Ozarks Environmental and Water Resources Institute (OEWRI)
Missouri State University (MSU)

Final Report

Dissolved Oxygen and Water Temperature Monitoring of the Big Piney River and Roubidoux Creek at Fort Leonard Wood, Missouri (October 2019-June 2021)

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SCOPE AND OBJECTIVES

Dissolved oxygen (DO) concentration is a critical component of aquatic habitat quality and low DO levels can be a significant contributor to water quality degradation in freshwater ecosystems (Hinck et al., 2011; Obrecht and Thorpe, 2011). In Ozarks streams, high DO levels have a positive relationship to native fish richness, macroinvertebrate indices, and groundwater inputs that generally maintain base flow and provide increased DO levels to these streams (Paukert et al., 2020). However, during the warm summer months, during extended dry periods, DO concentrations can decrease to low levels causing stress or even mortality in aquatic organisms (Munn et al., 2018). In general, warm water holds less DO than relatively cooler water (Mesner and Geiger, 2010). Additionally, during the day, aquatic vegetation releases DO into the water via photosynthesis, but at night DO levels drop significantly due to respiration resulting in relatively large diurnal variations in DO (Cornell and Klarer, 2008). Other contributing factors to low DO levels can be the decomposition of algae during eutrophic conditions, illegal spills/dumping of various substances or waste products, and physical barriers to flow such as dams (Butts and Evans, 1978; Mesner and Geiger, 2010). Aquatic organisms become stressed when DO levels are between 3-5 mg/L and mortality occurs when DO levels drop below 3 mg/L (Brown and Czarnezki, No Year; Fondriest, 2013). In Missouri, streams with DO concentrations below 6 mg/L in cold water fisheries and below 5 mg/L in cool and warm water fisheries for >10% of the measurements over seasonal critical periods can be considered impaired for low dissolved oxygen levels (CSR 2021; MDNR 2021).

The Big Piney River and Roubidoux Creek flow through the Fort Leonard Wood military installation located in Pulaski County, Missouri. These streams are managed as both a fishery and as critical endangered mussel habitat (Wilkerson, 2004). However, both streams have been affected by upstream land use changes, increased high intensity rainfall, small dams, and nonpoint source pollution generated from within the installation. To better understand seasonal DO patterns of these streams within the installation, the Army Corps of Engineers hired the Ozarks Environmental and Water Resources Institute (OEWRI) at Missouri State University to conduct a 10-month continuous DO, temperature, and stage monitoring of both streams. The specific objectives of this study are: 1) install five continuous DO/temperature sensors (three on Big Piney and two on Roubidoux Creek) on portions of both streams within the installation; 2) Install a continuous stage gage at each site to bridge the gap between USGS gaging stations located upstream and downstream of the sampling sites to evaluate flow variability; and 3) analyze the seasonal variability in DO and temperature at each site in relationship to water levels and recommended levels for a sustainable fishery. The results of this study will provide the information necessary to understand the spatial and temporal distribution of dissolved oxygen levels within the installation and will help natural resource managers produce remediation plans for periods of low DO levels in both river systems.

STUDY AREA

The Big Piney (1,956 km^2) and Roubidoux Creek (752 km^2) watersheds are located in the Ozarks Highland region in south-central Missouri (Figure 1). Both systems are major tributaries in the larger Gasconade River Basin (9,262 km^2) which flows north toward the confluence with the Missouri River. Both streams flow through a portion of the Fort Leonard Wood military installation in Pulaski County. This area of the Ozarks is part of the Salam Plateau physiographic region, which is underlain mainly by Ordovician- and Devonian-aged carbonate bedrock with remnants of Mississippian and Pennsylvanian limestone (Howe and Koenig, 1961). This soluble bedrock results in a karst region where sinkholes, springs, and losing streams are common. The upper sections of both watersheds are predominantly agricultural, mainly livestock grazing, while the lower part of each watershed is mostly forested including portions of the Mark Twain National Forest.

Site Descriptions

Big Piney River

There were three DO monitoring stations installed along the Big Piney River for this project: 1) Big Piney upstream of the lower dam (BPD); Big Piney upstream of the spring (BPS); and Big Piney near the quarry (BPQ). The site furthest downstream site (BPD) is located approximately 1 km upstream of the USGS gage (#06930060) located at the East Gate Road bridge and 600 m upstream of the lower dam (Figure 2, Table 1). The next site (BPS) is located 2.1 km upstream of BPD, just upstream of the Stone Mill Spring, and approximately 4.3 km downstream of the upper dam. The furthest upstream site (BPQ) is located 2 km upstream of the upper dam near the quarry and approximately 11 km downstream of the USGS gage (#06930000) located near Western Road. Discharge data collected at the USGS gaging stations was used to estimate discharge at each monitoring station.

Roubidoux Creek

There were two DO monitoring stations installed on Roubidoux Creek for this project: 1) located along Roubidoux Creek at Ft. Leonard Wood Road Number 8 (RC8); and 2) located along Roubidoux Creek at State Highway 17 (RC17). The farthest downstream site (RC8) is located approximately 2.1 km upstream of the USGS gage (#06928420) located at the Polla Road bridge and approximately 50 m upstream of Ft. Leonard Wood Road Number 8 low-water bridge (Figure 3, Table 1). The upstream site (RC17) is located 43.5 km upstream of RC8, just downstream of the USGS gaging station (#06928300) at State Highway 17. Discharge data from nearby USGS gaging stations was used as estimate for respective monitoring sites.

METHODS

Hydrology

Stream discharge and rainfall data were downloaded from USGS gaging stations located upstream and downstream of the project area and local precipitation gages through the Midwest Climate Center (cli-mate) website (MRCC, 2021). For this project, the long-term rainfall station at Waynesville (1941-present) was used to characterize precipitation over the monitoring period. Any missing data was obtained from the station located on Fort Leonard Wood (2002-present). These stations were both within 25 km of the DO monitoring stations. Precipitation analysis was accomplished by comparing the annual rainfall totals and monthly rainfall totals of the monitoring period to the 30-yr average. Discharge data was obtained from four USGS gaging stations that were located upstream and downstream of the monitoring stations on both streams (Table 2 and 3). At the Roubidoux Creek sites, the USGS gages were close enough to the DO monitoring stations that the discharge data was directly used for analysis at these sites. Along the Big Piney River, discharge was estimated using drainage area-discharge relationships at various stages to predict instantaneous flow at the DO monitoring stations (Appendix A).

Stage recorders were also deployed at BPQ and RC8 to capture water depth over the monitoring period that can be influenced by downstream obstructions (dam and low-water bridge). Stage data was recorded every 15-minutes using Hobo U20L-04 Water Level Loggers (OEWRI 2016). The level loggers were installed inside a PVC pipe assembly and secured to 1-2 m staff gages that were installed at each site (Appendix B: Photos 1-5). As water rises in the pipe, the level-logger uses the change in pressure to record changes in water level. An additional level logger was installed to measure barometric pressure used to compensate for barometric pressure changes. Raw data was downloaded periodically (≈ every 2-3 months) from the level loggers using the Hobo Waterproof Shuttle.

Dissolved Oxygen/Temperature Sensors

Continuous 15-minute DO measurements were collected using an Onset HOBO U26-001 Dissolved Oxygen Data Logger capable of measuring DO levels between 0 and 30 mg/L with an accuracy of 0.2 mg/L (Onset 2020). The DO logger is capable of operating in temperatures ranging from -5 and 40 °C. Methods used for installation and maintenance are described below.

Sensor Installation

The U26 loggers were installed at three sites on the Big Piney River (BPQ, BPS, and BPD) and two sites on Roubidoux Creek (RC8 and RC17) in October 2019 (Figures 2 and 3). All sites on the Big Piney River and FLW 8 are within the Fort Leonard Wood boundary. The HWY 17 logger on Roubidoux Creek is located 0.25 miles upstream (south) of the Fort Leonard Wood boundary. The loggers were installed along streambanks on trees or on existing wooden structures within a protective perforated PVC pipe (Appendix B: Photos 1 -6). Stage recorders and barometric pressure loggers were installed at BPQ and RC8 to measure fluctuations in water depth at these particular DO monitoring stations.

Download and Data Compensation

The U26 DO loggers were downloaded regularly, typically on a monthly basis when water level was low and the loggers were accessible. Data from the loggers were offloaded to the HOBO Optic USB Base Station. Additionally, at the time of data offloading, a Thermo Scientific Orion Star A223 Dissolved Oxygen Portable Meter (accurate within 0.2 mg/L or 2% of the reading) was used to measure the dissolved oxygen at the same time of the last logged reading on the HOBO U26-001 logger (ThermoFisher Scientific, 2015). This measurement, along with the barometric pressure and temperature, were recorded in a fieldbook and used to calibrate the U26-001 logger and help correct for measurement drift from sensor fouling. Data was compensated using the dissolved oxygen assistant within HOBOware Pro software.

Due to a flood depositing sediment inside the housing of the DO monitoring instrument at BPS in March of 2021, the typical compensation methods provided poor results. Fine sediment buried the DO instrument after the flood on March 14, 2021. This appears to have caused the area near the sensor to have much lower DO readings than what was in the water column. The typical compensation methods as described above caused the correction to be too high for data collected between February 23, 2021 and April 6, 2021. To fix this problem, DO concentrations from BPD were used to predict DO at BPS (Appendix C). This was accomplished by creating a relationship between DO concentrations at the two sites from the winter and early spring of 2020 over a similar discharge as in this period of 2021. This relationship was then applied to predict DO concentrations at BPS between February 23 and April 6, 2021.

Sensor Cap Replacement and Lab Calibration

Sensor caps were replaced 6-7 months after being initially launched. The sensor caps were replaced in May and December of 2020. Sensor caps were replaced by first removing the protective guard around the optical DO sensor and then removing the old sensor cap and O-rings. The optical DO sensor was then cleaned with a lint-free cloth. Then a lubricant was applied around the grooves where the O-rings are placed. New O-rings were placed into the grooves, the new sensor cap was placed on the logger and the protective guard was reinstalled (Appendix D).

A lab calibration was performed to initialize the new sensor cap. To perform the lab calibration, the sensor was connected to a laptop and the cap was initialized in HOBOware Pro. Then a 100% saturation calibration was performed. The sensor was placed a in a rubber boot containing a moist sponge, creating a 100% saturated environment. The barometric pressure was recorded within HOBOware Pro and after 15 minutes the DO value from the logger was recorded. Then the 0% saturation calibration was performed. This was done by placing the logger into a vessel containing Sodium Sulfate, which contains zero oxygen. After 15 minutes, the DO value from the logger was recorded. Then within HOBOware Pro the adjustments for 0% and 100% saturation were sent to the logger, the device was "launched", then cleaned with distilled water, and then placed back in the stream.

RESULTS AND DISCUSSION

Sample Collection

There were between 530-594 days of 15-minute temperature and dissolved oxygen readings recorded at the Big Piney River monitoring stations and 590-604 days of data collected at the Roubidoux Creek stations (Figures 4-8, Table 4). The loggers were installed in October 2019 and removed in June 2021 after recording over 20-months of data. Continuous data were collected over two different periods with approximately a 1-3 week gap in May 2020 due to flooding that prevented data recovery and sensor cap replacement. At the Big Piney sites, the initial period started on October 1, 2019 and ended April 30, 2020. The DO sensors were then restarted on May 22, 2020 and continuous data was collected until April 6, 2021. Data for BPS and BPQ ended on April 6, 2021 due to flood damage and sensor malfunction, but records extend to June 8, 2021 for BPD. The initial monitoring period at the Roubidoux Creek sites began on October 15, 2019 and ended May 10, 2020. The DO sensor at RC17 was restarted on May 14 and RC8 was restarted on May 22, 2020. Continuous data was then collected at both sites on Roubidoux Creek until June 8, 2021. Overall, there are 10-months of continuous data at all sites from June 2020 through March 2021 that includes the summer of 2020.

Hydrology

Annual and monthly rainfall over the monitoring period was wetter than the average over the last 30-years. During the period of 1991-2020, average annual rainfall was 119.5 cm/yr (Figure 4). Annual rainfall totals in 2019 and 2020 exceeded that average by about 20 cm each year, an increase of about 17%. Annual rainfall was above average in seven of the last ten years.

Monthly rainfall totals exceeded the 30-yr average monthly rainfall totals in 14 of the 20-month monitoring period (Figure 5). The drier months tended to be in the late fall and winter with only July 2020 having lower than normal rainfall in the hot summer months when drought is typically expected. These data suggest that the monitoring period was wetter than normal, but recent increases in rainfall over the last decade has been observed throughout the Midwest and is expected to continue suggesting this may be the new normal (Vose et al. 2012; Pavlowsky et al. 2016).

Discharge over the monitoring period varied between the two watersheds as the Big Piney River is spring-fed and Roubidoux Creek is classified as a losing stream within Fort Leonard Wood. Discharge in the Big Piney River has a mean annual discharge of >30 m^3/s and minimum 7-day discharge of >5.7 m^3/s at both gages during WY2020 (Table 3). In contrast, Roubidoux Creek had a mean annual discharge of between 7-9 m^3/s and 7-day minimum flow at or near 0 m^3/s for WY2020. While the drainage area of the Big Piney River is substantially larger than Roubidoux, annual runoff in the Big Piney River exceeded 66 cm while there was 55.4 cm of runoff at the upper Roubidoux Creek gage and only 38.4 cm of runoff at the lower gage. These data show the impact of the losing section of the Roubidoux Creek which receives approximately 30% less runoff than the upstream gage and can be dry during periods of the year. This losing section extends for 28.5 km from about river station 34.5 km, through Fort Leonard Wood, to river station 6.0 km near Roubidoux Spring downstream of Interstate 44.

DO and Temperature Data

Big Piney River

The variability in DO, temperature, and discharge follows a similar pattern at the three sites along the Big Piney River over most of the monitoring period, except for the two sites below the upper dam in the Spring of 2020. Continuous 15-minute data over the monitoring periods shows the predicted inverse relationship between DO and temperature (Figures 6-8). Additionally, in the warm, low flow summer periods, DO is not only low, but also has high diurnal variability. However, at BPS and BPD, very high diurnal variability in DO concentrations were measured in the spring of 2020. There could be several possible reasons for this to occur, but the specific cause is unknown at this time. This period is present at both sites between a series of relatively high flow events. Perhaps a runoff event was responsible for depositing sediment, or other substance, with high biological oxygen demand (BOD) that caused this short-term high variability period in the record. It appears that the DO levels were back to normal after a series of higher flow events.

Continuous monitoring data shows that DO concentrations are lower at the sites located below the upper dam, with periods of relatively low concentrations compared to the furthest upstream site. Over the three sites along the Big Piney River, average DO concentrations ranged from 10.0-10.5 mg/L and with the coefficient of variation (i.e., 100 % x (s/mean) varied between 17.4-22.4% over the monitoring period (Table 4). Site BPS is the first site below the upper dam and was the most variable (22.4%) over the monitoring period with DO concentrations ranging from 0.1-15.5 mg/L. BPS had the longest period with low DO levels during the sampling period with approximately 2.7% of the time where DO concentrations were below 6.0 mg/L, 0.9% of the time below 5.0 mg/L (Table 5). The DO threshold for cold water fisheries is 6 mg/L and 5 mg/L for cool and warm water fisheries (CSR 2021). In contrast, site BPQ is located above the upper dam had DO concentrations ranging from 5.2-15.9 mg/L and a CV% of 18%. At BPQ <0.1% of the monitoring period had DO levels below 6 mg/L and DO concentrations were never less than 5.0 mg/L. This suggests that flow conditions below the upper dam are potentially being affected by anoxic seepage inputs, dam effects, or other oxygen-depleting processes. However, downstream of the spring, BPD is less variable (17.8%) with DO values ranging from 2.8-14.8 mg/L. Conditions here show improvement compared to the upstream site with only 1.3% of the monitoring period below 6.0 mg/L DO and 0.4% below 5.0 mg/L. The low DO levels at BPS and BPD are isolated to the spring and summer of 2020. However, these low DO concentrations did not exceed 10% of the seasonal period for either threshold. Based on these data, the Big Piney River is not impaired for DO at these three sites.

In the Big Piney River, temperature variations in the flow tended to follow DO variability trends with the site directly below the upper dam having the highest temperature recorded among the three sites. Average flow temperature was consistent across the three sites ranging from 13.1-13.3 °C. All three sites had a minimum temperature recorded of 0.0 °C. However, the highest temperature recorded at each of the site perhaps partially explains the changes in DO levels between sites. At BPQ above of the upper dam, the highest temperature recorded was 28.5 °C. At BPS below the upper dam, the highest temperature recorded was 28.9 °C. While the difference in the maximum temperatures between these two sites is relatively low, this does suggest that water in the impoundment is warmer than what is typical for the river. Relatively, cooler water can hold more DO than warmer water and this may become important during the dry, warm summer months when there is less water entering the impoundment from upstream (Obrecht and Thorpe, 2011). Downstream at BPD, the spring has a measurable influence on water temperature as BPD has the lowest max, mean, and median values of any sites during the summer.

Roubidoux Creek

The relationship between DO, temperature, and discharge at the two Roubidoux Creek sites follows a similar pattern and like the Big Piney sites below the upper dam, have low DO and high variability in the Spring of 2020. Again, continuous data over much of the monitoring periods shows the predicted inverse relationship between DO and temperature and DO is low, with high variability in the warm, low flow summer season (Figures 9-10). Very high diurnal variability in DO concentrations were also measured in the spring of 2020 at the Roubidoux Creek sites. As discussed previously this period is present at both sites between a series of relatively high flow events, they may have deposited something that increased the BOD causing this short-term high variability period in the record. The DO levels were back to normal after a series of higher flow events at these sites as well. This is just a possible explanation for the abnormally low DO levels to occur, but the specific cause is unknown.

DO concentrations at the two sites along Roubidoux Creek are more variable than along the Big Piney River and are susceptible to long periods of low DO during the warm, dry periods of the year when very low flows occur. Upstream of the installation at RC17, the average DO concentration was 9.5 mg/L ranging from 0.3-15.3 mg/L over the monitoring period (Table 4). In contrast, the site close to where the stream leaves the installation (RC8), the average DO concentration was 8.6 mg/L ranging from 0.1-15.9 mg/L. Roubidoux Creek mean DO values were 10-15% lower than along the Big Piney River. RC17 had a period of low DO levels with approximately 8.6% of the monitoring period with DO concentrations below 6.0 mg/L while RC8 had about 17.2% of the period below 6.0 mg/L (Table 5). The period of time these stations had DO levels below 5.0 mg/L was 4.6% and 10.7% at RC17 and RC8 respectfully, which may stress aquatic organisms. During the summer of 2020, RC17 was below 5 mg/L 22% of the time. At RC8, DO levels were below 5 mg/L 29.8% of the time in the spring of 2020, 26.2% of summer 2020, and 17.8% of the time during the spring of 2021. These data suggest that during the warm summer months during low flow periods in the creek, DO levels can remain very low for extended periods and can approach anoxic levels. Without fresh water coming into the pool formed behind the bridge, DO levels likely get very low at night in the summer (Brown and Czarnezki, No Year). However, since this segment of Roubidoux Creek is within a losing section of the stream, the low-water bridge may artificially retain water in this section that would otherwise likely be dry. Based on these data, the Roubidoux Creek is impaired for DO at both sites.

As with the Big Piney River sites, temperature data variability in Roubidoux Creek tended to follow DO variability trends with RC8 having the highest temperatures. Average temperature did not vary between the two sites ranging from 13.1-13.3 °C and both had a minimum temperature recorded near 0.0 °C (Table 4). However, the highest temperature recorded at

RC8 was 32.0 °C and 30.4 °C at RC17. This suggests that the during the dry summer months water held behind the low-water bridge can get warmer than the upstream site when it likely becomes disconnected from daily flows below the losing section of the stream. Again, warm water holds relatively less oxygen than cooler water. However, this is within a losing section of the Rubidoux Creek and may not have water at all if the low-water bridge was not there.

Seasonal Variability

<u>Big Piney River</u>

Along the Big Piney River DO levels were lowest during the summer and highest during the winter, but the range of concentrations within a season varied by site. In 2020, mean DO concentrations were lowest at all sites within any season ranging from 7.5 mg/L at BPS to 7.9 mg/L at BPQ (Table 6). In the winters of 2020 and 2021, average DO concentrations were the highest among the seasons at all sites, ranging from 12.1 mg/L at BPD to 12.5 mg/L at BPS during the winter of 2021. Stream temperatures averaged 23.7 °C at BPD to 24.5 °C at BPS in the summer of 2020 and from 6.4 °C at BPS to 6.6 °C at BPQ in the winter of 2021. Average winter 2021 temperatures were 1.6-1.9 °C colder than winter 2020. However, variation in DO within seasons was highest during different periods at each site. At BPQ, the highest season variability occurred in the fall of 2020 when the highest seasonal DO concentrations were recorded having a CV% of 16.1%. The highest in-season variability at BPS occurred in spring 2020 when the lowest seasonal DO levels were recorded and had a CV% of 19.5%. However, at BPD downstream of the spring the highest in-season variability occurred in the summer 2020 with a CV% of 15.2%. Again, this suggests the spring discharge to the river above this site moderates the high variation in DO levels measured upstream. Overall, downstream seasonal DO and temperature likely fluctuate due to the influence of the upper dam and spring flows, but seasonal variability between sites are all within one standard deviation suggesting differences are not significant (Figure 11). This is somewhat misleading since DO levels can be very low over very short periods, but over the majority of the monitoring period DO levels at these sites are not significantly different. However, the lower limit of the variance within one standard deviation of the mean DO concentration is above 6.0 mg/L showing DO levels are above that level >80% of the time within any one season.

<u>Roubidoux Creek</u>

Seasonal DO concentrations along the Roubidoux Creek were highest in the winter and lowest in the summer, but variability at the downstream site was significantly higher in the spring. During summer 2020, average DO concentrations ranged from 5.8 mg/L at RC8 to 6.4 mg/L at RC17 (Table 7). The 5.8 mg/L at RC8 is just above the 5.0 mg/L threshold for warm and cool aquatic species and these data show 50% of the summer DO readings were below 6.0 mg/L. DO variability at both sites is lowest in the winter, with CV% <9% over each winter at both sites. Variability tends to be higher in the summer at RC17, with a seasonal CV% of 27.1%, and higher in the spring at RC8, with CV% >35% over both spring sampling periods. This is likely due to the variation in flows over the spring, which can range from very low where the pool above the bridge is stagnant, to very high spring storms. Seasonal water temperature trends were similar at both sites with means ranging from 5.1-5.3 °C in the winter and 25.1-26.2 °C in the summer. Variability in seasonal temperature at both sites was lowest in the summer (CV% <10%) and highest in the winter (CV% >55%). Downstream, DO concentrations decrease from RC17 to RC8 during every season over the monitoring period (Figure 11). However, as with the Big Piney sites, the in-season variability between the two sites is within one standard deviation for six of the seven seasons sampled with the lone exception being the winter of 2020. This suggests the seasonal differences in DO concentrations between the two sites are not significant. However, the lower limit of the variance within one standard deviation of the mean is lower than 5.0 mg/L in the spring and summer of 2020 showing that low DO levels occurred during those times. Further, downstream variations in temperature do not appear to coincide with differences in DO levels at these sites suggesting karst connections are more likely influencing changes in DO at the downstream site.

CONCLUSIONS

OEWRI conducted a continuous DO and temperature monitoring study on the Big Piney River and Roubidoux Creek at Fort Leonard Wood Missouri from October 2019-June 2021. The purpose of this study was to assess the variability in DO and temperature in both streams related to minimum DO requirements for aquatic organisms. The specific objectives of this study were: 1) install five continuous DO/temperature instruments (three on Big Piney and two on Roubidoux Creek) on portions of both streams within the installation; 2) Install a continuous stage gage at each site to bridge the gap between USGS gaging stations located upstream and downstream of the sampling sites to estimate flow variability; and 3) analyze the seasonal variability in DO and temperature at each site in relationship to water levels and recommended levels for a sustainable fishery. There are five main conclusions from this study:

1) **A series of DO sensors were installed along the Big Piney River and Roubidoux Creek at Fort Leonard Wood, Missouri to record continuous data over a 10-month period**. Continuous 15-minute data was collected at each site from October 2019 to May 2020 when high flows prevented necessary maintenance to occur, and no data was collected for a few weeks. By June 2020 the sensors were back recording and a full 10 months of

continuous data was collected ending in April 2021 along the Big Piney and June 2021 on Roubidoux Creek;

2) **Hydrological analysis suggests the monitoring period was wetter than the 30-yr average**. Annual rainfall totals in 2019 and 2020 exceeded the 30-year average by about 20 cm each year, an increase of about 17%. In addition, monthly rainfall totals exceeded the 30-yr average monthly rainfall totals in 14 of the 20-month monitoring period. These data suggest that the monitoring period was wetter than normal, but recent increases in rainfall over the last decade have occurred throughout the Midwest suggesting this trend is likely to continue;

3) **DO levels on the Big Piney River dropped below 5 mg/L for only a very short time over the monitoring period that was likely due to the influence of the upper dam, unknown seepage, or discharge inputs**. DO was generally lower and temperature higher below the upper dam at BPS and BPD than above at BPQ. Above the upper dam, DO levels never dropped below 5 mg/L at BPQ. Below the dam at BPS, DO levels were below 5 mg/L for less than 5% of the time over the entire monitoring period and <10% of the time during the summer of 2020. However, downstream of the spring at BPD, DO levels increased and temperature decreased that lessoned the amount of time DO levels were below the 5.0 mg/L threshold at this site. Included in these low DO values is a period of abnormally low DO levels in the spring of 2020 from an unknown cause. However, the Big Piney River is not impaired for DO at these three sites based on data collected for this study;

4) **Over the monitoring period, there were times that DO concentrations were very low at both sites along Roubidoux Creek**. DO concentrations were generally lower and water temperatures typically higher at the downstream site on Roubidoux Creek compared to the upstream site. However, both sites had periods of very low DO concentrations. Over the monitoring period, the upstream site had DO readings below 5.0 mg/L for 4.6% of the monitoring period and the downstream site was below that level for 10.7% of the time. Seasonally, RC17 had DO concentrations <5mg/L for >10% of the season during the summer of 2020 (22.0%), while this occurred at RC8 in the spring of 2020 (29.8%), summer of 2020 (26.2%), and the spring of 2021 (17.8%). Therefore, Roubidoux Creek is impaired for DO at both sites based on this study. The lower site is within a losing section of the stream and the pool above the low-water bridge can be disconnected from surface flows. Similar to the Big Piney, these low DO values include a period of abnormally low DO levels in the spring of 2020 from an unknown cause;

5) **Results of this study suggest karst landscapes can have both positive and negative impacts on DO levels in Ozarks streams.** The low DO levels on Roubidoux Creek appear to be controlled by the losing section of the stream that occurs on Fort Leonard Wood. In fact, without the low-water bridge at RC8 there may be no water at that site during hot, dry summers. Also, while it appears that the upper dam can have an influence on DO levels along the Big Piney River over short timeframes, the spring located downstream seems to moderate that influence.

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TABLES

Table 1. Locations and description of DO monitoring stations at Fort Leonard Wood, Missouri.

Name	Code	Northing (m)	Easting (m)	Distance (km)	Drainage Area (km^2)	Start Date	End Date	# of Readings	Days	Stage? (y/n)
Big Piney River			*Big Piney River*				*Big Piney River*			
Big Piney River near FLW Quarry	BPQ	4,175,488.644	581,890.303	41.7	1,507	10/2/2019	4/6/2021	50,922	530	y
Big Piney River upstream of Spring	BPS	4,177,283.433	584,328.717	35.4	1,522	10/2/2019	4/6/2021	50,942	531	n
Big Piney River upstream of Lower Dam	BPD	4,178,879.615	583,659.098	33.3	1,526	10/2/2019	6/8/2021	56,983	594	n
Roubidoux Creek			*Roubidoux Creek*				*Roubidoux Creek*			
Roubidoux Creek at Hwy 17	RC17	4,161,881.871	567,638.171	56.2	428	10/15/2019	6/8/2021	57,983	604	y
Roubidoux Creek at FLW 8	RC8	4,183,785.481	573,407.057	12.6	699	10/15/2019	6/8/2021	56,595	590	y

Table 2. Location and description of USGS gaging station near Fort Leonard Wood, Missouri.

Gage Name	Number	Northing (m)	Easting (m)	Distance (km)	Drainage Area (km^2)	Start Year
Big Piney River				*Big Piney River*		
Big Piney below Ft. Leonard Wood, MO	06930060	4,179,603.412	582,958.930	32.3	1,536	1999
Big Piney near Big Piney, MO	06930000	4,169,141.811	583,773.417	52.7	1,450	1999
Roubidoux Creek				*Roubidoux Creek*		
Roubidoux Creek at Polla Road below Ft. Leonard Wood, MO	06928420	4,183,096.414	571,986.102	10.5	707	2008
Roubidoux Creek above Ft. Leonard Wood, MO	06928300	4,161,829.425	567,618.839	56.3	427	1999

Table 3. Discharge summary for USGS gaging stations for Water Years 2020 and 2021.

Gage Name	Number	WY2020 Min Q (m^3/s)	WY2020 Mean Q (m^3/s)	WY2020 Max Q (m^3/s)	WY2020 Runoff (cm)	WY2021* Min Q (m^3/s)	WY2021* Mean Q (m^3/s)	WY2021* Max Q (m^3/s)	WY2021* Runoff (cm)
Big Piney River		*Big Piney River*				*Big Piney River*			
Big Piney below Ft. Leonard Wood, MO	06930060	6.86	34.6	725	71.1	6.03	22.2	351	45.5
Big Piney near Big Piney, MO	06930000	5.76	30.3	719	66.0	4.84	19.2	329	41.8
Roubidoux Creek		*Roubidoux Creek*				*Roubidoux Creek*			
Roubidoux Creek at Polla Road below Ft. Leonard Wood, MO	06928420	0.00	8.56	481	38.4	0.00	5.08	275	22.7
Roubidoux Creek above Ft. Leonard Wood, MO	06928300	0.31	7.49	549	55.4	0.20	4.76	204	35.2

* WY2021 values were calculated with incomplete datasets and partially unapproved discharge data from gaging stations available at the time this report was written.

Table 4. Range and variability in DO and temperature by monitoring site.

	Big Piney River			***Roubidoux Creek***	
	DO (mg/L)			DO (mg/L)	
Site	BPQ	BPS	BPD	RC17	RC8
n	50,922	50,942	50,938	57,393	56,595
min	5.2	0.1	2.8	0.3	0.1
mean	10.5	9.7	10.1	9.5	8.6
median	10.7	9.9	10.3	9.8	8.8
max	15.9	15.5	14.8	15.3	15.9
std	1.9	2.0	1.8	2.5	2.8
cv%	18.0	20.1	17.8	25.8	32.2
	Temperature (°C)			Temperature (°C)	
Site	BPQ	BPS	BPD	RC17	RC8
n	50,922	50,942	50,939	57,393	56,601
min	0.0	0.0	0.0	0.1	0.2
mean	13.3	13.1	12.9	13.1	13.3
median	11.3	11.1	11.0	11.8	12.0
max	28.5	28.9	28.0	30.4	32.0
std	6.5	6.9	6.7	7.2	7.9
cv%	49.0	52.8	51.6	55.1	59.1

Table 5. Overall and seasonal percentage of time DO levels were below important thresholds for aquatic organisms by monitoring site.

DO Threshold	% of Time Lower than Threshold							
	Entire Period	Fall 2019	Winter 2020	Spring 2020*	Summer 2020	Fall 2020	Winter 2021	Spring 2021
	Big Piney River							
	BPQ							
<5 mg/L	-	-	-	-	-	-	-	-
<6 mg/L	<0.1	-	-	-	0.3	-	-	-
	BPS							
<5 mg/L	0.9	-	-	4.5	2.0	-	-	-
<6 mg/L	2.7	-	-	8.3	9.4	-	-	-
	BPD							
<5 mg/L	0.4	-	-	1.9	1.0	-	-	-
<6 mg/L	1.3	-	-	3.3	5.3	-	-	-
	Roubidoux Creek							
	RC17							
<5 mg/L	4.6	-	-	8.6	22.0	-	-	-
<6 mg/L	8.6	-	-	13.6	39.9	0.3	-	2.8
	RC8							
<5 mg/L	10.7	-	-	29.8	26.2	0.5	-	17.8
<6 mg/L	17.2	-	-	38.1	52.1	2.4	-	22.9

* Incomplete record has 1-3 week gap depending on site.

Table 6. Seasonal range and variability of DO and temperature at Big Piney monitoring sites.

Site		DO (mg/L)									Temp (°C)							
			Fall	Winter	Spring	Summer	Fall	Winter	Spring			Fall	Winter	Spring	Summer	Fall	Winter	Spring
		All	2019	2020	2020	2020	2020	2021	2021		All	2019	2020	2020	2020	2020	2021	2021
BPQ	n	50,922	7,788	8,537	6,919	8,823	8,640	8,544	1,671	n	50,922	7,788	8,537	6,919	8,823	8,640	8,544	1,671
	min	5.2	7.1	9.3	7.0	5.2	7.4	9.1	9.1	min	0.0	5.2	4.7	10.1	17.4	5.0	0.0	9.2
	mean	10.5	10.8	11.5	9.4	7.9	11.0	12.3	10.4	mean	13.3	11.9	8.5	16.7	23.9	12.4	6.6	12.7
	median	10.7	10.8	11.5	9.4	7.8	10.7	12.3	10.4	median	11.3	10.7	8.4	15.3	24.0	11.6	6.4	12.7
	max	15.9	13.8	13.7	12.9	10.6	15.9	15.0	11.7	max	28.5	24.5	13.2	24.3	28.5	21.3	13.2	15.9
	sd	1.9	1.2	0.7	1.1	0.9	1.8	1.1	0.5	sd	6.5	3.7	1.7	3.9	2.0	4.0	2.8	1.3
	cv%	18.0	11.2	6.4	11.9	11.7	16.1	9.1	4.7	cv%	49.0	31.3	20.2	23.7	8.4	32.0	42.9	10.1
		DO (mg/L)									Temp (°C)							
Site			Fall	Winter	Spring	Summer	Fall	Winter	Spring			Fall	Winter	Spring	Summer	Fall	Winter	Spring
		All	2019	2020	2020	2020	2020	2021	2021		All	2019	2020	2020	2020	2020	2021	2021
BPS	n	50,942	7,784	8,544	6,924	8,830	8,640	8,544	1,676	n	50,942	7,784	8,544	6,924	8,830	8,640	8,544	1,676
	min	0.1	5.7	8.5	0.1	2.7	7.2	8.4	8.0	min	0.0	3.6	4.6	10.1	17.3	4.6	0.0	9.2
	mean	9.7	9.8	10.7	8.1	7.5	10.3	11.9	10.1	mean	13.1	10.8	8.1	16.8	24.5	12.4	6.4	12.7
	median	9.9	9.9	10.7	8.4	7.4	9.9	11.7	10.1	median	11.1	9.4	7.8	15.3	24.5	11.6	6.2	12.7
	max	15.5	12.5	13.1	12.0	10.6	14.9	15.5	11.4	max	28.9	25.4	12.8	24.2	28.9	21.9	13.1	15.9
	sd	2.0	1.2	0.7	1.6	1.2	1.6	1.2	0.6	sd	6.9	4.6	1.7	4.0	2.1	4.2	3.0	1.3
	cv%	20.1	12.2	6.2	19.5	15.8	15.8	9.9	5.5	cv%	52.8	42.4	21.5	24.1	8.4	33.5	46.2	9.9
		DO (mg/L)									Temp (°C)							
Site			Fall	Winter	Spring	Summer	Fall	Winter	Spring			Fall	Winter	Spring	Summer	Fall	Winter	Spring
		All	2019	2020	2020	2020	2020	2021	2021		All	2019	2020	2020	2020	2020	2021	2021
BPD	n	50,938	7,688	8,640	6,920	8,830	8,640	8,544	1,676	n	50,939	7,688	8,640	6,920	8,830	8,640	8,544	1,676
	min	2.8	6.4	7.6	2.8	3.1	6.9	9.3	8.8	min	0.0	3.7	4.5	10.1	17.0	4.8	0.0	9.2
	mean	10.1	10.5	10.9	8.8	7.8	10.2	12.1	10.4	mean	12.9	10.7	8.0	16.7	23.7	12.3	6.4	12.7
	median	10.3	10.6	10.9	8.9	7.8	10.3	11.9	10.3	median	11.0	9.3	7.7	15.2	23.7	11.5	6.2	12.7
	max	14.8	13.8	13.6	12.4	10.6	14.2	14.8	11.8	max	28.0	24.2	12.7	24.0	28.0	21.8	13.2	15.9
	sd	1.8	1.3	0.7	1.2	1.2	1.3	1.1	0.5	sd	6.7	4.4	1.8	4.0	1.8	4.0	2.9	1.3
	cv%	17.8	12.5	6.6	13.8	15.2	13.2	8.8	4.8	cv%	51.6	41.0	22.0	24.0	7.8	32.9	45.3	9.9

Table 7. Seasonal range and variability of DO and temperature at Roubidoux Creek monitoring sites.

Site		DO (mg/L)								Temp (°C)								
		All	Fall 2019	Winter 2020	Spring 2020	Summer 2020	Fall 2020	Winter 2021	Spring 2021		All	Fall 2019	Winter 2020	Spring 2020	Summer 2020	Fall 2020	Winter 2021	Spring 2021
RC17	n	57,393	6,480	8,544	8,626	8,830	8,640	8,544	7,729	n	57,393	6,480	8,544	8,626	8,830	8,640	8,544	7,729
	min	0.3	8.2	6.8	0.3	2.3	4.5	9.1	5.2	min	0.1	2.8	2.9	8.2	17.2	3.5	0.1	8.1
	mean	9.5	10.6	11.0	7.7	6.4	9.6	12.5	9.0	mean	13.1	8.9	7.1	16.3	25.1	12.1	5.3	15.5
	median	9.8	10.6	11.0	8.0	6.4	9.6	12.5	9.0	median	11.8	8.5	6.8	15.4	25.2	11.4	5.1	15.3
	max	15.3	14.2	13.9	12.1	13.1	14.3	15.3	13.2	max	30.4	16.2	12.9	25.8	30.4	22.6	12.5	24.0
	sd	2.5	1.2	0.9	1.7	1.7	1.7	1.1	1.6	sd	7.2	3.2	1.9	4.1	2.2	4.5	3.0	3.4
	cv%	25.8	11.3	8.4	22.2	27.1	17.9	8.5	17.7	cv%	55.1	36.2	27.2	24.9	8.8	37.4	55.7	21.7
Site		DO (mg/L)								Temp (°C)								
		All	Fall 2019	Winter 2020	Spring 2020	Summer 2020	Fall 2020	Winter 2021	Spring 2021		All	Fall 2019	Winter 2020	Spring 2020	Summer 2020	Fall 2020	Winter 2021	Spring 2021
RC8	n	56,595	6,469	8,544	7,860	8,822	8,640	8,544	7,716	n	56,601	6,469	8,544	7,860	8,828	8,640	8,544	7,716
	min	0.1	5.3	6.5	1.1	0.2	3.3	9.1	0.1	min	0.2	2.5	2.5	8.8	18.6	3.0	0.2	8.2
	mean	8.6	9.6	9.2	6.3	5.8	9.3	12.3	7.6	mean	13.3	8.5	6.6	17.3	26.2	12.3	5.1	16.4
	median	8.8	10.0	9.3	7.2	5.9	8.9	12.4	8.5	median	12.0	7.9	6.0	15.8	26.2	11.6	4.3	16.3
	max	15.9	12.0	11.3	11.8	10.3	15.5	15.9	12.2	max	32.0	17.7	12.6	27.6	32.0	23.1	13.3	26.4
	sd	2.8	1.5	0.7	2.4	1.5	2.0	0.9	2.7	sd	7.9	3.5	2.2	4.7	2.3	4.9	3.1	3.6
	cv%	32.2	15.2	7.9	39.0	26.3	21.6	7.6	35.6	cv%	59.1	41.4	33.9	27.3	8.8	39.9	60.4	21.9

FIGURES

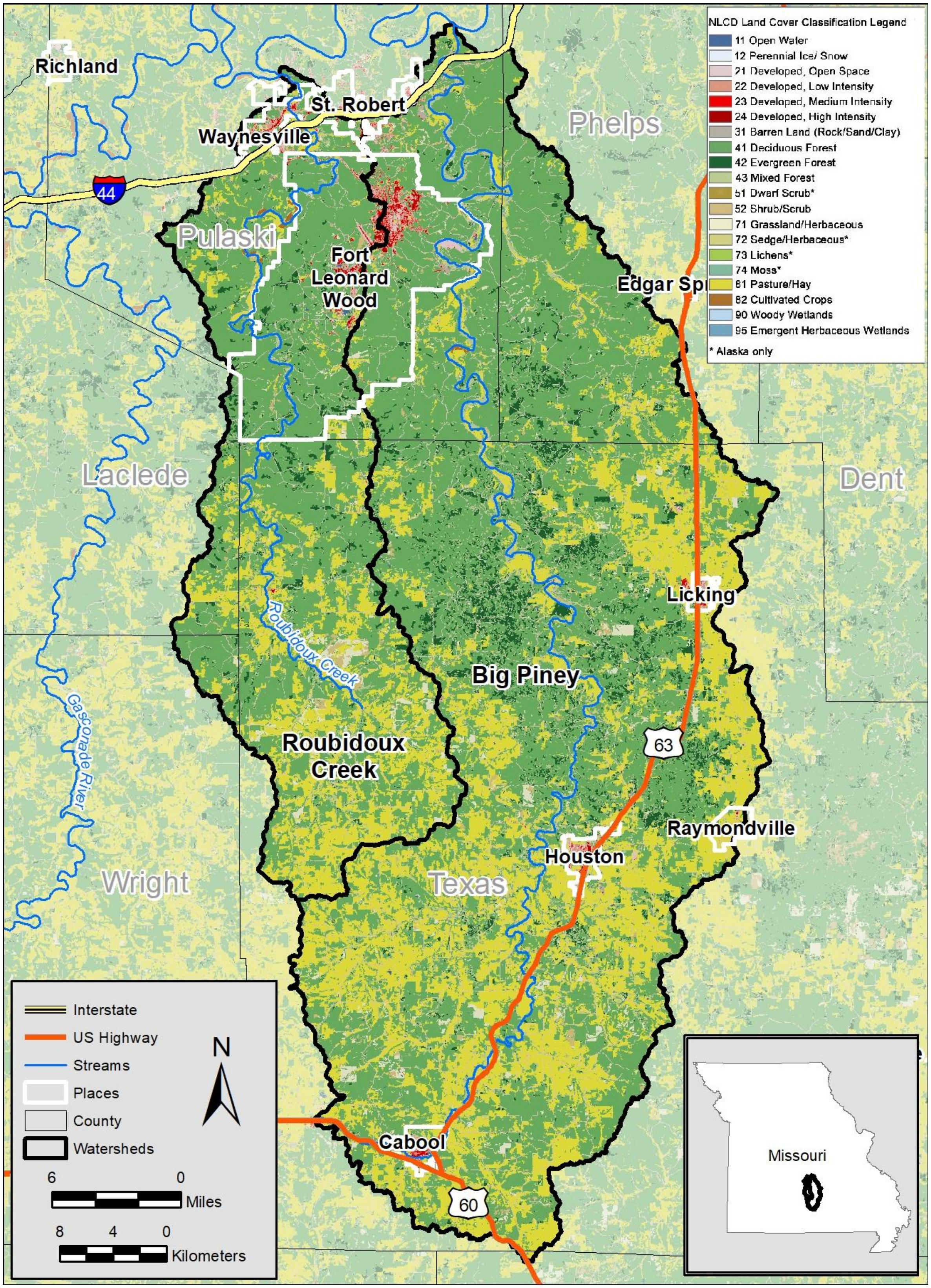

Figure 1. Big Piney and Roubidoux Creek Watersheds.

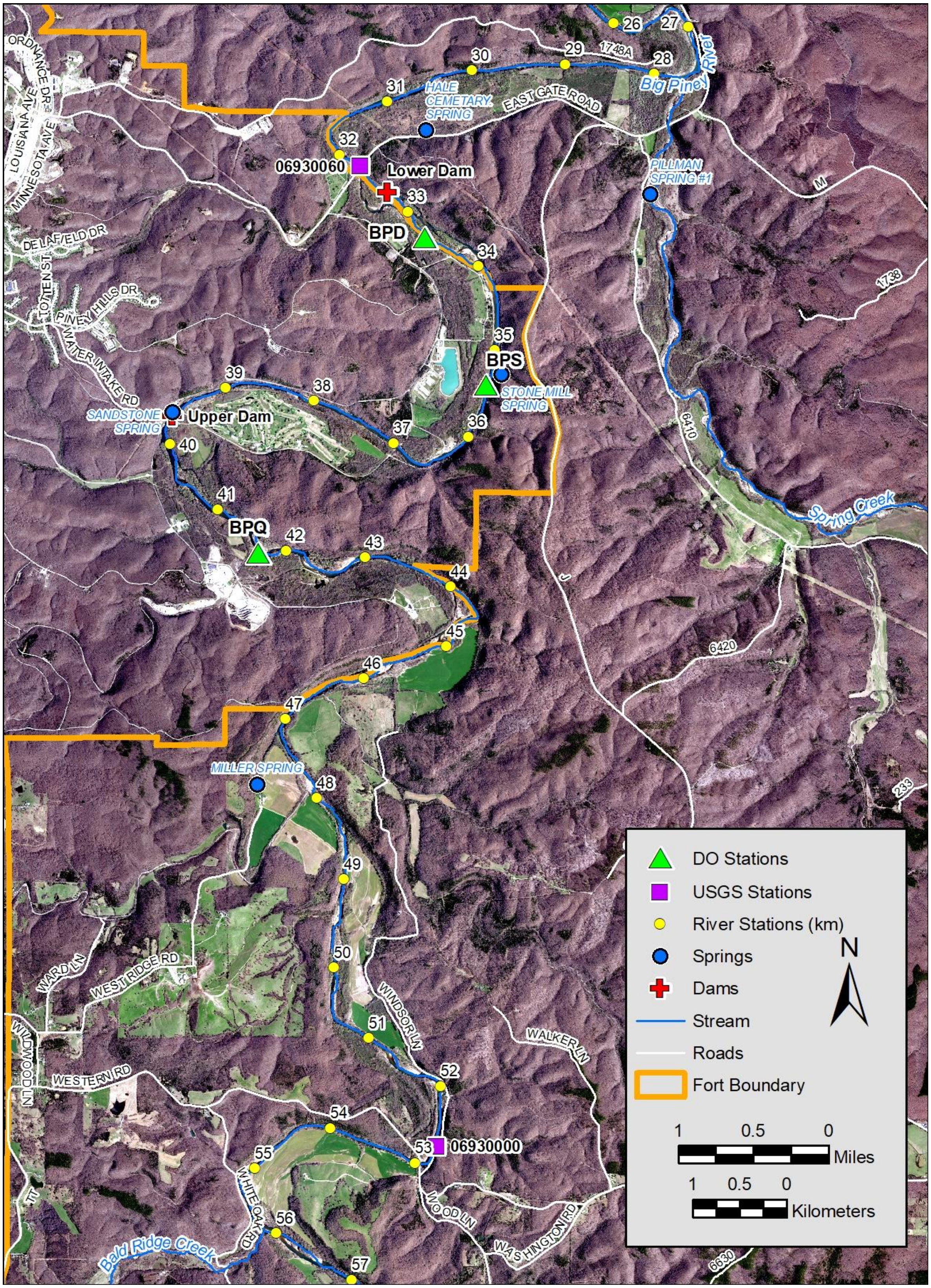

Figure 2. Big Piney River DO monitoring sites, USGS stations, and dam locations at Fort Leonard Wood.

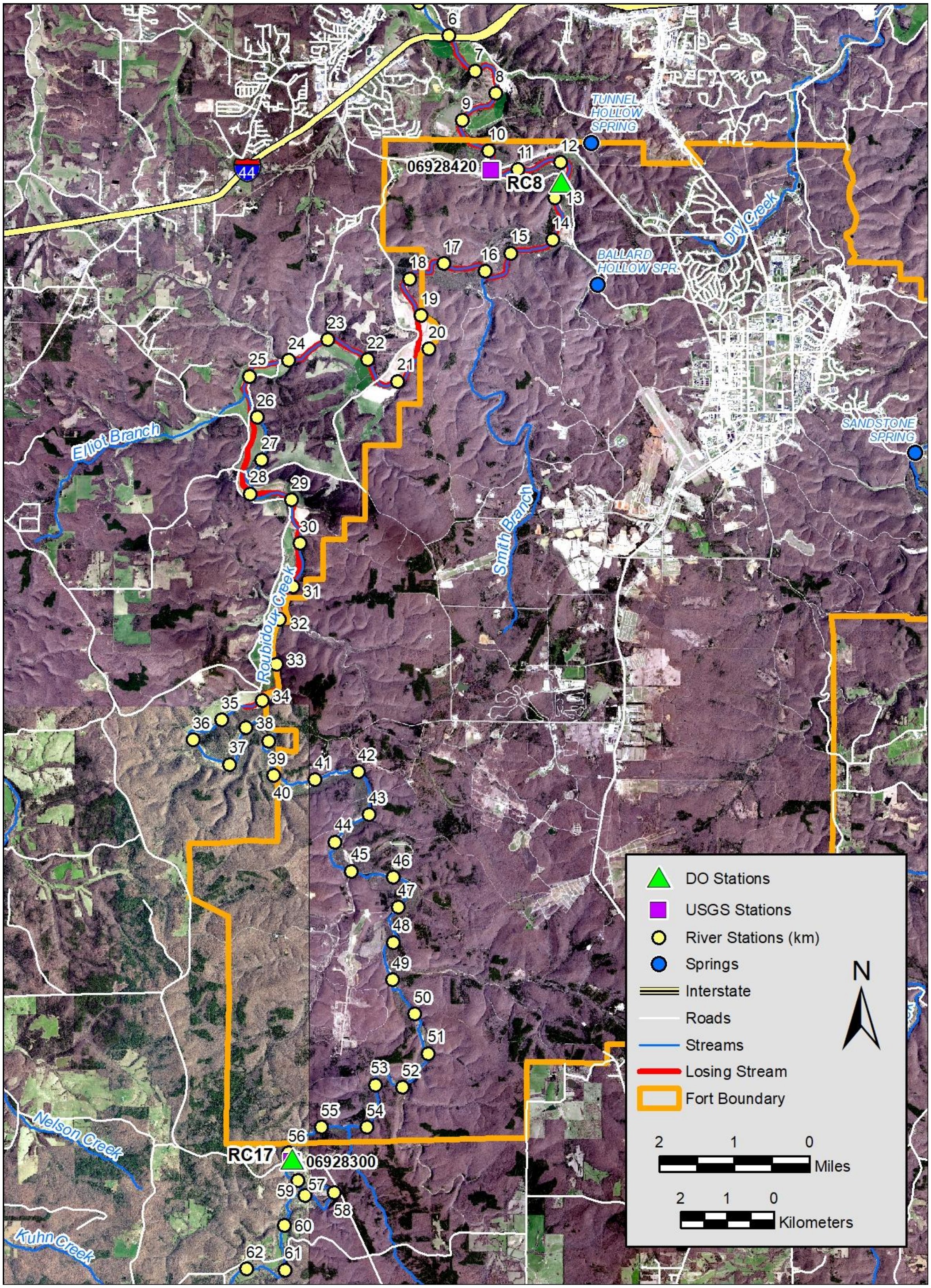

Figure 3. Roubidoux Creek DO monitoring sites and USGS stations near Fort Leonard Wood.

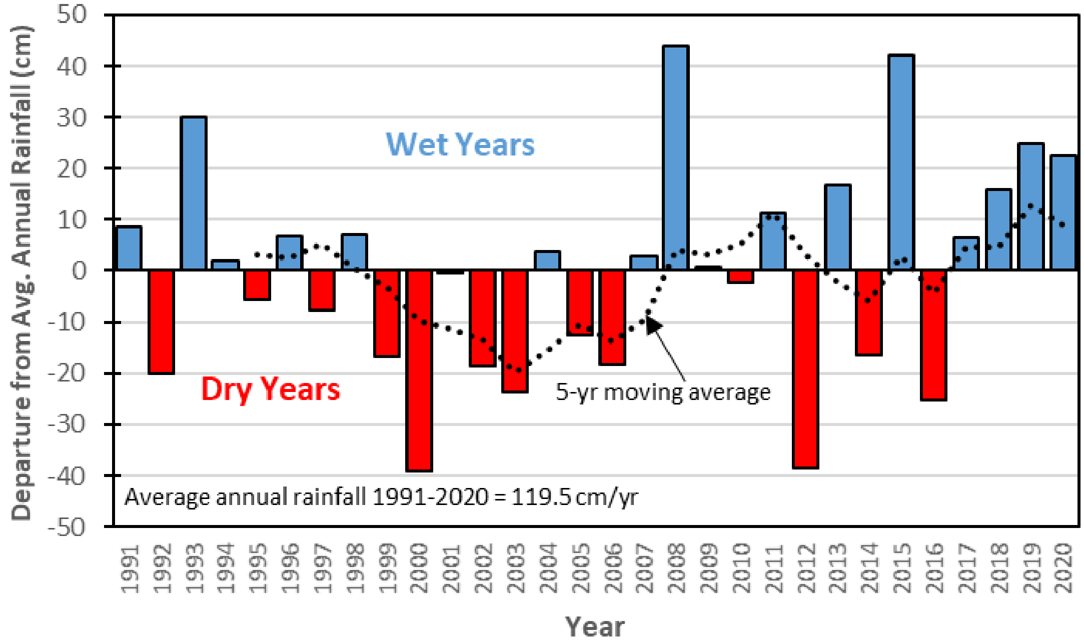

Figure 4. Yearly departure from the mean annual rainfall from 1991-2020 at Waynesville with a 5-yr moving average.

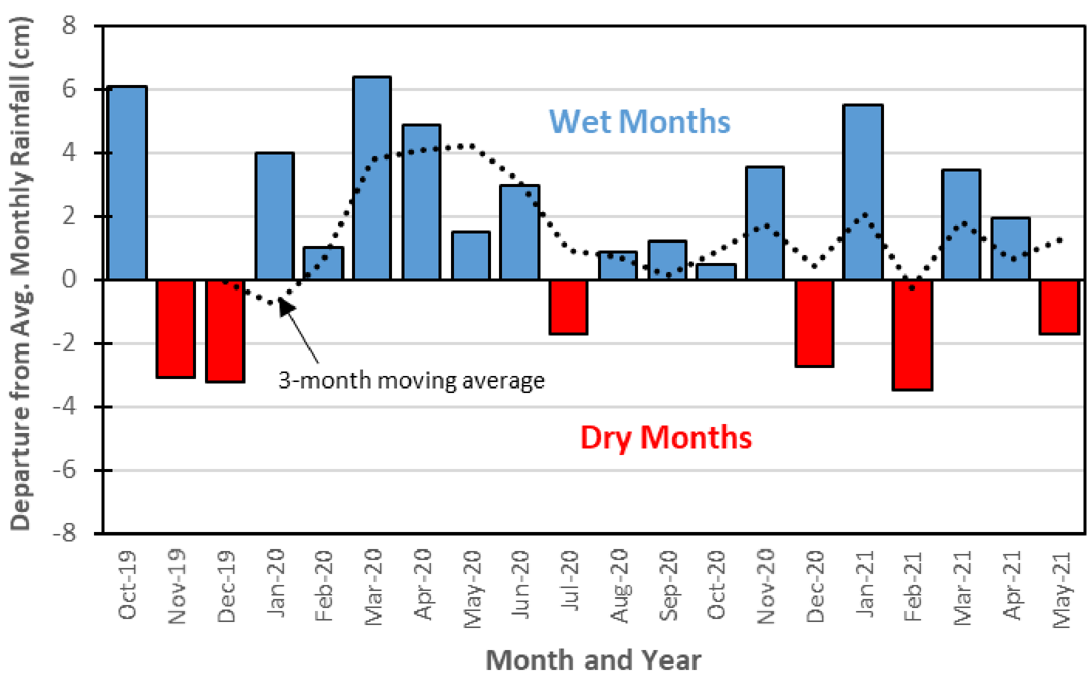

Figure 5. Departure from the 30-yr mean monthly rainfall over the monitoring period at Waynesville with a 3-month moving average.

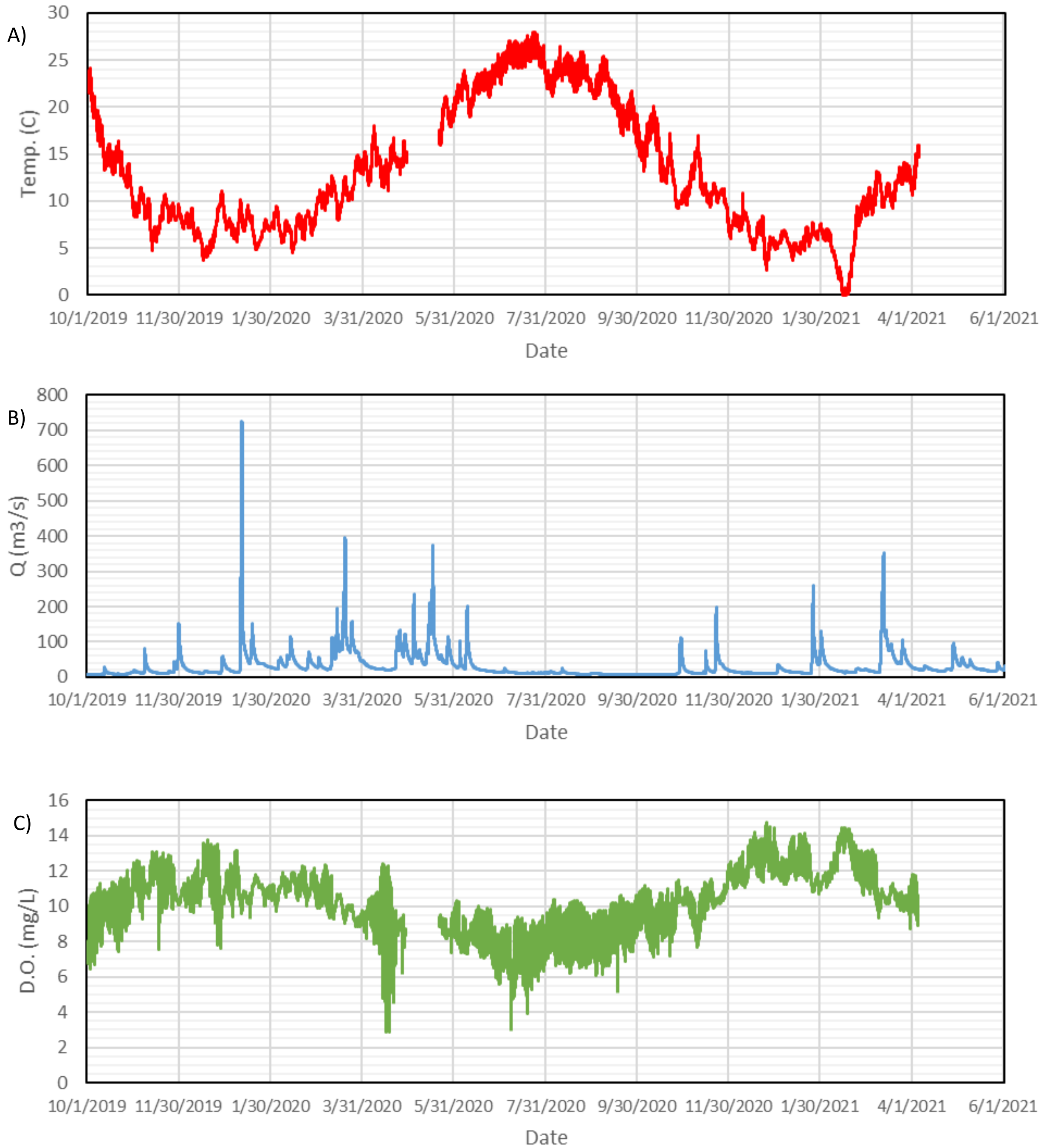

Figure 6. Continuous 15-minute A) water temperature, B) discharge, and C) dissolved oxygen readings at the BPD (Rkm = 33.3, Ad = 1,526 km^2).

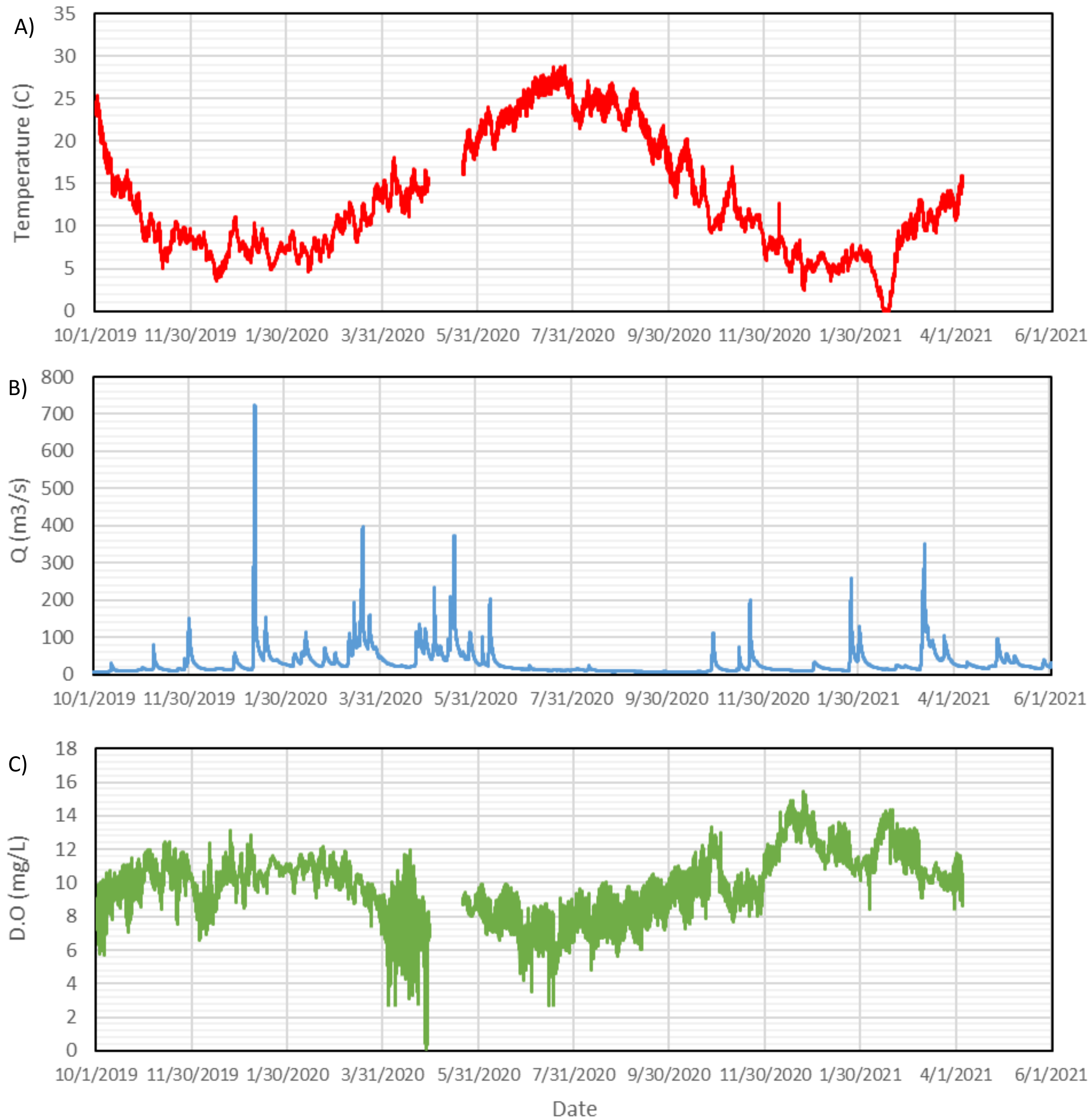

Figure 7. Continuous 15-minute A) water temperature, B) discharge, and C) dissolved oxygen readings at the BPS (*Rkm = 35.4,* Ad = *1,522* km^2).

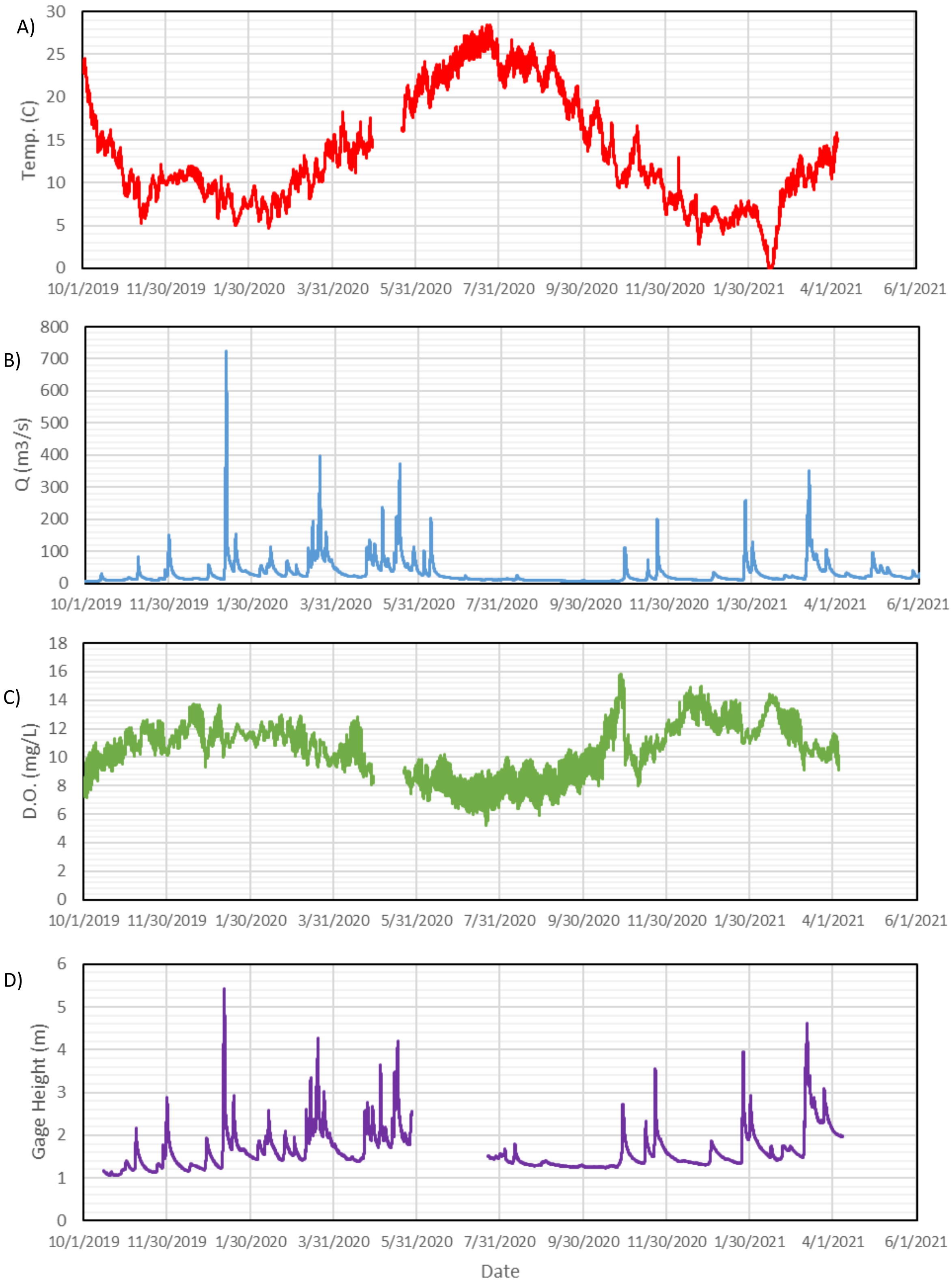

Figure 8. Continuous 15-minute A) water temperature, B) discharge, C) dissolved oxygen, and D) stage readings at the BPQ (Rkm = 41.7, Ad = 1,507 km^2).

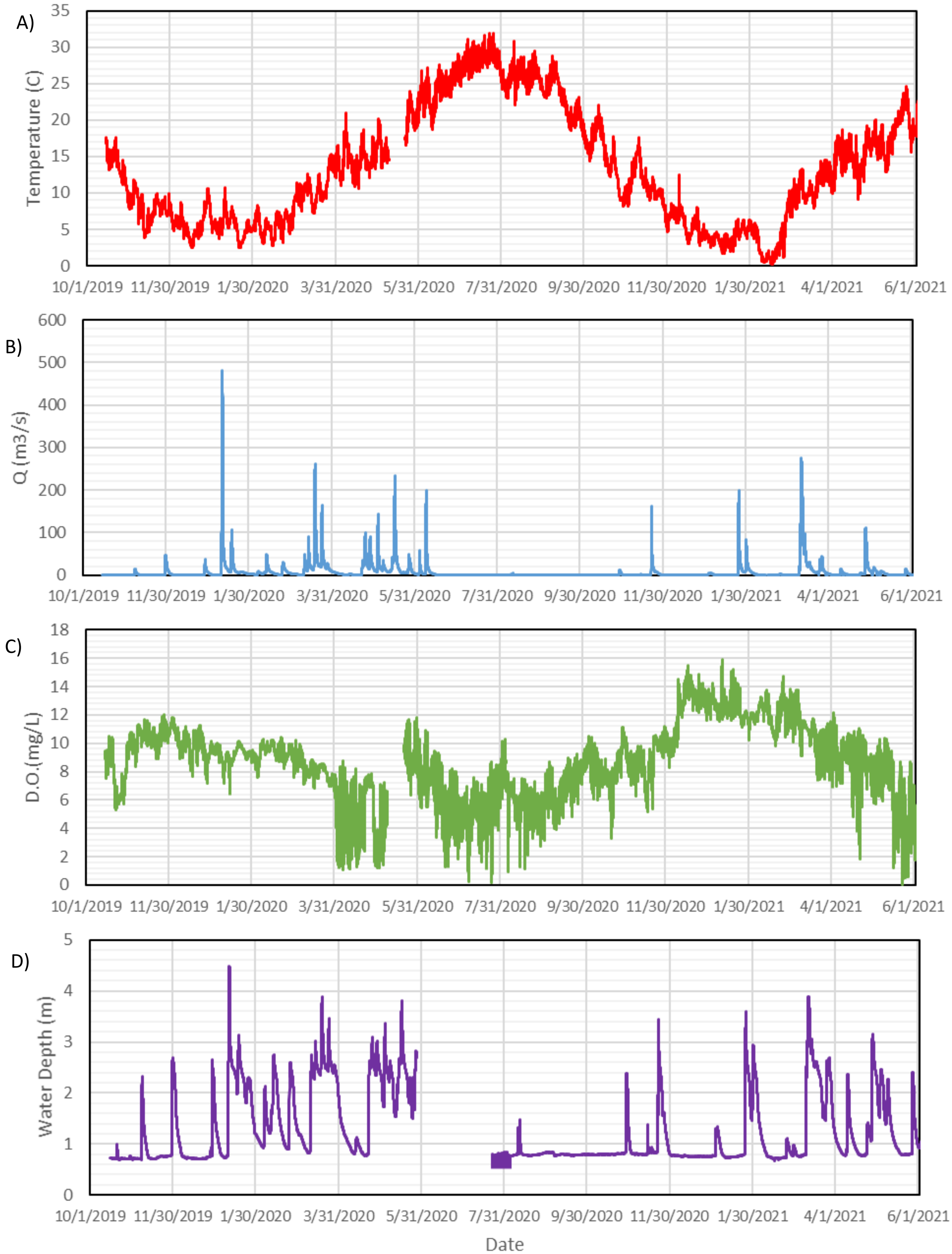

Figure 9. Continuous 15-minute A) water temperature, B) discharge, C) dissolved oxygen, and D) stage readings at the RC8 (Rkm = 12.6, Ad = 699 km^2).

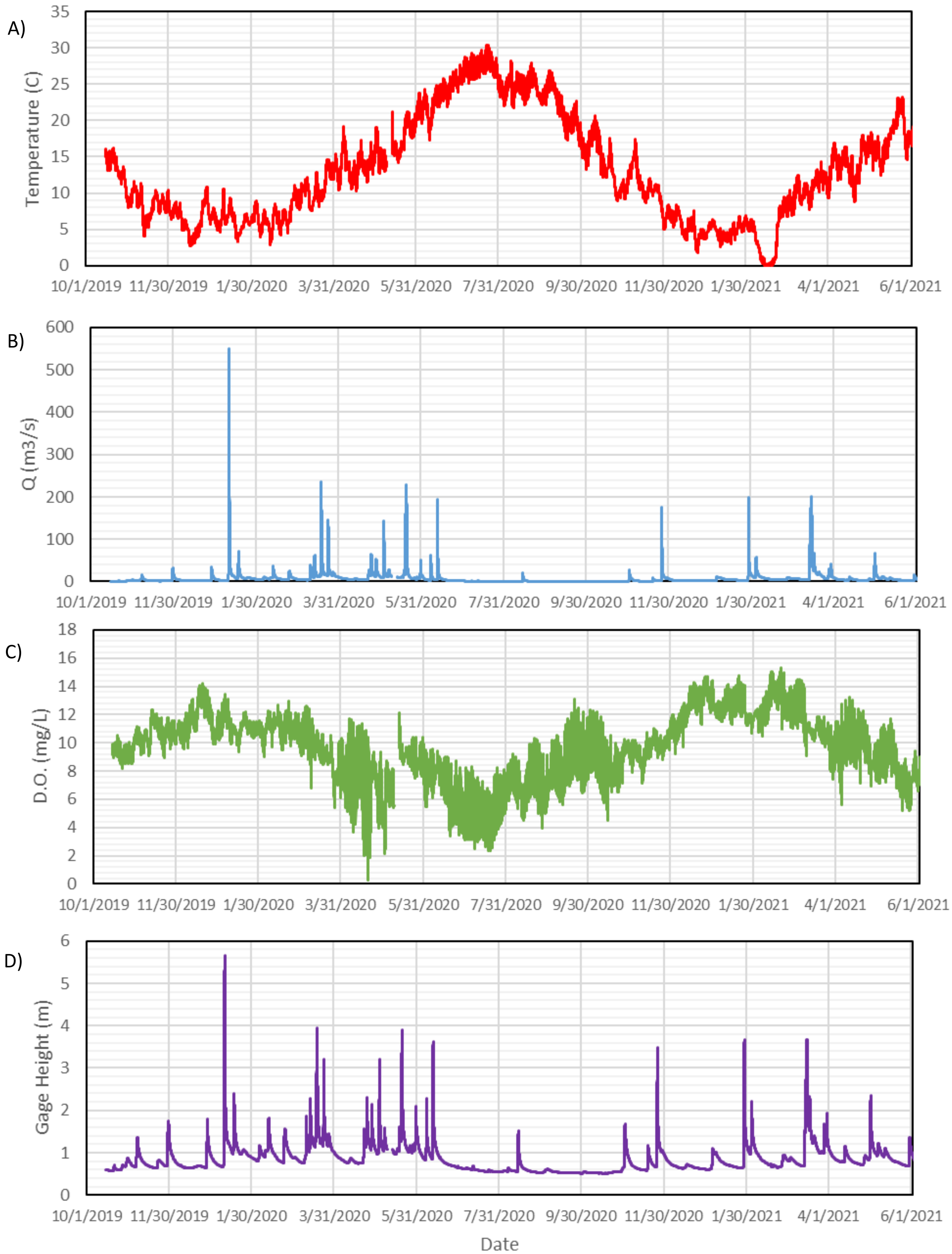

Figure 10. Continuous 15-minute A) water temperature, B) discharge, C) dissolved oxygen, and D) stage readings at the RC17 (Rkm = 56.2, Ad = 428 km^2).

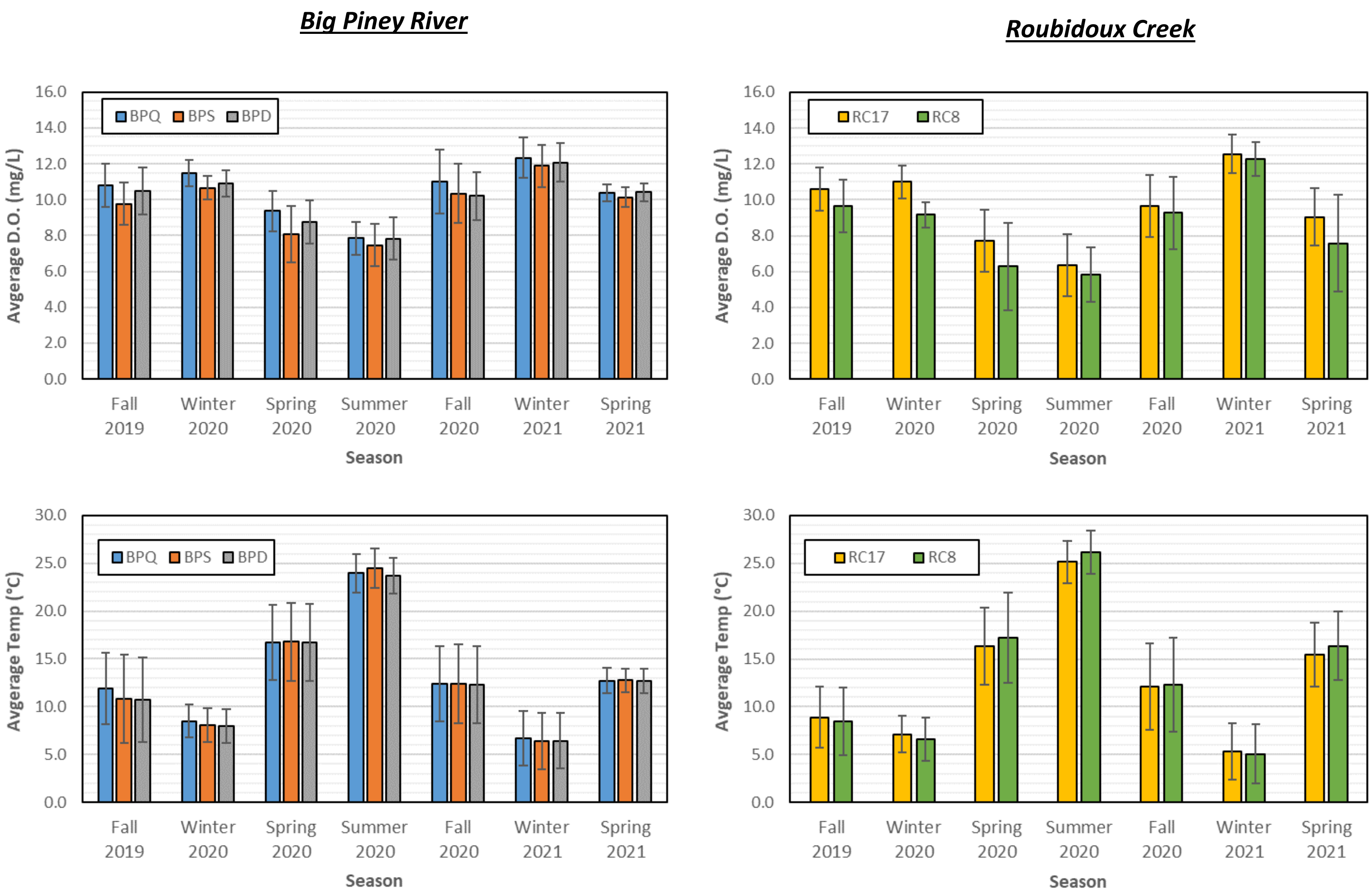

Figure 11. Seasonal average DO and temperature by monitoring site with +/- 1 standard deviation.

APPENDICES

Appendix A. Method used to Estimate Discharge at Big Piney River DO Monitoring Stations.

Discharge-Drainage Area Relationships

Discharge at each of the sites along the Big Piney River was estimated by creating relationships between drainage area and discharge values from WY2019 and 2020 at the USGS gaging stations upstream and downstream of the monitoring sites. The average of the two water years was used for the annual max, 10% exceedance, 50% exceedance, 90% exceedance, and the 7-day minimum discharges representing a range of flows throughout the year. The specific discharge values for each flow were then predicted at each monitoring station (Table 8 and Figure 12).

Table 8. Discharge and Drainage Area Equations for Big Piney River DO Monitoring Sites.

Water Year Discharge Statistics	Upstream USGS Gage 1,450 km^2 (m^3/s)	Downstream USGS Gage 1,536 km^2 (m^3/s)	m	b	BPQ 1,507 km^2 (m^3/s)	BPS 1,522 km^2 (m^3/s)	BPD 1,526 km^2 (m^3/s)
Annual Max	719	725	0.136981	265.38	723.1	724.1	724.4
10% Exceeds	55.9	68.9	3.646849	1.652E-10	64.3	66.7	67.3
50% Exceeds	12.4	19.9	8.184968	1.653E-25	17.0	18.5	18.9
90% Exceeds	7.0	8.4	3.230207	4.284E-10	7.9	8.2	8.2
Annual 7-day min	5.7	6.7	2.619457	3.003E-08	6.3	6.5	6.6

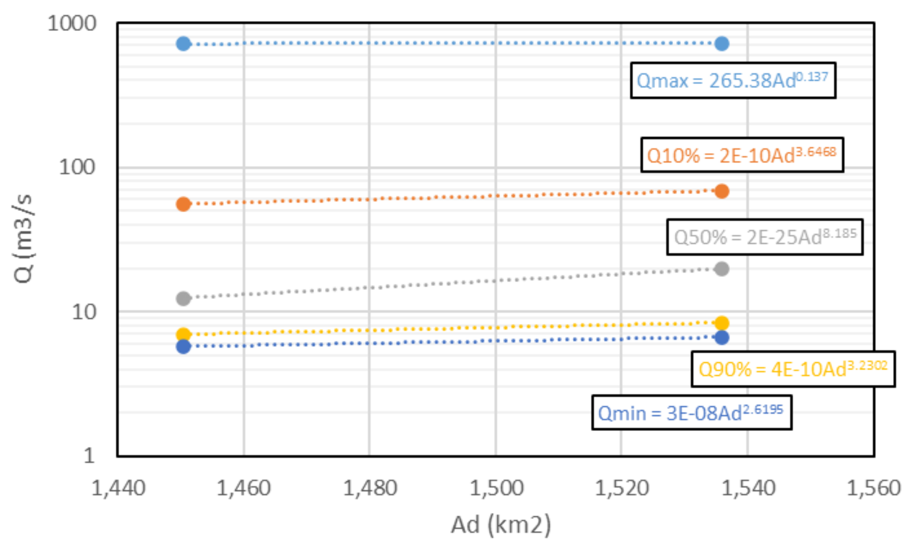

Figure 12. Discharge and Drainage Area Relationships for USGS Gages on the Big Piney River Above and Below the DO Monitoring Sites.

Instantaneous Discharge Estimates

Instantaneous 15-minute discharge was estimated at each of the DO monitoring sites using the relationship between discharge values at the upstream gage and predicted discharge values from the equation discussed above. The upstream gage was used because it had a more complete instantaneous discharge record compared to the downstream gage. This was done using the annual max, 10% exceedance, 50% exceedance, 90% exceedance, and the 7-day minimum discharges representing a range of flows throughout the year. Equations were developed for each site and applied to the data reported at the upstream gaging station over the monitoring period (Table 8 and Figure 13).

Table 9. Upstream USGS gaging station discharge and predicted discharge equations for Big Piney River DO Monitoring Sites.

Site	m	b
BPQ	0.9695	1.2702
BPS	0.9615	1.3512
BPD	0.9595	1.3736

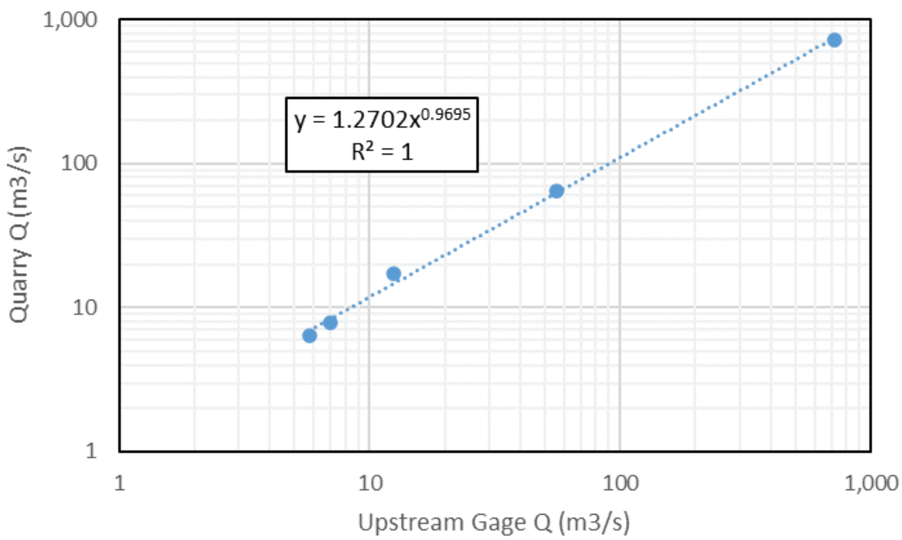

Figure 13. Example of the relationship between the reported discharge at the upstream gage and predicted discharge at the BPQ DO monitoring site.

Appendix B. Photos

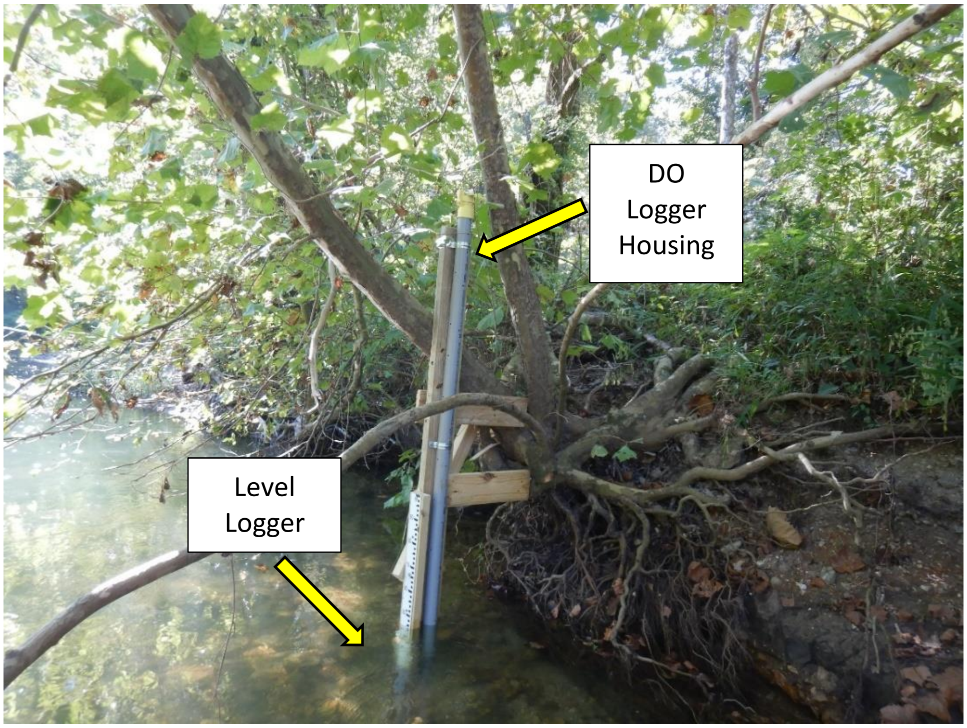

Photo 1. DO sensor housing and level logger at BPQ (10/1/2019).

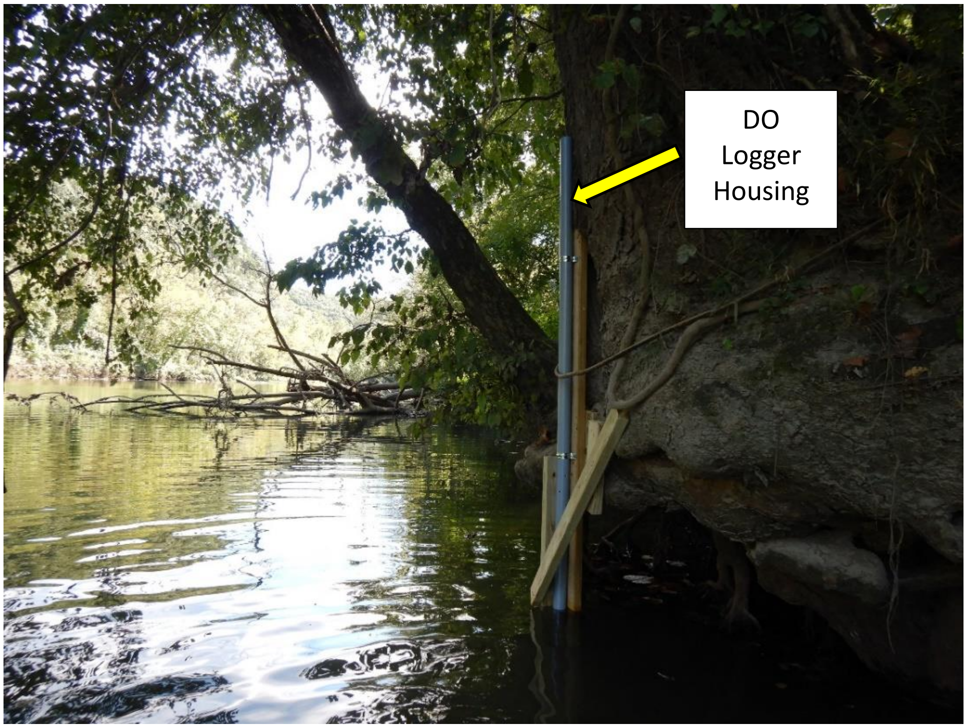

Photo 2. DO sensor housing at BPS (9/23/2019).

Photo 3. DO sensor housing at BPD (9/23/2019).

Photo 4. DO sensor housing at RC17 (10/1/2019).

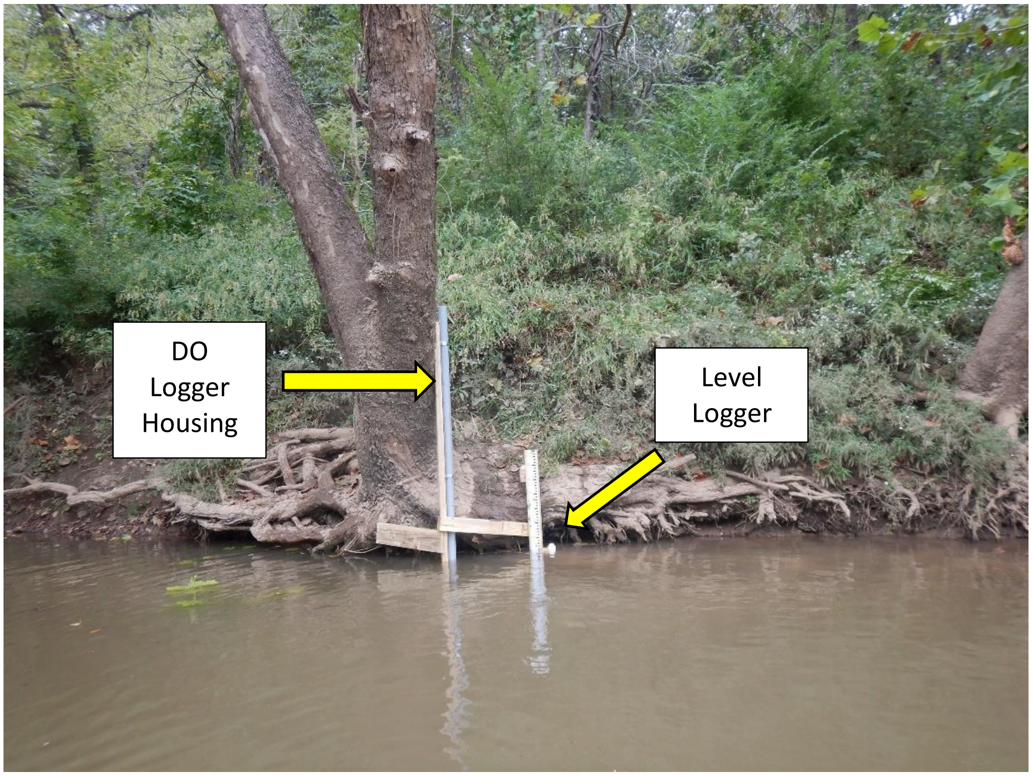

Photo 5. DO sensor housing and level logger at RC8 (9/24/2019).


Photo 6. Low-water bridge downstream of RC8 (5/31/2019).

Appendix C. Methods used in the estimation of DO at BPS for a portion of the continuous record.

Table 10. DO data from January-March 2020 used to predict DO at BPS February 23, 2021 to April 6, 2021.

Discharge (m3/s)	BPS DO (mg/L)	BPD DO (mg/L)
20	10.04	10.23
40	9.71	10.03
60	10.00	10.08
80	10.32	10.63
100	9.61	9.71
120	9.61	9.76
140	10.80	10.87
160	9.43	9.54
180	9.34	9.44
200	9.21	9.41
220	9.22	9.35
240	9.14	9.30
260	8.96	9.21
280	8.72	9.16
300	8.77	9.12
320	8.79	9.11
340	9.08	9.34
360	8.75	9.03

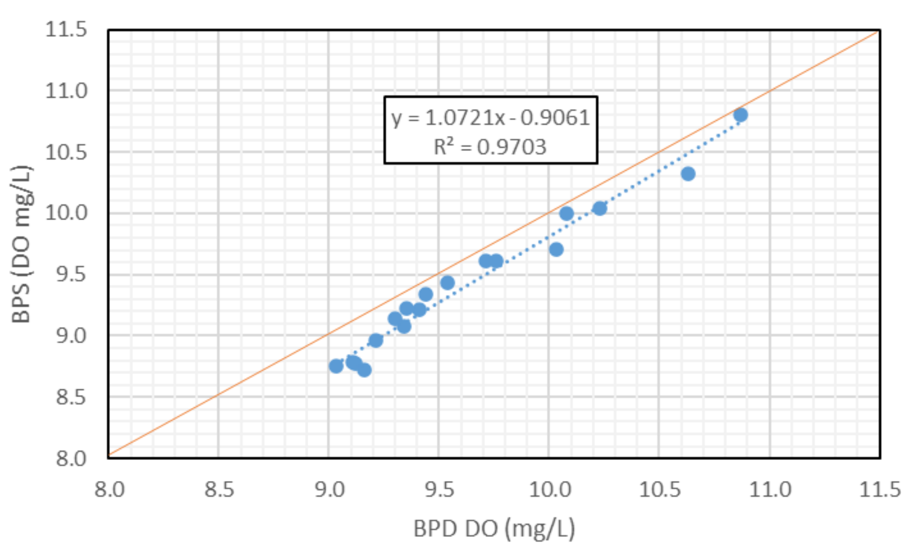

Figure 14. Regression equation used to predict BPS DO February 23, 2021 to April 6, 2021.

Appendix D. Onset Hobo U26-001 Dissolved Oxygen Logger Components.