Salmonid movements and thermal hydrodynamics at a montane river system confluence: thermal refugia in the Smith River basin

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EXECUTIVE SUMMARY

The Smith River is a popular recreational sportfishery in western Montana, but salmonid abundances there are relatively low and limited by high summer water temperatures and low discharges. Smith River tributaries may serve as thermal refuges and also as important spawning and nursery areas. Tenderfoot Creek was identified as one such tributary and was the subject of a detailed multi-year study, the goal of which was to evaluate the importance of Tenderfoot Creek to the salmonid populations of the Smith River. Contrary to expectations, Tenderfoot Creek was not used as a temporary thermal refuge by Smith River resident fish during periods of high water temperatures; rather, the outflow of Tenderfoot Creek may have been used instead. Moreover, methods used to identify thermally stressful conditions in 2012 may have not been as appropriate as previously thought. In addition, knowledge of Tenderfoot Creek's role as a nursery area was still incomplete. In 2014, I investigated salmonid movements and thermal hydrodynamics at the confluence between Tenderfoot Creek and the Smith River, evaluated the use of a remote monitoring point to describe temperature regimes in the Smith River, and developed a temperature model to estimate local temperatures in the Smith River using data from the remote monitoring point.

Salmonids used the cool direct and hyporheic discharges from Tenderfoot Creek as a thermal refuge within the Smith River. Water temperatures in the outflow of Tenderfoot Creek in the Smith River were cooler than those of the Smith River outside of this plume during the summer thermal stressful period; the mean difference between temperatures in the Tenderfoot Creek outflow and the Smith River outside of this coolwater plume was 2.9 °C and ranged from 0.5 °C to 6.1 °C. Because of this, use of the Tenderfoot Creek outflow was higher than would otherwise be expected for similar-sized areas in the Smith River; PIT-tagged fish preferred the

coolwater plume of the outflow over the area on the opposite bank, which ostensibly afforded better cover. Use of the coolwater outflow of Tenderfoot Creek by PIT-tagged fish increased when conditions in the Smith River outside of this plume became stressful. The Tenderfoot Creek outflow (as well as those of other coldwater tributaries) may be critical for salmonids when water temperatures in the mainstem river are stressful, so managers may want to consider limiting recreational use of outflow areas during such times.

Low numbers of juveniles were relocated on fixed antennas; I relocated only 19 of 229 tagged fish less than 150 mm long (1 of 21 Brown Trout, 1 of 36 Brook Trout, 1 of 32 Mountain Whitefish, and 16 of 140 Rainbow Trout). Most Rainbow Trout and the only Brook Trout remained within Tenderfoot Creek. One Brown Trout and Mountain Whitefish migrated downstream and entered the Smith River. Such low numbers of relocations necessitate caution in interpreting results but could suggest that juvenile Rainbow Trout and Brook Trout remain in Tenderfoot Creek.

The USGS gaging station 20.95 rkm upstream of the confluence with Tenderfoot Creek probably did not appropriately represent thermal conditions in the Smith River at the confluence in 2012, contrary to assumptions made in my thesis (Ritter 2015). A multiple regression temperature model developed using data collected in 2014 probably more accurately described thermal regimes in the Smith River in 2012. The mean difference between actual temperatures in the Smith River in 2014 and temperatures estimated by my model was 0.6 °C (maximum difference was 1.6 °C), whereas the mean difference between actual temperatures and the USGS gage station was 1.0 °C (maximum difference was 4.6 °C).

Conditions in the Smith River were therefore probably less stressful than suggested by the USGS gage station in summer of 2012, and thermal thresholds of salmonids were probably surpassed less frequently than previously thought. Estimated water temperatures in the Smith River tended to be lower (up to 2.2 °C) than those recorded by the USGS gage station in the summer of 2012. Accordingly, management decisions based on water temperatures recorded at a single site should be made with considerations of conditions throughout the Smith River; temperature models similar to those described in this report could be used to better understand relationships between the USGS gage station and other monitoring points throughout the Smith River basin.

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INTRODUCTION

Maintenance and restoration of hydrologic connectivity (the water-mediated transfer of matter, energy, or organisms within or between the elements of the hydrologic cycle; Pringle et al. 2001) in river networks are important to the conservation and management of fishes and fisheries (Van Kirk and Benjamin 2001; Bunn and Arthington 2002; Kondolf et al. 2006). Many native salmonid species in the Mountain West have become fragmented and isolated as a result of reduced hydrologic connectivity, occupying only portions of their historical ranges (Shepard et al. 2005; Gresswell 2011) because access to spawning, foraging, and juvenile rearing habitat has been reduced or lost (Northcote 1997; Rieman et al. 1997; Isaak et al. 2007). Accordingly, connectivity has been identified as a primary conservation strategy (Gresswell 2011). In addition, thermally suitable habitat for all trout is predicted to decrease 47% in the next 50-100 years (Wenger et al. 2011) because of increasing global air temperatures (Solomon et al. 2007). Maintaining connectivity to areas of thermal refuge such as coolwater tributaries can therefore be important, especially for salmonids in river systems of the U.S. Mountain West (Isaak et al. 2012).

Such concerns prompted Montana Fish, Wildlife and Parks to conduct a basin-wide study to evaluate the importance of maintaining salmonid habitat connectivity in the Smith River drainage in western Montana. Noted for its remote canyon and scenery, Smith River State Park is a popular destination for recreational floaters and fishermen alike. However, salmonid abundances there are relatively low and thought to be limited by high summer water temperatures and reduced discharges resulting from water management practices such as irrigation withdrawals. Tributaries of the Smith River provide supplemental flows and may also serve as thermal refuges, spawning and nursery areas, and foraging grounds for salmonids.

Tenderfoot Creek was identified as one such tributary and was the subject of a detailed multi-year study (Ritter 2015) by the Montana Cooperative Fishery Research Unit at Montana State University, the goal of which was to evaluate the importance of Tenderfoot Creek to the salmonid populations of the Smith River. The specific objective was to determine if Tenderfoot Creek was used as a thermal refuge, spawning and nursery habitat, or both. The study revealed a unique system with significant importance to the Smith River. Mountain Whitefish, Brown Trout, Rainbow Trout, and Brook Trout all used Tenderfoot Creek for spawning and rearing. In addition, mature Brown Trout established year-round territories within Tenderfoot Creek and Mountain Whitefish used Tenderfoot Creek to escape high flows in the Smith River. Contrary to expectations, Tenderfoot Creek was not used as a temporary thermal refuge by Smith River resident fish during periods of high water temperatures. Rather, it appeared that the high quality habitat in Tenderfoot Creek was fully occupied year-round by territorial adult Brown Trout, thereby preventing temporary residence by immigrants from the Smith River during summer low flow. However, I hypothesized that the cool thermal plume created by Tenderfoot outflows at its confluence with the Smith River may provide thermal refuge at such times; large aggregations of fish were observed in this plume in summer. In addition, knowledge of Tenderfoot Creek's role as a nursery area was still incomplete; a better understanding of movements of juvenile salmonids could provide insight to this role.

The primary goal of my efforts in 2014 was therefore to investigate salmonid movements and thermal hydrodynamics at the confluence between Tenderfoot Creek and the Smith River.

Specific objectives were 1) to determine if salmonids were using the outflow of Tenderfoot Creek as a thermal refuge rather than the tributary itself or other areas at the confluence with the Smith River, 2) to investigate salmonid movements year-round, with emphasis on spring, winter, and critical times of the year such as high or low temperatures and discharges, and 3) to investigate movement of juvenile salmonids, particularly to determine if they remain in Tenderfoot Creek or migrate to mature in the Smith River.

STUDY AREA

Tenderfoot Creek is a major tributary of the Smith River located between the Big Belt and Little Belt mountain ranges about 140 km north of Bozeman, Montana (Figure 1.1). Mean annual discharge of the Smith River at the USGS gaging station near Fort Logan, Montana, is 6.7 m^3/s. Tenderfoot Creek is a remote, largely undeveloped major tributary of the Smith River and is located about 26 km downstream of the beginning of Smith River State Park, a river corridor managed by Montana Fish, Wildlife and Parks that extends 95 km from the only put-in at Camp Baker downstream to the only take-out at Eden Bridge (Figure 1.1). The study area consisted of the lower 13.7 km of Tenderfoot Creek, extending from an impassable barrier to fish movement at rkm 13.7 downstream to the confluence with the Smith River, and the confluence itself (Figure 1.1).

Tenderfoot Creek enters the Smith River on an east-bank inside bend of the Smith River about 20.5 rkm downstream of Camp Baker. The confluence area stretched from 20 m above to 80 m below the mouth of Tenderfoot Creek in the Smith River and encompassed the entirety of the Tenderfoot Creek plume (Figure 1.2). A large outcropping of the canyon wall on the west bank opposite the confluence caused rapid transverse mixing of the Tenderfoot Creek plume and the Smith River, limiting its downstream influence. Substrate on the east side of the confluence area was cobble, whereas the opposite (west) side consisted of cobble and angular boulders and boulder fragments originating from the canyon cliffs above (Figure 1.3). Overhead vegetation was common on the west side of the river, whereas the east side (Tenderfoot Creek outflow) was scoured clear of vegetation (Figure 3). A large, deep (> 3 m) pool was present about 40 m downstream of the confluence on the west side of the Smith River (Figure 1.3). The combination of the deep pool and confluence of Tenderfoot Creek made this area a popular spot for recreational floaters to angle and picnic (Figure 1.3).

The fish assemblage of Tenderfoot Creek consists of Rocky Mountain Sculpin *Cottus bondi*, Mountain Sucker *Catostomus platyrhynchus*, Mountain Whitefish *Prosopium williamsoni*, Brook Trout *Salvelinus fontinalis*, Brown Trout *Salmo trutta*, and Rainbow Trout *Onchorhynchus mykiss*.

METHODS

Seasons

I defined seasons based on water temperature and hydrologic regimes in Tenderfoot Creek and the Smith River (Figure 1.4). Spring occurred after ice break-up but before discharge increased from snowmelt in the Smith River, from March 1 to May 1, 2014 (Figure 1.4). Runoff occurred as discharges increased, peaked, and subsided in Tenderfoot Creek and the Smith River, from May 2 to July 8, 2014 (Figure 1.4). The summer thermal stress period lasted from July 9 to August 20, when temperatures in the Smith River were highest (Figure 1.4). From August 21 to 24, a significant weather event (8.9 cm of rain recorded on the Stringer Creek SNOTEL in the upper watershed of Tenderfoot Creek) reduced water temperatures and increased discharges until August 31, 2014 (Figure 1.4). Autumn began on September 1 after high discharges subsided and continued as temperatures declined until the first significant snowstorm on November 9, 2014. This snowstorm marked the beginning of winter and caused temperatures to drop appreciably such that ice formed and remained in the Smith River and Tenderfoot Creek. Winter therefore began on November 10, 2014, immediately following this snowstorm and persisted beyond the time frame of the study (Figure 1.4).

Temperature Regimes

Stationary temperature loggers

A network of 9 temperature loggers (Onset Computer Corporation, HOBO Pendant Temperature Data Logger, Bourne, Massachusetts) was installed in Tenderfoot Creek and the Smith River to monitor temperatures at, across from, above, and below the confluence of Tenderfoot Creek with the Smith River (Figures 1.1 and 1.2). Temperature loggers were enclosed in protective PVC cases and affixed to rebar with wire or to boulders with underwater epoxy (Simpson Strong-Tie Company, FX-764, Pleasanton, California). Temperature loggers in Tenderfoot Creek and in the Smith River above the confluence were installed on March 27, 2014, whereas temperature loggers in the outflow of Tenderfoot Creek and across from the outflow were installed on July 12 and July 25, 2014, respectively. Retrieval of temperature loggers in and across from the outflow of Tenderfoot Creek occurred on November 5 and August 26, 2014, respectively. All other temperature loggers were retrieved on December 31, 2014. Temperature was recorded hourly.

I also used data collected by the United States Geological Survey (USGS) at the gauge station just below Eagle Creek in the Smith River about 20.7 rkm upstream of the mouth of Tenderfoot Creek because deployment of loggers at the confluence (rkm 0.0) often occurred later than desired in 2011 and 2012 (in mid-summer). Additionally, temperature loggers in the Smith River were often removed or repositioned by recreational floaters, which resulted in the loss of temperature data in 2012.

Confluence temperature mapping

Comprehensive temperature mapping of the Smith River and Tenderfoot Creek at the confluence was performed on July 12, August 1, and September 29, 2014 using a high-precision digital thermometer (ERTCO, Model T2011-45, Dubuque, Iowa). Temperature was measured along transects located 20 m above, and 20, 40, 60, and 80 m below the confluence (Figure 1.2). Along each transect, water temperatures in the water column were recorded at every horizontal meter beginning at the bottom and every 0.2 m to the surface. Data collection required 75 to 120 minutes and occurred in the afternoon.

Confluence temperature modeling

I determined spatial and temporal patterns in water temperature at, across from, above, and below the confluence of Tenderfoot Creek and the Smith River by interpolating between measurements from in situ transect temperature mapping and nearby stationary temperature loggers. This allowed me to estimate temperatures on a fine spatial scale and also to account for locational differences in the shape and timing of diel temperature fluctuations. Sine-based models are often used to quantify diel fluctuations in water temperature because such fluctuations are cyclic (Arrigoni et al. 2008; Vatland et al. 2015). However, diel temperature fluctuations in the Smith River and Tenderfoot Creek during the summer thermal stress period were not symmetric (i.e., water temperatures increased faster than they decreased and often decreased to a lesser extent; Figure 1.5). I therefore split diel fluctuations in water temperature into warming and cooling periods to improve the fit of my sine-based model (e.g., Vatland et al. 2015; Figure 1.5). I used the following sinusoid model to estimate temperature 0.2 m above the bottom at every meter of each transect (at the confluence, 20 m above, and 20, 40, 60, and 80 m below the confluence) at 0800, 1100, 1400, 1700, 2000, and 2300 hours on July 12 and August 1, 2014, and at 1700 on September 29, 2014:

$$T_{i,m} = T_0 + A_{i,m} \sin\left[2\pi t / P_{i,m}\right]$$

where *i* is time segment (h); *m* is location (m); *t* is time of temperature measurement (h); *A* is amplitude (° C); *P* is period (h); *T* is predicted stream temperature (° C), and T_0 is the y-intercept (° C).

Thermal thresholds of salmonids

I used the long-term upper incipient lethal temperature (UILT) to identify thermally stressful conditions for salmonids in the Smith River and Tenderfoot Creek. The long-term

UILT, which is typically referred to as the ultimate upper incipient lethal temperature (UUILT), is defined as the maximum temperature attainable by acclimation at which 50% of the test subjects survive in a laboratory setting for at least 30 days (Fry 1971; Elliott 1981; Kilgour 1985; Selong et al. 2001) (Table 1.1). Because long-term UILT estimates have not been determined for Brown Trout, I estimated their long-term UILT by subtracting 3 °C from the short-term (7-day) UILT values, as long-term UILTs are 2 to 4 ºC lower than the 7-day values (Selong et al. 2001; Bear et al. 2007) (Table 1.1). I included thermal thresholds for Westslope Cutthroat Trout because this species was historically abundant in the Smith River and hybridized with introduced Rainbow Trout.

PIT-tagging

Six-hundred and fourteen fish were tagged with 32-, 23-, and 12-mm long PIT (134 kHz HDX passive integrated transponder) tags (Oregon RFID, Portland, Oregon) in Tenderfoot Creek and the Smith River in 2014. Coupled with the 793 tagged from 2010 to 2012, a total of 1,407 fish were tagged in the system (Table 1.2). However, many fish tagged prior to 2014 may no longer be present because of mortality; assuming a generalized 50% annual mortality rate (Budy et al. 2008; Carlson and Letcher 2003), only 127 fish from this time period may have been present. Two-hundred and twenty-six fish were tagged in the Smith River and 249 fish were tagged in Tenderfoot Creek within 0.8 rkm of the confluence (Figure 1.6). Many more fish were tagged in the Smith River in 2014 than in 2010, 2011, and 2012 (Figure 1.6). Species tagged were Brook Trout, Brown Trout, Burbot, Mountain Whitefish, and Rainbow Trout (Table 1.2). Two-hundred and twenty-nine fish less than 150 mm were tagged with 12-mm PIT tags (36 Brook Trout, 21 Brown Trout, 32 Mountain Whitefish, and 140 Rainbow Trout). Fish were captured with a backpack electrofisher (Smith-Root, Inc., Model 12-B, Vancouver, Washington), mobile anode electrofisher (Smith-Root, Inc., Model VVP-15B, Vancouver, Washington), and angling.

Fixed Antenna Stations

A network of four fixed antenna stations was constructed to monitor the movements of PIT-tagged fish (Figure 1.1). Two were installed in Tenderfoot Creek to monitor use of this tributary at Jeep Trail station (rkm 9.8) and the confluence station (rkm 0.0) (Figure 1). Two were installed in the Smith River to monitor and compare use of different areas in the confluence at the Tenderfoot Creek outflow station (in the outflow of Tenderfoot Creek in the Smith River) and at the Smith River opposite station (directly opposite the outflow of Tenderfoot Creek in the Smith River) (Figures 1.1 and 1.2).

Antenna stations in Tenderfoot Creek consisted of a PIT-tag reader (Oregon RFID, multi-antenna HDX reader, Portland Oregon), two stream-width antennas, and a tuning board for each antenna (Oregon RFID, standard remote tuner board, Portland, Oregon). A pair of stream-width antennas was positioned at each site about 3 m apart to infer direction from sequential detections (Armstrong et al. 1996; Connolly et al. 2008; Lucas et al. 1999; Zydlewski et al. 2006). Antennas were placed in areas of fast current where fish would be unlikely to stay for long periods of time, such as shallow-water riffles, to prevent multiple repeat detections and investigate movements throughout and in or out of Tenderfoot Creek (rather than the localized use of the area of the antenna). Antennae were tuned to the target read range of 0.3m. (Table 1.3).

Antenna stations in the Smith River consisted of a PIT-tag reader (Oregon RFID, multi-antenna HDX reader, Portland Oregon), three antennas, and a tuning board for each antenna (Oregon RFID, standard remote tuner board, Portland, Oregon). Unlike those installed in

Tenderfoot Creek, antennas in the Smith River were placed to estimate localized use of PIT-tagged fish. Three antennas at the Tenderfoot Creek outflow station were oriented flat on the bottom and extended the width of the coolwater plume produced by Tenderfoot Creek (Figure 1.2). Three antennas at the Smith River opposite station of similar size were oriented flat on the bottom directly across from the Tenderfoot Creek outflow station to directly compare use of both areas (Table 1.3 and Figure 1.2). However, the abundance of iron ore in the substrate around the Smith River opposite station interfered with antenna detection ranges (Table 1.3 and Figure 1.7).

These stations operated in some combination during 2014; stations in Tenderfoot Creek (Jeep Trail and confluence stations; rkm 9.8 and 0.0, respectively) were maintained from March 26 to at December 12 whereas the Tenderfoot Creek outflow station was operated from July 12 to November 3 (Figure 1.8). The Smith River opposite station was only operated from July 23 to August 24 (Figure 1.8), but allowed me to directly compare use of the cooler water in the Tenderfoot Creek outflow to use of the warmer water outside of this plume by PIT-tagged fish during the summer thermal stress period (Figure 1.2). A high-water event on August 21 inundated the Smith River opposite station and permanently ceased its operation for the remainder of 2014.

Portable Antenna Surveys

Portable antenna surveys were conducted to complement the network of fixed antenna stations. Three portable antenna designs were used: a raft-mounted antenna (similar to that described by Fetherman et al. 2014), a modified version of the two-person design described for use on the Big Hole River, Montana (S. Vatland, Montana State University, personal communication), and a completely submersible unit operated by a snorkeler (described by Ritter

2015). Portable antenna surveys of Tenderfoot Creek were conducted monthly from July to October of 2014. A survey of the Smith River was conducted in August of 2014 using the raft-mounted antenna, but no tagged fish were relocated.

Redd Counts

Redd counts were performed in October to estimate spawning Brown Trout in Tenderfoot Creek. Two surveyors progressed upstream or downstream, taking care not to step on redds. Location of each redd was recorded in UTM using a handheld GPS unit (Garmin International, Inc., eTrex Venture, Olathe, Kansas) and marked on a satellite photo. Lateral location within the stream (facing downstream: left, middle, or right) of each redd was recorded.

Unlike 2010, 2011, and 2012, the entire study area (rkm 0.0 to 13.7) was surveyed for redds in 2014. Previously, the entire study area was not surveyed within a single year because the periods between the beginning of spawning activity and the onset of inclement weather that precluded access were short; the upper half of the study area (rkm 6.6 to 13.7) was surveyed in October of 2010 and the lower half of the study area (rkm 0.0 to 6.6) was surveyed in October of 2011 and 2012.

Mountain Whitefish Video Surveys

Pole-mounted video cameras (GoPro, Hero 2, San Mateo, California) were used to capture images of concentrations of Mountain Whitefish to estimate their numbers spawning in the lower 3 km of Tenderfoot Creek in October of 2012 and 2014. Large aggregations of Mountain Whitefish were not present in Tenderfoot Creek outside of the normal spawning period (October through December) so we assumed such aggregations consisted of sexually mature fish that were present to spawn. A camera operator performed a single pass by walking slowly upstream on the shallow side of each pool deeper than 1.0 m (*N* = 21). The camera was submerged using a 2.0-m pole angled to provide the broadest field of view. The operator moved cautiously and maintained a distance of at least 3 m between the camera and the aggregated fish to avoid alarming them. A video file was created for each pool surveyed, resulting in 21 individual videos. Frame captures of each video were created using image-editing software (VideoLAN, VLC Media Player, Paris, and Adobe Systems, Photoshop 7.0, San Jose, California). Frame captures allowed for more accurate counts by providing still images rather than motion pictures. The video was viewed frame by frame until fish in the previous frame capture were out of view, at which time the next frame capture was viewed. This was continued until the entire pool was viewed. A grid was superimposed on each frame capture to assist in counting all individuals and to reduce the likelihood of counting individuals twice. The total number of fish in each of the 21 pools was summed to count the minimum number of spawning Mountain Whitefish in the lower 3 km of Tenderfoot Creek.

RESULTS

Temperature Regimes

Confluence area

Water temperatures in the outflow of Tenderfoot Creek in the Smith River were less than those of the Smith River outside of this plume during the summer thermal stressful period (Figures 1.9 and 1.10). The mean difference between temperatures in the Tenderfoot Creek outflow and the Smith River outside of this coolwater plume was 2.9 °C . In fact, estimated temperatures in the outflow of Tenderfoot Creek in the Smith River at 1700 hours were less than even those in Tenderfoot Creek, by 2.8 and 1.5 °C on July 12 and August 1, 2014, respectively (Figure 1.11), probably as a result of hyphorheic contributions close to the bank. Accordingly, thermal thresholds of salmonids were surpassed less frequently and by fewer degrees in the outflow of Tenderfoot Creek than measured elsewhere in the Smith River (Figures 1.9). Water temperatures in Tenderfoot Creek also tended to be less than those in the Smith River in 2014, especially during summer months, but the opposite was true in late October and November (Figure 1.4).

The thermal effect of Tenderfoot Creek within the Smith River extended about 5 m out into the mainstem of the Smith River and continued for at least 40 m downstream (Figure 1.10). Rapid transverse mixing of this plume with the Smith River probably reduced the downstream thermal effect by homogenizing temperatures. The cooling influence of the Tenderfoot Creek outflow therefore ended somewhere between 40 and 60 m downstream of the confluence; no thermal effect was evident along the 60-m and 80-m transects.

The size and intensity of the Tenderfoot Creek plume changed over time. The thermal effect of the outflow was narrower and differences between temperatures in the outflow and the

Smith River were lower on August 1 than on July 12, 2014 (Figure 1.12). This change was also recorded by the network of stationary temperature loggers, when upper and lower temperatures in the outflow of Tenderfoot Creek were inverted on July 27, 2014 (Figure 1.13). Eventually the outflow of Tenderfoot Creek was higher than that of the surrounding Smith River on September 29, 2014 (Figure 1.14), probably an artifact of groundwater input.

Movement

I relocated 344 of 1,408 fish tagged for these studies on all portable and stationary antennas in 2014 (Table 1.4). Two-hundred and fifty-three of these relocations were of fish tagged in 2014 (Table 1.4). I relocated more fish (N = 252) on the confluence station in Tenderfoot Creek than any other station or method, followed by the Tenderfoot outflow station (N = 132), portable antennas (N = 112), Jeep Trail station (N = 33), and Smith River opposite station (N = 19) (Figure 1.16). More Mountain Whitefish were relocated than any other species (Table 1.4).

Confluence area

Tagged fish were located in the Tenderfoot Creek outflow more than would be expected for similar-sized areas in the Smith River, suggesting PIT-tagged fish preferred this plume over the area on the opposite bank during periods of thermal stress; 18% (41 of 226) of all fish tagged in the Smith River within 1 rkm of the confluence with Tenderfoot Creek were detected on the outflow station during the summer thermal stress comparison period (July 23 to August 20, 2014), whereas only 2% (5 of 226) were detected on the Smith River opposite station. In addition, the total number of individual fish relocated on the Tenderfoot Creek outflow station (N = 50) was much higher than that on the Smith River opposite station (N = 12) during this period, as were the numbers of total detections (3,358 compared to 43) and unique detections (218 compared to 14) (Figures 1.17 and 1.18). Detections on the Tenderfoot outflow station tended to occur when temperatures were high, whereas the opposite was true for the Smith River opposite station (Figure 1.18).

PIT-tagged fish were detected more in the coolwater outflow of Tenderfoot Creek when thermal conditions in the Smith River outside of this plume became stressful. In addition to occurring on days when Smith River water temperatures were high (Figure 1.18), detections on the Tenderfoot outflow station also increased as the number of consecutive hours Smith River water temperature exceeded 20 ºC accumulated over the course of a day (Figures 1.19 and 1.20). Moreover, the 55 tagged fish recorded at the Tenderfoot outflow station during the summer thermal stress period were detected 7,529 times over 39 days ($\bar{x} = 137$ detections per fish). In contrast, the 132 fish relocated on the same station during autumn (define above) were detected only 2,442 times over 63 days ($\bar{x} =$19 detections per fish). The number of unique detections recorded on the confluence station during the summer thermal stress period was identical to that on the Tenderfoot outflow station (N = 55). However, similar to what I observed in 2012, most of these detections (N = 32) were Mountain Whitefish exiting Tenderfoot Creek and entering the Smith River. Only 13 fish were observed making upstream movements into Tenderfoot Creek during this period.

PIT-tagged fish detected in the Tenderfoot Creek outflow during periods of thermal stress tended to be large individuals that probably had comparatively low thermal tolerances. Mean length of fish detected on the Tenderfoot Creek outflow station was 332 mm, whereas the mean length of fish tagged in 2014 was 222 mm and the mean length of all tagged fish in these studies was 254 mm. Large fish therefore accounted for the most detections on the Tenderfoot Creek outflow station (Figure 1.21) and may have excluded smaller individuals from the cooler water. During the summer thermal stress period, fish were detected more at the outflow of Tenderfoot Creek after temperatures had peaked each day, generally from late at night (2100 hours) to early in the morning the next day (0600 hours) (Figure 1.22). In contrast, fish detections on the Smith River opposite station occurred throughout the day and were highest in late morning (1000 hours) and early morning the next day (0500 to 0800 hours) (Figure 1.23).

The number of tagged fish in the Tenderfoot outflow increased appreciably during the summer precipitation event (Figure 1.16), possibly to forage in the less turbid water (Figure 1.23). Conversely, the number of fish detected on the confluence station was comparatively lower (Figure 1.16). The timing of the detections on the Tenderfoot outflow station during this precipitation event differed from those during the summer thermal stress period in that they occurred mostly before midnight (Figure 1.24).

Juvenile salmonids

I relocated only 19 of 229 tagged fish less than 150 mm long (1 of 21 Brown Trout, 1 of 36 Brook Trout, 1 of 32 Mountain Whitefish, and 16 of 140 Rainbow Trout); I relocated a higher proportion of large (> 100 mm) individuals. Movements of fish less than 150 mm long were mostly over small distances and often near original tagging locations (Figure 1.25).

Most juvenile Rainbow Trout and Brook Trout probably stayed in Tenderfoot Creek for their first year; only large individuals (TL > 100 mm) were observed moving out of Tenderfoot Creek. Nine Rainbow Trout were relocated near where they were first tagged. Four Rainbow Trout moved downstream from their tagging site in Tenderfoot Creek (Figure 1.25). Three of these fish entered the Smith River (Figure 1.25), but two were larger than 100 mm. Three larger (TL = 135, 143, and 146 mm) Rainbow Trout moved upstream from their tagging location, and two of these were tagged in the Smith River and relocated in Tenderfoot Creek (Figure 1.25). One of these individuals moved into Tenderfoot Creek during the summer thermal stress period (Figure 1.25). The only relocated Brook Trout (TL = 89 mm) was found slightly downstream of its tagging location at rkm 9.8 in Tenderfoot Creek on October 10, 2014 (Figure 1.25).

One Brown Trout (TL = 87 mm) moved a short distance downstream from its tagging location at rkm 0.6 in Tenderfoot Creek and entered the Smith River on October 9, 2014 (Figure 1.25). One Mountain Whitefish (TL = 124 mm) moved a large distance downstream from its tagging location at rkm 6.6 in Tenderfoot Creek and entered the Smith River on October 12, 2014 (Figure 1.25).

Brown Trout

Movements of Brown Trout were rarely detected and were most frequent during the summer and autumn, presumably because of thermoregulatory and spawning activity. I relocated only 14 of 123 Brown Trout that were tagged from 2010 to 2014 (Table 1.4) and their movements consisted mostly of small upstream or downstream movements in or out of Tenderfoot Creek. No Brown Trout were detected moving into Tenderfoot Creek when water temperatures in the Smith River were high. Moreover, fewer Brown Trout were detected on the confluence station during the summer months in 2014 than in 2011 and 2012 (Figure 1.26). Brown Trout were repeatedly detected on the Tenderfoot outflow station during the summer when temperatures in the Smith River were stressful (Figure 1.26). Similar to 2011 and 2012, Brown Trout activity in 2014 ceased following a dramatic decrease in water temperature associated with a major precipitation event and then increased in autumn during the spawning period (Figure 1.26). Multiple Brown Trout were relocated on September 15 and 16, 2014, on the Tenderfoot outflow station just before an increase in unique detections on the confluence station on September 17 (Figure 1.26), suggesting these movements may have been associated with pre-spawning.

Mountain Whitefish

Movements of Mountain Whitefish were commonly detected; I therefore relocated a large proportion thereof (277 of 644; Table 1.4). A large upstream migration of 9.8 rkm was observed during spring and runoff (April 4 to June 7), although it was less punctuated than that observed in spring of 2013 (Figure 1.27). A summer downstream migration (July 9 to August 15) occurred after Smith River runoff had subsided (Figure 1.28) and occurred later in 2014 than in 2012, presumably because Smith River runoff subsided later as well (Figure 1.28). Mountain Whitefish made frequent small upstream and downstream movements in or out of Tenderfoot Creek, especially during the spawning period. Mountain Whitefish began to use the Tenderfoot outflow in autumn just before unique detections on the confluence station increased possibly as a staging area prior to performing their spawning migration into Tenderfoot Creek (Figure 1.29). The number of unique detections on the confluence station was highest when the water temperature of Tenderfoot Creek and the Smith River was nearly the same (Figure 1.29). A large group of Mountain Whitefish (N = 26) was observed leaving Tenderfoot Creek within a 2-hour period before the onset of the first significant snowstorm and subsequent start of winter on November 9, 2014. Following this storm, Mountain Whitefish were detected leaving Tenderfoot Creek periodically until December 11, which coincided with ice formation on Tenderfoot Creek (Figure 1.29).

Rainbow Trout

Movements of Rainbow Trout were commonly detected despite relocating only a small proportion of tagged fish (52 of 541; Table 1.4). An upstream movement of 9.8 rkm by only 2 individuals occurred in spring, presumably to spawn (April 10 to May 31 and June 16); many more were observed in spring of 2013 (N = 10) (Figure 1.30). Small upstream and downstream movements in or out of Tenderfoot Creek occurred in summer and autumn (Figure 1.30).

Burbot

I relocated 1 of 4 Burbot tagged in the Smith River (Table 1.4). This individual (TL = 355 mm) moved upstream into Tenderfoot Creek on August 23 during the summer precipitation event and remained there until August 28, 2014. This Burbot was known to have retained a 32-mm PIT tag for at least 18 days in the peritoneal cavity (from August 10 to August 28, 2014).

Spawning

Brown Trout

More Brown Trout redds (N = 111) were found in 2014 than in 2011 (N = 69) and 2012 (N = 90) (Figure 1.31). The highest number of redds was found around rkm 3.0 (Figure 1.31). Only 6 Brown Trout redds were found above rkm 6.6, only one of which was above rkm 7.1.

Mountain Whitefish

Many fewer Mountain Whitefish (N = 3,041) were counted in 2014 than in 2012 (N = 7,568) during video surveys of the lowermost 3 km of Tenderfoot Creek, despite identical effort and relocation of a larger proportion of individuals on the confluence station (27% in 2014 compared to 19% in 2012).

DISCUSSION

Outflow of Tenderfoot Creek as a Thermal Refuge

Salmonids used the cool direct and hyporheic discharges from Tenderfoot Creek as a thermal refuge within the Smith River. Thermal conditions in the Smith River in summer, though not necessarily lethal, may have been stressful enough to adversely affect growth, feeding, development, and reproductive capacity; thermal thresholds were surpassed frequently in the Smith River in 2014. Water temperatures in the outflow of Tenderfoot Creek were much lower than in the Smith River and probably cooler than Tenderfoot Creek itself in areas. Accordingly, salmonids had a higher rate of detection in the coolwater plume of Tenderfoot Creek in the presence of such conditions, and could explain why fish were not previously observed using Tenderfoot Creek itself as a thermal refuge (Ritter 2015). The number of total detections, unique detections, and detections per fish on the Tenderfoot outflow station suggest prolonged and repeated use of this plume during periods of thermal stress. Because the Tenderfoot Creek outflow is in the mainstem of the Smith River, fish could avoid extended exposure to stressful temperatures without physically moving into Tenderfoot Creek itself, thereby expending less energy (Petty et al. 2012) and probably reducing predation risk from piscivorous birds and mammals by avoiding shallow water (Power 1987). Moreover, fish could easily access the thermal gradient it provides and still forage in warmer, more productive river water (Petty et al. 2012). Indeed, diel timing of detections on the Tenderfoot Creek outflow station (after daily temperatures peaked) suggests fish may have been using the cooler temperatures to exploit metabolic benefits as well as thermoregulate. Although metabolic rates increase with temperature, metabolic efficiency is usually highest at cooler temperatures (Elliott 2010).

Fish were detected more at the outflow of Tenderfoot Creek over the area opposite in the Smith River, even though it offered less overhead and submerged cover. Substrate on the opposite (west) side consisted of cobble and large angular boulders, and overhead vegetation was common. In contrast, substrate on the east side (Tenderfoot Creek outflow) consisted of cobble and the bank was scoured clear of vegetation. Even so, the high numbers of individual fish (50) and unique detections (218) recorded on the Tenderfoot outflow station suggest prolonged use by multiple individuals, whereas lower numbers (12 and 14) on the Smith River outflow station suggest limited use (i.e., fish did not remain after initial detection). The reduced detection range of the Smith River outflow station probably did not prevent relocation of PIT-tagged fish appreciably because trout tend to stay close to the substrate except when surface feeding (Heggenes and Saltveit 1990). Furthermore, diel timing of detections on the Smith River outflow station were not indicative of thermoregulatory behavior.

The Tenderfoot Creek outflow was dominated by large, presumably territorial individuals that may also have inhibited smaller individuals from occupying the cooler water. As salmonid body size increases, optimal growth temperature and thermal tolerance decreases (Beauchamp 2009). Occupation of the coolwater plume was therefore more important to large fish that also were more likely to be socially dominant. Accordingly, these larger fish may have defended the optimal habitat within the Tenderfoot Creek outflow from smaller fish. The largest trout excluded others from the coldest areas in northeastern Oregon streams (Ebersole et al. 2001), and large, adult Bluegill prevented smaller juveniles from occupying areas of optimum temperature in a laboratory setting (Beitinger and Magnuson 1975).

Although a large proportion of tagged fish used the Tenderfoot Creek outflow, the comparatively short thermal influence of the Tenderfoot Creek outflow downstream in the Smith

River probably prevented more fish from finding it. The cues necessary to elicit thermoregulatory behavior were not spatially prominent because rapid transverse mixing of the cooler water homogenized temperatures 40-60 m downstream. Mixing of tributary water with that of the mainstem river can be influenced by the physical attributes of the confluence (Baird and Krueger 2003; Nielsen et al. 1994); the large outcropping of the canyon wall on the east side of the river combined with high water velocity probably expedited such mixing. Over 100 fish were observed downstream of the confluence of a tributary and river in New York of similar sizes to Tenderfoot Creek and the Smith River during snorkel surveys when thermal stress was high, but the cooling influence was 80-160 m downstream (Baird and Krueger 2003). I observed about 200 fish downstream of the mouth of Tenderfoot Creek in the Smith River on August 7, 2012, when temperatures were above 20 °C. It is likely that most of these fish were occupying the cooler water, even though I did not explicitly count individuals in the Tenderfoot Creek outflow.

Managers may want to consider limiting recreational use of the Tenderfoot Creek outflow area (as well as those of other coldwater tributaries) when conditions in the Smith River are thermally stressful and discharges are sufficient enough to permit recreational floating. The mouth of Tenderfoot Creek is a popular fishing and picnicking spot for recreationists floating Smith River State Park, but such activities may dissuade salmonids from accessing the cooler water of the outflow there when water temperatures are high. Overhead disturbances such as rafts and boats elicit behavioral avoidance responses in fishes, including salmonids (Ellis et al. 2013), and may displace fish to warmer, more stressful temperatures. Aggregations have also been observed in the outflow of Hound Creek, another major tributary of the Smith River (M. Lance, Montana State University, personal communication).

Juvenile Salmonids

Low numbers of relocations on fixed antennas necessitate caution in interpreting results; nevertheless, such low numbers could suggest that juvenile Rainbow Trout and Brook Trout remain within Tenderfoot Creek rather than migrate to the Smith River during their first year. Age-0 adfluvial Brown Trout in Europe rarely moved more than a few hundred meters from their original tagging locations (Vatland and Caudron 2015). Relocations that suggest downstream movement in Tenderfoot Creek may have actually been smaller trout more susceptible to tag-induced mortality that died and then drifted over stationary antennas small distances from tagging locations. However, my tagging protocol should have had no ill-effect on survival (Richard et al. 2013) and two of the three Rainbow Trout that were observed moving downstream into the Smith River were large, presumably 2-year old individuals (Watschke 2006).

It is unclear if juvenile Brown Trout remained or perished in Tenderfoot Creek or emigrated to the Smith River before becoming large enough to tag. Only 1 of 21 tagged juvenile Brown Trout was relocated, but the observed downstream movement of this individual coupled with the lack of Brown Trout 100-200 mm and existence of large, presumably piscivorous residents in Tenderfoot Creek (Ritter 2015) could suggest that juvenile Brown Trout emigrated to the Smith River to find protection from predatory conspecifics. This differs from tributaries of Lake Geneva, where only 10% of age-0 Brown Trout actually emigrated from tributaries in autumn (Vatland and Caudron 2015). However, these were juveniles of a highly migratory adfluvial population where large adults were uncommon in tributaries with limited carrying capacity (Vatland and Caudron 2015).

It is uncertain if Mountain Whitefish successfully emigrate to the Smith River or fall prey to large piscivorous trout before doing so. Downstream migration of juvenile Mountain Whitefish to large river, winter habitat is common; PIT-tagged fish in the Methow River were observed moving into the Columbia River in autumn (Benjamin et al. 2014), and floy-tagged fish moved downstream to deep water in the North Fork Clearwater River (Pettit and Wallace 1975). However, Tenderfoot Creek was a permanent residence for large, presumably dominant Brown Trout (Ritter 2015). I have observed such individuals consume Mountain Whitefish in Tenderfoot Creek. Juvenile Mountain Whitefish more susceptible to predation may therefore be consumed before reaching the Smith River.

Low detection range of 12-mm PIT tags probably precluded a higher number of relocations of juvenile salmonids. 12-mm PIT tags have smaller detection ranges than larger tags (23- and 32-mm) (Zydlewski et al. 2006). This coupled with the deep water of Tenderfoot Creek and tendency for juvenile salmonids to hide in substrate and deep water suggests tagged fish may have avoided detection by portable antennas (Hayes and Baird 1994). Antenna detection range can often be improved when tuned specifically for 12-mm PIT tags (rather than 23- and 32-mm) (S. Vatland, Nez Perce Tribe Department of Fisheries Resources Management, personal communication); future portable antenna surveys should therefore be designed specifically for 12-mm or 23-mm and 32-mm PIT tags, rather than both.

Mountain Whitefish

Mountain Whitefish made annual upstream migrations into Tenderfoot Creek in spring and autumn and downstream migrations out of Tenderfoot Creek into the Smith River in summer and before winter, similar to 2012 and 2013 (Ritter 2015). Mountain Whitefish made an upstream migration into Tenderfoot Creek of 9.8 rkm in 2014 after runoff had subsided, presumably to forage (Baxter 2002); however, it occurred later and over a longer time than in 2013 (Ritter 2015). Mountain Whitefish were also detected exiting Tenderfoot Creek just after spawning in autumn 2014, suggesting that the Smith River is used as wintering habitat.

Even though a higher proportion of tagged fish were relocated on the confluence station in autumn in 2014 than in 2012, there may have been fewer spawning fish in the population than that observed in 2012. Variability among years was measured with video surveys (estimates or counts) whereby 4,527 fewer fish were counted during video surveys in 2014 than in 2012. Mountain Whitefish abundances and year-class strengths fluctuated among years (Ritter 2015). In addition, Mountain Whitefish tagged in autumn in Tenderfoot Creek have been relocated in other tributaries of the Smith River the following autumn, which indicates some level of variable spawning site fidelity in mature fish (M. Lance, Montana State University, personal communication).

Brown Trout

Brown Trout redd counts performed in 2011 and 2012 were probably slight underestimations of spawning effort because they ended before all redds were encountered, at rkm 6.6. Nevertheless, because only 6 redds were observed above rkm 6.6 in 2014, previous redd counts should provide some measure of year to year variation. Future surveys should therefore encompass the first 7.1 rkm of Tenderfoot Creek.

TABLES

Table 1.1. Summary of short- and long-term upper incipient lethal temperatures (UILTs) and upper growth limit temperatures of juvenile salmonids. Long-term and upper growth limit values for Brown Trout were estimated by subtracting 3.0 ºC from short-term UILT estimates (Selong et al. 2001; Bear et al. 2007).

Species	Short-term UILT (ºC)	Long-term UILT (ºC)	Upper growth limit (ºC)	Reference
Brown Trout	24.7 (7 d)			Elliott 1981
		21.7		
			19.5	Elliott et al. 1995
Westslope Cutthroat Trout	24.1 (7 d)	19.6 (60 d)	20.0	Bear et al. 2007
Rainbow Trout	26.0 (7 d)	24.3 (60 d)	24.0	Bear et al. 2007
Mountain Whitefish	23.6 (7 d)	22.6 (33 d)	22.2	Brinkman et al. 2013

Table 1.2. Numbers of Brown Trout, Rainbow Trout, Brook Trout, Mountain Whitefish and Burbot tagged in Tenderfoot Creek and the Smith River from 2010 through 2014.

	Number tagged					
Year	Brown Trout	Rainbow Trout	Brook Trout	Mountain Whitefish	Burbot	Total
2010	33	148	38	20	0	239
2011	30	128	12	48	0	218
2012	8	88	5	235	0	336
2014	52	177	39	342	4	614
Total	123	541	94	645	4	1407

Table 1.3. Dimensions, vertical detection ranges, and volumes of detection ranges of individual fixed antennas at stations in the Smith River. Detection ranges were determined using a 32-mm PIT tag.

Station	Antenna	Length (m)	Width (m)	Area (m^2)	Vertical detection range (m)	Volume of detection range (m^3)
Tenderfoot outflow	Upper	4.0	0.42	1.68	0.49	0.86
	Mid	4.0	0.52	2.08	0.70	1.1
	Lower	4.3	0.35	1.51	0.64	0.73
Smith River opposite	Upper	4.5	0.33	1.49	0.17	0.45
	Mid	4.0	0.38	1.52	0.20	0.42
	Lower	4.5	0.30	1.35	0.25	0.29

Table 1.4. Numbers and proportions of Brown Trout, Rainbow Trout, Brook Trout, Mountain Whitefish, and Burbot relocated in Tenderfoot Creek and the Smith River from March through November, 2014. N = number of individuals of a taxon relocated and $\hat{p}$ = proportion of individuals of a taxon relocated.

	Numbers and proportions relocated											
	Brown Trout		Rainbow Trout		Brook Trout		Mountain Whitefish		Burbot		Total	
Year tagged	N	$\hat{p}$	N	$\hat{p}$	N	$\hat{p}$	N	$\hat{p}$	N	$\hat{p}$	N	$\hat{p}$
2010	1	0.03	4	0.03	0	0	2	0.1	0	0	7	0.03
2011	2	0.07	7	0.05	0	0	11	0.23	0	0	20	0.09
2012	2	0.25	10	0.11	0	0	53	0.23	0	0	65	0.19
2014	9	0.17	31	0.17	1	0.03	211	0.61	1	0.25	253	0.41
Total	14	0.11	52	0.09	1	0.01	277	0.43	1	0.25	344	0.24

FIGURES

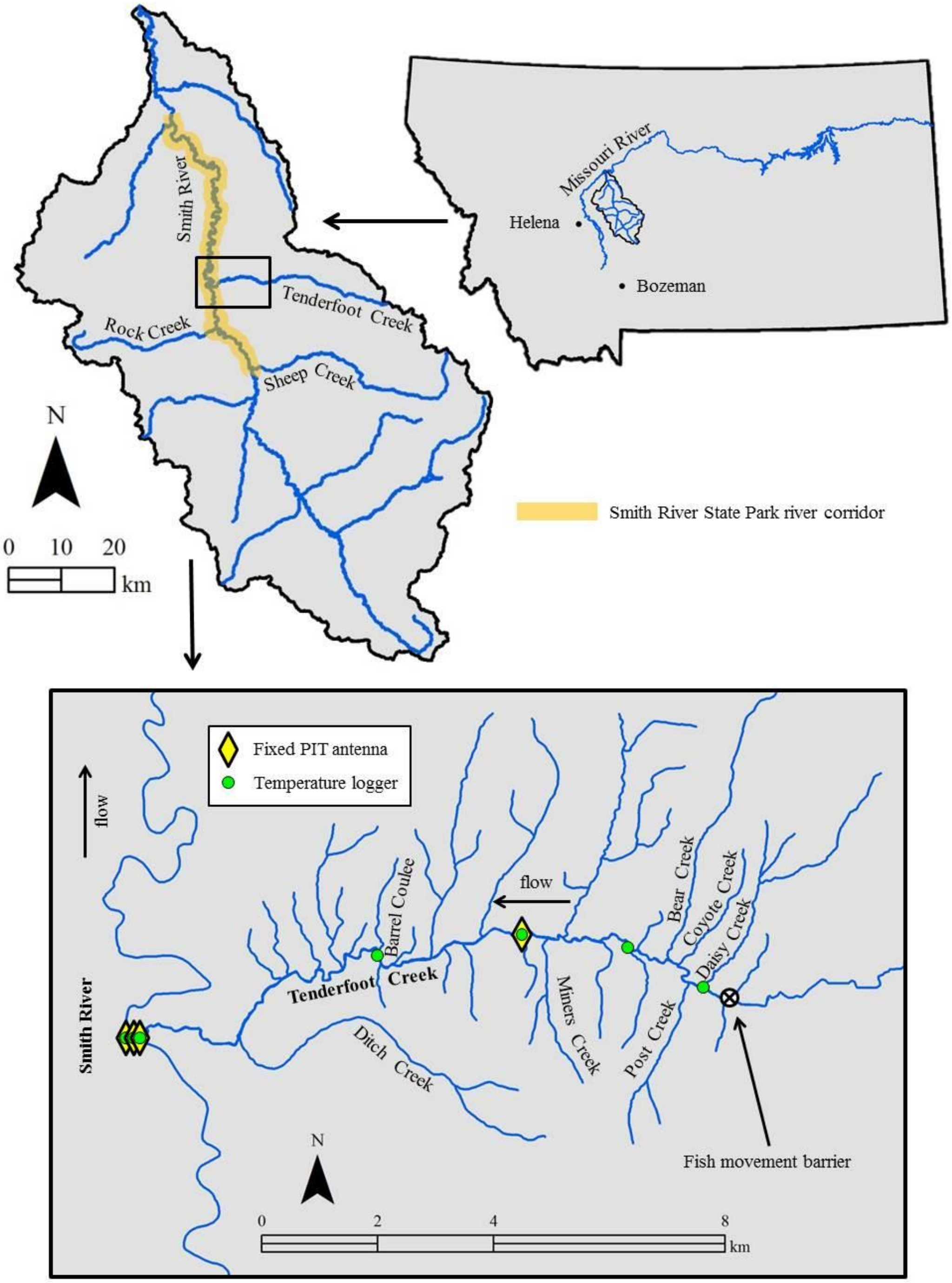

Figure 1.1. The Smith River and its major tributaries and lower Tenderfoot Creek and its major tributaries. Yellow diamonds represent locations of fixed PIT antenna stations. Green circles represent locations of temperature loggers. Yellow diamonds with green circles inside of them represent temperature loggers installed at fixed PIT antenna stations.

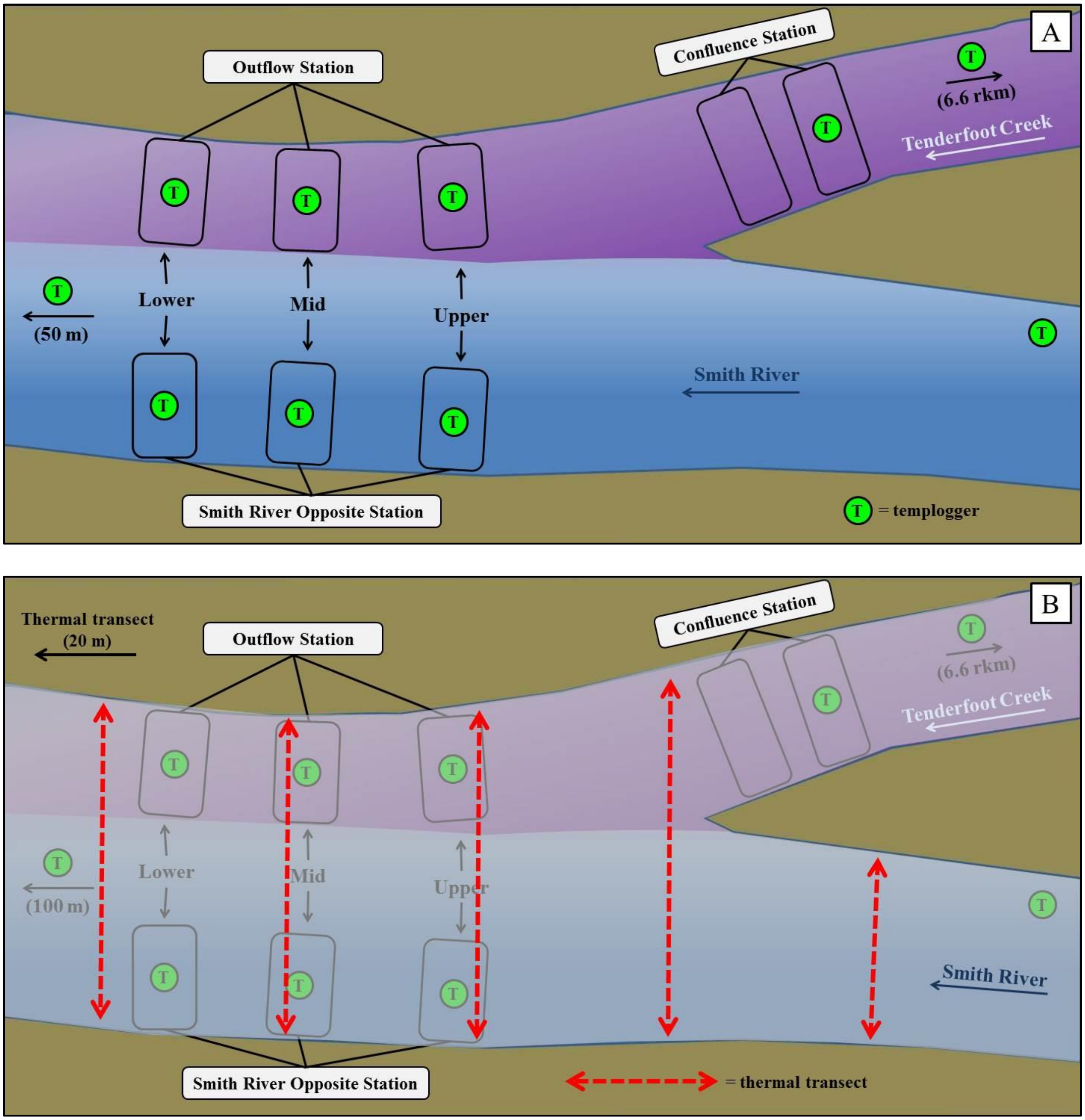

Figure 1.2. Locations of temperature loggers and fixed antenna stations (A) and locations of thermal transects (B) at the confluence of Tenderfoot Creek and the Smith River. Thermal transects were taken at the confluence, 20 m above, and 20, 40, 60, and 80 m below the confluence on July 12, August 1, and September 29, 2014.

Figure 1.3. The plume of Tenderfoot Creek in the Smith River (highlighted in purple with photo-editing software) looking west on August 24, 2014 (A), and the confluence of Tenderfoot Creek and the Smith River, looking east, on July 19, 2014, at about 1700 hours (B).

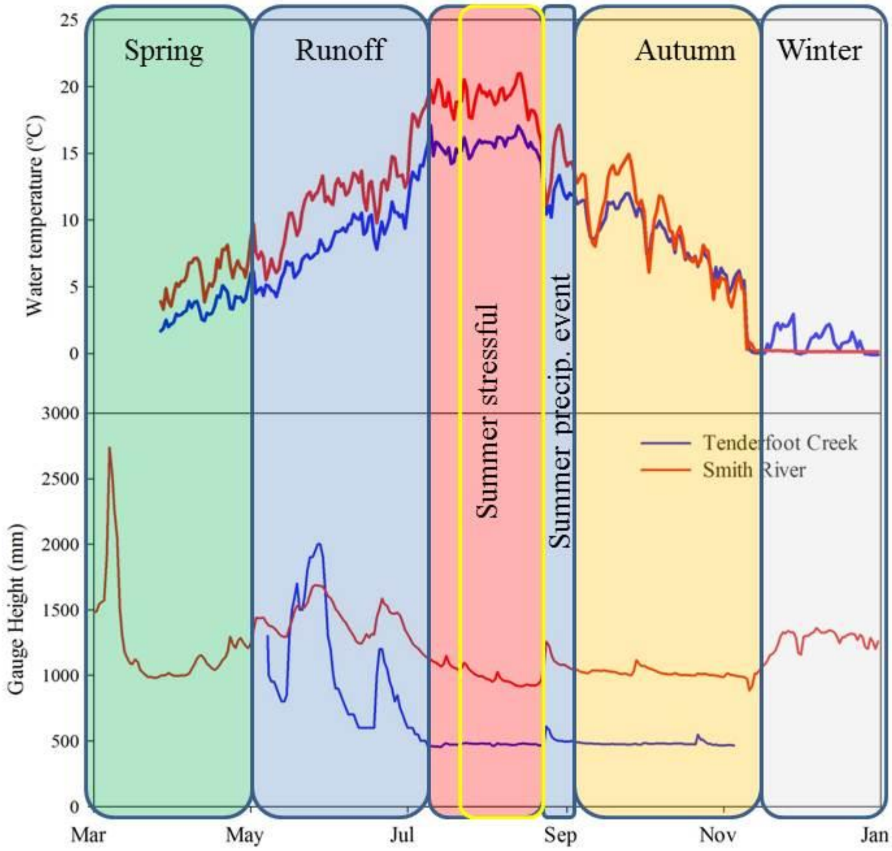

Figure 1.4. Sampling seasons and temperature and flow regimes of Tenderfoot Creek and the Smith River in 2014. The box outlined in yellow represents when both the Tenderfoot outflow station and Smith River opposite station were running and use of these stations by PIT-tagged fish could be directly compared (i.e., the summer thermal stress comparison period).

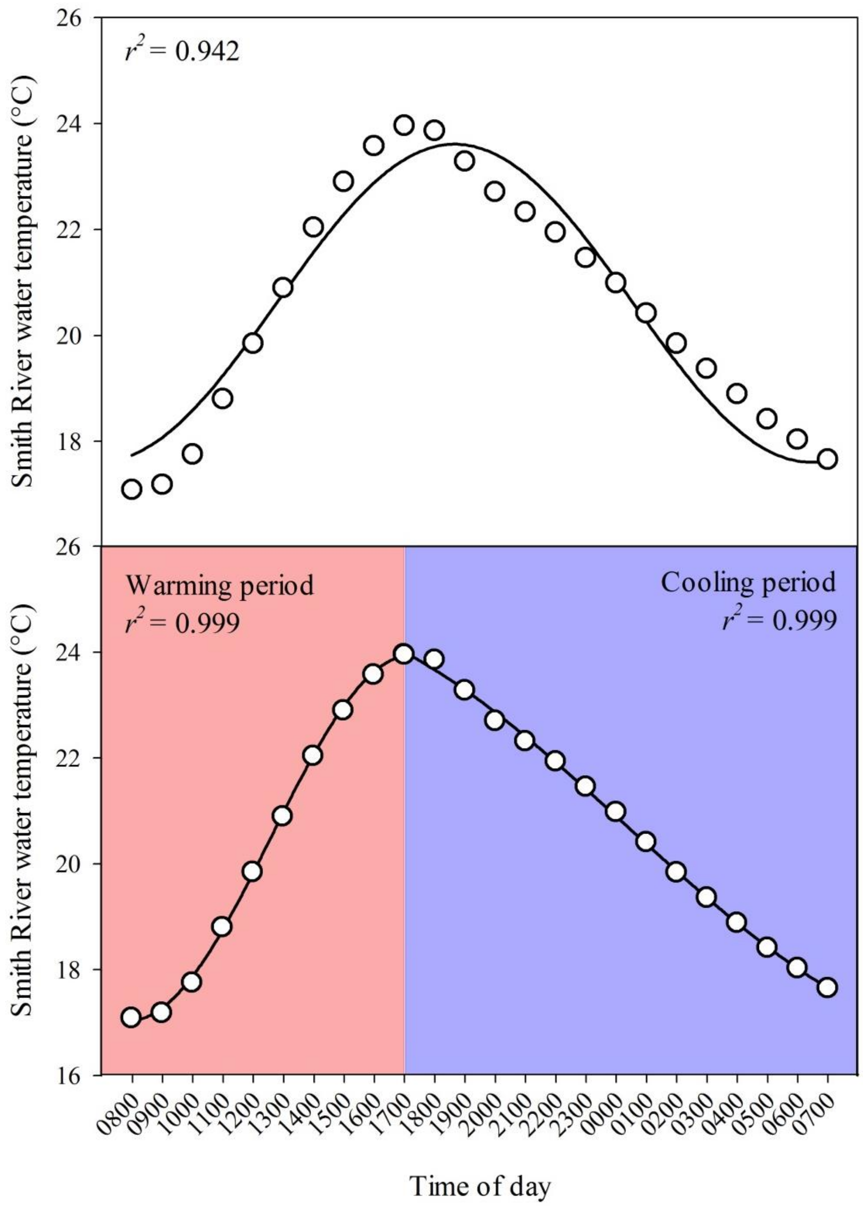

Figure 1.5. Example of asymmetry in diel water temperature fluctuation on August 1, 2014. White circles represent temperatures recorded by a temperature logger in the Smith River 50 m above the confluence of Tenderfoot Creek with the Smith River. Black lines represent sine-based models fit from 0800 to 0700 (next day) hours in the top plot, and separately from 0800 to 1700 and 1700 to 0700 (next day) hours. Adapted from Vatland et al. 2015.

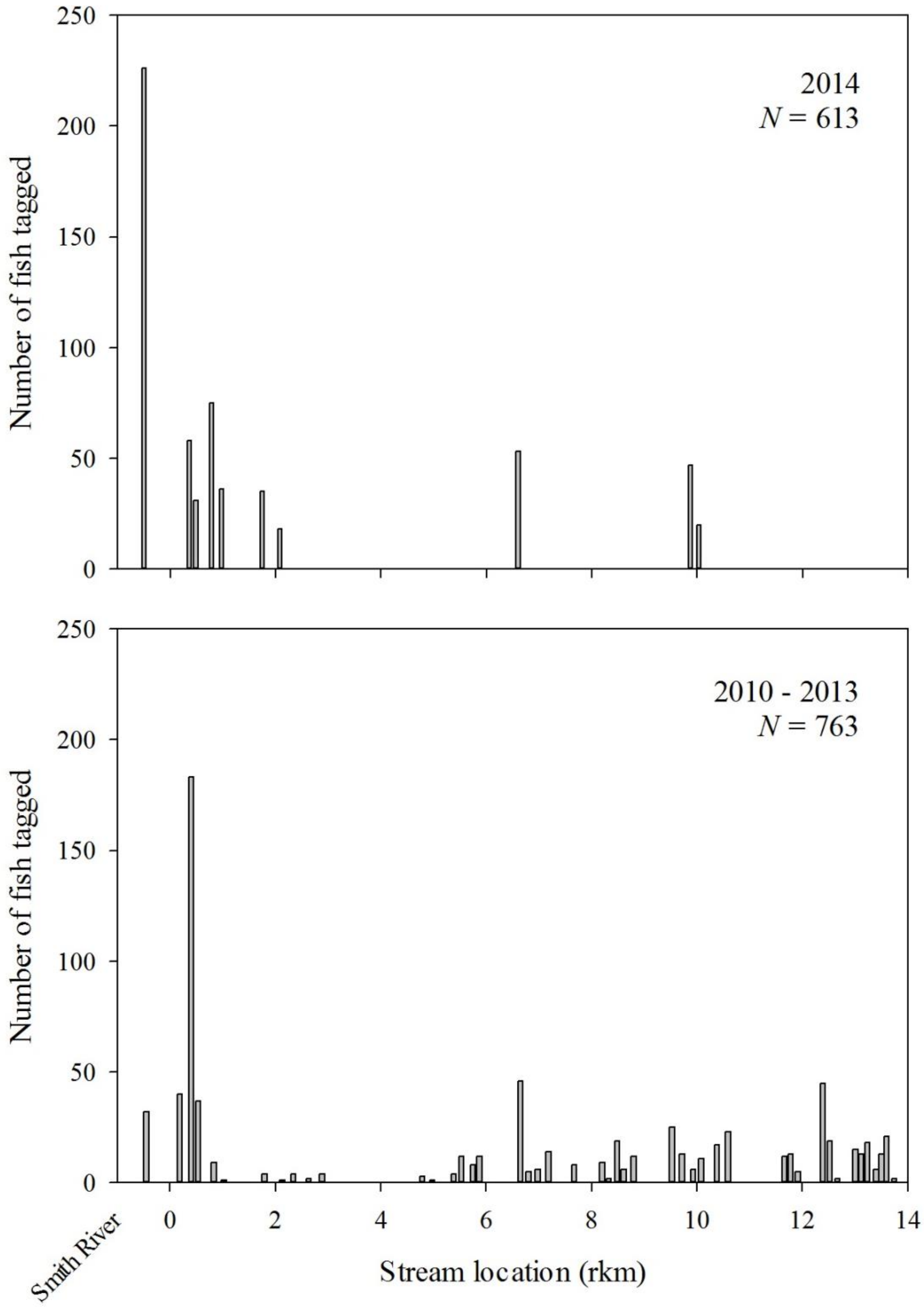

Figure 1.6. Comparison of the distribution of tagging locations of fish tagged in Tenderfoot Creek and the Smith River in 2014 and 2010 through 2013. Fish were collected by electrofishing and angling in 2014 and by electrofishing, angling, seining, and use of a fish weir from 2010 to 2013. Stream location is the distance from the confluence with the Smith River.

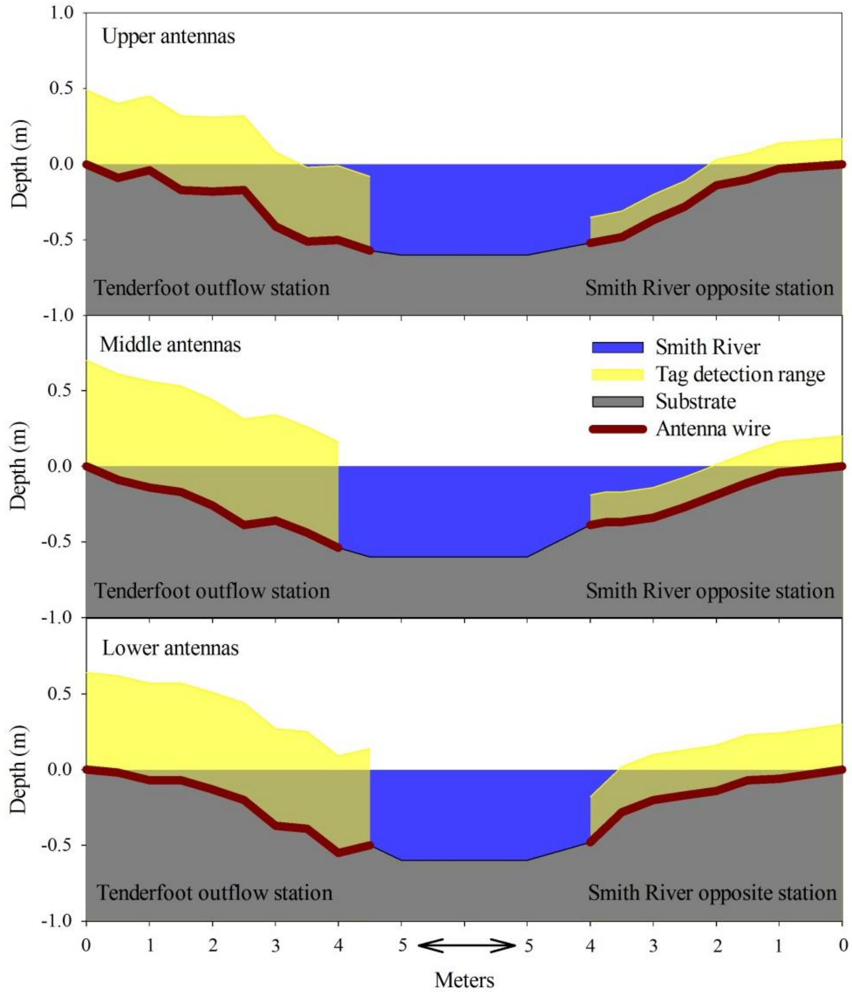

Figure 1.7. Vertical detection ranges of individual antennas of the Tenderfoot outflow and Smith River opposite stations. Translucent yellow areas represent vertical detection ranges of antennas and red lines represent the wires of those antennas. Gray areas represent the substrate and blue areas represent water in the Smith River. The width of the Smith River is not shown to scale to ease comparison of antenna vertical detection ranges.

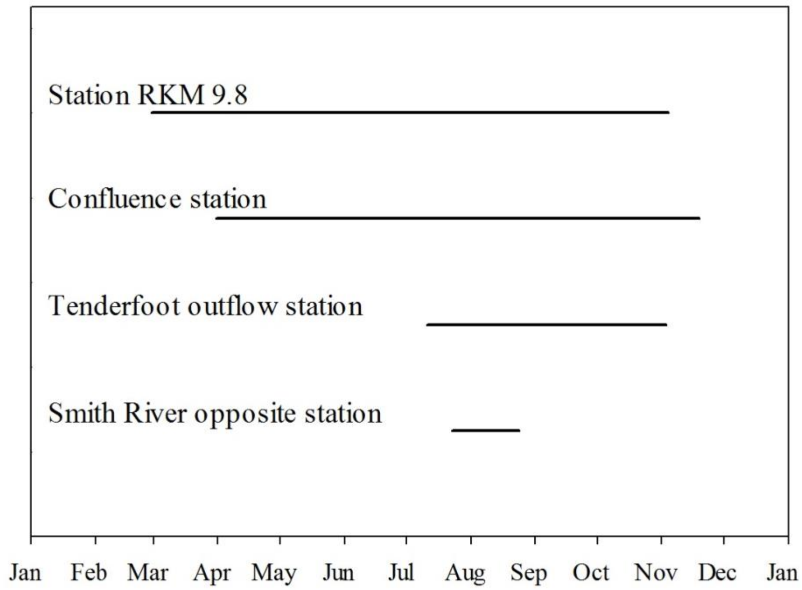

Figure 1.8. Operation times of fixed antenna stations in Tenderfoot Creek and the Smith River during 2014.

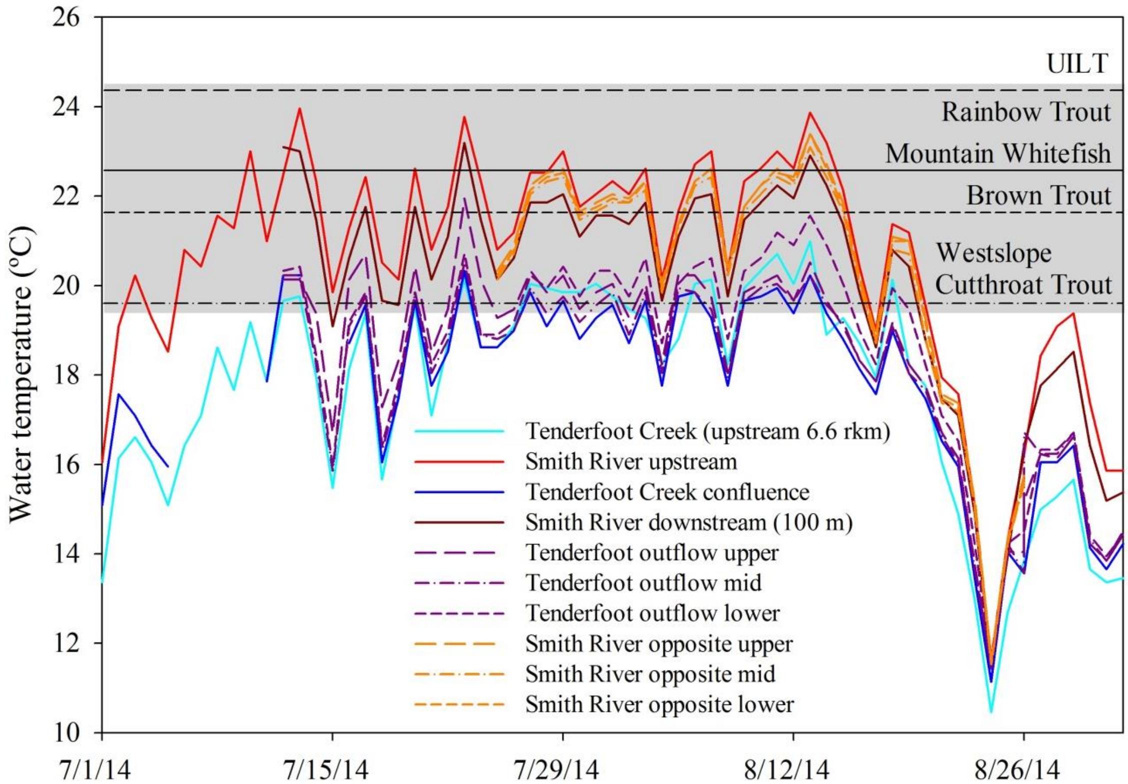

Figure 1.9. Maximum water temperatures recorded in Tenderfoot Creek and the Smith River in the summer of 2014. Water temperatures recorded in the Smith River are shown in warm colors whereas water temperatures recorded in Tenderfoot Creek or the Tenderfoot Creek outflow in the Smith River are shown in cool colors. UILTs are long-term estimates (> 30 d) as determined by other studies or estimated from existing short-term UILTs (7 d) and are displayed within the light gray region. Locations of temperature loggers are shown in Figures 1 and 2.

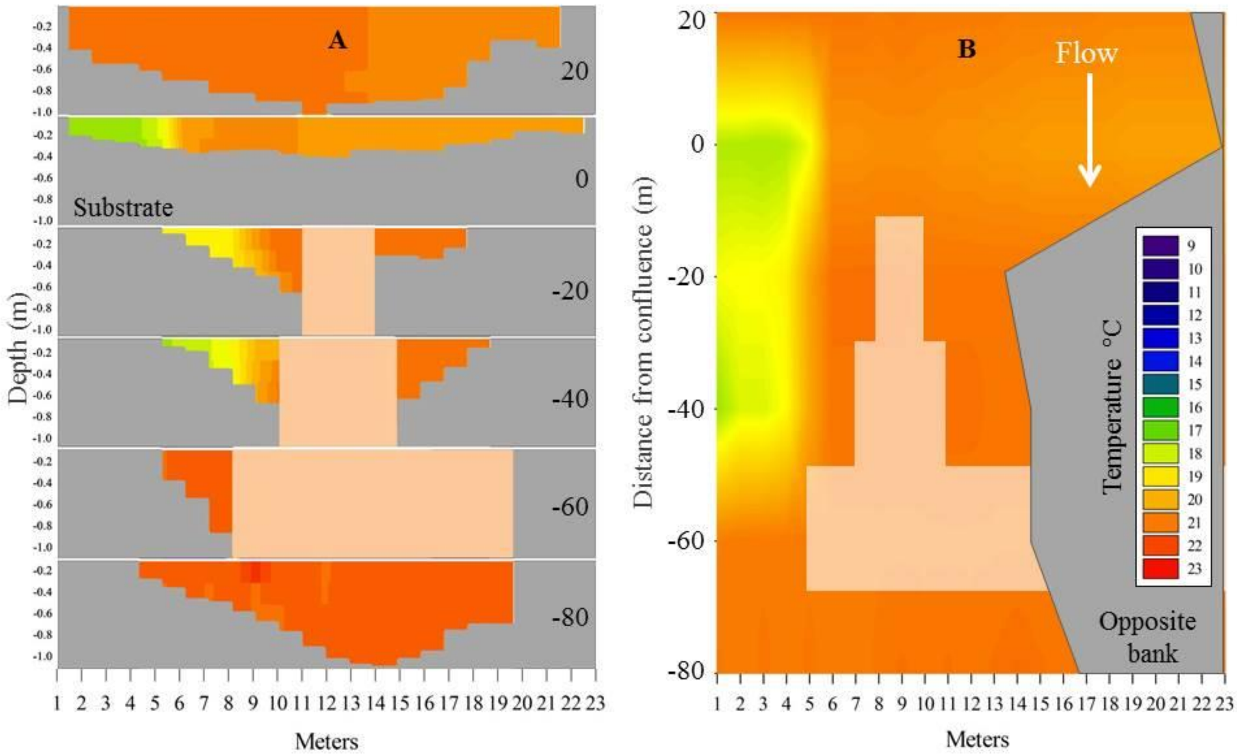

Figure 1.10. Depth and temperature profiles (A) and thermal map of bottom temperatures (B) estimated at 1700 hours on July 12, 2014. Translucent white regions represent areas that could not be sampled because of excessive water velocities or depths. The dark gray regions represent substrates and banks.

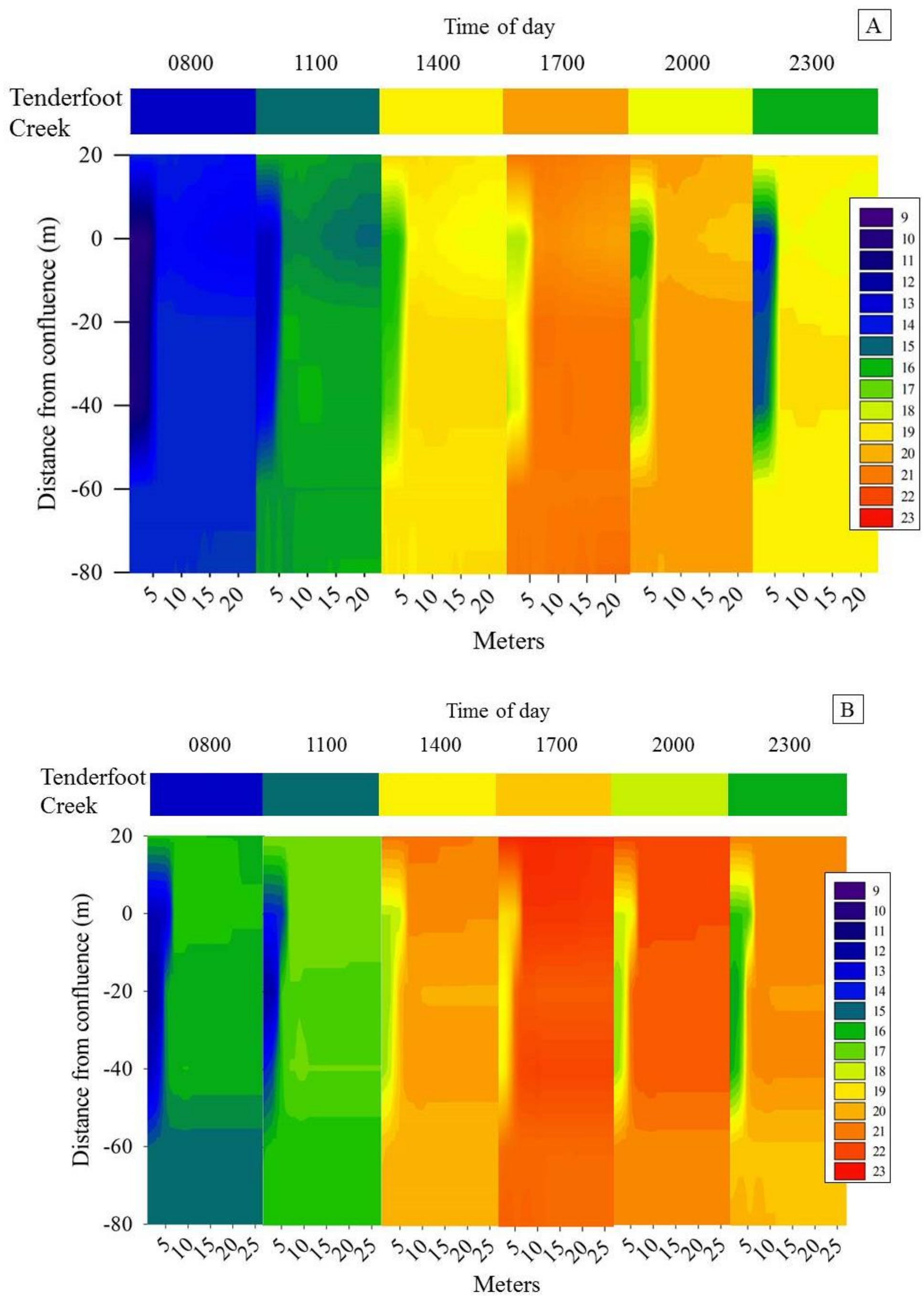

Figure 1.11. Estimated bottom temperatures of the outflow of Tenderfoot Creek and Smith River and actual temperatures of Tenderfoot Creek taken by a stationary temperature logger on July 12 (A) and August 1, 2014 (B), at 0800, 1100, 1400, 1700, 2000, and 2300 hours. Actual temperatures of Tenderfoot Creek are represented by the top row whereas estimated temperatures of the Tenderfoot Creek outflow and Smith River are represented by the thermal maps below. Temperatures are shown as a gradient; warmer colors represent higher temperatures and cooler colors represent lower temperatures. The Tenderfoot Creek outflow is identified by the cooler colors on the left of each thermal map.

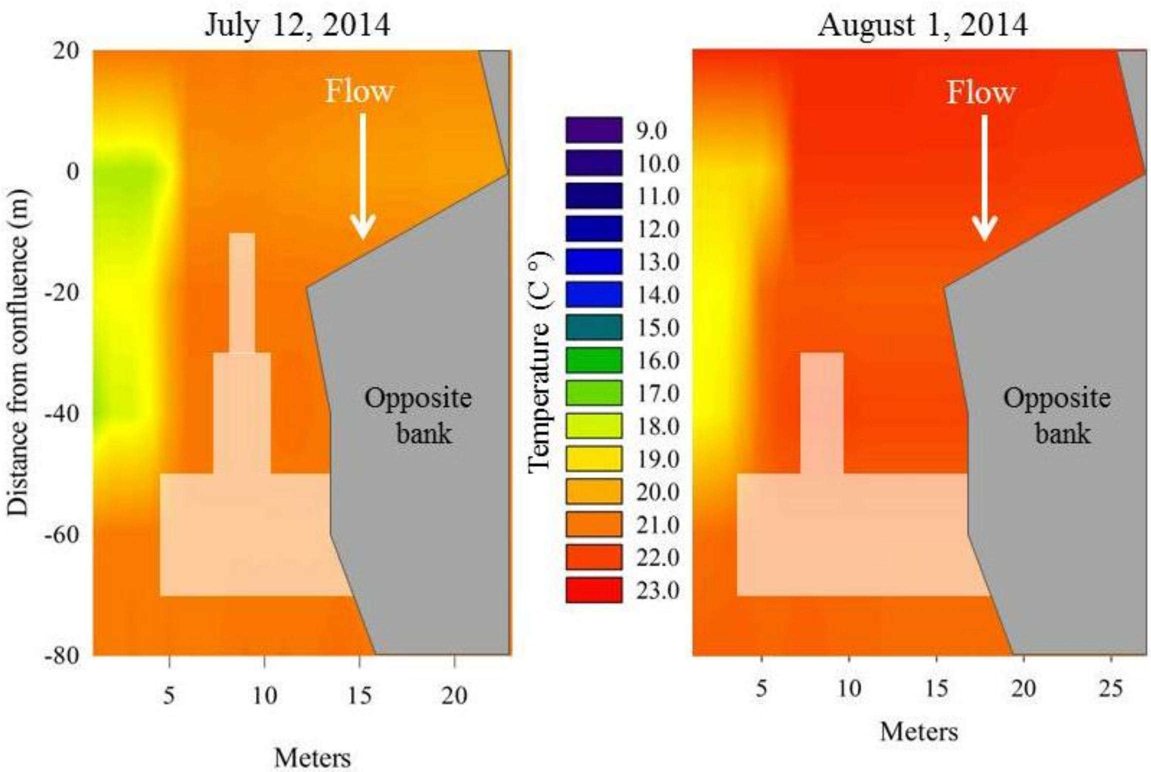

Figure 1.12. Estimated bottom temperatures of the outflow of Tenderfoot Creek and the Smith River on July 12 and August 1, 2014, at 1700 hours. Translucent orange regions represent areas that could not be sampled because of excessive water velocities or depths. The dark gray regions represent the bank.

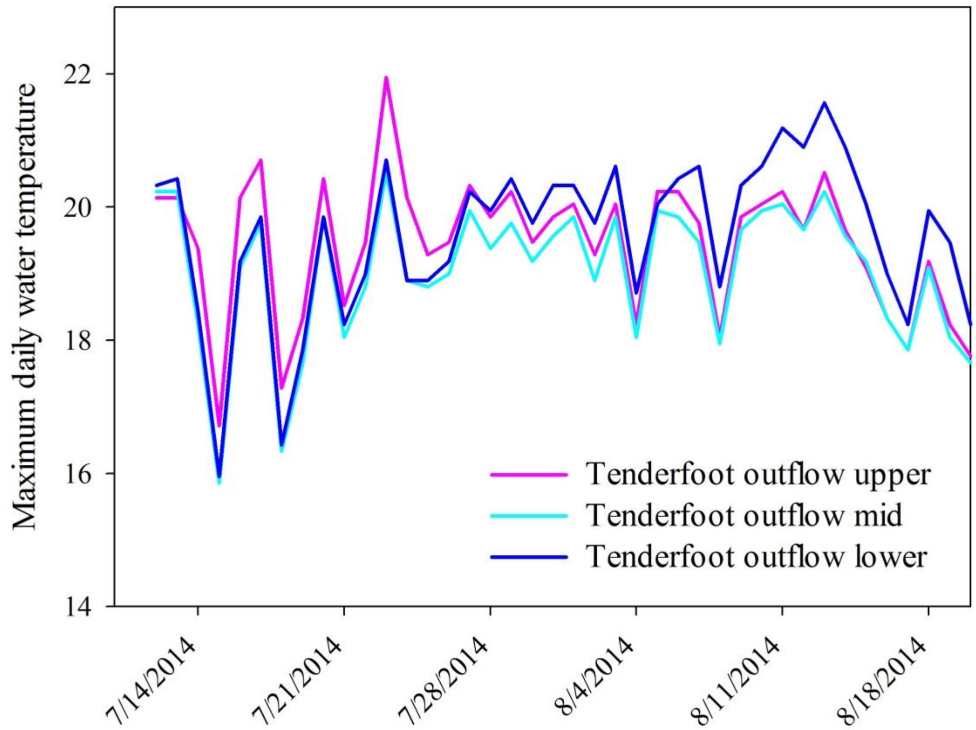

Figure 1.13. Maximum daily temperatures recorded by stationary temperature loggers in the outflow of Tenderfoot Creek in the Smith River.

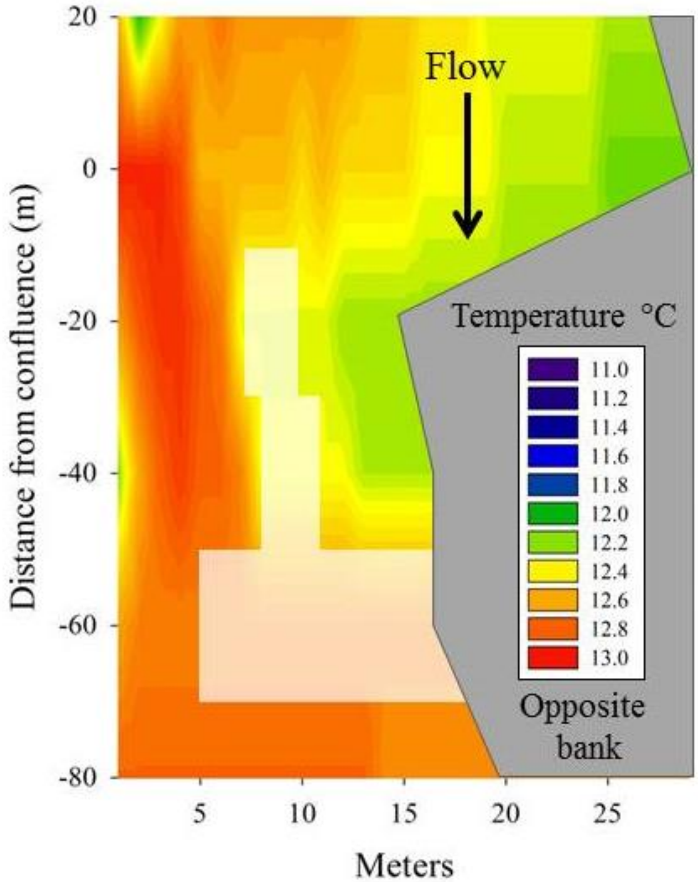

Figure 1.14. Estimated bottom temperatures of the outflow of Tenderfoot Creek and the Smith River on September 29, 2014, at 1700 hours. Translucent white regions represent areas that could not be sampled because of excessive water velocities or depths. The dark gray region represents the bank. Note that the temperature gradient used in this thermal map is at a finer scale than in the previous thermal maps.

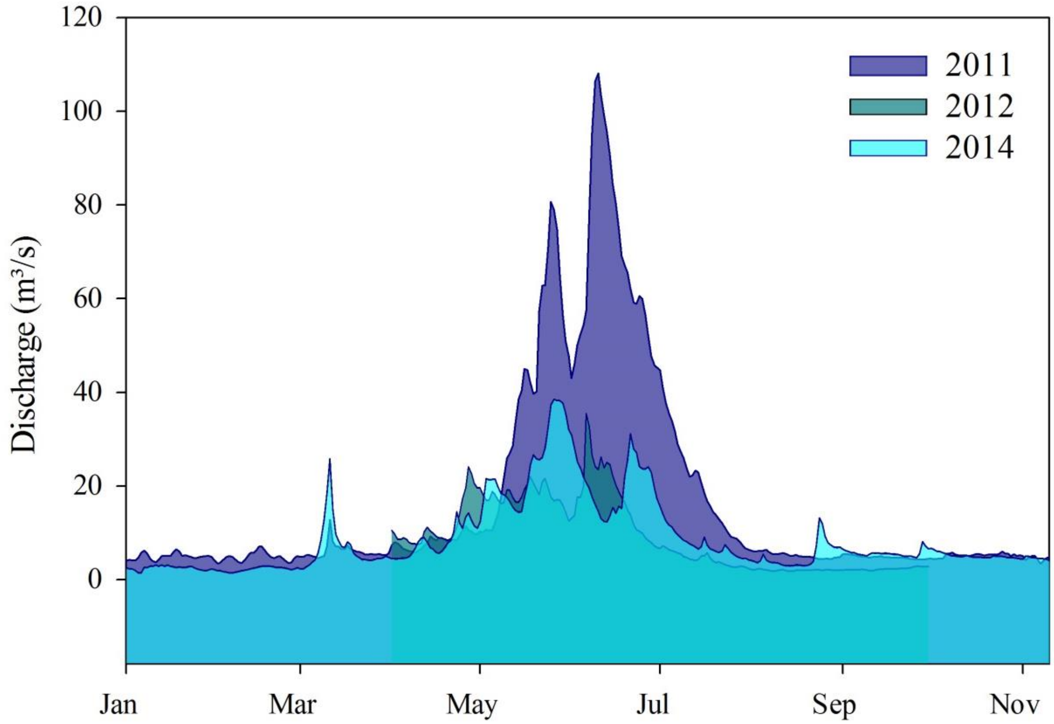

Figure 1.15. Mean daily discharges of the Smith River during 2011, 2012, and 2014 recorded at the USGS gauge station 20.95 rkm upstream of the mouth of Tenderfoot Creek.

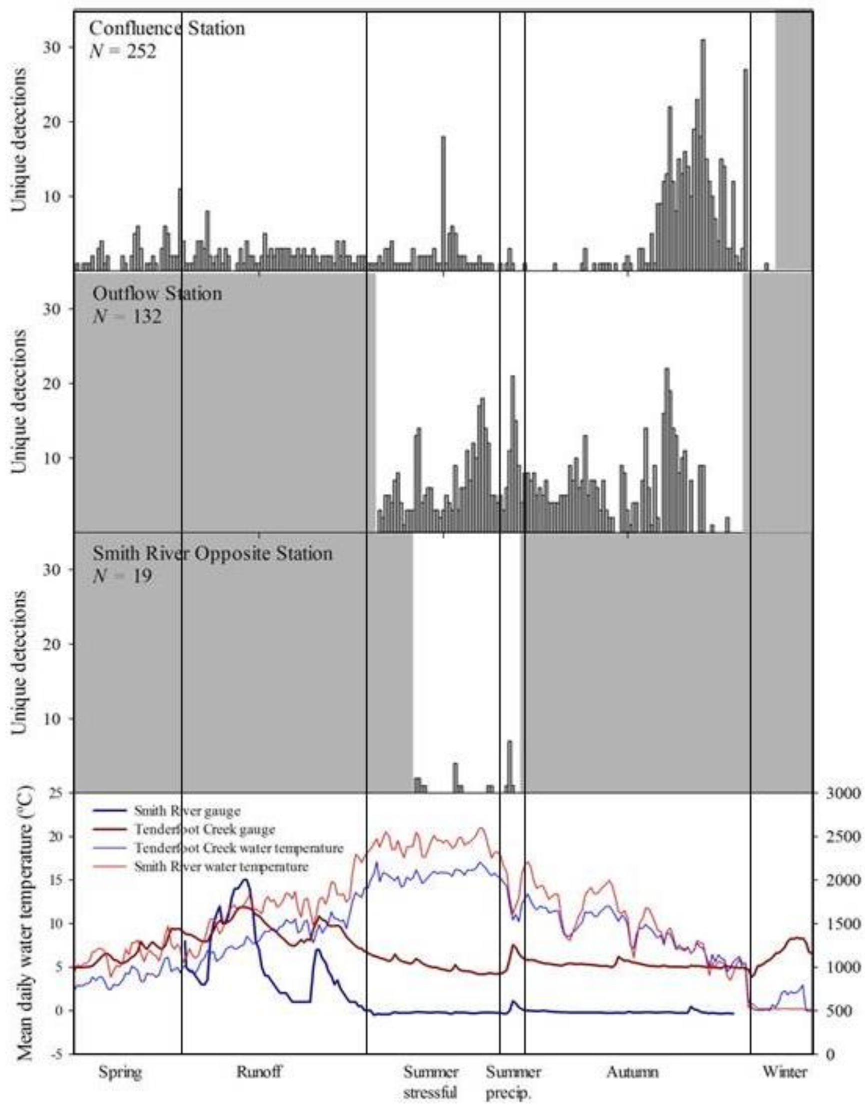

Figure 1.16. Unique detections on the confluence station, Tenderfoot outflow station, and Smith River opposite station and mean daily water temperatures and gage heights of Tenderfoot Creek and the Smith River in 2014. Unique detections are defined as one detection per day per individual and are represented by bars. Continuous red and blue lines represent mean daily water temperatures and gauge heights, respectively. Shaded areas indicate when stations were not operating.

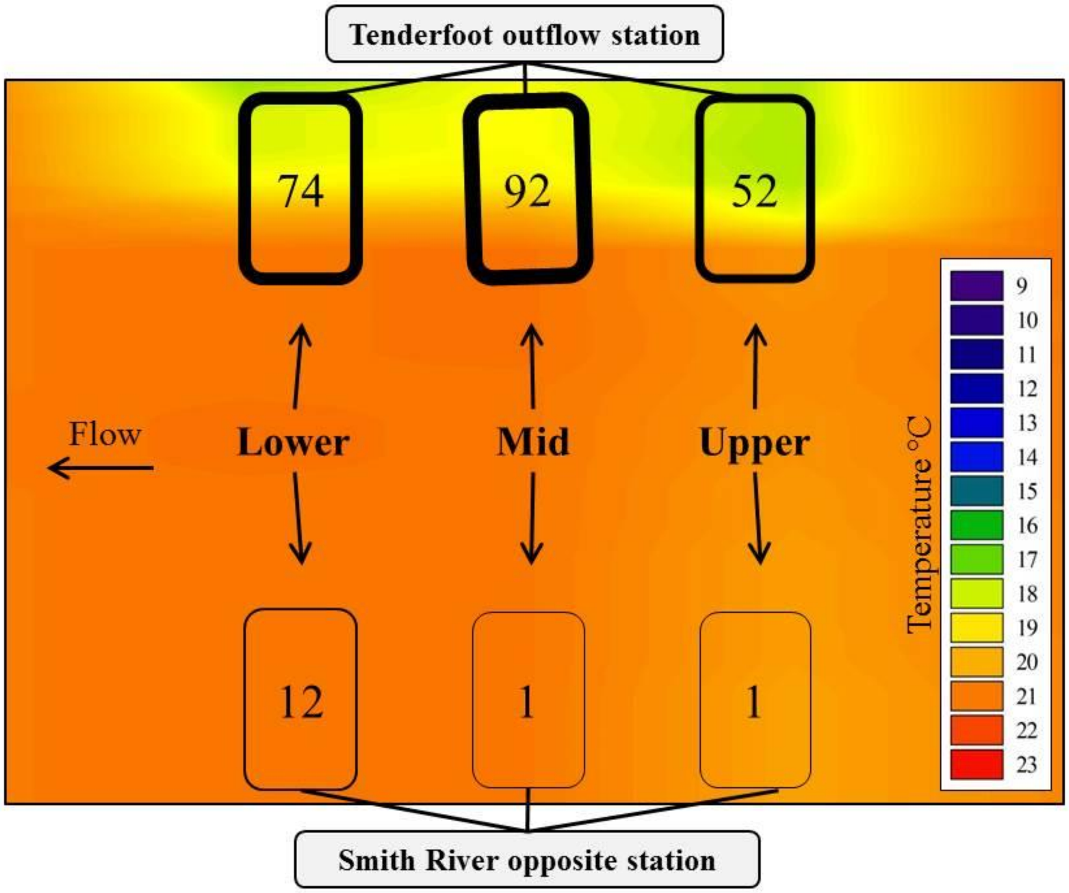

Figure 1.17. Number of detection days on each antenna of the stations in the Smith River during the summer thermal stress comparison period superimposed on a thermal map of the confluence for August 1, 2014, at 1700 hours. The thicknesses of antenna lines represent the numbers of detection days on each antenna.

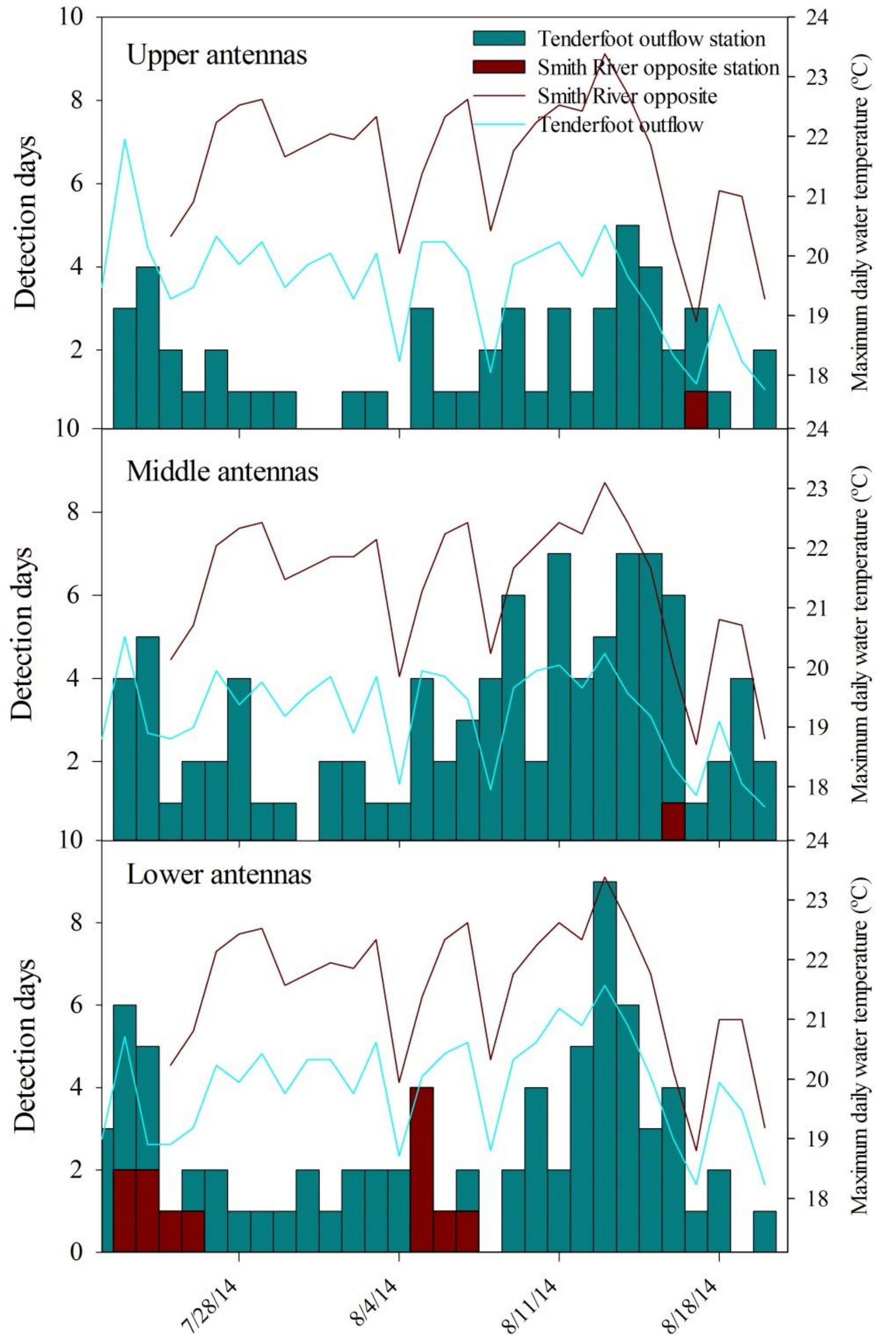

Figure 1.18. Detection days and maximum daily water temperature for each antenna of the Smith River stations during the summer thermal stress comparison period. Blue bars represent detection days on the Tenderfoot outflow station whereas red bars represent detection days on the Smith River opposite station. Solid blue lines represent maximum daily water temperatures measured by temperature loggers in the Tenderfoot outflow whereas solid red lines represent maximum daily water temperatures measured by temperature loggers across from the outflow in the Smith River.

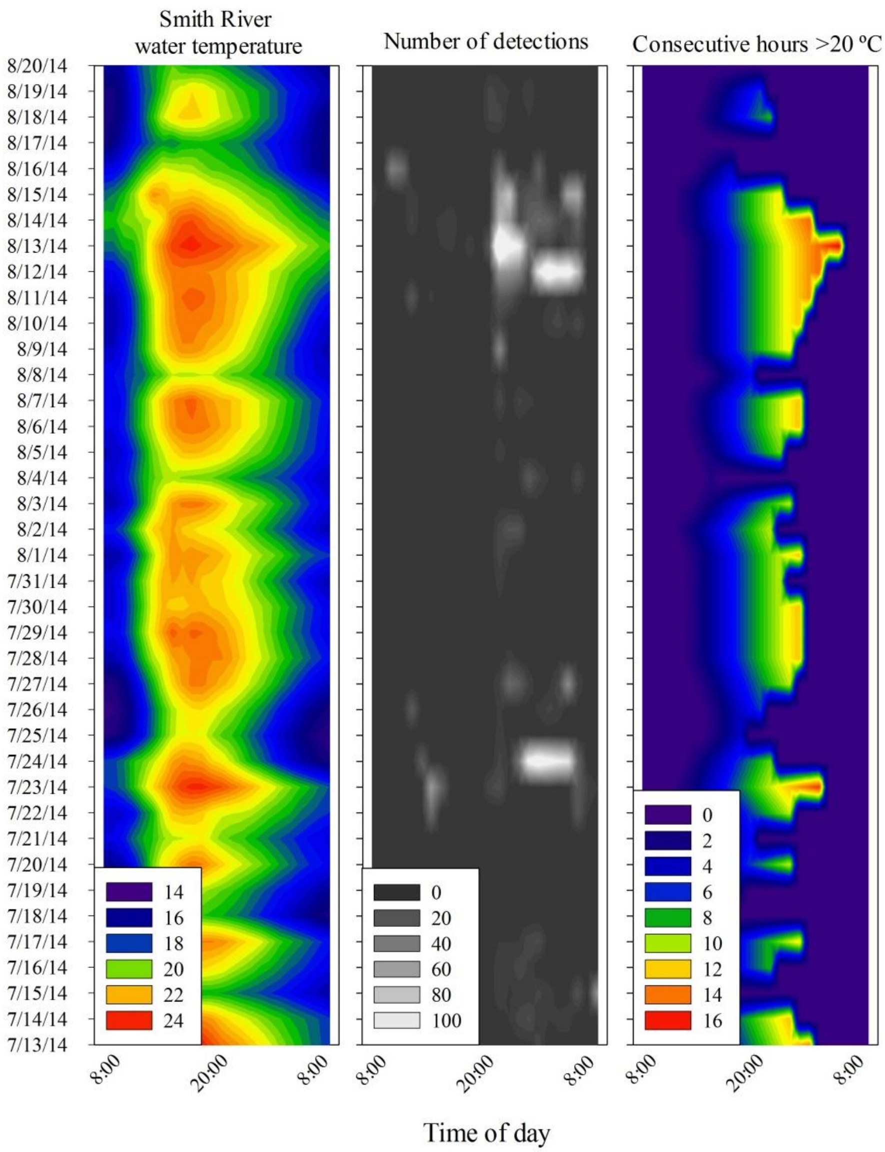

Figure 1.19. Smith River water temperatures, numbers of detections on the Tenderfoot outflow station, and numbers of consecutive hours Smith River water temperatures exceeded 20 ºC by day and time. Each row on the y-axis represents one day during the summer thermal stress period. The x-axis represents the time of day beginning at 0800 hours and ending at 0800 hours the next day. Warmer gradients represent higher temperatures and numbers of consecutive hours exceeding 20 ºC. Brighter, whiter gradients represent high numbers of detections occurring simultaneously. Adapted from Dugdale et al. 2015.

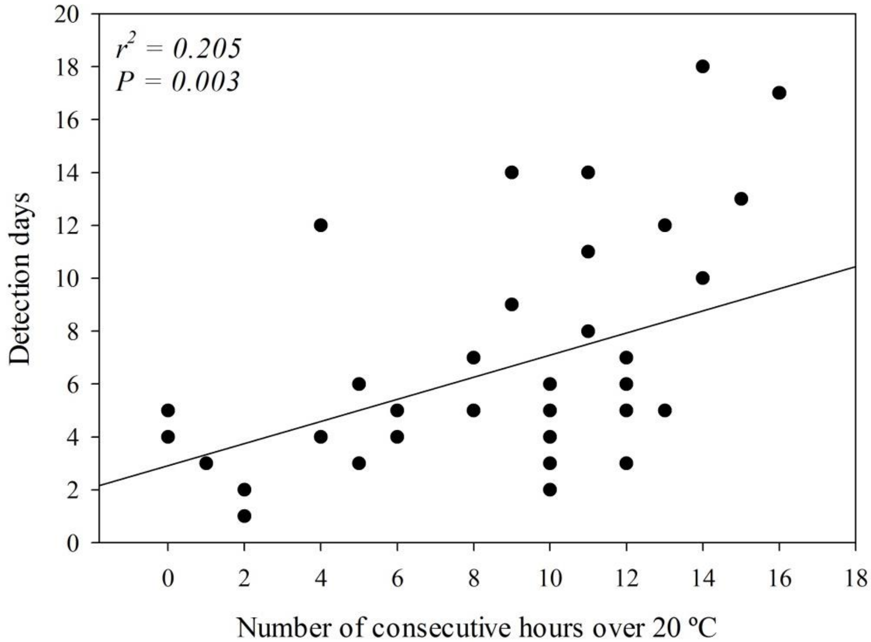

Figure 1.20. The relationship between fish detection days on the Tenderfoot outflow station and consecutive hours Smith River water temperatures exceeded 20 ºC from July 12 to August 20, 2014.

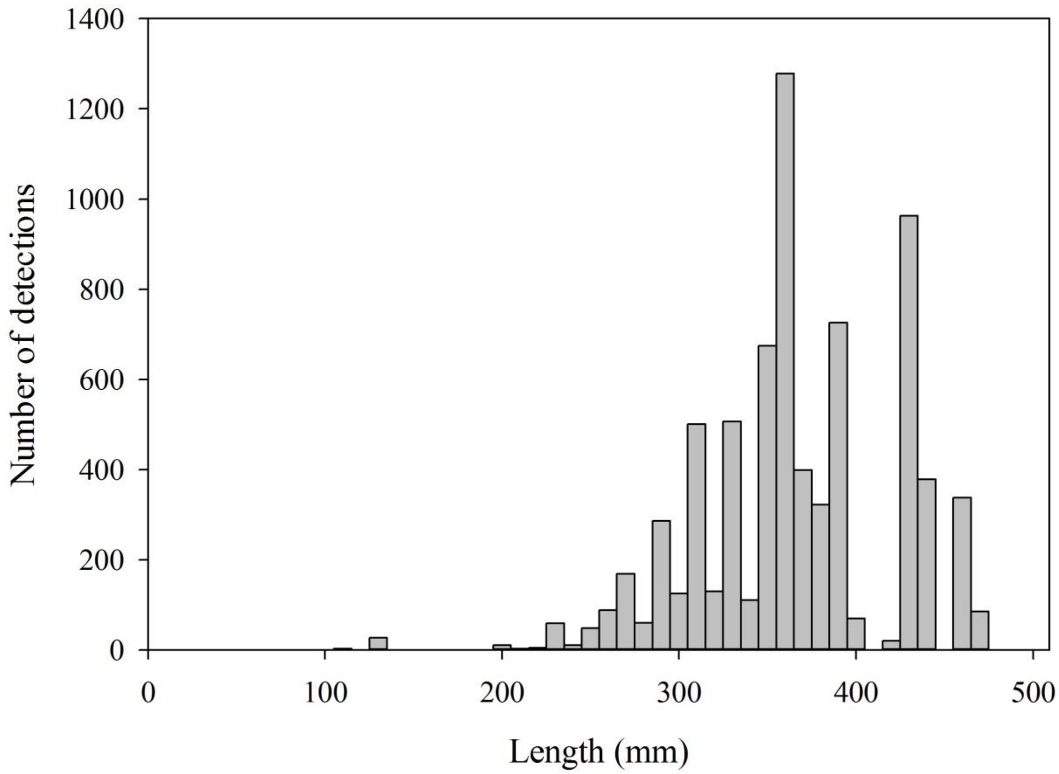

Figure 1.21. Total number of detections recorded on the Tenderfoot Creek outflow station by length of fish during the summer thermal stress period.

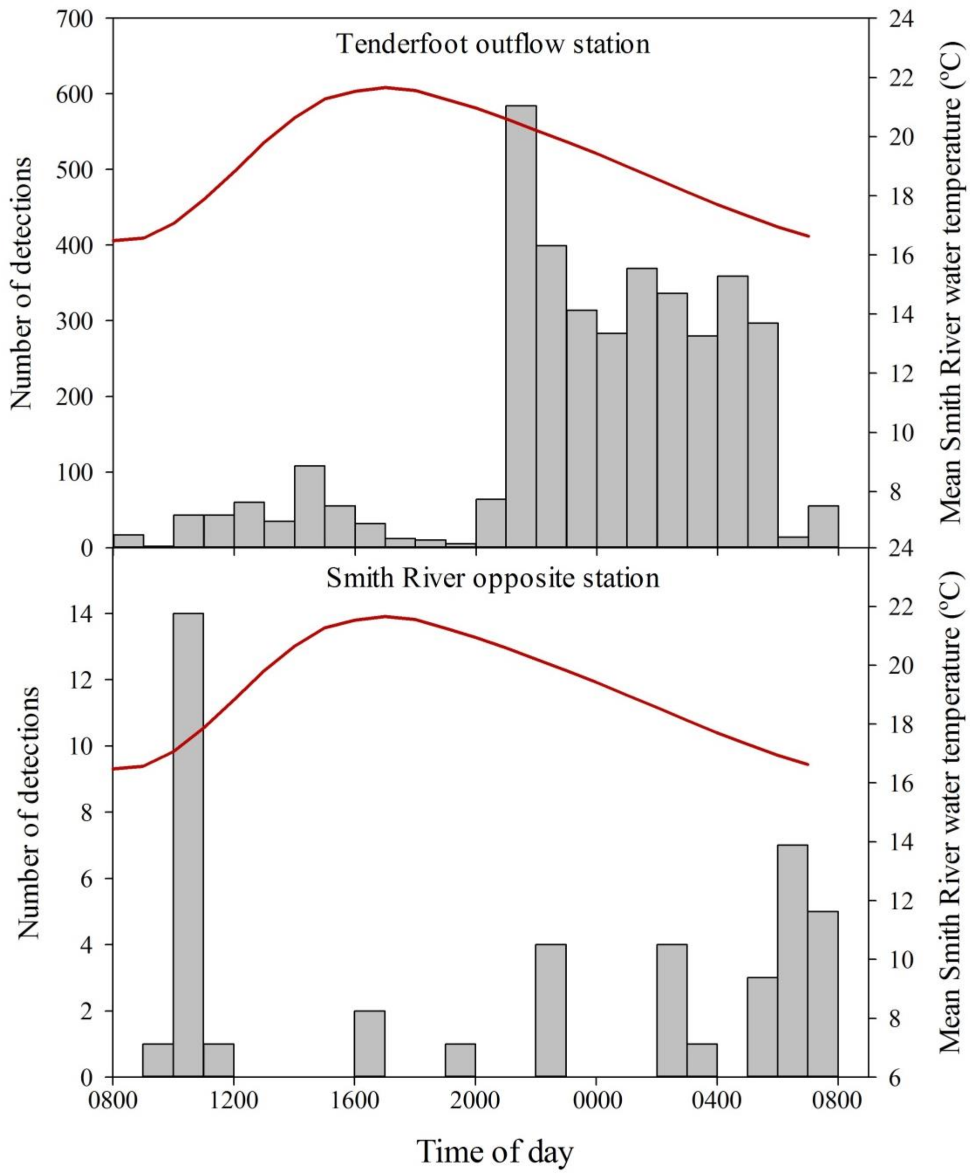

Figure 1.22. Numbers of detections recorded on the Tenderfoot outflow and Smith River opposite stations and mean Smith River water temperatures by hour during the summer thermal stress comparison period. Bars represent the numbers of detections and the solid red lines represent hourly mean Smith River water temperatures.

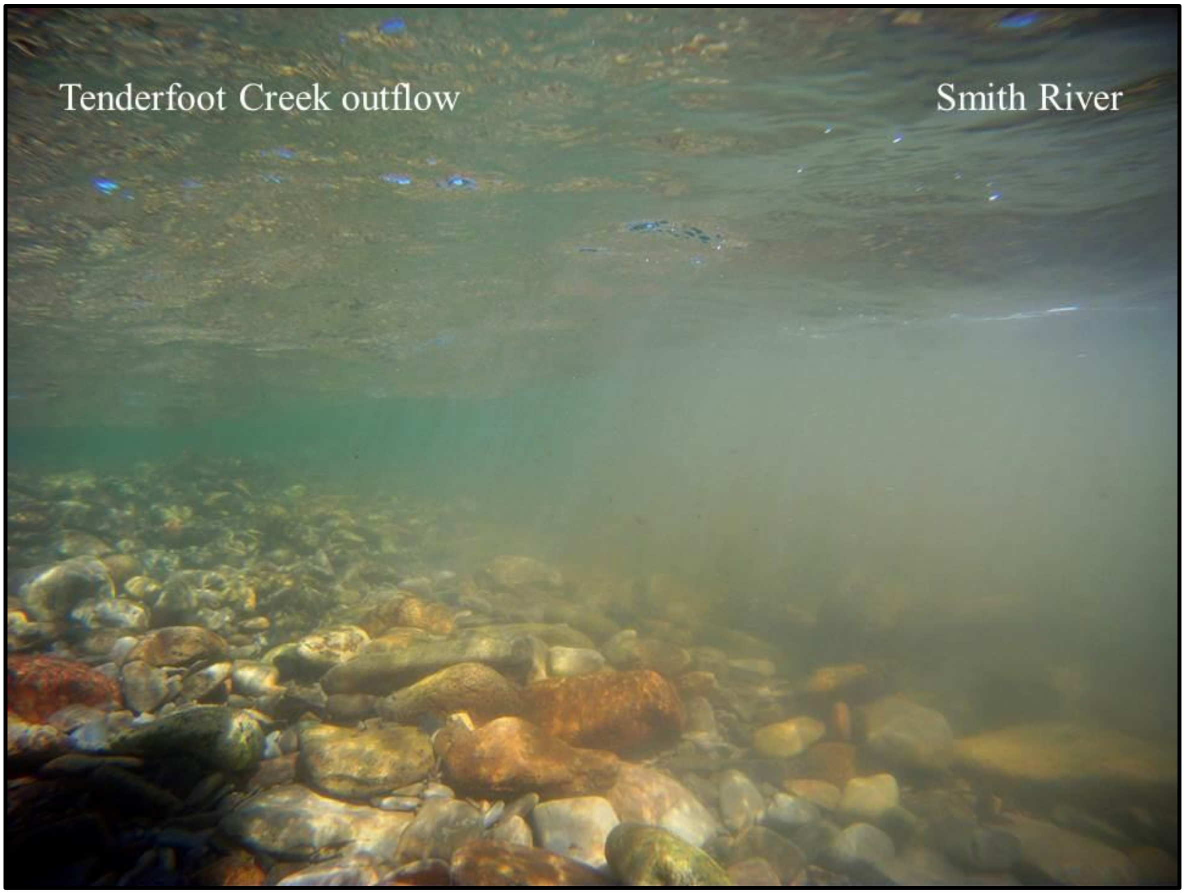

Figure 1.23. Convergence of the comparatively clear water of the Tenderfoot Creek outflow (left) and turbid water of the Smith River (right) on August 23, 2014.

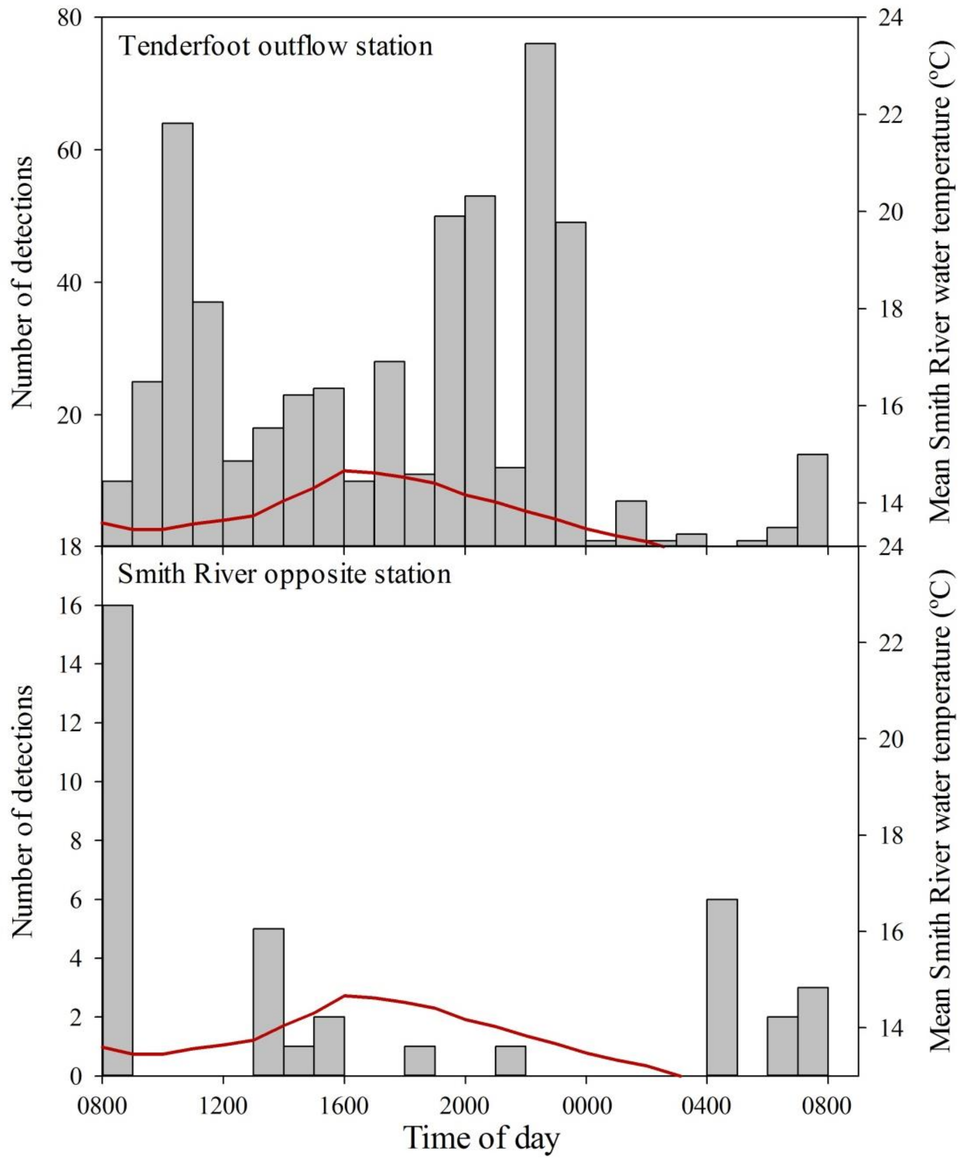

Figure 1.24. Numbers of detections recorded on the Tenderfoot outflow and Smith River opposite stations and mean Smith River water temperatures by hour during the summer precipitation event. Bars represent the numbers of detections and the solid red lines represent hourly mean Smith River water temperatures.

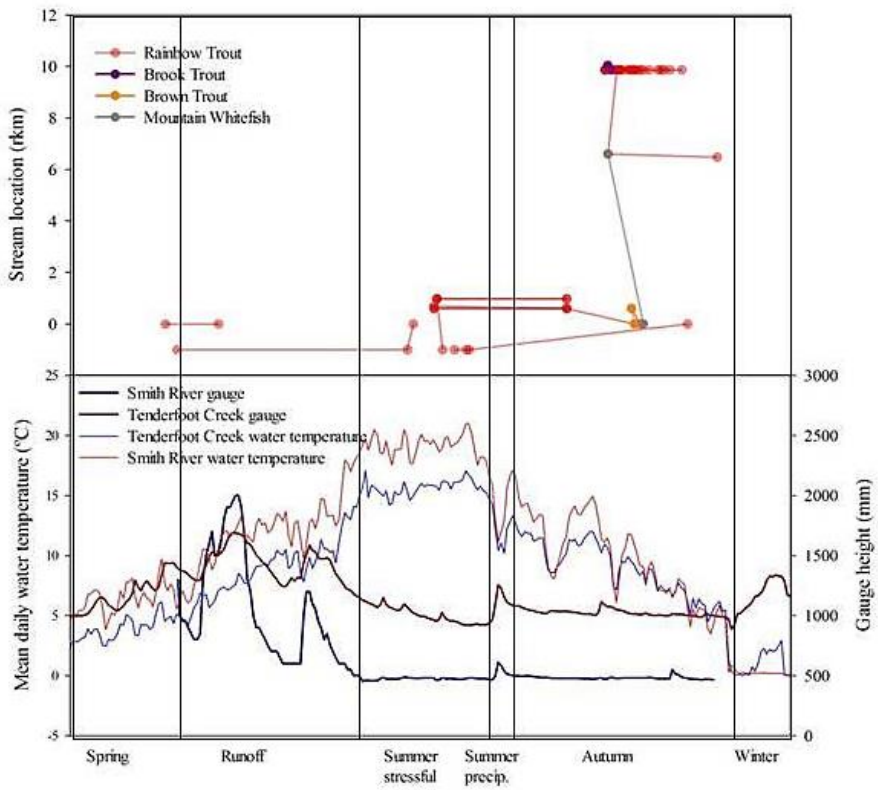

Figure 1.25. Observed movements of tagged juvenile salmonids (TL < 150 mm) in 2014 and mean daily water temperatures and gage heights of Tenderfoot Creek and the Smith River. Circles represent individual fish and solid lines represent movements (or lack thereof) of those individuals. Stream location is the distance from the confluence with the Smith River. Values below 0 rkm represent fish either above or below the confluence in the Smith River.

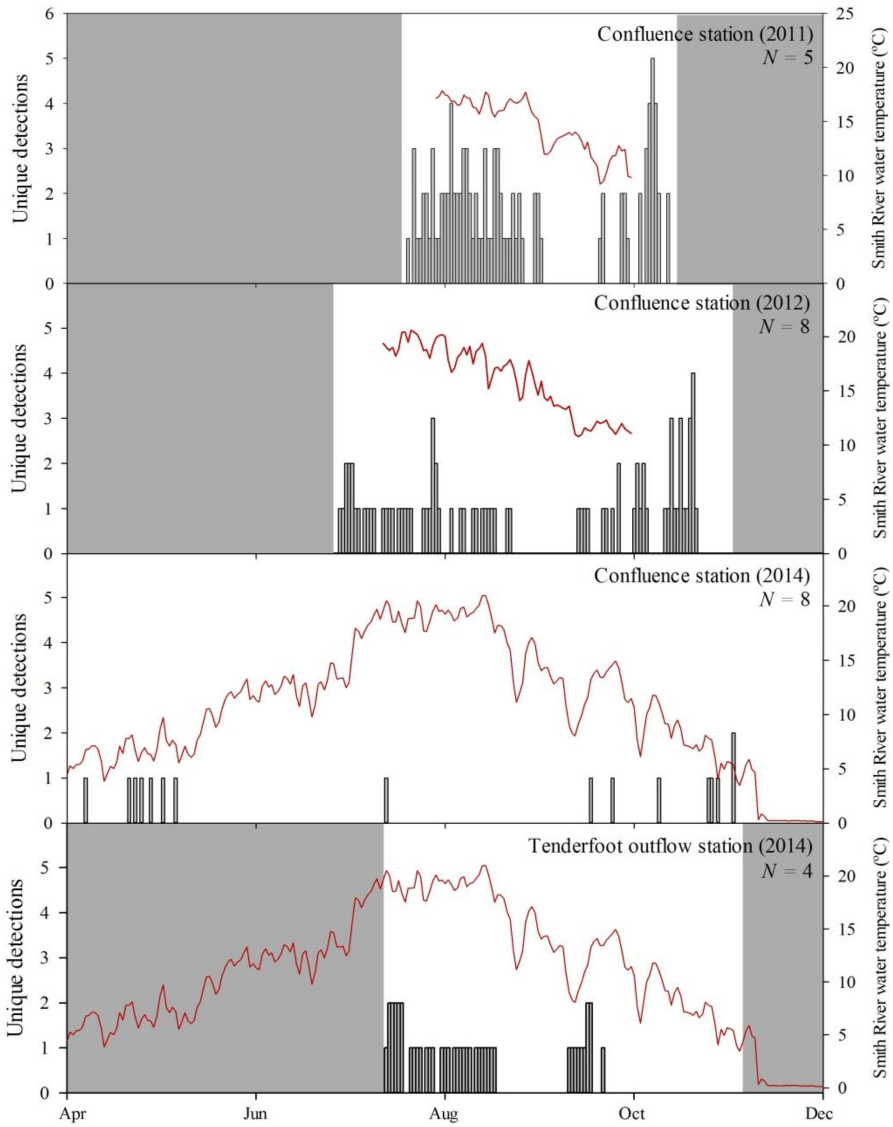

Figure 1.26. Unique detections of Brown Trout in 2011, 2012, and 2014 on the confluence and Tenderfoot outflow stations. Unique detections are defined as one detection per day per individual and are represented by bars. The continuous red lines represent Smith River water temperatures. The first major drops in water temperature in autumn were associated with weather systems that produced precipitation each year. Shaded areas indicate when stations were not operating.

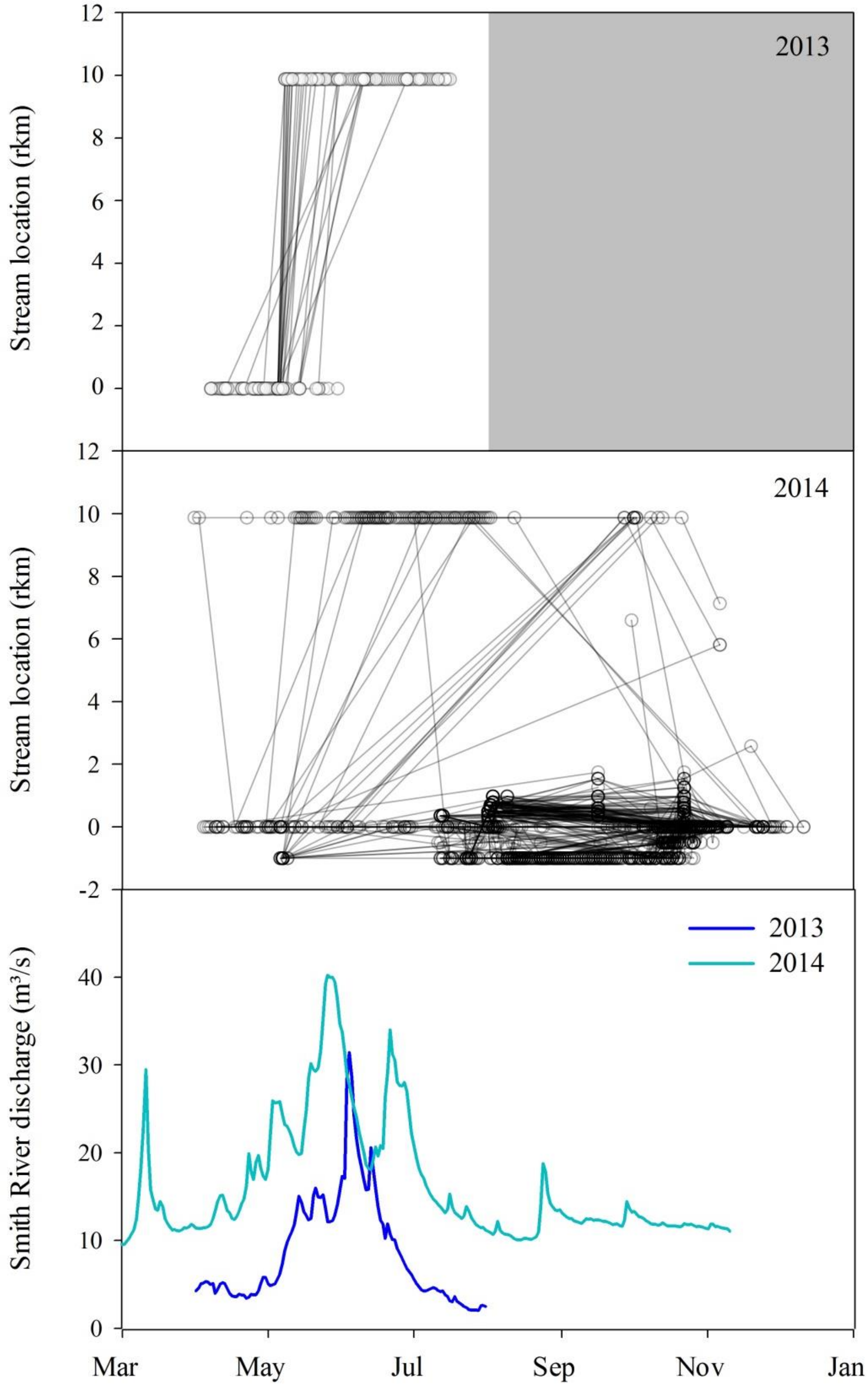

Figure 1.27. Observed movements of tagged Mountain Whitefish and Smith River discharges in 2013 and 2014. Circles represent individual fish and solid lines represent movements (or lack thereof) of those individuals. Stream location is the distance from the confluence with the Smith River. Values below 0 rkm represent fish either above or below the confluence in the Smith River. The shaded area indicates when stations were not operating.

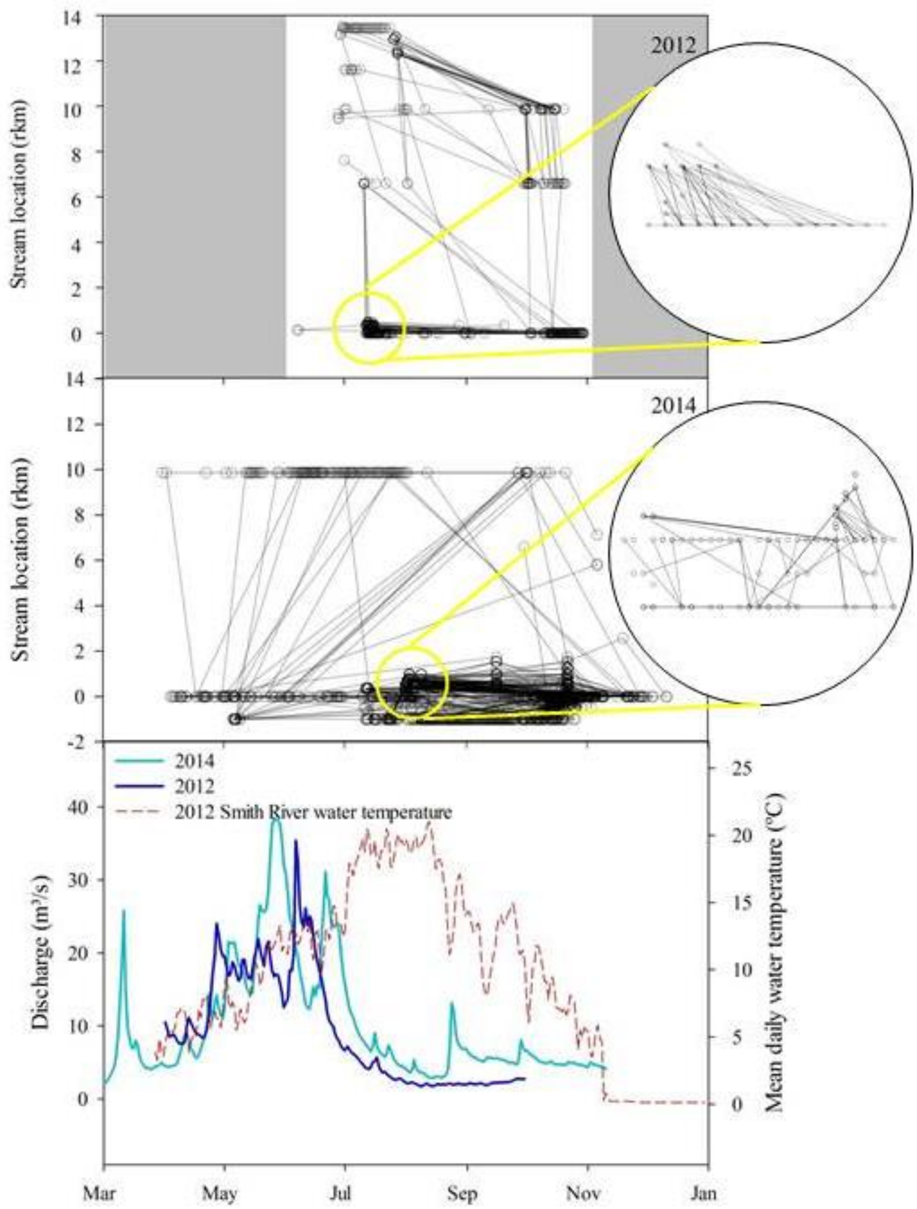

Figure 1.28. Observed movements of tagged Mountain Whitefish, Smith River discharges in 2012 and 2014, and mean daily Smith River water temperature in 2012. Open black circles represent individual fish and solid lines represent movements (or lack thereof) of those individuals. Stream location is the distance from the confluence with the Smith River. Values below 0 rkm represent fish either above or below the confluence in the Smith River. The shaded areas indicate when stations were not operating. Yellow circles indicate when summer downstream migrations occurred.

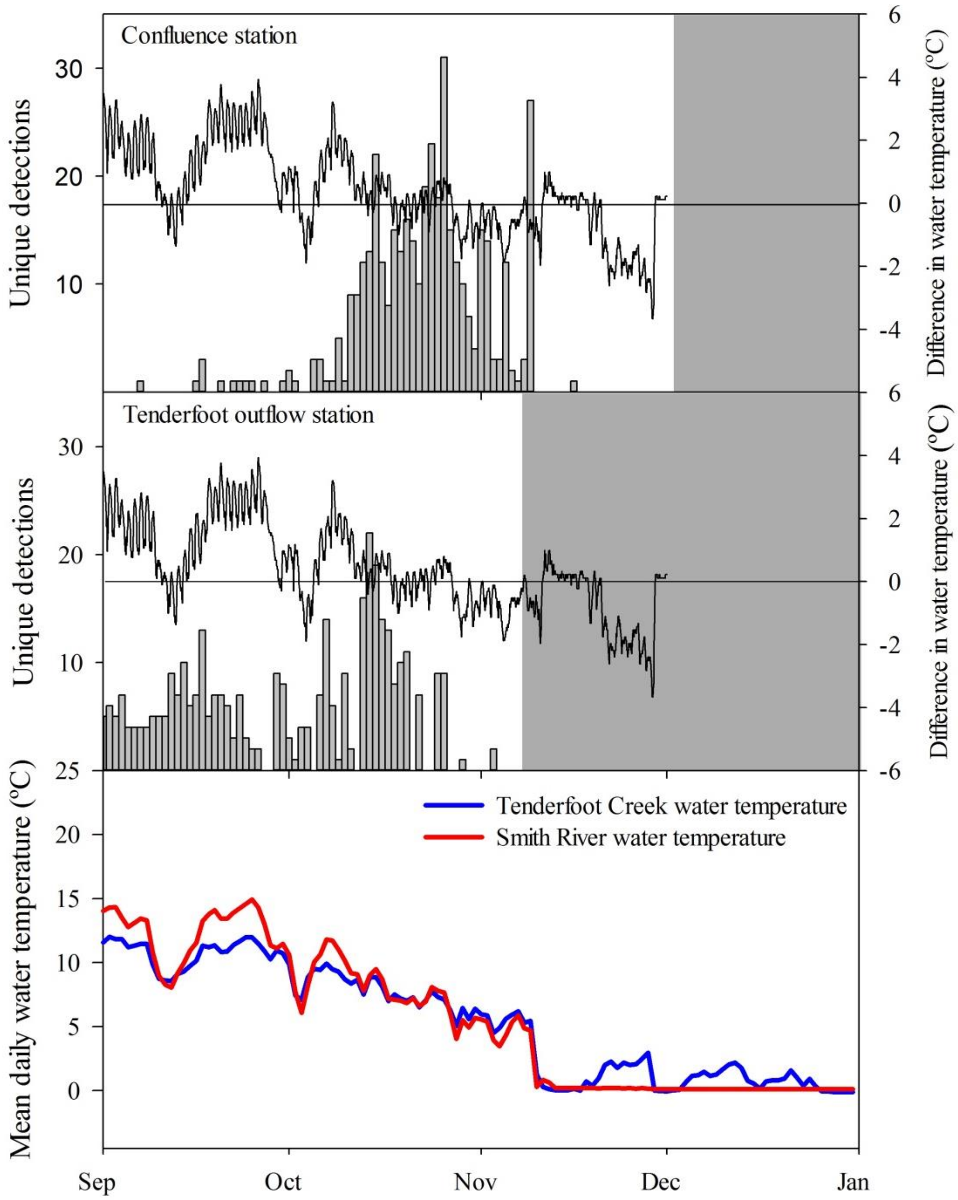

Figure 1.29. Unique detections of Mountain Whitefish on the confluence and Tenderfoot outflow stations, differences between Tenderfoot Creek and Smith River water temperatures, and mean daily water temperatures of Tenderfoot Creek and the Smith River in autumn and winter of 2014. Unique detections are defined as one detection per day per individual and are represented by bars. The solid black lines represent the differences between Tenderfoot Creek and Smith River water temperature. Negative values indicate when Tenderfoot Creek water temperature was warmer than that of the Smith River. Solid blue and red lines represent mean daily water temperatures of Tenderfoot Creek and the Smith River, respectively. Shaded areas indicate when stations were not operating.

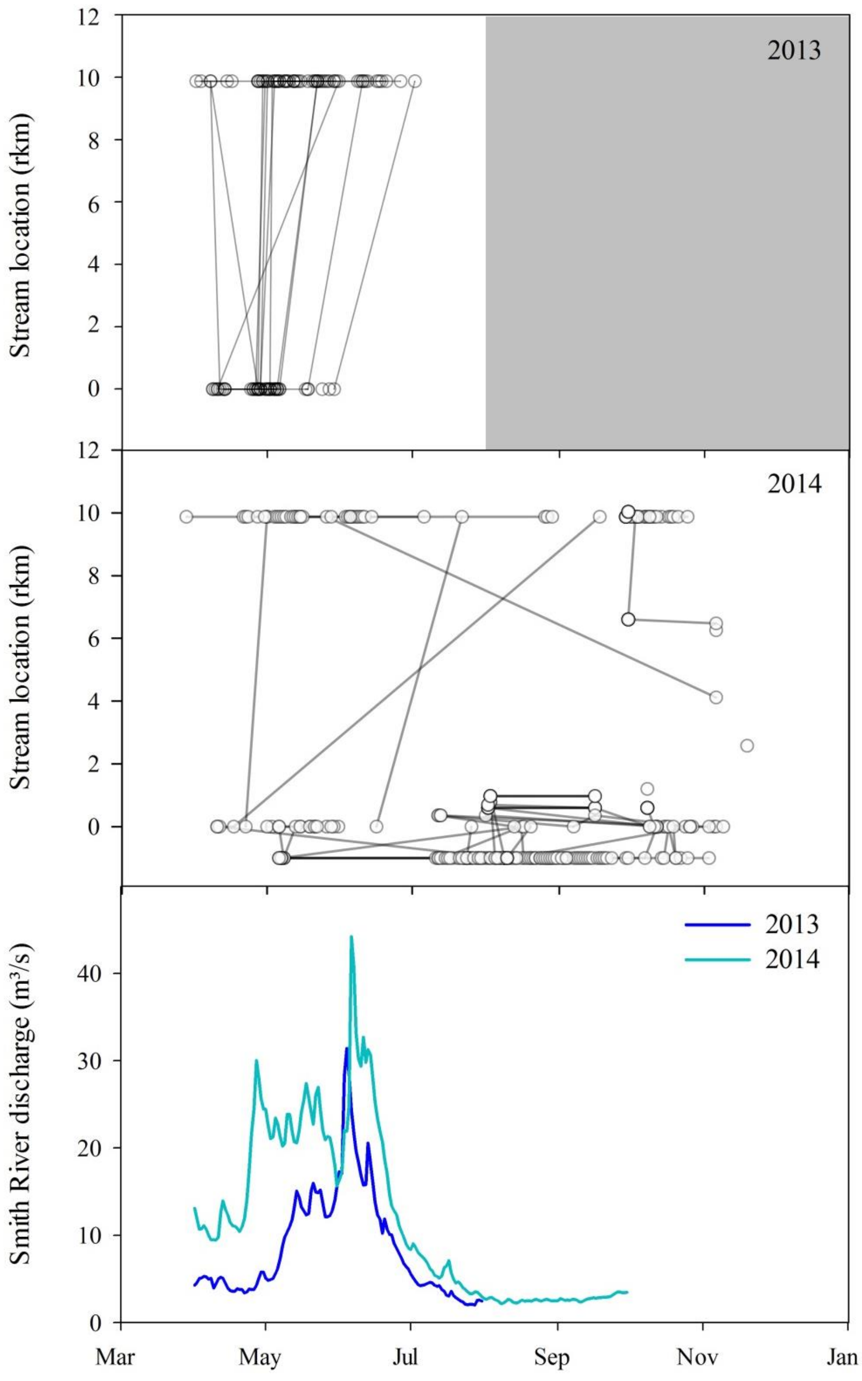

Figure 1.30. Observed movements of tagged Rainbow Trout and Smith River discharges in 2013 and 2014. Circles represent individual fish and solid lines represent movements (or lack thereof) of those individuals. Symbols without connecting lines indicate fish that were tagged and never relocated. Stream location is the distance from the confluence with the Smith River. Values below 0 rkm represent fish either above or below the confluence in the Smith River. The shaded area indicates when stations were not operating.

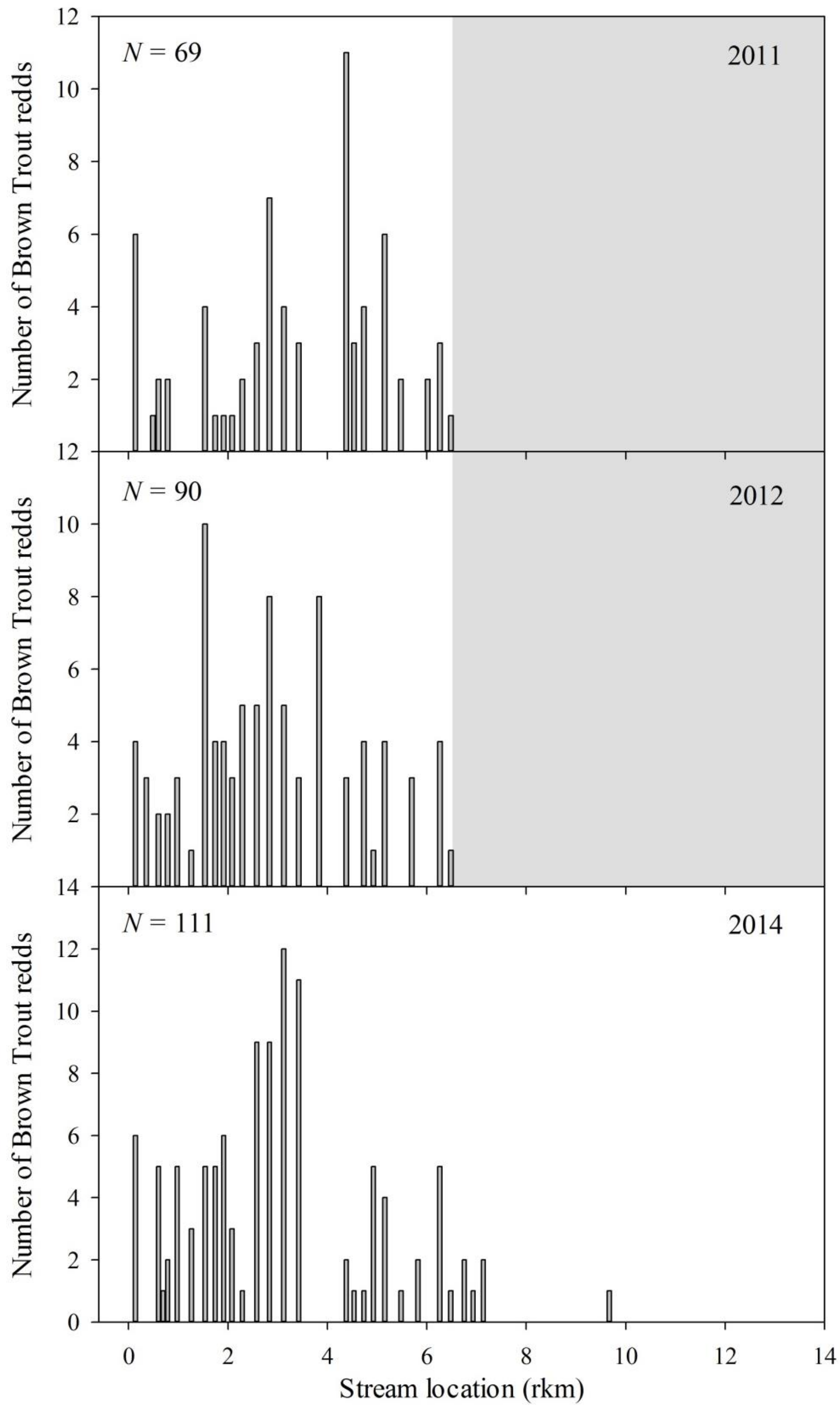

Figure 1.31. Distributions of Brown Trout redds determined by surveys of the first 6.6 km of Tenderfoot Creek from the confluence with the Smith River in late October of 2011 and 2012 and by surveys of all 13.7 km of Tenderfoot Creek in late October of 2014. Translucent gray areas indicate where spawning surveys were not conducted in 2011 and 2012 but were conducted in 2010 and 2014. No redds were observed in 2010.

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Evaluation of a remote monitoring station and development of a temperature model to describe local temperature regimes

INTRODUCTION

Evaluation of a tributary as a possible thermal refuge requires an understanding of thermal regimes and the capability to identify thermally stressful conditions. However, this can be challenging because water temperatures can be spatially and temporally heterogeneous (Vatland et al. 2015). The level of understanding can therefore be limited by the scales of spatial and temporal resolution incorporated in the temperature monitoring framework (Fausch 2002). Making inferences for an entire stream based on a single monitoring point may therefore not be appropriate unless relationships between that point and others downstream are known (Vatland et al. 2015).

Tenderfoot Creek was evaluated as a potential thermal refuge for salmonids in the Smith River basin as part of a multi-year study (Ritter 2015). However, thermally stressful conditions in 2012 were identified by using data collected by the United States Geological Survey (USGS) at the gage station just below Eagle Creek in the Smith River about 20.95 rkm upstream of the mouth of Tenderfoot Creek instead of temperature loggers within the study area. This is because temperature loggers in the Smith River were removed or displaced by recreational floaters. Such use seemed appropriate based on 2011 data, because water temperatures recorded by the gaging station and my temperature loggers were similar. However, discharges were unusually high in 2011 and may have homogenized temperature regimes.

The 2014 study afforded me an opportunity to investigate the temperature relationships between the gage station and stationary temperature loggers further. If discharges were similar in

2014 and 2012, temperature regimes may have also been similar. Furthermore, if the differences between the USGS gaging station and on-site temperatures in 2012 were similar to those observed in 2014, my use of the USGS data in Ritter 2015 may not have been appropriate, and conditions previously identified as thermally stressful may have not existed or existed to a lesser extent.

A secondary goal of my efforts in 2014 was to therefore evaluate the use of the USGS gage station 20.95 rkm upstream as a surrogate for thermal conditions in the Smith River in the confluence area in 2012. Specific objectives were to 1) investigate temperature relationships between the confluence area and gage station in 2014, 2) develop a model to estimate temperatures in the Smith River in the confluence area, and 3) use this model to more accurately identify thermally stressful conditions in 2012.

STUDY AREA

Tenderfoot Creek is a major tributary of the Smith River located between the Big Belt and Little Belt mountain ranges about 140 km north of Bozeman, Montana (Figure 2.1). Mean annual discharge of the Smith River at the USGS gaging station near Fort Logan, Montana, is 6.7 m^3/s. Tenderfoot Creek is a remote, largely undeveloped major tributary of the Smith River and is located about 26 km downstream of the beginning of Smith River State Park, a river corridor managed by Montana Fish, Wildlife and Parks that extends 95 km from the only put-in at Camp Baker downstream to the only take-out at Eden Bridge (Figure 2.1). The study area consisted of the lower 13.7 km of Tenderfoot Creek, extending from an impassable barrier to fish movement at rkm 13.7 downstream to the confluence with the Smith River, and the confluence itself (Figure 2.1).

METHODS

Temperature Regimes

Stationary temperature loggers

A network of temperature loggers (Onset Computer Corporation, HOBO Pendant Temperature Data Logger, Bourne, Massachusetts) was installed in Tenderfoot Creek and the Smith River to monitor temperatures in Tenderfoot Creek and the Smith River (Figure 2.1). Temperature loggers above the confluence and within Tenderfoot Creek were installed in the same locations as in Ritter (2015) to allow for direct comparisons. Temperature loggers were enclosed in protective PVC cases and affixed to rebar with wire or to boulders with underwater epoxy (Simpson Strong-Tie Company, FX-764, Pleasanton, California). Temperature loggers in Tenderfoot Creek and in the Smith River above the confluence were installed on March 27, 2014, and retrieved on December 31, 2014. Temperature was recorded hourly.

Confluence area Smith River temperature model

I used multiple regression to develop three equations for estimating maximum, minimum, and mean daily temperatures in the Smith River 50 m above the confluence with Tenderfoot Creek. Water temperatures recorded by the USGS gage station (20.95 rkm upstream of the confluence with Tenderfoot Creek) and temperature loggers in Tenderfoot Creek were used as predictor variables because they were highly correlated with those in the Smith River 50 m above the confluence in 2014. Air temperature and discharge also explained much of the variation in water temperature; I therefore also used air temperatures collected by the Stringer Creek SNOTEL meteorological station in the upper watershed of Tenderfoot Creek (30 km from the confluence of Tenderfoot Creek and the Smith River) and discharges measured by the USGS gage station as predictor variables. I used data collected from 184 days of the open-water period (March 31 to September 30, 2014) to develop the following general regression equation:

$$T = Y_0 + [gage\_station\_temp]x + [Tenderfoot\_temp]x + [air\_temp]x + [discharge]x$$

where T is estimated daily maximum, minimum, or mean temperature (° C) and Y_0 is the y-intercept.

Diel temperature model for July 31, 2012

Diel fluctuations and thermal conditions were described on July 31, 2012, when the highest temperature during the multi-year study (Ritter 2015) of Tenderfoot Creek was recorded in the Smith River by the USGS gage station. To estimate the diel temperature cycle 50 m above the confluence in the Smith River on this day and compare directly to Ritter 2015, I used the maximum daily temperature multiple regression equation to estimate maximum temperature and modeled the diel temperature cycle using a sinusoid function (Vatland et al. 2015). I split diel fluctuations in water temperature into warming and cooling periods to improve the fit of this sine-based model (Vatland et al. 2015). I used the following sinusoid function to estimate hourly temperatures in the Smith River on July 31, 2012, 50 m above the confluence of Tenderfoot Creek:

$$T_{i,m} = T_0 + A_{i,m} \sin\left[2\pi t / P_{i,m}\right]$$

where *i* is time segment (h); *m* is location (m); *t* is time of temperature measurement (h); *A* is amplitude (° C); *P* is period (h); *T* is predicted stream temperature (° C), and T_0 is the y-intercept (° C).

Thermal thresholds of salmonids

I used the same two temperature thresholds described in Ritter (2015) to identify thermally stressful conditions for salmonids in the Smith River and Tenderfoot Creek: the long-term upper incipient lethal temperature (UILT) and the upper growth limit temperature. I defined the long-term UILT, which is typically referred to as the ultimate upper incipient lethal temperature (UUILT), as the maximum temperature attainable by acclimation at which 50% of the test subjects survive in a laboratory setting for at least 30 days (Fry 1971; Elliott 1981; Kilgour 1985; Selong et al. 2001) (Table 2.1). The upper growth limit temperature is the maximum temperature at which growth occurs and usually coincides with lethargy and cessation of feeding (Selong et al. 2001; Bear et al. 2007) (Table 2.1). In general, these values tend to be almost identical (Selong et al. 2001; Bear et al. 2007) (Table 2.1). I used long-term UILT determinations in favor of more common 7-d UILT estimates because the longer duration of exposure allows for detection of delayed effects that would otherwise be missed in short-term tests (Bear et al. 2007). However, because long-term UILT estimates have not been determined for Brown Trout and Brook Trout, I estimated their long-term UILTs and upper growth limits by subtracting 3 °C from the short-term (7-day) UILT values, as long-term UILTs are 2 to 4 ºC lower than the 7-day values (Selong et al. 2001; Bear et al. 2007) (Table 2.1).

RESULTS

Evaluation of gage station based on 2014 temperature regimes

Water temperatures recorded by the United States Geological Survey (USGS Eagle Creek gage station, 20.95 rkm upstream of Tenderfoot Creek) were probably not representative of those in the study area in 2012, even though they were similar to temperatures at stationary loggers in the study area in 2011. Maximum Smith River water temperatures recorded by the gage station were up to 4.6 °C higher than those recorded by my temperature loggers in the Smith River (50 m upstream of Tenderfoot Creek) in 2014, but only up to 1.7 °C higher in 2011 (Figure 2.2). Because water temperatures recorded by the gage station in 2014 were similar to those in 2012, temperatures in the Smith River in 2012 were also probably lower directly above the confluence than those 20.95 rkm upstream at the USGS gage station. Thermal conditions in the Smith River at the confluence in 2012 were therefore probably similar to those observed in 2014 (Figure 2.3), as were hydrologic regimes (Figure 2.4). Levels of stress on salmonids were probably also comparable, although the timing of such stress may have differed (Figure 2.3). In contrast, thermal conditions in the Smith River in 2011 were far less stressful on salmonids (Figure 2.3), resulting from an unusually high water year (Figure 2.4).

Evaluation of confluence area Smith River temperature model

Temperature data from the stationary temperature logger in the Smith River 50 m above the confluence with Tenderfoot Creek in 2014 fit the equations well; r^2 and RMSE (root mean square error) for maximum, minimum, and mean daily temperatures were 0.98, 0.97, and 0.98, and 0.79, 0.85, and 0.67 °C, respectively. Estimated maximum water temperatures were underestimated during part of the summer thermal stress period (July 12 to July 30, 2014), but the maximum difference was only 1.9 °C, and the mean difference was 0.6 °C (compared to 4.6 °C and 1.0 °C, respectively, of the USGS gage station) (Figure 2.5). However, estimated temperatures were still closer to actual values than the USGS gage station (Figure 2.5) and I therefore used the equations to estimate Smith River water temperatures in 2012.

Evaluation of gage station based on temperature model

Conditions in the Smith River were probably less stressful than suggested by the USGS gage station in summer of 2012. Estimated water temperatures in the Smith River 50 m above the confluence tended to be lower (up to 2.2 °C) than those recorded by the USGS gage station, especially in summer (Figure 2.6). Accordingly, thermal thresholds of salmonids were probably surpassed less frequently than described in Ritter (2015) (Figure 2.7). Estimated maximum water temperatures in the Smith River in 2012 exceeded the long-term UILTs of Brown Trout on 25 days (compared to 34), of Mountain Whitefish on 16 days (compared to 20), of Rainbow Trout on no days (compared to 3), and of Brook Trout on 28 days (compared to 34) (Figure 2.7). Maximum water temperature in the Smith River exceeded the upper growth limits of Brown Trout on 43 days (compared to 58), of Mountain Whitefish on 18 days (compared to 21), of Rainbow Trout on no days, and of Brook Trout on 28 days (compared to 34) (Figure 2.7). On July 31, 2012, when the maximum annual temperature was estimated (23.8 °C), water temperatures exceeded the long-term UILTs of Brown Trout, Mountain Whitefish, Rainbow Trout, and Brook Trout for 6, 4, 0, and 6 hours (compared to 9, 6, 2, and 9) (Figure 2.8). The upper growth limit temperatures of Brown Trout, Mountain Whitefish, Rainbow Trout, and Brook Trout were surpassed on this day for 11, 5, 11, and 7 hours (compared to 13, 7, 13, and 9) (Figure 2.8). Days when the estimated mean temperature was above the long-term UILTs and upper growth limits were the most stressful to fish because the period of stress exceeded the period of recovery. However, this only applied to the upper growth limit of Brown Trout in 2012, when 4 such days occurred (compared to 10) (Figure 2.7). Though conditions in the Smith River were probably less stressful than previously thought, they were still at levels that fish would be expected to avoid if possible.

DISCUSSION

The USGS gaging station at Fort Logan (20.5 rkm upstream of Tenderfoot Creek) was not an appropriate surrogate for thermal conditions in the Smith River in the confluence area in 2012. I had used it as such in my previous analyses because my temperature loggers in the Smith River were vandalized in 2012 (Ritter 2015). Such use seemed appropriate based on 2011 data, when water temperatures recorded by the gaging station and my temperature loggers were similar (Figure 2.2), but discharges were unusually high in 2011 and may have homogenized temperature regimes.

Estimated summer temperatures 50 m above the confluence were lower than those recorded at the gage station and as such, thermal thresholds of salmonids were probably surpassed less frequently. Levels of stress on salmonids were therefore probably not as high as described in Ritter (2015). Indeed, conditions in the Smith River may have been suitable enough to dissuade fish from moving into Tenderfoot Creek as previously expected (Ritter 2015), especially given the accessibility of cooler temperatures in the Tenderfoot Creek outflow.

Management decisions based on water temperatures recorded at a single site should be made with considerations of conditions throughout the Smith River. In general, water temperatures tend to increase in a downstream direction (Vannote et al. 1980). However, I observed temperatures up to 4.6 ºC cooler 20.95 rkm downstream in 2014, underscoring the amount of possible thermal heterogeneity in the Smith River basin. A more comprehensive network of stationary loggers or extensive temperature modeling would enhance understanding of temperature regimes and help identify management strategies (Vatland et al. 2015). Temperature models similar to those described in this report could be used to better understand relationships between the USGS gage station and other monitoring points throughout the Smith River basin, thereby enhancing decision-making processes for fisheries managers.

TABLES

Table 2.1. Summary of short- and long-term upper incipient lethal temperatures (UILTs) and upper growth limit temperatures of juvenile salmonids. Long-term and upper growth limit values marked with an asterisk were estimated by subtracting 3.0 ºC from short-term UILT estimates for that particular species (Selong et al. 2001; Bear et al. 2007).

Species	Short-term UILT (C º)	Long-term UILT (C º)	Upper growth limit (C º)	Reference
Brown Trout	24.7 (7 d)			Elliott 1981
		21.7*		
			19.5	Elliott et al. 1995
Westslope Cutthroat Trout	24.1 (7 d)	19.6 (60 d)	20.0	Bear et al. 2007
Rainbow Trout	26.0 (7 d)	24.3 (60 d)	24.0	Bear et al. 2007
Brook Trout	24.5 (7 d)			McCormick et al. 1972
		21.5*	21.5*	
Mountain Whitefish	23.6 (7 d)	22.6 (33 d)	22.2	Brinkman et al. 2013

FIGURES

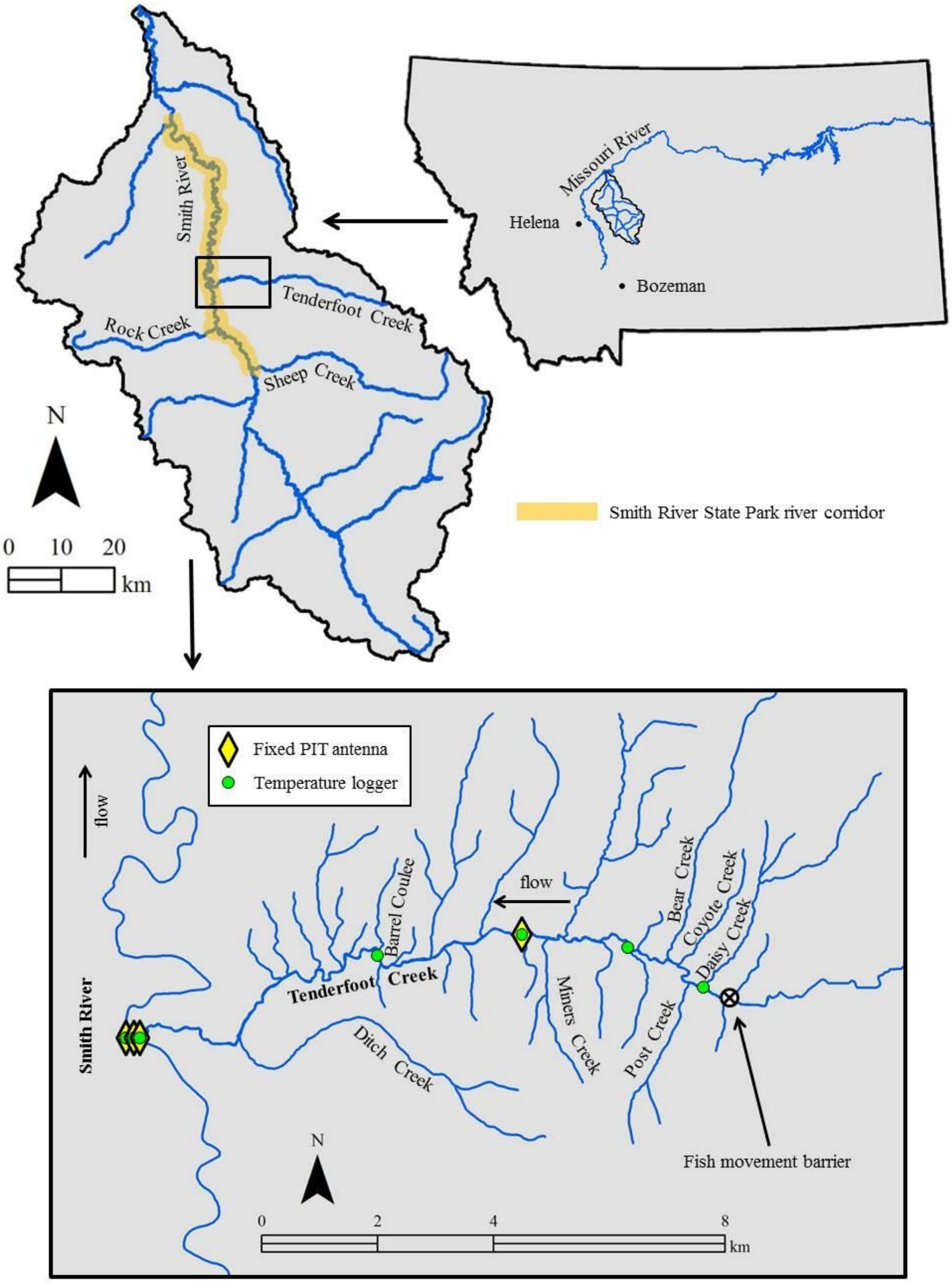

Figure 2.1. The Smith River and its major tributaries and lower Tenderfoot Creek and its major tributaries. Yellow diamonds represent locations of fixed PIT antenna stations. Green circles represent locations of temperature loggers. Yellow diamonds with green circles inside of them represent temperature loggers installed at fixed PIT antenna stations.

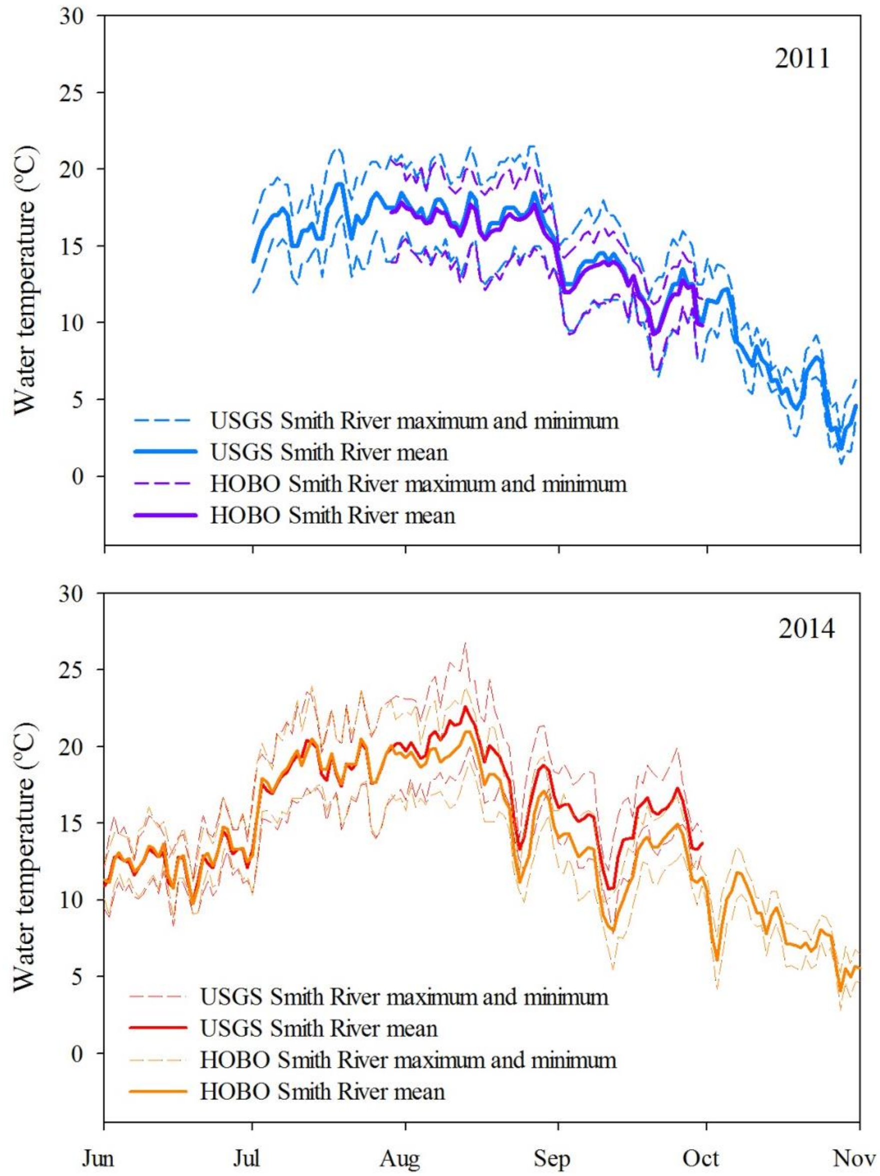

Figure 2.2. Comparisons of daily Smith River water temperatures recorded by the USGS gaging station below Eagle Creek about 20.95 rkm upstream of Tenderfoot Creek and by on-location temperature loggers 50 m upstream of Tenderfoot Creek in the Smith River in 2011 and 2014.

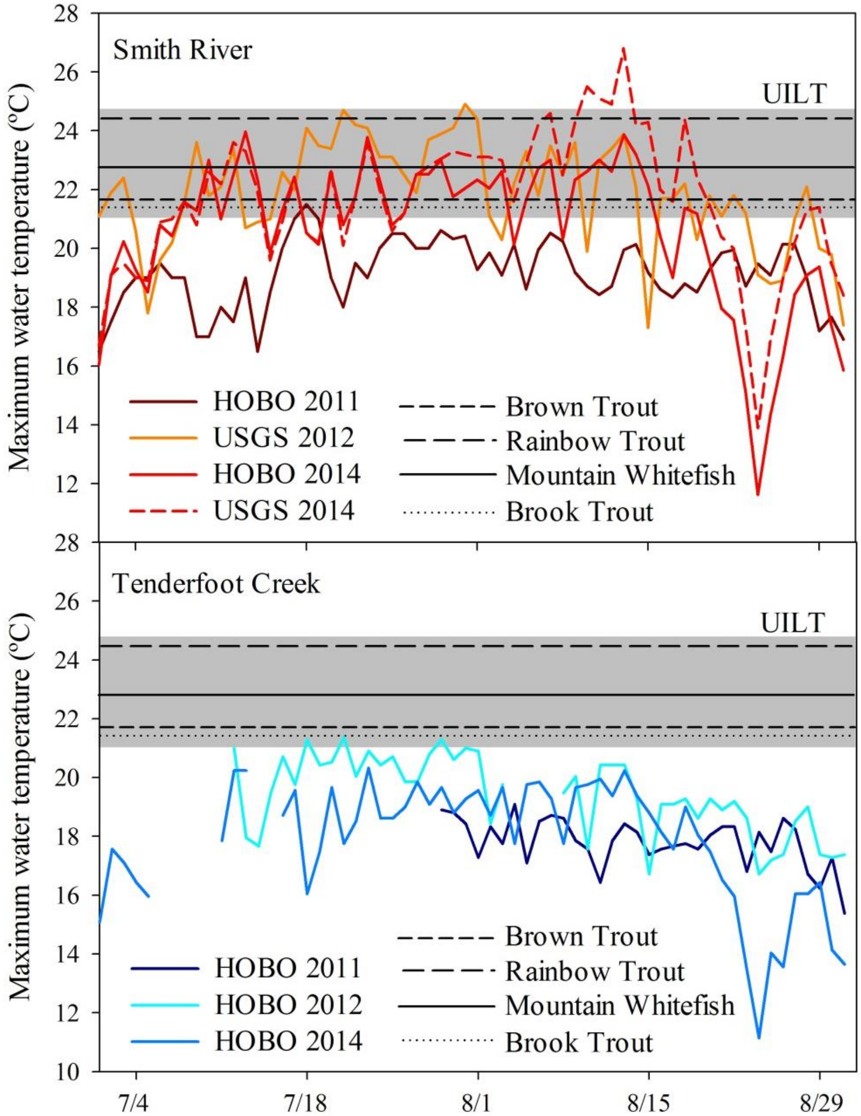

Figure 2.3. Comparisons of maximum water temperatures in the Smith River (A) and Tenderfoot Creek (B). UILTs are long-term estimates (> 30 d) as determined by other studies or estimated from existing short-term UILTs (7 d) and are displayed within the light gray region.

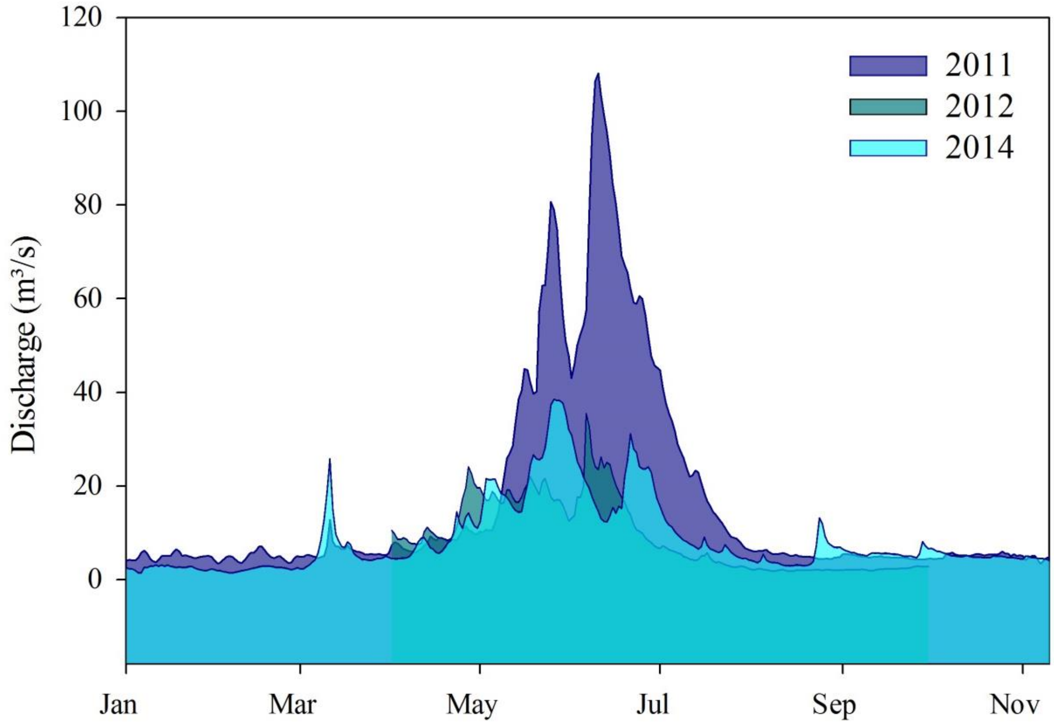

Figure 2.4. Mean daily discharges of the Smith River during 2011, 2012, and 2014 recorded at the USGS gauge station 20.95 rkm upstream of the mouth of Tenderfoot Creek.

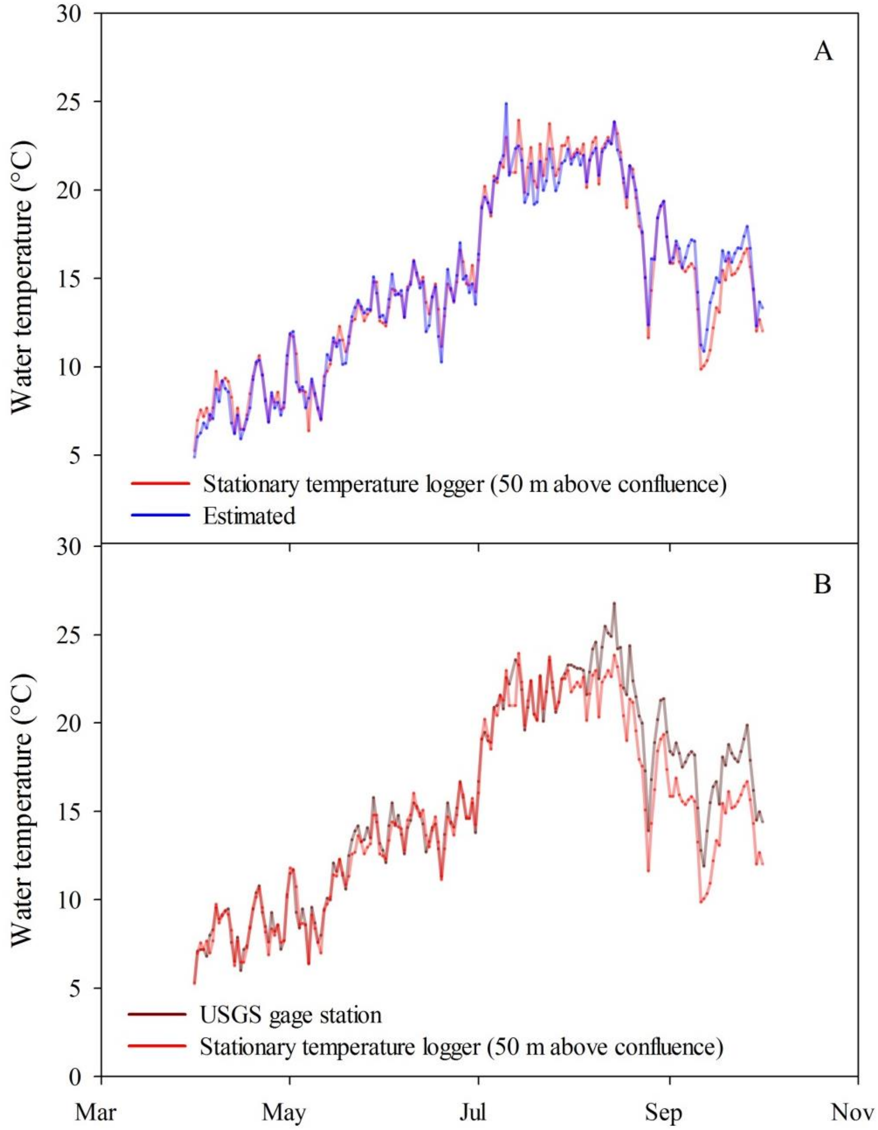

Figure 2.5. Comparisons of daily maximum water temperatures in 2014 recorded by the stationary temperature logger in the Smith River 50 m above the confluence to that estimated by the confluence area temperature model (A) and the USGS gage station in the Smith River 20.95 rkm upstream of the confluence of Tenderfoot Creek (B).

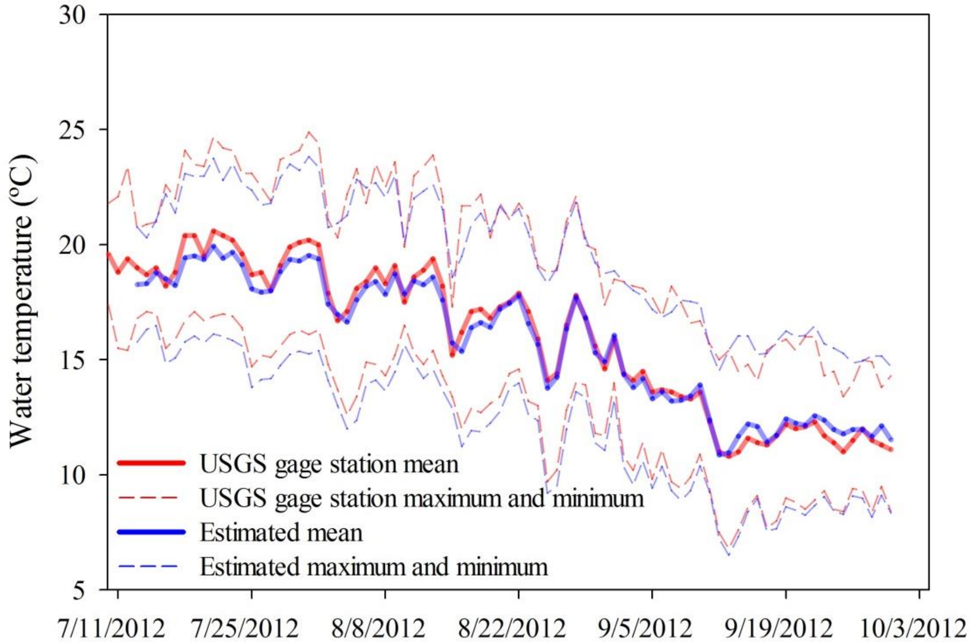

Figure 2.6. Comparisons of daily maximum, minimum, and mean water temperatures in 2012 recorded by the USGS gage station below Eagle Creek 20.95 rkm upstream of the confluence with Tenderfoot Creek and estimated by the confluence area temperature model.

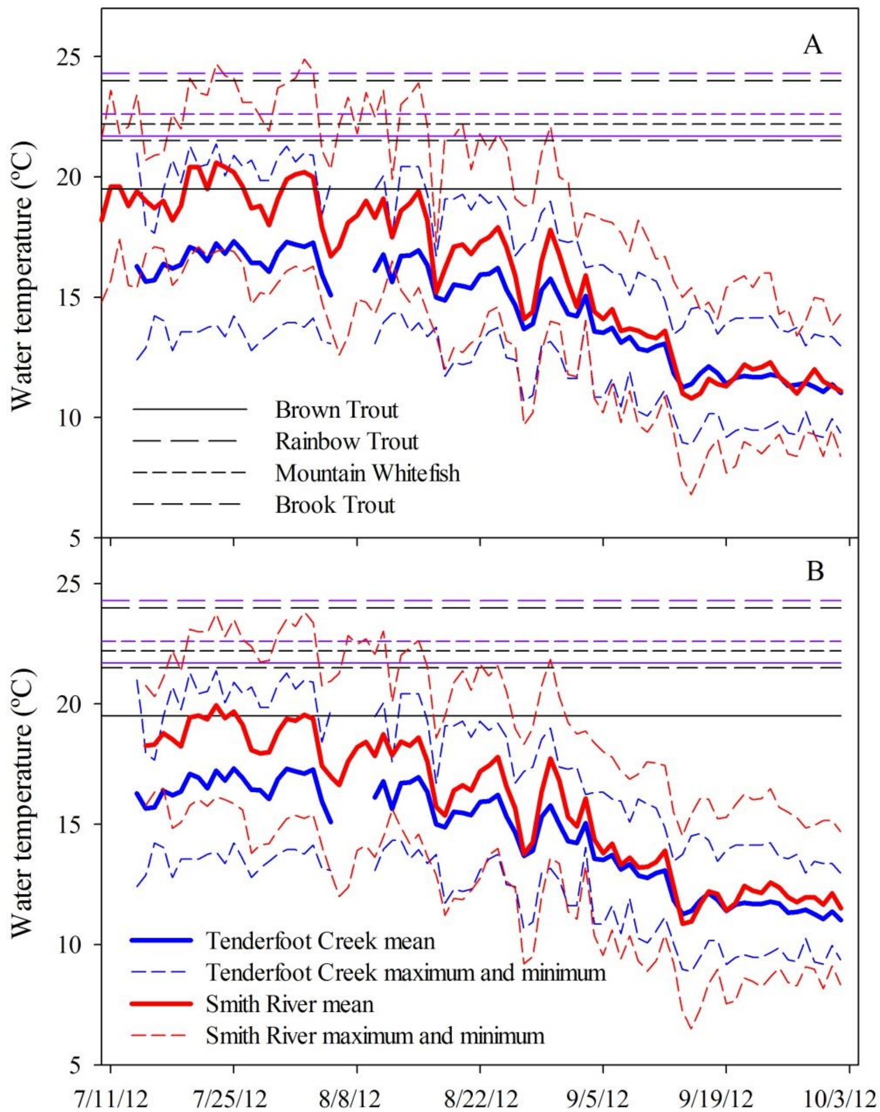

Figure 2.7. Comparisons of maximum, mean, and minimum daily water temperatures in 2012 recorded in Tenderfoot Creek at rkm 0.0 and in the Smith River at the USGS gage station (A) and estimated by the confluence area temperature model (B). UILTs are long-term estimates (> 30 d) as determined by other studies or estimated from existing short-term UILTs (7 d) and are represented by purple lines. Upper growth limit temperatures are represented by black lines. Brook Trout long-term UILT and upper growth limit temperatures were estimated from an existing short-term UILT as the same value (21.5 ºC).

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