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Impacts of Beaver Dams on Mountain Stream Discharge and Water Temperature

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IMPACTS OF BEAVER DAMS ON MOUNTAIN STREAM DISCHARGE AND WATER TEMPERATURE

by

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Approved:

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Abstract

Beaver dam complexes have been shown to affect the hydrologic processes controlling river systems. These processes include surface and groundwater exchanges, water chemistry and temperature variations, and river discharge magnitudes. Majerova et al. (2015) explored the effects of beaver dams on surface and groundwater exchanges and water temperature by evaluating three years of water discharge and temperature data recorded at multiple locations within a small stream in northern Utah. They found that beaver dams increase the water surface elevation and force water into the floodplain resulting in increased inundation and groundwater recharge. They additionally found that beaver dams increase residence time of the water and together with increased surface area, generally result in increased water temperature at reach scales. Majerova et al. (2015) noted the importance of long-term data sets to more fully understand the impact of beaver dams on river systems. Towards this end, this report builds on the original study by extending the daily average water temperature and discharge time series at three locations along a 1.3 km section of Curtis Creek in Northern Utah to provide insight into the long-term effects of the beaver dam complexes. The entire data set spans 2008-2018 and represents periods before the beaver dams were built, during dam construction and various levels of dam maintenance, and after the dams breached or washed out after beaver were trapped in the area. The original 3 years of data presented in Majerova et al. (2015) showed that an increase in beaver dams generally increased the baseflow discharge and water temperature variations during the summer. However, longer term data that represent a larger range of annual flows and different states of dam building and maintenance show that beaver dams only increase baseflow discharge when the dams are relatively young and consistently inundate the floodplain. This suggests that beaver dam complex age and pond sedimentation is important for understanding groundwater exchanges. When comparing the streamflow data, weather data, and daily average water temperatures together, it is clear that beaver dams do consistently increase water temperatures, but local weather and longer term hydrologic conditions are also important factors affecting (or contributing to) water temperature variations. A review of the sub-daily water temperature data for a single week in September, revealed a daily variation of approximately 0.7°C without beaver dams and approximately 5°C with beaver dams. This represents a significant change in daily water temperatures and highlights the need to investigate shorter temporal scale influences on long term temperature responses.

Acknowledgements

It is important to recognize the help, guidance, and continued patience of my advisor Dr. Bethany Neilson. Dr. Neilson has gone above and beyond the requirements of a graduate advisor. Not only has she helped me complete this research project but also grow as a student and individual. Her guidance has helped me learn more about beaver dams and also how to see the world differently; to look at a system and begin to understand and think about all the components and connections that allow the system function. I thank her for her effort, example, and friendship in helping me complete my graduate studies.

My graduate advisor committee members, Dr. Jeffery Horsburgh and Professor Austin Ball have been enormously helpful and I thank them for their help in this project. Both have spent significant time reading, providing feedback, and helping me become a better writer. I have taken courses from both and have directly benefited from their hard work and dedication to educating students to the best of their ability. I also recognize and thank the various funding sources for this project including the Utah Water Research Laboratory, the Utah Division of Wildlife Resources, and the U.S. Forest Service.

I also recognize the efforts of several students that have worked to gather this data over the last 13 years. In particular, Milada Majerova completed the initial research required to make my research possible and I thank her for all her contributions to this effort. Hyrum Tennant also provided significant help and insight into the study area and the data that were collected. Many prior students from the Neilson Research Group including Trinity Stout, Cami Snow, Noah Schmadel, Jon Bingham, Quin Bingham, Oscar Marquina, Andrew Hobson, Mitchell Rasmussen, and Tyler King helped collect, organize, and store the data required for my research.

Finally, I thank my amazing wife, Marlee for putting up with so many long days and late nights. She continually offered motivation to keep trying when I got frustrated or struggled to understand my research. Without her, I would not have been able to complete this project or my graduate studies.

Thank you,

Timothy R. Clark

Introduction

The influence of beaver dams on rivers has been studied since the early 1900s (Majerova et al., 2015). However, little to no research has been done regarding the long-term effects of beaver dam complexes on reach scale hydrologic responses over the entire lifecycle of a beaver dam complex (before, during, and after dam construction; partial dam breaches due to high flow; different stages of dam maintenance; and after abandonment) because these comprehensive data sets are difficult to obtain. Previous research has established that the construction of beaver dams results in pools that increase the water surface elevation and decrease water velocities (Meetemeyer and Butler, 1999; Pollock et al., 2007; Rosell et al., 2005). In addition, damming of the water also increases the inundation of the floodplain (Gurnell, 1998), which influences local groundwater table elevations (Hill and Duval, 2009; Lautz and Siegel, 2006). The resulting increases in groundwater table elevations influence groundwater exchanges (gains and losses), and during lower flow periods the mounded groundwater table creates a head gradient toward the river. These gaining conditions result in higher discharge above the normal baseflow (Story et al., 2003; Westbrook et al., 2006).

When studying the effect of a series of beaver dams on larger reach scales, Nyssen et al. (2011) found that water retained by the dams during high flows resulted in increased baseflows. Others (Gurnell, 1998; Burns and McDonnell, 1998) identified similar trends when multiple beaver dams were evaluated together. These studies show the importance of evaluating longer reaches that capture a series of beaver dams, or dam complexes and the role of higher flow periods on baseflows. Mountain streams usually have large annual variations in discharge and high spring runoff associated with snowmelt. It is during these spring events that local groundwater table elevations are raised and should provide insight regarding conditions during low flow periods.

Majerova et al. (2015) also emphasized the importance of evaluating beaver dam complexes, rather than just individual dams, for understanding the combined effects on groundwater influences and temperature variability over time. They showed the importance of temporal scales in understanding these influences and highlighted the value of long-term observations for understanding changes over multiple years. They found that groundwater gains decrease instream temperatures at small scales, while the beaver dam ponds created larger surface areas and slower water velocities that result in increased reach scale warming due primarily to solar radiation influences (Majerova et al., 2020). While this work illustrated the effects of beaver dams on the complex relationship between water temperature and groundwater gains and losses over three years, these relationships have not been studied over longer periods of time. However, the effects of beaver dams on several independent hydrologic elements have been studied. For example, Lautz and Siegel (2006) showed that beaver dams break the longitudinal hydraulic gradient of the river into head drops (at the dams) which increases hyporheic exchange and results in cooling influences (Neilson et al. 2010, King and Neilson 2019). It is also well established that surface water temperature is primarily dictated by the weather (including solar radiation, air temperature, humidity, and wind speed) and the associated air-water interface heat exchanges (e.g., King et al. 2016), channel structure (e.g., Schmadel et al. 2015), and shading due to riparian vegetation (e.g., Sinokrot and Stefan, 1993; Webb et al., 2008). As noted by Gurnell (1998), beaver dams increase water surface elevations, which lead to larger inundated areas and increase heat exchanges at the air water interface.

Depending on the underlying topography and channel geometry, beaver dams may create significant increases in the water surface area. As Cook (1940) explained, this expansion in water surface area allows solar radiation, commonly the largest source of heat in streams (Evans et al., 1998; Johnson, 2004; Webb and Zhang, 1997), to be a critical factor in increasing surface water temperature.

In general, the literature reviewed in preparation of this document is consistent that beaver dams result in increased infiltration and groundwater recharge, which often results in increased surface water discharge during baseflows. The literature also shows that beaver dams generally result in increased water surface area which often results in greater warming. However, as noted by Majerova et al. (2015), different temporal and spatial scales are important in understanding the effects of beaver dams and, depending on the spatial scales monitored, water temperatures may both increase and decrease resulting in increased thermal heterogeneity. Additionally, they found that early in the life of beaver dams and complexes there were significant influences on baseflow periods, and the return of this cold groundwater during low flow and high-water temperatures is important for maintaining thermal heterogeneity in the system (Majerova et al., 2020). In an effort to build on the findings of Majerova et al. (2015), this report adds seven years of data (2011 to 2018) to the initial 3 years of data (2008-2010) shown in Majerova et al. (2015). The study area includes a 1,250-meter reach of Curtis Creek in Northern Utah. This dataset includes measurements before dam construction had begun (2008), during many years of construction and partial breaching (2009 – 2015), and after the beaver dams were abandoned (2016 – 2018). This unique data set provides insight regarding the long-term effects of beaver dam complexes on discharge, water temperature, and groundwater exchanges.

Site Description

Curtis Creek is a tributary of the Blacksmith Fork River located in northern Utah and drains a portion of the Bear River mountain range (Figure 1). The lower portion of Curtis Creek is in a relatively broad mountain valley with a coarse-grained alluvial fan made up of gravel, cobbles, and boulders with some sediments (Majerova et al., 2015).

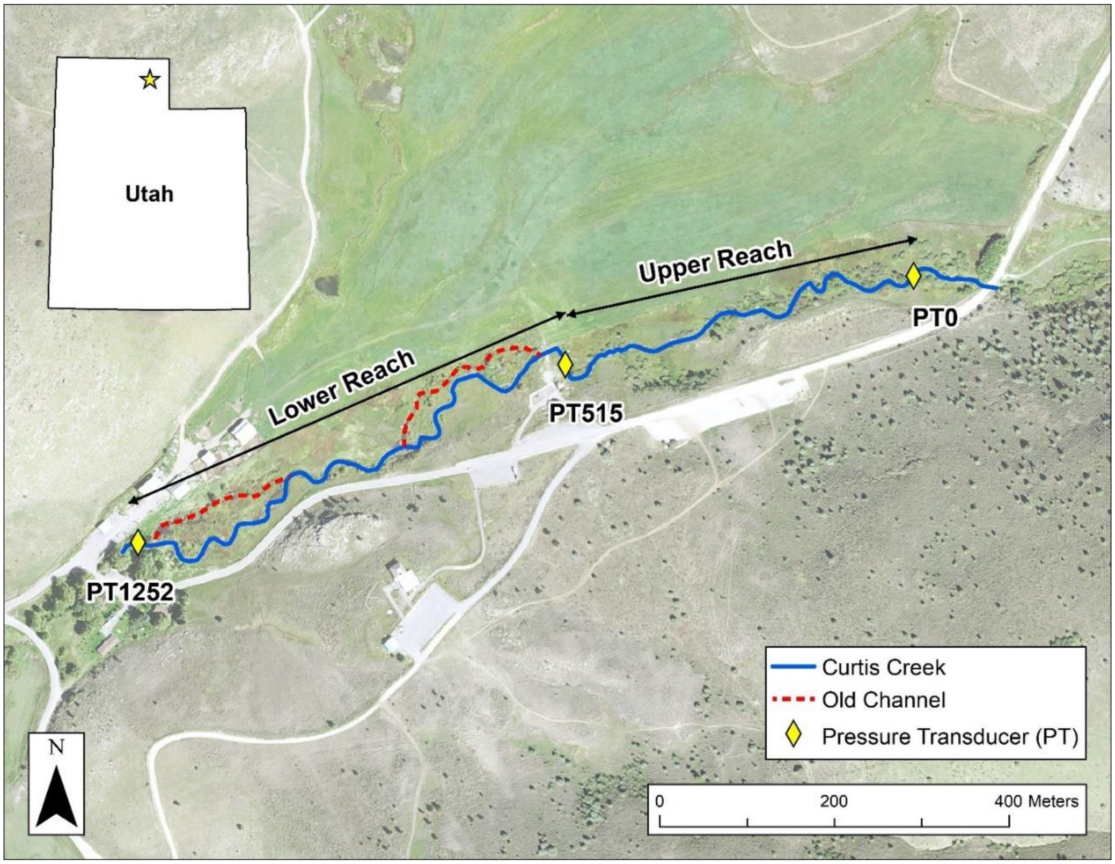

Figure 1. Lower Curtis Creek located in northern Utah. Curtis Creek was realigned by UDWR in 2001 to the current channel. The old channel shown in the figure is the channel that UDWR abandoned when the Curtis Creek was realigned. Due to shallow groundwater seeps and surface irrigation, some water continuously flowed in the old channel.

Curtis Creek is a second order, snowmelt dominated watershed with annual high and low flows of approximately 1,800 Ls^{-1} and 200 Ls^{-1}, respectively (Majerova et al., 2015). During the 2008-2018 study period, spring high flows and summer low flows were highly variable. This included an unusually wet 2011 that resulted in high flows reaching approximately 5,000 Ls^{-1} that resulted in substantial flooding and overbank flow. 2017 was also an unusually wet year with a baseflow approximately 10 times greater than the other years.

This study focuses on data collected along approximately 1,250 meters of lower Curtis Creek that flows through Hardware Ranch, a wildlife management area managed by the Utah Division of Wildlife Resources (UDWR), approximately 15 miles east of Hyrum, Utah. In 2001, UDWR rerouted parts of the lower section of the study reach, leaving some portions of the creek abandoned (shown as Old Channel in Figure 1). The banks of the new channel were reinforced with boulders, root wads, logs, and erosion control blankets. The rerouted portion of Curtis Creek has a strong meander that has an average bed slope of 0.017. Additionally, there is a canal used to flood irrigate a field adjacent to the floodplain north of Curtis Creek. Irrigation usually takes place from mid-May to late-September and excess water has been observed to traverse the entire field and cause increases in discharge at various locations over the study reach from return flows (Majerova et al., 2015).

In past years, Hardware Ranch allowed heavy grazing from the elk near the banks of the Curtis Creek, resulting in little to no riparian vegetation in the lower portion of the reach. Around 2005, UDWR constructed a fence preventing any elk from grazing near the creek banks. The fence allowed some regrowth of woody vegetation, primarily willows, along the creek. It is expected that this regrowth of willows helped attract beaver to the area (Majerova et al., 2015) because this was the primary material used in dam construction.

Three pressure transducers were installed within the study reach, PT0, PT515, and PT1252, where the numerical portion of the designation indicates river meters downstream. PT0 and PT1252 were used to denote the beginning and ending of the study reach. PT515 was used to separate the study reach into the upper and lower reaches (Figure 1).

The first beaver activity was reported in the lower reach in 2009. Beaver activity steadily grew from 2009 and peaked in 2015. The beavers were then removed between the winter of 2015 and spring 2016. The lack of beaver to maintain the dams resulted in all the dams breaching or washing out in 2016 and further degradation occurred during the 2017 high flow year through 2018 when measurements ceased.

Upper Reach. The upper reach is approximately 500 meters long with a relatively narrow, 2 to 4-meter wide, cross section. The upper reach has significant riparian vegetation comprised mainly of willows and trees. It also has a slightly steeper channel slope than the lower reach. North of this portion of the reach are several groundwater seeps that drain to the creek. Data collection began in 2008 before there was any beaver activity reported in the area. This allowed for data to be collected through 2008 and most of 2009 before there was any beaver activity in the study area. This period of data allowed for the base differences between the upper and lower reaches to be identified. Knowing the initial differences between the two reaches allowed the upper reach to be used as a control reach with no beaver activity initially reported. However, the beaver constructed four dams in the upper reach (Figure 2) from 2014 to 2015. The upper reach was thus not a useful control during these years. All four dams were constructed in the lower half of the upper reach, near PT515. An additional dam was built upstream of PT0 in 2015, outside of the study reach, that appeared to influence measurements at PT0.

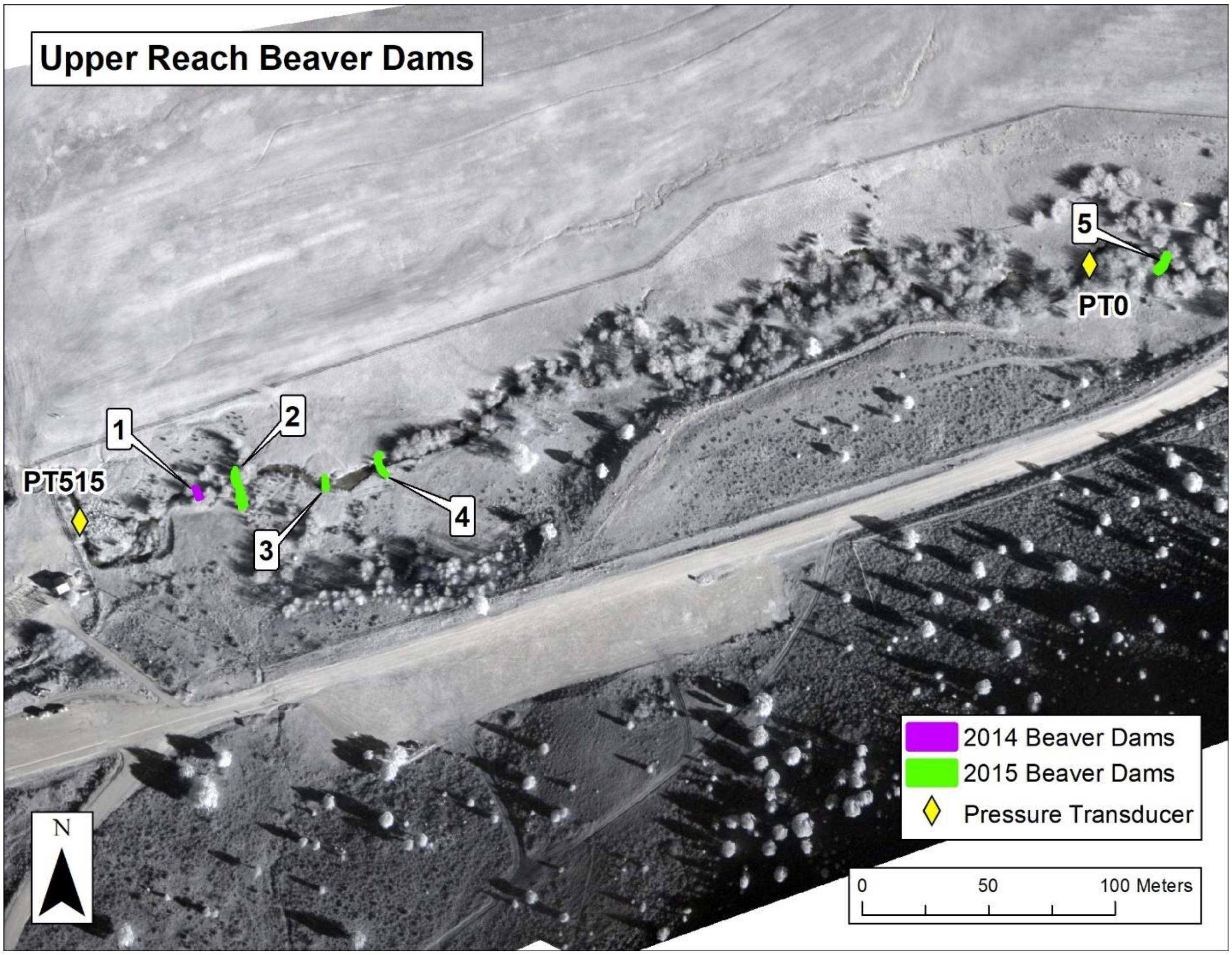

Figure 2. Curtis Creek Upper Reach with dam locations and dates shown.

The first beaver dam in the upper reach was built in 2014 (Figure 2, Dam 1). This dam was the farthest downstream in the upper reach, was built in a relatively narrow section of the creek and breached in 2016. The three other dams in the upper reach were built in 2015. The largest dam (Figure 2, Dam 2) was initially constructed in August 2015. Through the spring of 2016, this dam grew significantly and pushed a large amount of water into the floodplain. By August 2016, due to lack of maintenance, the dam breached resulting in the pond draining, sediments being transported downstream, and the creek slowly returning to the original channel.

The next upstream dam (Figure 2, Dam 3) was constructed in August 2015. This dam was small and created some backwater, but did not overflow into the floodplain. Dam 3 was washed out sometime during the summer in 2016. The final dam built in the upper reach in 2015 was Dam 4. This dam was larger than dams 1 and 3 and created substantial backwater and floodplain inundation. Like the other dams in the upper reach, Dam 4 breached in 2016.

It should be noted that a single beaver dam was built upstream of PT0, just outside the study reach (Figure 2, Dam 5). This dam was initially a beaver dam analog (BDA) installed by the Utah Department of Natural Resources (DNR) on May 5, 2015. A BDA consists of posts driven into the channel bed and banks that are hand-woven with willow branches to mimic a beaver dam. The

BDA created a 0.5 to 1-meter head gradient in the creek. The DNR removed the BDA on August 31, 2015; however, the beaver built a new dam in the same location in the fall 2015 (Dam 5). The new, beaver-built dam was also breached sometime in the fall 2016.

Lower Reach. The lower reach is approximately 750-meters long with a slightly lower channel slope than the upper reach. The lower reach also has little riparian vegetation, when compared to the upper reach, comprised mainly of grasses, shrubs, and small willows. Significant beaver activity was recorded in the lower reach from 2009 to 2015. The beaver activity began at the downstream end of the lower reach in 2009. The dams that continued to be built were placed further and further upstream and resulted in many beaver dams being built downstream of PT515 in 2015. Over the study period, 46 beaver dams were reported in the lower reach (Table 1). Each of the years are discussed in more detail with the associated figures.

Table 1. Number of beaver dams built, breached, and total number of dams in the lower reach in each year of the study period.

Year	Dams Built	Dams Breached	Total Annual Dams
2008	0	0	0
2009 (Figure 3)	3	0	3
2010 (Figure 4)	6	0	9
2011 (Figure 5)	0	3	6
2012 (Figure **6**)	4	0	10
2013 (Figure 7)	7	0	17
2014 (Figure 8)	8	0	25
2015 (Figure 9)	18	0	43
2016 (Figure 10)	0	43	0
2017	0	0	0
2018	0	0	0

By 2016 beaver activity ceased (due in part to trapping). The lack of dam maintenance resulted in all the dams being breached or completely washed out by the end of the fall 2016. No sign of new beaver activity was present throughout 2016. In 2017, additional deterioration of dams occurred due to high spring runoff, and there was again no sign of activity throughout the year.

Beaver Dams in 2009. Three beaver dams were built in the lower reach in 2009 (Figure 3). These were the first dams reported in the lower reach. Dam 1, the most downstream dam, was built in June 2009. This dam was continually maintained through the study period until the beaver were trapped in 2016, and it breached soon after. Dam 2, the central dam, was built in August 2009. Dam 2 was regularly maintained from its construction until 2016 when it breached due to a lack of maintenance. Dam 3, the most upstream dam, was constructed in July 2009. Dam 3 was maintained continually from 2009 to 2011. From 2011 to the spring 2014 the dam was not maintained, but did not breach or wash out. During the summer of 2014, it started being maintained and was raised approximately 30-cm. The dam was raised again in the spring of 2015 resulting in water spilling onto the floodplain. Dam 3 was also breached in 2016.

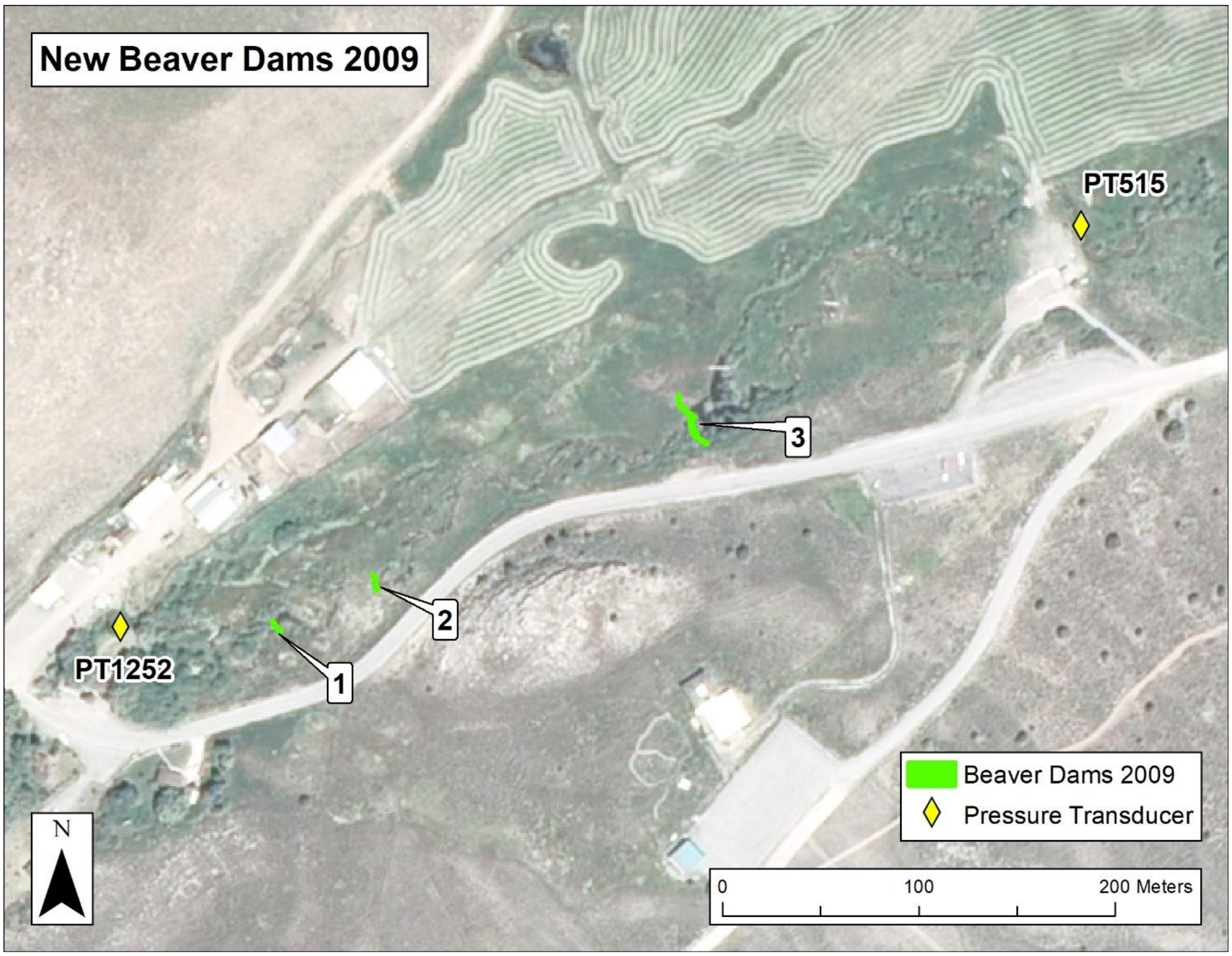

Figure 3. New beaver dams in the lower reach in 2009.

Beaver Dams in 2010. Six new beaver dams were built in the lower reach in 2010 (Figure 4). Dam 4 was the most downstream dam built in 2010. In 2014, Dam 4 was expanded farther across the creek and was present until 2016 when it breached. Dam 5 was a smaller dam built in 2010. This dam was regularly maintained from 2010 to 2016 and breached in 2016. Dams 6, 7, and 8 were each built during the summer of 2010. These dams were maintained from 2010 to 2011. During 2011, these three dams were washed out as a result of high spring discharge. Dam 9 was the furthest upstream dam built in 2010. This dam breached in 2011 and again in 2013. After each of these breaches, the dam was rebuilt. During the spring of 2014, Dam 9 breached again and almost completely washed away. Dam 9 was not rebuilt after 2014.

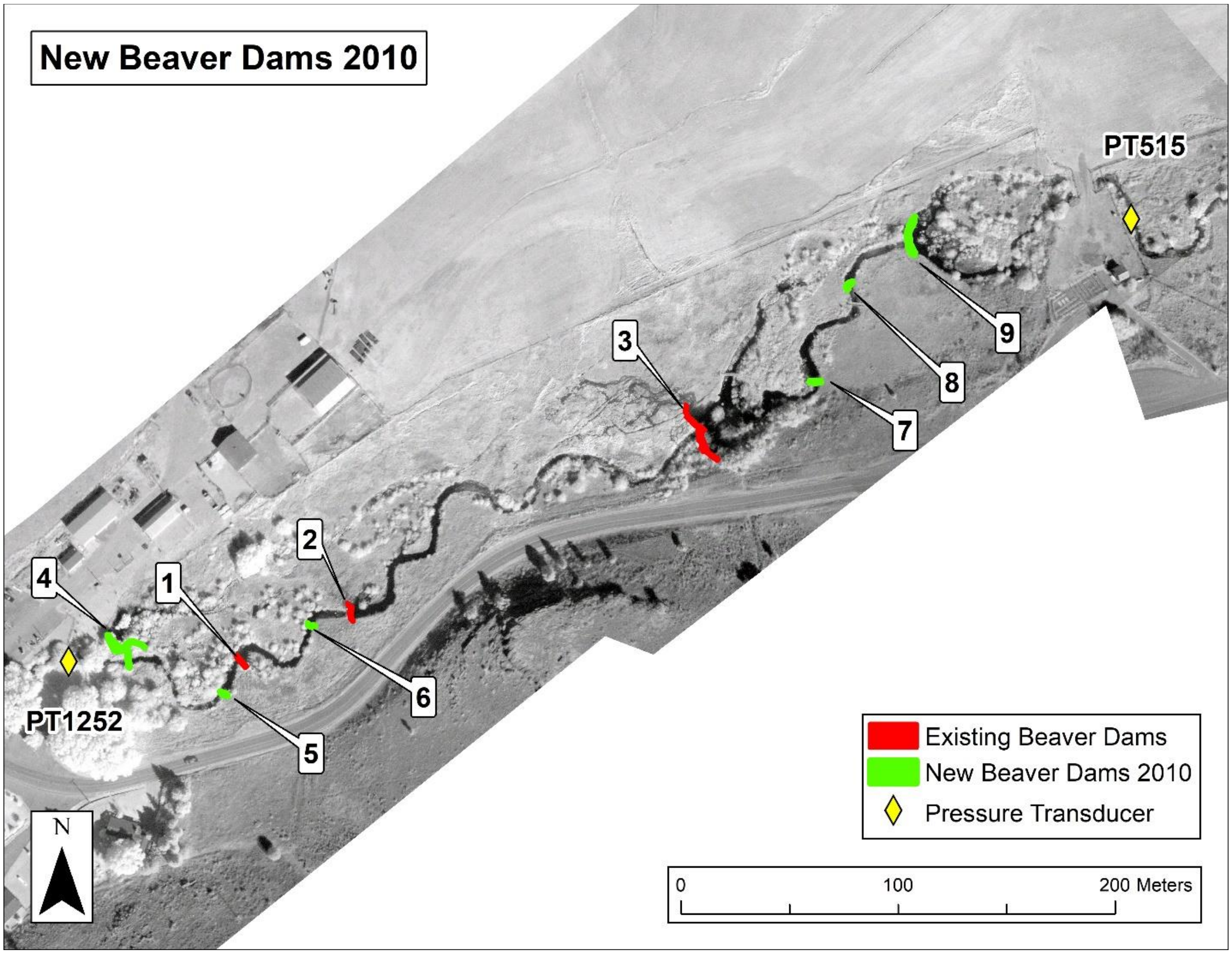

Figure 4. New and existing beaver dams in the lower reach in 2010.

Beaver Dams in 2011. No new beaver dams were built in 2011 (Figure 5). As noted previously, dams 6, 7, 8, and 9 washed out from the high discharge in 2011. Dam 9 was rebuilt after it washed out in 2011. Dam 9 breached again in 2013 and was almost completely gone after the spring of 2014. By 2016, dam 9 was completely gone.

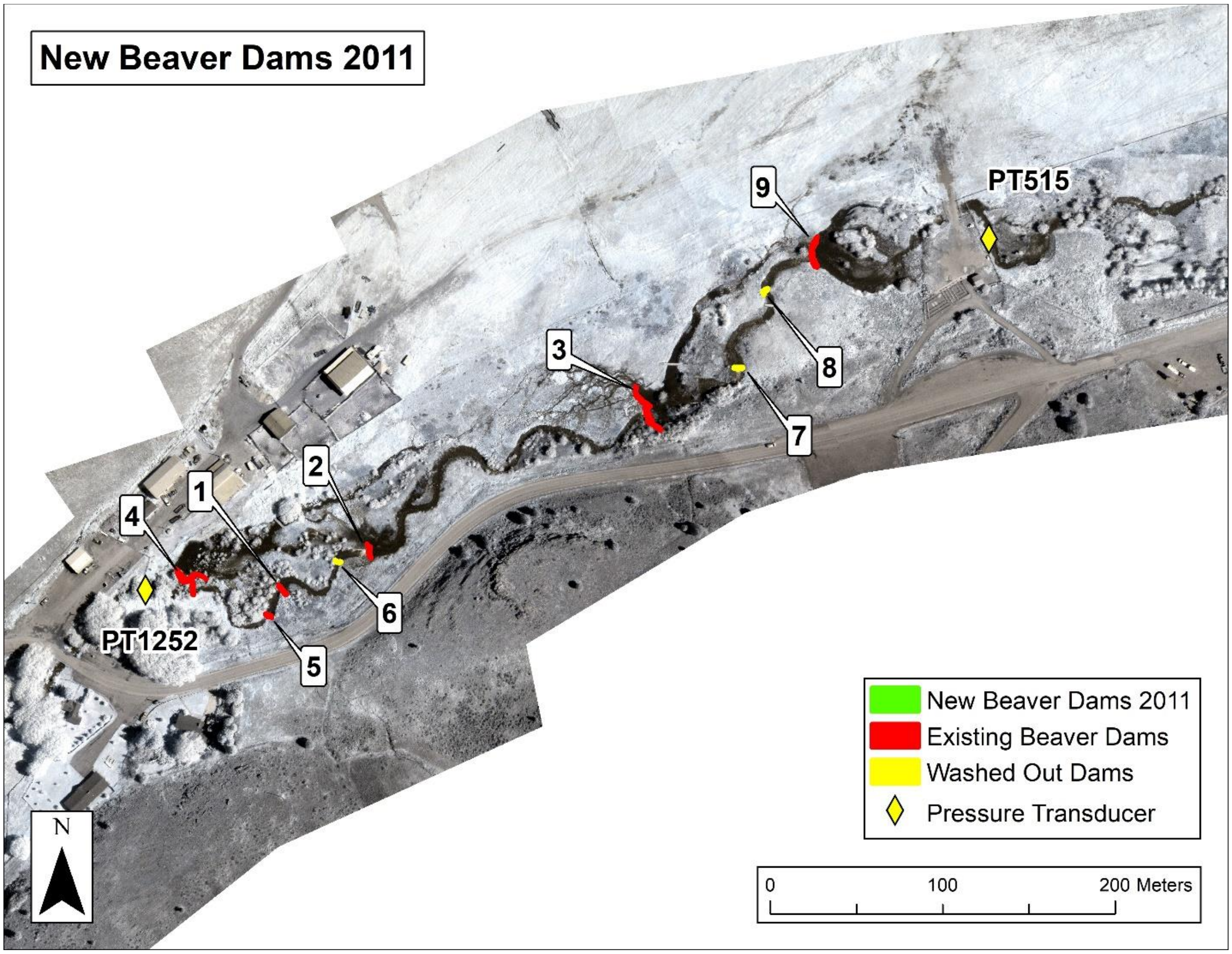

Figure 5. New and existing beaver dams in the lower reach in 2011.

Beaver Dams in 2012. Four new beaver dams were built at the downstream end of the lower reach in 2012 (Figure 6). This downstream section of the lower reach contains a small area of land that is located between the old and relocated channels. The area in between the channels is only slightly higher in elevation and, when the discharge was high enough, water would flow between the channels and eventually it scoured many new smaller side channels. A combination of these side channels scouring down and increased water surface elevations in the primary channel due to downstream beaver dams led to water regularly flowing between these channels. The four dam complexes built in 2012 were in these new side channels and the old channel. These dams were relatively small and remained in place until 2016 when the dams washed out.

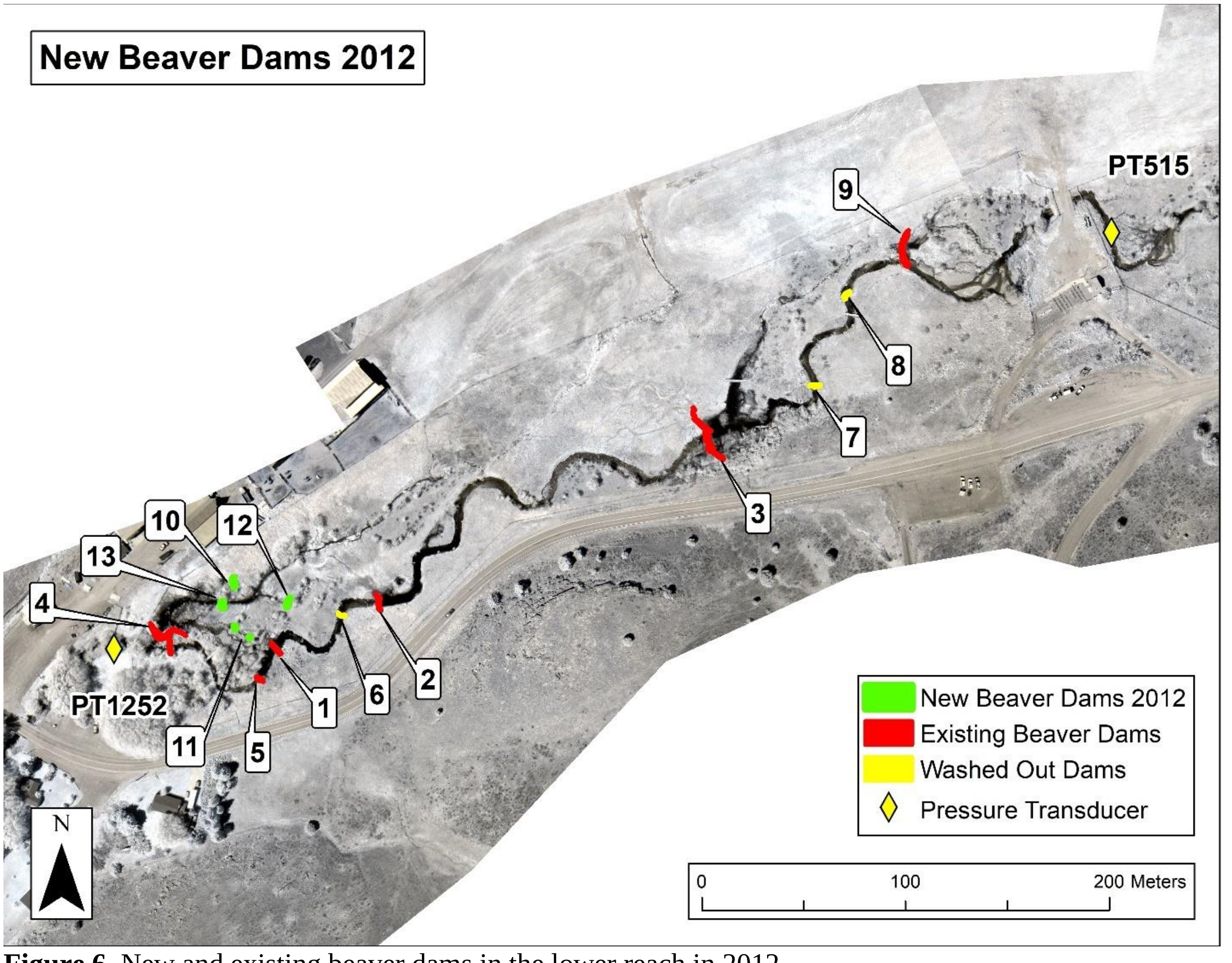

Figure 6. New and existing beaver dams in the lower reach in 2012.

Beaver Dams in 2013. Six new dams were built in the downstream end of the lower reach in 2013 (Figure 7). An additional dam (Dam 14) was built in the spring of 2013 just downstream of PT1252, outside of the lower reach. This dam was removed in November 2013 to prevent the backwater created by the dam from influencing PT1252. Dam 14 was rebuilt in the fall of 2014 and was removed again at the end of April 2015. Dam 15 was built under a bridge across the creek in 2013; however, the bridge and dam were removed in November 2013. Dam 16 was built and removed multiple times from 2013 to 2014 and breached in 2016. Dams 17, 18, 19, and 20 were built in 2013 and naturally breached in 2016.

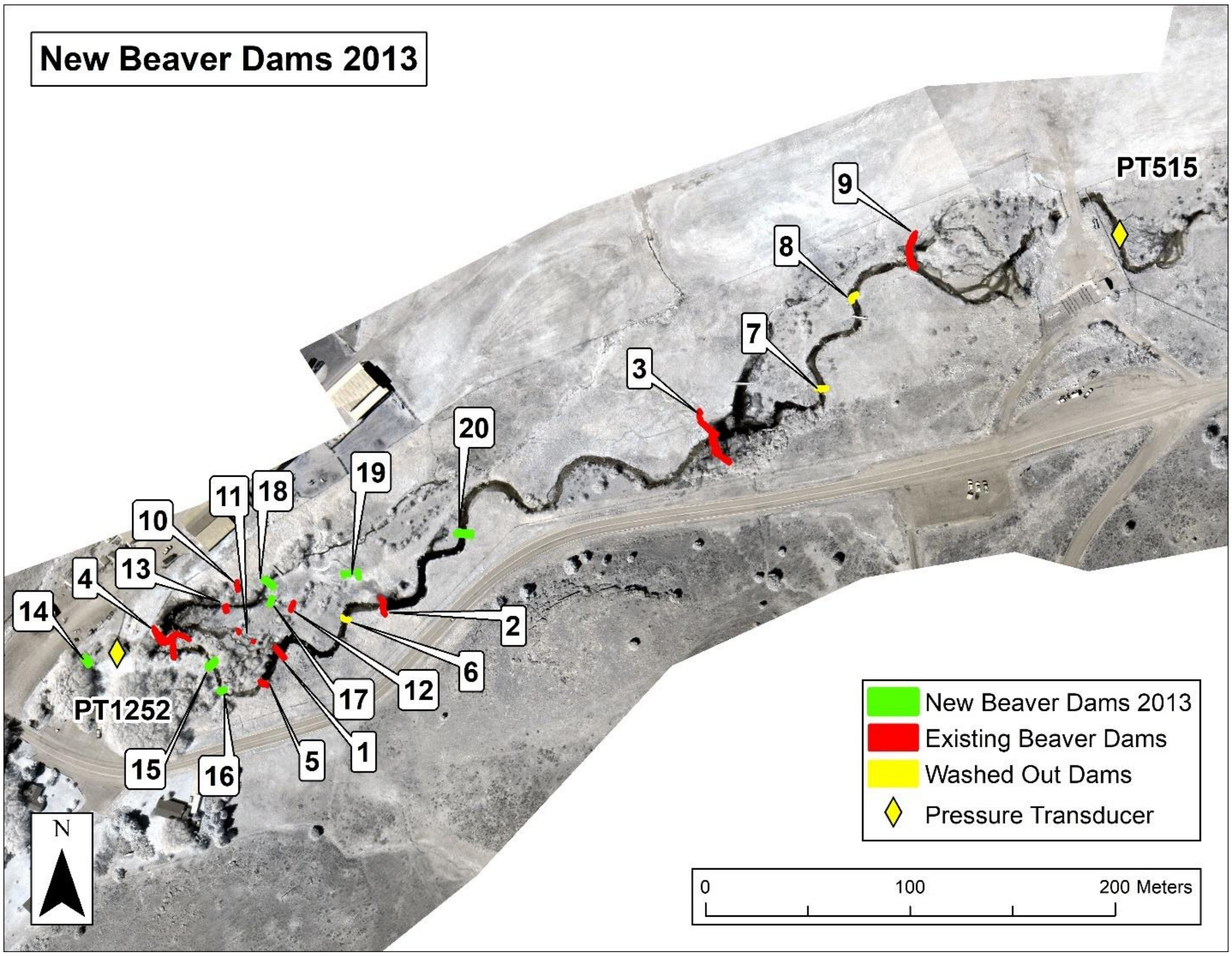

Figure 7. New and existing beaver dams in the lower reach in 2013.

Beaver Dams in 2014. Eight new dams were built in 2014 (Figure 8). These dams showed a shift from the downstream to mid and upstream sections of the lower reach. Dams 21, 23, and 27 were built in 2014 and were washed out by 2016. The date that these dams breached or washed out was not recorded. Dams 22 and 25 were built in 2014 and expanded in 2015. As with the other dams, these dams breached during 2016.

Dam 24 was only the base of a dam and was not completed. The dam base was not present in 2016. The date that the dam washed away is unknown but occurred sometime between 2014 and 2016. Dam 26 was a small structure consisting of soft plants and some woody material including what appeared to be a fence post and was not present in 2016. Dam 28 was built in the culvert under the bridge, plugging the culvert, in 2013. The backwater created by the dam submerged PT515. The dam was removed at the end of April 2015 but was immediately rebuilt. The dam was again removed in September 2015 and was rebuilt again.

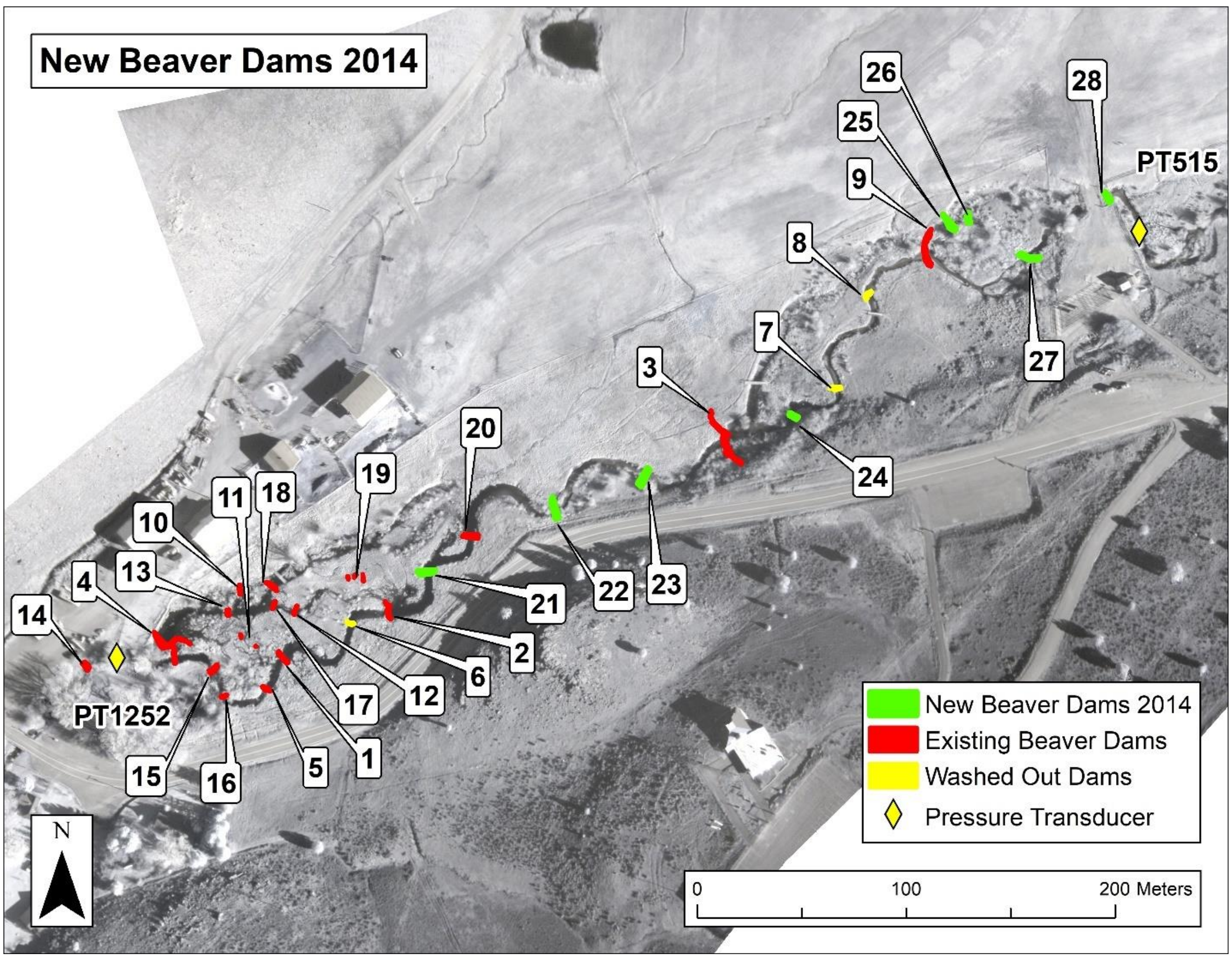

Figure 8. New and existing beaver dams in the lower reach in 2014.

Beaver Dams in 2015. Significant beaver activity was recorded in 2015, especially in the upstream section of the lower reach. 18 new dams were surveyed in 2015 (Figure 9). Most of these dams were relatively small, but still caused floodplain inundation. All the dams constructed in 2015 were breached or washed out in 2016. Dam 42 was the largest dam built in 2015 and caused flooding back to Dam 44. Dam 44 was large enough to cause a relatively constant flow of water into the old channel. Dam 47 filled the culvert under the road just upstream of the dam.

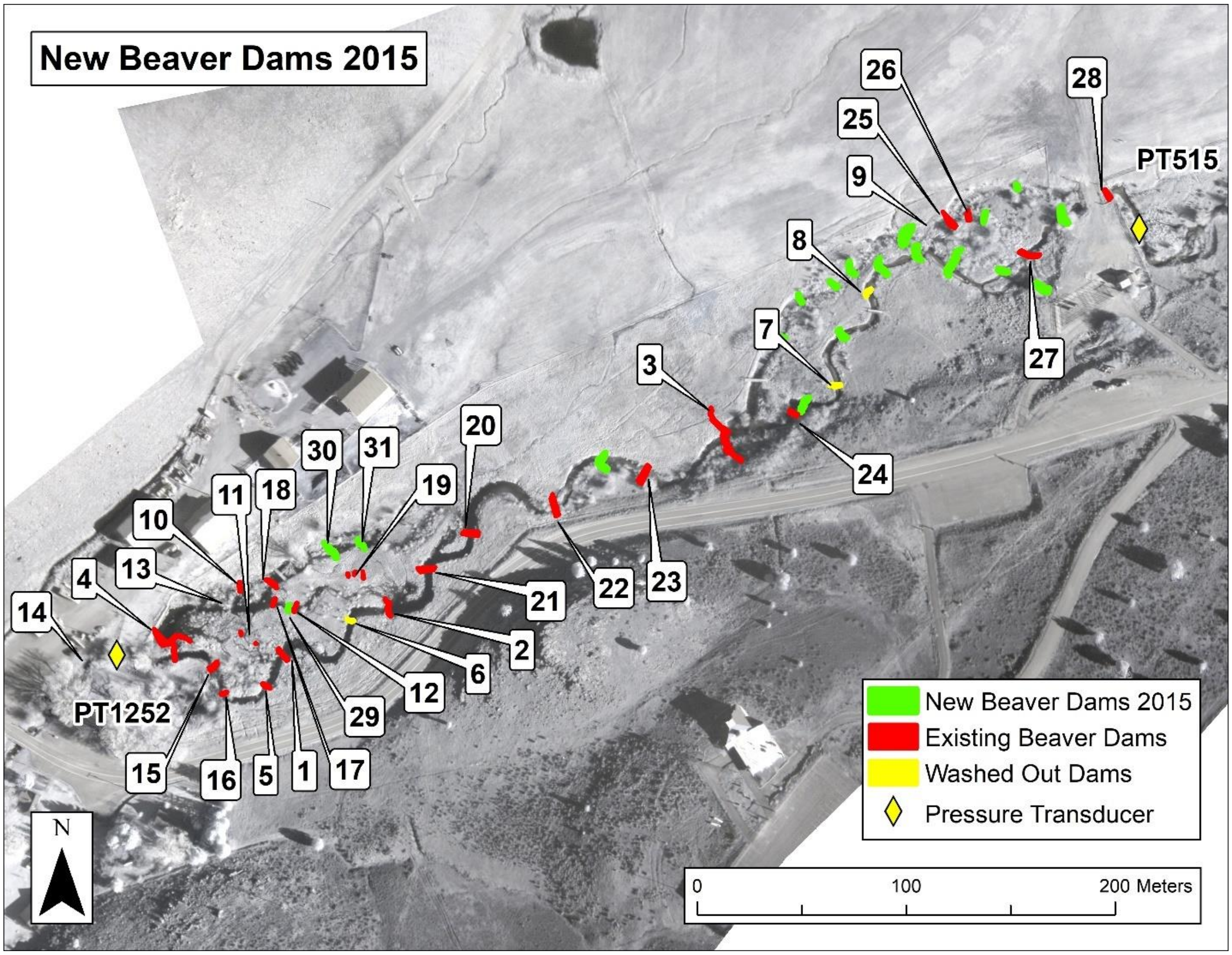

Figure 9. New and existing beaver dams in the lower reach in 2015.

Beaver Dams in 2016. As noted, during the end of 2015 and the beginning of 2016 the beaver were trapped and removed from the area. The removal of the beaver meant that the dams were no longer maintained and resulted in the remaining dams either breaching or washing out during 2016 (Figure 10).

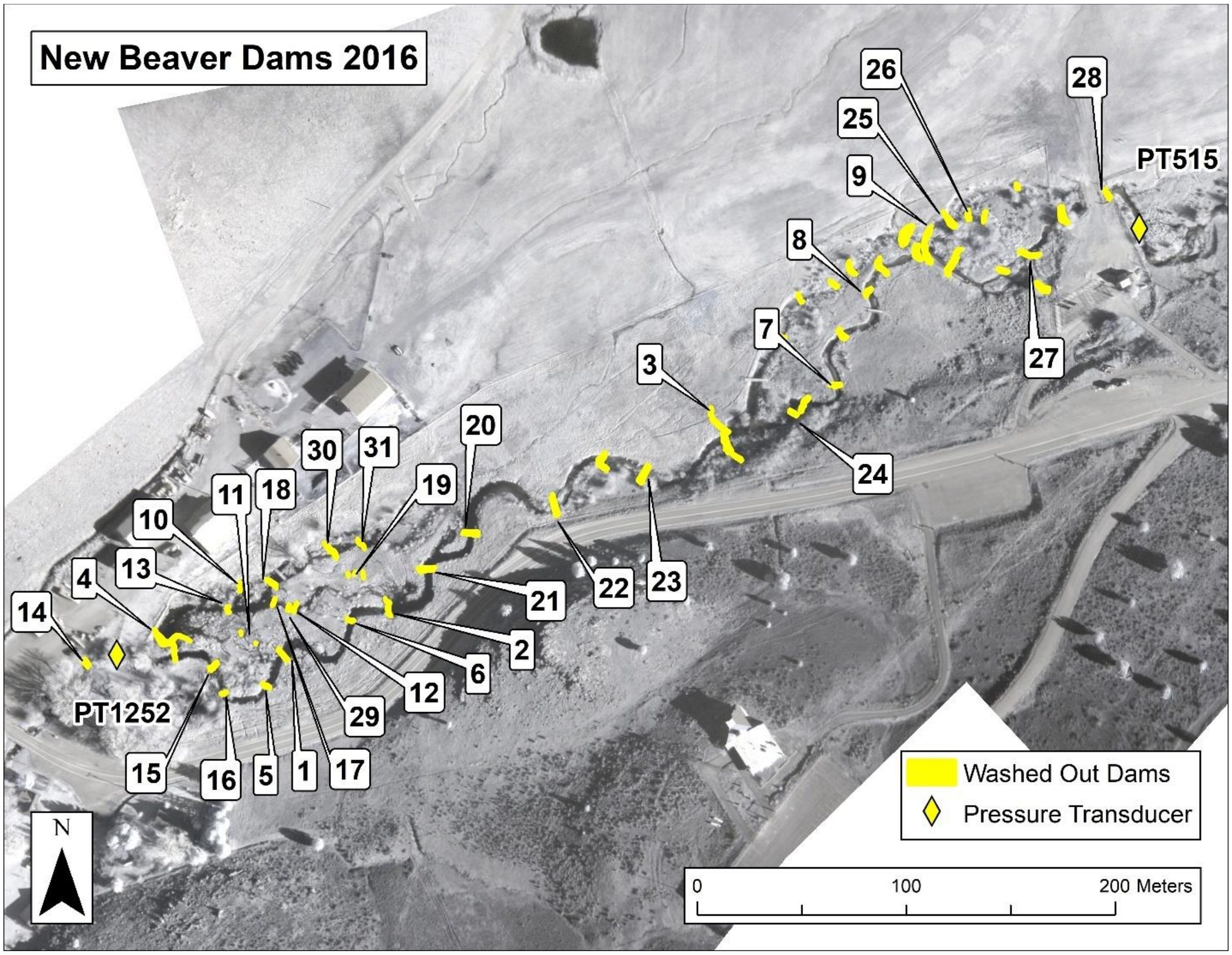

Figure 10. Beaver dams breached in the lower reach in 2016.

No beaver activity was reported within the study reach during 2017 and 2018; however, during site visits in 2020 there was significant beaver activity in the downstream portion of the lower reach. This recent activity included the construction of two new beaver lodges and a dam stretching approximately 20 meters long between the old channel and the current channel in the lower reach.

To help visualize the longevity and potential impact of the dams built in the lower reach, the duration (year of construction through the year the dam breached) of each dam was plotted (Figure 11) for the lower reach. All but three of the dams in the lower reach breached in 2016. The other three dams breached in 2011.

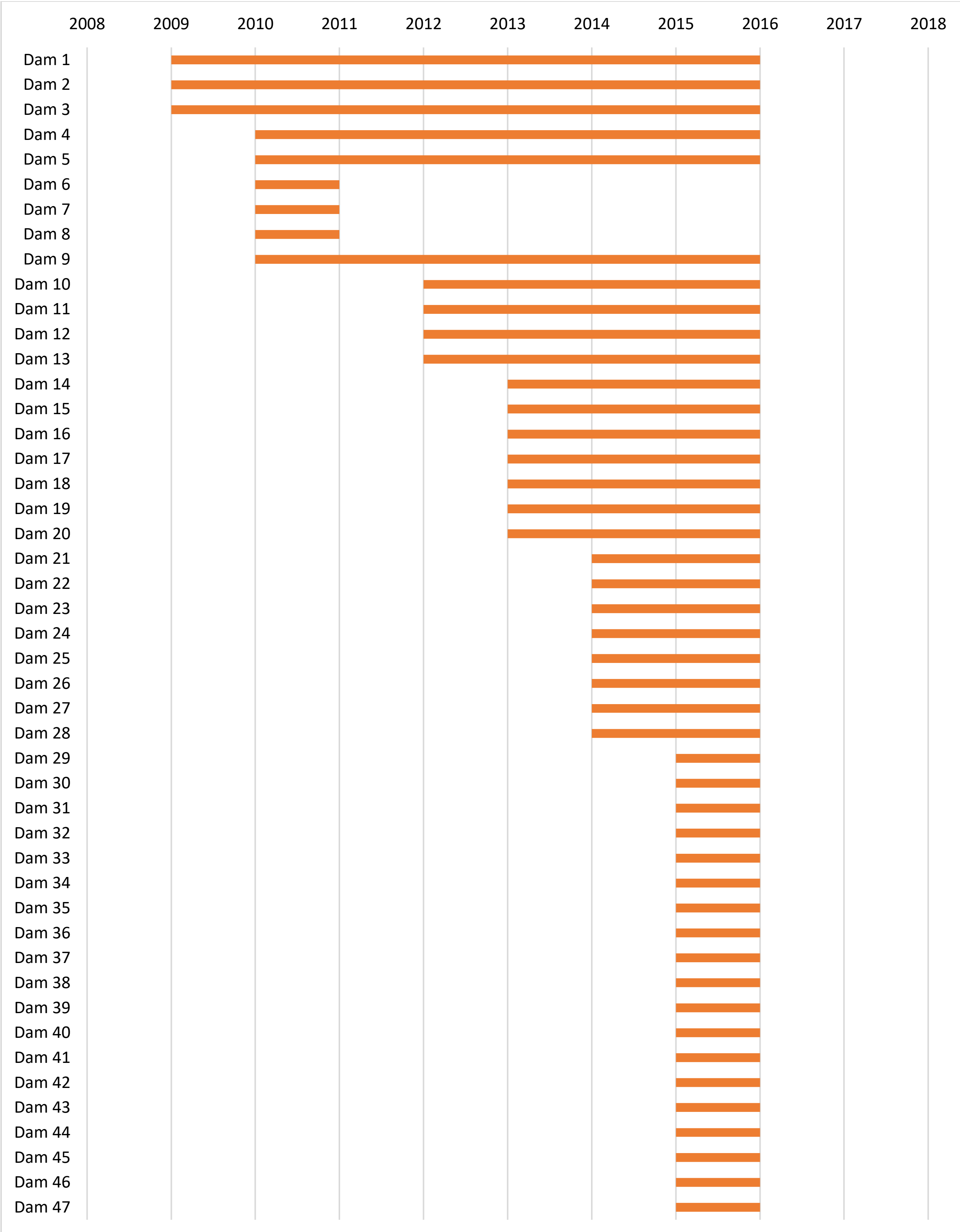

Figure 11. Age and overlap of the dams in the lower reach.

Methods

Three pressure transducers were installed in the study reach as described previously. These pressure transducers were used to measure water depth and temperature. The water depth was used to estimate the discharge using rating curves developed for each pressure transducer station. The methods for the data collection and analysis are described in this section.

Data collection. The pressure transducer used to record water depth at PT0 was a Campbell Scientific SPXD 600 Pressure Transducer and was installed in 2007. As noted, this pressure transducer was replaced with a SPXD 610 in 2009. A SPXD 610 was installed at PT515 (2008) and PT1252 (2007). The SPXD 610 was capable of recording water temperature while the SPXD 600 was not. The SPXD 610 had water temperature accuracy of ±0.2°C, and both pressure transducers had water depth accuracy of ±0.1%. PT515 and PT1252 were installed in 2008 and 2007, respectively.

As the pressure transducers aged, they were replaced with Campbell Scientific CS 451 pressure transducers installed in 2014. The CS 451 pressure transducers were also rated for water temperature accuracy of ±0.2°C and water depth accuracy of ±0.1%. Both the SPXD 610 and the CS 451 pressure transducers were paired with Campbell Scientific CR-206 data loggers. The CR-206 data loggers were programmed to measure water temperature and depth every 30 seconds and record the average temperature and depth every five minutes (Majerova et al., 2015).

At each of the pressure transducers, field discharge measurements were taken at different flowrates over the study period using either a Marsh McBirney Flow-Mate 2000 or a SonTek Flow Tracker. These units were used to measure the water velocity across the channel, and then the velocity-area method was used to calculate the discharge of the creek (Majerova et al., 2015).

Data Analysis. To estimate the discharge in Curtis Creek over time, rating curves were developed for each of the pressure transducer stations. A rating curve is used to determine the discharge in a river at a given water depth and location along the channel. The rating curves and confidence bounds were developed following the methods described by Schmadel et al. (2010) and Majerova et al. (2015). These methods use a power function (Equation 1) to describe the discharge in a river as a function of water depth.

$$Q = aZ^b \qquad \text{(Equation 1)}$$

Where:
a and b are coefficients from the rating curve
Q is the discharge (Ls^{-1})
Z is the water depth reported by the pressure transducer (m)

To determine the a and b coefficients, a power function trendline was applied to the discharge measurements to establish the rating curve over a period when channel conditions were stable for each pressure transducer station. Following the methods outlined in Schmadel et al. (2010), the

95% confidence bounds for each rating curve were also established. These confidence bounds were later used to determine the confidence intervals for calculated discharges and potential gains or losses over a reach. The rating curves developed for each pressure transducer changed over time due to changes in the channel geometry or movement of the pressure transducers to new locations. Explanations for adjustments to the rating curves are documented in Appendix A.

Discharge Data. Using the rating curves, discharge in Curtis Creek was calculated at each pressure transducer station over time. The discharge data represents conditions before any dams were constructed (2008), during construction and various stages of dam maintenance (2009-2015), and after the dams were no longer maintained (2016-2018). The ten-year time series of discharge data provide some context of the variability of flow from year to year. During the colder months (typically November through March) the creek periodically froze, resulting in inaccurate pressure transducer measurements. Therefore, the discharge in the study reach was plotted for a subset of each year (April 1 to November 1). Spring runoff in the area usually begins to increase discharge in April and typically peaks in May. As water temperatures are most affected during low flows, additional plots were created for discharge from July to October of each year.

As noted previously, discharge in the creek ranges from approximately 200 to 1,800 Ls^{-1}. The raw data collected by the pressure transducers contained anomalous values that resulted in calculated discharges in excess of 28,000 Ls^{-1}. These values were removed and replaced with an average of the data values immediately before and after the invalid measurement. This process was automated using a computer script to isolate any discharge value greater than 14,000 Ls^{-1}. Given the relatively stable nature of the flows during the relevant times of year in this watershed (July through October), this approach is reasonable. A more detailed explanation of the quality control process for developing this script is provided in Appendix B. These were the only changes made to the discharge data.

To provide insight into the reach scale groundwater exchanges occurring over these different phases of beaver dam complex development and flow conditions, the change in discharge (ΔQ) and percent change in discharge ($\%\Delta Q$) for the upper reach (PT0 to PT515) and the lower reach (PT515 to PT1252) were plotted. ΔQ was calculated by subtracting the discharge calculated at the downstream pressure transducer from the discharge calculated at the upstream pressure transducer. The $\%\Delta Q$ was calculated by subtracting the calculated discharge at the downstream pressure transducer from the upstream calculated discharge and then dividing by the upstream discharge. These calculations are used to determine if the upper and lower reaches were gaining or losing. Gaining conditions, represented by a positive ΔQ and $\%\Delta Q$ values, occur when the discharge in the creek is increasing. The primary source for gains in this system is groundwater or excess irrigation from the field adjacent to the creek. Losing refers to a decrease in discharge, is primarily due to river water recharging groundwater in this system, and is represented by negative ΔQ and $\%\Delta Q$ values.

Water Temperature. To understand the influence of the various states of beaver dam complexes and the relationship to instream temperature variability, we examined temperatures at the extents of the upper and lower reach. To do this, average daily temperatures derived from the 5-minute pressure transducer data were plotted from July 1 to October 1 for each year.

Similar to the pressure data, the water temperature data contained inaccurate measurements with water temperatures recorded in excess of 50 °C. Quality control for the water temperature data was automated by using a computer script to isolate any temperature value greater than 30°C. These values were removed and replaced with an average of the data values immediately before and after the erroneous measurement. A more detailed explanation of the quality control process for developing this script is provided in Appendix B.

In addition to plotting the average daily water temperature at each pressure transducer, the average hourly change in temperature (ΔT) and percent change in temperature ($\%\Delta T$) for the upper reach (PT0 to PT515) and the lower reach (PT515 to PT1252) were also plotted. ΔT was calculated by subtracting the water temperature at the downstream pressure transducer station from the upstream pressure transducer. The $\%\Delta T$ was calculated by subtracting the temperature at the downstream pressure transducer from the upstream pressure transducer water temperature and then divided by the upstream pressure transducer water temperature. The ΔT and $\%\Delta T$ in the upper and lower reaches were used to determine if the water temperature was warming (increasing) or cooling (decreasing) across each reach.

Weather Data. As noted previously, local weather conditions control heat exchanges at the air water interface and is, therefore, a primary factor in variation of water temperature (Sinokrot and Stefan, 1993; Webb et al., 2008). The primary weather components that affect or can help explain water temperature variations are solar radiation and air temperature. At the study site, solar radiation and air temperature were recorded by the weather station adjacent to the study reach every 15 minutes. This data was used to determine the average daily air temperature and total daily solar radiation. Solar radiation is significantly affected by cloud cover; therefore, the sum of the daily solar radiation was used instead of average daily solar radiation. The average daily air temperature and total daily solar radiation were plotted with the change in discharge and water temperature to help explain some of the water temperature patterns.

Air temperature, solar radiation, and water temperature fluctuate on an hourly basis. Although this report is primarily focused on the long-term changes in water discharge and temperature, it is important to recognize these within day cycles. To show these variations, the average hourly discharge, water temperature, air temperature, and solar radiation were plotted for a short period to highlight the shorter temporal scale variability.

Average Age of Beaver Dams. The age of the beaver dam gives an indication of the condition of the dam and the pool created by the dam. To help understand the impacts of the beaver dams, the average age of the beaver dams in each year were plotted. The average age of the dams was calculated by averaging the age, in years, of all the active beaver dams in each year. For example, if a dam was constructed in 2009 and had not breached or washed out by 2014, the dam would be five years old. All the dams breached or washed out in 2016; therefore, the average dam age in 2016, 2017, and 2018 was zero years.

Results

Similar to many other watersheds, the peak discharge in Curtis Creek varies significantly from year to year due to different snowpack and precipitation patterns. These annual differences in

discharge need to be accounted for when determining the effects of beaver dams on instream temperatures and flow regimes. To provide insight into the hydrologic variability present during this study period, the average daily discharge at each pressure transducer was plotted (Figure 12 and Figure 13). These plots show that 2011 and 2017 were unusually wet years with peak discharges more than double those of the other study years.

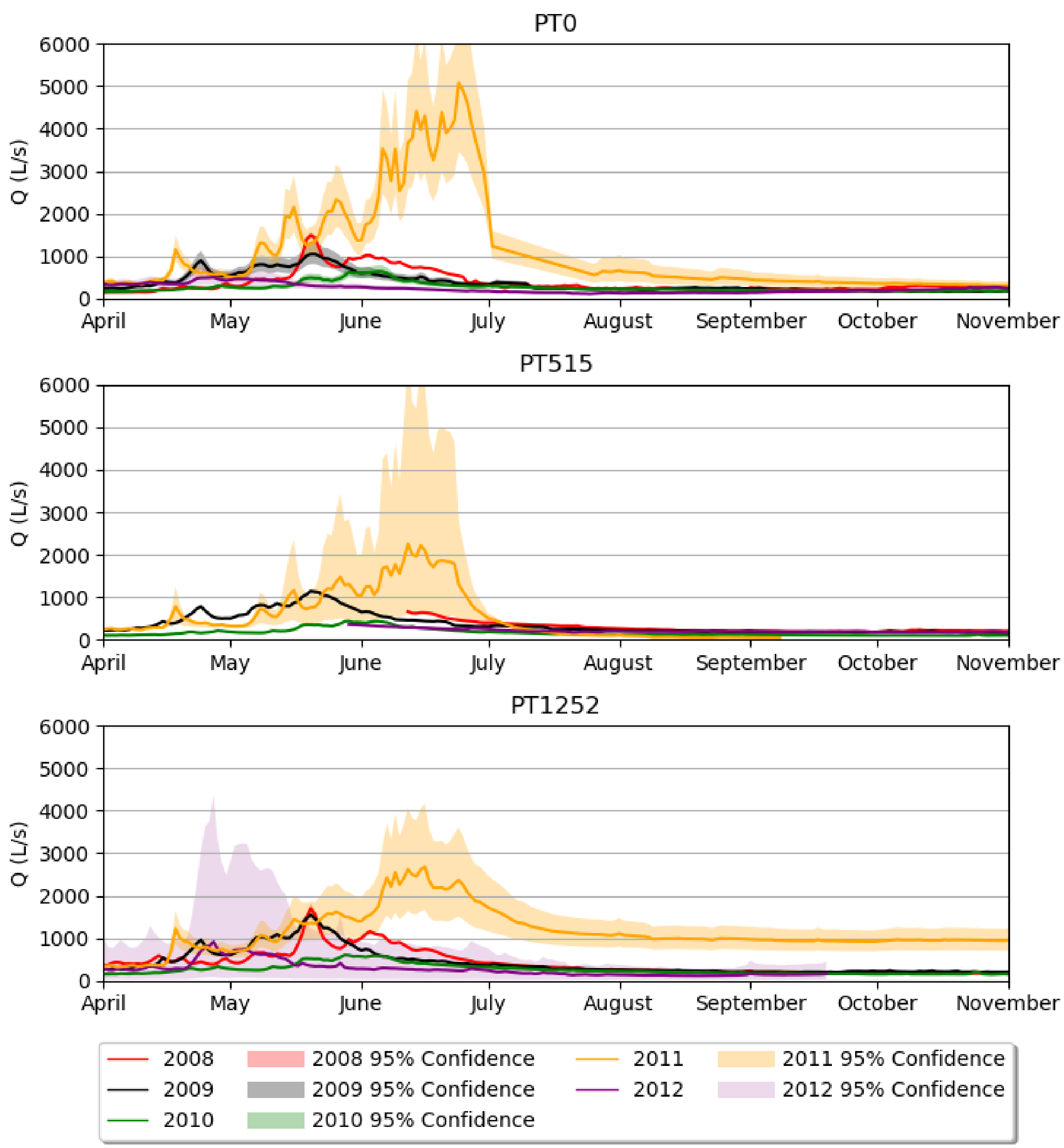

Figure 12. Discharge at PT0, PT515, and PT1252 from 2007 to 2012. As shown, the daily discharge varies significantly from year to year with 2011 being extremely high. To capture the annual variability of the other years, the maximum plotted discharge was set to 2,000 Ls^{-1}. Discharge was only plotted for the months of April to November due to freezing of the water in the colder months (December through March). The shaded areas represent the 95% confidence bounds for the flow estimates from the rating curves. The

confidence bounds are shown for each year in each plot; however, some bounds are too small to see on the plots above. Note that there is significant uncertainty in the rating curve associated with the very high flow years due to limited high flow measurements.

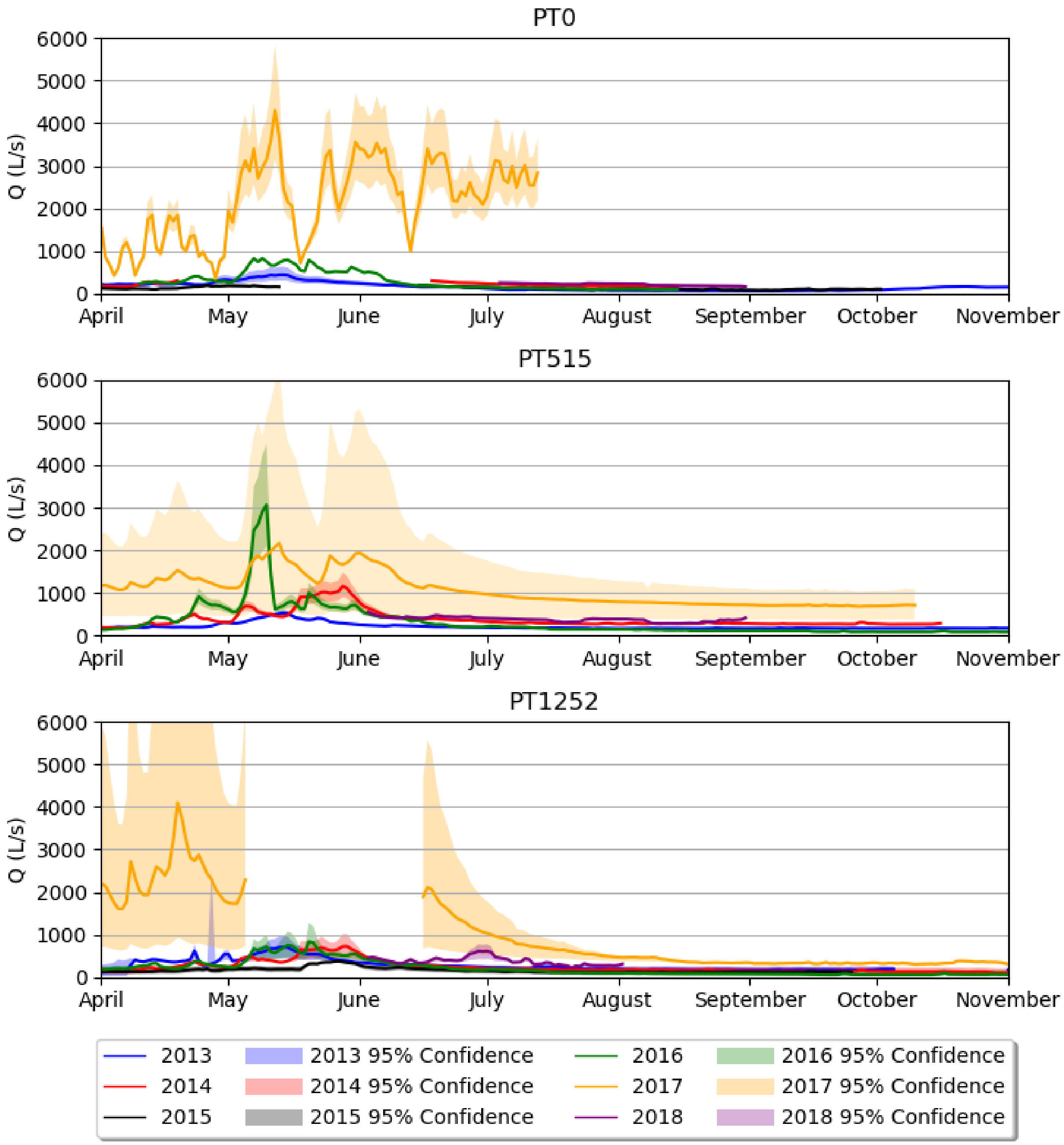

Figure 13. Discharge at PT0, PT515, and PT1252 from 2013 to 2018. As shown, the annual discharge varies significantly from year to year with 2017 being extremely high. To capture the temporal variability of the other years, the maximum plotted discharge was set to 2,000 Ls^{-1}. Discharge was only plotted for the months of April to November due to the water freezing in the colder months (December through March). The shaded areas represent the 95% confidence bounds for the flow estimates from the rating curves. Note that there is significant uncertainty in the rating curve associated with the very high flow years due to limited

high flow measurements. Also note that while the confidence intervals are included for every discharge, some are too small to be seen in the plot.

Although Figure 12 and Figure 13 are useful to determine the annual variability in discharge, surface water temperatures are most variable during periods of low flow. To determine the effects of the beaver dam complexes more accurately on discharge and water temperature, the average daily discharge was plotted again for the months of July to October during the Creek's baseflow conditions (Figure 14 and Figure 15).

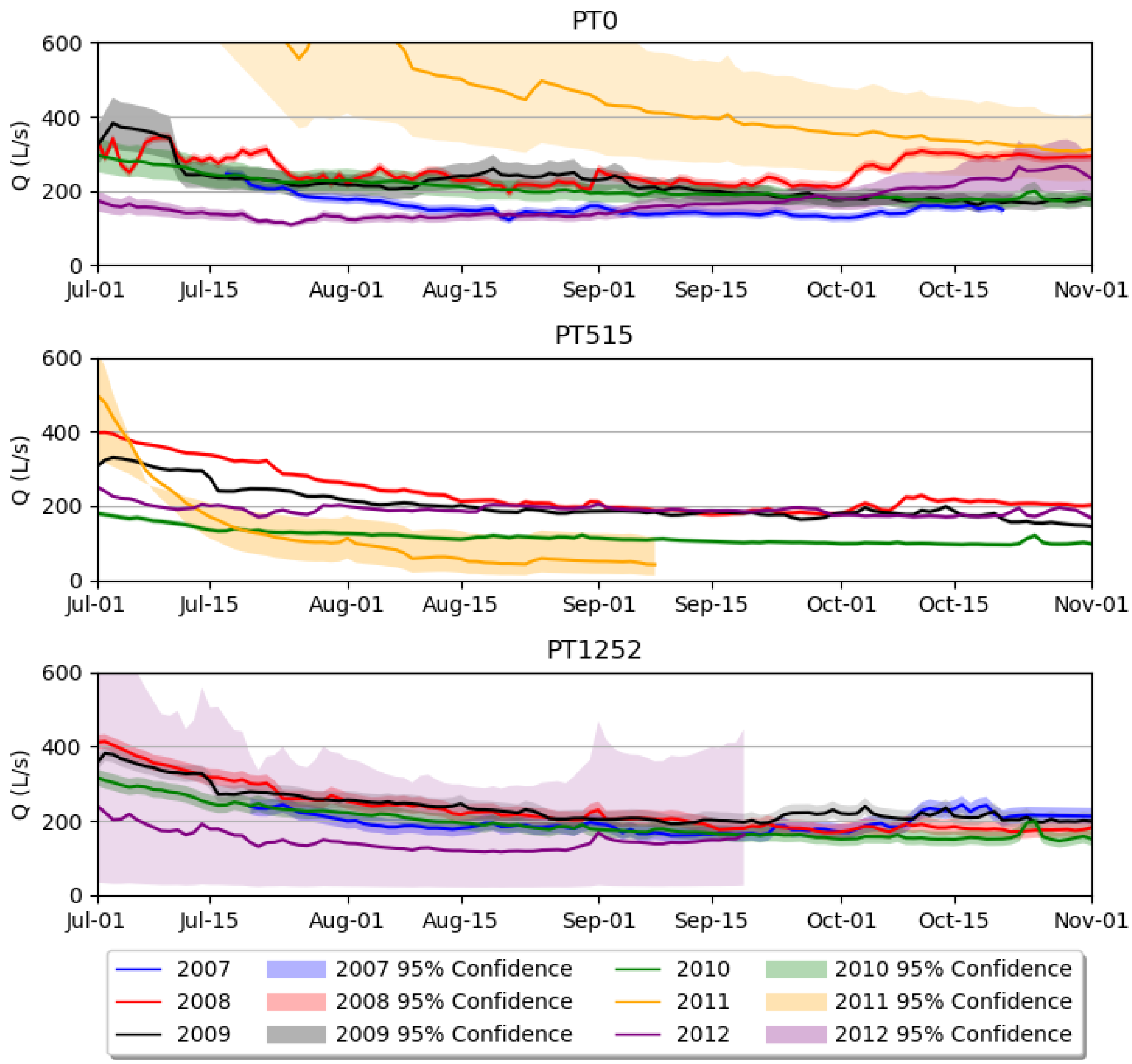

Figure 14. Average daily discharge at PT0, PT515, and PT1252 from 2007 to 2012 from July through October during summer baseflow. Note that the confidence bounds for most years are quite narrow, but for 2012 at PT1252 they are extremely large. This indicates that the data collected in 2012 at PT1252 is relatively low quality and will not be used in this analysis.

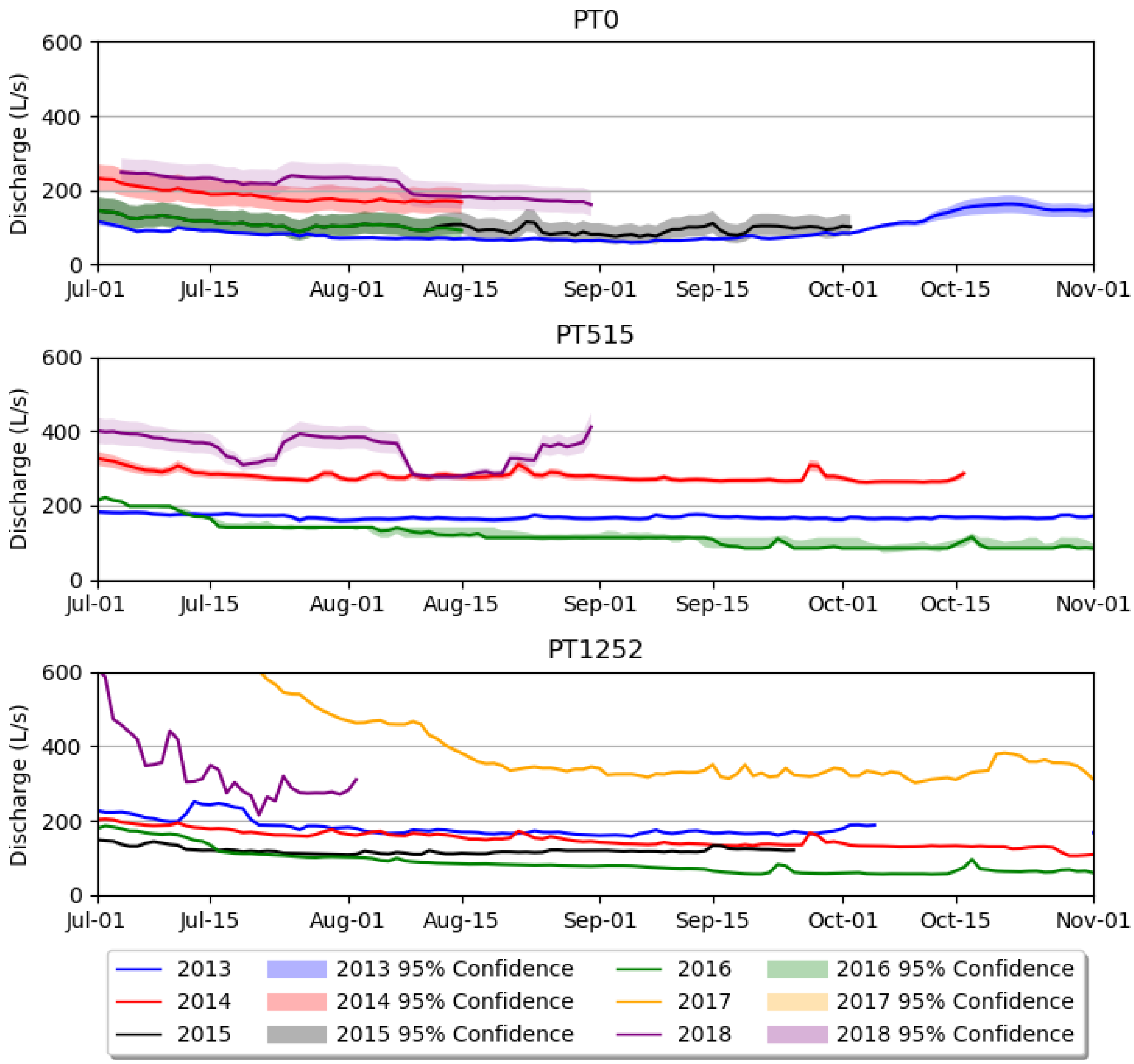

Figure 15. Average daily discharge at PT0, PT515, and PT1252 from 2013 to 2018 from July through October during summer baseflow. Note that the 95% confidence bounds for PT1252 were removed for this plot. The confidence bounds for baseflow at PT1252 were relatively small and all overlapped making the plot difficult to read, therefore the bounds were removed.

To help illustrate the annual air temperature variations, the average monthly air temperature was also plotted for each year that data were collected (Figure 16).

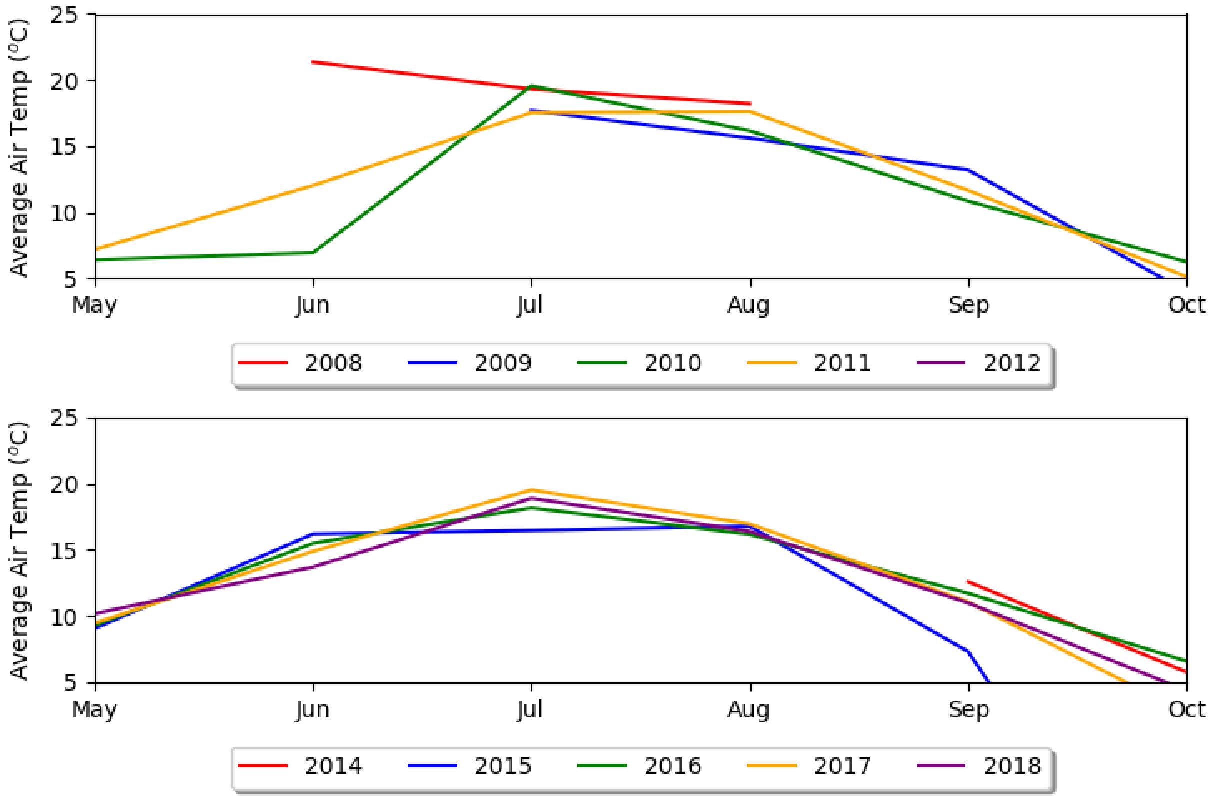

Figure 16. Average monthly air temperature for each year.

To understand the changes in discharge and water temperatures over the study reach for each year, ΔQ, $\%\Delta Q$, ΔT, and $\%\Delta T$ were plotted with air temperature and solar radiation for baseflow conditions (July to October). As discussed previously, the upper reach was supposed to be a study control with beavers only constructing dams in the lower reach. However, the upper reach can only be used as a control from 2009 to 2013 due to the series of four dams being built in the upper reach in 2014 and 2015.

2008. The data collected in 2008 was used to establish the behavior of Curtis Creek before any beaver dams were built. The data indicates that the upper reach was slightly gaining in July, neutral in August, and slightly losing in September. The lower reach stayed relatively neutral throughout 2008 (Figure 17).

The pressure transducer installed at PT0 (Summer 2007) did not have the capability to record water temperature. Therefore, the change in water temperature across the upper reach could not be calculated. In addition, the pressure transducer at PT1252 malfunctioned and did not record water temperatures in the second half of July and all of August. The recorded water temperatures at PT515 and PT1252 do show that the water in the lower reach slightly increased in temperature. Solar radiation and air temperature data were only available from July 15 to August 3 in 2008 (Figure 17).

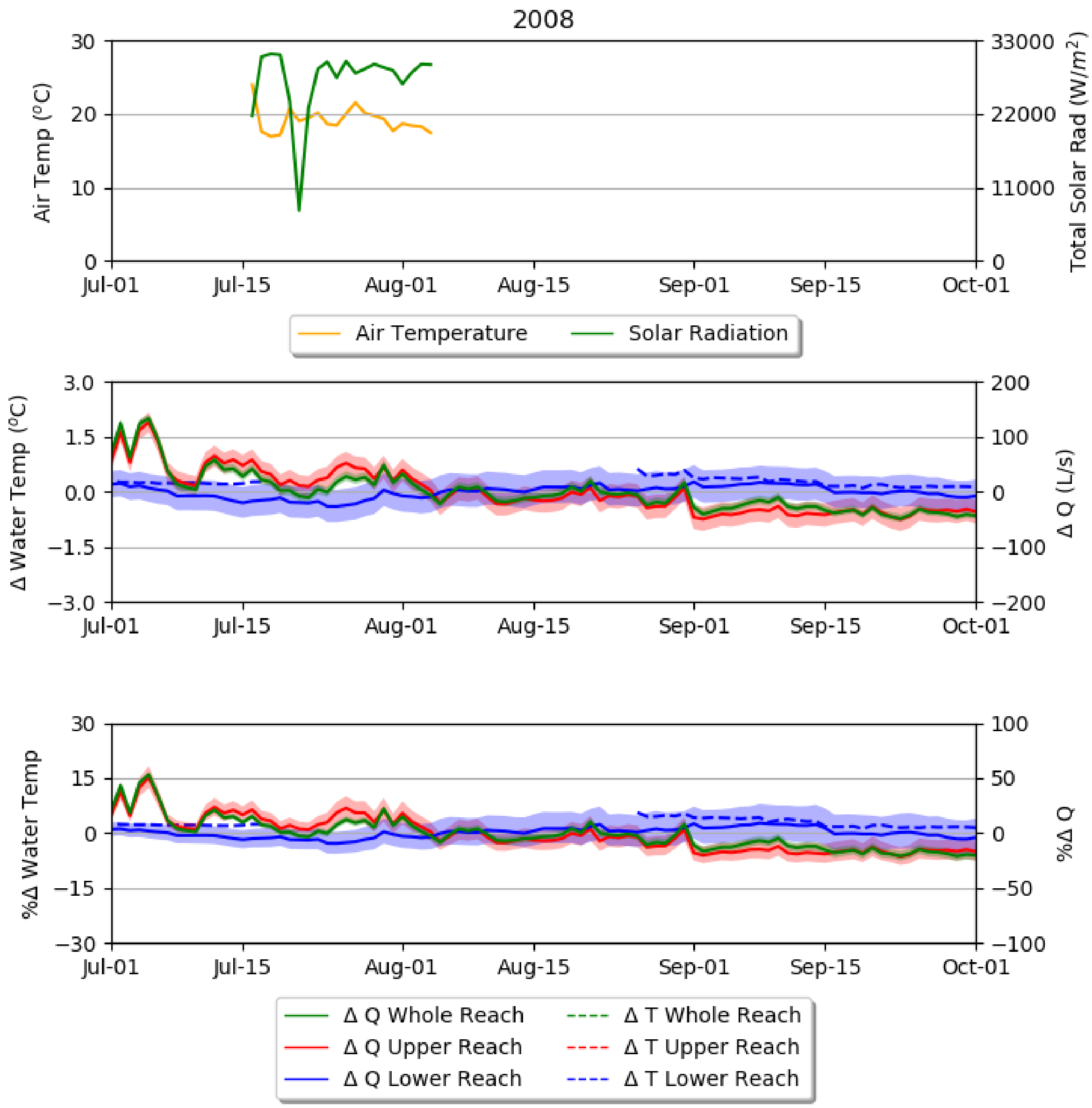

Figure 17. Change in discharge and water temperature compared to air temperature and solar radiation for 2008.

2009. Three new beaver dams were built in the lower reach in 2009. These were the first dams built in the study reach. During the summer of 2009, the upper reach was losing from July to October (-3%) while the lower reach was slightly gaining (+2%). Water temperature in the lower reach was slightly increasing throughout the summer (0.3°C). A new pressure transducer was installed at PT0 in August. The new pressure transducer had the ability to record water temperature. The water temperature in the upper reach was also slightly increasing but increased less than the lower reach (Figure 18).

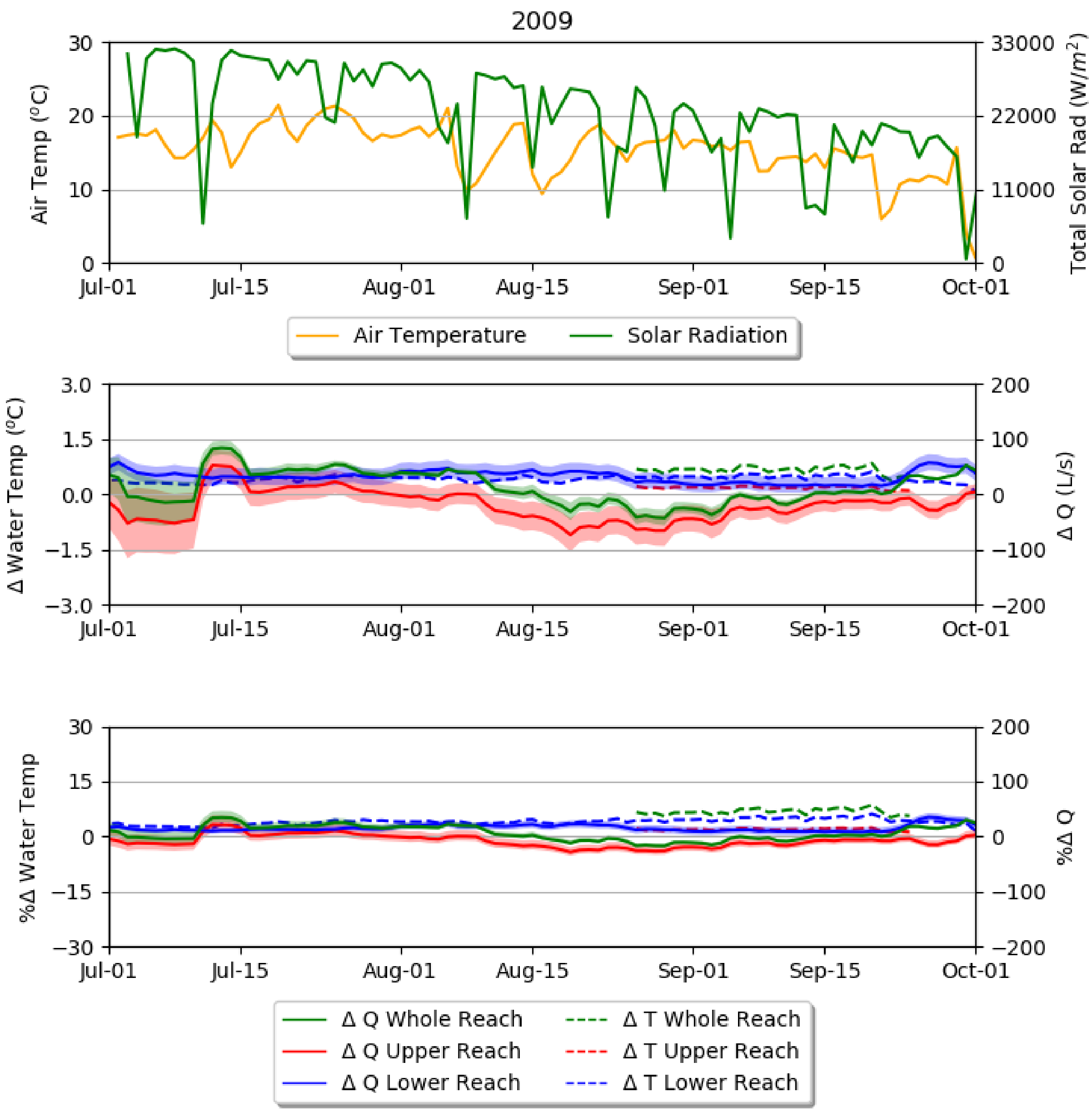

Figure 18. Change in discharge and water temperature compared to air temperature and solar radiation for 2009.

2010. In 2010, six additional beaver dams were built in the lower reach. These new dams increased the total number of dams in the lower reach to nine with no dams in the upper reach. All the dams in the lower reach appeared to be well maintained. The upper reach was losing throughout the summer (-30%); however, the volume of water lost decreased from July to October. The lower reach followed a similar pattern and was gaining throughout the summer (+55%); however, the volume of water gained decreased almost linearly from July to October. The water temperature in both the upper and lower reach increased throughout the study period; although the water temperature in the lower reach increased by approximately 1°C, almost twice as much as the increase in the upper reach (0.5°C) (Figure 19).

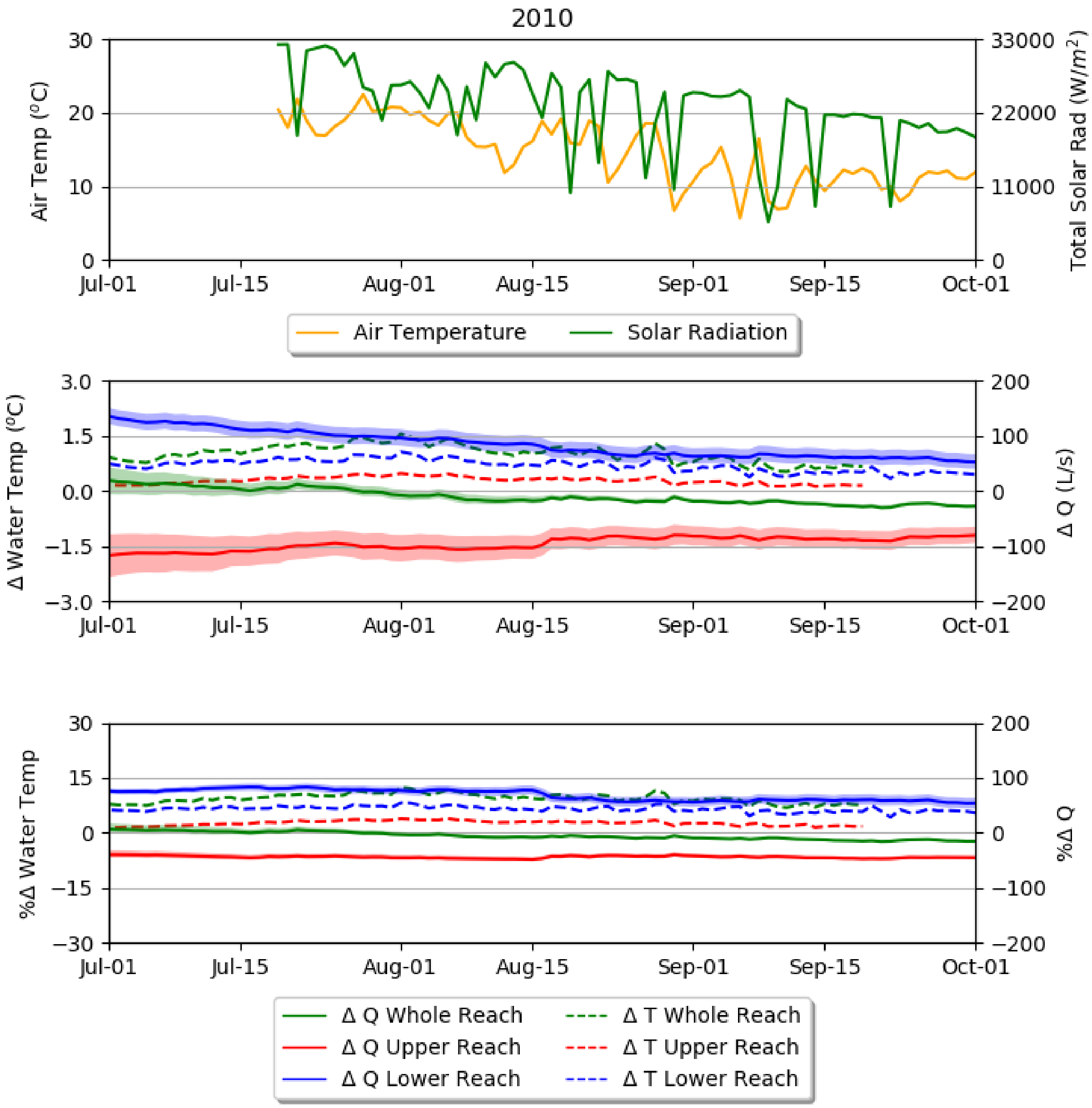

Figure 19. Change in discharge and water temperature compared to air temperature and solar radiation for 2010.

2011. In 2011, no new beaver dams were built in the lower reach while three of the dams built in 2010 were washed out. This reduced the total number of dams in the lower reach to six. There were no beaver dams reported in the upper reach in 2011. Due to the relatively large uncertainty bound, actual discharge values in 2011 are inaccurate; however, the data does show that the upper reach was losing while the lower reach was gaining. The water temperature in the upper reach stayed relatively neutral while the water temperature increased in the lower reach by about 1°C (Figure 20).

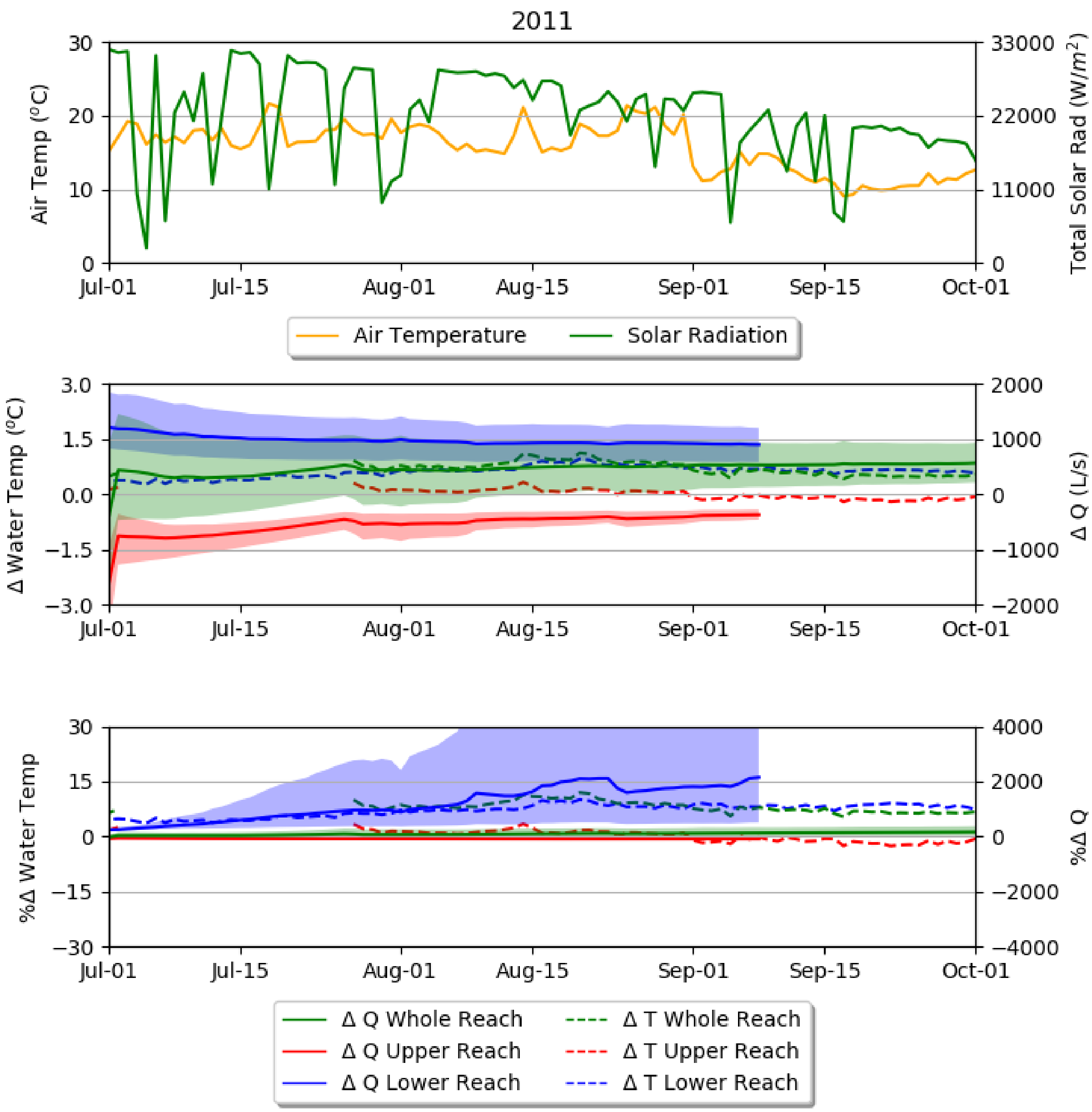

Figure 20. Change in discharge and water temperature compared to air temperature and solar radiation for 2011. Note the scale for change in discharge is different.

2012. In 2012, four beaver dams were built in the lower reach. Each of these dams were in the downstream section of the lower reach. This increased the total number of dams in the lower reach to 10. No beaver dams were built in the upper reach in 2012. The upper reach was gaining throughout the summer. The lower reach appeared to be losing; however, these flow data have relatively large uncertainty bounds and will not be included in the evaluation of the effects of the beaver dams on the creek. From July 2012 to July 2014, PT0 failed to record water temperatures. This equipment failure prevented the change in water temperature in the upper reach from being plotted. On average the water temperature in the lower reach increased approximately 1.4°C throughout the summer (Figure 21).

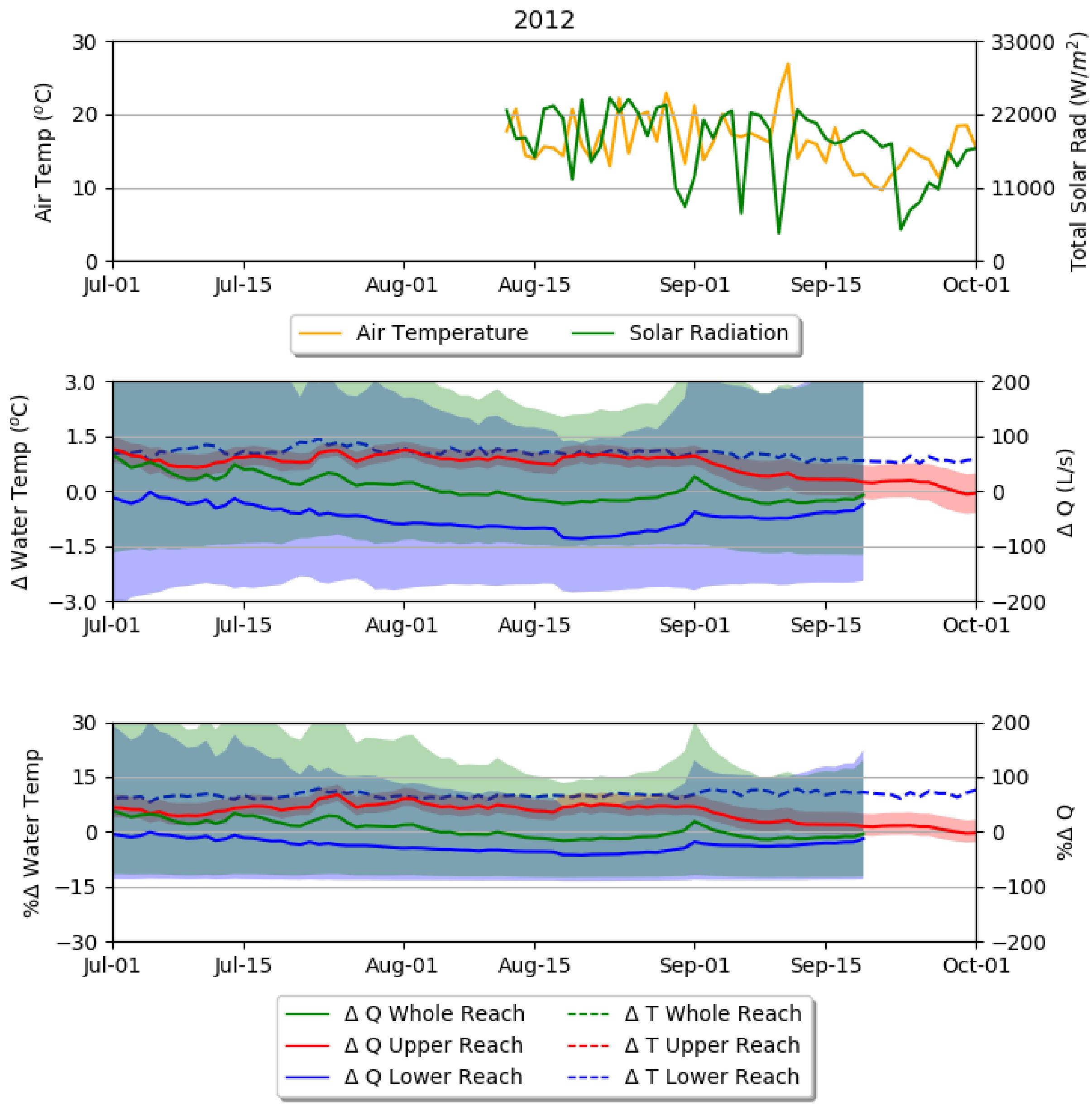

Figure 21. Change in discharge and water temperature compared to air temperature and solar radiation for 2012.

2013. Six new dams were built in the lower reach during 2013. These six dams were all located in the downstream section of the lower reach and increased the total number of dams in the lower reach to 16. The upper reach appeared to be gaining throughout the summer. The gains in the upper reach increased the baseflow in the creek by up to 170%. This is a large increase in discharge in the creek was most likely be due to increased flood irrigation in the field adjacent to the creek as the creek was gaining in the upper reach and relatively neutral in the lower reach. The lower reach discharge stayed nearly neutral throughout the summer. Water temperature data were not available for PT0 and PT515 in 2013 preventing the calculation of the change in water temperature in the upper and lower reaches. Air temperature data was also not available for 2013 (Figure 22).

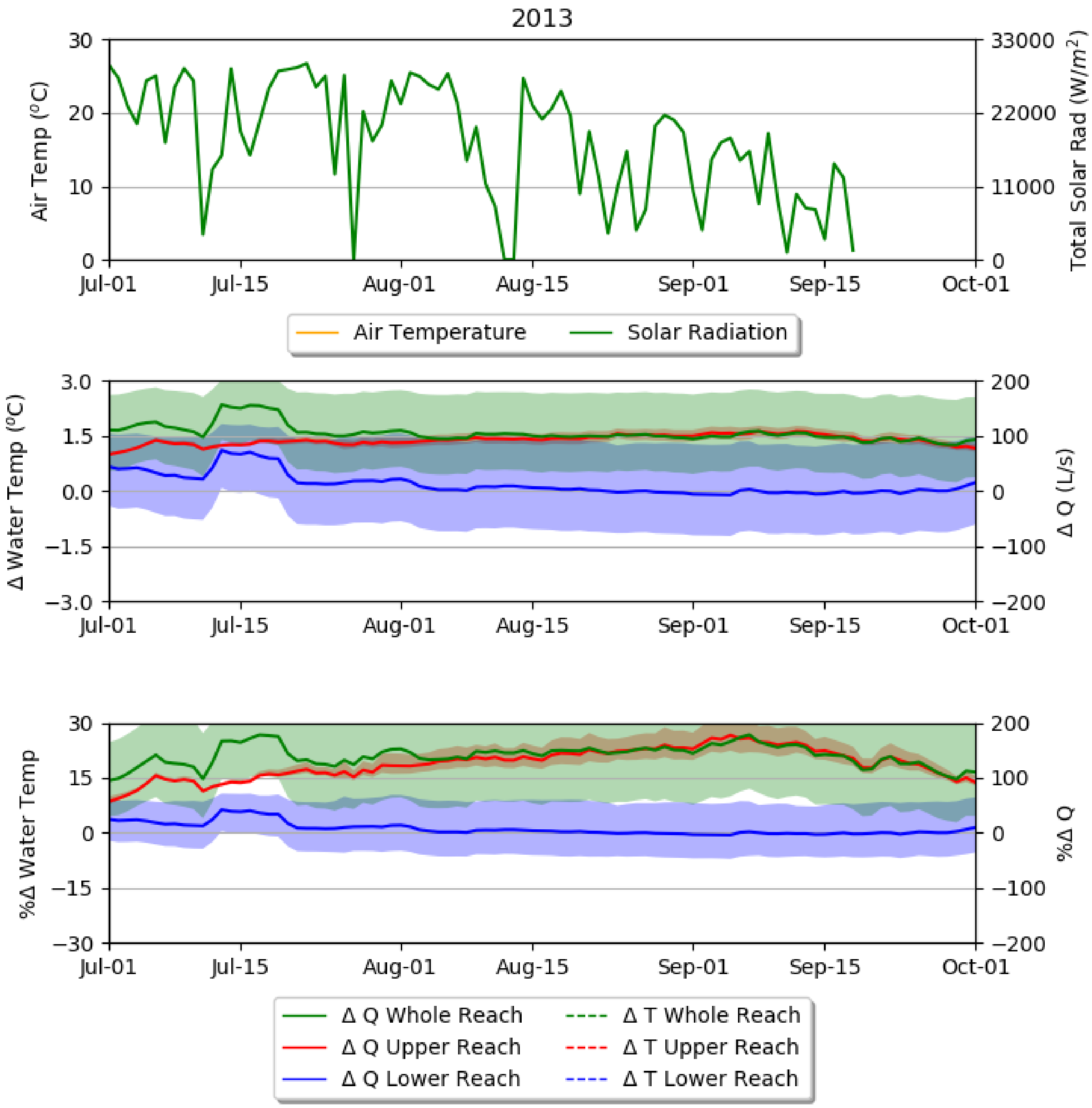

Figure 22. Change in discharge and water temperature compared to air temperature and solar radiation for 2013.

2014. Eight new dams were built in the lower reach 2014. The eight new dams brought the total number of dams in the lower reach to 25. In addition, a single dam was built at the downstream end of the upper reach in 2014. Unfortunately, discharge and water temperature data for PT0 was not available after August 15; however, before that date, the upper reach was gaining, increasing by approximately 50%. The lower reach was consistently losing throughout the summer, decreasing by approximately 50%. Water temperature increased in both reaches; however, the lower reach increased approximately 1.2°C, almost twice as much as in the upper reach (0.7°C). Weather data was unavailable before September 2014(Figure 23).

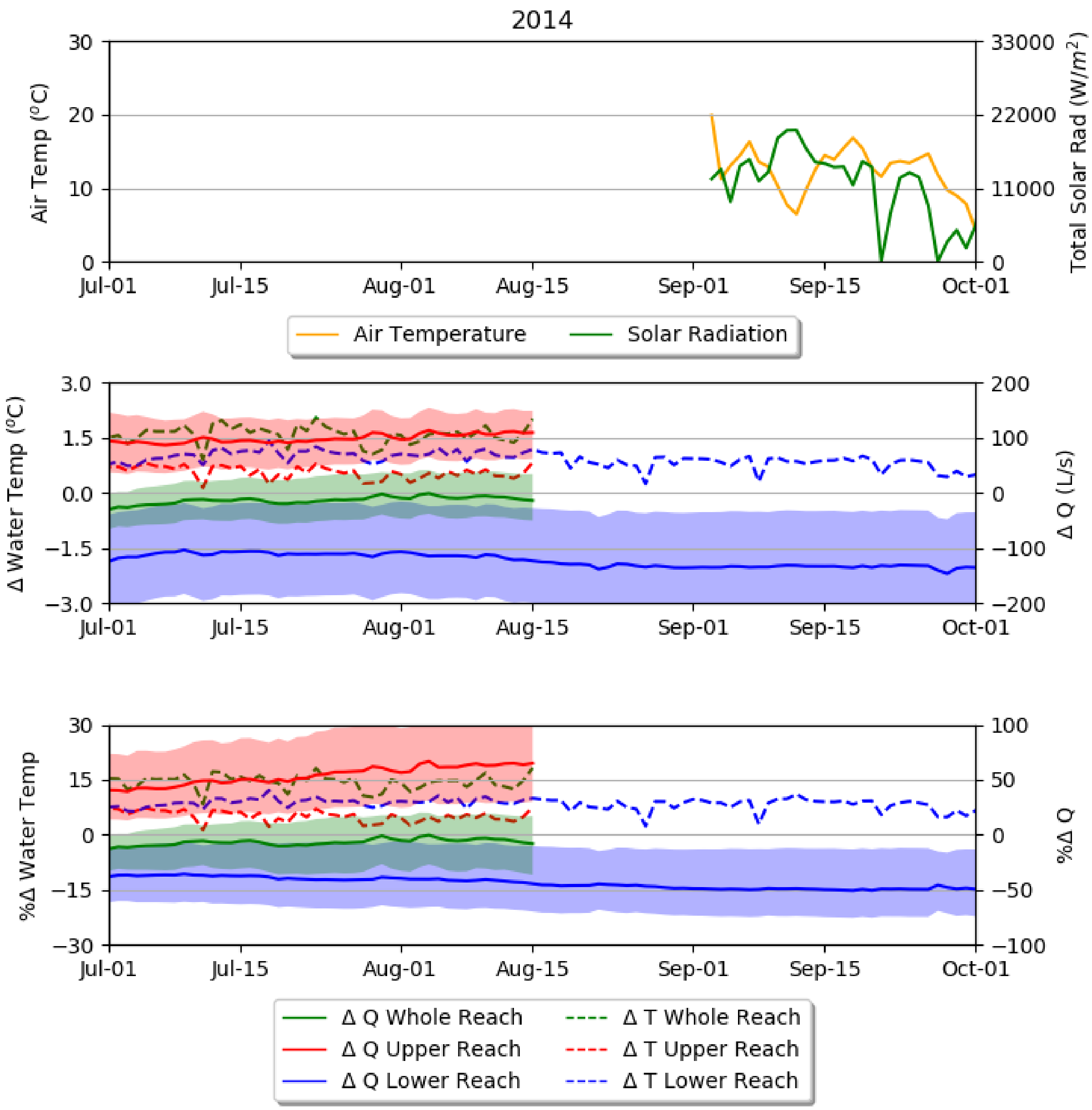

Figure 23. Change in discharge and water temperature compared to air temperature and solar radiation for 2014.

2015. In 2015, 18 new dams were built in the lower reach. The total number of dams in the lower reach at the end of 2015 was 43. The majority of the new dams in 2015 were concentrated in the upstream portion of the lower reach. One of the new beaver dams was built just downstream of PT515, which resulted in inaccurate water depth measurements due to the dam backwater. In addition, three new dams were also built in the upper reach bringing the total number of dams in the upper reach to four. The four dams in the upper reach were all built in the downstream portion of the upper reach. This data is not included in this analysis, instead, the change in discharge along the entire study reach (PT0 to PT1252) is shown (Figure 24). The data indicates that the water temperature in the upper reach stayed relatively constant while the lower reach increased by almost 2°C. This larger increase in water temperature is due to the increasing number of beaver dams and the unusually low flows in 2015.

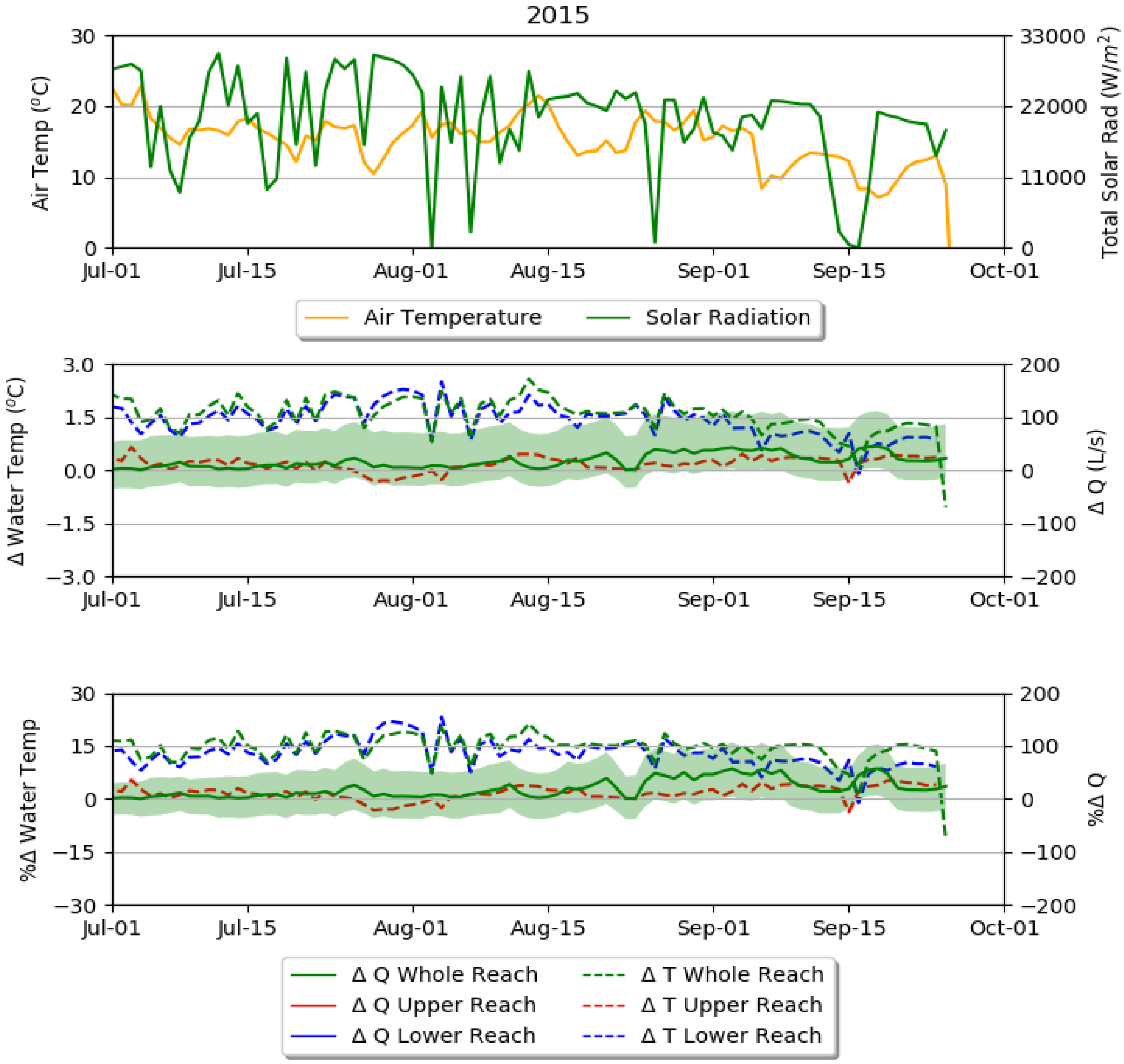

Figure 24. Change in discharge and water temperature compared to air temperature and solar radiation for 2015.

2016. The beaver were removed by trapping in the area at the end of 2015 and the spring of 2016. The loss of the beaver and lack of dam maintenance resulted in the breaching or washing out of all the dams in the study reach. The upper reach was gaining in 2016 (+44%) while the discharge in the lower reach was losing in 2016 (-39%). PT0 malfunctioned and stopped recording water temperature on August 15, 2016. The water temperature increased in both reaches by approximately 0.8°C (Figure 25).

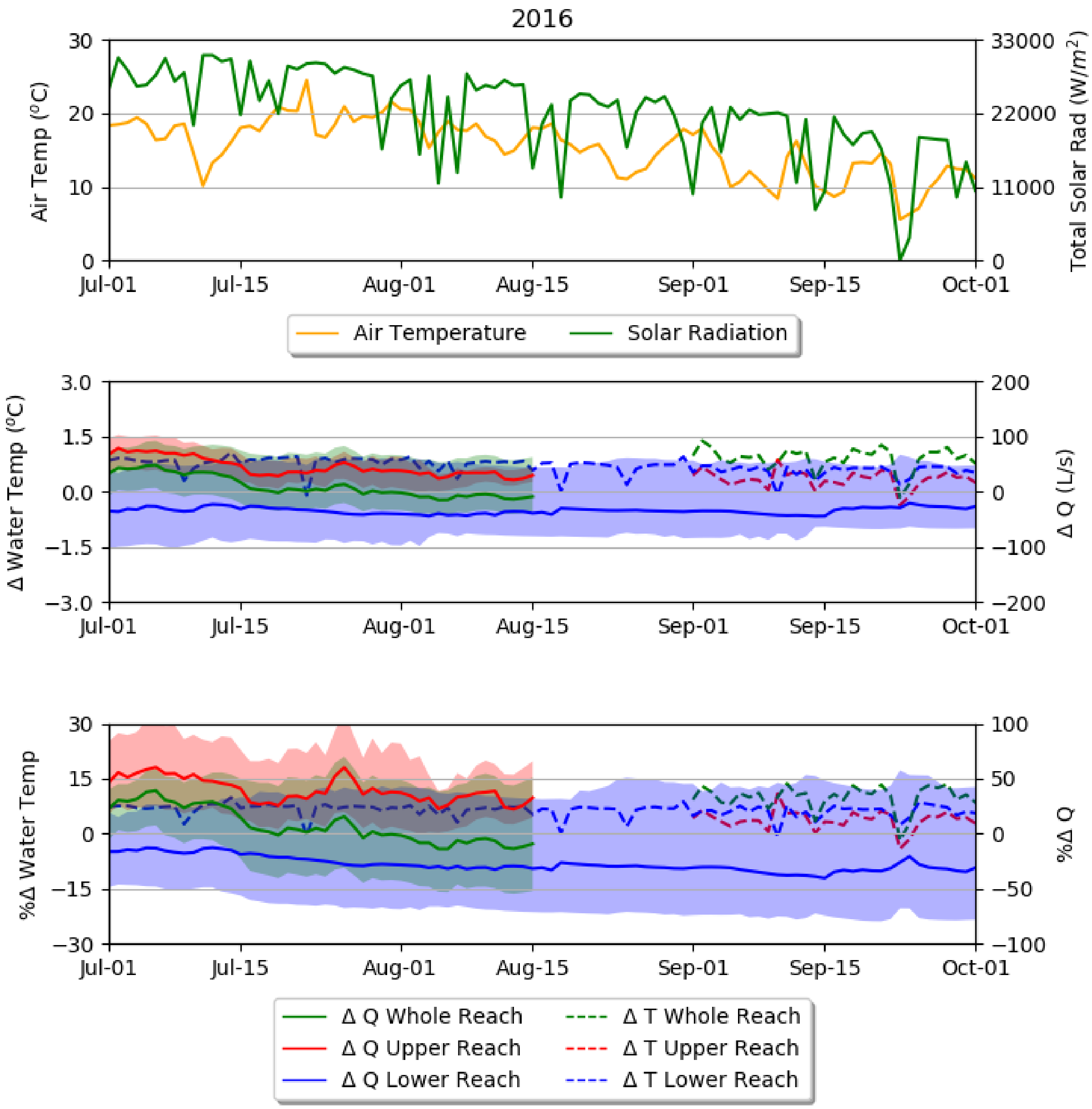

Figure 25. Change in discharge and water temperature compared to air temperature and solar radiation for 2016.

2017. As in 2016, there was no beaver activity reported in 2017. It is expected that the remnants of the dams continued to be washed out in 2017. Due to the relatively high flows in 2017, the water depth data collected at PT0 was inconsistent and only data from the first few days of July were included in this analysis. From this data, it appeared that the upper reach was losing for the first two weeks of July 2017. In addition, the lower reach was also consistently losing through the summer of 2017. Similar to 2016, the water temperature increase in both reaches was approximately 0.4°C (Figure 26).

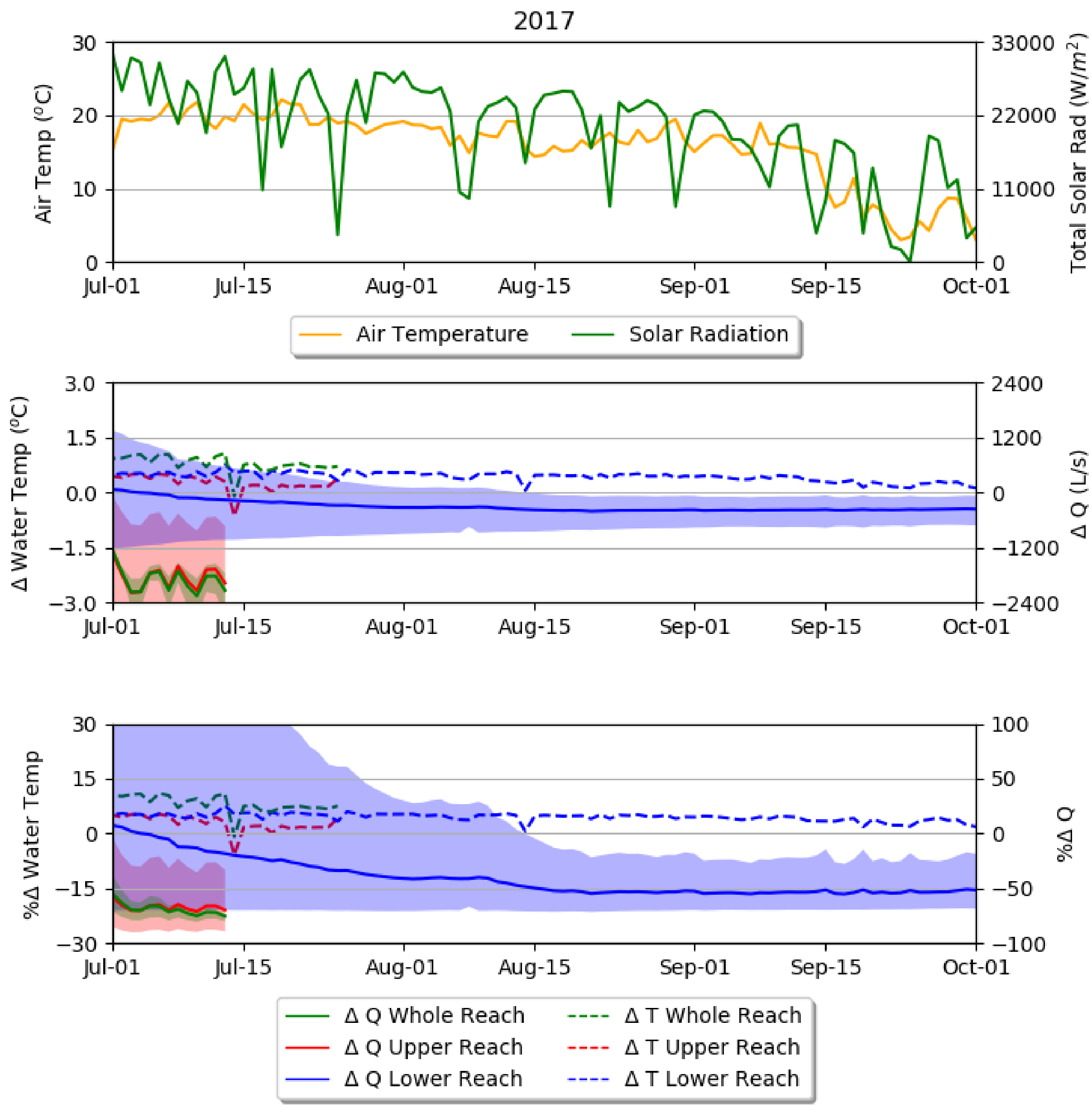

Figure 26. Change in discharge and water temperature compared to air temperature and solar radiation for 2017. Note the scale for change in discharge is different.

2018. As with 2016 and 2017, no beaver activity was reported in 2018. The discharge data collected in 2018 is relatively inconsistent and is not included in the analysis of this report. The temperature increase in the upper reach (0.3°C) was slightly less than the lower reach (0.4°C). However, the difference in the change in water temperature between the upper and lower reaches in 2018 was less than during the periods with beaver dams (Figure 27).

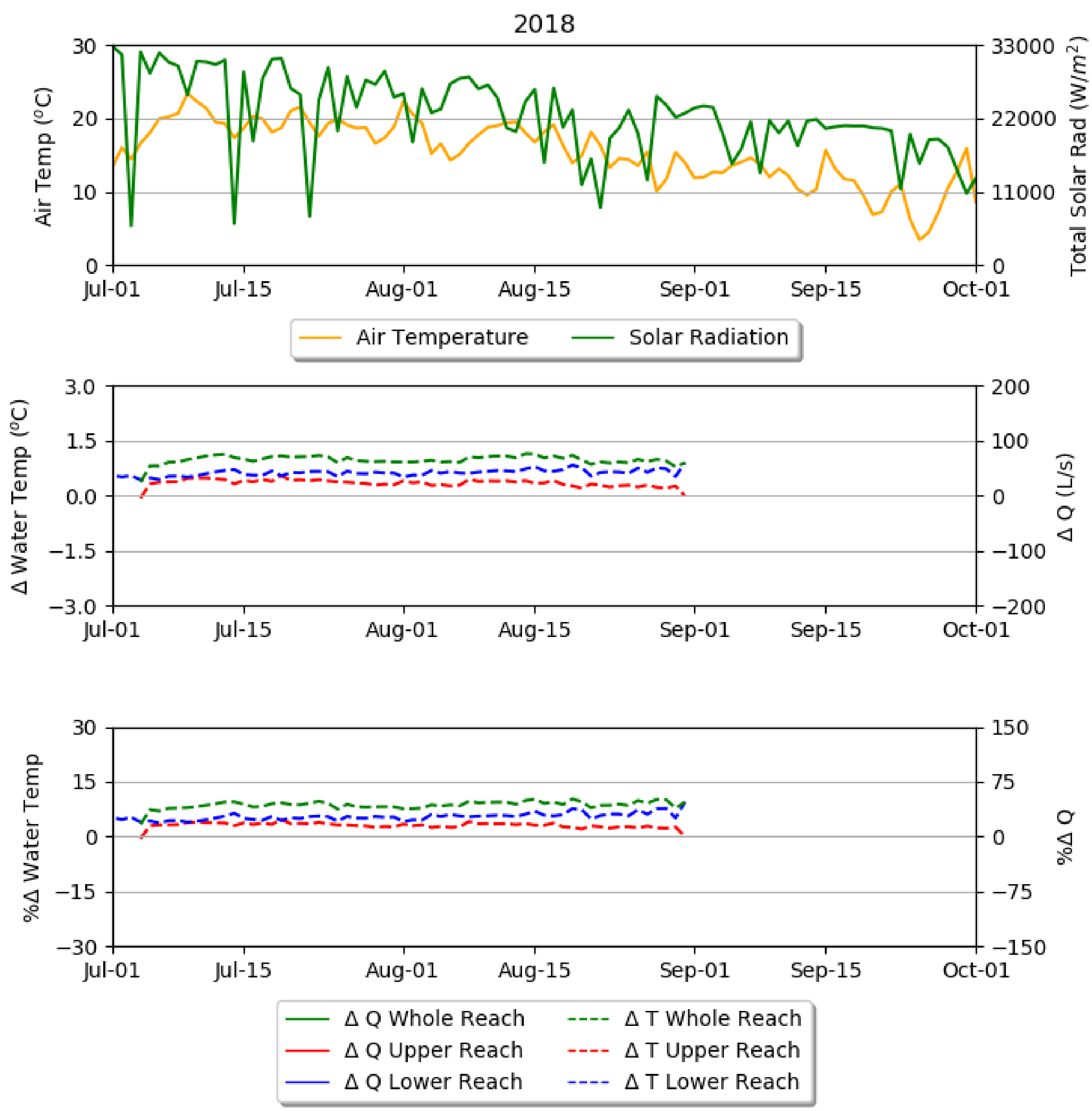

Figure 27. Change in discharge and water temperature compared to air temperature and solar radiation for 2018.

To aid in understanding the effects of beaver dams, the average change in discharge over July 1 to October 1 for the upper and lower reach was compared to the number of beaver dams in each year (Figure 28).

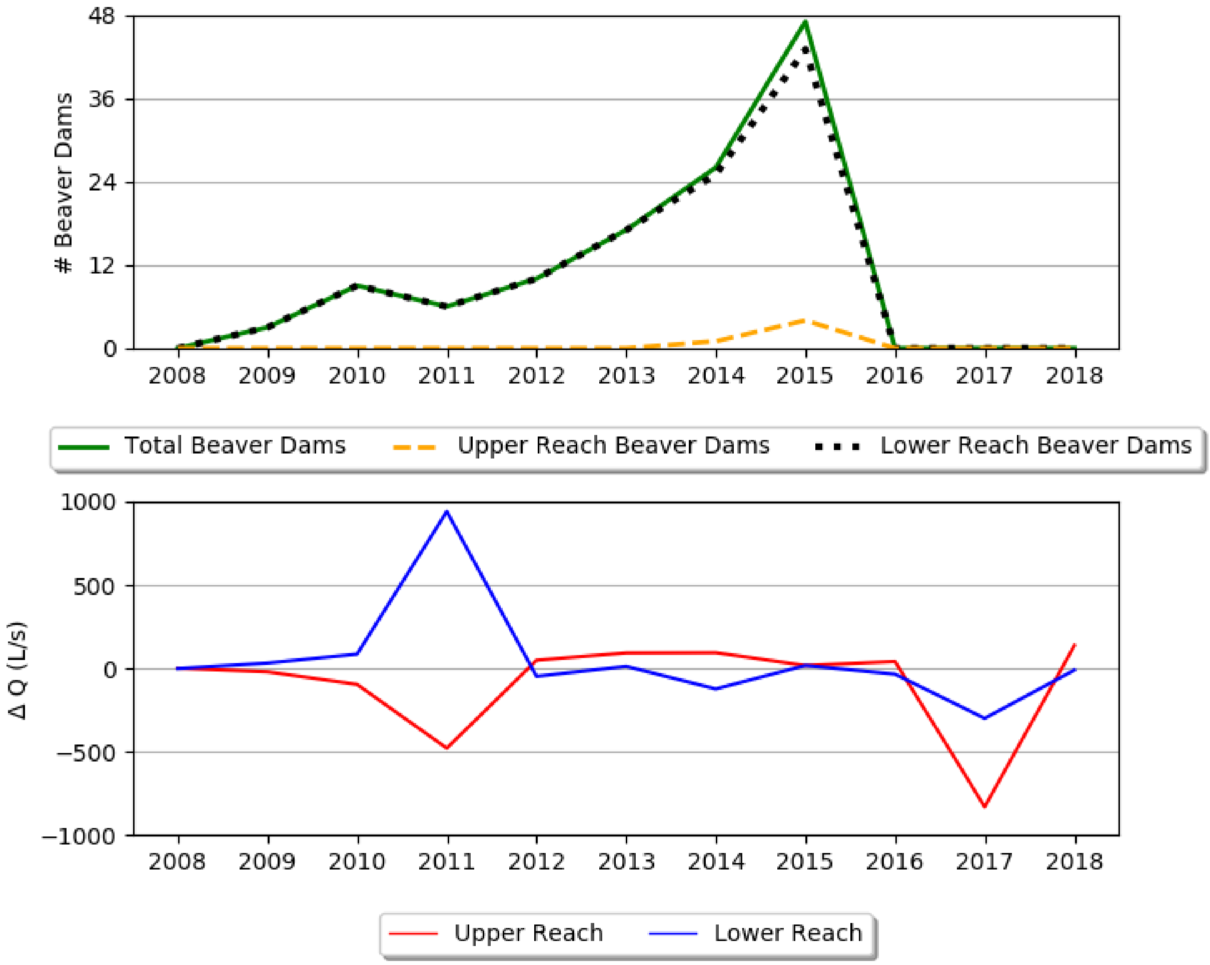

Figure 28. Average gains and losses in the upper and lower reaches for each year compared to the number of beaver dams in the lower reach. PT515 was inundated by a downstream beaver dam in 2015 preventing the calculation of the change in discharge in the upper and lower reaches that year. Note that 2015 is the change in discharge across the entire reach (PT0 to PT1252).

As with the discharge in the creek, the average change in water temperature from July 1 to September 30 for each year was plotted (Figure 29).

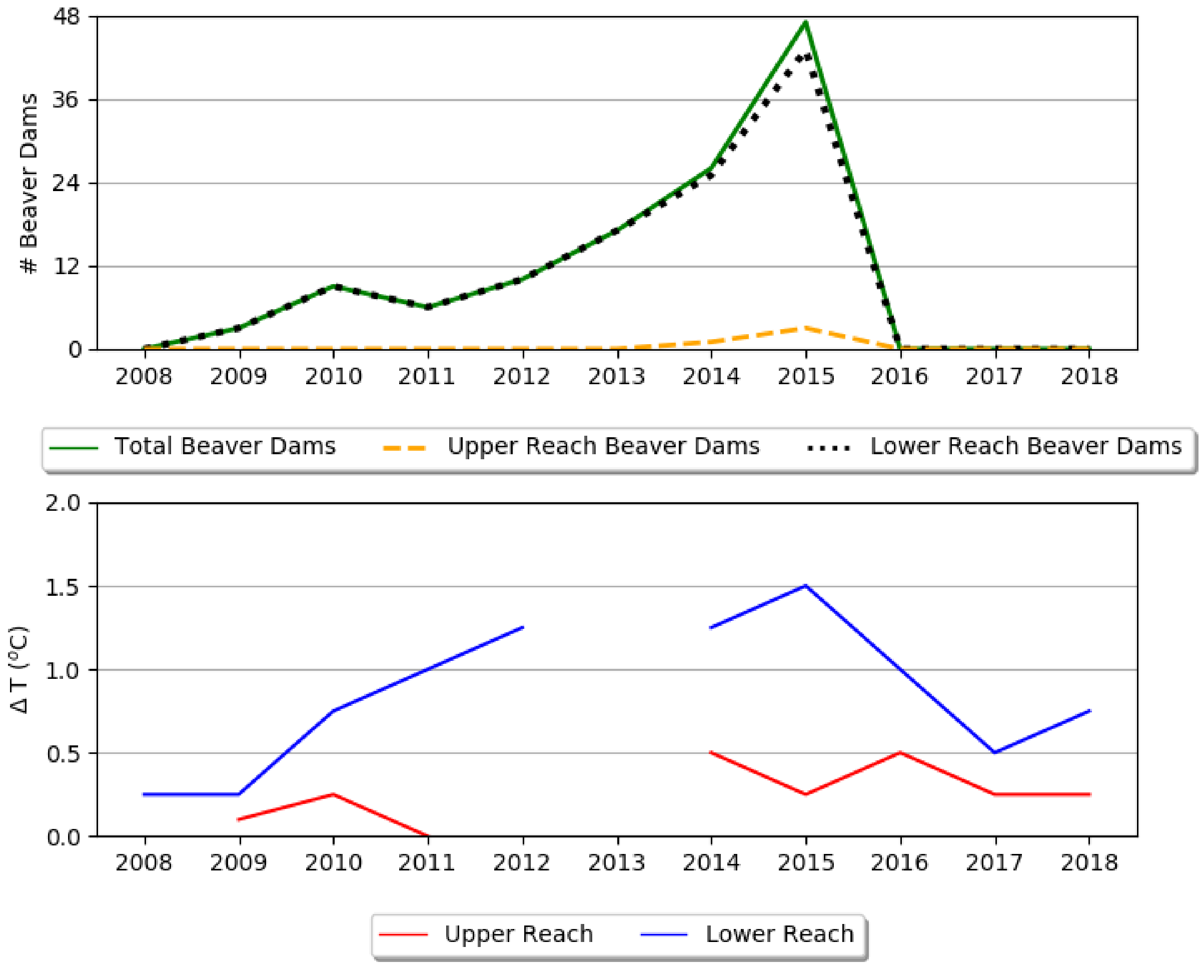

Figure 29. Average change in water temperature from July 1 to September 30 for each year plotted with the number of beaver dams in the upper and lower reaches. As noted previously, PT0 did not have the capability to record water temperature until the PT was replaced in 2009. PT0 malfunctioned in 2012 and 2013 and did not record water temperatures. PT515 also malfunctioned in 2013 and did not record the water temperature.

As beaver dams age, the pools created by the dams slowly fill with sediments. These sediments can create a confining layer at the bottom of the pool that prevents groundwater recharge. The sediment build up also reduces the volume of water that the dam retains. This may lead to more water being pushed to the floodplain during high flows. The average age of all the beaver dams in study reach for each year is presented in Figure 30.

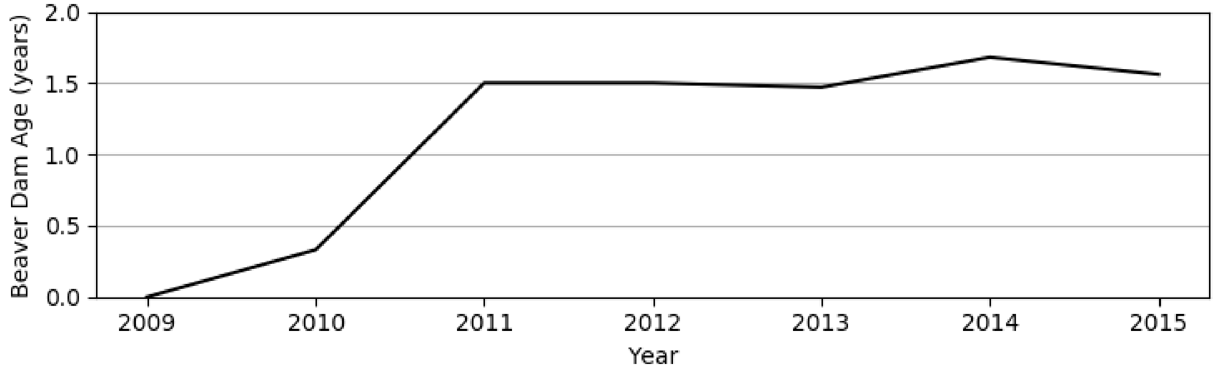

Figure 30. Average age of the beaver dams in the upper and lower reaches in each year. In 2008 there were no active beaver dams in the lower reach. In 2016 to 2018 there were also no active beaver dams reported in the lower reach. However, the remnants of several beaver dams that were not entirely washed out were still present, but they were not accounted for when calculating the average age of the beaver dams.

By only looking at the average daily changes, the discharge and water temperature changes in a single day are lost. These daily changes do not appear to directly impact the general, ten-year estimations of the hydrologic impacts of beaver dams, but are still important for understanding the smaller temporal scale impacts. To account for these changes, the average hourly solar radiation, air temperature, water temperature, and discharge were plotted instead of daily averages for September 7 to September 15, 2009 (Figure 31). This time period was chosen to show an example in the within day variable water temperatures when limited beaver dams were present.

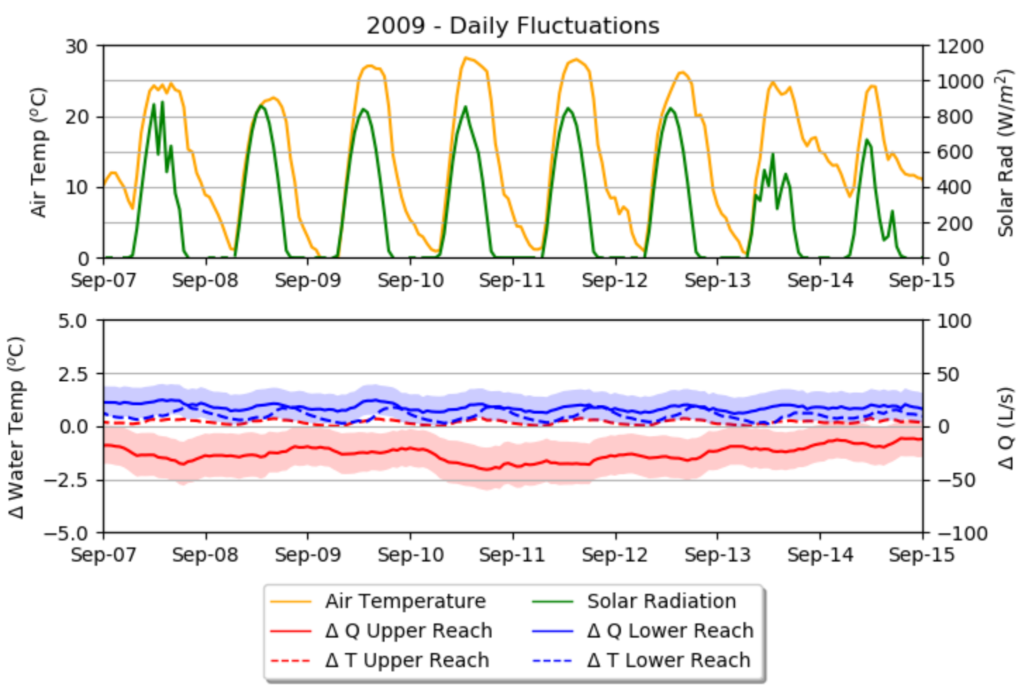

Figure 31. Hourly average change in air temperature, solar radiation, water temperature, and discharge from September 7 to September 15, 2009.

For comparison to a period when the largest number of beaver dams were present, the average hourly ΔQ and ΔT for 2015 for the same period (September 7 – 15) was also plotted (Figure 32).

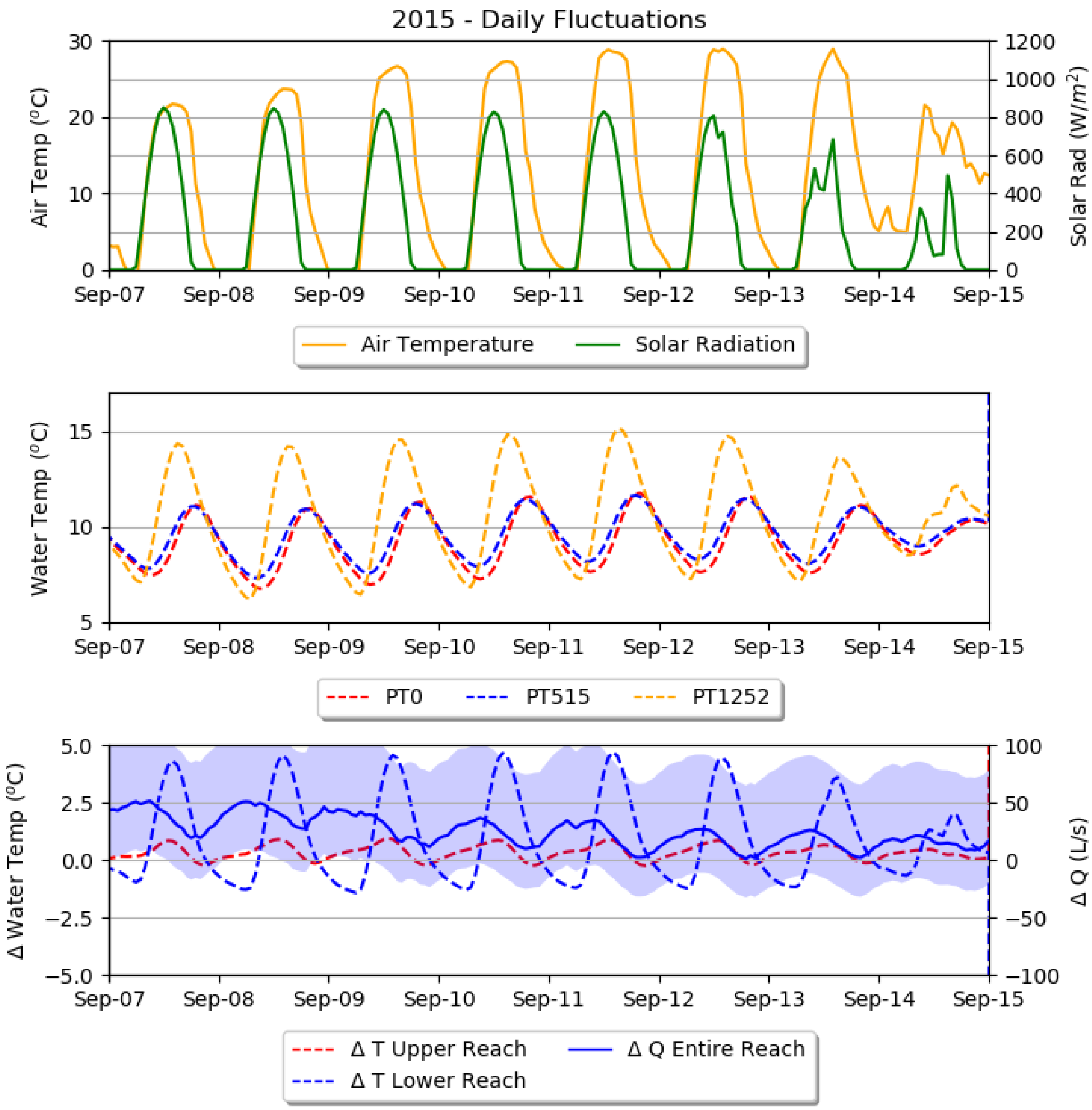

Figure 32. Solar radiation, air temperature, actual water temperature, and average hourly ΔQ and ΔT from September 7 to September 15, 2015. Note the difference in scale for ΔT in 2009 and 2015.

These plots show the significance of air temperature and solar radiation in the changes in 15 minute water temperature responses. The diel water temperature follows the same trend as the air temperature and solar radiation with approximately a 4-hour time delay. The delay is due to water having a higher specific heat than air, which causes the water to warm and cool slower. It is also important to note the relatively large difference in the average hourly ΔT in 2009 and 2015.

In summary, the lower reach was gaining in 2009 to 2011 and losing in 2014 and 2017. The change in discharge in the lower reach was relatively neutral in the other years. The upper reach was slightly gaining in 2012 to 2016 and 2018 while slightly losing in 2009 to 2011 and 2017. The lower reach warmed by approximately 0.25 °C in 2008 and 2009. After the beaver began building dams in the lower reach the average warming increased to approximately 1.25 °C (2011 to 2016). Warming in the upper reach stayed relatively constant at approximately 0.25°C except in 2014 and 2016 when the warming reached 0.5°C. A visual summary of the gains/losses and warming the reaches is presented in Figure 33.

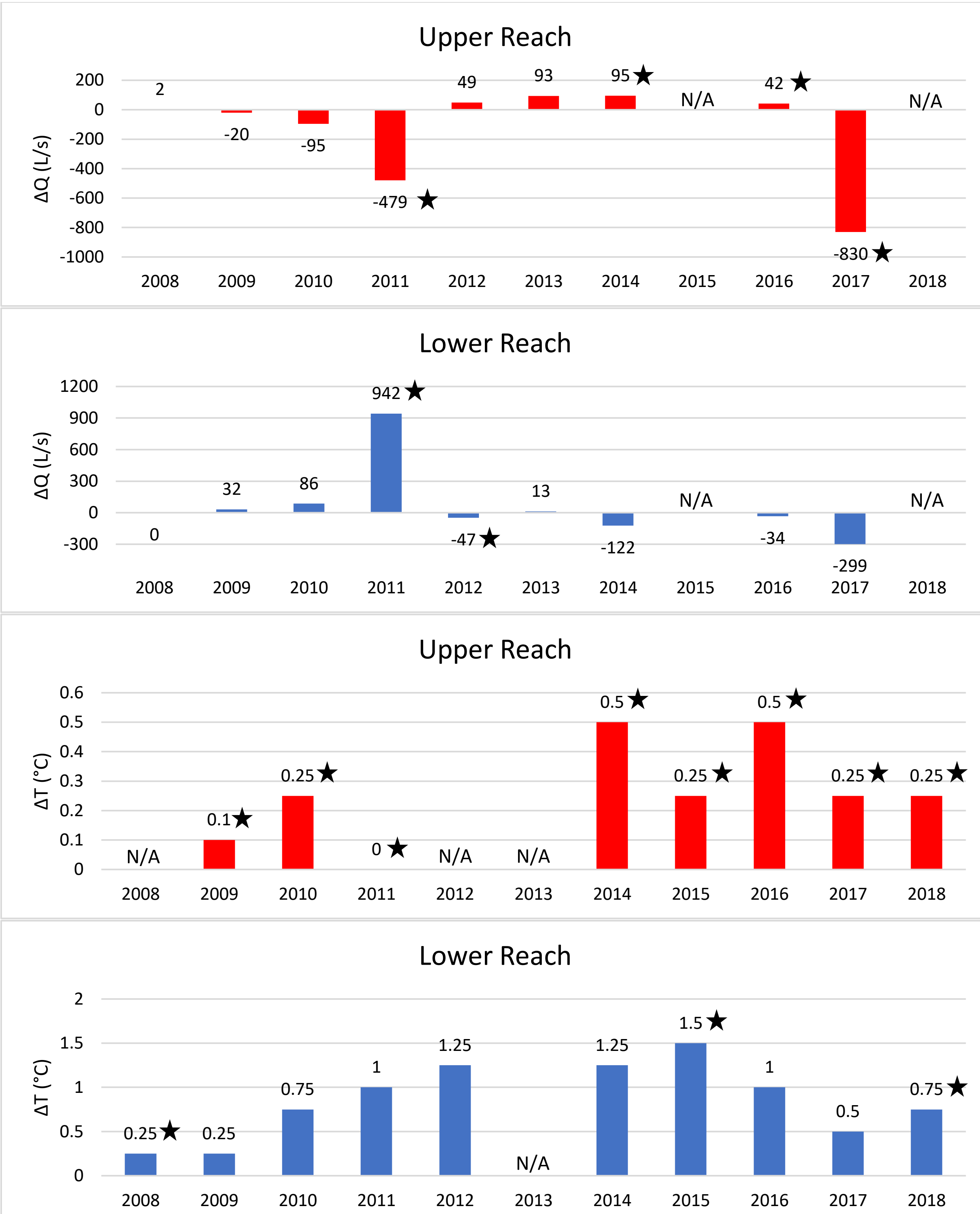

Figure 33. Average gains/losses and warming in the upper and lower reaches averaged over July 1 to October 1 for each year. Temperature data in the lower reach was unavailable in 2013. Temperature data were unavailable in the upper reach in 2008, 2012, and 2013. Note: Averages with stars are partial datasets.

Discussion

As noted by Majerova et al. (2015), many studies have been completed that to determine the effects of beaver dams on stream flow, temperature, and habitat in general. Many of these studies do not have long term discharge and temperature measurements to support their respective conclusions, and therefore, have resulted in mixed or contradictory results. To provide insight into why these studies have such varied conclusions, this 10-year data set of discharge, water temperature, air temperature, and solar radiation can be used to help explain long term influences of beaver dam complexes on controlling hydrologic processes. To aid in this analysis, the number and location of the beaver dams in each year (Figure 3 through Figure 10) were compared with the hydrologic and climatic data collected in each year (Figure 17 through Figure 27).

The first year that data were gathered, 2008, serves as a baseline for the creek conditions before any beaver activity was observed. The upper reach was intended to be used as a control relative to the lower reach with no beaver activity. This was the case for 2009-2014; however, as noted previously, the dams were built in the upper reach in 2014 and 2015. To help with interpretation, it is important to note that these dams were located close together in the lower section of the upper reach, were relatively low head dams with small ponds, and breached in 2016. So, while this condition is not a perfect control for these years, the impacts of beaver dams in the upper reach were limited.

Although no beaver activity was reported in the study reach in 2016, 2017, and 2018; these years are meant to provide insight into the duration of the channel structure changes on groundwater exchanges and temperature variability. Even with no beaver activity and all the dams reportedly breached, the remnants of several dams still created backwater effects in some portions of the creek and some large head gradients remained throughout the lower reach.

Upper Reach Discharge. The upper reach was losing from 2008 to 2011, consistent with losses in this reach documented by of Schmadel et al. (2010, 2013). During these years, there were no beaver dams in the upper reach. In 2012, the upper reach began gaining. As the first beaver dam was not built in the upper reach until 2014, the gains in 2012 and 2013 cannot be attributed to beaver activity, rather they are more likely due to higher local water table from precipitation or potential changes of irrigation practices.

In 2014 and 2015, four beaver dams were built in the upper reach. These beaver dams were not large enough to cause the creek to flow into the floodplain. As such, there were no significant gains in 2014 and 2016 when compared to 2012 and 2013. Again, this indicates that the gains in 2014 and 2016 are most likely due to changes in larger scale groundwater conditions or irrigation practices. The presence of beaver dams in the upper reach and no significant gain in discharge illustrate the need for beaver dams that inundate the floodplain to have any effect on groundwater exchanges.

2017 showed significant losses in the upper reach, but it was another unusually wet year. It was reported that due to significant sediment transport upstream of PT515, water flooded over the creek banks and scoured side channels. Some of this bypassed PT515 (Figure 34), resulting in these

misreported channel scale losses. In 2020, these side channels were still visible where the water flowed.

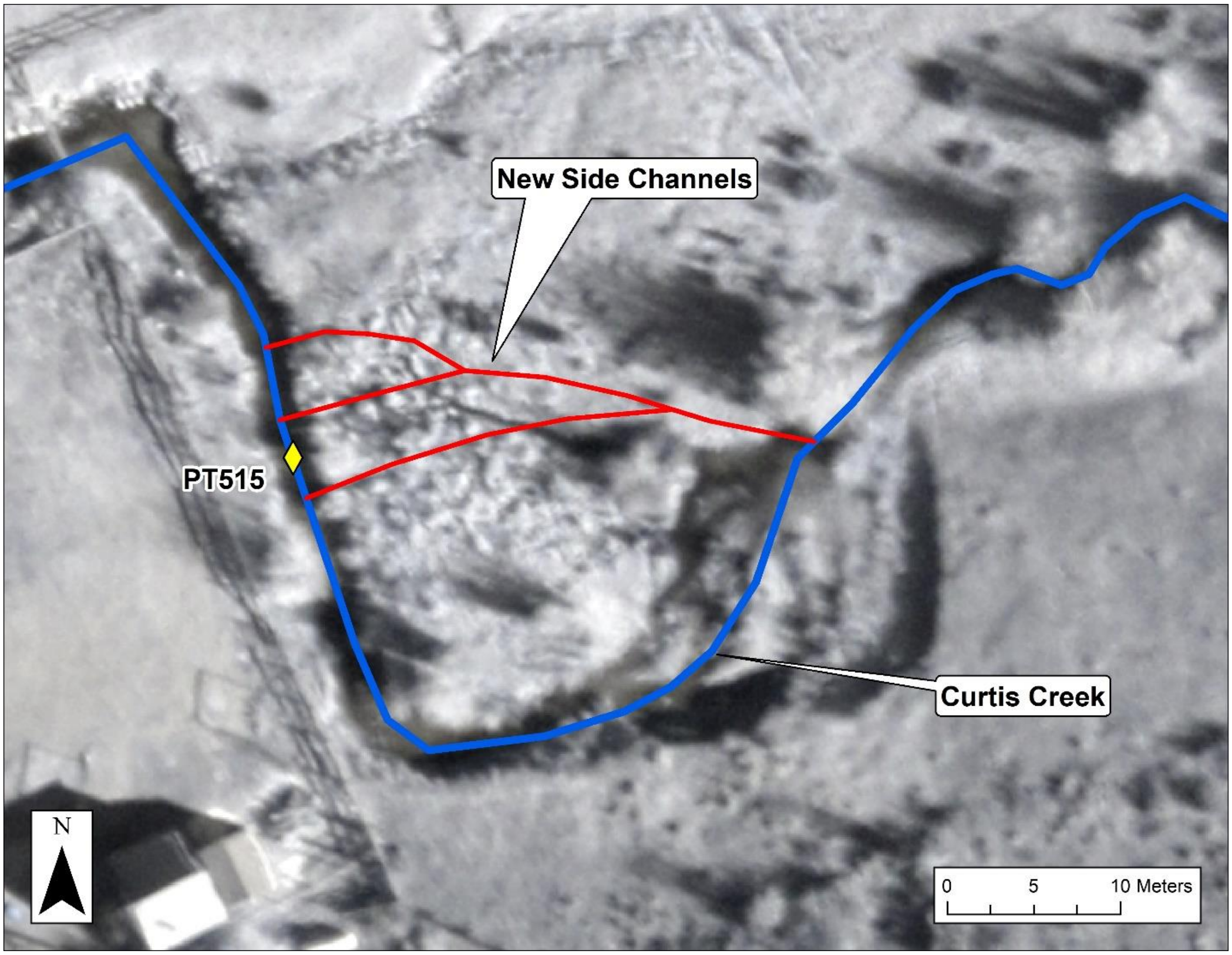

Figure 34. Overland flow due to flooding upstream of PT515 in 2017.

Any flow in the side channels bypassing PT515 decreases the discharge reported at PT515. This would translate into a loss in the upper reach, which may explain why the discharge decreased so much in the upper reach in 2017. In 2018, the upper reach returned to a slightly gaining system indicating that the flow in the side channels in 2017 was most likely the cause for the upper reach to appear to be losing.

Lower Reach Discharge. Consistent with the findings of Schmadel et al. (2010) and Majerova et al. (2015), we found that the presence of beaver dams in the lower reach initially resulted in gaining conditions during baseflows. These gains were seen in 2009 through 2011 in the lower reach. In 2011, water flooding onto the floodplain from Dams 2 and 3 (built in 2009) and Dam 9 (build in 2010) can be clearly seen (Figure 35). Flooding in 2010 can also be seen in the aerial photographs (Figure 4).

Figure 35. Flooding due to beaver dams in 2011. The numbers represent the dam number as shown in Figure 3 and Figure 4.

These dams increased the inundation of the floodplain during the spring runoff and increased infiltration, further mounding the water table. The flooding caused by these three dams, as well as the relatively young age of the dams, are expected to be the main cause for the significant gains during low flows in 2011 in the lower reach.

In 2014, the creek was slightly losing, but in 2013, it was relatively neutral. Two factors are expected to be the cause of the shift from gaining in 2008-2011 to losing in 2013-2014. First is a lack of water being pushed into the floodplain in 2013 and 2014. During 2013 and 2014, Curtis Creek did not experience the same surface flooding that occurred in 2010 and 2011. Thus, recharge and changes to the local water table adjacent to the stream were limited. It is also important to note that several dams (3, 9, 14, 15, 16, and 24) appeared to be poorly maintained during 2013 and 2014. The lack of dam maintenance allowed more water to remain in the stream, again reducing floodplain inundation and decreased groundwater recharge.

The second potential cause for the shift from gaining to losing is sediment deposition in the pools created by the beaver dams. During 2011, the discharge in Curtis Creek was very high. With the relatively steep channel slope, the water velocity can be very high and cause significant sediment

movement (including fines and gravel) in the channel. When these sediments reach the pools, the water velocity decreases, and sediments are deposited. Over the study period, all the dams that lasted more than a few years were filled with sediment deposits, in part due to upstream dam breaching, many of which were still visible three years later, in 2020. The sediment deposits in the pools raised the channel bed elevation and thus increased the water surface elevation relative to the groundwater table elevation. If the dams were no longer maintained and the floodplain inundation was limited, the raising of the surface water elevation can reverse head gradients between the surface water and the groundwater. If this head gradient is large enough, the surface water can be lost to groundwater.

These factors resulted in the ΔQ and %ΔQ for 2013 in the lower reach to be relatively small, 100 Ls^{-1} and 0%, respectively (Figure 22). In 2014, ΔQ was approximately the same is in 2013 at 100 Ls^{-1}; however, the %ΔQ was significantly larger, approximately 40% (Figure 23). This is explained by 2013 being a relatively dry year with lower baseflows than 2014 (Figure 15). The differences between 2013 and 2014 in the lower reach illustrate the importance of accounting for annual variations in discharge.

In 2015, many new dams were built in the upstream section of the lower reach. The high density of dams built in a small location resulted in significant floodplain inundation in the upstream section of the lower reach, although much less than in 2010 and 2011. The backwaters created by a dam at the upstream end of the lower reach flooded PT515 and resulted in inaccurate water depth measurements. Without reliable data from PT515, the ΔQ across the lower reach could not be calculated. However, the ΔQ across the entire study area (PT0 to PT1252, Figure 24) showed that the creek gained from PT0 to PT1252. The gains are expected to be from the increased floodplain inundation caused by the large number of beaver dams built at the upstream end of the lower reach.

In 2016 and 2018, there was a relatively small ΔQ in the lower reach. In 2016, there was no beaver activity reported in the lower reach and all the existing dams were reported to be breached. In addition, the discharge in 2016 was the lowest recorded in the study period. The lack of beaver activity and low discharges are the causes of the neutral conditions in 2016. In 2017, the creek was losing in the lower reach. This is expected to be a result of the head gradient caused by the pools being filled with sediment deposits increasing the elevation of the channel bed.

Water Temperature. As shown in Figure 29, the water temperature at the end of the study reach (PT1252) is always higher than at the beginning of the study reach (PT0). This warming in the system is expected unless there are significant thermal resets throughout the reach. As noted, the increase in water temperature is primarily due to local weather conditions, with the solar radiation often being the most important (Sinokrot and Stefan, 1993; Webb et al., 2008). In addition, note that without beaver dams (2008), the change in water temperature in the lower reach was greater than in the upper reach (Figure 17). This is a result of several factors, the largest being shading. The upper reach has significant vegetation that covers the water surface, prevents solar warming. Another key factor is the channel geometry. As noted, the upper reach has a steeper bed slope than the lower reach and a relatively narrow channel with a smaller water surface area. The steep slope results in higher water velocities and lower residence times than in the lower reach. Lower residence times result in less time for the water to be warmed while the small water surface area results in less warming from solar radiation.

Upper Reach Water Temperature Changes. While the data from 2012 and 2013 is missing, the change in water temperature in the upper reach increased in 2014 and 2015 when the beaver dams were built relative to 2011. The beaver dams in the upper reach primarily increased the water depth but did not increase the water surface area. However, the dams did increase the residence time of the water in the upper reach and allowed for increased warming from solar radiation although this warming was limited due to riparian vegetation.

If the number of beaver dams directly correlates with the increase in water temperature, the change in water temperature in the upper reach should have been the largest in 2015. However, the increase in water temperature in 2015 (4 dams) (Figure 24) was less than 2014 (1 dam) (Figure 23) and 2016 (no dams) (Figure 25). The average daily discharge in 2014 and 2015 were relatively similar; however, the average daily discharge in 2016 was significantly less (Figure 15). The lower discharge in 2016 would allow the water temperature to increase more than in 2015. In addition, when reviewing the average air temperature, 2015 was significantly cooler than 2014 and 2016 (Figure 16). The lower air temperature in 2015 provides some additional information regarding smaller increases in water temperature when compared to 2014. However, the average increase in water temperature in 2015 is still larger than the increases each year spanning 2009 to 2011 before any beaver dams were built. As there were more dams in the upper reach in 2015 than 2009, this shows that beaver dams did cause the water temperature in the upper reach to increase.

Lower Reach Water Temperature Changes. In the lower reach, the increase in water temperature was always greater than in the upper reach. This is due to the limited riparian shading and consistently larger water surface areas in the lower reach due to damming. The change in water temperature in the lower reach increased sharply in 2010 (Figure 19) and 2011 (Figure 20). In these years, there was extensive flooding and very large water surface areas (Figure 35). Consistent with Cook (1940) the larger water surface area resulted in increased warming of the water in 2010 (Figure 19) and 2011 (Figure 20). The change in water temperature continued to increase in 2012 (Figure 21) and 2014 (Figure 23) although not as sharply as in 2010 and 2011 (Figure 29). The increase in 2012 and 2014 is expected to be a result of increasing beaver dams and increased residence times. In 2015, the change in water temperature sharply increased again (Figure 24). The large increase in beaver dams in the upstream section of the lower reach is expected to be the primary cause of this sharp increase.

After the beaver were removed at the end of 2015 and the beginning of 2016, the increase in water temperature in the lower reach declined, bottoming out in 2017. The decline in water temperature is largely due to the beaver being removed and the dams breaching and washing out. As with the upper reach, the increase in water temperature in 2017 was still larger than in 2008 and 2009 (Figure 29). But, the baseflow in 2017 was approximately 50% larger than in 2008 and 2009. The larger discharge in 2017 would result in a smaller increase in water temperature due to more energy being required to warm a larger volume of water. In addition, the average monthly air temperature in 2017 was only slightly higher than in 2008 and 2009 (Figure 16). These factors suggest that the beaver dams created a longer lasting alteration of the channel geometry (e.g., increased surface areas and decreased depths) resulting in perpetually raised water temperatures. In 2018, the change in water temperature increased relative to 2017 (Figure 29). The air temperatures in 2017 and 2018

were roughly the same (Figure 16); although, the discharge in 2017 was much larger than in 2018, which can explain greater warming (Figure 15).

Daily Variations in Water Temperatures. Daily average water temperatures show that the beaver dam complexes cause warming over the study reach. As shown in Figure 31 and Figure 32, using daily average water temperature fails to account for the daily variations in water temperature. In 2009 and 2015, the daily water temperature in the upper reach fluctuated by approximately 0.4°C and 1°C, respectively. In 2015, the upper reach warmed almost twice as much as in 2009, but had baseflows slightly lower than 2009 (Figure 14 and Figure 15) allowing for a larger ΔT. In addition, there were also four actively maintained beaver dams in the downstream section of the upper reach that increased water residence times and increased temperatures due in part to limited vegetation in this part of the reach.

In the lower reach, the ΔT is much more dramatic. In 2009, ΔT increased by approximately 0.7°C (Figure 31) while in 2015 the temperature increased by almost 5°C (Figure 32). This increase in warming in 2015 is due to the 43 actively maintained dams present in the lower reach. These dams significantly increased the water retention time while also increasing the water surface area. It is also interesting to note the difference in response times in the water temperature in 2009 and 2015. The peak in the ΔT in the lower reach in 2015 was similar to the peak in air temperature and solar radiation while the 2009 peak water temperature occurred almost four hours later. This is most likely due to the larger surface areas and shallower water depths in 2015 allowing the water to warm, and cool, much faster than in 2009.

Conclusion

The objective of this report was to build on the findings of Majerova et al. (2015) by including seven additional years of data to evaluate the longer-term impacts of beaver dam complexes on Curtis Creek. The data set used for this analysis included water temperatures and flow rates at different locations in the study reach over a 10-year period (2008 to 2018). Weather data were collected by the climate station located adjacent to a study reach and provided air temperature and solar radiation values throughout the study period.

Similar to the findings presented by Majerova et al. (2015), we found that the beaver dams initially resulted in gaining groundwater conditions during low flow periods. However, this was only the case when the dams caused water to inundate the floodplain and increase the nearby groundwater table. When the discharge decreased, the mounded water table reversed head gradients and groundwater returned to the creek, increasing the discharge. This occurred in 2009, 2010, and 2011. When the dams were not maintained or flooding did not occur, the groundwater elevations were similar to or lower than the surface water elevation and resulted in neutral conditions. It is also hypothesized that sediment deposition in the ponds can again reverse the head gradient between the surface water and the groundwater when the dams were not maintained and result in losses from the creek. This is expected to be the cause of the losing conditions in 2012, 2014, and 2016.

In reviewing the water temperature data, before any dams were built, the daily increase in water temperature in the upper reach was less than the lower reach. This is due to the more extensive

vegetation providing shading in the upper reach, preventing solar warming. After the dams were built in both reaches, the water temperature increased over each reach. This was due to the increased surface area and residence times created by the dams. It was also noted that even after the dams breached or washed out in 2016, the increase in water temperature was still greater than the original conditions (2008) before any dams were built. This is expected to be due to the sediment deposition in the pools created by the dams and the resulting longer term changes in channel geometry. The sediment deposited decreased the channel bed slope and changed channel geometry, thus increasing residence times compared to the pre-dam conditions. This allowed the water temperature to warm more than before the dams were built. It was also noted that increase of water temperature in the lower reach in 2018 was larger than in 2017 even though there was no beaver activity reported in the area. This change was due to the significantly larger discharge in 2017 than 2018. This shows the importance of accounting for the multitude of factors that affect water temperature.

The importance of daily water temperature variations was also shown. Before the beaver built significant numbers of beaver dams, the water temperature would fluctuate less than 1°C over a single day (Figure 31). When the number of beaver dam complexes peaked in 2015, the water temperatures fluctuated by almost 5°C in a single day. These large daily temperature fluctuations are a result of the beaver dams increasing the water surface areas allowing the water to warm and cool much faster.

In summary, when beaver dams redirect water into floodplains during high flow periods, groundwater levels are elevated and can result in groundwater discharge to the creek during baseflow conditions. However, as beaver dams age, fill with sediments, and are no longer maintained, the head gradient between the creek and the groundwater can be reversed and may result in losses to the groundwater during baseflow conditions. It was shown that beaver dams increase residence times contributing to increases in water temperature. However, extended data show that even after the dams breached or washed out, the water temperature increases at the reach scale were greater than before the dames were constructed due to channel changes from sediment accumulation in ponds. It was also shown that, while beaver dam complexes can significantly impact reach scale water temperatures, local weather is still a key control over water temperatures.

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Appendix A – Pressure Transducer Rating Curves

Appendix A contains the rating curves that were developed for each of the three pressure transducers installed in Curtis Creek from 2007 to 2018. The rating curves were developed by regressing field discharge measurements to depths reported by the pressure transducer. The power equation (Equation 1) was used to describe each rating curve.

$$Q = aZ^b \qquad \text{(Equation 1)}$$

Where:
a and b are coefficients from the rating curve
Q is the discharge (Ls^{-1})
Z is the water depth reported by the pressure transducer (m)

Uncertainty in the development of these rating curves is accounted for with the 95% confidence bounds. The 95% confidence bounds are calculated as described by Schmadel et al. (2010) and Majerova et. al (2015). The uncertainty bounds accounts for possible errors in equipment measurements (pressure transducer or discharge measurements).

Due to a multitude of factors, each pressure transducer required the development of several rating curves over the years due to channel changes or the need to relocate a pressure transducer. The cause of each rating curve shift is described below.

Pressure Transducer at Station 0 (PT0)

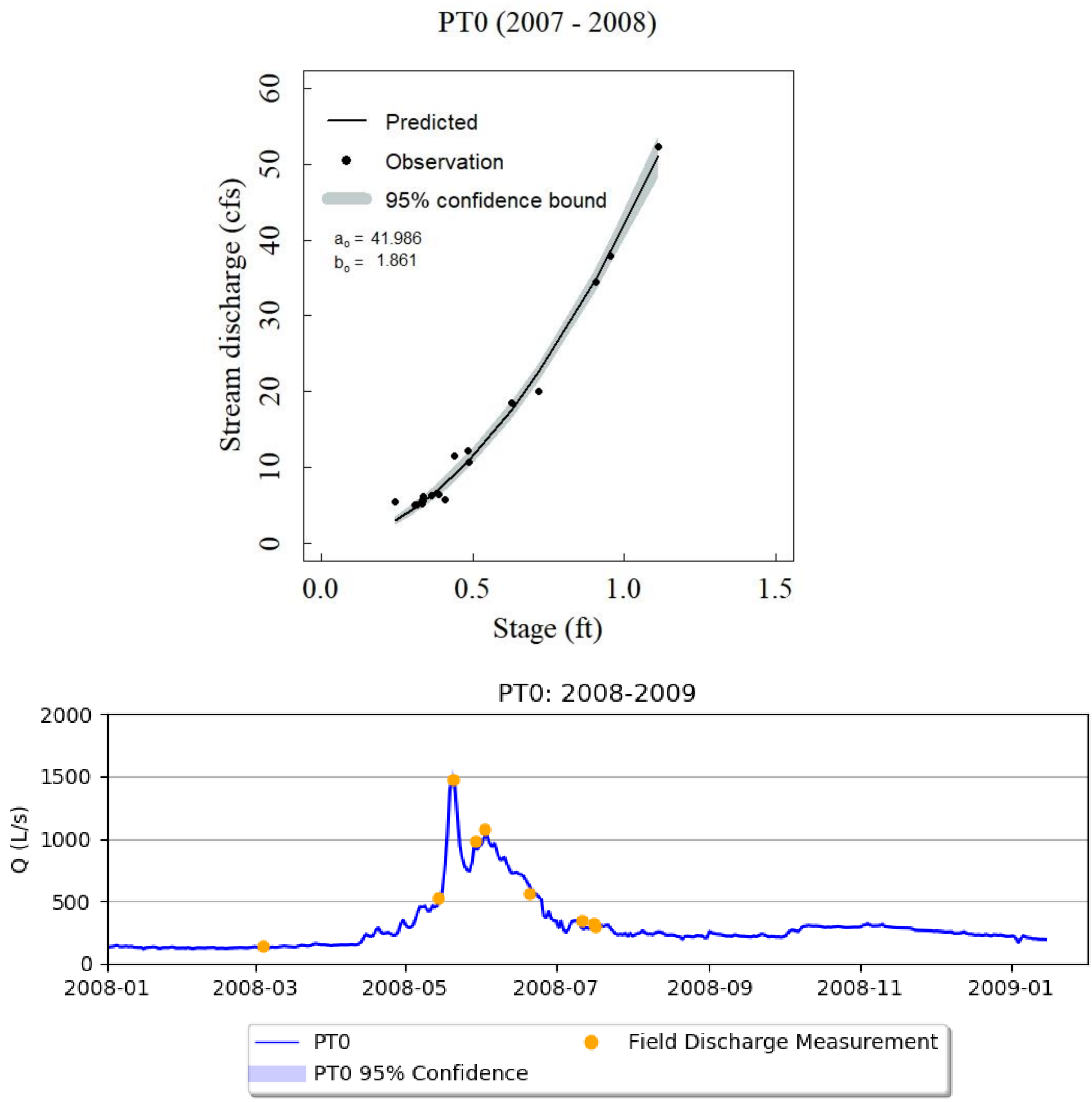
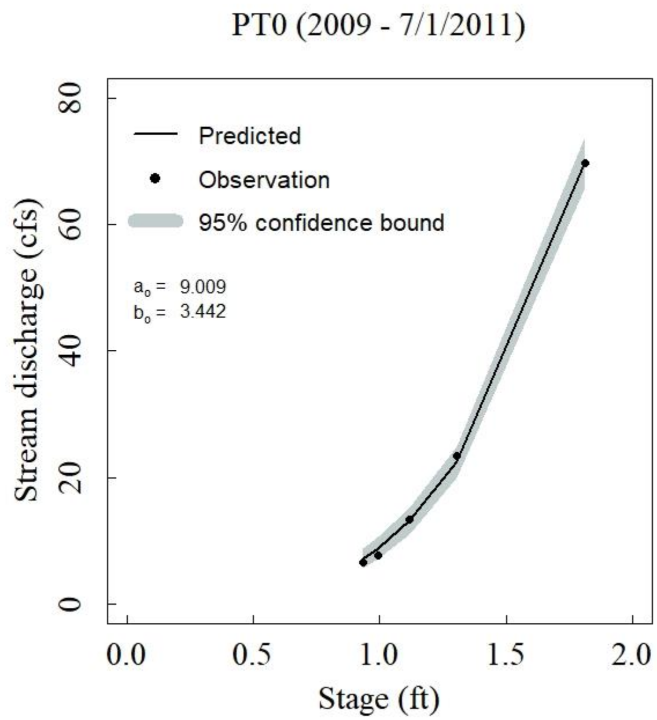


Figure A1. PT0 rating curve effective from July 20, 2007 to January 15, 2009. This is the first rating curve developed for the Curtis Creek at PT0. The pressure transducer stopped functioning on January 15, 2009 and was replaced on March 2, 2009.



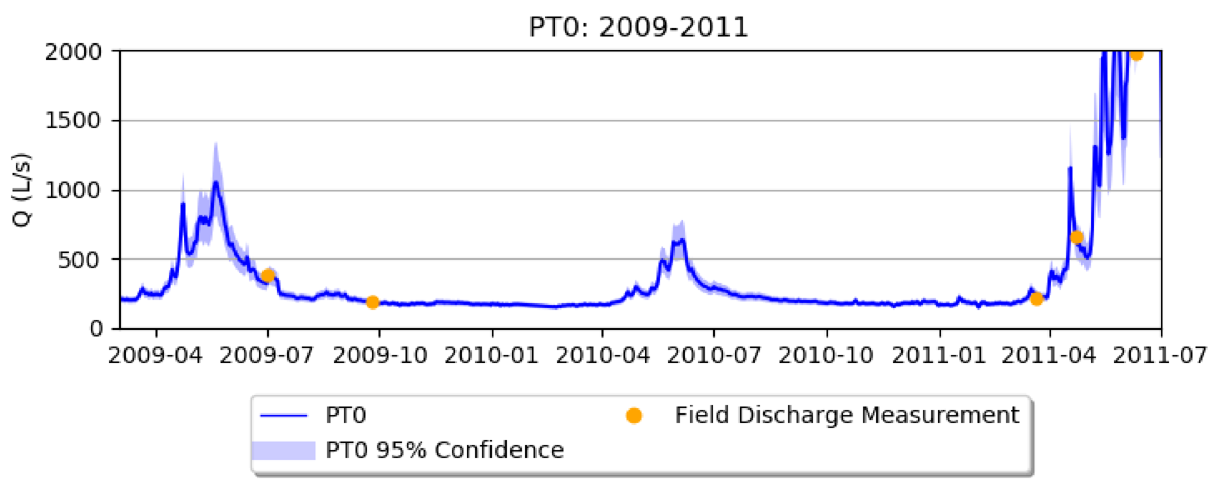


Figure A2. On March 2, 2009 the pressure transducer at PT0 was replaced. The new sensor recorded until July 1, 2011. On July 1, the pressure transducer was hit and covered by debris in the water due to unusually high discharge. On July 27, 2011 the debris was cleared, and the pressure transducer was reinstalled. The reinstallation of the pressure transducer caused the shift in the rating curve.

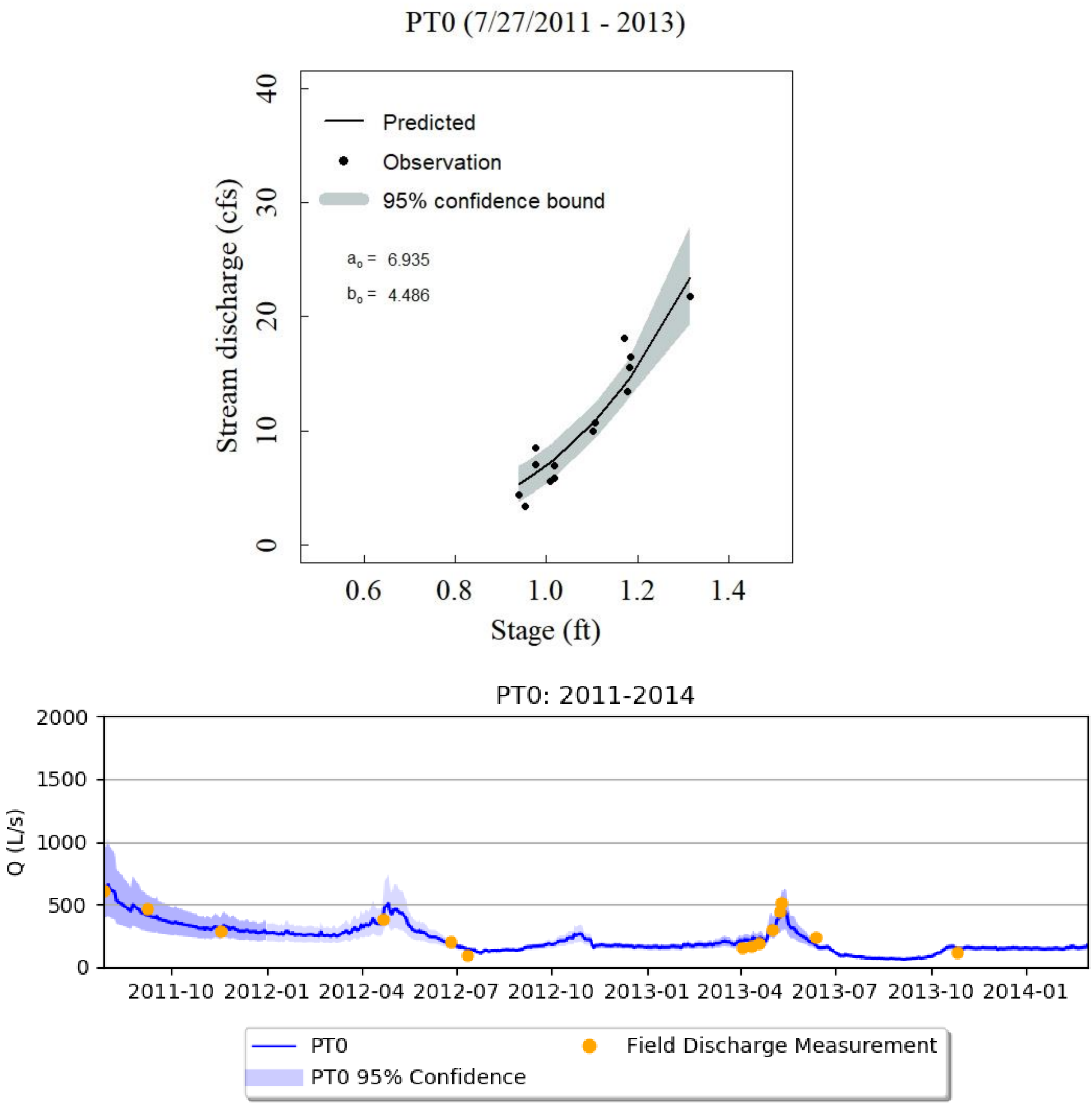


Figure A3. The reinstalled pressure transducer required a new rating curve to be developed. This rating curve was applied from July 27, 2011 to March 6, 2014 when a new pressure transducer was installed. The new pressure transducer required a new rating curve to be developed for Curtis Creek.

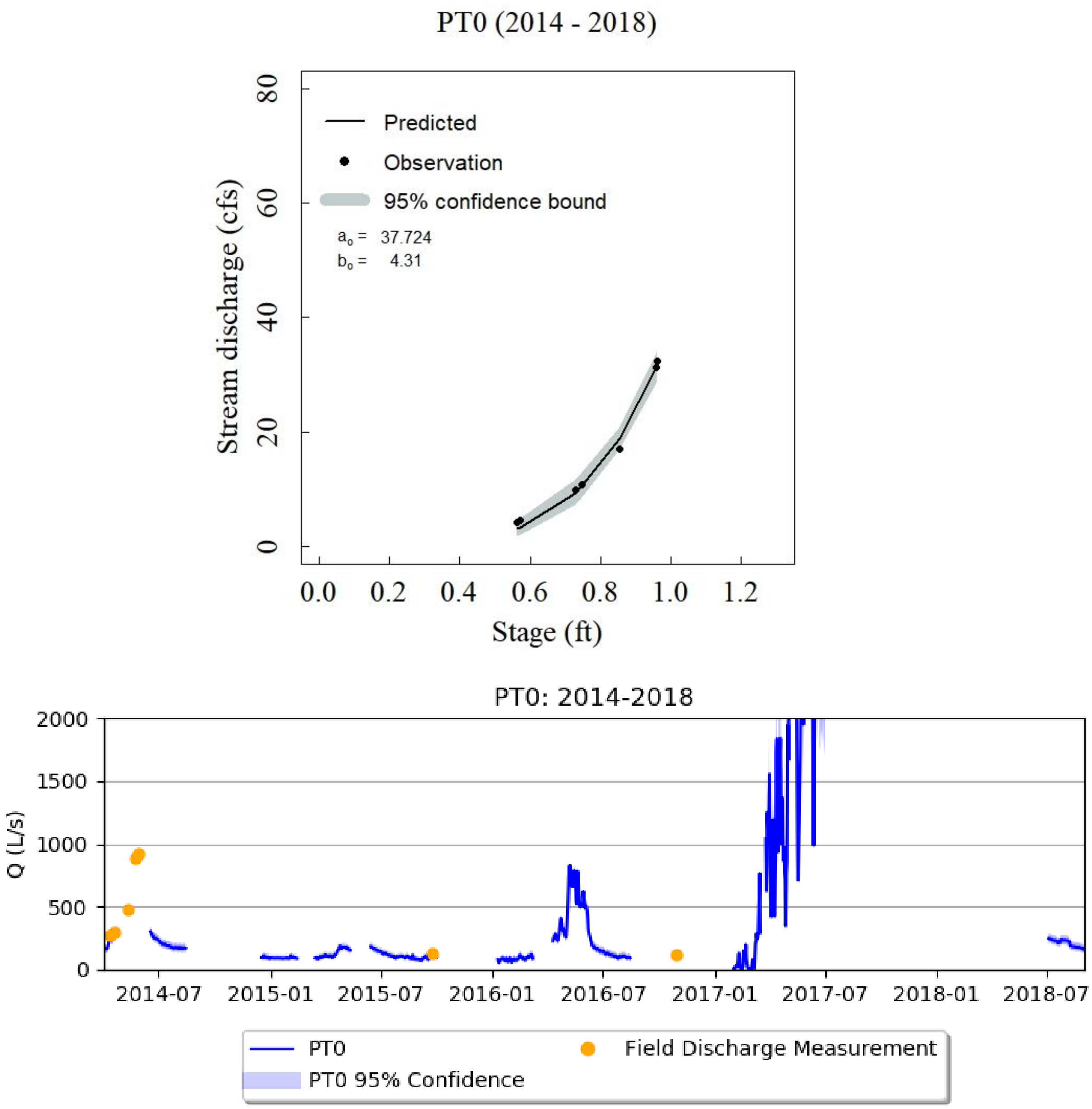
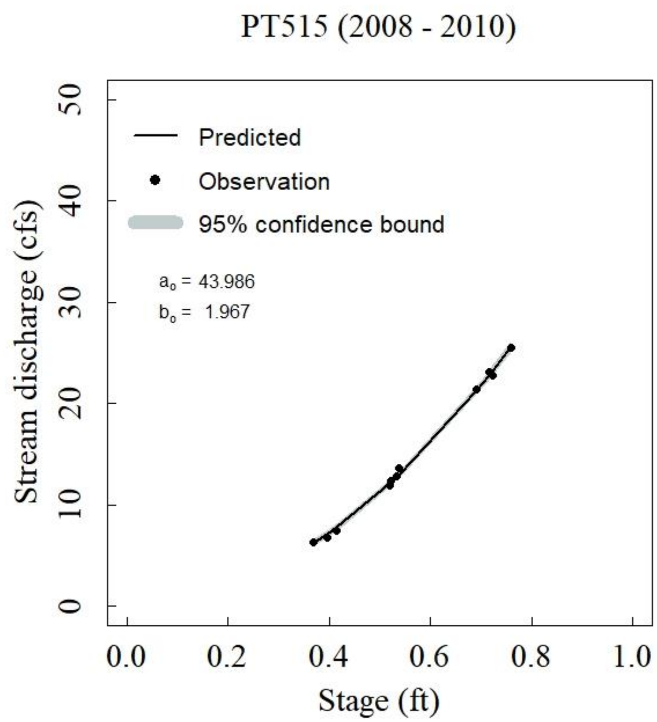


Figure A4. A new pressure transducer was installed on March 6, 2014. This resulted in a rating curve shift from the previous rating curve. This rating curve was applied to the river through the end of 2016. In May 2015, a beaver dam analog (BDA) was installed by the Department of Natural Resources (DNR) just upstream of PT0. As designed, the beaver built a dam on the BDA upstream of PT0. It was noted in 2017 (a wetter than average year) that the dam upstream from PT0 was causing water to flow around the banks resulting in inaccurate depth measurement. Due to this inaccuracy, the data collected at PT0 after 2016 is not included in this analysis.

Pressure Transducer at Station 515 (PT515)



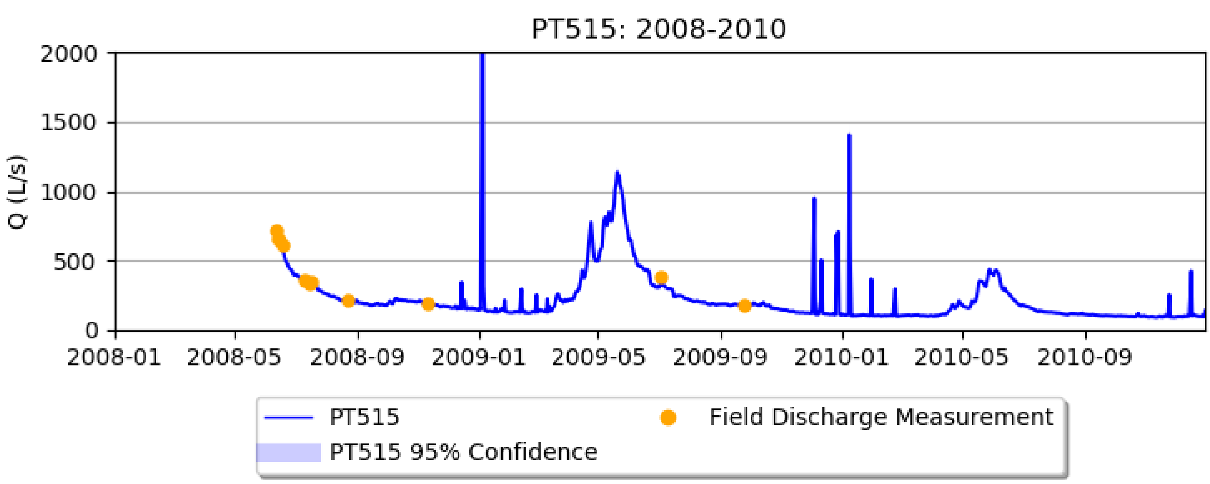


Figure A5. PT515 was installed in early 2008. A rating curve was developed and applied from 2008 to 2010. The Curtis Creek experienced unusually high discharge in 2011. The relatively high discharge in the Creek had not been captured before and required the rating curve to be shifted to accurately calculate the discharge at high flows.

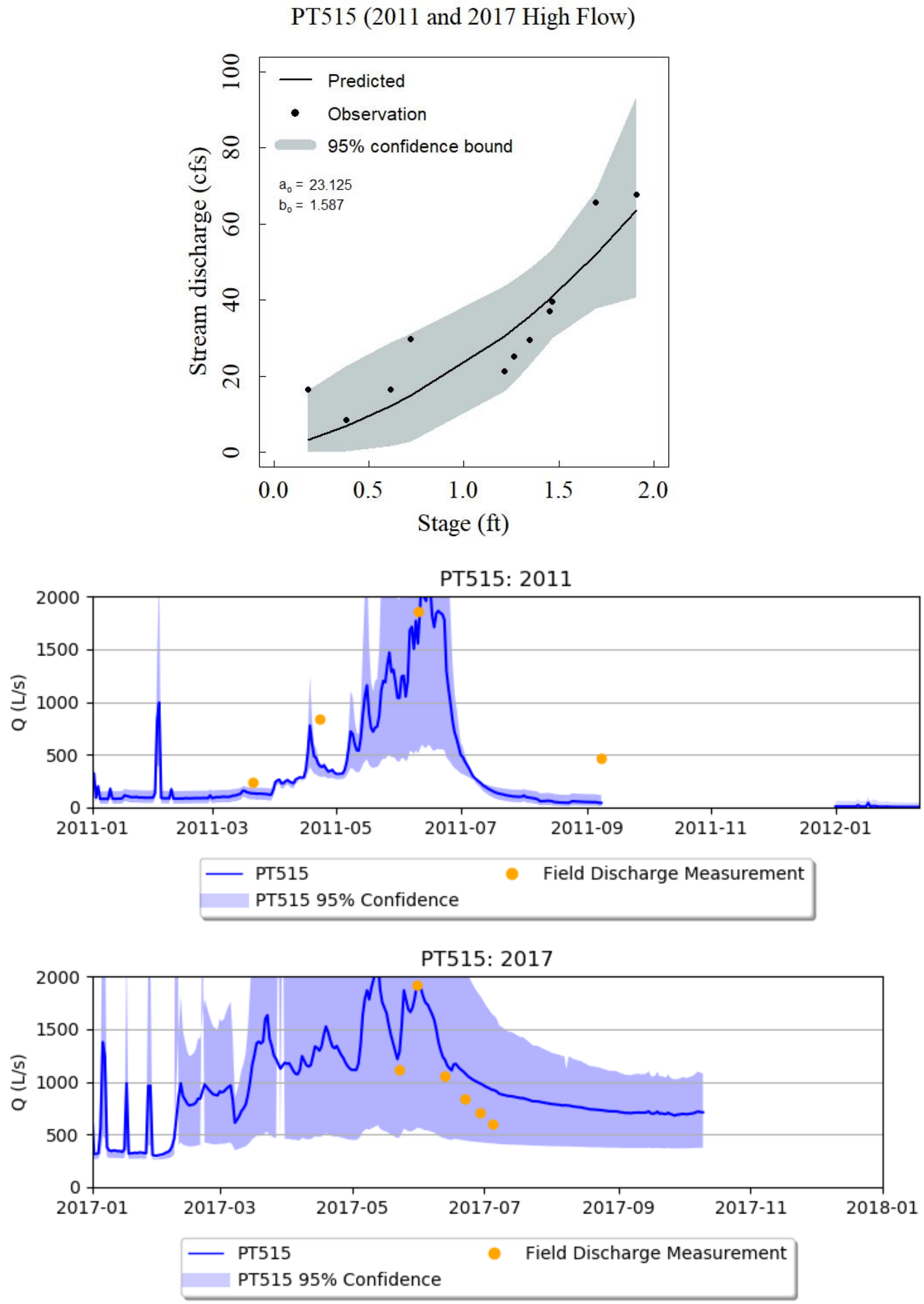
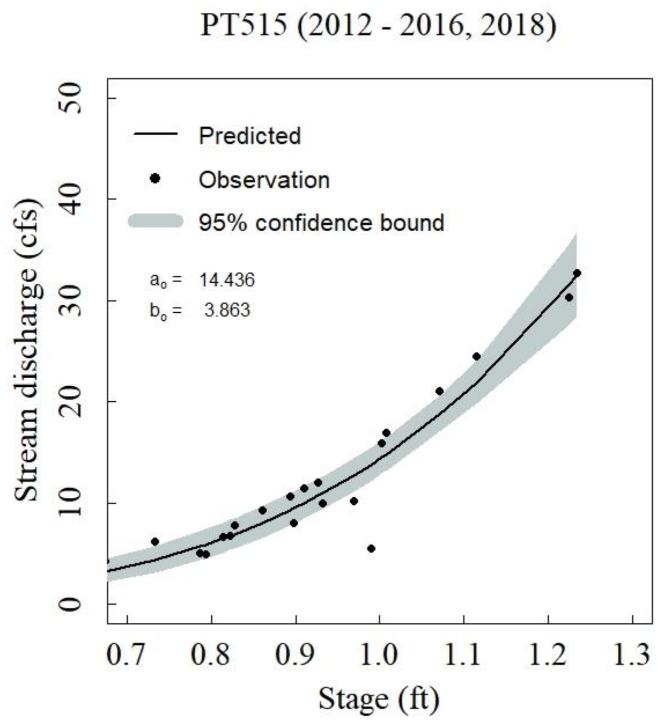


Figure A6. The Curtis Creek experienced unusually high discharge in 2011 and 2017. The relatively high discharge in the Creek had not been captured before and required the rating curve to be shifted to accurately calculate the discharge at high flows. The exact date when the high flows began is unknown; however, the only the data from the months of April to November are used in this analysis. Therefore, the rating curve for 2008 to 2010 is applied through the end of 2010 and the high flow rating curve is applied to all of 2011 and through February 2012. In the February 2012, the beaver built a dam close enough downstream of PT515 to cause the pressure transducer to be in the pool. PT515 was moved approximately 10 meters upstream, out of the pool created by the beaver dam on May 29, 2012. This rating curve is applied to the depths measured from 3/2/2011 to 2/11/2012 and all of 2017.



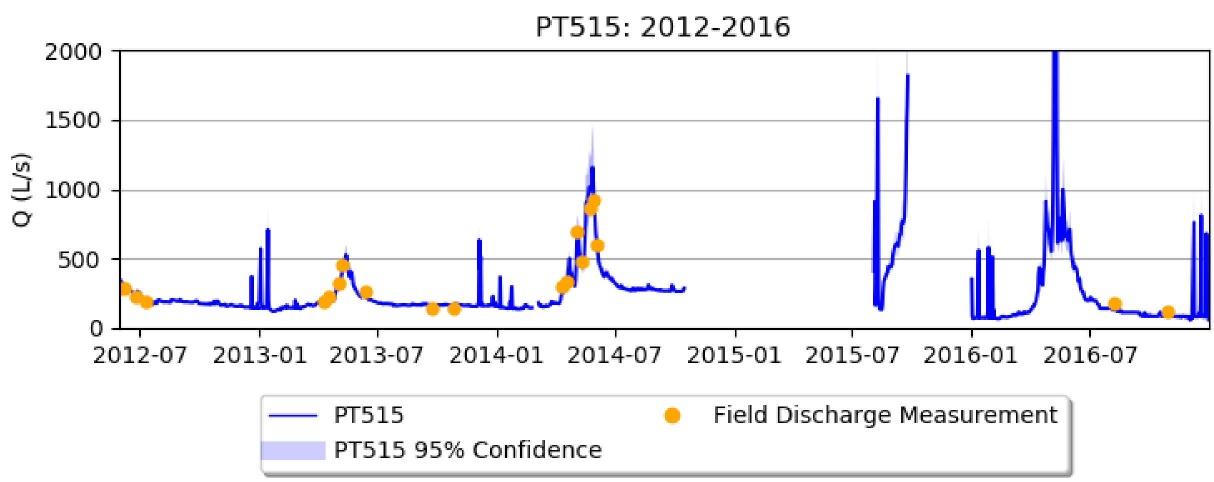
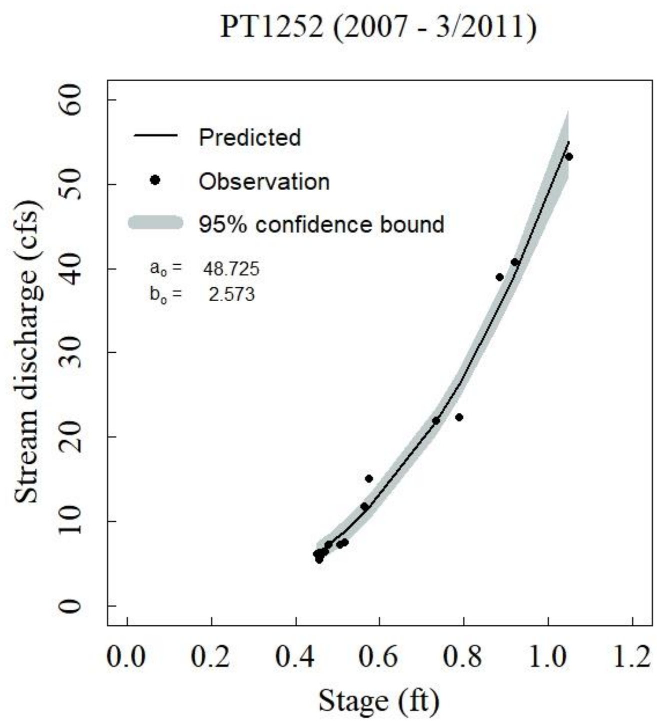


Figure A7. When PT515 was moved upstream on May 29, 2012, a new rating curve was developed. This rating curve is applied through the end of 2016 and for the depths recorded in 2018 when the downstream beaver dam was removed. The removal of the beaver dam caused the water depth at PT515 to decrease slightly as velocity of the water increased. This resulted in the need to develop a new rating curve.

Pressure Transducer at Station 1252 (PT1252)



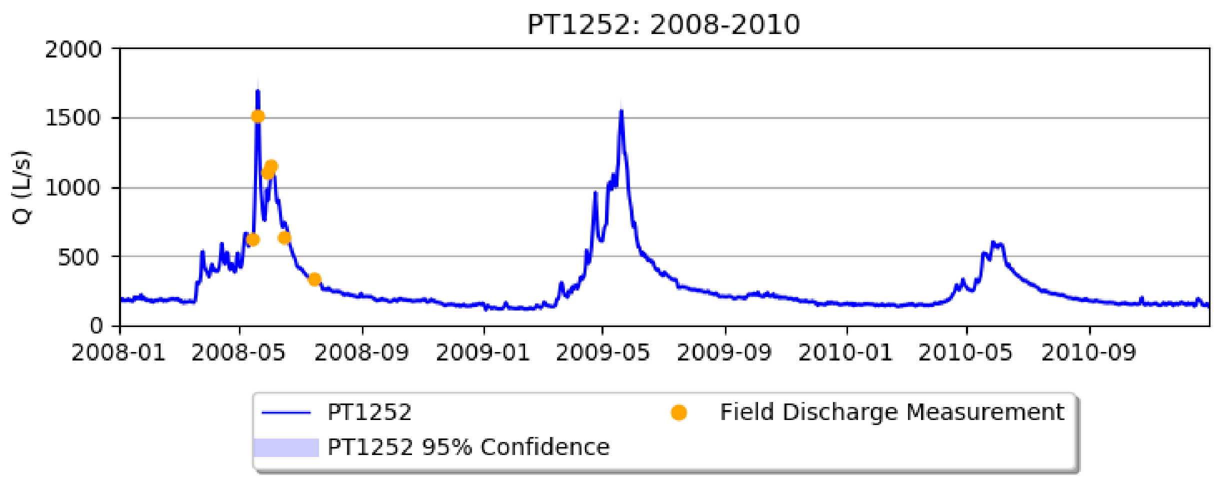


Figure A8. PT1252 was installed on July 20, 2007. The rating curve developed for the first period of discharge data ranged from 2007 to March 2011. Spring 2011 was an unusually wet year with relatively high discharge and required the development of a new rating curve.

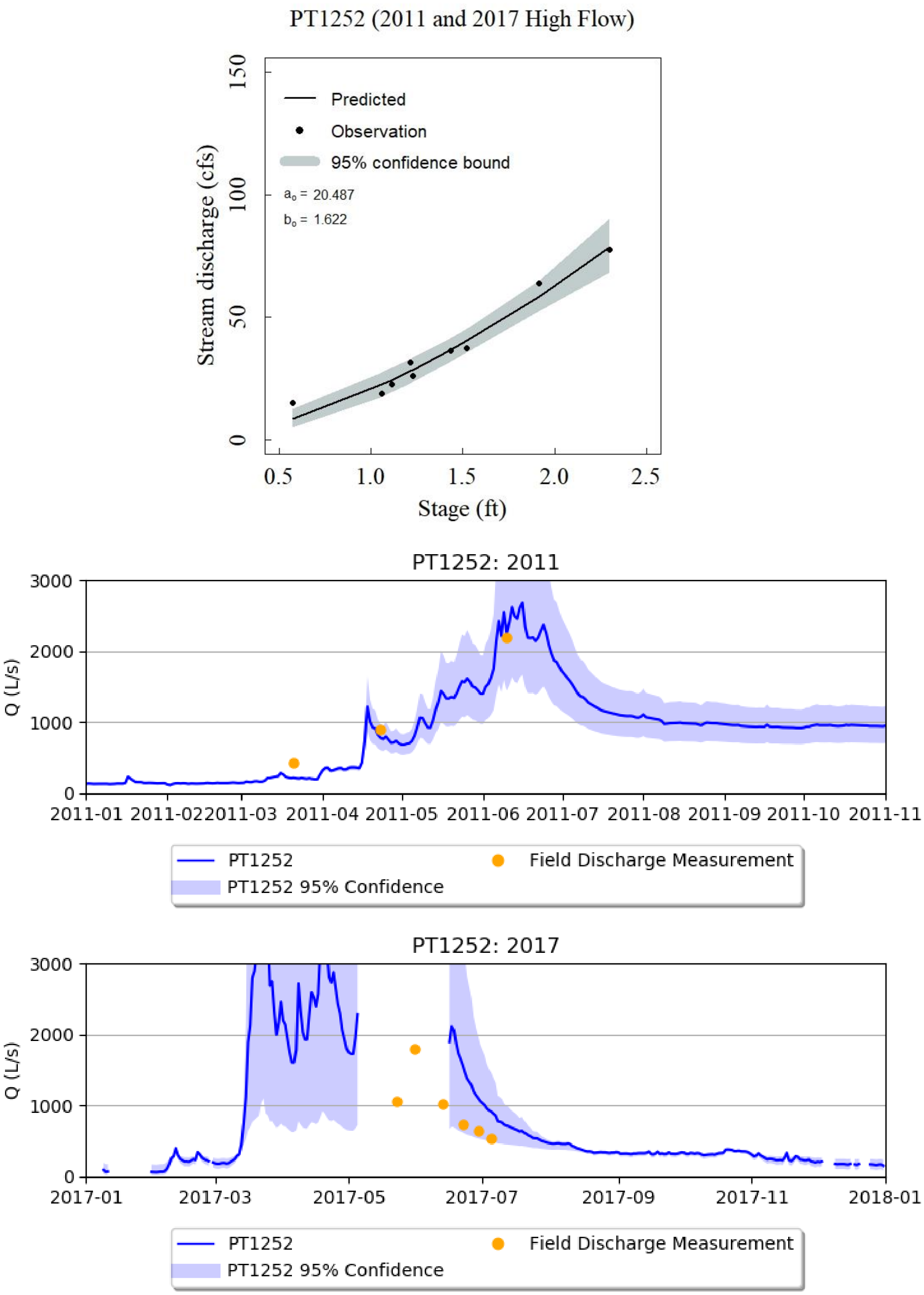
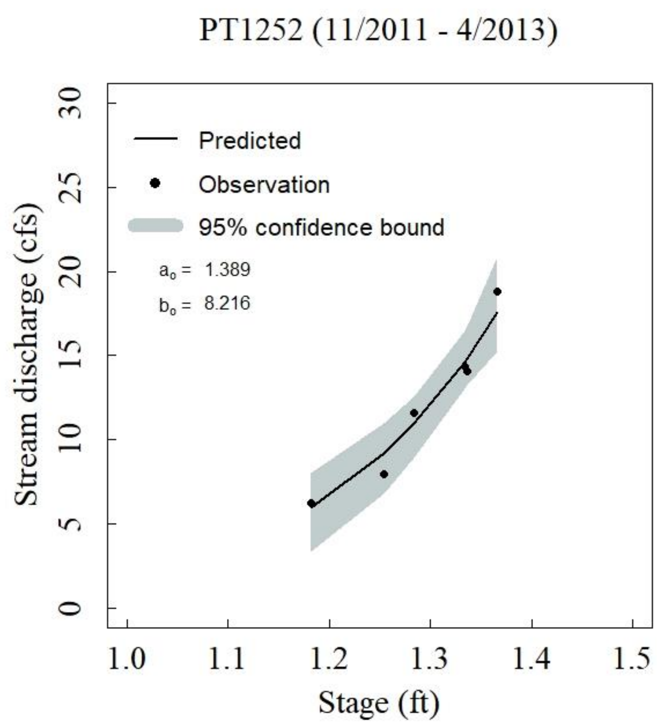


Figure A9. The rating curve developed during 2011 and 2017 was used to reflect the unusually high discharge in the Curtis Creek. This rating curve is applied to depths measured from late March 2011 to November 2011 and all of 2017. A new rating curve was developed starting in November 2011.



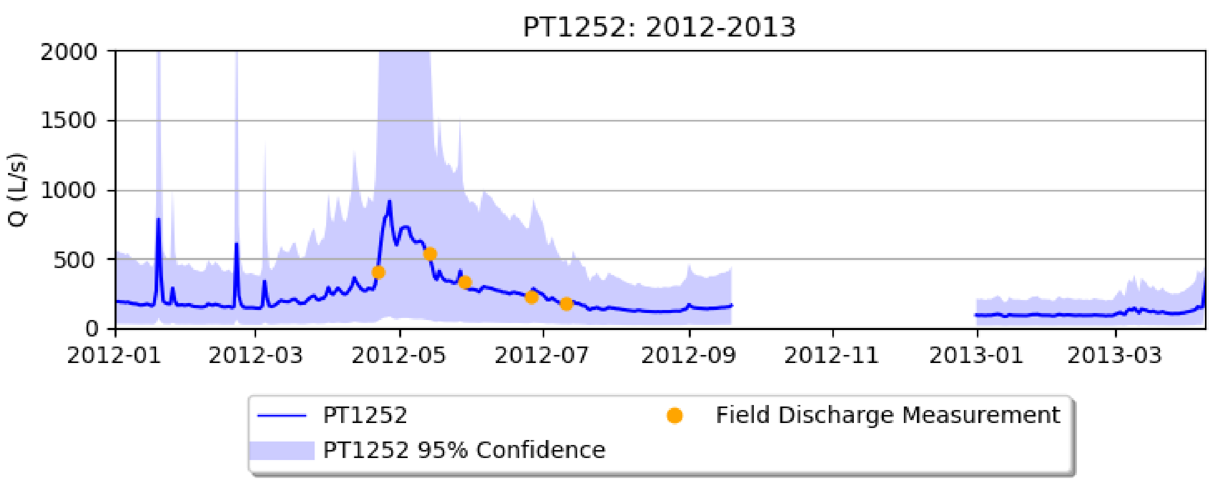
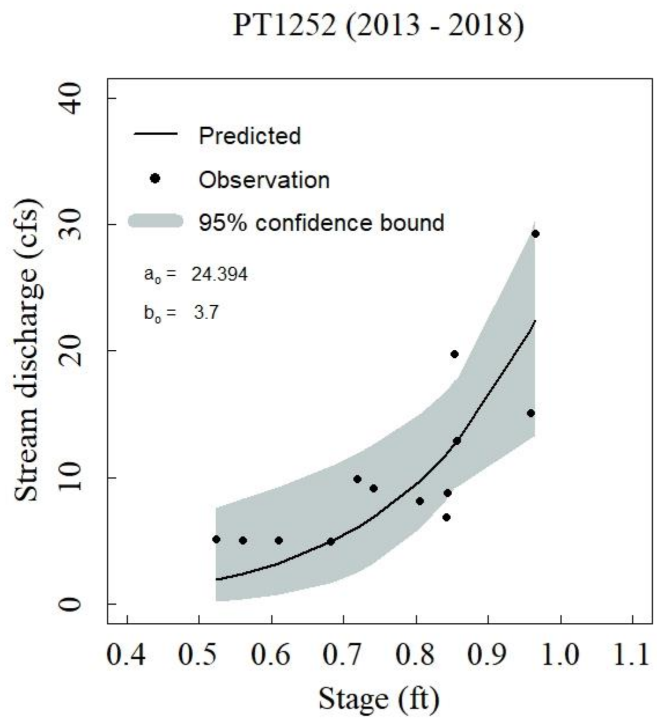


Figure A10. The rating curve was developed from November 2011 through April 8, 2013. Due to the high flows that occurred in 2011, the general channel geometry changed enough to require development of a new rating curve. A new pressure transducer was installed on April 8, 2013. The installation of a new pressure transducer required a new rating curve to be developed.



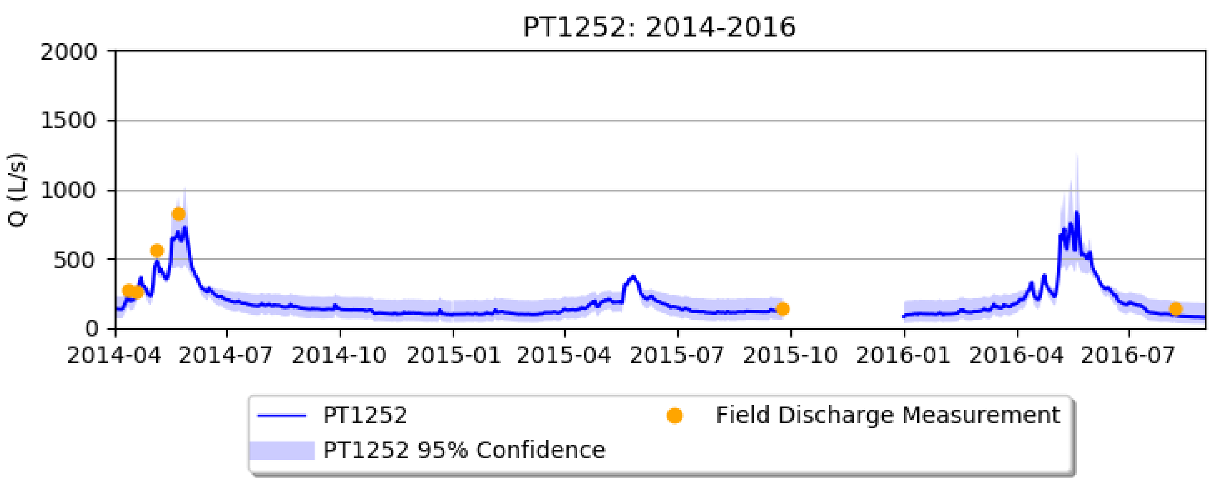


Figure A11. When a new pressure transducer was installed on April 8, 2013, a new rating curve was developed. The new rating curve was applied to the pressure transducer readings through August 2018 when the pressure transducer was removed (excluding 2017).

Appendix B – Methodology for Data Quality Control

The raw water temperature and discharge data measured by the pressure transducers included many anomalous values. These values resulted in calculated discharges in excess of 28,000 Ls^{-1} and water temperatures over 30°C. An example of the anomalous water temperature values measured in 2014 is presented in Figure B1.

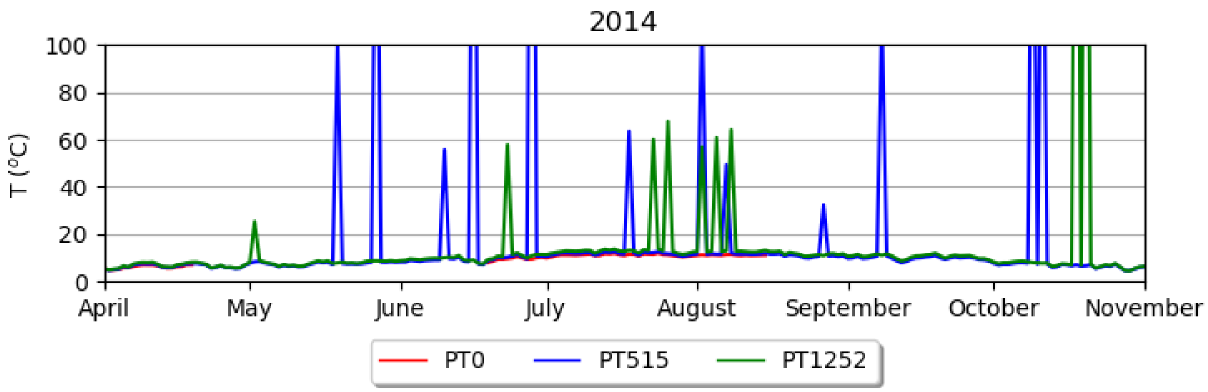


Figure B1. 2014 daily average water temperatures.

As seen, the water temperature measured at PT515 and PT1252 included many data points over 30°C. Similar anomalies are seen in every year of the study at each pressure transducer station. Finding and removing all the anomalous values manually would be a difficult and time-consuming process; therefore, a script was developed to automate this quality control process for both the water temperature and depth. This appendix details how this script was developed and verified to ensure that only anomalous values were removed.

To simplify the quality control process, the example plot was updated only include one pressure transducer, PT1252 in this example (Figure B2).

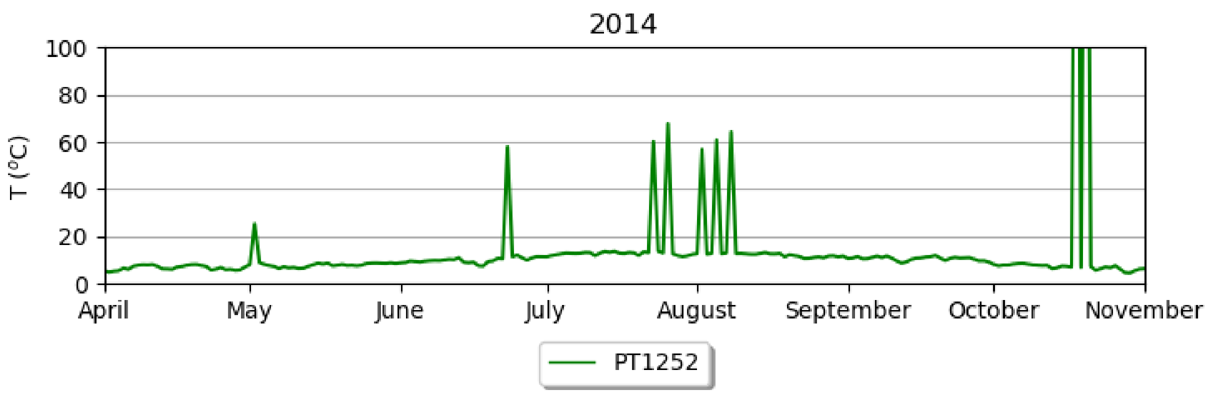


Figure B2. 2014 average daily water temperature data recorded at PT1252.

The plot was recreated to focus on the area with the most anomalous values, July 15 through August 15 (Figure B3).

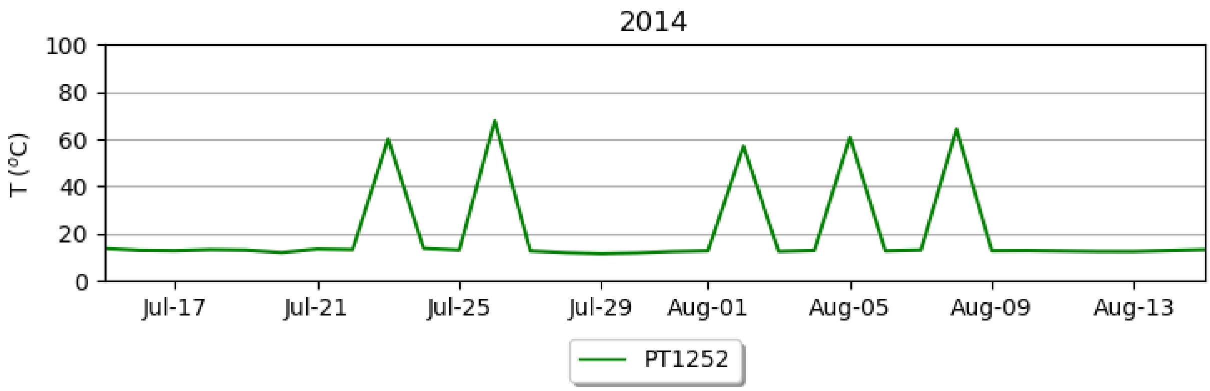


Figure B3. Average daily water temperatures recorded at PT1252 during July and August 2014.

Now with the plot focusing on five anomalous values, it is shown that these values occurred on July 23 and 26 and August 2, 5, and 8. Knowing the date that the anomalous value occurred allows the raw data file to be reviewed manually to find the anomalous value. The raw data files contain measurements every 5 minutes resulting in 288 data points every day. Isolating the specific day that an anomalous value occurred allowed us to review a single day rather than the approximately 105,000 data points recorded at each pressure transducer each year. By reviewing the raw data files, it was confirmed that each of these days contained at least one anomalous data value, usually larger 100°C.

A loop and an if statement were used in the script to remove any values greater that 30°C. This resulted in breaking the plotted water temperature into segments where the anomalous values were removed. This plot allows us to review what data was removed and compare it to the plot including the anomalous values. This process ensured that only the anomalous values were removed (Figure B4).

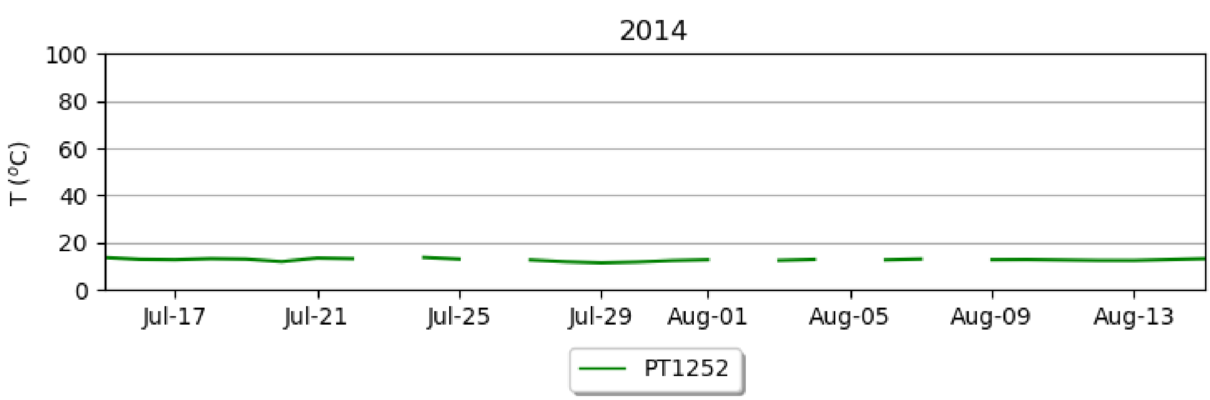


Figure B4. 2014 average daily water temperatures with anomalous values removed.

The script was updated to replace each anomalous data value with the average of the datapoints immediately before and after the value. This resulted in filling the holes in the previous plot. The corrected datapoints were plotted in a different color (red) to show all the values that were corrected. This final plot allows us to see what the corrected values are and how they relate to the surrounding data values (Figure B5).

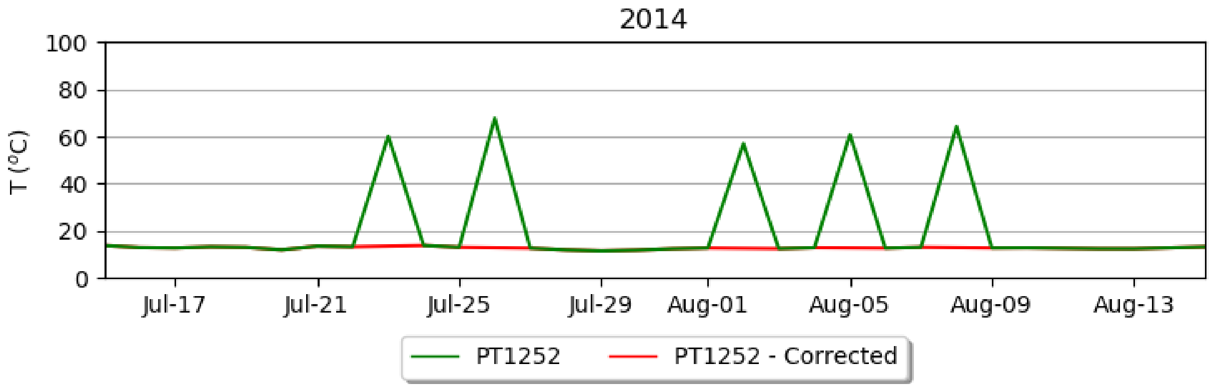


Figure B5. The daily averages that exceeded 30°C were removed and replaced with the average of the water temperatures immediately before and after the removed data point. The corrected data points are shown in red.

The same process was used for the discharge. The only difference in the discharge quality control process was the limit in the if statement in the script. For the discharge, any discharge measurement exceeding 14,000 Ls^{-1} was replaced with the data values immediately before and after the anomalous value.

This same process was repeated several times for each pressure transducers at different times in the year. This allowed us to know that the script was accurately replacing the anomalous data values, dramatically simplifying the quality control process when compared to manually reviewing the data.