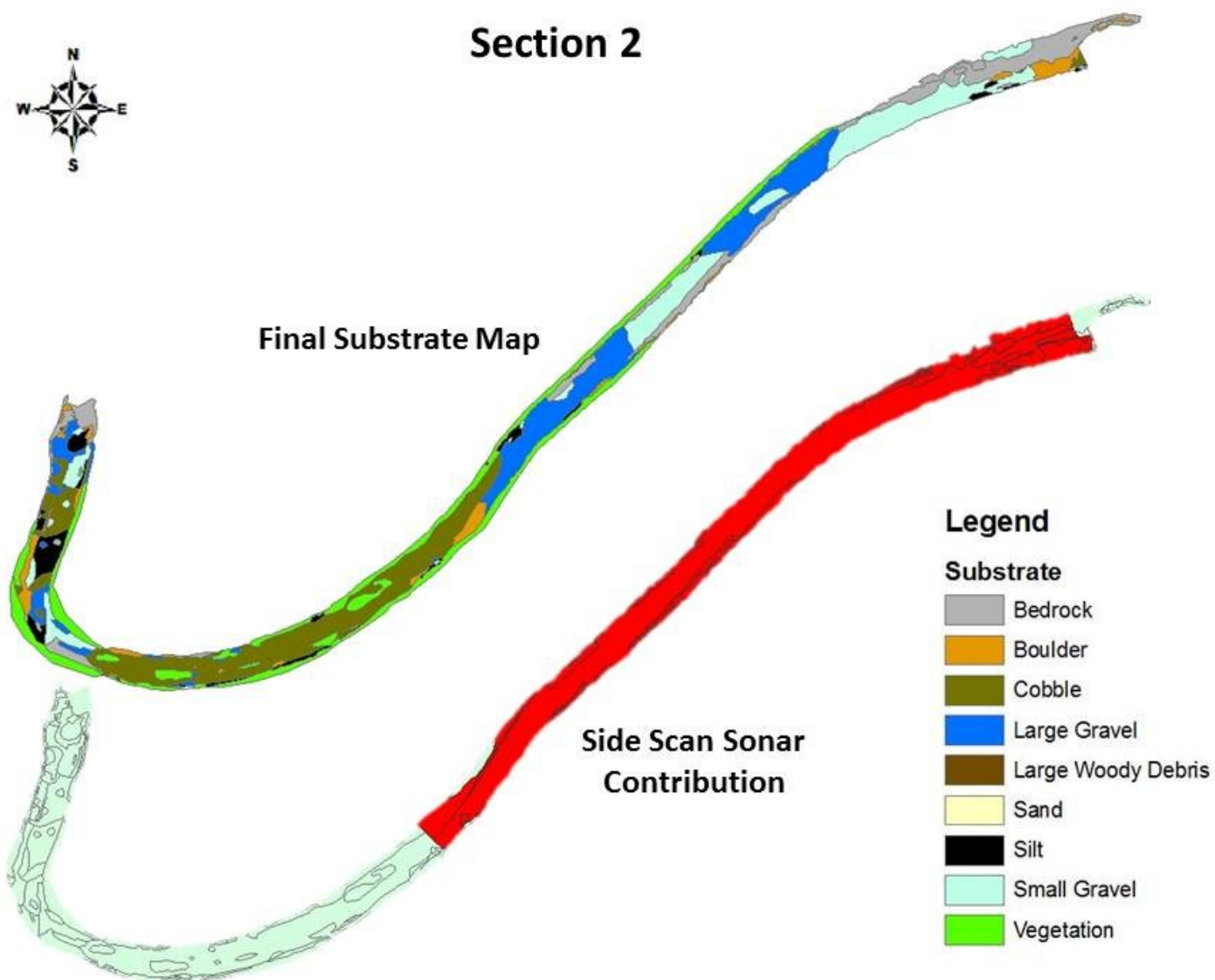
Figure 2.4: Final substrate map for study section two of the Canyon Reservoir tailrace and portion contributed by side scan sonar (2010-2015). Red areas delineate side scan sonar survey areas.
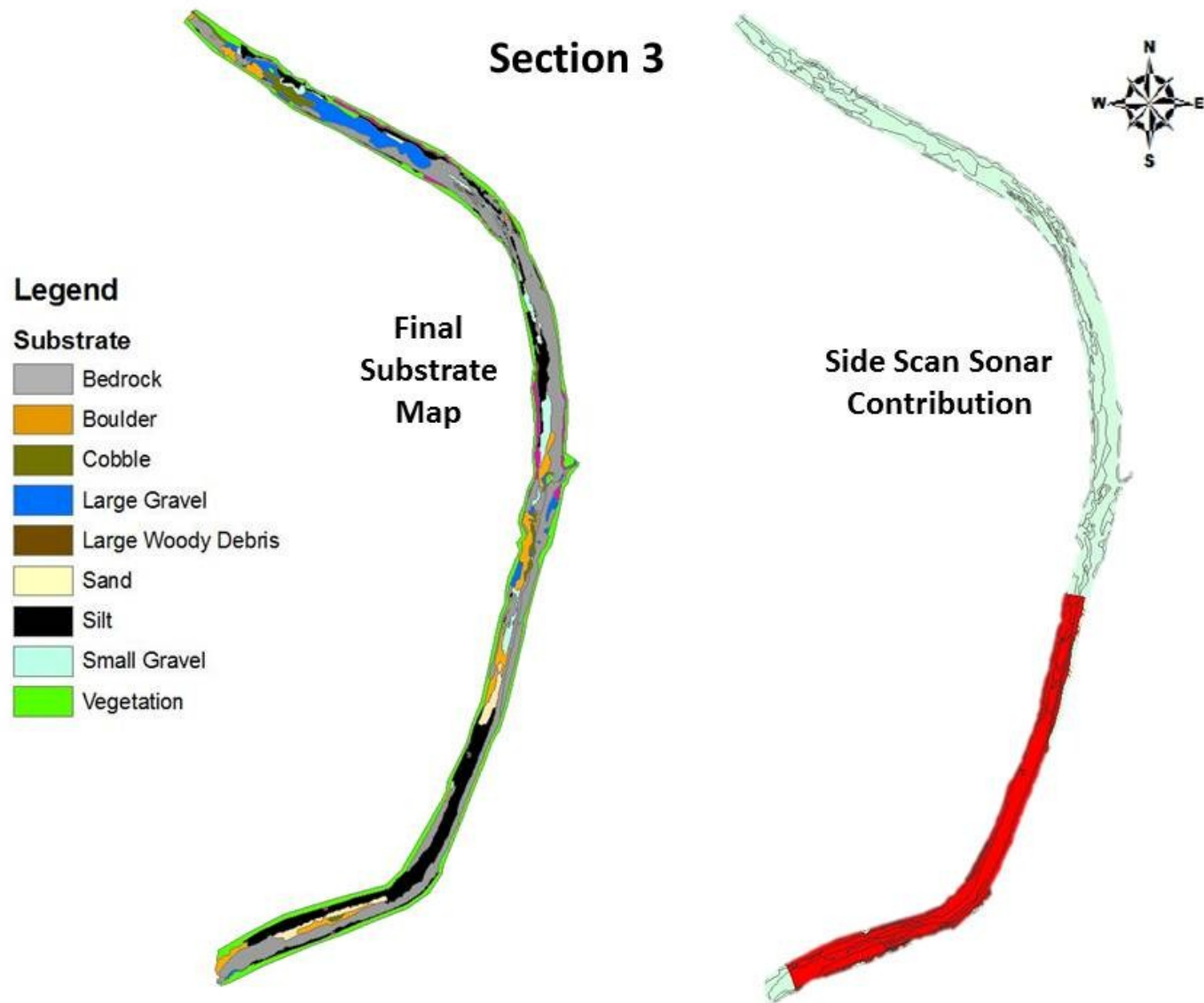
Figure 2.5: Final substrate map for study section three of the Canyon Reservoir tailrace and portion contributed by side scan sonar (2010-2015). Red areas delineate side scan sonar survey areas.

LITERATURE CITED

Anima, R., F.L. Wong, D. Hogg, and P. Galanis. 2007. Side-scan sonar imaging of the Colorado River, Grand Canyon: U.S. Geological Survey Open-File Report 2007-1087, 15 pp.

Daugherty, D.J., D.L. Bennett, B. VanZee, T. Morgan, and J. Tibbs. 2015. Effects of water-level reductions on littoral habitat and recreational access in Brazos River reservoirs, Texas. Journal of the Southeastern Association of Fish and Wildlife Agencies, 2: 1-7.

Fish, J.P. and H.A. Carr. 1990. Sound underwater images. Lower Cape Publishing, Orleans, Massachusetts.

Flowers, H.J. and J.E. Hightower. 2015. Estimating sturgeon abundance in the Carolinas using side scan sonar. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 7:1, 1-9.

Flug, M., H. Seitz, and J. Scott. 1998. Measurement of stream channel habitat using sonar. Regulated Rivers Research and Management 14: 511-517.

Goclowski, M.R., A.J. Kaeser, and S.M. Sammons. 2012. Movement and habitat differentiation among adult shoal bass, largemouth bass, and spotted bass in the upper Flint River, Georgia. North American Journal of Fisheries Management, 00: 1-15.

Hale, R.S., J.K. Horne, D.J. Degan, and M.E. Conners. 2003. Paddlefish as potential acoustic targets for abundance estimates. Transactions of the American Fisheries Society, 132:4, 746-758.

Humminbird®. 2011. 1158c Combo, 1158c DI Combo, and 1198c SI Combo operations manual. Eufaula, Alabama.

Kaeser, A.J. and T.L. Litts. 2008. An assessment of deadhead logs and large woody debris using side scan sonar and field surveys in streams of southwest Georgia. Fisheries, 33:12, 589-597.

Kaeser, A.J. and T.L. Litts. 2010. A novel technique for mapping habitat in navigable Streams using low-cost side scan sonar. Fisheries, 35:4, 163-174.

Kaeser, A.J., T.L. Litts, and T.W. Tracy. 2012. Using low-cost side-scan sonar for benthic mapping throughout the lower Flint River, Georgia, USA. River Research and Applications. 11 pp.

Kappenman, K.M. and B.L. Parker. 2007. Ghost nets in the Columbia River: methods for locating and removing derelict gill nets in a large river and an assessment of impact to white sturgeon. North American Journal of Fisheries Management, 27:3, 804-809.

McCarty, A.L. 2014. Habitat associations of lower Mississippi River floodplain fishes on St. Catherine Creek National Wildlife Refuge. The School of Renewable Natural Resources, Louisiana State University and Agricultural and Mechanical College, Baton Rouge, Louisiana. 66 pp.

Roghair, C.N., and D.R. Nuchols. 2005. Guide to stream habitat characterization using the BVET methodology in the George Washington-Jefferson National Forest, Virginia. Center for Aquatic Technology Transfer. 24 pp.

Singer, J., J. Atkinson, P. Manley, P. McLaren. 2006. A sediment trend analysis of the Buffalo River area of concern. Report prepared for U.S. Environmental Protection Agency, Great Lakes National Program Office, Chicago. 148 pp.

Singer, J., J. Atkinson, P. Manley, P. McLaren. 2008. Understanding sediment dynamics using geological and engineering approaches: a case study of the Buffalo River area of concern, Buffalo, New York. International Journal of River Basin Management, 6:1, 1-10.

SonarTRX. 2015. SonarTRX website. http://www.sonartrx.com/web/. Accessed 2015 May 29.

Wensink, R. 2005. A novel method for surveying low head rivers. Master's thesis. Ohio State University, Columbus, Ohio. 42 pp.
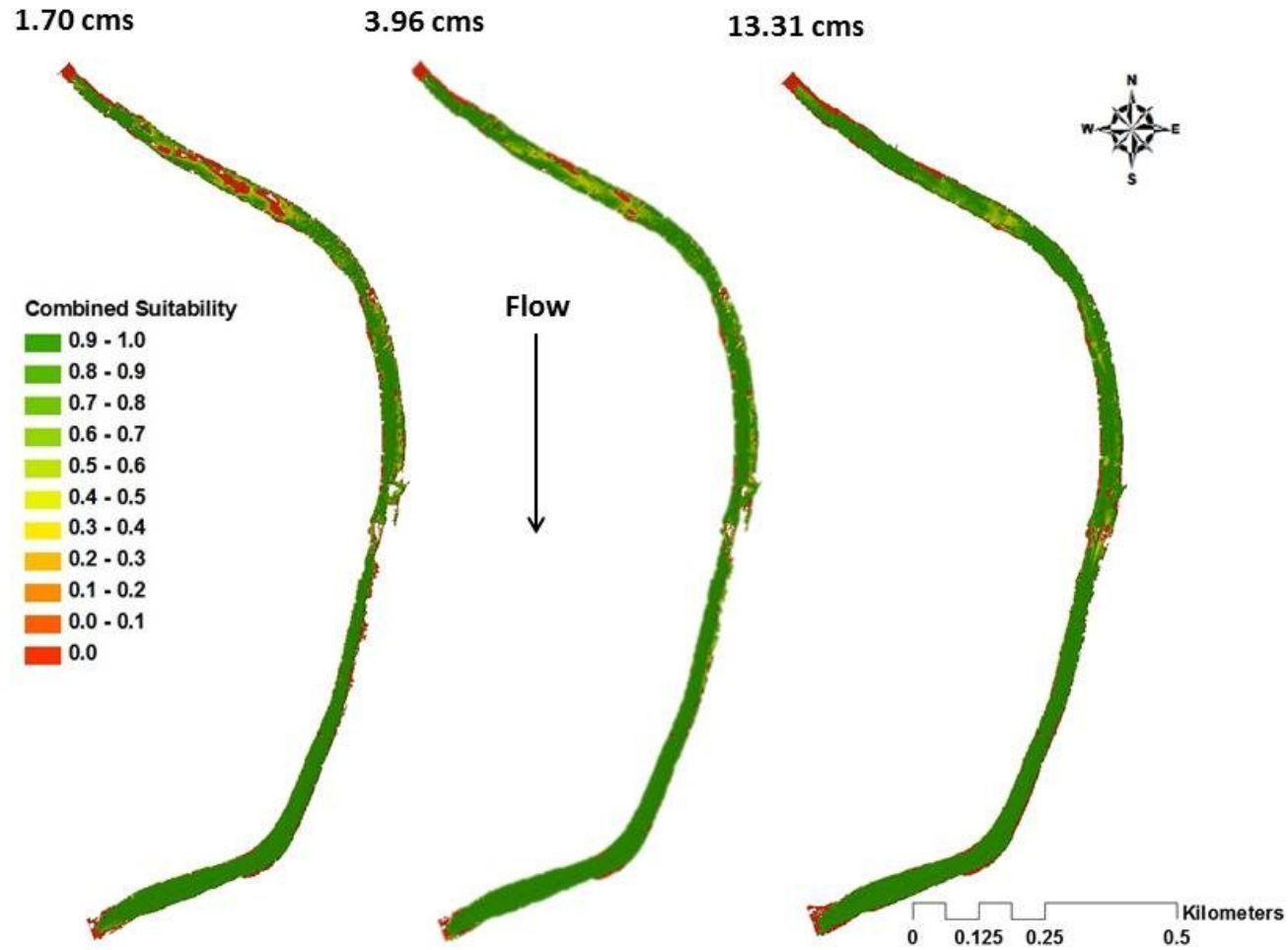
APPENDIX I
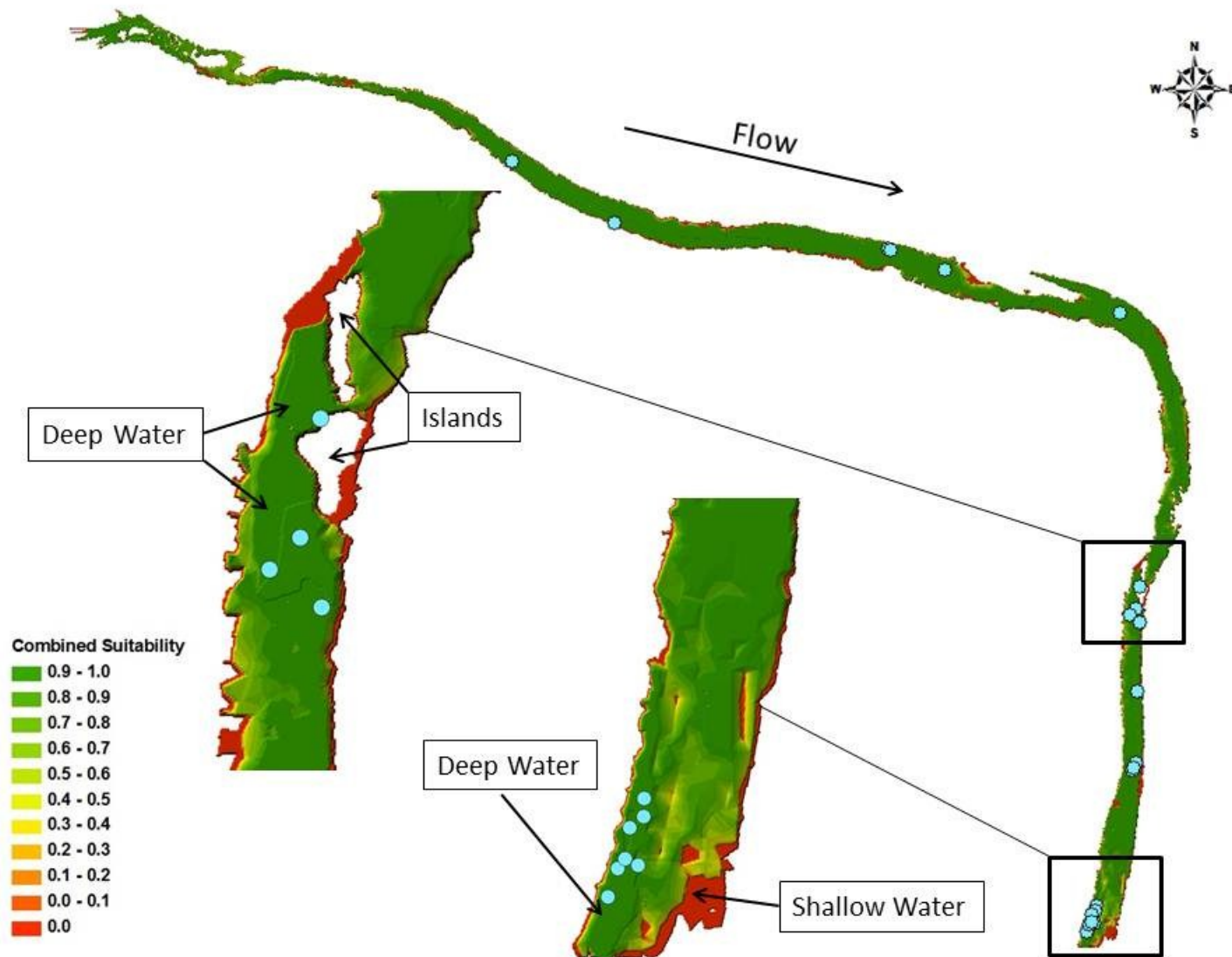
ADULT RAINBOW TROUT HABITAT SUITABILITY MAPS
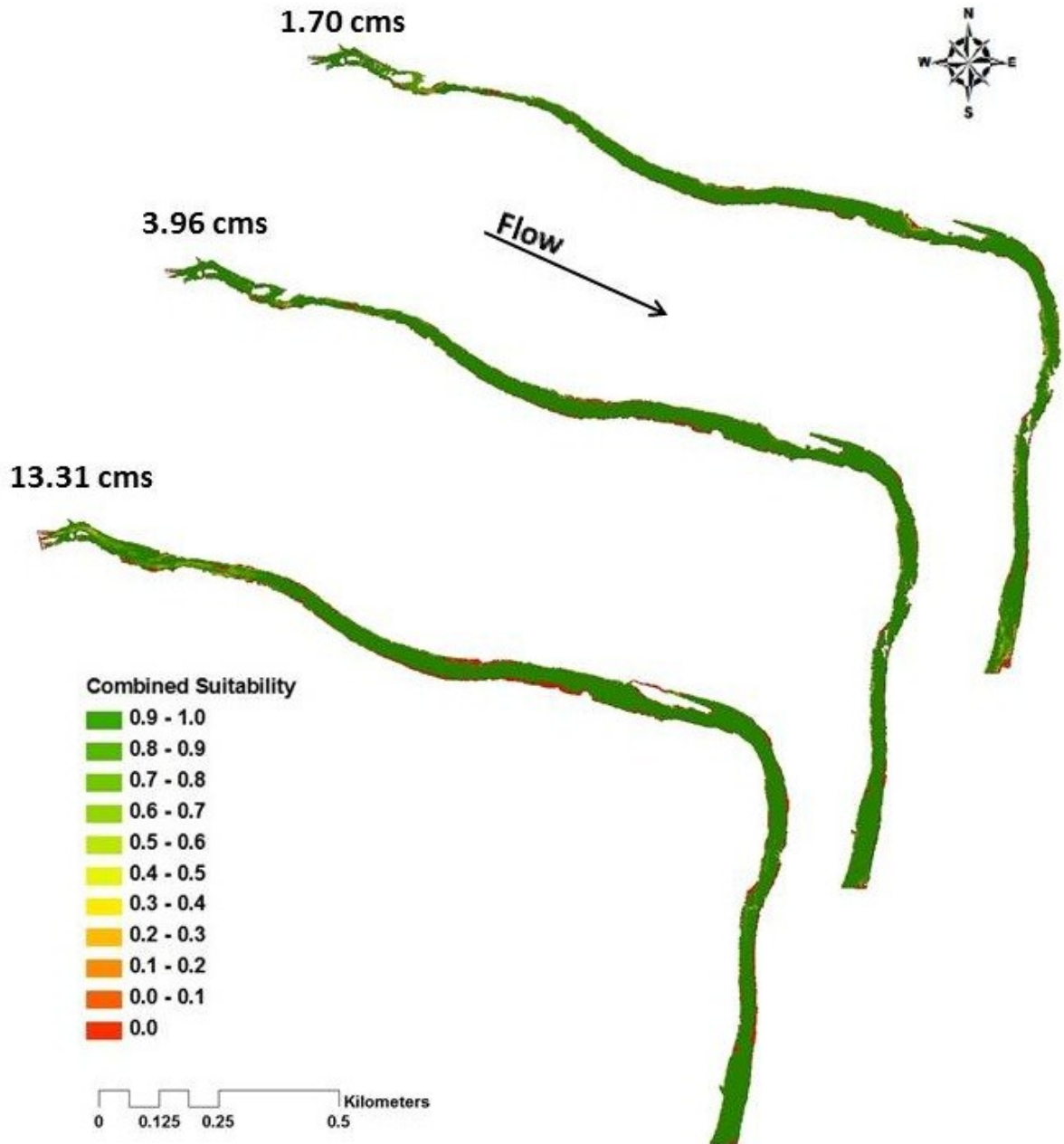
Adult Rainbow Trout habitat suitability for study section one of the Canyon Reservoir tailrace (2010-2015). Modeled discharges shown represent 1.70 cms, 3.96 cms, and 13.31 cms (80%, 50%, 20% flow exceedance).

Adult Rainbow Trout habitat suitability for study section two of the Canyon Reservoir tailrace (2010-2015). Modeled discharges shown represent 1.70 cms, 3.96 cms, and 13.31 cms (80%, 50%, 20% flow exceedance).

Adult Rainbow Trout habitat suitability for study section three of the Canyon Reservoir tailrace (2010-2015). Modeled discharges shown represent 1.70 cms, 3.96 cms, and 13.31 cms (80%, 50%, 20% flow exceedance).

Example of adult Rainbow Trout locations versus habitat combined suitability for study section one on the Canyon Reservoir tailrace (1.70 cms), (2010-2015). Trout locations are represented by light blue circles. Indications of water depth are included in the map.

THEORETICAL HABITAT IMPROVEMENT
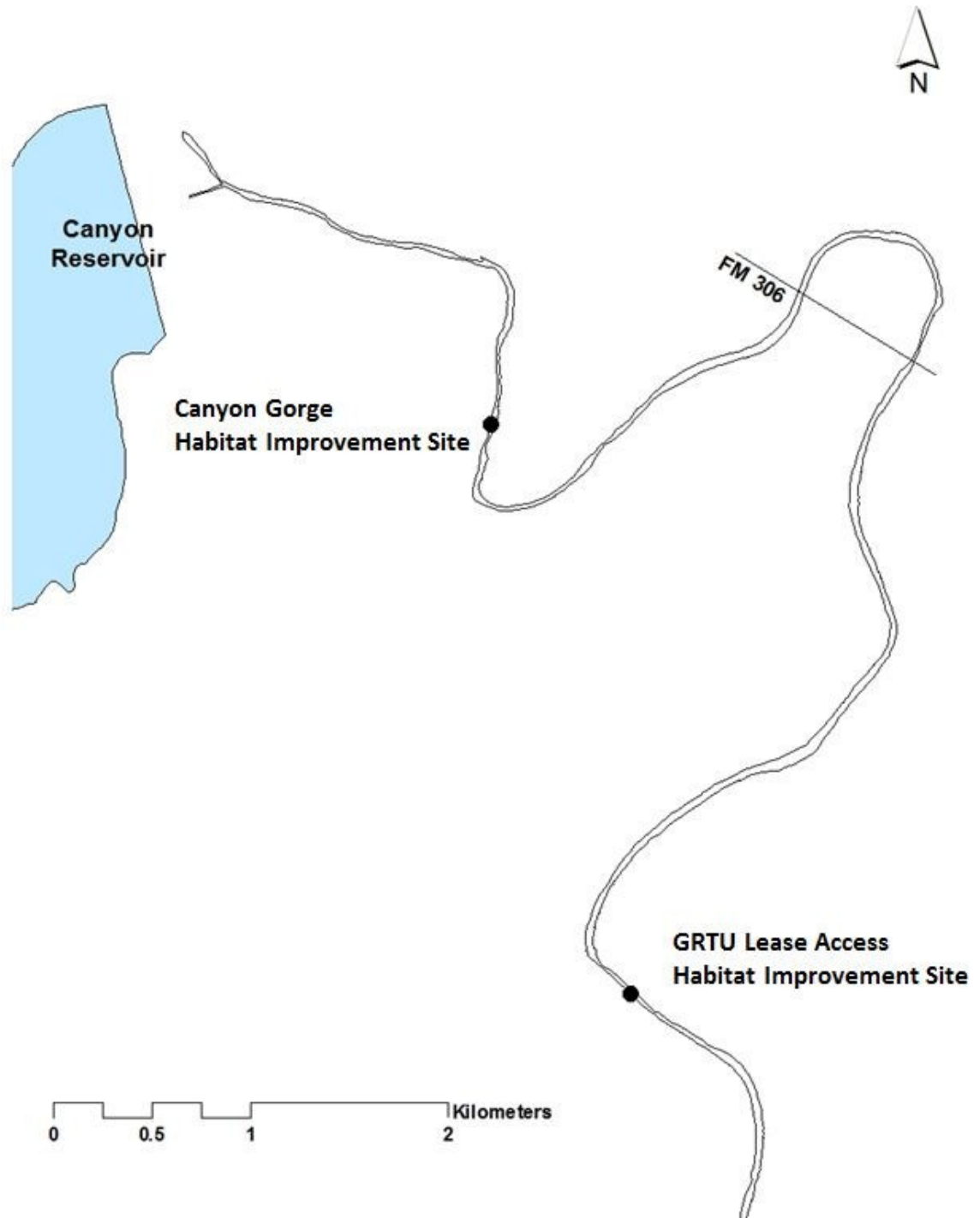
Theoretical habitat improvement sites on the Canyon Reservoir tailrace (2015).

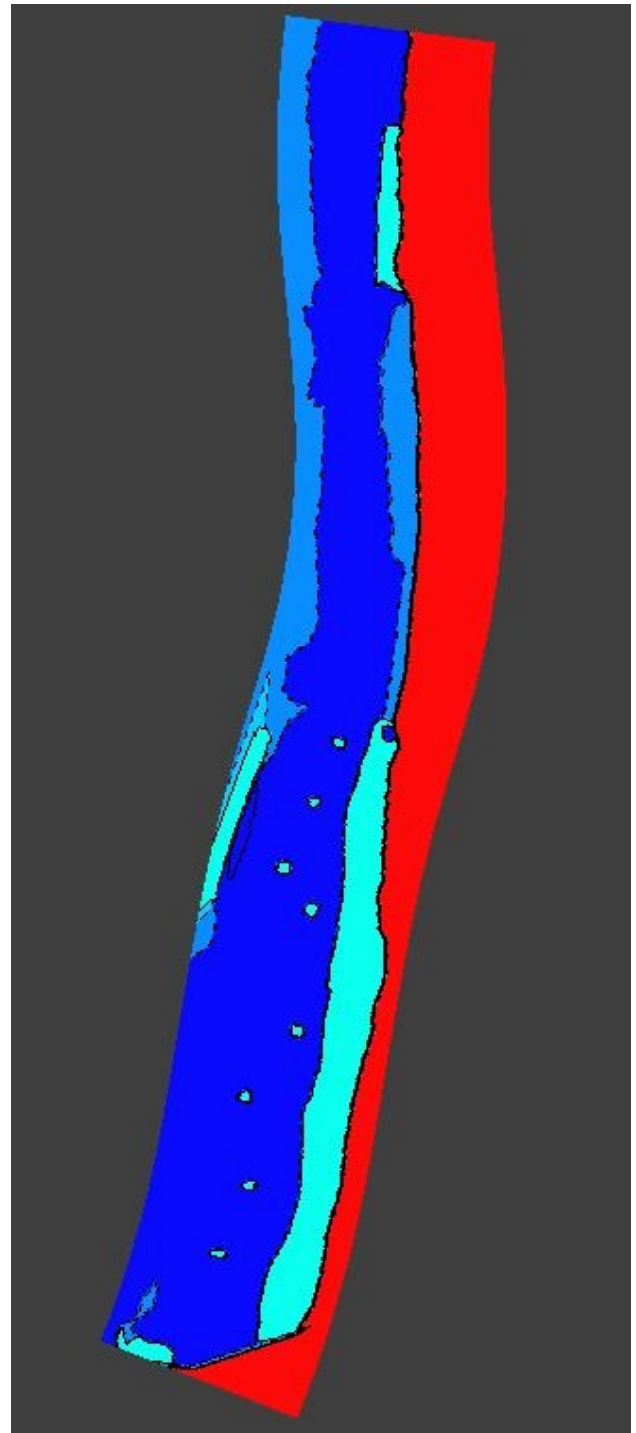**Current Topography**   **Theoretical Topography**

FLOW
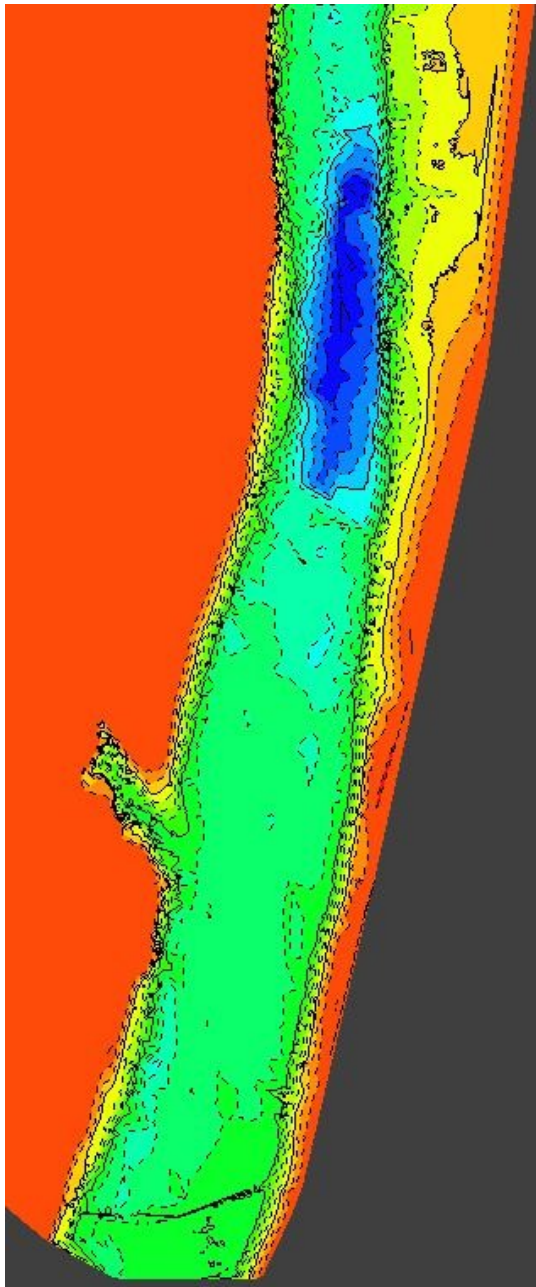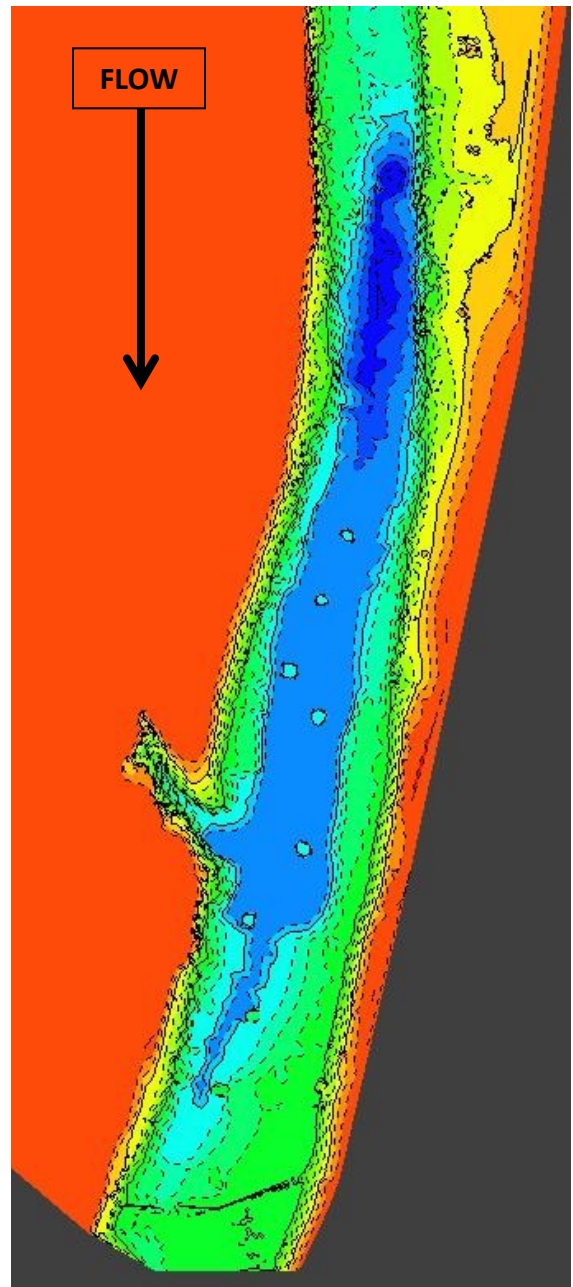
Comparison of current topography (2015) and theoretical topography after habitat improvement for the Canyon Gorge area on the Canyon Reservoir tailrace. Green colors indicate shallow water and blue colors indicate deeper water. Orange and yellow colors are outside of the river channel.
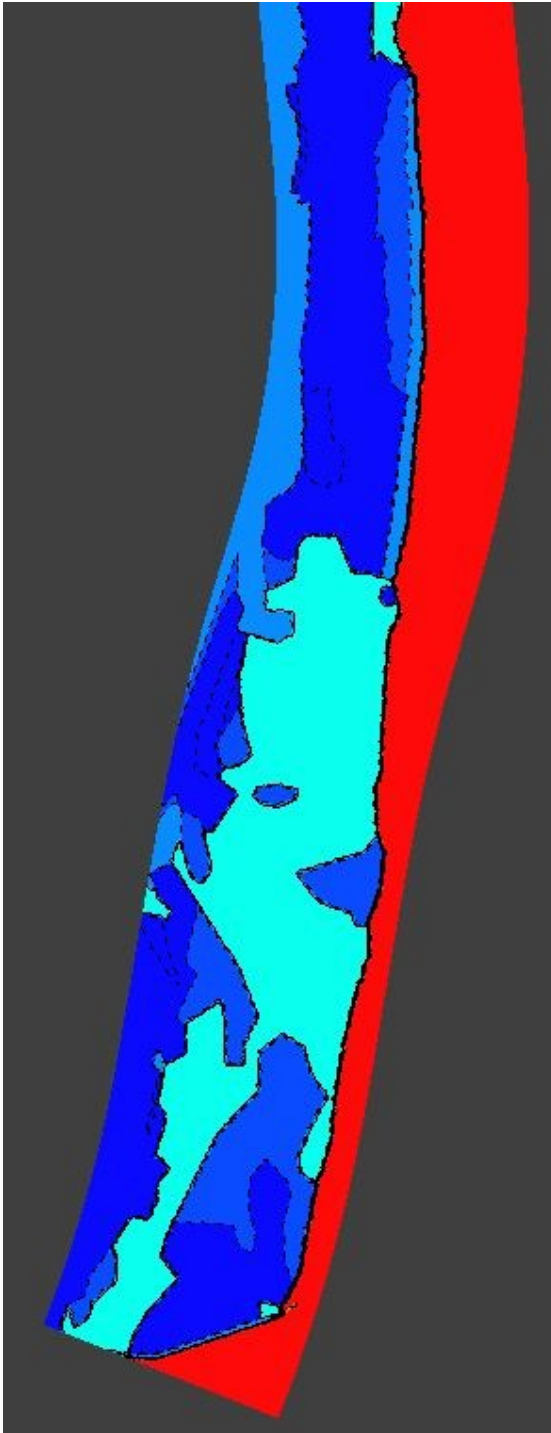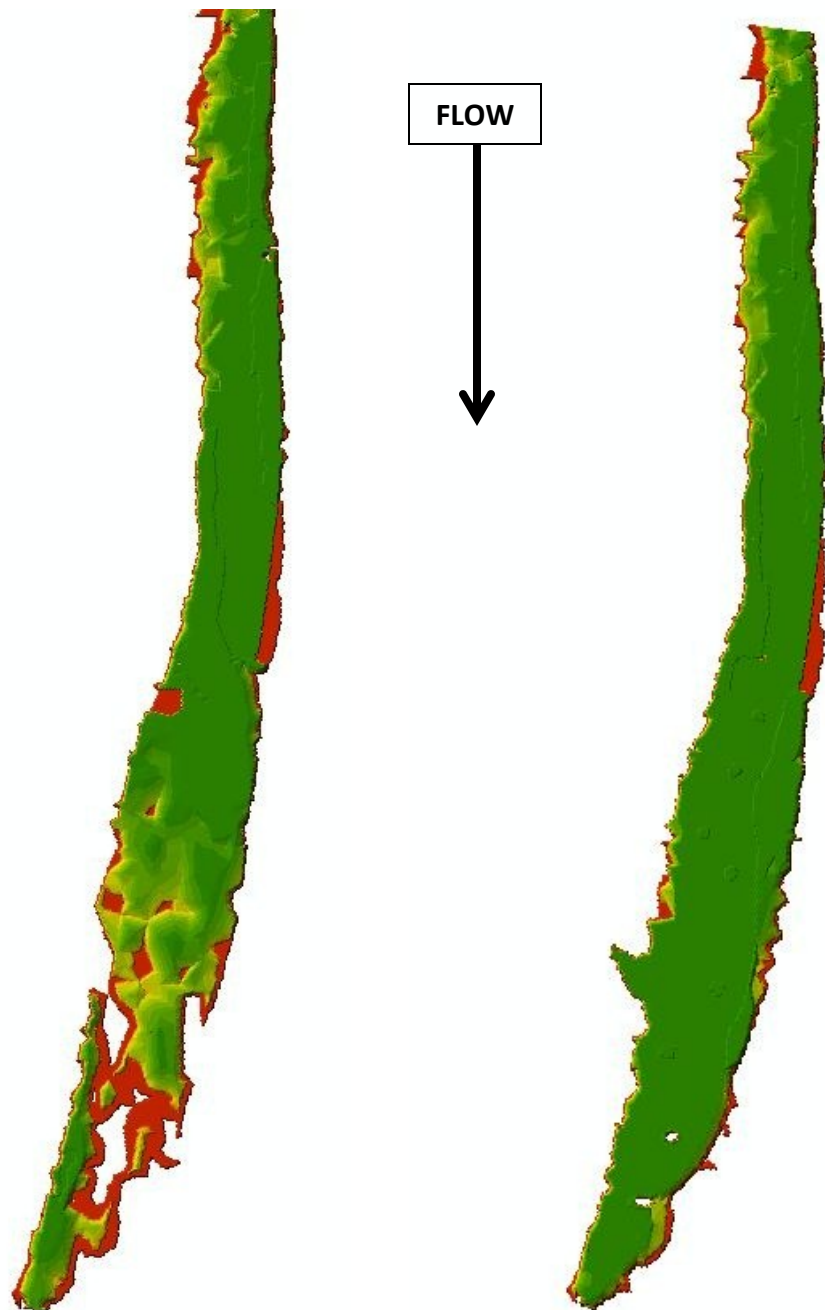
Current Substrate   **Theoretical Substrate**

Comparison of current substrate (2015) and theoretical substrate after habitat improvement for the Canyon Gorge area on the Canyon Reservoir tailrace. Dark blue = bedrock, medium blue = cobble, light blue = boulder, red = terrestrial area.
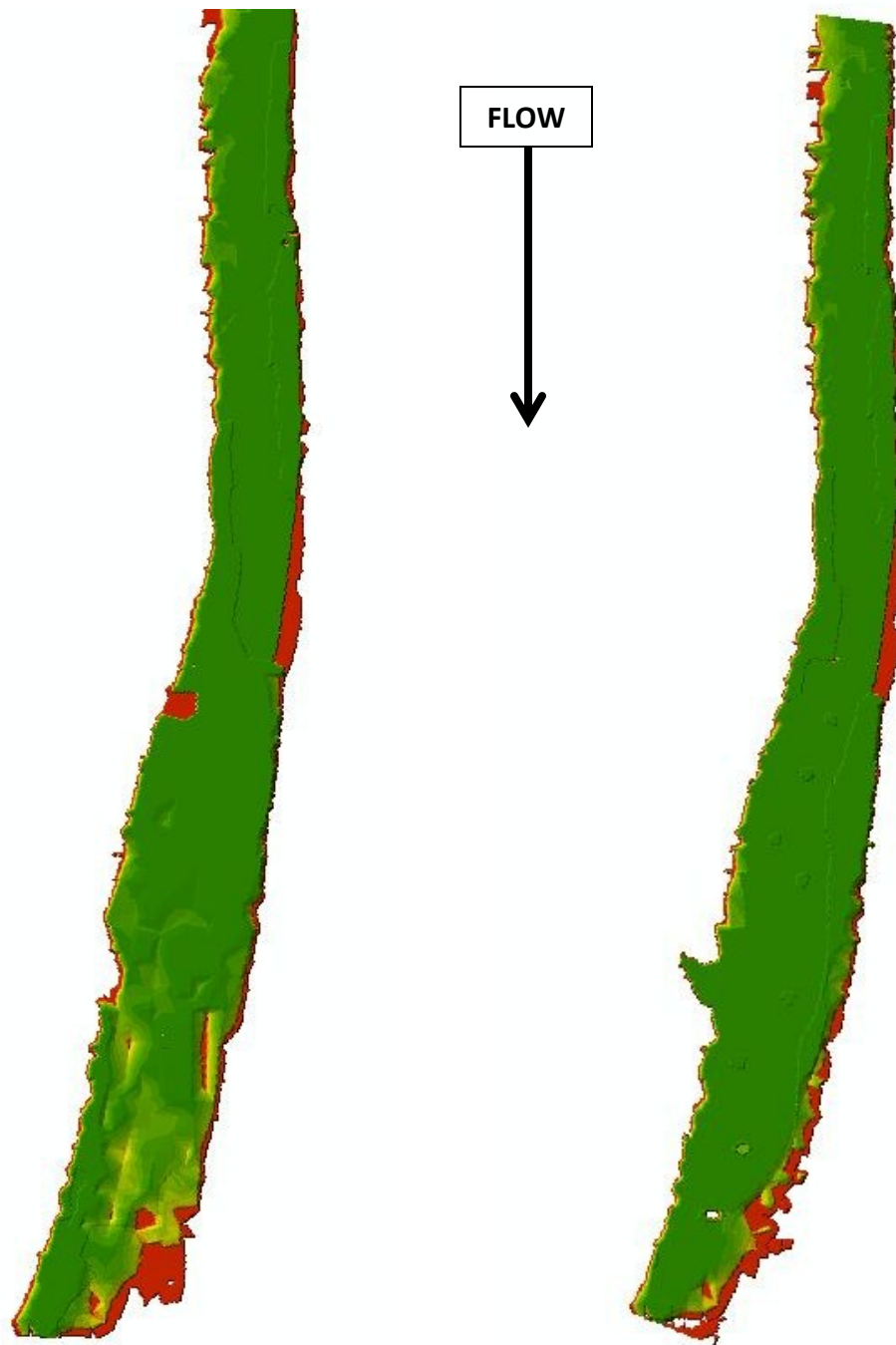
Current Suitability   **Suitability After Improvement**

FLOW

Comparison of current suitability (2015) versus suitability after theoretical habitat improvement at 0.57 cms for the Canyon Gorge area of the Canyon Reservoir tailrace. Green indicates optimal habitat, orange and red indicate poor habitat. White areas within channels indicate dewatered areas.

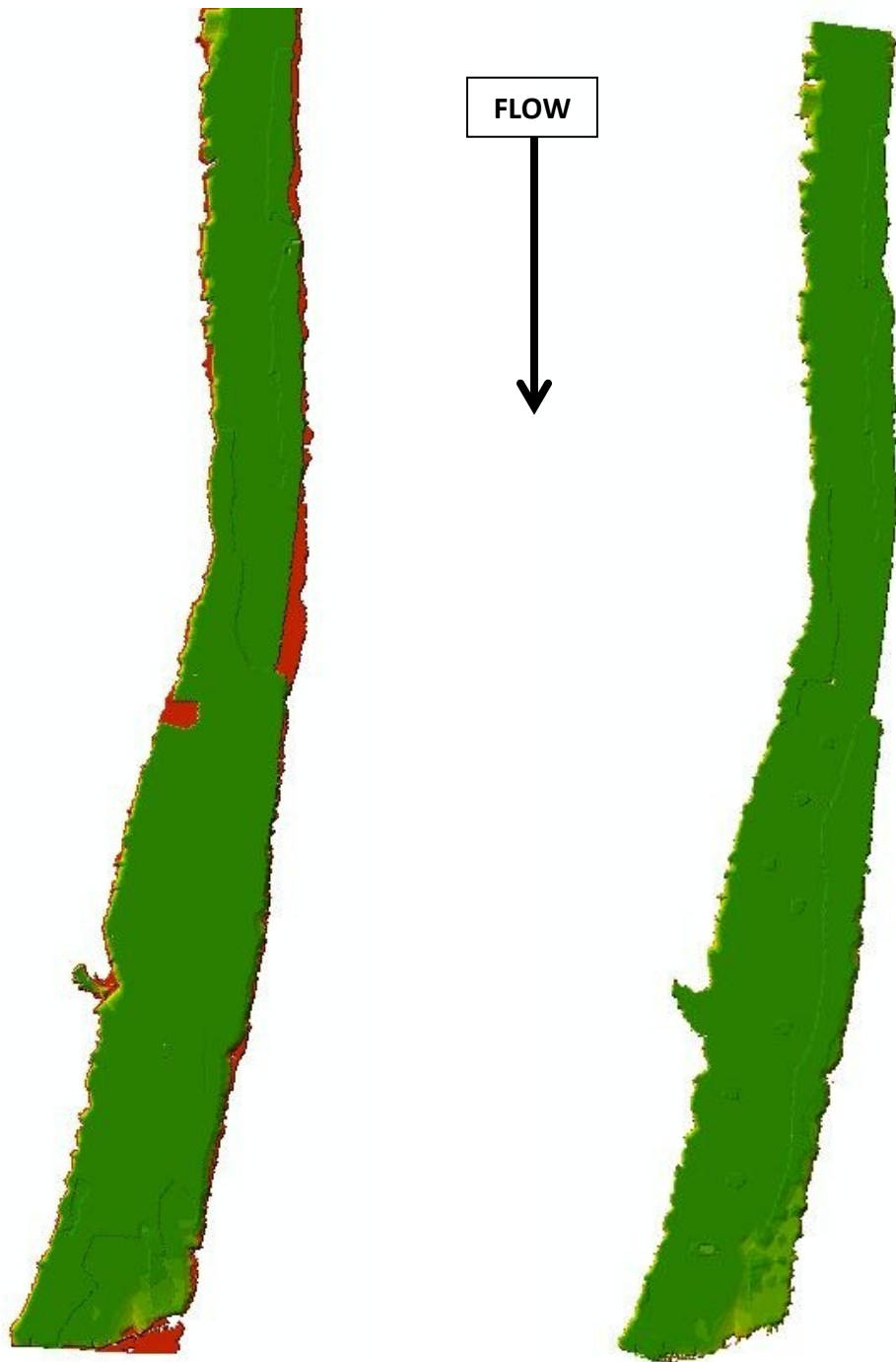**Current Suitability**   **Suitability After Improvement**

Comparison of current suitability (2015) versus suitability after theoretical habitat improvement at 1.70 cms for the Canyon Gorge area of the Canyon Reservoir tailrace. Green indicates optimal habitat, orange and red indicate poor habitat. White areas within channels indicate dewatered areas.
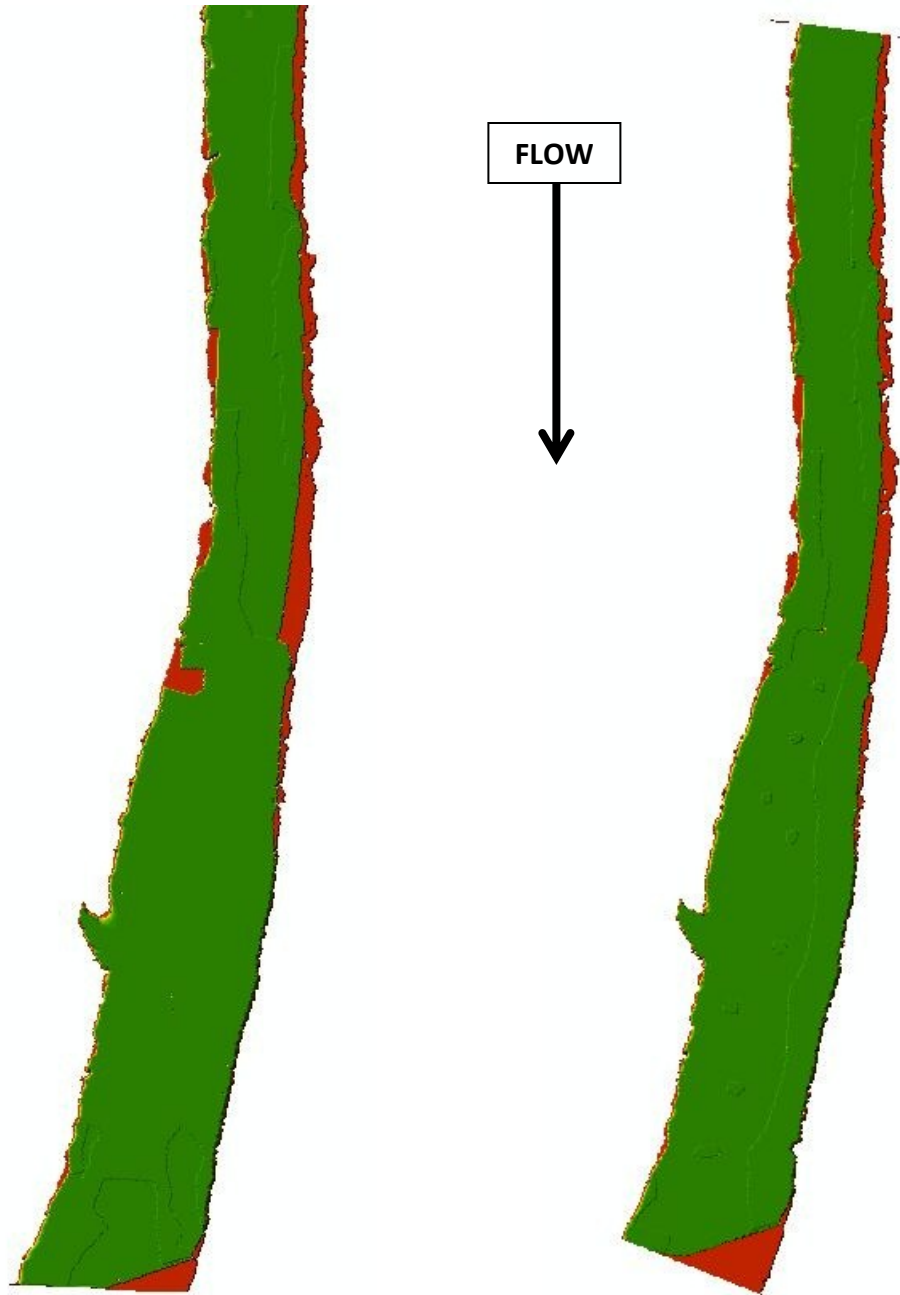
Current Suitability **Suitability After Improvement**

FLOW

Comparison of current suitability (2015) versus suitability after theoretical habitat improvement at 3.96 cms for the Canyon Gorge area of the Canyon Reservoir tailrace. Green indicates optimal habitat, orange and red indicate poor habitat. White areas within channel indicate dewatered areas.

**Current Suitability**   **Suitability After Improvement**

Comparison of current suitability (2015) versus suitability after theoretical habitat improvement at 13.31 cms for the Canyon Gorge area of the Canyon Reservoir tailrace. Green indicates optimal habitat, orange and red indicate poor habitat. White areas within channel indicate dewatered areas.
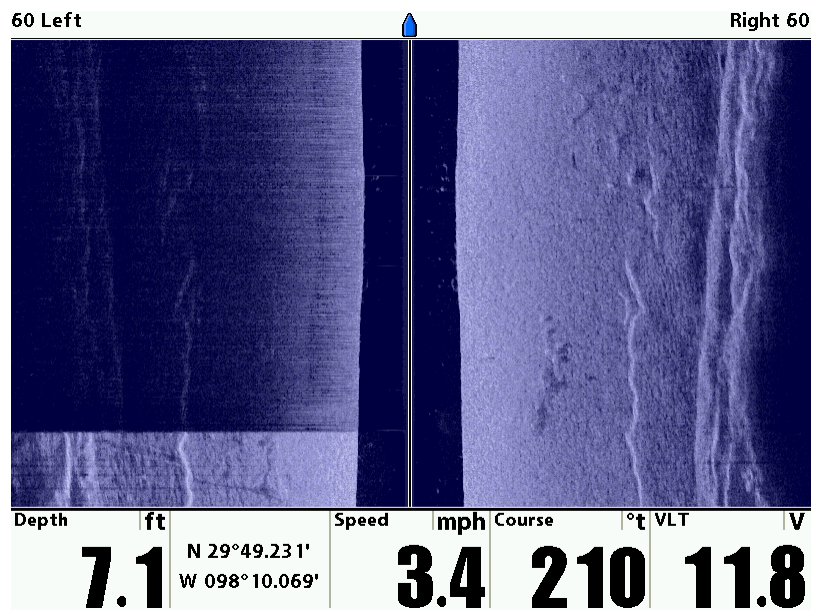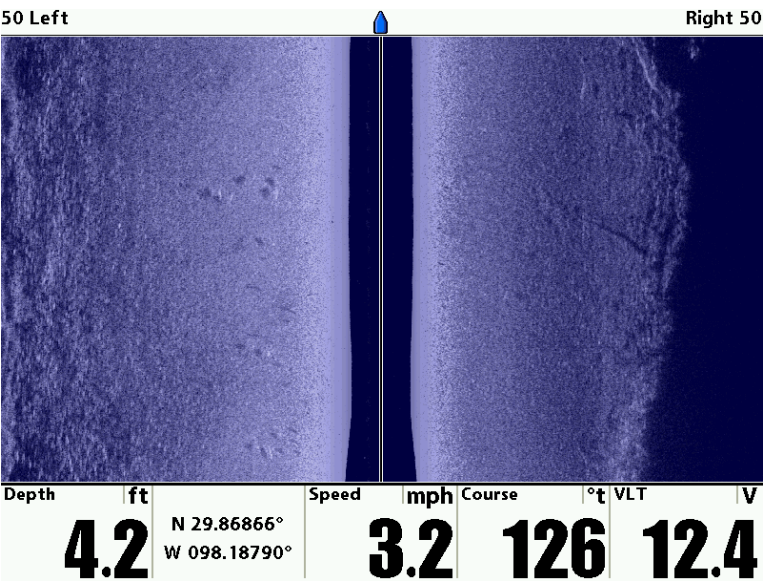
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APPENDIX III

SIDE SCAN SONAR IMAGERY

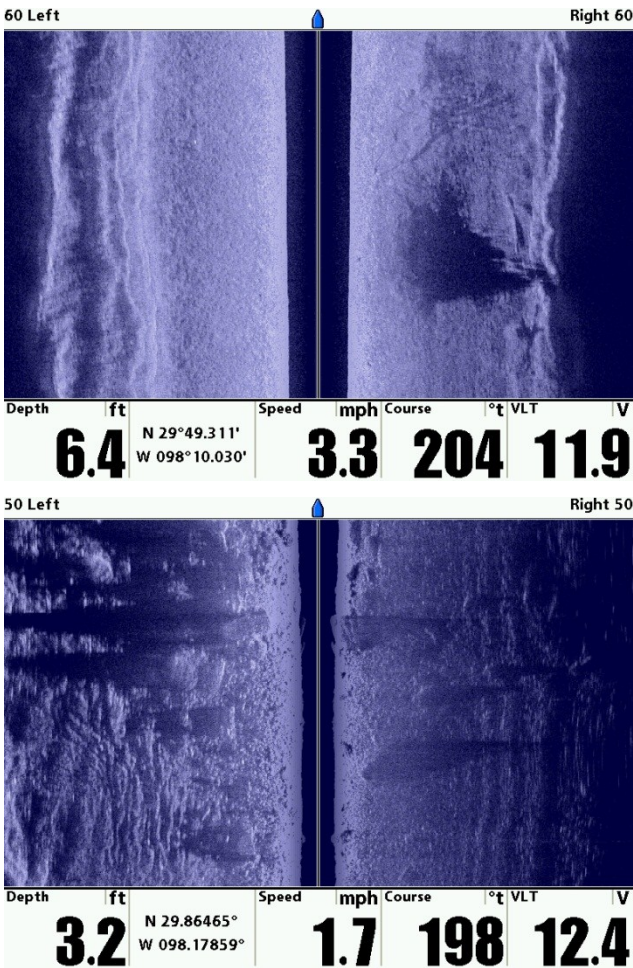**Signal disruption due to waves causing transducer to break water surface.**
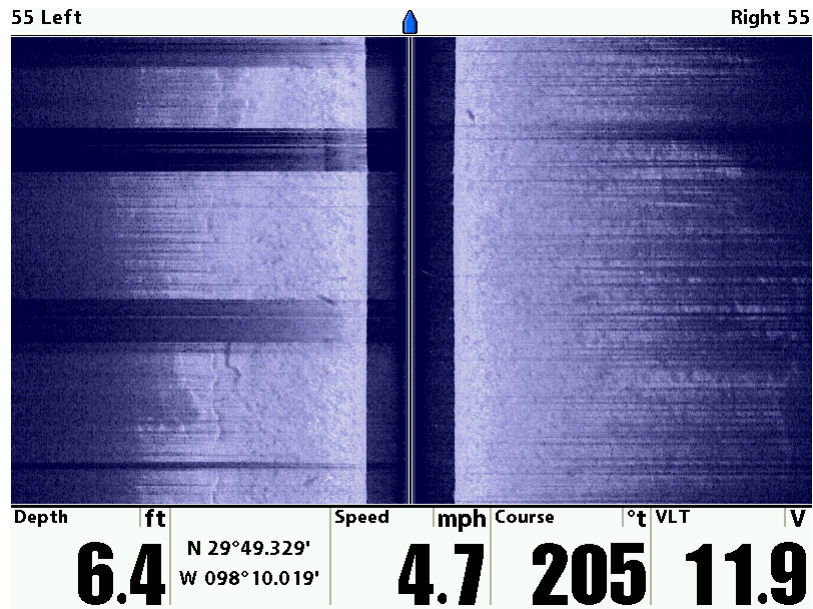
Signal disruption due to debris on the transducer.

Left bank out of range.

Depth: **4.2** ft N 29.86866° W 098.18790° Speed: **3.2** mph Course: **126** °t VLT: **12.4** V

Sonar shadow caused by underwater hump (top) and boulders (bottom).

Depth: **6.4** ft N 29°49.311' W 098°10.030' Speed: **3.3** mph Course: **204** °t VLT: **11.9** V

Depth: **3.2** ft N 29.86465° W 098.17859° Speed: **1.7** mph Course: **198** °t VLT: **12.4** V

ADDITIONAL TROUT DATA
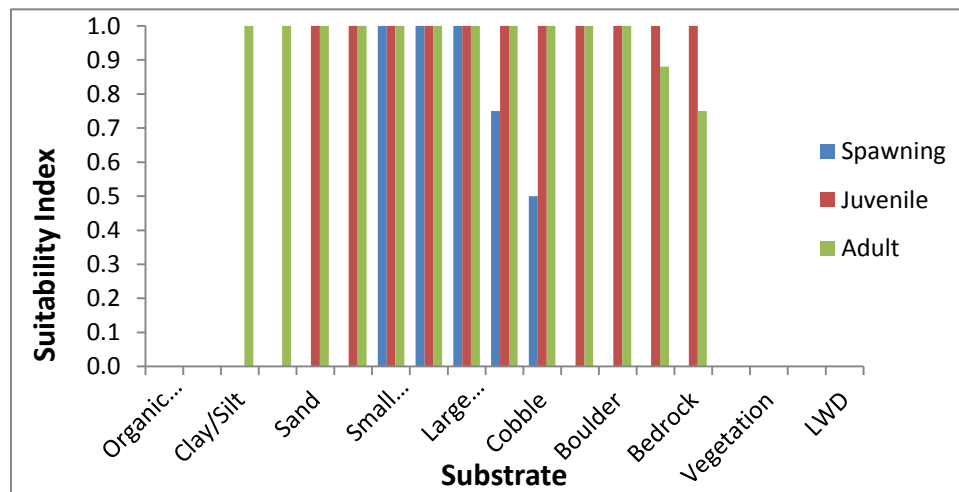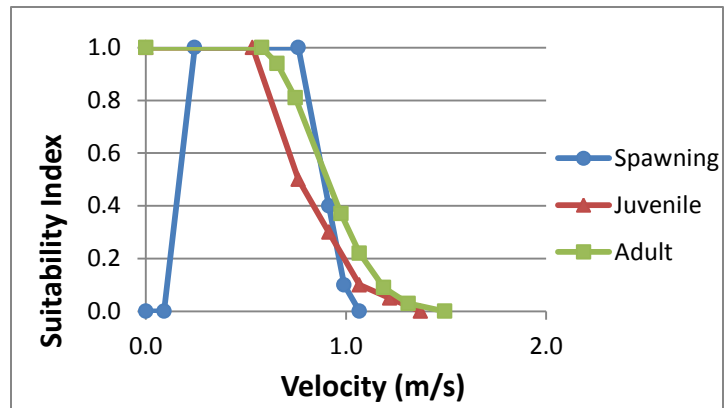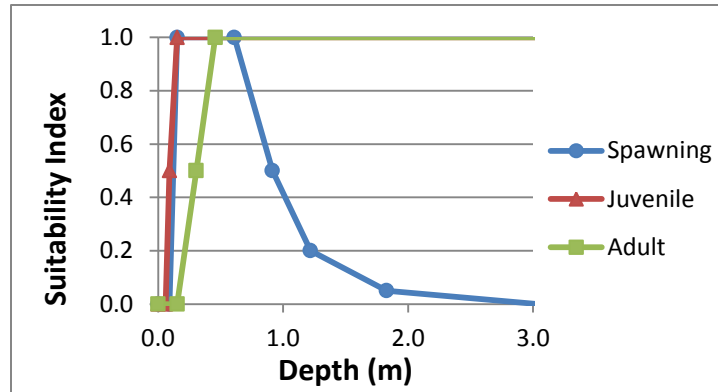
Habitat suitability criteria (HSC) for spawning, juvenile, and adult trout on the Canyon Reservoir tailrace (2010-2015).

Overall weighted usable area (WUA) for spawning, juvenile, and adult Rainbow Trout on the Canyon Reservoir tailrace (2010-2015). Values are scaled to percent of maximum WUA. Vertical lines represent average annual flow exceedance levels.

Literature sources for HSC used for juvenile Rainbow Trout in the Canyon Reservoir tailrace study (2010-2015).
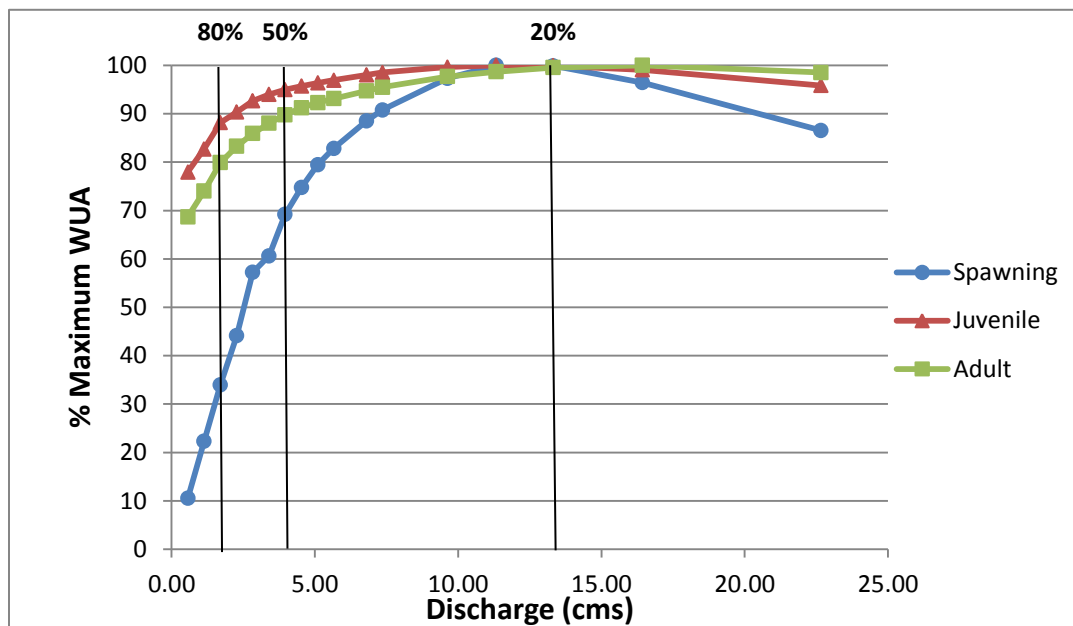
Source	Curve Type	Category	Data Analysis	Data Collection	Location
Lambert et al. (1987)	Suitability	2	FA	SN/OB	California
Moyle & Baltz (1985)	Suitability	2	FA	SN/OB	California
Cochnauer & Elms-Cockrum (1986)	Probability-of-use; IDFG	2	FA	U	Idaho
Bovee (1978)	Probability-of-Use	2	FA	U	Oregon/Washington
Baltz & Moyle (1981)	Suitability	2	FA	SN/OB	California
Raleigh et al. (1984)	Suitability	2	FA/RO	SN/U	California/B.C./Utah
Hill & Hauser (1985)	Suitability	2	U	U	Tennessee
USFS (1985)	GAWS (Suitability)	2	FA	U	U.S. Western
TRPA (2004)	Suitability	2	FA	SN/OB/RD	Klamath R. (Bypass Reach)
TRPA (1991)	Suitability	2	FA	SN/OB	Klamath R. (Buck/Grizzly Crks.)
PCWA (2008)	Suitability (Envelope)	1	FA	LT	California (American R.)
Hoffman et al. (2002)	Suitability	2	FA	SN/SCUBA	Montana (Kootenai R.)
SCE (2004)	Suitability	1	FA	LT/SN/OB	California (Big Creek ALP)
Rempel (2012)	Suitability	2	FA	EL/NT	British Columbia (Big Fraser R.)
Jowett (2008)	Suitability	2	FA	EL/OB/LT	New Zealand Rivers
R2 Resource Consultants (2008)	Suitability	1	PJ	LT	Washington State Fallback Curves
R2 Resource Consultants (2008)	Suitability	2	FA	SN/RD/OB	Washington (Sultan R.)
Beecher and Caldwell (2013)*	Preference	3	FA	SN/LT	WDFW Large Streams (13 studies)
Caldwell et al. (1999)*	Preference	3	FA	SN	Washington (Big Quilcene R.)
USFWS (2008)*	Suitability	2	FA	SN/LT	California (Yuba R.)
Hampton (1988)*	Preference	3	FA	SN	California (Trinity R.)
Caldwell (2004)*	Preference	3	FA	LT	Washinton (Chehalis R. basin)

*Steelhead Trout

Literature sources for HSC used for spawning Rainbow Trout in the Canyon Reservoir tailrace study (2010-2015).

Source	Curve Type	Category	Data Analysis	Data Collection	Location
Bovee (1978)	Probability-of-Use	2	RO/FA	U	B.C./Idaho/Oregon/California
Lambert et al. (1987)	Suitability	2	FA	SN/OB	California
Cochnauer & Elms-Cockrum (1986)	Probability-of-use; IDFG	2	FA	U	Idaho
Corning & Elliot (1987)	Utilization	2	FA/RO	RD	Alaska
Sando (1981)	Suitability	2	FA	RD	Montana (Beaverhead R.).
Sando (1981)	Suitability	2	FA	RD	Montana (Yellowstone R.)
Raleigh et al. (1984)	Suitability	2	RO	RD	Oregon/Idaho/B.C./California
Hill & Hauser (1985)	Suitability	2	U	U	Tennessee
USFS (1985)	GAWS (Suitability)	2	RO/FA	U	U.S. Western
PacifiCorp (2004)	Suitability	1	PJ	LT	Washington (Lewis R.)
SCE (2004)	Suitability	1	FA	LT/SN/OB	California (Big Creek ALP)
R2 Resource Consultants (2008)	Suitability	1	PJ	LT	Washington State Fallback Curves
Beecher and Caldwell (2013)	Preference	3	FA	SN/LT/RD	WDFW Small Streams (2 studies)
Caldwell et al. (1999)*	Preference	3	FA	SN	Washington (Big Quilcene R.)
NHC (2004)	Suitability	1	FA	LT	Washington (Spokane R.)
USFWS (2010)	Suitability	2	FA	RD	California (Yuba R.)
Thurow (1994)**	Suitability	2	FA	RD/OB	Idaho (Pine Creek)
Caldwell (2004)*	Preference	3	FA	LT	Washinton (Chehalis R. basin)
Stillwater Sciences (2012)*	Suitability	1	PJ	LT	California (Tuolumne R.)
Sitka Electric Department (2005)*	Suitability	1	FA	LT/OB	Alaska (Sawmill Creek)
Hampton (1988)*	Preference	3	FA	SN	California (Trinity R.)

*Steelhead Trout
**Yellowstone Cutthroat Trout