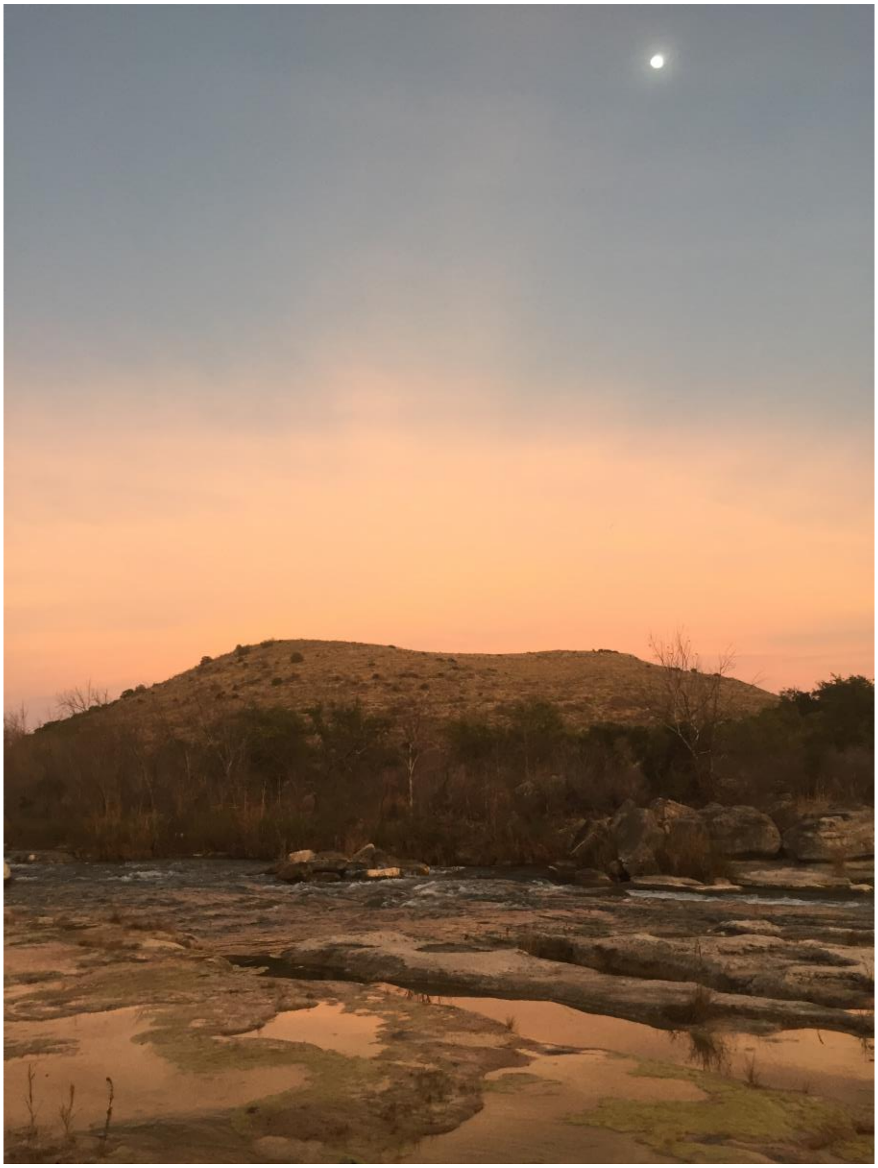
Monitoring the effects of groundwater level on spring and stream discharge, stream temperature, and habitat for *Dionda diaboli* in the Devils River

Final Report for Contract Period:
September 1, 2015 to August 31, 2018



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CONTRACTUAL NOTES

Service Award Number

USFWS: TX E-173-R-1, F15AP00669

UT Austin: UTA15-000983

Note on this Final Report

This Final Report presents the results of hydrologic monitoring of groundwater level, spring and stream discharge, and stream temperature within *Dionda diaboli* habitats in the Devils River from September 1, 2015 to September 30, 2018 (we do, however, present data collected before and after the contracted field monitoring program start and end dates).

Comparison of Actual Accomplishments with Goals and Objectives as Detailed in Approved Scope

We completed all goals and objectives outlined in contract.

Description of Reasons Why Established Goals Were Not Met, if Appropriate

N/A

Any Other Pertinent Information Relevant to Project Results

Additional work conducted beyond the scope in the contract includes:

- Measuring longitudinal stream temperature using fiber optic distributed temperature sensing (FO-DTS),
- Installing temperature loggers along longitudinal profiles in (1) Devils River from Finegan Springs downstream to Blue Hole spring and including two sites within the site channel formed by Blue Hole spring and (2) Dolan Creek from vicinity of U.S. Geological Survey stream gauge (Figs.1,3) to the confluence with the Devils River, and
- Estimating surface water temperature along ~500 m stretch of the Devils River affected by several groundwater seeps around Finegan Springs using Forward Looking Infrared Systems (FLIR) microbolometer mounted on a small, unmanned aerial vehicle (i.e., drone).

EXECUTIVE SUMMARY

Essential to developing effective instream flow recommendations in highly groundwater-dependent streams is an understanding of how variations in groundwater level affects spring flows, and how these groundwater inputs maintain stream flows and provide thermal buffering to aquatic habitats. Up to 75% of Devils River streamflow is comprised of groundwater and, via Lake Amistad, provides ~15% of the water to the Lower Rio Grande (Green et al., 2014). However, throughout Texas and the western U.S., groundwater development has desiccated or substantially reduced flows in spring-fed streams (Brune, 2002; Hoagstrom et al., 2011; Unmack and Minckley, 2008). Groundwater development proposed for Val Verde County threatens to reduce spring flows to the Devils River and potentially decrease or destroy habitat for the Devils River minnow (*Dionda diaboli*). Particularly during droughts, other species of state and federal conservation interest such as the Texas Hornshell (*Popenaias popeii*) freshwater mussel (FWS, 2018) will likely be stressed because pumped groundwater would otherwise have discharged into the river. This study aims to improve the understanding of the relationship between groundwater, spring discharge, and stream flows in the Devils River. In light of proposed groundwater development projects, this information is urgently needed to inform conservation strategies that maintain aquatic habitats of target species.

The objective of this study is to generate hydrologic data needed to understand the relationships between groundwater, spring discharge, and stream flows within aquatic habitats of *D. diaboli* (Hardy, 2014; Kollaus and Bonner, 2012; Robertson, 2011, 2014), *P. popeii* (Randklev et al., 2018), and other species of conservation interest in the Devils River. Specifically, the goals of this study are to monitor (1) meteorological parameters, (2) stream discharge and temperature, (3) spring physical parameters, and (4) groundwater levels in and around the Devils River at the Texas Parks and Wildlife (TPWD) State Natural Area (SNA) and The Nature Conservancy (TNC) Dolan Falls Preserve.

Our key findings to date include:

- Dynamic groundwater levels of ~10–20 ft indicative of groundwater recharge correlate with ephemeral channel flows in Dolan Creek.
- Most other wells, particularly those at locations far from the Devils River, show static groundwater levels with essentially no change.

- Spring water conductivity and temperature change rapidly following floods, indicating important fast-flow groundwater recharge in Dolan Creek—and the importance of developing groundwater management strategies within the Dolan Creek drainage.
- Spring flow in study area provide up to 71% of Devils River discharge at Dolan Crossing, indicating that managing groundwater to maintain spring flows is essential to conserving instream flows on the Devils River—particularly during droughts.
- Spring flows are critical to provide thermal buffering and maintain instream flows, particularly during summer and droughts.
- The Finegan Spring complex was consistently 22.6 ± 0.3° C, while instream temperatures varied from 5–30° C with surface waters entering the reach (upstream) at 21.0 ± 5.7° C and exiting (downstream) at 22.7 ± 4.2° C.
- Instream water temperatures showed high thermal sensitivity to watershed air and soil temperatures, explaining that on average over 70% of the seasonal and daily variations in stream water temperatures is caused by changes in air temperature. However, stream water temperatures showed little to no correlation to spring temperatures.
- Daily maximum air temperature has increased 0.35° C per decade over the watershed. Using a robust multiple linear regressive model (mean error of 0.8° C), we found daily maximums incoming surface water are increasing at 0.30° C per decade while below the spring complex at 0.16° C per decade. Note that these trends were only significant for daily maximum water temperatures.
- Model-derived persistent and catastrophic temperature thresholds (from the perspective of aquatic biota) above 30° C occurred 13 and 43 days at upstream locations, respectively (following the approach of Castelli et al., 2011). Below the spring complex, the 30° C persistent and catastrophic temperature thresholds are reduced to 6 and 12 days, respectively. Thus, continuous periods above threshold temperatures should trigger management actions (e.g., collecting *P. popeii* individuals for translocation to a fish hatchery until temperature maxima reduce).
- An ongoing study monitoring substrate temperature and stream stage at riffles where *P. popeii* has been detected (funded under separate contract, but informed by this study) will improve understanding of how various instream flow recommendations may conserve aquatic habitats by considering thermal buffering when determining stream flow thresholds and groundwater management goals that maintain Devils River spring flows.
- Ongoing processing of bathymetric and topographic Lidar (funded under separate contract) will provide a primary input dataset to aquatic habitat models, which can be used to assess habitat suitability under a range of instream flow scenarios for ~70 km of the Devils River from Lake Amistad to the stream's headwaters.

One clear result of the study is the spring discharge is the only thermal refugia for aquatic life in the Devils River. Although wide ranges of temperatures were observed, springs inputs provide a buffering capacity that maintains important aquatic habitats. Even with increases in air temperature caused by climate variability, these springs provide consistent thermal buffers and habitat provided spring discharge remains constant. Groundwater elevations appear to be relatively steady in the area; however, the continued collection of hydrogeologic data over a larger area may allow us to deduce the location of a possible “trigger well” further afield from the study area at which regional-scale fluctuations in groundwater level is well correlated with longer-term spring discharge trends. Climate variability and well development pose a threat to the semi-arid groundwater dependent Devils River; however, the monitoring programs implemented here can inform management and improve the outcomes of management actions. Ultimately, the results of this and other ongoing hydrology and biology studies can be used to inform the development of a physical habitat model, which when used in conjunction with a groundwater model, can be used to understand how instream flows may change in response to groundwater development scenarios in the basin. While we apply this approach to aquatic habitats in the Devils River of Texas, this research approach may be used to inform conservation in other semi-arid, highly groundwater dependent streams with important species of state and federal conservation interest.

1. INTRODUCTION

1.1 Purpose of this Report

This report presents the results of "Monitoring the effects of groundwater level on spring and stream discharge, and stream temperature in habitats of *Dionda diaboli* in the Devils River" (Section 6 Grant #TX E-173-R-1, F15AP00669). This study monitors (1) meteorological parameters, (2) stream stage (and estimates stream and spring discharge), (3) groundwater levels, (4) physical parameters of surface water and springs, and (5) Evaluates historic surface water and groundwater data and other studies in and around the Devils River at the TPWD State Natural Area (SNA) and TNC Dolan Falls Preserve (Figs.1,2,3). In light of proposed groundwater development projects, the objective of this study is to improve understanding of the relationship between groundwater and spring discharge within the habitats of the Devils River Minnow (*Dionda diaboli*) and other species of state and federal conservation interest (e.g. Texas Hornshell, *Popenaias popeii*). Ultimately, this work may be used to inform the development of management strategies for successful conservation of Devils River aquatic habitats.

1.2 Study Area

The study site includes a portion of the perennial reach of the semi-arid, groundwater-dependent Devils River within the Texas Parks and Wildlife Department (TPWD) Devils River State Natural Area (SNA) and The Nature Conservancy (TNC) Dolan Falls Preserve (Preserve; Figs.1,2,3) in Val Verde County, Texas. The primary study site is located in the vicinity of Finegan Springs and the confluence of the Devils River and Dolan Creek, ~60 km north of Del Rio and ~250 km west of San Antonio (Figs. 1,2,3). This reach is considered an Ecologically Significant Stream Segment due to its relatively intact ecosystem and high species diversity (Omernik and Griffith, 2014; TPWD, 2012).

The uniqueness of the aquatic ecosystem of the Devils River is in part due to perennial water in a relatively arid climate with average annual precipitation: ~46–56 cm/yr (PRISM, 2018b) and mean annual temperature:18–20°C (PRISM, 2018a). In addition, the area is situated at the confluence of three ecoregions: the Chihuahuan Desert, Edwards Plateau, and Southern Texas Plains (Omernik and Griffith, 2014; TPWD, 2012). Land use in Val Verde County comprises shrub/scrub (~94%), grasslands/herbaceous (~2%), open water (Lake Amistad, Pecos River, Devils River, ~2%), deciduous forest (~1%), and developed land (Del Rio and other towns, ~1%; MRLC, 2018). Developed land historically included urbanized areas and conventional oil and gas production primarily from the Lower Ellenburger Group (Canter et al., 1993). However, as of January 2018, there has also been limited unconventional oil and gas development using a combination of direction drilling and hydraulic fracturing (IHS, 2018). Additionally, parts of the Devils River watershed in Val Verde County have been identified for potential sites for construction of wind power generation turbines.

1.3 Conceptual Hydrological Model of the Devils River

The Edwards-Trinity (Plateau) Aquifer is a karstified aquifer present throughout the study area and Val Verde County. The aquifer provides important groundwater discharge to springs and seeps flowing into the Devils River that maintains flows, particularly during summer and droughts. Within the study area, the aquifer is comprised of two formations of the Lower Cretaceous Edwards Group (Figs. 1,4): the unconfined Segovia Formation and the underlying Fort Terrett Formation (Barnes, 1977). The Segovia Formation forms cliffs and higher-topography. The Fort Terrett Formation forms the base of Dolan Creek and the Devils River near Dolan Crossing. This formation is generally flat lying and despite fractures present in outcrop, no major faults are mapped in the study area (Barnes, 1977). Recharge to the aquifer occurs primarily through infiltration of episodic flows in ephemeral stream channels that comprise the Devils River watershed, such as Dolan Creek, the Dry Devils River, and the upper Devils River (Anaya and Jones, 2009). Groundwater flows generally from the north to south along preferential flow paths paralleling the stream channels (Green et al., 2014). Natural spring discharge occurs where stream channels have eroded down since development of the Balcones Fault system in the Early Miocene (Abbott, 1975; Green et al., 2014; Woodruff, 1977) and intersected the water table. Springs discharge near the Segovia Formation-Fort Terrett Formation contact, where limestone dissolution along this horizon (possibly the Kirschberg evaporite zone) allows preferential groundwater flow (Veni & Assoc., 1996). In addition to springs being maintained by ephemeral stream flows draining into the Devils River, Veni (1996) postulated that the Devils River may lose water (when it flows) to the aquifer from the channel ~32 km to the north of Finegan Springs, with groundwater flowing south and subsequently discharging in the springs. Wells primarily used for watering livestock also discharge groundwater; however, some agriculture irrigated with groundwater is present adjacent to the Devils River channel in the north-central portion of Val Verde County.

1.4 Aquatic Habitats for Species of State and Federal Conservation Interest

A primary motivation of this study is concern for conservation of aquatic species receiving protection under the Endangered Species Act (ESA). At the start of this study, the study area had one federally threatened (FT) fish species, the Devils River Minnow, *Dionda diaboli* (FWS, 1999). The Devils River also hosts a federally endangered (FE) freshwater mussel species, the Texas Hornshell *Popenaias popeii*, which was listed as federally endangered (FE) in March 2018 (FWS, 2018). The stream also provides aquatic habitats for three state threatened (ST) fish species, including the Proserpine Shiner *Cyprinella proserpina*, Conchos Pupfish *Cyprinodon eximius*, and Rio Grande Darter *Etheostoma grahami* (TPWD, 2012, 2014). Some of these species move within aquatic habitats in response to seasonal water temperature changes. In addition to characterizing the importance of groundwater inputs to maintain Devils River stream flows for both riverine and spring-associated species, understanding the role of relatively constant-temperature groundwater discharge through springs is essential for maintaining thermal refugia and seasonally preferred habitats for spring-associated species. Thus, an increased understanding of the influence from spring discharge in maintaining river flows and thermal regimes is paramount for species conservation in light of historic and potential future threats to the river system.

D. diaboli was historically found in spring-fed Rio Grande tributaries of Kinney and Val Verde counties of Texas and in Coahuila, Mexico (Fig.2; FWS, 1999, 2005; Garrett et al., 2004; Garrett et al., 1992; Kollaus and Bonner, 2012). However, surface water and groundwater development since the 1950s, human alteration of stream habitat, and other factors substantially reduced *D. diaboli*'s range (Ashworth and Stein, 2005; Brune, 2002; FWS, 2005, 2007, 2008; Sharp, 2001). Thus, within the species' Texas distribution, it is now found only in Pinto Creek, San Felipe Creek, and the Devils River (Fig.2).

In light of *D. diaboli*'s reduced range, TPWD conducts annual fish surveys in the Devils River (Robertson, 2014) and several studies have investigated the species' biology in the Devils River (Garrett et al., 1992; Hardy, 2014; Harrell, 1978; Hubbs and Brown, 1956; Hubbs and Garrett, 1990; Kollaus and Bonner, 2012; Phillips et al., 2011; Robertson and Winemiller, 2003; Robertson, 2011). Climate variability—including drought—and proposed groundwater pumping, may reduce groundwater inputs to spring-influenced environments, further threatening habitat availability (Kollaus and Bonner, 2012; Robertson, 2011). Thus, this study will increase the understanding of hydrology within habitats of *D. diaboli* and other aquatic species of conservation interest in the Devils River.

1.5 Understanding Groundwater-Surface Water Interactions to Maintain Instream Flows

Essential to developing effective instream flow recommendations in highly groundwater-dependent streams is an understanding of how variations in groundwater level affects spring flows, and how these groundwater inputs maintain stream flows and provide thermal buffering. Thus, the goal of this study is to collect hydrologic data in the Devils River from groundwater, springs, and streams, which can be used to inform how various groundwater management scenarios could affect instream flows. Ultimately, such data could also be used as primary inputs to an aquatic habitat model to quantify how instream flows under various groundwater development—and potentially climatic—scenarios may conserve streamflow for aquatic habitats of target species. Thus, this study, which improves the understanding of the relationship between groundwater, spring discharge, and streamflow in the Devils River, is urgently needed to maintain adequate flows for aquatic habitats of target species in light of proposed groundwater development projects.

1.6 Study Objectives

The objective of this study is generate hydrologic data needed to understand the relationships between groundwater, spring discharge, and streamflow within *D. diaboli* habitats (Hardy, 2014; Kollaus and Bonner, 2012; Robertson, 2011, 2014), *P. popeii* (Randklev et al., 2018), and other species of conservation interest. Specifically, the goals of this study are to monitor (1) meteorological parameters, (2) stream stage and discharge, (3) groundwater levels and quality, (4) spring discharge and physical parameters, and (5) instream temperatures in and around the Devils River at the TPWD State Natural Area (SNA) and TNC Dolan Falls Preserve (Figs.1,3). Refer to Tables 1 and 2 and Figs.1 and 3 for a summary of hydrologic data collected and the implications of these data to improving maintenance of instream flows.

Specifically, this study:

1. Increased understanding of the influence of climatic variability on aquatic habitat by monitoring meteorological parameters, including air temperature and relative humidity, precipitation, wind speed and direction, and short-wave solar radiation;
2. Continuously monitored Devils River stage upstream and downstream (Dolan Crossing) of Finegan Springs and measured instantaneous discharge to develop a stage-discharge relationship, enabling calculation of spring discharge. These new data provide an understanding of how streamflow fluctuates in response to changing groundwater levels and climatic conditions and filled a gap in streamflow measurement on the Devils River;
3. Measured groundwater levels to understand baseline groundwater variability before possible groundwater pumping projects start;
4. Monitored spring and stream water temperature and salinity (e.g., specific conductance) to understand rainfall-runoff and spring flow relationships affecting streamflow;
5. Recorded water temperature using loggers installed in *D. diaboli* habitat in lateral transects in the vicinity of Finegan Springs (Site 5, Kollaus and Bonner, 2012) and longitudinally in Dolan Creek and the Devils River downstream from Finegan Springs to its confluence with Dolan Creek. This reach of Devils River has important *D. diaboli* habitat with temperature that varies temporally from seasonal changes in streamflow and climate (Hardy, 2014; Kollaus and Bonner, 2012; Robertson, 2011).
6. Evaluated surface water and groundwater data collected by previous studies in order to place this study within a historical context; and
7. Assessed the relationship between the monitoring data collected in this study with modeled groundwater levels (Green, 2014) and existing habitat modeling (Hardy, 2014) to understand potential impact of future groundwater pumping on aquatic habitats, including those of *D. diaboli*.

While not originally formally proposed under the Section 6 grant, we also:

1. Measured diurnal water temperature variations in the stream thalweg during semi-quarterly field trips using fiber optics distributed temperature sensing (FO-DTS) deployed ~500 m

upstream and ~600 m downstream of Finegan Springs (Fig.3). Such data illustrates groundwater inputs as well as the temporal stability of thermal refugia;

2. Collected thermal infrared imagery of surface water temperature around spring discharge sites using a microbolometer (i.e., Forward Looking Infrared Systems, FLIR) mounted on a small unmanned aerial vehicle (i.e., drone). Water surface thermal imagery was collected along ~500 m stretch of the Devils River affected by several groundwater seeps around Finegan Springs (Abolt et al., 2018).

Additionally, as part of work funded under a separate SWG grant, stream water temperature and stage are being collected in riffles where endangered Texas Hornshell (*Popenaias popeii*) individuals have been found. These data will be used by researchers to understand how habitat quality changes (using temperature as a proxy) and to understand the effects of thermal buffering and flow thresholds that maintain mussel habitat under a suite of discharge conditions (e.g., Gates et al., 2015; Maloney et al., 2012).

2. METHODS

2.1 Meteorological parameters (Task 5)

The weather station (Fig.3) near Dolan Crossing was reestablished in October 2015 with a new power supply, solar panel and datalogger. In February 23, 2016. The malfunctioning meteorological sensors were replaced including air temperature (T_a) and relative humidity (Rotronic HC2S3), solar radiation (Eppley Model 8-48 Pyranometer), wind speed and direction (R. M. Young Wind Sentry, Model 03002), and soil temperature (T_s) (Campbell Scientific, 107), installed at 10 cm depth. The original precipitation gauge (Texas Instruments) was rewired, cleaned and calibrated. A self-contained barometric pressure sensor (In-Situ BaroTROLL) is kept in the enclosure primarily for post-processing stage recorders. The aboveground sensors are at 2.8 m. Each sensor is sampled every 5 seconds and averaged every 30 minutes. We manually downloaded the data during each site visit. Daily potential evapotranspiration (PET) is calculated using the Penman equation based on maximum and minimum T_a and relative humidity, mean wind speed, and solar radiation.

2.2 River stage and discharge (Task 4)

River stage was measured at locations Upstream and Downstream of the Finegan Spring Complex (Fig.3) by installing absolute pressure transducers (In-Situ Rugged TROLL 100) in a mount affixed to the limestone stream bottom. The Downstream location was installed on June 18, 2015 and the Upstream on October 20, 2015. Internal data loggers sampled stage and temperature every 15 minutes. Data were manually downloaded at each site visit, during which instantaneous discharge was measured using an acoustic Doppler velocimeter (ADV; FlowTracker SonTek, 2014) following the approach of Rantz et al. (1982a).

River stage was calculated from post-corrected pressure data to eliminate barometric pressure effects using barometric pressure data recorded at the weather station (following the general approach of Spane, 2002). We estimated stream discharge (Q) by converting continuous river stage measurements using a stage-discharge relationship after the approach of Rantz et al. (1982b). We developed a rating curve using the instantaneous discharge measurements and the 24 hour averaged (centered around the time of the discharge measurement) stage measurement using the following equation:

$$Q = p(G - e)^N \quad [1]$$

Where G is the stage height, e is the gauge height of effective zero-flow, p is the discharge when (G-e) is 1, and N is the slope of the rating curve. For the Downstream location, e was set to 0 ft. For the Upstream location, graphical methods were used to determine any changes in e by observing a parallel shift in the rating curve.

2.3 The contribution of Finegan Springs and Blue Hole spring to Devils River discharge was calculated by subtracting upstream from downstream discharge when the stage measurements were within the range of the instantons discharge measurements. Groundwater levels from shallow and deep monitoring wells (Task 1)

Groundwater level was measured at two observation wells using absolute pressure loggers (In-Situ unvented Level Troll 500 and AquaTROLL 200) hung within the well casing and affixed at the surface using 1/16-inch stainless steel cable (Fig.1,3). On October 22, 2015, a logger was installed in the shallow well (total depth 251 ft below top of casing, logger at 215.5 ft btoc) and on October 21, 2015 in a deep monitoring well (total depth 666 ft below top of casing, logger at 550 ft btoc).

The shallow well was located ~1,000 ft south of Dolan Creek's currently active channel and on a hill <60 ft above the stream channel. The well was selected to understand possible groundwater recharge from ephemeral creek flows. The deep well was located on a plateau >400 ft above the channel and ~2 miles east of Dolan Creek and was selected to characterize potential diffuse recharge. Groundwater levels were sampled at 1-hour intervals and data were manually downloaded during site visits.

2.4 Water temperature and specific conductance (Tasks 2,3)

2.4.1 Spring temperature and specific conductance (Task 2)

Temperature is a direct measure of the energy status of a system. Water temperature (T_w) affects biological activity and growth, geochemical reaction rates, and solubility of minerals and oxygen. Electric conductivity is a measure of the ability of material to conduct electric current, which is proportional to T_w. Specific conductance (SC) is simply electrical conductivity normalized to 25° C. Dissolved ions in solution conduct more charge, providing an indication of total dissolved solids in water and an indicator of water quality. Spring temperatures and SC were measured to elucidate rainfall-runoff response in major springs flowing into the Devils (i.e., direct recharge from Dolan Creek or longer groundwater flow paths). These data are useful because rainwater, surface water, and groundwater are expected to have different temperatures and SC. We installed conductivity-temperature sensors (HOBO U24-001; Onset, 2014a) at Finegan Springs on June 16, 2015 and Blue Spring on June 18, 2015 sampling at 15-minute intervals (Fig.3). During site visits, data were manually downloaded and physical water parameters (i.e., temperature, pH, SC) were collected with a hand-held multi-meter (YSI 556 MPS)(YSI, 2018).

2.4.2 Instream water temperature and specific conductance (Task 3)

Temperature and specific conductance of river water were measured to investigate mixing of surface and spring waters near Finegan and Blue springs within an important reach of *D. diaboli* habitat that varies temporally from seasonal changes in streamflow and climate (Hardy, 2014; Kollaus and Bonner, 2012; Robertson, 2011). We measured T_w (TidbiT v2, UTBI-001; Onset, 2014b) along two lateral transects below the Finegan Spring complex (i.e., Site 5, Kollaus and Bonner, 2012; Fig.4, loggers 1 through 10). Along each lateral transect, we installed five loggers across the channel from shallow bank into the thalweg and across to the other bank. Each sensor was housed in a protective vinyl cap and affixed with a concrete anchor to a rock on the bottom of the stream. Water temperature loggers were also installed longitudinally down Devils River and into Blue Spring and along Dolan Creek (Fig.3, loggers 11 through 20). For each longitudinal transect, loggers were attached to the downstream side of boulders in the stream channel using waterproof epoxy in protective PVC enclosures (using a similar design to Isaak et al., 2013) ~2 ft below water level. Temperature loggers were also affixed to 1.5-ft rebar hammered into gravel substrate comprising riffles where *P. Popenaias* has been identified in surveys by TPWD biologists (Fig.3, loggers 21 through 24).

Lastly, we measured river specific conductance (SC) upstream and downstream of Finegan Springs and in Blue Hole and Rock Art Spring (Dolan Creek Drainage; Fig.3). We installed conductivity-temperature sensors (HOBO U24-001; Onset, 2014a) at Finegan Springs on June 16, 2015 and Blue Spring on June 18, 2015 and Rock Art Spring on February 8, 2017 sampling at 15-minute intervals (Fig.3). During site visits, data were manually downloaded and physical water parameters (i.e., temperature, pH, specific conductance) were collected with a hand-held multi-meter (556 MPS; YSI, 2018).

2.5 Comparison of data with other studies (Task 7)

We proposed to synthesize our results with other studies, particularly providing a comparison of our measured fluctuation of groundwater levels and stream discharge with resultant groundwater levels from a numerical groundwater model. We also proposed to compare our streamflows with the existing habitat model by Hardy (2014) to evaluate possible changes in *D. diaboli* habitat resulting from future groundwater pumping. Green and others at the Southwest Research Institute (Green et al., 2014) presented a hydrogeologic conceptual model for the Devils River watershed where high-capacity wells are located along preferential groundwater flow paths which parallel modern stream channels. Toll et al. (2017b) developed this conceptual model into a numerical groundwater simulation and used it to evaluate the potential effects on streamflows resulting from two groundwater pumping scenarios.

2.6 Historical hydrogeologic and hydrologic data (Task 6)

We compiled historic groundwater and surface water monitoring data—and associated precipitation recordings—from the Texas Water Development Board (TWDB) and the U.S. International Boundary and Water Commission (IBWC). We accessed groundwater levels measured from four monitoring wells in and around the study area from TWDB (TWDB, 2018a, b). Recent discharge data from the IBWC (IBWC, 2018) are available online; however, historic data must be acquired from IBWC using a Freedom of Information Action (FOIA) request. To this end, we used historic discharge data acquired from IBWC from TNC (Smith, 2018b) for four IBWC stream gauges on the Devils River. Historic groundwater level, surface water discharge, and precipitation data associated with gauges were used to construct two sets of hydrographs: one for the study period and one for the entire period of record (i.e., starting 2007–2009 for wells and 2004–2005 for stream gauges).

2.7 Instream temperature modeling and long-term trends

Linear correlation between environmental covariates (e.g. T_a or T_s) and T_w are attractive for modeling long-term climatic influence on instream temperatures (Mohseni and Stefan, 1999). The general formulae are:

$$T_w(t) = A + BT_a(t) \quad [1]$$

Or

$$T_w(t) = A + BT_s(t) \quad [2]$$

Where T_w, T_a and T_s temperature [C] either at or averaged over some specified time interval (*t*). Least squares, linear regression is used to determine the constant (*A*) and slope (*B*) of this relationship, which generally proves to be linear above freezing and below 30° C. For shorter time intervals ($t < 1$ day), time lags can be incorporated (Stefan and Preud'homme, 1993). Here, we use Eq. [1] and [2] to model each instream monitoring location hourly and daily (mean, maximum, and minimum) intervals. We assess the statistical significance ($p<0.05$) from a parametric Student t-Test and the model performance by means of the correlation coefficient (R^2) and root mean square error (RMSE) as

$$RMSE = \left[\frac{1}{n}\int_{i=1}^{n}(S_i - O_i)^2\right]^{1/2} \quad [3]$$

Where n is the number simulated (*S*) and observed (*O*) data. RMSE measures the average magnitude of the error between model prediction and observed data in equivalent units. A lower RMSE indicates better prediction.

We also developed a more complex, multiple linear regressive (*mlr*) model that incorporates both the daily mean Downstream stage (G_L) and solar radiation (R_s) by least-square regression

$$T_w(t) = C_0 + C_1T_a(t) + C_2T_s(t) + C_3G_L + C_4R_S \quad [4]$$

Where the additive combination of these five parameters (C_0 to C_4) is determined by least-squares linear regression. We chose to focus on G_L because of the more static gauge height of effective flow (*e*) over time (see results) due to the stable limestone channel at the Dolan Crossing.

Lastly, we use stepwise (*sw*) linear regression, which iteratively adds and removes predictor variables (T_a, T_s, G_L, and R_s) as the p-value of the F static either improves or degrades the model performance. The final model may include interactions, products and power functions of the predictors. Thus, the *sw* model is indicative of our lowest possible RMSE that empirically predicts T_w given all of our measurement (predictor) variables; however, it is explicitly trained for the observation data and not useful outside these bounds; it is essentially our 'best' achievable fit over our data collection period.

As with most field-based studies, we are only able to monitor environmental data over a relatively short period, which is <1000 days herein. Sensor failures, data loss, and other inconsistencies that come with data collection challenge such research. However, we can supplement our data collection if we can find consistent and statically significant relationships with other long-term climate reanalysis products. The North American Land Data Assimilation System Project (NLDAS) Phase 2 is a land surface model over the conterminous United States initiated as a joint collaboration between federal agencies and university partners (Mitchell et al., 2004). The NLDAS data archive consists of a primary forcing data set, which is used to drive four independent land surface models. This forcing data and model output begin in 1979 and run through the present with a 2-3 day latency. The primary forcings data set consists of 11 hourly climatic variables including precipitation, air temperature, long- and short-wave radiation, and humidity at 2 m (Xia et al., 2012). These data are gridded at 1/8° (~12 km) spatial resolution and available in GRIB format at http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings.

We use the Devils River Hydrologic Unit Codes (HUC) for HUC8, HUC10, and HUC12 to extract by mask T_a and R_s from the primary forcing data, and T_s from the Noah land surface model output. Note the HUC number is inversely proportional to watershed area and a HUC8, HUC10 and HUC12 references 23, 7 and 3 NLDAS cells, respectively. We then averaged each cell into an hourly value and calculated the daily mean, max and minimum T_a and T_s, and daily mean R_s for each HUC size.

Next, similar to our *mlr* $T_w(T_a, T_s, R_s)$ model presented above, we replace our observed weather data with NLDAS T_a, T_s, and R_s and derive optimal coefficients over the study period. Finally, we apply the *mlr* to a 30-year NLDAS record to model T_w at each instream location, creating daily time series of mean, maximum and minimum Tw for trend analysis. Implicitly we assume that the *mlr* developed over a relatively short time is applicable over the past 30-years. This assumption means spring flow, spring temperature, stream cover, etc., are similar. Considering the remoteness of the Devils River, this is more valid than most other rivers in Texas, but it remains intrinsic to our trend analysis.

For each location and forcing variables (T_a and T_s), we determine the temperature anomaly (T_{anom}) or the departure from the long-term (30 year) average where a positive (or negative) anomaly indicates warmer (or cooler) than average temperature. First, the 30-year daily mean, maximum, and minimum were calculated. These data were binned incrementally by day of year (DOY) in intervals (i = 1:30 days) to assess temporal autocorrelation (i.e. verify time-independent data). Once the minimum *i* was determined (i.e. where autocorrelation was insignificant at 1 lag), an annual climatology was calculated by averaging each DOY bin over the 30-year record. The temperature anomaly (T_{anom}) was then determined by subtracting this climatology from each predicted T_w averaged over *i*. We found that serial correlation was reduced ($R<0.2$) at one lag when $i > 5$ but not eliminated (Ljung-Box Q-test, $P<0.05$ for lags of 1*i*, 5*i* and even 10*i*). We chose to bin the data weekly (i = 7) and monthly; the latter is preferred in the climate literature. However, critical above-threshold temperatures are generally less than ~30 days (Section 9), so we are trying to preserve enough data to maintain persistent summer extremes while also minimizing statistical issues in trend analysis.

In essence, the T_{anom} removes covariance and seasonal signal allowing the long-term, linear trend to be calculated with least-squares linear regression and statistical significance ($p<0.05$) from a parametric Student t-Test which assumes the data are normally distributed and the residuals have a zero mean with constant variance. We attempted to minimize these assumptions by T_{anom}; however, we also perform a non-parametric Mann-Kendall test which determines the monotonic significance ($p<0.05$) of any trend which may be linear or non-linear and makes no assumption about the residuals.

2.8 Thermal Habitat Thresholds

Thermal tolerance of fishes is a combination of biotic and abiotic factors that includes acclimation temperature and thermal history (Chung, 2001). We determined the frequency and duration uniform continuous above threshold (UCAT) thermal events from time series analysis (Castelli et al., 2011). Originally applied to environmental flow conditions under a given threshold (Capra et al., 1995; Parasiewicz, 2008), UCATs essentially count events over a given temperature threshold, computing each event duration and taking its ratio to total length of time series. These ratios are shown as the cumulative frequency verse the cumulative duration. We repeated this procedure in 1°C increments for daily maximum T_w at the Upstream and Downstream (end-member) locations using data between June 1 and September 30 from the 30-year models time series data mentioned prior. Inflection or breakpoints between catastrophic and critical threshold days were determined using piece-wise linear regression. We present more detail on the interpretation of this analysis in the Section 3.8.

2.9 Fiber optic distributed temperature sensing (DTS) and thermal Infrared (TIR) imagery; (additional, un-scoped task)

In addition to the work originally proposed, we collected four DTS surveys near Finegan Springs (Fig.3). The four surveys are of varying lengths on 10/20/15 (26 hours), 02/24/16 (40 hours), 9/27/16 (14 hours), and 2/8/17 (25 hours). For each survey, the DTS was positioned in the thalweg below the Finegan Springs complex by unspooling two fiber optic cables: ~400 m upstream and the other ~600 m downstream. The DTS (N4386B, Agilent Technologies, Böblingen, Germany) sends discrete laser pulses down a continuous, looped 2 km optical fiber (BRUsens Temperature 85C mobile, 4.6 mm, Brugg Kabel AG, Switzerland), where it scatters and returns to the detector. The incidental Ramen and Brillouin backscattering allows us to estimate stream temperature along the entire length of the cable (Selker et al., 2006; Tyler et al., 2009). The Agilent DTS allows for a 1 m spatial sampling with 0.1° C. Double-ended DTS measurements were collected every 90 seconds and averaged every 6-minutes at 1-m intervals. Differential attenuation along the fiber optic cable was directly measured using double-ended measurement configuration in the instrument software. The dynamic offset of the DTS was corrected using controlled water baths with ~25 m of cable coiled in each. Two water baths, one ambient and one ice, were constantly mixed using an aquarium bubbler during data collection. Water temperatures in each bath were monitored using platinum resistance thermometers and used to correct raw temperature trace files (Van de Giesen et al., 2012). Corrected temperature vectors upstream and down were concatenated and averaged over the collection period to produce a continuous longitudinal mean (and standard deviation) of 1 m stream temperatures.

During the final DTS survey (2/9/17), we also measured rivers surface temperature using two different unmanned autonomous vehicle-mounted (UAV) thermal infrared (TIR) cameras. In particular, we developed a post processing method to stabilize imagery from the Forward Looking Infrared Systems (FLIR, Wilsonville, Oregon, United States) Vue Pro, an economical microbolometer weighing approximately 100 g. We processed a mosaic of 230 still frame images and compared it with the unprocessed imagery and with ground-based observations of temperature at discrete points. We also compare the stabilized mosaic with another produced by using the FLIR Tau2, a more expensive camera, which uses a proprietary algorithm to stabilize imagery at the time of data acquisition. The latter was collected by colleagues at the Center for Transformative Environmental Monitoring Programs (CTEMPS) funded by the National Science Foundation. Abolt et al. (2018) details this methodology and results more comprehensively.

Although TIR imagery is sensitive only to temperature in the "skin," or top ~100 μm, of the water column, it can reveal useful information regarding the relative size and extent of groundwater plumes originating from springs on or near the streambank, particularly during winter, when groundwater is most likely to be relatively warm and buoyant. Our goal here was to evaluate the utility of using TIR to locate spring seeps along the spring complexes of the Devils River.

3. RESULTS

We present the results (1) over this reporting period beginning with our first field installation in July 2015 through the latest data collection in April 2018 and (2) modeled over 30 years. The former is termed 'Study Period' and the latter 'long-term'. The study period for each temperature monitoring location is presented in Figure 5 indicating that the period of record ranges from ~1000 days for our weather data to ~800 days for more instream data (a summary of monitoring infrastructure is provided in Tables 1,2). We will add to the study period with each future data collections scheduled for fall 2018, spring 2019, and into fall 2019. The modeling will be updated with each new data collection until it is finalized for publication.

3.1 Meteorological parameters (Task 5)

Maximum air temperatures (T_a) reached 40° C each year of the study generally in either July or August (Table 3). Minimum T_a reached freezing most winter months (December, January, and February) with January 2017 being particularly extreme (Figure 6). Late summer and early fall tend to produce more rainfall often in excess of 100 mm. Annual precipitation totaled 739 mm in 2016 and 560 mm in 2017 (Table 3). The thirty year normal (1981-2010) mean annual precipitation is 517 mm at Finegan Spring (PRISM, 2018) making both years slightly above normal. Precipitation was generally less than potential evaporative (PET) demand given the aridity index (AI = PPT/PET) was 0.44 and 0.34 in 2016 and 2017, respectively, which classifies our Devils River observations as semi-arid ($0.2 < AI < 0.5$). However, the monthly AI was greater than one during four months of this study: October 2015, August 2016, December 2016, and May 2017 (Table 3, Figure 6). These periods indicate times when water inputs likely exceed outputs resulting in greater river discharge (next Section).

Both hourly (Figure 7) and daily (Figure 8) meteorological data display seasonal trends in T_a and soil temperatures (T_s), humidity and solar radiation (R_s). The prevailing wind direction is to the northwest in all seasons expect winter (Figure 9), essentially following the topography of the Devils River Canyon. Occasional strong winds came in from the north during winter months (as the jet stream moved west and cold Canadian air rapidly descended down across the central Plains and into the lower Rio Grande region). Such fronts caused dramatic drops in temperatures (T_a)

which is exchanged with the soil and water surface, lowering both T_s and T_w. As will be discussed later, the covariation between T_w and either T_a or T_s is particularly strong at non-spring locations.

3.2 River stage and discharge (Task 4)

Continuous, relative stage recorded at Upstream and Downstream sites is shown on Fig. 10. Discharge measurements and estimated percent of spring discharge comprising Dolan Crossing flow is shown in Table 4. Stream and spring discharge on May 9, 2017 was approximately half of what that measured on Sept. 27, 2016. Discharge rating curves are shown on Fig. 11 and were used to convert relative stage to an estimate of continuous discharge (Fig. 12) (Rantz et al., 1982b). However, several problems were identified in our discharge estimates, particularly with the Upper stage logger. For example, the downstream site is relatively well constrained in a flat, limestone channel with relatively vertical banks with sediment secured by woody vegetation roots. Conversely, due to private land access constraints (as well as the natural characteristics of the stream), the channel at the upstream is not well constrained as would be ideal (i.e., see Rantz et al., 1982a). Here, the bottom of the channel is also limestone; however, a gravel riffle ~50 m upstream of the logger crosses the channel at a ~45° angle and this sediment partially dams the stream on river left. Thus, some of the stream flow could pass thru this sediment and not be included in instantaneous discharge calculations (thus, under-estimating discharge). In addition, this riffle and sediment "dam" could be re-worked in floods—as may have occurred in June 28–29, 2016 when an ~4-ft deep flood passed over the logger (Fig.10; another flood occurred on April 4, 2017; however stage receded to pre-flood level within ~24 hours)—causing the rating curve to be different before and after a flood. At the upper site, ~10 m of ~10-cm long aquatic vegetation was found near the river left shore, which may have introduced some error to instantaneous discharge measurements, despite a qualitatively low percent of total discharge passing through this portion of the stream section (and also explaining why vegetation was able to grow there). A further limitation in the generation of our rating curve is that the stream is "flashy" and floods pass quickly (i.e., apart from a few higher flows, stage seldom varies more than 0.5 m). Thus, no instantaneous discharge measurements were recorded during floods or higher flows shortly thereafter (when a flood occurs, it starts receding within a few hours). Thus, our point discharge measurements were made during a relatively narrow range of discharge. As a result, subsequent analyses were done using relative stage.

3.3 Groundwater levels from shallow and deep monitoring wells (Task 1)

Groundwater monitoring results are presented on Fig. 13. The shallow monitoring well, which is located ~1000 ft from Dolan Creek, shows increases of groundwater level as much as ~35 ft. Increases in groundwater levels of ~10–20 ft. correlate with peaks in discharge measured at the Dolan Creek gauge. However, in the winter and spring of 2017, flows in Dolan Creek cause an increase in groundwater level in the shallow well. In the deep monitoring well, groundwater level remained essentially unchanged, with the exception of ~1-ft increase in ~5 days (August 20–24, 2016) following heavy precipitation (~150 mm in August 2016). Specific conductivity measured in the shallow monitoring well is noisy and does not have a clear correlation with groundwater levels. For both the shallow and deep wells, groundwater temperature is relatively constant.

The static groundwater elevations (Figure 13a) of the shallow (~1445 ft) and deep (1430 ft.) are well above the river at ~1340 ft. The relative difference between these wells (~15 ft) is likely due to some reduction in hydraulic conductivity between Dolan Creek ephemeral recharge and discharge at Finegan Spring. The lack of response in the deeper well, albeit over a short observational window, indicates a less episodic more diffuse recharge source. The elevational head of roughly 100 ft above the rivers provides the hydraulic gradient needed to maintain consistent spring discharge.

We installed the logger in the deep monitoring well on 21 October 2015. Our electric water level sounder measurements noted a depth to water of 464 ft (i.e., groundwater elevation of 1430 ft). Notes written on the windmill tower by the driller state a depth to water of 464 ft on 21 November 1964, which is surprising as it is exactly the same depth to water more than 50 years later. The lack of response to rain events and consistency between these depths implies a very stable water table, and insignificant effects of episodic recharge at this well. Unfortunately, observations in the deep monitoring well ended 1 September 2016 when we could not reinstall the transducer due to what we believe was a partial collapse and/or obstruction in the well's uncased, open borehole. We tried to measure groundwater level using an electric water level sounder tape; however, with 475 feet of tape in the well, (we sounded a partial obstruction at ~446 ft below top of casing), the sounder did not indicate water (which was at 463.35 feet in September 2016). Thus, we re-installed a logger in a second deep monitoring well in August 2017 (at 29.914316°, -100.948691°)

3.4 Temperature and specific conductance (Tasks 2,3)

3.4.1 Spring specific conductance and temperature (Task 2)

Spring monitoring shows that Finegan Springs, Blue Hole, and Rock Art Springs (where data available) appear to have similar behaviors. Specific conductance at the springs (Figure 14a) is relatively constant and decreases following heavy precipitation events, resulting in lower salinities, which is consistent with other karst terranes (i.e., fast-flow recharge paths and slower moving groundwater). Temperature is relatively constant, showing some seasonal fluctuations (±0.5C), and deviations correlate (positively and negatively) with some, but not all, of the larger precipitation events (Figure 14b).

We had some difficulties with the Onset U24 temperature-conductivity loggers. The logger at Finegan Springs was briefly pushed out of the orifice by high flows following heavy precipitation in April 2016, which we remedied by attaching the logger in this and other springs to a rebar hammered into the substrate. In Dolan Creek, logger #20 was installed in ~1.5 ft of water in the USGS gauge pool; however, the epoxy mount failed before September 2016 and is now zip-tied to the USGS staff gauge.

3.4.2 River temperature and specific conductance (Task 3)

River water is slightly fresher (~400 μS/cm) at the Upstream site compared to Dolan Crossing (Figure 15a) since solute is added from the springs where SC is ~500 μS/cm. Rain events tend to decrease SC but only for short intervals. River temperature (Figure 15b) reveals the importance of spring discharge when comparing the difference (Figure 15c) between Downstream and Upstream (ΔT). In winter, T_w Downstream is nearly ~4° C warmer in the winter and up to 3° C cooler in the summer. Spring discharge, which is approximately half of the downstream discharge, is from groundwater inputs with a nearly constant T_w of 23° C (see next section) that buffers temperature extremes well below the complex.

3.4.3 Instream Water Temperatures

Instream T_w of springs (Figure 16a) from Tidbits also shows a very modest seasonal signal which is also in phase with Ta. In other words, spring T_w is highest in July when T_a approaches its maximum, suggesting the flow path is either particularly fast (e.g. no time lag) or the sensors are simply heating with their surroundings. Given the accuracy of these sensors (0.2° C) and the gaps in these time series, we will forgo any major conclusion for now regarding these oscillations.

The Longitudinal Transect (Figure 16b) spans 2800 m between our Downstream Location (0 m) at Dolan Crossing to the Upstream gauging location (2800 m). Additional instream Tidbit sensors are located at 1574 m (#11), 1462 (#12), 842m (#13) and 659m (#14). Similar to Figure 15c, Upstream T_w amplitudes are attenuated by spring inputs the entire length of this transect.

The Upper (Figure 16c) and Lower (Figure 16d) Lateral Transects begin on the eastern bank (spring input side) and progress to the far bank. The middle positions (7,8,9 and 2,4) reach essentially 23° C in summer with little diurnality. In winter, the sensors, regardless of position are highly correlated and much more dynamic. These sensors are on the streambed under variable water depths ranging from 0.5 m on near the banks to 2 m in pools. As will be discussed later, these spring fed rivers can stratify when turbulence is low and cooler water goes to the bottom. In summer, spring discharge drops to the thalweg and river waters stay near the surface. In winter, the Upstream input is colder and dynamically linked to Ta and the entire stream bottom heats and cools rapidly. Spring water would essentially flow on top. We will revisit these data in Section 8.

The measured cumulative distribution functions [F(x)] of spring temperatures indicate nearly constant temperatures of 23° C. The Upstream (Figure 17b) has a wider distribution both laterally with more extreme Tw variations on the far bank (#10) than the Downstream (Figure 17c) transect. The F(x) for both Ta and Ts (Figure 17d) are essentially buffered by thermal capacities of water and inputs from the springs as shown longitudinally in Figure 17e. Finally, the short transect down Dolan Creek ending in the lower Devils River (20 – 17) shows much cooler Tw upstream (Figure 17f).

The daily instream temperature amplitudes (i.e., diurnal range in temperature) are also presented for T_a, T_s, DS_{20}, and BH_{16} (Figure 18a) to illustrate the buffering capacity of water at the Downstream location against the extreme amplitudes of T_a which can exceed 20° C per day, down to T_a (~10° C). Note, BH16 was the only spring location to show any diurnal amplitude. Similarly, the Downstream Lateral Transect (Figure 18b) shows greater amplitudes in the shallower near- (#1) and far-banks (#5) from the springs while the deeper locations in the thalweg (#2 and 4) have much lower amplitudes of 2° C. Depending the condition, the ideal environmental Tw for biota should exist provided spring discharge remains consistent.

3.5 Instream water temperature modeling and long-term trends

An apparent correlation between air temperature (T_a) and water temperature (T_w) was present throughout the Devils River in all non-spring locations. Qualitatively, T_w generally showed a strong seasonality overprinted with a random diurnal variability, which mimics changes in T_a. Generally, there is some lag time between T_a and T_w (T_s also lags behind T_a). Using hourly data, we ran a correlation matrix from -24 to +24 hour lags preserving the highest correlation coefficient (R) and its lag periods (Figure 19). The correlations with T_w were particularly high ($R > 0.8$) for both T_a and T_s but at nearly all locations it was higher with T_s (Figure 20a). The lag between T_a and T_w at nearly all instream locations was 2 to 3 hours and between 0 to -1 lag hours for T_s (Figure 19b). Note, negative lags indicate earlier arrival at one location than another. Correlation between all instream sensors was particularly high for all but the Dolan Transect (#17-20). Note that spring locations were already removed due to low correlations ($0 < R < 0.4$). Table 5 presents the coefficient of determination (R^2) between all instream T_w and T_a at both hourly and daily (mean, maximum, and minimum) time scales and each locations temperature sensitivity (*B* from Eq. [1]). A higher *B* indicates greater sensitivity to thermally driven heat advection while a lower *B* is likely more indicative of groundwater inputs. Spring locations had much lower *B* values, typically near zero, while Upstream had the highest *B* for all metrics (Table 5). In general, Ta can explain over 70% of the variability in T_w although each location has a unique relationship.

We use this relationship [T_w(T_s, T_a, R_s and G_L)] to develop four predictive models of T_w based on linear regression with either T_a or T_s, and a multiple linear regression (*mlr*) and a stepwise (*sw*) non-linear models that use a combination of all four variables. At hourly time steps, averaged over all instream locations, the $T_w(T_s)$ produced a lower RMSE (1.2° C) and higher R^2 (0.74) than $T_w(T_a)$ which is likely due to the reduced time offset in T_s (Table 6). At daily times steps, combining T_a, T_s and R_s into the *mlr* model resulted in a mean RMSE of < 1° C for daily mean and minimum T_w, with daily maximum being slight over 1° C. The addition of downstream river stage (G_L) improved our model, reducing the RMSE by ~0.1° C. The *sw* regression reduced the RMSE to 0.63° C and R^2 of 0.91 for daily mean Tw; this is essentially the best we can do using our meteorological data. Given the 0.5° C accuracy of our temperature sensors, these are good predictions but are also limited to our study period. If we can find similar correspondence to longer duration measurements (e.g. NLDAS climate data), we can significantly increase our time scale and have predictive capabilities that are ~ 1° C.

First, we compare each NLDAS variable aggregated to HUC_{12}, HUC_{10} and HUC_8 against our metrological observations. Regardless of aggregation size, the NLDAS T_a has very good correspondence to our measured T_a (Figure 20a). The HUC_{12} daily mean T_a has an adjusted R^2 of 0.96, a RMSE of 1.57° C, a slope of 0.95, and an intercept of -0.1° C. For T_s, our observations were generally warmer (+4.6° C), again regardless of HUC size (Figure 20b). For example, HUC_{12} had an adjusted R^2 of 0.92 and RMSE of 2.1° C. The largest difference was seen for daily mean R_s (Figure 20c) with NLDAS biased consistently higher (+1.6 MJ m^2 d^{-1}) and occasionally considerable greater. This bias is not particularly surprising given our station is located in the valley bottom and likely shaded by the surrounding hills. The HUC_{12} has a RMSE of 4.0° C and an adjusted R^2 of 0.71, which despite the bias, may prove to be a better watershed representation of R_s than our measured data.

Next, we replaced the predictor variables (e.g. T_a, T_s, R_s) based our weather station data with NLDAS aggregated HUC_{12} values and developed a new coefficient for Eq. [1] and [2]. Note we do not have river stage (G_L) data available, despite its improvement to our model. The performance of each model is presented in Figure 21 using a cumulative RMSE for the two linear models plus the *mlr* model using all three predictors. Much like our prior results, T_s produced lower RMSE values than T_a; however, the *mlr* clearly outperforms both. Regardless of daily T_w mean, maximum, or minimum, the *mlr* reduced the higher RMSE values (Table 6). Thus, our *mlr* model appears robust over the ~1000 days of available observations used to validate it. We present a summertime snapshot of 2017 modeled daily maximum T_w results using NLDAS T_a, T_s and *mlr* models from the Upstream to Downstream location (Figure 22). The models tend to capture the warming trend until July, then a frontal pattern in early August drops temperatures and finally fall arrives in late September. Given our assumptions, we can now produce 30-years of T_w data for each instream location using the HUC_{12} *mlr* model.

Annual and season cycles resulting from the earth's orbit around the sun and its tilted axis of rotation complicate the distinction of trends even in long-term time series. We use the weekly and monthly anomalies, calculated as the residual between our observation and the 30-year mean to reduce the serial autocorrelation of our *mlr* modeled T_w data. These residuals also tend to have a normal distribution and a zero-mean, which improves the robustness of least-squares linear regression for trend detection. A temperature anomaly is the departure from the long-term mean and can be either positive (warmer) or negative (cooler) than the reference value (Figure 23). Of note, both the daily maximum T_a and T_s increase by 0.35° and 0.30° C/decade, respectively over the HUC_{12} area. Given our models are based on NLDAS HUC_{12} predictors; it is not surprising that our T_w also shows increasing trends over the past 30 years. Assuming spring T_w and discharge have remained consistent, instream locations with greater temperature sensitivities (*B*) show higher trends for increasing T_w. We illustrate this with our highest *B* found Upstream (Figure 23c) and a lower *B* from the Downstream (Figure 23d); the trends were 0.156° and 0.119° C/decade, respectively. We found that all of the correlations to daily maximum T_a, T_s and predicted T_w were significant ($p<0.05$) based on either t-Test or Mann-Kendall trend test (Table 7). No significant trend was detected for daily minimum and only daily mean T_a and #19 at the Dolan Creek outflow were significant based on Mann-Kendall tests. Given that the springs buffer this system from temperature extremes, any change to spring discharge could significantly amplify the climate change signal (0.35° C/decade).

3.6 Uniform Continuous Above-Threshold Results

The magnitude, frequency, and duration of instream T_w was quantified using uniform continuous above-threshold (UCAT) which determines the cumulative time waters are above a given temperature threshold. From a given T_w time series, the cumulative duration over an explicit daily maximum threshold temperature (e.g. 30° C) totaled in proportion to the total number of days. Here, we restrict our total days to June 1 to September 30 over the 30*years of simulated daily maximum T_w, which equivalent to persistent maximum T_w in Castelli et al. (2011). The UCAT curves are essentially a three dimensional space of duration (x-axis), frequency (y-axis), and maximum daily T_w (z-axis) where common verses uncommon events are denoted by rapid changes in slope from ‘persistent’ to ‘catastrophic’ (Parasiewicz, 2008) as illustrated in Figure 24.

As noted, the Upstream location generally has warmer summer temperatures than the Downstream given that ~50% of the river flow is from spring discharge. The summertime daily maximum T_w at the Upstream (Figure 25a) is generally above 26° C but seldom greater than 31° C, whereas the Downstream (Figure 25b) is seldom above 29° C. To evaluate persistent and catastrophic conditions, we focus on the extremes temperatures and their inflections in the duration curves (Figure 24), which mark periods of rapid change in these distributions (Castelli et al., 2011). For Upstream (Figure 25c), it is persistent to have T_w at 30° C for 12 days and catastrophic at 42 days. For Downstream (Figure 25d), critical thresholds are reached when T_w is 29° C for 12 days and catastrophic at 37 days. These results are also presented in Table 7. Without direct measurements of species-dependent lethality from laboratory experiments or field data, these thresholds can be reasonable criteria for management action. Ongoing research by others on such threshold for *P. popeii* will generate such data.

3.7 Fiber optics distributed temperature sensing (DTS) and the thermal infrared (TIR) data collection; (additional, un-scoped task)

Four DTS survey were conducted under two different conditions: (1) Warm Surveys (20 October 2015 and 28 September 2016) when river water was generally warmer than spring waters (~23° C) and (2) Cold Surveys (2 February 2014 and 8 February 2017) when river waters (~15° C) were colder than springs. We originally chose these periods to have the greatest differences in T_w to exemplify the surface/groundwater mixing signal. In all situations, the DTS cables was in the thalweg and resting on either the limestone bottom or perhaps vegetation. The upstream end (distance ~400 m) extended well above Finegan Springs (Figure 3) and ended (distance ~600 m) upstream of Blue Hole. Collections times varied but all were sampled over the course of at least one diurnal cycle with the goal to define spring inputs, which should be areas of low variance over a 24-hr period.

In both warm situations, we found strikingly low variance along the entire 1 km of cable (Figure 26a and 26c). Regardless of position or time of day, the DTS temperatures were essential 23° C or equivalent to spring waters. Conversely, during our first Cold Survey (Figure 26b), DTS temperatures were much cooler upstream (fiber section 200—400 m) then warmed to 17° C below Finegan and Blue Springs, yet all data show much higher variance of ± 3° C. Similarly in 2017's Cold Survey (Figure 26d), we observed a warming below 100 m with cooler temperatures upstream and high variance along the entire cable length. The DTS temperature anomaly (Figure 27) is slightly warmer upstream (>100 m) during both Warm Surveys but essentially very constant along the entire cable while Cold Surveys are nearly 1° C warmer <100 m.

During our final Cold Survey, we also collected thermal infrared temperature (TIR) data using an unmanned aerial vehicle (Figure 28; see Abolt et al., 2018 for study details). TIR captures the skin temperature of the water. Clearly, cooler water upstream mixes with two warmer spring inputs and mixes downstream. The DTS distance of 400 m upstream is in these cooler river waters. The warmer spring which enter water with little mixing and essentially floats atop the river water and mixing only modestly. Considering that the DTS thalweg temperatures show high diurnal variance (i.e. river water), this would imply instream stratification. Conversely, the Warm Surveys show little diurnal variation implying the spring waters are remaining in the thalweg and not fully mixing within this reach, albeit certainly mixing below Dolan Falls.

This stratification is notable at the Upper transect (Figure 29a) just below the Finegan Spring complex when the spring-side bottom temperatures (#6) remains constant at 23° C and shows very little oscillations until the first large flood pulse arrives on 11 November 2015. This event mixes waters on the stream surface, which are now cooler than 23° C. This surface water temperature signal remains on the river bottom all winter, as noted in 2016 Cold DTS survey (20160224; Figure 26). The first Warm Survey (20151020) was synchronous with a period when all the instream temperatures converged. The Lower Transect (Figure 29b) is approximately 150 m downstream of the Upper Transect. The bottom T_w records are warmer until a modest cold front arrives a few days prior to our second Warm Survey (20160928) which homogenized T_w of the DTS measurement period at the Lower Transect. Unfortunately, the Upper Transect sensors malfunctioned during this DTS survey. However, it seems plausible that thermal stratification in the Devils River is likely between Finegan Springs and Dolan Falls.

4. DISCUSSION

4.1 Effects of Groundwater and Surface Water Development

Throughout the western U.S and Texas, groundwater development has dried or substantially reduced flows in other groundwater-dependent, spring-fed streams (Brune, 2002; Hoagstrom et al., 2011; Unmack and Minckley, 2008). Groundwater pumping of the Edwards-Trinity (Plateau) Aquifer west of San Antonio correlates with reduced flows of Comal and San Marcos springs (RECON Environmental Inc. et al., 2012). For example, during the drought of the 1950s, groundwater extraction increased, resulting in the drying of Comal Springs 1956 and reduced flows in San Marcos Springs (Votteler, 1998). Aquatic habitats at the sources of the Comal and San Marcos rivers host several currently threatened and endangered species and those awaiting decision to potentially receive protection under the Endangered Species Act (Blanton & Associates Inc., 2018; RECON Environmental Inc. et al., 2012). In response to threats to spring flow-dependent aquatic habitats from groundwater pumping, litigation to protect spring flows and maintain habitat resulted in the creation of the Edwards Aquifer Authority (EAA; Sierra Club v. Babbitt, 1993), which oversees groundwater extraction in Uvalde, Medina, and Bexar counties and a portion of Comal, Caldwell, Guadalupe, and Hays counties. In addition, groundwater conservation districts oversee pumping in Crockett, Edwards, Kinney, Medina, Schleicher, Sutton, and Uvalde counties.

Despite protections to springs between San Antonio and Austin, groundwater extraction in much of the Devils River watershed is not regulated. Because a groundwater conservation district has not yet been formed by an act of the Texas Legislature, landowners in Val Verde County can pump unlimited quantities of groundwater, regardless of potential reductions in discharge of springs maintaining the Devils River. Taking advantage of this gap in groundwater regulation, companies have proposed pumping groundwater and exporting it out of Val Verde County (Gleason, 2013; Satija, 2014). Furthermore, some landowners have recently begun selling groundwater for hydraulic fracturing in the Val Verde Basin (Smith, 2018a). In light of possible threats to springs and lack of regulation, a groundwater model has been developed to forecast aquifer depletion resulting from proposed Val Verde County groundwater development projects (Green et al., 2014; Toll et al., 2017a). Because groundwater and surface water are interconnected in the Devils River watershed (Green et al., 2014), large-scale groundwater pumping proposed for Val Verde County threatens to decrease spring flow to the Devils River and reduce habitats for *D. diaboli* and other species of conservation interest—particularly during droughts—because pumped groundwater would otherwise have supplemented baseflow in the stream.

4.2 Historical hydrogeologic and hydrologic data (Task 6)

Effective management strategies for a groundwater-dependent stream such as the Devils River must be informed by what the river and associated aquifer have already experienced. Thus, we present hydrographs of historic groundwater level (Figure 30), surface water discharge (Figure 31) over our study period and the full time series data (Figures 32). One obvious feature of the groundwater elevations is the decreasing elevation down drainage (Figure 30a–30e). However, while our shallow well and TWDB 5463401 are extremely dynamic with many feet of groundwater level change, the other wells we reviewed have much more consistent groundwater level records. In addition, the unconfined TWDB well 7001707, which is located ~1500 ft east of the Devils River and within Leon Spring Canyon, shows groundwater level fluctuations of only inches, despite its proximity to streams.

One basic observation in the recent (post-2014) streamflow data is that this is a "flashy" stream where high-flows are rare towards the headwaters and in the upper basin (i.e., Cauthorn Ranch, Baker's Crossing) and become more prevalent as the drainage area increases downstream (i.e., at Pafford Crossing) and also within tributary streams (i.e., Dolan Creek and Dry Devils).

The goal of separate, ongoing work by The Nature Conservancy (Smith, 2018b) is to evaluate historic discharge data using Indicators of Hydrologic Alteration (IHA) software (Richter et al., 1996) to determine how high-flows and baseflow may have changed throughout the historic record. However, the period of stream flow record available for study is clearly not long enough to assess pre-groundwater development flows (IBWC collection began circa-2005). Nevertheless, this IHA evaluation may be useful to assess the streamflow regime under relatively current pumping conditions. In addition, visual inspection of the Baker's Crossing and Pafford Crossing records suggest that baseflow may be declining; however, this may be a result of faulty stream gauges.

4.3 Comparison of data with other studies (Task 7)

We make inferences as to how Devils River streamflow and associated aquatic habitats may change because of proposed groundwater development in Val Verde County. The numerical groundwater model of Toll et al. (2017b) found that the current estimate of groundwater pumping in the Devils River watershed (48,000 m^3/day; 14,000 acre-ft/year) was likely responsible for drying springs in the upper watershed. The simulations also found that a hypothetical wellfield ~10 mi (17 km) upstream of Pecan Springs pumping 1,817 m^3/hr (8,000 gallons/min; 12,900 acre-ft/yr) would dry additional springs providing groundwater inputs to the river and move the current stream's headwater further downstream.

4.4 Implications for Maintaining Instream Flows and Conserving Aquatic Habitats

Within this regional, historic hydrogeologic context of streamflow, groundwater movement, and spring discharge, Veni (1996) postulated that the Devils River, when it flows, recharges the aquifer ~32 km to the north of Finegan Springs. This recharged water then later provides groundwater to the spring complex. The farthest upstream IBWC gauge (Cauthorn Ranch; Figs. 31a, 32a) recorded a flood in June 2016, which is only time the stream flowed at this location during our study. Then, our monitoring revealed elevated spring discharge peaking in September 2016 (Fig. 12b), which suggests a possible 3-month travel time from the upper Devils River to Finnegan Springs with a groundwater velocity in aquifer ≈355 m/day. However, Dolan Creek—which is ~1,250 feet from Finegan Springs at its closes point, and thus, a more likely location for groundwater recharge to occur which then discharges in the springs—flowed several times, starting in March 2016. This time corresponds with when discharge at Finegan Springs began to rise (Fig. 12b). Flows in Dolan Creek essentially stopped for the 2016-2017 winter after last flowing in September 2016 (Fig. 14d). The winter of 2016-2017 also coincides with reduced discharge at Finegan Springs (Fig. 12b). This evaluation of flood flows in Dolan Creek, Devils River discharge, and Finnegan Springs-Blue Hole spring discharge suggests that groundwater recharge from Dolan Creek may provide a greater portion of spring flows than recharge occurring in the Devils River further upstream. Regardless, groundwater pumping throughout Val Verde and other counties in the Devils River watershed should be managed so that groundwater levels in Edwards-Trinity (Plateau) Aquifer do not experience drawdown, which changes discharge and temperature outside ranges aquatic biota need to survive. For our study section, this may be particularly important in the Dolan Creek watershed so that flows, when they occur, result in groundwater recharge instead of “filling up” cones of depression in the aquifer (i.e., pumping-induced groundwater level declines). Longer groundwater flow paths from recharge areas to springs, as suggested by Veni (1996) are surely important at a regional/county scale; however, additional monitoring data—such as a monitoring well network over a larger area—may be needed to elucidate these streamflow-groundwater-spring connections. Regardless, groundwater must be managed to maintain spring flows in the Devils River drainage.

How to manage groundwater and surface water as a linked resource and preserve aquatic habitats, however, remains an important policy question being played out across the U.S. and globally today (Currell, 2016; Gleeson and Richter, 2017; Harrington et al., 2017; Rohde et al., 2017). For example, the San Pedro River watershed east of Tucson, Arizona is another highly groundwater-dependent stream and one of the last free-flowing desert streams in the United States (Barlow and Leake, 2012; Leake and Pool, 2010; Stromberg et al., 1996). In the San Pedro Valley, groundwater and surface water are connected. Thus, similarly to the Devils River watershed, wells may pump groundwater that would otherwise flow to the river—and eventually pull water out of the river towards well fields, resulting in reduced streamflow or drying the river. Another recent example of surface water and groundwater connection is, the Texas-New Mexico Supreme Court case which highlights the interstate dispute over how groundwater pumping may have reduced Rio Grande flows (Garrick et al., 2018). In addressing limitations of groundwater policies protecting groundwater flows to streams, California’s 2014 Sustainable Groundwater Management Act (Rohde et al., 2017) also includes a unique provision that groundwater be pumped at rates that avoid undesirable results, which include “depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water”. How legal and policy actions translate to practical management strategies—particularly for streams where groundwater and surface water are connected—continues to be a goal of natural resource management decision makers.

In the case of the Devils River, protecting streamflow requires quantifying how groundwater pumping may in fact affect the river’s discharge. Importantly, Toll et al. (2017b) suggest that no amount of pumping is “safe” in terms of how it may impact the river. Thus, improved forecasts of the possible effects of pumping on discharge and how the type and location of monitoring wells is selected is required to identify potential deleterious groundwater declines before they critically reduce spring discharge. To this end, recent studies have investigated how best to monitor highly groundwater-dependent streams and ecosystems. For example, Currell (2016) recommends that protecting groundwater-fed streams requires that the source aquifer for springs be established. The groundwater modelling of Toll et al. (2017b) informs this question, particularly as its results are consistent with groundwater throughout the Devils River, Dolan Creek, and Dry Devils watersheds providing important flows to springs. What is needed, then, are forecasts of the timing and extent of groundwater declines and how they may affect spring discharge. In a similar case, Harrington et al. (2017) recommend that monitoring wells be located between a groundwater discharge zone and well fields so that an early warning of possible pumping effects on springs may be noted. To provide this information, Harrington et al. (2017) suggests a groundwater model be used to "determine the amount of upgradient drawdown that corresponds to allowable reduction in spring flow. …" Thus, groundwater models may be used to identify trigger levels at specific monitoring locations upgradient from springs. While additional simulations of possible wellfield locations and pumping rates are needed to assess the timing and extent of possible spring dewatering, the groundwater model of Toll et al. (2017b) could also be used to design a monitoring well network to provide early warning of drawdown caused by pumping which could ultimately reduce spring flows to Devils River. The results of this modeling could then be used to inform "spring triggers" as part of a groundwater monitoring network ultimately set up as part of a future groundwater conservation district, or established by another organization (e.g., TNC, TPWD, etc.).

4.5 Translating Science to Management Decisions

The hydrologic data generated by this study can be directly used by TPWD and FWS to implement key parts of the Devils River Minnow Recovery Plan, in addition to the Recovery Plan for *P. popeii*, when it is completed. Recovery actions include a Groundwater Management Plan for stream flow protection (Action 1.4.3) that ensures protection for the Devils River habitat and its watersheds (Action 1.4.2), which groundwater modeling by Toll et al. (2017b) should include the entire Devils River watershed. Thus, management actions by a future groundwater conservation district in Val Verde County may not have sufficient spatial extent to be entirely effective. A GCD in Val Verde GCD, if and when one is created, should collaborate with GCDs in neighboring counties to establish annual groundwater development volumes that maintain spring flows contributing to the Devils River. In support of this goal, this study monitored stream flows in the Devils River (Recovery Action 1.4.4) to provide an estimate of current spring discharge rates. Our monitoring of water temperature and conductivity provide a snapshot of current conditions in *D. diaboli* habitat (Recovery Action 1.4.5). The results of this study will be conveyed to state, federal, and local stakeholders to increase opportunities for successful aquatic habitat conservation for a suite of species in the Devils River.

4.6 Assumptions and Limitations of this Approach

This study represents an important first step to improve our understanding of Devils River hydrogeology and improve conservation outcomes. However, our study does have some important limitations. For example, meteorological data are only collected at one site in the watershed, which may result in high-intensity, localized precipitation being missed. We have characterized continuous stream stage at two sites and collected instantaneous discharge; however, these discharge measurements are biased to low-flows when it is safe to wade into the river. Furthermore, the river is so flashy, that it is difficult to arrive at the river after a heavy rain is detected to conduct discharge measurements. Thus, we had to truncate higher flows outside the range of our measurements from the calculated discharge record. In addition, only one of our two stream pressure transducer locations was satisfactory. We have confidence in the Downstream site, which is in a regularly shaped, rock-bottom channel; however, the Upstream site is situated adjacent to a riffle and includes dozens of feet of gravel substrate and aquatic vegetation, which may adversely affect discharge measurements. In terms of groundwater levels, we had good luck at the shallow monitoring well; however, the partial collapse of the deep well interrupted this record and we had to relocate this sensor to a different well. Our empirical models relating Tw to other environmental data assume watershed, surface water flows, and spring discharge remain similar to the training periods.

Regarding our stream and spring temperature, stage, and conductivity loggers, we had several issues common to field work, including:

(1) we were unable to find some loggers in the lateral transects, which may have moved during floods or been obscured by aquatic vegetation growth;
(2) some loggers affixed to rocks using waterproof epoxy were lost or had to be re-affixed;
(3) spring loggers may have been pushed out of spring vents during high discharge;
(4) one stream pressure transducer was ripped off its mount during a flood and subsequently found by a researcher from another university;
(5) Specific conductance measurements are prone to fouling by chemical and organic deposition on electrodes which can results in drift and bias;
(6) Monitoring wells were few and far, impossible to access after rain, and requiring significant effort to reach in general;
(7) Historic groundwater level and stream flow records by IBWC, TWDB, and USGS are short or truncated, complicating analysis;
(8) DTS fiber was not permanently installed and was difficult to deploy in the same location every survey;
(9) The weather station is located in a valley which results in limited open-sky and valley-derived wind patterns that may not be related to the meso-scale meteorological patterns;

4.7 Ongoing and Recommended Future Studies

This study is a starting point from which several ongoing studies may build to develop the science needed for successful conservation of the Devils River and its aquatic habitats.

4.7.1 Improving rating curve to calculate discharge from stage

Additional instantaneous discharge measurements are needed to improve the rating curve (ongoing under a separate contract). While it may not be feasible, it would be good to move the Upstream pressure transducer to a location where the channel is more regularly shaped and better constrained by channel banks that are "armored" with woody vegetation or limestone.

4.7.2 Monitoring Hydrology at Riffles Where P. Popenaias Has Been Found

Three In-Situ Rugged TROLL 100 (In-Situ, 2018) temperature-level loggers were installed (under a separate contract) on March 20, 2018 at the water-substrate interface at three riffles where *P. popeii* has been detected (three loggers per riffle, including near the upstream site, at the head of the pool Finegan Springs, and ~1 mi downstream of Dolan Crossing). The loggers are recording substrate temperature and stream stage at 30-min intervals. This ongoing data acquisition, which was funded under a separate grant, may be used to inform instream flow recommendations by understanding variability in water depth over the riffles and the effects of thermal buffering under a suite of discharge conditions. The results of this study may be integrated with ongoing reasearch by Charles Randklev at Texas A&M Unversity (similar to Gates et al., 2015; Maloney et al., 2012) determining how thermal tolerances and temperature thesholds may affect Texas Horneshell reproduction and survival. The results of this study may also be used to inform development of conservation actions to mitigate potential threats to *P. popeii* identified in the Texas Hornshell Species Status Assessment (SSA, FWS, 2016), which include:

1. <u>Water quality impairment</u>. For example, an increase or decrease in water temperature and resulting potential reduction in dissolved oxygen which may result from changes in spring flows. Unionid mussels such as the Texas Horshell prefer thermally-buffered stream segments, particularly during summer or drought low-flows (Maloney et al., 2012). However, reduced springflows could adversely affect thermal buffering and potentially eliminate aquatic habitats for Texas Hornehsll (Maloney et al. 2012).
2. <u>Increase in Fine Sediment.</u> Groundwater depletion may also change the streamflow regime and alter or reduce the magnitute and frequency of high-flow pulses which potentially "flush out" fine sediments from riffles and cracks in limestone which Texas Hornshell occupy.
3. <u>Loss of Flowing Water.</u> As suggested by groundwater modeling of Toll et al. (2017b), groundwater production has decreased the flowing length of the Devils River and additional pumping may further reduce the perennial stream extent, particularly in the upstream reaches. It is possible that extensive groundwater development could begin to increase the frequenting and length of desiccation of the riffle at the upstream monitoring site observed towards the start of this study at the tail end of the 2011–2013 drought (Robertson, 2014). Similarly, this drying may also increase predation, as animals such as raccoons have easier access to mussel beds, as was observed 2011–2013.
4. <u>Climate Change.</u> The evaluation of climate changes since 1980 and the effects of air temperature on Devils River water temperature provide important insights into water temperatures under future climate conditions. We have found that an increase in air temperature is responsible for much of the changes in water temperature.

Because Texas Hornshell evolved at the same time as *D. Diaboli* and the larger native fish communtiy, it is reasonable to assume that increasing the understanding of *P. popeii* habitats (FWS, 2016, 2018) would also benefit the Devils River Minnow and other Devils River species of greatest conservation need (SGCN; TPWD, 2012, 2014).

4.7.3 Airborne Bathymetric and Topographic Lidar Survey

Airborne Light Detection and Ranging (Lidar) bathymetric and topographic survey data was acquired during last week of March 2018. Devils River and Dolan Creek water depth and water surface elevation was mapped, in addition to land surface elevation within a buffer of ~100 m surrounding the Devils River from Lake Amistad to its headwaters ~70 km upstream (to 10 km south of Juno, Texas; essentially the entire extent of the Devils River shown on Fig.2). Sensors included Airborne Hydrography AB "Chiroptera I" Lidar using green laser for bathymetry (wavelength=0.515 µm) and red laser (near infrared, wavelength=1.064 µm) for topography. Visual aerial imagery was collected with a Hasselblad 50 MB camera. Sensors were flown on a Texas Department of Transportation (TxDOT) Flight Services Cessna TU206G (N147TX). Integration of airborne with kayak-mounted GoPro camera and fish finder-type sonar data will be used to create bathymetric and terrestrial digital elevation models (DEM) of the perennial portion of the Devils River. The bathymetric and topographic Lidar DEMs will provide a primary input dataset to aquatic habitat models (to be completed by others), which can be used to assess habitat suitability for a suite of aquatic species (including *D. diaboli* and *P. popeii*) under a range of instream flow scenarios. The Lidar survey data may also be used to potentially classify stream mesohabitats and map aquatic vegetation.

4.7.4 Monitor headwaters of Devils River and Dolan Creek

The Finegan Spring complex was approximately 50% of the Devils River discharge at Dolan Crossing. The upstream waters were moderated by these inputs; however, these surface waters are also derived from groundwater discharge at Pecan Springs some 50 km upstream. Groundwater development is more intense in the Pecan Springs area. Therefore a potential for downstream impacts is likely large and data gaps clearly exist in these headwaters. Ideally, a monitoring program would include up and down stream stage recorders at Pecan Springs. A rating curve would need to be developed to determine spring discharge. Temperature and SC would be needed in the spring and upstream/downstream to determine mixing. Lastly, any abandoned groundwater wells could be instrumented to inform models down the road. Weather data is being recorded in Juno by TWDB, but more is better.

While not currently funded, it would be good to expand groundwater monitoring to the headwaters of Dolan Creek, given the high likelihood that Dolan Creek flows cause groundwater recharge which discharges in Finegan Springs and Blue Hole.

4.7.5 Groundwater modeling to inform groundwater management that protects streamflow

Further work is clearly needed to quantify the effects of various possible pumping schemes on flows to the river. In terms of how declines in streamflow resulting from future groundwater pumping may affect aquatic habitats of *D. diaboli* (and other species of conservation interest), we are currently unable to ascertain exact results. However, using the available results of Toll et al. (2017b) and the results of the habitat model by Hardy (2014) we can forecast with reasonable certainty that additional groundwater pumping will reduce physical habitats for the native fish community. In fact, Hardy (2014) states that "Decreased spring flows as a result of increased groundwater withdrawal could have a negative impact on the quantity of habitat available to native fish species in this system." Thus, additional future work is needed to expand groundwater and hydraulic modeling to assess in more detail how groundwater development may reduce aquatic habitats.

5. CONCLUSIONS

Several important conclusions resulted from this study, including:

- Increases in groundwater levels of ~10–20 ft correlate with floods in Dolan Creek (USGS 2014) and increases in spring discharge. Thus, managing groundwater pumping in the Dolan Creek watershed—in additional to regionally—is clearly essential to conserving spring flows, instream flows, and aquatic habitats for species of state and federal conservation interest.
- River water is slightly fresher (~400 μS/cm) at the Upstream site compared to Dolan Crossing (Figure15a) since solute is added from the springs where SC is ~500 μS/cm. Rain events tend to decrease SC but only for short intervals.
- Spring discharge, which is approximately half of the downstream discharge, is from spring inputs with nearly constant T_w of 23° C.

- Spring T_w is highest in July when T_a approaches its maximum, suggesting the flow path is either particularly fast (e.g. no time lag) or the sensors are simply heating with their surroundings.
- Devils River temperature measured in lateral transects show that the middle, deepest portion of the river is essentially 23° C (a similar temperature to springs) in summer with little diurnalality. In winter, stream temperature, regardless of location in lateral or longitudinal transects, is highly correlated and much more dynamic (i.e., all sensors record similar temperatures and have larger temperature fluctuation in winter than in spring).
- Springs discharge waters with a nearly constant temperature mix with surface waters that vary diurnally and seasonally providing important thermally-stable habitat throughout the year. Variance in stream temperatures and lateral mixing can also help determine spring discharge. Spring flows in our study area provide up to 71% of Devils River discharge at Dolan Crossing, indicating that managing groundwater to maintain spring flows is essential to conserving instream flows on the Devils River. Thus, spring flows provide critical thermal buffering and maintain instream flows, particularly during summer and droughts.
- Meteorological data—particularly air temperature—can be used to understand (1) effects of daily and seasonal ambient temperature conditions (noted by Kollaus and Bonner 2012) on water temperature on *D. diaboli* habitat.
- Increasing air temperatures have been buffered by consistent spring temperatures over the past 30 years; however, any perturbation to either spring discharge or temperature could exacerbate warm water conditions.
- In conjunction with instream thermal data and DTS, results may be used to infer spatial distribution of thermal preferences of aquatic organisms and inform habit models.
- Continued development of groundwater models is needed to accurately forecast how given groundwater pumping scenarios may affect spring discharge and resulting stream flows.
- Aquatic habitat models, informed by ongoing biological studies evaluating thermal tolerances for *P.* popeii, need to be developed to assess effects of various instream flow scenarios on the target species. To this end, ongoing processing of bathymetric and topographic Lidar, visible imagery, and sonar bathymetry acquired by BEG in Spring 2018 for ~70 km of the Devils

River and the perennial reach of Dolan Creek may eventually be used as a primary input to these future physical habitat models.

5.1 Monitoring recommendations

One clear result of the study is the spring discharge is the only thermal refugia for aquatic life in the Devils River. Thus, natural resource managers cannot wait until springs dry up to reactively manage groundwater pumping. In addition to continuing to monitor the shallow monitoring well (which is too close to springs to make an effective “sentinel” well per Harrington et al., 2017), we suggest expanding the well monitoring network throughout Val Verde County and the Devils River watershed. New monitoring wells are especially important in upper Dolan Creek drainage, given the importance of Dolan Creek recharge in maintaining springs in the study area. Given the hypothesized longer-distance groundwater recharge flow paths of Veni & Assoc. (1996) from the Upper Devils River Basin to Finegan Springs, additional monitoring wells throughout the Upper Devils River basin should be considered. It may also be prudent to include monitoring wells in the Dry Devils River watershed, which flows infrequently but may have important groundwater flows paralleling the ephemeral stream channel (per findings of Green et al., 2014). Stream discharge (to deduce spring discharge) should be continued, alongside existing and new groundwater monitoring data.

Per Harrington et al. (2017) it is important to “set [groundwater] trigger levels at monitoring locations some distance upgradient from GDEs [groundwater-dependent ecosystems] that maintain the necessary condition or threshold…that supports the biological objective…” To this end, the collection of additional hydrogeologic data over a larger area may allow us to deduce the location of a possible “trigger well” further afield from the study area in which regional-scale fluctuations in groundwater level is well correlated with longer-term spring discharge trends. Once ongoing field data collection of stage and substrate temperature in *P. popeii* riffles is complete, it can be integrated with laboratory study results of the species’ thermal tolerance. This biological information can then be used to identify “the biological objective(s)” and “identify the hydrologic condition or threshold that supports the biological objective” to enable integrated groundwater-surface water management (following the monitoring schema of Harrington et al., 2017). This biological data, in addition to continued discharge and temperature data collection can be used to develop physical habitat models. Alongside continued collection of groundwater levels in the study area and the larger watershed, the groundwater model of Toll et al. (2017b) could be used "to determine the amount of upgradient drawdown that corresponds to that allowable effect" and "account for time lags between pumping and declines in discharge" (following the approach of Harrington et al., 2017). Thus, continued collection of hydrologic and hydrogeologic data is needed to develop, calibrate, and validate groundwater models and stream physical habitat models so that the linkage of informed groundwater management results in effective conservation of aquatic habitats for target species.

5.2 Implications and Importance

This study increases our understanding of the relationship between climatic variability, groundwater withdrawals, spring discharge, and water quality within habitats for a semi-arid, groundwater-dependent, karstic stream. We illustrate this approach in the Devils River of Texas assessing water quality and availability within habitats of *D. diaboli* and other species of conservation by collecting basic groundwater, spring, streamflow, and climatic data (Figs.1,2,3). The hydrologic data generated by this study can assist implementation by TPWD, TNC, and the U.S. Fish and Wildlife Service (FWS) of key parts of the Devils River Minnow Recovery Plan. These contributions include:

- Monitoring stream flows in the Devils River (Recovery Action 1.4.4),
- Monitoring existing physical and chemical habitat of *D. diaboli* (Recovery Action 1.4.5), and, ultimately,
- Informing development of a Groundwater Management Plan that ensures protection for the Devils River habitat and its watersheds (Recovery Action 1.4.2) by managing pumping to result in spring flows that result in stream flow protection (Recovery Action 1.4.3).

This study can also increase the understanding of *P. popeii* habitats, inform development of the Recovery Plan for *P. popeii*, and assist with successful conservation of other Devils River species of greatest conservation need (SGCN; TPWD, 2012, 2014). In particular, the results of the hydrology study can be used to inform management of threats to *P. popeii* identified in the Texas Hornshell Species Status Assessment (SSA, FWS, 2016). Ultimately, this study may improve conservation outcomes for the Devils River ecosystem and its species by informing groundwater management strategies that result in meeting instream flow targets—a topic of ongoing work by TPWD, TNC, and FWS.

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8. TABLES

Table 1. Monitoring infrastructure: Logger installation details

Logger Type	Logger Name	Latitude	Longitude	Comment_1	Serial # 1	Install #1	Serial #2	Install #2
Well	Shallow	29.958283	-100.964371	Total depth: 251 feet below top of casing Logger at 215.5 ft below top of casing	329943	10/22/2015	511863	5/8/2017
Well	Deep - 1	29.920570	-100.934551	Total depth: 666 feet below top of casing Logger at 550 ft below top of casing	331538	10/21/2015		
Well	Deep - 2	29.914330	-100.948680	Total depth: 615 feet below top of casing Logger at 500 ft below top of casing Depth to water: 457	-	11/16/2017		
Cond.-Temp.	Dolan Crossing	29.886018	-100.993486	Dolan Crossing	10720182	6/18/2015	10952237	9/26/2016
Cond.-Temp.	Devil's River Upstream	29.903480	-101.008372	Devil's River Upstream	10745248	10/20/2015		
Cond.-Temp.	Finnegan Spring	29.900193	-100.997869	Finnegan Spring	10720181	6/16/2015		
Cond.-Temp.	Blue Spring	29.893814	-100.994526	Blue Spring	10720167	6/18/2015	20089019	5/9/2017
Cond.-Temp.	Dolan Creek, "Rock Art Spring"	-	-	-				
Stage	Dolan Crossing	29.886018	-100.993486	Dolan Crossing	411660	6/18/2015		
Stage	Devil's River Upstream	29.903480	-101.008372	Devil's River Upstream Cabin	398457	10/20/2015	398457	11/15/2017
Temp.	1	29.899315	-100.997814	Downstream logger transect	10723016	6/17/2015		
Temp.	2	29.899276	-100.997895	Downstream logger transect	10723017	6/17/2015		
Temp.	3	29.899239	-100.997985	Downstream logger transect	10723018	6/17/2015		
Temp.	4	29.899218	-100.998038	Downstream logger transect	10723019	6/17/2015		
Temp.	5	29.899195	-100.998101	Downstream logger transect	10723020	6/17/2015		
Temp.	6	29.900660	-100.998735	Upstream logger transect	10723021	6/17/2015		
Temp.	7	29.900636	-100.998772	Upstream logger transect	10723022	6/17/2015		
Temp.	8	29.900613	-100.998805	Upstream logger transect	10723023	6/17/2015		
Temp.	9	29.900561	-100.998871	Upstream logger transect	10723024	6/17/2015		
Temp.	10	29.900522	-100.998918	Upstream logger transect	10723025	6/17/2015		

Table 1. Monitoring infrastructure: Logger installation details (cont.)

Logger Type	Logger Name	Latitude	Longitude	Comment_1	Serial # 1	Install #1	Serial #2	Install #2
Temp.	11	29.899226	-100.997912	Devils, longitudinal	10723026	2/24/2016		
Temp.	12	29.898309	-100.997444	Devils, longitudinal	10723027	2/24/2016		
Temp.	13	29.893123	-100.995001	Devils, longitudinal	10723028	2/24/2016		
Temp.	14	29.891694	-100.994110	Devils, longitudinal	10723029	2/24/2016		
Temp.	15	29.892940	-100.994567	Blue Spring	10723030	2/24/2016		
Temp.	16	29.893495	-100.994472	Blue Spring	10723031	2/24/2016		
Temp.	17	29.885523	-100.993235	Dolan Creek	10723032	2/26/2016		
Temp.	18	29.886497	-100.992457	Dolan Creek	10723033	2/26/2016		
Temp.	19	29.886902	-100.991896	Dolan Creek	10723034	2/26/2016		
Temp.	20	29.888223	-100.989661	Dolan Creek	10723035	2/26/2016		
Temp.	21	29.903500	-101.008830	Texas hornshell riffle, upstream	10723036	9/27/2016		
Temp.	22	29.903560	-101.008770	Texas hornshell riffle, upstream	10723037	9/27/2016		
Temp.	23	29.902641	-101.001044	Texas hornshell riffle, downstream	10723038	9/29/2016		
Temp.	24	29.902608	-101.001056	Texas hornshell riffle, downstream	10723039	9/29/2016		
Temp.	FinneganU24_1 (31)	29.900193	-100.997869	Finnegan U24 temp check	20044571	2/7/2017		
Temp.	BlueU24_1 (32)	29.893814	-100.994526	Blue spring U24 temp check	20044572	2/7/2017		
Temp.	Dolan Creek USGS gauge bubbler line (33)			Logger missing	20044573	2/7/2017		
Temp.	Dolan Creek "Fig Tree" spring (34)	29.888300	-100.989270	Logger missing	20044574	2/7/2017		
Temp.	Dolan_Spring_2_U24_1 (35)	29.890820	-100.985150	Dolan spring U24 temp check "Rock art" spring	20044575	2/7/2017		
Temp.	36			Devils River Upstream temp check	20044576	2/7/2017		
Temp.	37			Dolan's Crossing temp check	20044577	2/7/2017		
Meteorological	Weather station	29.886416	-100.995434	Baro Logger in weather station	412014	6/18/2015		

Table 2. Summary of field instrumentation and implications of results. See Figs. 1,2,3 for location of monitoring equipment.

Hydrologic Data	**How Data Collected**	**Implications of Results**
Meteorological parameters	Meteorological station recording data averaged into 1-hour intervals including air temperature and relative humidity (Vaisala, HMP60), precipitation (Texas Electronics, TE525), wind speed and direction (R.M. Young, Wind Sentry), and short-wave solar radiation (Eppley, Diffuse Pyranometer, Model 8-48)	Meteorological data can be used to understand (1) effects of daily and seasonal ambient temperature conditions (noted by Kollaus and Bonner, 2012) on water temperature on *D. diaboli* habitat and also (2) the relationship between precipitation, groundwater levels, spring physical parameters, and stream discharge.
Stream stage and stream flow (i.e., discharge)	In-Situ Rugged TROLL pressure loggers (In-Situ, 2018b) installed in a steel pipe housing fixed to limestone stream bottom with Red Head LDT 3/8 x 3-inch concrete anchors using Bosch hammer drill with 5/16-inch drill masonry drill bit. During quarterly field trips instantaneous discharge measure with a FlowTracker acoustic Doppler velocimeter (ADV, SonTek 2014).	Springs provides ≤71% of stream discharge at Dolan Crossing. Managing groundwater to maintain spring flows is essential to conserving instream flows on the Devils River. Stream flow could be used as input to future aquatic habitat model.
Groundwater levels	In-Situ AquaTroll pressure transducers (unvented; In-Situ, 2018b) recording groundwater level and temperature at 1-hour intervals in two monitoring wells. Corrected for atmospheric pressure using In-Situ BaroTroll (In-Situ, 2018a).	Increases in groundwater levels in shallow monitoring well correlate with floods in Dolan Creek (IBWC, 2018; USGS, 2018). Understand variations in instream flows depending on spring flow changes associated with groundwater level fluctuation.

Table 2. Summary of field instrumentation and implications of results (cont.)

Hydrologic Data	**How Data Collected**	**Implications of Results**
Spring and stream water conductivity and temperature	HOBO U24-001 conductivity-temperature sensors (Onset, 2014a) logging at 15-minute intervals. Field physical water parameters (i.e., temperature, pH, conductivity, dissolved oxygen) measured using a YSI 556 MPS (YSI, 2018).	Spring water conductivity and temperature change rapidly following floods (IBWC, 2018; USGS, 2018), indicating important fast-flow groundwater recharge in Dolan Creek. Managing groundwater pumping in the Dolan Creek watershed—in additional to regionally—is important to conserve spring flows supporting instream flows. Understand the rainfall-runoff response of major springs feeding the Devils River (i.e., fast-flow, local recharge or slower, regional recharge).
Stream water temperature	TidbiT water temperature data loggers (Onset, 2014b) recording at 15-minute intervals in lateral and longitudinal transects.	Spring flows are critical in providing thermal buffering and maintain instream flows, particularly during summer and droughts. Characterize seasonal stream temperature changes and thermal buffering from spring inflows. Thermal data to be used to parameterized aquatic habitat temperature model.

Table 2. Summary of field instrumentation and implications of results (cont.)

Hydrologic Data	How Data Collected	Implications of Results
Temperature of stream and spring water surface	Thermal infrared imagery acquired with FLIR Vue Pro mounted on 3DR Iris+ unmanned aerial vehicle (UAV).	In conjunction with in-stream thermal data and DTS, results may be used to infer spatial distribution of thermal preferences of aquatic organisms.
Temperature of stream measured with fiber optics distributed temperature sensing (FO-DTS)	Agilent (now AP Sensing) Linear Pro Series N4386B DTS system (serial number: DE47501139, calibration options: H04 002 400 052) with two 1-km Brugg cables (Fiber type: 2FGBA, order number: 2013C01190). Data were collected every 90 seconds and averaged every 6-minutes at 1-m intervals.	Springs discharge water with nearly constant temperature, which mixes with surface water that vary diurnally and seasonally providing important thermally-stable habitat throughout the year.

Notes: 1. Use of trade names for a device does not constitute or imply a product endorsement. 2. Detailed results of The University of Texas at Austin Bureau of Economic Geology Lidar studies to be published in a forthcoming manuscript.

Table 3. Monthly climate summary from weather station

		T_a mean C	max C	min C	**PPT** total mm	**PET** total mm	**PPT/PET**	**PPT** Annual mm	**PET** Annual mm
2015	8	30.1	40.4	21.5	30.2	210	0.1		
2015	9	28.0	36.7	17.2	0.5	163	0.0		
2015	10	22.8	36.9	6.4	186.9	119	***1.6***		
2015	11	15.6	27.3	-0.4	12.4	56	0.2		
2015	12	11.5	28.6	-1.3	50.0	78	0.6	280	626
2016	1	9.7	29.0	-1.7	15.0	90	0.2		
2016	2	14.1	29.9	-2.6	16.0	116	0.1		
2016	3	18.2	32.4	4.1	62.5	145	0.4		
2016	4	21.7	33.7	4.3	89.9	169	0.5		
2016	5	24.5	35.2	9.4	28.7	154	0.2		
2016	6	28.0	38.2	15.2	109.7	205	0.5		
2016	7	31.4	39.6	22.8	4.3	229	0.0		
2016	8	28.6	40.8	19.4	188.0	169	***1.1***		
2016	9	26.2	35.0	14.8	110.0	150	0.7		
2016	10	23.5	32.1	10.1	0.5	128	0.0		
2016	11	17.7	30.5	3.8	54.4	68	0.8		
2016	12	11.6	26.3	-4.6	60.2	45	***1.3***	739	1667
2017	1	12.5	29.3	-7.0	7.6	88	0.1		
2017	2	16.5	34.5	2.6	31.8	104	0.3		
2017	3	20.0	33.0	7.7	16.0	129	0.1		
2017	4	21.9	34.3	5.9	42.2	167	0.3		
2017	5	24.7	35.6	9.5	176.3	168	***1.0***		
2017	6	28.6	39.5	17.4	42.7	212	0.2		
2017	7	30.3	40.0	22.0	4.1	212	0.0		
2017	8	29.3	38.7	16.8	50.0	182	0.3		
2017	9	27.1	39.6	15.8	120.1	133	0.9		
2017	10	20.7	34.0	1.2	36.3	119	0.3		
2017	11	17.1	32.6	0.9	1.3	52	0.0		
2017	12	10.1	25.6	-3.0	31.2	43	0.7	560	1609
2018	1	8.7	24.5	-8.6	0	83	0.0		
2018	2	14.5	29.0	-1.5	22.9	70	0.3		

Table 4. Stream discharge measurement and Percent of Spring Discharge

Date Upstream Site	Date Lower (Dolan Crossing)	Stream Discharge, Upper (cfs)	Stream Discharge, Lower (cfs)	Finegan Springs Discharge (cfs)	Percent Stream Discharge from Finegan Springs (%)	Q[1]	Comments
18-Jun-15	18-Jun-15	-	-	-	-	0	Downstream logger installed by UT Austin. Upstream logger not installed. No discharge measured. Fieldwork completed under The University of Texas at Austin Jackson School of Geosciences seed grant.
28-Sep-15	29-Sep-15	11	38	27	71%	1	TPWD
20-Oct-15	20-Oct-15	16	44	28	63%	1	UT Austin. Upstream logger installed by UT Austin. Fieldwork done under USFWS/TPWD Section 6 grant.
-	13-Jan-16	-	71	-	-	2	TPWD. Downstream discharge only.
25-Feb-16		29	59	30	51%	2	UT Austin
13-Jun-16	12-Jun-16	45	82	36	44%	4	UT Austin
27-Sep-16	27-Sep-16	103	176	73	42%	5	UT Austin
4-Oct-16	4-Oct-16	88	134	46	35%	5	TPWD
9-Feb-17	9-Feb-17	41	79	38	48%	6	UT Austin
9-May-17	9-May-17	47	82	35	42%	7	UT Austin
5-Oct-17	5-Oct-17	151	196	45	23%	9	TPWD
15-Nov-17	15-Nov-17	58	92	34	36%	9	UT Austin. Fieldwork completed under The University of Texas at Austin Jackson School of Geosciences SWG grant.
20-Mar-18	20-Mar-18	19	54	35	66%	11	UT Austin

Notes. [1]Q indicates quarter from start of contract during which activity took place. Q 0 is work done before contract start.

Table 5. Water temperatures correlation to T_a at hourly and daily time scales, where B is from equation [1] and R^2 is the coefficient of determination.

	$T_w(T_a)$ HOURLY				Daily MEAN		Daily MAX		Daily MIN	
	N	**B**	**R^2**	**N**	**B**	**R^2**	**B**	**R^2**	**B**	**R^2**
	Hours			*Days*						
1	21126	0.36	0.79	882	0.43	0.89	0.46	0.81	0.38	0.91
2	18585	0.34	0.72	777	0.42	0.87	0.42	0.75	0.40	0.89
4	16590	0.41	0.77	693	0.49	0.88	0.49	0.79	0.46	0.90
5	21126	0.44	0.78	882	0.52	0.89	0.52	0.80	0.50	0.90
6	21150	0.31	0.69	883	0.39	0.83	0.36	0.73	0.38	0.85
7	21126	0.38	0.76	882	0.46	0.87	0.44	0.79	0.45	0.90
8	8670	0.43	0.76	363	0.53	0.89	0.50	0.79	0.50	0.91
9	21127	0.44	0.74	882	0.54	0.88	0.50	0.76	0.53	0.90
10	11214	0.49	0.79	469	0.59	0.91	0.59	0.82	0.55	0.91
11	15113	0.39	0.76	630	0.47	0.87	0.47	0.79	0.45	0.90
12	15135	0.41	0.76	631	0.51	0.88	0.51	0.79	0.48	0.90
13	15134	0.44	0.76	631	0.54	0.88	0.51	0.79	0.52	0.91
14	15135	0.42	0.75	631	0.52	0.87	0.50	0.79	0.50	0.90
16	15135	0.05	0.69	631	0.05	0.80	0.05	0.56	0.05	0.75
17	18057	0.32	0.89	753	0.32	0.94	0.38	0.90	0.29	0.91
18	13781	0.31	0.89	576	0.31	0.94	0.37	0.89	0.29	0.91
19	18057	0.30	0.88	753	0.29	0.95	0.36	0.90	0.26	0.89
20	18057	0.38	0.75	753	0.45	0.86	0.43	0.69	0.44	0.88
23	4589	0.50	0.72	192	0.66	0.88	0.68	0.80	0.59	0.86
FS	7533	0.00	0.09	316	0.00	0.13	0.00	0.03	0.00	0.13
BH	7557	0.02	0.58	316	0.02	0.73	0.02	0.62	0.02	0.79
RA	9712	0.01	0.05	406	0.01	0.05	0.00	0.03	0.01	0.04
36	9711	0.04	0.07	406	0.03	0.10	0.04	0.01	0.03	0.03
Up	20405	0.56	0.75	853	0.69	0.88	0.69	0.79	0.65	0.91
Down	24106	0.43	0.80	1006	0.50	0.90	0.52	0.83	0.46	0.92

Table 6. Predictive model performance in root mean square error (RMSE) and coefficient of determination (R^2) for hourly and daily water temperatures (T_w) using observed and NLDAS prediction variables in linear, multi-linear (*mlr*) and step-wise (*sw*) models.

	Hourly T_w	
Predictor	**RMSE [C]**	**R^2**
T_a	1.50	0.68
T_s	1.22	0.74

	Daily Mean T_w		Daily Max T_w		Daily Min T_w	
Predictor(s)	**RMSE [C]**	**R^2**	**RMSE [C]**	**R^2**	**RMSE [C]**	**R^2**
T_a	1.01	0.78	1.47	0.69	0.98	0.79
T_s	0.98	0.79	1.23	0.74	0.98	0.79
***mlr*(T_s, T_a, R_s)**	0.91	0.81	1.16	0.77	0.94	0.80
***mlr*(G_L, T_s, T_a, R_s)**	0.84	0.83	1.04	0.80	0.89	0.81
***sw*(Z_l, T_s, T_a, R_s)**	0.63	0.91	0.75	0.88	0.75	0.88

	NLDAS mean T_w		NLDAS max T_w		NLDAS min T_w	
Predictor(s)	**RMSE [C]**	**R^2**	**RMSE [C]**	**R^2**	**RMSE [C]**	**R^2**
T_a	0.97	0.79	1.40	0.70	1.01	0.78
T_s	0.86	0.81	1.14	0.76	1.04	0.78
***mlr*(T_s, T_a, R_s)**	0.84	0.83	1.08	0.78	0.91	0.81

Table 7. Long-term trends in daily mean, maximum and minimum air and soil temperatures and water temperatures at each monitoring location using 30-year-anomalies from *mlr* (T_s, T_a, R_s). The trends (dT/decade) are presented using a t-test (p-value) and a non-parametric Mann-Kendall test with significant trends (p<0.05) are denoted with a '1'.

	Daily Mean			**Daily Maximum**			**Daily Minimum**		
Location	**dT_w/dec**	**P**	**M-K**	**dT_w/dec**	**P-value**	**M-K**	**dT_w/dec**	**P**	**M-K**
T_a	*0.188*	0.01	1	*0.345*	2E-05	1	0.050	2.31	0
T_s	0.101	0.10	0	*0.299*	3E-05	1	-0.053	2.20	0
1	0.037	0.08	0	*0.092*	2E-04	1	0.008	0.71	0
2	0.047	0.04	0	*0.096*	1E-04	1	0.022	0.76	0
4	0.054	0.04	0	*0.111*	7E-05	1	0.017	0.91	0
5	0.058	0.04	0	*0.120*	6E-05	1	0.019	0.97	0
6	0.040	0.07	0	*0.084*	1E-04	1	0.011	0.78	0
7	0.053	0.04	0	*0.106*	7E-05	1	0.020	0.90	0
8	0.059	0.03	0	*0.116*	3E-05	1	0.022	0.97	0
9	0.060	0.04	0	*0.121*	6E-05	1	0.020	1.04	0
10	0.051	0.08	0	*0.121*	8E-05	1	0.014	1.06	0
11	0.049	0.05	0	*0.104*	1E-04	1	0.017	0.84	0
12	0.053	0.05	0	*0.113*	1E-04	1	0.019	0.90	0
13	0.056	0.05	0	*0.115*	1E-04	1	0.021	0.98	0
14	0.054	0.05	0	*0.110*	2E-04	1	0.023	0.93	0
16	0.004	0.17	0	*0.012*	3E-06	1	-0.002	0.11	0
17	0.042	0.02	0	*0.102*	5E-06	1	0.001	0.61	0
18	0.042	0.02	0	*0.100*	5E-06	1	0.002	0.61	0
19	*0.042*	0.01	1	*0.100*	4E-06	1	0.002	0.58	0
20	0.047	0.06	0	*0.107*	2E-05	1	0.004	0.94	0
23	0.064	0.07	0	*0.146*	1E-04	1	0.027	1.15	0
Up	0.079	0.03	0	*0.156*	1E-04	1	0.033	1.24	0
Down	0.054	0.06	0	*0.119*	1E-04	1	0.017	0.95	0

Table 8. Uniform continuous above threshold (UCAT) results at the Upstream and Downstream locations derived from 30-year daily maximum T_w using *mlr* modeling.

	Threshold Temperature	28 C	29 C	30 C	31 C
Upstream	Persistent duration (days)	44	28	13	8
	Catastrophic duration (days)	85	57	43	22
Down	Persistent duration (days)	35	12	6	NA
	Catastrophic duration (days)	84	37	12	NA

9. FIGURES

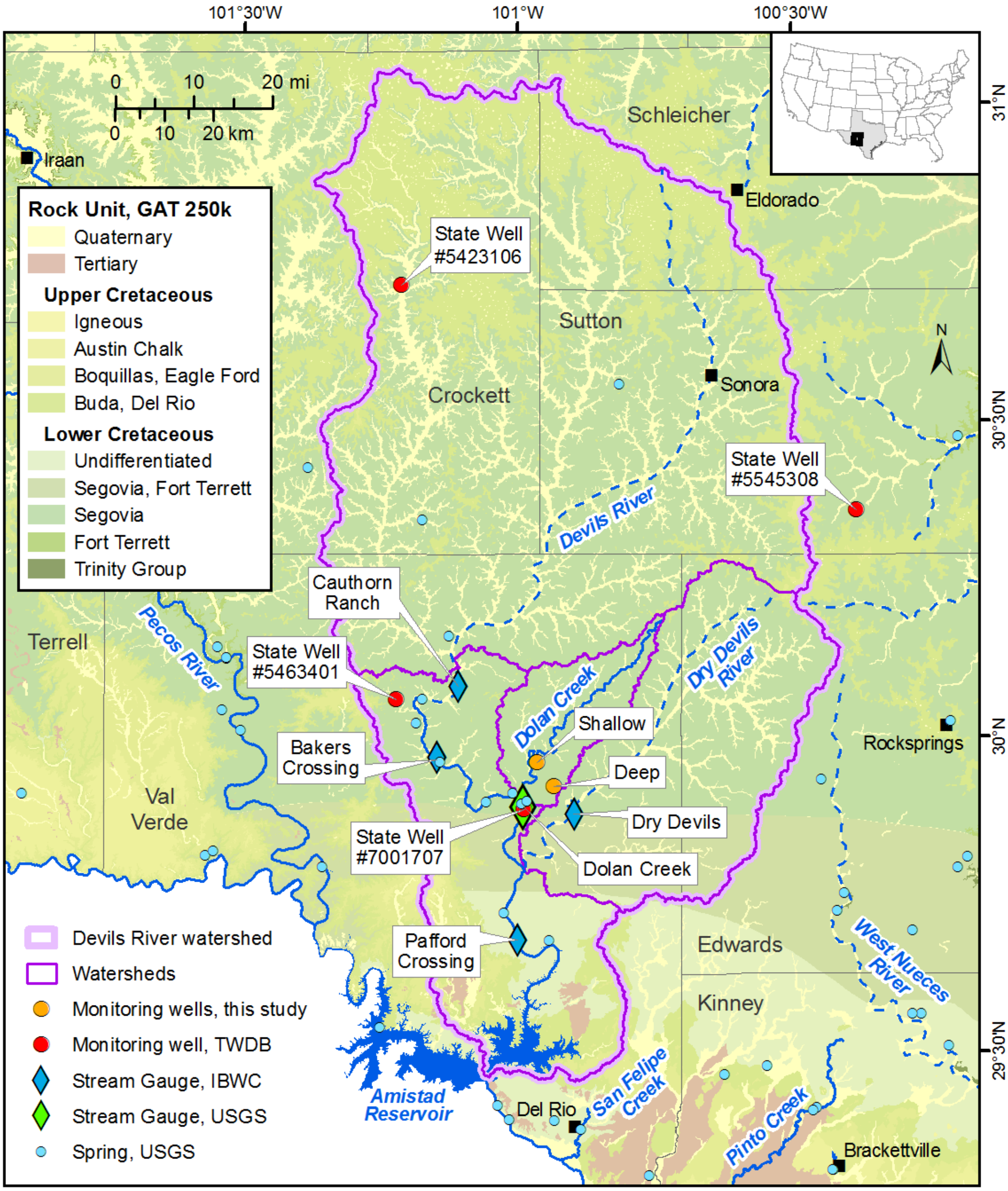

Figure 1. Overview map of the Devils River watershed, TWDB well locations, IBWC and USGS stream gauges.

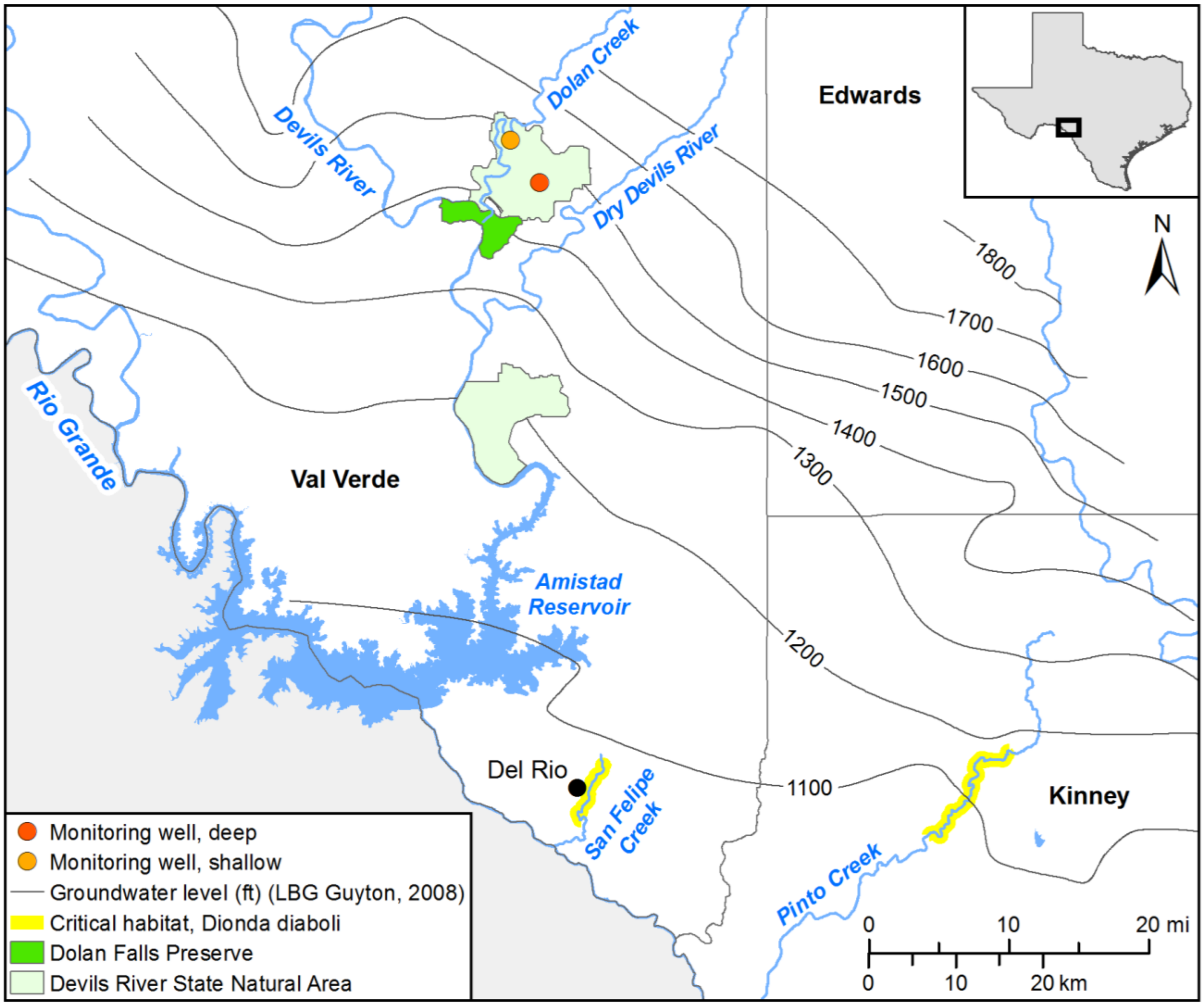

Figure 2. Study area, regional groundwater potentiometric surface, and D. diaboli critical habitat.

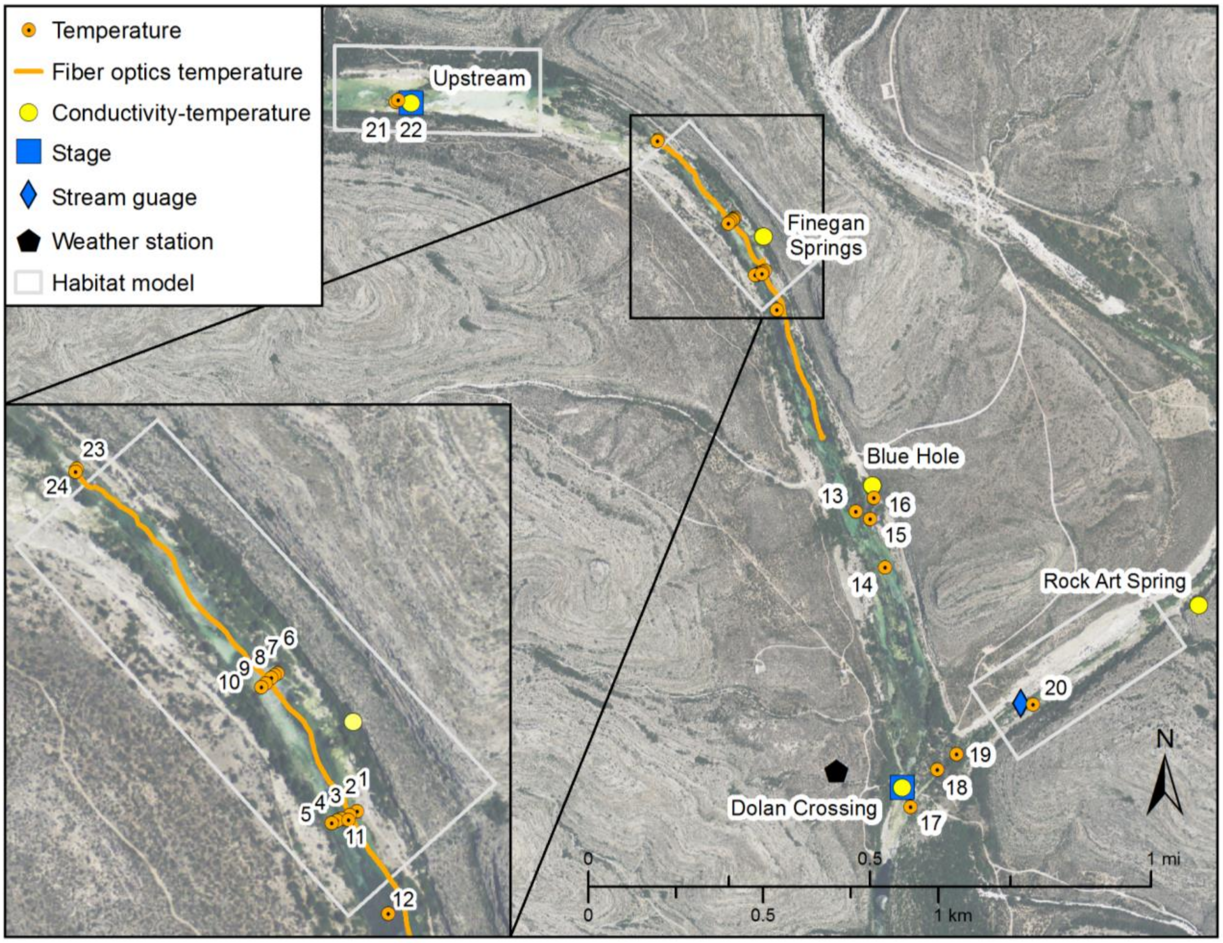

Figure 3. Study area including stream temperature monitoring locations (Lateral and Longitudinal Transects), spring discharge, and stream discharge measurement within the *D. diaboli* habitat model domains. The stream gauge is USGS 08449100 Dolan Ck abv Devils River nr Comstock, TX.

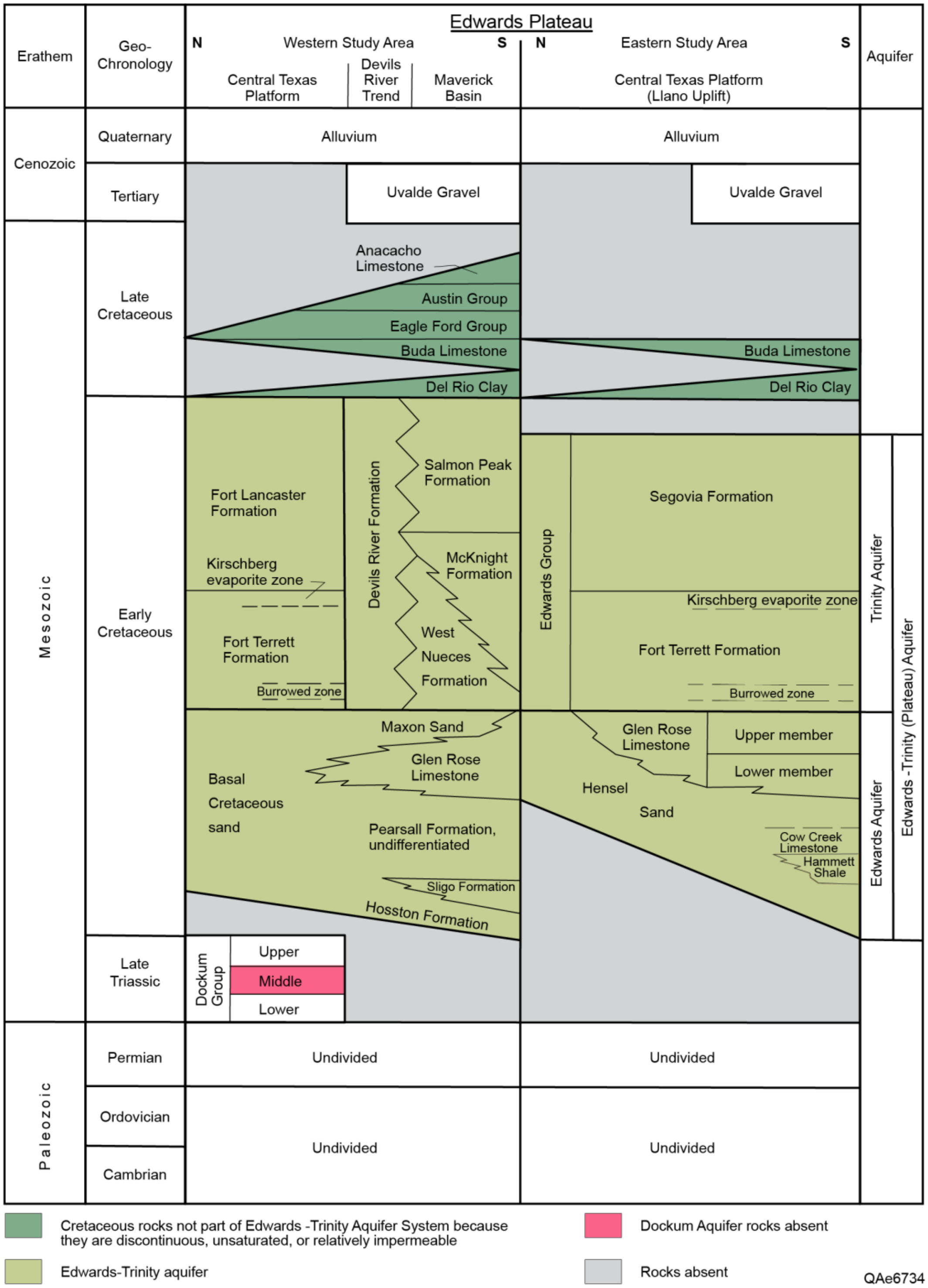

Figure 4. Generalized hydrostratigraphy of the Edwards Plateau in the study region of the Devils River. (After Barker and Ardis, 1996; Barnes, 1977; Rose, 1972)

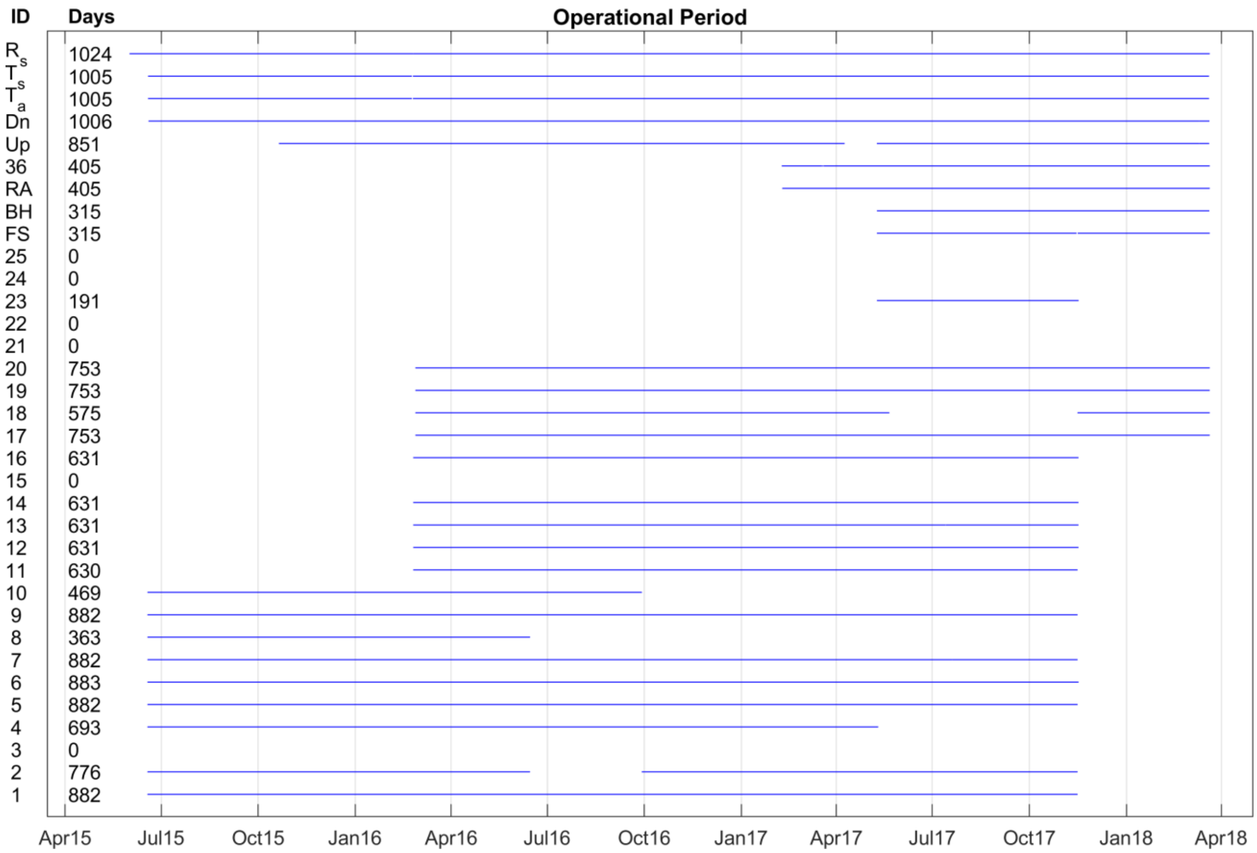

Figure 5. Operation period for each instream water temperature (T_w) sensors for this reporting period.

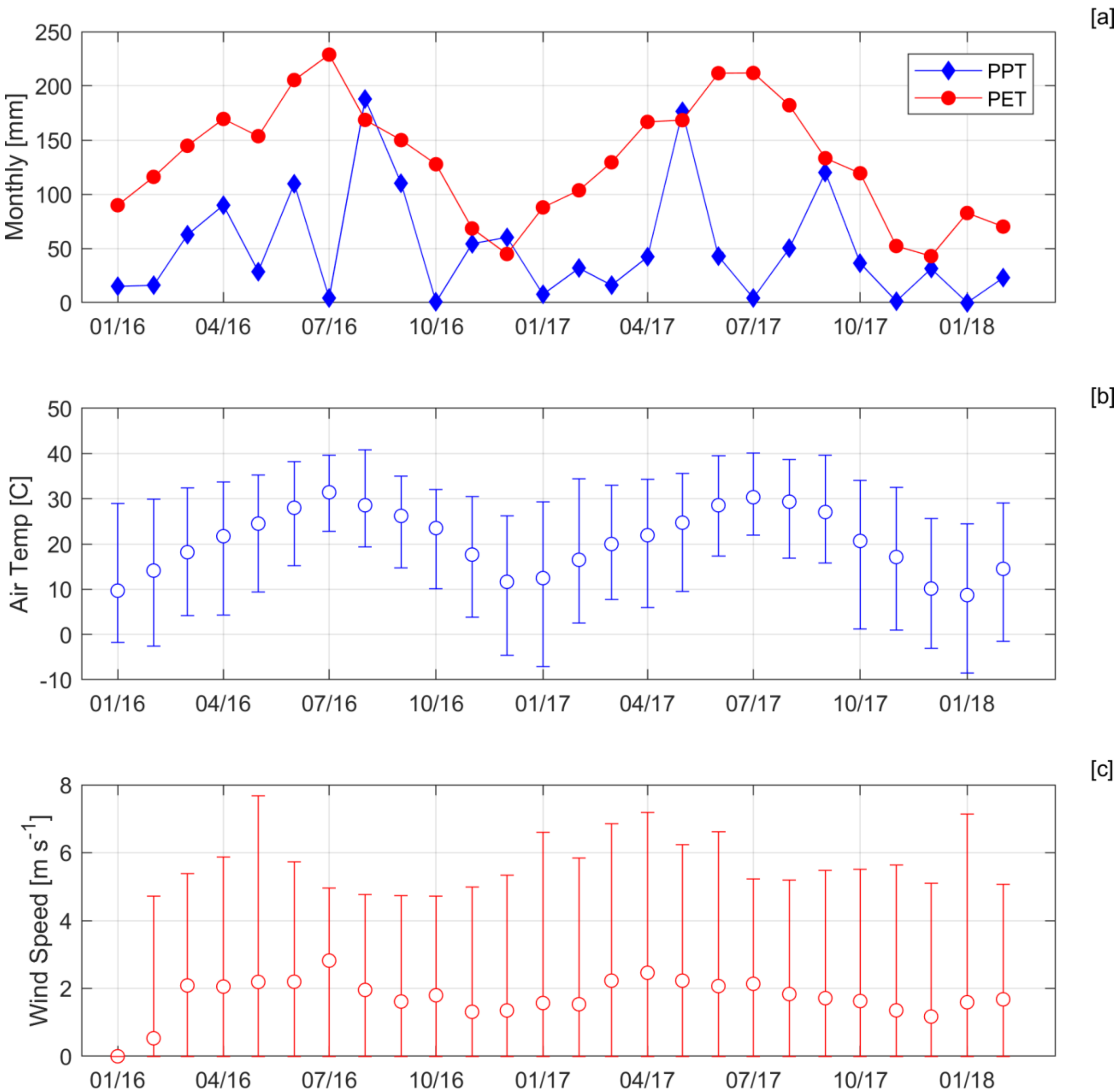

Figure 6. Monthly meteorological summaries of [a] rainfall (PPT) and potential evapotranspiration (PET), [b] air temperature and [c] wind speed. Symbols indicate mean values and bars indicate monthly max and min values.

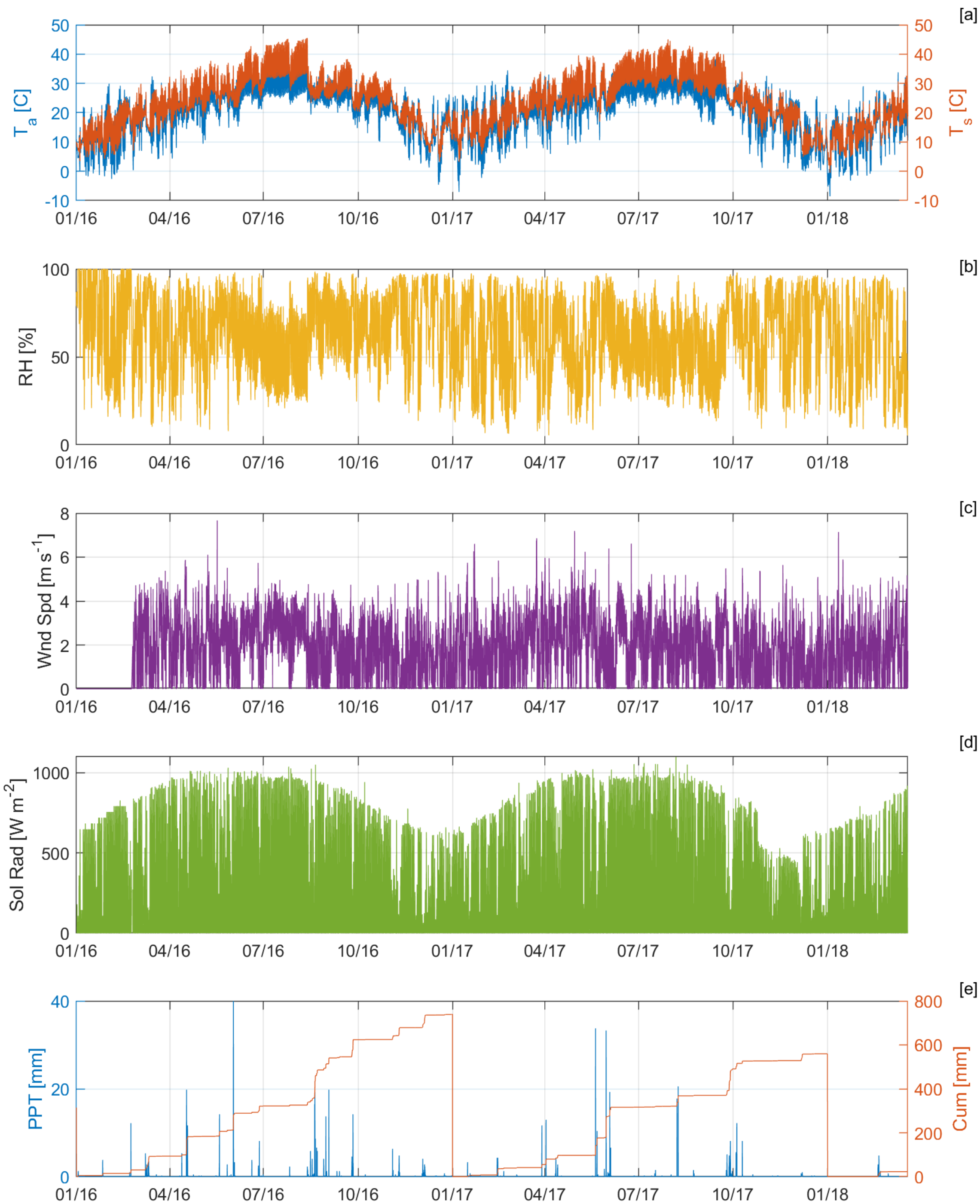

Figure 7. Hourly meteorological data recorded for [a] air temperature (T_a) in blue and soil temperature (T_s) in red, [b] relative humidity, [c] wind speed, [d] short-wave solar radiation, and [e] hourly and annual rainfall totals.

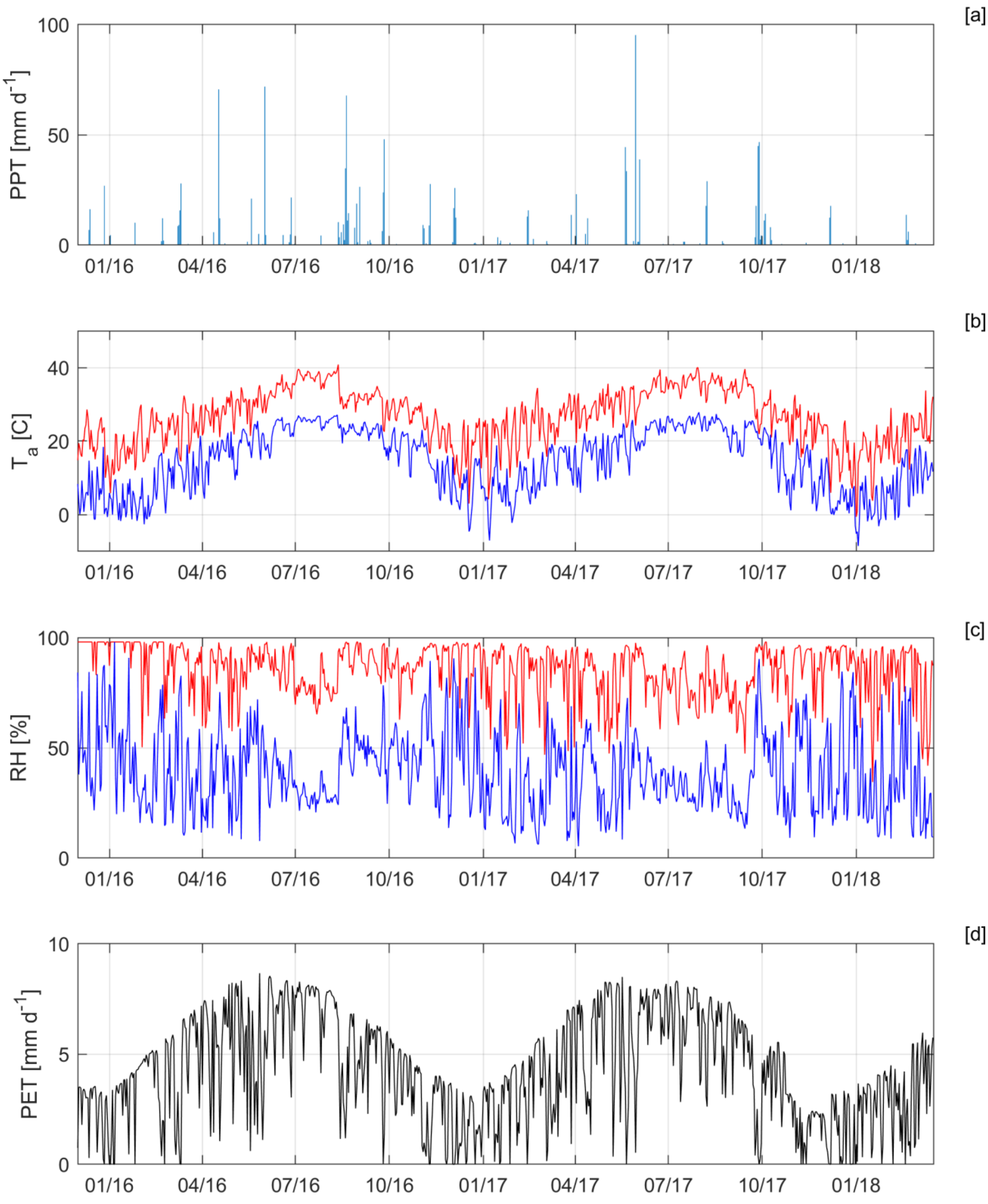

Figure 8. Daily meteorological data for [a] rainfall, [b] maximum (red) and minimum (blue) air temperatures (T_a), [c] relative humidity, and [d] potential evapotranspiration (PET).

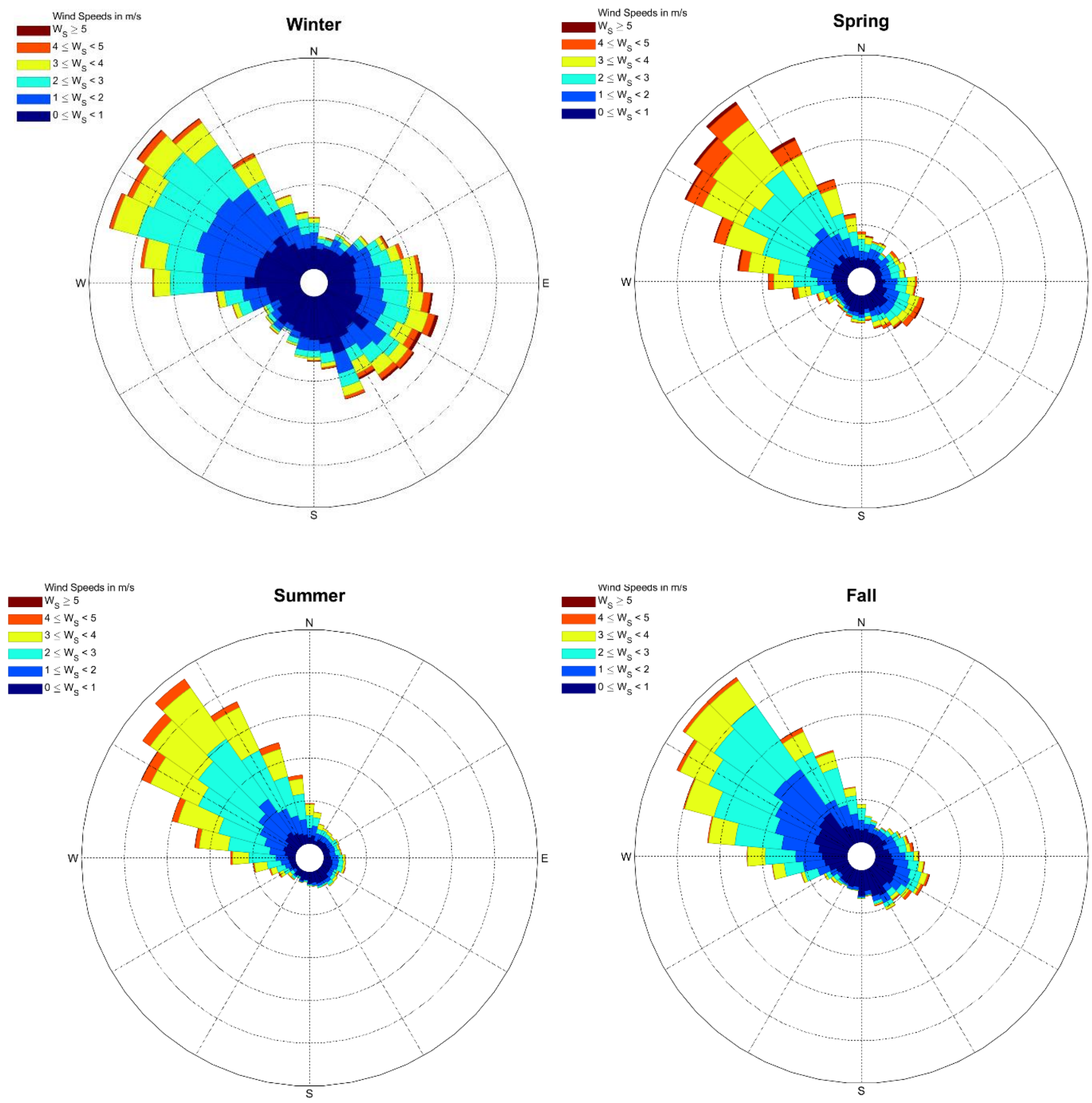

Figure 9. Wind roses by season indicating prevalent wind directions and speeds.

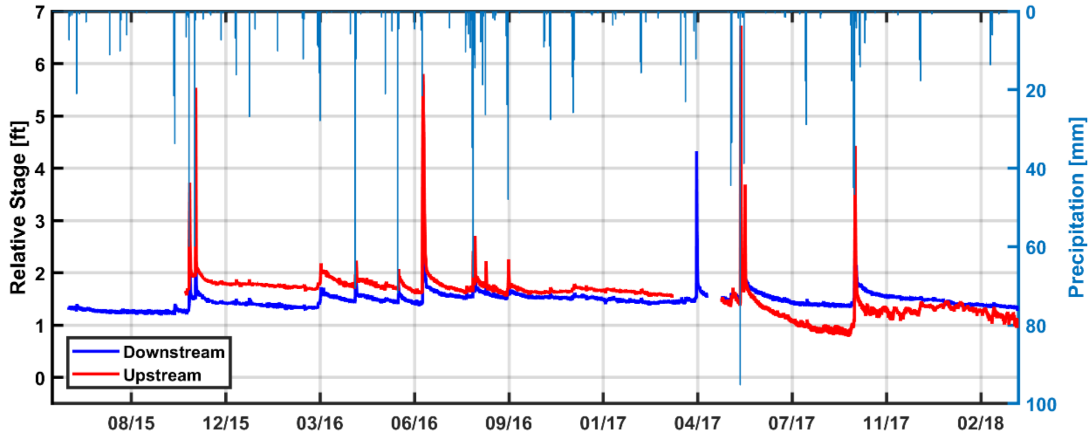

Figure 10. Relative stage recorded at the Upstream and Downstream (Dolan Crossing) locations and daily precipitation over the study period.

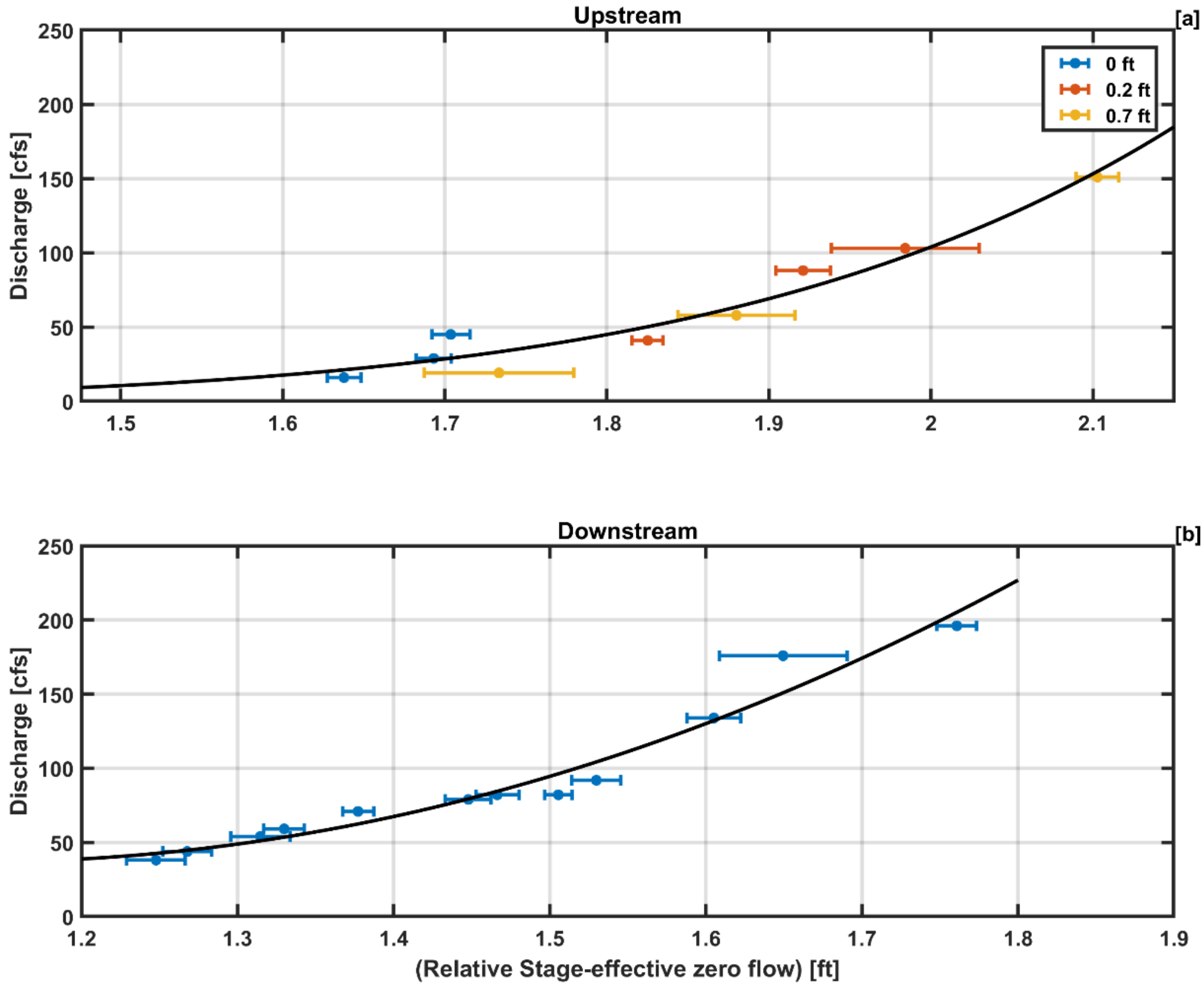

Figure 11. Discharge rating curve at the [a] upstream site and [b] downstream locations. For the Upstream location, shifts in discharge intercept are indicated by blue (October 2015 to June 2016), red (October 2016 to February 2017), and the yellow (October 2017 to March 2018).

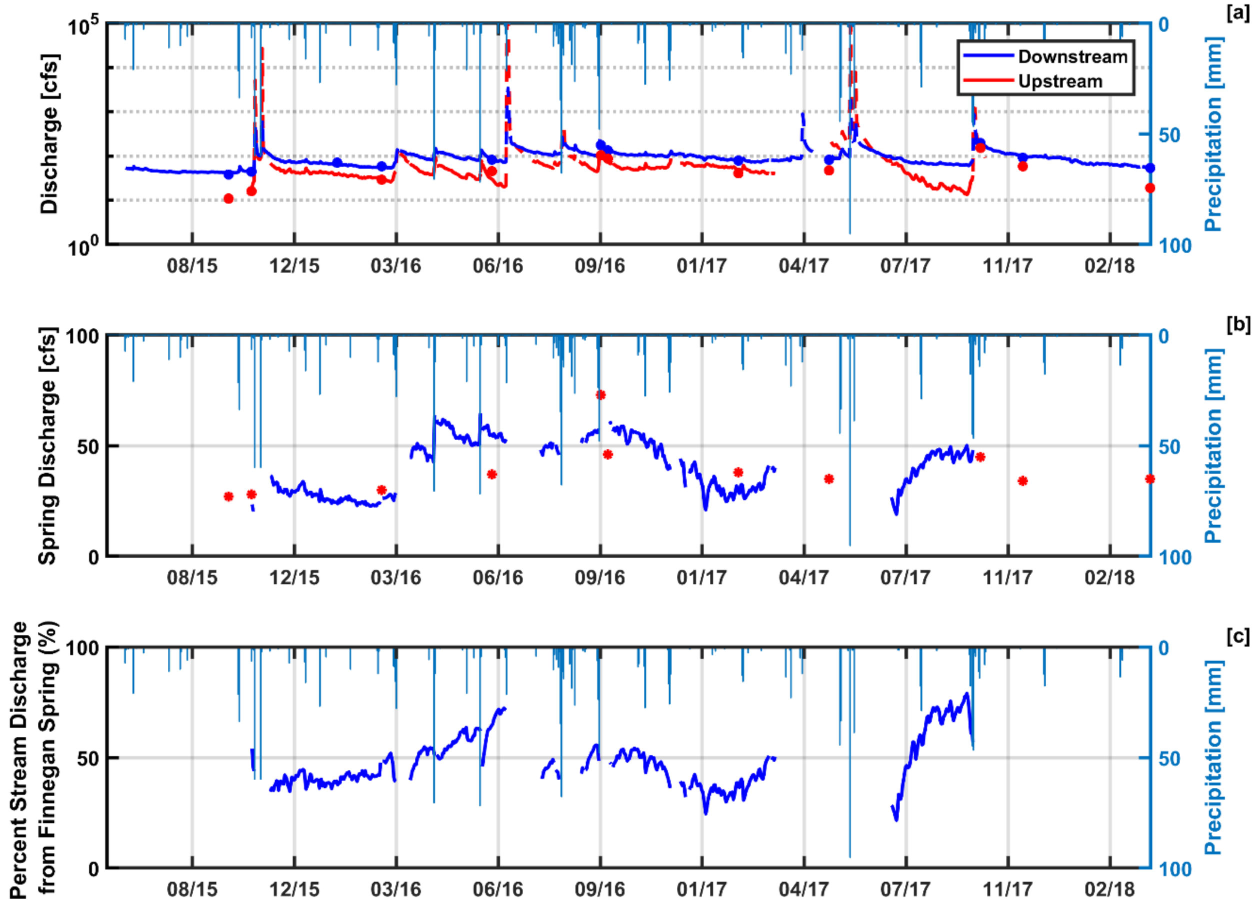

Figure 12. [a] Devils River stream discharge at Upstream and Downstream locations, [b] estimated spring discharge by difference, and [c] the percentage of spring flow contribution to total discharge. Symbols denote actual discharge measurements over the study period.

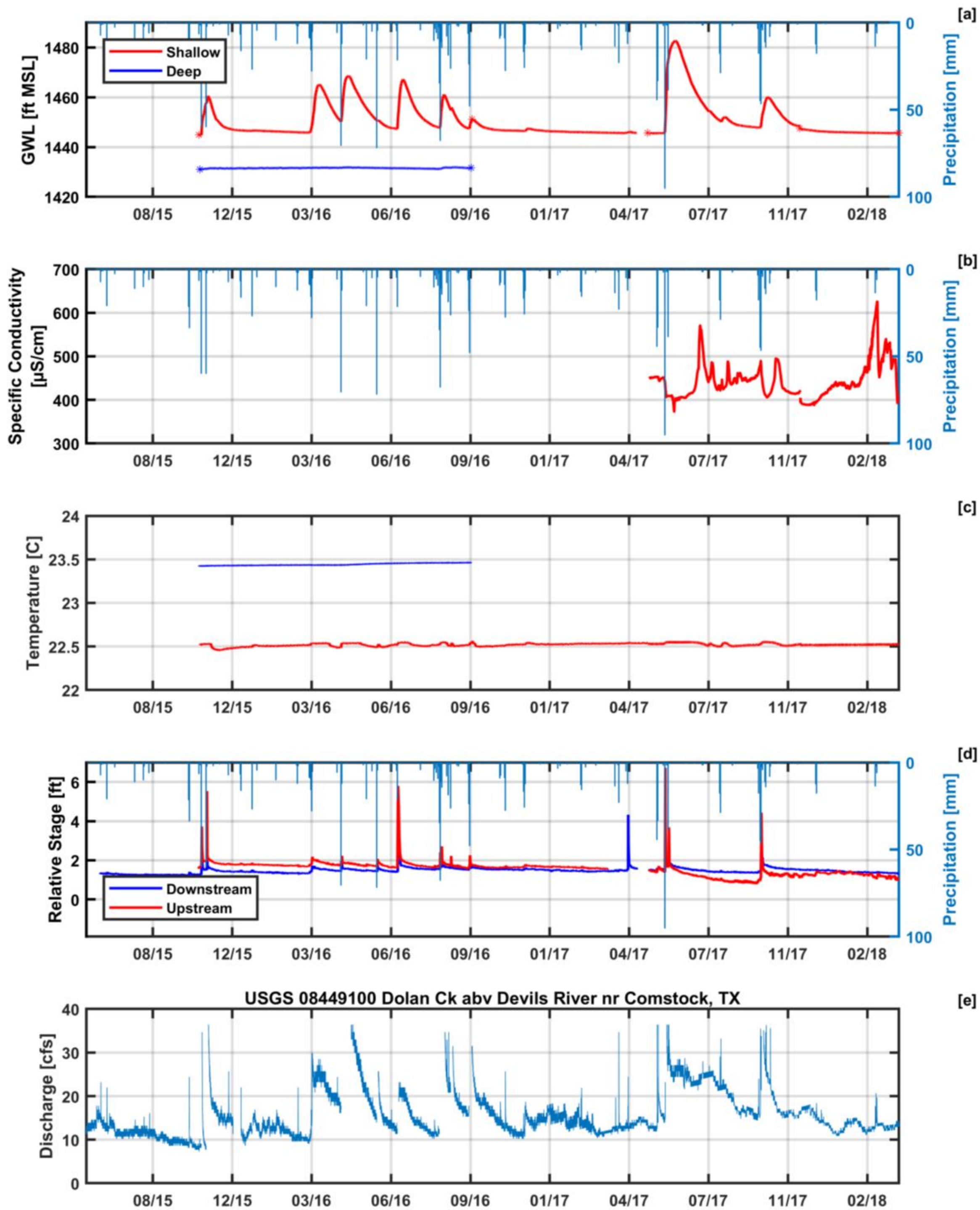

Figure 13. [a] Groundwater level in ft above mean sea level, [b] specific conductivity and [c] temperature of the groundwater, [d] relative stages of the Devils River and [e] Dolan Creek discharge measured at USGS gauge 08449100.

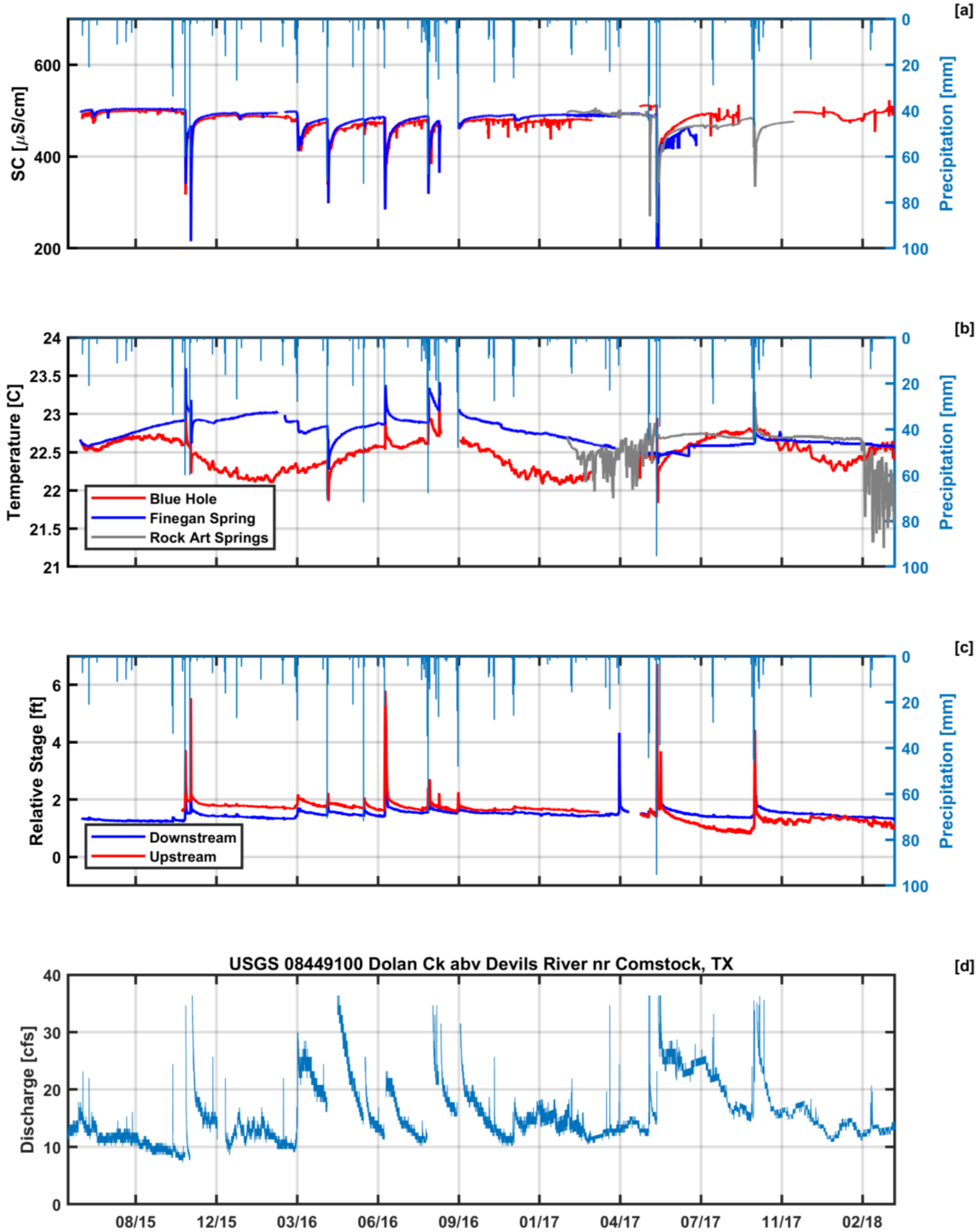

Figure 14. [a] Specific conductance and [b] temperatures from spring discharge at Blue Hole, Finegan and Rock Art. [c] The relative stages of the Devils River and [d] Dolan Creek discharge measured at USGS gauge 08449100 are shown for comparison.

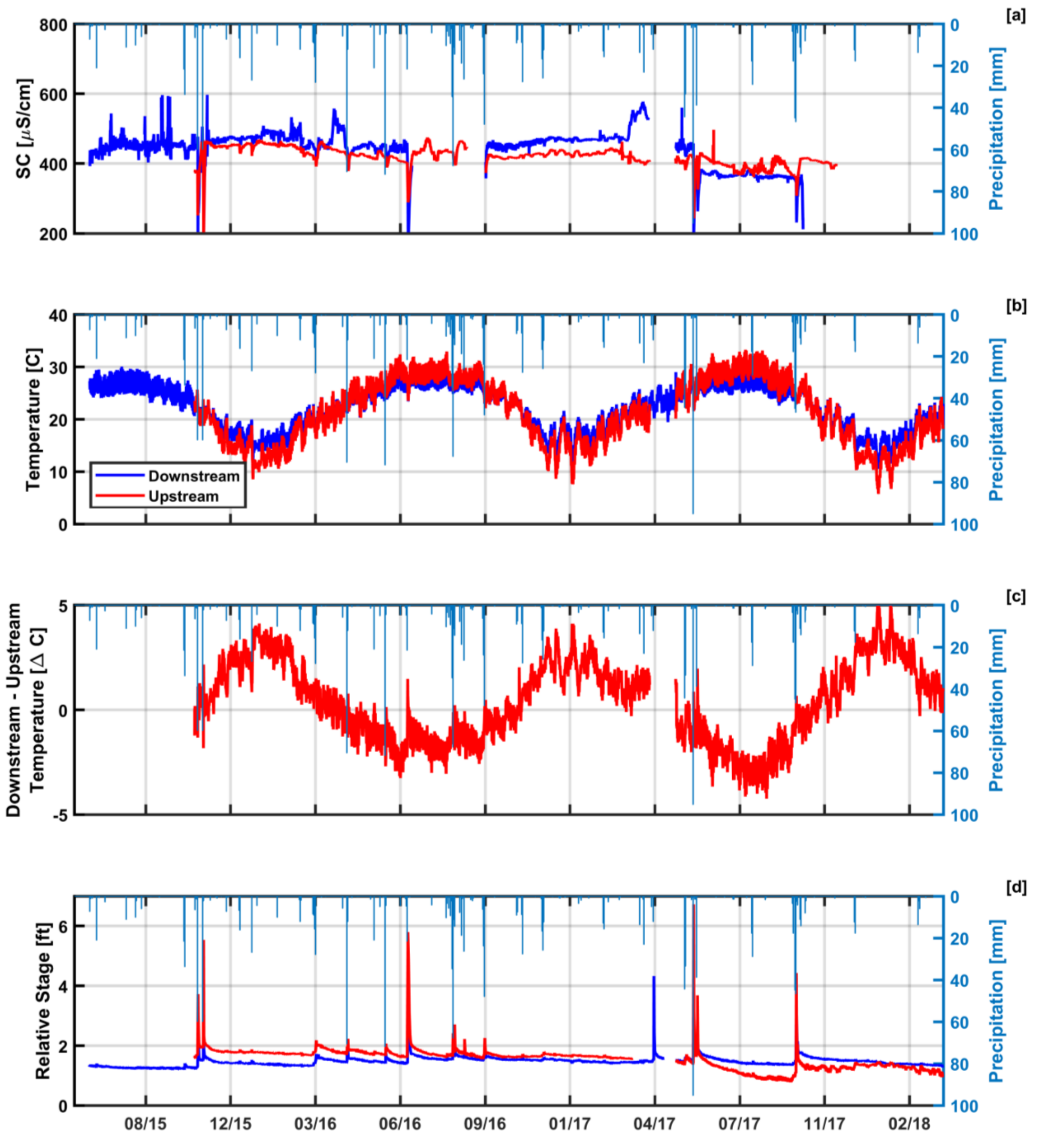

Figure 15. [a] Specific conductance and [b] temperature of the Devils River at Upstream and Downstream locations. [c] The temperature difference between Downstream and Upstream represents the spring input and [d] relative stages for reference.

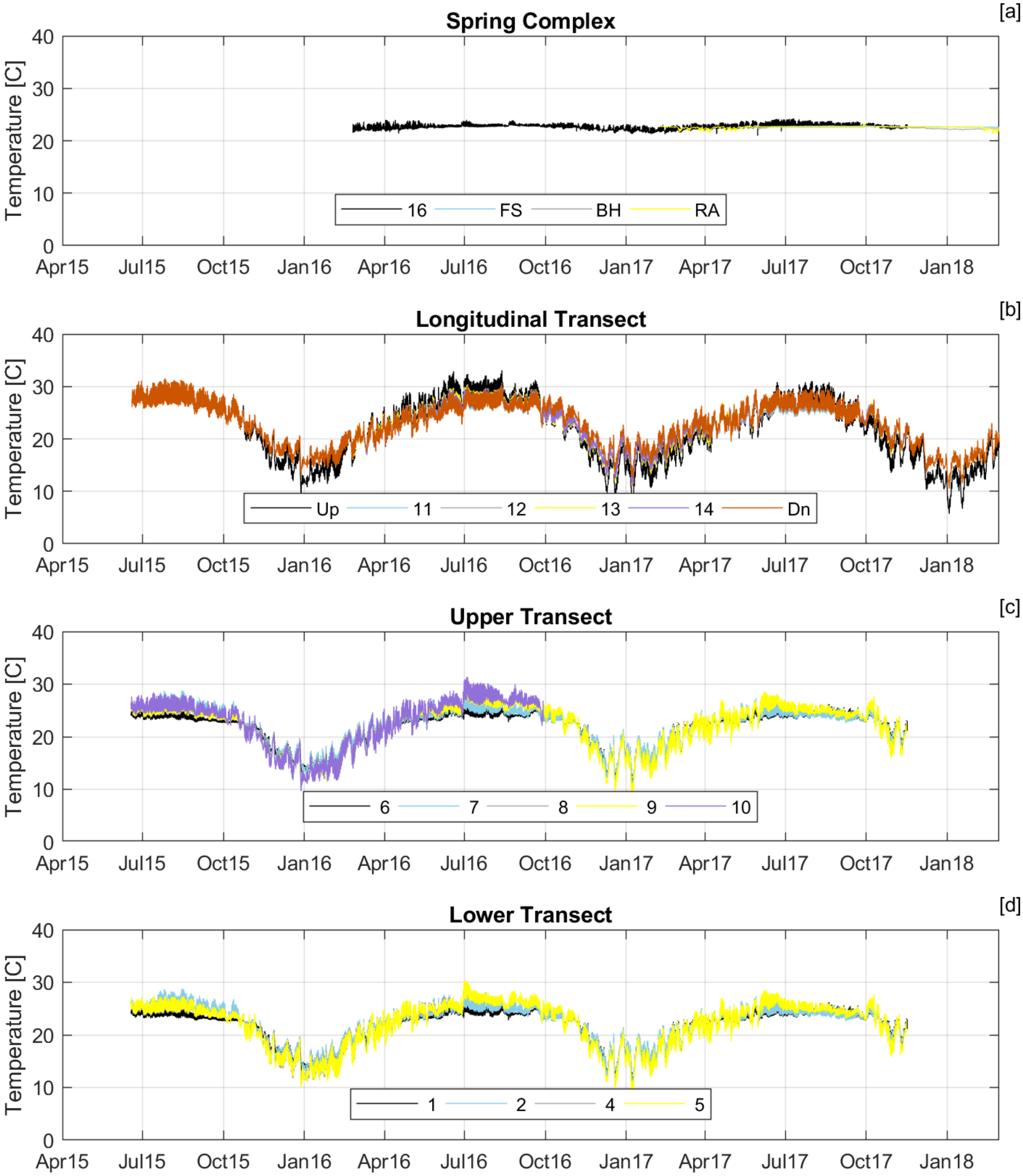

Figure 16. Instream hourly temperatures for [a] stream complex of Blue Hole (16 and BH), Finegan Spring (FS) and Rock Art Spring (RA), [b] the downstream Devils River longitudinal transect, [c] upper lateral transect, and [d] lower lateral transect.

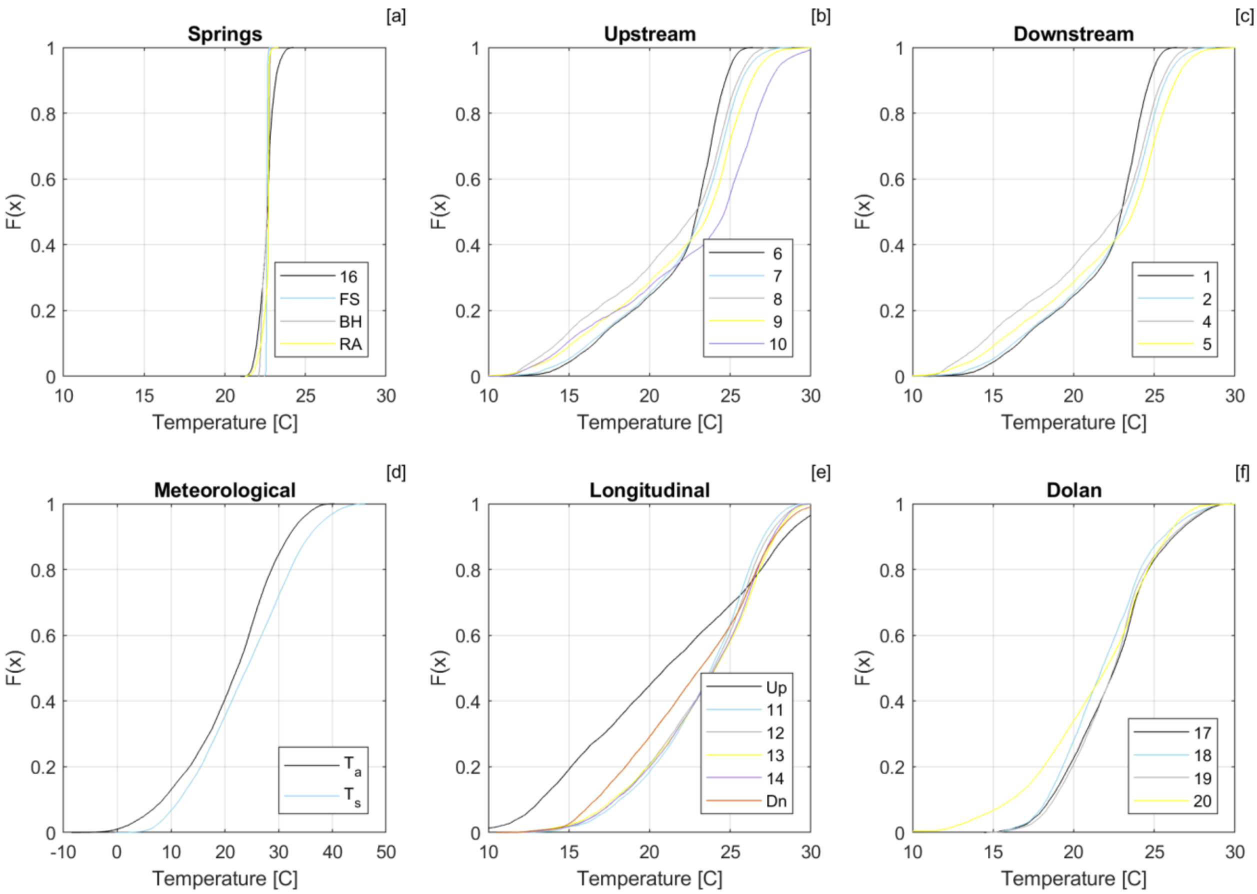

Figure 17. Cumulative distribution functions of hourly instream temperatures of [a] springs, [b] Upstream transect, [c] Downstream transect, [d] air temperature (T_a) and soil temperature (T_s), and Longitudinal transect of the [e] Devils River and [f] Dolan Creek.

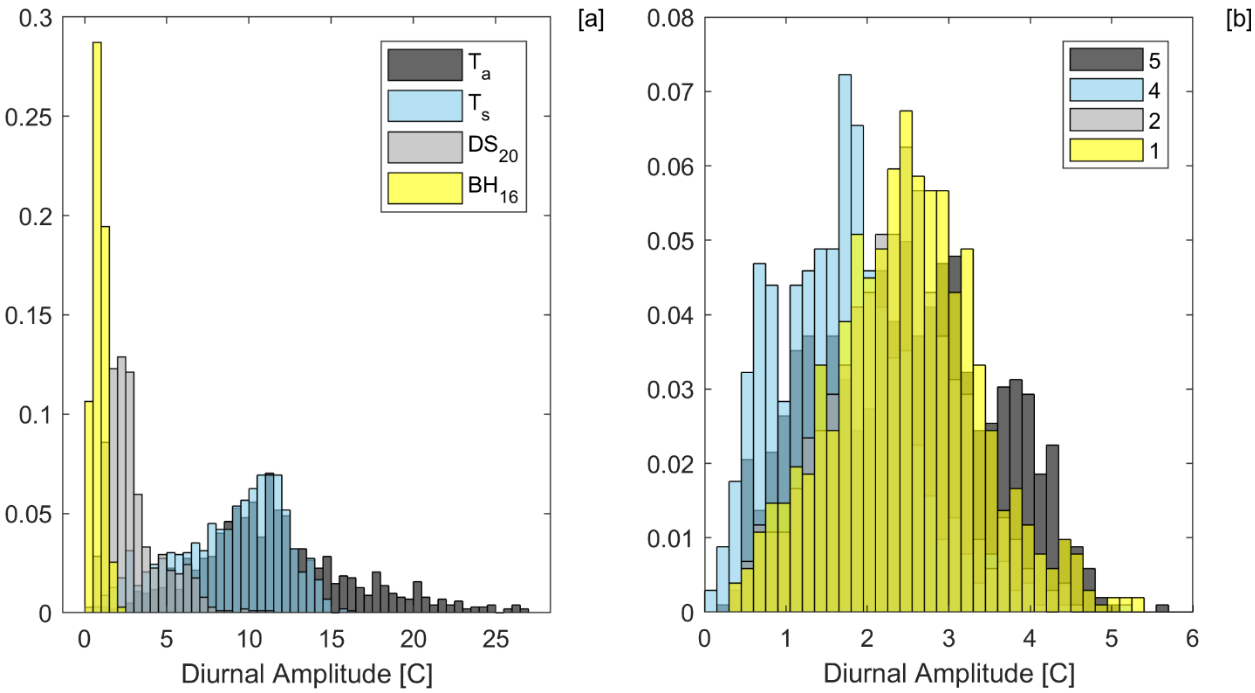

Figure 18. Histograms of daily instream temperatures amplitudes for [a] end members ranging from air temperature (T_a) to Blue Hole (BH) and [b] laterally from west bank (5) to the east (1) below Finegan Springs.

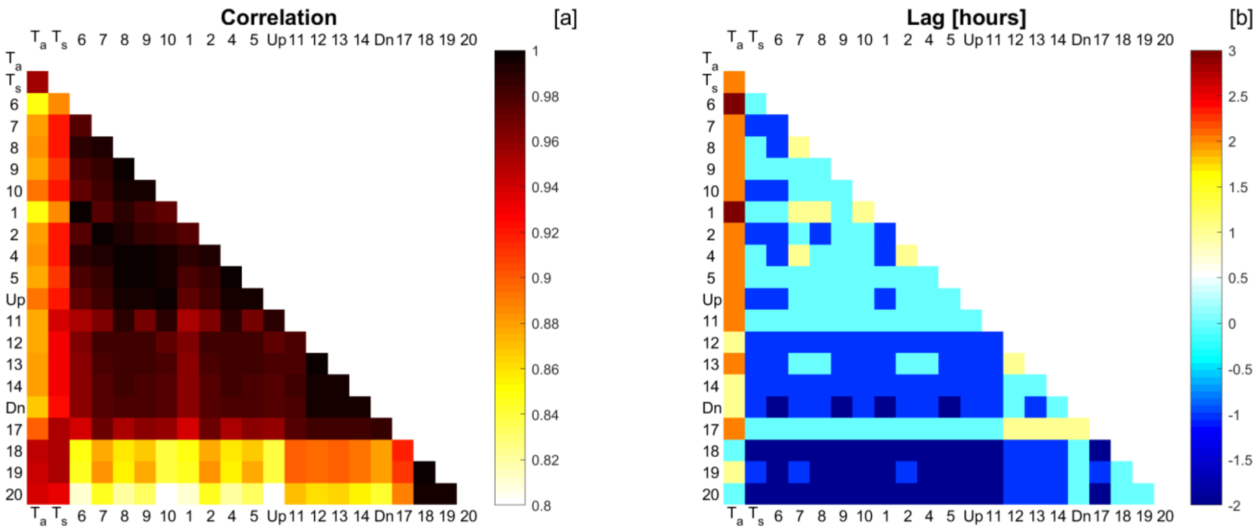

Figure 19. [a] Instream hourly temperature correlation matrix and [b] lag time in hours to reach maximum correlation over the period of record.

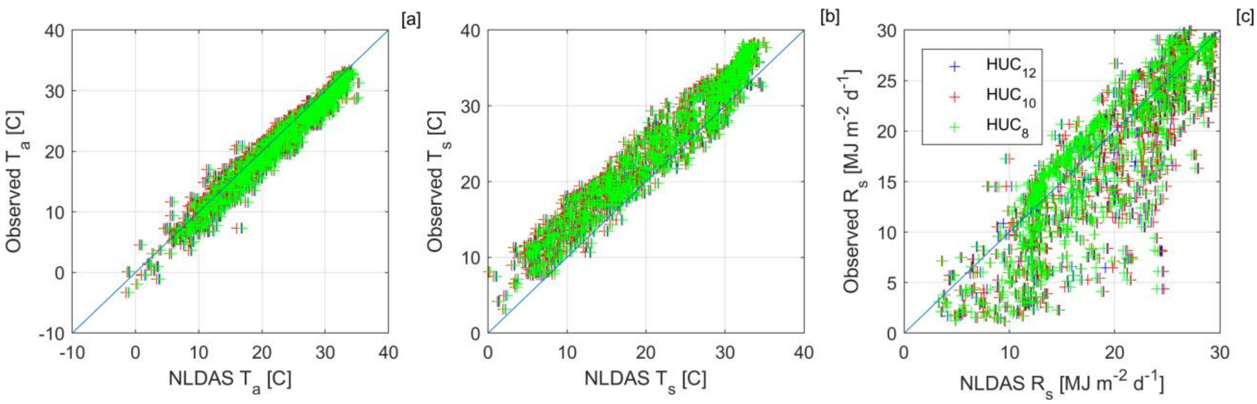

Figure 20. Comparison between the NLDAS model aggregated to HUC_8, HUC_{10} and HUC_{12} scales and observed [a] hourly air temperature (T_a), [b] hourly soil temperature (T_s), and [c] daily accumulated solar radiation (R_s).

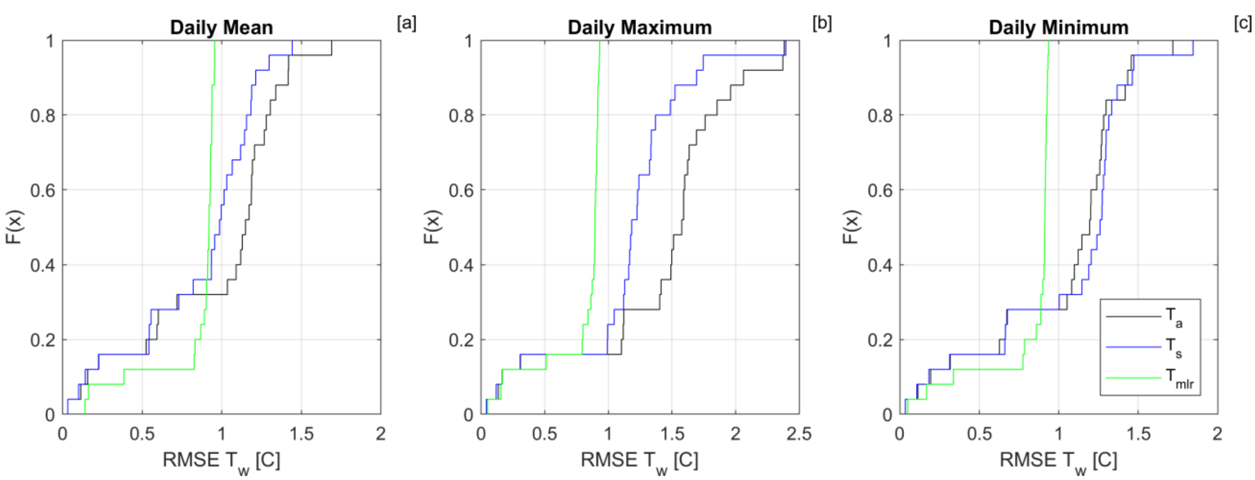

Figure 21. Cumulative distribution of linear model prediction error (RMSE) for daily [a] mean, [b] maximum, and [c] minimum water temperatures (T_w) using NLDAS air temperature (T_a), soil temperature (T_s), and multiple linear regression (T_{mlr}) at each instream monitoring location.

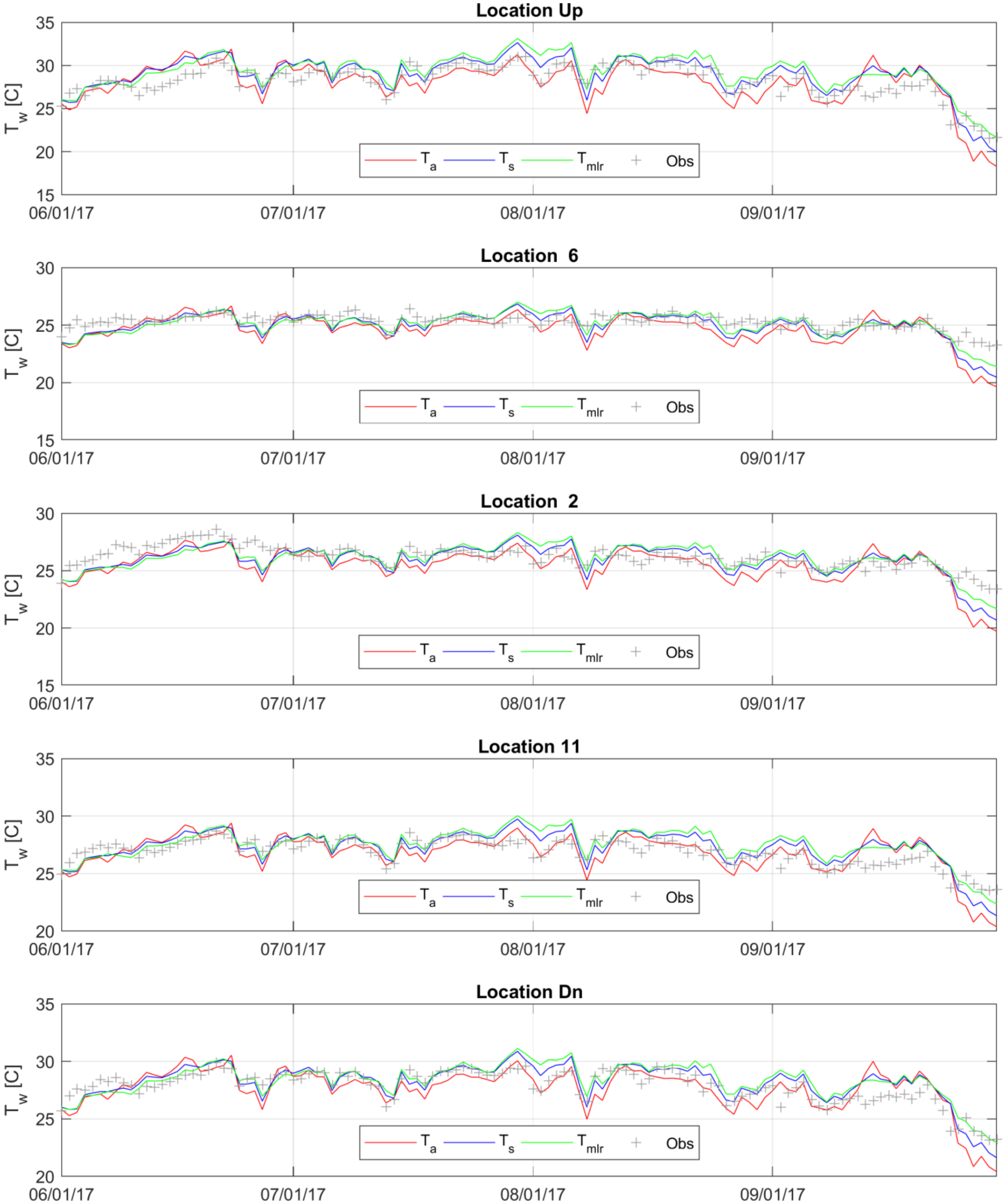

Figure 22 . Time series plot of modeled instream daily maximum temperatures (T_w) using NLDAS T_a, T_s, and T_{mlr} to predict daily at monitoring locations Upstream to Dolan Crossing.

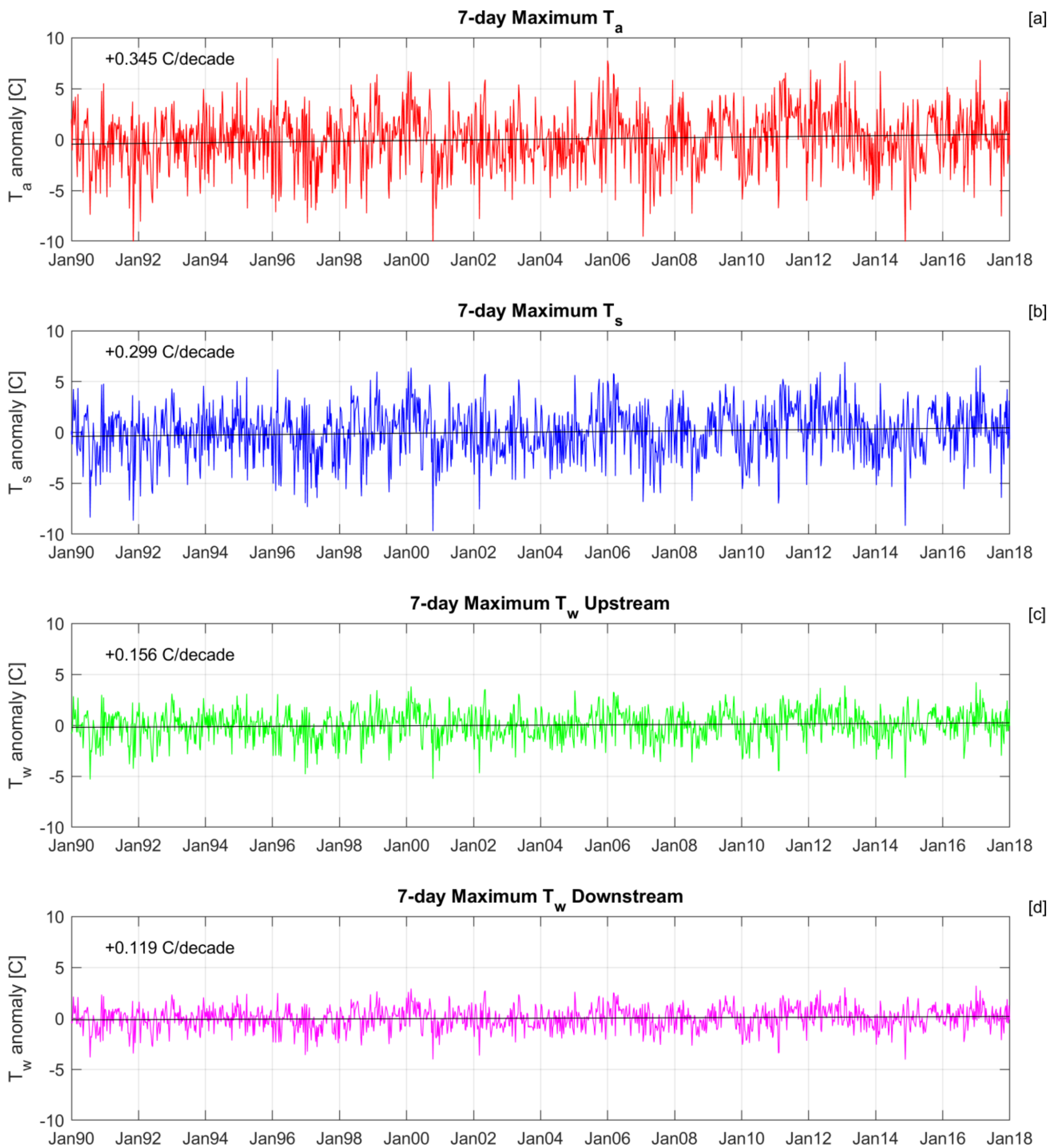

Figure 23. Long-term, 7-day temperature anomaly and decadal trend for maximum daily [a] air temperature, [b] soil temperature, [c] upstream water temperature, and [d] downstream instream water temperature based on NLDAS forcing data and multiple linear regression.

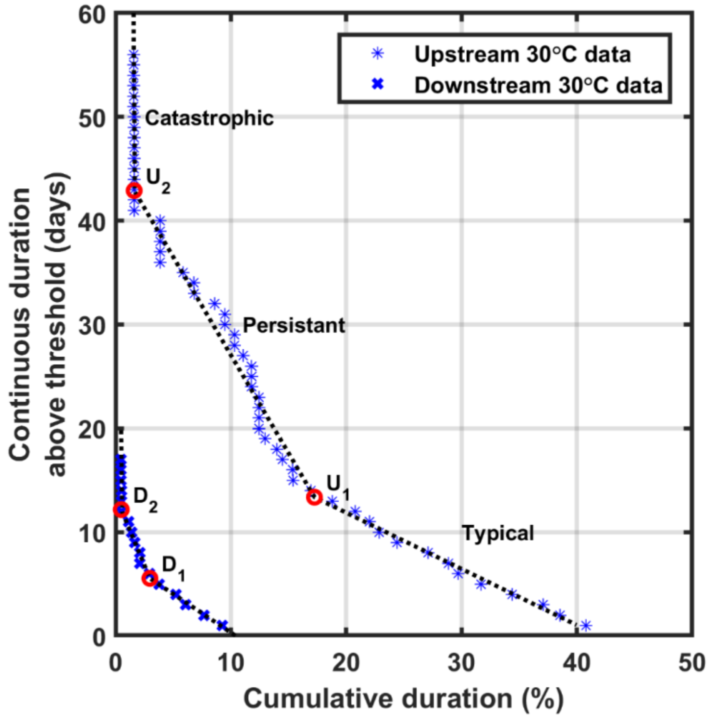

Figure 24. Example of a piecewise linear regression for June 1 –Sept 30 for the upstream and downstream location at 30 C. The dashed lines are the piecewise linear regression and the circle are the inflection points. U1 and D1 are the shortest persistent duration for the Upstream and Downstream location respectively while U2 and D2 are the longest persistent duration.

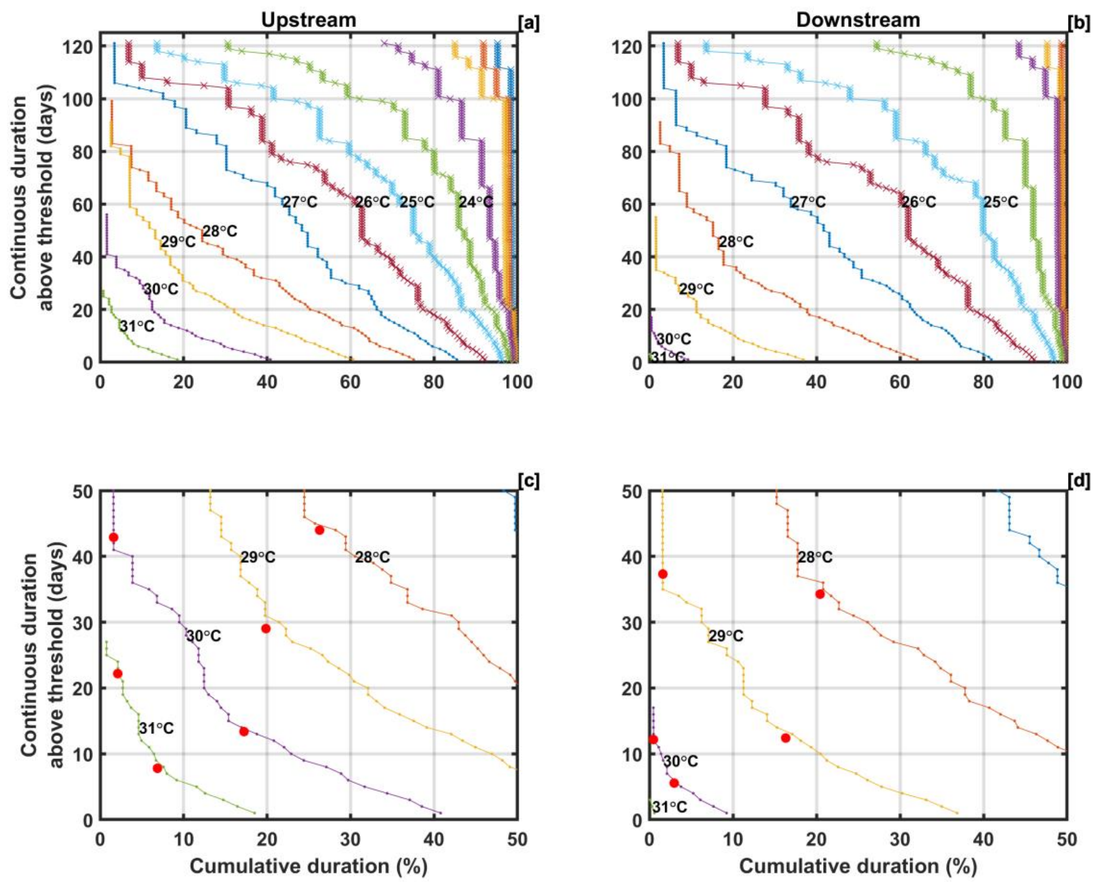

Figure 25. UCAT using data from 30-yr maximum daily T_w between June 1-Sept 30 at the upstream location and downstream locations. The lower panel [c &d] are zoomed to indicate inflection points in each probability distribution.

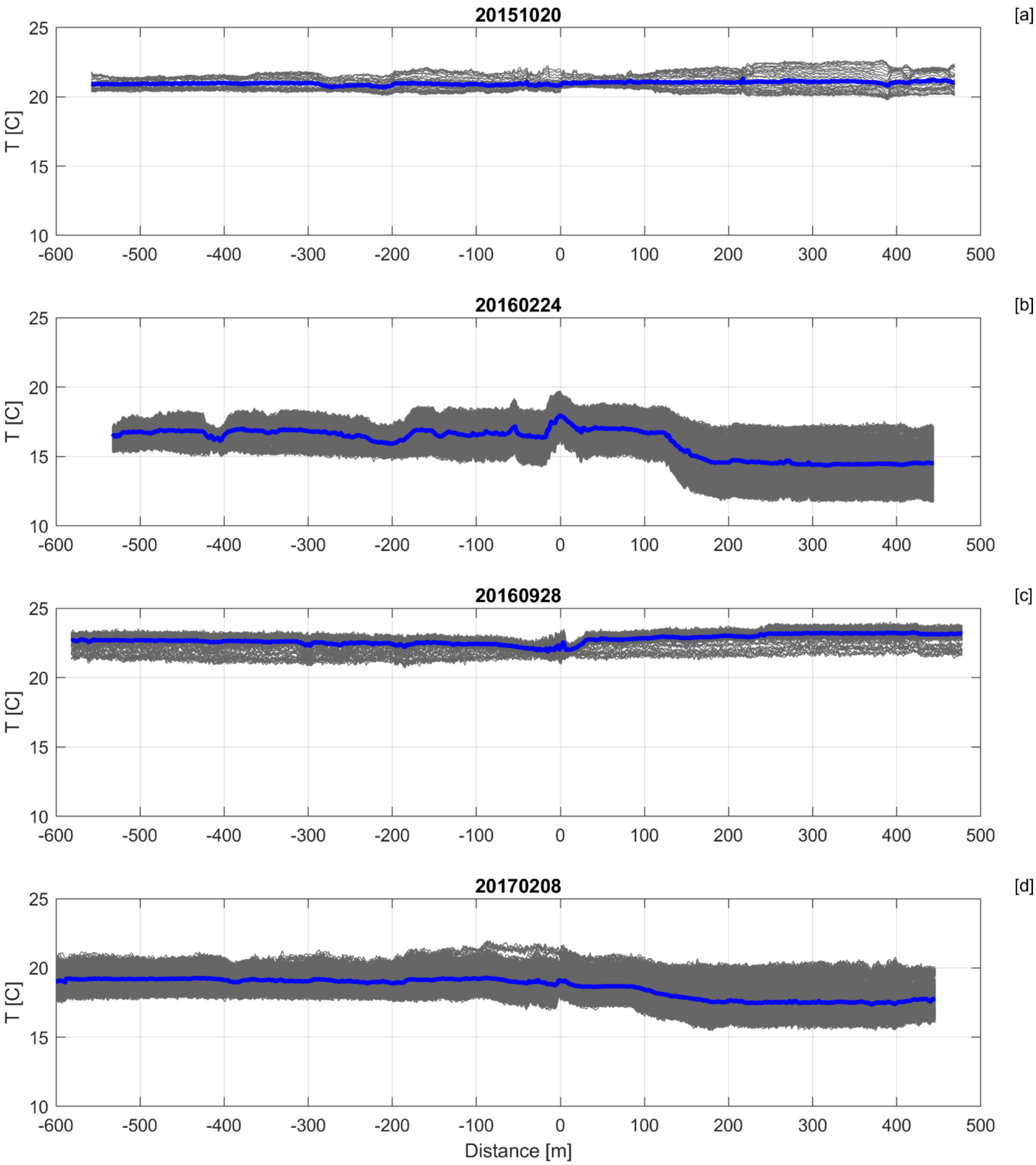

Figure 26. Instream distributed temperature sensing fiber optic measurements for [a] October 2015, [b] February 2016, [c] September 2016 and [d] February 2017. Gray lines indicate 6-minute measurements aggregated into mean (blue) for the measurement period. The origin distance (0 m) begins on the rock ledges heading ~ 400 m upstream and ~ -600 m downstream.

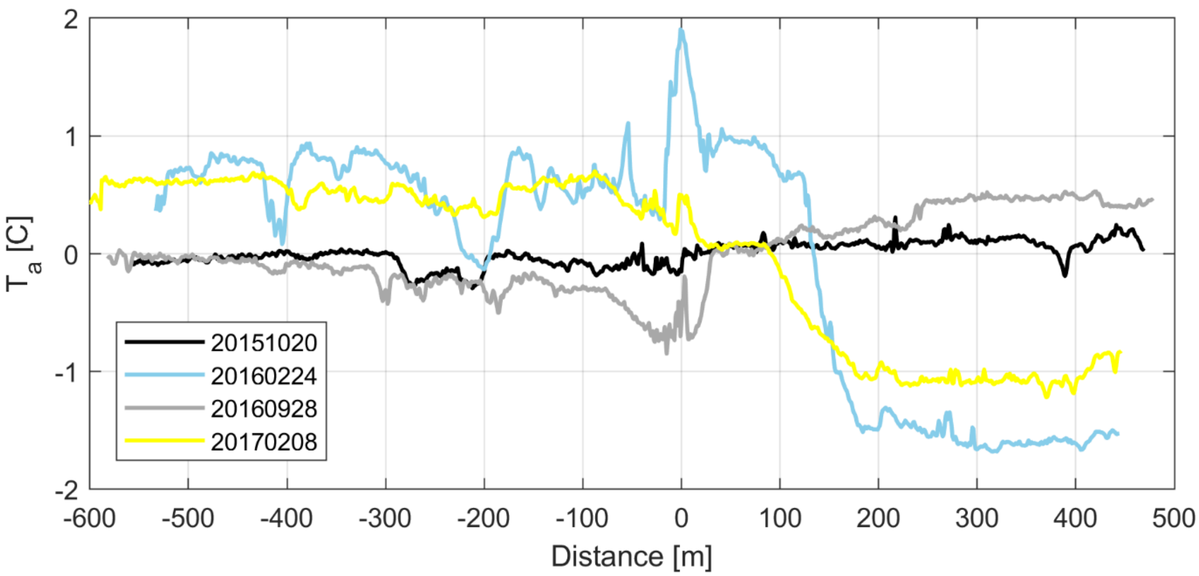

Figure 27. Mean instream distributed fiber optic temperatures anomalies for each measurement period from upstream (right) to downstream (left). Positive anomalies indicate warmer temperatures along the fiber.

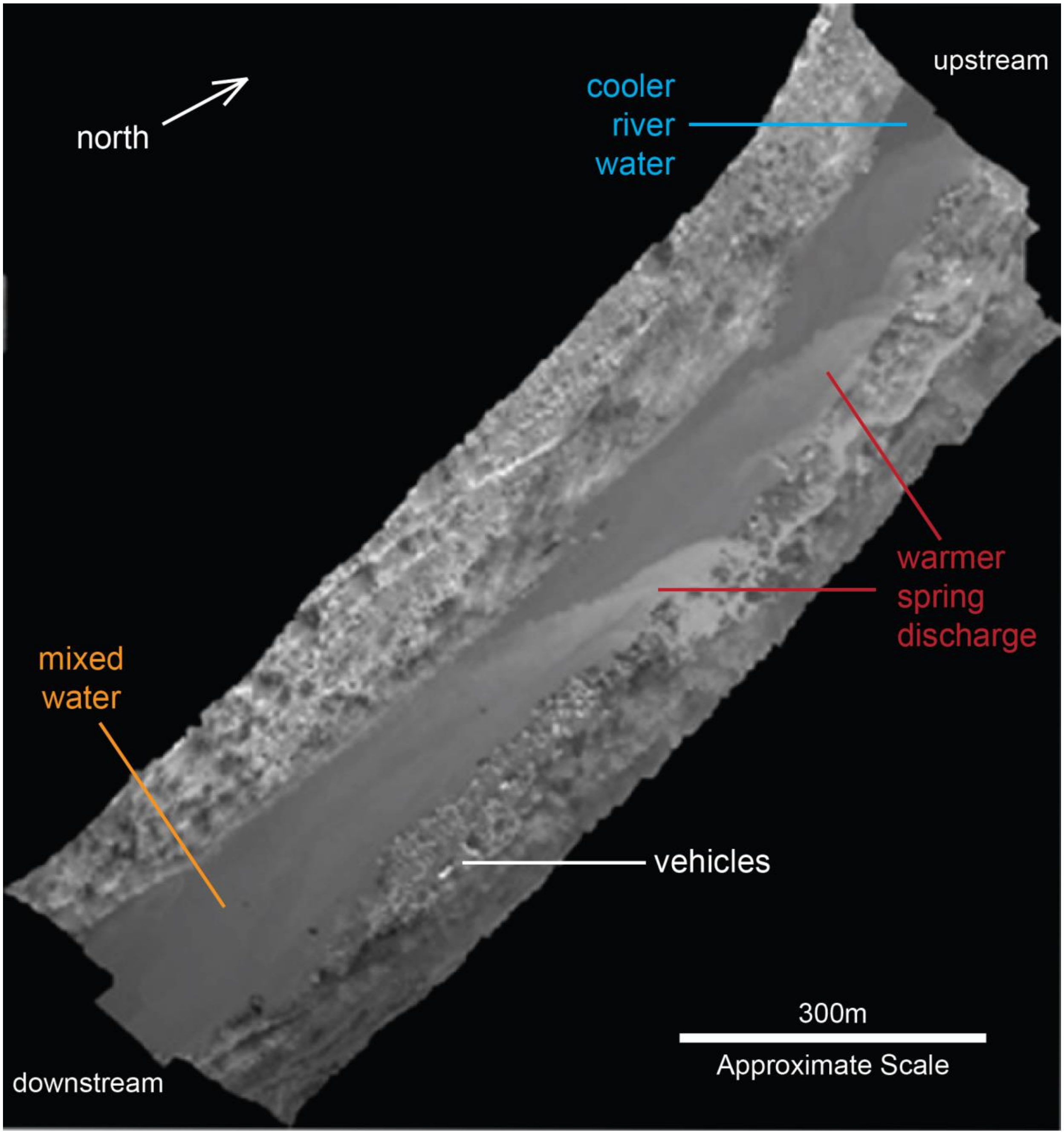

Figure 28. Thermal infrared UAS imagery of Devils River and spring run water relative surface temperature (lighter gray=warmer)

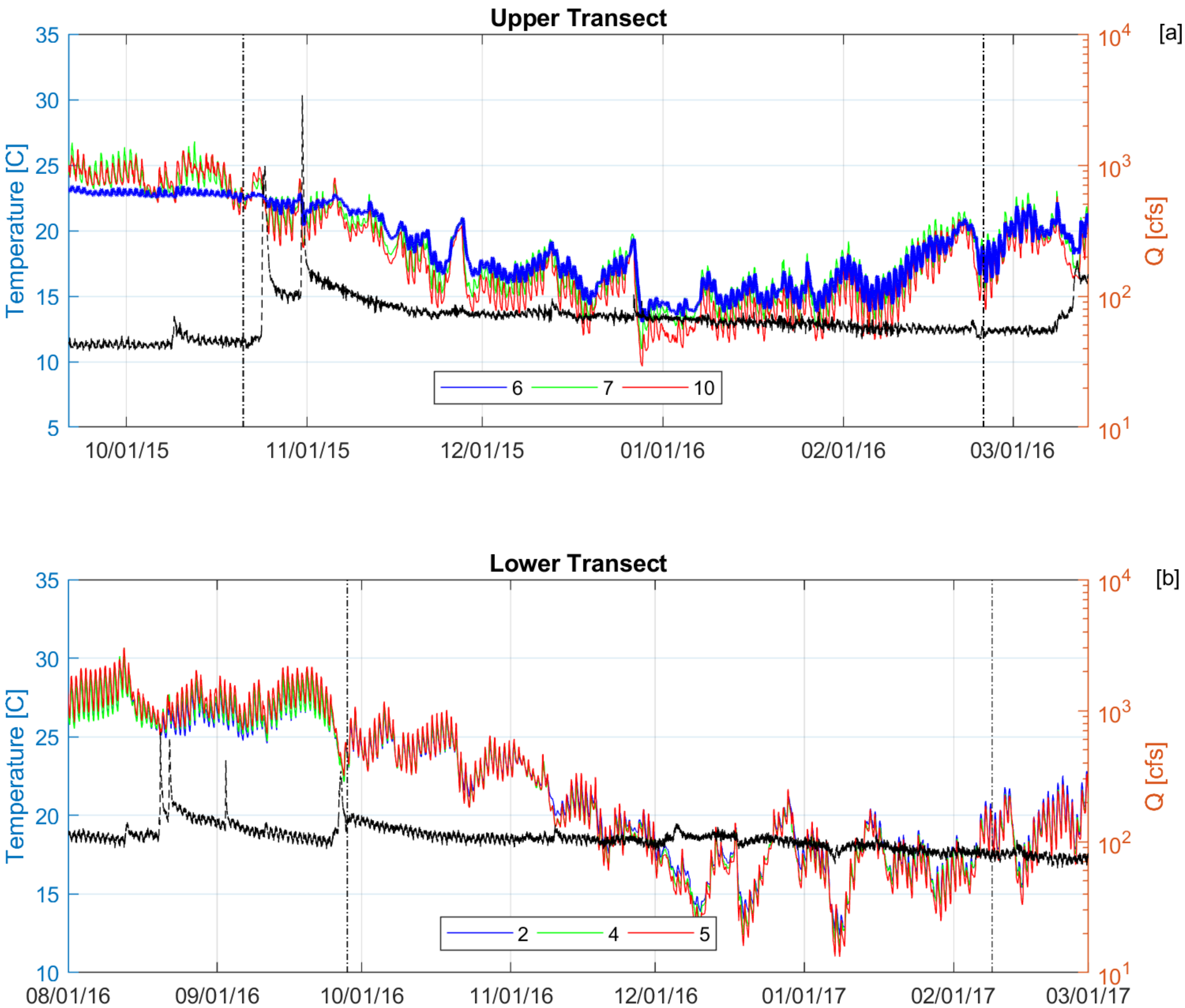

Figure 29. Instream Tw of river bottom along the (a) upper and (b) lower Tidbit transects and stream discharge at Dolan Crossing. Dashed lines denote DTS survey collection times.

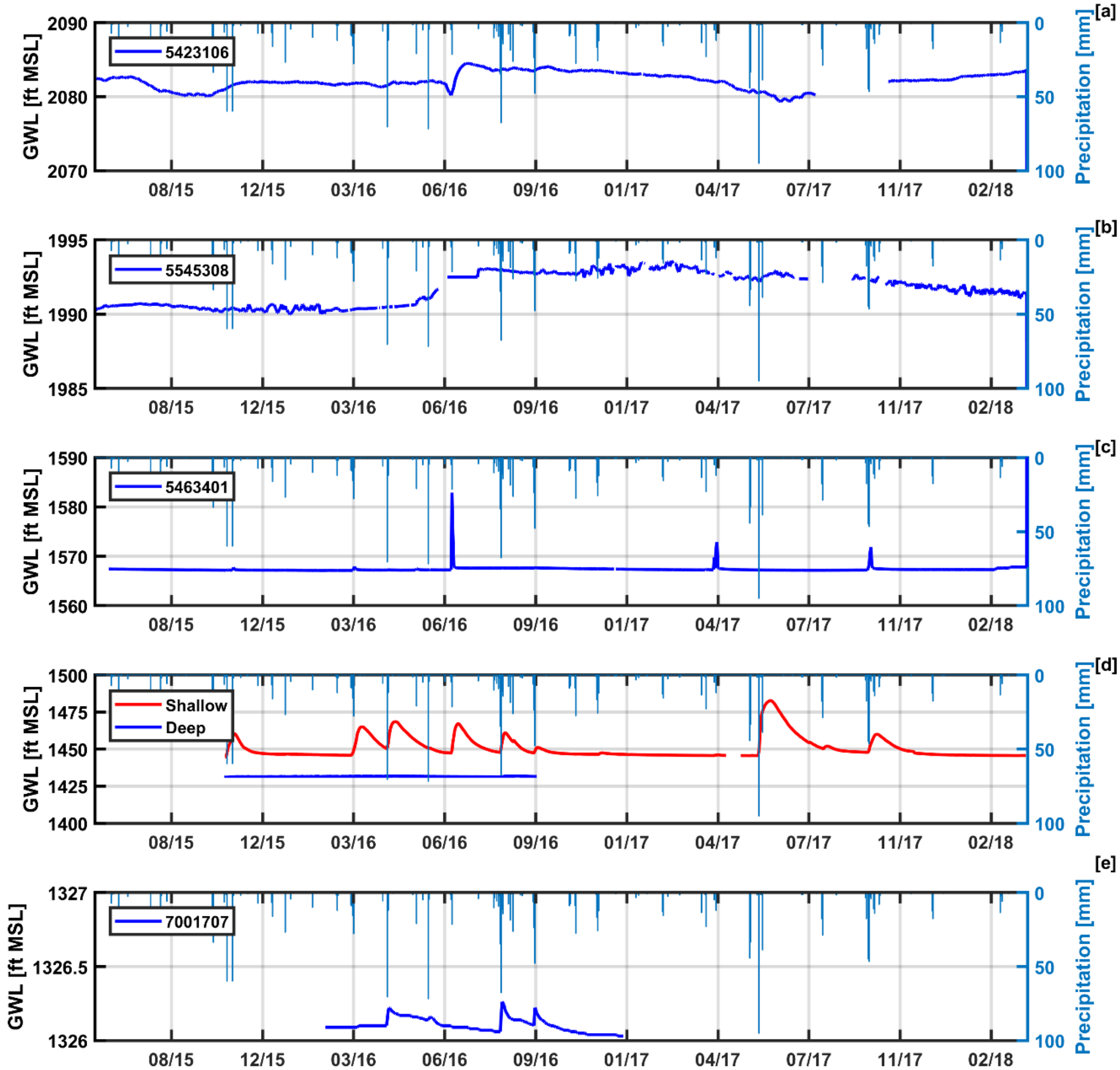

Figure 30. Groundwater levels heading downriver from [a] TWDB well 5423106 in Ozona, TX [b] TWDB well 5545308 southeast of Sonora, TX, [c] TWDB well 5463401 southwest of Juno, TX, [d] our Shallow and Deep Devils River wells in the SNA, and [D] TWDB well 7001707 near Dolan Falls.

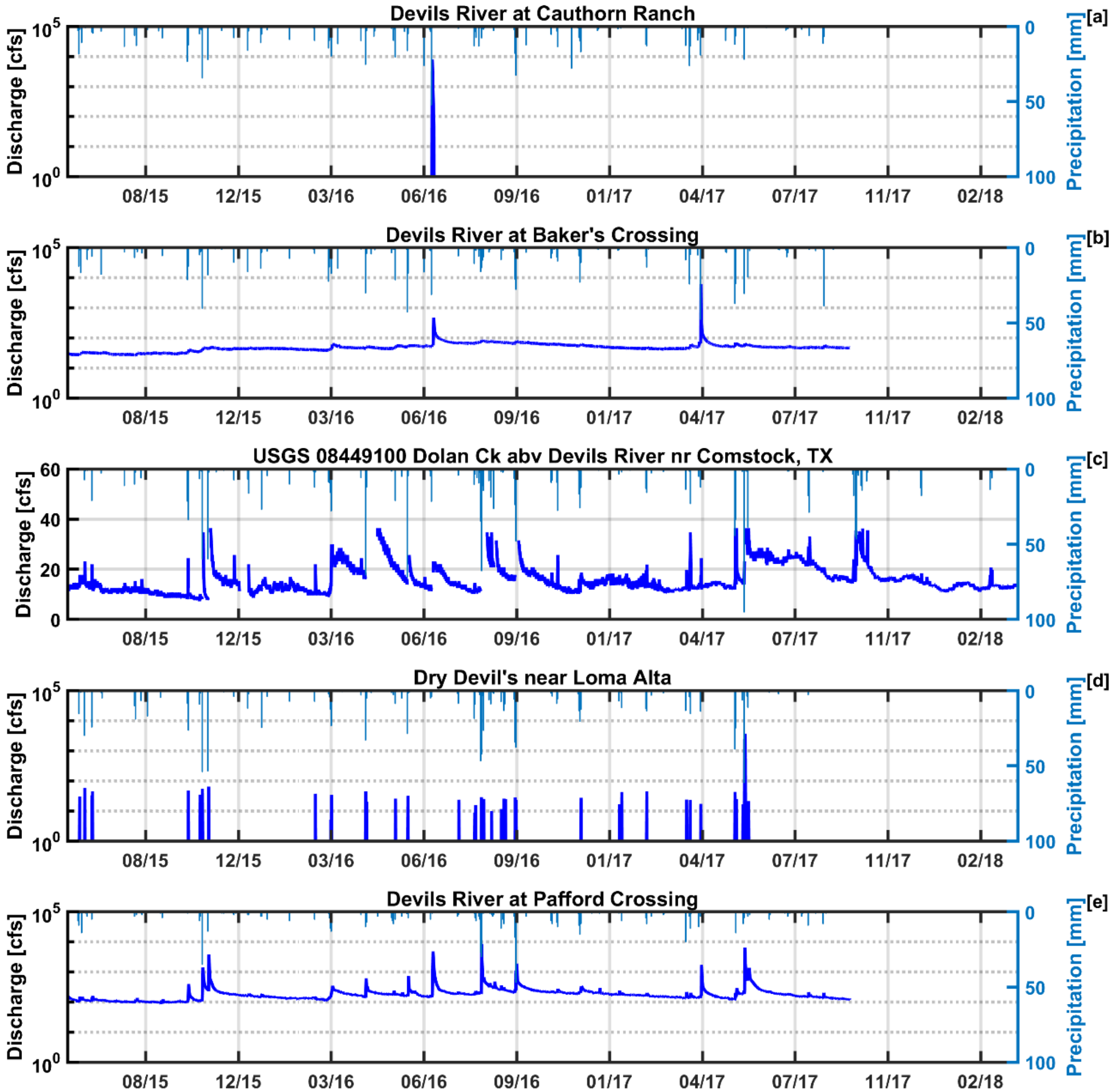

Figure 31. Downstream discharge and rainfall data at [a] Cauthorn Ranch, [b] Baker's Crossing, [c] Dolan Creek, [d] Dry Devils River, and [e] Pafford Crossing during the study period.

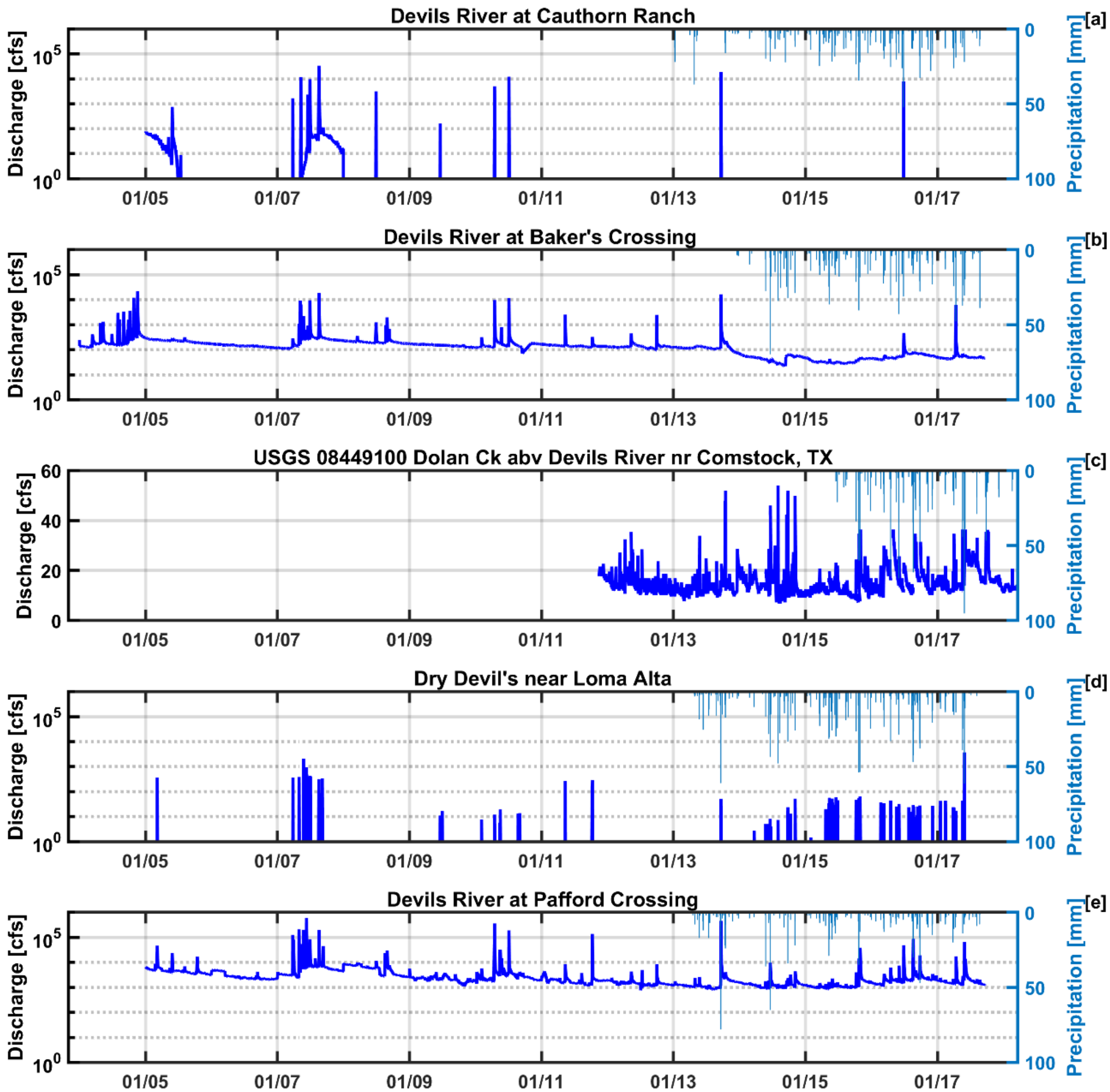

Figure 32. Downstream discharge and rainfall data at [a] Cauthorn Ranch, [b] Baker's Crossing, [c] Dolan Creek, [d] Dry Devils River, and [e] Pafford Crossing over the entire period of record.