THESIS

MOVEMENT PATTERNS, REPRODUCTION, AND POTENTIAL IMPACTS OF CLIMATE CHANGE ON THREE NATIVE FISHES IN THE UPPER WHITE RIVER DRAINAGE, COLORADO

Submitted by

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ABSTRACT

MOVEMENT PATTERNS, REPRODUCTION AND POTENTIAL IMPACTS OF CLIMATE CHANGE ON THREE NATIVE FISHES IN THE UPPER WHITE RIVER DRAINAGE, COLORADO

Habitat alterations and introduction of non-native fishes have reduced the distributions of Flannelmouth Sucker *Catostomus latipinnis*, Bluehead Sucker *Catostomus discobolus*, and Roundtail Chub *Gila robusta* to less than 50% of their historic ranges in the Colorado River basin. Main-stem Colorado River habitat has been widely altered by construction of dams and is a main driver in the decline of native fishes. Tributaries are sometimes less altered than main-stem habitat, and may be important areas for life history processes such as spawning, but their role in population maintenance of Flannelmouth and Bluehead Sucker populations is poorly understood. Using mark-recapture techniques, I evaluated the use of tributaries as spawning areas for Flannelmouth and Bluehead suckers.

Suckers were captured with fyke nets as they migrated upstream into Coal Creek, a tributary of the White River, presumably to spawn, and were PIT tagged and released. The PIT tagged fish were subsequently detected using two remote PIT tag antenna arrays placed in Coal Creek, one near the mouth and the other 2 km upstream. Suckers began to migrate into Coal Creek, in late May of 2012 and 2013 when water temperatures reached 9–12°C. Water temperature likely cued spawning movements because fish captures and PIT tag detections in Coal Creek occurred at similar temperatures in both years, despite different flow patterns. However, within 24 hours of capture and handling, the majority of suckers abandoned Coal

Creek, and returned to the main-stem White River. Suckers not handled and detected only by PIT tag detector arrays remained resident in Coal Creek for an average of 10–12 days (1–32 days) depending on year and species. Handling-induced movement rendered abundance estimation of the Coal Creek population difficult and such post-handling movements should be considered when designing mark-recapture studies for these species.

Tagged Flannelmouth and Bluehead suckers returned to Coal Creek in subsequent years, demonstrating >40% spawning site fidelity. High levels of site fidelity indicated that small tributaries may be important spawning habitat for these species. Finally, remote PIT tag detections also showed that 81% of tagged fish returning to Coal Creek were not also captured in fyke nets. Hence, remote PIT tag antenna arrays allowed stronger inference regarding movement and tributary use by these species than could be achieved using just fyke nets. This research shows that tributaries are an important part of Flannelmouth and Bluehead suckers life history and should be considered when developing management strategies for these species.

Climate change may also alter flow and water temperature regimes in the upper Colorado River basin and impact native fish communities. Climate change models generally predict decreased stream flow and increased water temperatures. A better understanding of the impacts of flow and water temperature on the life histories of these species should lead to more informed management and allow assessments of how climate change will impact extant populations.

Fish community sampling showed that the upper White River was pristine, as native fishes were > 90% of those captured. Timing of reproduction for Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub along a 150 river kilometer longitudinal gradient of a main-stem White River reach and two tributaries revealed that water temperature was the dominant environmental factor cueing reproduction for all three species. Flannelmouth Sucker, Bluehead

Sucker, and Roundtail Chub reproduction began earlier in spring at warmer, lower-elevation, downstream locations and progressed longitudinally upriver in later spring or early summer as water temperatures increased. In tributaries, warmer water temperatures initiated reproduction by suckers earlier than in the adjacent main-stem White River. Timing of reproduction (based on detection of larvae) was 20-29 days earlier in 2012 than 2013 at the same locations due to earlier warming in the low flow year 2012. Daily growth microincrements in otoliths of larvae showed hatching dates were also earlier in 2012 due to warmer water temperatures and first hatching dates were progressively later in the year upstream.

Presence of larvae and otolith-derived hatching dates demonstrated a distinct and predictable progression of first reproduction in an upstream direction associated with warming water. There was also a clear upstream limit to reproduction for all three species. The upstream limit for Roundtail Chub was at a lower elevation than for either sucker species. A regression model was used to predict water temperature during fish spawning seasons as a function of covariates air temperature, date, elevation, and flow. Using published climate change projections for water temperature and flow, the regression model showed that both years of this study were warmer than average and 2012 conditions approximated those for potential climate change scenarios modeled. Lower flows and warmer air temperatures as a result of climate change will result in earlier reproduction and may expand the upstream limits of thermally suitable habitat for reproduction by these three fishes, while reducing habitat size.

Expansion of habitat for reproduction upstream does not ensure population persistence, as most juvenile recruitment for Flannelmouth Sucker and Bluehead Sucker occurred only in downstream reaches of the White River study area, and recruitment for Roundtail Chub was limited everywhere. Thus, populations of these species may require a network of suitable

riverine habitat, including tributaries, along a relatively extensive longitudinal continuum, to promote survival of life stages needed for population persistence. The long-term implications of climate change are unknown and managers should strive to perpetuate this valuable and relatively pristine native fish community in the upper White River drainage as a vestige of the native fish communities that formerly existed throughout the Colorado River basin.

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DEDICATION

For Mom and Dad who supported me in all of my endeavors, nurtured my interest in aquatics early in life, and instilled in me a deep respect for nature.

For my wife Kalen who shares her life with me and supports me unconditionally

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INTRODUCTION

Tributaries are important sources of habitat diversity in a drainage network because they increase channel complexity, substrate diversity, and depth variation (Benda et al. 2004; Moyle and Mount 2007; Pracheil et al. 2009). Tributaries also influence main-stem river environmental conditions such as water temperature, flow, and sediment loads (Benda et al. 2004; Moyle and Mount 2007). Tributary habitat and abiotic processes may increase species diversity and are important for many riverine fish to complete their life histories, especially in systems where main-stem habitat is highly altered and degraded (Stevens et al. 1997; Moyle and Mount 2007; Pracheil et al. 2009; Pracheil et al. 2013). Tributaries are increasingly important for conservation of riverine fish because they are often less degraded than main-stem habitat and conservation of tributaries is often more realistic than main-stem habitats that have been altered for hydropower or transportation (Moyle and Mount 2007; Pracheil et al. 2013).

Tributaries provide essential habitat for reproduction and early life history for many riverine fishes. In the Colorado River basin, main-stem impoundments have drastically altered the river environment, thereby increasing the importance of tributaries for endangered fishes. For example, Humpback Chub *Gila cypha* in the lower Colorado River basin are known to migrate into tributaries for spawning and currently the majority of Humpback Chub spawn in the Little Colorado River because it has a natural thermal regime, flow pattern, and sediment load (Gorman and Stone 1999; Coggins et al. 2006; Van Haverbeke et al. 2013). The Little Colorado River provides essential spawning habitat that is rare or unavailable in the main-stem Colorado

River due to the influence of upstream Glen Canyon Dam releases on flow and water temperature (Gorman and Stone 1999; Coggins et al. 2006). Colorado Pikeminnow *Ptychocheilus lucius* and Razorback Sucker *Xyrauchen texanus*, both endangered fish native to the Colorado River basin, were once abundant in the main-stem Colorado River and larger tributaries. Habitat degradation in the main-stem extirpated these species from much of their historic range and upstream tributary habitat such as the Green and Colorado rivers now support the strongest populations (Bestgen 1990; Modde et al. 1996; Osmundson and Burnham 1998; Bestgen et al. 2006). Colorado Pikeminnow exhibit fidelity to spawning reaches and make annual roundtrip migrations, presumably cued by stream flow, of nearly 800 km in length (Tyus 1990; Irving and Modde 2000; Bestgen et al. 2007). Razorback Suckers also make long seasonal migrations to spawning locations, which may be motivated by both flow and water temperature cues (Tyus and Karp 1990; Irving and Modde 2000; Bestgen et al. 2011). More recent research has documented the importance of smaller tributaries for reproduction and use by Colorado Pikeminnow and Razorback Sucker (Budy et al. 2009; Bottcher et al. 2013; Fresques et al. 2013; Webber et al. 2013).

Less is known about movements and tributary use by non-endangered native fishes of the Colorado River basin such as the Flannelmouth Sucker *Catostomus latipinnis* and Bluehead Sucker *Catostomus discobolus*. Understanding movement patterns and tributary use by Flannelmouth and Bluehead suckers will be critical for formulating conservation strategies and it has been suggested that protection of tributaries may be the most realistic means to protect fish populations, particularly in regulated rivers (Moyle and Mount 2007; Pracheil et al. 2009; Pracheil et al. 2013). Flannelmouth and Bluehead suckers have experienced large declines in distribution and abundance in the last century (Bezzerides and Bestgen 2002). Declines are partially due to habitat and abiotic alterations in main-stem river habitat (Martinez et al. 1994; Bezzerides and Bestgen 2002; Sweet and Hubert 2010). Bezzerides and Bestgen (2002) suggested that tributary use by Flannelmouth and Bluehead suckers may be one reason that these species have not experienced more dramatic declines, such as those seen in the four federally listed (endangered), large-bodied fishes that were once widespread in main-stem habitat in the Colorado River basin.

Flannelmouth and Bluehead suckers have been classified as both migratory and sedentary (Chart and Bergersen 1992; Douglas and Marsh 1998; Beyers et al. 2002; Compton et al. 2008; Budy et al. 2009; Sweet and Hubert 2010). Some studies on Flannelmouth Sucker have documented spawning migrations up to 200 kilometers while other studies found them to occupy narrow home ranges (Chart and Bergersen 1992; Bezzerides and Bestgen 2002; Budy et al. 2009). Bluehead Sucker movement studies indicated shorter migrations up to 35 kilometers; however, other studies indicated little to no movement (Compton et al. 2008; Budy et al. 2009; Sweet and Hubert 2010). Spawning migrations into tributary habitat have been noted for Flannelmouth Sucker in Bright Angel Creek in the lower Colorado River basin (Weiss et al. 1998). In the upper Colorado River basin both Flannelmouth and Bluehead suckers have been documented migrating into McKinney Creek to spawn (Compton et al. 2008). The mixed movement patterns of these species and variable distances moved may be partly due to study protocols and methods. For instance, inferences about movement based on mark-recapture studies and generalizations about movement patterns are uncertain because recapture rates are low (Chart and Bergersen 1992; Douglas and Douglas 2000; Breen and Hedrick 2009). Additionally, mark-recapture studies are not well suited to estimating movement because little is known about fish movement between the initial marking and subsequent recaptures. A potential improvement to traditional mark-recapture methods is the use of stationary PIT tag antenna arrays to passively sample tagged fish. Antenna arrays may increase recapture numbers and detect tags continuously throughout the year, potentially allowing better inferences regarding movement patterns (Greenberg and Giller 2000; Connolly et al. 2008; Johnston et al. 2009).

My study had two main objectives. First, I evaluated native sucker tributary use and spawning site fidelity in the upper White River, CO using mark-recapture methods and stationary PIT tag antenna arrays. Second, I evaluated the timing of spawning movements into these tributaries and the role of water temperature and flow in cueing these movements. This study will add to the limited ecological knowledge about tributary use by these species in the upper Colorado River basin and allow managers to make better-informed decisions regarding actions needed to conserve these species.

Background/Life history

Flannelmouth Sucker and Bluehead Sucker are large-bodied, Colorado River native fishes that were once widespread and abundant throughout the Colorado River basin. Bezzerides and Bestgen (2002) indicated that each species occupied 50% or less of its historical range by year 2000 and extant populations were declining in many localities. Declines of both species are attributed to alteration of habitat and introduction of non-native fishes. Dams have altered runoff patterns, changed thermal regimes, fragmented fish populations, and reduced naturally high sediment loads in downstream river reaches (Martinez et al. 1994; Collier et al. 1996; Poff et al. 1997; Ward et al. 2002). Non-native piscivores threaten native fishes by preying upon and competing for resources with adult, juvenile, and larval native fish (Martinez et al. 1994; Bestgen et al. 2006). Hybridization between the non-native White Sucker *Catostomus commersonii* and both the Flannelmouth and Bluehead sucker threatens the genetic integrity of these native species in most extant populations (Quist et al. 2009).

Flannelmouth and Bluehead suckers are members of the family Catostomidae. The Flannelmouth Sucker is differentiated from other suckers by its lack of a scraper plate on the lower jaw, large fleshy lobes on its upper and lower lips, narrow caudal peduncle, and numerous small scales along the lateral line. Typical adults are green or bluish-grey dorsally, yellow to dark-orange ventrally, and are between 400–500 mm in total length (Bezzerides and Bestgen 2002). Flannelmouth Suckers primarily inhabit pools and runs.

Bluehead Sucker is characterized by its prominent scraper plates on the upper and lower jaws, blue head, notches on the lateral margins of the upper and lower lips, and lack of papillae on the anterior face of the upper lip. Bluehead Suckers typically measure 300–450 mm TL but may vary in size depending on the river. Bluehead Suckers primarily inhabit riffles and runs.

Study area

The White River headwaters are in the Flat Tops Wilderness in northwestern Colorado. The White River flows west through Colorado and Utah, draining approximately 13,000 km^2 until it joins the Green River near Ouray, UT (Lanigan and Berry 1981; Chart and Bergersen 1992; Martinez et al. 1994). Taylor Draw Dam, the only main-stem dam on the White River, impounded Kenney Reservoir beginning in October, 1984 (Figure 1.1). The White River upstream from Kenney Reservoir to the confluence of the North Fork and South Fork of the White River, about 150 river kilometers (rkm), was chosen as the study site because it is one of the last relatively large, unobstructed, free-flowing river sections in the upper Colorado River basin and was thought to contain relatively robust native fish populations including

Flannelmouth and Bluehead suckers (Chart and Bergersen 1992). Snowmelt is the dominant water source in the White River and runoff usually occurs from mid-April through late June; flow typically peaks in early June with an average maximum flow of 91.5 m^3/s (23.7–186.5 m^3/s: Figure 1.2). Base flows occur from July through March. Summer thunderstorms periodically increase flow and turbidity.

The White River study area represents a continuum from an upstream coldwater environment to a downstream warmwater environment. Other studies used the confluence of the White River with the Green River as rkm 0; this location is 177 river kilometers downstream from the Kenney Reservoir-White River inflow area (Chart and Bergersen 1992; Martinez et al. 1994). In this study, rkm 0 was at the Kenney Reservoir-White River inflow area. The upstream coldwater portion of the study area begins at the confluence of the North Fork and South Fork of the White River and continues downstream through the town of Meeker, CO (rkm 100–151). This section is typical of other coldwater environments in which salmonids are the dominant fishes (Rahel and Hubert 1991; Griffith 1993). The channel form is pool-riffle-run with predominantly cobble substrate. Downstream from rkm 100 near Meeker to rkm 68, the river transitions from cold to warm water and supports both warmwater and coldwater species. The downstream portion of the study area (0-68 rkm) is a warmwater environment where salmonids are few or non-existent and warmwater species such as Flannelmouth and Bluehead suckers dominate the fish community. The channel form in the downstream portion is a uniform run with substrate composed of predominantly sand in low velocity areas and cobble in higher velocity locations. The main-stem White River is 30–40 m wide throughout the study area.

In April 2011, I deployed five HOBO temperature loggers in the main-stem White River and 15 in tributaries. Temperature was recorded once per hour, and data were downloaded in autumn of each year, 2011–2013. These twenty temperature loggers were deployed to evaluate potential sucker thermal habitat throughout the basin. However, temperature data are reported for only those sites used by each sucker species (See pilot study below). Flow data were gathered from three U.S. Geological Survey (USGS) gauges on the main-stem White River.

Pilot Study (site selection and capture methods)

In April 2011, surveys revealed seven potential tributaries for native sucker spawning: Crooked Wash, Piceance Creek, Flag Creek, Curtis Creek, Coal Creek, Miller Creek, and North Elk Creek. Based on presence of mostly perennial flows and presence of Flannelmouth or Bluehead suckers, Piceance Creek and Coal Creek were selected for this study. All other streams surveyed were not suitable due to barriers, ephemeral reaches, or cold water temperatures.

The confluence of Piceance Creek and the White River is at an elevation of 1,740 m above sea level (ASL) and 68 rkm upstream from the Kenney Reservoir-White River inflow area (rkm-0). Piceance Creek flows through a landscape dominated by sagebrush *Artemisia spp*, pinyon pine *Pinus edulis,* and juniper *Juniperus osteosperma*. The channel is approximately 2.5 m wide and the substrate is predominantly sand. The confluence of Coal Creek and the White River is located at 1,935 m (ASL) and rkm 118. Coal Creek flows through an agricultural valley dominated by irrigated fields. The channel is approximately 5 m wide and the substrate is a mix of cobble and sand.

Irrigation practices alter flows in both Piceance and Coal creeks but in different ways. During base flow periods, temporary dams in Piceance Creek divert water into irrigation canals and reduce or eliminate flow in the stream channel. In contrast, flow in Coal Creek is enhanced beginning in spring by an upstream irrigation ditch that diverts water from the main-stem White

River to the Coal Creek drainage. Thus, flow in Coal Creek is higher due to irrigation returns from diversions of White River water than may have occurred historically.

METHODS

Fyke nets

Fyke nets were used to capture Flannelmouth and Bluehead suckers in Coal Creek in 2011, 2012, and 2013. Sampling in 2011 was exploratory but indicated that fyke nets could be used to capture relatively large numbers of native suckers. I deployed four double-winged nets that opened facing downstream to capture fish migrating upstream in spring, presumably to spawn. Net wings anchored in stream substrate were 5 m long and 2 m high, and large enough to block the entire creek. I placed the cod end of nets in slow-moving water to minimize stress on captured fish. Preliminary sampling in 2011 occurred periodically for 2–3 day periods from late June through July. In 2012 and 2013 fyke nets remained in Coal Creek continuously from early May through mid-June. Nets were removed when catch rates fell to less than one fish per day for a full week. Fish were removed from nets daily. Fyke nets were placed in Piceance Creek during May of 2012 but no fish were captured. Piceance Creek sampling efforts were abandoned after that and all tributary sampling was focused on Coal Creek for the remainder of this study.

Species & PIT tag data

Fish captured in fyke nets and with electrofishing (see below) were identified, measured (TL [mm]), weighed (g), and sex was determined by the expression of gametes (eggs or milt) in sexually mature adults. Each fish was scanned prior to PIT-tagging to assess if it was previously tagged. I implanted 32 mm Oregon RFID Passive Integrated Transponder (PIT tag) in all suckers > 230 mm TL and all PIT tags were scanned prior to insertion to ensure they were functioning.

PIT tags were inserted into the body cavity behind the pelvic fin using a tag injector with a sterilized needle 3.7 mm in diameter.

Remote PIT tag antenna arrays

I installed two remote PIT tag antenna arrays in Coal Creek during the first week of April in 2012. The downstream antenna array was placed 200 m upstream from the confluence with the White River (Downstream Antenna Array), and the other 1800 m upstream from the confluence (Upstream Antenna Array). Individual antennas consisted of a 50 cm wide loop formed by a 10 gauge wire that encompassed the entire width of the creek. Each antenna array consisted of two antennas separated by 1–2 m (Figure 1.3) to allow direction of movement to be assessed. Antenna arrays were placed in riffles 20–25 cm deep and anchored to the streambed. The antennas had a read range of 45–60 cm and arrays were placed in shallow water so tags would be detected in the entire water column. The arrays were powered with two deep-cycle 12V batteries that were changed weekly when data were downloaded.

I condensed tag detection data by using only the first and last detection of a fish each day at each array to reflect daily movement patterns. The antenna data illuminated behavior patterns of suckers post-handling and enabled us to determine antenna efficiency because both the number of fish tagged and the antenna detections were known and compared. As tagged fish returned to Coal Creek in subsequent years, antenna detections were used to determine when fish returned and how long they remained in Coal Creek.

Population estimates

To estimate the population size of suckers in the main-stem White River, two-pass, mark-recapture sampling was conducted with raft electrofishing at three locations in 2012 (Reach 1 [rkm 11– 14], Reach 2 [rkm 85– 86], and Reach 3 [rkm 112– 116]) and two locations in 2013 (Figure 1.1). Reach 1 was sampled twice in 2013 on May 4; both passes were completed on the same day. The second two-pass sampling in Reach 1 was done on June 26–27; one pass was done each day. Two rafts were deployed simultaneously, one for each side of the river channel. Electrofishing was done with a Smith-Root Inc. Generator Powered Pulsator (GPP) with a 60 Hz pulsed direct current (DC). Voltage and amperage were adjusted to maximize taxis and minimize injury and stress to all fish; each raft had two anodes at the front and two cathodes at the back. Each raft had a three-person crew including two netters and one boat operator. These data were used to estimate the population sizes of Flannelmouth and Bluehead suckers in the main-stem White River. To estimate population sizes, I used a Lincoln-Peterson estimator with a Chapman correction (Chapman 1951). I calculated 95% confidence intervals to account for the low number of recaptures (Ricker 1975). Even though Reach 1 was sampled four times in 2013 because 52 days passed between sampling this reach, I treated each two-pass sampling event as separate estimates because closure assumptions were likely violated. Only fish greater than 230 mm TL were used for the abundance estimate.

RESULTS

Tributary Use

Flannelmouth and Bluehead suckers entered Coal Creek in early May of both 2012 and 2013 when water temperatures were rising and flows were high or declining (Figure 1.4). Flannelmouth Suckers first entered Coal Creek on May 14 in 2012 when temperatures in the White River near Coal Creek reached 11.0°C and Coal Creek temperatures reached 12.5°C (Figure 1.5). However, the majority of Flannelmouth Suckers were captured from May 23 to June 8 in 2012 when White River water temperature averaged 12.3°C (8.9–14.5°C) and Coal Creek was warmer at 13.9°C (10.0–16.2°C). In 2013, Flannelmouth Suckers were first captured in Coal Creek on May 18 when water temperature reached 8.2°C in the White River and 11.7°C in Coal Creek. The majority of fish were captured from May 26 to June 12 when mean water temperature was 10.6°C (8–12.7°C) in the White River but was warmer at 14.4°C (12.0–16.8°C) in Coal Creek. The average flow in the main-stem White River during the peak capture period for Flannelmouth Sucker was 17.0 m^3/s (11.5–22.2 m^3/s) in 2012 when flows were declining. The average flow in the main-stem White River during the peak capture period for Flannelmouth Sucker was 39.5 m^3/s (26.9–50.7 m^3/s) in 2013 across three flow peaks.

Bluehead Sucker movement into Coal Creek from the White River largely overlapped that for Flannelmouth Suckers in each of 2012 and 2013. The first Bluehead Suckers entered Coal Creek on May 15 in 2012 when water temperatures in the White River adjacent to Coal Creek reached 10.3°C (Figure 1.4) and Coal Creek temperatures reached 13.3°C. The majority of Bluehead Sucker captures in Coal Creek occurred between May 23 and June 5 in 2012 when the water temperature averaged 11.9°C (8.9–14.2°C) in the White River and 13.5°C (10.0–16.2°C) in Coal Creek. Bluehead Sucker first entered Coal Creek on May 25 in 2013 when the water temperature was 9.5°C in the White River and 13.5°C Coal Creek. The majority of Bluehead Sucker captures occurred between May 30 and June 11 in 2013 when water temperature averaged 11.1°C (8.9–12.4°C) in the White River but was warmer at 14.7°C (12.0–16.8°C) in Coal Creek. The flows during the peak capture period for Bluehead Sucker during both 2012 and 2013 were similar to that for Flannelmouth Sucker.

Suckers captured in Coal Creek with fyke nets during 2011, 2012 and 2013 were composed entirely of large-bodied adults (Figure 6). Flannelmouth Suckers were larger and outnumbered Bluehead Suckers by a ratio of 6:1 in 2012 and 7:1 in 2013. The mean total length for Flannelmouth Suckers was 472 mm TL (385–570 mm TL) in 2011, 455 mm TL (381–554 mm TL) in 2012 and 470 mm TL (413–576 mm TL) in 2013. Bluehead Sucker mean TL was 414 mm TL (357-469 mm TL) in 2011, 390 mm TL (340–460 mm TL) in 2012 and 412 mm TL (365–480 mm TL) in 2013.

Gamete expression for suckers captured in Coal Creek positively identified more males than females for both species in both years. In 2012, 96 of the 224 Flannelmouth Suckers captured expressed milt and 35 expressed eggs. In 2013, 91 of the 157 Flannelmouth Suckers captured expressed milt and 10 expressed eggs. In 2012, 21 of the 40 Bluehead Suckers captured expressed milt and 3 expressed eggs. In 2013, 12 of 23 Bluehead Suckers captured expressed milt compared to 2 that expressed eggs. The remainder of suckers captured in Coal Creek did not express gametes so gender was not identified. The relatively low number of fish with positive determinations of sex made sex-specific comparisons difficult.

PIT tag antenna detections of recaptured suckers indicated similar trends in tributary use compared to those for fyke net captures. In 2012, Coal Creek PIT tag antennas first detected movement of Flannelmouth Suckers on May 16, two days after the first fyke net capture. Bluehead Suckers were first detected on May 13, one day earlier than the first fyke net capture in 2012. In 2013, antennas in Coal Creek first detected Flannelmouth Suckers on May 16, two days earlier than the first fyke net capture. Bluehead Suckers were first detected on May 17, one day earlier than the first fyke net capture.

Antenna detections from suckers returning to Coal Creek in years after they were initially tagged did not show a substantial difference in residence time between sucker species. For example, Flannelmouth Suckers spent an average of 10.7 days in residence (1–16; n=10) in Coal Creek during 2012 and 10.5 days (1–32; n=74) during 2013 (Table 1.1). Bluehead Suckers returning to Coal Creek spent an average of 11.2 days in residence (1–27; n=6) in 2012 and 11.8 (1–30; n=20) days in 2013.

Antenna efficiency

Antenna arrays in Coal Creek, each comprised of two separate antennas, had high detection rates of suckers tagged and released in Coal Creek; 100% for 2012 (264 of 264) and 99.5% (179 of 180) for 2013 (Table 1.2), based on detections by at least one antenna array. Of the 444 fish tagged and released during 2012 and 2013, 436 were detected by the most downstream antenna array as fish were presumably exiting Coal Creek (See behavior section below; Figure 1.3). Seven fish were detected moving downstream by the upstream antenna array but were not detected at the downstream antenna array, and one fish was not detected at all. We do not know the fate of the eight fish never detected exiting Coal Creek. Considering the read range of the antennas (45–60 cm) and the depth of the water (20–25 cm), it is unlikely that these fish exited Coal Creek while the antenna arrays were operational. The antennas were only briefly shut down once per week for 10–20 minutes to download data and change batteries. Therefore, it is likely that these eight fish remained in Coal Creek between the downstream and upstream antenna arrays during the summer field seasons.

Site fidelity

Flannelmouth and Bluehead suckers exhibited spawning site fidelity to Coal Creek from one year to the next. Tagged fish were recaptured in subsequent years in fyke nets or detected by antenna arrays. Antenna arrays detected a much higher percentage of fish returning. For example, fyke net captures demonstrated that Flannelmouth Suckers had site fidelity rates of 2–3% and Bluehead Suckers between 3–6% (Table 1.2). Antennas detected many more tagged suckers in Coal Creek than fyke nets and thus demonstrated levels of site fidelity of 45% and 22% for Flannelmouth Suckers initially tagged in 2011 and 2012, respectively. Similar site fidelity rates were observed by antenna detections for Bluehead Suckers demonstrating site fidelity rates of 40% and 13% for fish initially tagged in 2011 and 2012, respectively (Table 1.2).

Fyke net efficiency

Preliminary sampling in 2011 with fyke nets indicated sucker captures occurred with minimal man-power and minimized stress on captured fish. However, comparing fyke net captures to antenna detections indicated that fyke nets were not efficient at sampling suckers. For example, of the 84 Flannelmouth Suckers detected by the antennas returning to Coal Creek, only 7 (8%) were recaptured in fyke nets. Fyke net efficiency was better for Bluehead Suckers but still low; of the 28 detected by the antennas, only 14 (50%) were recaptured with fyke nets.

Behavior

Antenna detections revealed that the majority of native suckers captured and handled in Coal Creek exited within 24 hours (Table 1.3), resulting in few individuals available for recapture in subsequent sampling within a year. The unexpected emigration occurred whether suckers were captured and tagged for the first time or had been previously tagged and were simply scanned for tag presence. In 2012, 84% of Flannelmouth Suckers left Coal Creek within 24 hours of being handled, and an additional 4.9% left in the subsequent 24-hour period. In 2013, 81.5% of Flannelmouth Suckers exited Coal Creek within 24 hours of being handled, followed by an additional 5.7% in the subsequent 24 hour period. In 2012, 87.5% of Bluehead Suckers exited Coal Creek within 24 hours of being handled, and an additional 7.5% left in the next 24 hour period. In 2013, 69.5% of Bluehead Suckers left within 24 hours of being handled and 13.0% left in the second 24-hour period. Suckers recaptured in fyke nets in subsequent years exhibited the same behavior as those after the initial capture, because 15 of the 21 suckers recaptured exited Coal Creek within 24 hours of being handled. Antenna detection data suggest that handling alone, with or without tagging, is sufficient to cause emigrations from Coal Creek. Post-handling emigration violated the closure assumption for closed capture abundance estimation techniques so abundance estimation for suckers in Coal Creek was not attempted.

Population estimates

Although relatively large numbers of suckers were captured during White River raft electrofishing, the few recaptures resulted in imprecise estimates of abundance (Tables 1.4 and 1.5). A larger number of Flannelmouth Suckers were captured and tagged in the main-stem White River compared to Bluehead Suckers in both 2012 and 2013. Flannelmouth Sucker abundance was lower in downstream reaches than upstream reaches. Abundance estimates from sampling in 2012 resulted in the smallest population of Flannelmouth Suckers at the most downstream section Reach 1. Abundance estimates from Reach 2 were the largest, followed by Reach 3. In 2013 Flannelmouth Sucker abundance estimates were again lower for the downstream section Reach 1 compared to Reach 3. Reach 2 was not sampled in 2013. Bluehead Suckers were only recaptured in main-stem sampling during 2012 in Reach 3.

DISCUSSION

My study highlights the potential importance of tributaries for native suckers in the upper Colorado River basin and it is likely that movement into Coal Creek is a seasonal spawning migration. All fish captured in the spring were large adults and many exhibited spawning coloration or expressed gametes (also see Chapter 2). My study resulted in three important insights into native sucker reproduction. First, suckers are probably responding to a thermal cue that initiates migration. Second, both sucker species showed high spawning site fidelity, which was detectable only by antenna arrays. Third, most suckers in both species emigrated from Coal Creek within 48 hours after being captured.

Seasonal movement of suckers into Coal Creek demonstrated high levels of site fidelity from one year to the next. For example, PIT tag detections of Flannelmouth and Bluehead suckers indicate that up to 45% of adult spawning fish return in subsequent years. Spawning in Coal Creek was substantiated in a separate study (see Chapter 2). High levels of site fidelity highlight the importance of tributaries for sucker spawning and the need to include tributaries in habitat conservation efforts. Additionally, estimates of site fidelity may have been low because fish emigrating due to the handling effect (discussed below) may have influenced other individuals not to move into Coal Creek.

Antenna detections showed that the majority of suckers moved out of Coal Creek within 24 hours of being captured and handled, whereas fish that were detected but not handled did not emigrate immediately. The rapid emigration was surprising and would not have been apparent without PIT tag antenna arrays. Rapid emigration has three major consequences of interpreting our data. First, movement of fish out of Coal Creek after handling explains the low recapture rates of suckers in the year that they were initially tagged and reduced my ability to estimate abundance or other vital rates. Second, it limited inferences on natural behavior patterns of suckers occupying Coal Creek. For example, most suckers were captured before reaching the second antenna and that limited how far upstream they might have traveled or how long they would have stayed in Coal Creek. Finally, emigration of captured suckers may have lowered site fidelity rates by altering the behavior of other individuals entering Coal Creek to spawn, causing them to abandon spawning. Continued operation of remote antennas in Coal Creek in subsequent years without deploying fyke nets is recommended to determine whether site fidelity rates were affected by nets.

Our movement results were similar to those for American Shad *Alosa sapidissima*, which showed that more than 50% of fish abandoned their upstream spawning migrations less than 24 hours after being captured, handled, and tagged (Bell 1985; Barry 1986; Moser 2000). Studies on salmonids have also shown unexpected post-handling movement downstream when fish were captured during an upstream spawning migration (Bernard et al. 1999; Makinen et al. 2000; Young et al. 2006). Makinen et al. (2000) showed that 100% of tagged Atlantic Salmon *Salmo salar* made immediate downstream movement upon release.

Post-handling emigration may also give insight into low recapture rates observed during White River mark-recapture abundance estimation sampling. Low recapture rates in main-stem electrofishing sampling resulted in imprecise population abundance estimates. One possible explanation for low recaptures could be post-handling emigration during electrofishing sampling similar to that seen for suckers in Coal Creek, making them unavailable for recapture. I feel this is a likely explanation, but low recaptures could also be due to large population size and insufficient numbers of marked fish. Low recapture rates of suckers have been observed in previous studies and limited the assessment of both long-term and short-term movement patterns (Chart and Bergersen 1992; Douglas and Douglas 2000; Breen and Hedrick 2009) and handling-related movement may also explain the low recapture rates seen in other studies. The use of remote PIT tag antenna arrays in the main-stem White River upstream and downstream of the sampling locations to evaluate the movement patterns of suckers post sampling could be used to address this issue.

Antenna arrays detected fish movement more effectively than recapture of tagged fish with fyke nets. A total of 81% (91 of 112) of suckers that returned to Coal Creek were not captured in fyke nets. Large numbers of fish bypassed the nets even though the entire channel was blocked by carefully-placed fyke nets at 3–4 locations. The antenna detections indicated that fyke nets were ineffective for subsequent recapture of marked individuals, but I used fyke nets for initial capture and marking because they induced less stress on fish and have lower mortality rates than other sampling gear (Hopkins and Cech 1992).

The response of suckers post-handling and the utility of remote PIT tag antenna arrays to passively assess fish movement post-capture in mark-recapture studies should be considered when designing monitoring studies for sucker species. My observed emigration rates of suckers in Coal Creek post-handling would produce overestimates of population size if unaccounted for, highlighting the need for long-term mark-recapture studies and the use of passive gear such as PIT tag antennas for recapture. Specifically, further research into the movement patterns of suckers post-handling in main-stem habitat will help managers to estimate population sizes with low recapture rates by assessing emigration in main-stem locations. Remote PIT tag antenna arrays in the main-stem would also enhance understanding of seasonal movement, home range, and migration patterns, especially if antenna arrays are operated year round including when traditional sampling is not possible due to extreme flow conditions or presence of ice.

Flannelmouth and Bluehead suckers spawning is likely cued by water temperature (Bezzerides and Bestgen 2002; Zelasko et al. 2011). In Coal Creek, water temperatures suitable for spawning were reached in early May of 2012 and 2013, when we observed large, ripe, adult Flannelmouth and Bluehead suckers entering the creek. The size and condition of these fish, in addition to subsequent collection of larvae from both species in Coal Creek (see chapter 2), indicated that suckers were spawning in Coal Creek. Tributaries may provide important habitat for suckers as they are often warmer, more productive, and harbor fewer predators than main-stem habitat (Weiss et al. 1998; Douglas and Douglas 2000; Paukert and Rogers 2004). My data indicated that temperatures in Coal Creek were on average 2.5–4˚C warmer than main-stem temperatures when suckers occupied Coal Creek. Warmer water temperatures in Coal Creek may allow earlier spawning (see Chapter 2). The advantage to earlier spawning is increased larval growth and development before the onset of winter, the most perilous time for most age-0 fish (Kaeding and Osmundson 1988; Thompson et al. 1991; Coleman and Fausch 2007).

Movement into tributary habitat may be cued by main-stem environmental conditions such as water temperature and flow (Weiss et al. 1998). It appears that temperature was more important to sucker movement into Coal Creek than flow. The average temperature in the main-stem White River when suckers entered Coal Creek was similar both years, but flow rates were different. Flow rates in 2013 were more than double those in 2012 and exhibited multiple peaks when suckers entered Coal Creek, compared to lower flows in 2012 that were declining from peak. This indicated that flow rates may not be the primary cue for sucker movement. Some studies have noted that native fishes begin spawning migrations as seasonal flow declines (Tyus

1990; Tyus and Karp 1990; Irving and Modde 2000; Osmundson 2011). Our data showed a similar pattern in 2012 when suckers entered Coal Creek as flow declined. However, in 2013 suckers moved into Coal Creek during a highly fluctuating period during peak flow. Additional data will be necessary to understand the role of spring flows on sucker spawning, but my data indicated that flow may not be the primary cue.

My study provides the first documentation of small tributary use by Flannelmouth and Bluehead suckers in a system with no obstructions to upstream movement and natural thermal and flow regimes. Additionally, suckers in the White River were not confined by anthropogenic barriers with the exception of Taylor Draw Dam 118 rkm downstream from Coal Creek. Despite having sufficient spawning habitat in the main-stem White River, both sucker species used the Coal Creek tributary for spawning. Larval collections in a separate study revealed that suckers spawned successfully in Coal Creek and in the main-stem White River adjacent to Coal Creek during 2012 and 2013, but the proportion of the sucker population that spawned in Coal Creek could not be estimated (see Chapter 2). Similarly, Flannelmouth Suckers were known to migrate into tributaries in the lower Colorado River basin. However, the lower Colorado River is highly regulated by large main-stem impoundments that impair migration and alter the hydrograph and sometimes depress thermal regimes below that suitable for spawning by Flannelmouth Sucker (Weiss et al. 1998). In the upper Colorado River basin, suckers migrated into McKinney Creek, a small tributary to Muddy Creek in Wyoming (Compton et al. 2008). However, McKinney Creek provided the only option for upstream movement due to a significant fish barrier located in Muddy Creek upstream of the confluence with McKinney Creek. The barrier confounded determination of whether fish would have occupied McKinney Creek if they had access to upstream habitat in Muddy Creek. My study provided evidence that tributary spawning was an important component of sucker life history in an environment not impacted by dams.

Although not dammed, the upper White River is not pristine because it was altered by irrigation ditches that moved water off-channel and reduced flows in some areas (Piceance Creek) while increasing flows in others (Coal Creek). The dichotomy between the two tributaries evaluated in this study could be applied to management decisions when considering flow requirements for streams. Coal Creek benefited from increased flow from an irrigation return ditch and showed high levels of site fidelity and use by suckers for spawning. The increased flow may improve access and fish passage within Coal Creek, especially in low water years when culverts may impede fish passage. Coal Creek is a good case study for a win-win situation for both irrigation and fish conservation. Additional improvements could be made in Coal Creek if large culverts that acted as barriers to upstream fish movement were remediated. Passage of these barriers could make upstream habitat accessible for native fish as well as provide a more secure passage for water through Coal Creek during floods. In contrast, Piceance Creek flows were greatly decreased from irrigation ditches that removed water and no sucker spawning movements were detected.

A better understanding of the role of thermal cues, movement, and tributary use for spawning suckers in other areas within the Colorado River basin will enhance our understanding of Flannelmouth Sucker and Bluehead Sucker ecology and aid management decisions for future conservation of these native species. Understanding temperature thresholds that initiate movement into tributaries and subsequent spawning could allow managers to specifically cater management to enhance sucker spawning in locations where these species are in decline. For example, mapping software and temperature data could be used to identify potential spawning tributaries, evaluate access from the main-stem into tributaries and assess whether minimum flow requirements meet the needs of fish migrating upstream. Understanding movement patterns and their timing may allow for remediation of hybridization between native suckers and the White Sucker and predation by non-native fishes. Focusing on tributaries for invasive species removal or exclusion, especially during the sucker spawning season, may enable managers to ameliorate hybridization and predation effects in some sucker populations. Because tributaries are smaller habitats and more easily manipulated and controlled than main-stem habitat, operating temporary fish passage structures to actively exclude non-native fish from spawning areas may be a practical way to reduce hybridization and predation. My study highlights the importance of tributary habitat, which is generally overlooked and not included in management plans for these species (Douglas and Marsh 1998; Douglas and Douglas 2000; Bottcher et al. 2013). Maintaining connectivity within tributary habitat and between tributary and main-stem habitat should be a focus of management goals to preserve all the life histories of these native fishes.

TABLES

TABLE 1.1–Mean and range of days that Flannelmouth Suckers (FMS) and Bluehead Suckers (BHS) spent in Coal Creek on their return in years after they were PIT tagged. All of these fish were initially PIT tagged in Coal Creek. These data are from remote antenna array detections.

Year	BHS	FMS
2012	11.2 (1-27) n=6	10.7 (1-16) n=10
2013	11.8 (1-30) n=20	10.5 (1-32) n=74

TABLE 1.2–Mark-recapture data for the number and percentage (%) of Flannelmouth Sucker (FMS) and Bluehead Sucker (BHS) captured with fyke nets (Fish Tagged), and recaptured by remote PIT tag antenna arrays (Antenna Detection) and fyke nets (Fyke Net Recaptures). All of the captures and recaptures occurred in Coal Creek. Data from the upstream and downstream remote antenna arrays were combined (Antenna Detection).

			Antenna Detection		Fyke Net Recaptures	
Species	Tagging Year	Fish Tagged	2012	2013	2012	2013
FMS	2011	40	16 (40)	18 (45)	2 (5)	2 (5)
	2012	224		50 (22)		3(1)
BHS	2011	35	9 (26)	14 (40)	6 (17)	5 (14)
	2012	40		5 (13)		3 (8)

TABLE 1.3–Number and percentage (%) of Flannelmouth Suckers (FMS) and Bluehead Suckers (BHS) captured in fyke nets, PIT tagged (Marked) in Coal Creek in 2012 and 2013, then subsequently detected on the most downstream antenna array leaving Coal Creek within 24 hours (Day 1) and 48 hours (Day 2) of being implanted with a PIT tag.

			Exited Coal Creek	
Species	Year	Marked	Day 1	Day 2
FMS	2012	224	189 (84)	11 (5)
FMS	2013	157	128 (82)	9 (6)
BHS	2012	40	35 (88)	3(8)
BHS	2013	23	16 (70)	3 (13)

TABLE 1.4–Number of Flannelmouth Suckers (FMS) and Bluehead Suckers (BHS) PIT tagged (Mark) and recaptured (Recap) on multiple two-pass, mark-recapture studies on the main-stem White River in 2012 and 2013. Reach 2 was not sampled in 2013. Two separate two-pass mark-recapture studies were conducted in Reach 1 during 2013; the numbers are combined in this table to illustrate the low recapture numbers.

		2012		2013	
Species	Location	Mark	Recap	Mark	Recap
FMS	Reach 1	212	21	148	13
FMS	Reach 2	190	4	--	--
FMS	Reach 3	254	15	193	6
BHS	Reach 1	4	0	4	0
BHS	Reach 2	17	0	--	--
BHS	Reach 3	75	3	45	0

TABLE 1.5–Population estimates and 95% confidence intervals of Flannelmouth Sucker (FMS) and Bluehead Sucker (BHS) from three, two-pass, mark-recapture events using raft electrofishing on the main-stem White River in 2012 and 2013. Reach 2 was not sampled in 2013. Insufficient numbers of Bluehead Suckers were recaptured to produce abundance estimates, and no Bluehead Suckers were recaptured in Reach 1 in either year. Two separate abundance estimates were done in Reach 1 in 2013, two passes were done on May 4 and then one pass was done each day on June 26 and 27.

		Population Estimates		
		2012	2013	
Species	Location	June	May	June
FMS	Reach 1	434 (284-696)	202 (90-504)	296 (90-503)
FMS	Reach 2	1637 (731-4095)	--	--
FMS	Reach 3	998 (620-1700)	--	1311 (651-2870)
BHS	Reach 1	No recaptures	No recaptures	No recaptures
BHS	Reach 2	No recaptures	--	--
BHS	Reach 3	368 (151-1392)	--	No recaptures

FIGURES

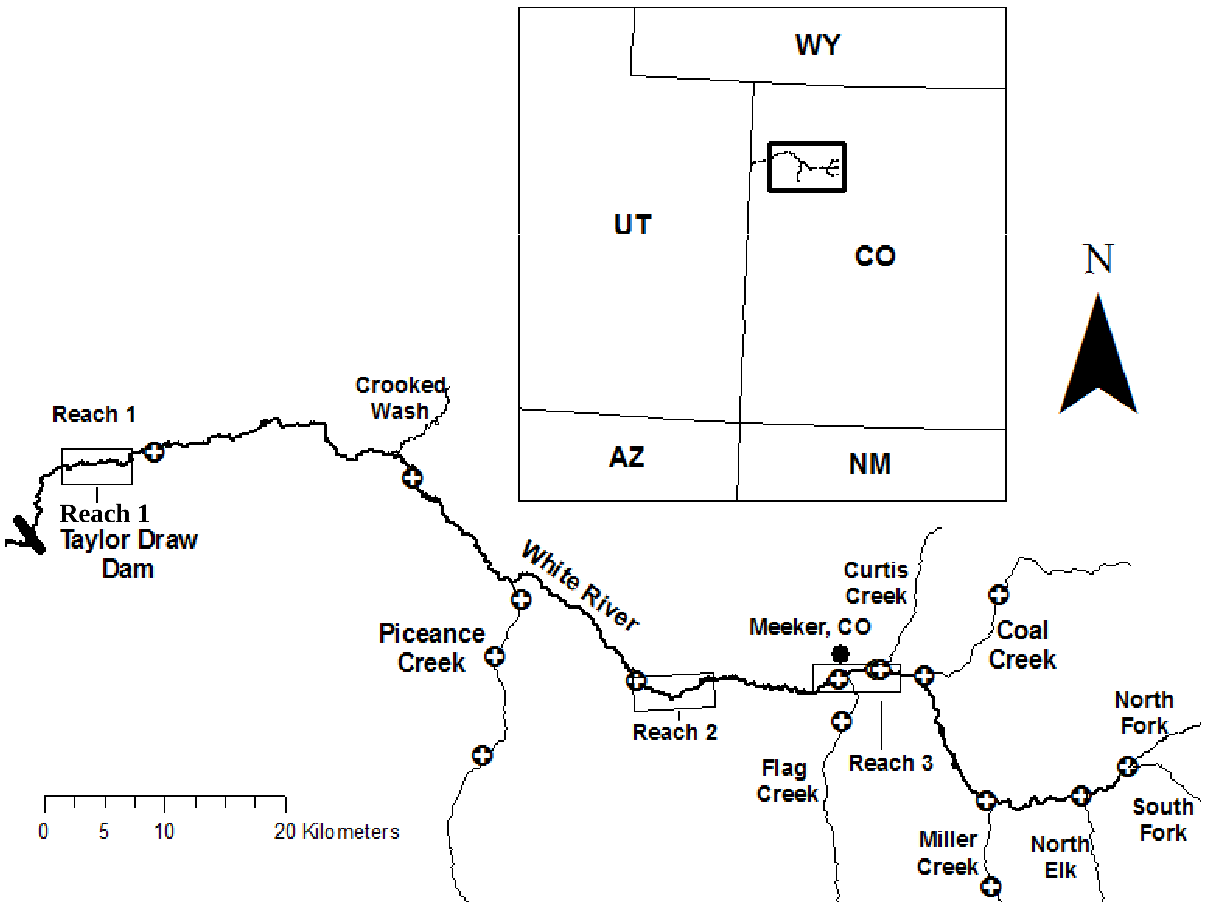

FIGURE 1.1–Map of the upper White River drainage, CO, depicting tributaries, three raft electrofishing reaches outlined in rectangles, and temperature logger locations indicated by crosses.

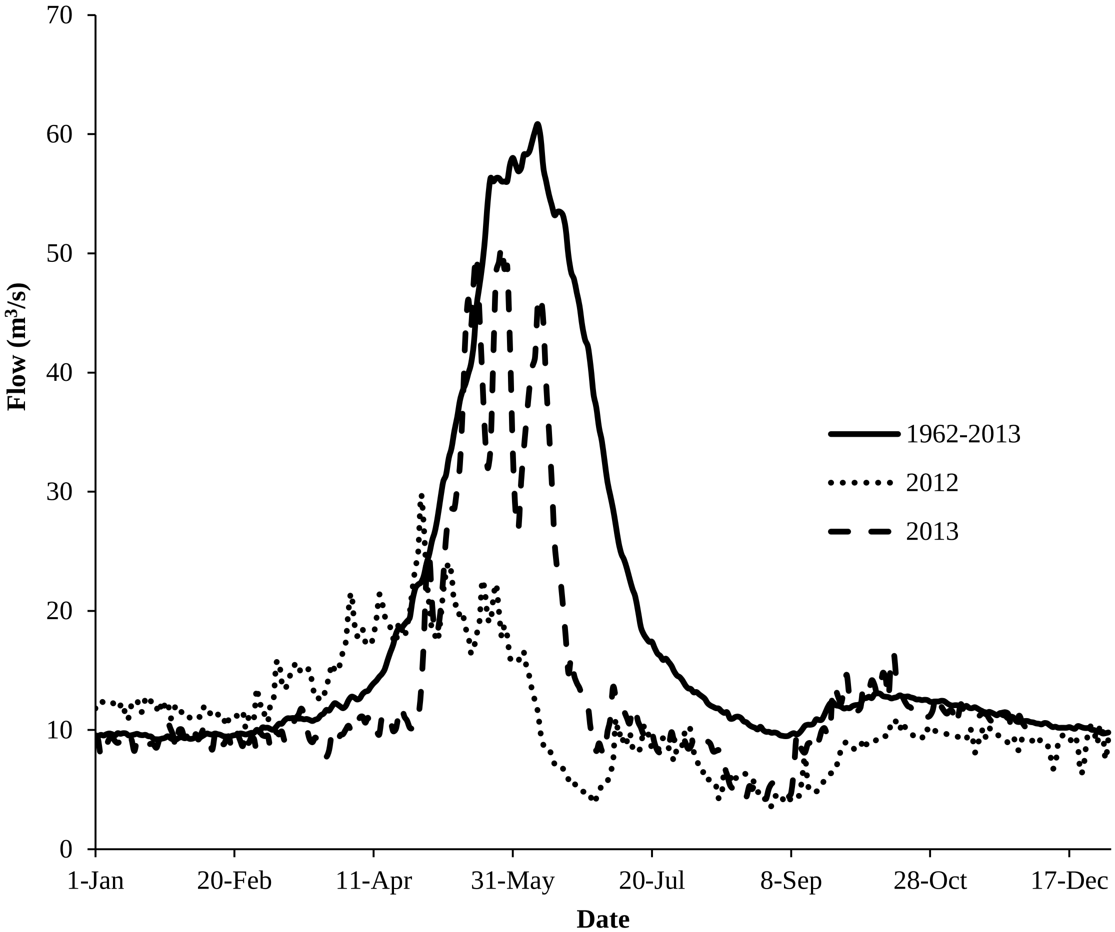

FIGURE 1.2–Mean daily flow (m^3/s) of the White River, CO (U.S. Geological Survey gauge #09304800) for the period of record (1962-2013) and study years 2012 and 2013.

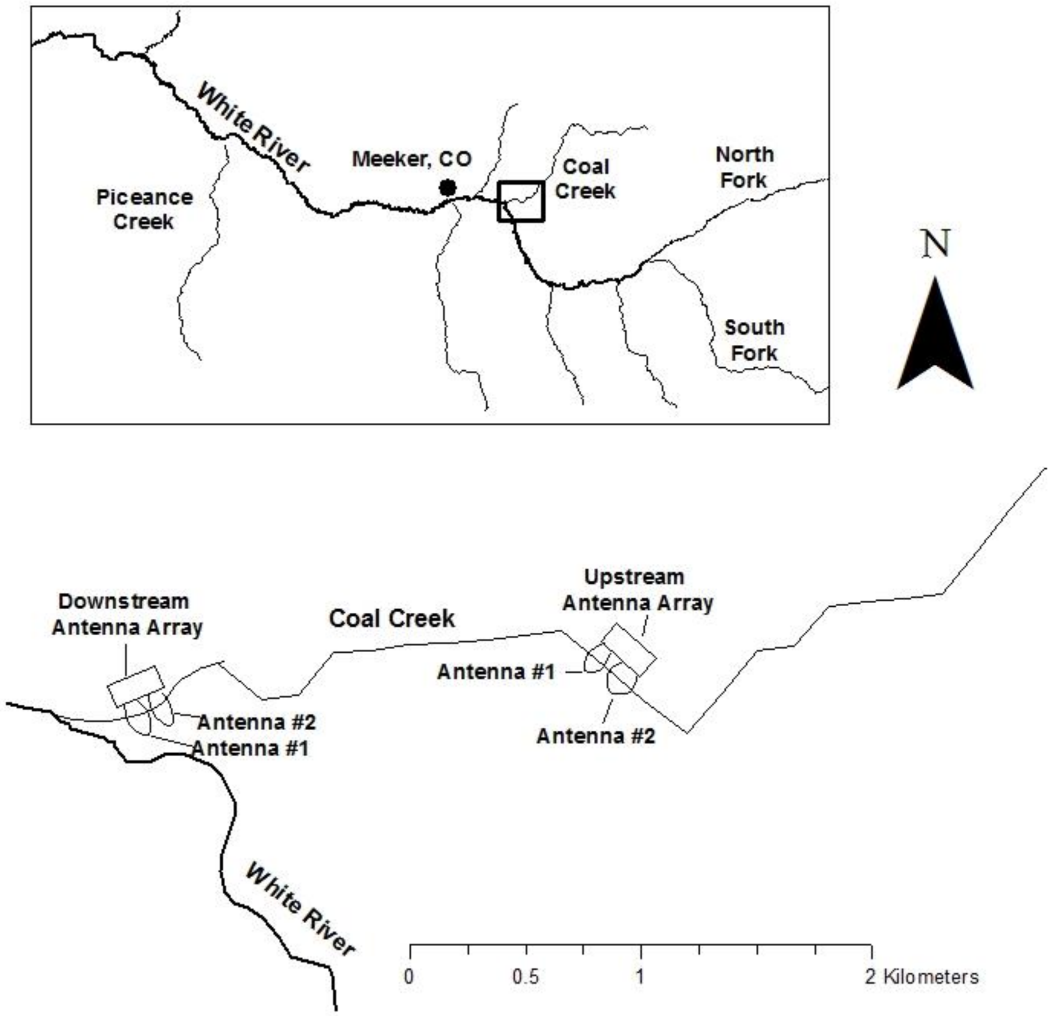

FIGURE 1.3–Map of Coal Creek depicting the placement of the two remote PIT tag antenna arrays and their proximity to the main-stem White River, CO in 2012–2013.

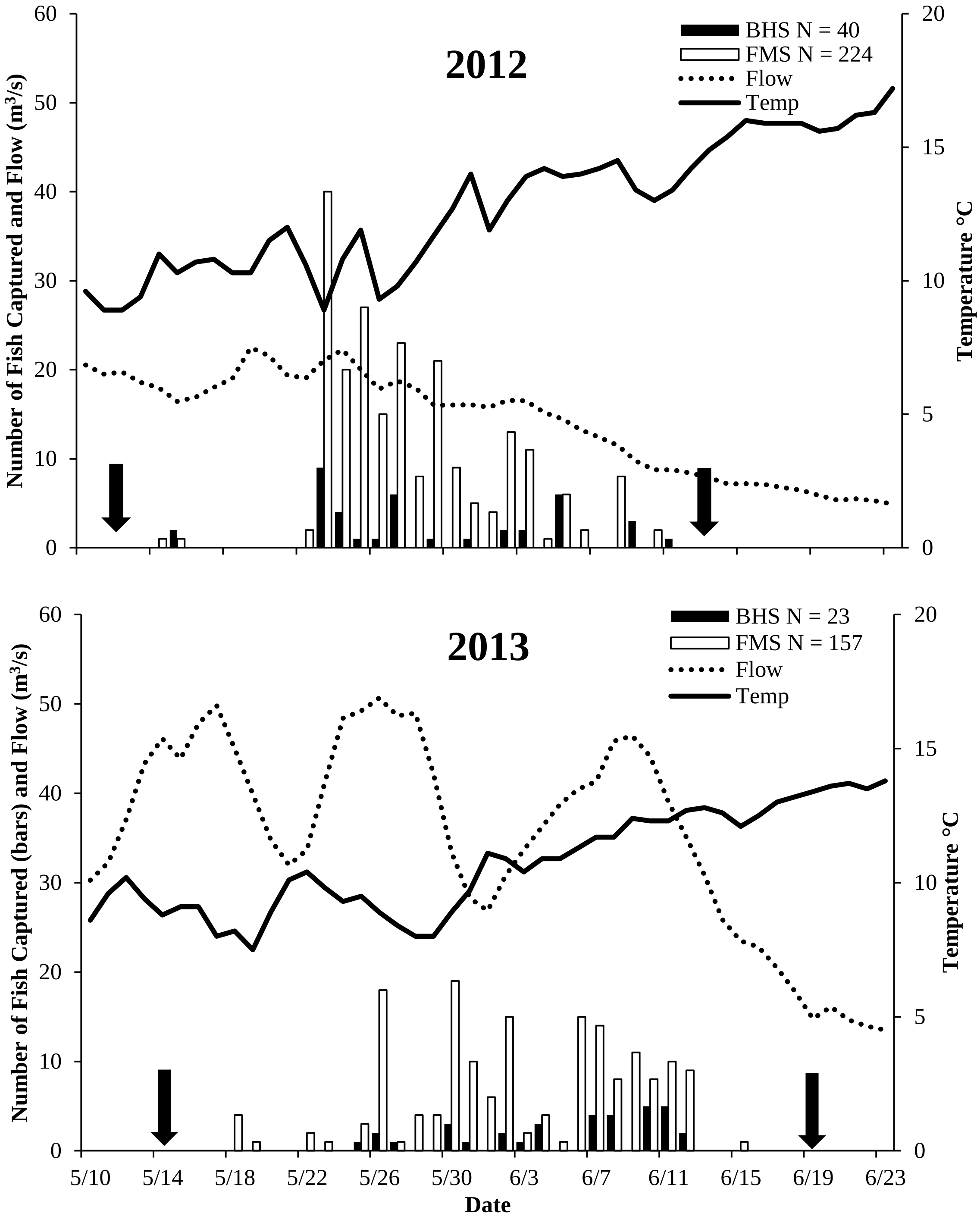

FIGURE 1.4–Seasonal timing and number of Flannelmouth Suckers (FMS) and Bluehead Suckers (BHS) captured in fyke nets in Coal Creek in 2012 and 2013 (bars). Mean daily flow (m^3/s; dotted line) and mean daily water temperature (°C; solid line) for the main-stem White River near Coal Creek (U.S. Geological Survey gauge #09304200) are indicated by the solid line on the secondary (right) y-axis for the top and bottom graphs respectively. The arrows represent the day that the fyke nets were placed and removed from Coal Creek.

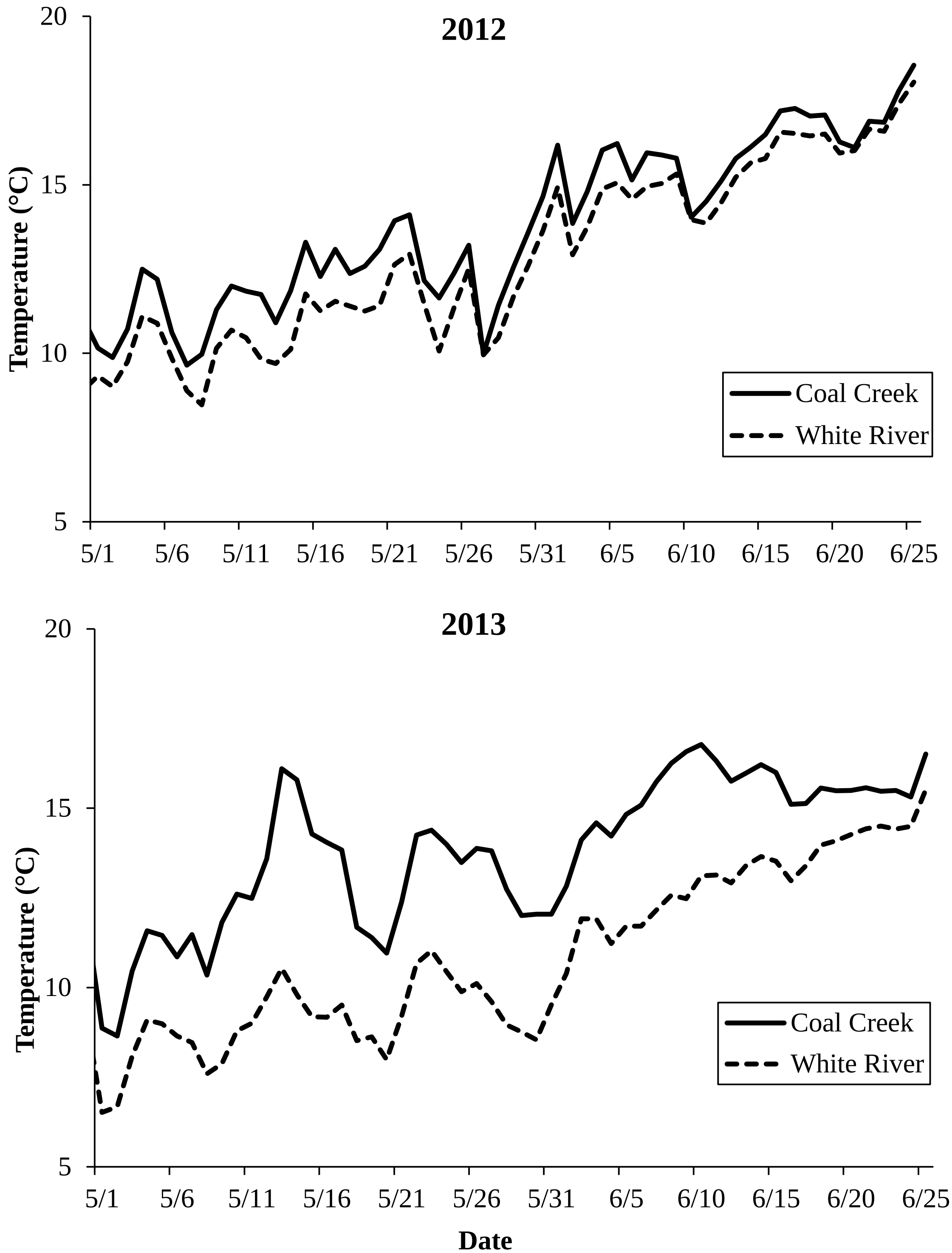

FIGURE 1.5–Mean daily water temperature (°C) of Coal Creek (solid line) and the main-stem White River (dashed line) near Coal Creek (U.S. Geological Survey gauge #09304200) during the sucker spawning period in 2012 and 2013.

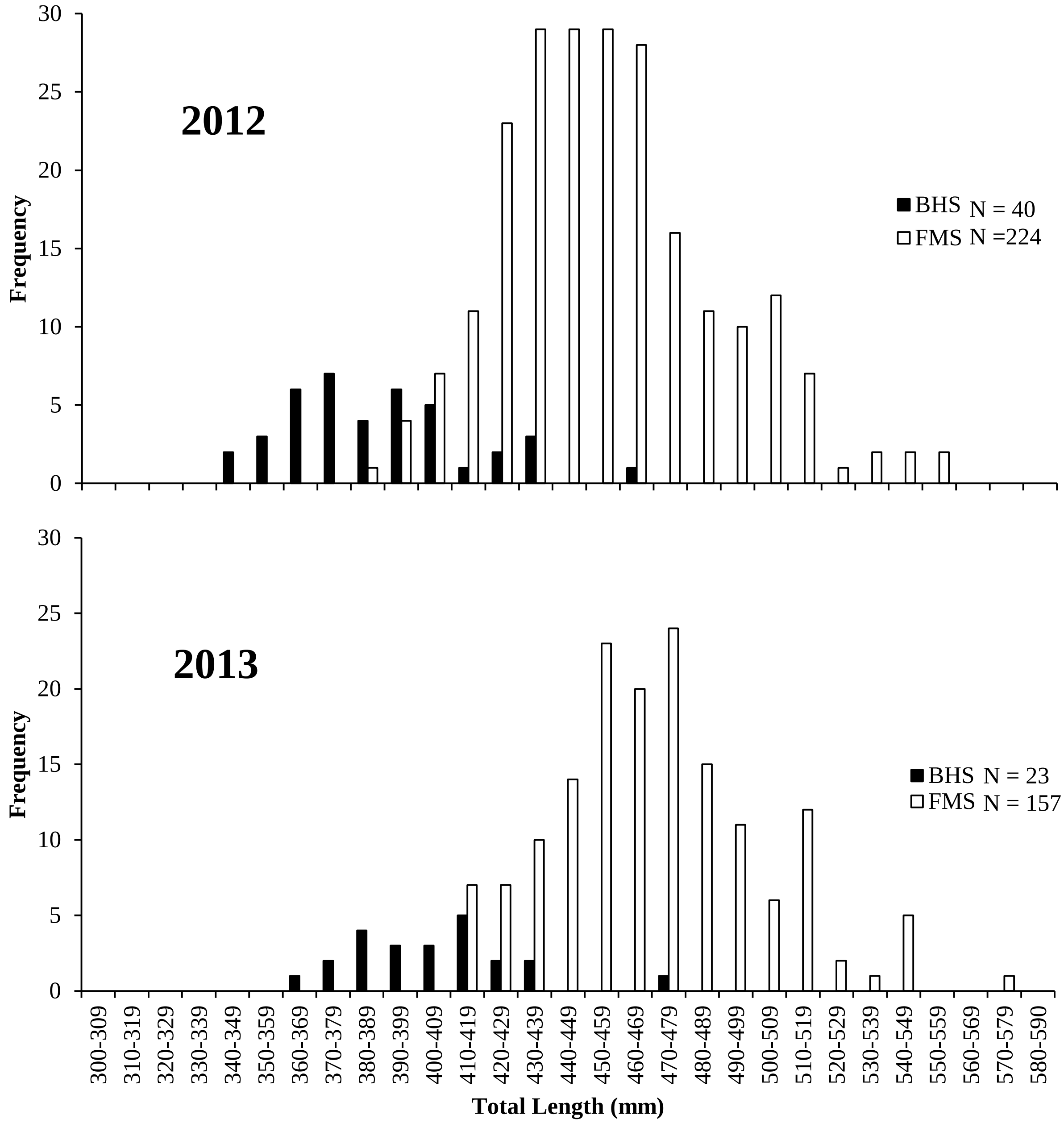

FIGURE 1.6–Length frequency histograms (mm total length) of Flannelmouth Suckers (FMS) and Bluehead Suckers (BHS) captured in fyke nets in Coal Creek, during May and June, 2012 and 2013.

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CHAPTER 2: EFFECTS OF WATER TEMPERATURE AND FLOW ON REPRODUCTION OF FLANNELMOUTH SUCKER, BLUEHEAD SUCKER, AND ROUNDTAIL CHUB IN THE UPPER WHITE RIVER DRAINAGE, COLORADO

INTRODUCTION

In river ecosystems, flow and water temperature are key factors regulating life histories of aquatic organisms (Coutant 1987; Poff et al. 1997; Olden and Naiman 2010). Flow alters turbidity, channel geomorphology, spawning habitat suitability, and may signal migration or spawning events (Collier et al. 1996; Poff et al. 1997; Poff et al. 2007). Water temperature is comparable in value to other ecological resources such as food and habitat and fish have been shown to exhibit niche partitioning based on thermal conditions (Magnuson et al. 1979; Coutant 1987). Furthermore, thermal conditions may limit species distributions (Brett 1971; Magnuson et al. 1979; Coutant 1987; Armour 1991). For example, the distribution of native trout species throughout the Rocky Mountains has been drastically reduced due to increased water temperature in downstream reaches (Selong et al. 2001; Rieman et al. 2007; Isaak et al. 2012; Roberts et al. 2013). Additionally, suitable water temperature may influence reproduction by initiating development of gonads and by cueing spawning events when water temperature thresholds are reached (Coutant 1987; Armour 1991; Olden and Naiman 2010).

Water temperature and flow are closely associated with the life histories of two endangered, large-bodied, Colorado River basin native fishes; the Colorado Pikeminnow *Ptychocheilus lucius* and Razorback Sucker *Xyrauchen texanus.* Colorado Pikeminnow synchronously migrate long distances, up to 400 kilometers in one direction, presumably based on flow cues (Tyus 1990; Irving and Modde 2000; Osmundson 2011). Although flow may cue spawning migrations, the upstream limits of Colorado Pikeminnow habitat are known to be dictated by thermal constraints (Osmundson 2011). Cues for Razorback Sucker spawning migration may include both flow and water temperature (Tyus and Karp 1990; Modde and Irving 1998; Bestgen et al. 2011). In snowmelt-driven systems, such as streams in the Colorado River basin, high seasonal variation and correlation between changes in flow and water temperature often confound understanding of which factor is most influential for reproduction by native fish. In addition, anthropogenic alterations of water temperature and flow further complicate understanding the relationship between the environment and the life histories of native fish (Moyle and Mount 2007; Poff et al. 2007; Olden and Naiman 2010).

Reproductive patterns and the environmental cues that initiate reproduction for non-endangered Colorado River basin fishes such as the Flannelmouth Sucker *Catostomus latipinnis*, the Bluehead Sucker *Catostomus discobolus*, and the Roundtail Chub *Gila robusta* (herein after referred to as the three species) are less understood. Flannelmouth and Bluehead sucker spawning begins in early spring to early summer and the onset of sucker spawning is hypothesized to be cued by water temperature (Chart and Bergersen 1992; Weiss et al. 1998; Bezzerides and Bestgen 2002; Zelasko et al. 2011). Roundtail Chub spawning occurs on the descending limb of the hydrograph and is also thought to be initiated by thermal cues (Kaeding et al. 1990; Brouder et al. 2000; Bezzerides and Bestgen 2002). However, there is uncertainty concerning environmental cues responsible for initiating reproduction and an evaluation of the effects that climate change may have on this relationship has not been attempted.

Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub are large-bodied, Colorado River native fishes, once widespread and abundant throughout the upper Colorado River basin. Bezzerides and Bestgen (2002) suggested that each species occupied 50% or less of its historical range by year 2000 and extant populations were declining in many localities. Declines of these species can be attributed to alterations of habitat and introduction of non-native fishes. Climate change models for the Colorado River basin predict reduced flows and increased air temperatures, which will result in increased water temperatures and may impact these three species life histories. The overall goal of my study was to evaluate the reproductive patterns of the Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub in the upper White River basin. I had four objectives. The first was to assess how the timing of reproduction differed among locations and species along a main-stem White River longitudinal gradient. The second was to determine the spawning distribution limits of each species in the White River. The third was to evaluate how the initiation of reproduction related to patterns of water temperature and flow for each species in both main-stem and tributary habitat. The fourth was to develop a predictive stream water temperature model to assess how climate change may impact the distribution and timing of Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub reproduction within the study area. This research should enhance the understanding of the timing and spatial distribution of reproduction by these three species and may allow managers to make better informed decisions regarding conservation actions for these declining native fishes.

Background/ Life history

The Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub are large-bodied, Colorado River native fishes, once widespread and abundant throughout the upper Colorado River basin. Bezzerides and Bestgen (2002) suggested that each species occupied 50% or less of its historical range by year 2000 and extant populations were declining in many localities. Declines of these species can be attributed to alteration of habitat and the introduction of non-native fishes. Dams have altered runoff patterns, changed thermal regimes, fragmented fish populations and reduced naturally high sediment loads in downstream river reaches (Martinez et al. 1994; Collier et al. 1996; Poff et al. 1997; Ward et al. 2002). Non-native piscivores threaten native fish species by preying on and competing for resources with adult, juvenile, and larval native fish (Martinez et al. 1994; Bestgen et al. 2006). Hybridization between the non-native White Sucker *Catostomus commersonii* and both the Bluehead Sucker and Flannelmouth Sucker threatens the genetic integrity of these species in most extant populations (Quist et al. 2009).

Flannelmouth Sucker and Bluehead Sucker are members of the family Catostomidae. Flannelmouth Sucker is differentiated from other suckers by its lack of a scraper plate, large fleshy lobes on its upper and lower lips, narrow caudal peduncle, and numerous small scales along the lateral line. Typical adults are green or bluish-grey dorsally, yellow to dark-orange ventrally, and typically measure between 400–500 mm in total length (TL) (Bezzerides and Bestgen 2002). Flannelmouth Suckers primarily inhabit pools and runs.

Bluehead Sucker is characterized by its prominent scraper plates on the upper and lower jaws, blue head, notches on the lateral margins of the upper and lower lips, and lack of papillae on the anterior face of the upper lip. This benthic fish is typically 300–450 mm TL but may vary in size depending on location. Bluehead Suckers primarily inhabit riffles and runs.

Roundtail Chub is a member of the *Gila* genus. Roundtail Chub can be readily identified by a combination of morphologic characteristics, and by lack of other definitive characteristics of similar *Gila* species, such as the nuchal hump of the Humpback Chub *Gila cypha* and the thin and elongated caudal peduncle of Bonytail *Gila elegans*. Typical Roundtail Chubs are between 200–300 mm TL but grow upwards of 500 mm TL. Non-breeding adult Roundtail Chubs are green to bluish-grey dorsally and silvery-white ventrally. Breeding adults express tubercles and red-orange coloring along their ventrolateral surface and on all fins except the dorsal fin.

All three species are long-lived, which may enable their populations to withstand poor reproductive years (Bezzerides and Bestgen 2002). They all evolved in systems characterized by highly variable runoff patterns, high turbidity, and few predators (Bestgen et al. 2006). These species spawn over gravel bars and eggs are adhesive and demersal.

Study area

The White River headwaters are in the Flat Tops Wilderness in northwestern Colorado. The White River flows west through western Colorado into Utah, draining approximately 13,000 km^2 until it joins the Green River near Ouray, UT (Lanigan and Berry 1981; Chart and Bergersen 1992; Martinez et al. 1994). Taylor Draw Dam, the only main-stem dam on the White River, impounded Kenney Reservoir beginning in October, 1984 (Figure 1). The White River upstream of Kenney Reservoir to the confluence of the North Fork and South Fork of the White River was chosen as the study site because it is one of the last large, unobstructed, free-flowing river sections in the upper Colorado River basin and was thought to contain relatively robust native fish populations including Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub (Chart and Bergersen 1992). Snowmelt is the dominant water source in the White River and runoff usually occurs from mid-April through late June. The flow typically peaks in early June with an average maximum flow of 91.5 m^3/s (23.7–186.5) m^3/s (Figure 2). Base flows occur from July through March. Summer thunderstorms periodically increase flow and turbidity.

The White River in the study reach represents a continuum from a coldwater environment upstream to a warmwater one downstream. Other studies used the confluence of the White River with the Green River as rkm 0; this location is 177 river kilometers downstream from the Kenney Reservoir-White River inflow area (Chart and Bergersen 1992; Martinez et al. 1994). In this study rkm 0 was at the Kenney Reservoir-White River inflow area. The upstream coldwater portion of the study area is delineated approximately by the confluence of the North Fork and South Fork of the White River downstream through the town of Meeker, CO (rkm 100–151). The upstream section is typical of other coldwater environments in which salmonids are the dominant fishes (Rahel and Hubert 1991; Griffith 1993). The channel form is pool-riffle-run with predominantly cobble substrate. Downstream from rkm 100 near Meeker to rkm 68, the river is a transition area and supports both warmwater and coldwater species. The downstream portion of the study area, a warmwater environment where coldwater salmonids are few or non-existent, is between rkm 0–68. The channel form in the downstream portion is a uniform run with substrate composed of predominantly sand in low velocity areas and cobble in higher velocity locations. The main-stem White River is 30–40 m wide throughout the study area.

In April 2011, surveys revealed seven potential tributaries for spawning by my study species: Crooked Wash, Piceance Creek, Flag Creek, Curtis Creek, Coal Creek, Miller Creek, and North Elk Creek. Based on presence of mostly perennial flows and presence of Flannelmouth or Bluehead suckers, Piceance Creek and Coal Creek were selected for this study. All other streams surveyed were not habitable due to barriers, ephemeral reaches, or cold water temperatures. The confluence of Piceance Creek and the White River is at an elevation of 1,740 m above sea level (ASL) and 68 rkm upstream from the Kenney Reservoir-White River inflow area (rkm-0). Piceance Creek flows through a landscape dominated by sagebrush *Artemisia spp*, pinyon pine *Pinus edulis,* and juniper *Juniperus osteosperma*. The channel is approximately 2.5 m wide and the substrate is predominantly sand. The confluence of Coal Creek and the White River is located at 1,935 m (ASL) and rkm 118. Coal Creek flows through an agricultural valley dominated by irrigated fields. The channel is approximately 5 m wide and the substrate is a mix of cobble and sand.

Irrigation practices alter flows in both Piceance and Coal creeks but in different ways. During base flow periods, temporary dams in Piceance Creek divert water into irrigation canals and reduce or eliminate flow in the stream channel. In contrast, flow in Coal Creek is enhanced beginning in spring by an upstream irrigation ditch that diverts water from the main-stem White River to the Coal Creek drainage. Thus, flow in Coal Creek is higher than occurred historically due to irrigation returns from diversions of White River water.

METHODS

Water Temperature

In April of 2011, I deployed five water temperature loggers in main-stem White River and 15 in various tributaries to evaluate the role of water temperature in Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub reproduction on a basin-wide scale (Figure 1). Temperature loggers in the main-stem were equally spaced at about 30 rkm intervals (rkm 14, 47, 82, 116, 142). I deployed these loggers in 2011 to ensure sufficient coverage of water temperature patterns across the basin. However, only data from Coal Creek, Piceance Creek and the main-stem White River will be discussed further. The loggers recorded water temperature every hour. Each autumn, I retrieved temperature loggers, downloaded the data, and redeployed them. The temperature logger deployed at rkm 14 on the main-stem was never recovered so no data were available from that location.

Presence of fish larvae in samples

I sampled larval fishes at 20 sites throughout the upper White River basin to assess reproduction patterns and how larval presence changes spatially and temporally. Twelve main-stem White River sites were evenly distributed from the upstream end of Kenney Reservoir (rkm 0) to rkm 142, which was just downstream of the confluence of the North Fork and South Fork of the White River (Figure 1). I also sampled fish larvae at 8 stations in Coal Creek and Piceance Creek. In 2013, I added two additional main-stem sampling sites at rkm 118.5 and rkm 121. Fish larvae sampling site locations were mostly determined by equal spacing across the basin, but ease of access and private land accessibility were also factors. Each station was sampled every five days from May 14–July 25 in 2012 and from May 17–July 30 in 2013. I concentrated sampling effort in nearshore, low-velocity habitat where densities of fish larvae are known to be highest (Haines and Tyus 1990; Muth and Snyder 1995). All fish larvae were sampled during daylight hours with either a 1.2 x 1.2 m seine with 0.8 mm mesh or 500 micron mesh dip net measuring 47 x 28 cm at the mouth and 38 cm in depth. The type of sampling gear used at sites was dependent on water level and habitat; the larger seine was used in deeper and more complex habitat and the dip net was used in smaller and shallower habitat. I sampled 30 m of nearshore habitat at each location and preserved labeled samples of larval fish in 100% ethanol, with a minimum volume ratio of ethanol to fish of 5:1. Samples were stored in plastic bags and returned to the laboratory for identification. Specimens were identified to species using published keys (Snyder 1981; Snyder and Muth 2004), verified by a second investigator, measured to the nearest 0.5 mm TL, counted, and cataloged.

To describe how the onset of reproduction differed spatially and temporally across the study area, I used presence of early life stages of fish, presumably just post-emergent, in samples to demonstrate how the first presence of larvae differed among sampling sites and years. I used only mesolarvae or earlier life stages (Flannelmouth Sucker ≤ 17 mm TL, Bluehead Sucker ≤ 17 mm TL, Roundtail Chub ≤ 12 mm TL) of each species as an index of timing of reproduction because fish that small were recently hatched (see results sub-section: "Reproduction timing based on otolith aging"; Snyder and Muth 2004; Snyder et al. 2005).

The initial presence of larvae and hatch dates (below) are used to describe the pattern of reproduction spatially and temporally in this study. These metrics were used because the variability in incubation time for eggs at different water temperatures made prediction of timing of spawning difficult. Incubation time varies depending on the specific water temperature at a particular site that may vary longitudinally, between years, and potentially within microhabitats at the same time and location (Gillooly et al. 2002).

Hatch dates

Hatch dates of sucker and chub larvae were determined by counting daily growth microincrements in otoliths extracted from a sub-sample of larvae. Validation of aging techniques in fish biology is important to determine the accuracy and precision of the aging technique (Beamish and McFarlane 1983; Campana 2001). Although no validation study of this technique was done for my study species, otolith microincrement counts as a means to determine hatch dates has been validated for aging larvae of many other fish species (Pannella 1971; Campana and Neilson 1985). In addition, other studies have documented that counting daily increments in otoliths to determine hatch dates of larvae for other cypriniform fishes, including the Razorback Sucker and Colorado Pikeminnow, native fishes of the Colorado River basin, was a valid technique (Hoff et al. 1997; Bestgen and Bundy 1998; Bundy and Bestgen 2001; Ellsworth et al. 2010). Therefore, I felt confident that daily increment counts in otoliths of sucker larvae that I aged could be used to estimate hatching dates of larvae. Aging Roundtail Chub using counts of daily growth microincrements in otoliths was validated in a previous study (Brouder 2005). Brouder (2005) found that this technique was accurate 70% of the time and was accurate within 1–2 days 80–90% of the time, respectively.

Flannelmouth and Bluehead sucker larvae used for age estimation were selected from two main-stem sampling sites at rkm 47 and 118. The sites were chosen to represent the potential longitudinal variation in water temperature and flow in the White River and to assess the role of these factors in relation to initiating reproduction in these fishes. Larvae collected from three tributary sites were chosen for aging by otolith increment counts to evaluate potential differences between tributary and main-stem hatch dates (two sites in Coal Creek at 0.7 rkm and at 2.0 rkm from the confluence and one site in Piceance Creek at 2.8 rkm from the confluence, Figure 1) in 2012 and 2013. Both Coal Creek sites were treated as a single location. All suckers used in otolith aging were metalarvae or younger, which means Flannelmouth Suckers were ≤ 24 mm TL and Bluehead Suckers were ≤ 20 mm TL (Snyder and Muth 2004). Ten fish from each site were selected for aging by otolith microincrement counts, with the exception of the 2012 Bluehead Sucker sample from rkm 118 and the 2012 Flannelmouth Sucker sample from rkm 47, where only nine individuals metalarvae or younger were available from those collections.

Roundtail Chub were selected for aging by otolith increment counts from four main-stem sites (rkm: 4, 18, 47, and rkm 68) for 2012 and 2013. Due to low numbers of Roundtail Chub larvae at rkm 4 and 18, these sites were combined and treated as a single site. Ten individuals were selected from each site for each year, and all were metalarvae (≤ 15 mm TL) or younger (Snyder et al. 2005).

Photos of larvae were taken with a Spot Insight 2 camera (Diagnostic Instruments Inc., Sterling Heights, MI) mounted on an Olympus SZX7 microscope (Olympus America, Center Valley, PA). Larvae were measured to the nearest 0.01 mm TL using the Image-Pro Express software package (Media Cybernetics, Inc., Rockville, MD) prior to otolith extraction. Otoliths were extracted from larvae with forceps and a fine probe under the same microscope. Both left and right lapilli were removed when possible and mounted on a 75 x 25 mm glass slide in immersion oil. A single reader counted all increments in otoliths on a compound microscope at 1,000X magnification using transmitted light followed by an additional count either at least one day later or after 20 other otoliths had been counted. The second count was considered blind because sufficient time had passed or a sufficient amount of other otoliths had been counted that the reader had no recollection of the initial count. A third blind count was conducted if there was disagreement between the first and second counts. If the third count agreed with either of the previous counts, then the third count was determined to be the most accurate. A fourth count was conducted if the third count disagreed with both of the previous counts. If the forth count agreed with any of the previous counts, then the forth count was determined to be the most accurate. There was never a situation when all four counts disagreed.

To calculate the hatch date of the earliest larvae collected, I created regression equations to calculate age (days) as a function of length (TL mm). Because otolith increment counting is time intensive, we could not use this method to age fish from every location. Therefore, the regression equations were used to calculate the age of individuals that were not aged by counting the daily growth increments in otoliths. I measured larval fish to the nearest 0.5 mm TL, from the same sample time period, location, and size distribution as the fish aged by otolith increment counts. Using the length measurements and the regression, I estimated fish age. I calculated hatch dates by subtracting the calculated age from the sample date of the individual larvae. The fish that were aged using their mean TL to predict age were selected from the collection to match the size and collection date to the fish aged by otolith increment counts. Using fish of similar size and collection dates ensured that the measured fish were exposed to similar growing conditions as those aged by otolith increment counts. In the main-stem White River, we counted increments in otoliths from larvae collected from an upstream location (rkm 118) and a downstream location (rkm 47) and combined these into one sample to construct a regression equation for the main-stem White River. I used this regression to age fish collected at rkm 82, a mid-river sampling location. Tributary regression equations remained separate.

Stream temperature model and predictions

I developed a predictive stream temperature model using multiple regression to predict water temperature as a function of flow, air temperature, date, and elevation (Isaak et al. 2010). Ultimately, predictions can be used to assess how stream temperature may be altered by climate change and how these changes might impact reproduction by the Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub. I developed several models using different combinations of predictor variables and then compared the AIC values of the models to select the best combination of predictor variables (Burnham and Anderson 2002). Solar radiation data were not available for the study area so that variable was not used in my model. I obtained six years of data (2008–2013) for air temperature, flow, and elevation for three locations on the White River (U.S. Geological Survey [USGS] gauges: 09306290, 09304200, and 09304800). I built the regression model using data from 2008–2012, and used 2013 data to validate accuracy of model predictions. The time period 2008–2012 included one of the highest and the lowest flow years on record, so a range variability was included that enhanced prediction capability. For example, in 2011, the White River recorded a peak flow of 156.3 m^3/s and had relatively low water temperatures compared to a low peak flow of 32.8 m^3/s in 2012, when water temperatures were warmer (Figure 2). Although the average flow for 2008–2012 showed a higher peak than the long-term average, the timing and duration of the spring flow was similar (Figure 3). Flow and water temperature data from USGS gauges were not available during the entire year due to the periodic presence of ice from October through March. Therefore, I restricted the predictive stream temperature model to the period April 1–August 31, which encompassed the spawning period of all three species (Kaeding et al. 1990; Chart and Bergersen 1992; Brouder et al. 2000;

Bezzerides and Bestgen 2002; Zelasko et al. 2011). I used daily air temperature data from the Meeker Airport, Meeker, CO, for all locations in the final model.

I used the stream temperature model to predict when water temperatures associated with the first presence of larvae for each species would occur on average at different locations throughout the basin and considered this my baseline model. I created the baseline model using mean data for all variables from the period 1997–2013. I restricted the baseline model to these years because air temperature data, an important predictor variable, were not available for earlier years. The mean daily flow for this time period showed similar patterns to the long-term mean for available data (1901–2013, Figure 3).

To evaluate how climate change may alter the timing and spatial distribution of water temperatures associated with reproduction by the Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub, I manipulated air temperature and flow in the baseline model to mimic changes in air temperature and stream flow anticipated from climate change scenarios in the published literature (Christensen et al. 2004; McCabe and Wolock 2007). Climate change models specific to the Colorado River basin predicted that flow could decrease by 17% and was associated with an increase in air temperature of 2°C (Christensen et al. 2004; McCabe and Wolock 2007). To mimic the Colorado River basin predictions, I modeled a 2°C increase in air temperature with a 20% reduction in flow. Additionally, I altered each climate change prediction to model more extreme climate change events (an air temperature increase of 4°C with a 50% reduction in flow). To bracket the climate change predictions in the event that climate change results in increased flow or cooler temperatures, I also modeled a 2°C decrease in air temperature with a 20% increase in flow.

Main-stem adult fish distribution

We completed several two-pass, mark-recapture, raft electrofishing samples to assess the distribution of Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub adults in the main-stem White River. Mark-recapture sampling was conducted in the White River at three locations (Reach 1 [rkm 11– 14], Reach 2 [rkm 85– 86], and Reach 3 [rkm 112– 116]) in 2012 and two locations (Reaches 1 and 3) in 2013 (Figure 1). Two rafts were deployed simultaneously, one on each side of the river channel. Electrofishing was done with a Smith-Root Inc. Generator Powered Pulsator (GPP) with a 60 Hz pulsed direct current (DC) and each raft had two anodes at the front and two cathodes at the back. Voltage and amperage were adjusted to maximize taxis and minimize injury and stress to all fish. A three-person crew operated each raft, including two netters and one boat operator. All fish that were captured were held in a livewell. When livewells were either 50% full or we had electrofished roughly 500 m of stream, fish were identified, measured (TL [mm], weighed [g]), sexed (when possible), scanned for PIT tags, and PIT tagged if one was not detected. Electrofishing effort was recorded in seconds.

RESULTS

Temperature and flow

Within the main-stem White River, water temperatures varied longitudinally from upstream to downstream, varied between years, varied between seasons, and were correlated to both flow and air temperature (Figure 4). In early April of both years, the water temperatures were cool and similar among years compared to large differences among years in May–August. In 2012, early warm air temperatures initiated spring runoff earlier than in 2013 when low air temperatures delayed the beginning of spring runoff until May 1. White River water temperatures during late spring and summer were 6–8°C warmer at rkm 18 compared to rkm 146 for 2012 and 2013 (Figure 4). The most downstream locations, rkm 18.5 and 47.5, showed the smallest difference in water temperature between any two locations. Water temperatures upstream (rkm 146) rarely exceeded 16°C. A comparison between 2012 and 2013 showed that peak water temperatures at each location were about the same for both years but sites warmed earlier and more gradually in 2012 than 2013. For example, at rkm 18.5, water temperatures reached 19°C on June 1 in 2012 but not until June 25 in 2013. However, peak water temperatures at rkm 18.5 of about 23°C were reached about the same time, on June 29 in 2012 and on July 1 in 2013 because water temperatures increased 1°C per day from June 26–30 in 2013. As flows decreased in early summer, water temperatures increased, and peaked in late June or July during low summer base flows.

There were substantial differences in water temperature among tributaries and main-stem White River sites as well. During the presumptive sucker spawning period in spring, mean daily water temperatures in Piceance Creek were warmer than the main-stem White River at rkm 82.5

by 1–4°C in 2012 and 2–6°C in 2013. The largest differences in water temperatures longitudinally across the White River were May 9–22 in 2012 and May 10–June 6 in 2013. The mean daily water temperature in Coal Creek was 1–2°C warmer than the main-stem White River near Coal Creek in 2012 and 4–5°C in 2013. The largest differences in water temperatures between Coal Creek and the White River were May 10–26 in 2012 and May 10–31 in 2013.

Flow varied between years in terms of timing of runoff and magnitude but varied only slightly spatially across the study area at any specific date (Figure 4). In 2012 the peak flow reached only 32.8 m^3/s on April 27, consistent with warm air temperatures early in the year, while in 2013 the peak flow reached 52.9 m^3/s on May 17, consistent with cooler air temperatures later in the year. Flow in 2012 gradually subsided and reached base flow in mid-June. In contrast, the White River in 2013 had three main peaks and reached base flow on about July 1.

Fish community composition and species distribution

Early life stages of Flannelmouth Sucker and Bluehead Sucker were abundant in seine and dip net samples collected in the White River drainage, and comprised 27.7 and 41.5% of all fish collected in 2012 (n = 10,935) and 2013 (n = 16,410), respectively. Each species was distributed throughout most of the drainage including lowermost Coal Creek, three sites in Piceance Creek, and through most of the main-stem White River, except for the uppermost two sampling sites (Table 1; Figure 5). All specimens captured were larvae or age-1 fish, based on lengths at capture (< 60 mm TL). Roundtail Chub was less abundant and comprised 9.2 and 1.2% of all fish collected in 2012 and 2013, respectively. Roundtail Chub was collected only in the downstream portion of the main-stem White River, and was not detected in tributary samples.

All specimens captured were larvae or age-1 fish, based on lengths at capture (≤ 40 mm TL). Overall, native fishes dominated the fish assemblage and comprised 91.5 and 95.8% of all fish collected, with Speckled Dace *Rhinichthys osculus* as the most abundant (39.2%, 2012) or second-most abundant (23.4%, 2013) species captured in samples in each year.

Reproduction timing based on presence of fish larvae

Flannelmouth Sucker and Bluehead Sucker larvae were first detected downstream in the White River in mid-May in 2012 and early June in 2013 and progressively later in the year at upstream sites. In 2012, the first detection of Flannelmouth Sucker larvae occurred downstream at rkm 0 and 4, on May 21 and 35 days later upstream at rkm 118 on June 25 (Figure 6). In 2013, first detection of the year for Flannelmouth Sucker larvae occurred downstream at rkm 0 on June 10 and 28 days later upstream at rkm 118 on July 8. In 2013, Flannelmouth Sucker larvae were detected at rkm 121, the most upstream locality that sucker larvae were detected. However, they were detected on the first sampling occasion (July 8) at this site so date of first presence was unknown.

Bluehead Sucker larval presence showed a similar longitudinal pattern as Flannelmouth Sucker. In 2012, the first detection of Bluehead Sucker larvae occurred downstream at rkm 4 on May 14, and 46 days later upstream at rkm 118 on June 29 (Figure 7). In 2013, the first Bluehead Sucker larvae were detected downstream at rkm 0 on June 14 and then 38 days later upstream at rkm 121 on July 22. Thus, earliest and latest dates for sucker larvae presence over the two years and all study sites ranged over a 10-week (69 days) period.

Unlike dates of first capture, water temperatures at the first detection of sucker larvae were similar among sampling sites and years. The first presence of Flannelmouth Sucker and

Bluehead Sucker larvae at most White River sampling locations corresponded relatively closely to when water temperatures warmed to about 16°C for both 2012 and 2013 (Figures 6 and 7).

Similar to that of suckers, Roundtail Chub larvae were first detected in downstream samples and were progressively detected at upstream sites on later dates only in 2012. In 2012 the first detection of Roundtail Chub larvae occurred downstream on June 12 at rkm 4, then later in the season on July 14 at rkm 68, the most upstream location where larvae were detected (Figure 8). Unlike 2012, the first detection of Roundtail Chub larvae in 2013 occurred simultaneously at rkm 4, 18, and 68 on July 8. The first presence of Roundtail Chub was only loosely associated with mean daily water temperatures of 20°C (Figure 8).

In addition to longitudinal differences in timing of first detection of larvae (presumably because of earlier spawning downstream) in the White River, larvae of the Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub were detected much earlier in the warmer and lower flow year of 2012 than in 2013 (Table 2). For example, I detected the first Flannelmouth Sucker larvae at rkm 0 on May 21 in 2012 and 20 days later on June 10 in 2013. Bluehead Sucker showed a similar pattern, with the first presence detected downstream on May 14 in 2012 and 27 days later on June 10 in 2013. The initial detection of Roundtail Chub larvae was June 12 in 2012; almost a month earlier than in 2013 on July 8.

Sucker larvae were detected earlier in samples collected in Coal Creek than in the adjacent main-stem White River. In 2012, Flannelmouth Sucker larvae were detected in Coal Creek four days earlier than the adjacent main-stem habitat and Bluehead Sucker larvae were first detected on the same day in Coal Creek and the main-stem. In 2013, larvae of both sucker species were detected in Coal Creek 8 days earlier than in the adjacent main-stem White River site.

Sampling at progressively higher elevation sites demonstrated an upstream limit to reproduction for all three species. In 2012, Flannelmouth and Bluehead sucker larval samples were detected at rkm 118 but not at 132, which suggested that the upstream limit for their reproduction occurred between those locations. In 2013, I added two sample locations upstream of rkm 118, at rkm 118.5 and 121, to more precisely estimate the upper limit of sucker spawning. Additional sampling at these locations indicated that suckers spawned as far upstream as rkm 121 in 2013, but larval suckers were never detected at rkm 132 during both years of this study. Therefore, the upper extent of sucker reproduction in those years was between rkm 121 and 132. Roundtail Chub larvae were never detected upstream of rkm 68 during the repeated stationary sampling in this study, indicating that Roundtail Chub spawning was limited to the downstream sections of the upper White River.

Reproduction timing based on otolith aging

For both sucker species in both years, water temperatures were between 12–16°C at first hatching regardless of the time or location. Main-stem hatch dates showed a clear longitudinal progression, where the earliest hatch dates of both sucker species occurred downstream and then later in the season occurred upstream consistent with warming water temperatures (Figures 9–10). The peak of Flannelmouth Sucker hatch dates occurred earlier downstream at rkm 47 on May 15 in 2012 and June 6 in 2013 compared to upstream at rkm 118 on June 6 in 2012 and June 23 in 2013. Similarly, Bluehead Sucker peak hatch dates occurred earlier downstream at rkm 47 on May 15 in 2012 and June 8 in 2013 compared to upstream at rkm 118 on June 21 in 2012 and June 23 in 2013. The earliest sucker hatch dates occurred 13-16 days prior to the first detection of larvae at the same location.

Tributary spawning locations did not follow the same longitudinal pattern of hatching dates as the main-stem White River reproduction. Instead, suckers in Piceance Creek, with the mouth located at rkm 68, had the earliest hatching dates in 2012 for any site, May 5 and May 4 for Flannelmouth Sucker and Bluehead Sucker, respectively. Hatching dates for suckers in Coal Creek were earlier than observed in the main-stem White River site closest to Coal Creek in both years. Flannelmouth Suckers hatched in Coal Creek six days earlier that in the main-stem near Coal Creek in 2012 and 15 days earlier in 2013. Bluehead Suckers hatched 11 days earlier in 2012 and six days earlier in 2013 in Coal Creek than in the adjacent main-stem habitat. In 2013 only two Flannelmouth Sucker larvae were collected in Piceance Creek and no Bluehead Sucker larvae were collected, which precluded aging and hatch date estimation.

Both sucker species hatched earlier in 2012 than in 2013 at all locations. The peak hatch dates recorded for Flannelmouth Sucker in the main-stem White River at the most downstream sites were 21 days earlier in 2012 than in 2013. Bluehead Sucker peak hatch date was 20 days earlier in 2012 than in 2013 at the most downstream locations. At the most upstream location, the difference in the peak hatch date between years was only 14 days for Flannelmouth Sucker. The peak hatch date for Bluehead Sucker at the most upstream site was only 2 days earlier in 2012 than 2013. However, the majority of Bluehead Suckers hatched about a week earlier in 2012 than 2013. There was also a difference in the timing of hatching between the downstream and upstream locations between years. In 2012, peak hatch date for Flannelmouth Suckers in the main-stem White River was 21 days earlier at rkm 47 compared to rkm 118, while in 2013 the difference was slightly less at 17 days. Similarly, Bluehead Suckers showed a difference of 36 days between the peak hatch date at rkm 47 and rkm 118 in 2012 and 15 days in 2013.

Comparing the hatch dates for Flannelmouth and Bluehead suckers at the same location during the same year indicated they were similar between the two species. An exception to uniform hatching times for these species is the White River at rkm 118 in 2012, where the range of hatch dates overlaps. However, Flannelmouth Sucker peak hatch date was on June 9 compared to June 21 for Bluehead Sucker. In 2013, the sucker hatch date ranges overlapped at each location, but the peak hatch date for Flannelmouth Suckers at rkm 47 and 82 were on average 3–4 days earlier than Bluehead Suckers.

Hatching of Roundtail Chubs occurred later than for suckers, and when water temperatures rose to 16–20°C, regardless of longitudinal position of sampling sites. Hatch date distributions for the Roundtail Chub larvae differed longitudinally among sites and between years (Figure 11). In 2012, the peak hatch date occurred on June 6 at rkm 47 and 19 days later on June 25 upstream at rkm 68. In 2013, the peak hatch date occurred on June 21 downstream at rkm 4 and 12 days later on July 3 upstream at rkm 68. Comparing the hatch dates for Roundtail Chub at the same locations between the years showed that hatching occurred earlier at all locations in 2012 (a warmer year with low flows) than in 2013. The earliest Roundtail Chub hatch dates in 2012 were 11-20 days earlier than first detection of larvae in 2013 at the same location.

I compared the mean lengths (mm TL) of fish aged by counting the daily growth increments in their otoliths to those that were aged using the age–length regression equation to ensure that length differences would not bias the outcome of the age estimations (Table 3). I found that there was no substantial difference between the means of the total lengths of fish aged by otolith increment counts and those aged using the age–length regression (Table 4). In 2012, the mean TL of the otolith-aged fish was only 0.7 mm less than mean TL of fish aged using the age–length regression. In 2013, the difference in the lengths of the fish aged by otolith increment counts and the fish aged using the age-length regression was -0.2. The age–length regression equations calculated using ages obtained from otolith increment counts can be found in Table 3.

Predictive stream temperature model

Our predictive stream temperature model included air temperature, elevation, Julian date, and flow and was the second best model in AIC selection. The addition of interaction and quadratic terms produced slightly better (lower) AIC values than those for models that did not include these terms (Table 5). However, the addition of these terms resulted in very small changes to water temperature predictions. Additionally, the model with no quadratic or interaction terms was the second highest ranked model and the R^2 values differed by only 0.0033 between models with and without quadratic terms. To simplify interpretation of the model, we used the model without quadratic terms because it fit the data well and was more intuitive (Table 5).

I validated stream temperature model predictions against independent water temperature data at three locations in 2013 and a single location in 2014 (Figure 12). Predicted stream temperatures were highly correlated ($r^2 = 0.94$) with observed water temperatures and 93–95% of the variability in water temperature was accounted for by the predictor variables (Figure 12; Table 6). The predictor variables differed in their effect on the model. Positive coefficients for air temperature and Julian date indicated that water temperature increased as air temperatures warmed and with time of year (later). This was in contrast to negative coefficients for elevation and flow, which indicated predicted water temperatures were warmer at lower elevations and during lower flows. Air temperature and elevation were the most influential variables affecting water temperature predictions, as evidenced by the large *t*-values (Table 6).

I compared the timing and location of the first observed stream temperatures of 16°C in 2012 and 2013 to the baseline stream temperature model and climate change scenarios modeled to understand what type of scenario these years best represented for sucker reproduction. In both years, first observed water temperatures of 16°C, the temperature most closely associated to first detection of sucker larvae, occurred earlier than predicted by the baseline stream temperature model (Figure 13). For instance, water temperatures at rkm 18 reached 16°C four weeks earlier than predicted in 2012 and two weeks earlier in 2013. Water temperatures in 2012 closely matched the most extreme climate change scenario that I modeled; a 4°C increase in air temperature and a 50% decrease in flow. Water temperatures in 2013 closely matched the climate change scenario of a 2°C increase in air temperature and a 20% decrease in flow. However, in 2013, model water temperature predictions were underestimated because water temperature reached 16°C at rkm 146 while the model predicted that 16°C would not occur upstream of rkm 130. The most upstream location at which sucker larvae were found, rkm 121, was also the most upstream location at which 16°C was predicted to occur in the baseline model.

I also compared the timing and location of the first observed stream temperatures of 20°C in 2012 and 2013 to the baseline stream temperature model and climate change scenarios modeled to understand what type of scenario these years best represented for chub reproduction. I used the model to predict when water temperatures of 20°C would be achieved, a level most closely associated with the first detection of Roundtail Chub larvae (Figure 14). In 2012, observed water temperatures reached 20°C earlier than any of the climate change predictions evaluated in this study. The most extreme climate change scenario predicted 20°C a week later than observed in 2012 (Figure 14). The 2013 water temperatures most closely resembled the most extreme climate change scenario; a 4°C increase in air temperature and a 50% decrease in flow. This scenario also predicted that water temperatures of 20°C would be reached up to rkm 90; observed water temperatures in 2012 and 2013 did reach 20°C at rkm 82 but not at rkm 116. I did not measure water temperatures between rkm 82 and rkm 116 and could not determine the precise upstream limit of 20°C. However, this range does encompass the location of the most upstream model prediction of 20°C which was at rkm 90.

Main-stem fish distribution

Adults of all three species were detected in Reach 1 (rkm 11–14) and Reach 2 (rkm 85–86 [short length due to high fish density]) in the main-stem White River. Flannelmouth and Bluehead suckers were detected in Reach 3 (rkm 112–116), but not Roundtail Chubs. Length frequency distributions from main-stem electrofishing showed a full range of size classes for suckers in the most downstream reach (Reach 1) but an absence of suckers <340 mm TL (excluding larvae) in two most upstream reaches (Table 7; Figure 15). The downstream reach (Reach 1) supported both small (juveniles) and large suckers (Flannelmouth Suckers 60–566 mm TL, Bluehead Suckers 74–374 mm TL). Roundtail Chubs were found in Reach 1 and Reach 2, but not Reach 3 and all were adult chubs 291–508 mm TL; no juvenile or small adult Roundtail Chub were detected during this study.

The catch per unit effort (CPUE) of the study species differed greatly among reaches and years. Flannelmouth Suckers had the highest CPUE among the three species (Table 8). The highest CPUE rates for Flannelmouth Sucker were in Reach 2 in 2012 (only 1.1 river kilometers were shocked for a total of 1829 seconds due to high fish densities) followed by Reach 3, then

Reach 1. In 2013, Flannelmouth Sucker CPUE rates for Reach 3 were more than seven times higher than for Reach 1. Bluehead Sucker CPUE rates for 2012 and 2013 were higher in upstream reaches than downstream. The CPUE rates for both sucker species dropped substantially from 2012 to 2013. Roundtail Chub CPUE rates were similar between location and year. Roundtail Chub CPUE rates for 2012 and 2013 were similar for all reaches.

DISCUSSION

My results indicated that timing of reproduction of Flannelmouth Sucker, Bluehead Sucker and Roundtail Chub in the upper White River, whether based on presence of larvae in samples or back-calculated hatching dates, was primarily dictated by water temperature rather than flow. Reproduction occurred in a narrow range of water temperatures and began in the main-stem White River in warmer downstream locations and proceeded longitudinally upriver as water temperatures increased. Additionally, reproduction occurred earlier in tributaries than adjacent main-stem habitats because tributary habitat was warmer. Water temperature predictions under climate change scenarios closely matched observed temperatures in 2012 and 2013, indicating those low flow years matched well with potential future warming conditions (Christensen et al. 2004; McCabe and Wolock 2007). Modeling climate change projections showed that water temperatures will warm earlier in the year, and result in earlier spawning and extend thermally suitable spawning habitat upstream.

Although water temperature and flow are undoubtedly related, flow patterns did not directly influence the timing of Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub reproduction. At any given time during the study, flow patterns varied only slightly spatially. Therefore, if changes in flow initiated spawning, the timing of both first presence of larvae and hatch dates would have occurred synchronously along the longitudinal extent of the river. Additionally, flow patterns in 2012 and 2013 were quite different. In 2012, flows were low and exhibited one distinct peak, while in 2013 flows were moderate and exhibited several peaks throughout runoff. Despite large difference in runoff patterns between years, spawning proceeded longitudinally from downstream to upstream over a duration of 28–46 days for suckers and 0–30 days for the Roundtail Chub, indicating that the initiation of spawning was dependent on water temperature rather than flow. Differences across years in timing of reproduction, earlier in 2012 than 2013 by as much as 30 days, also suggested that day length was not an important factor signaling onset of reproduction.

The water temperature most closely related to first detection of sucker larvae was 16°C, consistent with Carter et al. (1986), who found that first presence of sucker larvae captured by drift nets in the Colorado River occurred at 16°C. The longitudinal pattern of first larval detection that began downstream and then proceeded upstream later in the year extended over 28–46 days depending on the year and species. Larvae were detected substantially earlier in 2012 than in 2013 because water temperature was warmer in 2012 due to low runoff. Larval Flannelmouth Sucker and Bluehead Sucker hatch dates also indicated that sucker reproduction is cued by water temperature. Regardless of location and year, hatch dates occurred at 12–16°C, and showed a longitudinal pattern with the earliest hatch dates at downstream locations, then later in the season at upstream locations. The range of water temperatures associated with hatch dates is a result of variation in egg incubation periods, which can vary greatly over a small spatial scale (Gillooly et al. 2002). Timing of sucker reproduction when evaluated by presence of larvae and hatch dates showed that reproduction occurred earlier in tributaries than nearby main-stem habitat. Tributaries were warmer than main-stem habitat, again indicating that reproduction is water temperature dependent.

Presence of larval Roundtail Chub coincided most closely with water temperatures of 20°C and chub larvae hatched at 16–20°C across all locations for both years. Detection of Roundtail Chub larvae from repeated sampling stations across the basin showed that chub larvae were limited to the lowermost 68 river kilometers of the study area and water temperatures in this reach generally differed by less than 1°C. The smaller water temperature variation in this reach probably resulted in a weaker relationship with water temperature than observed with the sucker species. In 2012 there was a clear trend of reproduction beginning in downstream locations and progressing upstream. However, in 2013 presence of larval chub occurred nearly synchronously across locations. The first presence of Roundtail Chub larvae occurred earlier in 2012 compared to 2013 due to warmer temperatures in 2012.

Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub each showed clear upstream limits to reproduction, based on presence of larvae in samples. The upstream limit to sucker reproduction occurred between rkm 121–132 and reproduction upstream of rkm 121 may be limited by water temperature. Water temperatures of 16°C did occur above rkm 132 in both years of the study. However, it is likely that water temperatures of 16°C occurred too late in the season for these locations to support sucker reproduction. Reproduction may be controlled by prolonged exposure to a given water temperature which is necessary for successful development of gonads and I speculate that upstream locations do not have a sufficient number of days at these water temperatures (Hansen et al. 2001; Gillooly et al. 2002). Lack of reproduction upstream of rkm 121 does not seem a result of lack of suitable spawning habitat, because the channel form and substrate types were similar upstream and downstream of apparent distributional limits of the species. Previous monitoring of fish populations in the upper White River by Colorado Parks and Wildlife showed that no Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub were detected between rkm 142–146 (pers. comm. B. Wright, Colorado Parks and Wildlife), which supported the idea that the upper limit of sucker reproduction in the upper White River occurred between rkm 121–142. Preliminary data collected in 2011 showed that 16°C was not recorded upstream of rkm 82, demonstrating that water temperature is annually variable. Lower water temperatures will delay the timing of reproduction and potentially delay development of larvae, which may lower larval survival rates or negate reproduction altogether in upstream areas. Additional research demonstrated that lower water temperatures in 2013 delayed peak spawning migrations of suckers into Coal Creek by as much as 7 days compared to 2012 (see Chapter 1). The upper limit of Roundtail Chub larvae, based on seine and dip net sampling, was consistent between years at rkm 68 (with the exception of one sampling event discussed below) and main-stem sampling indicated that Roundtail Chub adults were present at rkm 82. Larval and adult distribution suggests that Roundtail Chub were confined to the downstream areas of the study site and that successful reproduction was limited to the lowermost reaches of the river.

Based on presence of larvae, and hatching dates back-calculated from otolith increments, reproduction by Flannelmouth and Bluehead suckers in the White River was not spatially or temporally segregated. Although the peak hatch dates of suckers at the same location did not match exactly, the range of hatching dates overlapped at each location. Additionally, a separate study showed that the timing of spawning migrations of Flannelmouth and Bluehead suckers into Coal Creek each occurred nearly synchronously in each of 2012 and 2013 (see Chapter 1). Others have noted reproduction by Flannelmouth and Bluehead suckers may be spatially and temporally segregated during spawning. Zelasko et al. (2011) estimated that peak spawning occurred two weeks earlier in Flannelmouth Suckers compared to Bluehead Suckers. Further, spatial separation of these sucker species during reproduction was also noted (Compton et al. 2008; Sweet and Hubert 2010). I did not calculate the time of peak reproduction, but hatch dates and larval presence both indicate minor temporal separation and no spatial segregation between these species in the upper White River.

Water temperature modeling based on anticipated changes in climate (reduced flow and increased warming) indicated that water temperatures will increase and likely induce earlier spawning by Flannelmouth and Bluehead suckers, as well as Roundtail Chub, and potentially extend reproduction farther upstream in the White River. Observed water temperatures in 2012 were similar those predicted by the most extreme climate change scenario that I modeled and no shift in reproduction by suckers farther upstream was observed in that year. The lack of sucker reproduction upstream of rkm 121 (based on presence of larvae) during 2012 suggests that other factors may be limiting at this time. It may be that reproduction in upstream habitat may be determined by long-term conditions rather than annual differences in water temperatures, such that if water temperatures were on average warmer upstream, suckers may move upstream over time. However, warmer predicted water temperatures would result in earlier reproduction. Earlier reproduction might have a positive impact on survival of early life history stages of these fishes because it would enable more growth before the onset of winter, which is a period of high mortality for age-0 fishes (Kaeding and Osmundson 1988; Thompson et al. 1991; Coleman and Fausch 2007). Projected climate trends will likely not impact the presence of the Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub at downstream locations within the study area as these species were historically found throughout the Colorado River basin in much warmer environments (Brouder 2001; Bezzerides and Bestgen 2002; Brouder et al. 2006). Although no studies of upper thermal tolerances have been done for Flannelmouth Sucker and Bluehead Sucker a closely related species the Razorback Sucker has been shown to tolerate water temperatures up to 36°C (Carveth et al. 2006). Carveth et al. (2006) also evaluated thermal tolerances of Roundtail Chub and found them to withstand water temperatures up to 36°C. The most extreme climate change scenario that was modeled in this study, a 4°C increase in air temperature and a 50% decrease in flow, predicted water temperatures would not reach 23°C at the warmest downstream locations. Therefore, it is unlikely that Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub will be detrimentally impacted by warmer water temperatures under climate change scenarios in the upper White River. However, a factor not considered in the stream temperature model is the increase in water demand from development and irrigation as human populations grow. Increased water usage due to warmer air temperatures and lower precipitation would likely result in lower flows and could magnify the effects of climate change on this native fish community.

The baseline stream temperature model, based on long-term average flow and air temperature, predicted a later occurrence of 16°C throughout the main-stem than observed during both years of this study. This indicated that both study years were warmer than average and may be examples of climate-changed environments in the future. Both years were below average years in terms of spring runoff magnitude and volume, particularly 2012, which resulted in water temperatures reaching spawning temperatures earlier than the baseline stream temperature model predicted. In fact, water temperatures observed for 2012 closely resembled the climate change scenario of a 4°C increase in air temperature and 50% decrease in flow, which is more than double the projected increases in air temperature and flow reductions (Christensen et al. 2004; McCabe and Wolock 2007). Water temperatures in 2013 resembled the climate change scenario of a 2°C increase in air temperature and 20% decrease in flow.

Interestingly, the baseline stream temperature model predicted that rkm 121 would be the most upstream location to achieve 16°C, which matched well with the observed upstream extent of successful sucker reproduction based on larval presence. The match between the baseline model predictions and the observed upstream extent of larval presence indicated that the long-term average water temperature of first larval presence was a good metric to predict the upper limits of successful spawning for these species. Using long-term average water temperatures to predict the upstream limits to reproduction (based on presence of larvae) for these species in other systems could be a powerful tool to determine distribution of successful reproduction on a larger spatial scale. Further research into whether this method is accurate for predicting the upper limits to reproduction for these species in other locations should be pursued.

The baseline stream temperature model predicted that 20°C would occur later than I observed and would not occur upstream of rkm 47; however, Roundtail Chub larvae were repeatedly detected upstream to rkm 68 during both years of my study and adults were detected even farther upstream. This suggested that even though water temperatures of 20°C were most closely associated with first presence of Roundtail Chub larvae, 20°C was not strongly associated with first reproduction. Perhaps water temperature at first presence of larvae was not a good metric to determine the upstream limit to successful reproduction in chubs. Larval presence does not account for the time that chub eggs incubate, or the amount of time that larval chub reside in or near the substrate. A better metric for predicting the distribution of successful chub reproduction might be the water temperature at reproduction, which is known to be about 18°C (Muth et al. 1985). The baseline stream temperature model predicted that the upstream extent of 18°C was at rkm 91, which was only five river kilometers upstream of Reach 2 where we detected adult Roundtail Chub with electrofishing. A comparison of the observed water temperatures to the baseline stream temperature model, for average air temperatures and stream flows, showed that 20°C occurred a month earlier in 2012 than was predicted by the model and three weeks earlier in 2013. Although no Roundtail Chub larvae were detected at rkm 82 in 36 sampling events over the duration of this study a few chub larvae were detected between rkm 82-

–86 during sampling on June 27, 2012. This demonstrated that chubs did successfully reproduce in one year upstream of rkm 68, but the few fish detected may indicated this may have been an anomalous event in a low flow and warm water temperature year.

Length frequency data indicated that upstream White River reaches (Reach 2 rkm 82–86 and Reach 3 rkm 112–116) supported exclusively adult suckers (>340 mm TL). Only in the downstream reach (Reach 1 rkm 11–14) were a range of sizes present, from juveniles to adult-sized fish (60–340 mm TL), indicating that this may be important habitat for recruitment of young. Absence of juvenile Flannelmouth and Bluehead suckers from tributaries also suggested the lower White River may be an important recruitment area for the entire population, including upstream reaches. This is similar to recruitment patterns for Colorado Pikeminnow in the Green River basin, where juvenile populations rear in downstream reaches of the Green River and, over time, move upstream as large juveniles or young adults into upstream reaches where little or no recruitment otherwise occurs (Bestgen et al. 2007). Similarly, research on the Weber River, Utah, showed that length frequency distributions of Bluehead Suckers in upstream reaches were composed primarily of large adult suckers and downstream reaches supported juvenile to adult-sized fish (Webber et al. 2012). Webber et al. (2012) hypothesized that the paucity of smaller fish (<400 mm) in the upper reach was caused by predation by non-native piscivores. After the construction of Kenney Reservoir, Bluehead Suckers downstream of Taylor Draw Dam declined from 30% of the fish community to less than 0.05% (Martinez et al. 1994). The decline of Bluehead Suckers was attributed to Kenney Reservoir preventing larvae spawned upstream of the reservoir from drifting to downstream habitat (Martinez et al. 1994). Both predation and lack of larval drift from upstream spawning could potentially explain the paucity of young suckers documented in the upper reaches of the White River during my study. Both Brown Trout *Salmo* *trutta* and Rainbow Trout *Oncorhynchus mykiss* were also abundant upstream and probably prey on young suckers, limiting recruitment in that reach. Further research into the fate of larvae is needed to understand how predation and larval drift influence population structure along the longitudinal gradient of the White River.

Roundtail Chub length frequency data indicated a complete lack of recruitment in the upper White River. Large adult chubs were detected in downstream Reach 1 (rkm 11–14) and Reach 2 (rkm 82–86) and larvae were detected from rkm 0–68. However, no juvenile or small adult chubs < 300 mm TL were detected during this study. It may be that chub larvae drift downstream into Kenney Reservoir, where chubs were once common (Martinez et al. 1994). During my study, fish populations were not sampled in Kenney Reservoir. However, Kenney Reservoir is a shallow, warmwater reservoir that may provide excellent habitat for young Roundtail Chubs. Lack of young chubs in the main-stem White River indicates that this population may not be viable if lack of recruitment continues and further study is warranted.

Understanding the relationship between water temperature and reproduction for Flannelmouth Sucker, Bluehead Sucker, and Roundtail Chub should help resource managers make more informed decisions regarding flow requirements and water usage to maintain native fish populations. Using water temperature to evaluate potential reproductive habitat could be a management tool to identify barriers to upstream spawning migrations or stream restoration sites. Low flows during this study resembled future climate change scenarios and indicated that all three species could successfully reproduce in those conditions. Reduced habitat size under climate-change-induced flow reductions would certainly reduce population abundance, which may be partially offset by expansion upstream into thermally suitable habitat. However, the long-term implications of climate change are unknown and managers should strive to perpetuate this valuable and relatively pristine native fish community in the upper White River drainage as a vestige of the native fish communities that formerly existed throughout the Colorado River basin.

TABLES

TABLE 2.1–Percent composition (%) of Bluehead Sucker, Flannelmouth Sucker, Roundtail Chub and Other species (introduced as well as native species) captured in seine and dip net samples in the upper White River drainage, Colorado, from mid-May through late July 2012 and 2013. The total length (TL) is displayed parenthetically below percent composition for each taxon and the total fish captured during each year is below.

	2012	2013
Species	% (TL range, mm)	% (TL range, mm)
Bluehead Sucker	13.8 (10–58)	23.9 (8–27)
Flannelmouth Sucker	13.9 (12–52)	17.6 (9–34)
Roundtail Chub	9.2 (8–40)	1.2 (7–26)
Other	63.2	57.4
Total fish captured	10,935	16,410

TABLE 2.2–Date of the first detection of Flannelmouth Sucker (FMS), Bluehead Sucker (BHS), and Roundtail Chub (RTC) larvae at the most downstream sampling locations (rkm 0 and 4) and the difference between the timing of first detection of larvae between years 2012 and 2013.

Species	Date of first larvae (rkm 0–4)		Difference between years
	2012	2013	
FMS	21-May	10-Jun	20
BHS	14-May	10-Jun	27
RTC	12-Jun	11-Jul	29

TABLE 2.3–Age as function of length regression equations for Flannelmouth Sucker (FMS), Bluehead Sucker (BHS), and Roundtail Chub (RTC) in the upper White River basin constructed from measured lengths of larval fishes aged by counting the daily growth microincrements in their otoliths. Age is presented in days (d) and the length represents total length (TL) measured in mm for all three species.

		Regression equations	
Species	Location	2012	2013
FMS	Main-stem	Age (d) = (TL)*0.88 + 3.42	Age (d) = (TL)*1.19 – 5.72
	Coal Creek	Age (d) = (TL)*0.70 + 7.28	Age (d) = (TL)*2.73 – 26.05
	Piceance Creek	Age (d) = (TL)*0.95 + 6.42	
BHS	Main-stem	Age (d) = (TL)*2.87 – 25.70	Age (d) = (TL)*2.24 – 19.64
	Coal Creek	Age (d) = (TL)*2.46 – 15.85	Age (d) = (TL)*1.21 + 0.06
	Piceance Creek	Age (d) = (TL)*1.57 – 4.20	
RTC	Main-stem	Age (d) = (TL)*1.49 – 0.11	Age (d) = (TL)*2.33 – 14.11

TABLE 2.4–Total number (Total) and mean total length (TL) of Flannelmouth Sucker (FMS), Bluehead Sucker (BHS), and Roundtail Chub (RTC) larvae aged by counting the daily growth microincrements in their otoliths (otolith aged) compared to larvae aged by their TL (mm) applied to the age as a function of TL regression equation (measured). Larvae were aged from samples at four locations on the White River (White R.), one location in Piceance Creek, and one location in Coal Creek.

		2012				2013			
		Otolith aged		Measured		Otolith aged		Measured	
Collection Site	Species	Total	TL	Total	TL	Total	TL	Total	TL
White R. 47.5 rkm	FMS	10	16.1	54	16.6	10	16.1	71	16.5
White R. 47.5 rkm	BHS	10	14.8	97	14.2	10	14.9	70	14.3
Coal Creek	FMS	10	16.1	41	16.9	10	16.0	44	16.0
Coal Creek	BHS	10	14.5	8	16.3	10	14.4	12	15.9
Piceance Creek	FMS	10	16.0	0	N/A	--	--	--	--
Piceance Creek	BHS	10	15.0	0	N/A	--	--	--	--
White R. rkm 118	FMS	10	16.8	2	17.5	10	16.1	49	16.9
White R. rkm 118	BHS	9	14.1	0	N/A	10	14.9	59	15.0
White R. 4&18rkm	RTC	10	18.1	0	N/A	10	12.1	8	11.5
White R. 68 rkm	RTC	10	14.4	11	15.4	10	13.1	46	12.9

TABLE 2.5–Summary statistics for candidate multiple regression models used to predict stream temperature in the upper White River, CO. Five years of data were used to construct these regressions (2008–2012). Predictor variables Julian date (JDay), flow (Q), elevation (Elev), and air temperature (ATemp) were evaluated for model selection.

Number of variables in the Model	R^2	AIC	SSE	Variables in the Model
5	0.9468	282.89	2989.91	JDay* Q* Q^2* Elev* ATemp
4	0.9425	491.90	3232.50	JDay* Q* Elev *ATemp
4	0.9278	1107.88	4059.14	JDay *Q^2* Elev* ATemp
4	0.9261	1171.31	4155.45	Q *Q^2* Elev* ATemp
3	0.9166	1497.54	4691.55	Q* Elev *ATemp
3	0.8921	2192.87	6066.72	Q^2 *Elev* ATemp
3	0.8765	2558.86	6945.68	JDay* Elev *ATemp

TABLE 2.6–Summary output for the multiple regression equation used to build the stream temperature model in the upper White River. Five years of data were used to create this regression (2008–2012).

Predictor Variables	*b*(SE)	*t*	*P*-value	R^2
Intercept	31.9369 (0.3854)	82.8718	< 0.0001	0.94
Julian Date (0-365)	0.0313 (0.0009)	34.8786	< 0.0001	
Flow (cfs)	-0.0012 (< 0.0001)	-55.6625	< 0.0001	
Elevation (feet)	-0.0050 (0.0001)	-76.8421	< 0.0001	
Air Temperature (˚C)	0.4736 (0.0062)	76.6630	< 0.0001	

Table 2.7–Mean and range TL (mm) of Flannelmouth Suckers (FMS), Bluehead Suckers (BHS), and Roundtail Chubs (RTC) captured during main-stem electrofishing on the White River, CO. Reach 2 was not sampled in 2013.

		2012 Total Length (mm)		2013 Total Length (mm)	
Location	Species	Mean	Range	Mean	Range
Reach 1 (rkm 11–14)	FMS	400	103–546	321	60–566
	BHS	163	103–276	162	74–374
	RTC	429	373–507	407	291–508
Reach 2 (rkm 85–86)	FMS	478	357–586	--	--
	BHS	410	346–478	--	--
	RTC	475	455–487	--	--
Reach 3 (rkm 112–116)	FMS	463	392–581	474	410–590
	BHS	410	340–492	417	353–468
	RTC	--	--	--	--

TABLE 2.8–Mean and range of catch per unit effort (CPUE) of Flannelmouth Suckers (FMS), Bluehead Suckers (BHS), and Roundtail Chubs (RTC) captured while electrofishing three reaches on the main-stem White River during 2012 and 2013. CPUE was calculated as the average number of fish per hour of sampling. Densities of fish were very high in Reach 2 so only 1.1 river kilometers were electrofished. Reach 2 was not sampled in 2013 and no Roundtail Chubs were captured in Reach 3.

		Reaches		
Species	Year	1 (rkm 11–14)	2 (rkm 85–86)	3 (rkm 112–116)
FMS	2012	70 (10–94)	364 (68–518)	119 (77–366)
	2013	22 (0–40)		152 (31–292)
BHS	2012	1 (0–4)	33 (20–52)	70 (15–85)
	2013	4 (0–28)		36 (4–67)
RTC	2012	4 (0–13)	10 (12–40)	0
	2013	3 (0–17)		0

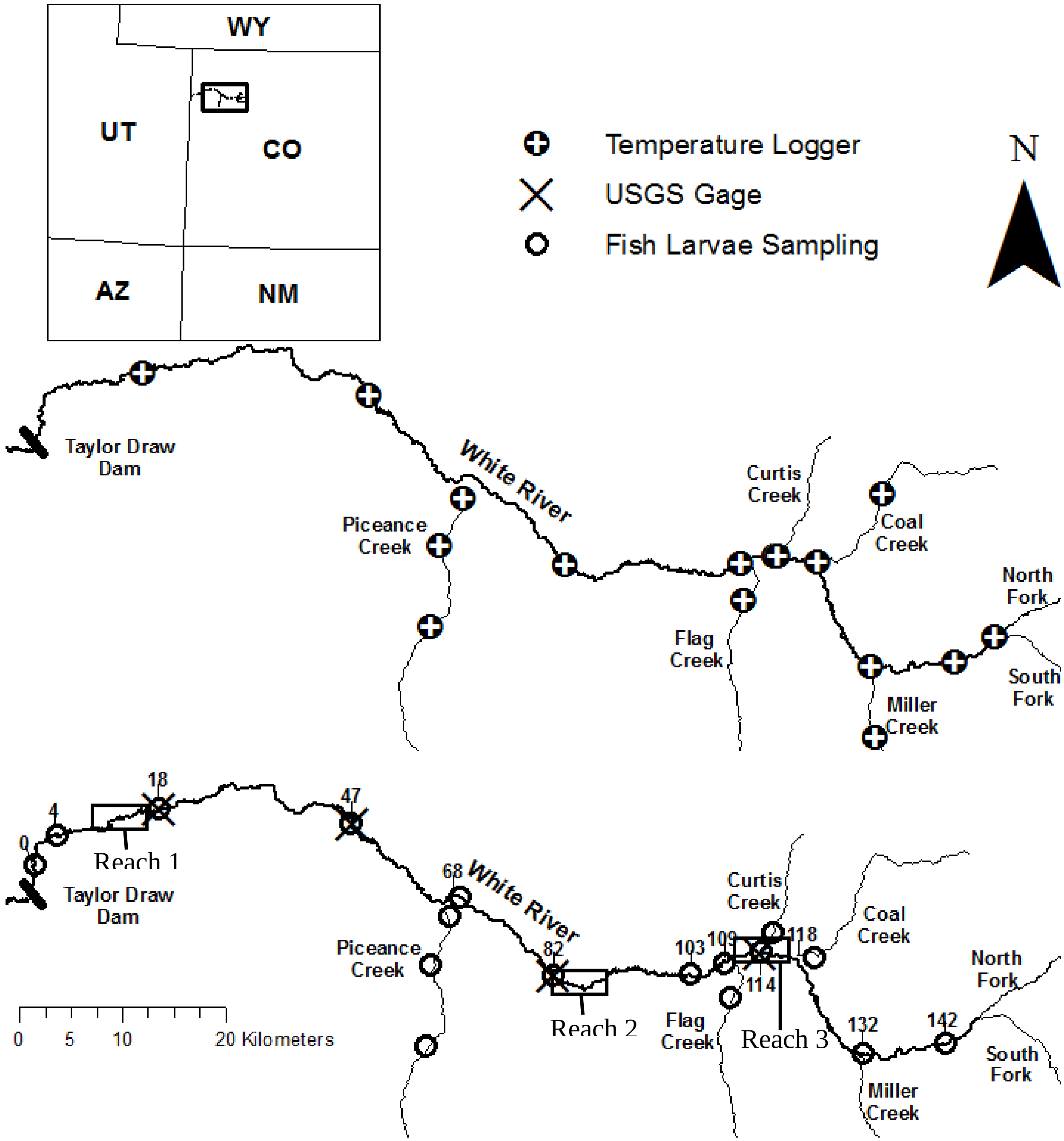

FIGURE 2.1–Map of the upper White River, CO and selected tributaries depicting the locations of water temperature loggers, U.S. Geological Survey temperature and flow gauges, larval sampling stations, and electrofishing reaches.

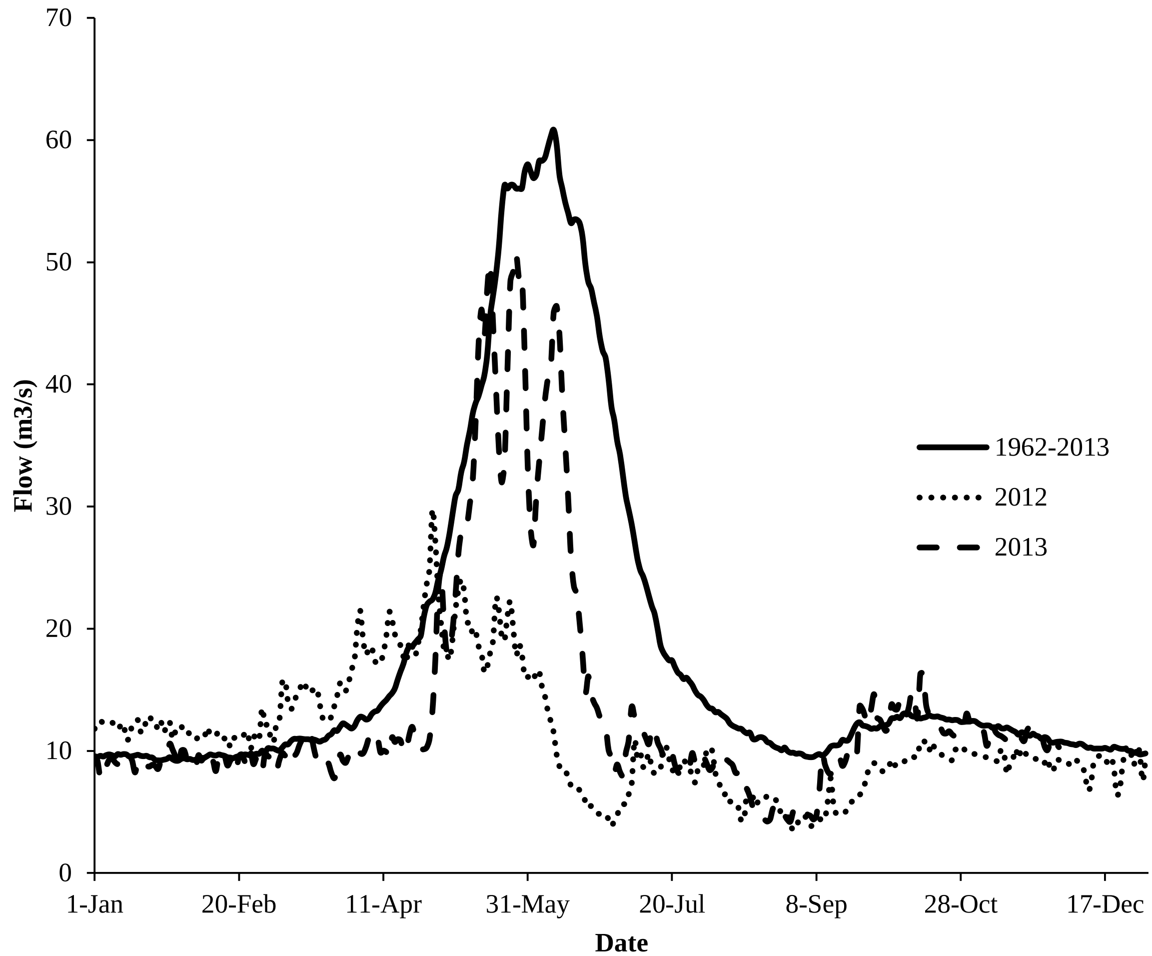

FIGURE 2.2–Mean daily flow for the White River, CO (U.S. Geological Survey gauge #09304800) for period of record (1962-2013) and study years 2012 and 2013.

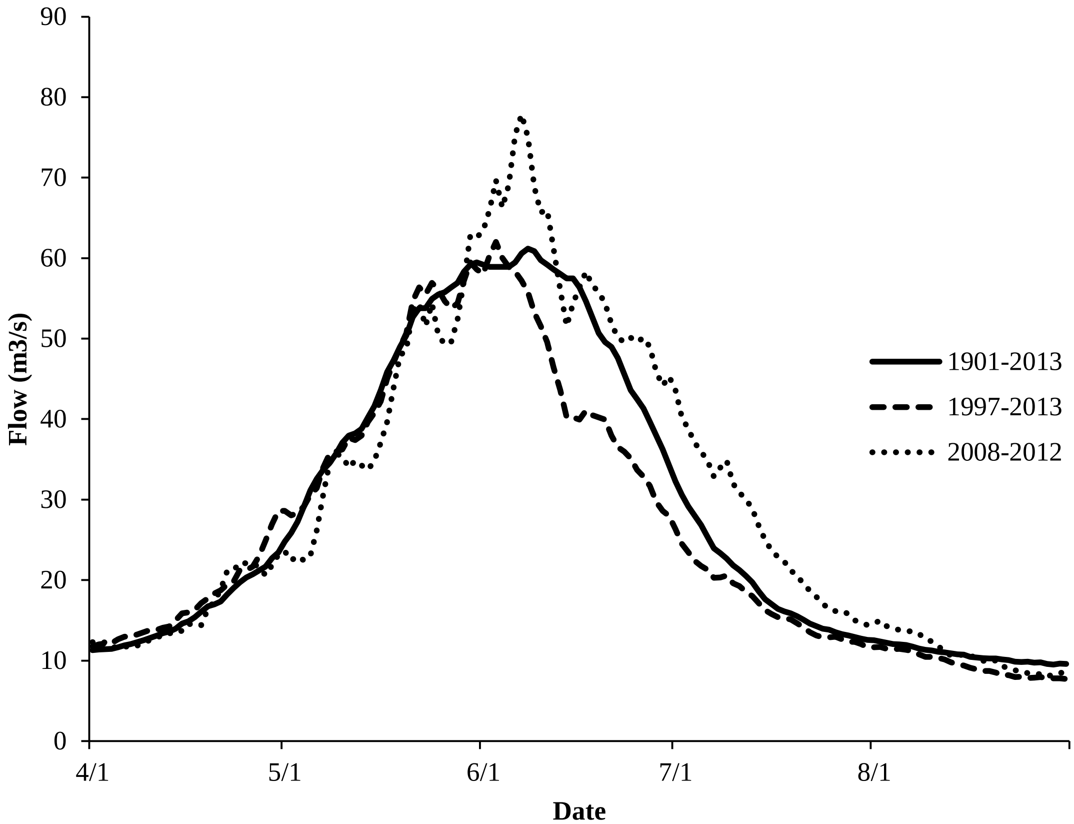

FIGURE 2.3–Comparison of mean daily flow for two time periods (1997–2013 and 2008–2012) compared to the historic record (1901-2013). All flow records are from U. S. Geological Survey gauge #09304500.

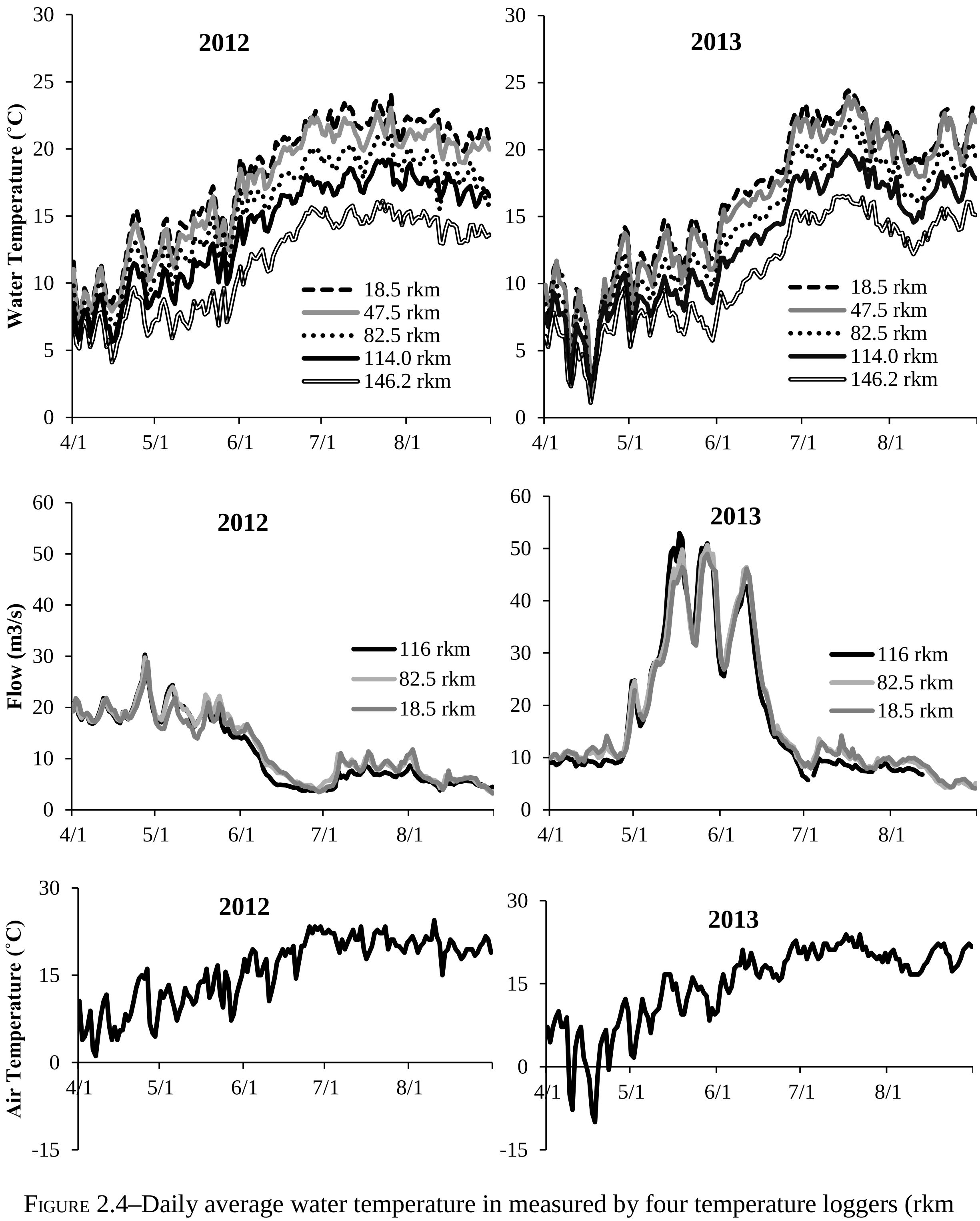

FIGURE 2.4–Daily average water temperature in measured by four temperature loggers (rkm 47.5–146.2) and one U.S. Geological Survey gauge (#09306290) located at rkm 18.5 and the mean daily flow measured by three U.S. Geological Survey gauges (#09306290, 09304200, 09304800). Air temperature data is from the Meeker Airport Weather Station.

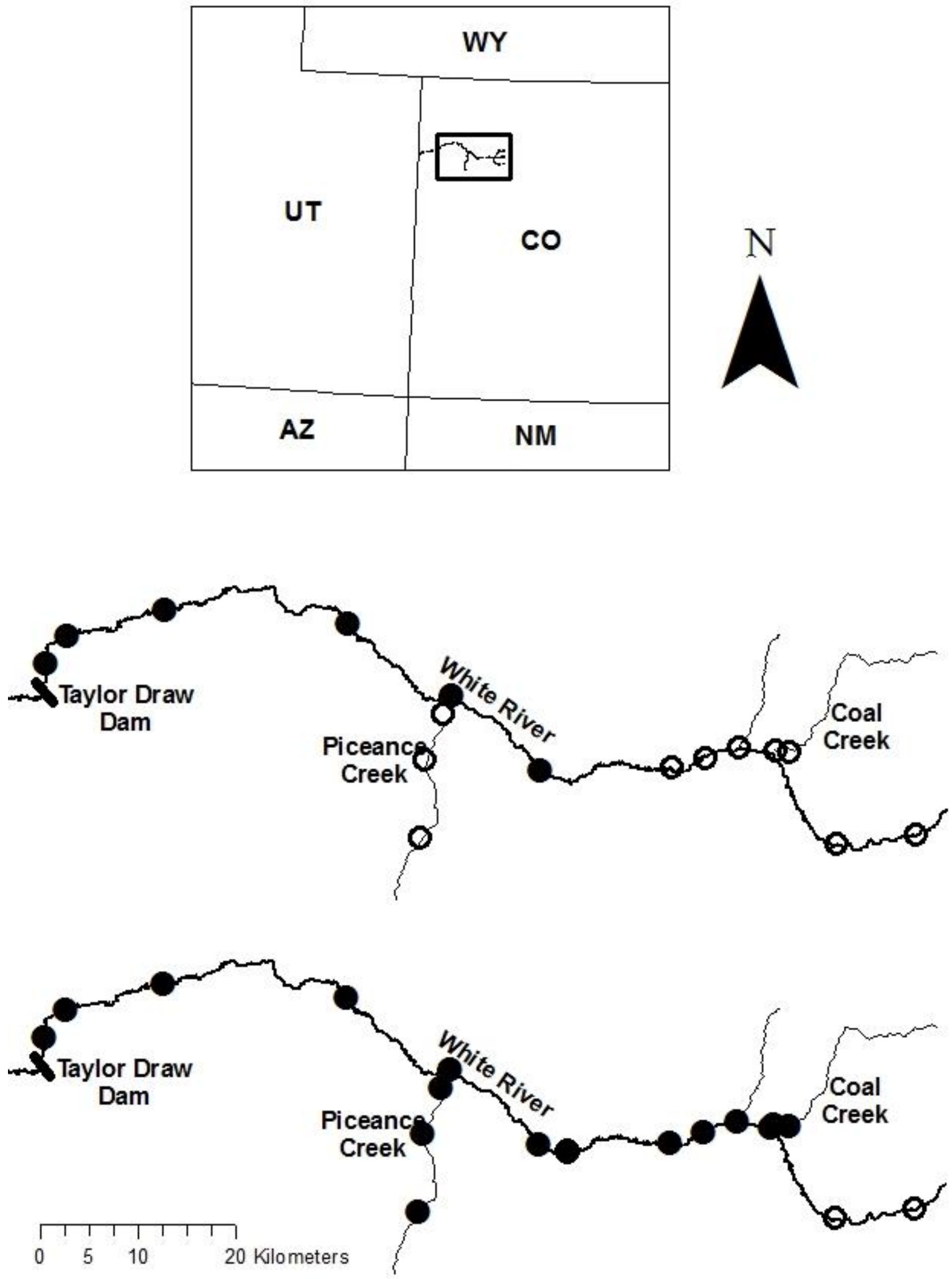

FIGURE 2.5–Presence (filled circles) and absence (open circles) of Roundtail Chub (upper map), and Flannelmouth Sucker and Bluehead Sucker (lower map, distributions identical) at sampling locations in the upper White River drainage, Colorado.

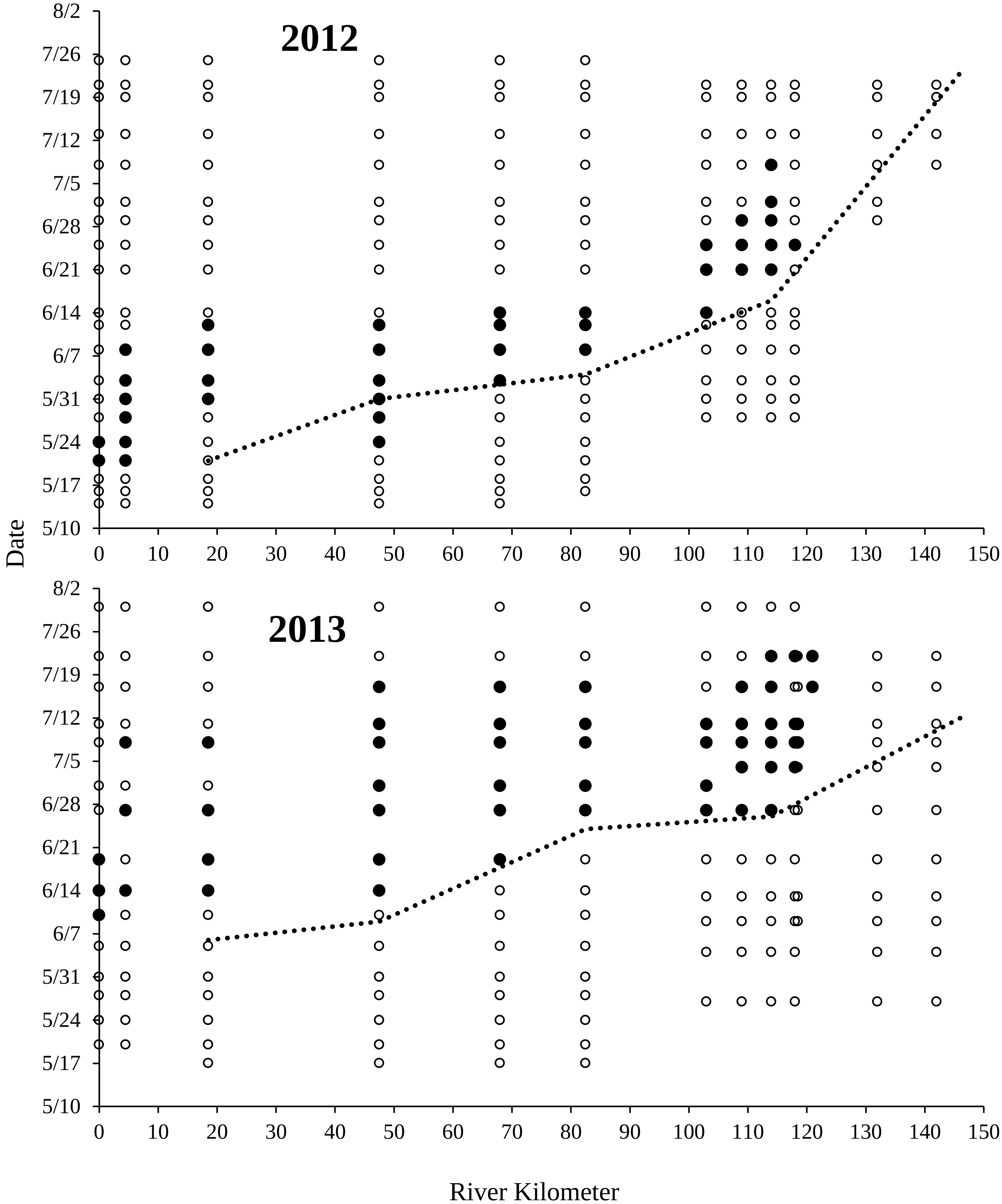

FIGURE 2.6.–Time of presence (filled circles) and absence (open circles) of Flannelmouth Sucker mesolarvae detected in the main-stem upper White River, CO, for study years 2012 (12 stations) and 2013 (14 stations, rkm 118.5, and 121 added). The temperature logger recordings (dotted line) show the difference in observed mean daily temperature of 16˚C and the presence of larvae.

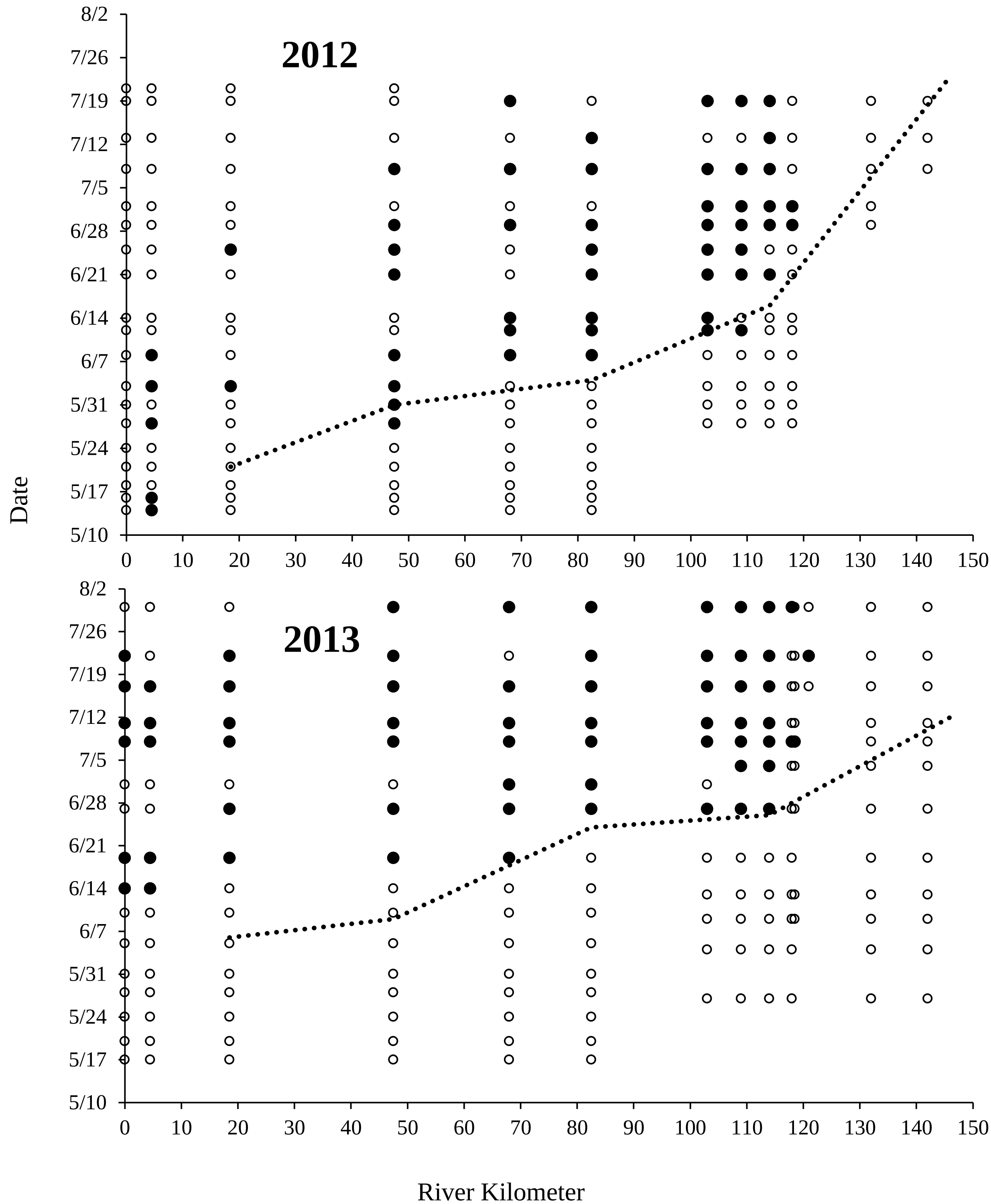

FIGURE 2.7–Time of presence (filled circles) and absence (open circles) of Bluehead Sucker mesolarvae detected in the main-stem upper White River, CO, for study years 2012 (12 stations) and 2013 (14 stations, rkm 118.5, and 121 added). The temperature logger recordings (dotted line) show the difference in observed mean daily temperature of 16˚C and the presence of larvae.

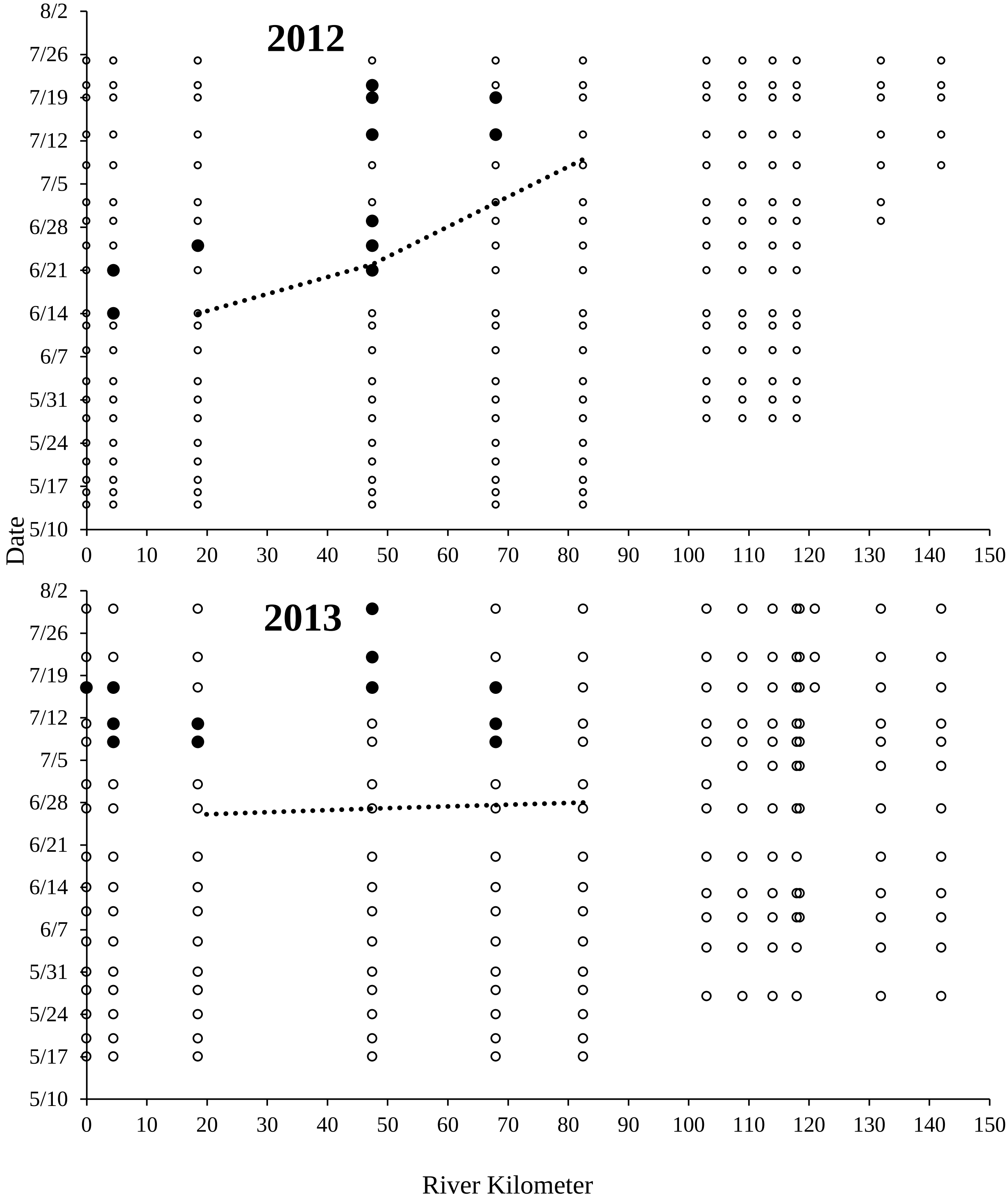

FIGURE 2.8–Time of presence (filled circles) and absence (unfilled circles) of Roundtail Chub mesolarvae detected in the main-stem upper White River, CO, for study years 2012 (12 stations) and 2013 (14 stations, rkm 118.5, and 121 added). The temperature logger recordings (dotted line) show the difference in observed mean daily temperature of 20˚C and the presence of larvae.

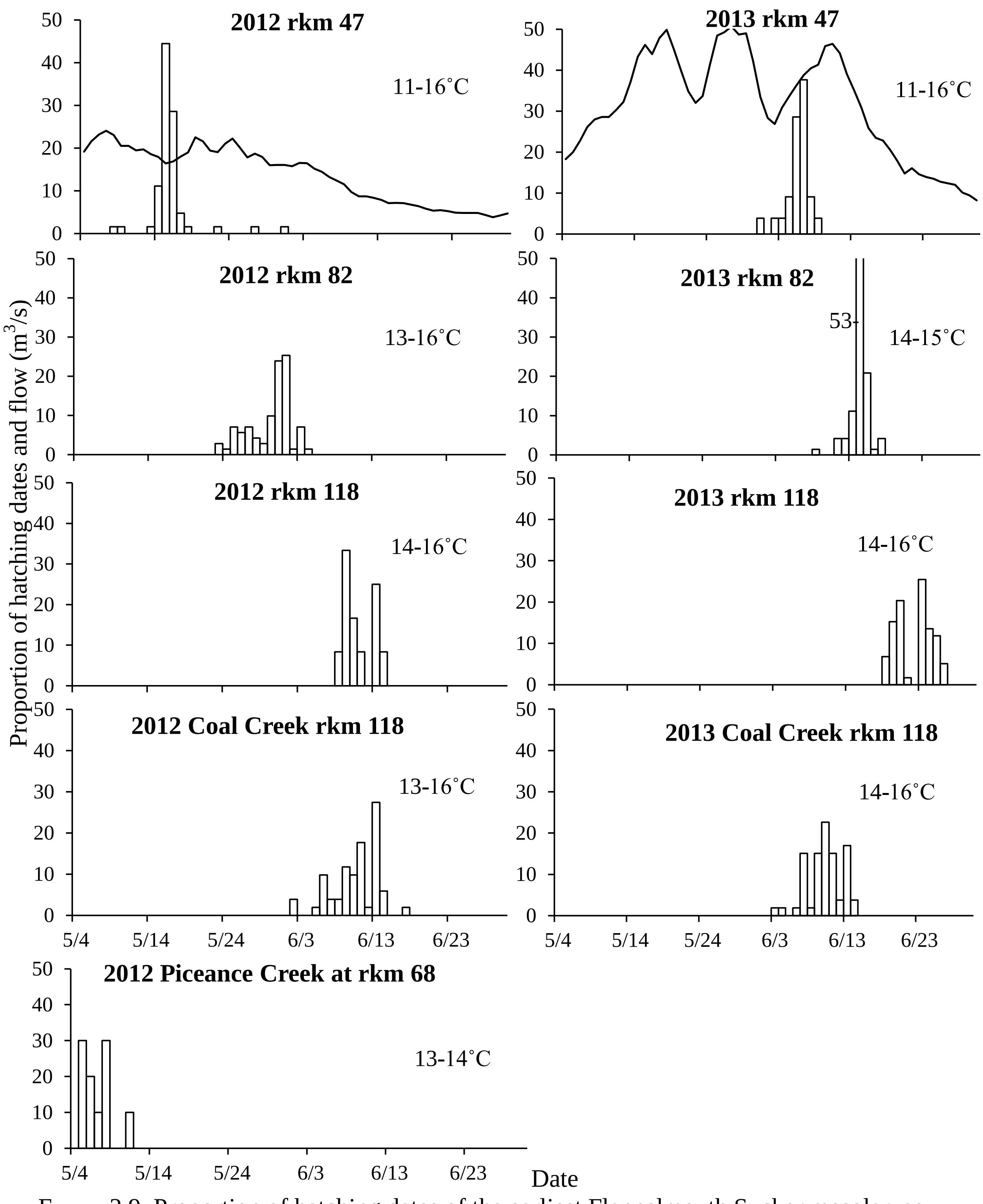

FIGURE 2.9–Proportion of hatching dates of the earliest Flannelmouth Sucker mesolarvae collected at three main-stem White River, CO, locations (rkm 47, 82, 118) and two tributary locations relative to the flow (U.S. Geological Survey Gauge # 09304800) from May 4–June 30, 2012 and 2013. The mean daily temperature is reported for the range of hatch dates at each site. Larvae were not detected in Piceance Creek in 2013.

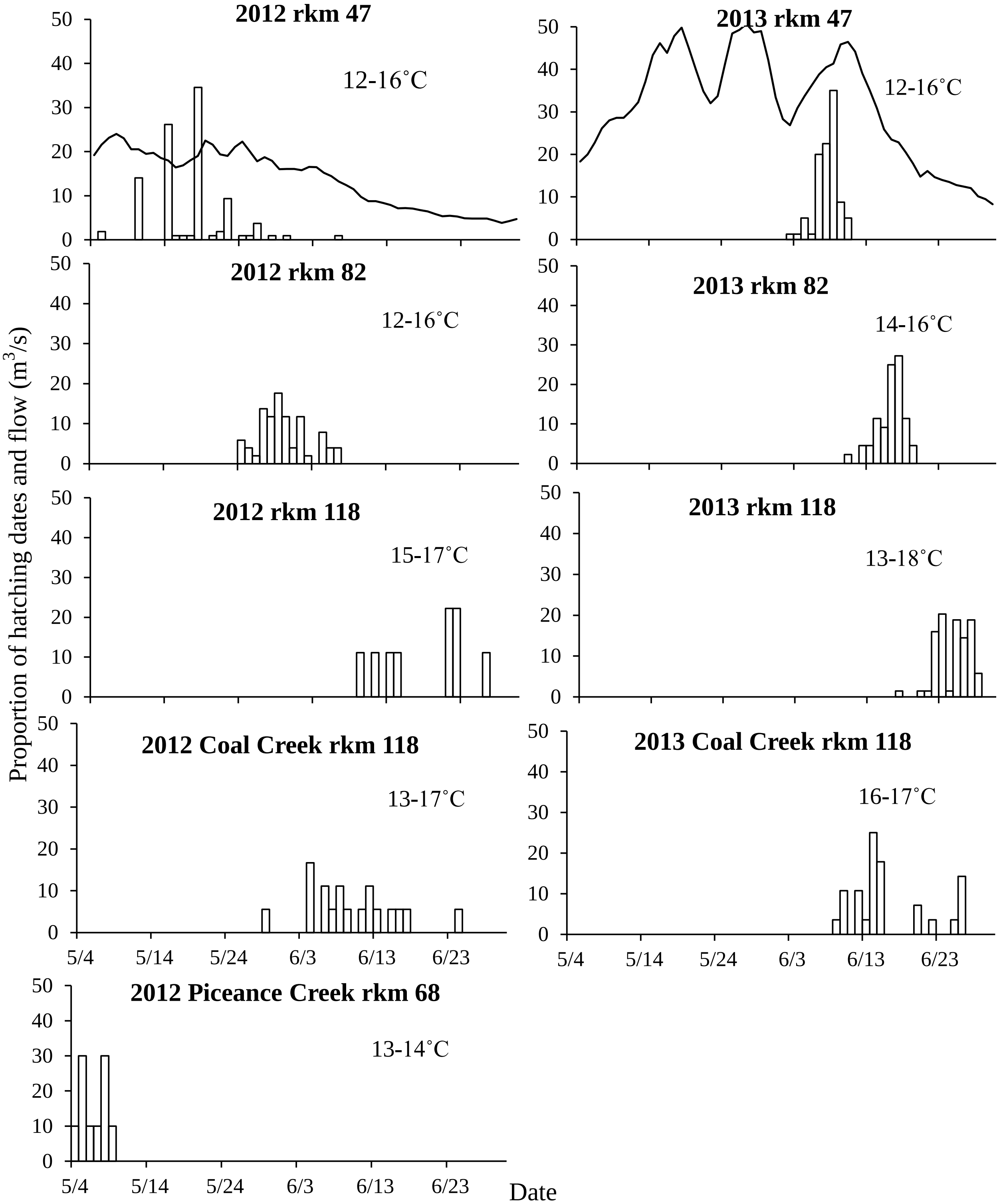

FIGURE 2.10–Proportion of hatching dates for the earliest Bluehead Sucker mesolarvae collected at three main-stem White River, CO, locations (rkm 47, 82, 118) and two tributary locations relative to the mean daily flow (U.S. Geological Survey gauge #09304800) May 4–June 30, 2012 and 2013. The mean daily temperature is reported for the range of hatch dates at each site. Bluehead Sucker larvae were not detected in Piceance Creek in 2013.

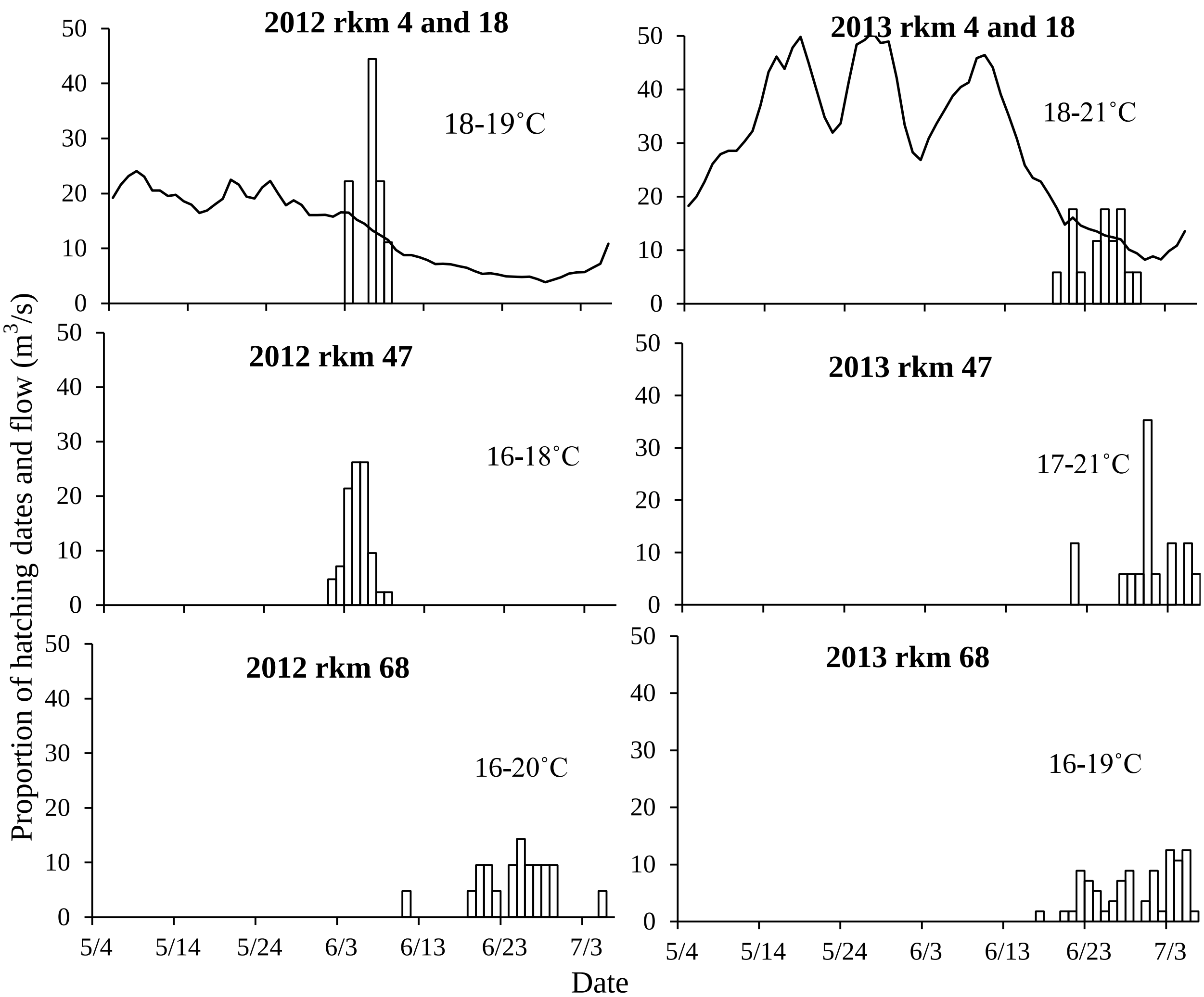

FIGURE 2.11–Proportion of hatching dates for the earliest Roundtail Chub mesolarvae collected at three main-stem White River, CO, locations in 2012 and 2013 relative to the mean daily flow (U.S. Geological Survey gauge # 09304800) from May 4–July 6, 2012 and 2013. The mean daily temperature is reported for the range of hatch dates at each site. No Roundtail Chub larvae were detected in tributaries during this study.

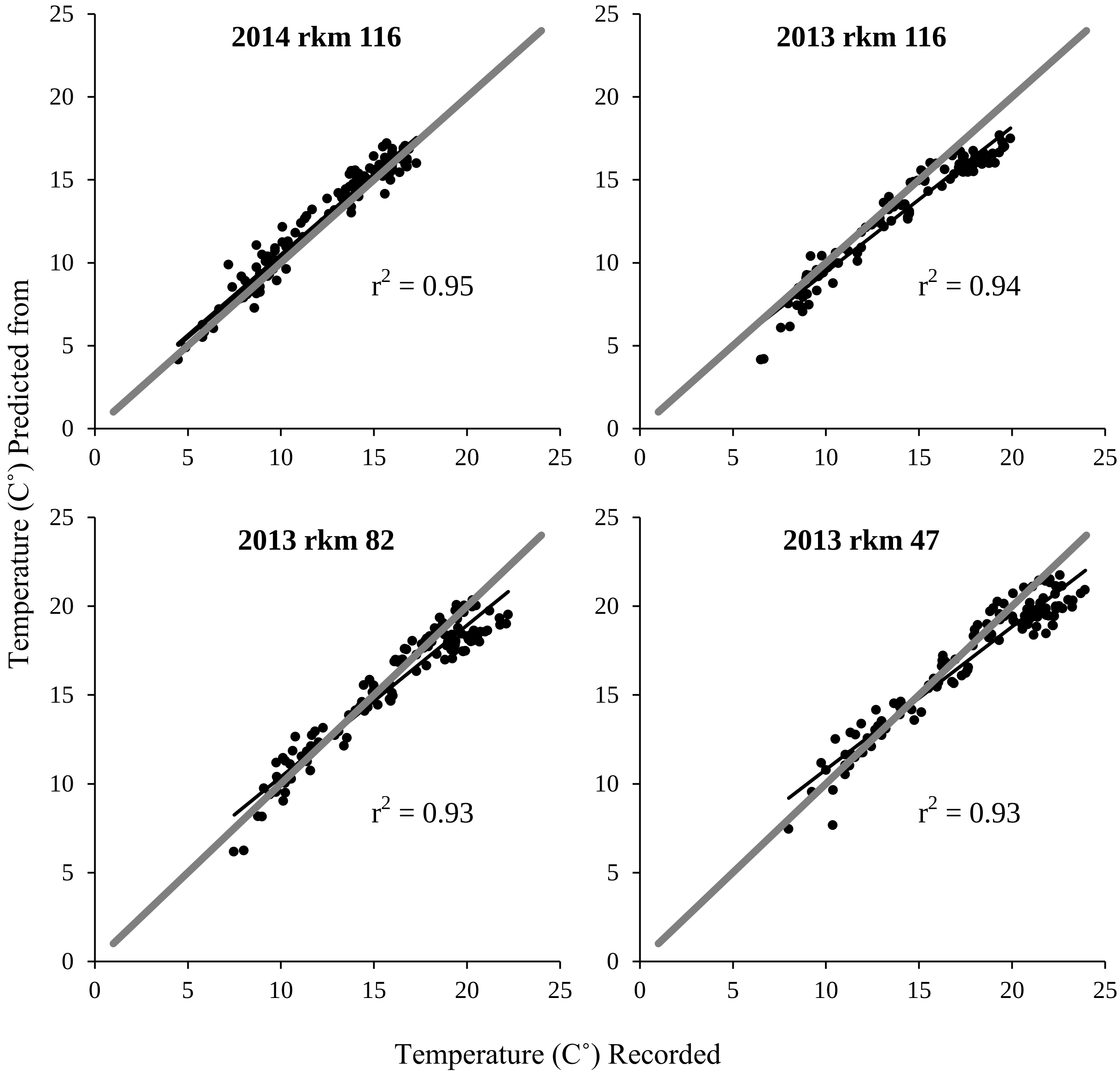

FIGURE 2.12–Comparison of predictions of water temperature from the stream temperature model developed in this study, and the temperature recorded by three temperature loggers in 2013 rkm 116, 82, and 47 respectively, and one 2014 record from U.S. Geological Survey gauge #90304200 at rkm 116. All temperatures are from the main-stem White River, CO. The slope of the regressions (black line) and a slope of 1 (grey line) are plotted for comparison.

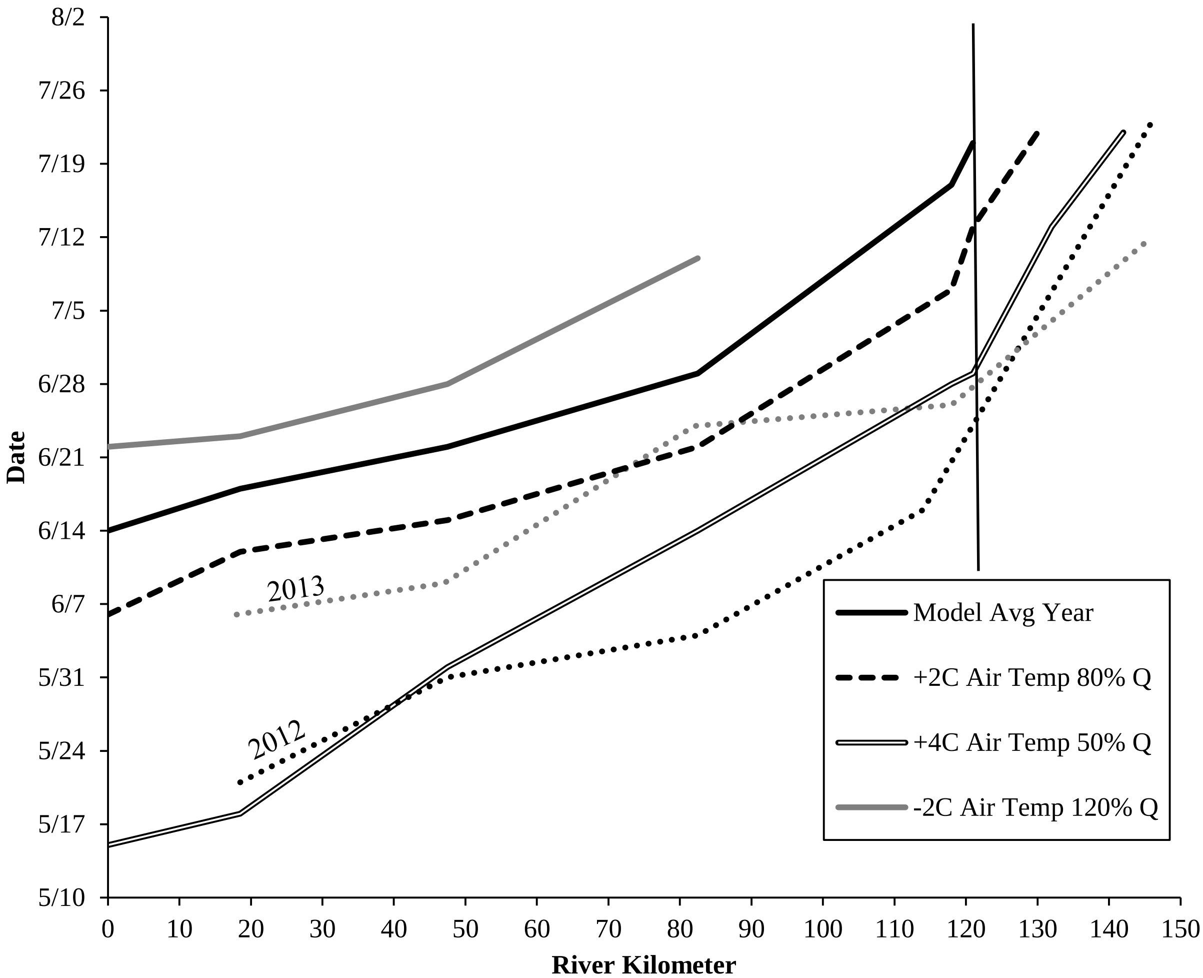

FIGURE 2.13–Time of stream temperature model predictions of 16˚C, the temperature most associated with the first presence of sucker larvae, for an average year using data from 1997–2013 (solid black line) and three manipulations of flows and air temperatures to assess climate change scenarios. One scenario represents a 2˚C decrease in summer air temperature and a 20% increase in flow (grey line), another scenario represents a 2˚C increase in summer air temperature and a 20% reduction in flow (dashed black line), and the third scenario represents a 4˚C increase in air temperature and a 50% decrease in flow (hollow line). The date and river kilometer when 16˚C was first recorded for 2012 and 2013, the dotted lines (labeled), are also plotted for comparison to the average and climate change scenarios. The vertical black line depicts the most upstream location (rkm 121) that Flannelmouth and Bluehead sucker larvae were detected during this study.

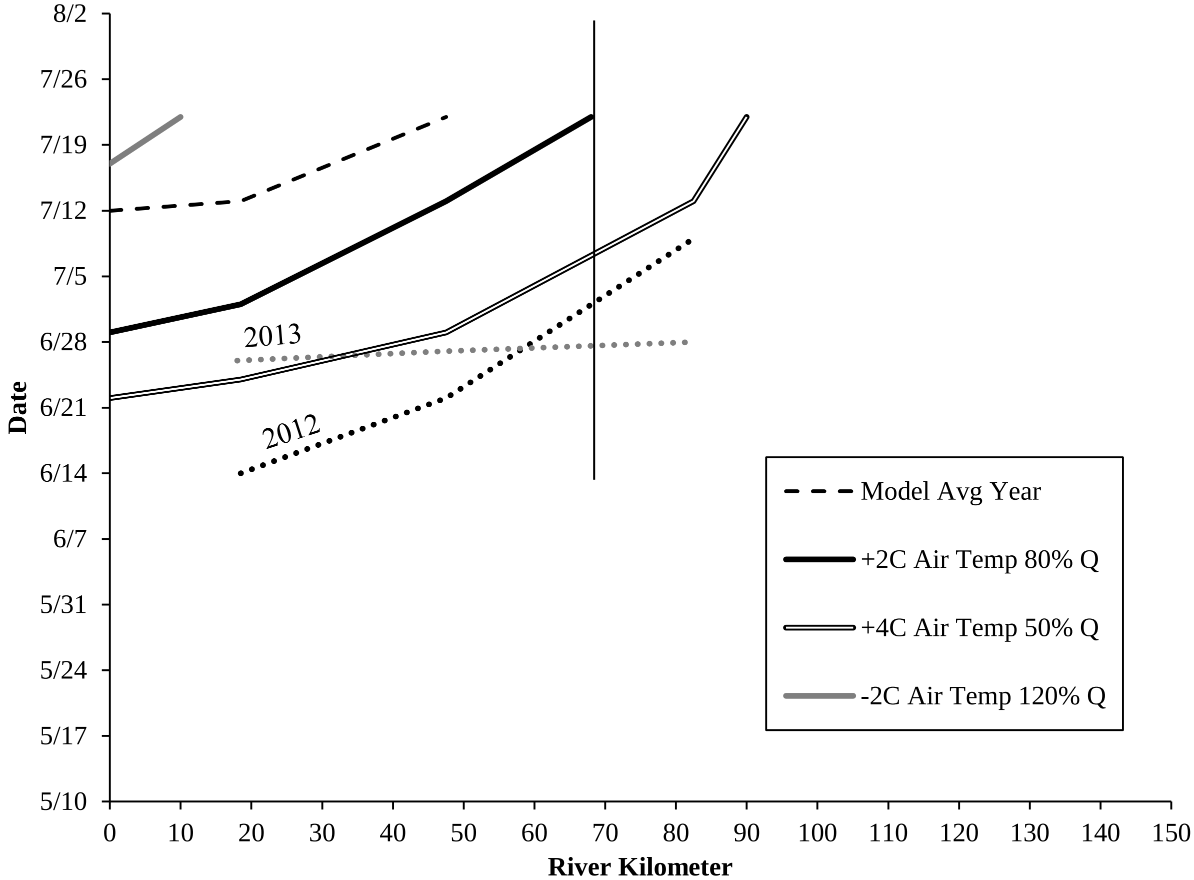

FIGURE 2.14–Time of stream temperature model predictions of 20˚C, the temperature most associated with the first presence of Roundtail Chub larvae, for an average year using data from 1997–2013 (solid black line) and three manipulations of flows and air temperatures to assess climate change scenarios. One scenario represents a 2˚C decrease in summer air temperature and a 20% increase in flow (grey line), another scenario represents a 2˚C increase in summer air temperature and a 20% reduction in flow (dashed black line), and the third scenario represents a 4˚C increase in air temperature and a 50% decrease in flow (hollow line). The date and river kilometer when 20˚C was first recorded for 2012 and 2013, the dotted lines (labeled), are also plotted for comparison to the model average and climate change scenarios. The vertical black line depicts the most upstream location (rkm 68) that Roundtail Chub larvae were detected during this study.

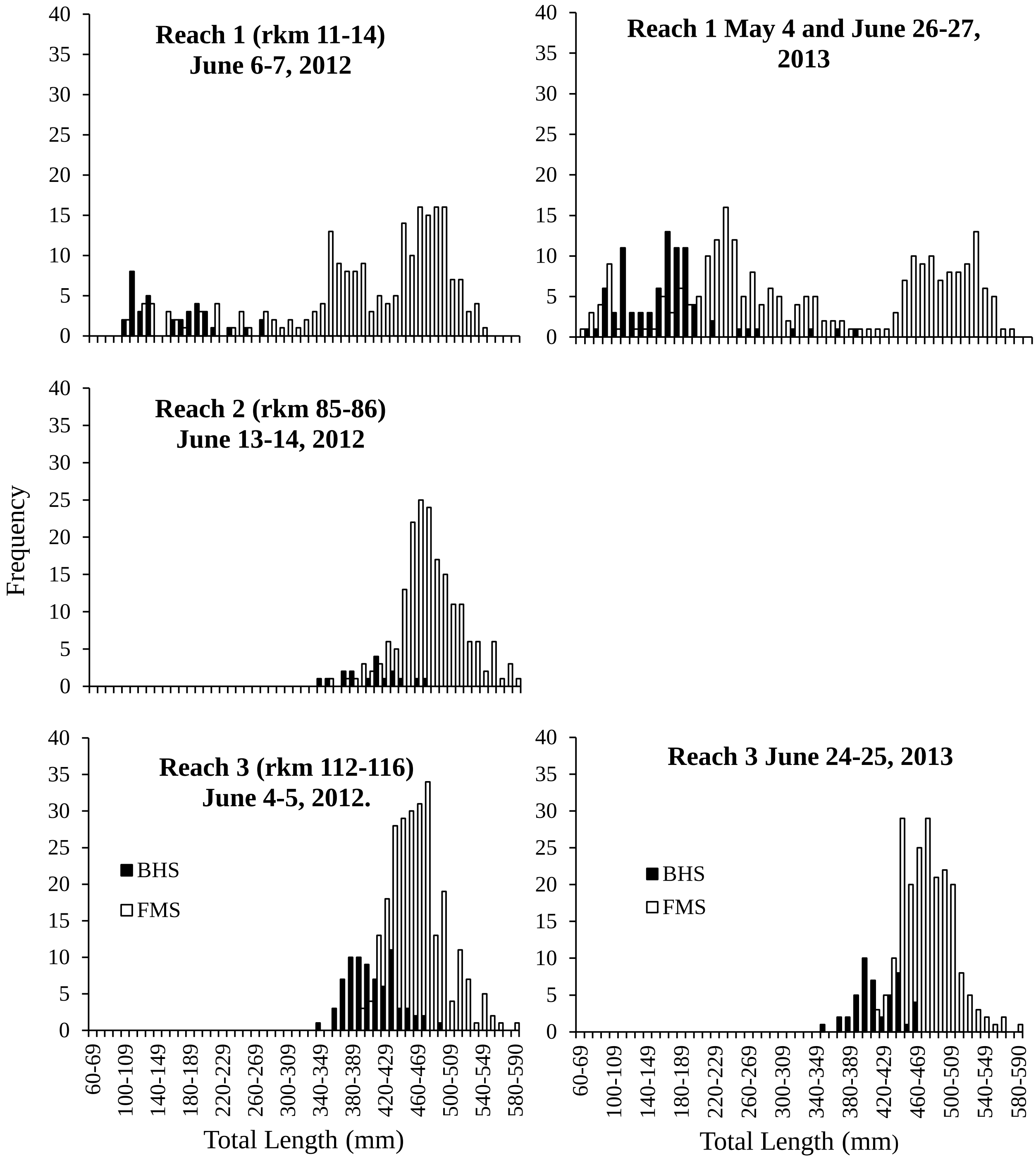

FIGURE 2.15–Length frequency (TL [mm]) histograms of Bluehead Suckers (BHS) and Flannelmouth Suckers (FMS) captured during multiple-pass electrofishing of the White River in 2012 and 2013. One electrofishing pass was conducted per day, with the exception of Reach 1 May 4, 2013 when both passes were done on the same day. Reach 2 was not sampled in 2013.

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