Temperature Dynamics and Trends in Upper Klamath Basin Tributaries: Assessment of The Klamath Tribes Long-Term Thermograph Monitoring Program

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EXECUTIVE SUMMARY

Key Points

- The effect of river flow on water temperatures varies by site, with stronger effects in the warmer Sprague River and weaker effects in cool spring-dominated systems (e.g., Wood and Williamson rivers).
- Increased flow due to water rights enforcement was associated with water temperatures approximately 2 °C cooler at one of the stations assessed in this study: the North Fork Sprague River at Ivory Pine Road, but there were few detectable changes elsewhere.
- Despite curtailment of surface water diversions, measured flows at many sites remained below Klamath Tribes instream claim levels. Model predictions indicate that meeting instream flow claims would reduce temperatures in the Sprague River by up to 2–3 °C, with greatest effects in March–July and relatively little effect in August–September.
- The percentage of sites and months meeting fish suitability criteria for optimal temperature conditions were highest in the Wood and Westside sub-basins, intermediate in the Williamson and Spencer sub-basins, and lowest in the Sprague sub-basin.

Background

An understanding of water temperature dynamics in the ancestral area of the Klamath Tribes is important for several reasons: 1) thermal suitability of habitat in the Klamath Basin affects seasonal movement, production, and distribution of redband trout and bull trout, 2) pending removal of Klamath River dams will allow recolonization by cold-water anadromous fish including salmon and steelhead, and 3) irrigation curtailments due to enforcement of the Klamath Tribes senior instream water rights since 2013 have the potential to alter streamflow-temperature relationships. Our study area encompassed the Williamson, Sprague, and Wood rivers, other tributaries of Upper Klamath Lake (UKL), and Spencer Creek, a tributary to the Klamath River in Oregon (Figure ES-1).

The objectives of this study were to 1) characterize the spatial and temporal patterns and variability in water temperatures in 1993–2020, 2) assess the suitability of water temperatures to support different life stages of native anadromous and resident salmonids in 2013–2020, 3) assess changes in flow before and during water rights enforcement (multiple periods analyzed ranging from 1982 to 2021), and 4) assess changes in water temperatures before and during water rights enforcement (2003–2012 vs. 2013–2020), and 5) assess long-term water temperature trends related to climatic conditions for the periods 2003–2020 and 2012–2020. Although we do not discuss the biological importance of temperature changes occurring over the study period or due to effects of water rights enforcement, the analyses generated could be used by other scientists for such evaluations.

Data Compilation and Preparation for Analysis

We acquired hourly water temperature data from the Klamath Tribes for 2003–2020 (years vary by site), supplemented by data from the U.S. Geological Survey (2005–2020), U.S. Bureau of Land Management (2001–2014), U.S. Forest Service (1993–2012), and Oregon Department of Environmental Quality (1999–2004). Following an extensive quality control process, we paired temperature data from 66 sites (Figure ES-1) with streamflow, air temperature, and April 1 snowpack. We focused on daily maximum temperatures (T_{max}) but in some case also assess daily mean temperatures (T_{mean}).

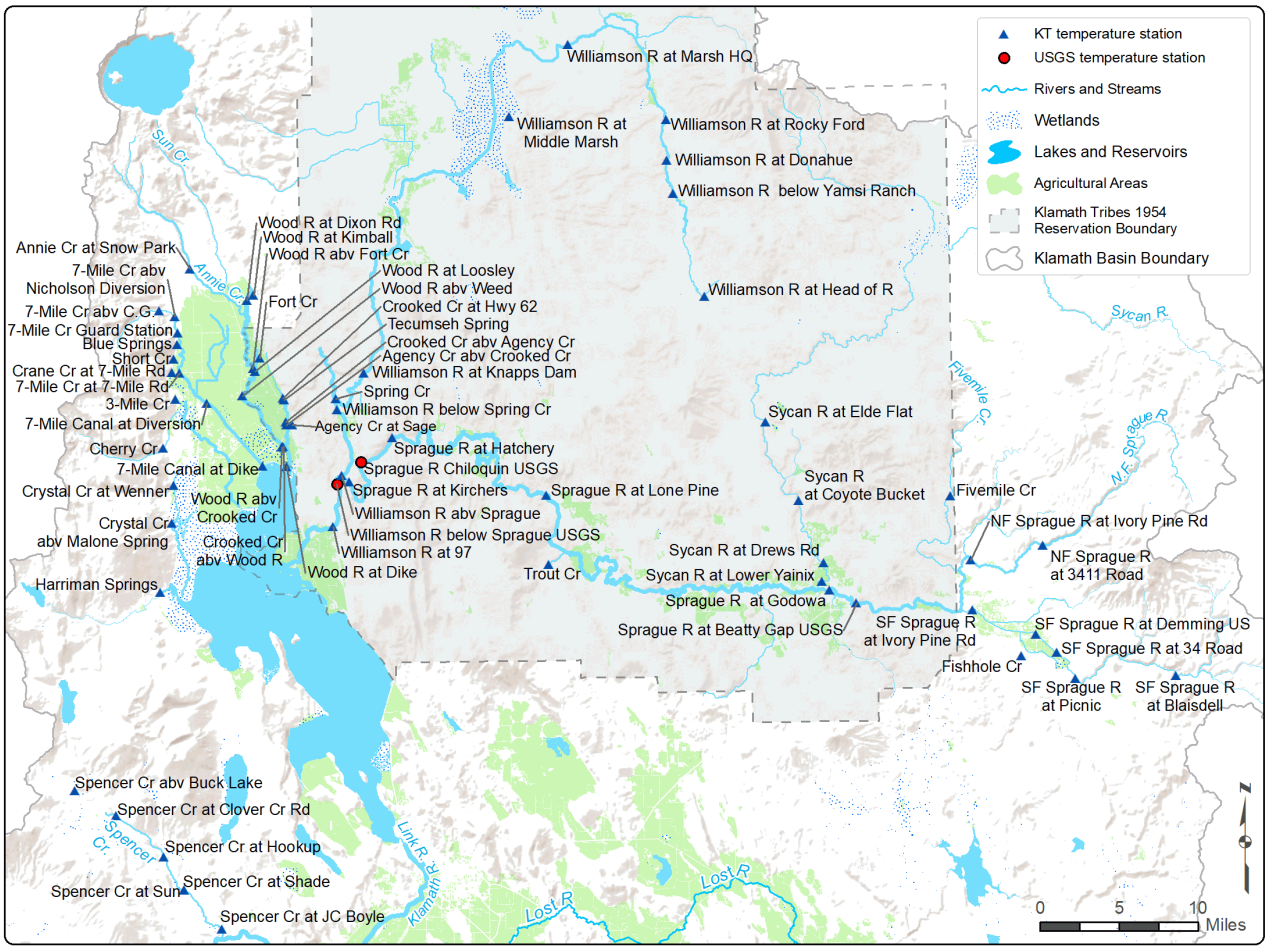

Figure ES-1. Map showing locations of the Klamath Tribes and USGS temperature monitoring stations.

Where and when does flow affect water temperatures?

To determine where and when flow affects water temperatures, we categorized all available 1993–2020 temperature records for each site and day of year (1 to 366) into three flow categories (high, medium, and low) and compared temperatures among categories. Flow effects on T_{max} substantially differed among sites and months (Figure ES-2). Sites close to major spring sources (including Spring Creek, head of Williamson River, Wood River at Dixon Rd, Agency Creek at Sage, Tecumseh Spring, and many Westside springs) have near-constant temperatures that vary little regardless of flow or month. Wood River stations generally showed the least temperature variation among flow categories. At the opposite extreme are Spencer Creek sites where during early July, T_{max} was approximately 4 °C warmer under low flow conditions than under high-flow conditions. At sites in the Sprague River and its largest tributaries including Sycan River, late May temperatures were up to 2–6 °C warmer under low flow conditions than under high-flow conditions, with greatest effects at the South Fork Sprague River at Picnic station. Temperature was also consistently higher under low flow conditions at North Fork Sprague River at Ivory Pine Rd. from April through October. A few sites show the opposite pattern, including Williamson River below Sprague where summer temperatures are cooler in low-flow conditions than in high-flow conditions, due to less dilution of Spring Creek's constant cold water by the warmer Sprague River.

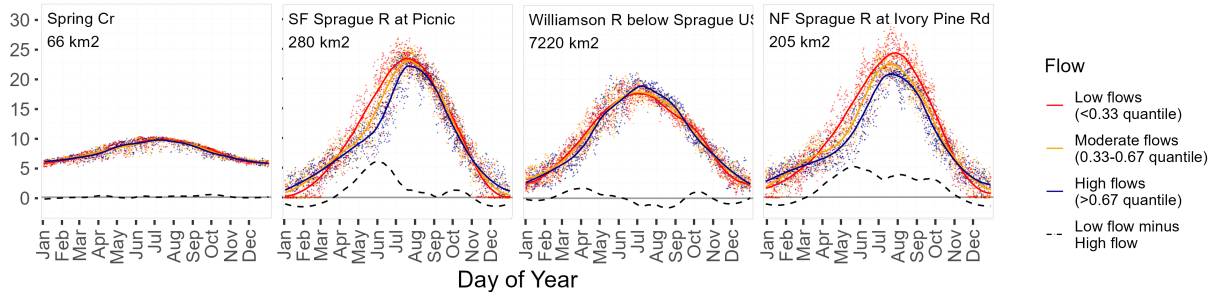

Figure ES-2. Measured T_{max} for dates when flow was low, typical, or high (shown by color) at four example long-term monitoring sites. Lines are GAM smoothers fit to points, shown as visual aids. Dashed black lines are the temperature difference between low-flow and high-flow conditions.

Effect of water rights enforcement on flows

To assess the effects of water right enforcement on flows, we summarized previous literature and conducted original analyses. Previous analyses, most of which evaluated the first few years of regulation, found that regulation increased flows in the Sprague River approximately 50 cfs, which is several times lower than estimates of total agricultural consumptive use in the pre-regulation era, suggesting either widespread non-compliance with the curtailments (i.e., unauthorized irrigation), increased groundwater withdrawals affecting surface flows, an overestimation of ET by Risley (2019), and/or that the effects of the curtailments have been underestimated. Walker and Kann (2022a) found that this flow increase appears to have originated almost entirely from the North Fork Sprague River, likely due to changes in operation of a single diversion.

To isolate the effect of water rights enforcement, climatic differences between the pre-regulation era and regulation era must be accounted for. To guide our analyses, we defined the "pre-regulation" era as 2003–2012 and the "regulation" era as 2013–2021 for flow analyses and 2013-2020 for temperature analyses because 2021 temperature data were not yet available. Many sites indicated generally earlier peak flows and lower April and May flows in the regulation era than in the pre-regulation era, suggesting a warmer and drier climate during the regulation era. That the adjacent unregulated Chewaucan and Rogue rivers showed similar earlier and lower spring peak flows during the regulation era provides support for those trends being climate driven. Despite generally lower flows during the spring, some sites in the Wood, Sprague, Sycan, and lower Williamson rivers had higher summer flows in the regulation era, indicating regulation-driven effects (Figure ES-3; see pre-regulation years [grey lines] generally below those of the regulation years [colored lines] during August and September at the Sprague River at Chiloquin example location). In this case Chewaucan River and Rogue River summer flows were lower during the regulation era providing strong evidence that higher flows in the Sprague River were regulation-driven. In addition, linear relationships between snowpack and precipitation with gauged flow in the lower Sprague and Williamson rivers indicated that the amount of annual flow produced for a given amount of snowpack or precipitation was generally higher during the pre-regulation era compared to the regulated era, whereas the opposite occurred for August flow especially in drier years (see Figure 16 in report). That regulation era flows in August were higher than pre-regulation flows for a given amount of snowpack or precipitation supports the idea that flow increases were regulation-driven for the Sprague and lower Williamson systems. For both August and annual periods, Wood River flows were consistently higher during the regulation era than the pre-regulation era for given snowpack or precipitation quantities, also indicating a likely effect of regulation.

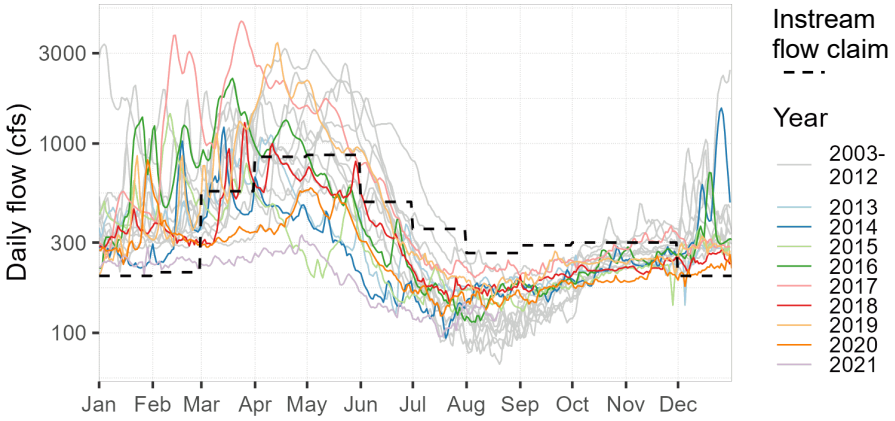

Figure ES-3. Annual USGS hydrographs and Klamath Tribes instream claim for years in pre-regulation (2003–2012) and regulation eras (2013–2021) at Sprague River at Chiloquin (gage 11501000, instream claim 641)

Comparison of water temperatures in pre-regulation and regulation eras and the potential effect of water rights enforcement

With the exception of North Fork Sprague River at Ivory Pine Road, measured data and models indicated little thermal effects of water rights enforcement. An evaluation of model residuals (see report Figure 20) and comparison to measured temperatures at sites relatively unaffected by regulation (Figure ES-4) showed that T_{max} and T_{mean} were approximately 2 °C cooler during the regulation era than in the pre-regulation era at North Fork Sprague River at Ivory Pine Road. This site is located several miles downstream of a major diversion that was frequently curtailed during the regulation era, and identified by Walker and Kann (2022a) as the area with the largest regulation-driven flow change in the Sprague River.

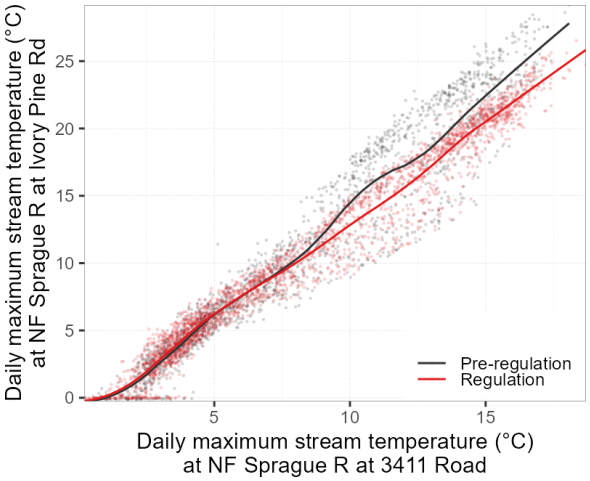

Figure ES-4. Comparison of measured T_{max} at North Fork Sprague River at Ivory Pine Road and at North Fork Sprague River at 3411 Road (a site relatively unaffected by regulation) in the pre-regulation and regulation eras. Lines are LOESS smoothers fit to daily points, shown as visual aids.

Despite curtailment of surface water diversions during the regulated era, measured flows at many sites frequently remained below the levels specified by instream claims (Figure ES-3). We used a generalized additive model (GAM) to predict the difference in T_{max} between a scenario using measured flows (the same data the model was calibrated with) to a scenario in which flows were held at or above the instream claims. For sites where flow was empirically shown to have relatively little effect on temperatures (i.e., Wood and Williamson sub-basins—see Figure ES-2 and report Figure 11 and Figure 12), the model predicted that meeting instream claims would have little effect on temperatures (<1.0 °C, see report Figure 18a). Likewise, where flow was empirically shown to have greater effects on temperatures (i.e., Sprague River sub-basin), our model predicted that temperatures would cool up to 2–3 °C if instream claims could be met

(Figure ES-5). For the Sprague and Sycan systems the greatest cooling effects of meeting claims were predicted in March–July, likely due to a combination of those being the months when instream claims are higher and flow has greater effects on temperature. However, we acknowledge that our modeling approach does not differentiate between climate-driven flow variation (e.g., high summer flows due to high spring snowpack) and regulation-driven flow variation (e.g., high summer flows due to less diversions for irrigation), which may have different effects on temperatures—the model represents total flow and was calibrated based on all available dates. While greatest differences in flow between the pre-regulation and regulation era in the Sprague River occurred in August and September, similar to the smaller effect of flow on temperatures empirically observed later in the summer, our models also predicted that meeting instream claims in those months would decrease temperature <1.0 °C.

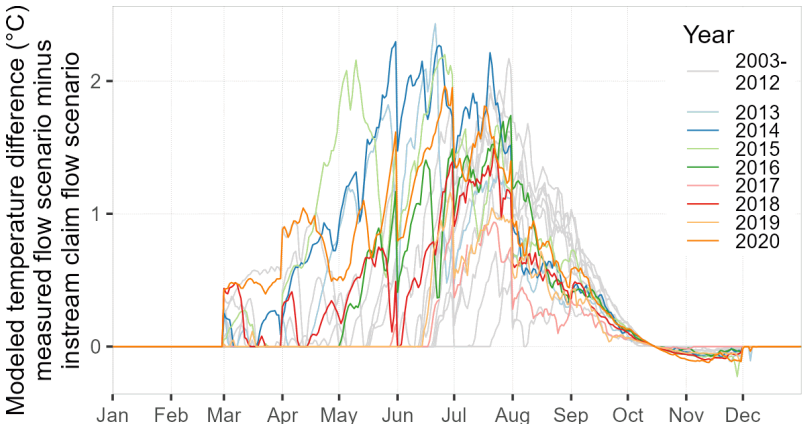

Figure ES-5. Modeled temperature differences between a scenario using measured flows and a scenario using the greater of measured flows or Klamath Tribes instream flow claims, for each day with measured temperatures and flow 2002–2021 for the Sprague River at Chiloquin station.

Finally, although empirical and modeling results indicated that increased flow had relatively little effect on in-stream temperatures in the Wood River system, remotely sensed July surface water temperatures indicated that increased Wood River flow rate during the regulated era was associated with expansion of the Agency Lake thermal refuge area important for redband trout in the Upper Klamath Lake system (Figure ES-6).

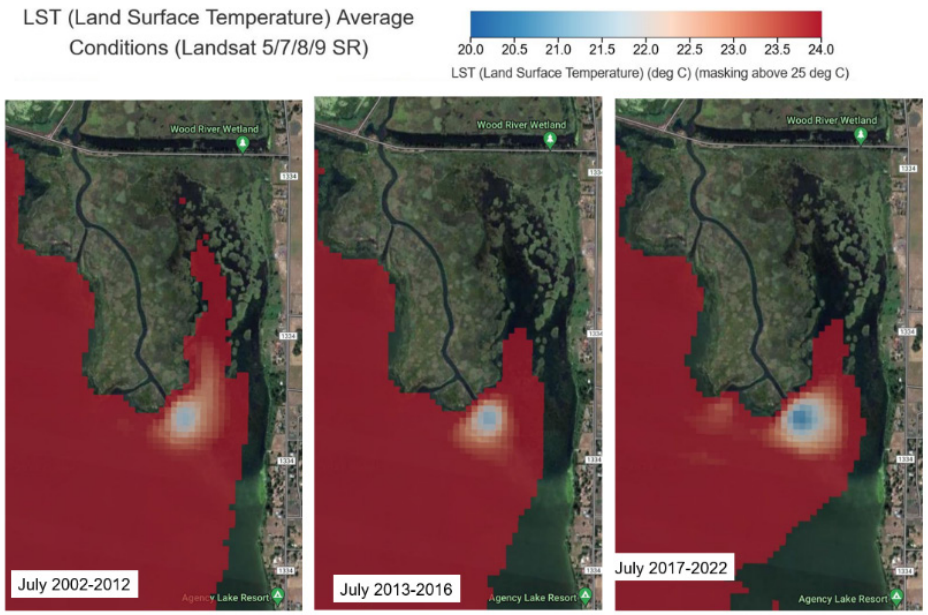

Figure ES-6. Remote-sensed mean July surface water temperatures where the Wood River enters Agency Lake for three time periods: July 2002-2012 (pre-regulation), 2013-2016 (partial regulation), and 2017-2022 (full regulation). Values represent the average of all cloud-free 30-meter resolution pixels for the month of July.

Long-term trends in water temperatures

We used linear mixed-effects models and regression models to calculate slopes (°C/decade) of monthly temperature trends at individual sites and all sites collectively, from 2003 to 2020 at 17 sites only in Sprague River and Spencer Creek, and from 2012 to 2020 at 30 sites. For the 2003–2020 period, slopes for all sites collectively were greatest (i.e., more rapid temperature increases) in the months of April, May, and June (Figure ES-7); however, temperatures during these months were highly variable from year to year and strength of evidence is weak at individual sites. For all sites collectively from 2003–2020 only the October slope indicated a cooling trend, but for 2012 to 2020 July through November slopes indicated cooling trends (see report Figure 22b).

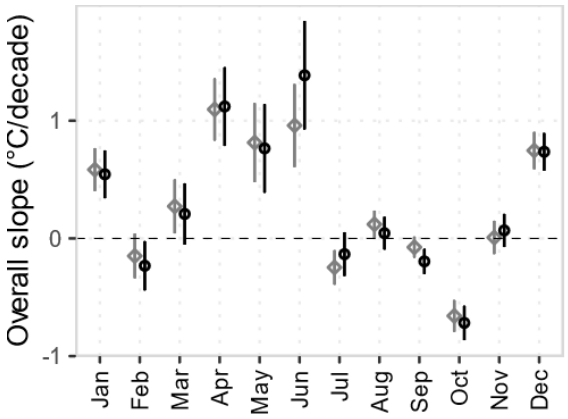

Figure ES-7. Overall slopes for monthly mean and monthly mean daily maximum temperature for 2003–2020 derived from 17 sites. Bar ends are 95% confidence intervals. Positive slopes indicate month that increased during the study period while negative slopes indicate months that decreased during the study period

Biological suitability

To assess thermal suitability for fish habitat, for each site we compared the 7-day average of daily maximum (7DADM) temperatures to criteria adapted from Dunsmoor and Huntington (2006) and ODEQ (2022) for: 1) adult chinook and steelhead migration, 2) juvenile chinook rearing, 3) juvenile steelhead rearing, 4) salmon and steelhead spawning, and 5) bull trout spawning and juvenile rearing. The percentage of sites and months meeting criteria for optimal conditions were highest in the Wood and Westside sub-basins, intermediate in the Williamson and Spencer sub-basins, and lowest in the Sprague. Figure ES-8 shows criteria for juvenile chinook rearing.

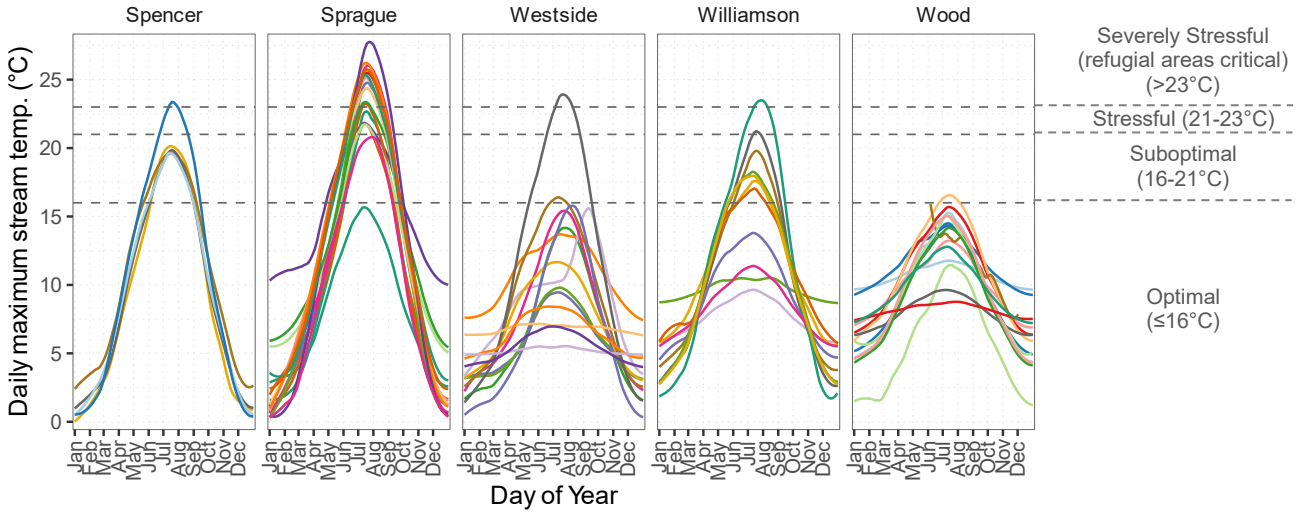

Figure ES-8. Temperature suitability for juvenile chinook salmon rearing at 64 sites, based on suitability categories adapted from Dunsmoor and Huntington (2006). Each line represents long-term averages (loess smoother, fit to all available days in the regulation era [6/17/2013-12/31/2020]) for an individual site, assigned a random color. Sites with <100 days of data are excluded.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 DESCRIPTION OF STUDY AREA

Our primary study area includes the Williamson River, Sprague River, and Wood River tributaries of Upper Klamath Lake (UKL), Oregon (Figure 1). In addition, we also include the watershed of Spencer Creek, a tributary to the Klamath River. Descriptions of the geology, climate, land cover, land use, and aquatic habitats of the Upper Klamath Basin are available in the *Upper Klamath Basin Watershed Action Plan* (UKBWAP Team 2021), *Klamath Basin Integrated Fisheries Restoration and Monitoring Synthesis Report* (ESSA 2017, ESSA and Klamath Basin Working Groups 2023), *Lower Sprague-Lower Williamson Watershed Assessment* (Rabe and Calonje 2009), and *Upper Sprague Watershed assessment* (Snyder et al. 2007), *Klamath Reservoir Reach Restoration Prioritization Plan* (O'Keefe et al. 2022), and *Spatial and Temporal Nutrient Loading Dynamics in the Sprague River Basin* (Walker and Kann 2022a).

1.2 PREVIOUS STREAM TEMPERATURE ASSESSMENTS

Water temperatures have long been identified as an important factor influencing seasonal movement, production, and distribution of redband trout and bull trout within the study area, and have been a priority for fisheries management and research (ODFW 1997). The proposed removal of the Klamath Hydroelectric Project dams downstream of our study area would allow anadromous fish including steelhead and chinook to recolonize tributaries of the Upper Klamath Basin, providing further motivation to understand water temperature conditions. Some rivers and streams in the project area are listed as impaired under the Clean Water Act Section 303(d) for temperature, and Oregon Department of Environmental Quality has established Total Maximum Daily Loads for the Williamson River and its tributaries including the Sprague River (ODEQ 2002; Watershed Sciences 2000) and Spencer Creek (ODEQ 2019, Watershed Sciences 2002). In addition to the TMDLs, previous assessments of stream temperatures within the study area include thermal infrared surveys (Watershed Sciences 2000, 2002, 2008; ODEQ 2002), bull trout studies (Buchanan et al. 1997, Light et al. 1996, Benjamin et al. 2016), redband trout studies (Armstrong et al. 2021, Hahlbeck 2021, Hahlbeck et al. 2022), salmon reintroduction assessments (Dunsmoor 2012, Huntington and Dunsmoor 2006, Ramos 2020, ODFW and the Klamath Tribes 2021, Ramos and Ward 2023), watershed assessments (David Evans and Associates, Inc. 2005, Rabe and Calonje 2009, Snyder et al. 2007), habitat restoration planning (O'Keefe et al. 2022), modeling (Friedrichsen et al. 1996), and analysis of climate effects and long-term trends (Asarian et al. 2020).

In addition to the local analyses mentioned in the previous paragraph, the NorWeST[1] stream temperature model used observed temperature data, Geographic Information Systems (GIS) data, and a multivariate spatial statistical model to produce a spatially continuous prediction of mean August temperature throughout the entire stream network (Chandler et al. 2016; Isaak et al. 2016, 2017), later expanded to all 12 months (FitzGerald et al. 2021).

[1] http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

1.3 THE KLAMATH TRIBES WATER RIGHTS

After several decades of legal and administrative proceedings, the Klamath Tribes were first able to enforce their senior instream water rights to UKL tributaries in 2013 (Wood 2019, NARF 2021). These instream claims vary by location and date, with components for physical habitat, riparian habitat maintenance, and structural habitat maintenance (ACFFOD 2014). The compliance points for these claims are located within the Klamath Tribes' 1.8 million-acre 1954 Reservation boundary (Figure 1), but diversions upstream of these boundaries are also subject to curtailment.

The Upper Klamath Basin Comprehensive Agreement (UKBCA) was signed by the Klamath Tribes, Upper Klamath Basin irrigators, and state and federal agencies in April 2014. In the UKBCA, in exchange for a Tribal Economic Development Fund and landowners agreeing to a Water Use Program (WUP) and Riparian Program, the Klamath Tribes agreed to not enforce their full instream claims. From 2014 through 2016, instream flows were regulated to the UKCBA's Specified Instream Flows (SIF). By early 2017 interim milestones of the UKBCA were not achieved and the Klamath Tribes requested that OWRD fully enforce their determined water rights. Timelines of water rights enforcement are discussed in more detail in Section 2.9.1 below. In this report, we use several different terms interchangeably to describe this issue: water rights enforcement, flow regulation, and irrigation curtailments.

1.4 STUDY OBJECTIVES

The objectives of this study were to 1) characterize the spatial and temporal patterns and variability in water temperatures in 1993–2020, 2) assess the suitability of water temperatures to support different life stages of native anadromous and resident salmonids in 2013–2020, 3) assess changes in flow before and during water rights enforcement (multiple periods analyzed ranging from 1982 to 2021), 4) assess changes in hydrology and water temperatures before and during water rights enforcement (2003–2012 vs. 2013–2020), and 5) assess long-term water temperature trends related to climatic conditions for the periods 2003–2020 and 2012–2020. Although we do not discuss the biological importance of temperature changes occurring over the study period or due to effects of water rights enforcement, the analyses generated could be used by other scientists for such evaluations.

2 METHODS

2.1 STREAM TEMPERATURE DATA SOURCES ACQUIRED AND COMPILED

Stream temperature data for the years 1993 through 2020 were acquired from the Klamath Tribes and other sources (Figure 2, Figure 3, Figure 4).

2.1.1 KLAMATH TRIBES AMBODAT (FORMERLY DEPARTMENT OF NATURAL RESOURCES AQUATICS PROGARAM)

We acquired water temperature data from the Klamath Tribes (KT) at 64 stations across from 2003–2020. Onset Stowaway® or Hobo Pro® loggers were used to collect water temperature data hourly, resulting in nearly four million records collected over seventeen years. Standard operating procedures for data collection are described in KTRS (2016) and include pre- and post-deployment calibration using a National Institute of Standards and Technology-certified thermometer (Dunsmoor 2012).

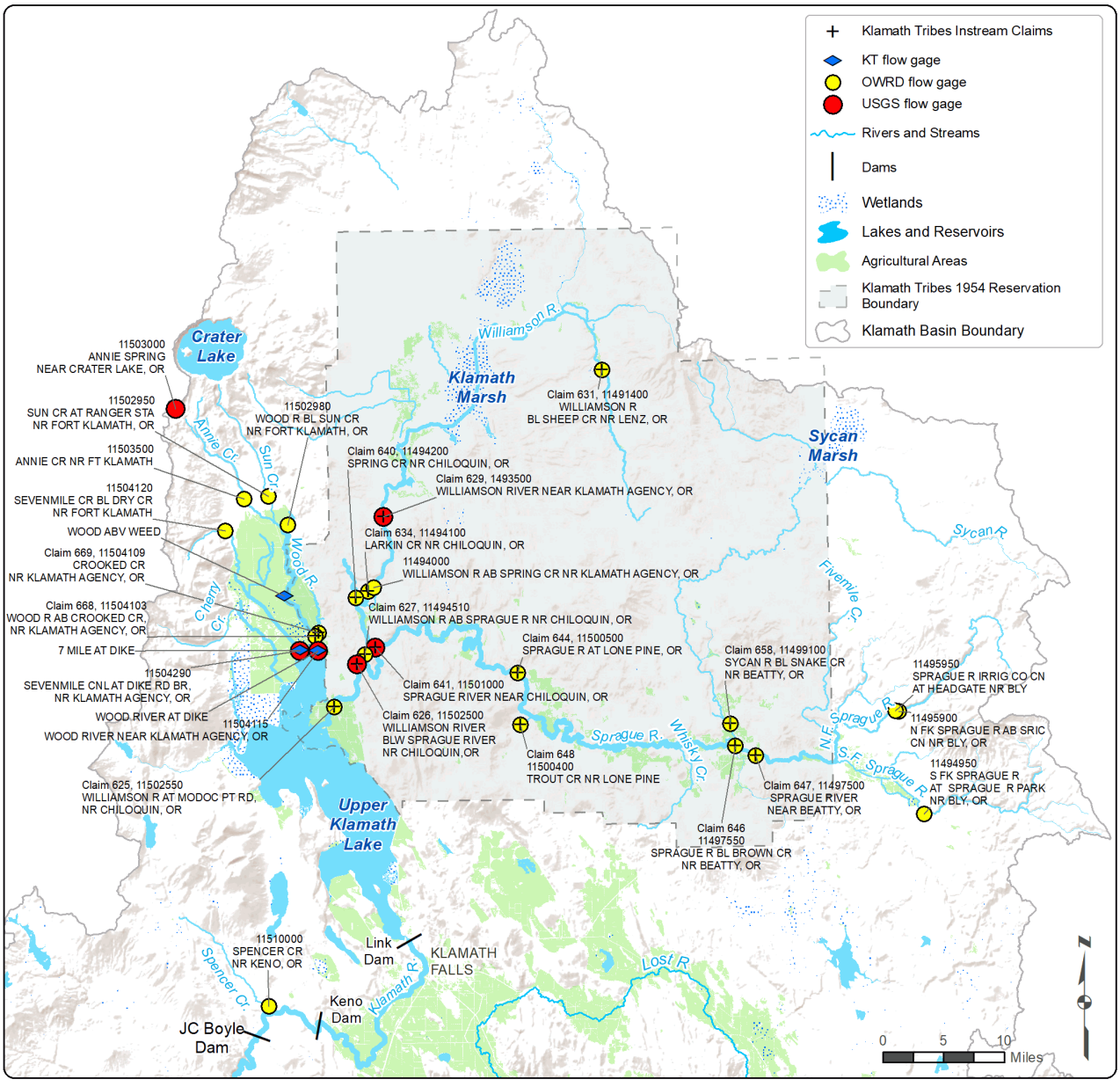

Figure 1. Map showing project area, flow gages, and a subset of Klamath Tribes instream flow claim compliance points that are associated with a flow gage. Many additional instream claims are not shown here.

2.1.2 U.S. GEOLOGICAL SURVEY (USGS) NATIONAL WATER INFORMATION SYSTEM (NWIS)

We used the R dataRetrieval package (De Cicco et al. 2022) to obtain USGS temperature data from the National Water Information System (NWIS) for three gages: Williamson River below Sprague River (downloaded through 2020), Sprague River near Chiloquin (downloaded through 2020), and Wood River near Klamath Agency (only available through June 2017) (Figure 3, Figure 4). We did not compile USGS temperature data for the Sprague River near Beatty for 11/21/2007–8/23/2010 because the KT data included those dates.

2.1.3 NORWEST

NorWeST compiled data for the years 1993–2011 in the tributaries of Upper Klamath Lake and Spencer Creek (Isaak et al. 2017). These data were collected by several different entities, as described in the sections below. Since these data were well-organized and had already undergone thorough QAQC, we were able to integrate them with relatively little effort. We compiled these data for all sites within our study area (not shown here), but the only analyses we used them for were to extend the period of record for the KT sites (Figure 3, Figure 4).

2.1.3.1 USGS FOREST AND RANGELAND ECOSYSTEM SCIENCE CENTER (FRESC)

Some data collected by the USGS Forest and Rangeland Ecosystem Science Center (FRESC) not included in the NWIS database (Section 2.1.2) were separately compiled by NorWeST (Figure 4).

2.1.3.2 U.S. BUREAU OF LAND MANAGEMENT

NorWeST compiled stream temperature data collected by the Klamath Falls office of the U.S. Bureau of Land Management (US BLM) in Spencer Creek (Figure 3). These data were initially compiled by Asarian et al. (2020) prior to inclusion in NorWeST. We did not obtain the US BLM's stream temperature data for Wood River, some of which span as far back as 1997 (US BLM 2005).

2.1.3.3 OREGON DEPARTMENT OF ENVIRONMENTAL QUALITY (ODEQ)

The Oregon Department of Environmental Quality (ODEQ) monitored stream temperatures in the study area in the late 1990s and early 2000s as part of TMDL studies (Section 1.2, Figure 3, Figure 4).

2.1.3.4 U.S. FOREST SERVICE

NorWeST compiled stream temperature data collected by the U.S. Forest Service Freemont-Winema National Forest (FWNF) as part of their Aquatic and Riparian Effectiveness Monitoring Plan (AREMP) in the study area through the year 2011 (Figure 3, Figure 4).

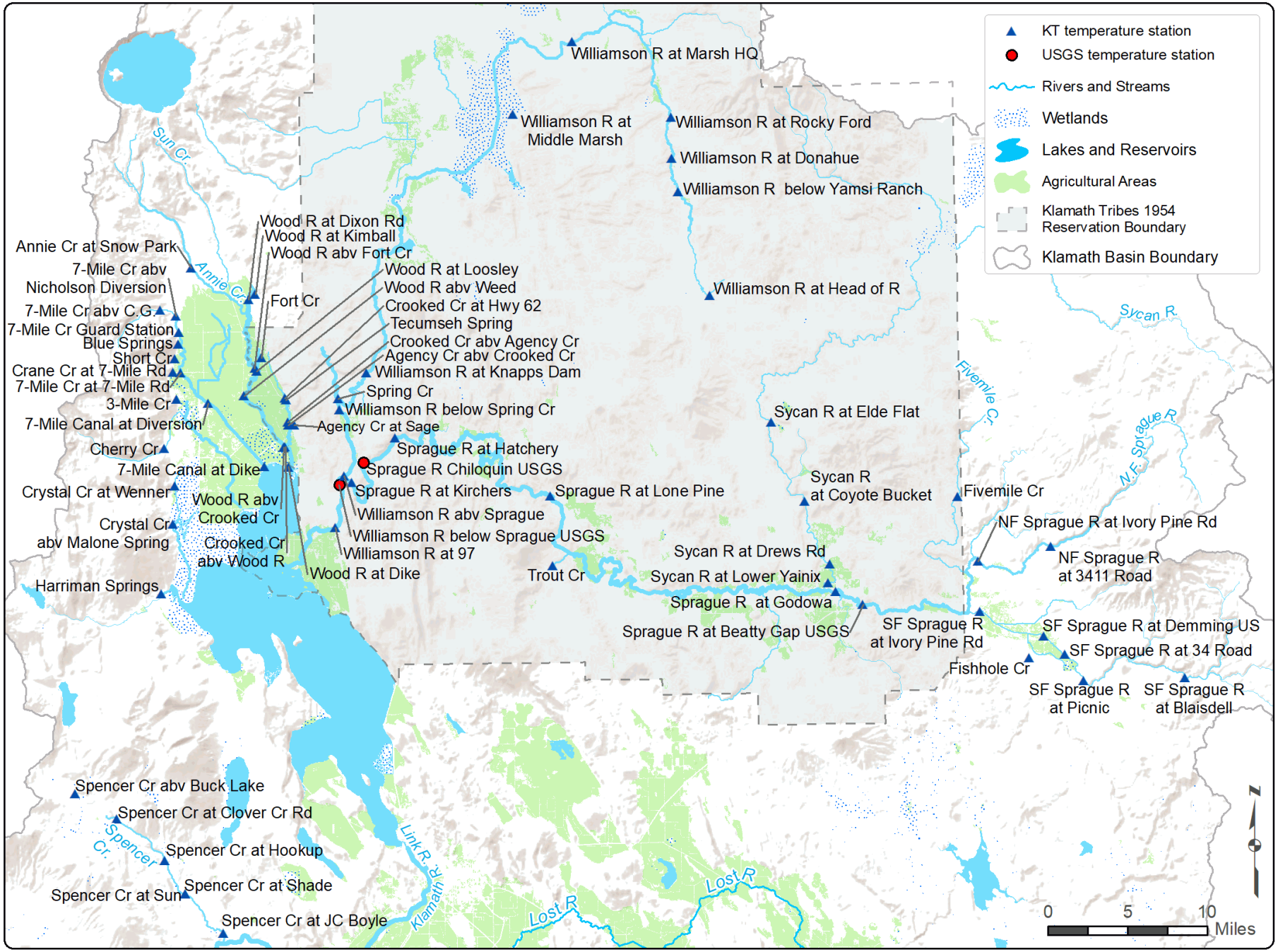

Figure 2. Map showing locations of the Klamath Tribes and USGS temperature monitoring stations.

Figure 3. Period of record available for Klamath Tribes and others stream temperature monitoring sites in the Wood River, Westside, and Spencer Creek sub-basins. Names on left side combine our standardized site names with drainage area from NHDPlus. Names on right side are data providers' original codes.

Figure 4. Period of record available for Klamath Tribes and others stream temperature monitoring sites in the Sprague River and Williamson River sub-basins. See Figure 3 for legend key to data sources and additional notes.

2.2 STREAM TEMPERATURE DATA NOT ACQUIRED

The Oregon Water Resources Department (OWRD) provides near real-time online access to water temperature data at 14 of its flow gaging sites[2]. However, we only became aware of these data when the project was nearly complete and so they are not included in our analyses. These temperature records span back to between 2015 and 2020 at most sites. Most, but not all, of these sites are near Klamath Tribes' temperature monitoring sites and could be evaluated in a future effort.

Additional temperature datasets we are aware of that we did not compile include USFS post-2011 data (Section 2.1.3.4) and data associated with the literature cited in Section 1.2.

2.3 QUALITY CONTROL AND CLEANING OF STREAM TEMPERATURE DATA

Data collected with continuous probes, such as the temperature data that are the subject of this project, must be cleaned/trimmed to remove data corrupted when a probe malfunctions or is exposed to air either during pre/post deployment or when water levels decline over the course of the season. To account for varying condition of the datasets among data sources and years, we initiated a rigorous screening and trimming process informed by protocols from Dunham et al. (2005), Sowder and Steel (2012), and U.S. EPA (2014). All data values for the period when the sensors appear to be exposed to air were removed, but the data from the remainder of the probes' deployment when water was flowing in the respective stream reaches were retained. Additional details on the processes we used are provided in Asarian (2017).

2.4 CALCULATION OF DAILY AND SEASONAL SUMMARIES

2.4.1 DAILY SUMMARY STATISTICS

Klamath Tribes data were acquired at their original 60-minute temporal resolution. On days when data completeness was at least 80% (e.g., at least 19 out of the maximum possible 24 measurements must be present), we calculated daily summary statistics including number of measurements, minimum, maximum, mean, and range. All metrics were calculated using R 4.2.1 (R Core Team 2022). All other temperature datasets (USGS and NorWeST) had already been summarized on a daily basis before we acquired them.

2.4.2 INITIAL CALCULATION OF SEASONAL AND MONTHLY SUMMARY STATISTICS

Key seasonal temperature metrics were selected based on a review of previous stream temperature analyses (Welsh et al. 2001, Dunham et al. 2005, McCullough 2010) and calculated for each site and year. Figure 5 illustrates these metrics at a hypothetical site. Details on

[2] Sites with temperature data available online at https://apps.wrd.state.or.us/apps/sw/hydro_near_real_time are: 11494000 WILLIAMSON R AB SPRING CR NR KLAMATH; 11491400 WILLIAMSON R BL SHEEP CR NR LENZ, OR; 11494510 WILLIAMSON R AB SPRAGUE R NR CHILOQUIN, OR; 11495900 N FK SPRAGUE R AB SRIC CN NR BLY, OR; 11497500 SPRAGUE R NR BEATTY, OR, 11497550 SPRAGUE R BL BROWN CR NR BEATTY, OR; 11500400 TROUT CR NR LONE PINE; 11500500 SPRAGUE R AT LONE PINE, OR; 11502550 WILLIAMSON R AT MODOC PT RD, NR CHILOQUIN, OR; 11503500 ANNIE CR NR FT KLAMATH; 11504040 FORT CR NR FORT KLAMATH, OR; 11504103 WOOD R AB CROOKED CR, NR KLAMATH AGENCY, OR; 11504109 CROOKED CR NR KLAMATH AGENCY, OR; 11504120 SEVENMILE CR BL DRY CR NR FORT KLAMATH; 11510000 SPENCER CR NR KENO, OR

calculating these metrics are provided in Asarian et al. (2020). In addition to these seasonal metrics, for any month for which data were available for 90% (i.e., 28 of 30 or 31) of days, we calculated mean monthly temperature as the average of all daily average temperatures within the month, and mean daily maximum monthly temperature as the average of all daily maximum temperatures within the month (Figure 5 shows example for August).

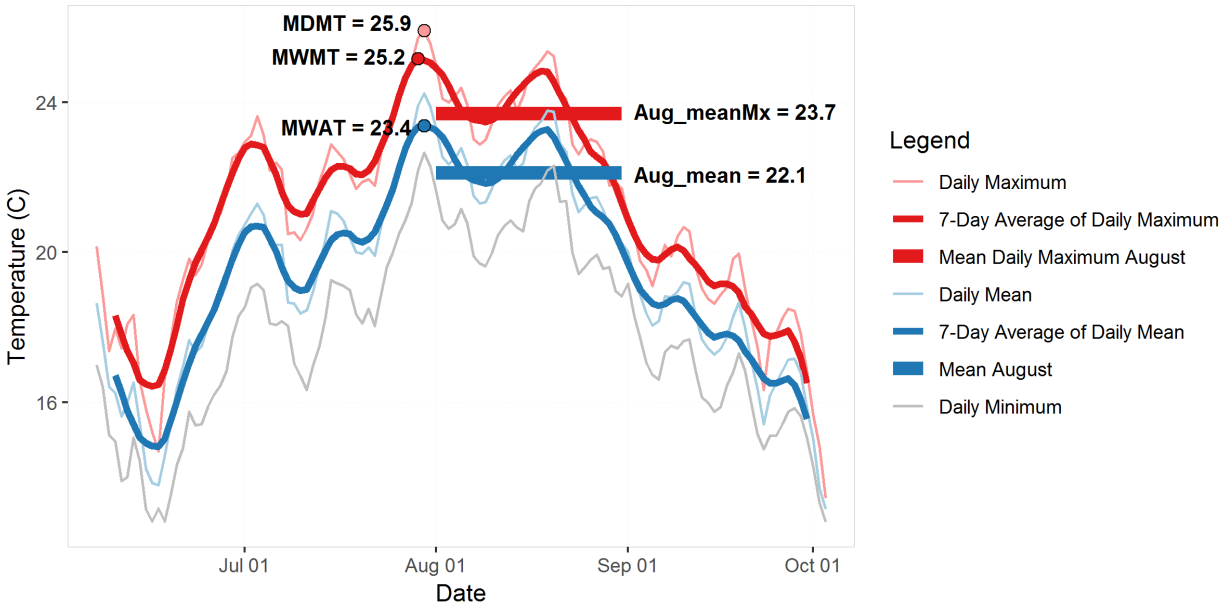

Figure 5. Daily time series of daily maximum (T_{max}), daily mean (T_{mean}), daily minimum (T_{min}), 7-day average of daily maximum (7DADM), and 7-day average of daily mean (7DADA) water temperatures for a year at a hypothetical site. Maximum daily maximum temperature (MDMT), maximum weekly maximum temperature (MWMT), and maximum weekly average temperature (MWAT) are the highest annual values for T_{max}, 7DADM, 7DADA, respectively. Mean daily maximum August temperature (Aug_meanMx), and mean August temperature (Aug_mean) are also shown.

2.4.3 REFINING SEASONAL STATISTICS ACCORDING TO DATA COMPLETENESS

Seasonal summary statistics are relatively simple to calculate when data are available for the entire warm season (i.e., June–Sept.); however, some datasets only contained data for part of the summer season and thus had to be screened for comparability. For example, seasonal statistics may be biased low if they are calculated from only a short period and did not include the warmest days of the year. To avoid an unnecessary loss of important information by excluding an entire season of data when gaps occurred, seasonal statistics were initially calculated for all years and sites (see Section 2.4.2), and values were then either retained (i.e., kept) or excluded (i.e., deleted) based on data completeness.

Using methods from Asarian (2017), we applied an automated multi-step procedure to screen data completeness. Since MWMT, MWAT, and MDMT almost always occur in July or August, seasonal statistics were retained[3] for datasets which included all of July and August[4]. For

[3] Seasonal statistics were initially calculated for all years and sites. Values were then either retained (i.e., kept) or excluded (i.e., deleted) based on data completeness.
[4] In actuality, the dates were June 28 through September 3 because the 7DADM and 7DADA require data to be present for three days before and three days after.

datasets that were missing some days in July or August, seasonal statistics were only automatically retained if the data were present at that site for each day on which that statistic occurred in at least two other sites[5]. This approach makes maximal use of available data while minimizing the chance that un-representative statistics were retained.

2.5 ASSIGNING STREAM TEMPERATURE MONITORING SITES TO STREAM NETWORK GIS

All stream temperature datasets had x-y spatial coordinates (e.g., UTM or latitude/longitude); however, assigning each site to a GIS stream network (rather than solely x-y coordinates) greatly increases the utility of the data. We selected the National Stream Internet (NSI) Hydrography Network[6] as the GIS stream network due to its use in the NorWeST model. NSI network was created by the U.S. Forest Service's Rocky Mountain Research Lab by modifying the NHD-Plus[7] Version 2 medium-resolution (1:100,000-scale) hydrography layer for all streams in the contiguous United States. NHD-Plus contains a large database of descriptors for each reach (e.g., stream name, watershed area, stream gradient, etc.) which are useful for organizing (i.e., sorting and grouping) sites and can be used as predictor variables in analyses. Each stream temperature monitoring station was assigned to reaches in the NSI network using methods similar to Asarian (2017).

2.6 ENVIRONMENTAL DATA USED IN STREAM TEMPERATURE MODELS

As described in the following sections, we used a variety of environmental and GIS data in our analyses.

2.6.1 DRAINAGE AREA

Drainage area (i.e., contributing watershed area) for each reach was obtained from NHDPlus/NSI. In NHDPlus, drainage area at the bottom of a reach is assigned to all sites within that reach. Reaches split at tributary confluences, so most reaches are only a few kilometers long such that drainage area does not increase much from the top to the bottom of a reach; however, in headwater reaches, drainage area can increase several-fold along the reach, so the drainage areas assigned to some temperature monitoring sites may be inflated relative to the actual drainage area for that reach. For a few temperature sites on small streams or springs that were not included in the 1:100,000 scale NHDPlus Version 2, we assigned drainage areas from NHDPlus High Resolution, a recent 1:24,000 scale version of NHDPlus (Buto and Anderson 2020).

2.6.2 AIR TEMPERATURE

PRISM[8] (Parameter-elevation Regressions on Independent Slopes Model) combines data from ground-based weather stations with GIS data and a statistical model to produce a spatially continuous 4-km grid of climate variables including air temperature and precipitation (Daly et al. 2008). Daymet is another gridded temperature dataset that uses different methods and has a 1-km resolution (Thornton et al. 2021). We obtained daily 1993–2020 time series of PRISM and Daymet daily mean air temperatures for each of our temperature monitoring stations using the

[5] We chose two sites as the threshold rather than one site because a single site might have unique characteristics or a data quality issue whereas two or more sites should indicate a more widespread pattern.
[6] http://www.fs.fed.us/rm/boise/AWAE/projects/NationalStreamInternet/NSI_network.html
[7] http://www.horizon-systems.com/nhdplus/NHDPlusV2_home.php
[8] http://www.prism.oregonstate.edu

daymetr (Hufkens et al. 2018) and climateR[9] packages, respectively. For each of these two datasets, we calculated three air temperature metrics: daily mean air temperature (A_1), a two-day weighted air temperature (A_{2w}), and three-day weighted air temperature (A_{3w}), calculated as follows, where A_i is mean air temperature on day i:

$$A_{2w} = \frac{A_i + (0.5 * A_{i-1})}{1.5} \quad (1)$$

$$A_{3w} = \frac{A_i + (0.5 * A_{i-1}) + (0.25 * A_{i-2})}{1.75} \quad (2)$$

2.6.3 STREAMFLOW

Flow (i.e., discharge) data were used during the temperature data QA process and in subsequent analyses. We acquired daily flow data from the USGS (accessed using the dataRetrieval package in R), OWRD (accessed using the url function in R), and Klamath Tribes (Figure 1, Figure 6). The Klamath Tribes daily flow data obtained for the Wood River and Sevenmile Canal/Creek systems were based on a combination of continuous gages and biweekly measured flows with methods as described in Walker and Kann (2022b). For analysis, we assigned each temperature station to the flow station we expected would most closely represent its flow, given geographic proximity, tributaries, diversions, etc. We refer to these approximate matches as "watershed flow," preferencing longer-term flow gages spanning all or nearly all the duration of data available at a temperature station (Figure 7). In addition, if a temperature station had flow data available at the same (or close enough to be practically identical) location, we assigned that flow as secondary "local flow" station, even if it only covered part of the duration of temperature data (Figure 7). We used the watershed flow for analyses that spanned all (or nearly all) stations and local flow for analyses restricted to the subset of stations where local flow was available.

2.6.4 APRIL 1 SNOWPACK

We used annual time series of modeled April 1 (the typical annual peak) snow water equivalent (SWE) from University of Arizona (UA) (Broxton et al. 2016, Dawson et al. 2018, Zeng et al. 2018) snowpack estimates at a 4km resolution by combining ground-based measurements of SWE and snow depth with gridded PRISM precipitation and temperature data (Daly et al. 2008). We used a polygon of our project area to extract an annual SWE time series 1982–2021 and assigned this same time series to all temperature sites. In the future, custom SWE summaries could be generated for the watershed associated with each temperature site (Siegel et al. 2022). We ranked years 1982–2021 by snowpack to define five water year types: Critically Dry (<20th percentile), Dry (20–40th percentile), Normal (40–60th percentile), Wet (60–80th percentile), Extremely Wet (>80th percentile). Water year types were only used to provide hydrologic context (Section 3.1) and were not used in models.

[9] https://github.com/mikejohnson51/climateR

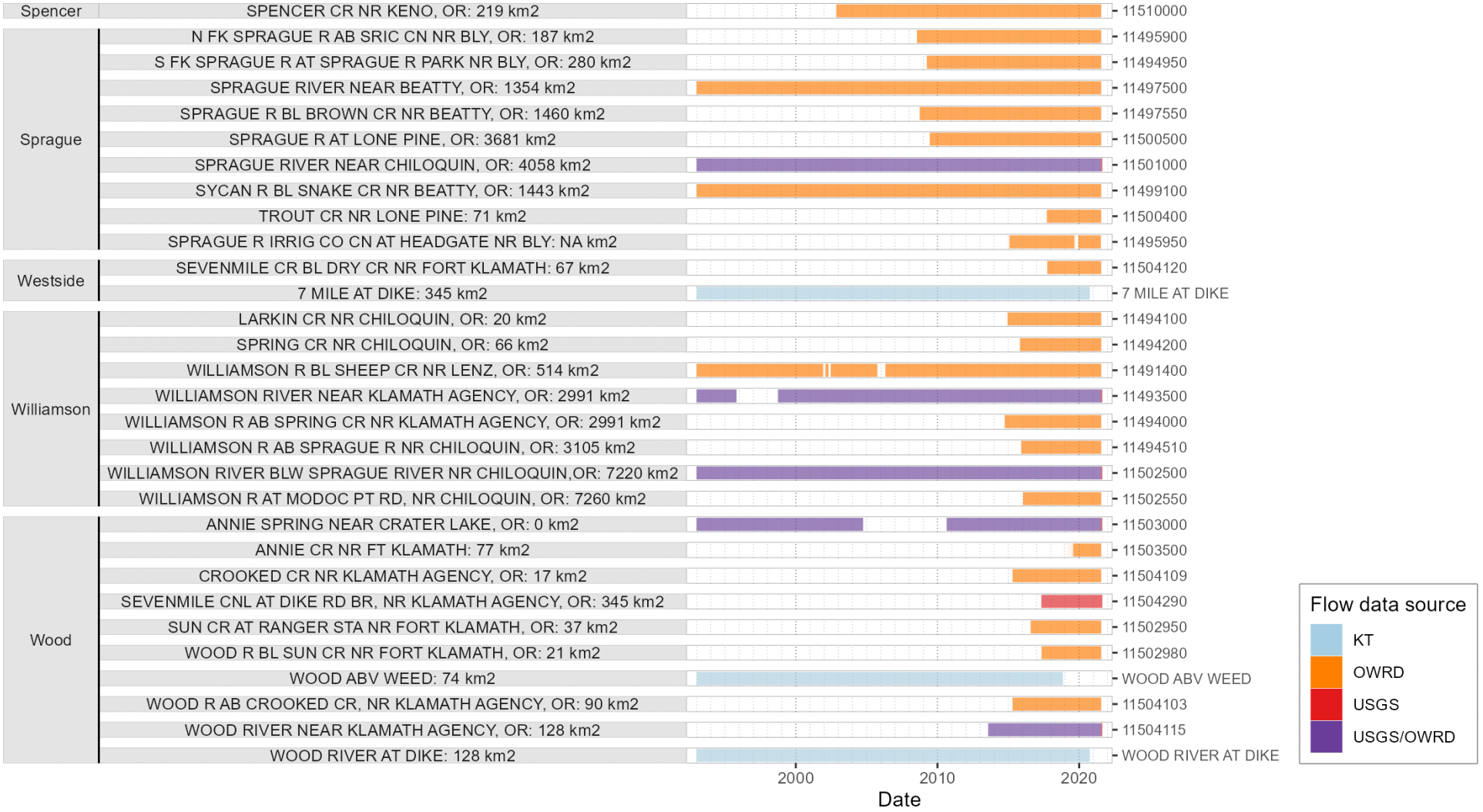

Figure 6. Period of record available for flow monitoring sites the project area for 1993–2020. Names are on left side, codes are on right site. OWRD's gage 11504040 FORT CR NR FORT KLAMATH, OR has flow data available 2015–present but was accidentally excluded from our analyses and this graph. USGS gage 11495800 N FORK SPRAGUE RIVER AT POWER PLANT, NEAR BLY, OR has data for 1993–2012 but we did not utilize it because we were unclear on how its flows are affected by an adjacent run-of-the-river hydroelectric power plant.

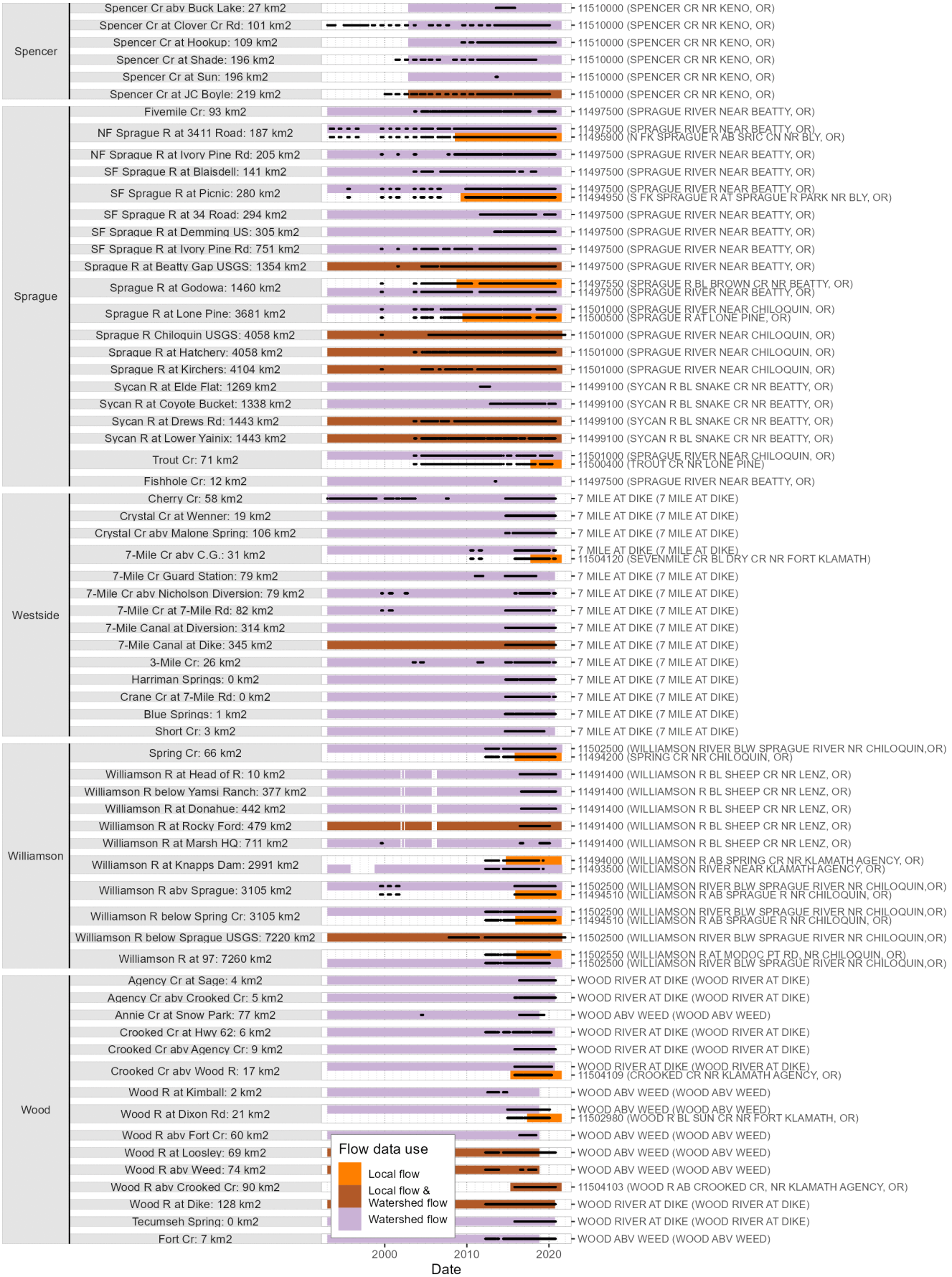

Figure 7. Flow data sites (names on right side) assigned to each temperature monitoring site (names on left side). Black dots are days with measured temperature data.

2.7 ASSESSING WHERE AND WHEN FLOW AFFECTS STREAM TEMPERATURES

At each site, we used smooth additive quantile regression models (Cade and Noon, 2003; Fasiolo et al., 2020) to calculate the flow associated with two quantiles (0.33 and 0.67, equivalent to 67% and 33% exceedance probabilities, respectively) for each day of the year (Figure B35), using the qgam R package (Fasiolo et al., 2020) with a 12-knot cyclic cubic regression spline ("cc"). At each site we then categorized each date into one of three categories of flow quantiles (high is >0.67 quantile, moderate is 0.33–0.67 quantile, low is <0.33 quantile). These categories were used to assess stations where flow affected stream temperatures (Section 3.2) by plotting observed stream temperatures for each flow category and fitting a LOESS smoother to the points within each site and flow category. Divergence of the LOESS smoothers among flow categories then indicated flow-related temperature differences. We performed this analysis for both local flow and watershed flow, but only report the results for watershed flow because results were not appreciably different and watershed flow allows examination of far more sites and dates than does local flow.

2.8 CALIBRATION AND VALIDATION OF DAILY STREAM TEMPERATURE GENERALIZED ADDITIVE MODELS

We modeled daily stream temperatures using hierarchical generalized additive models (GAMs) with day of year (D), air temperature, daily flow, and an autocorrelation term as predictors, adapting methods previously applied in the Klamath/Trinity Basin by Asarian et al. (2022, 2023).

Prior to modeling, we converted flow from cfs to specific discharge (i.e., flow per unit of watershed area, in units of mm/d). In addition, to improve numerical stability, we standardized air temperature and flow variables by centering and scaling (i.e., subtracting the mean, then dividing by the standard deviation).

All GAMs were developed in the mgcv R package version 1.8-41 using the bam function (Wood 2017), fit using restricted maximum likelihood (REML). Model terms included smooth non-linear functions with wiggliness determined by a smoothing penalty (Pedersen et al. 2019, Wood 2017). We used cyclic cubic regression splines ("cc") as the smoother for D and thin plate regression splines ("tp") as smoothers for other covariates. To improve prediction under new conditions and avoid overfitting (Jackson et al. 2018; Siegel & Volk 2019), we limited smoothers for air temperature and flow to a maximum of three knots. D was allowed up to six knots. We included interactions between D and the other covariates (flow and air temperature) to allow effects to vary seasonally. In these partially nonlinear interactions, the linear slope of one variable (e.g., flow) varied as a smooth nonlinear function of D (Jackson et al. 2018, Siegel & Volk 2019). All sites were included in a single hierarchical model, with sites allowed to have factor smoothers for D, air temperature, and flow (Pedersen et al. 2019). Models included an AR-1 autocorrelation error structure. We initially fit the model without an autocorrelation term, and then re-fit with an autocorrelation term, assigning a rho value based on the initial model's lag-1 autocorrelation (Baayen et al. 2018; van Rij et al. 2019, 2020).

We developed several sets of models, used for different purposes. First, for 24 sites where long-term (≥1000 days and ≥4 years) local flow and stream temperature data were available, we tested 12 models each of T_{max} and T_{mean} using combinations of three air temperature variables (A_1, A_{2W}, and A_{3W} calculated from Daymet and PRISM) and three flow variables (local flow, watershed flow, and April 1 snowpack) and interactions, calibrated using data from all available dates (1993–2020). We used Bayesian information criterion (BIC) scores to select the best (i.e., lowest

BIC score) of these 12 models as well as assess which flow and air temperature variables performed best. We used the selected model to predict T_{max} under an instream flow claims scenario (Section 2.9.5). Second, for 58 sites where long-term (≥1000 days and ≥4 years) temperature (but not necessarily flow) data were available, we tested 6 models each of T_{max} and T_{mean} using combinations of three air temperature variables (A_1, A_{2W}, and A_{3W} calculated from Daymet and PRISM) and two flow variables (watershed flow and April 1 snowpack, but not local flow because it was not available at all sites) and interactions, calibrated using data from all available dates (1993–2020). After selecting the best snowpack model based on BIC scores, we applied the selected model to predict T_{max} for sites with data before and after the start of flow regulation (Section 2.9.6).

To evaluate model performance, we used leave-one-year-out (LOYO) cross-validation (CV) where data were split into annual blocks and the following steps were repeated for each year: year withheld, model refit using remaining data, and predictions compared to withheld data using root mean squared error (RMSE).

2.9 EFFECTS OF FLOW REGULATION

2.9.1 DEFINING ERAS BASED ON WHEN FLOW REGULATION OCCURRED

Based on OWRD Watermaster records, literature review (Hess and Stonewall 2014, Wood 2019, Velpuri et al. 2020), and discussions with Klamath Tribes staff, we attempted to reconstruct a timeline of flow regulation for each stream. OWRD Watermaster records provide a detailed accounting of regulation priority dates for each stream from 2015 to present which were standardized and compiled with considerable effort (Figure B34), but we were unable to obtain similarly detailed information for 2013 and 2014. Wood (2019) provides regulation dates for the Sprague River only. Given this lack of geographically specific information for the entire time period, we simplified our approach and defined the *"regulation era"* as beginning June 17, 2013 (Wood 2019) and the *"pre-regulation era"* being all prior dates. As noted above in Section 1.3, from 2014 through 2016, instream flows were regulated to the UKCBA's Specified Instream Flows (SIF) instead of the Klamath Tribes full claim amounts. Following disintegration of the UKBCA in 2017, the Klamath Tribes resumed enforcing their full instream claims in 2017, with a Watermaster regulating users to a time immemorial priority date starting on April 4, 2017. For analyses requiring eras to be split at calendar or hydrologic years, we define the pre-regulation era as ending in 2012.

2.9.2 HYDROLOGIC EFFECTS OF FLOW REGULATION

We reviewed and summarized literature regarding previous assessments of the hydrologic effects of regulation (Hess and Stonewall 2014, Risley 2019, Velpuri 2020, Walker and Kann 2022a, Wood 2019). Only one of the previous assessments of the hydrologic effects of flow regulation included 2017–2020 (Walker and Kann 2022a), none included 2021, and most focused solely on the Sprague River at Chiloquin, so we attempted our own assessment to quantify the effects of flow regulation on streamflow at multiple gages for the full 2013–2021 regulated era.

We used three methods for assessing the hydrologic effects of the curtailments. First, we plotted daily time series of flows during the pre-regulation and regulation eras to determine if differences were readily apparent. Although this qualitative approach did not account for climatic differences between the eras, it was nonetheless informative. The second method was a relatively simple approach using linear regression to relate April 1 snowpack and annual precipitation to monthly and annual gaged flows during the pre-regulation era and regulated era.

Results from this analysis are presented in Section 3.2.

The third method was more complex and used GAMs to relate flows at five long-term gages in the Sprague, Williamson, and Sycan Rivers to gaged flows in the Chewaucan and Fall rivers during years prior to regulation (1972–2012). We developed several models and then used Bayesian information criteria (BIC) to select final models for both daily flows and monthly flows. After model validation we then predicted daily and monthly flows for the 2013–2021 regulated era, and compared those predictions to measured flows. Methodological details and full results from this analysis are presented in Appendix C while a short summary of results is provided in Section 3.4.2.

2.9.3 GROUPING SITES INTO ADJUDICATION CATEGORIES

Based on a review of the OWRD Points of Diversion GIS maps, aerial imagery, OWRD Watermaster records (Figure B34), water rights claims, flow gage data (including OWRD's dashboard[10]), estimated groundwater discharges (Gannett et al. 2007), we grouped temperature sites into four adjudication categories (Figure 8) prior to conducting our temperature analyses:

- *Upstream of all diversions*: sites with no known diversions upstream. Impounded springs (e.g., Blue Springs) were categorized as upstream of diversions if we thought measured temperatures more closely reflected source temperatures than impoundment effects.
- *Outside adjudication*: sites located outside the geographic scope of the adjudication with waters not flowing downstream into the Klamath Tribes 1864 Reservation boundary area (Figure 1).
- *Diversions with low % of baseflow*: sites within the geographic scope of the adjudication, but where we expect that water calls will have relatively little effect on flows because the cumulative rate of diversions is low (approximately <10%) relative to summer baseflow.
- *Affected by adjudication*: sites within the geographic scope of the adjudication whose summer baseflows are likely to be affected by >10% by water calls. In addition, we included two Sevenmile Canal sites because a portion of their flow is derived from the West Canal that receives flow diverted from the Wood River system (GMA 2011) and thus were likely to be affected by the adjudication despite not being within the adjudication boundary.

We used the above adjudication categories to inform several different analyses aimed at quantifying the potential effects of flow regulation on stream temperatures, described in the following sections.

[10] https://apps.wrd.state.or.us/apps/wr/klamath_sif_dashboard/Charts.aspx

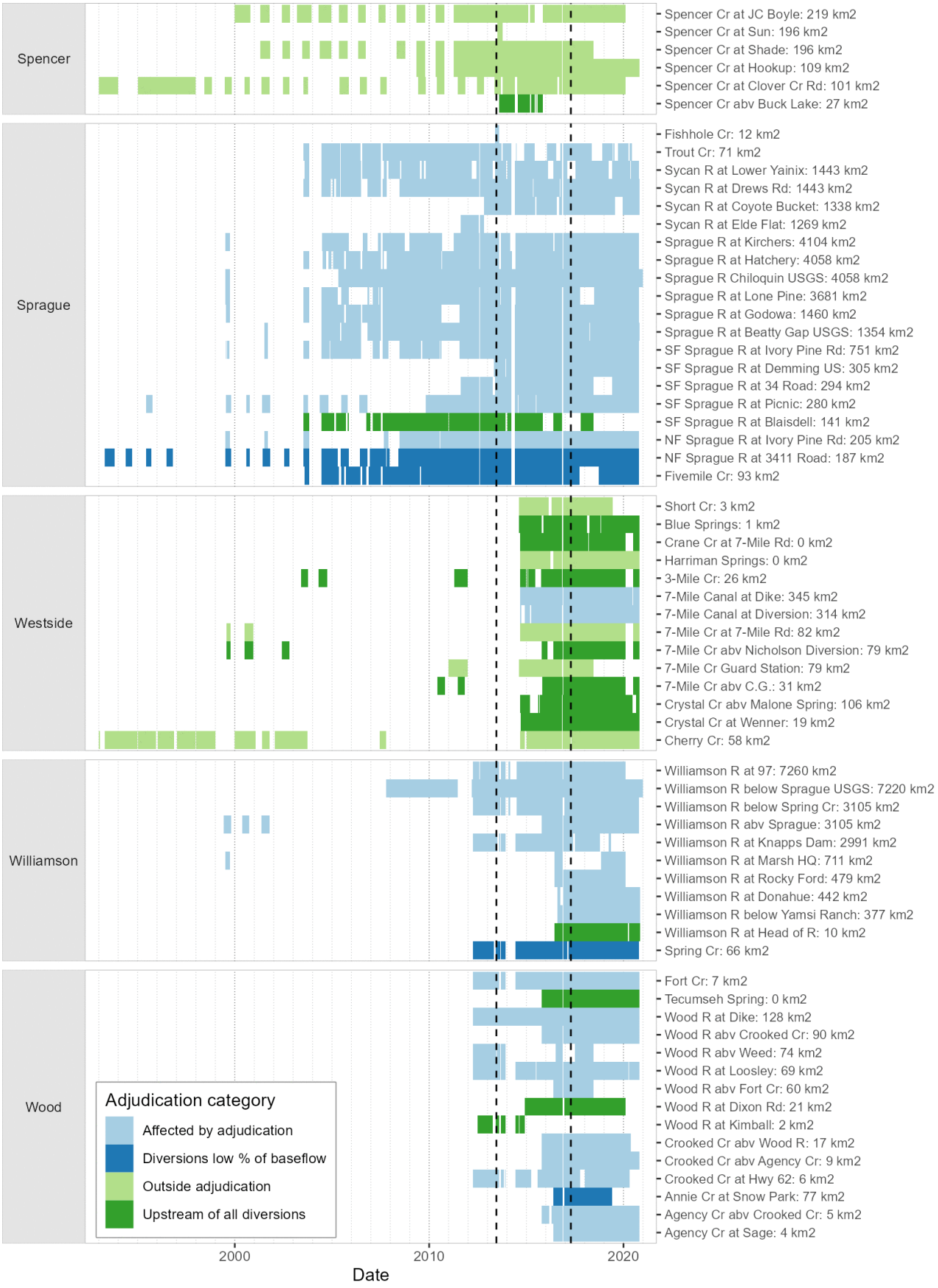

Figure 8. Temperature monitoring sites color-coded by adjudication category. Vertical dashed lines mark the start of regulation on 6/17/2013 and full regulation on 4/17/2017.

2.9.4 COMPARING MEASURED TEMPERATURES AT RELATIVELY UNAFFECTED/AFFECTED SITES BEFORE AND DURING REGULATION

Three Sprague River sites whose hydrology we characterized in Section 2.9.3 as relatively unaffected by the adjudication—because they were upstream of all diversions (South Fork Sprague River at Blaisdell) or diversions were a low percent of baseflow (Fivemile Creek and North Fork Sprague River at 3411 Road)—had ≥1000 days and ≥4 years of temperature data in the 1/1/2003–6/16/2013 pre-regulation era (Figure 8). From several Spencer Creek sites that are outside the adjudication area and met these same data availability criteria, we selected Spencer Creek at JC Boyle because it had the most year-round data in the pre-regulation and post-regulation eras. We compared temperatures at these 4 unaffected sites (3 Sprague, 1 Spencer) with 13 sites whose hydrology we characterized as affected by adjudication that also had many years of pre-regulation data. We used non-linear LOESS (locally estimated scatterplot smoothing) regression to evaluate whether the relationship between these sites changed from the pre-regulation era and the regulation era.

2.9.5 MODELING TEMPERATURES UNDER AN INSTREAM CLAIMS FLOW SCENARIO

As described above in Section 2.8, at 24 sites where long-term local flow and temperature data were available, we calibrated generalized additive models (GAMs) to predict T_{max} based on day of year, air temperature, and local flow. We applied the best of these models to predict T_{max} under two scenarios at 16 sites where measured temperature data, local flow data, and instream claims were all available. The first scenario predicted T_{max} using measured local flows (the same data that the model was calibrated with) as the flow input. The second scenario predicted T_{max} under a scenario in which flows were held at or above the instream claims (i.e., all measured flows greater than the instream claim were retained, but on dates when measured flows were less than instream claims they were replaced with the instream claims). For dates when measured flows were less than the instream claims, we calculated the difference in T_{max} between the two scenarios (i.e., how much cooler or warmer were temperatures predicted to be under the instream claim scenario than the measured scenario).

2.9.6 COMPARING DIFFERENCES BETWEEN MODELED AND MEASURED TEMPERATURES BEFORE AND DURING REGULATION

As described above in Section 2.8, at 58 sites where long-term temperature (but not necessarily flow) data were available, we calibrated generalized additive models (GAMs) to predict T_{max} based on day of year, air temperature, and April 1 snowpack. We used snowpack for this model because it is a proxy for flow (e.g., see regression analyses in Section 3.4.2), but is not itself affected by flow regulation. Although it would have been optimal to calibrate the model using only data from the pre-regulation era, due to pre-regulation era data gaps we calibrated the model using data from all years (1993–2020) to maximize data availability. We applied the best of these models to predict a time series of T_{max} under the same conditions for which the model was calibrated. For the 20 sites where ample data were available in both the pre-regulation (1/1/2003–6/16/2013) and regulation (6/17/2013–12/31/2020) eras, we compared measured T_{max} to modeled T_{max} (i.e., model residuals calculated as measured minus predicted) to see if the model systematically over-predicted or under-predicted T_{max} in either era, which could indicate the effects of flow regulation.

2.9.7 REMOTE SENSING OF SURFACE WATER TEMPERATURES IN AGENCY LAKE AT MOUTH OF WOOD RIVER

We used land surface temperature data from the thermal band of the NASA/USGS Landsat satellites to assess July surface water temperatures in Agency Lake at the mouth of the Wood River, an area previously identified as an important thermal refuge for redband trout (Tinniswood et al. 2010). We used the Climate Engine website (Huntington et al. 2017) to summarize these data from Collection 2 Tier 1 of the Landsat 5, 7, 8 and 9 satellites[11]. Landsat Collection 2 land surface temperature data are atmospherically corrected and have been validated with lake surface water temperatures (Herrick et al. 2023). For each 30-meter resolution pixel we calculated the average temperature from all available July dates in three time periods (2002–2012 pre-regulation, 2013–2016 partial regulation, and 2017–2022 full regulation). Landsat satellites return approximately every eight days, but Tier 1 data are available less frequently due to exclusion of dates with data quality issues such as clouds. Data for the 2017-2022 period can be viewed online at: https://climengine.page.link/mSJR.

2.10 BIOLOGICAL SUITABILITY

To assess thermal suitability for fish habitat, for each site we calculated the percent of days in each month that had measured 7DADM temperatures within criteria primarily adapted from Dunsmoor and Huntington (2006) and ODEQ (2022), excluding sites and months that did not have at least 28 days of data. We focus our analysis on the 6/17/2013-12/31/2020 regulation era, but also provide results for the 1/1/2003-6/16/2013 pre-regulation era in an appendix. Prior to calculating 7DADM from T_{max}, we filled gaps of up to two consecutive days of missing data using linear interpolation.

Dunsmoor and Huntington's (2006) analysis of the thermal suitability of Klamath River and Upper Klamath Lake for anadromous salmonids was also previously applied to the tributaries of Upper Klamath Lake by Huntington and Dunsmoor (2006), and provided criteria for parsing temperatures into optimal, suboptimal, stressful, and severely stressful ranges for: 1) adult chinook salmon and steelhead migration, 2) juvenile chinook salmon rearing, and 3) juvenile steelhead rearing. For adult chinook salmon and steelhead migration, they provided two severely stressful ranges, one for April 1 to July 30 (>21 °C) and another for August 1 to November 30 (>22 °C). We made only two adaptations to their approach: 1) for simplicity we only considered 7DADM temperatures whereas they considered both 7DADA and 7DADM temperatures, 2) we applied their thresholds to all months, whereas they applied them only for April–November. The thresholds are shown in figure legends in the results Section 3.6.

For salmon spawning and bull trout, we used criteria based on ODEQ (2022) because none were available from Dunsmoor and Huntington (2006). ODEQ (2022) uses these numeric criteria to determine whether waterbodies should be listed under the federal Clean Water Act as having impaired water temperatures. According to OAR 340-041-0028, the *Bull trout spawning & juvenile rearing* numeric criterion is 12.0 °C 7DADM and the *Salmon & trout rearing & migration* numeric criterion is 13.0 °C 7DADM. We only applied the bull trout criterion to sites[12] on reaches designated on ODEQ maps[13] as bull trout habitat for spawning and juvenile

[11] https://support.climateengine.org/article/69-landsat

[12] Wood River at Dixon Rd, Wood River at Kimball, Annie Creek at Snow Park, 3-Mile Creek, Cherry Creek, Fort Creek, 7-Mile Creek above Campground, 7-Mile Creek abv Nicholson Diversion, and South Fork Sprague at Blaisdell

[13] https://www.oregon.gov/deq/FilterRulemakingDocs/figure180a.pdf. Future efforts could cross reference these reaches with those designated by USFWS as critical bull trout habitat (U.S. Fish and Wildlife Service, 2010). Our brief review indicated that bull trout critical habitat (https://fws.maps.arcgis.com/home/webmap/viewer.html?webmap=9d8de5e265ad4fe09893cf75b8dbfb77 maps) is

rearing. Since dams currently block fish passage, ODEQ has not yet designated any waters as *Salmon & trout rearing & migration* areas[14]. In addition, there are no designated time periods for spawning in the Upper Klamath Basin. However, based on the adjacent Rogue River Basin[15], where ODEQ's designated spawning periods range from September 15 to June 15, we excluded the months July and August from for our analysis.

ODEQ has other temperature criteria that we did not explicitly evaluate, but can still be assessed using our summaries because they correspond to values used from Huntington and Dunsmoor (2006). For example, ODEQ's 20 °C *Migration corridor (salmon & steelhead)* and *Lahontan cutthroat or redband trout* criteria match the border between the Suboptimal and Stressful categories of Adult chinook salmon and steelhead trout migration, ODEQ's 18 °C *Salmon & trout rearing & migration* matches the border between the Optimal and Suboptimal categories of Adult chinook salmon and steelhead trout migration, and ODEQ's 16 °C *Core cold water habitat* matches the border between the Optimal and Suboptimal categories of Juvenile chinook rearing.

2.11 LONG-TERM TRENDS IN STREAM TEMPERATURE

Establishing a meaningful and rigorous framework for quantitively assessing long-term temperature trends was challenging due to the large number of sites, variable durations of records available at each site, intermittent data gaps, and other issues. The selection of start and end periods for statistical trend assessment can affect results (Walker and Kann 2022a). Trend assessment is best suited for detecting changes that happen gradually and consistently over time, but our study period here contains several step-changes in flow regulation (i.e., initial regulation in 2013, commencement of regulation to SIF flows in 2014, then regulation to full instream claims in 2017) that affected sites differently.

Based on a review of data availability, we evaluated trends for two time periods: 2003–2020 and 2012–2020. The 2003–2020 period begins when the Klamath Tribes started their water temperature monitoring program in the Sprague River. The 2012–2020 period begins when the Klamath Tribes expanded their monitoring to the Williamson and Wood rivers. Prior to calculating monthly means we first filled gaps of up to two consecutive days of missing data using linear interpolation. For each site and year, if data were available for 90% (i.e., 28 of 30 or 31) of days in a month we then calculated monthly averages of T_{max} and T_{mean}. We evaluated trends using linear mixed-effects models and regression models to calculate slopes and evaluate statistical significance (Asarian et al. 2020) for sites and months that had a minimum of 75% (14 of 22 for the 2003–2020 period or 7 of 9 for 2012–2020) of potential monthly averages present. Models were fit using R 4.2.1 (R Core Team 2022) and the lme4 package version 1.1-31 (Bates et al. 2015). Two models were run for each month, one to provide an overall slope representing all sites and another to provide separate slopes for each individual site. The first was a linear mixed-effects model with a fixed effect of year and a random effect that allowed the intercept to vary by site. The year coefficient provides the single linear slope representing the trend of all long-term sites. The second was a linear regression model with year as a fixed effect and an interaction of year and site. The year coefficient for each individual site provides a linear slope

nearly identical to ODFW use designations in the Sprague River but more expansive in the Wood and Westside sub-basins.

[14] In anticipation of dam removal ODFW and the Klamath Tribes (2021) have broadly classified potential Chinook salmon habitat in the Upper Klamath Basin, and these areas could be included in a future effort.

[15] https://www.oregon.gov/deq/FilterRulemakingDocs/figure271b.pdf

for each individual long-term site. We used the associated p-values[16] provided by the lmerTest package (Kuznetsova et al. 2017). To obtain 95% confidence intervals for year slopes, we multiplied the standard error by 1.96.

3 RESULTS AND DISCUSSION

3.1 HYDROCLIMATIC CONTEXT

River flows in the Upper Klamath Basin have been declining in recent decades (Asarian and Walker 2016). At the gages with the longest periods of records, annual flow duration curves show lower flows during 2003–2012 than 1920–2002 (Figure 9). Since flow regulation began in 2013, the highest exceedance flows (i.e., late summer flows) have increased in the Sprague River, Sycan River, and the Williamson River downstream of the Sprague River, despite no increases in flow for moderate and low exceedances, indicating flow regulation elevated late summer flows (Figure 9). Across the period 1982–2021, annual flow, April 1 snowpack, and annual precipitation have all declined, while August flows in the Sprague and lower Williamson River have increased since 2013 (Figure 10a-d). While there are no consistent comparable flow gages for unregulated rivers within the Upper Klamath Basin, the nearby unregulated Chewaucan River did not show increasing August flows since 2013 (Walker and Kann 2022a), providing further evidence that regulation was the cause of the August flow increases in the Sprague and lower Williamson River. While inter-annual patterns in April 1 snowpack and annual precipitation are largely similar, 2013–2015 had extremely low snowpack while precipitation was only below average, and 2020–2021 had extremely low precipitation while snowpack was moderate (Figure 10a-b). Inter-annual patterns in April 1 snowpack and annual precipitation are explored further with respect to the effects of water regulation in Section 3.4, below. Air temperatures in the project area also appear to have increased in the months of May–September during the period 1982–2021 (Figure 10e). Smoke from wildfires, previously shown to decrease water temperatures in the Klamath Basin (David et al. 2018, Asarian et al. 2020) appears to have increased in recent years including 2021 when the Bootleg Fire burned a large percentage of the Sprague River sub-basin (Figure 10f).

[16] We recognize that these P-values are unreliable due to uncertainty regarding the number of degrees of freedom; however, we choose to use them as an index of evidence given lack of other suitable methods.

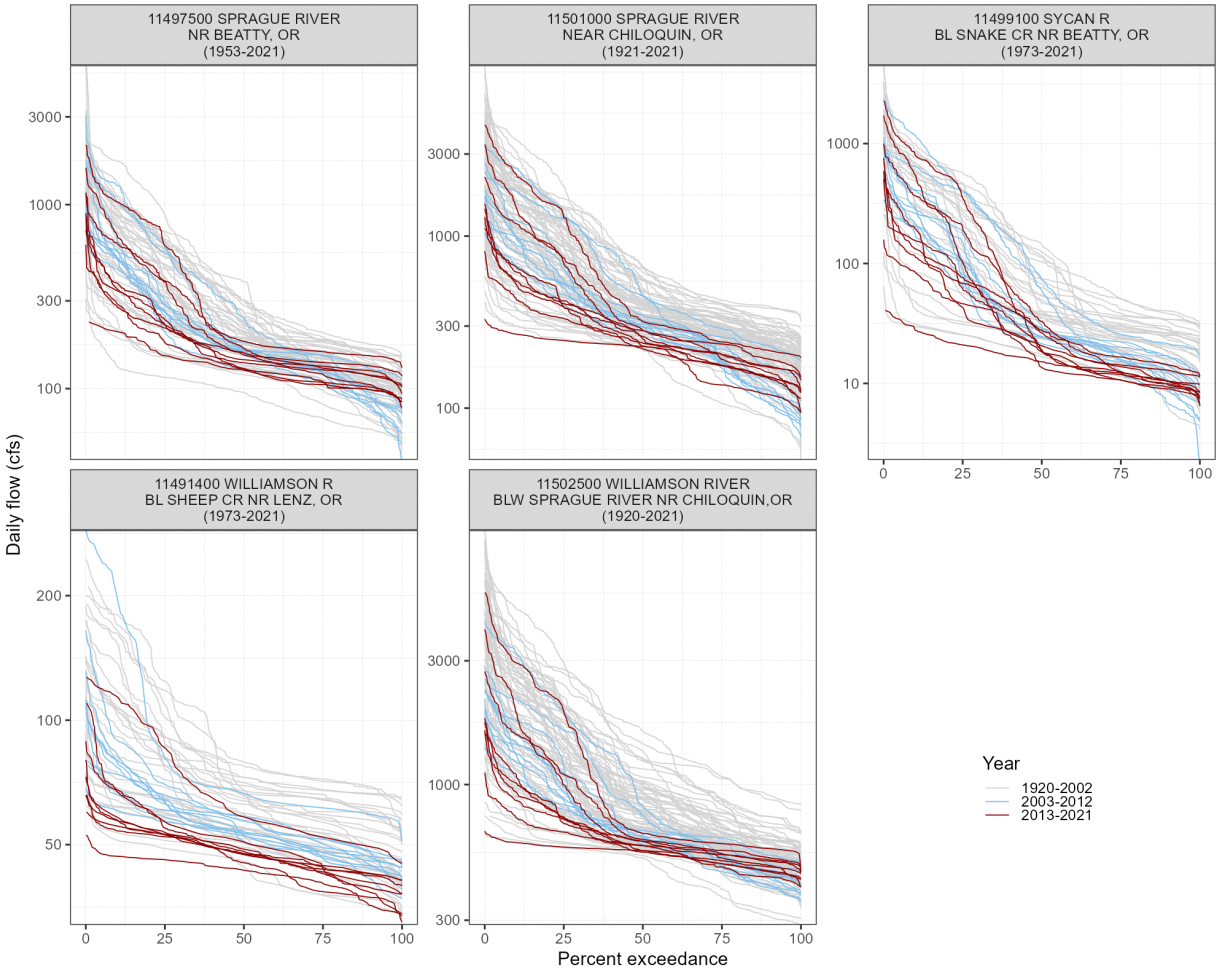

Figure 9. Annual flow duration curves for USGS and OWRD gages in the project area with the longest periods of record.

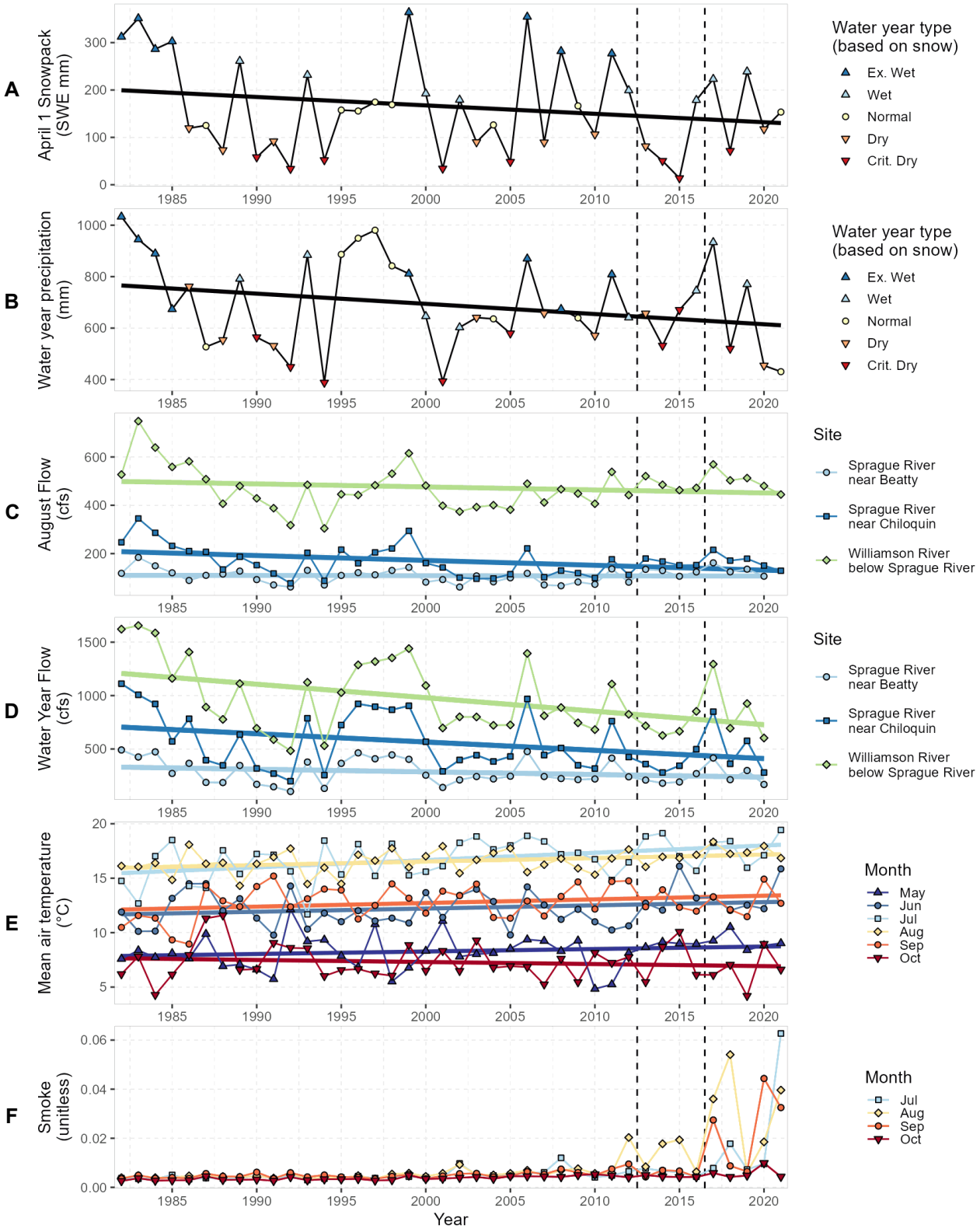

Figure 10. Annual time series 1982–2021 of: A) project area mean of water year precipitation from PRISM model, B) project area mean of April 1 snowpack from UA model, C) mean August flow at selected USGS gages, D) mean water year flow at selected USGS gages, E) project area monthly mean air temperature from PRISM model, and F) project area monthly mean atmospheric black carbon (an estimate of wildfire smoke) for months of July–October from MERRA2 re-analysis (Randles et al. 2017). Vertical dashed lines at 6/17/2013 and 4/4/2017 are the start of flow regulation and the Klamath Tribes enforcement of their full instream claims, respectively.

3.2 WHEN AND WHERE DOES FLOW AFFECT STREAM TEMPERATURE?

To assess spatial and temporal effects of flow on stream temperature, for each site we categorized each date into high (>0.67 quantile), moderate (0.33–0.67 quantile) or low (<0.33 quantile) watershed flow quantiles, and plotted observed stream temperatures for each watershed flow category (Figure 11 and Figure 12). Daily maximum temperatures associated with the three flow categories were substantially different among sites. At sites close to major spring sources (including Spring Creek, head of Williamson River, Wood River at Dixon Rd, Agency Creek at Sage, Tecumseh Spring, and many Westside springs), water has a near constant temperature and varied little regardless of flow or season (Figure 11 and Figure 12). In general, the various Wood River stations showed the least variation in temperature related to flow classes (Figure 13). At the opposite extreme are multiple sites on Spencer Creek where during early July, daily maximum temperatures were approximately 4 °C warmer under low flow conditions than under high-flow conditions (Figure 12 and Figure 13). At sites in the Sprague River and its largest tributaries including Sycan River, late May temperatures were up to 2–6 °C warmer under low flow conditions than under high-flow conditions, with greatest effects at South Fork Sprague River at Picnic (Figure 11 and Figure 13). The effect of flow pattern on daily mean temperatures were similar to those of daily maximum temperatures, but slightly lower (Figure 13).

A few sites show trends opposite to those of other sites, including Williamson River below Sprague where temperatures are cooler in June through September under low-flow conditions than during high-flow conditions, presumably because the constant flow and cold water from Spring Creek are diluted by warmer Sprague River water during higher flows but not lower flows. Similarly, the Williamson above Sprague is cooler under low-flow conditions during May–July because Spring Creek's cold water is diluted by upstream waters including Klamath Marsh during periods of higher flow. The effect of low flows was also pronounced at the NF Sprague at Ivory Pine Rd. station, where April-October low flows were associated with ~2 to 5 °C higher maximum temperatures (Figure 11).

The effect of flow on summer temperatures was generally strongest at sites located in warmer river reaches than in cooler tributaries or cold springs.

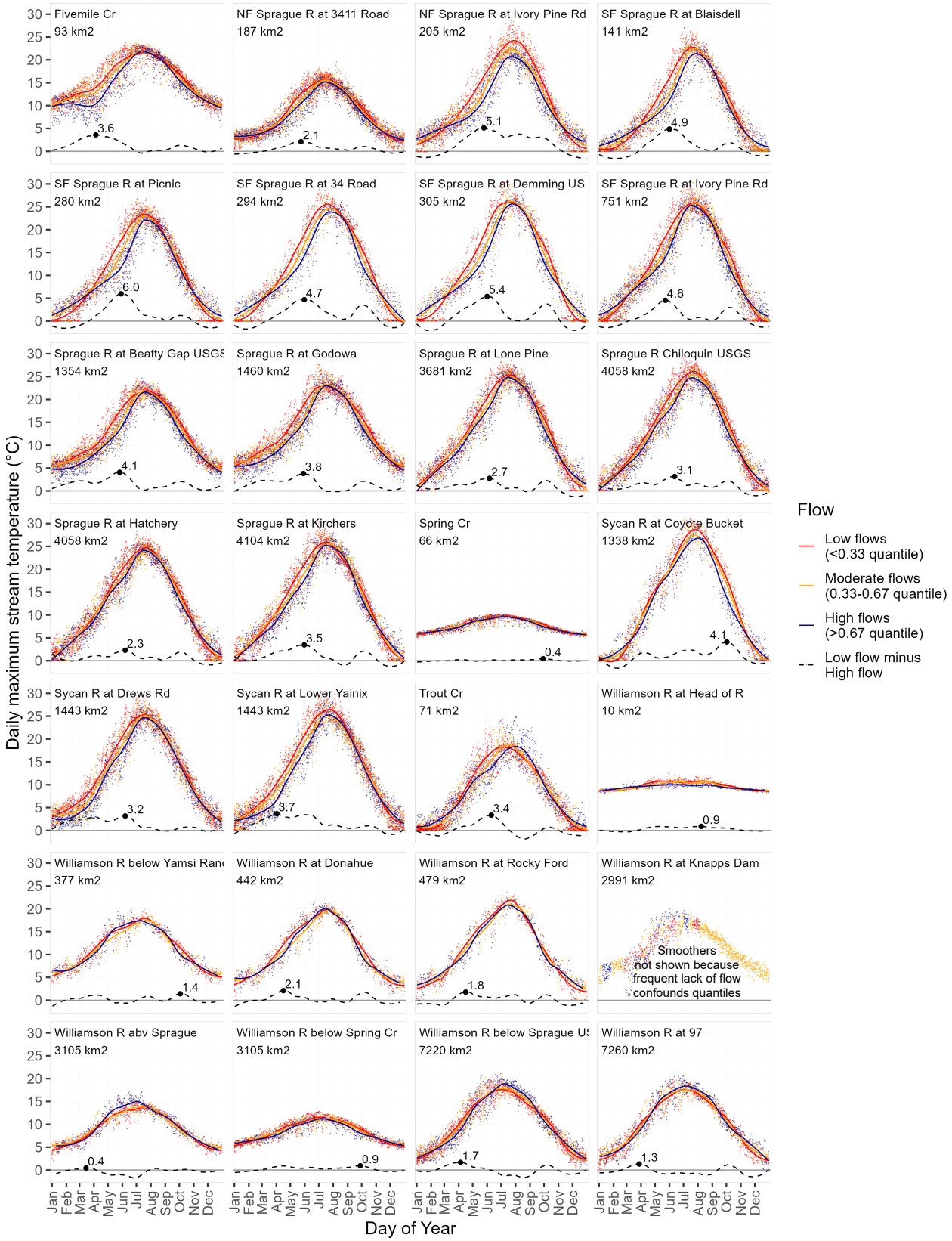

Figure 11. Measured T_{max} for dates when watershed flow was low, typical, or high quantile (shown by color) at 28 long-term monitoring sites in the Sprague and Williamson Rivers in 1993–2020. Lines are GAM smoothers fit to points, shown as visual aids. Dashed black lines are the temperature difference between low-flow and high-flow conditions, with maximum values labeled.

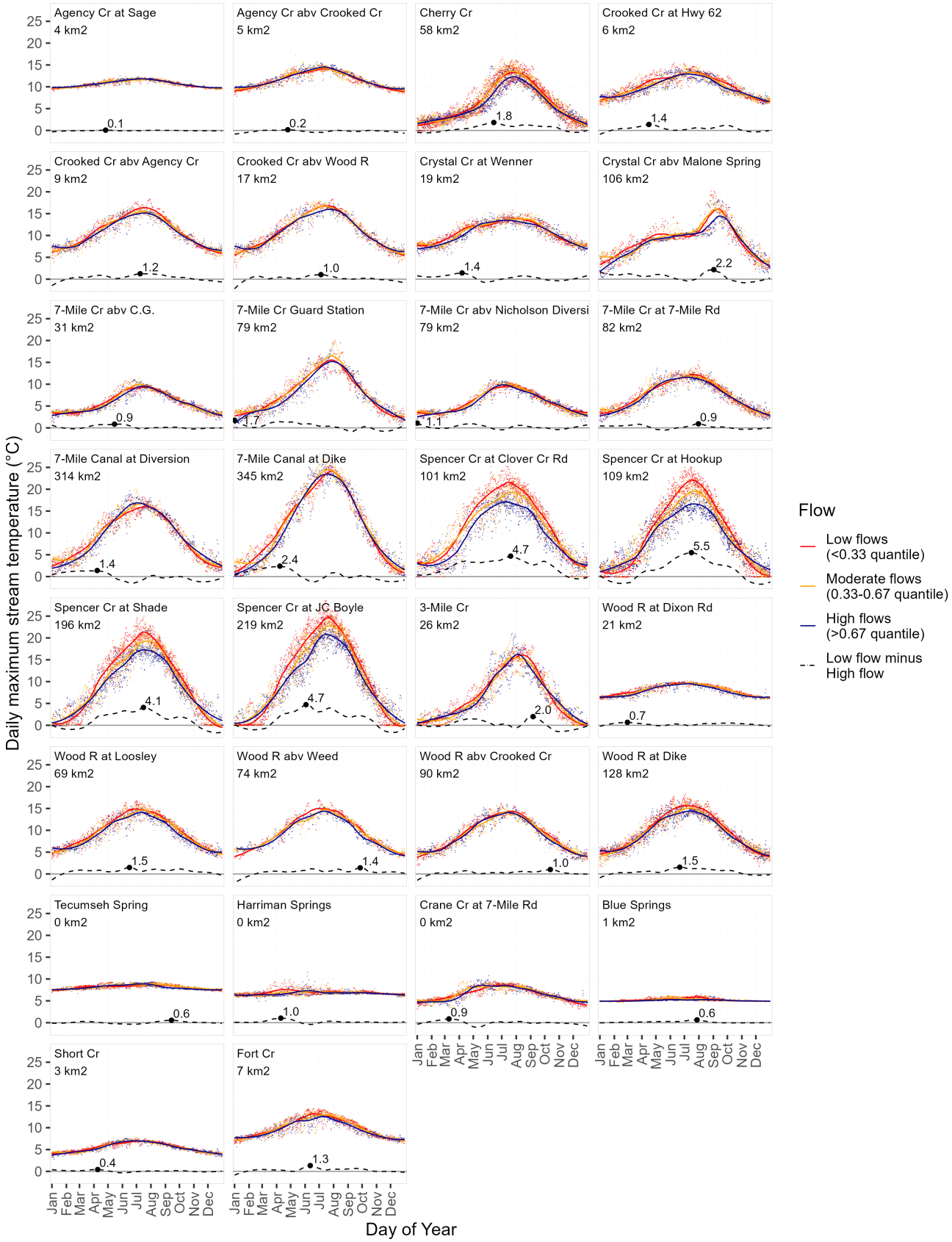

Figure 12. Measured T_{max} for dates when watershed flow was low, typical, or high quantile (shown by color) at 30 long-term monitoring sites in the Wood, Westside, and Spencer areas in 1993–2020. Lines are GAM smoothers fit to points, shown as visual aids. Dashed black lines are the temperature difference between low-flow (red) and high-flow (blue) smoothers, with maximum values labeled.

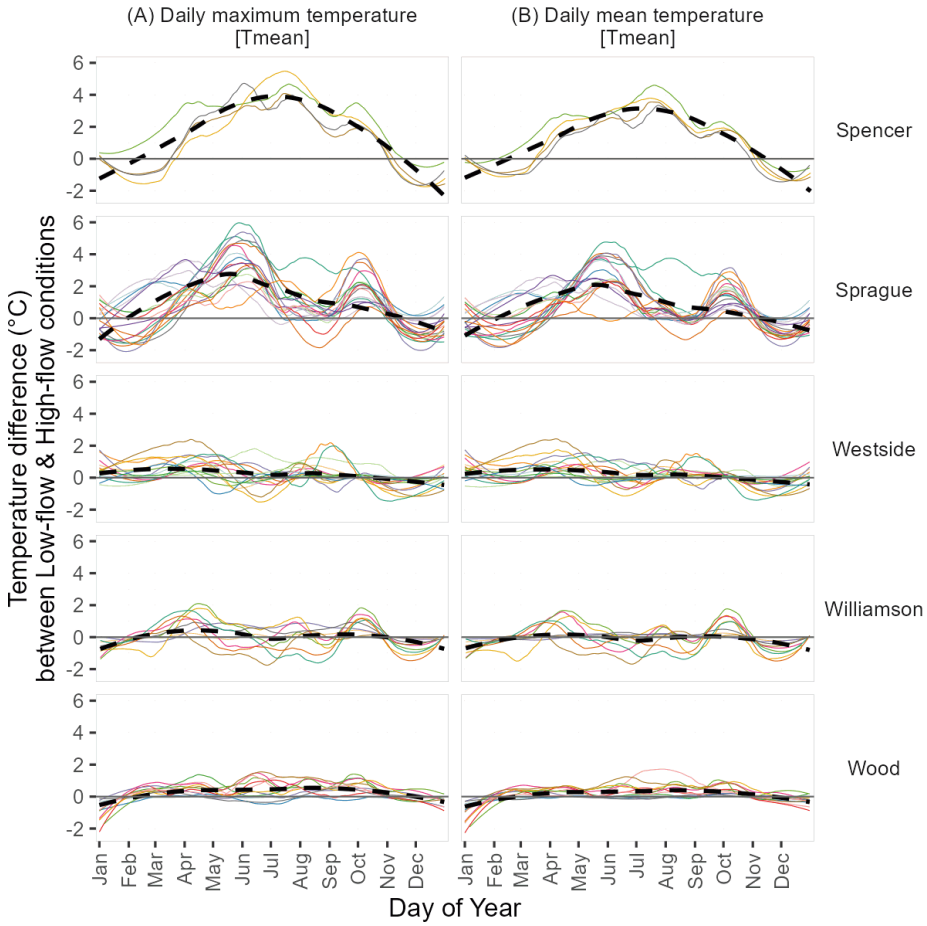

Figure 13. Temperature differences between dates when watershed flow was low (0.10–0.33% quantile) or high (0.67–1.00 quantile) at 58 long-term monitoring sites, for (a) T_{max} and (b) T_{mean}. Each line represents an individual site (same data as black lines in Figure 11 and Figure 12), assigned a random color. Dashed black lines are LOESS smoothers, shown as visual aids.

3.3 TEMPERATURE MODEL CALIBRATION AND VALIDATION

Evaluation of BIC scores provide some insights regarding the importance of variables and model structures. For both T_{max} and T_{mean}, within the 24 sites where both local flow and temperature data were available, the choice of air temperature variable had a greater effect on BIC scores than did the choice of flow variable (i.e., when models were sorted by BIC scores, they group first by air temperature [best was Daymet 3-day air temperature, then PRISM 2-day air temperature, then Daymet 3-day air temperature, worst was Daymet 1-day air temperature] and then by flow variable [i.e., local flow was better than watershed flow) (Table A1). Models with April 1 snow-water equivalent (SWE) performed worse than models with local flow or watershed flow (Table A1). The model with the lowest BIC score was selected to model T_{max} for an instream claims flow scenario (Section 3.4.4). This model predicts temperatures based on local flow, Daymet 3-day air temperature, day of year, and interactions between day of year and the other covariates (flow and air temperature) that allow effects to vary seasonally, including factor smooths that allow each site to have a unique relationship with flow and air temperature. In cross-validation, this model had a root mean squared error (RMSE) of 1.09 °C for T_{max} and 0.96 °C for T_{mean} (Figure A30).

At the 58 sites with long-term temperature (but not necessarily local flow), the effect of the choice of air temperature and hydrology variables were similar to those at the 24 sites discussed in the previous paragraph, with Daymet 3-day air temperature being the best air temperature variable and watershed flow outperforming SWE (Table A2). Even though watershed flow outperformed SWE, we chose the SWE-based model for the analyses in Section 3.4.5 (Comparing Differences Between Modeled and Measured Temperatures Before and During Regulation) because that comparison requires a hydrology variable not influenced by instream flow regulation. This selected model, identical in structure to that described in the previous paragraph except that it used SWE instead of local flow, had an RMSE of 1.24 °C for T_{max} (Figure A32) and 0.97 °C for T_{mean} (Figure A33).

3.4 EFFECTS OF FLOW REGULATION

3.4.1 PREVIOUS ASSESSMENTS OF PRE-REGULATION vs. REGULATION HYDROLOGIC EFFECTS

The effects of the Klamath Tribes water rights enforcement on instream flows have been assessed previously using statistical models, primarily at the Sprague River gage at Chiloquin. Hess and Stonewall (2014) compared several methods for the year 2013, all based on comparisons to a Composite Index Year (CIY; with diversions, based on years 1977, 1981, 1990, 1991, 1994, and 2001 whose flows in spring were similar to 2013). Based on these analyses, Hess and Stonewall (2014) estimate that irrigation curtailments increased June–September 2013 flows by 14,100 AF in the Sprague River and 5,500 AF in the Wood River. Evenly splitting these flows across the 122-day June–September period yields 58 cfs for the Sprague River and 23 cfs for the Wood River. Wood (2019) calibrated a machine learning model using 17 predictor variables (e.g., groundwater depth in a Sprague River monitoring well, Fall River streamflow, and various climate datasets) from 33 pre-regulation years (1980–2012) to predict daily flow of Sprague River at Chiloquin. Wood (2019) then assessed the effects of irrigation curtailment in four regulation years (2013–2016) by comparing model predictions to gaged flows. Cumulative instream flow increases from irrigation curtailment varied by year from a high of 12,600 AF in 2013 (equates to 52 cfs if spread evenly across June–September) to a low of 65 AF in 2016.

Walker and Kann (2022a) assessed potential impacts of the Klamath Tribes' water rights calls by comparing seasonal variations in flows between the years before (WY 2002 – 2012) and during (WY 2013 – 2020) the water use restrictions. The largest changes between these periods included higher summer flows (by as much as approx. 50 cfs in August) during the regulation period along the mainstem Sprague River as well as the lower North Fork at Ivory Pine. Comparisons of flow between sites suggested the majority of these summer flow increases occurred between the North Fork at 3411 Road and North Fork at Ivory Pine, likely due to changes in the operation of the North Fork Ditch diversion, which normally transfers large quantities of water to the South Fork drainage. Further comparison to a streamflow gauge in the neighboring unregulated upper Chewaucan River indicated that the higher Sprague River flows during the regulation in July – September were not likely due to background climatic/hydrologic conditions and confirmed Sprague River flows were as much as 50 cfs higher for a given Chewaucan River flow during the regulation period as compared to prior years.

Velpuri et al. (2020) estimated evapotranspiration (ET) from agricultural fields using the Operational Simplified Surface Energy Balance (SSEBop) (Senay et al 2013) remote sensing method that integrates 30-m resolution imagery from the Landsat satellite with reference

evapotranspiration data from the 4-km resolution gridMET dataset (Abatzoglou 2013). Analyses were limited to the months of June–September because irrigation curtailments did not occur prior to June and the peak growing season ends in September. By comparing ET in pre-regulation base years (2004, 2006, 2008–2010) to regulation target years (2013–2016), Velpuri et al. (2020) estimated effects of irrigation curtailment on ET (ΔET), with an additional calculation of the "extra water available" (EWA) for streamflow that adjusts for precipitation. Among the four years, ΔET ranged from a high of 35 hm^3 (28,000 AF) in 2013 to a low of 19 hm^3 (15,000 AF) in 2016, and EWA ranged from a high of 48 hm^3 (39,000 AF) in 2013 to a low of 18 hm^3 (15,000 AF) in 2016. Spreading this volume evenly across June–September yields a range of 64–118 cfs for ΔET and 70–160 cfs for EWA, although there is considerable uncertainty in the timing of when this water becomes streamflow. Additional high-resolution satellite-based ET GIS datasets are available for recent years not included by Velpuri et al. (2020)[17], and once summarized on watershed scales should allow EWA estimates to be made for 2017 to the present. The U.S. Bureau of Reclamation is currently developing annual satellite-based ET estimates for most of the Klamath Basin, including the Sprague River sub-basin, from 1980–2020 as part of its updated Klamath Natural Flow Study[18]. These estimates will soon be available for public use and could be applied to estimate curtailment effects.

Using irrigation acreage and monthly net consumptive-use rates estimated for the 2014 Upper Klamath Basin Comprehensive Agreement (State of Oregon 2014), Risley (2019) estimated monthly consumptive use for watersheds upstream of several gages in the Upper Basin. These estimates peaked in July with 288 cfs for the Sprague River near Chiloquin (approximately evenly split between Sycan sub-basin, Lower Sprague sub-basin, and Upper Sprague sub-basin), 245 cfs for the Upper Williamson River sub-basin, 24 cfs for the Lower Williamson River sub-basin, and 52 cfs for the Wood River sub-basin. Risley (2019) did not attempt to quantify the curtailments, but the ET estimates provide an upper bound of streamflow increases that might occur with a total shutdown of irrigation.

The large difference between the total ET-based streamflow estimates reported by Risley (2019) and the other estimated streamflow changes (Velpuri et al. 2020, Hess and Stonewall 2014, Walker and Kann 2022b, Wood 2019) resulting from the curtailments suggests the possibility of either widespread non-compliance with the curtailments (i.e., unauthorized irrigation), increased groundwater withdrawals affecting surface flows, an overestimation of ET by Risley (2019), lower overall water availability due to reduced snowpack and increased temperatures, and other unanticipated and poorly understood watershed processes (e.g., groundwater and hyporheic-surface water interactions). It is also possible that Velpuri et al. (2020), Hess and Stonewall (2014), Walker and Kann (2022b), and Wood (2019) underestimated the effects of the curtailments. However, those results used widely differing methods yet provided estimates of increased streamflow due to curtailments that were in a similar range.

[17] Senay et al. (2022) later used the Google Earth Engine platform and SSEBop to estimate ET for every 30-m Landsat pixel the conterminous USA for 2010–2019, but these are not directly comparable to Velpuri et al. (2020) because they are summarized by calendar year not June–September. Monthly April–November ET estimates for 2004 and 2006 based on a different algorithm (METRIC: Mapping EvapoTranspiration at High Resolution and Internalized Calibration) were developed for the UKBCA (Snyder et al. 2012). The OpenET project (openetdata.org) applied SSEBop and other remote sensing methods to estimate ET for every 30-m Landsat pixel in the Western USA for 2017–present, but these data are not yet publicly available for large-scale summarization (Melton et al. 2021). ET estimates from an older version of SSEBop using data from the 1-km resolution MODIS satellites (Senay et al. 2013) is available for 2000–present, which we considered using to update Velpuri et al.'s (2020) analysis but decided not to for budgetary reasons.

[18] https://www.usbr.gov/mp/kbao/nfs.html

3.4.2 OUR ASSESSMENT OF PRE-REGULATION vs. REGULATION HYDROLOGIC EFFECTS

Several patterns are evident in comparisons of daily gaged flow time series between the pre-regulation and regulation eras, the first method we used to assess the hydrologic effects of regulation (Figure 14, Figure 15). During spring (primarily May), flows at most sites were generally higher during the pre-regulation era, suggesting a generally wetter climate during the pre-regulation era, as discussed in Section 3.1 above. The generally wetter climate in the pre-regulation era is also evidenced by higher flows at hydrologic reference gages in the Rogue and Chewaucan rivers, west and east our study area, respectively (Figure 15b). During spring, river flows are presumably more climate-driven and less affected by irrigation diversions compared to later in the summer when flows are much lower. Given the typical pattern of flow recession from spring snowmelt to late summer baseflow, if climate were the only factor affecting flows then lower spring flows should have resulted in lower summer flows. However, despite these lower flows during spring, sites in the mainstem Sprague River, lower Sycan River, and Williamson River below Sprague had higher flows July–September or August–September during the regulation era (Figure 14). These results are similar to those described above (Section 3.1) showing increased late-summer flows in the Sprague and Sycan Rivers despite a declining trend in snowpack and provide strong evidence that flow regulation was elevating these late summer flows. Wood River flows were also higher in the regulation era than the pre-regulation era, especially after enforcement of full instream claims started in 2017 (Figure 15a). Reduced diversions from the Wood River appear to have lowered flows during the regulation era in 7-Mile Canal at Dike, a site where flows are partially derived from the return of water originally diverted from the Wood River (Figure 15a).

The second method we used for assessing hydrologic effects of regulation was to use linear regression to explore relationships between April 1 snowpack and annual precipitation to monthly and annual gaged flows. During the pre-regulation era (1982–2012), annual flow at long-term gages was more correlated with annual precipitation than it was to snowpack (Figure 16). Conversely, August flow was more correlated to snowpack than it was to annual precipitation (Figure 16). For the months of April-July, the strength of correlations between flow and snowpack and precipitation varied by site and month (Figure B36). April 1 snowpack provides a simple and convenient proxy for dry season flow that is independent of the effects of flow regulation, although we acknowledge that it is an imperfect predictor because a warming climate is causing earlier snowmelt (Zeng et al. 2018), and previous drought years can have lingering effects on flow in subsequent years (Lapides et al. 2022) especially for Upper Klamath Basin springs that respond to precipitation at complex time scales including multiple years or even decades (Gannett et al. 2007, Mayer and Naman 2011). In the Sprague, Wood, and lower Williamson rivers, flow regulation appears to have increased the amount of August flow resulting from a given amount of snow or precipitation, with greatest effects in years with lower snow and precipitation (e.g., approximately 50 cfs at Sprague River and 100 cfs at lower Williamson River and Wood River) (Figure 14). Interestingly, in the Sprague and lower Williamson rivers, annual flows show the opposite pattern, with lower annual flows for a given amount of snow or precipitation during the regulation era than the pre-regulation era, likely a result of multi-year drought dynamics. In the Wood River, correlations between annual flow and precipitation or snowpack are weaker than at other sites (r^2 <0.29) (Figure 16b). In the Sycan River and upper Williamson River, annual and monthly (April–August) flow resulting from a given amount of snowpack or precipitation appears to be lower during the regulation era than the pre-regulation era (Figure 16, Figure B36).

Our third method for assessing hydrologic effects of regulation, using GAMs and Chewaucan River flows, showed mixed results (Appendix C). These Chewaucan-based models indicated higher flows in the regulated era during July–August by up to approximately 50 cfs in the Sprague River at Beatty and Chiloquin (which was similar to that determined by Walker and Kann (2022a), 100 cfs in the Williamson River below Chiloquin, with no increase in the upper Williamson River below Sheep Creek (Figure C50, Figure C51). However, for most periods outside of July and August, the daily and monthly models predicted lower flows than those observed during the regulated era, especially in the springtime (Figure C50, Figure C51). One process by which regulation could contribute to lower flows in the fall months is reduced groundwater recharge as a result of less flood irrigation during the spring and summer. Considering all available evidence, we think these models under-represent the flow increases resulting from regulation, except in July–August. These models primarily rely on instantaneously (i.e., no lags or consideration of previous time steps) translating Chewaucan River flows and therefore may be confounded by multi-year drought effects that may manifest differently at our study sites. In addition, the Chewaucan River has later runoff timing than the Sprague River, with Sprague flows receding more quickly in the spring than the Chewaucan (Figure 14, Figure 15b), perhaps due to the Sprague River having a larger percent of its watershed having lower elevations where snow would presumably melt earlier (Appendix C). We had initially hoped to use these models to develop flow scenarios as inputs into our temperature models, but given our lack of confidence in these results we elected not to do that.

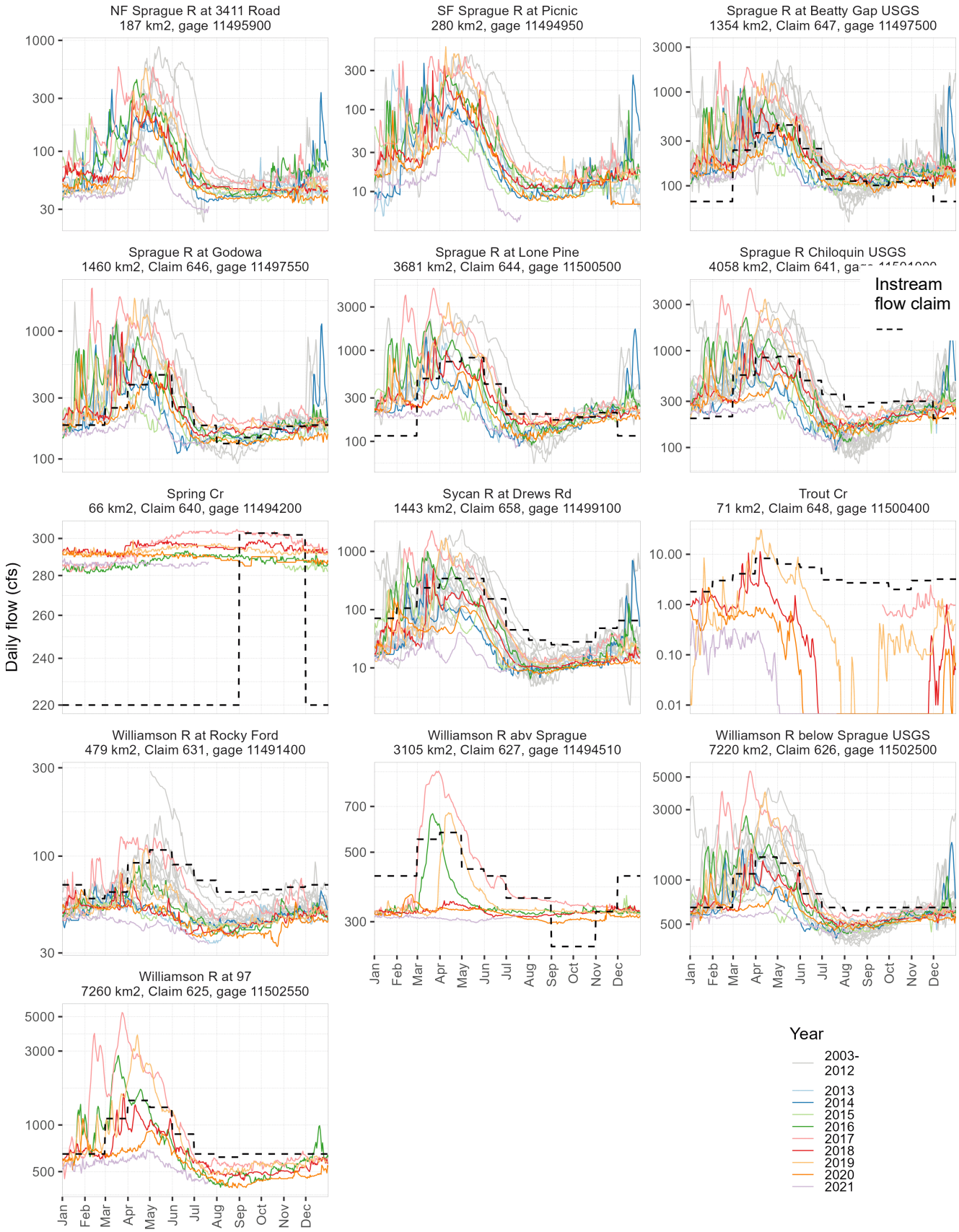

Figure 14. Annual hydrographs for years with available USGS, OWRD, and Klamath Tribes local flow data during the pre-regulation (2003–2012) and/or regulation eras (2013–2021) in the Sprague and Williamson sub-basins. Klamath Tribes instream flow claims are shown if applicable. Panel titles are labeled with temperature site name, drainage area, claim number, and flow gage number.

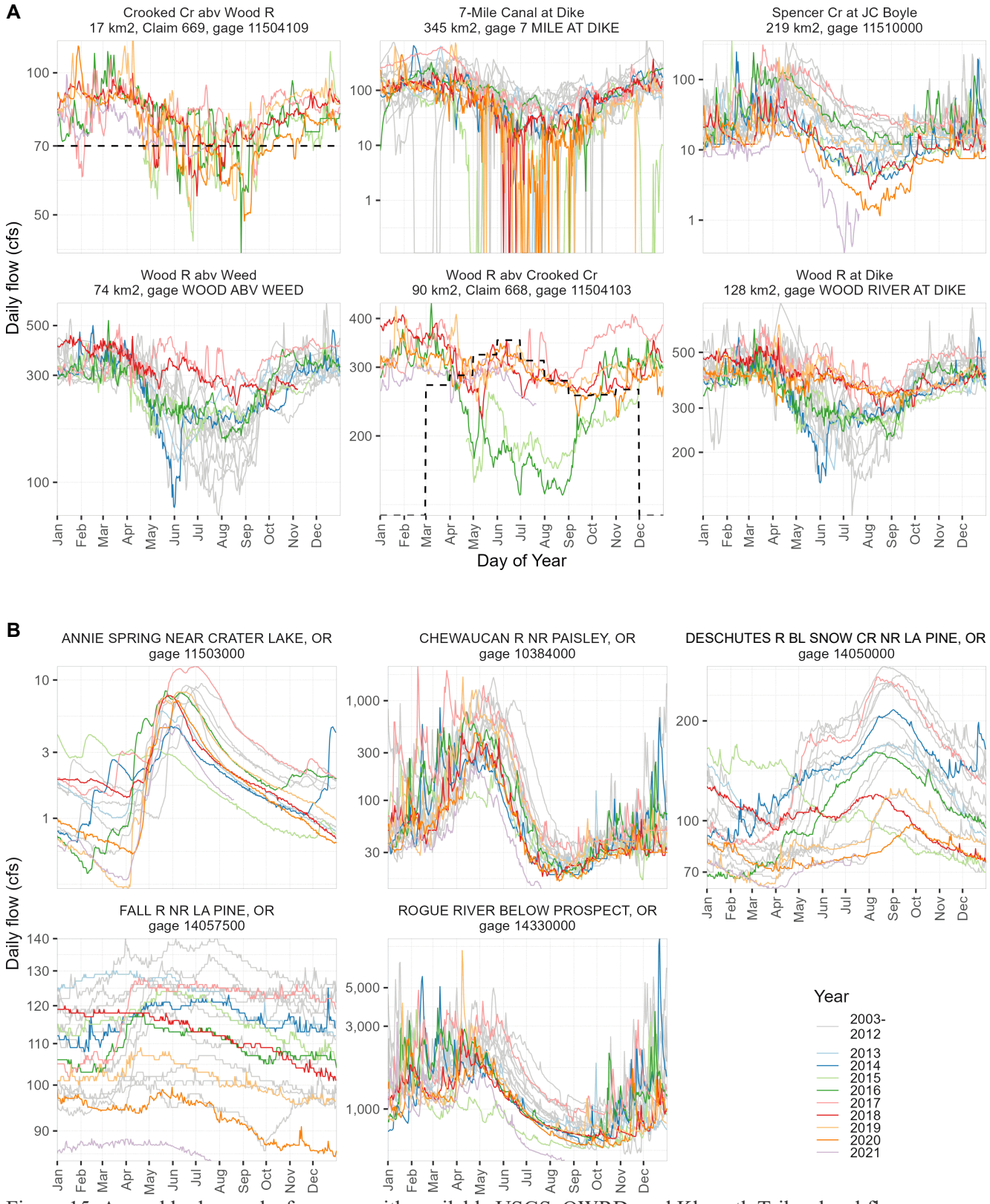

Figure 15. Annual hydrographs for years with available USGS, OWRD, and Klamath Tribes local flow data during the pre-regulation (2003–2012) and/or regulation eras (2013–2021) in (A) the Wood, Westside, and Spencer areas, or (B) reference gages from outside the Klamath Basin and Annie Spring. Klamath Tribes instream flow claims are shown if applicable. Panel titles are labeled with temperature site name, drainage area, claim number, and flow gage number. 7-Mile Canal has some negative flows, so to plot on log scale, all flow values <0.1 cfs were set to 0.1 cfs.

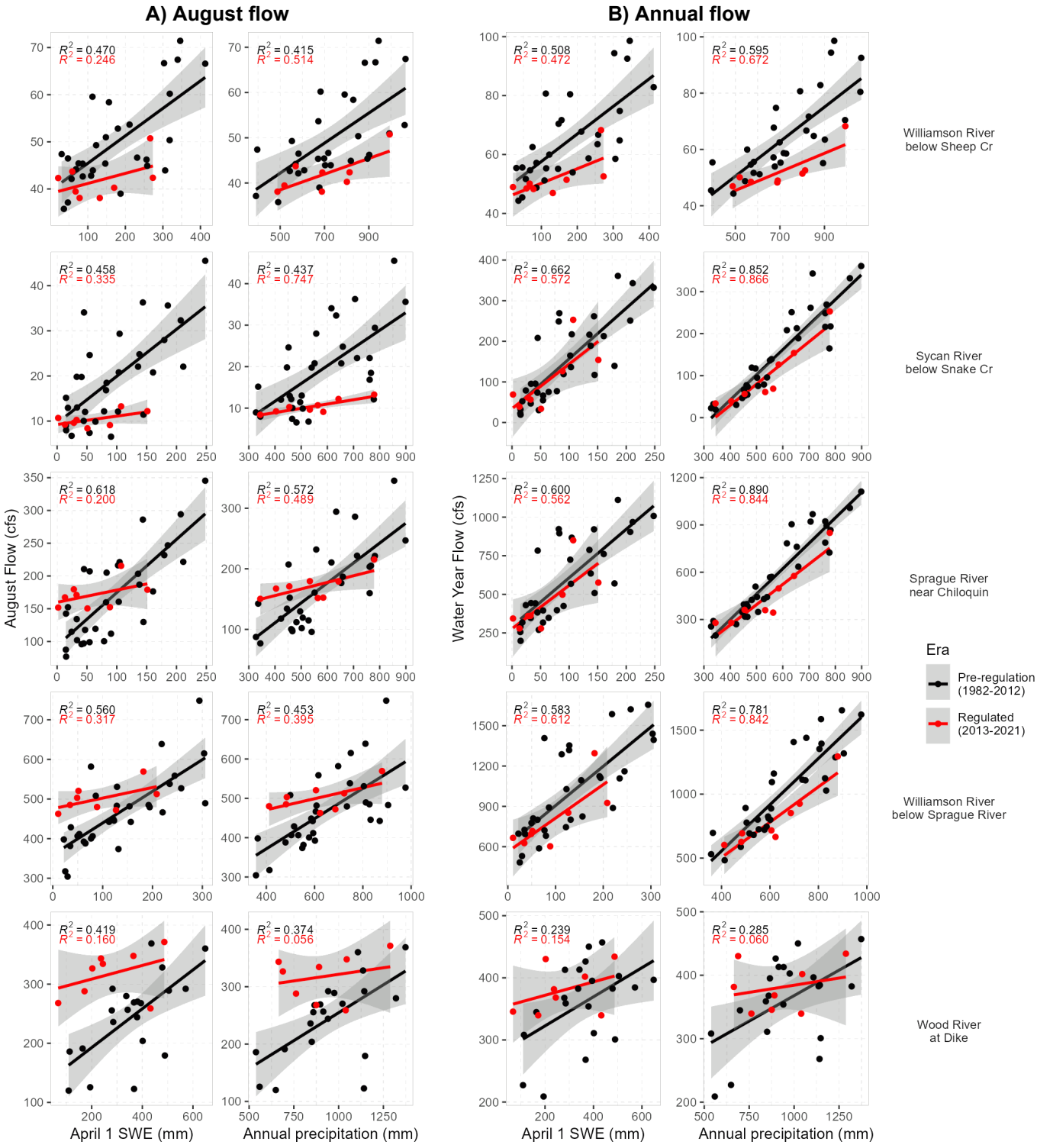

Figure 16. Regression of (A) August flow and (B) annual flow vs. April 1 snow water equivalent (SWE) and annual precipitation at five long-term flow gages in the pre-regulation and regulated eras. Gray shading is 95% confidence intervals. SWE and precipitation were calculated for each gage's contributing watershed, except for Sycan (uses data from Sprague watershed) and Williamson River below Sheep Creek (uses data from Williamson River upstream of Sprague).

3.4.3 COMPARISONS OF MEASURED TEMPERATURES AT SITES UNAFFECTED AND AFFECTED BY FLOW REGULATION

Of sites we characterized as having hydrology affected by flow regulation, only 13 had sufficient measured temperature data before and during regulation to compare to the 3 sites whose hydrology we characterized as relatively unaffected by regulation, either because they were not subject to water rights curtailment or the water right was a small proportion of the baseflow. The largest differences between the pre-regulation and regulation eras were at the North Fork Sprague River at Ivory Pine Road, where divergence of the LOESS lines show temperatures approximately 2 °C cooler for T_{max} (Figure 17) and T_{mean} (Figure B37) during the regulation era than in the pre-regulation area. In other words, during the regulation era temperatures in the mid- to upper range (>14-15 °C) were approximately 2 °C cooler for T_{max} at the North Fork Sprague River at Ivory Pine Road station subject to curtailment relative to the sites relatively unaffected by regulation (e.g., North Fork Sprague River at 3411 Road and South Fork Sprague River at Blaisdell). As discussed in Section 3.4.1 above, the North Fork Sprague River at Ivory Pine Road site showed increased flow during the regulation era (Walker and Kann 2022b) and is located several miles downstream of a major diversion that has been frequently curtailed during the regulation era.

A few sites have warmer temperatures during the regulation era than the pre-regulation era, at least for portions of the year (Figure 17), but these may be due to effects of lower flow due to drought. These include Trout Creek which has often gone dry in recent years whereas the sites we compared it to were perennial (Figure 14). For the Williamson River below Sprague River, shifts between pre-regulation and regulation are only evident compared to the South Fork Sprague River at Blaisdell, not the other sites, suggesting these changes were subtle. Flows in the Williamson River below Sprague are derived from a combination of the upper Williamson River (which have declined in recent years), and Spring Creek (very stable between years), and the Sprague River (where late summer flows have been elevated by flow regulation).

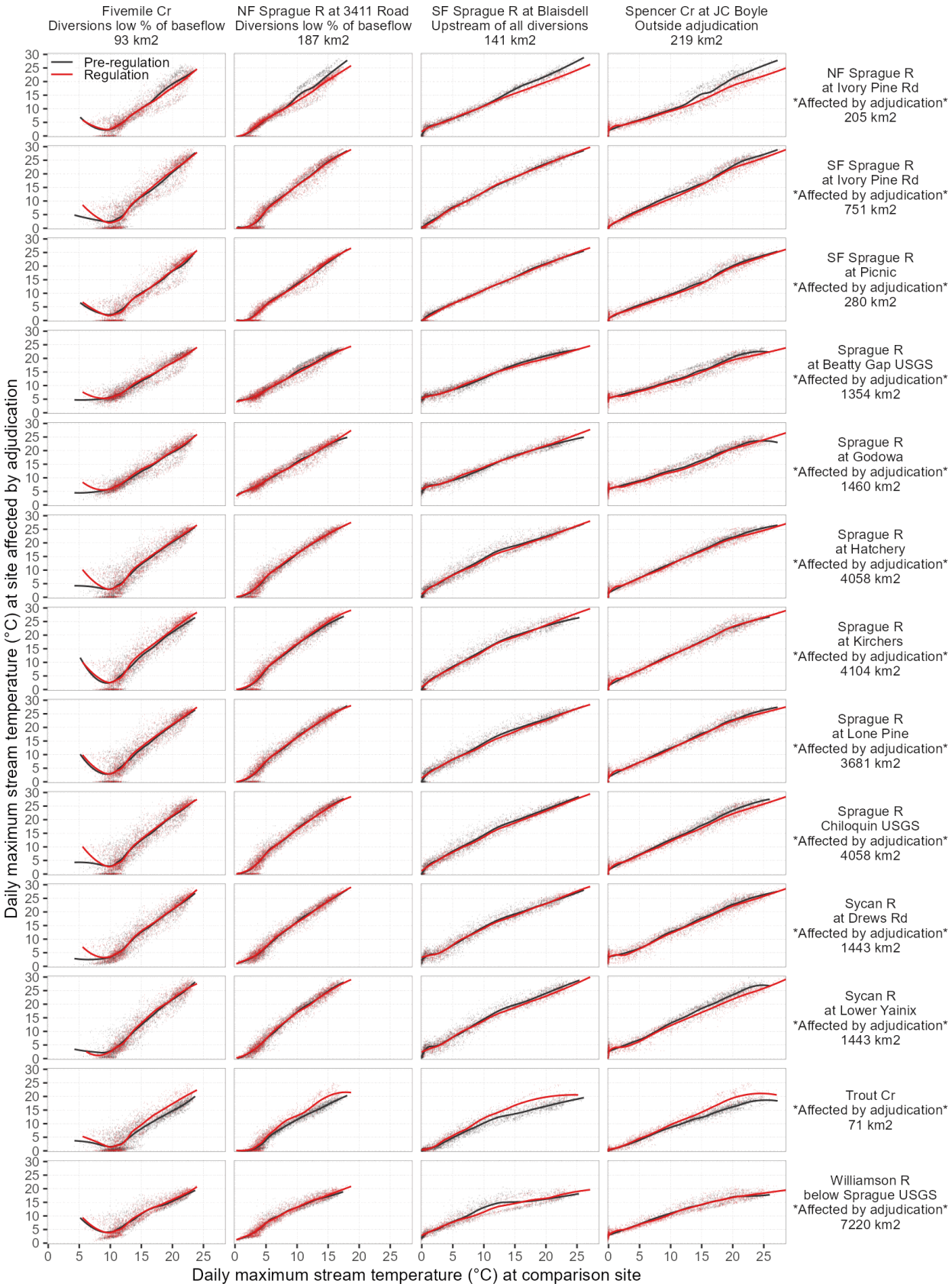

Figure 17. Scatterplots comparing measured T_{max} at four sites not affected by regulation (i.e., either not within the geographic scope of regulation or upstream of all diversions) and 13 sites expected to be affected by regulation. All sites shown have at least 1000 days of pre-regulation era temperature measurements. Lines are LOESS smoothers fit to points, shown as visual aids.

3.4.4 MODELING TEMPERATURES UNDER AN INSTREAM CLAIMS FLOW SCENARIO

Measured flows have remained below the levels specified by the instream claims at many sites during the regulated era (Figure 18b and Figure 19b), likely due to a combination of drought (i.e., naturally low flows), non-compliance (i.e., unauthorized diversions), and increased groundwater pumping due to lack of access to surface water. At 16 sites that had both local flow data available and a Klamath Tribes instream claim, we applied our local flow GAM to predict the difference in T_{max} between a scenario using measured local flows (the same data that the model was calibrated with) to a scenario in which any measured flows less than the claim were increased up to the claim, but flows already above the claim were left unchanged (Figure 18a and Figure 19a).

Results of the model predictions vary by site. In line with where we determined flow had relatively little effect on temperatures, such as most sites in the Wood and Williamson River sub-basins (see Section 3.2 above), our model also predicted that meeting instream claims would have little effect on temperatures (Figure 18a). In contrast, at other sites where flow was shown to have a greater effect on temperature, namely those in the Sprague River sub-basin, our model predicted that temperatures would cool up to 2–3 °C if instream claims could be met (Figure 19a). Greatest effects were predicted to occur in March–July (Figure 19a), likely due to a combination of flow having greater effects on temperature in those months and instream claims being higher in those months. While greatest differences in flow between the pre-regulation and regulation era in the Sprague River occurred in August and September, our models predicted that meeting instream claims in August and September would have relatively little effect on temperature (Figure 19b). This result is similar to the small effect of flow on temperatures empirically observed later in the summer (Section 3.2). We acknowledge that our modeling approach does not differentiate between climate-driven flow variation (e.g., high summer flows due to high spring snowpack) and regulation-driven flow variation (e.g., high summer flows due to less diversions for irrigation), which may have different effects on temperatures—the model represents total flow and was calibrated based on all available dates.

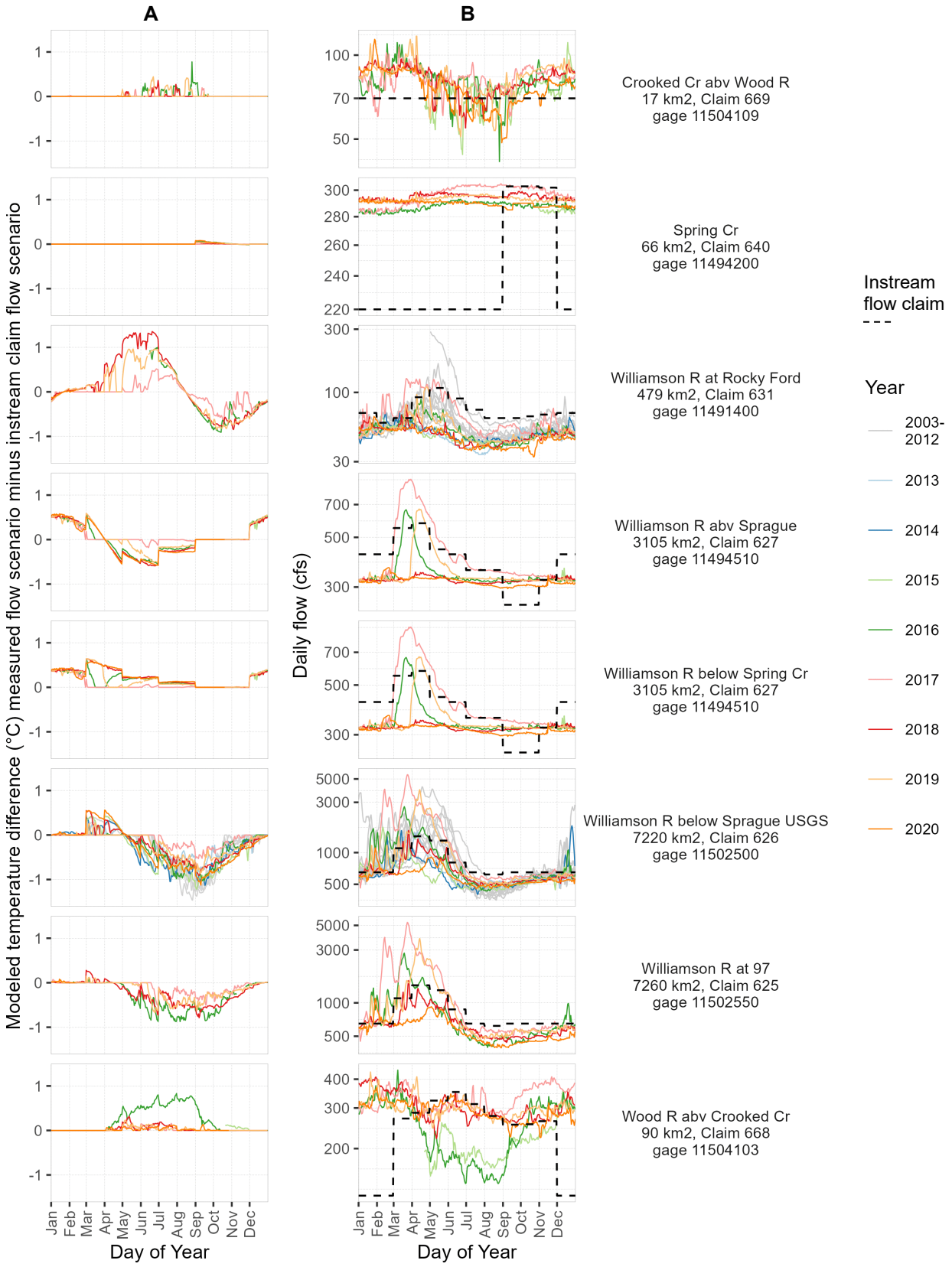

Figure 18. (A) Modeled temperature differences between a scenario using measured flows and a scenario using the greater of measured flows or Klamath Tribes instream flow claims, for each day with measured temperatures and flow 2003–2020 at sites in the Williamson and Wood watersheds. (B) Annual hydrographs for years during the pre-regulation (2003–2012) and/or regulation eras (2013–2020). Temperature differences above zero indicate that meeting instream flow claims would cool temperatures. Panel titles are labeled with temperature site name, drainage area, claim number, and flow gage number.

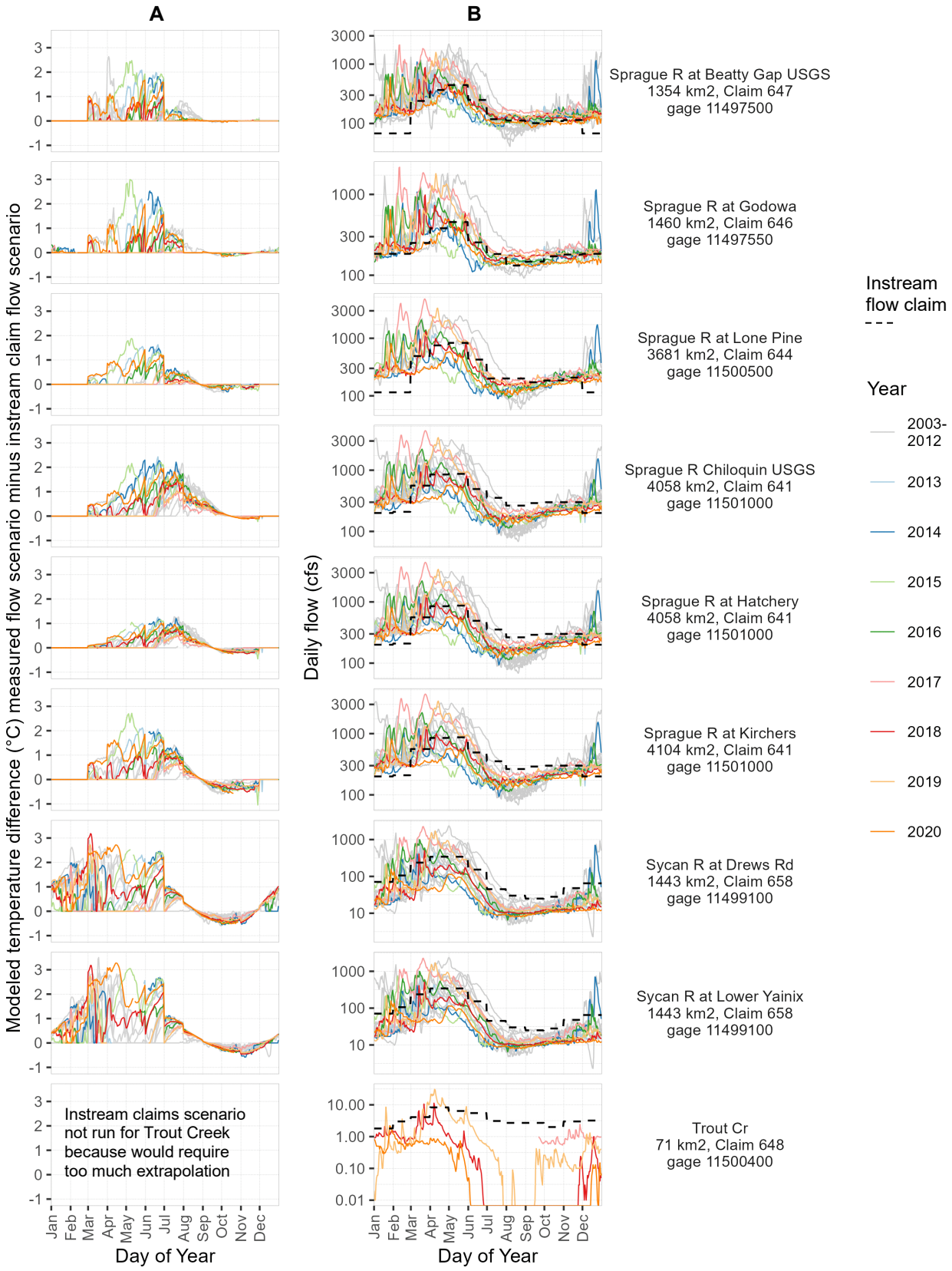

Figure 19. (A) Modeled temperature differences between a scenario using measured flows and a scenario using the greater of measured flows or Klamath Tribes instream flow claims, for each day with measured temperatures and flow 2003–2020 at sites in the Sprague River watershed. (B Annual hydrographs for years during the pre-regulation (2003–2012) and/or regulation eras (2013–2020). See Figure 18 caption for additional notes.

3.4.5 COMPARING DIFFERENCES BETWEEN MODELED AND MEASURED TEMPERATURES BEFORE AND DURING REGULATION

For 20 sites with a sufficient duration of pre-regulation temperature measurements, we compared differences in T_{max} between observed data and predictions from a GAM based on day of year, air temperature, and April 1 snowpack. By applying the model developed using data from both the pre-regulation and regulation eras to each era independently, systematic under-predicted or over-predicted temperatures in either era could indicate the effects of flow regulation (Figure 20). For the North Fork Sprague River at Ivory Pine Road station, modeled T_{max} was underpredicted by up to 2 °C during the pre-regulation era and overpredicted by a similar amount during the regulation era (Figure 20). The overprediction during regulation is in line with measured data showing lower temperatures during regulation (Section 3.4.3), and further indicates the likely effect of flow regulation at this site. The opposite occurred at Trout Creek, where modeled T_{max} was underpredicted during the regulation era, again confirming the results from Section 3.4.3, although the reasons for this pattern are unclear. For other sites, the differences in overprediction or underprediction between the two eras are mostly within the range of model error (~1 °C).

3.4.6 REMOTE SENSING OF SURFACE WATER TEMPERATURES IN AGENCY LAKE AT MOUTH OF WOOD RIVER

Although empirical and modeling results indicated that flow variation had relatively little effect on in-stream temperatures in the Wood River system (sections 3.2 and 3.4.4 above), remotely sensed July surface water temperatures indicated that increased Wood River flow rates during the regulated era were associated with an expanded area of cool water where the river enters Agency Lake (Figure 21). This area has been identified as an important thermal refuge for redband trout in the Upper Klamath Lake system (Tinniswood et al. 2010).

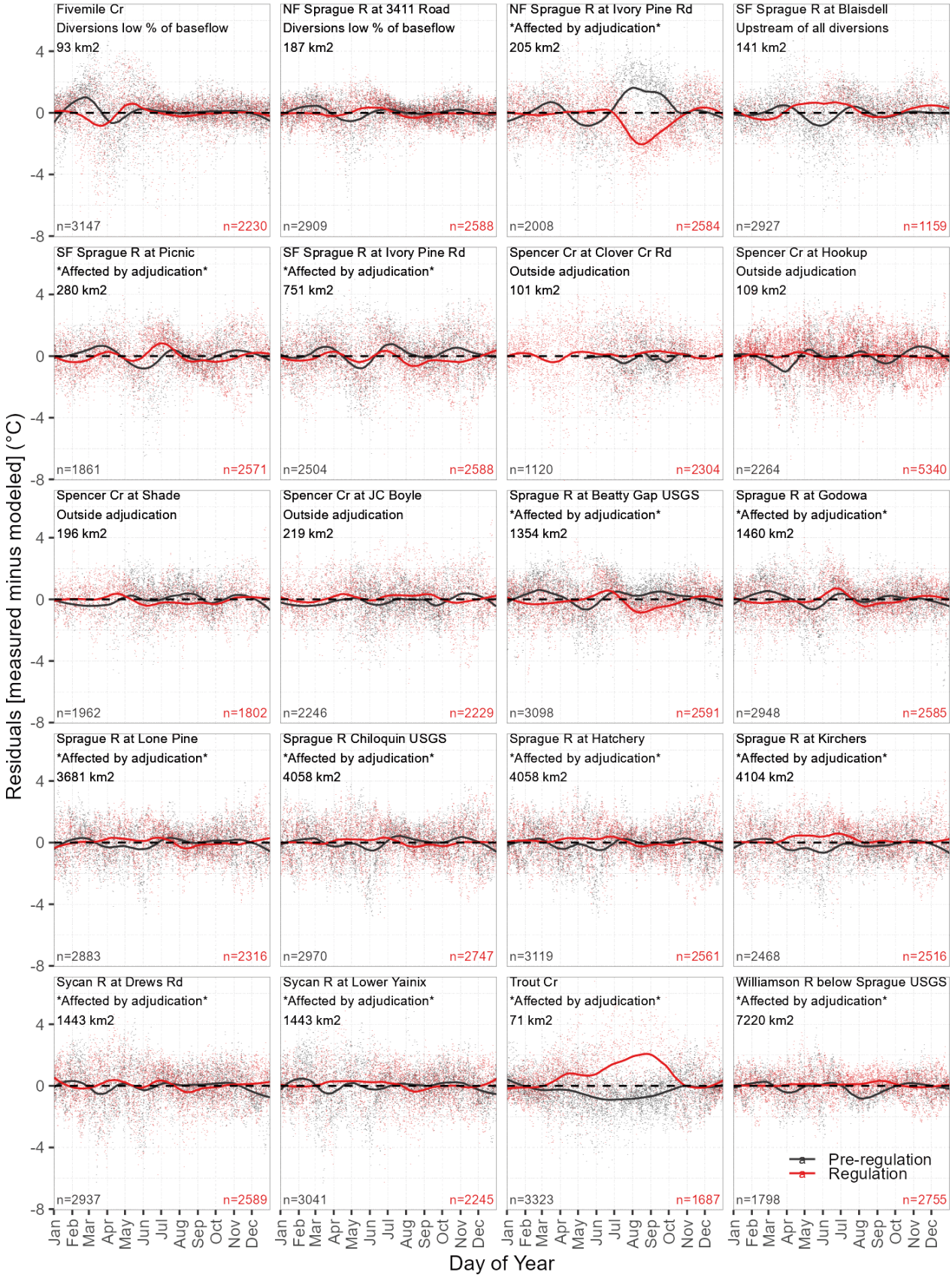

Figure 20. Comparison of model residuals (i.e., observed minus predicted) for T_{max} during the pre-regulation and regulation eras at 20 sites with at least 1000 days of pre-regulation era data. Lines are LOESS smoothers fit to points, shown as visual aids.

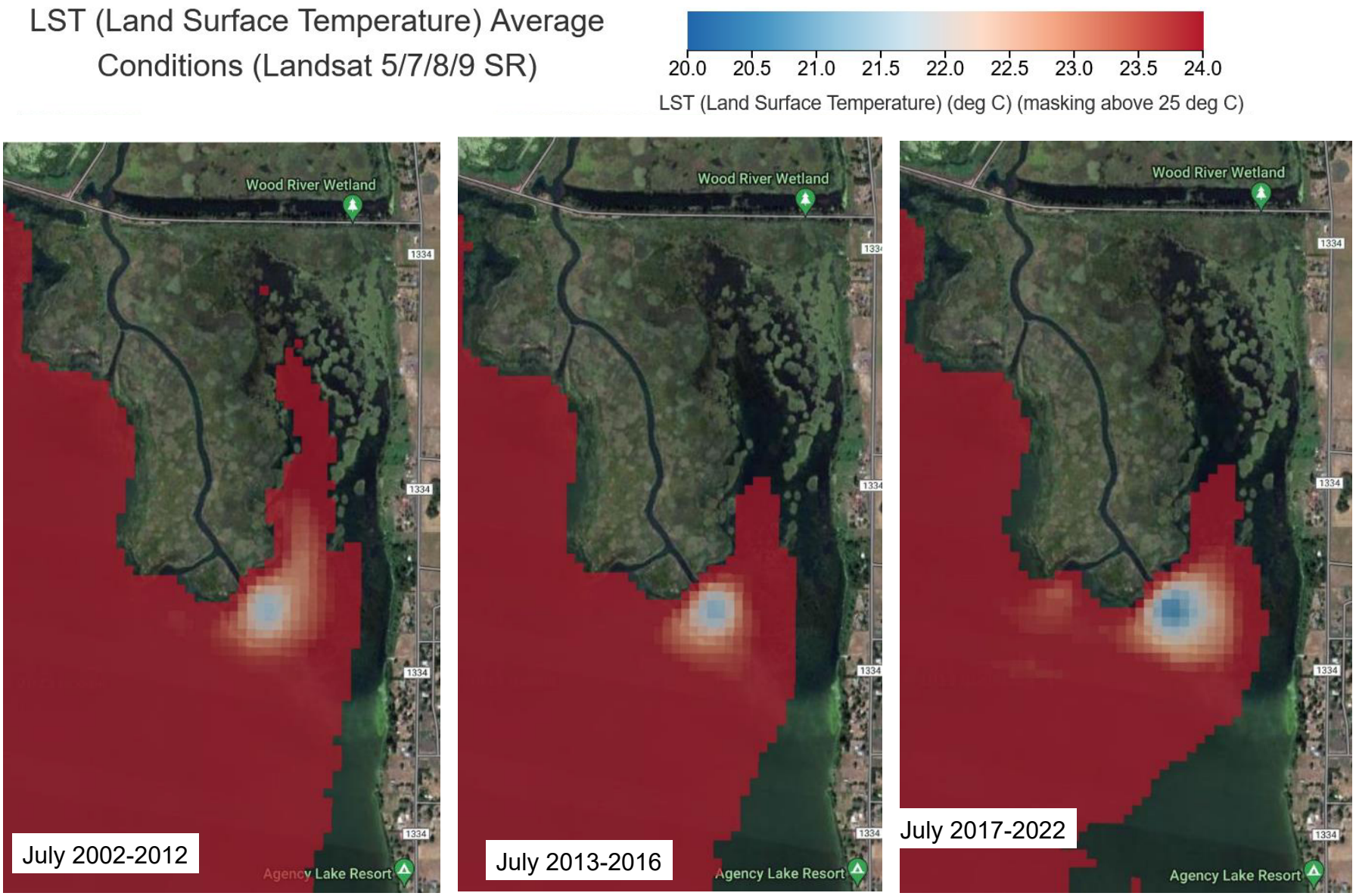

Figure 21. Remote-sensed mean July surface water temperatures where the Wood River enters Agency Lake for three time periods: July 2002-2012 (pre-regulation), 2013-2016 (partial regulation), and 2017-2022 (full regulation). Data are derived from the thermal band of NASA's Landsat satellites, generated using the Climate Engine website (https://climengine.page.link/mSJR). Values represent the average of all cloud-free 30-meter resolution pixels for the month of July.

3.5 LONG-TERM TRENDS IN STREAM TEMPERATURE

To test for the presence of long-term trends in monthly stream temperatures, we calculated slopes and applied statistical tests for only those stations and periods (2003–2020 and 2012–2020) with sufficient data as described in the methods (Figure 22 to Figure 22). Annual stream temperature time series graphs are available in Appendix B (Figure B38 to Figure B42), as are air temperatures and Williamson River flows (Figure B43). Monthly air temperatures and flows are highly variable from year to year (Figure B43), so any apparent stream temperature trends for a period as short as 2012–2020 may reflect that random variability and not meaningful or robust changes.

Overall slopes (i.e., pooling all long-term sites) differed by month and period (Figure 22). For the period 2003–2020 the overall slopes were greatest (i.e., more rapid temperature increases) in the months of April, May, and June (Figure 22), likely reflecting increasing air temperatures and decreasing Williamson River flows during some of those months (Figure B43); however, temperatures during these months were highly variable from year to year (Figure B38 to Figure B42) and strength of evidence is weak at individual sites (Figure 22). In contrast to rapid temperature increases for April, May, and June during the 2003–2020 period, for the 2012–2020 period the 95% confidence intervals for overall slopes for these months mostly intersect zero, except for mean temperatures in April (Figure 22). For all sites collectively from 2003–2020 only the October slope indicated a cooling trend, but for 2012 to 2020 July through November slopes indicated cooling trends (mean daily maximum only for August though). Cooling trends in stream temperature in February, March, July, September, October, and November in the 2012–2020 period coincide with cooling air temperatures (Figure B43) .

Except for positive slopes for the Sprague River at Kirchers for the months of July, August, and September, most individual sites had slopes less than or equal to zero for the 2003–2020 period (Figure 22). Some sites on the South Fork Sprague River had strongly negative slopes for the 2012–2020 period for a subset of the months June-November, with strongest declines in the South Fork Sprague River at Demming US and NF Sprague R. at Ivory Pine Rd. (Figure 22). The reasons for declining temperature at the South Fork Sprague River at Demming US are unclear and unfortunately there were no pre-regulation era data at this site. Monthly patterns in the range of slopes at individual sites (Figure 23) largely tracks overall slopes (Figure 22).

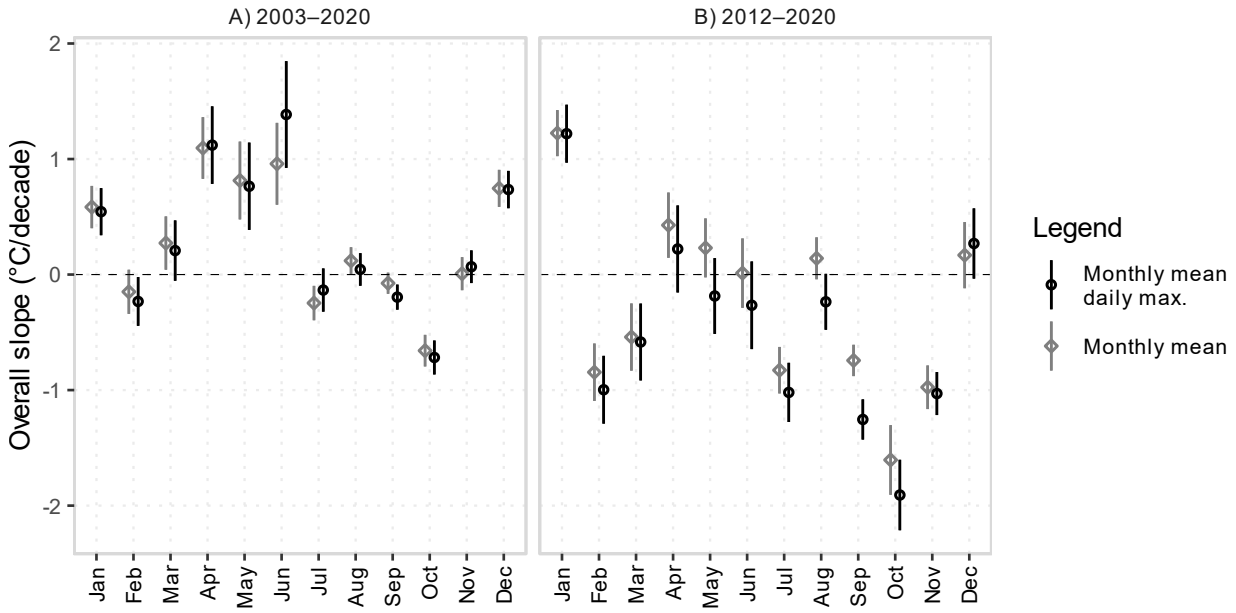

Figure 22. Overall slopes for monthly mean and monthly mean daily maximum temperature for A) 2003–2020 derived from 17 sites, and B) 2012–2020 trends derived from 30 sites. Bar ends are 95% confidence intervals. Positive slopes indicate metrics that increased during the study period while negative slopes indicate metrics that decreased during the study period

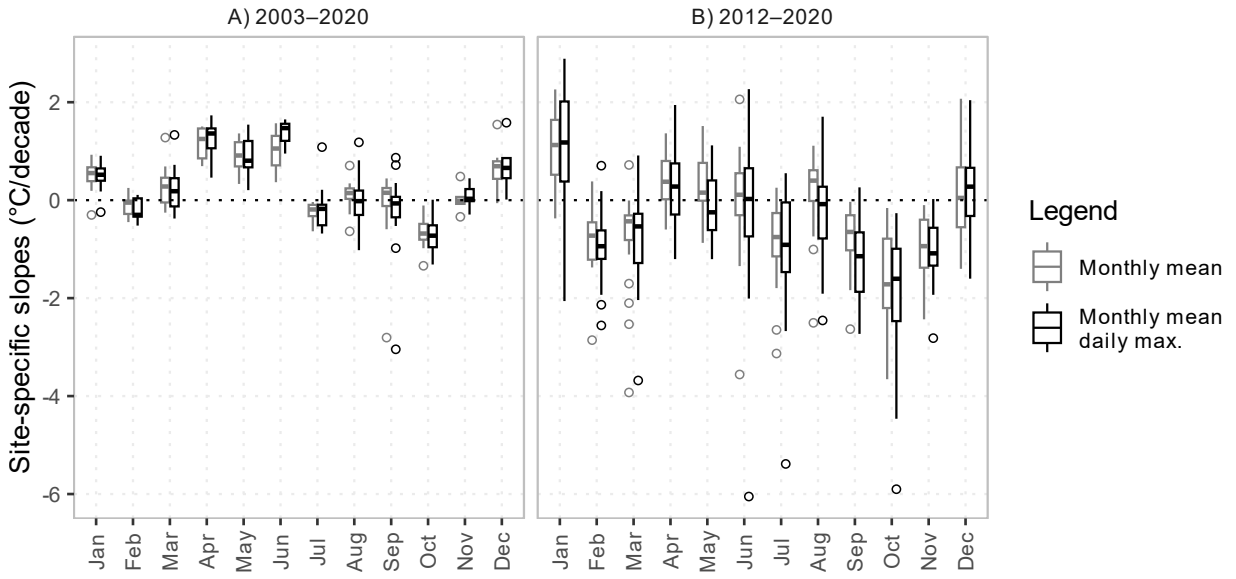

Figure 23. Boxplots showing the range of variation in slopes for monthly mean and monthly mean daily maximum temperature A) for 2003–2020 at 17 sites, and B) for 2012–2020 at 30 sites. The horizontal line inside the box is median, the upper and lower edges of the box are 25th and 75th percentiles, the upper whisker extends to the highest value that is within 1.5 times the interquartile range (75th minus 25th percentile) from the box's edge, and points plotted beyond the whiskers are outliers. Slopes for individual sites are presented in Figure 22.

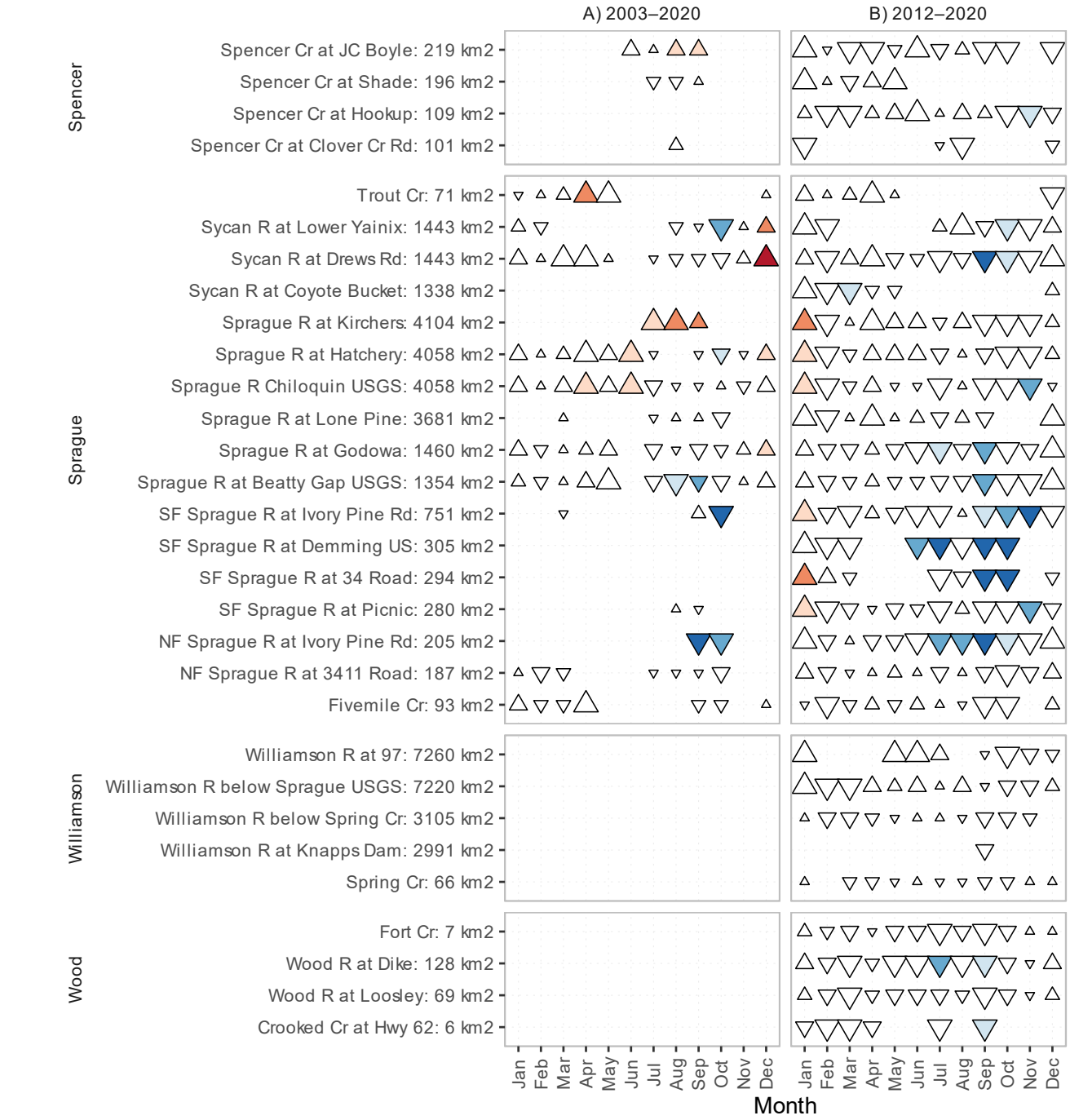

Figure 24. Site-specific slopes for trends in monthly mean daily maximum temperature for A) 17 sites for the years 2003–2020, and B) 30 sites for the years 2012–2020. Symbols are only shown for sites and months when data were available for ≥75% of years within the period. Symbol shape shows direction (increasing/decreasing), size shows magnitude (°C/decade), and shading shows strength of evidence (darker means stronger evidence). Annual time series graphs are available in Appendix B.

3.6 BIOLOGICAL SUITABILITY

Our analysis of temperature suitability in the regulation era (6/17/2013–12/31/2020) shows strong spatial and seasonal patterns in the adult chinook and steelhead migration (Figure 25), juvenile chinook rearing (Figure 26), and juvenile steelhead rearing temperature criteria (Figure 27):

- Sites in the Wood River sub-basin and Westside sub-basin were largely in the Optimal range for each of the suitability criteria, and over all months and years for which we had data coverage. The primary exception was 7-Mile Canal at Dike, where temperatures were Stressful or Severely Stressful for much of June–August.
- Patterns in the Williamson River were complex longitudinally. The Williamson River had Optimal temperatures at its headwaters (Head of Williamson River), then progressively warmed to a peak at Marsh HQ. During June and July, Williamson River Below Knapps Dam was mostly Optimal for juvenile steelhead rearing and adult salmon migration but Suboptimal for juvenile Chinook rearing. Spring Creek and the Williamson River above the Sprague River had Optimal temperatures for all criteria. Downstream of the Sprague River confluence the Williamson River has Suboptimal temperatures for juvenile chinook rearing in June and July but temperature remain mostly Optimal for juvenile steelhead rearing and adult salmon migration.
- Sites in the Sprague River and its major forks are mostly Stressful or Extremely Stressful during the peak of summer, except the North Fork Sprague River at 3411 Rd which remains Optimal even for juvenile chinook rearing except during brief periods of Suboptimal in July. Temperatures in Trout Creek are rarely Stressful, although the creek has dried up in the most recent years (Figure 14).

Of the sites with ODEQ-designated bull trout use, 7-Mile Creek above Nicholson Diversion, 7-Mile Creek above Campground, and Wood River at Dixon were the only sites where temperatures never exceeded the 12 °C 7DADM bull trout criteria (Figure 29). However, some of the spring-dominated sites without designated bull trout use also never exceeded 12 °C 7DADM: Williamson River Head of River, Spring Creek, Harriman Springs, Tecumseh Spring, Short Creek, Blue Springs, Crane Creek at 7-Mile Road (Figure 11, Figure 12).

Nearly all sites had no exceedances of the 13 °C 7DADM ODEQ salmon and steelhead spawning criteria from November through March (Figure 28). The only exception was Fivemile Creek, where temperatures sometimes exceeded that threshold in November, February, and March. Most sites had some exceedances of 13 °C from April–June and September–October, with exceptions including the spring-dominated sites mentioned in the previous paragraph.

Our approach to assessing the suitability of temperatures for supporting fish species strictly evaluates criteria exceedances, and does not include other factors such as bioenergetics, inter-species interactions, and other recent research highlighting the seasonal importance of warm water habitats to cold water fish (Armstrong et al. 2021, Hahlbeck et al. 2022).

Temperature suitability in the pre-regulation era (1/1/2003–6/16/2020) appeared to be generally similar to the regulation era (6/17/2013–12/31/2020) at most sites, although we did not quantitatively compare the two eras and comparisons are not possible at many sites due to lack of data. Results for the pre-regulation era are provided in Appendix B (Figure B44–Figure B48).

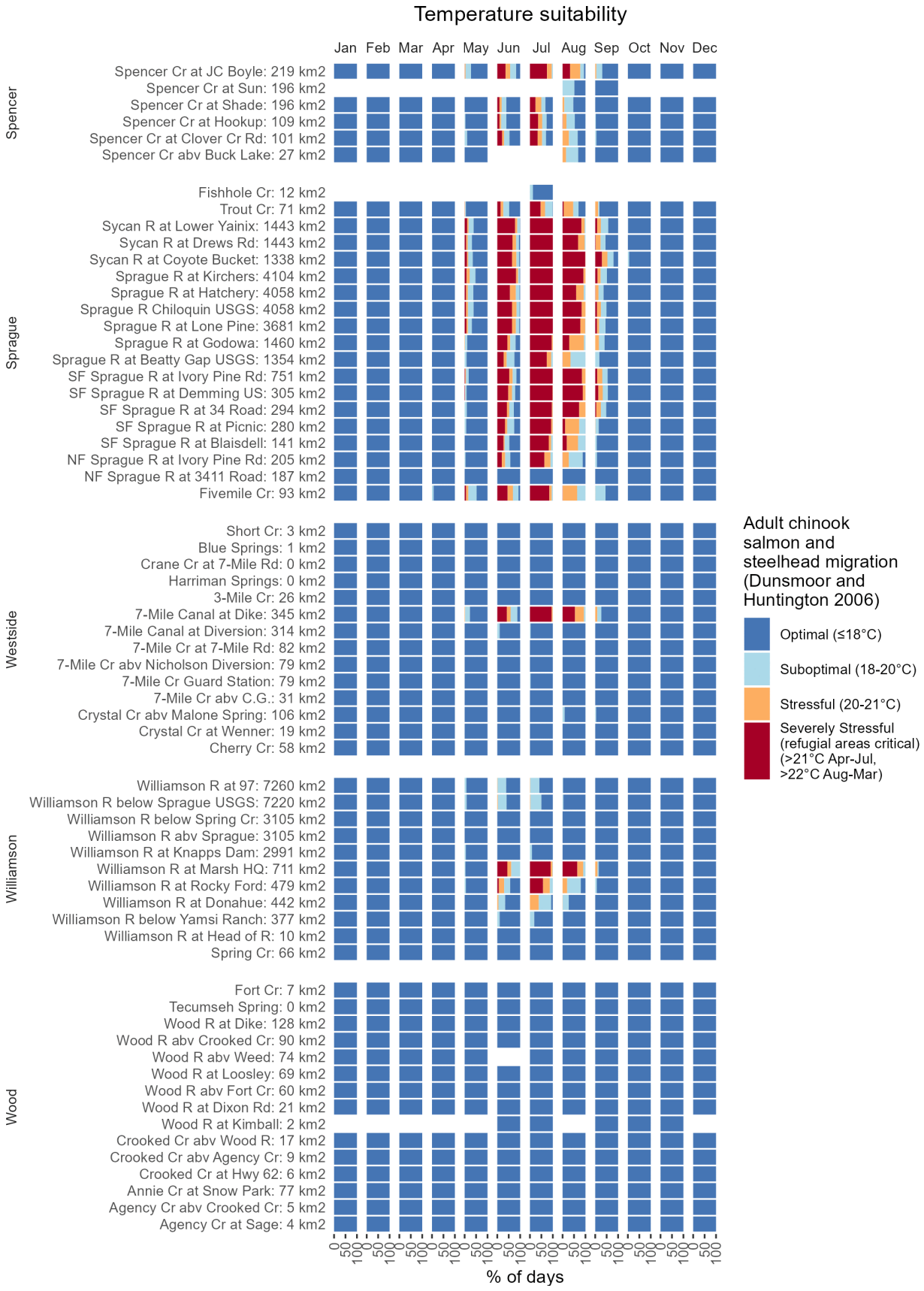

Figure 25. Temperature suitability for adult chinook salmon and steelhead, based on the percent of measured 7DADM temperatures per month in the 6/17/2013–12/31/2020 regulation era within suitability categories adapted from Dunsmoor and Huntington (2006). Sites and months with <28 days of data are excluded.

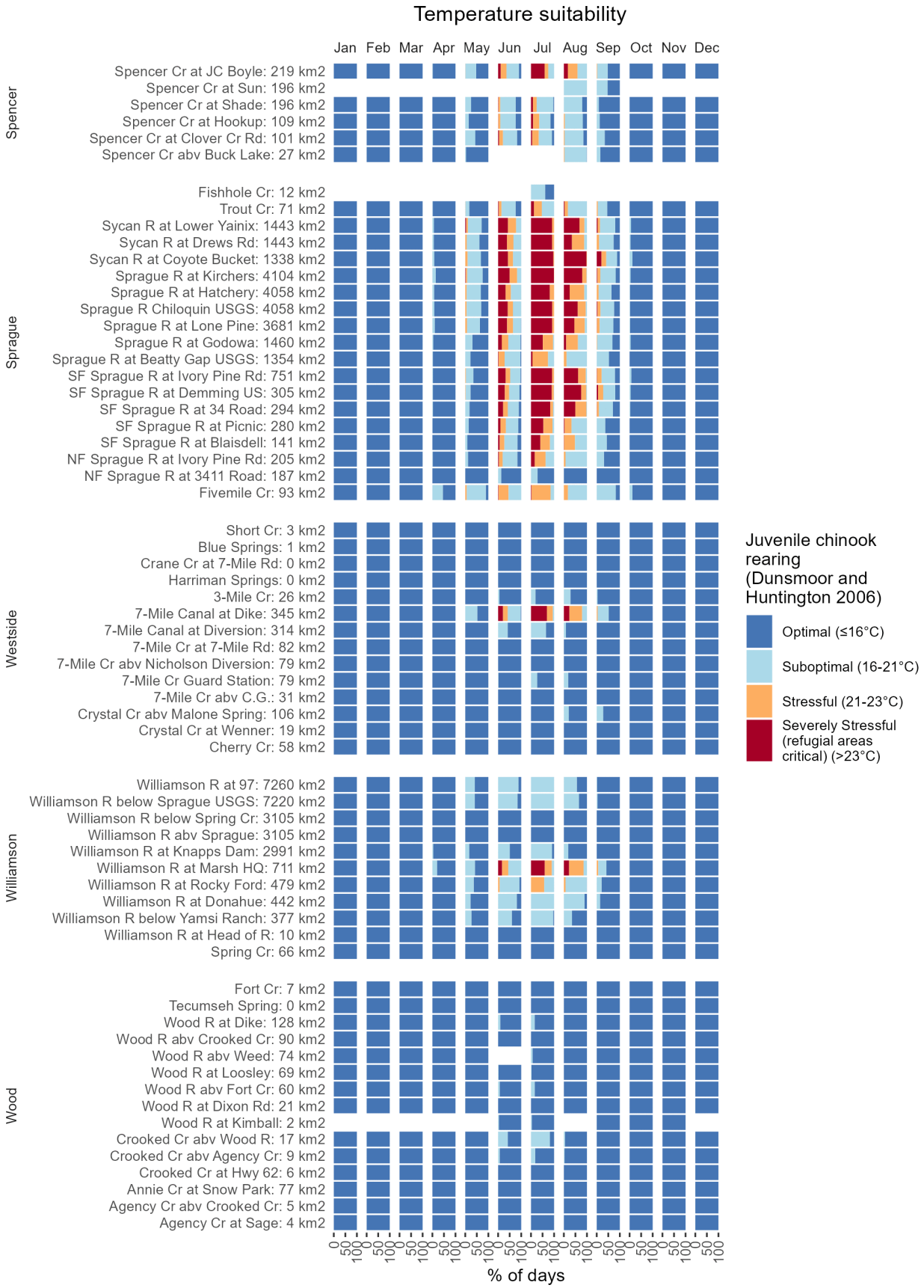

Figure 26. Temperature suitability for juvenile chinook salmon rearing, based on the percent of measured 7DADM temperatures per month in the 6/17/2013–12/31/2020 regulation era within suitability categories adapted from Dunsmoor and Huntington (2006). Sites and months with <28 days of data are excluded.

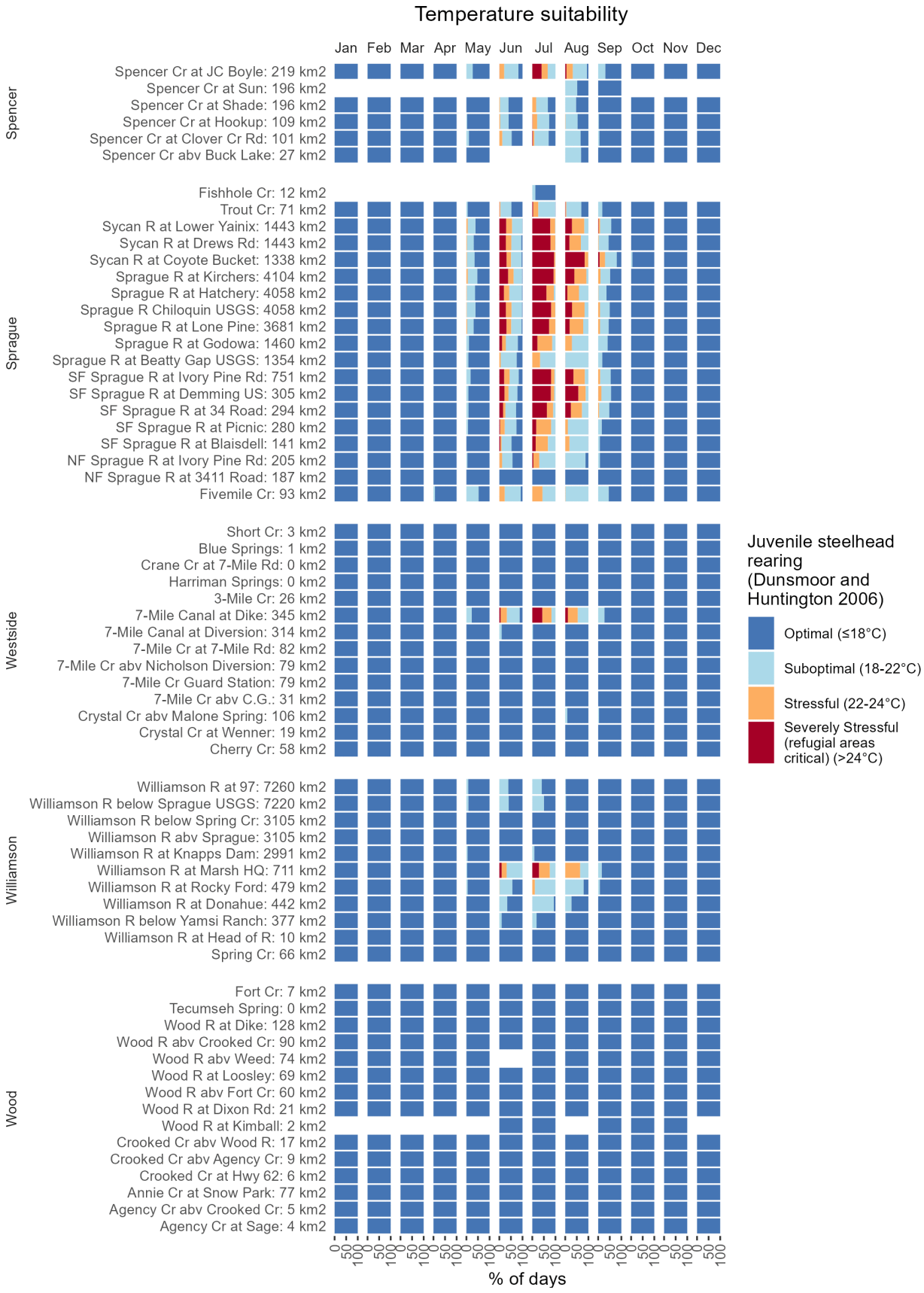

Figure 27. Temperature suitability for juvenile steelhead rearing, based on the percent of measured 7DADM temperatures per month in the 6/17/2013–12/31/2020 regulation era within suitability categories adapted from Dunsmoor and Huntington (2006). Sites and months with <28 days of data are excluded.

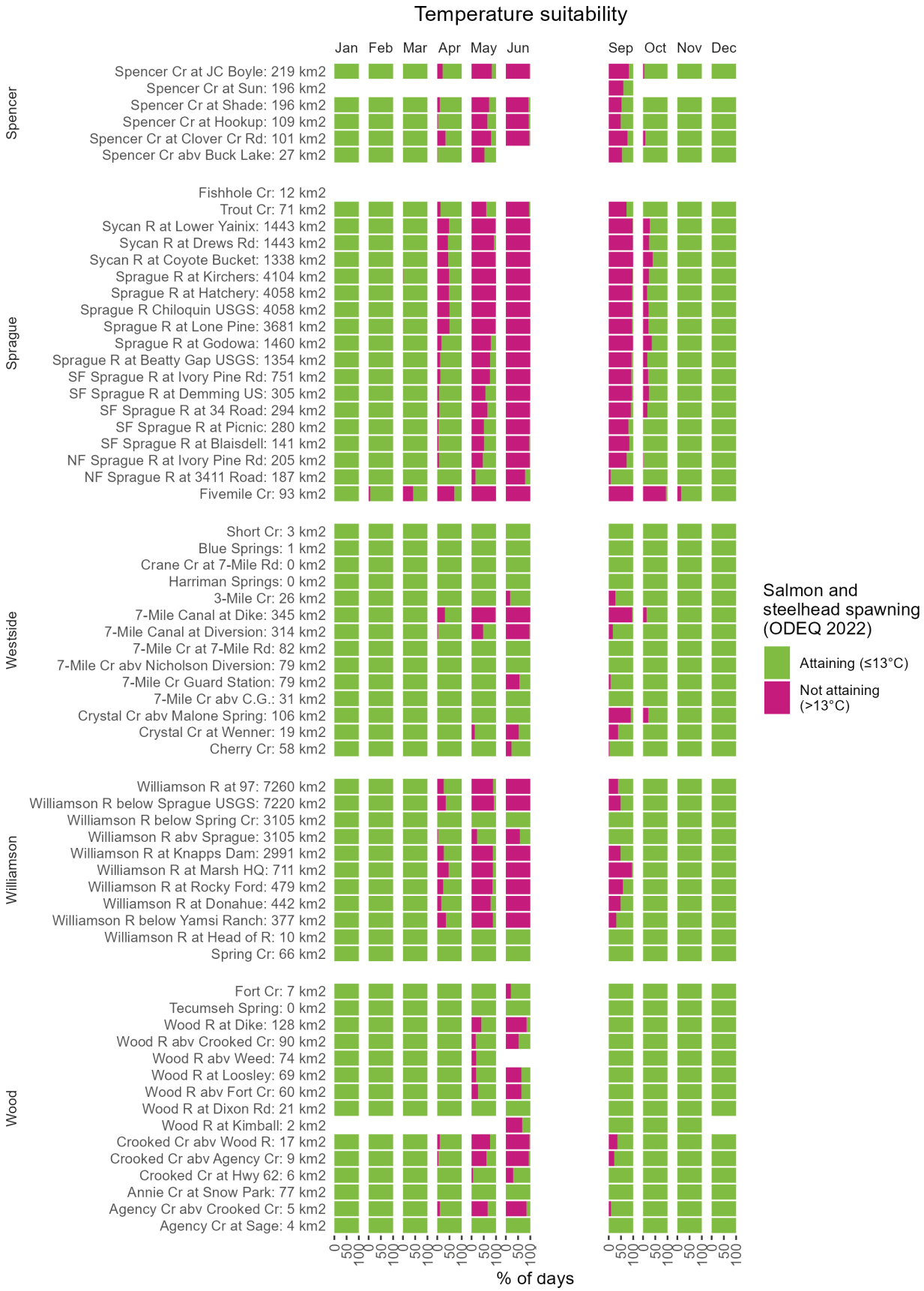

Figure 28. Temperature suitability for salmon and steelhead spawning, based on the percent of measured 7DADM temperatures per month in the 6/17/2013–12/31/2020 regulation era exceeding ODEQ (2022) criterion. Criterion not evaluated for July and August because no spawning is expected to occur. Sites and months with <28 days of data are excluded.

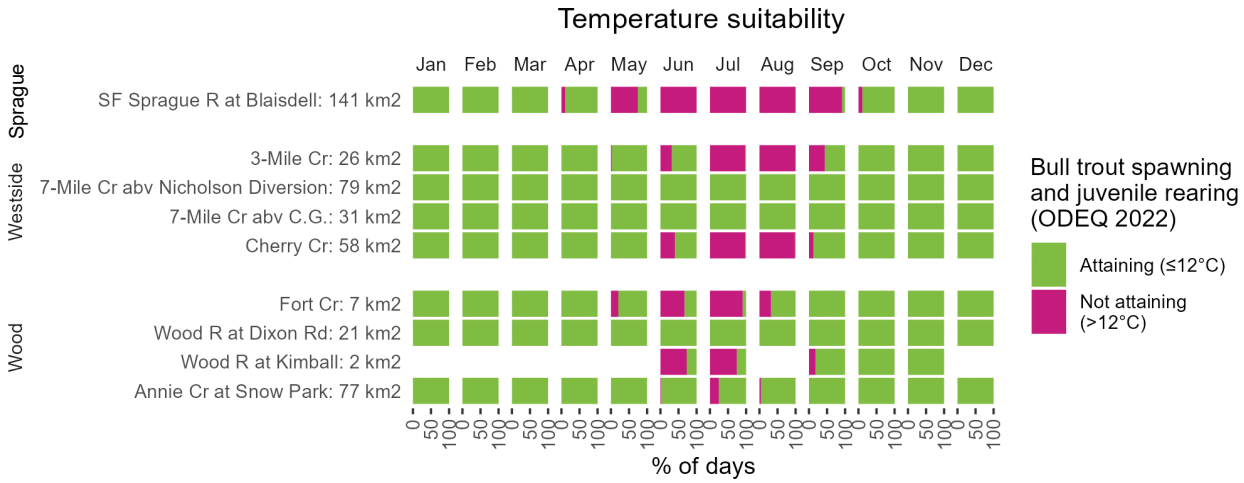

Figure 29. Temperature suitability for bull trout spawning and juvenile rearing, based on the percent of measured 7DADM temperatures per month in the 6/17/2013–12/31/2020 regulation era exceeding ODEQ (2022) criteria. Sites and months with <28 days of data are excluded.

4 RECOMMENDATIONS FOR CONTINUED MONITORING AND ADDITIONAL ANALYSES

The Klamath Tribes Ambodat exerts considerable effort in operating its temperature monitoring program, including maintaining, deploying, and retrieving temperature loggers and managing data. Continuation of this monitoring is essential for tracking restoration progress, informing adaptive management, and assessing climate change impacts. If resources were not available to continue the current level of monitoring, we have the following recommendations for streamlining the program while retaining much of its value:

- The best way to reduce effort would be to cease monitoring at most sites that are already being monitored by other entities, contingent upon coordination and communication about future changes (i.e., if another entity plans to stop monitoring a site in the future, the Klamath Tribes may want to resume monitoring there). For example, OWRD now monitors real-time temperatures at 14 sites (Section 2.2) and USGS monitors temperatures at its lower Sprague River and lower Williamson River gages (Section 2.1.2). We have not verified current status, but USFS and U.S. BLM may have continued monitoring at sites in Spencer Creek, 3-Mile Creek, and 7-Mile Creek; previously compiled by NorWeST (Isaak et al. 2017) and/or Asarian et al. (2020). We do not know what sites ODFW is currently monitoring, but that is another entity that could be coordinated with. The downside of ceasing monitoring at the sites already monitored by other entities would be the inability to use measured data to fill gaps due to equipment failures, vandalism, etc., so it may still be desirable for multiple entities to continue collecting data at the most critically important locations. For analyses that require continuous time series, gaps could be filled using methods other than measured data, including: 1) linear regression with nearby stations, 2) the GAM models we developed for this report, and 3) multivariate imputation methods (Josse and Husson 2016, Isaak et al. 2020).

- If available resources necessitated dropping additional sites, we recommend reducing the number of springs that are monitored. Temperatures at spring heads vary little, so once initial monitoring establishes baseline temperatures, the main reason to continue monitoring them is to track long-term changes that occur over years and decades as groundwater temperatures slowly respond to climate warming (Kurylyk and MacQuarrie 2014). For climate change monitoring, priority should be given to sites that provide a clean signal of the spring source without mixing with other waters (e.g., Blue Springs, Tecumseh Spring, Head of Williamson River). Temperatures at Harriman Springs show some odd fluctuations, possibly related to lake level or the nearby dock, so would probably be the first spring site to drop.

- Other sites to consider dropping would be Short Creek and Crane Creek at 7-Mile Road. These two sites have winter temperatures similar to the nearby Blue Springs (which combined with their proximity indicate they may be originating from a related aquifer), although they do have warmer temperatures in the remainder of the year. In addition, the temperatures of Crooked Creek above Agency Creek and Crooked Creek above Wood River are quite similar to each other, so the former could probably be dropped.

- The length of thermograph deployments could be increased, at least at some sites. Probes have been downloaded as often as every month or two in some past years. Since temperature probes are usually quite reliable, the length of field visits could probably be extended to approximately six months. For example, once in the early fall prior to winter high flows, and once in the late spring as flows are receding. After any particularly high winter flows, which may dislodge probes or cover them with sediment or debris, additional visits would be beneficial, especially at high-priority sites.

There are many additional analyses that would be beneficial to conduct on this large temperature dataset, including:

- The Bootleg Fire burned a large percentage of the Sprague River sub-basin in 2021. Temperature data from the years before and after the fire, combined with remote-sensed burn severity data, could be used to assess changes to water temperatures caused by the fire. Given the large area that burned with high severity, these temperature changes could be substantial and have the potential to impact critical Bull Trout populations in this area, as well as future reintroduction of spring Chinook. The Klamath Tribes Ambodat has secured funding for this analysis.

- U.S. Bureau of Reclamation is currently updating its Klamath Natural Flow Study. Results from this study could be used as scenario inputs into our temperature models to predict temperatures under unimpaired hydrographs. The Klamath Tribes Ambodat has secured funding for this analysis.

- We only filled short gaps (<2 days) in temperature records prior to calculating the monthly summaries used in our analyses of long-term trends, leading to many missing months. These trend assessments could be improved by filling additional gaps using methods discussed earlier in this section. This would expand the number of sites for which trends could be assessed. In addition, long-term trends in air temperature and flow could be assessed, and those trends, if any, could be used to project future water temperature trends.

- Using a combination of USGS and OWRD flow gages and bi-weekly flow measurements from the Klamath Tribes, Kann and Walker (2022b) developed continuous flow estimates for many sites in the Sprague River sub-basin. These flow estimates could be used to extend the local flow records used in our analyses, allowing models based on local flow to be extended to additional sites and years.

5 ACKNOWLEDGMENTS

We thank the Klamath Tribes for their comprehensive temperature monitoring effort, specifically to Brad Parrish for providing us with temperature data and answering questions about site locations, flow regulation, and hydrologic conditions, and to Stan Swerdloff and Mark Buettner for facilitating the project. Bill Tinniswood of ODFW provided information regarding ODEQ temperature criteria and hydrology of springs. Countless other people from many different entities contributed to collection and compilation of the stream temperature data included in this report. We thank Megan Skinner (USFWS) and Bill Tinniswood for providing helpful comments on our draft document.

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APPENDIX A: TEMPERATURE MODEL CALIBRATION & VALIDATION DETAILS

Table A1. Bayesian information criterion (BIC) scores for generalized additive models (GAMs) developed to predict water temperatures at 24 sites where long-term flow and water temperature data (≥1000 days, ≥4 years) were available. Key to abbreviations: DayMet = source of air temperature data, PRISM = source of air temperature data, A_1 = 1-day air temperature, A_{2w} = 2-day weighted air temperature, A_{3w} = 3-day weighted air temperature, Local Q = flow measured at site, Watershed Q = flow measured at other site upstream, SWE = April 1 snow water equivalent, D = Day of Year (1 to 366).

Parameter	Model number	Variables	BIC
Daily max.	3	DayMet A_{3w}, Local Q, D	170306
	7	DayMet A_{3w}, Watershed Q, D	170794
	2	DayMet A_{2w}, Local Q, D	172500
	11	DayMet A_{3w}, SWE, D	172946
	6	DayMet A_{2w}, Watershed Q, D	172977
	10	DayMet A_{2w}, SWE, D	174677
	4	DayMet A_1, Local Q, D	181480
	8	DayMet A_1, Watershed Q, D	181881
	12	DayMet A_1, SWE, D	182875
	1	PRISM A_{2w}, Local Q, D	195293
	5	PRISM A_{2w}, Watershed Q, D	195632
	9	PRISM A_{2w}, SWE, D	197163
Daily mean	3	DayMet A_{3w}, Local Q, D	118084
	7	DayMet A_{3w}, Watershed Q, D	118691
	11	DayMet A_{3w}, SWE, D	120970
	2	DayMet A_{2w}, Local Q, D	123978
	6	DayMet A_{2w}, Watershed, D	124481
	10	DayMet A_{2w}, SWE, D	126189
	1	PRISM A_{2w}, Local Q, D	139366
	5	PRISM A_{2w}, Watershed, D	139784
	9	PRISM A_{2w}, SWE, D	141841
	4	DayMet A_1, Local Q, D	146649
	8	DayMet A_1, Watershed Q, D	146937
	12	DayMet A_1, SWE, D	147821

Table A2. Bayesian information criterion (BIC) scores for generalized additive models (GAMs) developed to predict water temperatures at 58 sites with long-term (≥1000 days, ≥4 years) water temperature (but not necessarily flow) data. See caption of Table A2 for key to abbreviations.

Parameter	Model number	Variables	BIC
Daily max.	3	DayMet A_{3w}, Watershed Q, D	432330
	2	DayMet A_{2w}, Watershed Q, D	433445
	7	DayMet A_{3w}, SWE, D	436029
	6	DayMet A_{2w}, SWE, D	436512
	4	DayMet A_1, Watershed Q, D	442450
	8	DayMet A_1, SWE, D	444810
	1	PRISM A_{2w}, Watershed Q, D	483070
	5	PRISM A_{2w}, SWE, D	485882
Daily mean	3	DayMet A_{3w}, Watershed Q, D	270987
	7	DayMet A_{3w}, SWE, D	274972
	2	DayMet A_{2w}, SWE, D	279613
	6	DayMet A_{2w}, SWE, D	282650
	4	DayMet A_1, Watershed Q, D	322795
	1	PRISM A_{2w}, Watershed Q, D	324252
	8	DayMet A_1, SWE, D	324832
	5	PRISM A_{2w}, SWE, D	327847

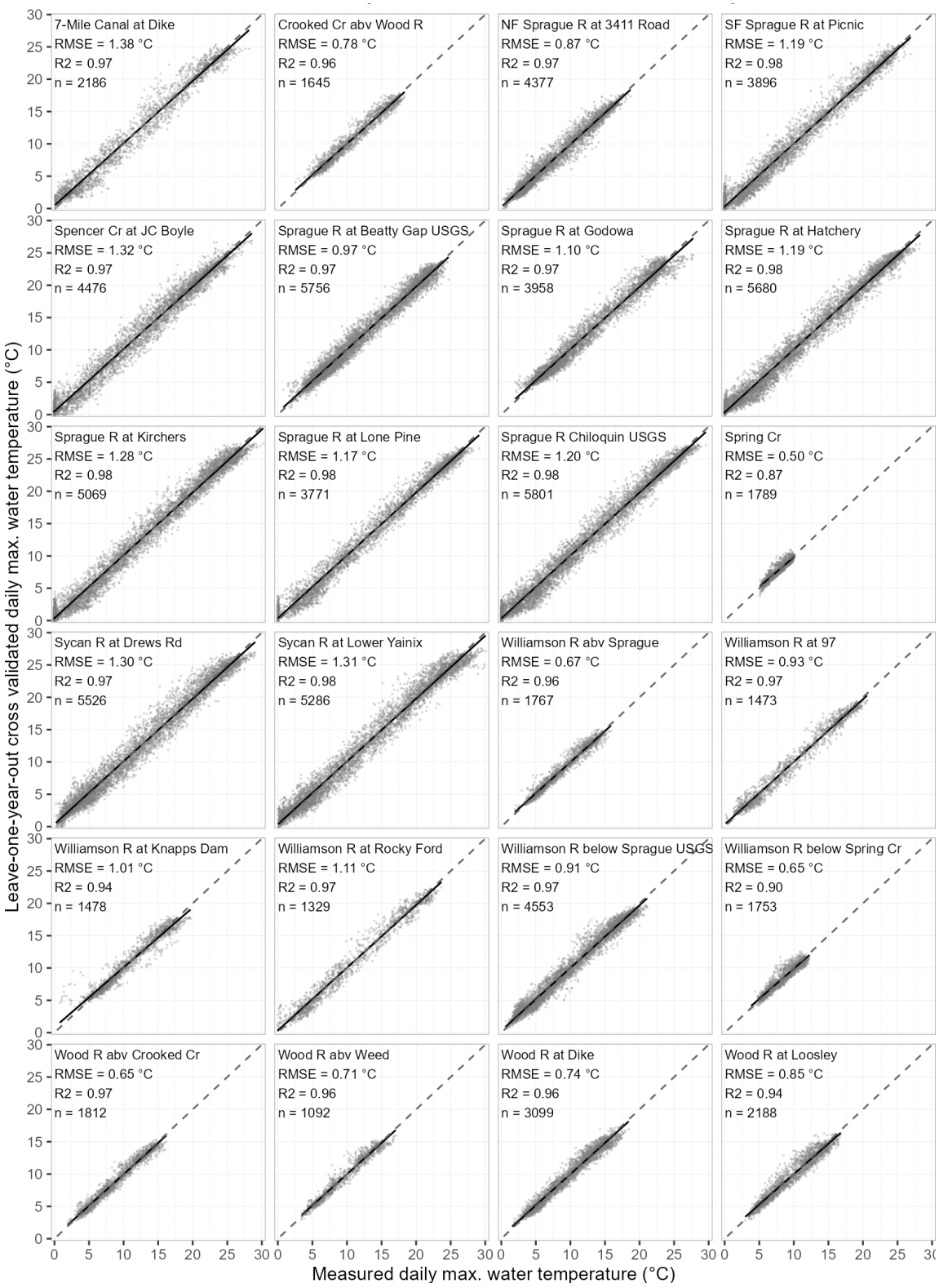

Figure A30. Comparison of measured daily maximum water temperatures and leave-one-year-out (LOYO) cross-validation (CV) model predictions for sites at 24 sites with available long-term (≥1000 days and ≥4 years) temperature and local flow data, 1993–2020. Model predictors are site, local flow, air temperature, and day of year. RMSE = root mean squared error (a measure of prediction accuracy), R2 = coefficient of determination ranging from 1 (perfect correlation) to 0 (complete lack of relationship between the variables), and n = number of days with measured temperature data.

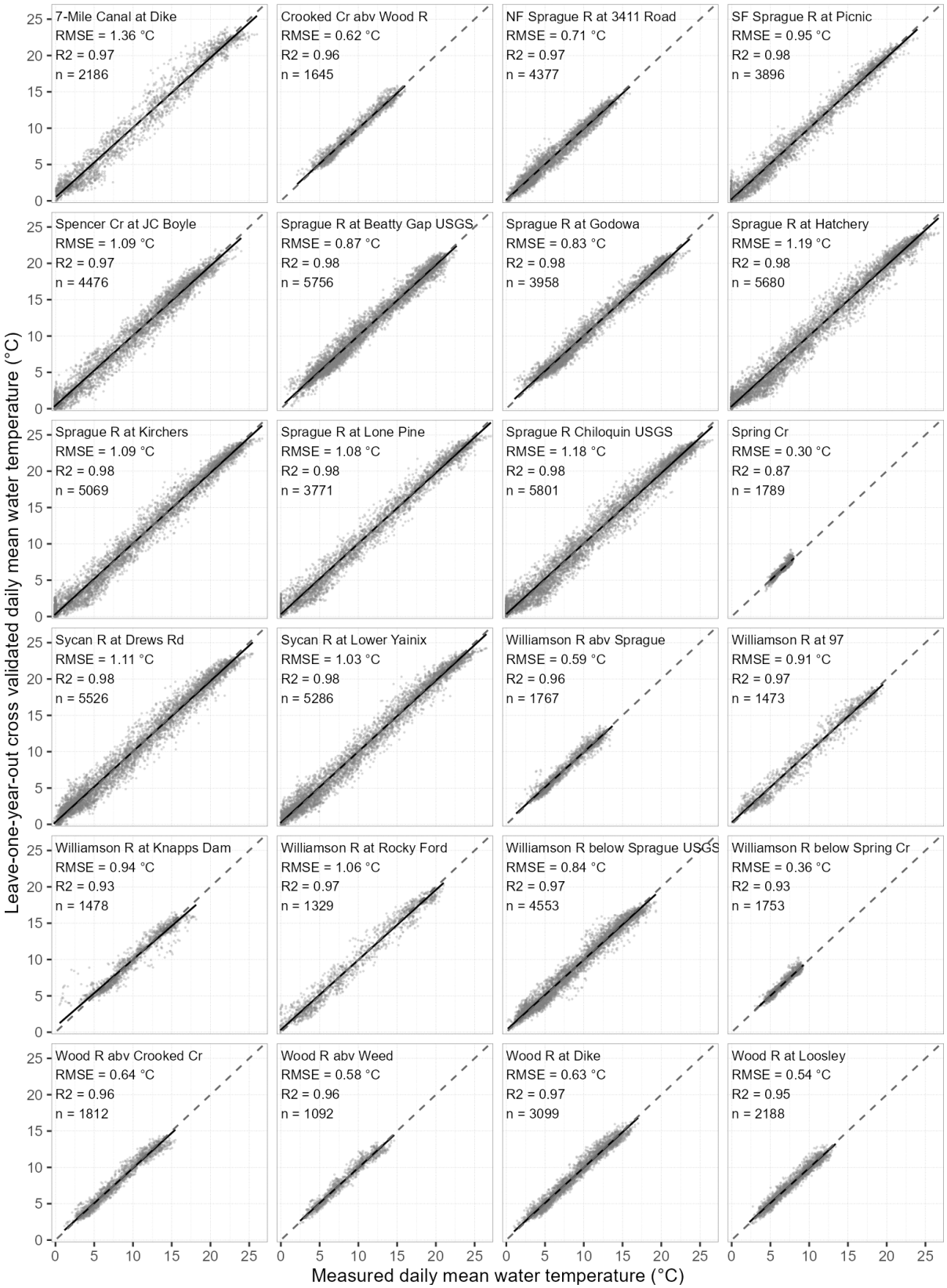

Figure A31. Comparison of measured daily mean water temperatures and leave-one-year-out (LOYO) cross-validation (CV) model predictions at 24 sites with available long-term (≥1000 days and ≥4 years) temperature and local flow data, 1993–2020. The model used site, local flow, air temperature, and day of year as predictors. See Figure A30 caption for explanation of RMSE, R2, and n.

Figure A32. Comparison of measured daily maximum water temperatures and leave-one-year-out (LOYO) cross-validation (CV) model predictions at 58 sites with available long-term (≥1000 days and ≥4 years) temperature (but not necessarily local flow) data, 1993–2020. The model used site, snowpack, air temperature, and day of year as predictors. See Figure A30 caption for explanation of RMSE, R2, and n.

Figure A33. Comparison of measured daily mean water temperatures and leave-one-year-out (LOYO) cross-validation (CV) model predictions at 58 sites with available long-term (≥1000 days and ≥4 years) temperature (but not necessarily local flow) data, 1993–2020. The model used site, snowpack, air temperature, and day of year as predictors. See Figure A30 caption for explanation of RMSE, R2, and n.

APPENDIX B: ADDITIONAL FIGURES

To reduce the length of the main body of the report, some additional figures have been placed in this appendix.

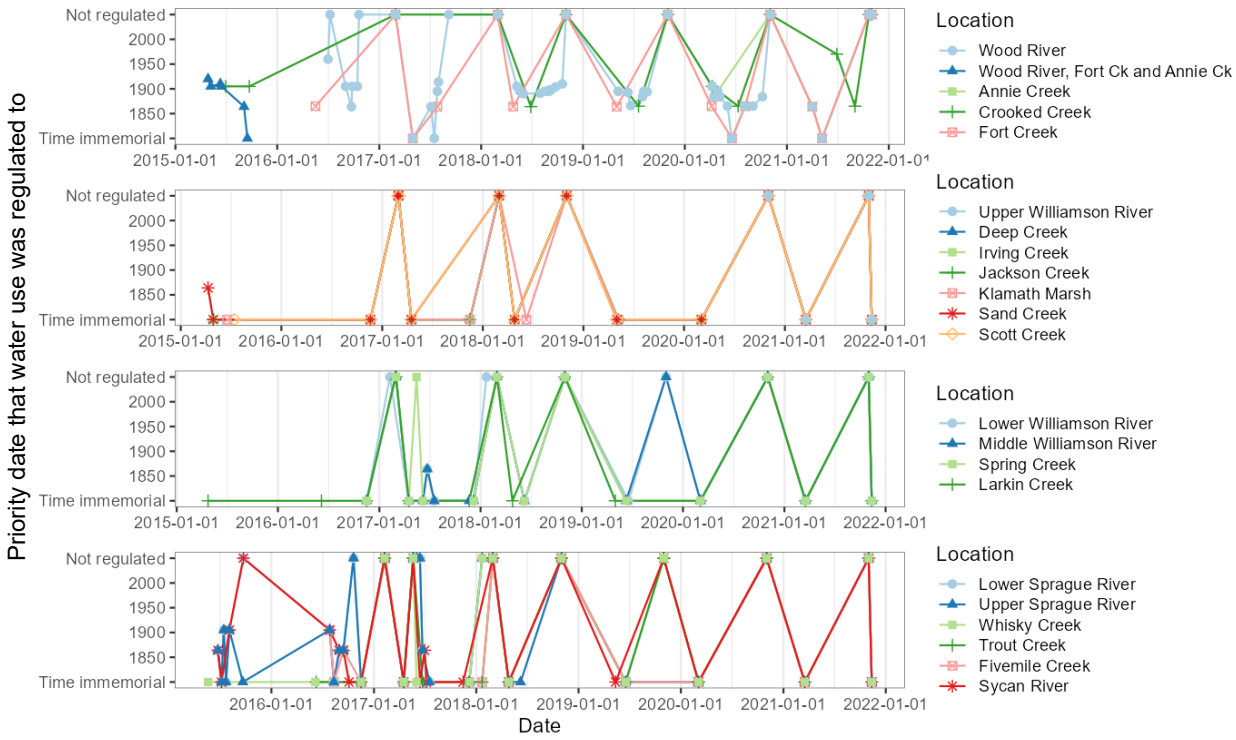

Figure B34. Time series of priority dates that water users were regulated to for each instream claim (or tributaries to instream claims) for the years 2015–2021. No data available for 2013–2014. Data summarized from OWRD Watermaster[19].

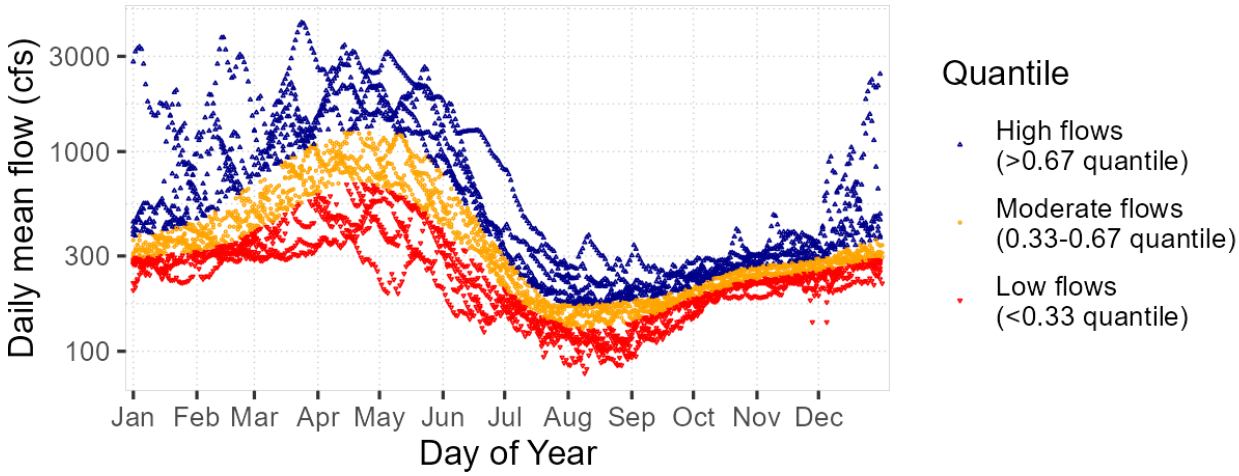

Figure B35. Quantiles of daily local flow for an example long-term monitoring site: Sprague River at Chiloquin USGS. See Section 2.7 for details.

[19] https://apps.wrd.state.or.us/apps/misc/dsb_area_status/Default.aspx?wm_district=17

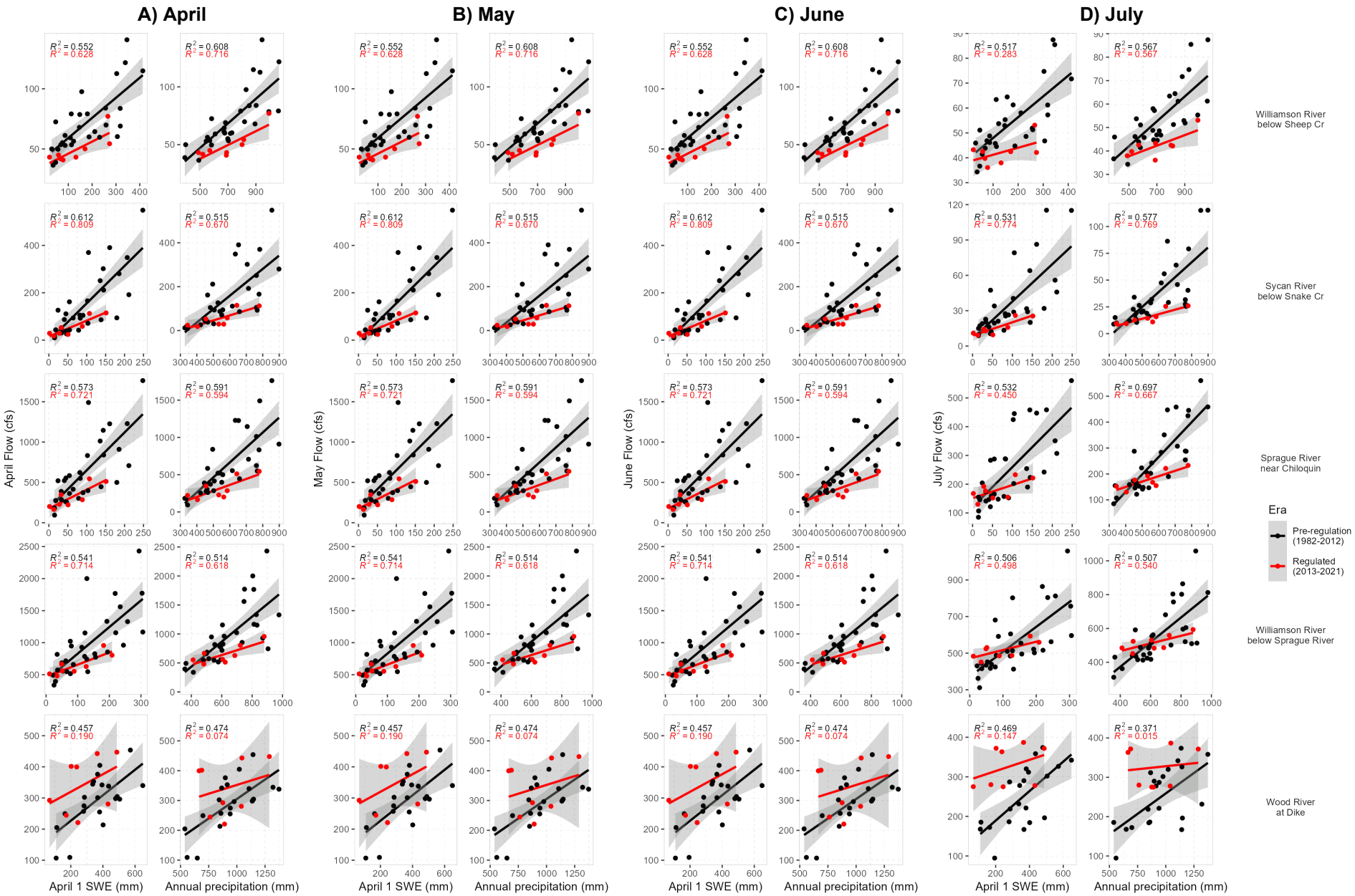

Figure B36. Regression of flow for the months of (A) April, (B) May, (C) June, (D) July vs. April 1 snow water equivalent (SWE) and annual precipitation at five long-term flow gages in the pre-regulation and regulated eras. Gray shading is 95% confidence intervals. SWE and precipitation were calculated for each gage's contributing watershed, except for Sycan (uses data from Sprague watershed) and Williamson River below Sheep Creek (uses data from Williamson River upstream of Sprague).

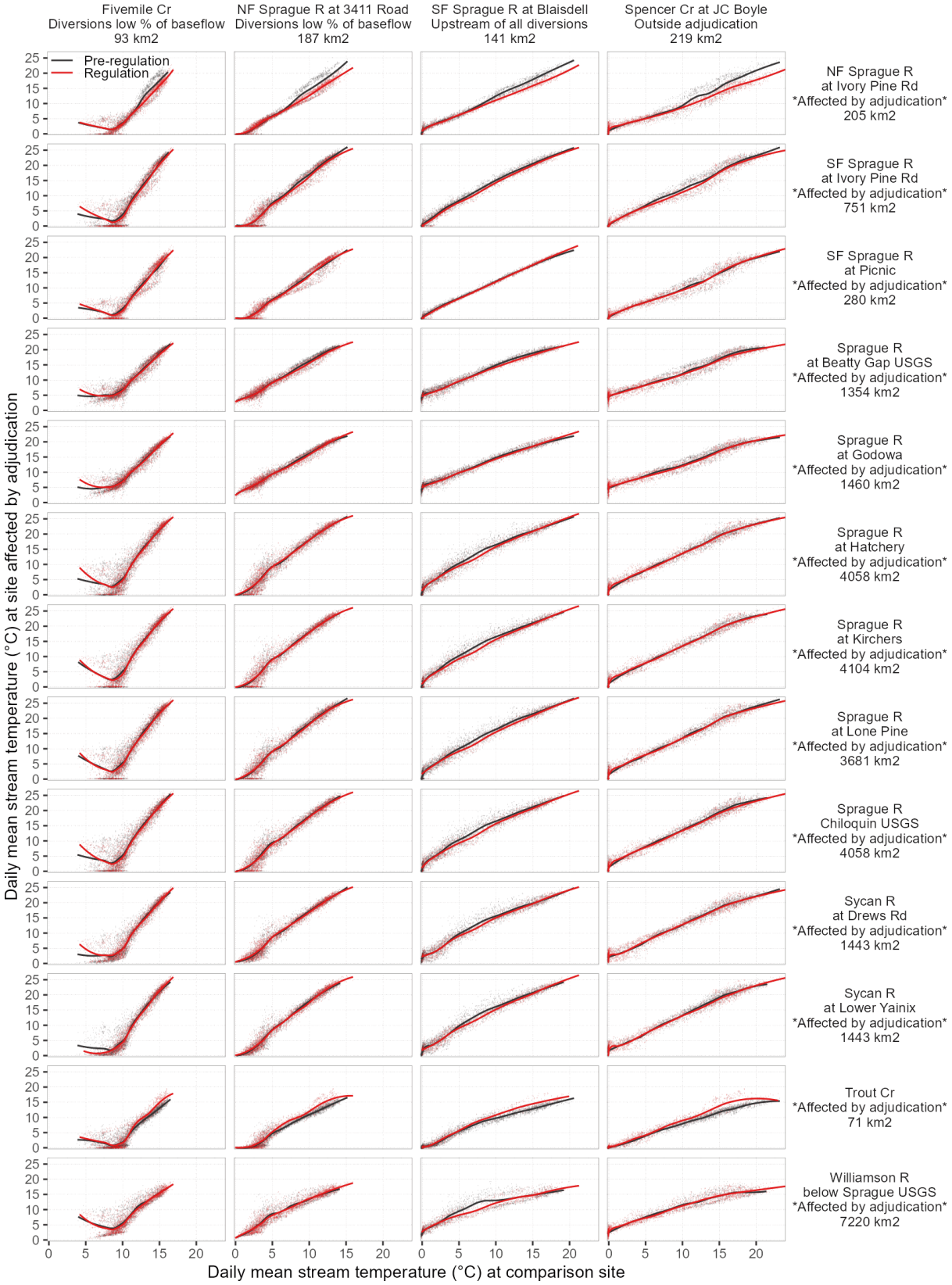

Figure B37. Scatterplots comparing measured T_{mean} during the pre-regulation and regulation eras at four sites not affected by regulation (i.e., either not within the geographic scope of regulation or upstream of all diversions) and 13 sites expected to be affected by regulation. All sites shown have at least 1000 days of pre-regulation era temperature measurements. Lines are LOESS smoothers fit to points, shown as visual aids.

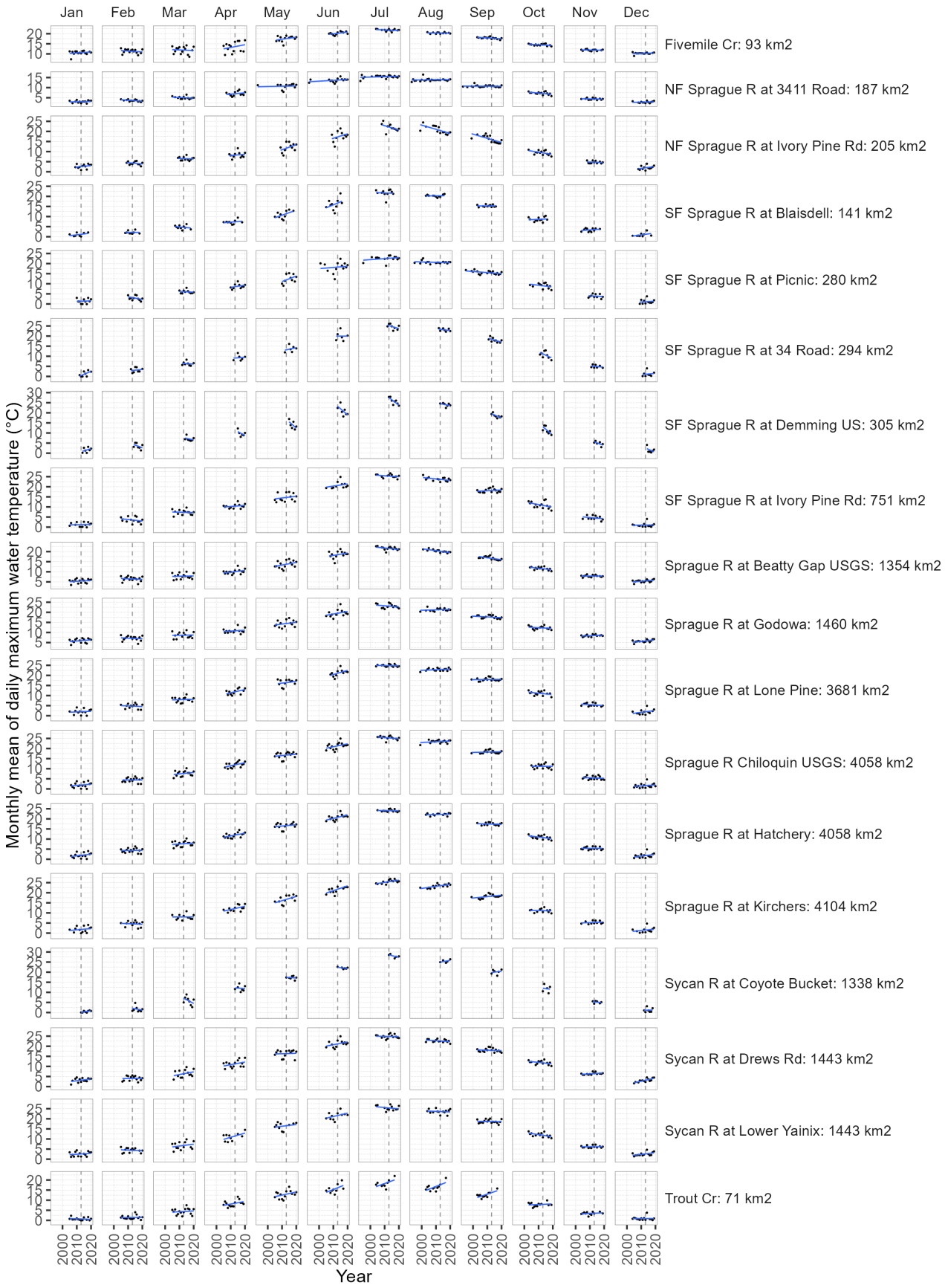

Figure B38. Time series of monthly average T_{max} measured at Sprague sites, 1993–2020, with linear trendline. Y-axis extent varies among sites, but the scale (i.e., spacing) does not.

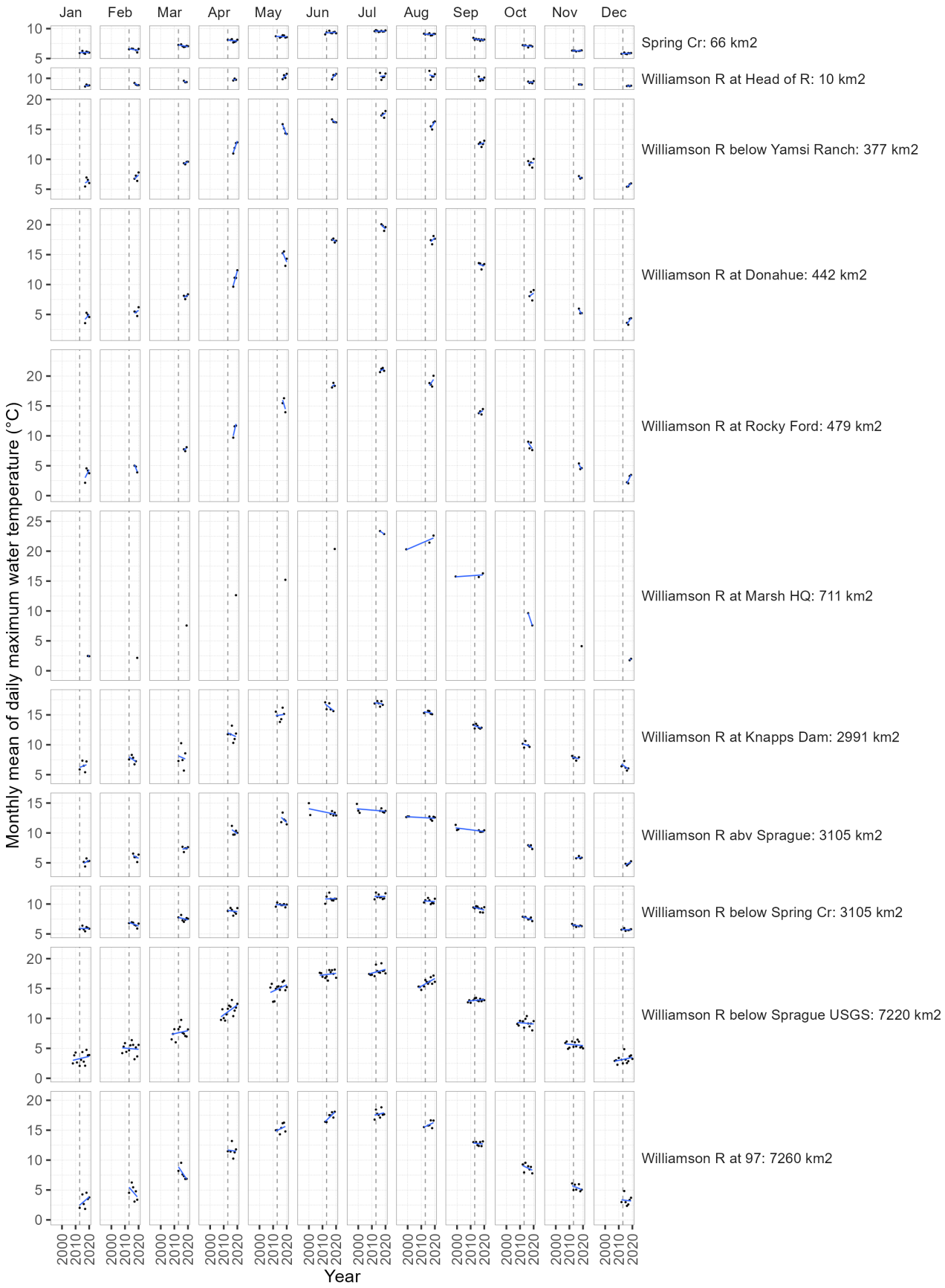

Figure B39. Time series of monthly average T_{max} measured at Williamson sites, 1993–2020, with linear trendline. See Figure B38 caption for additional notes.

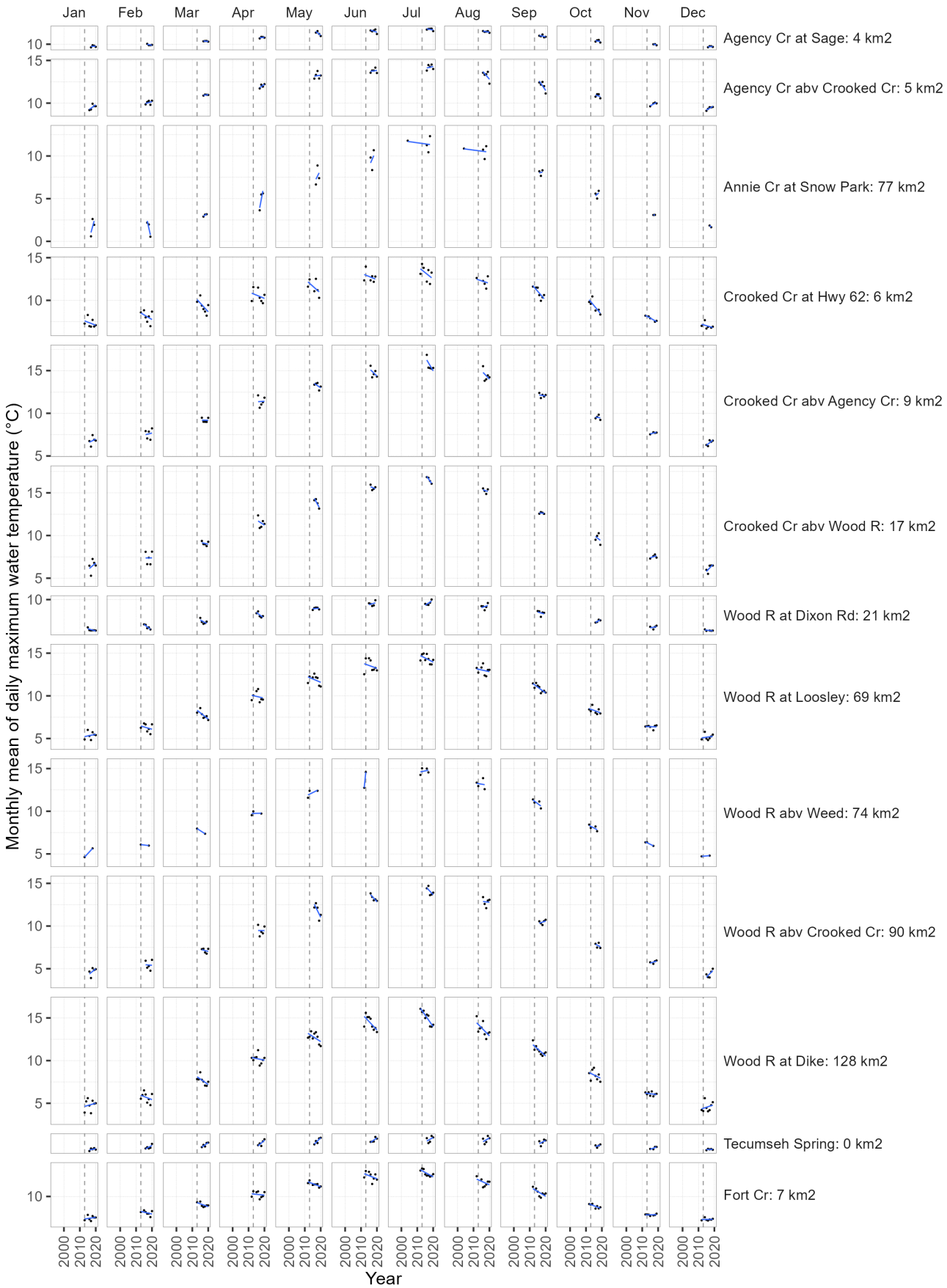

Figure B40. Time series of monthly average T_{max} measured at Wood sites, 1993–2020, with linear trendline. See Figure B38 caption for additional notes.

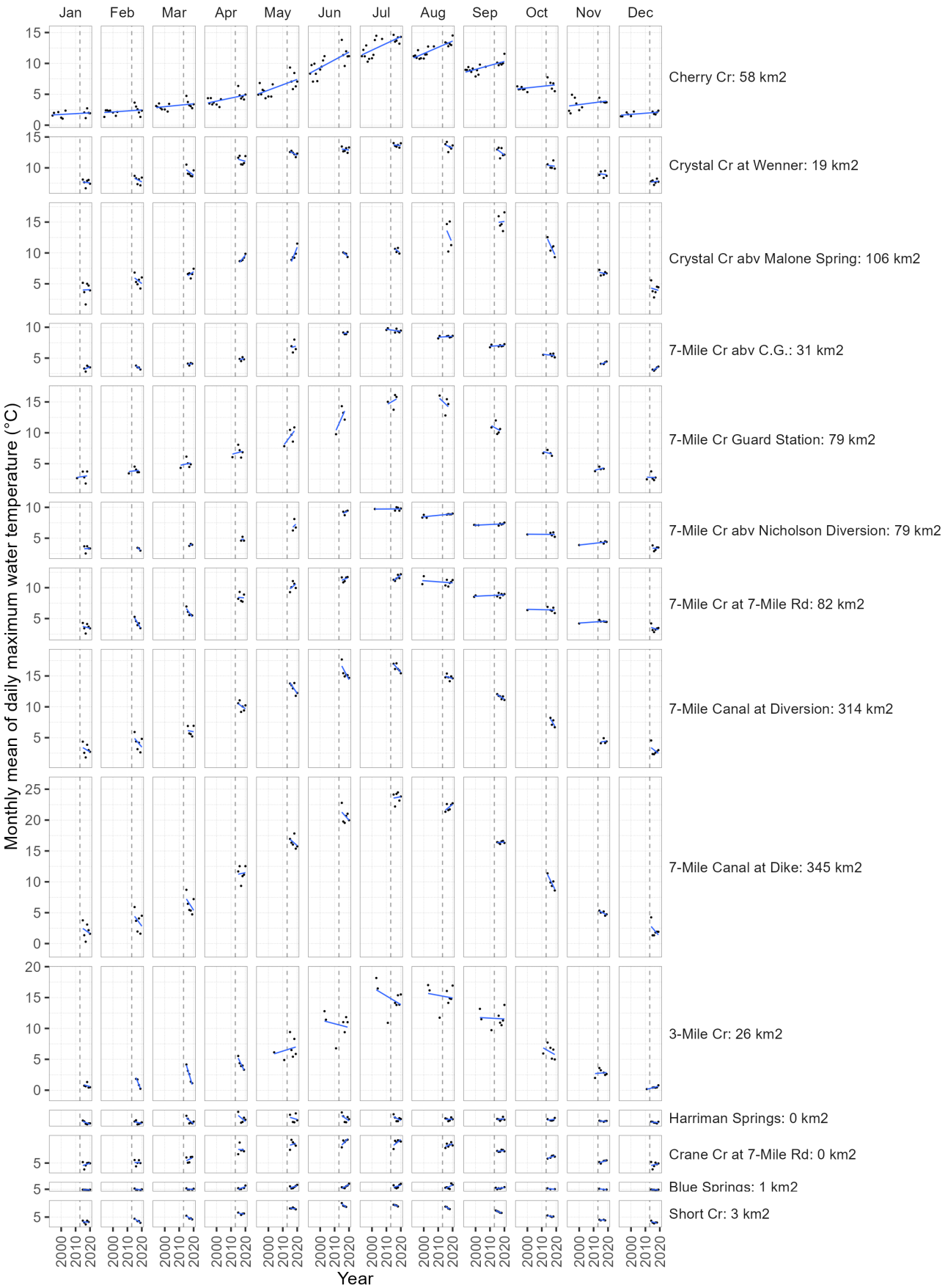

Figure B41. Time series of monthly average T_{max} measured at Westside sites, 1993–2020, with linear trendline. See Figure B38 caption for additional notes.

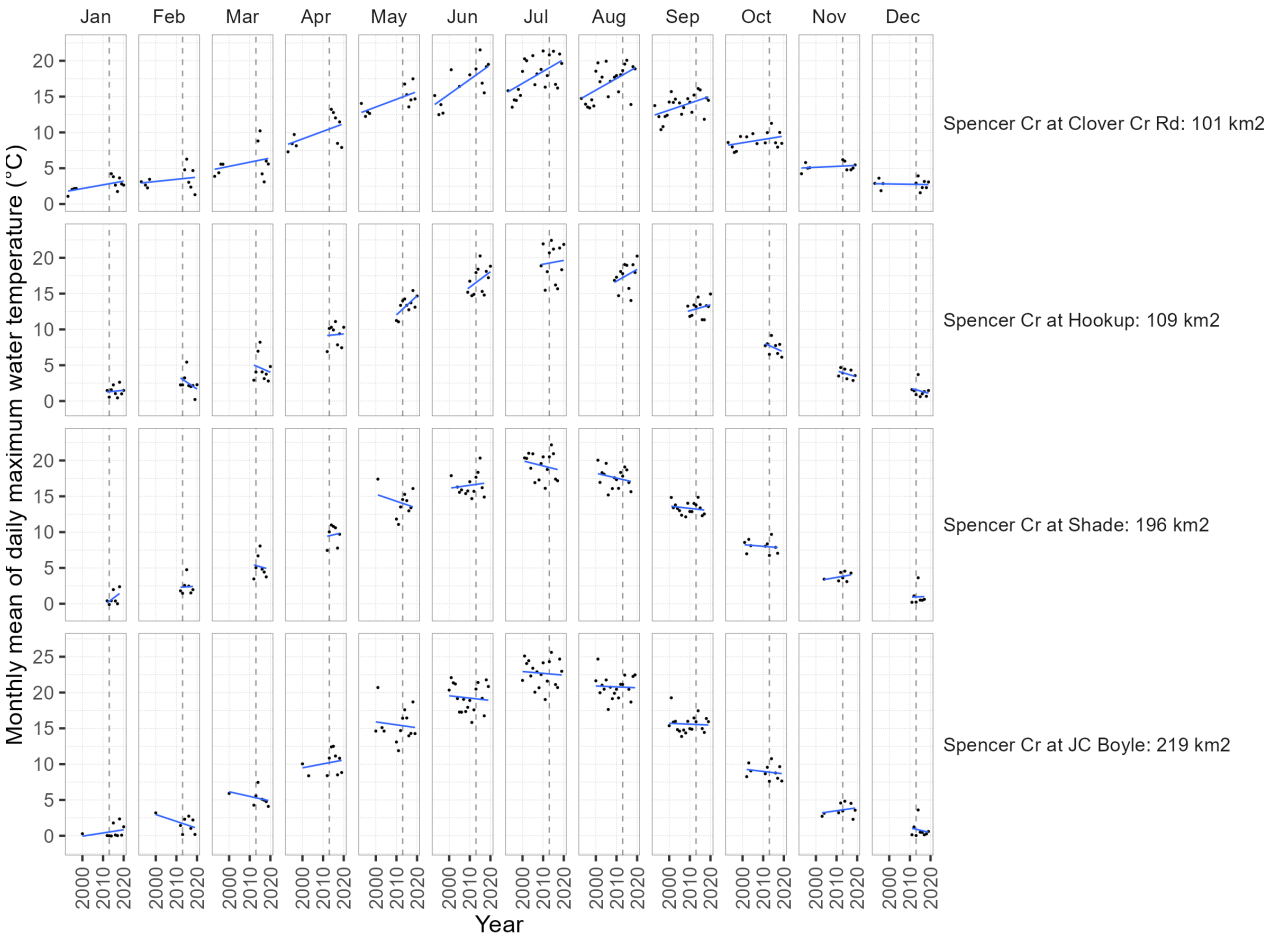

Figure B42. Time series of monthly average T_{max} measured at Spencer sites, 1993–2020, with linear trendline. See Figure B38 caption for additional notes.

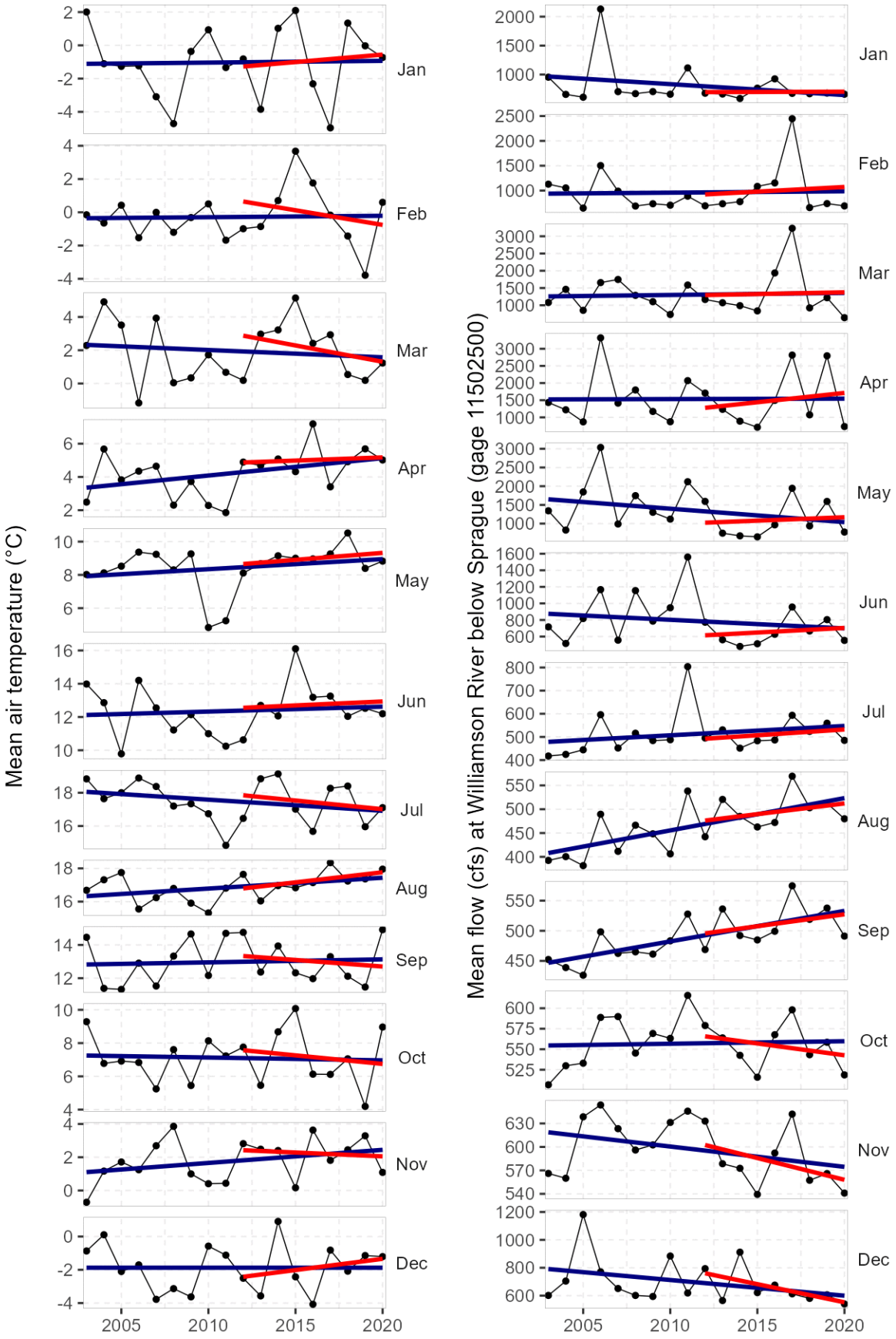

Figure B43. Time series of monthly average (a) PRISM air temperature and (b) flow of Williamson River below Sprague River for 2003–2020, with linear trend lines for 2003–2020 in blue and 2012–2020 in red.

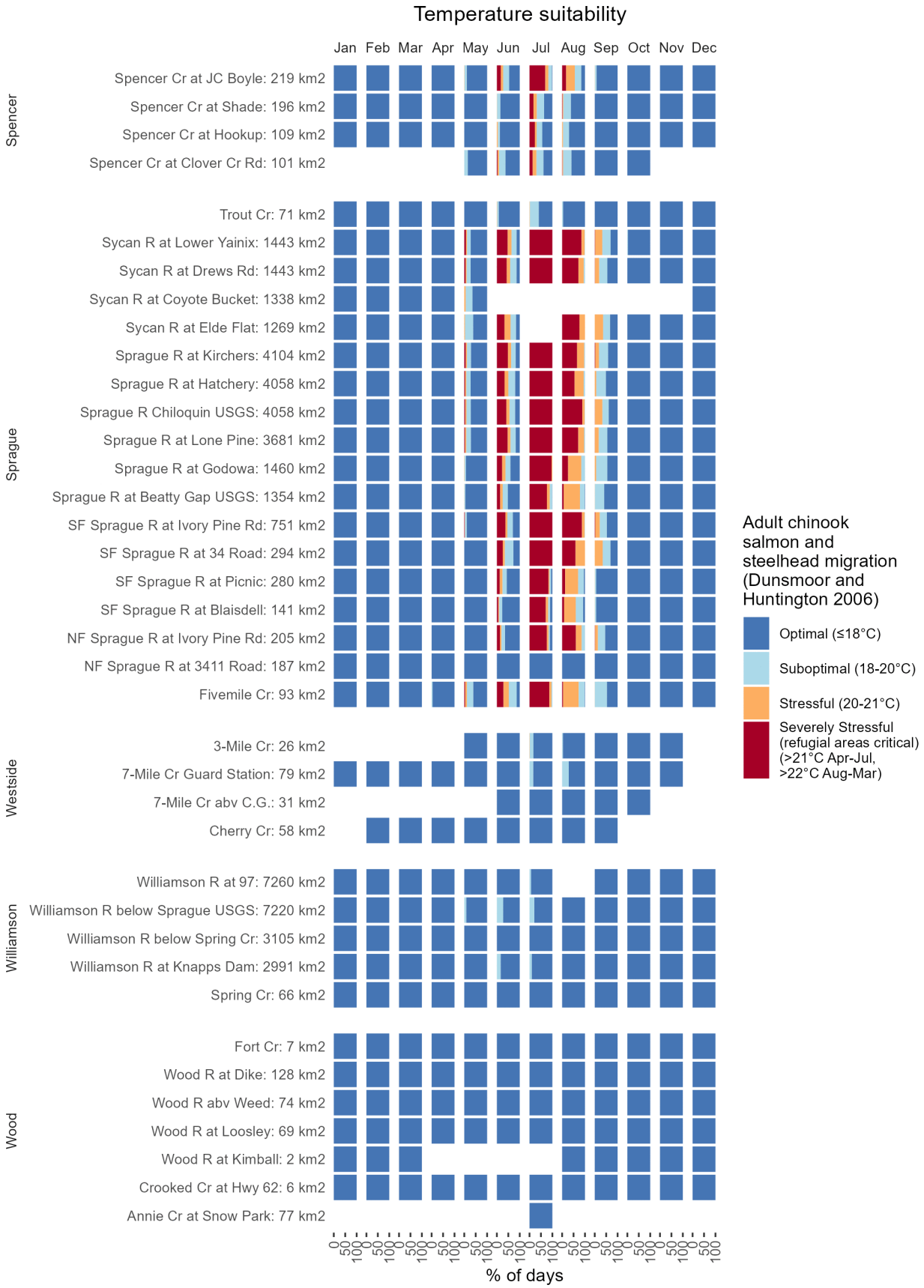

Figure B44. Temperature suitability for adult chinook salmon and steelhead, based on the percent of measured 7DADM temperatures per month in the 1/1/2003–7/16/2013 pre-regulation era within suitability categories adapted from Dunsmoor and Huntington (2006). Sites and months with <28 days of data are excluded.

Figure B45. Temperature suitability for juvenile chinook salmon rearing, based on the percent of measured 7DADM temperatures per month in the 1/1/2003–7/16/2013 pre-regulation era within suitability categories adapted from Dunsmoor and Huntington (2006). Sites and months with <28 days of data are excluded.

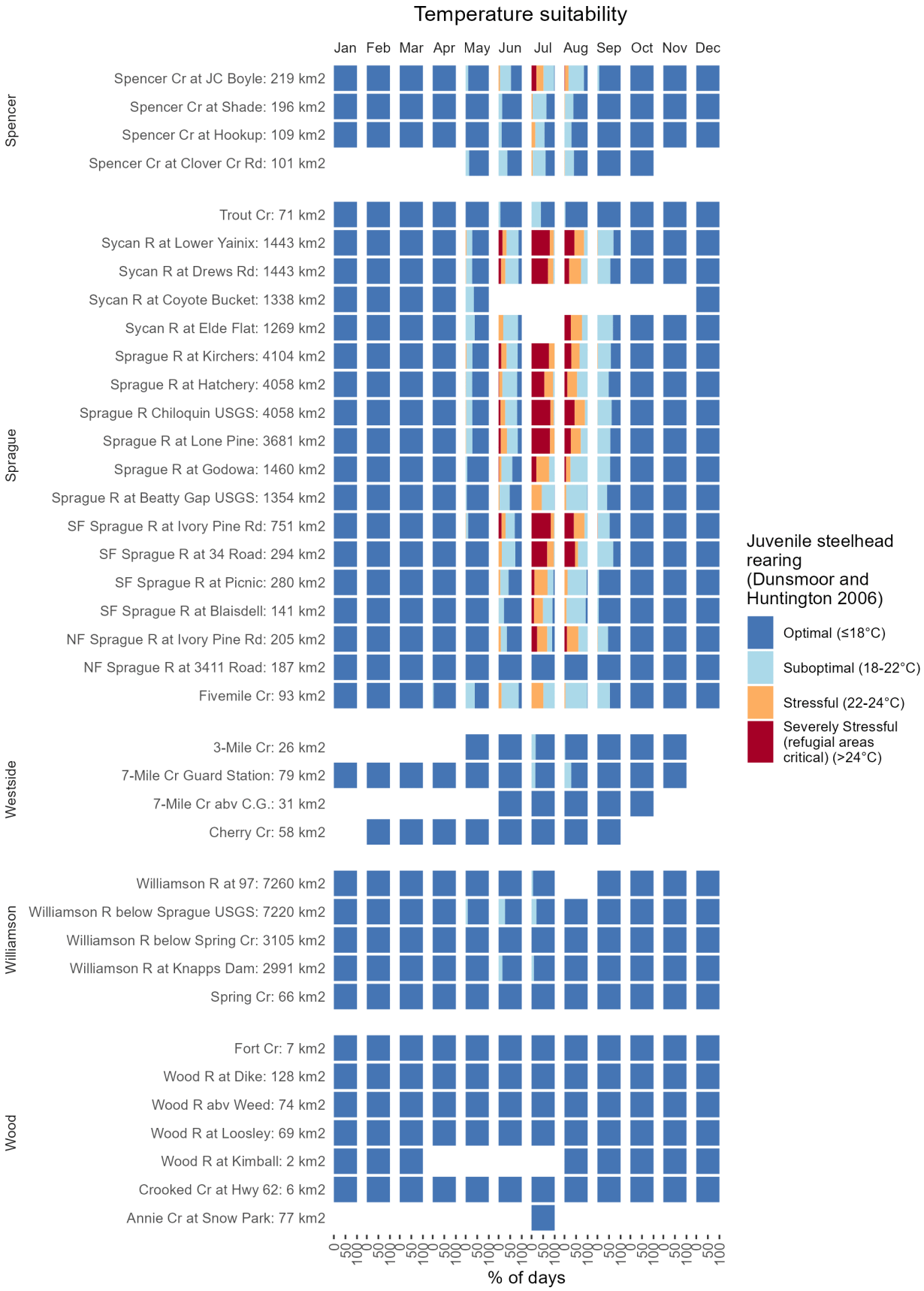

Figure B46. Temperature suitability for juvenile steelhead rearing, based on the percent of measured 7DADM temperatures per month in the regulation era (6/17/2013–12/31/2020) within suitability categories adapted from Dunsmoor and Huntington (2006). Sites and months with <28 days of data are excluded.

Figure B47. Temperature suitability for salmon and steelhead spawning, based on the percent of measured 7DADM temperatures per month in the 1/1/2003–7/16/2013 pre-regulation era exceeding ODEQ (2022) criterion. Criterion not evaluated for July and August because no spawning is expected to occur. Sites and months with <28 days of data are excluded.

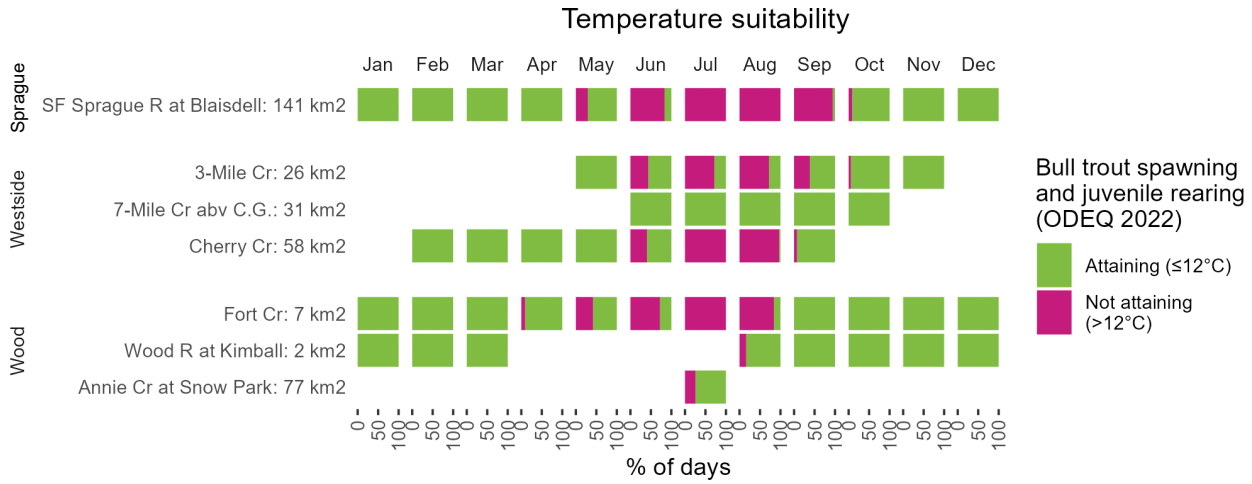

Figure B48. Temperature suitability for bull trout spawning and juvenile rearing, based on the percent of measured 7DADM temperatures per month in the 1/1/2003–7/16/2013 pre-regulation era exceeding ODEQ (2022) criteria. Sites and months with <28 days of data are excluded.

APPENDIX C: HYDROLOGIC EFFECTS OF FLOW REGULATION

Only one of the previous assessments of the hydrologic effects of flow regulation included 2017–2020 (Walker and Kann 2022), none included 2021, most focused solely on the Sprague River at Chiloquin (Section 3.4.1), so we attempted our own assessment to quantify the effects of flow regulation on streamflow at multiple gages for the full 2013–2021 time period. We began with exploratory analyses relating flow at five long-term gages affected by flow regulation (SPRAGUE RIVER NEAR CHILOQUIN, OR, SPRAGUE R NR BEATTY, OR, WILLIAMSON RIVER BLW SPRAGUE RIVER NR CHILOQUIN,OR, WILLIAMSON R BL SHEEP CR NR LENZ, OR, and SYCAN R BL SNAKE CR NR BEATTY, OR) to gages not affected by flow regulation that had been identified in previous analyses to be good predictors (CHEWAUCAN R NR PAISLEY, OR, ANNIE SPRING NEAR CRATER LAKE, OR, ROGUE RIVER ABOVE PROSPECT, OR, ROGUE RIVER BELOW PROSPECT, OR, FALL R NR LA PINE, OR, and DESCHUTES R BL SNOW CR NR LA PINE, OR), using data from the 50-year period 1972–2021.

Of the six gages evaluated, Chewaucan River had by far the highest correlation to our long-term gages of interest, so we selected it for further analysis. Using data for the 1972–2012 pre-regulation period, for each of the five long-term gages, we compared six GAMs that ranged from a single one-term linear regression using only Chewaucan River flow (GAM1) to more complex GAMs (Table C3). We selected a final model structure based on the lowest Bayesian information criterion score (BIC) (not shown). The final selected model GAM6 contains two terms: 1) linear slope of Chewaucan River flow that varies cyclically by day of year, and 2) nonlinear Fall River flow. We then used that same model structure to develop 10 models (for each of the five long-term gages we developed separate models for daily mean flow and monthly mean flow). To validate these models, we used leave-one-year-out (LOYO) cross-validation (CV) where data were split into annual blocks (i.e., steps repeated for each year: year withheld, model refit using remaining data, and predictions compared to withheld data using root mean squared error [RMSE]). Lumping all dates, the LOYO CV R^2 values for the daily models ranged from a low of 0.737 (Williamson River below Sheep Creek) to as high of 0.892 (Sprague River near Beatty) (Figure C49). LOYO CV R^2 values for the monthly models were higher, ranging from 0. 759–0.933 (not shown). At nearly all sites, models performed best in May and June (Figure C49). After validating the models, we used them to predict flows in the 2013–2021 regulated period, and compared those predictions to measured data (Figure C50). The daily model indicated that regulation increased flows in July–August by up to approximately 50 cfs in the Sprague River at Beatty and Chiloquin, 100 cfs in the Williamson River below Chiloquin, with no increase in the upper Williamson River below Sheep Creek (Figure C50), with similar results for the monthly model (Figure C51). However, for most of the remainder of the year, the daily and monthly models predicted that regulation strongly decreased flows (Figure C50, Figure C51). Considering all available evidence, we think these models under-represent the flow increases resulting from regulation (except in July–August) and we do not have confidence in these results. These models primarily rely on instantaneously (i.e., no lags or consideration of previous time steps) translating Chewaucan River flows, and therefore may be confounded by multi-year drought effects that may manifest differently at our study sites. In addition, the Chewaucan River has later runoff timing than the Sprague River, with Sprague flows receding more quickly in the spring than the Chewaucan, perhaps due to the Sprague River having a larger percent of its watershed having lower elevations where snow would presumably melt earlier.

Table C3. Structure of generalized additive models used to predict flows at five long-term gages of interest. Key to syntax and abbreviations used in the formulas. D = day of year from 1 (1 January) to 366 (31 December in leap year), Q.Chewaucan = mean flow of Chewaucan River near Paisley gage, Q.LaPine is mean flow of Fall River at Lapine gage. "s()" is a nonlinear function, "s(D, by =)" is a linear interaction that varies smoothly by D.

Model	**Formula**
GAM1: Q	Q.Chewaucan
GAM2: Q by D	s(D, by = Q.Chewaucan)
GAM3: Q, D	Q.Chewaucan + s(D)
GAM4: Qs	s(Q.Chewaucan)
GAM5: Qs, Q by D	s(Q.Chewaucan) + s(D, by = Q.Chewaucan)
GAM6: Q by D, Q.LaPine	s(D, by = Q.Chewaucan) + s(Q.LaPine)

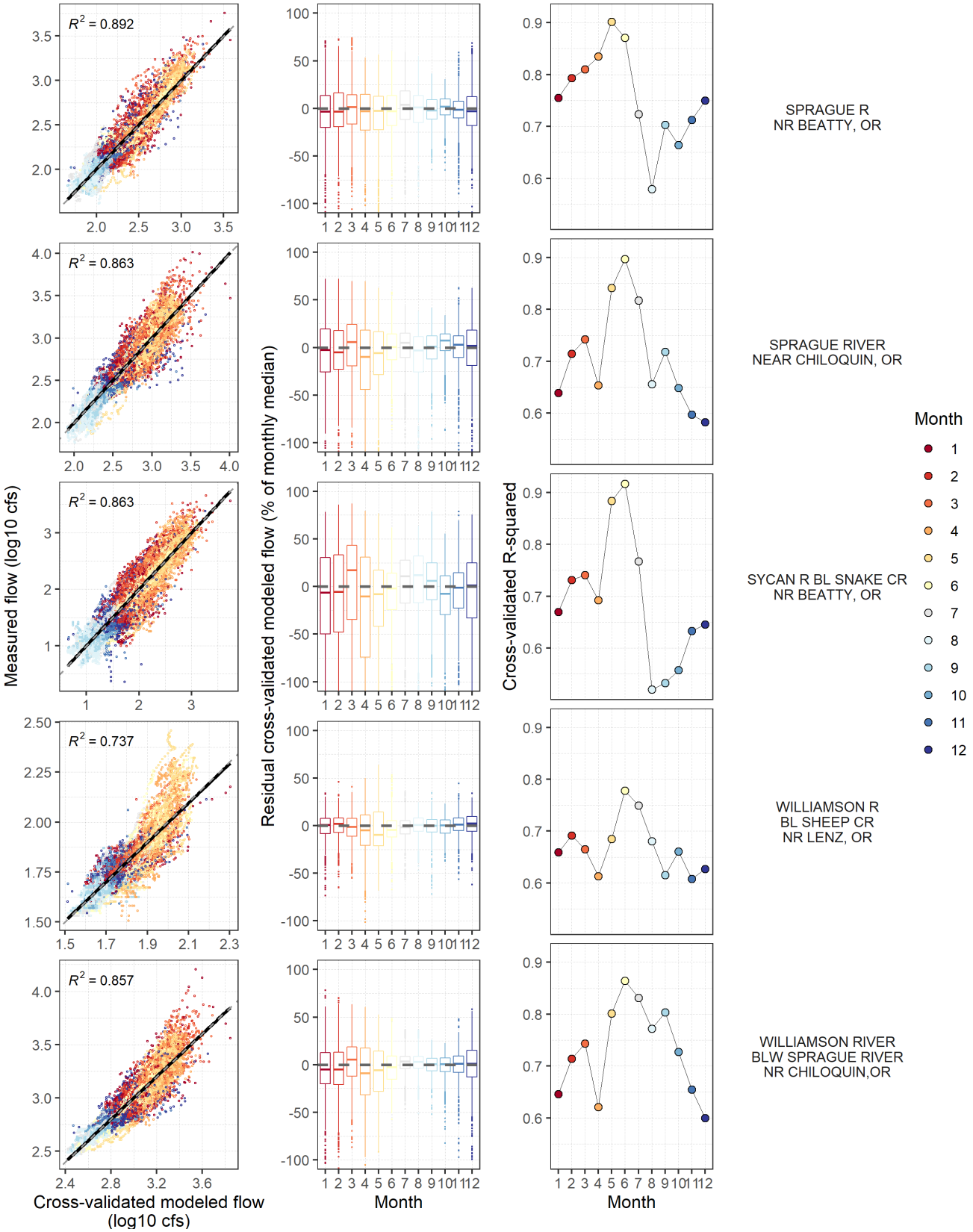

Figure C49. Performance of GAM6 model used to predict daily flow at five long-term gages in the Williamson, Sprague, and Sycan rivers in the years 1972-2021.

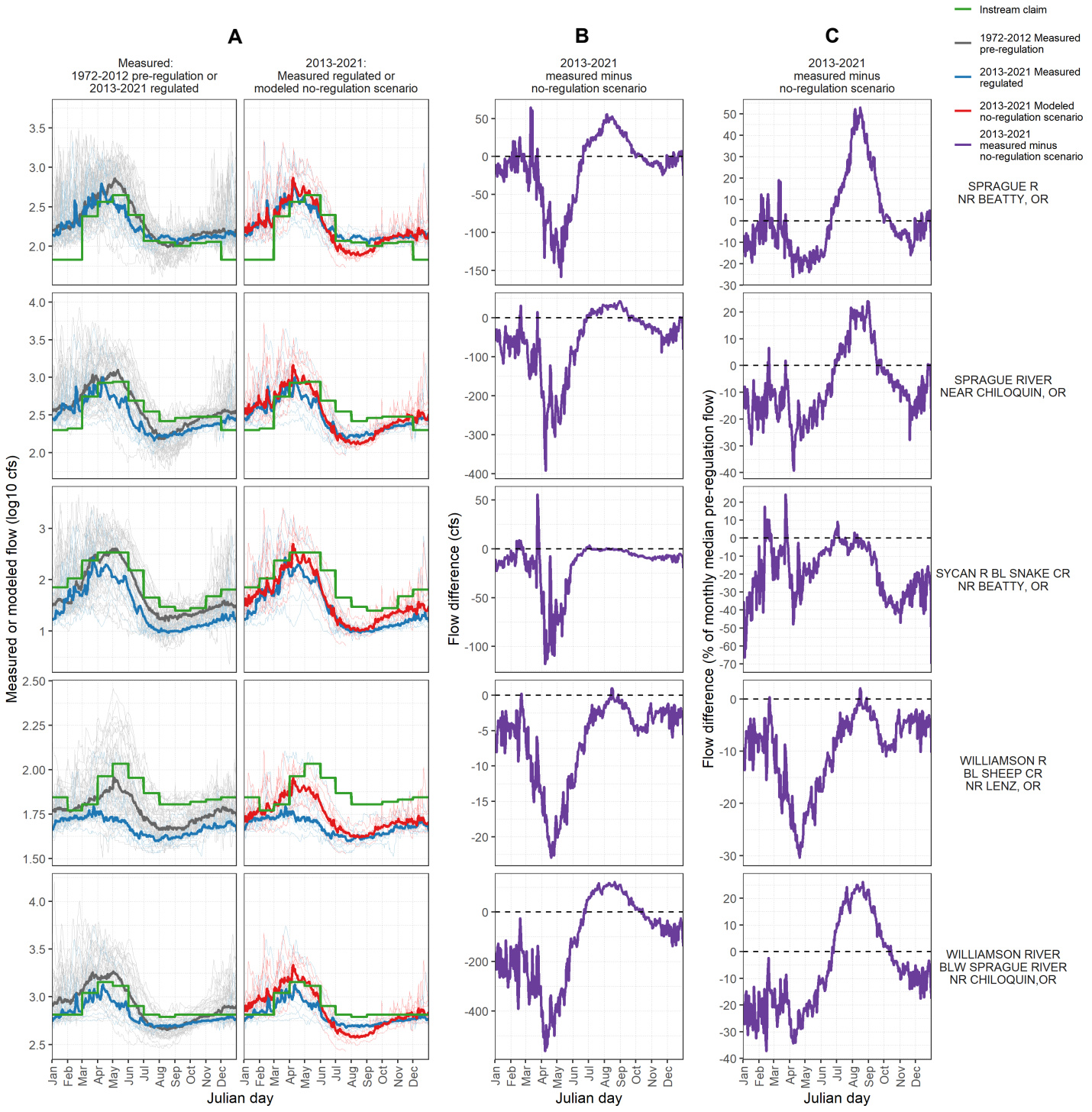

Figure C50. (A) Daily measured and modeled flows at five long-term gages, with The Klamath Tribes' water rights instream claims also shown. (B) and (C) Difference between the measured and no-regulation scenario, with values >0 indicating observed flows higher than expected based on the model calibrated from the pre-regulation era.

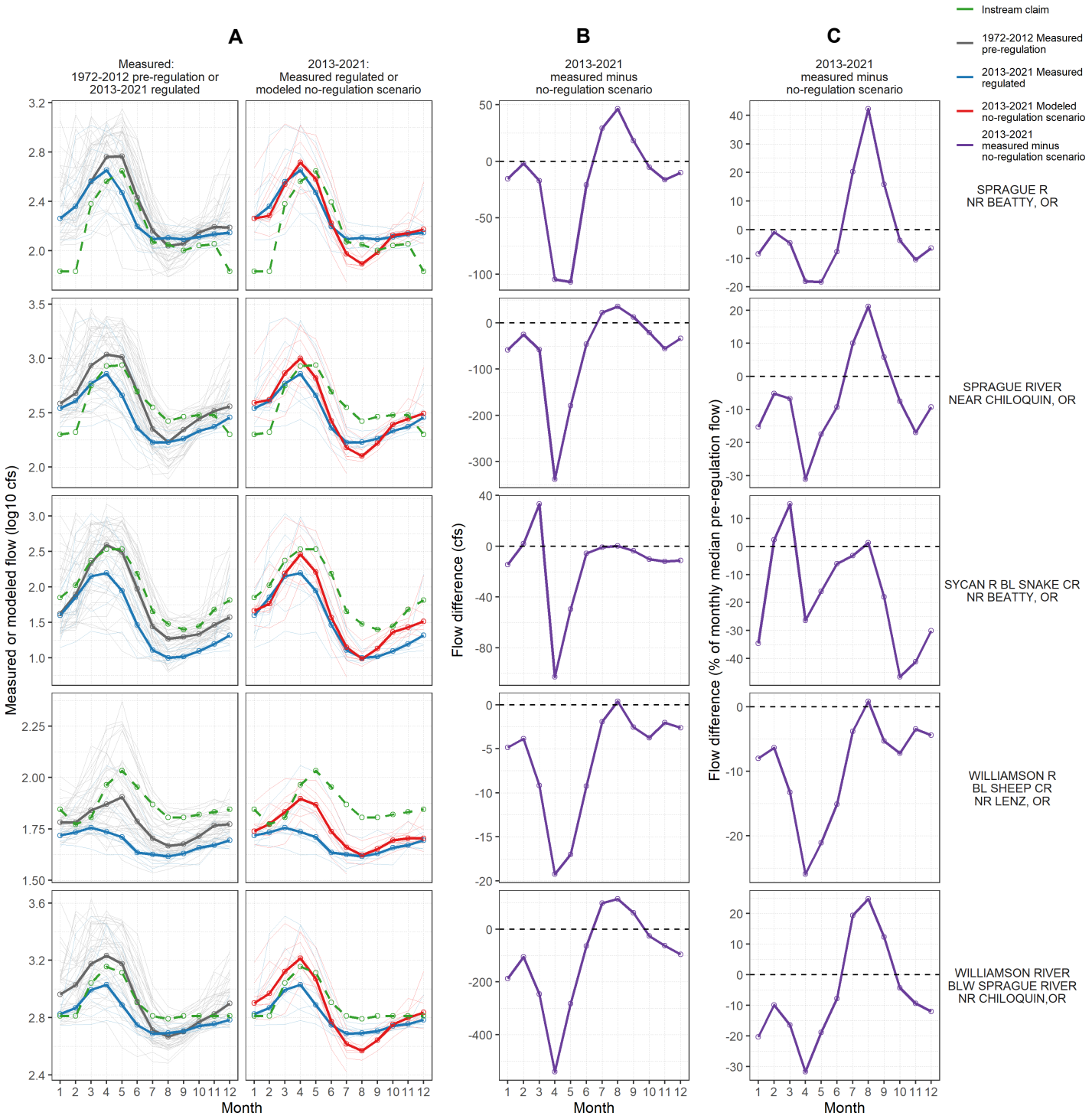

Figure C51. (A) Monthly measured and modeled flows at five long-term gages, with The Klamath Tribes' water rights instream claims also shown. (B) and (C) Difference between the measured and no-regulation scenario, with values >0 indicating observed flows higher than expected based on the model calibrated from the pre-regulation era.