Synthesizing 87 years of scientific inquiry into Trinity River water temperatures

J. Eli Asarian
Riverbend Sciences

Kyle De Juilio and **David Gaeuman**
Yurok Tribe Fisheries Program, Trinity River Division

Seth Naman
NOAA Fisheries

Todd Buxton
U.S. Bureau of Reclamation

August 16, 2023

Synthesizing 87 years of scientific inquiry into Trinity River water temperatures

J. Eli Asarian
Riverbend Sciences
Eureka, CA

Kyle De Juilio and **David Gaeuman**
Yurok Tribe Fisheries Program, Trinity River Division
Willow Creek, CA

Seth Naman
NOAA Fisheries
Arcata, CA

Todd Buxton
U.S. Bureau of Reclamation
Weaverville, CA

Prepared for:
Trinity River Restoration Program
Weaverville, CA

August 16, 2023

Suggested citation:

Asarian, J.E., K. De Juilio, S. Naman, D. Gaeuman, and T. Buxton. 2023. Synthesizing 87 years of scientific inquiry into Trinity River water temperatures. 180 p. + appendices. Prepared for the Trinity River Restoration Program, Weaverville, California.

Photo credits for cover page:

Clockwise from top-left: Trinity River downstream of Eagle Creek (E. Asarian, 8/13/2017), temperature logger (E. Asarian), Trinity River at Bucktail channel rehabilitation site (Aaron Martin, 4/24/2019), Trinity Dam and Trinity Reservoir (U.S. Bureau of Reclamation, date unknown).

EXECUTIVE SUMMARY

The Trinity River Record of Decision (ROD) was signed in 2000 to provide water and resources to aid restoration of fish and wildlife populations that were negatively affect by construction and operation of the Trinity River Division (TRD) of the Central Valley Project (CVP). The Trinity River Restoration Program (TRRP) provides an administrative and scientific framework to aid restoration of the Trinity River. The scientific framework included objectives that could be monitored, evaluated, and used to gage success in restoring anadromous fish populations and the ecological integrity of the river, notably with flow releases allocated according to water year types based on annual water yields (Critically Dry, Dry, Normal, Wet, and Extremely Wet).

In 2018, the Trinity Management Council (TMC), which oversees the TRRP, directed the TRRP to synthesize data, information, and learning that has occurred since the ROD. Accordingly, TRRP developed “synthesis reports” on fourteen topics to guide adaptive management. Because water releases from Lewiston Dam and their resulting temperatures at downstream locations are the primary drivers of biological populations in the Trinity River, the TRRP chose to develop a synthesis report focused on water temperatures. In this report, we compiled, summarized, analyzed, and modeled water temperature and hydrology data collected from the Trinity River, California to meet six objectives:

- Construct and populate a comprehensive quality-controlled water temperature dataset for analysis and archive it for future use;
- Evaluate patterns in the relationship between flow and temperature in space and time before the construction of the TRD, pre-ROD, and post-ROD;
- Evaluate how ROD flows have affected the thermal regime, temperature compliance, and biological objectives on the Trinity River;
- Evaluate temperature compliance across multiple years (pre-ROD and post-ROD);
- Update conceptual models on stream temperature dynamics in the Trinity River; and
- Develop management recommendations to provide water temperatures in the Trinity River that more efficiently meet restoration objectives of the TRRP.

We acquired river and tributary water temperature data from tribal, federal, state, and local agencies, consulting firms, and universities. The result is a set of stream temperature data for 252 sites at their original temporal resolution (sub-hourly to daily) compiled into a geographically referenced database containing 396,172 daily values, derived from 13 million original measurements. We also compiled hydrology and reservoir water temperature data in this database. These data were used to analyze existing conditions and develop model scenarios for pre-dam conditions and hypothetical management alternatives. From this effort, conceptual models were updated and used to explore water temperature dynamics on the Trinity River with comparisons made to regulated and unregulated rivers described in the literature.

Prior to construction of the TRD, the Trinity River exhibited complex temperature patterns that are normal to streams in regions with Mediterranean climates. These complex patterns span temporal, longitudinal, lateral, and vertical gradients, which drive the distribution, reproduction, growth, and migration of cold-blooded aquatic species such as fish, invertebrates, reptiles, and amphibians. Trinity and Lewiston dams and impacts from historic land use practices profoundly altered the thermal landscape in these dimensions, and regulated flow releases further exacerbated temperature impacts on the Trinity River. For comparative analysis, we defined four eras associated with management changes: pre-dam era (10/1/1911–1/20/1961), full diversion era (10/31/1963–4/30/1978), transitional era (5/1/1978–9/30/1999), and ROD era (10/1/1999–2019). ROD flows did not officially begin until Spring 2004, but we start the ROD era with hydrologic year 2000 because pre-ROD flows became increasingly similar to ROD flows.

When comparing the pre-dam era to the other eras, the largest impact to water temperatures in the Trinity River occurred at Lewiston. As is typical for rivers below large thermally-stratified reservoirs where water is released from cold depths, seasonal temperature variation has been severely reduced. With-dam seasonal minima and maxima have similar timing (January and August, respectively) as occurred pre-dam, but seasonal range in daily average temperatures has been compressed from 4–23 °C pre-dam to 7–10 °C with-dam. The flow regulation causes the river to be unnaturally warm in winter and cold in summer. Variation among years also declined at Lewiston from thermal dampening by the reservoir water bodies and the relative similarity of flow releases across years, regardless of annual variations in annual water yields or patterns in runoff. The downstream extent and severity of thermal impacts from the reservoirs and flow regulation varies with flows released from the dams. When dam releases are low, the thermal effects diminish more quickly than during high-flow releases when the entire length of the river below Lewiston Dam is strongly affected.

While the full diversion, transitional, and ROD era temperatures have more in common with one another than the pre-dam era, there are discernable management impacts associated with each era. Summer baseflows are a defining characteristic of each era and generally increased in magnitude to present. Spring and summer exhibited the greatest temperature change between eras, with increasing departure from unimpaired (i.e., pre-dam and pre-diversion) conditions as a result of less annual variation in flows, higher summer flows that extended cooler temperatures further downstream, and a shortened duration of warmer water temperatures in summer. Winter baseflows increased from 150 to 300 cfs in 1978 but are still much lower than the pre-dam era.

ROD flows were designed, in part, to meet temperature objectives for promoting salmonid populations. Temperature objectives for the Trinity River at Douglas City (18 miles downstream of Lewiston) and the North Fork Trinity River (40 miles downstream of Lewiston) were designed to protect salmonid adults, eggs, and embryos. Objectives at Weitchpec (located at the confluence with the Klamath River 112 miles downstream of Lewiston) were designed to provide suitable temperatures for smoltification (i.e., for juvenile salmonids to prepare for transition to saltwater), with any temperatures colder than the objectives considered sufficient or beneficial. Avoiding potentially detrimental effects of overly cold water were not prioritized during development of these criteria. Flow releases aimed at meeting these criteria have resulted in water that is so cold it can stunt the growth of juvenile salmonids and reduce their size at entry and survival in the ocean. With this in mind, we evaluated a new proposed temperature objective for optimizing juvenile salmonid growth at the confluence with the North Fork Trinity River. During the ROD era, water temperatures at this site did not reach the optimal range for juvenile salmonid growth (13–16.5 °C) until a month later than in the transitional era and the modeled unimpaired flow scenario (i.e., pre-dam and pre-diversion). ROD-era temperatures were in the optimal range for only 18% of the primary rearing period (April–June), compared to 26% and 21%, respectively, for the transitional era and the modeled unimpaired flow scenario. Upstream at Douglas City, these patterns and differences were even more pronounced with optimal rearing temperatures in 10% of ROD era days, 29% of transitional era days, and 19% of days in the modeled unimpaired flow scenario. The timing and percent of days with optimal rearing temperatures were relatively similar between the eras at Weitchpec because effects of the reservoirs and flow regulation on river water temperatures diminishes with downstream distance.

We evaluated compliance with temperature objectives in the ROD for the available period of record, which primarily spans the transitional and ROD eras, except at the Trinity River at Weitchpec where records also include the full diversion era. At Weitchpec, violations in temperature compliance were comparable between the transitional and ROD eras likely due to the similarity of managed flows, particularly baseflows, in these periods. While single temperature and location-based water temperature targets such as those at Weitchpec are simple to establish and evaluate, they inadequately assess whether the temporal and multi-dimensional temperature requirements in lotic systems are being met. We therefore recommend the development and implementation of a holistic approach to temperature management that assesses temperature objectives throughout the Trinity River.

Given the current inability to specify water temperatures released to the Trinity River, we investigated how adjusting flow releases from Lewiston Dam can better provide water temperatures that promote instream biology. The investigation compared ROD-specified flows to constant flows ranging from 300 to 4000 cfs and an unimpaired flow scenario. Results indicated that flows can be released from Lewiston Dam under current infrastructure constraints that would have substantially better biological effects than the current ROD flows. For example, the ROD specifies static winter baseflows (300 cfs) from October 15 through April 15, but our analyses indicated that increased flows in February and March in all water year types and in April of normal and wetter water years would provide temperatures that accelerate salmonid growth. Later, ROD flows that are elevated in comparison to unimpaired flows in late April through early summer supply cold water that suppresses salmonid growth, frog development, and benthic macroinvertebrates. The potential for lowering ROD flows in this period provides a significant opportunity for increasing the size and health of these populations in the Trinity River. Reducing flows to summer baseflow earlier in the year than under the ROD, particularly in normal, wet, and extremely wet years, would also benefit salmonid growth by allowing river temperatures to warm in a pattern that more closely mimics pre-dam water temperatures. Even if possible, we do not recommend returning temperatures entirely to the unimpaired scenario because access to high elevation, cold water habitat upstream of the dams has been lost. However, there are important ecological services for species growth, development, and life history cues for reproduction and migration provided by the pre-dam temperature regime that should be emulated including appropriately timed spring warming and fall cooling.

Hydraulic mining and flow regulation have simplified some reaches of the Trinity River to a single-thread channel that lacks shallow edge habitats, side channels, and floodplain ponds. Water temperatures are nearly uniform in these simplified reaches. We used modeling to show that channel rehabilitation work with heavy equipment that constructs shallow, slow-water habitats on the channel margins provides water temperatures that are warmer compared to deeper areas in the channel. The shallow, warm water substantially increases the range of water temperatures available to fish, invertebrates, amphibians, and reptiles. Our model results further indicated the temperature variations occurred during a wide range of seasons and flows, providing thermal habitat diversity capable of meeting the needs of a diverse aquatic species assemblage (e.g., Foothill Yellow-legged frog and salmonids).

We summarized potential impacts of climate change on Trinity River water temperatures using projected effects published in the scientific literature. Snowpack will decline substantially and winter rainfall will increase in the Trinity River basin as climate change increases air temperatures. The combination of more rain, less snow, and earlier snowmelt will cause earlier runoff and lower flows in spring and summer. Rising air temperatures will increase stream temperatures in all seasons, but warming will be greatest in spring and summer due to the aforementioned changes in hydrology. Reducing global greenhouse gas emissions would reduce the severity of these effects. In line with climate change projections, our analysis of long-term data showed that Trinity Reservoir temperatures have warmed in recent decades, even in the deepest and coldest portions of the reservoir. Trinity Reservoir is expected to be substantially impacted by climate change with warmer release temperatures caused by warmer inflow temperatures and lower end of September storage volumes that will result from increased water demand, earlier runoff, and the need to maintain greater flood control capacity.

Management of water temperatures released to the Trinity River are provided by the main and auxiliary outlet works of Trinity Dam, flow management through Lewiston Reservoir, and Trinity Reservoir storage. Both low Trinity Reservoir storage and low flows through Lewiston Reservoir can result in warm water releases to the river, which is most common in fall when salmon are spawning. While temperatures for juvenile salmonid rearing is a concern in spring, providing cold water temperatures for adult salmonids and their eggs becomes vital in late summer and fall. When the reservoir is drawn down to low levels (<0.75 million acre-feet), temperatures in the main outlet of Trinity Reservoir can exceed the thermal tolerance of salmonid eggs, the life stage that is most temperature sensitive. This can pose a risk to populations and require cold water releases from the auxiliary outlet works that bypasses turbines that generate electricity, such as occurred during severe droughts in 1977, 2014, and 2015. Had these droughts persisted for another year, even the auxiliary outlet may not have been cold enough to protect incubating eggs. With climate change, greater emphasis will need to be placed on conserving the cold-water pool in Trinity Reservoir, much like is currently adopted in Shasta Reservoir management.

Summary of important findings or confirmation of prior findings:

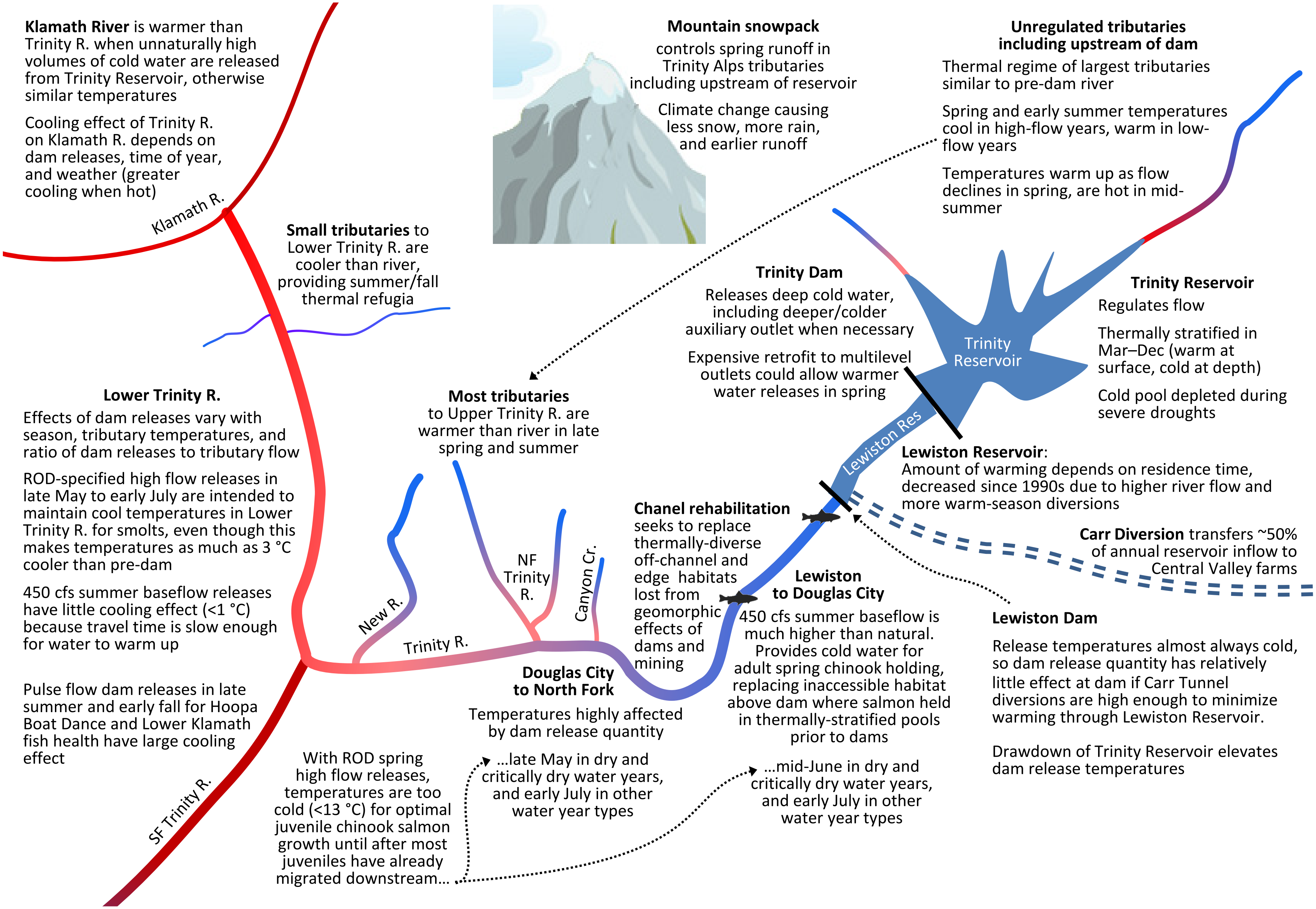
- Water released from Lewiston Dam into the Trinity River is nearly always too cold to support optimal juvenile salmonid growth during the primary rearing period (April-June).
- Elevating Lewiston Dam releases above 300 cfs winter baseflows before April in Dry years and May in Normal and wetter years would provide temperatures that benefit salmonids, invertebrates, and frogs by increasing food assimilation and development rates.
- April in Dry years and May in Normal and wetter years are the only time periods in spring when it is possible for temperatures in the entire Lewiston to Weitchpec reach of the Trinity River to approximate unimpaired (i.e., pre-dam) patterns.
- In May of Dry years and June of Normal and wetter years, elevated releases suppress growth of cold-blooded aquatic species.
- To provide cool water for meeting outmigration temperature criteria at Weitchpec, the ROD required large spring releases but did not consider the deleterious effects of these releases on juvenile salmonid growth in upstream reaches.
- Trinity Reservoir storage <0.75 million acre-feet in September, October, and November poses a notable risk of water releases that exceed the thermal tolerance of salmonid eggs and can cause mortality.

- Trinity Reservoir storage is likely to decrease and water temperatures are likely to increase in the future due to changes in runoff patterns from climate change.
- It is not clear that ROD water management has resulted in increased temperature compliance from the period of record available.

Based on our assessments, we make the following recommendations:

1. Monitor temperatures in the Trinity River upstream of Trinity Reservoir to better understand the natural temperature regime and its effects on water temperatures in Trinity Reservoir.
2. Flows in spring should recede beginning in April of Dry and Critically Dry water years and May of Normal and wetter water years to provide water temperatures in the Trinity River upstream of the North Fork Trinity River within the range that provides optimal juvenile salmonid growth (13–16.5 °C) and outmigration (16–18 °C).
3. Reduced emphasis on meeting ROD temperature targets for smoltification at Weitchpec. Instead, the goal should be a balance between growth, encouraging timely outmigration, and mitigating temperatures in the lower river that approach the thermal limits of juvenile salmonids.
4. Infrastructure of the TRD should be modified to enable finer flow and temperature management to be implemented for the benefit of the river ecosystem, including:
    a. Installation of a multi-level temperature control device in Trinity Reservoir;
    b. Removal of Lewiston Dam or construction of a new type of conveyance through or around Lewiston.
5. For Trinity Reservoir, an end of September storage minimum of 0.75 million acre-feet (MAF) should be adhered to following the recommendations of Bender (2012). This should be coupled with a multi-year drought contingency plan that specifies steps taken when reservoir storage is predicted to be less than 1.25 MAF in any year, assuming a multi-year drought is possible at any time.
6. An assessment of multiyear drought effects on Trinity Reservoir storage levels, water temperatures, and the resulting ability to meet temperature criteria in the Trinity River should be conducted.
7. Development of a tool for accurately predicting Trinity River water temperatures in summer at flows lower than RBM10’s current lower limit of around 350 cfs.

Figure ES-1. Conceptual model of the Trinity River and its reservoirs, showing key drivers of thermal dynamics and highlighting important management issues and biological effects.



Klamath River is warmer than Trinity R. when unnaturally high volumes of cold water are released from Trinity Reservoir, otherwise similar temperatures

Cooling effect of Trinity R. on Klamath R. depends on dam releases, time of year, and weather (greater cooling when hot)

Small tributaries to Lower Trinity R. are cooler than river, providing summer/fall thermal refugia

Mountain snowpack

controls spring runoff in Trinity Alps tributaries including upstream of reservoir

Climate change causing less snow, more rain, and earlier runoff

Unregulated tributaries including upstream of dam

Thermal regime of largest tributaries similar to pre-dam river

Spring and early summer temperatures cool in high-flow years, warm in low-flow years

Temperatures warm up as flow declines in spring, are hot in mid-summer

Trinity Dam

Releases deep cold water, including deeper/colder auxiliary outlet when necessary

Expensive retrofit to multilevel outlets could allow warmer water releases in spring

Trinity Reservoir

Regulates flow

Thermally stratified in Mar–Dec (warm at surface, cold at depth)

Cold pool depleted during severe droughts

Lower Trinity R.

Effects of dam releases vary with season, tributary temperatures, and ratio of dam releases to tributary flow

ROD-specified high flow releases in late May to early July are intended to maintain cool temperatures in Lower Trinity R. for smolts, even though this makes temperatures as much as 3 °C cooler than pre-dam

450 cfs summer baseflow releases have little cooling effect (<1 °C) because travel time is slow enough for water to warm up

Pulse flow dam releases in late summer and early fall for Hoopa Boat Dance and Lower Klamath fish health have large cooling effect

Most tributaries to Upper Trinity R. are warmer than river in late spring and summer

Lewiston Reservoir: Amount of warming depends on residence time, decreased since 1990s due to higher river flow and more warm-season diversions

Chanel rehabilitation seeks to replace thermally-diverse off-channel and edge habitats lost from geomorphic effects of dams and mining

Carr Diversion transfers ~50% of annual reservoir inflow to Central Valley farms

Lewiston to Douglas City

450 cfs summer baseflow is much higher than natural. Provides cold water for adult spring chinook holding, replacing inaccessible habitat above dam where salmon held in thermally-stratified pools prior to dams

Lewiston Dam

Release temperatures almost always cold, so dam release quantity has relatively little effect at dam if Carr Tunnel diversions are high enough to minimize warming through Lewiston Reservoir.

Drawdown of Trinity Reservoir elevates dam release temperatures

Douglas City to North Fork

Temperatures highly affected by dam release quantity

With ROD spring high flow releases, temperatures are too cold (<13 °C) for optimal juvenile chinook salmon growth until after most juveniles have already migrated downstream…

…late May in dry and critically dry water years, and early July in other water year types

…mid-June in dry and critically dry water years, and early July in other water year types

TABLE OF CONTENTS

LIST OF ELECTRONIC APPENDICES

These will be available on the TRRP DataPort (https://www.trrp.net/library/)

ELECTRONIC APPENDIX 1: MS Excel spreadsheet of stream temperature data for 1942–2019, including: a) daily summary table, b) annual summary table, c) site location table, and d) pivot charts for data exploration.

ELECTRONIC APPENDIX 2: comma-delimited text file (.csv) versions of the same data tables that are in Electronic Appendix 1.

ELECTRONIC APPENDIX 3: The original temporal resolution (15–120 minute) stream temperature data for 1990–2019 were too large for Excel (limited to 1 million rows), so instead are provided as a separate comma-delimited text file (.csv).

ELECTRONIC APPENDIX 4: Gap-filled water temperatures for several mainstem Trinity River sites: at Lewiston (daily min, mean, and max 1981–2019), at Douglas City (daily mean only 1987–2019), upstream of North Fork (daily mean only 1987–2019), and at Weitchpec (daily mean only 1964–2019). We did not gap-fill Lewiston 1942–1980, but include the measured data for the period as a convenience for future users.

ELECTRONIC APPENDIX 5: Daily mean temperature and flow estimates for Trinity River at Lewiston under no-dam scenario with unimpaired flow and unimpaired temperature, 1963–2019.

ELECTRONIC APPENDIX 6: Water temperature depth profiles for Trinity Reservoir measured by the U.S. Bureau of Reclamation approximately monthly, 1972–1990 and 1998–2020 (USBR 2020).

ELECTRONIC APPENDIX 7: U.S. Bureau of Reclamation hourly water releases from TRN – Trinity Lake, Trinity Dam, and Trinity Powerplant, January 2000 – February 2020.

Note: during the course of this project, we obtained many reports and datasets relevant to the Trinity River. We arranged to have many of these reports uploaded to the TRRP DataPort (https://www.trrp.net/library/) where future users can find them by searching on author name or title. In addition, the model input, output, and code files from the BETTER water temperature model for Lewiston Reservoir (JSA 1992, Kamman 1999b) have now been uploaded to the DataPort as a data package (Kamman 1999a).

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 PURPOSE, NEED, SCOPE, DEFINITIONS, AND OBJECTIVES

The study area for this project is the Trinity River Basin in northern California, from the headwaters downstream to the Klamath River at Klamath, including the mouths of major tributaries. The analyses focus on the water temperature-stream flow relationship of the mainstem Trinity River, while incorporating data and information from a variety of sources like tributary stream flows and temperatures, meteorological conditions and Trinity Reservoir storage and temperatures. Project objectives are to: 1) Evaluate spatial and temporal patterns in the flow-temperature response pre Trinity River Record of Decision (ROD); 2) evaluate temperature compliance across multiple years (Pre-ROD and Post-ROD); 3) evaluate how ROD flows (overall and individual components) have affected the thermal regime, temperature compliance, and biological objectives; 4) update conceptual models on stream temperature dynamics in the Trinity River; 5) compile stream temperature data from multiple sources and 6) develop management recommendations to more efficiently meet the objectives of the Trinity River Restoration Program (TRRP).

1.2 STREAM TEMPERATURE BASICS

1.2.1 PHYSICAL DRIVERS OF THERMAL DYNAMICS

Stream temperatures are determined by the net balance of surface and streambed heat fluxes (Figure 2; Caissie 2006, Webb et al. 2008, Dugdale et al. 2017). The relative importance of these fluxes varies with season, geography, and position within the stream network, but shortwave solar radiation, in the form of ultraviolet rays and visible light, is usually the most important (Johnson 2004, Caissie 2006). Longwave radiation (e.g., heat energy emitted from rocks following warming from the sun) can be both a source and sink, with the stream emitting radiation as well as receiving it from other objects such as clouds and riparian vegetation (Dugdale et al. 2017). Hyporheic exchange (i.e., movement of water from surface water into underlying sediments and back to the surface) can be an important component of heat budgets in some streams (Poole and Berman 2001, Ouellet et al. 2020). The magnitude of evaporative cooling (shown as latent heat in Figure 2) rises when relative humidity is low and air temperature is high (Mohseni and Stefan 1999) and is also affected by wind speed (Johnson 2004). Convection of heat from air to water (shown as sensible heat in Figure 2) is typically a relatively small component of stream heat budgets; however, air temperatures and stream temperatures are highly correlated because both respond to the same temporal patterns in solar heating (Johnson 2003).

Daily mean air temperature and stream temperature both follow an annual sinusoidal pattern, but stream temperature typically lags behind air temperature by days to months, with lag length dependent on factors such as groundwater dynamics and the availability of snowmelt for cooling stream flows (Johnson et al. 2020). Reservoir impoundments can increase the seasonal lag between air temperature and stream temperature (Cai et al. 2018).

Stream temperatures at headwaters are close to groundwater temperature which is similar to average annual air temperature at the upstream end of a drainage network (Kurylyk et al. 2015). During the warm season, mean daily stream temperatures generally increase as water flows from the headwaters towards the river's mouth before reaching an asymptote where temperatures do not appreciably change with downstream distance (Vannote et al. 1980, Segura et al. 2015) (Figure 3). However, a review of thermal infrared data from 53 Pacific Northwest rivers found that longitudinal temperature profiles were actually quite variable, with four additional patterns identified beyond the conventional asymptotic pattern (Fullerton et al. 2015).

Dams impound reservoirs and influence stream temperatures downstream, including by constricting temperature variation on daily and seasonal time scales (Cai et al. 2018, Olden and Naiman 2010). These influences are often particularly strong below large dams where cold water is released from the bottom of a thermally stratified reservoir (Olden and Naiman 2010). Dam influence on temperatures is often greatest near the dam but diminishes with distance downstream (Preece and Jones 2002). The distance and intensity of dam influence on downstream temperatures varies with dam release temperatures, dam release rates, tributary inputs, and meteorological conditions (Daniels and Danner 2020). In most undammed river systems, diel (24-hour) variability in temperature initially increases with distance from headwaters as stream channels widen and solar exposure increases, but then flattens and declines when increasing river flow provides thermal mass that dampens diel fluctuations (Caissie 2006) (Figure 3). However, large reservoirs that release water with a near-constant temperature, including Trinity Reservoir, can substantially alter downstream diel water temperature variability (Lowney 2000, Section 3.4.4).

During the spring and summer, river temperatures tend to be lower when river flows are higher because faster water velocity transports cool water from headwaters (or dam releases) downstream faster, and greater thermal masses are more resistant to heating than smaller water volumes (Daniels and Danner 2020).

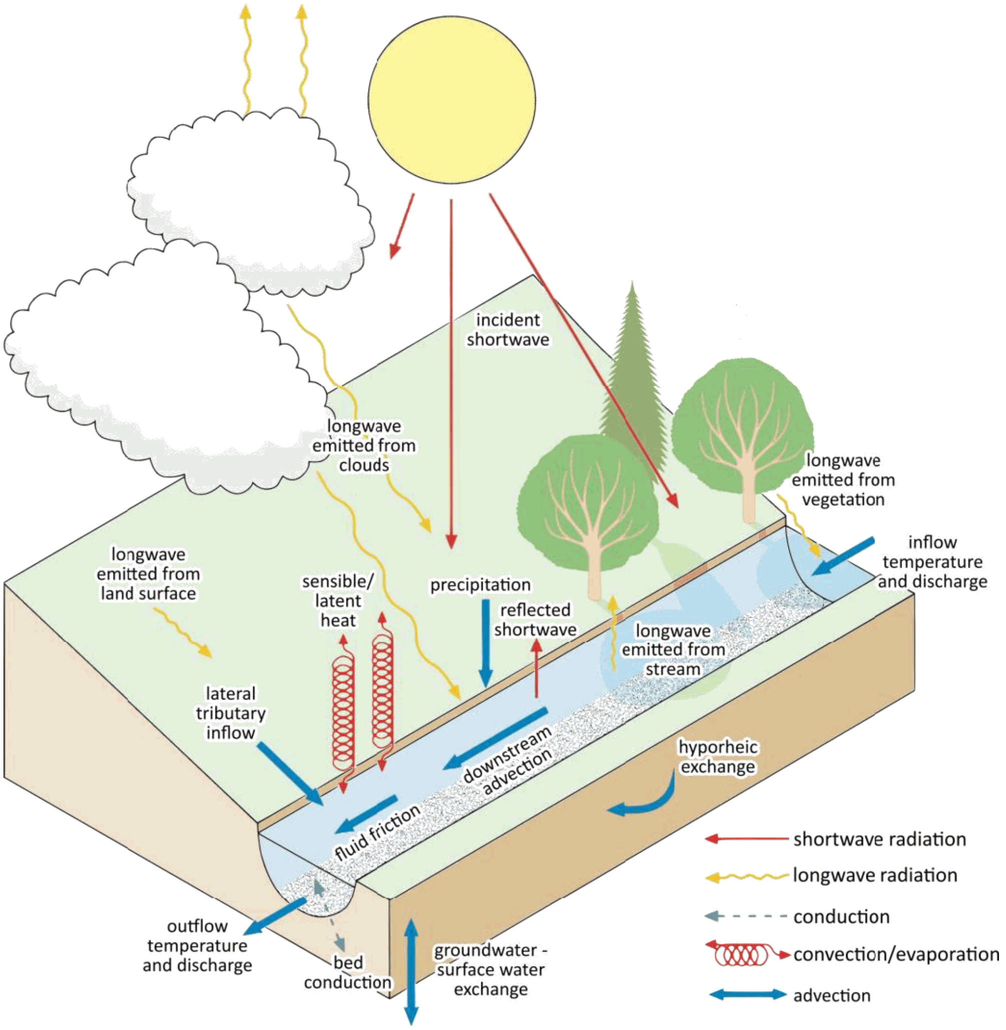


Figure 2. Energy and hydrological exchanges determining stream temperature (from Dugdale et al. 2017, modified from Hannah et al., 2008).

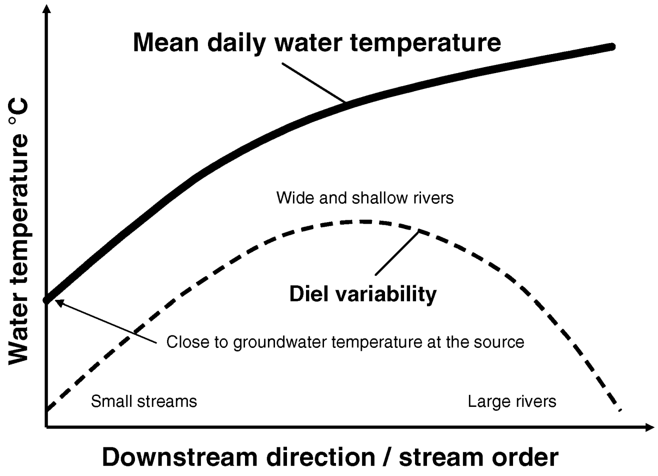


Figure 3. Mean daily and diel variability of water temperatures as a function of stream order/downstream direction for a typical river, not representative of the dam-regulated mainstem Trinity River (from Caissie 2006).

1.2.2 TEMPERATURE EFFECTS ON STREAM BIOTA

Most aquatic species in lotic (flowing) waters are ectotherms, meaning water temperature determines rates of all internal biochemical reactions which in turn affects metabolism, growth, and development. Water temperatures limit the range of species on both broad and finer geographic and temporal scales and can affect species composition (Steel et al. 2017). Salmonids are cold water fish with relatively narrow thermal tolerances that vary by season and life-stage (Beauchamp 2009; Carter 2005). In most fish species, spawning adults and incubating eggs have the narrowest thermal tolerances and are therefore the most vulnerable to climate change (Dahlke 2020). The importance of water temperature to salmonids is well recognized in the foundational documents of the TRRP and was expanded upon in the Integrated Assessment Plan (IAP):

> *"Temperature influences the immigration behavior of adults and viability of their gametes, fry emergence timing, virulence of fish diseases, strength of fish immune response, and growth of post emergent fish (Rich 1987; Boles 1988; Armor 1991). Temperature provides emigration cues, affects the smoltification process, and influences the size that fish attain prior to leaving the Trinity River basin for the ocean (Folmar and Dickhoff 1980; Wedemeyer et al. 1980; Rich 1987; Hoar 1988). Improving thermal regimes for freshwater life stages of anadromous salmonids will minimize pre-spawn mortality, maximize egg viability, reduce mortality of freshwater life history stages, and optimize growth and smoltification` for ocean survival. … The condition of smolts as they enter the ocean influences their survival to later life stages; studies have documented the [positive] relationship between size of smolts entering the ocean and survival to adults (Unwin and Glova 1997; Jokikokko et al. 2006)" (TRRP and ESSA 2009).*

Carter (2005) detailed the thermal requirements of all life stages of native salmonid species present in the Klamath Basin, based on a review of global scientific literature because basin-specific studies are limited. A recent laboratory study comparing Trinity River Hatchery fall-run Chinook Salmon to five other Western U.S. hatchery stocks found local adaptation among stocks to both temperature effects on metabolic rates and thermal tolerance (Zillig et al. 2023), suggesting examination of historic conditions, as well as current conditions, may be important when considering management actions to promote proliferation of locally adapted stock. Salmonids are stenothermic organisms and are evolved to survive over a relatively small range of temperatures, with the egg incubation stage being the most limiting. Salmonid temperature requirements vary slightly between the native species of the Trinity River, but in general high survival occurs from 6 – 10 °C for incubating salmonid eggs (Carter 2005). Rearing juvenile salmonids exhibit accelerated growth between temperatures of 10–19 °C, with the highest growth rates occurring near the high end of the range under high ration, and growth going to zero (or negative) below 5 °C for any rate of consumption (Figure B87). Returning adults will migrate upstream in temperatures up to 21 °C but prefer to hold in temperatures from 8–16 °C. Adults spawn in temperatures from 4.5–14 °C. Lethal limits of temperatures for salmonids are 24–25 °C for 50% mortality (Carter 2005).

Besides salmonids, other resident ectotherms can be negatively affected by regulated thermal regimes that are unnaturally cold. For example, summer temperature suppression has altered phenology and reduced survival and reproductive success of Foothill Yellow-Legged Frogs on the Trinity River (Wheeler et al. 2015, 2018; Railsback et al. 2016). Impacts to reproduction and development associated with Foothill Yellow-Legged Frogs also negatively impacts Western Pond Turtle populations that are smaller in the regulated mainstem Trinity River than the unregulated South Fork Trinity River (Ashton et al. 2015, Snover et al. 2015). These types of impacts likely also extend to many ectothermic species that comprise primary and secondary production which underpins the biological productivity of the Trinity River. For example, the time needed for mayfly larval development is inversely related to temperature, increasing from 45 days at 20 °C to 179 days at 10 °C (Sweeney and Vannote 1984). Because mayflies compose a large percentage of diet for juvenile steelhead in the Trinity River (Boles 1990), their suppression by cold water may negatively affect food availability and ration which affects fish growth. However, cold water can benefit salmonids by altering the metabolic rates and phenology of disease-causing organisms such as bacteria, trematodes (Schaaf et al. 2017, 2018), protozoans, including *Ichthyophthirius multifiliis* (Howell et al. 2019), and myxozoans, including *Ceratonova shasta* which is a prevalent parasite of juvenile Chinook Salmon in the Klamath River (Ray et al., 2012).

The complex interactions of the riverine community and the response to changes in thermal regime make managing for the system as a whole a difficult challenge. Understanding how the natural environment provided for the diversity of stream biota may offer some insight to managers. Lotic systems can offer substantial thermal diversity, allowing for micro-habitat selection by organisms to exploit thermal refugia (Brewitt et al. 2017; Sutton and Soto 2012). In lotic ecosystems, thermal refugia are created by thermal gradients in four dimensions; longitudinal, lateral, vertical, and temporal (Ward 1989). Variations in gradients along each axis occurs at multiple scales (e.g., diel and annual) and interact with each other to provide a mosaic of thermal habitats that comprise the thermal landscape and support the riverine ecosystem (Steel et al. 2017). Below dams, the effectiveness of managing water resources to meet thermal requirements for a diverse aquatic ecosystem community is complicated by the reduced geographic extent and range of elevations available, as well as constraints on the diversity of water temperatures available for release. These limitations can compress the range of, or space over which, gradients in water temperature are available to aquatic organisms (Olden and Naiman 2010). The specifics of these effects are explored in following sections of this report. Current management is the result of the best science available, but can be inhibited by administrative, legal, infrastructure and policy constraints. It remains unclear if the current infrastructure and available management mechanisms can provide the thermal landscape sufficient for recovery of the productive ecosystem historically present on the Trinity River.

1.3 OVERVIEW OF THE TRINITY RIVER WATERSHED

The Trinity River is the largest tributary to the Klamath River, draining approximately 2969 mi^2 (7,690 km^2) in northwestern California. The watershed is in a sparsely populated and mountainous area with elevations ranging between 300 ft (90 m) at the confluence with the Klamath River to more than 9000ft (2740 m) in the Trinity Alps (GMA 2001). The Trinity River drains the southern slopes of the Scott Mountains, Salmon Mountains, and Trinity Alps, which comprise the southern portion of the Klamath Mountain Province. The climate is characterized by dry summers and wet winters. High-elevation headwater areas typically accumulate a deep winter snowpack that occasionally contributes to large, short-duration floods when warm Pacific storms produce intense rain-on-snow events in a weather pattern locally known as the pineapple express.

Significant placer gold deposits occur throughout the watershed in Quaternary alluvial deposits and Pleistocene terraces, as well as in the Weaverville Formation, a fluvial gold bearing formation likely deposited during the Oligocene (Anderson 2008). Consequently, the Trinity

River and surrounding areas were massively disturbed by gold mining and other human activities beginning in the mid-1800s. Mining activities in the second half of the 19th century included hydraulic cannons to placer mine entire mountain sides, inundating the main valleys with large quantities of sediment. Upslope hydraulic mining continued well into the 20th century, while the valley floors were being excavated and inverted by dredge mining. Extensive timber harvesting that began in the second half of the 19th century and continuing into the 1980s also contributed to high sediment production rates.

In 1955 the United States Congress authorized construction of the Trinity River Diversion (TRD) to divert water from the Trinity River Basin in Northern California to the Sacramento River Basin and California's Central Valley. The system includes two dams: Lewiston Dam, located 112 miles (180 km) upstream of the Trinity River's confluence with the Klamath River, and Trinity Dam located 8 miles (13 km) farther upstream. Trinity Dam impounds a large storage reservoir, whereas Lewiston Dam is smaller and was built to regulate the releases into the Trinity River and the diversion to the Central Valley. Construction of the dams and diversion infrastructure was completed in 1963, after which up to 90% of the runoff from upstream of the dams was diverted to the Central Valley for the next decade.

1.4 TRINITY RIVER RESTORATION

Despite mining and other human impacts, the pre-dam Trinity River supported a commercial salmon and steelhead fishery (Moffett and Smith 1950) that declined precipitously after less than a decade of regulated flow (USFWS and HVT 1999). By the 1970s it was recognized that an increase in the annual release volume was necessary to recover anadromous fish populations in the river.

To that end, the Bureau of Reclamation (Reclamation), the U.S. Fish and Wildlife Service (USFWS), and the California Department of Fish and Game (CDFG) formed the Trinity River Task Force in 1971 to study the basin's fish and wildlife issues and prepare a plan for identification and mitigation of problems. Membership in the Trinity River Fishery Restoration Task Force included the U.S. Bureau of Indian Affairs, the California Department of Water Resources, Trinity County, Humboldt County, the Hoopa Valley Tribe, the Yurok Tribe, the U.S. Forest Service, the Bureau of Land Management, the U.S. Soil Conservation Service, the National Marine Fisheries Service (NMFS), the California Department of Forestry and Fire Protection, and the State Water Resources Control Board (SWRCB). The Trinity River Task Force sought to optimize Trinity River restoration efforts through the efficient and balanced use of cold-water reserves from Trinity and Lewiston reservoirs.

In 1981, the USFWS and the Water and Power Resources Service of the Central Valley Project entered into an agreement, signed by the Secretary of the Interior, to work cooperatively to halt further fishery declines and to begin an effective restoration program. The agreement also recognized the need for the completion of a Fish and Wildlife Management Plan and its implementation to successfully restore the anadromous resources of the Trinity River Basin. As a result, the Trinity River Restoration Act of 1984 (P.L. 98-541) authorized the Secretary of the Interior to formulate and implement a management program to restore fish and wildlife populations in the Trinity River Basin, and in 1985 Reclamation entered into a cooperative agreement with the CDFG, USFWS, and the NMFS to coordinate the operations of the TRD that impact fishery resources. The agencies attempted to establish the timing and proportion of inflow for releases from Trinity Dam and Lewiston Dam that would most efficiently utilize the cold water reserves available for use by the anadromous fishery. In recognizing the problem of balancing the needs to sustain the fishery resources in the Trinity River and the uses outside of the basin for water and power, flow allocations were established for normal, dry, and critically dry years for an evaluation period of twelve years. At the end of the evaluation period, the agreement called for the USFWS to submit a report to the Secretary of the Interior summarizing the effectiveness of restoration of flows and recommended an appropriate course of action for future management of Trinity River flows.

However, to protect adults, eggs, and embryos, of salmonids from high temperatures, the SWRCB issued Order WR 90-05 on May 5, 1990, which set terms and conditions for fishery protection and a schedule for completion of tasks associated with water rights permits, licenses, permitted applications and licensed applications for Reclamation's Central Valley Project. Due to Order WR 90-05 and successive years of dry-weather conditions between 1985 and 1990, and subsequent release of reduced flows to the Trinity River, the Secretary of the Interior amended the 1981 agreement to provide increased flows (equaling ~28% of annual inflow) to the Trinity River in 1991. The twelve-year evaluation period of Trinity River flows began in 1985 and ended in 1997 and resulted in the Trinity River Flow Evaluation Study Final Report (USFWS and HVT 1999).

In December of 2000, the Secretary of the Interior signed the Trinity River Record of Decision (ROD; USDOI 2000) dedicating 47% of inflow above the water project to environmental flow releases and establishing the Trinity River Restoration Program (TRRP) to implement the restoration strategy outlined in the Trinity River Flow Evaluation Study (USFWS and HVT 1999). That strategy incorporates five primary components: variable flow releases from Lewiston Dam for five water year types to drive geomorphic processes and maintain physical habitats, gravel augmentation to mitigate for the loss of coarse sediment trapped behind the dams, upland watershed restoration to manage fine sediment production, mechanical channel rehabilitation to accelerate physical habitat creation, and an adaptive management framework for applying monitoring results to guide future management decisions.

1.4.1 TEMPERATURE OBJECTIVES

Annual flow releases recommended to Reclamation by the TRRP are designed to provide improved physical habitat conditions in the river as well as provide suitable temperature regimes for anadromous salmonids. These include temperature thresholds protective of adult salmonids, eggs, and embryos that were established for the upper Trinity River by SWRCB Order WR 90-5 for Sept 15 – Dec 31, expanded in the 1993 SWRCB Water Quality Control Plan for the North Coast Region to include July 1 – Sept 14, and eventually adopted by the 2000 ROD. An additional set of objectives associated with juvenile salmonid outmigration and smoltification, originally proposed by the USFWS (Zedonis and Newcomb 1997) was also adopted by the 2000 ROD. The juvenile outmigration and smoltification criteria apply to the lower Trinity River at Weitchpec and vary by species, date, and water year type. All Trinity River temperature criteria are discussed in detail below in Section 4.1.1.

Table 1. Water temperature thresholds for adult salmonids, eggs, and embryos that were adopted by the 2000 ROD. Table values are daily averages not to be exceeded.

Date	Douglas City (RM 93.8)	North Fork Trinity River (RM 72.4)
*July 1 through Sept 14	60 °F (15.6 °C)	-
Sept 15 through Sept 30	56 °F (13.3 °C)	-
Oct 1 through Dec 31	-	56 °F (13.3 °C)

*Note: This was not established by SWRCB Order WR 90-05, but instead first appeared in the 1993 SWRCB Water Quality Control Plan for the North Coast Region, Interim Action Plan for the Trinity River, and was subsequently adopted in the 2000 ROD.

Table 2. Temperature thresholds for outmigration in the lower Trinity River from USFWS and HVT (1999).

Species and Date	Temperature Threshold
Steelhead (May 22)	<55.4 °F (13.0 °C) in Extremely Wet, Wet, Normal water years @ Weitchpec <59 °F (15.0 °C) in Dry, Critically Dry water years @ Weitchpec
Coho (June 4)	<59 °F (15.0 °C) in Extremely Wet, Wet, Normal water years @ Weitchpec <62.6 °F (17.0 °C) in Dry, Critically Dry water years @ Weitchpec
Chinook (July 9)	<62.6 °F (17.0 °C) in Extremely Wet, Wet, Normal water years @ Weitchpec <68 °F (20.0 °C) in Dry, Critically Dry water years @ Weitchpec

1.4.2 FLOW MANAGEMENT AND HYPOTHESES

The 2000 ROD specified that volume and timing of Lewiston Dam releases would vary by water year type, as defined by the projected annual inflow into Trinity Reservoir (US DOI 2000) (Figure 4, Table 3). These releases were specified in cubic feet per second (cfs) and designed to meet a variety of objectives including water temperature management.

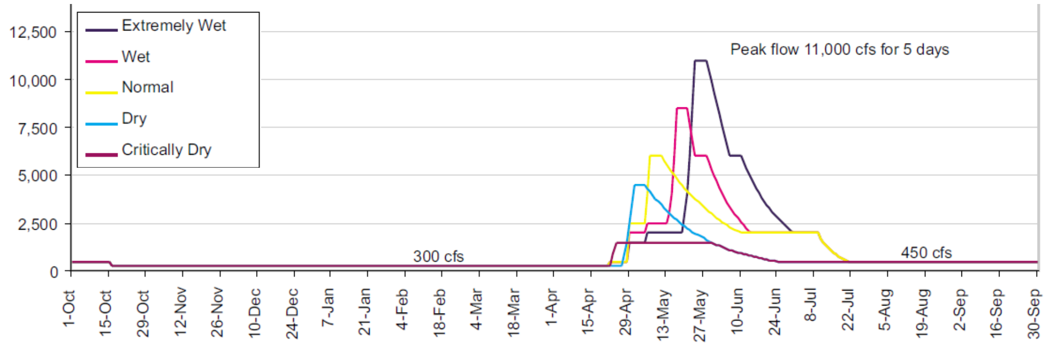


Figure 4. Releases from Lewiston Dam into the Trinity River proposed in the ROD by water year. Figure from USFWS et al. (2000).

Table 3. Annual flow releases from Lewiston Dam specified in the Trinity River Record of Decision for each water year types. Table adapted from USDOI (2000).

Water-year type	Flow volume (Acre-feet)	Peak flow (cfs)
Critically Dry	369,000	1,500
Dry	453,000	4,500
Normal	647,000	6,000
Wet	701,000	8,500
Extremely Wet	815,000	11,000

Hypotheses were developed in the Trinity River Flow Evaluation Report regarding how the Trinity River was impacted by dam construction and operation, and what could be done to reduce those impacts (Appendix O in USFWS and HVT, 1999). The hypotheses were organized into five sections: Winter Baseflow (October 16 to April 22–May 17), Fall/Winter Flood Flows, Ascending Limb of Snowmelt Peak (April 22 – May 24), Snowmelt Peak Flow (April 24–May 29), Descending Limb of Snowmelt Peak (May 5 – July 22), and Summer/Fall Baseflow (June 26 – October 15). We list the temperature-related hypotheses in the following sections so readers can understand the scientific context for the development of the ROD flow regime. In Section 7.1, we then use our findings to evaluate these hypotheses in light of our findings.

1.4.2.1 ASCENDING LIMB OF SNOWMELT PEAK FLOW (APRIL 22 TO MAY 24)

Temperature-related hypotheses in Appendix O in USFWS and HVT (1999) regarding the ascending limb were:

- “There are no substantial negative biological impacts associated with the timing of annual peak releases.”
- “The timing of the ascending-limb releases is optimal for anadromous fish species.

A competing hypothesis was “Timing and rate of Lewiston release up-ramp will substantially impact early life stage of anadromous salmonids (eggs, sac fry, fry) as well as amphibians and other wildlife species.”

1.4.2.2 DESCENDING LIMB OF SNOWMELT PEAK (MAY 5 TO JULY 22)

Temperature-related hypotheses in Appendix O in USFWS and HVT (1999) regarding the descending limb were:

- “Releases during this period can be used to control water temperatures between Lewiston Dam and Weitchpec within limits optimal for anadromous salmonids. Maintaining water temperatures near optimal levels will increase juvenile salmonid growth rates, increasing survival and production. Also, optimal water temperatures for outmigrating smolts will significantly increase total habitat for juvenile steelhead and coho salmon rearing in habitats throughout the mainstem”
- “Gradually decreasing flow releases, timed with increasing ambient air temperatures, causes mainstem temperatures to rise gradually throughout this period, initiating smolting. Gradually increasing water temperatures also encourages yellow-legged frogs to lay eggs, and increases tadpole growth rates”
- “Gradually decreasing flow releases, timed with increasing ambient air temperatures, causes mainstem temperatures to rise gradually throughout this period encouraging upstream migration of adult spring Chinook Salmon”

Thresholds for marginal and optimal water temperatures for anadromous salmonid life stages in the Trinity River were assumed based on values derived in other watersheds. Proposed management actions included assessing fish growth as a function of water temperature. The following were listed as temperature-related assumptions that should be tested:

- “Smolt survival in the Trinity and Lower Klamath River will increase as a result of better temperature conditions that promote smoltification”
- “Temperatures profiles throughout the River will be appropriate for locally adapted fish stocks.”
- “Temperature-control release requirements will not be appreciably different with temperature-control devices installed at Trinity Dam (i.e., a multi-level outlet structure).”
- “What are the thermal tolerances of Trinity River smolts? Test: Under controlled and natural setting, examine how water temperature affects smoltification of Trinity River parr and smolts.”
- “How does Trinity River water affect the water quality of the Klamath River? There is evidence that water quality conditions in the Klamath River may get really poor. Does this occur during spring outmigration, especially in Dry water years? If so, how is this affecting smolt survival? What about other life stages?”

While it is not included in the hypothesis in Appendix O, Chapter 5 of USFWS and HVT (1999) states:

> “Additionally, examination of water temperatures before and after construction of the TRD show *that spring and early summer water temperatures have become warmer throughout the Trinity River* as a result of storage/diversion of snowmelt runoff from the watershed above Trinity Dam (see Section 4.3.6). Increasing dam releases during the spring and early summer can improve or restore temperature conditions in the river that promote better growing conditions and smolt survival.” [*emphasis added*]

The cited Section 4.3.6 of USFWS and HVT (1999) does not provide documentation to support the claim that the Trinity River has become warmer in spring and early summer since construction of the TRD.

1.4.2.3 SUMMER/FALL BASEFLOW (JUNE 26 TO OCTOBER 15)

Temperature-related hypotheses in Appendix O in USFWS and HVT (1999) regarding summer/fall baseflow were:

- "If water temperatures less than 60° F downstream of Douglas City (June 26–October 15), then no temperature-related mortality will occur to adult spring Chinook Salmon and impacts to spring Chinook Salmon eggs developing *en vivo* will be negligible."
- "If water temperatures are near optimal, then juvenile salmon and steelhead growth rates and size at age will increase, increasing smolt-to-adult success."
- "Lewiston releases of 450 cfs for temperature needs will provide a greater benefit to adult spring Chinook Salmon, juvenile Coho Salmon, and juvenile steelhead, than the benefits associated with release of 300 cfs."

A potential competing hypothesis was "Reducing Lewiston releases below summer low flows will cause pools to stratify, providing optimal water temperatures in bottoms of deep pools." Unknowns listed include: 1) what Lewiston releases would lead to thermal stratification of pools above the North Fork, 2) what were summer temperatures used by holding spring Chinook Salmon prior to dam construction, 3) what temperatures are necessary for protections of various stages of Trinity River anadromous fishes, including spring-run Chinook Salmon, and 4) how will temperatures affect amphibians? Items listed as "What we know" included that empirical evidence indicates that Lewiston releases of 450 cfs will meet temperature targets at Douglas City and North Fork.

2 DATA AND METHODS

2.1 AVAILABLE DATA AND REPORTS

In the process of preparing this document, we reviewed a large number of previous reports relevant to Trinity River temperature dynamics. We reviewed reports from the 1950s prior to dam removal, data and modeling reports from the 1970s to the 1990s, reports generated during the development of USFWS and HVT (1999), and numerous reports developed during implementation of the TRRP. We gathered data from sources such as the U.S. Fish and Wildlife Service (USFWS), U.S. Forest Service (USFS), U.S. Geological Survey (USGS), California Data Exchange Center (CDEC), Reclamation, Yurok Tribe, Hoopa Valley Tribe, and several others. For a complete description of available data, reports, and sources see Appendix A. We compiled the stream temperature data from 252 sites at their original temporal resolution (sub-hourly to daily) into a database with 396,172 daily values, derived from 13 million original measurements, that is available for future use. The compiled period of record and data source for each mainstem Trinity River site is shown in Figure 5. Appendix A provides similar figures for tributaries and Klamath River sites.

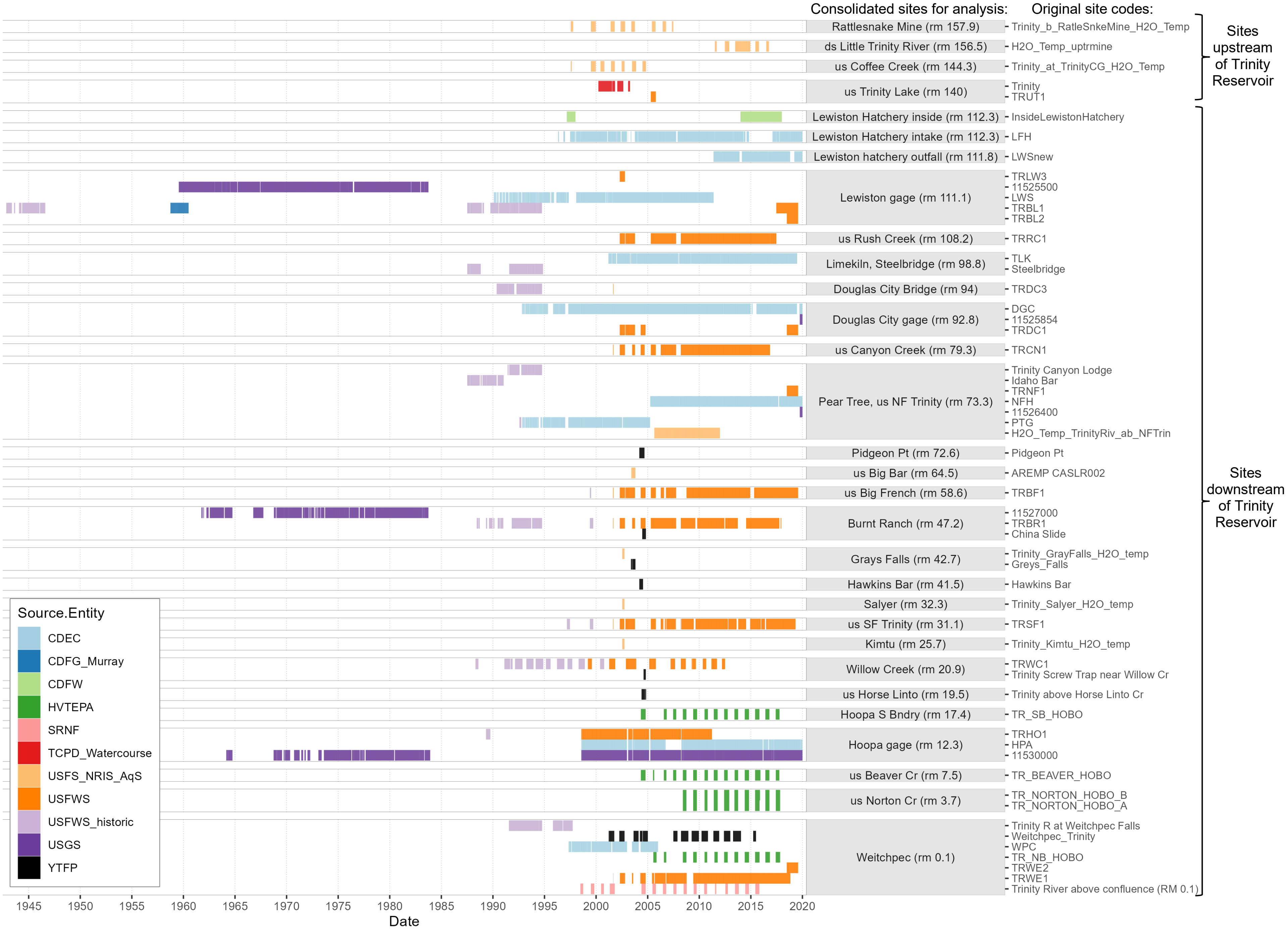


Figure 5. Sources, sites, and dates of mainstem Trinity River water temperature data compiled for use in this project, 1942–2020. us = upstream, rm = river mile.

2.2 AVAILABLE TEMPERATURE MODELS

Several temperature simulation models have been previously applied to the Trinity River and its reservoirs. USBR Central Valley Operations (CVO) currently simulates water temperatures in Trinity and Lewiston reservoirs using numerical models (Wittler 2010, CDWR and USBR 2016) including: 1) Reclamation's Temperature Model (RTM) which simulates monthly mean vertical temperature profiles and release temperatures for Trinity Reservoir and other Central Valley Project (CVP) reservoirs (USBR 2008), and 2) the upper Sacramento River Water Quality Model (RMA 2003) which simulates mean daily water temperatures for Trinity Reservoir, Lewiston Reservoir, and the Trinity River (USBR 2008). Reservoir models no longer in use include HEC (Rowell 1990), WQRRS (Deas 1999), and Box Exchange Transport Temperature and Ecology of Reservoirs (BETTER) (JSA 1992; Kamman 1999a, 1999b; USFWS et al. 2000).

TRRP currently uses the River Basin Model-10 (RBM10) model to simulate daily average river temperatures downstream from Lewiston Dam to the confluence of the Klamath and Trinity Rivers, and from Iron Gate Dam on the Klamath River downstream to the mouth of the Klamath River (Perry et al. 2011, Jones et al. 2016). The model uses a simple equilibrium flow model, instantly transmitting river flow downstream through each river segment each day. It uses a heat budget to calculate flux across the air-water interface, using inputs derived from gridded meteorological datasets. Model boundary conditions include flow and temperature for the Trinity River at Lewiston Dam and 14 tributaries to the Trinity River. In cross-validation of RBM10 predictions, root mean square error for eight Trinity River reaches ranged from 0.24 to 1.11 °C (Jones et al. 2016). Previous Trinity River models no longer actively used include the weekly average Stream Network Temperature Model (SNTEMP) (Zedonis 1996, Zedonis and Newcomb 1997) that was used for the Trinity River Flow Evaluation Study (USFWS and HVT 1999), and the hourly RMA-2/RMA-11 (Watercourse Engineering 2007, Sogutlugil 2012, Sogutlugil and Deas 2012).

Original modeling in this report primarily uses RBM10 (Section 2.3.3). In addition, we also apply the U.S. Bureau of Reclamation's Sedimentation and River Hydraulics (SRH-2D) two-dimensional, depth averaged hydraulic model (Bradley 2016) to evaluate lateral thermal diversity in the Oregon Gulch reach of the Trinity River (Section 5.1.4.1). Additional details on the history of models used for Trinity Reservoir, Lewiston Reservoir, the Trinity River, and Klamath River is provided in Section A.2 in Appendix A.

2.3 ANALYTICAL METHODS

In this section, we provide an overview of the analytical tools used in this report. In addition, we describe some specific applications, such as filling gaps and extending a period of record, that are not very instructive for their own sake but are used in support of other analyses. In other sections of the report (e.g., Section 3 and 4), we include descriptions of methods "of interest", immediately followed by the results of that analysis. For example, developing the unimpaired flow scenario for the Trinity River at Lewiston is a key piece of the report so is described in Section 3 rather than in this methods section.

2.3.1 STATISTICAL

To quantify the relationships between variables (e.g., the influence of streamflow or reservoir level on water temperatures) as well as fill gaps in data records, we used several statistical tools including linear regression, linear mixed effects models, and generalized additive models. All statistical models were developed in R version 4.01 (R Core Team 2020) using various packages, as described below. For a thorough description of our analysis methods, refer to Appendix B.

2.3.2 FILLING GAPS IN LEWISTON WATER TEMPERATURE RECORD

We filled gaps in Trinity River at Lewison temperatures using two methods. During a six-year gap in the years 2011–2017 caused by gage relocation, our estimates of daily minimum, mean, maximum temperatures based primarily on hatchery inflow temperatures were highly accurate (0.1–0.3 °C), so we treated them equally to measured data for most purposes in this report (Section 2.3.2.1). Our estimates filling shorter gaps in daily mean temperatures in other years based on multiple variables including reservoir dynamics were less accurate (0.88 °C), so we used them only for analyses requiring gap-free time series (i.e., RBM10 modeling) (Section 2.3.2.2). For future use, we provide these gap-filled temperature data in Electronic Appendix 4.

2.3.2.1 GAPS DUE TO GAGE RELOCATION

On May 22, 2011, the CDEC LWS (Trinity River below Lewiston) station was moved upstream approximately 3400 feet to a new location near the outfall of Trinity River Hatchery. Unfortunately, due to influence of hatchery outfall, the temperature signal changed substantially after relocation, rendering it not comparable with the previous data (Figure 6). Summer temperatures (especially daily maximum) were up to 3–4 °C greater post-relocation, and winter temperatures were also sometimes warmer. We assigned a new site code LWSnew to the post-relocation data and do not use those data for any analyses. This caused a six-year gap in the temperature record for this critically important location until USFWS began deploying a temperature probe at the old location in June 2017. Given the unique conditions that occurred during this period including the 2013–2015 drought and associated reservoir drawdown, we invested significant time to fill this gap, as well as additional shorter gaps in the 1996–2019 time period, as accurately as possible using the best available information– the CDEC LFH (Lewiston Fish Hatchery intake) station and CDFW's temperatures manually measured twice-daily inside the hatchery (Section A.5.1 in Appendix A). We first filled gaps in the LFH record with simple linear regression of the CDFW hatchery temperatures, with a separate model developed for each metric (daily minimum, daily mean, and daily maximum). The relationships between LFH and LWS temperatures are not entirely linear (particularly for daily minimums and daily maximums), so we used generalized additive models (GAMs) to predict daily LWS temperatures as function of LFH temperature, flow at USGS gage 11525500, day of the year, and an autocorrelation term, with a separate model developed for each metric. Not all models included all terms, and a final model for each parameter was selected based on professional judgement, informed by AIC and graphical review of outputs. Predictions were validated against the 2017–2019 USFWS data for TRBL1 (located at the long-term LWS site) and show excellent accuracy, with root mean squared error of 0.1–0.3 °C (Table B18). As a post-processing step, we set any daily maximum that was less than daily mean to the daily mean and set any daily minimum that was greater than daily mean to the daily mean. We use the predicted data only on days when good measured Lewiston data are not available, namely 904 days (in 2014–2017) based on the CDFW hatchery data and 1468 days (in 1997–2017, primarily in 1997, 2011–2014, and 2017) based on the LFH data.

Future users wishing to fill additional older gaps in the Lewiston record (most notably 10/1/1984–9/8/1987) could potentially use the 1960–1990 data that was transcribed from the hatchery logs for use in the BETTER model (Sections A.2.1 and A.5.1 in Appendix A), although the relationship between hatchery temperatures and river temperatures may be different (and presumably weaker) during those older decades than in recent decades, due to lower warm-season flows through the Lewiston Reservoir and changes to Lewiston Reservoir thermal curtains.

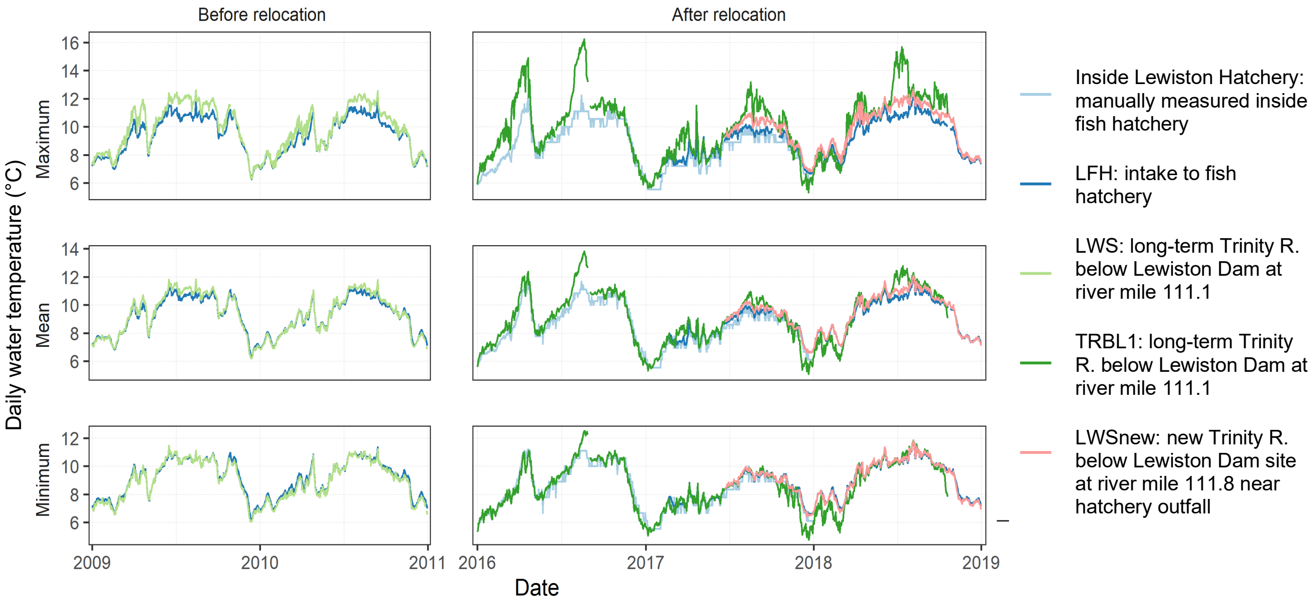


Figure 6. Comparison of daily water temperatures at sites near Lewiston Dam for example years before and after the May 22, 2011 relocation of station LWS upstream to a new location (LWSnew) influenced by the hatchery outfall and not representative of true river temperatures (i.e., daily max temperatures much higher at LWSnew than TRBL1 in summers 2017–2018). Instead of using the LWSnew data for analyses, we estimated river temperatures from data collected at LFH and Inside Lewiston Hatchery.

2.3.2.2 OTHER GAPS

To fill other gaps in the daily mean Lewiston temperature records, primarily 10/1/1984–9/8/1987 but also shorter gaps in other years, we used a generalized additive model (GAM). We experimented with several configurations of model variables and structures before selecting a final model that uses a 7-day trailing average of mean air temperature, daily combined outflow from Lewiston Reservoir (i.e., sum of USGS gages at Lewiston and Carr Powerhouse), an interaction between day of the year and Trinity Reservoir storage, and an AR-1 autocorrelation term. We used thin-plate spline smoothers for all model variables except day of the year for which we used a cyclic cubic regression spline to force a smooth transition between December and January. To avoid overfitting, all splines were limited to five knots except Trinity Reservoir storage which was limited to four knots. Following guidance from Baayen et al. (2018), we initially fit a model without the autocorrelation term, then re-ran the model with the autocorrelation term assigned a rho value based on the lag 1 autocorrelation (0.905) from the residuals of the initial model. Even after including the autocorrelation term, there was still some residual autocorrelation (lag 1 autocorrelation was 0.25). We validated the model using leave-one-year-out cross-validation, yielding an RMSE of 0.88 °C and R^2 of 0.67 (Figure B85 in Appendix B).

2.3.3 MODELING

We used the Klamath-Trinity RBM10 model[1] to compare river temperature between various scenarios (Table 4) for every day from January 1, 1980 to December 31, 2018. Section A.2.2

---

[1] https://sites.google.com/site/klamathtrinityinterfacehelp/

provides a brief overview of the RBM10 model (Perry et al. 2011, Jones et al. 2016). We primarily used RBM10 version 1.7.2, except for Section 3.4.6 (RBM10 version 1.7.4) and Section 5.1.2.2 (RBM10 version 1.7.5).

For the analyses of lateral thermal diversity in the Oregon Gulch reach of the Trinity River in Section 5.1.4.1, we used the U.S. Bureau of Reclamation's Sedimentation and River Hydraulics (SRH-2D) two-dimensional, depth averaged hydraulic model. The model solves the depth-integrated, dynamic wave approximation of the Navier-Stokes fluid flow equations with a finite-volume numerical method (Bradley 2016).

2.3.3.1 IMPROVEMENTS TO RBM10 MODEL BOUNDARY CONDITIONS

The RBM10 model interface is designed to allow users to easily be able to run their own scenarios (e.g., changes in dam releases, etc.) by loading a delimited text file with the boundary conditions for the scenario(s), consisting of the flow and temperature for the Trinity River at Lewiston Dam and 14 other tributaries. Prior to running scenarios, we improved the baseline ("historical" in RBM10 terminology) scenario by developing a new set of boundary conditions.

We compiled our own more complete set of measured temperature data (Section A.3 in Appendix A) for the Trinity River at Lewiston and the 14 tributaries. Sites with large increases in the amount of data include Rush Creek, New River, and North Fork Trinity River, with lesser gains in South Fork Trinity River, Willow Creek, Canyon Creek, and Indian Creek. Most New River temperature data used by Jones et al. (2016) is from USFS site "H2O_Temp_new1" in the river's middle reach (drainage area [DA] 342 km2) rather than the mouth (DA 605 km2); we had enough additional data to exclude this site and rely solely on lower New River data. Browns Creek is the only tributary where we use data not collected near the tributary's mouth (DA 191 km2) but rather 7 km upstream (DA 147 km2), the same data used by Jones et al. (2016). After completing the modeling, we realized that we could have also added summer 2011–2014 data from WRTC's Browns Creek site near B-Bar-K Bridge located only 2.5 km from the mouth (Section A.3.14.4 in Appendix A), previously compiled by Asarian (2016). WRTC has continued to collect data in additional years including 2018–2021.

After compiling the measured temperature data, we filled gaps in the records using methods that improve upon those used in the official RBM10 model (Jones et al. 2016). The most important of these gaps was the 2011–present data for Lewiston, where the gage had been relocated into the influence of the hatchery outfall so was no longer representative of well-mixed river conditions and we did not feel comfortable using it. We used regression with two hatchery temperature sites to fill this gap for 2011 until 2017 when USFWS resumed monitoring at the previous location (Section 2.3.2). The official version of RBM10 adapted the Mohseni et al. (1998) method of using non-linear regressions between water temperature and air temperature to fill all tributary temperature gaps including Lewiston, with a separate model used for the first and second half of the year to account for hysteresis (Jones et al. 2016). Our explorations of measured data in many tributaries indicated temperatures during spring runoff (April–July) were much cooler (up to approximately 5 °C) in wetter years than drier years (Section 3.2), so we developed GAM models to fill stream temperature gaps using air temperature, flow, and day of year (Section B.8 in Appendix B). In addition, previous research and our explorations indicated that Lewiston Reservoir temperatures were affected not just by air temperature, but also Trinity Reservoir water storage, day of year, and flow through Lewiston Reservoir (Section 3.3.2.2), so we developed GAM models using those variables to fill gaps in Lewiston temperatures (Section 2.3.2). The gaps we filled at the 14 tributary sites ranged in duration from days to decades while the gaps we filled at Lewiston ranged from days to several years. We used air temperature from

PRISM which does not start until 1981, so we retained the original RBM10 boundary conditions for all sites for 1980.

We also developed a slightly different method for generating tributary flows. Our method for tributary flows will not necessarily improve prediction of mainstem temperatures (or if it does, improvements will be limited in magnitude and duration), but instead is targeted at producing tributary hydrographs that are more realistic (i.e., less noise and artifacts) which should improve gap-filling of tributary temperatures (Section B.8 in Appendix B). Jones et al. (2016) used daily difference in flow between the Lewiston and Hoopa USGS gages to calculate a total tributary flow which was then apportioned among the 14 tributaries according to their watershed areas. Due to the real-life travel time of water between Lewiston and Hoopa (Section C.2 in Appendix C) when Lewiston flows are ramped up dramatically (or occasionally naturally due to precipitation-driven fluctuation), this causes differences between gages to be negative, which results in negative tributary flows in the RBM10 model. We use several refinements to improve the accuracy of the resulting flows and eliminate the negative values. First, since the South Fork Trinity River has its own long-term USGS flow gage which operated during the entire 1980–2018 period, we deduct the flow of that gage from the Lewiston to Hoopa flows as well as take that gage's watershed area into account when apportioning the flow among tributaries. Second, we calculate a 3-day moving average of gaged flow prior to taking the difference between gages, which reduces some random "noise" due to minor measurement errors, adapting an approach used in many Klamath River studies including PacifiCorp (2004) and Asarian and Kann (2013). Third, to partially offset some of the travel time between Lewiston and Hoopa, we use the prior day's flow at Hoopa rather than the current day's flow. Fourth, prior to apportioning the flow among tributaries by watershed area, if the flow is less than 56 cfs we set it at 56 cfs, based on an area-based extrapolation of gaged tributary flows during the peak of the 2013–2015 drought, when the lowest daily combined flows for the USGS gages for Indian Creek, North Fork Trinity River, and Rush Creek were 10.49 cfs, occurring in late September 2014. These three gages have a combined watershed area of 540.1 km^2, which is 20.7% of the total 3451.9[2] ungaged area from Lewiston to Hoopa (excluding South Fork Trinity and Grass Valley Creek because they are gaged separately). Dividing 10.49 cfs by 0.1564 yields 67.07 cfs, plus 5.26 cfs for Grass Valley Creek[2] is a total of 72 cfs. Unfortunately, our initial calculations used the wrong value for the ungaged drainage area, erroneously resulting in flow of 56 cfs (not 72 cfs) which we used for all analyses in this report. Since flows less than 56 cfs occurred on only 65 of 19,815 (0.3%) days in 1980–2018, and 56 cfs is relatively close to 72 cfs, this discrepancy is unlikely to meaningfully affect reported results and thus we did not undertake the substantial effort that would have been required to redo all RBM10 modeling in this report after this error was discovered.

We conducted some brief comparisons between measured and RBM10-modeled temperatures at five Trinity River stations spanning from Douglas City to Weitchpec. RMSE was 1.13 °C using the official RBM10 boundary conditions as inputs and 0.92 °C using our improved boundary conditions as inputs, indicating that our updated boundary conditions did improve model performance. These improved boundary conditions have now been provided to USGS and USBR, and a refined version of them will be incorporated into the next update of the Klamath-Trinity RBM10 model, scheduled for public release in 2023.

---

[2] We do not differentiate Grass Valley Creek in our typical calculation of total tributary flow (Hoopa gage minus Lewiston gage minus South Fork Trinity gage yields total tributary flow for the 2698.3 km^2 area). However, we exclude Grass Valley Creek (drainage area 95.4 km^2, with flow of 5.26 cfs in late September 2014) from the area-based extrapolation of minimum flows because its summer base flow is artificially elevated by Buckhorn Dam (Gaeuman 2013) so is not representative of other tributaries.

2.3.3.2 RBM10 SCENARIOS

We ran several RBM10 scenarios for the years 1980–2018, the maximum duration for which the model was available (Table 4). The first is the "historical releases" scenario that uses boundary conditions that are our best representation of observed reality for flow and temperature for each date in that time period, based on the methods described in Section 2.3.3.1. We use the term "historical" not to refer to a specific flow regime or era, but instead simply to mean the past as it occurred. The 1980–2018 period includes portions of the with-dam transitional era (5/1/1978–9/30/1999) and with-dam ROD era (10/1/1999–2019), as defined in Section 2.3.4 below. Other scenarios use different flows and/or temperatures for Lewiston Dam releases but the same temperatures and flows for the 14 primary tributaries between Lewiston Dam and Weitchpec (Table 4).

Table 4. RBM10 water temperature model scenario names and boundary conditions (i.e., model inputs) for Lewiston and tributaries. Numbers in parentheses refer to report section numbers.

Scenario name	Boundary conditions for Lewiston flows	Boundary conditions for Lewiston temperatures	Boundary conditions for Trib. flows	Boundary conditions for Trib. temperatures
Historical releases	Measured at USGS gage	Measured, with gaps filled by statistical model (2.3.2)	Calculated differences between gages (2.3.3.1)	Measured, with gaps filled by statistical model (B.8 in Appendix B)
ROD-specified	Specified by ROD according to water year type and day	Same as historical	Same as historical	Same as historical
Unimpaired flow, unimpaired temperature	No-dam flow regime, from regression of reservoir water balance and above-reservoir flow gage (3.4.1.1)	No-dam thermal regime, from statistical model calibrated to measured pre-dam temperatures (3.4.1.2)	Same as historical	Same as historical
Unimpaired flow, historical temperature	No-dam flow regime, from regression of reservoir water balance and above-reservoir flow gage (3.4.1.1)	Same as historical	Same as historical	Same as historical
300 cfs	350 cfs constant release	Same as historical	Same as historical	Same as historical
350 cfs	350 cfs constant release	Same as historical	Same as historical	Same as historical
450 cfs	450 cfs constant release	Same as historical	Same as historical	Same as historical
500 cfs	500 cfs constant release	Same as historical	Same as historical	Same as historical
1000 cfs	1000 cfs constant release	Same as historical	Same as historical	Same as historical
1500 cfs	1500 cfs constant release	Same as historical	Same as historical	Same as historical
2000 cfs	2000 cfs constant release	Same as historical	Same as historical	Same as historical
3000 cfs	3000 cfs constant release	Same as historical	Same as historical	Same as historical
4000 cfs	4000 cfs constant release	Same as historical	Same as historical	Same as historical

2.3.3.3 RBM10 ISSUES TO BE RESOLVED IN FUTURE MODEL UPDATES

MODEL PREDICTIONS APPEAR IMPLAUSIBLE WHEN LEWISTON RELEASES ARE LESS THAN 350 CFS

Initial examination of outputs of the unimpaired flow/temperature scenario indicated the model was predicting implausibly high temperatures in some reaches during low summer flows, including values as high as 38.8 °C daily average at RM47.6 in the reach spanning from Burnt Ranch to Burnt Ranch Transfer Station. For comparison, the highest daily average temperature measured in the mainstem Trinity River, mouth of South Fork Trinity River, and Klamath River downstream of Orleans are 26.0 °C (July 29, 2009), 27.1 °C (July 25, 2006), and 27.0 °C (July 7 and 8, 1968) respectively. We are unclear on the exact cause of these implausibly high temperatures, except that they only occur during very low flows, from which we assume there is a model calibration issue. One potential explanation is that Jones et al. (2016) states that water temperatures were negatively biased in initial simulations, so an additional calibration parameter was added that scaled the effect of water depth on heat exchange at the water surface. The implausibly high modeled temperatures (substantially above 30 °C) occurred in 2014, 2015, and 2019, which were Dry or Critically Dry years in which unimpaired flows at Lewiston dropped below 60 cfs. No values substantially above 30 °C were predicted on days when unimpaired flows at Lewiston were above 350 cfs. The lowest measured Lewiston releases during the 2001–2013 RBM10 model calibration period were also approximately 350 cfs (Jones et al. 2016). Given the lack of calibration at flows lower than 350 cfs, and the prediction of impossibly high temperatures under the unimpaired flow/temperature scenario on some days when flows were less than 350 cfs, we decided not to use model predictions for the unimpaired flow scenario on days when unimpaired Lewiston flows were less than 350 cfs. We do use model predictions for other scenarios (i.e., that use dam release temperatures rather than unimpaired temperatures) when Lewiston releases were less than 350, such as typical winter flows of 300 cfs. We acknowledge that selecting the flow threshold was a difficult decision and that the 350 cfs threshold might still utilize some potentially erroneous predictions when flows are close to the threshold, but a lower cutoff would have further restricted the seasons where temperatures could be assessed. Modeled temperatures when Lewiston flows are close to 350 cfs should be considered to have greater uncertainty. Based on our recommendations, USBR and USGS are currently updating and recalibrating the RBM10 model to provide accurate predictions with flows much lower than 350 cfs. Once this update is complete, it would be a relatively simple exercise to re-run the unimpaired flow/temperature scenario. The same input files can be re-used, the model just needs to be re-run.

UNDERESTIMATION OF KLAMATH RIVER FLOWS

In the current version of RBM10, Klamath River flows are underestimated because only the largest tributaries are represented. Klamath River flows upstream of the Trinity River confluence are calculated solely as the sum of four USGS flow gages: Klamath River below Iron Gate Dam, Shasta River near Yreka, Scott River near Fort Jones, and Salmon River at Somes Bar (Perry et al. 2011). Flows from many other tributaries are not included. Since temperatures in the Klamath River downstream of the Trinity River confluence are largely determined by the mixing of water from the Klamath and Trinity rivers, this underestimation of Klamath River flow likely affects the accuracy of model predictions downstream of the confluence during periods when the temperatures of the two rivers substantially differ. In particular, in the summer and early fall when the Klamath River is warm and flows are at seasonal lows, this appears to cause RBM10 to overpredict how much the Klamath River is cooled by cold water released from Lewiston Dam to provide flows for the Hoopa Valley Tribe's Boat Dance Ceremony (Section 3.4.6.3) or to improve water quality and reduce transmission of diseases affecting adult salmon in the Lower Klamath River (Section 3.4.6.4). In the future, representation of Klamath River flows in RBM10 could be improved by adding additional tributaries, with flows assigned according to tributary watershed area and accretions between mainstem Klamath River flow gages (Manhard et al. 2018).

2.3.4 DEFINING THERMAL REGIMES ERAS

The data analyzed in this report spans a period of 87 years and significant change in the form, function, and management of the Trinity River. To evaluate temperature effects of management actions, different eras associated with management changes must be defined. We define management eras as: pre-dam era (1911– 1/20/1961), with-dam full diversion era (10/31/1963–4/30/1978), with-dam transitional era (5/1/1978–9/30/1999), and with-dam ROD era (10/1/1999–2019). We ignore the 1/21/1961-10/30/1963 period of initial dam-filling because it was a one-time event and is not relevant to current management. We delineated eras subjectively based on reviewing graphs of the Trinity River at Lewiston flow data (see Section 3.4.1.3 for details including figures illustrating the seasonal flow and temperature regime of the Trinity River at Lewiston). While it is instructive to separate the past into eras for comparative analysis, we recognized that the borders between eras, and their names, are somewhat arbitrary because flow management sometimes changed incrementally over years. For example, based on the timing and magnitude of spring releases we define the ROD era as beginning in 2000, although alternatively it could be set as beginning in 2002 or 2005, and some years in the late 1990s had spring hydrographs relatively similar to the ROD era. In contrast, the May 1, 1978 increase in baseflow from 150 to 300 cfs was a clean and prominent flow management change that we defined as the border between the full diversion era and the transitional era. We also compare the historical eras to a modeled unimpaired flow scenario (1963–2019) without dams and diversion, which show variability similar to the pre-dam era but with the same climate and weather as the three with-dam eras.

2.3.5 UNITS

We standardized units throughout this report where possible. For temperature, we primarily use degrees Celsius (°C) from the International System of Units (SI) although we also refer to Fahrenheit (°F) for temperature criteria when defined as °F in source documents, in which case we also provide °C conversions. The intended audience for this report, managers and technical staff associated with the TRRP, are most familiar with this measure as it pertains to river management. We selected U.S. customary units' cubic feet per second (cfs) and Acre-feet (AF) as measure of discharge and volume for the same reason. For area, we use primarily use SI units of square meters (m^2) and square kilometers (km^2). For all other measures, and similar reasons as stated above, we selected U.S. customary units. There are instances in this report where figures from other reporting efforts or generated from models which utilize different units are present in the document, but this was kept to a minimum.

3 STREAM TEMPERATURE DYNAMICS OF THE TRINITY RIVER AND TRIBUTARIES

3.1 CONCEPTUAL MODEL OF RESERVOIR / RIVER THERMAL DYNAMICS

Figure ES-1 presents a graphical summary of the key drivers of thermal dynamics in the Trinity River, Trinity Reservoir, and Lewiston Reservoir, and highlights important management issues and biological effects. The details of these issues are discussed in the remainder of this report.

3.2 UNREGULATED TRIBUTARIES INCLUDING UPSTREAM OF TRINITY RESERVOIR

We begin our examination of stream temperature dynamics in the Trinity River watershed with an evaluation of the Trinity River's unregulated tributaries, including those upstream of Trinity Reservoir. These tributaries provide an instructive comparison with the regulated Trinity River downstream of Lewiston Dam discussed in later sections of this report.

Water temperatures in the Trinity River's unregulated tributaries show a strong seasonal cycle, reaching annual maxima in July–August as high as 20-29 °C and annual minima in December-February as low as 0 °C (Figure 7). Mid-summer temperatures tend to be higher at sites with larger drainage areas, although there are many exceptions to this trend (i.e., high temperatures at Rush Creek and low temperatures at Horse Linto Creek). At most sites, water year type appears to exert a strong influence on temperatures during spring runoff (April–July), with much cooler temperatures in wetter years than drier years. Of the sites shown in Figure 7, Grass Valley Creek has the most unique thermal regime, with less pronounced differences between winter and summer than the other sites, and greater interannual variability in winter than summer which is the opposite of the other sites. We attribute Grass Valley Creek's unique thermal regime to Buckhorn Dam which releases a cold summer baseflow of approximately 6 cfs (Gaeuman 2013), a large quantity relative to the creek's watershed size. Flows and water temperatures in several of these streams have been impacted by consumptive use for domestic, commercial, and agricultural uses (NMFS 2014).

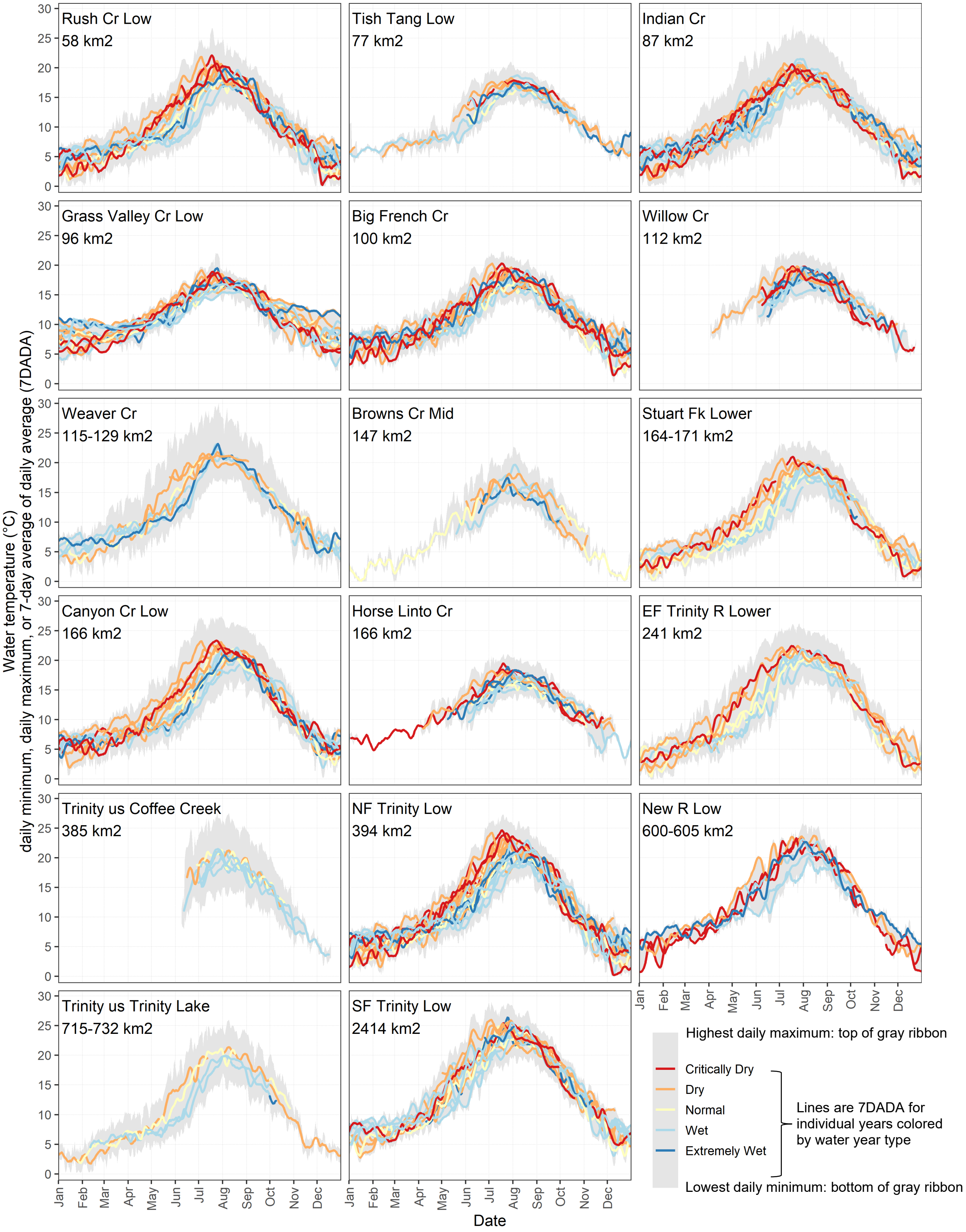


Figure 7. Water temperatures measured from 1990–2019 in major tributaries as well as the Trinity River upstream of Trinity Reservoir, with sites labeled and sorted by drainage area in square kilometers (km2). Years are color-coded by water year type. 7DADA = 7-day average daily average, shown here instead of 1-day average to make water year types more apparent. At New River and Horse Linto, most winter data were available only as daily averages, so daily max. and min. temperatures appear artificially compressed.

3.3 RESERVOIR AND DAM OPERATIONS

3.3.1 TRINITY DAM

3.3.1.1 PHYSICAL CHARACTERIZATION OF DAM, RESERVOIR, AND OUTLET WORKS

Trinity Dam is a zoned-earthfill structure that was completed in 1962, impounding Trinity Reservoir (Wahl and Cohen 1999). It has a structural height of 537.5 ft, a hydraulic height of 440 ft, a crest length of 2,450 ft, crest width of 40 ft, and crest elevation (El.) of 2395.0 ft (Wahl and Cohen 1999). The spillway intake (Figure 8) is an uncontrolled 54-ft diameter glory hole concrete structure with crest elevation 2370.0 ft and a design discharge of 22,400 cfs at water surface elevation 2388 ft (Wahl and Cohen 1999).

The reservoir is approximately 24 miles long, with the following design surface elevations and associated volumes (Table 5). Trinity Reservoir is released to Lewiston Reservoir and then either the Trinity River or diverted through the Carr Tunnels into Whiskeytown Reservoir. The river outlet works system consists of a concrete lined 28-ft diameter tunnel, an intermediate gate structure with a 10x20-ft fixed-wheel gate, and a 16-ft diameter steel penstock with branches to both the powerplant and the outlet works control structures (Wahl and Cohen 1999; Figure 9). The outlet works branch is an 11-ft diameter conduit that bifurcates into a pair of 7-ft diameter conduits, each leading to an 84-inch ring-follower gate and an 84-inch hollow-jet valve. The outlet works has a design discharge of 7,000 cfs at water surface elevation 2370.0 ft (Wahl and Cohen 1999; Figure 9).

The powerplant houses two 70 MW generators that were upgraded from the original equipment (50 MW generators) in 1984. Water is supplied to the Francis-type turbines through two 11-ft diameter penstocks with 158-inch butterfly valves as guard valves for the turbines. The turbines were equipped with both low-head and high-head turbine runners that could be interchanged on a seasonal basis in response to variation in reservoir water levels (Wahl and Cohen 1999). Rated discharge from the low-head runners is 2,300 cfs for each turbine, and rated discharge from the high-head runners is 2,050 cfs for each turbine (Wahl and Cohen 1999). Work to modernize the turbines was underway at the time this report was written.

The auxiliary outlet works at 1995.5 ft El. consists of a box intake structure, a 7-ft diameter concrete conduit, a gate chamber housing an 84-inch ring-follower gate and an 84-inch jet-flow gate, and an 8-ft oval shaped tunnel that slopes parabolically down to and exits freely into the spillway tunnel (Wahl and Cohen 1999; Figure 9). The design discharge of the auxiliary outlet works is 2,490 cfs at 2370 ft El, with reduced discharge capacity at lower reservoir elevations. The volume of water between the primary outlet and auxiliary outlet is 195,000 AF (Bender 2012). The auxiliary outlet bypasses hydropower generation and is only used when necessary (Deas 1998a, Kamman 1999b). This outlet is often relied upon during years of low end of September carryover storage (less than 900,000 af) when the river outlet works begins to entrain warmer stratification levels within the reservoir, making water temperatures released to the Trinity River and diverted to the Whiskeytown too warm to meet downstream temperature criteria for ESA-listed species.

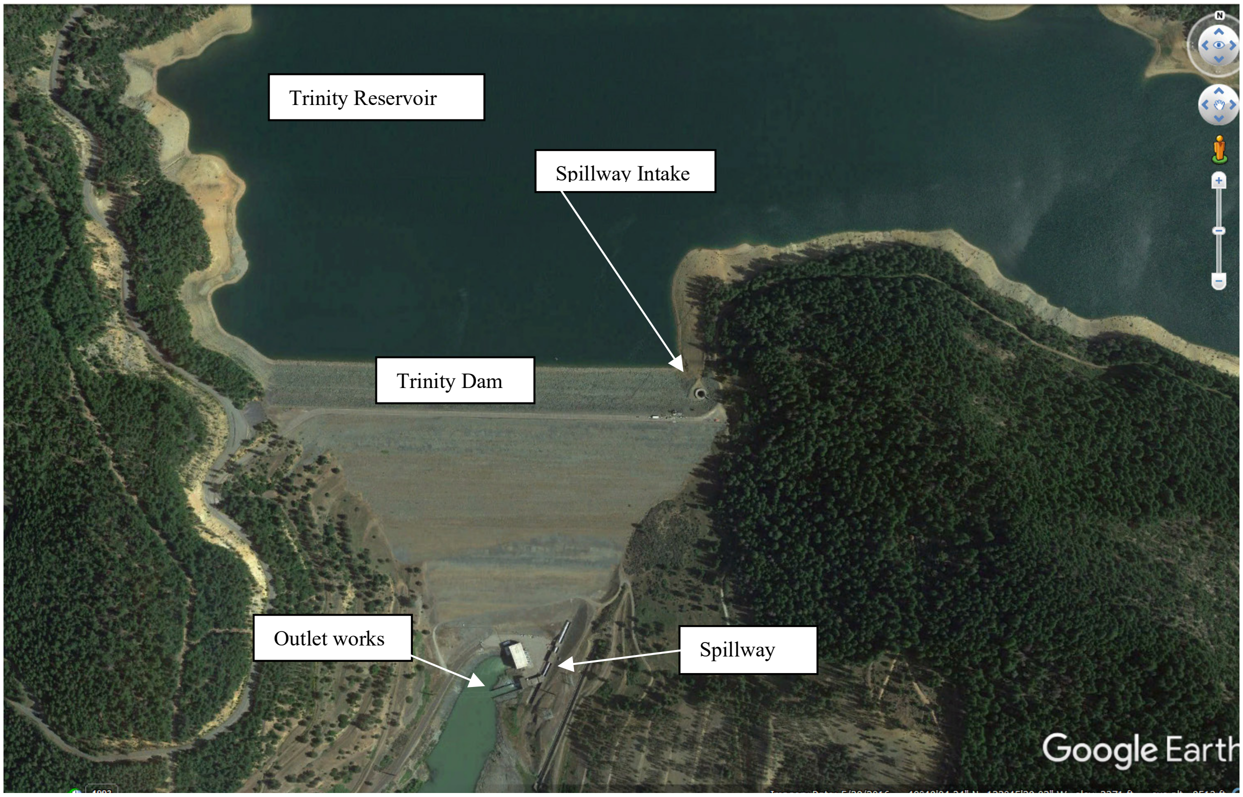


Figure 8. Overview of Trinity Dam and associated structures.

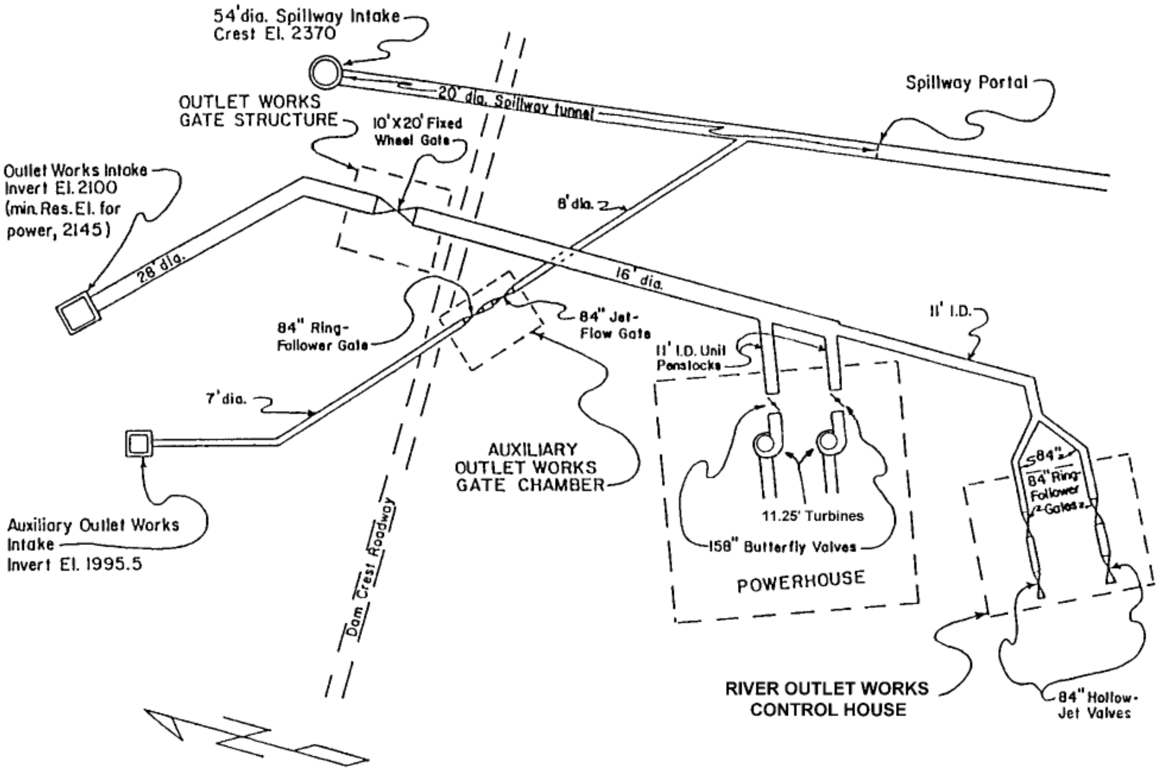


Figure 9. Schematic of spillways and outlet facilities at Trinity Dam (Wahl and Cohen 1999).

Table 5. Design feature elevations for Trinity Reservoir. Adapted from Wahl and Cohen (1999) and Kamman (1999b).

Design	Volume (af)	Elevation (ft)
Maximum water surface	2,760,900	2,388
Top of active conservation pool (Spillway Crest)	2,447,700	2,370
Main outlet works intake	162,231	2,100
Top of inactive storage	312,700	2,145
Auxiliary outlet works intake	10,259*	1995.5

Notes: *10,259 volume is for 1996 ft (Kamman 1999b).

3.3.1.2 RESERVOIR TEMPERATURE DYNAMICS, COLD WATER STORAGE POOL, AND DAM RELEASE TEMPERATURES

Water temperatures in Trinity Reservoir vary through time and depth in response to factors such as meteorological conditions, hydrologic inputs, and reservoir operations. While these factors each generally follow their own seasonal cycles, the timing and magnitude of these cycles can result in major differences in water temperatures between years. Previous reports assessing and modeling thermal dynamics of Trinity Reservoir include Weidlein (1971), Rowell (1979, 1990), Deas et al. 1997, Deas (1998a, 1998b), Watercourse Engineering (2002), RMA (2003), and Bender (2012). During January and February, reservoir water temperatures are relatively uniform across all depths (Figure 10). Like other deep lakes and reservoirs in temperate climates, Trinity Reservoir thermally stratifies seasonally, with warm water near the surface (epilimnion) and cold water at depth (hypolimnion) (Figure 10, Figure 11). Thermal stratification begins developing in March, reaching a maximum in July and August (Figure 10). The primary outlet and auxiliary outlet both withdraw water from the hypolimnion. These hypolimnetic releases are cold (i.e., <10 °C) except during prolonged droughts which can deplete the cold water pool (Figure 11e).

Water flowing into the reservoir descends to a depth that matches its temperature, but since some mixing occurs the inflow ultimately ends up at a depth slightly warmer than its original temperature (Rowell 1979). Given that the reservoir receives a large percentage of its inflows during winter and spring runoff, the temperature of inflow during that high runoff period is an important driver of reservoir water temperature (Watercourse Engineering 2002). A cold dry winter is not sufficient to cool the reservoir's depths; deep waters are cooled by filling with cold water (Deas 2008a).

Model results indicated that use of the auxiliary outlet can substantially decrease release temperatures (Deas 1998a, Kamman 1999b). The maximum capacity of the auxiliary outlet varies with reservoir elevation, ranging from 2,500 cfs when the reservoir is full (2370 ft water surface elevation, storage 2,447,654 acre-feet [AF]) to 0 cfs if the reservoir were to be drawn down to water surface elevation of 1995 ft (storage 10,259 AF) (Kamman 1999b). Kamman (1999b) noted that use of the auxiliary outlet works was not a standard practice, but it had been used as an emergency measure for durations of one to three months in July through October during droughts of 1977, 1991, 1992, and 1994, releasing volumes of approximately 0.3–1.2 million AF/year. We were only able to obtain a list of exact dates when the auxiliary outlet has been used from 2000 to present but it appears that frequency of use of the auxiliary outlet has increased over that time (Figure 20).

Rowell (1979) evaluated the potential to retrofit Trinity Dam with multilevel outlets to selectively release water from additional depths to manage temperature and turbidity, with the goals of increasing temperatures in winter and early spring to above 10 °C (50 °F) and decreasing temperatures to (12.8–16.7 °C [55–62 °F], variable by month) in late spring, summer, and early fall. Temperature benefits of multilevel outlets were found to be limited to spring (April–May) and fall (October–November). Benefits were not possible in December–March because all depths in Trinity Reservoir were uniformly cold and downstream tributaries contributed large volumes of cold water (Rowell 1979).

Since reservoir releases are withdrawn from the depths of the reservoir, as the reservoir is drawn down depth diminishes and temperatures rise (Figure 11, Figure 13, Figure 14) (Deas 1998, Bender 2012, Barajas 2016). Temperature increases are most severe when the reservoir is drawn down to very low levels during multi-year droughts such as 1977, 2014, and 2015 (Figure 11, Figure 12). The relationship between reservoir storage and water temperature at the elevation of the main outlet appears to be non-linear, with an inflection point around 1,250,000 AF where temperatures rise increasingly steeply as reservoir storage drops beyond this level (Figure 13, Figure 14). Low reservoir levels result in greater water temperature increases at the depth of the main outlet than the auxiliary outlet (Figure 11E, Figure 12, Figure 13). The relationship between reservoir elevation and water temperatures at the main outlet elevation appears to vary by month, with stronger effects when the reservoir is more thermally stratified (April–November) and weaker effects when the reservoir is less thermally stratified (December–March). Previous key findings, requirements, and/or recommendations on carryover storage include:

- *750,000 AF*: Bender (2012) found that end-of-September storage less than 750,000 AF is "potentially thermally problematic for cold water fish in the Trinity River."
- *600,000 AF*. NMFS (2000) general requirement to maintain carryover storage of 600,000 AF, except in dry and critically dry water years when needed to protect winter-run Chinook Salmon in Sacramento River.
- *900,000 AF*. Finnerty and Hecht (1992): "…it is likely that carryover storage on the order of 900,000 acre feet or slightly more may be needed to meet Trinity River requirements")
- *750,000-1,250,000 AF.* Deas 1998a "In general, elevated water temperature at the power/main intake elevation was an issue for carry-over storage of 750,000 AF. Only under certain circumstances was temperature a concern at 1,250,000 AF…"

Annual minimum storage less than 750,000 AF has occurred in 1977, 1992, 1993, 2014, and 2015 (Figure 15). Since initial filling in 1963, the lowest reservoir levels occurred in November 1977 (Figure 15). The 1977 late June profile (the latest profile available for that year, although temperatures almost certainly continued to rise) temperatures at the 2000 ft and 2125 ft depths (11-12 °C) were record highs for that time of year (Figure 10, Figure 12). In addition, Trinity River water temperatures measured downstream at Lewiston in early September 1977 reached a record 21.0 °C (see figures in Section 3.4.1.2). TRRP and ESSA (2009) recommended additional assessments of the level of carryover storage necessary to meet temperature objectives when consecutive dry water year types occur. To date, a thorough assessment of the effects a multiyear drought on Trinity Reservoir storage levels, water temperatures and the resulting ability to meet temperature criteria in the Trinity River has not been conducted.

Reservoir profiles indicate that in 1979, and to a lesser extent 1986, water at the depths of the primary and auxiliary outlets were much colder than any other year (Figure 11, Figure 12), although it is not clear why as reservoir storage, inflows, and air temperature were not abnormal in those years (Figure 12).

Temperatures in the deeper portions of the reservoir appear to be generally warmer in the years 1998–2019 than in 1972–1990 (Figure 11D, E, F). These warmer temperatures appear to be due in part to increased occurrence of lower reservoir levels in the 1998–2019 period; however, even when the reservoir is relatively full (i.e., >2 million acre-ft), temperatures at release depths were still approximately 1 °C warmer in the 1998–2019 period (Figure 13). Given that water temperatures in rivers throughout the Western U.S. have warmed in recent decades in response to climate change (Isaak et al. 2018), we speculate that rising temperatures within Trinity Reservoir might also be due to climate. There are no multi-decadal river water temperature datasets available upstream of the reservoir, so we cannot verify that hypothesis; however, air temperatures do appear to have risen since 1972 (Figure 11A), consistent with global climate change (Grantham 2018). We conducted some exploratory statistical analyses to assess correlations between air temperatures and reservoir water temperatures at the main outlet elevation, excluding periods when reservoir storage was very low (i.e., >1,250,000 AF) because reservoir storage appears to play such a dominant role in controlling temperatures at the main outlet depth under such conditions. In these analyses we used a 12-month trailing average of air temperature because the large thermal mass of the reservoir presumably responds to air temperatures at relatively long-time scales. We compared four linear mixed effects models for predicting water temperatures at the main outlet, all using a random intercept for month (because temperatures vary by month, as shown in Figure 12) but using different combinations of predictor variables (i.e., fixed effects) (Table C20 in Appendix C). The model that used only air temperature as a predictor variable performed better than alternative models that included reservoir storage (Table C20 in Appendix C). The air temperature coefficient in the best model was 0.49, meaning that for every 1°C increase in the 12-month trailing average of air temperature, temperatures at the main reservoir outlet are expected to increase by 0.49 °C when reservoir storage is ≥ 1,250,000 AF. We restricted this analysis to periods when the relationship between reservoir storage and temperature was linear (i.e., when reservoir storage is ≥ 1,250,000 AF); however, we recommend below in Section 8 that at some future date, non-linear methods such as generalized additive models (GAMs, Section B.4 in Appendix B) be applied to model release temperatures under all conditions. Since tributary inflow temperatures are an important driver of reservoir thermal dynamics (Watercourse Engineering 2002), future analyses should also include exploring the effects of tributary inflow temperatures on reservoir release temperatures. Tributary temperatures could be estimated using an approach similar to what we used for the tributary temperature model (Section B.8 in Appendix B) or the pre-dam Trinity River at Lewiston temperature model (Section 3.4.1).

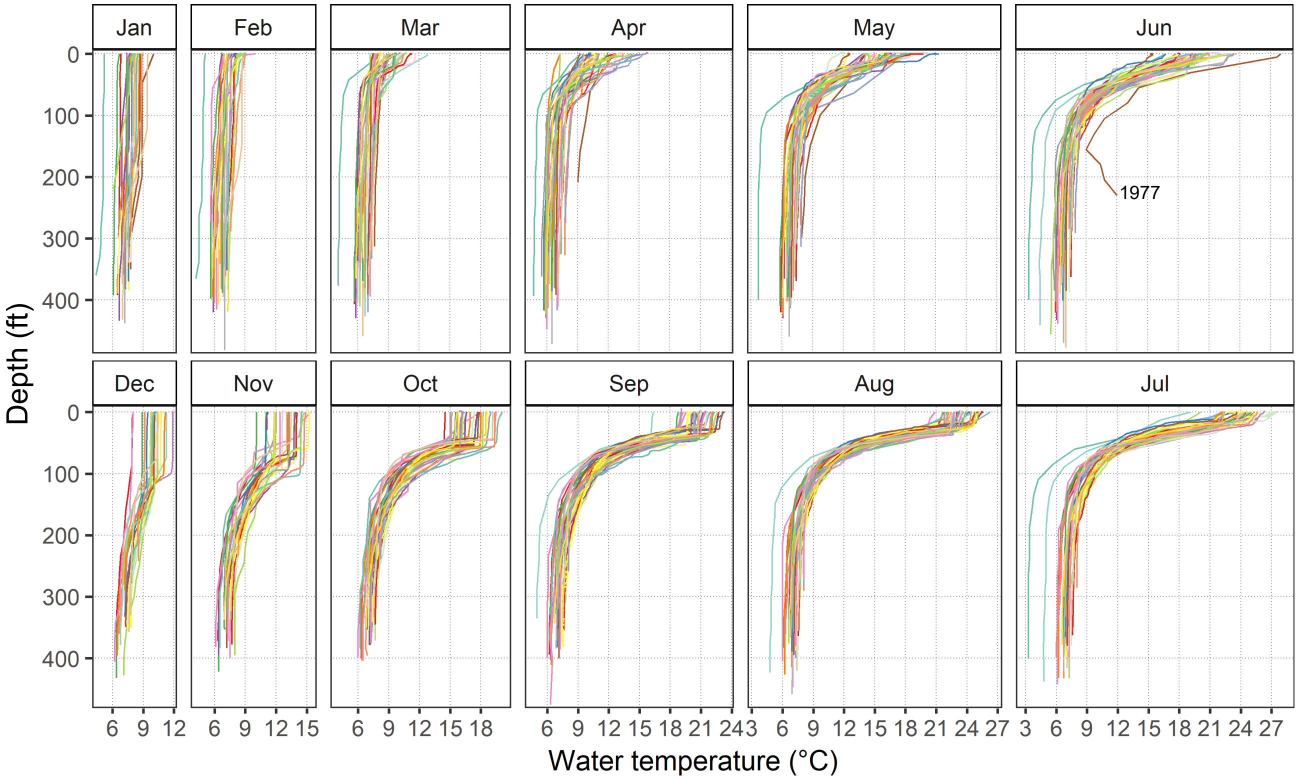


Figure 10. Water temperature depth profiles in Trinity Reservoir measured in the years 1973–2019 by USBR (2020), arranged clockwise by month. Colors are random, intended only to differentiate individual profiles. The June 27, 1977 profile is labeled.

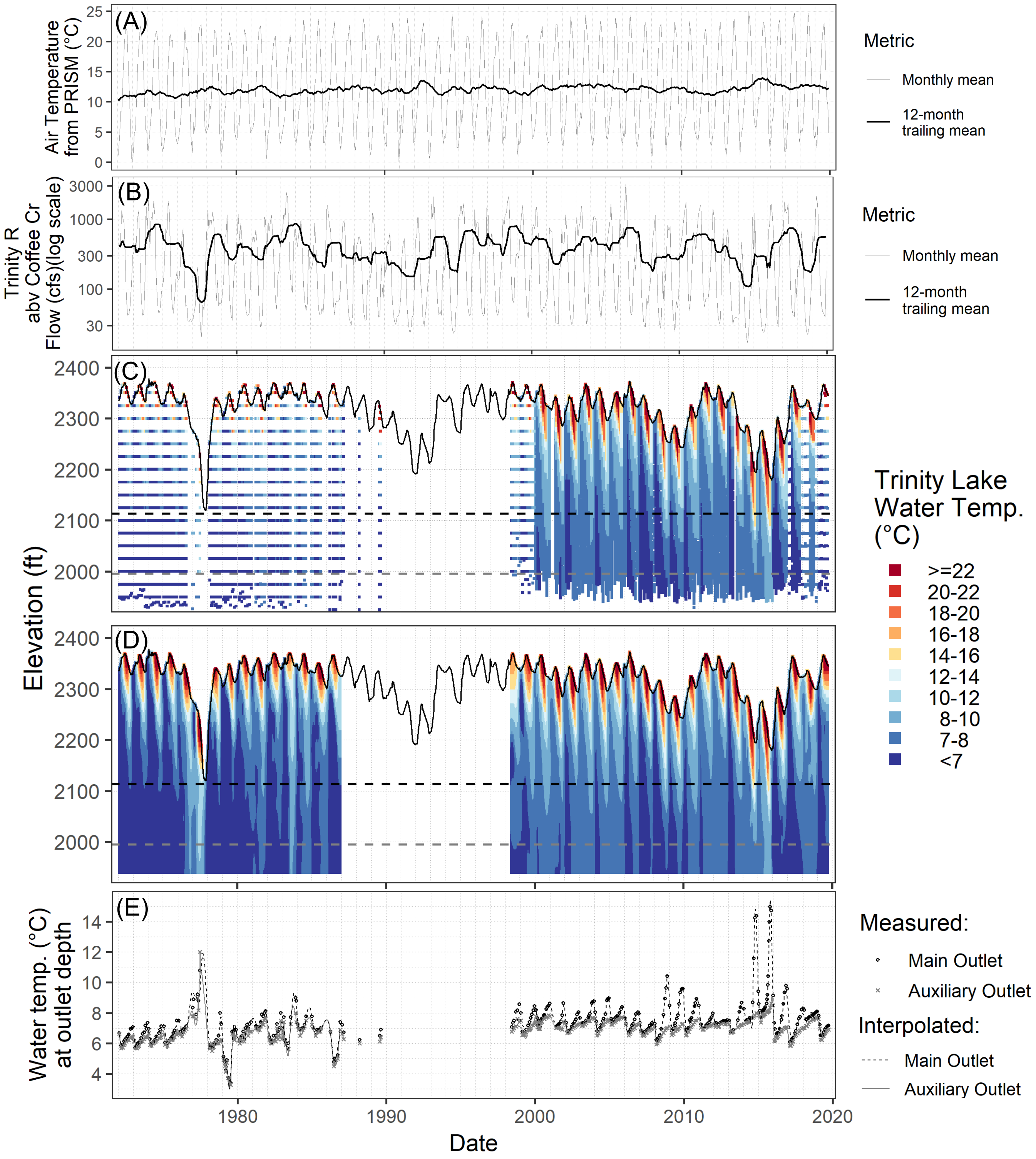


Figure 11. Trinity Reservoir time series for 1972–2019: (A) air temperatures from PRISM (Daly et al. 2008), (B) Trinity River flows above Coffee Creek from USGS, (C) water temperature depth profiles measured approximately monthly by USBR (2020), (D) weekly estimates of water temperature at 2-ft depth intervals interpolated from the measured profiles using fixed rank kriging, (E) water temperature at the depths of the main (2114 ft) and auxiliary outlets (1999.5 ft) from the monthly measured profiles and weekly interpolated profiles. Dashed lines in (C) and (D) are depths of the main and auxiliary outlets.

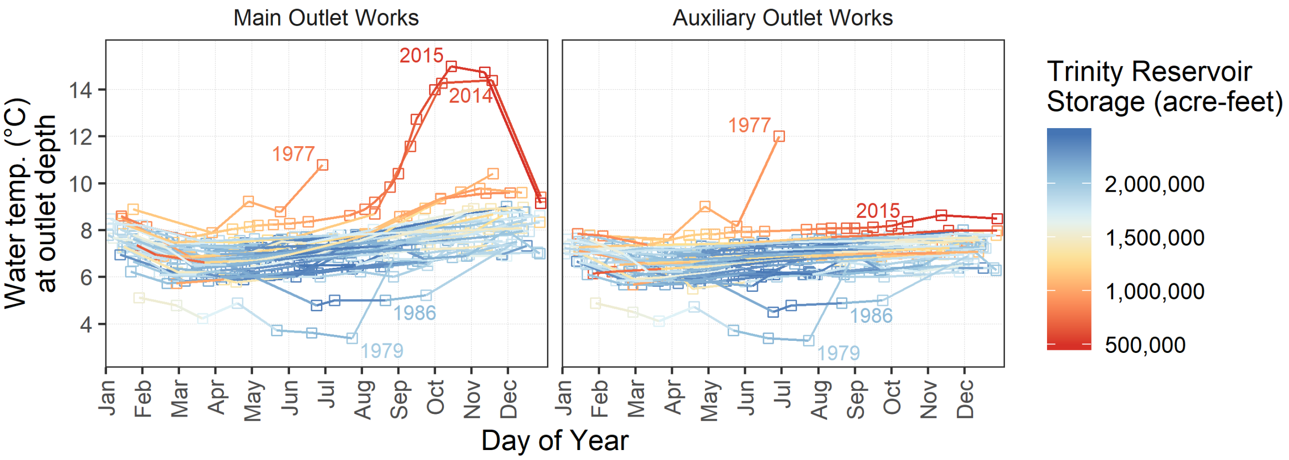


Figure 12. Seasonal patterns of water temperatures in Trinity Reservoir at elevations of the 28 ft diameter main outlet (centerline of 2114 ft) and auxiliary outlet (2000 ft) in the years 1972–2019, extracted from reservoir profiles measured by USBR (2020).

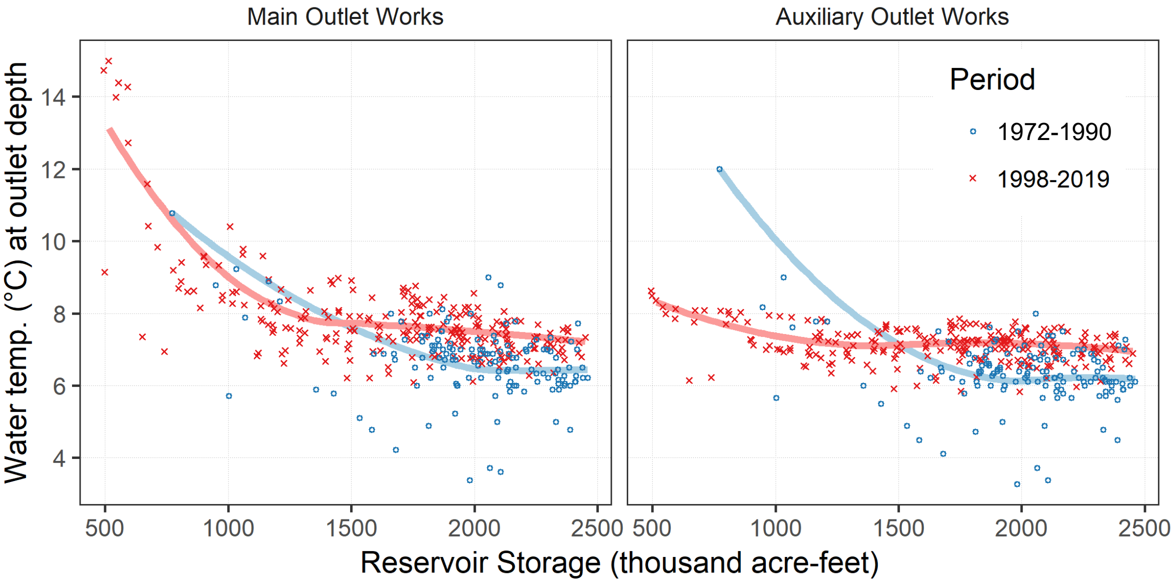


Figure 13. Comparison of the 1972–1990 and 1998–2019 time periods for the relationship of Trinity Reservoir storage volume to water temperatures at elevations of main outlet (2114 ft) and auxiliary outlet (2000 ft) for all months (January–December) in 38 years from 1972–2019, excluding years without data. Data extracted from reservoir profiles measured by USBR (2020). At low reservoir storage, a few high temperature values cause the blue trend line for 1973–1990 be higher than red trend line for the 1998–2019, but this an artifact of particular conditions that occurred in 1977 and not representative of the overall period[3]. Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers. Concept for figure adapted from Barajas (2016).

---

[3] In the 1973–1990 period, 1977 was the only year for which profiles are available when storage was below 1 million acre-feet. Due to extremely low inflow, in 1977 the reservoir never fully cooled down, so started the year warm and temperatures rose to high levels much earlier than in other years (Figure 12).

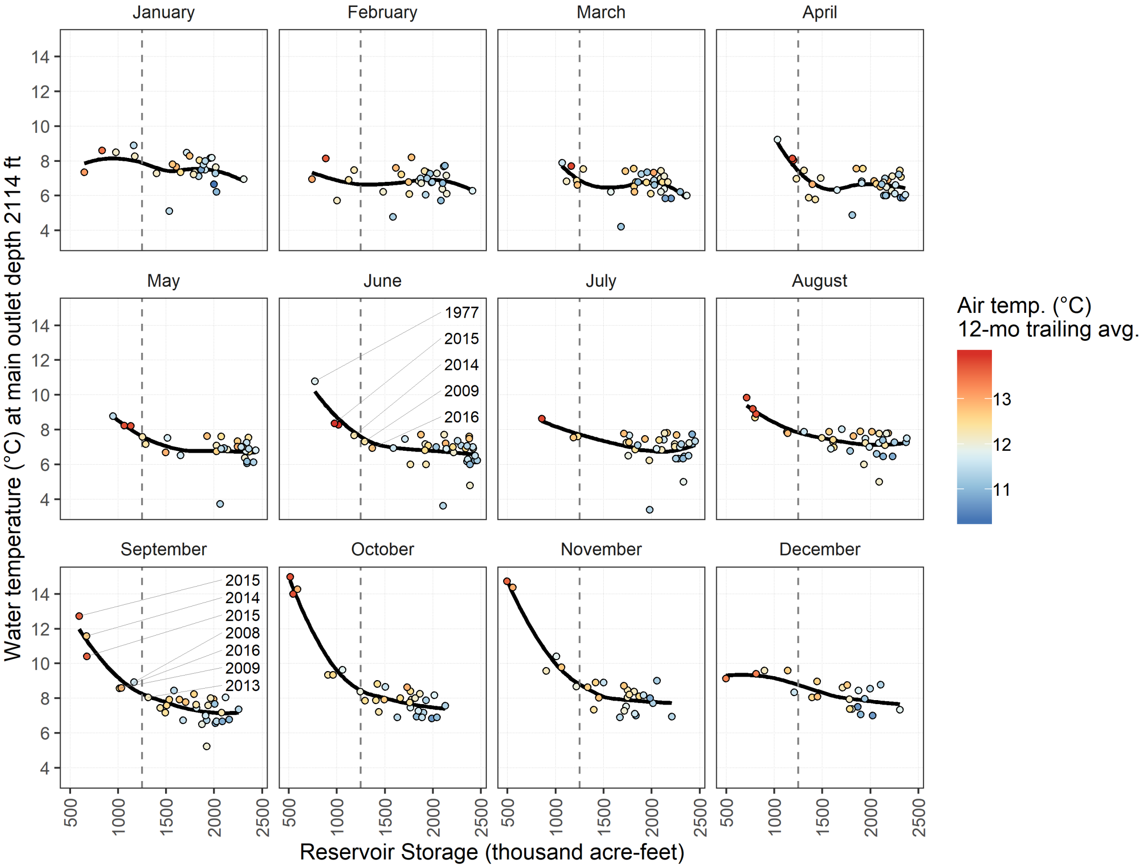


Figure 14. Relationship of Trinity Reservoir storage volume to water temperatures at main outlet elevation (2114 ft) for all months (January–December) in 38 years from 1972–2019, excluding years without data. Data extracted from reservoir profiles measured by USBR (2020). Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers. Vertical dashed line at 1,250 thousand acre-feet (AF) indicates approximate slope break below which temperatures rise steeply as reservoir storage declines, in months when reservoir thermally stratification is stronger (April-November). Concept for figure adapted from Barajas (2016).

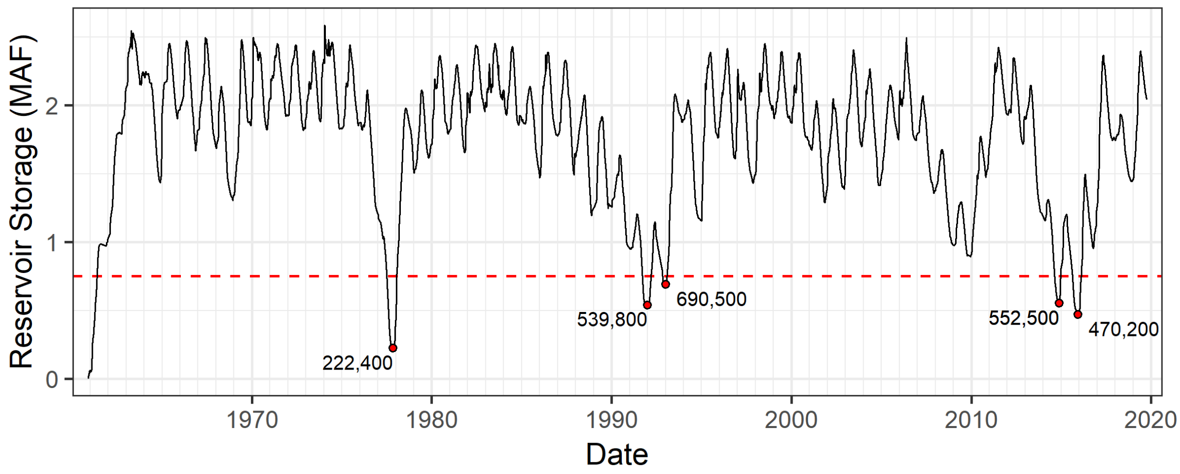


Figure 15. Reservoir water storage in Trinity Reservoir from November 1960 to September 2019. Data from USGS site 11525400. Dashed line at 0.75 million acre-feet (MAF) indicates the carryover storage level below which may be potentially thermally problematic for cold water fish in the Trinity River (Bender 2012). Minimum storage less than 0.75 MAF are labeled.

3.3.2 LEWISTON DAM, DIVERSION, AND FISH HATCHERY

3.3.2.1 PHYSICAL CHARACTERIZATION OF DAM, RESERVOIR, DIVERSIONS AND OUTLET WORKS, FISH HATCHERY

Lewiston Dam is owned and operated by the U.S. Bureau of Reclamation, and creates the seven-mile-long Lewiston Reservoir, which serves to re-regulate flows from Trinity Dam (Figure 16). A temperature curtain was installed in Lewiston Reservoir in 1992 to direct stratified colder water to intakes to Whiskeytown Reservoir (via the Carr Diversion), Trinity Hatchery, and the Trinity River (Vermeyen 1997; USBR 2012; Figure 16). Trinity River Hatchery, built to mitigate for lost salmonid production upstream of Lewiston Dam, lies immediately downstream of the dam. Facilities associated with Lewiston Dam are shown in Figure 16.

The dam is an earthen dam, 91 feet high and 754 feet long with a 25-foot crest width (USBR 2012; Figure 17). The 350-kilowatt (kW) Lewiston Powerplant is operated in conjunction with the spillway gates to comply with mandated flows in the Trinity River downstream of the dam (USBR 2012). The powerplant has a rated flow discharge capacity of 325 cfs but is currently under restriction to 80 cfs due to structural problems that can lead to stranding of fish in the stilling basin (USBR 2012).

Figure 16. Lewiston Dam and associated points of diversion and other facilities. Figure from USBR (2012). The diversion tunnel on the left (west) side of the image was used during dam construction and is not currently utilized.

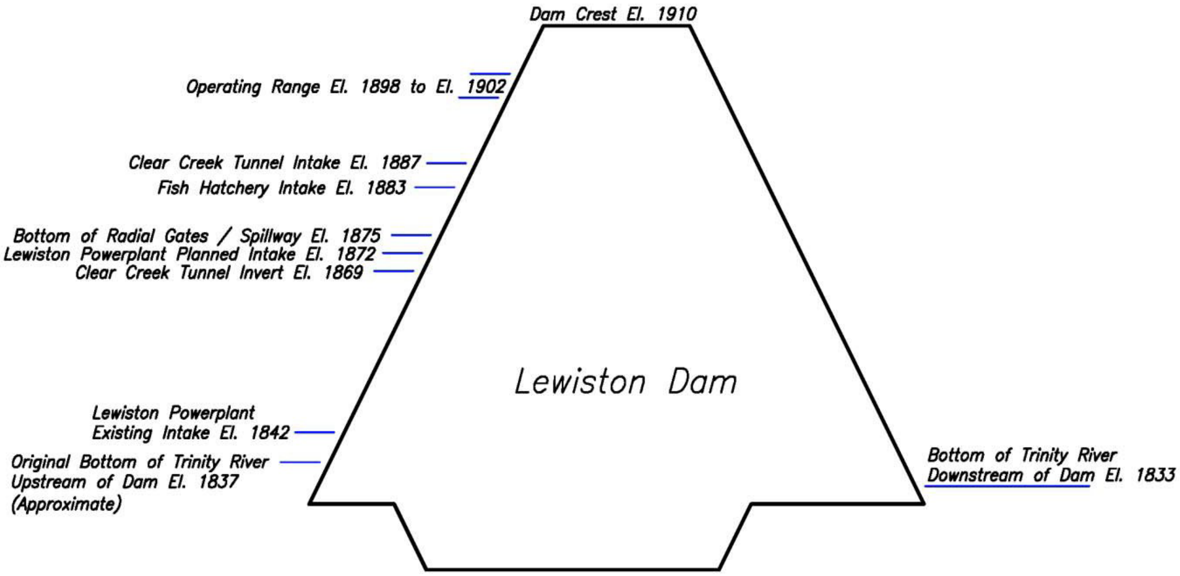


Figure 17. Elevations of features relative to Lewiston Dam (USBR 2012).

The Trinity River Hatchery receives its water from Lewiston Reservoir. Hatchery inflow is drawn from 12-foot strata lying between the 9- and 20-foot elevation levels (USBR and CDFW 2017). A four-foot-diameter pipe conveys the water. The volume diverted varies from 20 to 125 cfs depending on hatchery needs. Water enters the hatchery through an intake structure and an aeration facility capable of processing 130 cfs (USBR and CDFW 2017). Several changes to intake infrastructure have been made since hatchery construction. In 1975, a skimmer was installed to increase the fraction of warm surface water drawn into the hatchery intake (Boles 1985). A temporary curtain was installed around the Carr Powerhouse intake and tested in 1983, 1984, and 1986 (Boles 1985, 1987; Vermeyen 1997) but has been in and out of operation since that time. The Oak Bottom temperature curtain in Whiskeytown Reservoir prevents the water from Carr Powerhouse from mixing with that reservoir's epilimnion. An adjustable curtain was installed near the Trinity River Hatchery intake in 1992 which could be raised and lowered to adjust the water temperature at the hatchery's intake which is withdrawn from near the reservoir's surface, but the height adjustment is no longer functional (Darrick Muir, CDFW, and Derek Rupert, USBR, pers. comm., March 20, 2020).

3.3.2.2 INFLUENCE OF DAM OPERATIONS AND WATER DIVERSIONS ON TEMPERATURE DYNAMICS

The BETTER model which simulates temperatures in Lewiston Reservoir was developed by JSA (1992) and extended for additional years and scenarios by Kamman (1999a, 1999b) and USFWS et al. (2000). Other evaluations of water temperatures in Lewiston Reservoir include Boles (1985, 1987) who assessed whether a curtain installed around the Carr Powerhouse intake structure could increase water temperatures in the Trinity River Hatchery intake, and Vermeyen (1997) who summarized a series of studies intended to find methods to reduce water temperatures in the Trinity and Sacramento river systems including through the installation of a temperature control curtain in the Lewiston Reservoir. The Lewiston Reservoir curtain was installed in 1992 and is intended to prevent mixing of surface water during high flows, with a design informed by experiments with physical models (Vermeyen 1997). The reservoir curtain appears to have reduced temperature of releases from Lewiston Reservoir by 1.4°C (2.5 °F) after installation (Vermeyen 1997), although temperature gains through the reservoir are still a significant concern. USBR (2012) evaluated several alternatives for reducing temperature gains through the reservoir, including removing Lewiston Dam/Reservoir and/or routing Trinity Dam releases through a pipe or canal instead of through the reservoir. With current infrastructure, hydropower peaking operations at Trinity Dam can increase water temperatures in Lewiston Reservoir, so Vermeyen (1997) recommended not peaking during periods when temperature is a concern.

Water temperatures in Lewiston Reservoir are highly influenced by the volume of water released from Trinity Dam. When the Carr power plant diversion operates at full 3,200 cfs capacity, the high flushing rate replaces the volume of Lewiston Reservoir every approximately 2.5 days and water temperatures remain relatively cool (JSA 1992). In the summer when Trinity Dam releases are low, such as when the Carr diversion is not operating and releases to Trinity River are low, Lewiston Reservoir thermally stratifies within days and surface waters warm to between 15.6 and 21.1 °C (60–70 °F) (JSA 1992). Results from the BETTER model suggest that to meet downstream temperature objectives, flow rates through Lewiston Reservoir should be between approximately 800 cfs during the summer/early fall in normal year-types and up to 1,900 cfs during summer/fall in critically dry year types (Kamman 1999b). In the ROD era, the amount of water moving through Lewiston Reservoir in May has increased substantially (Figure 18, Figure 19). On a relative basis (i.e., percent of annual flow occurring in that month), June flows though the reservoir were also higher in the 2000–2019 ROD era than the 1963–1978 full diversion era and 1978–1999 transitional era, Figure 18), but were not higher than the 1963–1978 full diversion on an absolute basis (Figure 19). Relative to the 1963–1978 full diversion era, the seasonal timing of diversions into the Carr Powerhouse occurred later in the 1978–1999 transitional era and 2000–2019 ROD era (Figure 18).

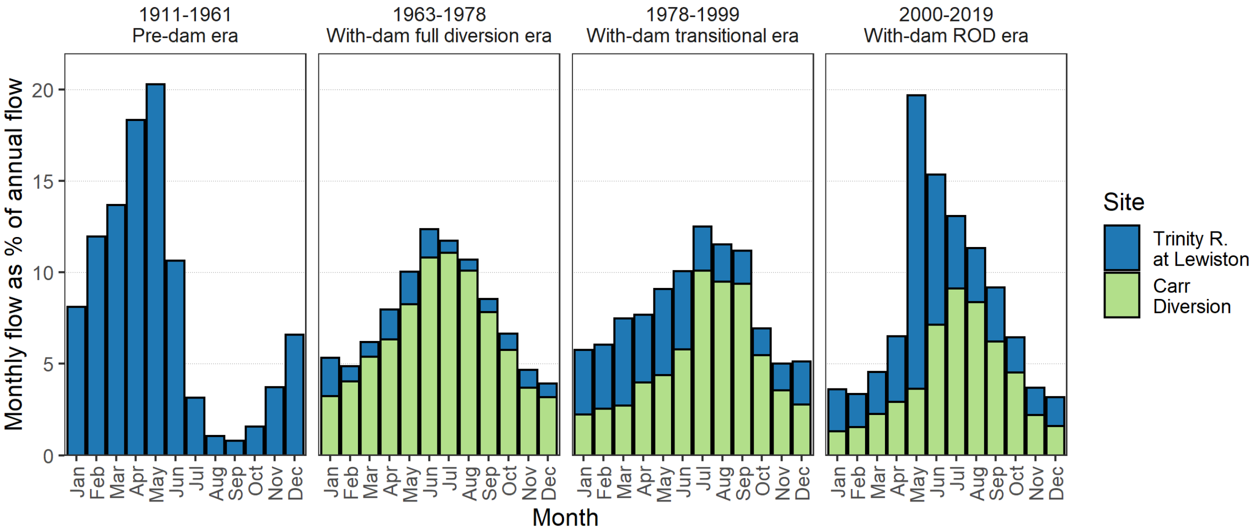


Figure 18. Comparison of monthly flow timing in the Trinity River at Lewiston (USGS gage 11525500) and the Carr Diversion (USGS gage 11525430) for three eras: pre-dam (10/1/1911–1/20/1961), with-dam full diversion (10/31/1963–4/30/1978), with-dam transitional (5/1/1978–9/30/1999), and with-dam ROD (10/1/1999–2019). The total outflow of Lewiston Reservoir is sum of these two sites (i.e., total height of the stacked bars). Values were derived by calculating total flows within each time period and month at the two sites, and then dividing by the total flow (summing all months at both sites) within the time period. Partial hydrologic years (i.e., 1961, 1964, and 1978) were excluded from this graph.

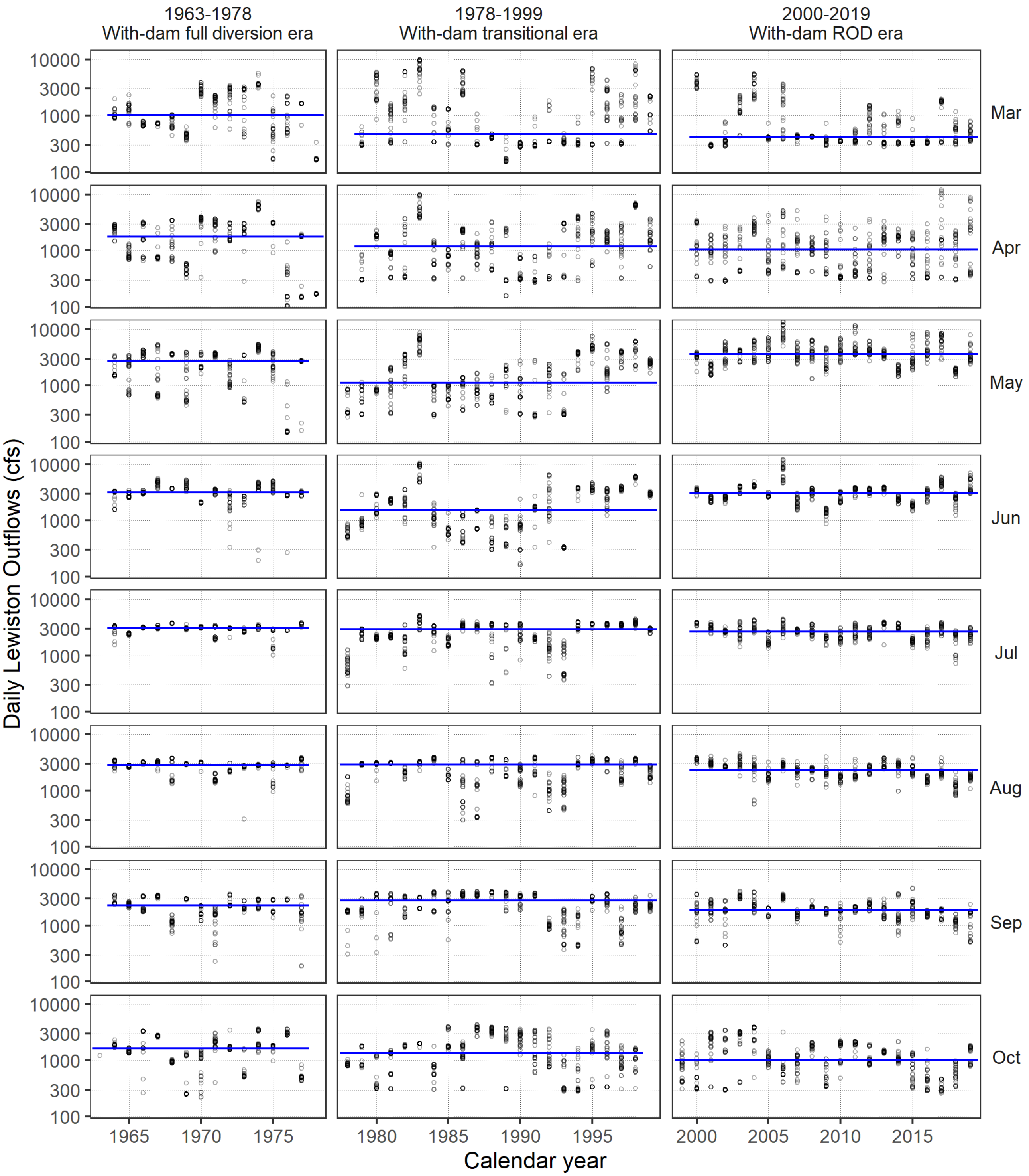


Figure 19. Time series of daily mean outflows from Lewiston Reservoir for hydrologic years 1963–2019 in the months of March–October. Each point on the graph is a single date. Horizontal blue lines represent the era median. Lewiston Reservoir outflows calculated as the sum of Trinity River at Lewiston (USGS gage 11525500) and the Carr Diversion (USGS gage 11525430). Y-axis is on log scale.

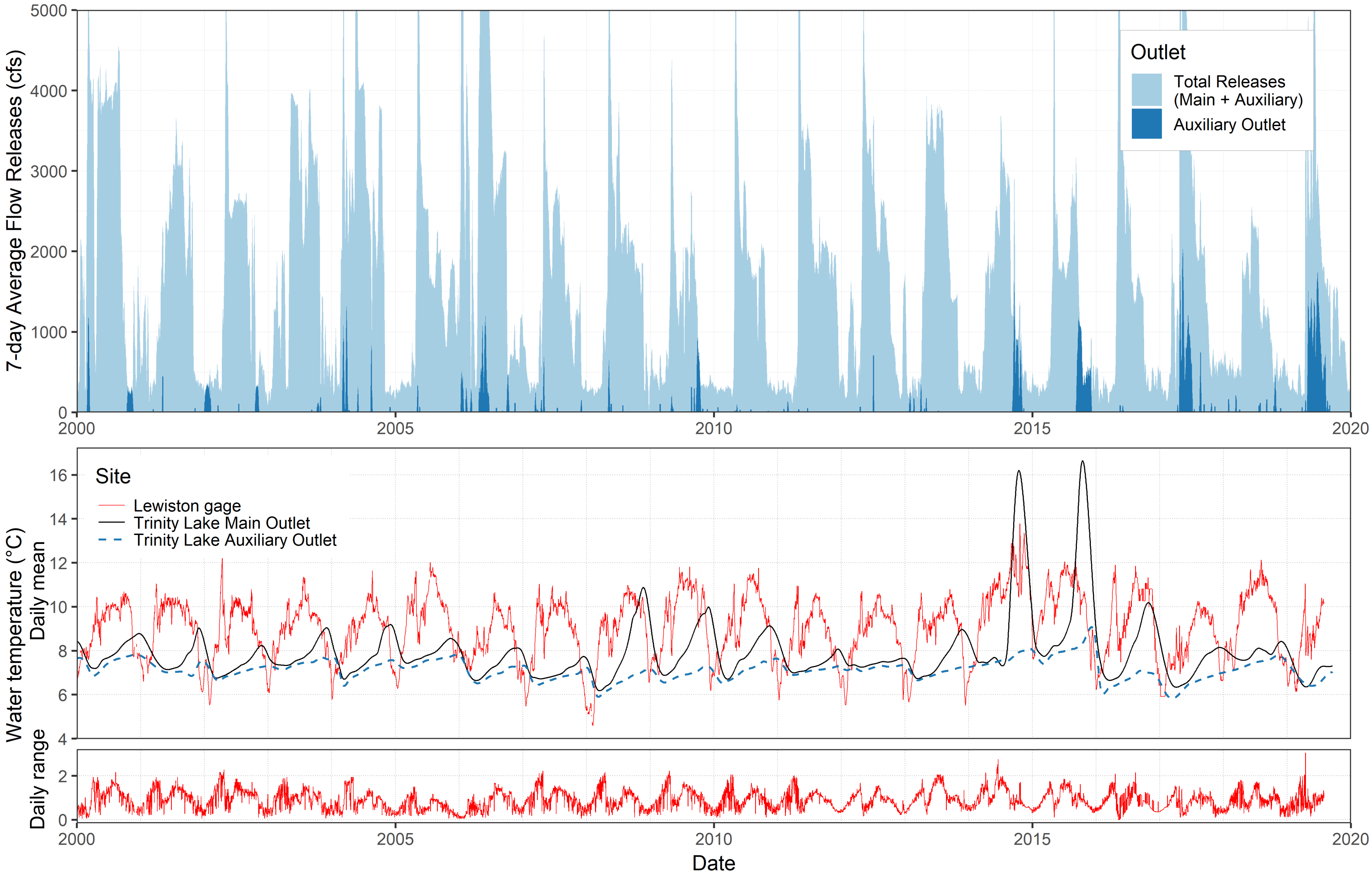


Figure 20. Lewiston Reservoir daily time series for 2000–2019: (A) Flow releases from Trinity Reservoir into Lewiston Reservoir, (B) water temperature at depths of main (2114 ft) and auxiliary outlets (1999.5 ft) in Trinity Reservoir from daily interpolation of USBR (2020) monthly measured profiles, and measured gap-filled temperatures at the Trinity River gage below Lewiston Dam from CDEC and USFWS. To make lower flows legible, the maximum value of the y-axis in (A) is set to 5000.

3.3.2.3 INFLUENCE OF HATCHERY OPERATIONS ON TEMPERATURE DYNAMICS

The effects of the hatchery operations on river temperatures are largely unknown and unassessed but would be due to a combination of: 1) the ratio of river flows to hatchery outflows, and 2) the temperature difference between the hatchery outfall and rivers temperatures. Hatchery diversions range from 20 to 125 cfs (USBR and CDFW 2017), so during base flows the hatchery could represent a substantial portion of total releases from Lewiston Dam. Presumably, temperatures change as water flows through the hatchery facilities, although we did not obtain any such data. Temperature might occasionally be manually measured during collection of water quality samples associated with the hatchery's National Pollutant Discharge Elimination System (NPDES) point-source discharge permit.

When installed in 1992, the hatchery curtain could be raised and lowered to adjust the water temperature in the hatchery's intake which is withdrawn from near the reservoir's surface, but the height adjustment is no longer functional. For the past approximately 10–20 years, the curtain has been stuck at a depth of approximately 15–20 feet (Darrick Muir, CDFW, and Derek Rupert, USBR, pers. comm., March 20, 2020).

3.4 TRINITY RIVER FLOW AND TEMPERATURE REGIME BELOW LEWISTON DAM

3.4.1 COMPARISON OF NATURAL, UNREGULATED FLOWS TO REGULATED FLOWS WITH DAM OPERATIONS

3.4.1.1 MODELING UNIMPAIRED LEWISTON FLOWS

We combined several approaches to generate a 1962–2019 time series of daily unimpaired (no dams/diversion) flows for the Trinity River at Lewiston. As detailed in the following paragraphs, our approach uses the Trinity Reservoir water balance during high-flow periods and combines flow gages with the water balance during low-flow periods. We consider these estimates to be adequate for our temperature modeling purposes but recognize that they may not be suitable for all applications and provide recommendations for future improvements at the end of this section.

USBR provides a daily estimate of Trinity Reservoir inflow as CDEC station CLE, based on a water balance using dam releases, precipitation, evaporation, and change in reservoir storage. At high flows, these estimated reservoir inflows generally appear to represent a relatively realistic hydrograph (i.e., shape approximately matches the flow measured at nearby unregulated rivers such as the Trinity River upstream of Coffee Creek and the Salmon River at Somes Bar). At low flows, the change in reservoir storage, which is difficult to precisely measure because even a small change in reservoir depth is a relatively large change in volume, dominates the water balance and causes wild fluctuations (including large negative values) in reservoir inflow on daily, weekly, or even monthly basis. These fluctuations likely represent accumulated errors of the water balance terms rather than actual inflows. During the high-flow portion of the year (generally periods with sustained inflows of >300-500 cfs, per details below), we use a 3-day moving average (i.e., average of day, day prior, and day after) of CDEC CLE reservoir inflows which smooths out some erratic day-to-day fluctuations such as those caused by rapid changes in reservoir releases.

We used a multi-step process for estimating daily reservoir inflows during the low-flow portion of the year. Simply put, we used a regression between the Trinity River above Coffee Creek gage and the CDEC CLE reservoir inflows to generate the "shape" of the daily hydrograph, then scale those daily flows so that the total flow volume within each year's low-flow period matched the total volume of CDEC CLE reservoir inflows. The specific steps are:

1) Starting in 2007, mid/late summer flows in drought years at the Trinity River above Coffee Creek gage exhibit day-to-day fluctuations on an approximately weekly cycle[4], apparently due to operations from a large diversion upstream. Since these fluctuations are not representative of overall reservoir inflows, we dampen them using a 7-day average when 7-day average flows are less than 33 cfs.

2) The low-flow period of each calendar year was defined as:
    a. Starting on the first day between day 100 (April 8 in non-leap year) and day 260 (September 15 in non-leap year) that has a 3-day moving average of CDEC CLE reservoir inflows less than 500 cfs.
    b. Ending on the last day between day 260 (September 15 in non-leap year) and December 31 that has a 3-day moving average of CDEC CLE reservoir inflows less than 300 cfs. If flows never rose above 300 cfs then the end date is December 31.

3) To estimate daily reservoir inflows during the low-flow portion of the year, we used LOESS (Locally Estimated Scatterplot Smoothing, Section B.2 in Appendix B) regression to model the 3-day moving average of CDEC CLE reservoir inflows based on measured flows at the Trinity River above Coffee Creek gage, using the period of overlapping record (11/1/1962-9/30/2019) (Figure 21). LOESS regression fits a flexible curve using polynomials. We used LOESS regression rather than linear regression because the linear regression predicted unrealistic near-zero reservoir inflows when Trinity River above Coffee Creek flows were at their lowest levels (Figure 21).

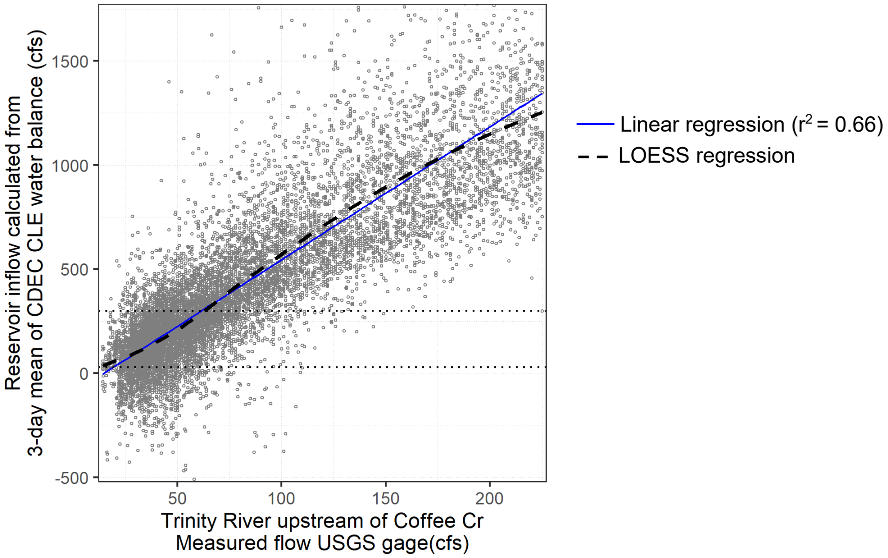


Figure 21. Comparison of daily measured flow in the Trinity River above Coffee Creek (USGS gage 11523200) and reservoir inflow calculated from water balance (3-day average of CDEC CLE). Horizontal dotted line at 28 cfs indicates the minimum 1911–1961 pre-dam flow measured in the Trinity River at Lewiston (USGS gage 11525500). Graph and regression were restricted to gaged flows less than 250 cfs.

---

[4] https://waterdata.usgs.gov/nwis/dv?cb_00060=on&site_no=11523200&period=&begin_date=2014-06-01&end_date=2014-10-01

4) For individual days during the low-flow period when either the 3-day moving average of CDEC CLE reservoir inflows or LOESS regression-based inflows exceed 1,000 cfs, we set the reservoir inflows equal to the 3-day moving average of CDEC CLE reservoir inflows. This helps better characterize short-lived peaks occurring within the low-flow period.

5) Within the low-flow period of each calendar year (excluding the individual peaks described in the previous step) we calculate the ratio of the sum of the 3-day moving average of CDEC CLE reservoir inflows to the sum of LOESS regression-based reservoir inflows. Apart from 1963, these flow volume ratios range from 0.46 to 2.18 (mean 1.24). We then multiply the LOESS regression-based reservoir inflows for each day by that year's ratio. The CDEC CLE reservoir inflows for 1963 appear to be erroneous, with extended periods of negative flow, so we did not apply the ratio for that year.

Following established convention[5] to account for local watershed area between Trinity Dam and Lewiston, we then multiply our estimated reservoir inflows by 1.04 to obtain our unimpaired flows estimates for the Trinity River at Lewiston (Figure 26 lower-right panel). The lowest modeled flow in the with-dam period (31 cfs on 9/2/2014–9/14/2014) is within 10% of the lowest gaged pre-dam flow (28 cfs on 7/30/1924), providing some confidence that our results are reasonable.

As supplemental "reality-check" on our reservoir inflow estimates during the low-flow period, we used the three-year pre-dam period of overlapping record (10/1/1957–11/23/1960) to develop a regression between the Trinity River above Coffee Creek (USGS gage 11523200) and at Lewiston (USGS gage 11525500). Flows at both gages were log-transformed prior to regression. The regression fit using all dates shows a high correlation (i.e., $r^2 = 0.97$) but the relationship does not appear to be completely linear, with predicted flows biased high at the lowest flows (i.e., when flows in Trinity River above Coffee Creek are less than 40 cfs) (Figure B83a in Appendix B). Since our primary use for these data is during low flows, we re-fit the regression using only dates when the flows in the Trinity River above Creek were ≤150 cfs ($r^2 = 0.91$, Figure B83b in Appendix B). This regression is derived from only three years of data with a limited range of hydrologic conditions but is nonetheless useful as check on our primary method. This linear regression of the Trinity River above Coffee Creek to the pre-dam Trinity River at Lewiston is relatively similar to the with-dam LOESS regression between Trinity River above Coffee Creek and the reservoir water balance (Figure B84 in Appendix B).

We derived these unimpaired flows estimates for use in water temperature analyses and believe that while they are adequate for that purpose, they could be further improved and in their current form may not be suitable for all future purposes. In particular, we caution against using these flow estimates for uses such as geomorphic analyses where precise estimates of peak flows are of primary interest. Our recommendations for future improvements to the low-flow estimates include manual review to select shorter individually chosen periods for application of multiple flow volume ratio adjustments within a year rather than our approach of applying a uniform flow volume adjustment ratio for the entire low-flow period.

---

[5] https://www.trrp.net/restoration/flows/summary/

3.4.1.2 MODELING UNREGULATED LEWISTON TEMPERATURES

To better understand how Trinity River water temperatures have been affected by flow regulation we developed a statistical model to predict Lewiston temperatures under an unimpaired scenario that we then compared to with-dam thermal regimes. Daily pre-dam water temperature data for the Trinity River at Lewiston are available from 11/2/1942– 8/9/1946 (Moffett and Smith 1950, Section A.3.4.3 in Appendix A) and 9/29/1958–1/20/1961 (Murray 1960, 1961; and USGS gage 11525500) (Figure 23). These data are valuable for understanding the thermal effects of Trinity and Lewiston dams and the associated diversion, but unfortunately the period of record (1938 days) is relatively short compared to data available for tributaries or with-dam Trinity River and does not represent the full range of natural variability present at longer time scales. Water year types for the six calibration water years with temperature data for the spring/summer season were: one Wet, four Normal, and one Dry. The lack of spring/summer calibration data from Critically Dry and Extremely Wet water year types poses a significant challenge for statistical modeling because extreme conditions have strong leverage in model calibration. Without calibration data from extreme years, the model must extrapolate and thus predictions are sensitive to assumptions and choices made during the model development process. This issue is most important for predictions during extreme years because these are furthest away from conditions observed during the calibration period; however, even predictions in moderately wet or dry years could be detrimentally affected.

After careful consideration and experimenting with several approaches, we decided the best approach for modeling pre-dam Trinity River at Lewiston temperatures was to use a hierarchical statistical approach capable of modeling temperatures not just in the pre-dam river but also other tributaries for which there are longer periods of record and better representation of hydrologic variability (Figure A80, Figure A81, Figure A82 in Appendix A). This approach allows borrowing strength (i.e., information) between sites so the measured thermal responses from other sites during extreme conditions can be applied to influence the predicted response of the site of interest, which in this case is the pre-dam Trinity River at Lewiston. We developed a generalized additive mixed model (GAMM, also referred to as a hierarchical generalized additive model [HGAM]) to predict daily mean stream temperature for the pre-dam Trinity River at Lewiston from flow, air temperature, day of year, and autocorrelation using methods very similar to those used for other tributaries (Section B.8 in Appendix B). The only differences were: 1) source of air temperature data (combination of PRISM and Livneh, instead of solely PRISM), 2) source of flow data (for flows at the pre-dam Trinity River at Lewiston site we used the USGS Lewiston gage, and for flows at tributary sites we used the USGS Trinity River above Coffee Creek gage, dividing both flows by the appropriate drainage area and converting units to millimeters per day), 3) only larger, snowmelt-dominated tributaries were included (Trinity River above Trinity Reservoir, Trinity River above Coffee Creek, East Fork Trinity River, Stuart Fork, North Fork Trinity River, and Canyon Creek), assuming that their thermal responses are most similar to the pre-dam Trinity River at Lewiston, and 4) we did not include a random effect for year because some years had short periods of record which resulted in high random effects (i.e., up to 1 °C) which could then have affected predicted values for those entire years. The PRISM air temperature data (Daly 2008) only spans back to 1981, so we extended them back to 1915 by regression with the Livneh (2013) gridded air temperature data for the overlapping period 1981–2011 ($r^2 = 0.99$, root mean squared error 0.89 °C). Because we assumed that stream temperatures in the tributaries and the pre-dam Trinity River are driven by the same processes, and our full tributary dataset included a much longer time period and wider range of hydrometeorological conditions, we did not do an extensive independent model selection process but rather used the variables and structure of the full tributary model, with the modifications described above. As with the tributary model, development of the pre-dam Lewiston model was a two-step process, with an initial model fit without autocorrelation term and then a final model fit with an autocorrelation term, assigning an autocorrelation rho value based on the lag 1 autocorrelation (0.805) from the residuals of the initial model. After inclusion of the autocorrelation term, there was no residual autocorrelation in the model residuals.

We validated the model using leave-one-year-out cross-validation, yielding an RMSE of 0.94 °C and R^2 of 0.98 for the pre-dam Trinity River at Lewiston, indicating excellent model fit (Figure 22, Figure 23). We did not use the predictions for other tributaries so do not report them here. As noted above, lack of site-specific calibration data for Critically Dry and Extremely Wet years contributes uncertainty to predictions during hydrologic conditions more extreme than relatively average conditions that occurred during the calibration period, although we have partially mitigated that by including other large snowmelt-dominated tributaries in the model.

After calibration, we applied the model to simulate temperatures in the entire 1915–1961 pre-dam period and a 1963–2019 unimpaired flow scenario (using flows generated in Section 3.4.1.1 above) which predicts what temperatures would have been without the dams and diversion.

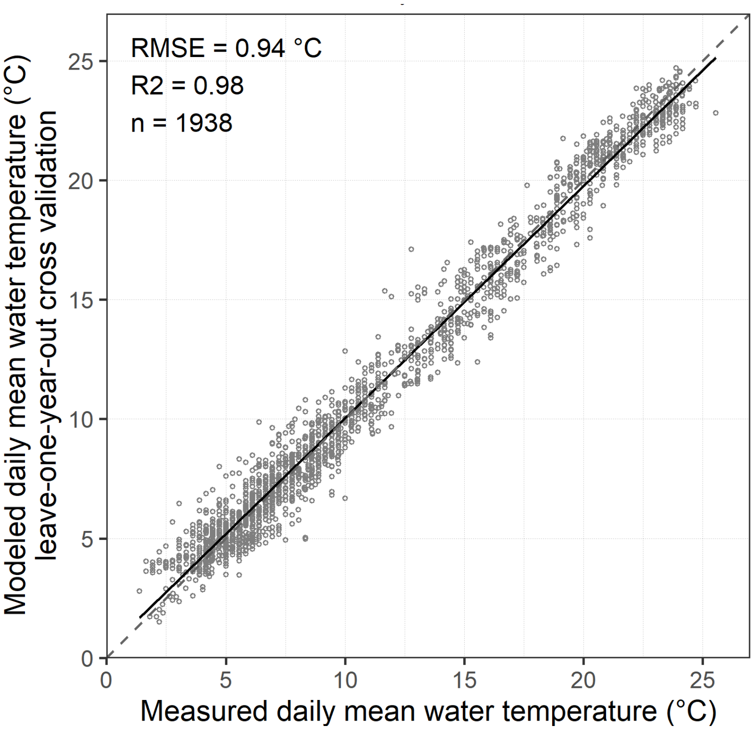


Figure 22. Comparison of measured and leave-one-year-out cross-validated predictions for daily mean water temperatures in the Trinity River at Lewiston for 1942–1946 and 1958–1961, prior to dam regulation. Model uses air temperature, flow, day of year, and autocorrelation. Data sources for observed water temperature: Moffett and Smith (1950), Murray (1960, 1961), and USGS (gage 11525500). 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. Solid black line is linear regression prediction and dashed line is 1:1 line.

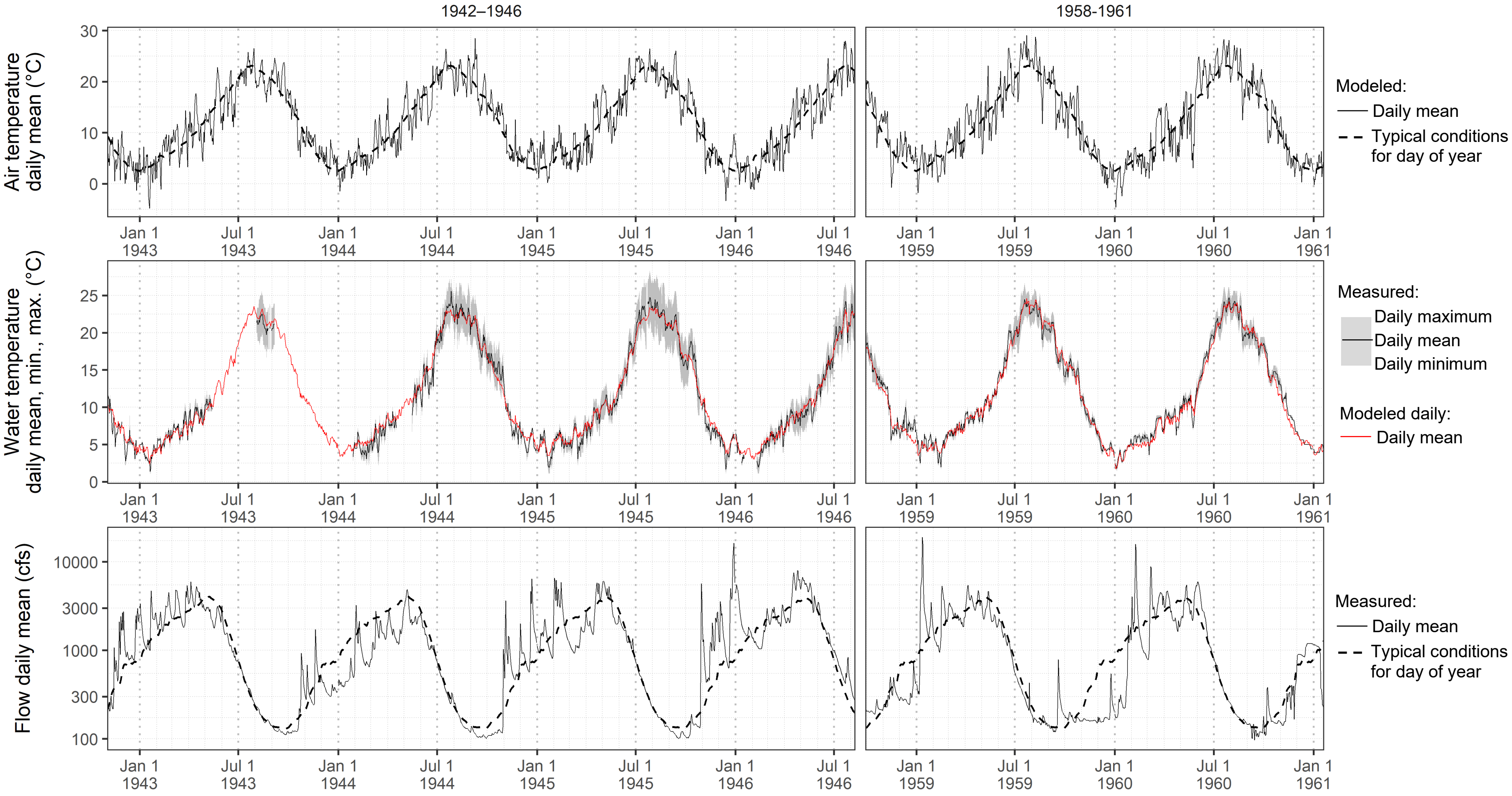


Figure 23. Daily time series of air temperature, water temperature, and flow for the Trinity River at Lewiston for 1942–1946 and 1958–1961, prior to dam regulation. Data sources: air temperature from gridded models (Livneh et al. 2013, Daly et al. 2008); measured water temperature from Moffett and Smith (1950), Murray (1960, 1961), and USGS (gage 11525500); modeled water temperature data from our analysis; and flow from USGS (gage 11525500). Dashed lines represent typical conditions, calculated as period-of-record (air temperature: 1915–2019, flow: 1911–1961 measured and 1963–2019 estimated unimpaired) median for each day of the year, smoothed with a 7-day average for legibility. Due to the short period of record, a typical conditions dashed line is not shown for water temperature.

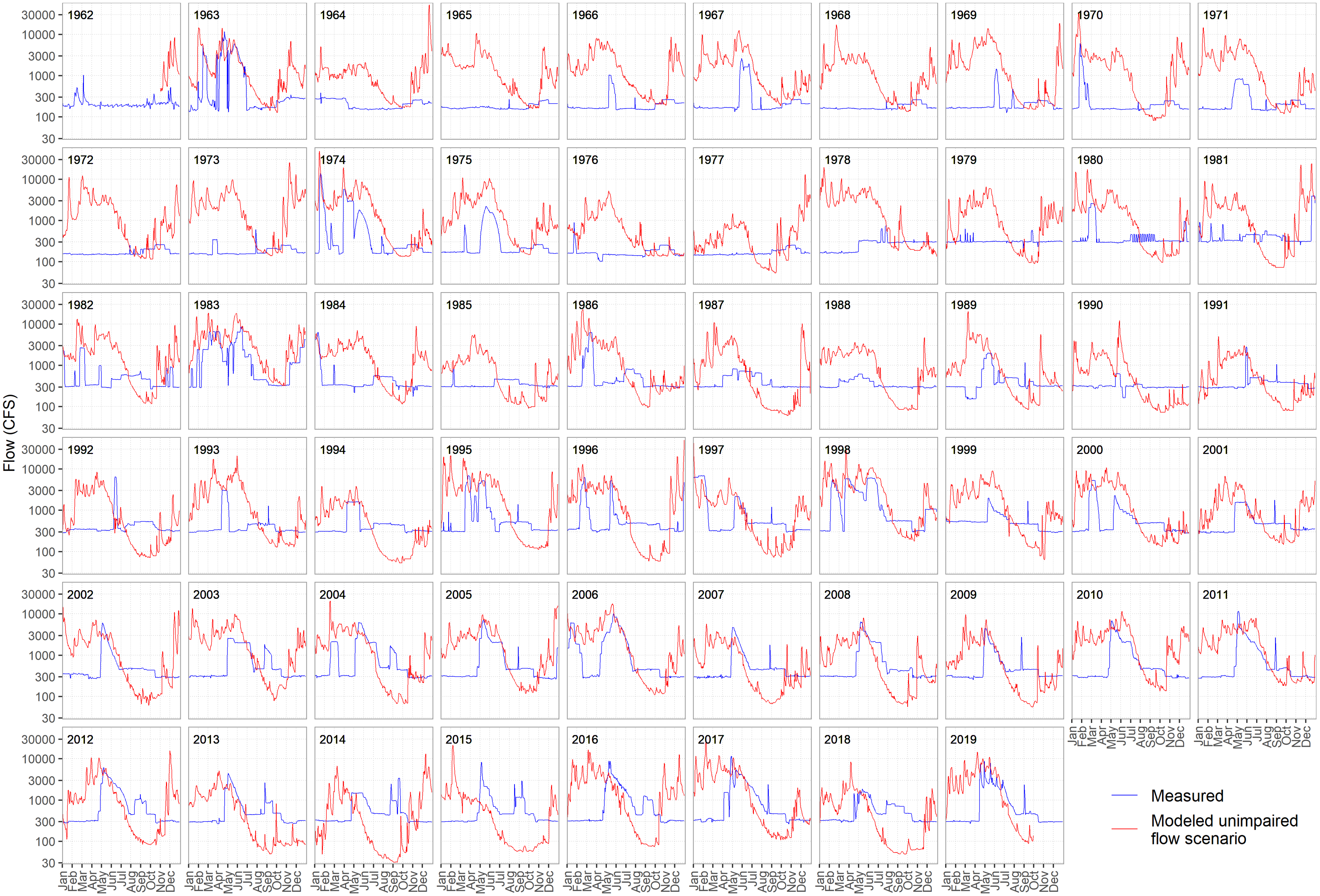


Figure 24. Daily mean flow time series for the Trinity River at Lewiston for each year 1962–2019, comparing measured flows to a modeled unimpaired flow scenario without dams and diversion.

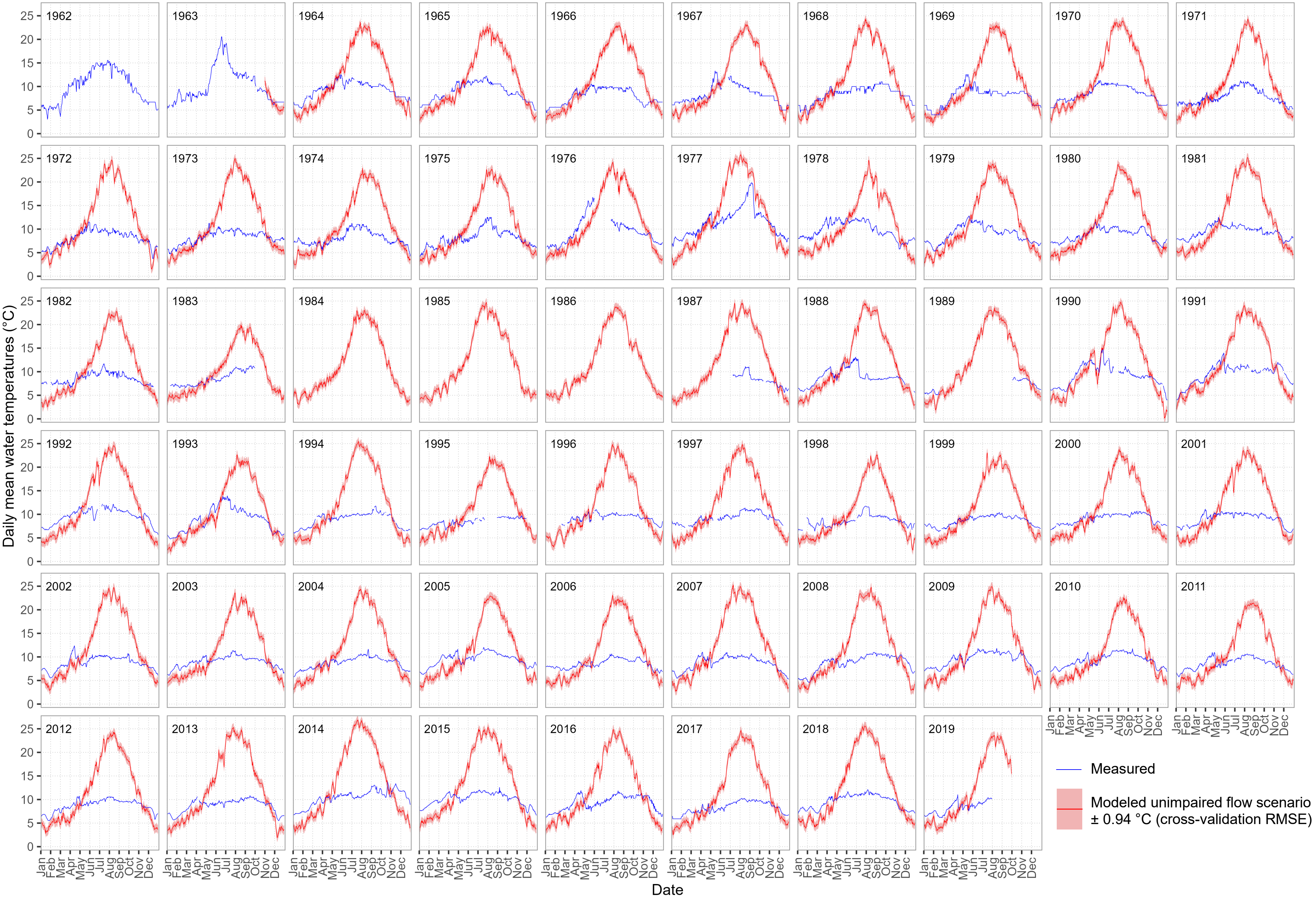


Figure 25. Daily mean temperature time series for the Trinity River at Lewiston for each year 1962–2019, comparing measured temperatures to a modeled unimpaired flow scenario without dams and diversion. Ribbon around model prediction line is ± 0.94°C, the root mean squared error (RMSE) from model cross-validation (Figure 22).

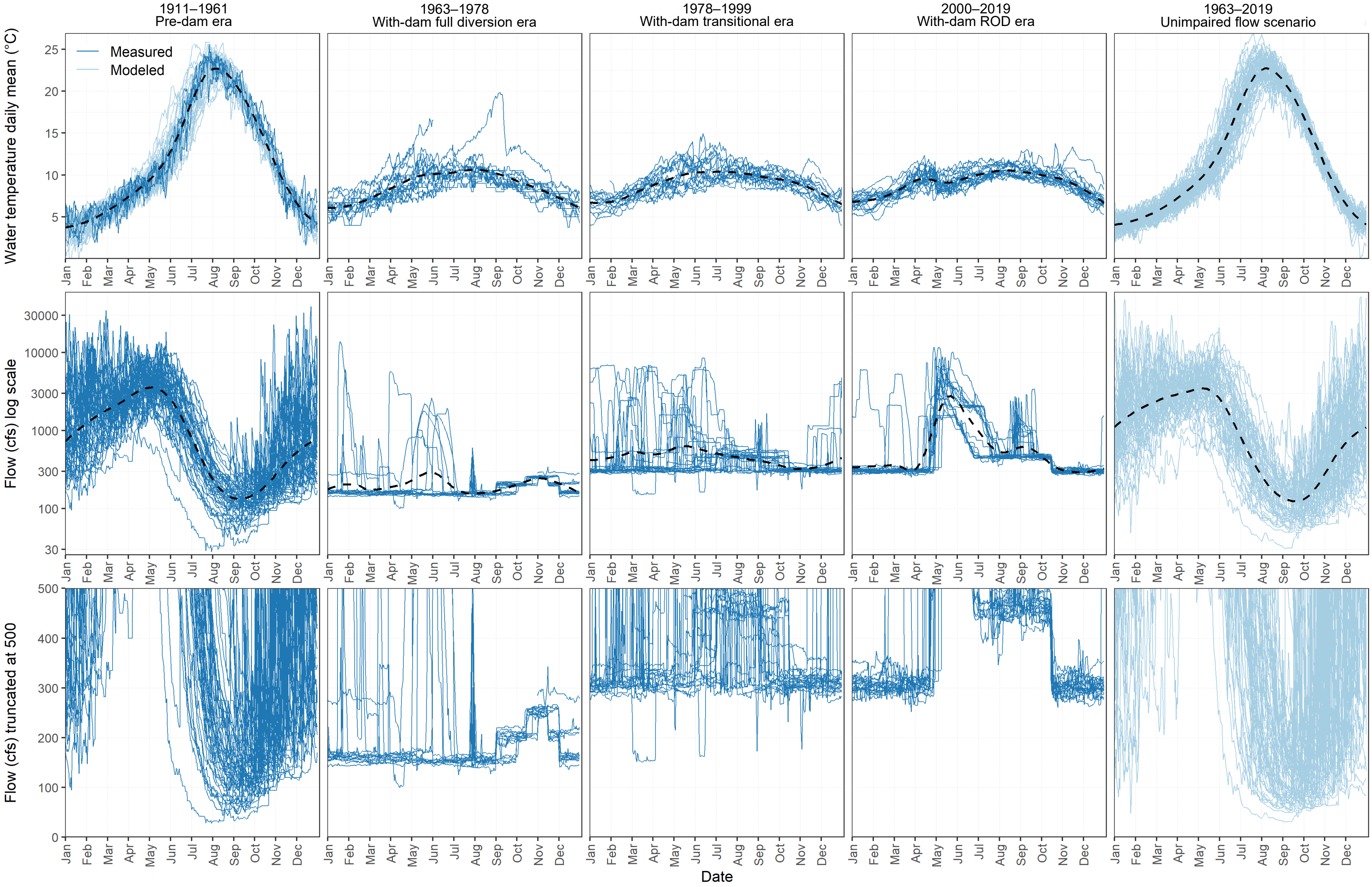


Figure 26. Daily time series of water temperature and flow for the Trinity River at Lewiston for each year 1911–2019, comparing the pre-dam era (10/1/1911–1/20/1961), with-dam full diversion era (10/31/1963–4/30/1978), with-dam transitional era (5/1/1978–9/30/1999), and with-dam ROD era (10/1/1999–2019), and a modeled unimpaired flow scenario (1963–2019) without the dams and diversion. Since there are only approximately six years of pre-dam temperature data (Figure 23) which did not include any drought years, modeled temperature data for additional pre-dam years are included to show the full range of variability. Dashed lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers fit to all data points in each panel. The 1/21/1961-10/30/1963 initial dam-filling period is not shown.

3.4.1.3 SUMMARY OF EFFECTS OF DAMS ON LEWISTON FLOWS AND TEMPERATURE

Using measured data and our model scenarios, we compared flows and temperatures in the Trinity River at Lewiston in different management eras: pre-dam era (10/1/1911–1/20/1961), with-dam full diversion era (10/31/1963–4/30/1978), with-dam transitional era (5/1/1978–9/30/1999), and with-dam ROD era (10/1/1999–2019) (Figure 26). The construction of the dams and associated diversion caused dramatic changes to flow and temperature of the Trinity River at Lewiston (Figure 26). Pre-dam era flows were dynamic with winter flows fluctuating in response to storm events, snowmelt causing an extended period of high runoff in winter thru early summer, a prolonged recession over summer reaching the lowest flows of the year in September or October, and finally rising again with the first fall rains. During the full diversion era approximately 90% of flow was diverted, with 150 cfs released most of the year (similar to the average minimum pre-dam flow) except during fall Chinook Salmon migration and spawning season when releases were increased to approximately 200 or 250 cfs. Additional flow was sporadically released in some years, primarily in January through June but many years included a short pulse flow in late July. Baseflows were increased from 150 to 300 cfs on May 1, 1978. In the transitional flow era, the amount and timing of additional flow released above baseflow was highly variable from year to year, in part due to experimental releases. Summer baseflows increased to 450 cfs in 1993. Volume of spring releases increased, and timing became very consistent during the ROD era.

In the pre-dam era as well as the unimpaired flow scenario, water temperatures in the Trinity River at Lewiston had a strong seasonal cycle, with daily mean temperatures of 5 °C in December–January, rising during spring until exceeding 20 °C for much of July through mid/early-September, and falling back to 5 °C in December (Figure 26). Temperatures in March-August, especially in May–July were much cooler in wetter years than drier years (Figure 27a), similar to other snowmelt tributaries such as Stuart Fork, East Fork Trinity River, and the Trinity River upstream of Trinity Reservoir (Figure 7). Daily maximum temperatures exceeded 25 °C in each summer with measured data during the pre-dam era (Figure 23), with a late summer diel range of approximately 3–7 °C. Since initially filling, Trinity Reservoir water released from the depth has resulted in typical daily mean temperatures of 10 °C in the Trinity River at Lewiston during the peak of summer (Figure 26), with a diel range of approximately 2 °C (Figure 20, Figure 40), although daily mean temperatures occasionally exceed 15 °C during droughts when the reservoir is drawn down and the water temperature at the intake depth warms (Figure 26, Section 3.3.1.2). This dam-driven temperature suppression in spring and early summer has profound effects on bioenergetics and growth of juvenile salmonids, explored in Section 5.1.2. Measured with-dam daily mean temperatures are typically cooler than in the modeled unimpaired flow scenario from May through early November, with a maximum difference of 12°C during late July/early August (Figure 27c). In April through August, with the strongest effects in June and July, the magnitude of the difference between with-dam temperatures and the modeled unimpaired flow scenario differs by water year type (Figure 27c), with larger differences in drier water year types that are driven primarily by warmer temperatures in the unimpaired flow scenario (Figure 27a). In November through mid-April, measured with-dam daily mean temperatures are typically warmer than the modeled unimpaired flow scenario by approximately 2.0 °C (Figure 27). Temperature effects on downstream reaches are presented in the next section of this report.

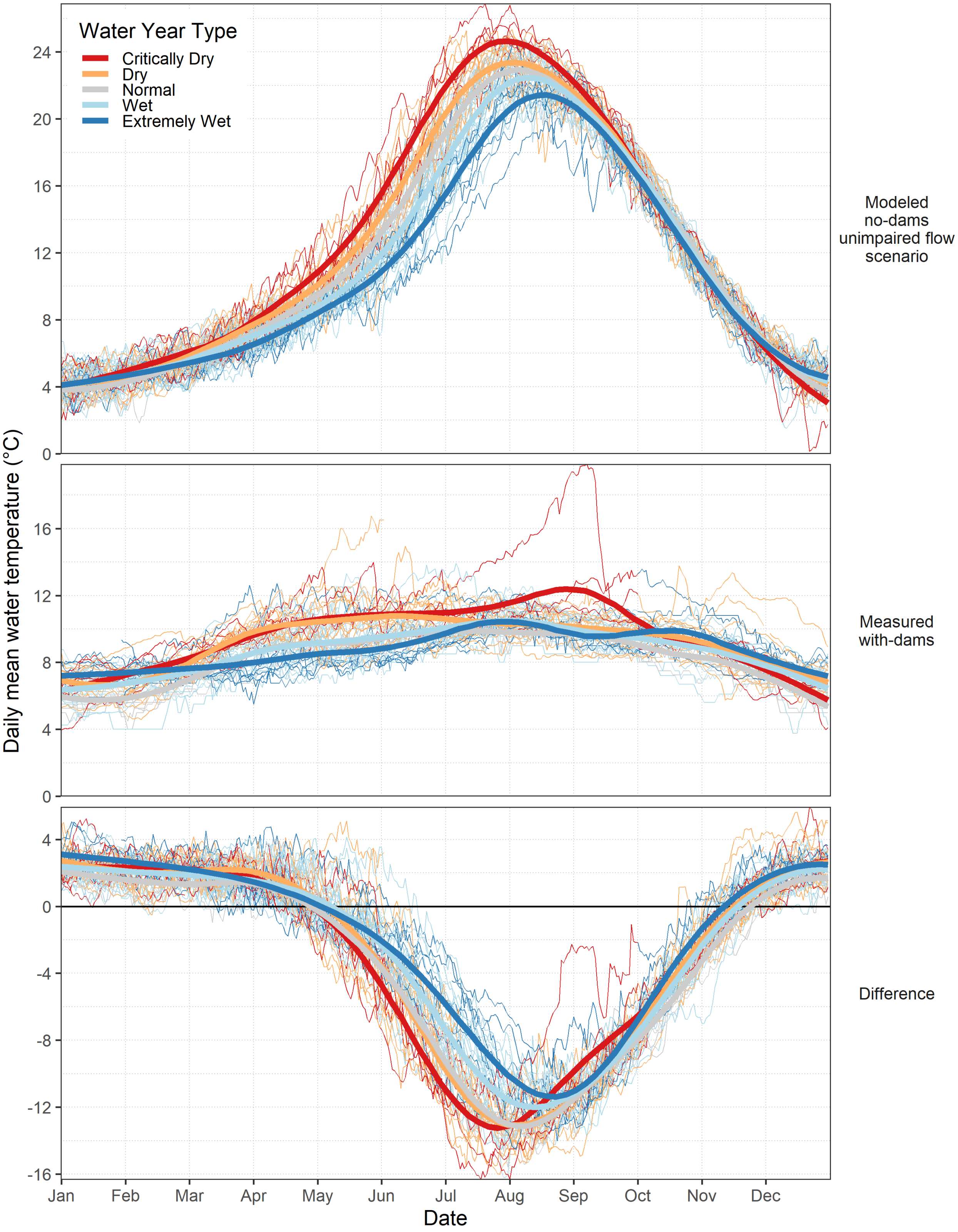


Figure 27. Daily mean water temperature time series for Trinity River at Lewiston 1963–2019, colored by water year type, showing (A) temperatures in a modeled no-dams unimpaired flow scenario, (B) measured with-dam temperatures, and (C) difference between the two. Thin lines are individual years while thick lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers.

3.4.1.4 DAM AND DIVERSION EFFECTS ON RIVER TEMPERATURES FROM LEWISTON TO WEITCHPEC

While the effects of Trinity Dam and associated diversion on water temperatures in the Trinity River at Lewiston are well-established (Section 3.4.1.3; Rowell 1979, Zedonis and Newcomb 1997, USFWS and HVT 1999), there is greater uncertainty in the effects on the lower Trinity River. In contrast to upper Trinity River where there are pre-dam continuous water temperature data for Lewiston (Figure 23: Moffett and Smith 1950; Murray 1960, 1961; USGS gage 11525500) and Douglas City (Moffett and Smith 1950), pre-dam data are almost completely lacking for the lower Trinity River, so the effects of damming and diversion must be estimated using models. To our knowledge, the only previous effort to directly model pre-dam temperatures in the lower river was Rowell (1979) (Figure 28). Rowell (1979) found that pre-project temperatures at Hoopa were approximately 0.6 °C (1 °F) cooler in April and approximately 1.7 °C (3 °F) cooler in May and June (Figure 28) than in the full-diversion with-dam era.

We used RBM10 to compare temperatures between a no-dam unimpaired flow scenario and a constant 350 cfs dam releases (Figure 29). We would have preferred to model the 150 cfs constant baseflows of 1963–1978 full diversion era, but 350 cfs is the lowest warm-season release that can reliably be modeled with RBM10 (Section 2.3.3.3) and is similar to the post-1978 baseflows of 300 cfs that occurred in the early transitional flow era. Our RBM10 model results at Willow Creek and Weitchpec comparing the 350 cfs dam releases and the no-dam unimpaired flow (i.e., pre-project) scenarios are similar to Rowell's results (i.e., temperatures are cooler in the unimpaired flow scenario for April–June) but the magnitude of differences is less in our results, especially for June (Figure 28 and Figure 29). Our results indicate that the unimpaired flow scenario is cooler than the 350 cfs constant dam release by approximately 0.5 °C in April, 1 °C in May, and 0.5 °C in June. There also appears to be longitudinal and water year differences in date at which the unimpaired flow scenario becomes warmer than the 350 constant dam release – May 1 at Lewiston regardless of water year type, mid-June at Weitchpec in Dry and Critically Dry water year types, and early July at Weitchpec in other water year types.

Results from Rowell (1979) are subject to a relatively high degree of uncertainty for several reasons: 1) due to lack of tributary temperature data, tributary temperatures were set through calibration, and 2) only four years were modeled (1964, 1974–1976). In addition, the monthly temporal resolution does not allow evaluation of temporal differences occurring at shorter time scales. Our RBM10 model results for the unimpaired scenario (i.e., no dam or diversion) (Figure 29) should be more reliable than Rowell (1979) due to use of a much larger amount of input data and calibration data. Our daily timestep also allows more fine-scale temporal evaluation of temperature predictions.

Zedonis and Newcomb (1997) did not directly model pre-dam temperatures in the lower river but made inferences that combined two separate pieces of evidence, namely that 1) measured temperatures indicate monthly average pre-dam temperatures at Lewiston were cooler than with-dam in April and similar in May (Figure 30), and 2) SNTEMP modeling indicates that when large volumes of cold water are released from Lewiston Dam water can travel downstream the full length of the Trinity River before heating more than a few degrees. They concluded "These larger flows would have resulted in a thermal regimen in the lower Trinity River that was as much as a 2.1°C colder (e.g., for the week of May 27 under median conditions) than contemporary flow conditions (8.5 cms (300 cfs))". Given that Zedonis and Newcomb (1997) modeling was based on cold releases from Lewiston Dam, instead of a unified quantitative analysis that actually modeled pre-dam temperatures at Lewiston and routed it downstream, we do not consider their inferences about pre-dam lower Trinity River temperatures to be as reliable as our modeling. In summary, while we agree with Zedonis and Newcomb (1997) and Rowell (1979) that April–June lower Trinity water temperatures were cooler in the pre-dam era than in the with-dam full diversion era, our modeling indicates that they overestimated the magnitude of these differences. Analyses by Zedonis and Newcomb (1997) were a core component informing the establishment of the new flow regime set forth in the Trinity River Flow Study (USFWS and HVT 1999) and later codified in the ROD.

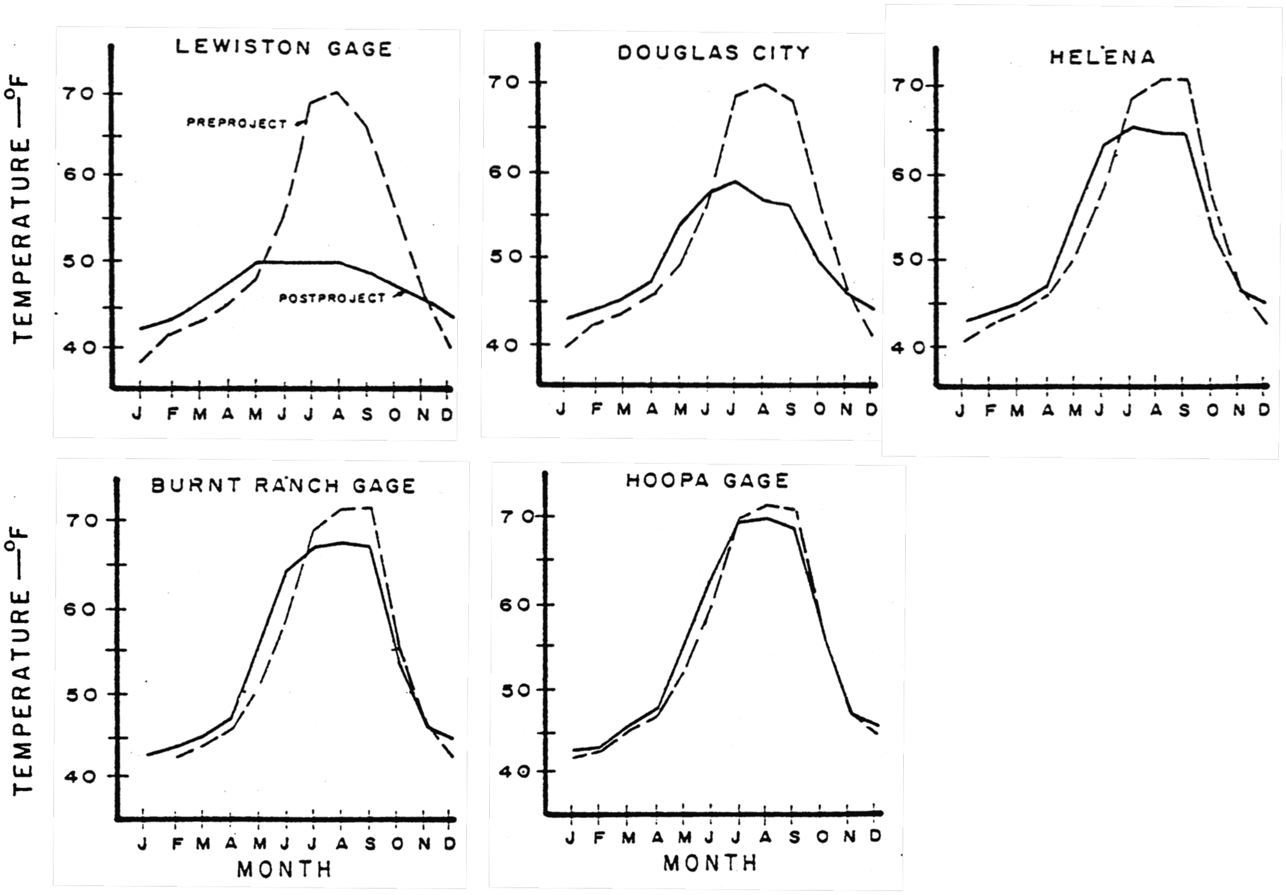


Figure 28. Modeled average monthly water temperatures at several locations of the Trinity River before and after construction of the Trinity River Division. Figure adapted from Frederiksen, Kamine and Associates (1980) and Zedonis and Newcomb (1997), but original source is Rowell (1979).

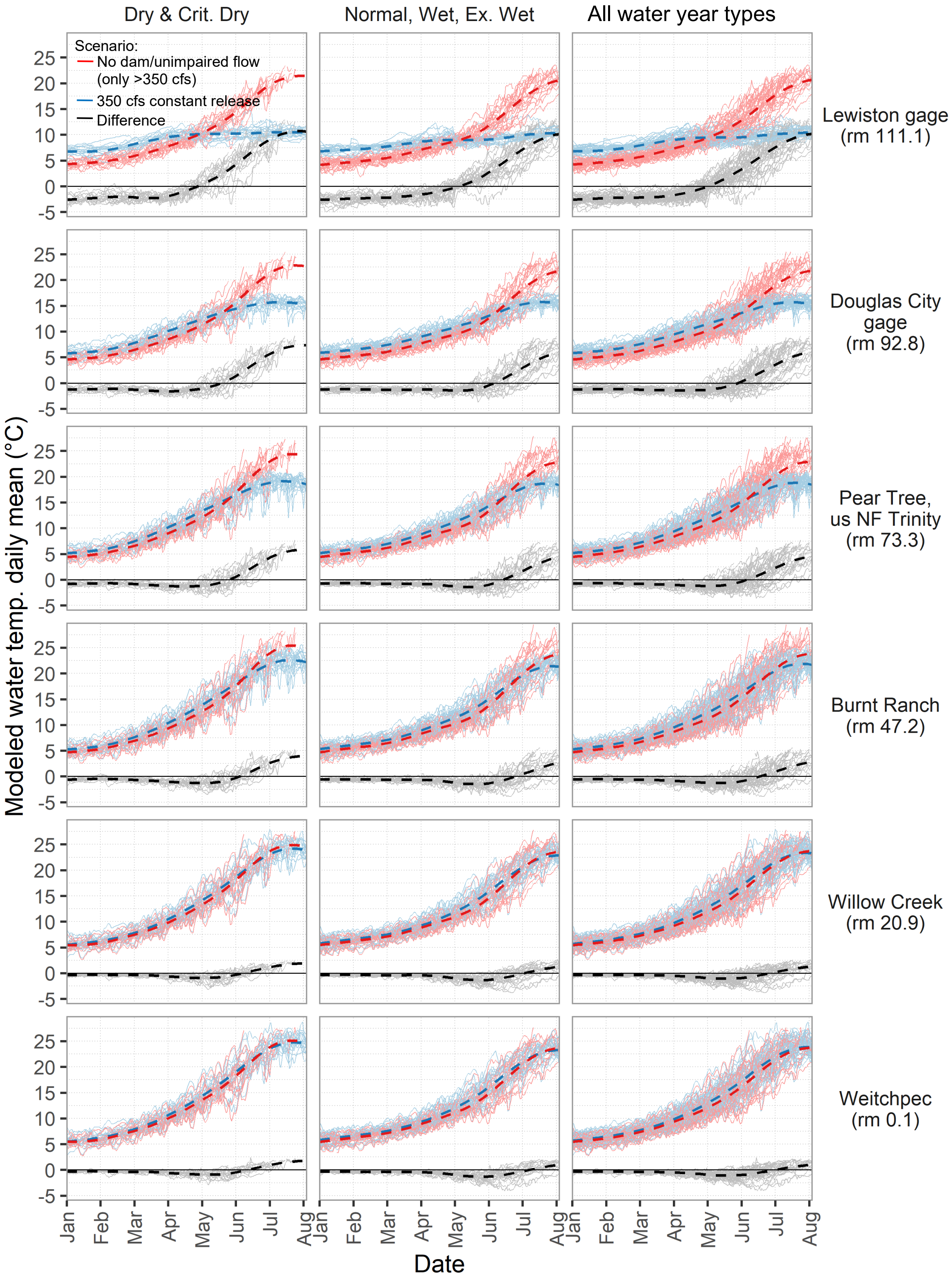


Figure 29. Daily mean water temperatures for the months of January–July at selected mainstem Trinity River sites modeled with RBM10 comparing two scenarios (no-dam unimpaired flow and constant 350 cfs dam release) and condensed actual water year types (Dry/Critically Dry and Normal/Wet/Extremely Wet) for years 1980–2018. The RBM10 model was not calibrated for Lewiston releases less than 350, so days with unimpaired Lewiston releases less than 350 cfs are not shown. Dashed lines are GAM (generalized additive model) smoothers representing typical conditions for the time of year.

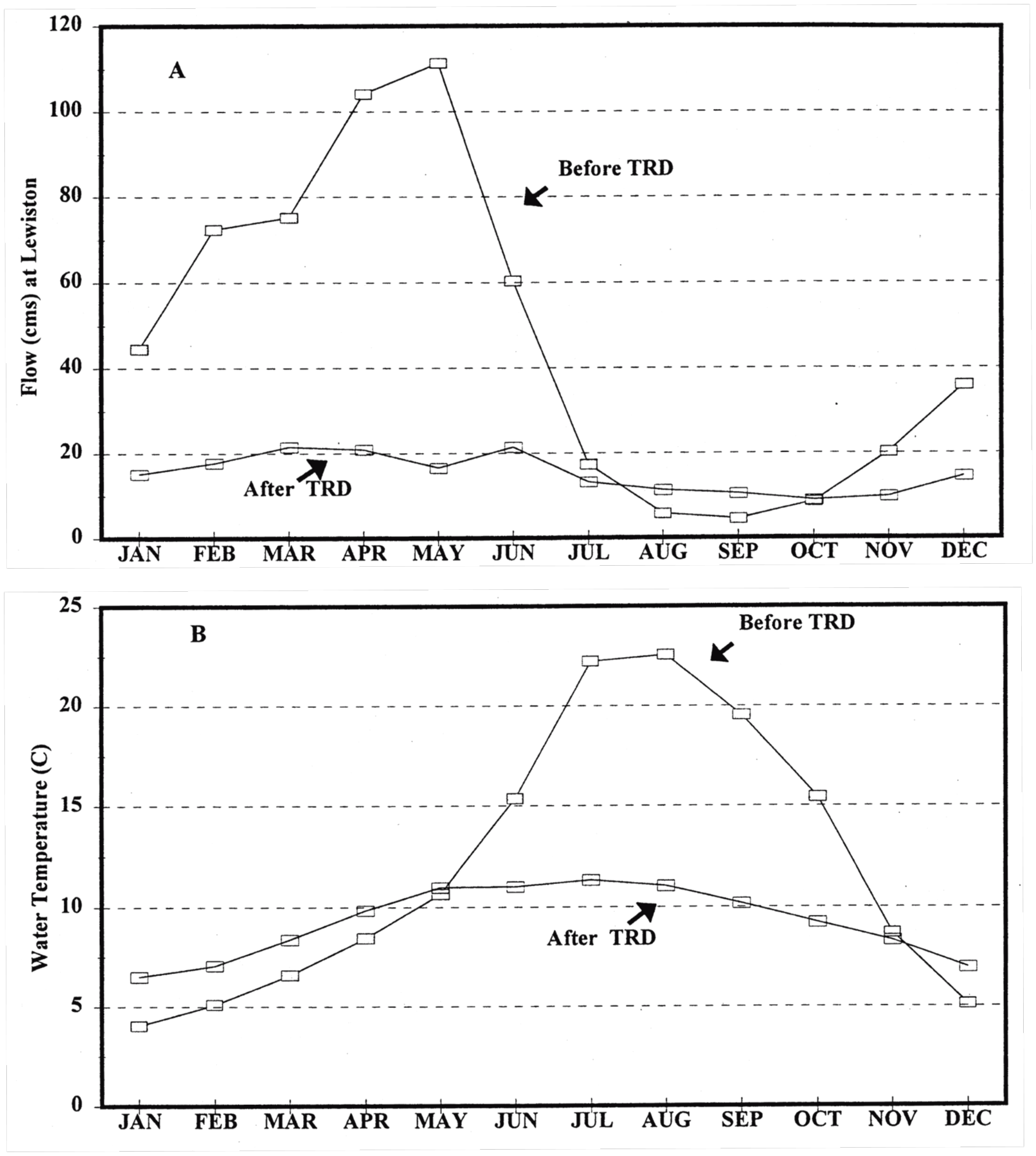


Figure 30. Average monthly river flow (A) and water temperatures (B) at Lewiston before and after construction of the Trinity River Division in 1963. Flow data are from 1912 to 1959 (before) and 1978 to 1994 (after), and water temperature data are from 1942 to 1946 and 1959 to 1960 (before), and 1964 to 1983 and 1987 to 1992 (after). Figure adapted from Zedonis and Newcomb (1997) Figure 2A and 2B.

3.4.2 AMBIENT EFFECTS

3.4.2.1 AIR TEMPERATURE AND SOLAR RADIATION

Many studies from around the United States (Mohseni et al. 1998), Western United States (Isaak et al. 2017), Pacific Northwest (Mayer 2012, Luce et al. 2014), and Klamath Basin (David at al. 2018, Asarian et al. 2020) have found a strong correlation between air temperature and water temperature; however, this correlation does not necessarily imply causation (Johnson 2003; Caissie 2006). Air temperature and water temperature are highly correlated because both respond to the same temporal patterns in solar heating (Johnson 2004). Solar radiation that reaches the water surface is the most important term in stream energy budgets (Johnson 2003). In contrast, convection of heat from air to water is less important process (Johnson 2004).

Air temperature sensitivity is the expected change in stream temperature per unit change in air temperature (Mayer 2012, Luce et al. 2014). When using a multiple regression model to predict stream temperature, the air temperature sensitivity is the model's air temperature coefficient. These values typically range from 0–1 °C air/°C water. Example air temperature sensitivity was 0.44 °C/°C in the Salmon River watershed (Asarian et al. 2019), 0.22 °C/°C for the lower Klamath River and adjacent coastal tributaries (Asarian et al. 2017), 0.47 °C/°C for 104 Pacific Northwest streams (Mayer et al. 2012), and 0.51 °C/°C for 246 Pacific Northwest streams (Luce et al. 2014). The sensitivity of stream temperatures to air temperature are discussed further in Section 6.2 (Climate change).

3.4.2.2 SHADING

Topographic (i.e., hills, mountains, and stream banks) and riparian shading affect temperatures of lotic waters, including the Trinity River (Zedonis 1994). Topographic and riparian shade both vary over the year in response to the sun's position in the sky (i.e., solar elevation and azimuth angles). Since many riparian trees are deciduous (e.g., willow, cottonwood, alder, maple), riparian shade is also affected by the annual cycle of leaf-on and litter fall.

Watercourse Engineering (2007) conducted a GIS analysis to calculate topographic shade on the Trinity River as part of the sub-daily temperature model; however, the final report does not present any summaries of topographic shade or its effect on simulated water temperature, and we were unable to obtain model files or original spreadsheets with the data.

The RBM10 model (Jones et al. 2016) and the Watercourse Engineering (2007) sub-daily model do not include the effect of riparian shading, but the older SNTEMP model does (Zedonis 1994, Zedonis and Newcomb 1997). Applying SNTEMP to model potential effects of feather edge and side channel projects on the upper Trinity River temperatures by increasing channel width and decreasing riparian shading, Zedonis (1994) concluded that riparian vegetation had only relatively minor effects on temperatures at the two Lewiston flow releases modeled (300 cfs and 800 cfs). Combined effects of increased channel width and decreased riparian shading (these effects were not modeled separately) were greatest in hot, dry years during Lewiston releases of 300 cfs in July, where Trinity River warmed by up to 0.16 °C at Douglas City and 0.30 °C at Trinity Canyon Lodge upstream of the North Fork; however, effects were much smaller at higher Lewiston flows, during other months, and other climate/water year types. The effect of riparian vegetation on temperature is likely greater in the reach from Lewiston to Douglas City than in downstream reaches (Watercourse Engineering 2007). Riparian vegetation has been mapped for the Restoration Reach (HVT and McBain & Trush 2006, 2007) and at individual habitat restoration sites (Alvarez et al. 2011). Recent river-wide calculations of riparian shading do not currently exist but could be derived from existing Lidar data (Buffington et al. 2014).

3.4.2.3 WILDFIRE SMOKE

Smoke produced by wildfires can reflect solar radiation, reducing air and river temperatures (David et al. 2018). These cooling effects are particularly strong when multi-day thermal inversions form, which trap smoke in river canyons and valleys (David et al. 2018, Kochanski et al. 2019). For both air and water, smoke has a greater cooling effect on daily maximum temperature than daily mean temperature (David et al. 2018, Asarian et al. 2020).

Smoke cooling of water temperatures is an episodic phenomenon with seasonal patterns, occurring only when smoke is present. Years with major smoke production in the Klamath-Trinity Basin include 1987, 1999, 2002, 2006, 2008, 2012–2015 (David et al. 2018), 2017 (Asarian et al. 2020), and 2018. NASA satellites provide high-resolution daily remote-sensed records of smoke prevalence since 2000 (Lyapustin et al. 2018), but smoke data prior to 2000 are much lower quality (Asarian et al. 2020). August typically has more smoke than other months, but any day June–October can also have substantial amounts of smoke in some years (David et al. 2018, Asarian et al. 2020). In 2008, several large fires started abnormally early (late June) and burned through the entire summer, cooling river temperatures across much of the Klamath Basin (David et al. 2018; Asarian et al. 2020). Not coincidentally, as discussed below in Section 4.3.1, 2008 was the only year on record with zero exceedances of the juvenile outmigration temperature criteria in the Trinity River at Weitchpec. To date, smoke cooling of water has been assessed using statistical approaches (David et al. 2018; Asarian et al. 2020) but not energy budget simulation models.

An analysis of 87 long-term stream temperature monitoring sites in the Klamath Basin, including the Trinity River at Weitchpec, found that smoke had a greater cooling effect in August than in July and September (Asarian et al. 2020). For mean daily maximum August stream temperature, smoke had the greatest cooling effect in tributaries with larger drainage areas (e.g., 2.4°C for the 751mi^2 Salmon River Basin), the least cooling effect in tributaries with the smallest drainage areas (0.1°C for a 3.9 mi^2 tributary), and an intermediate effect in the mainstem Klamath and Trinity rivers (1.5–1.6°C). Cooling effects of smoke may be diminished in small tributaries because riparian and topographic shading provide greater protection from solar radiation for streams than wider mainstem rivers (Asarian et al. 2020).

David et al.'s (2018) analysis of the cooling effects of smoke on river temperatures included two sites in the Trinity River watershed. Multiplying the smoke coefficient (i.e., cooling per unit of smoke) from David et al.'s (2018) statistical models by the highest smoke level observed during the study period provides an estimate of expected cooling under the smokiest conditions. For the South Fork Trinity River near its mouth and the Trinity River at Weitchpec, the expected cooling under the smokiest conditions was 3.4 °C and 2.5 °C, respectively, for daily maximum temperatures, and 2.1 °C at both sites for daily mean temperatures.

Smoke is harmful to human health (Mott 2002) which limits the practicality of using it as a management tool for cooling rivers. However, there may be specific instances in which it would be appropriate. For example, given the cultural importance of spring-run Chinook Salmon, the Karuk Tribe's (2019) Climate Adaptation Plan calls for the use of prescribed fire to generate smoke and cool rivers as an emergency measure during acute conditions such as a severe drought.

3.4.3 TRIBUTARY EFFECTS ON MAINSTEM CONDITIONS

3.4.3.1 FLOW

The largest tributaries to the Trinity River are South Fork Trinity River, New River, and North Fork Trinity River (Figure 31). Relative flow contributions of tributaries and Lewiston releases to Trinity River flow varies strongly by time of year and site. Not surprisingly, the cumulative contribution of flow from tributaries is greater at downstream sites than sites closest to the dam

(Figure 32). For example, in January–March, the ratio of river flow to Lewiston releases is approximately 3 at Douglas City but greater than 10 at Weitchpec. The relative contribution of Lewiston release increases when ROD flow spring releases start and continue rising through summer (Figure 32) because baseflow releases are many times greater than unimpaired flows. By early September, flows at upper Trinity River sites are almost entirely derived from Dam releases in all water year types. At Weitchpec, early September flows are about 1.2–1.7 times Lewiston releases, depending on water year type. When the first substantial rains occur in September or October, tributary flows increase and generally continue to rise through January (Figure 32). Relative to an unimpaired flow scenario, tributary contributions in the historical dam-regulated scenario are similar in May and June, lower in July through early October, and much higher November through April (Figure 33).

3.4.3.2 TEMPERATURE

The effect of tributaries on temperatures in the mainstem Trinity River varies dynamically with time and space according to the flows and temperatures of each tributary and each mainstem site. Effects will be greatest when a tributary's flow is high relative to the mainstem and the greater the difference in its temperatures compared to the mainstem. Multiple tributaries can have cumulative effects, although the distance between tributary inputs will diminish these effects. For most of the year, temperatures and flows in tributaries are less altered by human activities than the dammed and diverted mainstem; however, water diversions during summer and early fall can deplete flows in tributaries such as Rush, Indian, Weaver, and Browns Creeks where there are substantial human populations and/or agriculture.

The Trinity River temperature monitoring network is designed to capture broad longitudinal patterns, not to bracket (i.e., both upstream and downstream) tributaries, so we use the RBM10 model to evaluate tributary effects. RBM10 model results indicate that the largest tributary-driven changes occur downstream of the North Fork Trinity River, New River, and South Fork Trinity River (Figure 34), which is not unexpected given that they are the largest tributaries, and RBM10 tributary flows are largely based on watershed area (Figure 31). The South Fork Trinity River is warmer than mainstem Trinity River in most months, while the North Fork is warmer only in June–September and the New River is warmer only August–September of all water year types as well as June-July in Normal, Wet, and Extremely Wet water year types. On a monthly average basis, tributaries of the upper Trinity River are typically colder than the mainstem in November–March, except for Grass Valley Creek which is typically warmer (Figure 34). Tributary flows appear to have relatively little impact on water temperatures during October, November, and March. During winter (December-February), somewhat counter-intuitively, as tributaries are generally cooler than mainstem rivers, Trinity River water temperatures at Douglas City and Above North tend to be warmer during days with high tributary flows (i.e., winter storms) (Figure 36), likely due to warmer air temperatures during rainstorms increasing water temperatures in the tributaries and the mainstem, relative to cold, low-flow, clear-sky conditions. As air temperatures rise in March and April, the situation reverses and high flows from melting snow in upper Trinity River tributaries are associated with cooler Trinity River water temperatures at Douglas City and Above North Fork (Figure 36). Willow Creek, Horse Linto Creek, and Tish Tang Creek, as well as tributaries on the Hoopa Reservation including Mill Creek are not shown in Figure 34 because they are not included in RBM10, all offer potential to provide thermal refugia (Section 5) in April–October because their temperatures are cooler than the mainstem Trinity River.

Under a scenario with unimpaired mainstem flow and no dams, the temperature differences between the mainstem and tributaries are much reduced, especially between Lewiston and the North Fork (Figure 35). Temperature differences between tributaries and the lower Trinity River would be similar to current conditions (Figure 35), but we speculate that the volume of cold-water refugia available to fish at the mouths of lower tributaries in late summer (Naman 2005, Section 1.2.2) would increase due to relative contributions of mainstem and tributary flows.

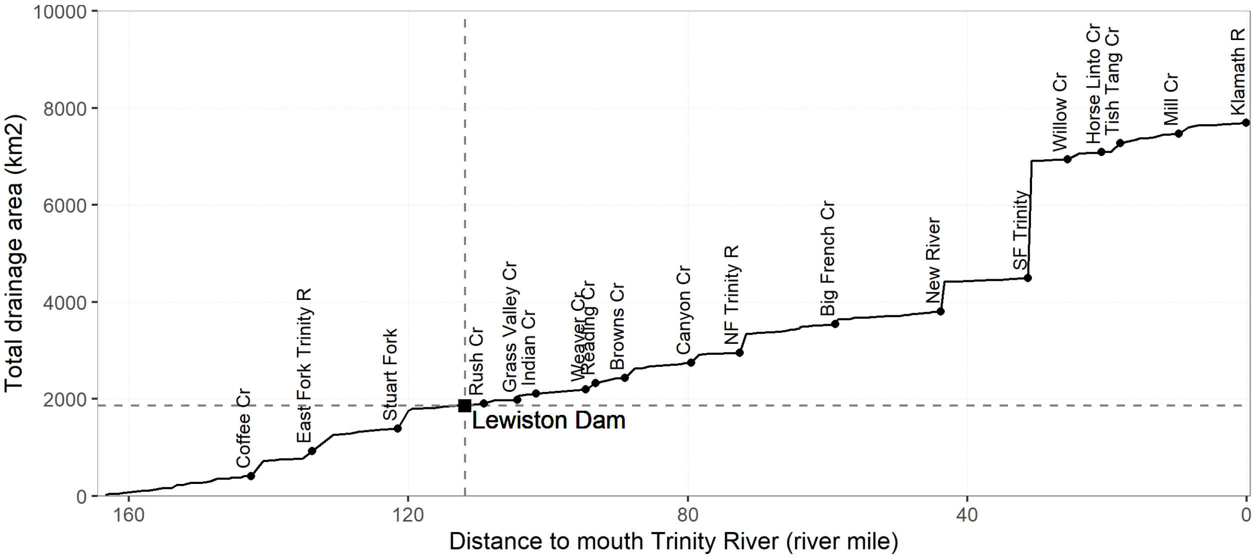


Figure 31. Profile of the Trinity River showing drainage area (km2 = square kilometers) and major tributaries from headwaters to its mouth where it flows into the Klamath River. Rise in drainage area downstream of tributary indicates tributary size. Intersection of dashed lines is Lewiston Dam. Data sources: drainage areas from NHDplus, river miles from TRRP.

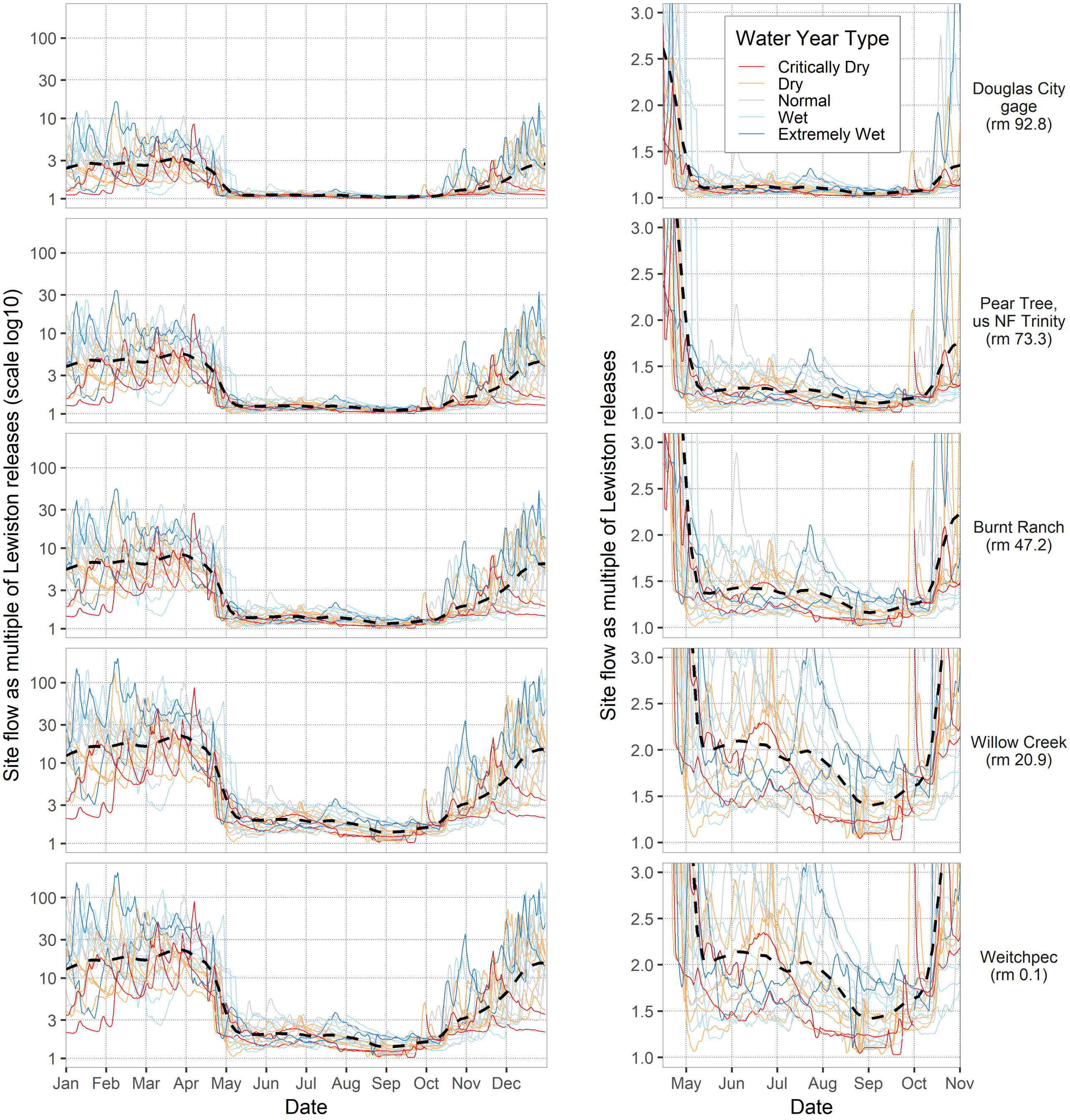


Figure 32. Daily flow at selected mainstem Trinity River sites as a ratio of Lewiston releases, from the RBM10 historical scenario for each year 2000–2018. Flows from RBM10 model. Dashed black lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers fit to all data points in each panel.

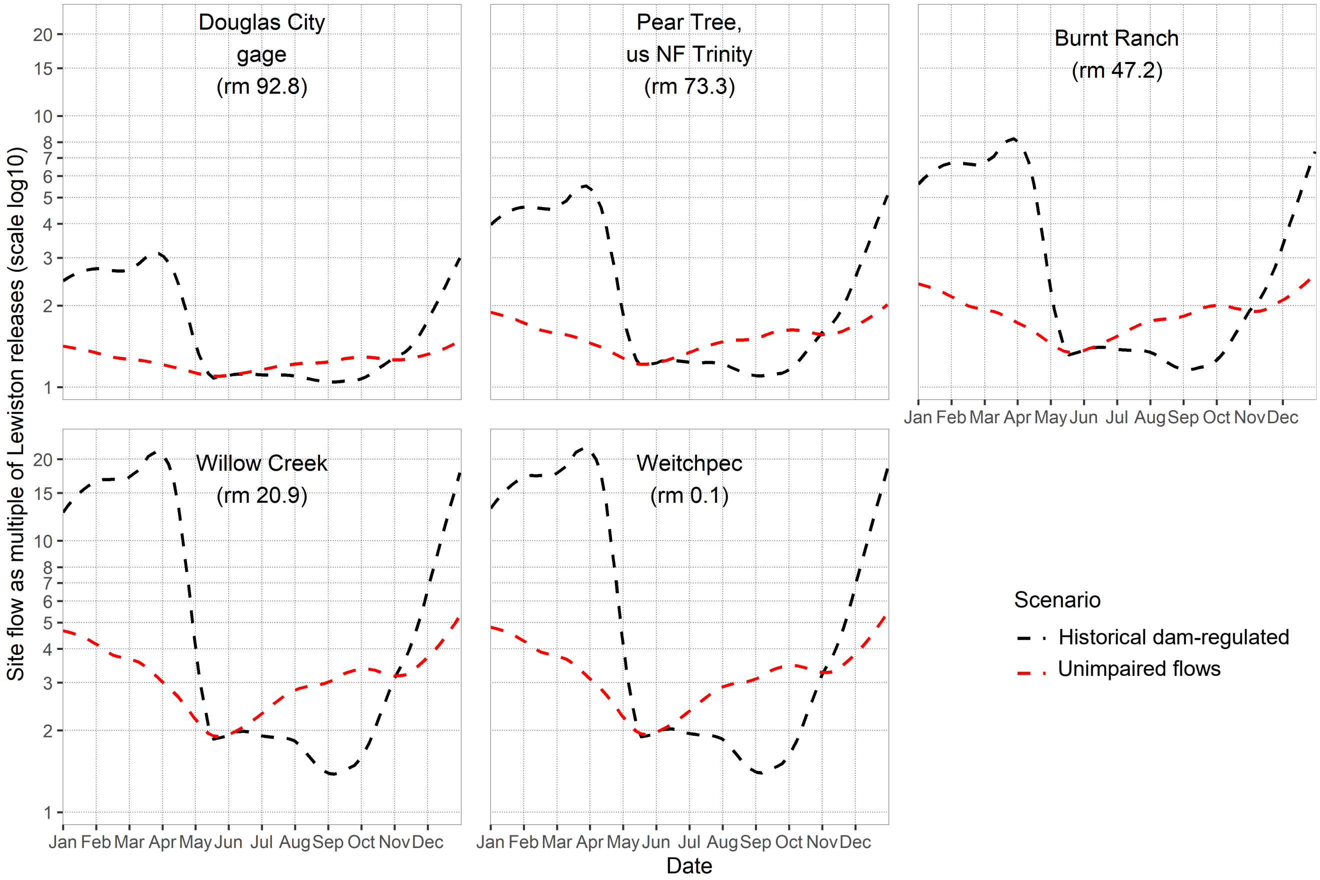


Figure 33. Seasonal patterns in 2000–2018 daily flow at selected mainstem Trinity River sites as a ratio of Lewiston releases, comparing the RBM10 historical dam-regulated flow scenario and unimpaired (i.e., no dams or diversion) flow scenario. Flows from RBM10 model. Dashed lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers representing typical conditions for the time of year (black dashed line is same as Figure 32).

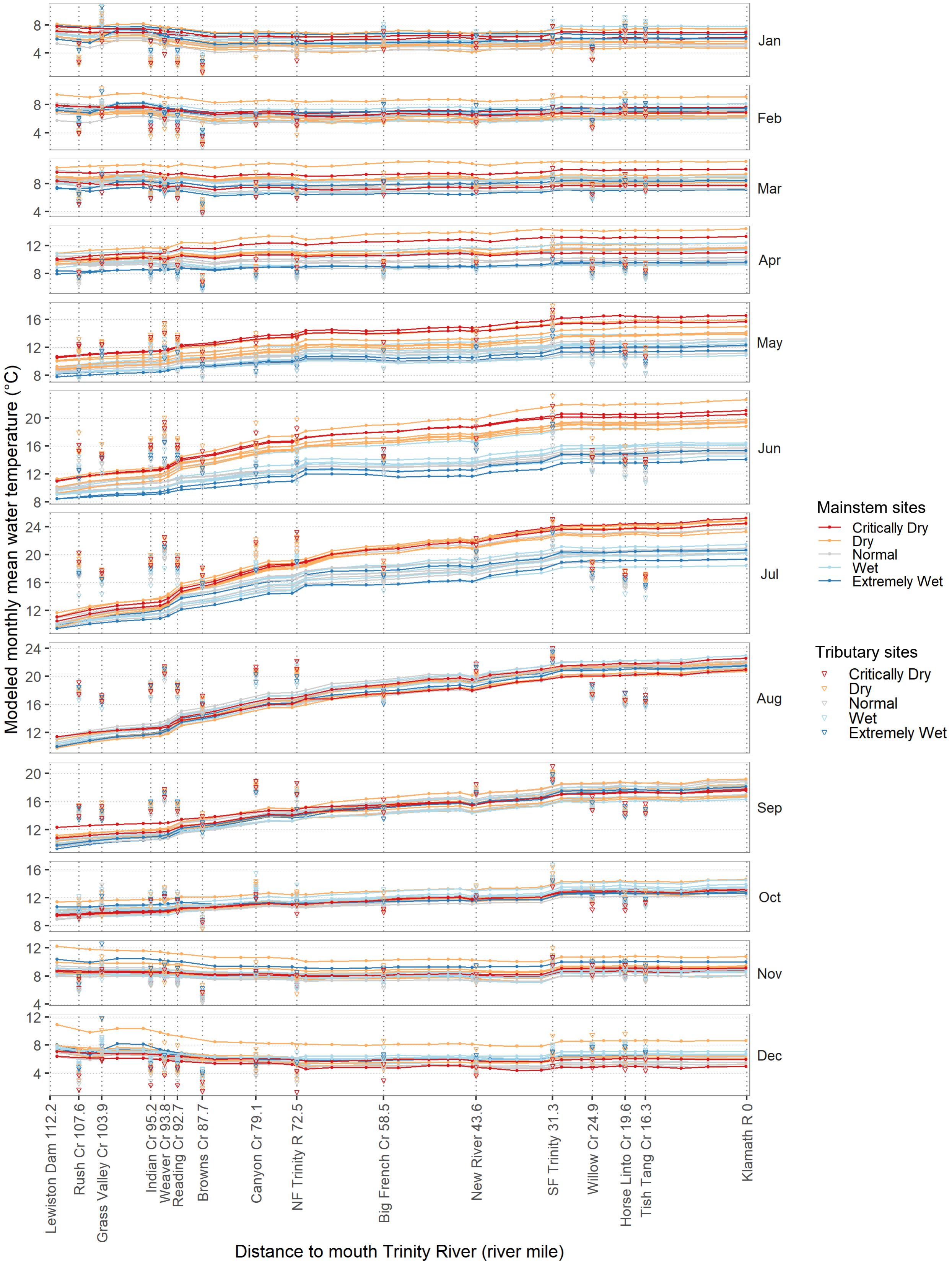


Figure 34. Profile of RBM10-modeled monthly mean mainstem Trinity River temperatures by river mile, for the years 2000–2018 under the historical scenario. X-axis is labeled by tributaries and river miles from Appendix A of Jones et al. (2016). Each line is a different hydrologic year. Dots are reporting nodes, typically reach mid-points. Positions of Indian Creek and Weaver Creek are adjusted for legibility.

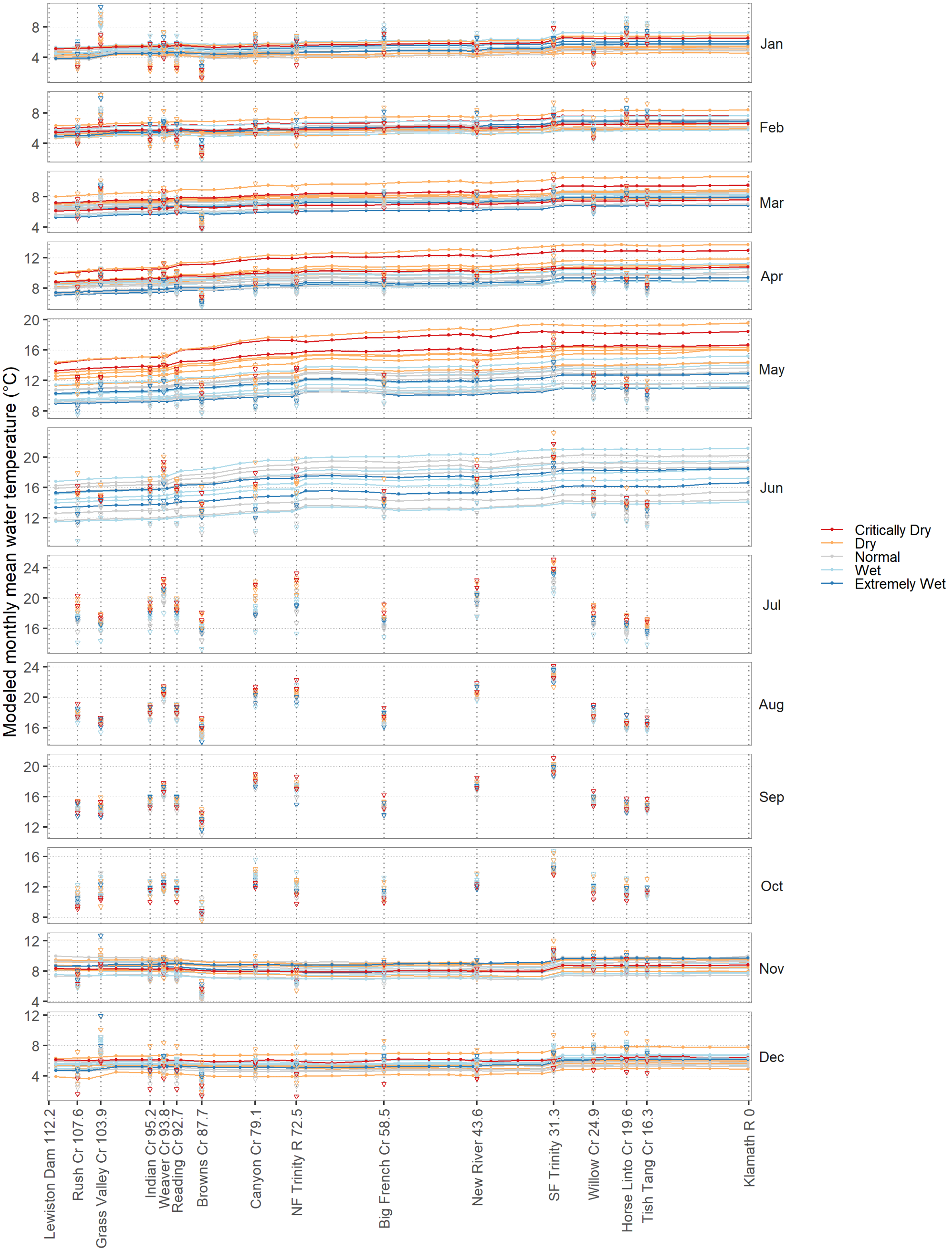


Figure 35. Profile of RBM10-modeled monthly mean mainstem Trinity River temperatures by river mile, for the years 2000–2018 under a scenario with Lewiston releases set to unimpaired flows and without-dam temperatures. Only days with Lewiston flows >350 cfs are included, so data not shown for June in Dry and Critically Dry water year types or July–October because there are too few days to be representative. See Figure 34 for additional notes.

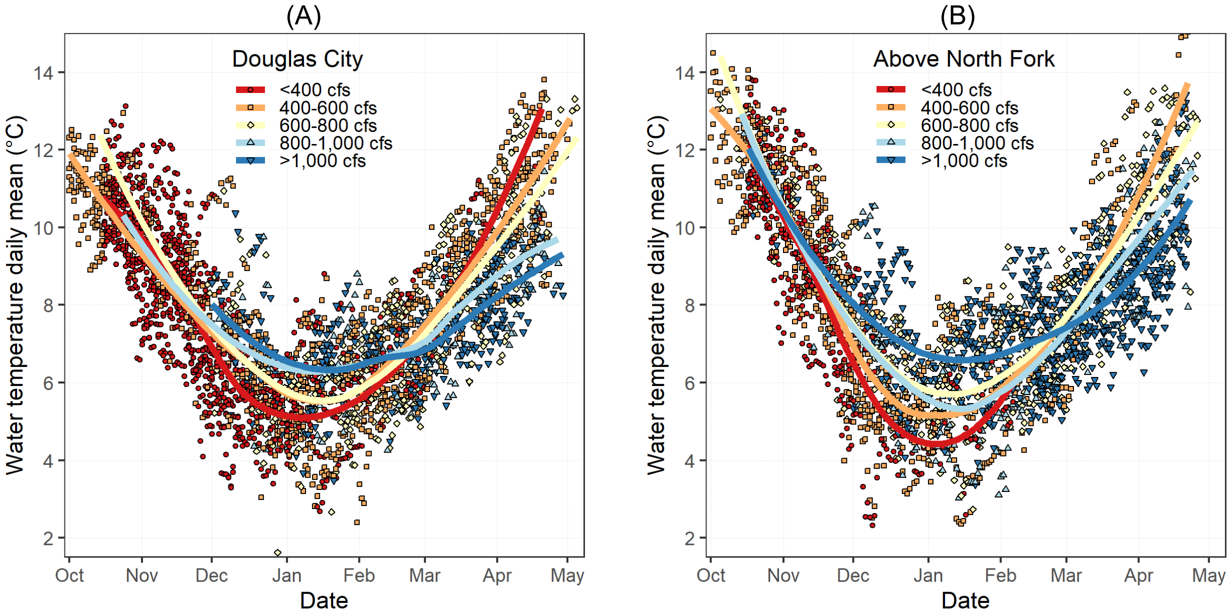


Figure 36. Measured daily mean water temperature at (A) Douglas City, and (B) Above North Fork as a function of date, for every day when Lewiston releases were less than 450 cfs in the months of October–May of the years 2002–2019. Points are grouped according to measured flow. Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers representing typical conditions for the time of year.

3.4.4 EFFECTS OF FLOW REGULATION ON RIVER TEMPERATURES

3.4.4.1 THERMALLY STABLE NODES AND ANTINODES RESULTING FROM FLOW REGULATION

Thermally stable river nodes of minimum diel (daily cycle) temperature range often form on regulated rivers approximately 24 and 48 hours travel time downstream of the dam, with corresponding anti-nodes of maximal diel variability at 12 and 36 hours travel time (Lowney 2000, Watercourse Engineering 2007), including on the Klamath River (Deas and Orlob 1999) and Sacramento River (Lowney 2000). These nodes and antinodes are detectable in some outputs from the hourly Trinity River RMA-2/RMA-11 model (Figure 37) but are not always apparent at summer baseflow (Watercourse Engineering 2007).

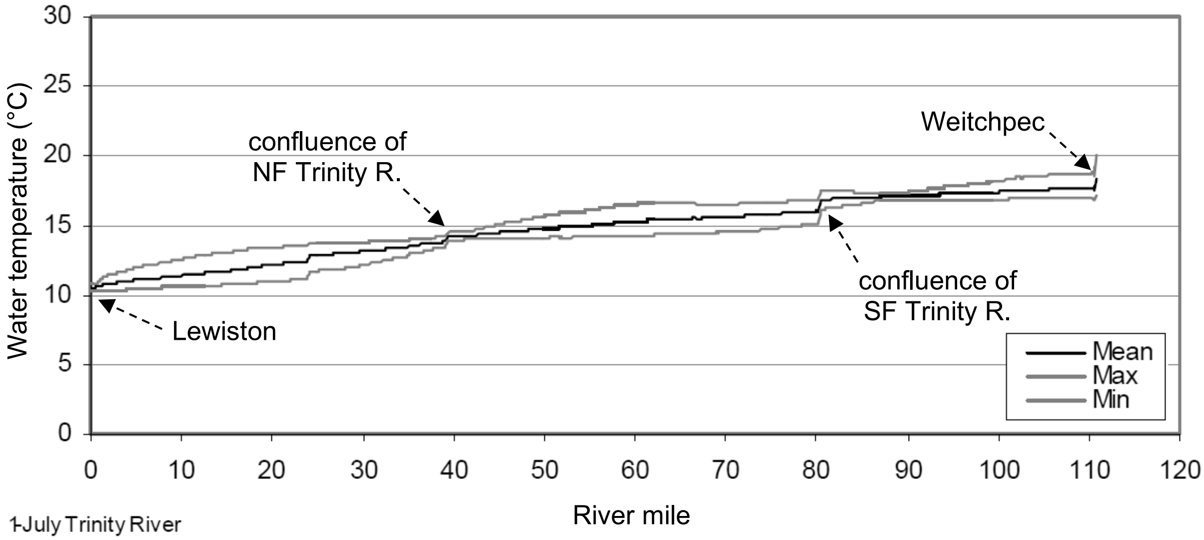


Figure 37. Model predictions of maximum, mean, and minimum water temperatures in the Trinity River showing nodes of minimum diel variation at RM 40 [Rkm 64, near confluence with North Fork of the Trinity River] and RM 90 [Rkm 145, near Horse Linto Creek] on July 1, 2005 with 2,060 cfs Lewiston flows. Figure from Watercourse Engineering (2007).

3.4.4.2 DIEL TEMPERATURE PATTERNS

As demonstrated throughout this report, flow regulation has strongly modified the temperature regime on the Trinity River from pre-dam conditions; however, diel (within day) variations in water temperature continue to generally exhibit a downstream trend that is common to unregulated systems (Figure 3, Figure 38, Figure 39), though temperature patterns associated with headwater streams now occur at lower elevation and over a shorter linear distance than would have occurred in an unimpaired Trinity river. Specifically, the daily range in temperature for 2000–2019 increased from Lewiston (rm 111.1) to a peak at Limekiln Gulch (rm 98.8), then was lower at Douglas City (rm 92.8) and upstream of Canyon Creek (rm 79.3), then rising again to a secondary peak upstream of the NF Trinity River (rm 73.3), and then strongly declined to Big French Creek (rm 58.6) and continuing at relatively low values through Weitchpec (rm 0.2; Figure 38 and Figure 39). As hypothesized in Figure 3, temperatures at Limekiln, Douglas City, and above the NF Trinity River are slightly to the left of the peak in the generalized diel variability curve and stations further downstream lie to the right where daily variations in temperature reduce with increased drainage area. Daily mean temperatures also increased with downstream distance from Lewiston to Weitchpec as Figure 3 hypothesizes. The daily mean temperatures are higher further downstream due to longer travel times and channel widening increasing thermal inputs that warm the flow more than tributary inputs cool it. Diurnal variations are higher with upstream distance because dam regulation provides a near-constant source temperature and flow volumes are lower which provides less thermal mass to dampen temperature variations. The measured data do not show a downstream 'node' with a range as low as Lewiston that was predicted by models (Section 3.4.4.1); however, the lower range at the Douglas City and upstream of Canyon Creek stations in conjunction with the substantially higher values upstream (Limekiln) and downstream (upstream of NF Trinity River) do resemble muted versions of node/anti-node behavior. Seasonal plots show a dramatic decline in daily range during ROD spring releases at some sites, especially Rush Creek, Limekiln, and upstream of NF Trinity River (Figure 39).

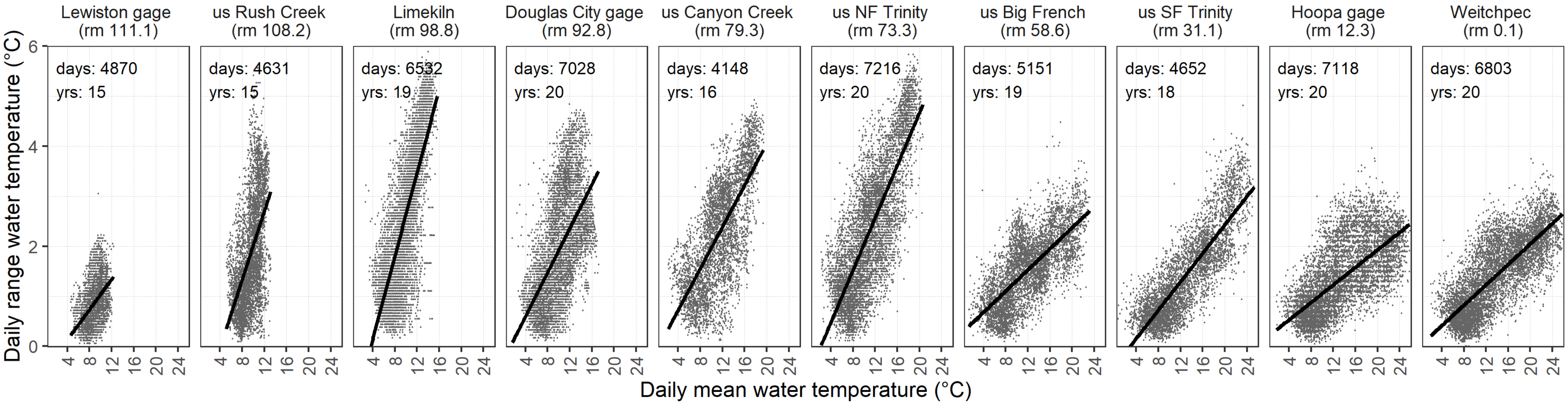


Figure 38. Daily range in measured water temperatures as a function of daily average water temperature at stations on the Trinity River from 2000–2019. Daily range was calculated as daily maximum minus daily minimum. If multiple data sources were available for a single station and day, their values were averaged prior to plotting. The period of record varies by station, with labels in the upper-left corner of each panel show the number of days and years of available data.

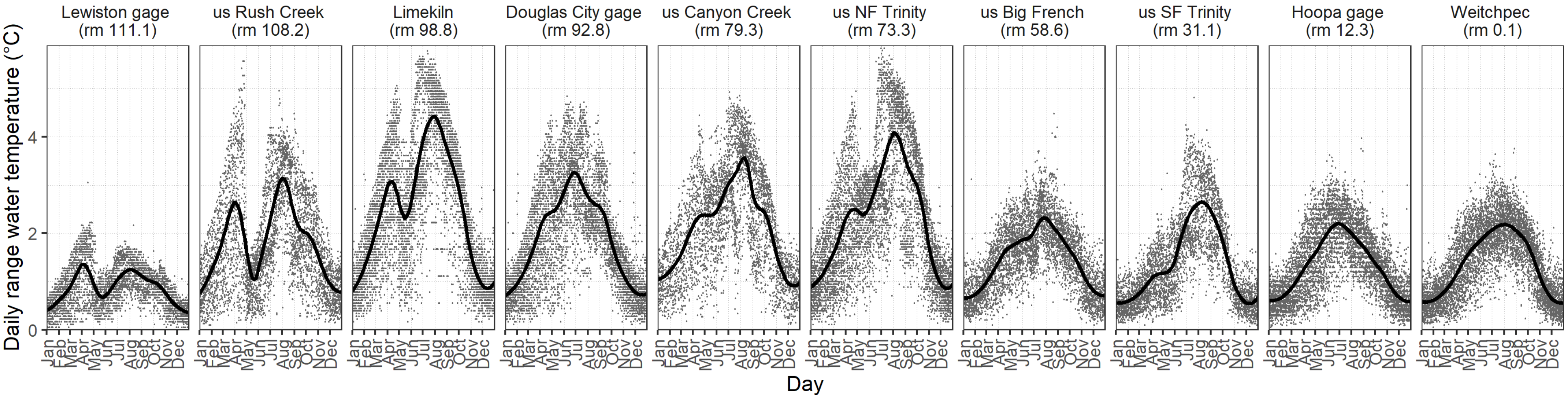


Figure 39. Daily range in measured water temperature as a function of day at stations on the Trinity River for 2000–2019. See Figure 38 for additional notes.

3.4.5 TEMPERATURE EFFECTS OF 2000 RECORD OF DECISION (ROD) FLOW RELEASES

3.4.5.1 COMPARE PRE-DAM, PRE-ROD, AND POST ROD TEMPERATURE REGIMES

Temperature records are critical to understanding impacts of management and adhering to objectives and compliance-related goals. In the ROD era, there are ample temperature measurements to characterize the longitudinal and temporal thermal regime. Less temperature data are available for previous eras, especially the pre-dam era and 1963–1978 full diversion eras (Figure A80 found in Appendix A) so our understanding of thermal dynamics in those eras is more limited. Current modeling tools are ill equipped to assess downstream effects of Lewiston releases below 350 cfs in summer months (Section 2.3.3.3), which have not been observed for decades on the Trinity River but were commonplace prior to and immediately after flow regulation. Based on our recommendations, USBR and USGS have begun the process of updating and recalibrating the RBM10 model to be able to provide accurate predictions at flows much lower than 350 cfs, but for now we must rely on limited temperature data that do exist, supplemented by model results when appropriate.

A seasonal sine wave pattern of thermal change is common for rivers in temperate climates (Johnson et al. 2020). Dam building and operations compressed the amplitude of this seasonal pattern on the Trinity River by strongly reducing the summer maximum, and to a much less extent by increasing the winter minimum. These effects are strongest at Lewiston Dam and diminish downstream, but the rate of downstream recovery is dependent on magnitude of Lewiston releases. Other than Lewiston Dam, no temperature data are available for the 1963–1978 full-diversion era upstream of Burnt Ranch where temperatures appear to follow a typical seasonal pattern (Figure 40, Figure 41). In the ROD era, there is a "kink" in the annual thermal pattern where instead of continuing typical seasonal increase, temperatures drop in late April or May with onset of spring high flow releases. These high flows speed movement of water from the cold depths of Trinity Reservoir through Lewiston Reservoir which decreases Lewiston release temperatures and also causes water to rapidly flow downstream in the river which decreases temperatures all the way down the Trinity River's full length. The kink is strongest at Douglas City but persists downstream through the remainder of the restoration reach, and in some years all the way to Burnt Ranch (Figure 40, Figure 41). The most significant biological impacts occur upstream of Douglas City, where ROD-era spring temperatures are so cold they are rarely within the optimal range for juvenile salmonid growth (Section 4.3.2).

Prior to regulation, the longitudinal thermal profile of the Trinity River was relatively flat, with Lewiston daily average temperatures within 3.6 °C of Weitchpec temperatures (Table 6, Figure 35). This longitudinal gradient in temperature now has a much broader range of 11.6 °C in July with dam release temperatures and implementation of ROD flows (Table 6, Figure 34). It is reasonable to assume that under transitional era management the range was very similar, since release temperatures have remained fairly consistent and cooling caused by Lewiston releases is minimal in Weitchpec, but it is likely that reduced summer baseflows resulted in a much steeper gradient in the stretch of river directly below Lewiston Dam.

Table 6. RBM10-modeled monthly mean mainstem Trinity River temperatures at selected sites for the period 2000–2018, comparing the historical dam-regulated flow scenario to a scenario with Lewiston releases set to unimpaired flows and without-dam temperatures. For April, May, and June only, results are also provided for two condensed water year types: “D, CD” = Dry and Critically Dry, “N, W, EW” = Normal, Wet, and Extremely Wet.

		Historical dam-regulated flows scenario							No dam/unimpaired flow scenario						
		Temperature (°C)				Temp. (°C) change from Lewiston			Temperature (°C)				Temp. (°C) change from Lewiston		
Water year type	Month	Lewiston	Douglas City	North Fork	Weitchpec	Douglas City	North Fork	Weitchpec	Lewiston	Douglas City	North Fork	Weitchpec	Douglas City	North Fork	Weitchpec
All	Jan	6.9	6.2	5.6	6.1	-0.7	-1.3	-0.8	4.5	4.9	4.8	5.8	0.4	0.3	1.3
All	Feb	7.5	7.0	6.5	7.1	-0.5	-1.0	-0.4	5.3	5.7	5.8	6.7	0.4	0.5	1.4
All	Mar	8.6	8.5	8.2	8.7	-0.1	-0.4	0.1	6.5	7.1	7.4	8.3	0.6	0.8	1.7
All	Apr	9.7	10.3	10.5	11.1	0.6	0.8	1.4	8.3	9.0	9.5	10.5	0.7	1.2	2.2
All	May	9.0	10.3	11.2	13.3	1.2	2.2	4.3	11.1	12.0	12.8	14.2	0.9	1.7	3.1
All	Jun	9.8	12.2	14.0	17.6	2.4	4.2	7.8	15.1	16.2	17.3	18.6	1.1	2.2	3.6
All	Jul	10.3	14.1	16.9	21.9	3.8	6.6	11.6							
All	Aug	10.5	13.8	16.5	21.7	3.3	6.0	11.2							
All	Sep	10.3	12.3	14.0	17.7	2.0	3.7	7.5							
All	Oct	9.7	10.7	11.2	13.2	0.9	1.4	3.5							
All	Nov	9.0	8.7	8.3	8.9	-0.3	-0.7	-0.1	8.6	8.5	8.2	8.7	-0.1	-0.4	0.1
All	Dec	7.5	6.6	5.9	6.3	-0.9	-1.5	-1.2	5.3	5.6	5.4	6.3	0.3	0.1	0.9
D, CD	Apr	10.0	11.1	11.5	12.3	1.1	1.6	2.3	9.1	10.0	10.7	11.8	0.9	1.6	2.7
D, CD	May	9.8	11.2	12.5	15.0	1.5	2.7	5.2	13.0	14.2	15.3	16.7	1.3	2.4	3.8
D, CD	Jun	10.5	13.7	16.1	20.2	3.1	5.6	9.7	17.2	18.8	20.2	21.2	1.6	2.9	4.0
N, W, EW	Apr	9.5	9.9	9.9	10.4	0.4	0.4	0.9	7.8	8.4	8.9	9.8	0.6	1.0	1.9
N, W, EW	May	8.6	9.7	10.5	12.4	1.1	1.9	3.8	10.1	10.8	11.4	12.8	0.7	1.3	2.6
N, W, EW	Jun	9.3	11.3	12.8	16.0	1.9	3.5	6.7	14.4	15.4	16.4	17.8	1.0	2.0	3.4

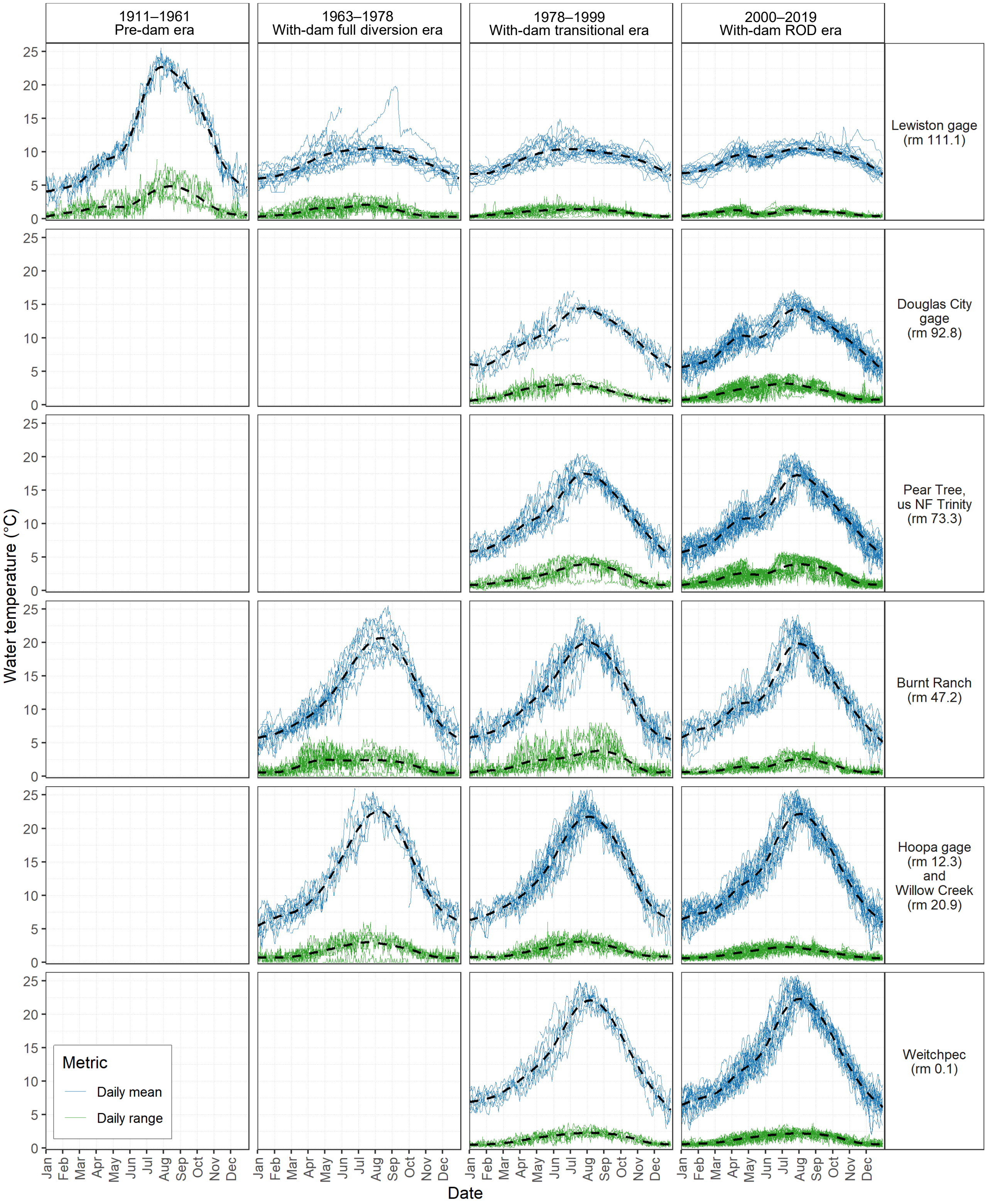


Figure 40. Time series of water temperature daily mean and daily range measured in the Trinity River at Lewiston for 1942–2019, comparing the pre-dam era (1942–1/20/1961), with-dam full diversion era (10/31/1963–4/30/1978), with-dam transitional era (5/1/1978–9/30/1999), and with-dam ROD era (10/1/1999–2019). Dashed lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers fit to all data points in each panel. USGS Burnt Ranch temperatures for 1961–1983 are extremely variable from year to year, suggesting they may be unreliable. The 1/21/1961-10/30/1963 initial dam-filling period is not shown.

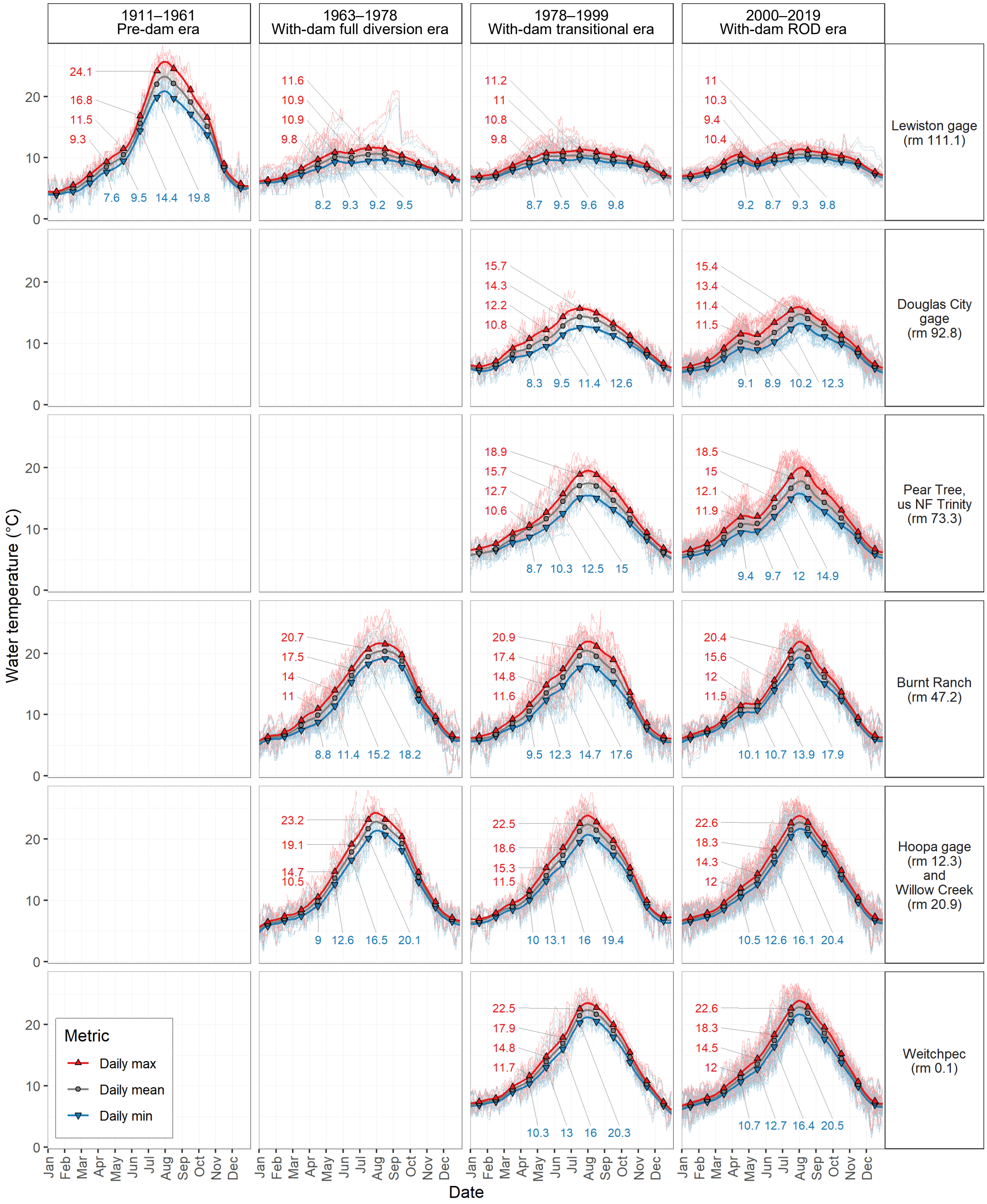


Figure 41. Daily minimum, mean, and maximum water temperatures measured in the Trinity River at Lewiston for 1942–2019, comparing the pre-dam era (1942–1/20/1961), with-dam full diversion era (10/31/1963–4/30/1978), with-dam transitional era (5/1/1978–9/30/1999), and with-dam ROD era (10/1/1999–2019). Symbols (circles and triangles) are monthly means with April–July labeled, thin lines are daily time series, and thick lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers. USGS Burnt Ranch temperatures for 1961–1983 are extremely variable from year to year, suggesting they may be unreliable. The 1/21/1961–10/30/1963 initial dam-filling period is not shown.

3.4.5.2 *EFFECT OF ROD WATER VOLUME ALLOCATION (VARIES BY WATER YEAR)*

Measurements from the years 2000–2019 indicate that water temperatures vary by water year type in the ROD era (Figure 42 and Figure 43). The seasonal rise in daily mean temperatures that occurs from April through July in dry and critically dry years is delayed in normal, wet, and extremely wet years, and peak values in late July/early August are not as high (Figure 43).

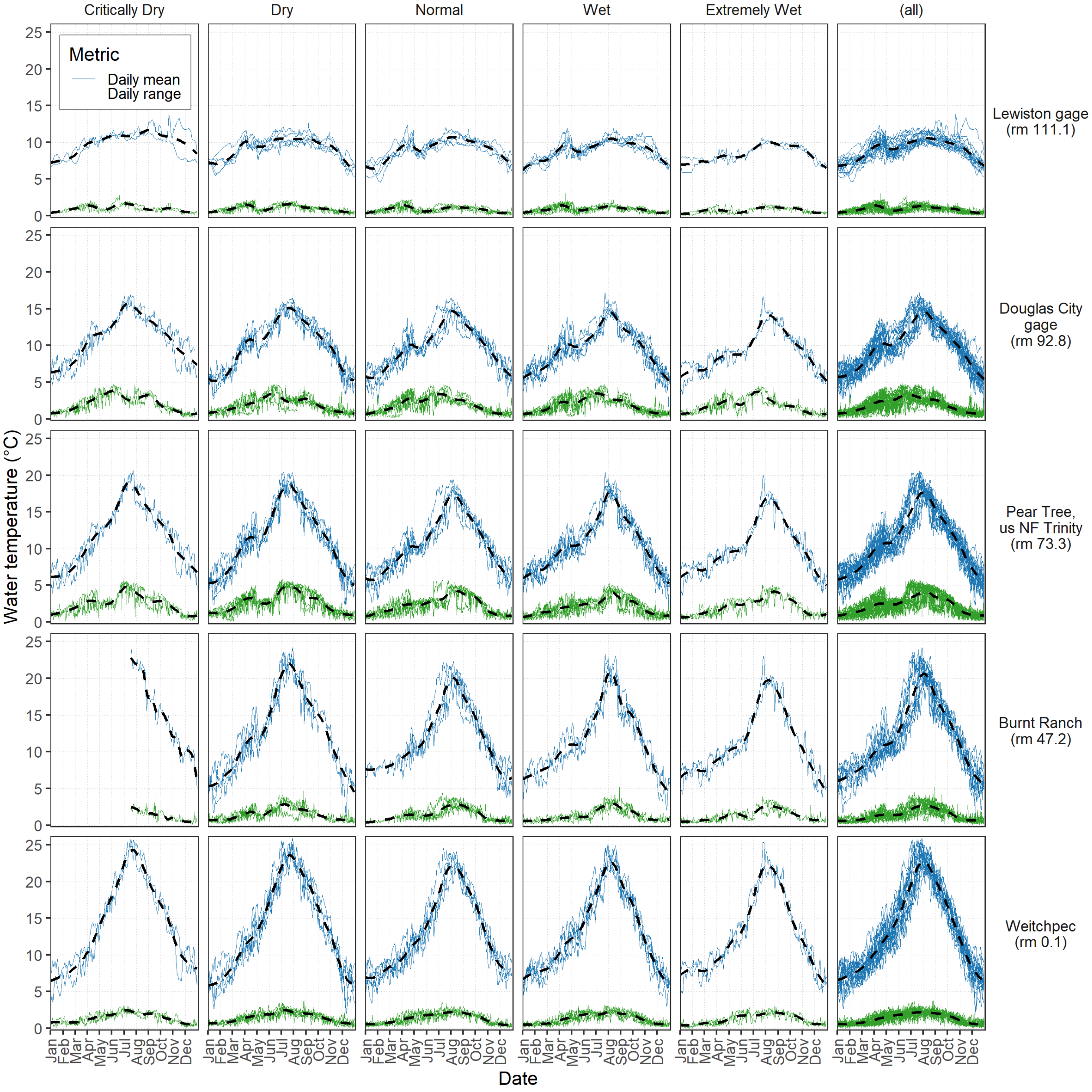


Figure 42. Time series of water temperature daily mean and daily range measured at selected mainstem Trinity River sites comparing forecasted water year types (critically dry, dry, normal, wet, and extremely wet) during the ROD era (2000–2019). For 2001–2018, we use forecasted water year type because it sets ROD flows, but for 1999 we use actual water year type because forecasts were unavailable. To keep calendar years together, temperatures for October-December are grouped here according to the classification of the preceding water year. Dashed lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers fit to all data points in each panel.

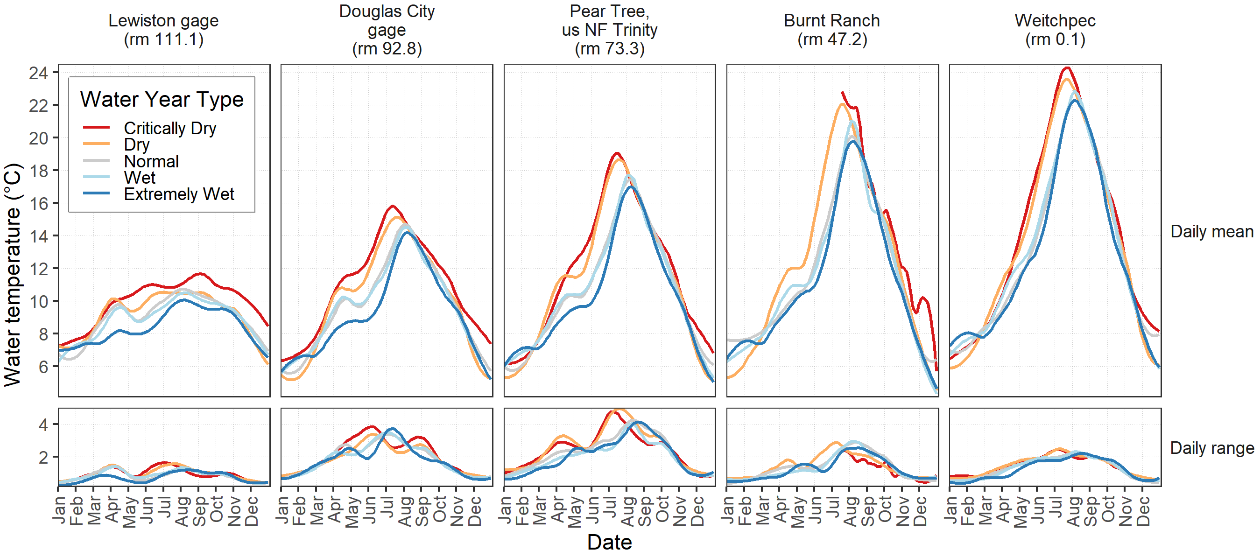


Figure 43. Seasonal patterns in water temperature daily mean and daily range measured at selected mainstem Trinity River sites comparing water years types (critically dry, dry, normal, wet, and extremely wet) during the ROD era (2000–2019). Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers of daily time series from Figure 42. See Figure 42 caption for additional notes.

3.4.5.3 EFFECT OF HYDROGRAPH COMPONENTS ON RIVER TEMPERATURES

The ROD flow release schedules varied according to water year type (Figure 4). The flow releases are composed of individual components, including winter baseflow, spring high-flow releases (peaking at 1,500, 4,500, 6,000, 8,500, or 11,000 cfs), bench (2,000 cfs in normal or wetter years only), spring ramp down, summer baseflow (450 cfs), and winter baseflow (300 cfs) (Figure 4). Under TRRP's adaptive management framework, total annual release volumes have remained as specified in the ROD but the daily hydrographs have evolved, as discussed below (Figure 44, Figure 45).

In this section, we evaluate thermal effects of each hydrograph component using a combination of approaches, including review of past reports, graphical review of measured data, and application of the RBM10 temperature model. Each hydrograph component occurs for a specific portion of the year, although timing can vary by water year type or individual year, so part of how we evaluate the effects of a hydrograph component is to compare it to alternative flow regimes for the same period of the year.

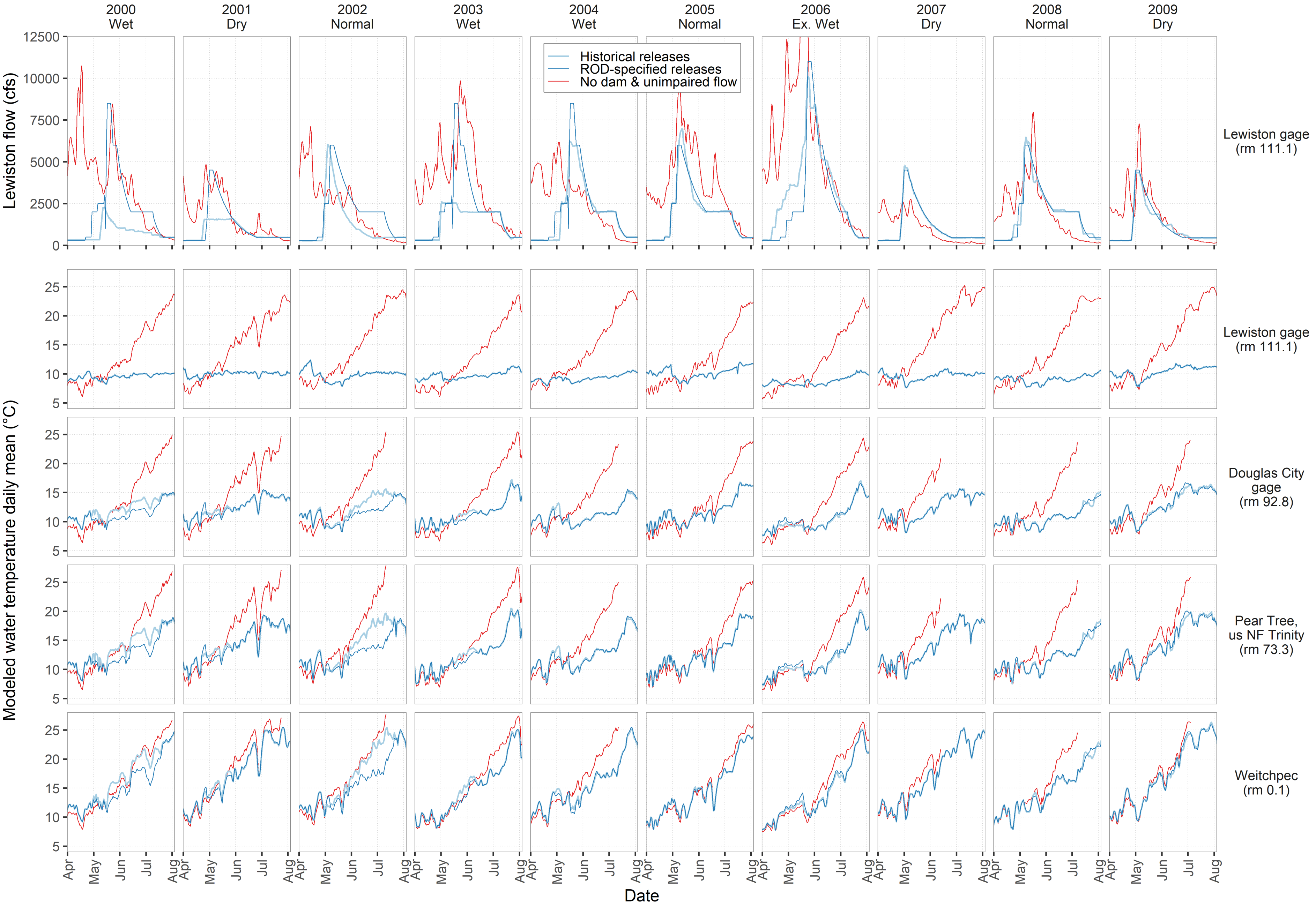


Figure 44. Daily time series of Lewiston releases and daily mean water temperatures predicted by RBM10 under three Lewiston release scenarios (historical, ROD-specified, and no-dam unimpaired flow) for April 1-July 31, 2000–2009. Years are labeled by forecasted water year type except 2000 which is labeled by actual water year type. Y-axis is truncated at 12,500 cfs flows. Unimpaired temperatures downstream of Lewiston not shown if unimpaired Lewiston releases are <350 cfs.

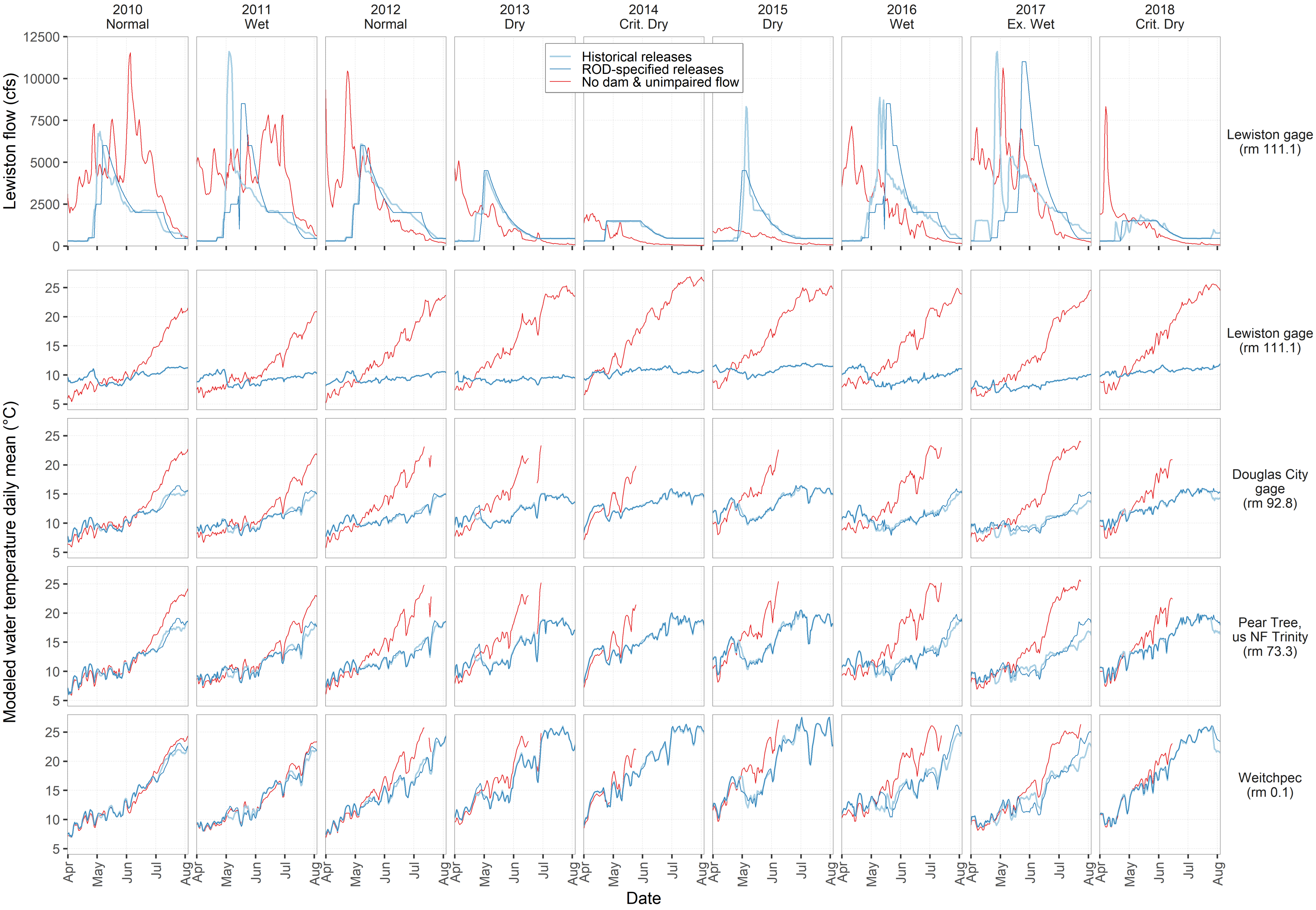


Figure 45. Daily time series of Lewiston releases and daily mean water temperatures predicted by RBM10 under three Lewiston release scenarios (historical, ROD-specified, and no dam unimpaired flow) for April 1-July 31, 2010–2018. Years are labeled by forecasted water year type. Unimpaired temperatures downstream of Lewiston not shown if unimpaired Lewiston releases are <350 cfs.

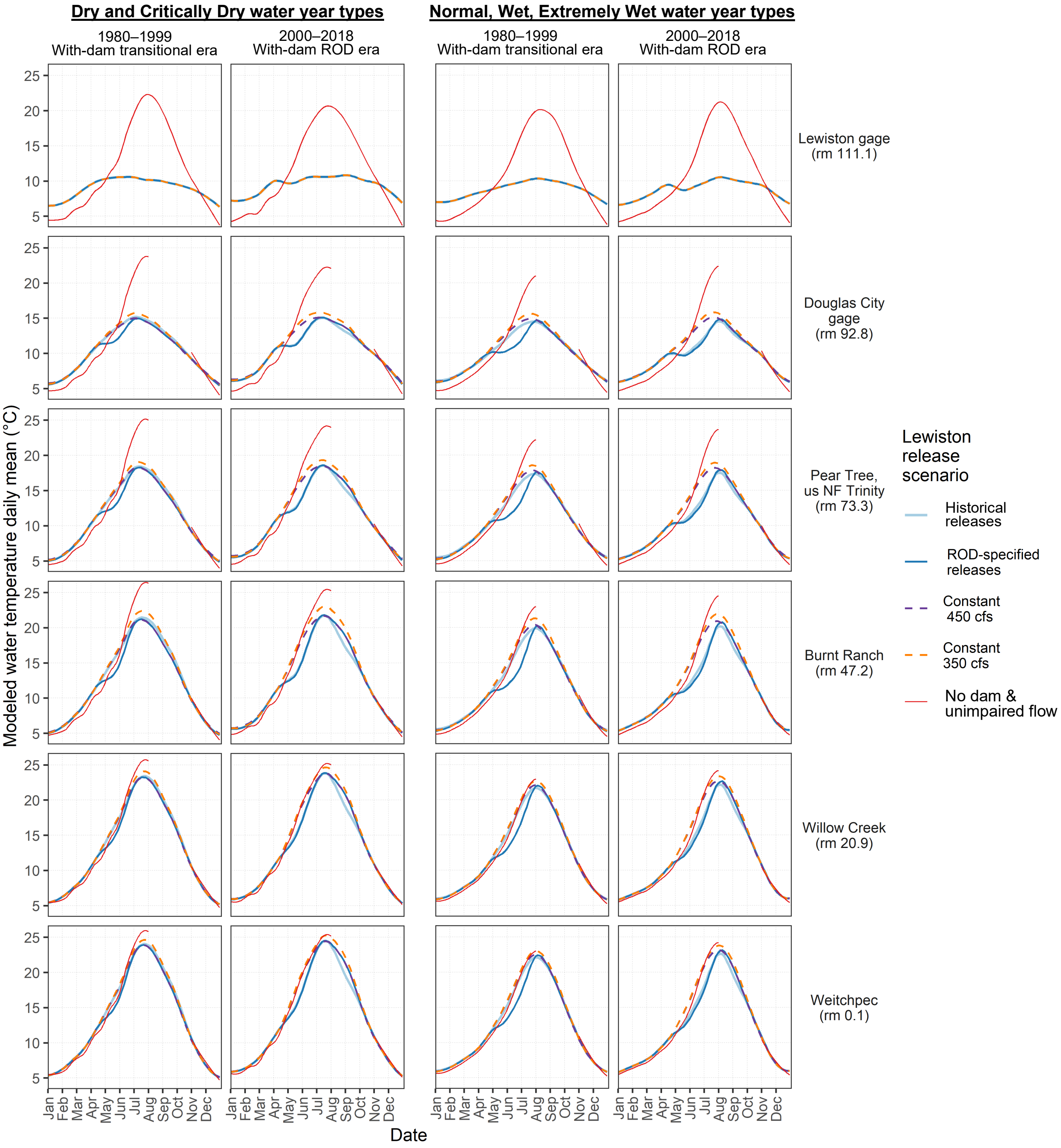


Figure 46. Smoothed daily mean water temperatures at selected mainstem Trinity River sites modeled with RBM10 under five Lewiston release scenarios (historical, ROD-specified, constant 350 cfs, constant 450 cfs, and unimpaired flow/temperature), comparing flow eras (transitional 1980–1999 and ROD 2000–2018) and condensed water year types (Dry/Critically Dry and Normal/Wet/Extremely Wet). For 2000–2018, we use forecasted water year type because it sets ROD flows, but for 1980–2000 we use actual water year types because forecasts were unavailable. The RBM10 model was not calibrated for Lewiston releases less than 350 cfs during summer months, so days with unimpaired Lewiston releases less than 350 cfs during summer are not shown. Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers representing typical conditions for the time of year, fit with all data within the period, scenario, and condensed water year type.

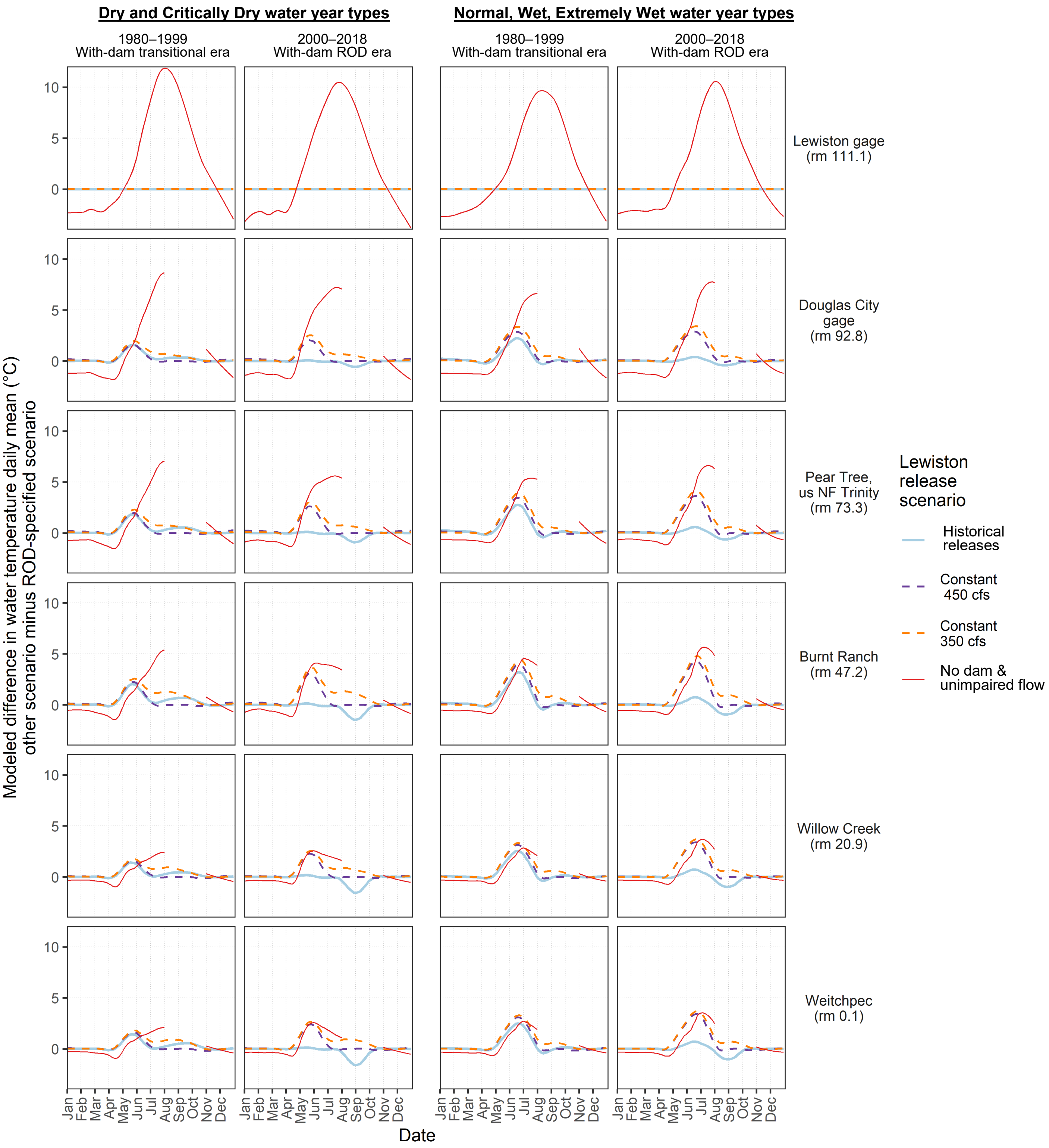


Figure 47. Smoothed difference in RBM10-modeled daily mean water temperatures at selected mainstem Trinity River sites between ROD-specified flow scenario and four other Lewiston release scenarios (historical, constant 350 cfs, constant 450 cfs, and unimpaired flow/temperature), comparing flow eras (transitional era 1980–1999 and ROD era 2000–2018) and condensed water year types (Dry/Critically Dry and Normal/Wet/Extremely Wet). Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers representing typical conditions for the time of year, fit with all data within the period, scenario, and condensed water year type. See Figure 46 for additional notes.

SUMMER BASEFLOW

Prior to dam construction, summer baseflows in the Trinity River at Lewiston followed a seasonal recession that was highly variable from year to year (Figure 26), according to factors such as snowpack and the timing and magnitude of storm events. Summer baseflow releases in the years following dam construction were 150 cfs until 1978 when summer baseflows were increased to 300 cfs (Figure 24, Figure 26). Since 1993, summer baseflows for July 1 – September 30 are generally maintained above 450 cfs although they occasionally drop below that levels for short periods.

The ROD summer baseflows are 450 cfs, spanning from June 26 – October 15 in Critically Dry and Dry years and July 22 – October 15 in other water year types (Figure 4). These flows were set to comply with temperature criteria (Section 4.1) intended to maintain suitable temperatures in the Trinity River above the North Fork confluence for holding and spawning of spring-run Chinook Salmon and spawning fall-run Chinook Salmon (USFWS and HVT 1999). Specifically, the criteria are: 1) not to exceed 60 °F (15.6°C) at Douglas City July 1– Sept 14; 2) not to exceed 56 °F (13.3°C) at Douglas City Sept 15 – Sept 30; and 3) Oct 1 – Dec 31 not to exceed 56 °F (13.3 °C) above North Fork confluence. SNTEMP modeling indicated that dam releases required to meet these criteria varied with Lewiston Dam release temperatures and hydrometeorological conditions (USFWS and HVT 1999). Releases of 450 cfs were predicted to meet the criteria under almost all conditions, except when dam release temperatures were high (>55 °F, >12.8 °C) in median and hot-dry year types (Table 7). Releases of 300 cfs were predicted to result in many exceedances of the 60 °F (15.6°C) July 1 – Sept 14 criteria at Douglas City at higher Lewiston releases temperatures but none at lower release temperatures (Table 7). USFWS and HVT's (1999) review of empirical data for 1992–1994 and 1996–1997 indicated that the criteria were almost always met when releases were 450 cfs, except when dam release temperatures were >=53 °F (11.7 °C) in July of 1992 and 1993. Our review of criteria compliance for 1987–2019 indicated some post-ROD years have many days of exceedances even though Lewiston summer releases are generally at or above 450 cfs (Section 4.3.1). Exceedances in 2003, 2005, 2006, 2009, 2014, 2015, and 2018 appear to occur when the hottest air temperatures of the season overlap with elevated Lewiston release temperatures. A brief period of 385 cfs dam releases, less than typical ROD 450 cfs summer baseflow, also likely contributed to the exceedances in 2003. In 2018, shutdown of the Carr powerhouse slowed transit of water through Lewiston Reservoir and contributed to exceedances of temperature criteria (Buxton 2019).

Prior to 1987, temperatures were only monitored at USGS gages at Lewiston, Burnt Ranch, and Hoopa, so we are unable to assess temperatures in the upper Trinity River until 1987. Consistent temperature monitoring at Douglas City began in 1990, which when combined with the 1987–1988 Steel Bridge/Limekiln data contains several years where summer baseflows fell below 450 cfs which can be used to assess the thermal effects of lower baseflows (Figure 48). The years 1988–1993 had more exceedances of adult temperature criteria than most other years since, which appear to be due to a combination of lower summer baseflows (300 cfs) and higher Lewiston release temperatures. In 1990, the highest Douglas City temperatures occurred when air temperatures were relatively mild, but Lewiston release temperatures were high. Summer baseflows substantially less than 300 cfs have occurred only once since 1987. In June 1990, Lewiston released were dropped to approximately 160 cfs for a one-week period, but air temperatures were low (approximately 16 °C 7DADA) and dam release temperatures were abnormally high (15 °C), providing a unique set of conditions that is not necessarily generalizable yet led to Douglas City temperatures as high as 18 °C that persisted even after flows increased back to 300 cfs.

Lewiston Dam releases have much less influence on the lower Trinity River than the upper Trinity River. As a result, measured temperatures at Hoopa and Weitchpec during late summer are similar in the ROD era and transitional era (Figure 40), in contrast to spring and early/mid-summer when temperatures are cooler in the ROD era due to spring high flow releases, especially in normal and wetter water year types. RBM10 modeling suggests that the temperature difference between constant release of 350 cfs (lowest warm-season release that the RBM10 model is calibrated for) and 450 cfs (ROD summer baseflow) is approximately 1 °C during peak of summer (late July/early August) (Figure 46, Figure 47). RBM10 modeling predicts that August and September flows at Weitchpec would be approximately 1 °C cooler under historical (i.e., actual) Lewiston releases than under exact ROD-specified hydrographs (Figure 46, Figure 47), possibly due to releases for non-ROD purposes such as the Hoopa Tribe's Boat Dance and cooling the Lower Klamath River.

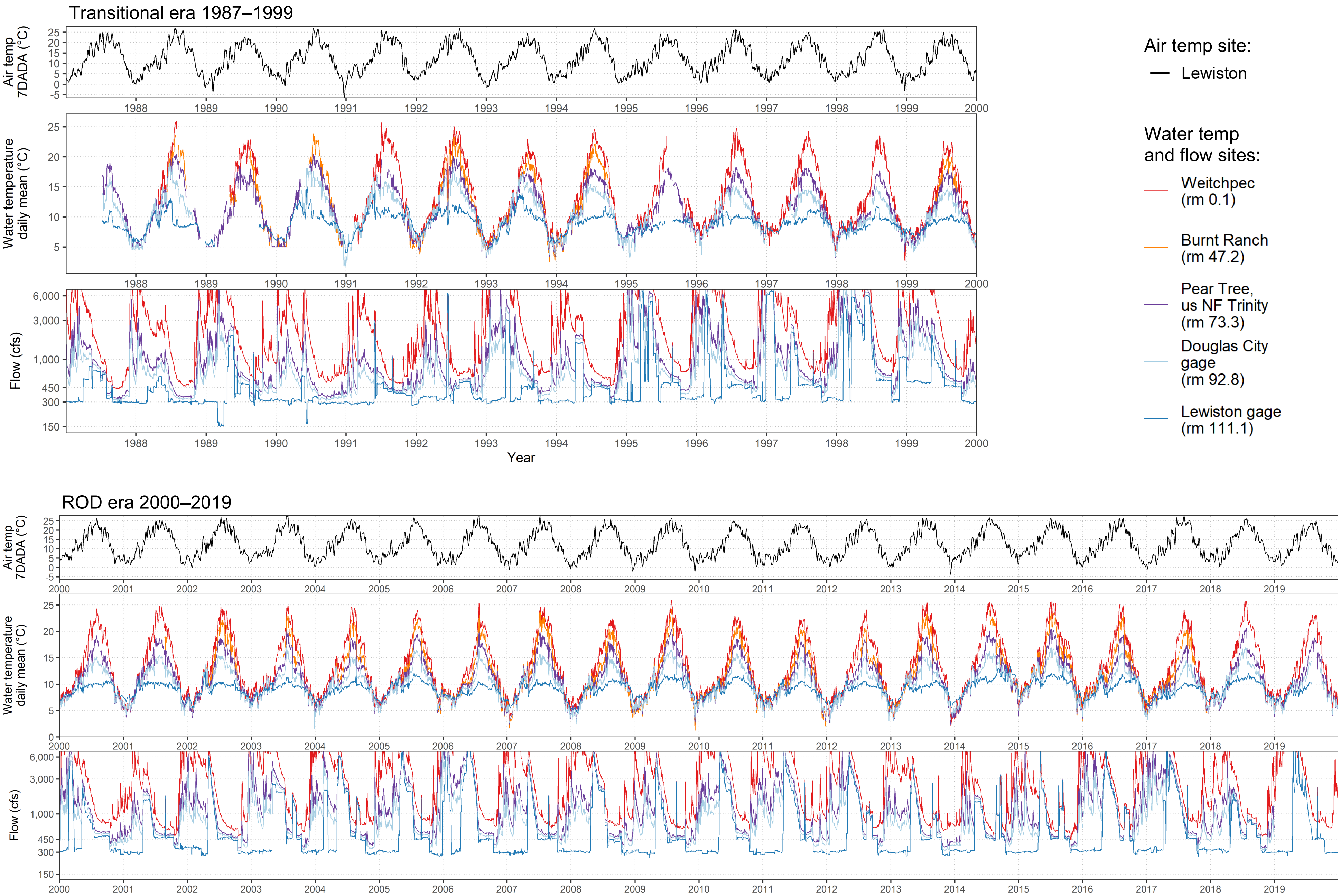


Figure 48. Daily time series of water temperatures, flows, and air temperature at selected mainstem Trinity sites, 1987–2019. Some temperatures are estimated by regression with adjacent stations (Sections 2.3.2 and B.7). Y-axis is truncated at 6,000 cfs flows. Flow data sources: USGS measured (Lewiston 1987–2019, Hoopa 1987–2019, Weitchpec 2019, us NF Trinity 2019, and Douglas City 2019) and RBM10 modeled (Weitchpec 1987–2018, us NF Trinity 1987–2018, and Douglas City 1987–2018). Air temperature data source: PRISM (Lewiston). 7DADA = 7-day average daily average daily average daily average.

Table 7. Stream Network Temperature Model (SNTEMP) temperature predictions (weekly average) for the Trinity River at CRWQCB-NCR Objective locations- Douglas City (RM 93.8) and the confluence of the North Fork Trinity River (RM 72.4). Bolded values indicate the temperature would not be met. CW = cold-wet year type, Med = median year type, and HD = hot-dry year type. Table from USFWS and HVT (1999).

WaterTemperaturePredictions(°F)																	
	Dam		**LewistonDamReleases(cfs)**														
	Release	**Target**	**150**			**300**			**450**			**600**			**1000**		
Week	**Temp**	**Temp**	**CW**	**Med**	**HD**	**CW**	**Med**	**HD**	**CW**	**Med**	**HD**	**CW**	**Med**	**HD**	**CW**	**Med**	**HD**
DouglasCity-MinimumReleaseWaterTemperatures																	
01-Jul	50.0	60	57.1	**60.2**	**63.9**	55.7	57.7	59.6	54.9	56.3	57.4	54.1	55.2	56.1	53.1	53.7	54.1
08-Jul	48.7	60	57.6	**60.8**	**64.0**	55.6	57.6	59.2	54.4	55.7	56.7	53.6	54.5	55.2	52.3	52.8	53.1
15-Jul	47.7	60	58.2	**61.5**	**64.2**	55.7	57.5	58.8	54.1	55.3	56.0	53.2	53.9	54.5	51.6	52.0	52.2
22-Jul	47.3	60	58.6	**61.9**	**64.2**	55.8	57.5	58.6	54.0	55.1	55.7	53.0	53.7	54.1	51.3	51.7	51.8
29-Jul	48.6	60	59.0	**62.6**	**64.9**	56.3	58.2	59.4	54.7	56.0	56.6	53.7	54.6	55.0	52.2	52.7	52.9
05-Aug	47.7	60	58.8	**62.1**	**64.0**	55.7	57.4	58.3	53.9	55.0	55.6	52.9	53.7	54.1	51.3	51.7	52.0
12-Aug	46.9	60	58.2	**61.3**	**63.1**	54.9	56.5	57.4	53.0	54.1	54.7	52.0	52.8	53.2	50.5	50.9	51.1
19-Aug	47.1	60	57.6	**60.6**	**62.1**	54.4	56.1	56.8	52.7	53.8	54.3	51.8	52.6	52.9	50.3	50.8	50.9
26-Aug	47.1	60	56.5	59.7	**61.0**	53.6	55.4	55.9	52.0	53.3	53.7	51.2	52.2	52.4	49.9	50.5	50.7
02-Sep	47.1	60	55.3	58.4	59.9	52.8	54.6	55.4	51.4	52.7	53.2	50.7	51.7	52.0	49.6	50.2	50.4
09-Sep	47.1	60	54.0	57.5	58.8	51.9	54.0	54.5	50.7	52.3	52.6	50.1	51.3	51.6	49.2	49.9	50.2
16-Sep	46.9	56	52.7	**56.4**	**57.6**	51.0	53.2	53.8	50.0	51.6	52.0	49.5	50.7	51.1	48.7	49.5	49.6
23-Sep	46.9	56	51.2	55.1	**56.3**	49.9	52.3	52.9	49.2	51.0	51.4	48.9	50.2	50.5	48.3	49.2	49.3
DouglasCity-MaximumReleaseWaterTemperature																	
01-Jul	56.1	60	58.5	**62.0**	**66.0**	58.1	**60.6**	**63.1**	58.0	**60.2**	**61.7**	57.7	59.2	**60.6**	57.4	58.4	59.2
08-Jul	55.6	60	59.2	**62.9**	**66.4**	58.5	**61.0**	**63.1**	58.4	**60.2**	**61.5**	57.8	59.2	**60.3**	57.2	58.2	58.8
15-Jul	52.9	60	59.6	**63.2**	**66.2**	58.1	**60.3**	**61.9**	57.4	58.8	59.8	56.5	57.7	58.5	55.5	56.2	56.7
22-Jul	52.7	60	**60.1**	**63.8**	**66.4**	58.4	**60.5**	**61.9**	57.5	58.9	59.6	56.6	57.7	58.3	55.5	56.1	56.5
29-Jul	52.7	60	**60.3**	**64.1**	**66.6**	58.4	**60.6**	**61.9**	57.4	58.9	59.6	56.5	57.7	58.3	55.4	56.1	56.5
05-Aug	52.0	60	**60.1**	**63.6**	**65.8**	57.9	60.0	**61.0**	56.8	58.1	58.8	55.9	56.9	57.4	54.7	55.4	55.6
12-Aug	53.1	60	**60.2**	**63.6**	**65.7**	58.2	**60.2**	**61.3**	57.2	58.5	59.2	56.4	57.5	58.3	55.4	56.1	56.5
19-Aug	52.3	60	59.3	**62.6**	**64.2**	57.3	59.3	**60.1**	56.3	57.6	58.2	55.6	56.6	57.0	54.6	55.2	55.6
26-Aug	51.6	60	58.1	**61.5**	**62.8**	56.2	58.2	59.0	55.2	56.6	57.1	54.5	55.7	55.9	53.7	54.4	54.5
02-Sep	51.4	60	56.9	**60.2**	**61.7**	55.3	57.3	58.1	54.5	55.9	56.4	53.9	55.0	55.4	53.2	53.9	54.1
09-Sep	52.9	60	56.0	59.9	**61.2**	55.2	57.6	58.3	54.8	56.5	56.9	54.4	55.8	56.1	54.0	54.9	55.0
16-Sep	51.1	56	54.2	58.1	**59.4**	53.3	55.8	**56.5**	52.9	54.7	55.1	52.6	54.0	54.3	52.2	53.1	53.2
23-Sep	51.3	56	52.7	56.5	**58.1**	52.4	55.0	55.8	52.3	54.2	54.6	52.1	53.6	54.0	51.9	52.9	53.1
NorthForkTrinityConfluence-MinimumReleaseWaterTemperatures																	
01-Oct	46.6	56	51.2	**57.0**	**59.2**	50.6	54.9	**56.3**	49.8	53.2	54.2	49.8	52.5	53.3	49.2	51.1	51.6
08-Oct	46.6	56	49.1	54.7	**57.4**	48.8	53.0	54.8	48.5	51.8	53.2	48.4	51.1	52.2	48.1	49.9	50.6
15-Oct	45.9	56	47.3	52.2	55.0	47.2	50.9	52.8	47.0	50.1	51.5	47.0	49.5	50.6	46.9	48.6	49.3
22-Oct	46.4	56	45.4	50.0	52.3	45.6	49.4	51.0	45.7	48.9	50.1	45.9	48.6	49.6	46.2	48.2	48.8
29-Oct	46.2	56	43.5	47.5	50.3	43.7	47.4	49.4	44.0	47.3	48.9	44.2	47.2	48.5	44.7	47.1	48.0
05-Nov	46.2	56	42.3	45.6	48.3	42.6	45.8	47.9	42.9	46.0	47.7	43.1	46.1	47.5	43.7	46.3	47.3
12-Nov	45.5	56	41.1	43.6	45.8	41.4	44.0	45.9	41.6	44.4	45.9	41.9	44.6	45.9	42.5	45.0	46.0
19-Nov	43.3	56	40.0	41.8	44.0	40.2	42.1	44.0	40.4	42.4	44.0	40.6	42.6	44.0	41.0	43.0	44.0
26-Nov	42.6	56	39.2	40.5	42.7	39.4	40.9	42.8	39.5	41.2	42.9	39.8	41.5	43.0	40.1	41.9	43.0
03-Dec	43.2	56	38.9	39.8	41.9	39.1	40.4	42.3	39.2	40.8	42.6	39.5	41.2	42.8	39.9	41.8	43.1
10-Dec	43.5	56	38.5	39.3	41.3	38.8	39.9	41.9	38.9	40.5	42.4	39.2	40.9	42.6	39.7	41.7	43.1
17-Dec	42.6	56	38.3	38.7	41.1	38.5	39.3	41.6	38.6	39.8	41.9	38.9	40.2	42.1	39.3	40.9	42.4
24-Dec	40.6	56	38.3	38.4	40.5	38.4	38.8	40.6	38.4	39.0	40.7	38.6	39.3	40.8	38.8	39.7	41.0
NorthForkTrinityConfluence-MaximumReleaseWaterTemperatures																	
01-Oct	51.1	56	51.7	**57.6**	**59.8**	51.7	**56.3**	**57.8**	51.7	55.3	**56.5**	51.7	54.8	55.7	51.7	53.8	54.4
08-Oct	51.1	56	49.7	55.4	**58.1**	50.0	54.6	**56.5**	50.3	54.0	55.5	50.5	53.7	54.9	50.8	53.1	53.9
15-Oct	50.5	56	47.9	53.0	55.8	48.4	52.6	54.6	48.8	52.3	53.9	49.1	52.1	53.4	49.6	51.8	52.7
22-Oct	50.0	56	45.8	50.6	52.9	46.4	50.6	52.3	46.9	50.6	52.0	47.3	50.6	51.8	48.1	50.6	51.4
29-Oct	49.8	56	43.7	48.0	50.9	44.3	48.6	50.8	44.8	48.9	50.7	45.2	49.1	50.7	46.2	49.5	50.6
05-Nov	52.0	56	42.7	46.4	49.3	43.3	47.6	50.1	44.0	48.5	50.6	44.6	49.1	50.9	45.9	50.1	51.4
12-Nov	53.1	56	41.5	44.6	47.2	42.2	46.4	48.8	42.9	47.5	49.7	43.6	48.5	50.5	45.1	49.9	51.4
19-Nov	52.3	56	40.4	42.9	45.6	41.1	44.7	47.5	41.7	45.9	48.5	42.4	47.0	49.3	43.7	48.6	50.4
26-Nov	51.1	56	39.6	41.5	44.2	40.2	43.2	46.0	40.7	44.4	47.1	41.3	45.4	47.9	42.5	47.1	49.1
03-Dec	48.9	56	39.1	40.5	42.9	39.6	41.8	44.5	40.0	42.9	45.4	40.4	43.8	46.2	41.5	45.2	47.2
10-Dec	47.5	56	38.7	39.7	42.0	39.1	40.9	43.4	39.5	41.8	44.3	39.8	42.6	45.0	40.7	44.0	45.9
17-Dec	46.0	56	38.4	39.1	41.7	38.8	40.1	42.8	39.1	40.9	43.5	39.4	41.7	44.1	40.2	42.9	44.8
24-Dec	45.3	56	38.4	38.9	41.3	38.7	39.8	42.3	39.0	40.5	42.9	39.3	41.1	43.4	40.0	42.3	44.2

WINTER BASEFLOW

Prior to dam construction, winter baseflows in the Trinity River at Lewiston were highly dynamic in response to rain and snowmelt. The ROD winter baseflows are a flat 300 cfs (Figure 4), continuing the winter flow regime that has been in place since 1978 when flows were increased from the original with-dam 150 cfs release (Figure 24, Figure 26). The winter release temperatures at Lewiston Dam are approximately 2 °C warmer than pre-dam conditions (Figure 26, Figure 27). As the river picks up tributaries en route, river temperatures are within approximately 1 °C of pre-dam conditions by the North Fork and less than 0.5 °C warmer than pre-dam temperatures by Weitchpec (Figure 46, Figure 47, Figure 49).

Due to abundant contributions from unregulated tributaries, variations in quantity of water released from Lewiston have much less effect on downstream river temperatures in winter than in summer. For example, in the RBM10 scenario with historical (i.e., measured with dam) Lewiston dam-release temperatures and unimpaired (i.e., without dam) flow, the modeled temperatures in November through March are within 0.5 °C of the historical scenario at all downstream sites (Figure 49). In addition, Safety of Dams releases provide a few opportunities to assess the thermal effects of Lewiston releases that are higher than 300 cfs, although such releases are also likely to occur only during high-flow years when tributary flows are presumably also high, so results may not be generalizable to drier conditions. Our analysis of Safety of Dams releases finds that large January releases (6,000 cfs) can warm temperatures at downstream sites by up to approximately 1.5 °C (Section 3.4.6.1).

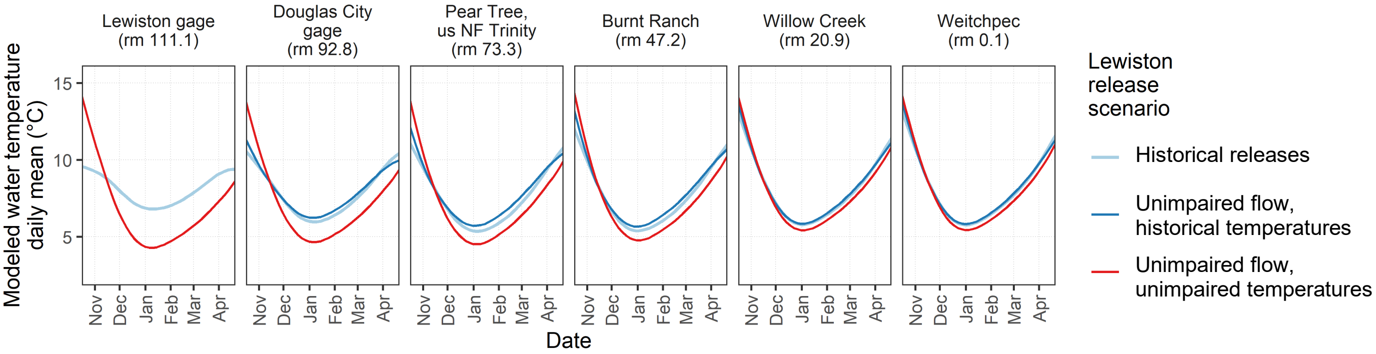


Figure 49. Smoothed daily mean water temperatures for 1980–2019 from October 15 through April 20 at selected mainstem Trinity River sites modeled with RBM10 under three Lewiston release scenarios. Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers representing typical conditions for the time of year, fit with all data within the period and scenario.

SPRING HIGH FLOW RELEASES AND RAMP DOWN

Pre-dam spring flows in the Trinity River at Lewiston were variable based on snowmelt and storm events (Figure 26). Our modeling (Figure 27) indicates that pre-dam temperatures followed the same seasonal and interannual trends as other large unregulated tributaries, with temperatures warming early in drought years and remaining cool later in wet years (Figure 7). Following dam construction, spring releases were 150 cfs from 1961–1978 (with sporadic additional releases), then at least 300 cfs with additional releases of variable timing and magnitude beginning around 1986 (Figure 24, Figure 26).

The ROD specified spring high-flow releases to begin on April 22 or 23 and peak at 1,500, 4,500, 6,000, 8,500, or 11,000 cfs, depending on the water year type. After decreasing from their peaks, the ROD specified that spring flow releases continue until 450 cfs summer baseflows are reached on June 26 in Dry and Critically Dry years or July 22 in other water year types. Our focus in this report is on temperature rather than geomorphic effects, so we devote most of our attention here to timing, duration, and general magnitude of the high-flow period rather than what happens during the few days with the highest flow. Total release volumes are determined according to the projected water year type, but the daily flow release scheduled is set annually each spring by the Trinity Management Council based on recommendations from the TRRP Flow and Temperature Workgroup. Since adoption of the ROD in 2000, the flow schedules have evolved under and adaptive management framework. Changes to hydrographs since adoption of the ROD include: 1) spring releases start earlier in some years, 2) peak releases occur earlier, 3) replacements of the 2,000 cfs ROD-specified bench with a gradual ramp down, and 4) multiple peaks instead of a single peak (Figure 44, Figure 45):

1) In several years, the spring flow releases have started earlier than the ROD-specified April 22 or 23 (e.g., 2019; Buxton 2020; Figure 50). Although a primary purpose of the spring flow releases is to enhance conditions for juvenile Chinook Salmon, on average approximately 60% of these fish have already migrated downstream of the Pear Tree rotary screw trap by the April 22 average start date of flow releases (Naman et al. 2020).

2) The ROD specified that the timing of peak releases depended on water year, with earliest peaks in Critically Dry years and later peaks in Extremely Wet years (Figure 4). Since 2010, these delays are reduced and releases reach their peaks up to a month earlier than specified in the ROD (e.g., 2017) (Figure 45).

3) The ROD specified a 2,000 cfs bench in June through early July for Normal, Wet, and Extremely Wet water year types (Figure 4), but since 2010, this has been replaced with a gradual ramp down (Figure 24, Figure 44, Figure 50), intended to promote recruitment of riparian cottonwood trees (HVT and McBain Assoc. 2016).

4) Beginning in 2017, releases have had multiple flow peaks rather than the single peak specified in the ROD (Figure 45, Figure 50) to enhance sediment transport and more efficiently accomplish geomorphic work (Gaeuman and Stewart 2017).

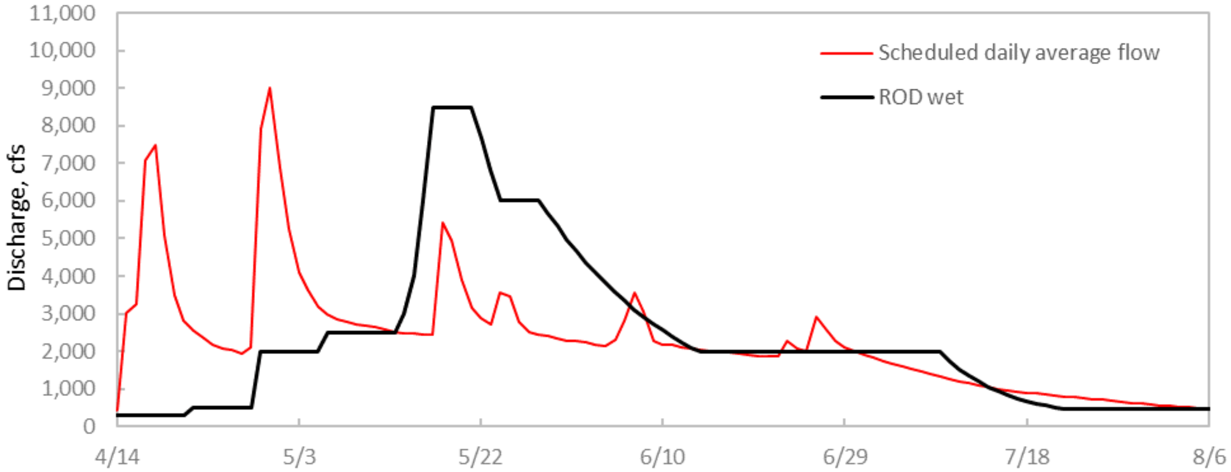


Figure 50. ROD-specified and scheduled daily average flows for the 2019 spring flow release period (April 14 – August 5). Figure from Buxton (2020).

Following annual lows in January, temperatures in the Trinity River (Figure 42, Figure 46) and tributaries (Figure 7) begin to steadily rise. In the ROD era, sudden onset of Lewiston spring high flow releases in late April causes river temperatures to decline sharply (Figure 42), in contrast to the thermal pattern of tributaries (Figure 7) and model predictions of the unimpaired river which continue rising (Figure 46). This decline is apparent at least as far downstream as Burnt Ranch (Figure 42). As air temperatures continue warming and flows (both river releases and tributary inputs) decline from their peaks, river temperatures again commence warming in May (Figure 42). The high-flow ROD releases decline back down to the 450 cfs summer baseflows by June 26 in Dry and Critically Dry years or July 22 in other water year types. The second and fourth columns of Figure 47 show modeled differences in predicted temperatures of up to 4 °C between ROD-specified releases and a flat 450 cfs release (purple dashed line) in the 2000–2018 ROD era. The effect of water year type is apparent, with the longer period of higher flows in Normal, Wet, and Extremely Wet years extending the period when temperatures are cooler and increasing the magnitude of cooling (Figure 46, Figure 47). The scenarios with constant releases of 350 cfs or 450 cfs have temperatures much closer to the unimpaired flow/temperature scenario than do the scenarios with high-flow releases (Figure 46), especially at lower sites such as Willow Creek and Weitchpec. At Weitchpec and Willow Creek, the 450 cfs scenario is 0-1 °C warmer than the impaired flow/temperature scenario in April–May, transitioning to be up to 2 °C cooler in late June and July (Figure 46).

The magnitude of the cooling effect of spring and summer releases from Lewiston depends on the amount of water releases, with the SNTEMP model showing that relative to a 300 cfs release, a release of 2,000 cfs cools Weitchpec temperatures by 5 °C for hot-dry July 1 meteorological conditions, 4°C on a median July 1, and 2 °C on a cold-wet July 1 (Zedonis and Newcomb 1997). At 6,000 cfs, Weitchpec temperatures are predicted to approach 14 °C regardless of meteorological conditions (Zedonis and Newcomb 1997).

As noted above, the ROD-specified 2,000 cfs bench in June through early July of Normal Wet, and Extremely Wet years has been replaced in the past decade with a gradual ramp down (e.g., 2010, 2011, 20012, 2016, 2017) (Figure 45). As a result of this change, temperatures initially warm faster (as flows drop below 2,000 cfs sooner) but then stay cooler longer as flows do not reach the 450 cfs summer baseflow until then the end of July or early August.

In Figure 47 the first column (Dry and Critically Dry water years in the 1980–1999 transitional era) and third column (Normal Wet, and Extremely Wet water years in the 1980–1999 transitional era) compare model predictions for the historical (i.e., actual Lewiston releases for the period) flow scenario (light blue) and a ROD-specified release scenario, indicating that had ROD-specified flows been in effect during the 1980–1999 period, temperatures would have been generally 1–3 °C cooler than the historical flow scenario in May–June of Dry and Critically Dry water years and May–July other water years. The measured temperature data for 1978–1999 and 2000–2019 shows similar trends as the modeled data (i.e., cooler temperatures during ROD spring releases) (Figure 40).

3.4.6 TEMPERATURE EFFECTS OF OTHER FLOW RELEASES (NON-ROD)

3.4.6.1 WINTER/SPRING SAFETY OF DAMS RELEASES

When the sum of free storage volume in Trinity Reservoir, diversions through Carr Tunnel, and scheduled flows on the Trinity River are insufficient to accommodate projected water inputs from storms in winter and early spring, flow is released to make room for flood storage and provide a buffer against catastrophic dam failure. These "Safety of Dams" (SOD) releases occurred in February and March in the wet water year of 2004 and respectively in December and April in the extremely wet water years of 2006 and 2017. We used RBM10 to evaluate these flow release effects on Trinity River discharges and water temperature compliance at Douglas City, Pear Tree upstream of the NF Trinity River, and at Weitchpec and found they had an increasing influence on discharge with proximity to Lewiston and differential effects on temperature at these stations relative to ROD-specified flow releases that would have otherwise occurred (Figure 51). RBM10 estimates that relative to ROD-specified flows, the SOD releases warmed the Trinity River in all years they occurred except in water year 2017 when temperatures were decreased slightly at Douglas City (Table 8). Daily average temperature differences between the SOD flows and the scheduled ROD flows were less than 1.5 °C, indicating SOD-induced temperature changes likely have only nominal effects on the stream biota. SOD releases also occur during or after periods of high tributary runoff which helps dilute dam releases and buffers SOD-driven temperature changes (Section 3.4.3.2).

Table 8. RBM10 estimates of daily average temperature (°C) differences between Safety of Dams (SOD) releases and ROD-specified flows had they been released at the same time of year. Positive values indicate that additional releases warmed river temperature while negative values indicate cooling. Maximum is the day with the most positive difference, minimum is the day with the most negative difference, and total is degree-days of difference (i.e., the sum of all daily differences during the release period).

Station	Water year 2004 (2/17/04 – 3/15/04)			Water year 2006 (12/27/05 – 2/17/06)			Water year 2017 (4/5/17 – 4/20/17)		
	Total	Maximum	Minimum	Total	Maximum	Minimum	Total	Maximum	Minimum
Douglas City	2.4	0.5	-0.4	25.0	1.2	0	-2.8	0.2	-0.6
Pear Tree	7.8	0.5	0	21.8	1.3	0	2.3	0.4	0
Weitchpec	0.4	0.1	-0.2	8.7	0.6	0	0.4	0.1	-0.1

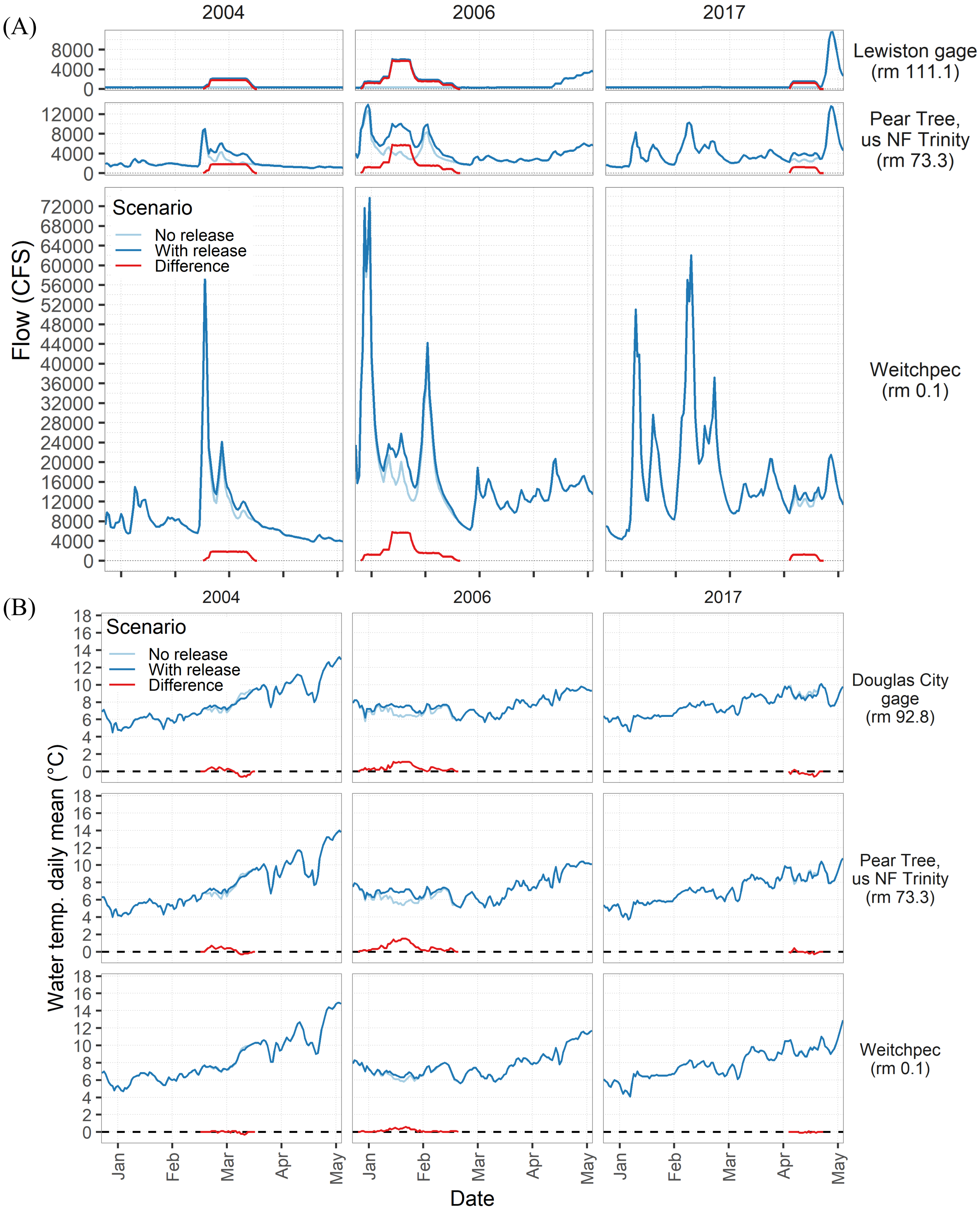


Figure 51. Daily time series of modeled (A) flow and (B) temperature effects 2004, 2006, and 2017 Safety of Dams releases from Lewiston Reservoir into the Trinity River.

3.4.6.3 SUMMER PULSE FLOWS FOR HOOPA VALLEY TRIBAL BOAT DANCE CEREMONY

In summer of odd-numbered years since 1989, a pulse of water is released from Lewiston Reservoir into the Trinity River for the Hoopa Valley Tribe's Boat Dance Ceremony, with the only exception being 2003 when the Ceremony was instead accommodated by an extended Klamath River flow augmentation release (Section 3.4.6.4). Since 2001, Boat Dance flows have peaked between 1,610 and 2,750 cfs and involved 3,433 to 15,588 AF of water above summer baseflow (Figure 24, Table 9). Boat Dance Flows are an anomaly to the natural flow regime of the Trinity River, which would exhibit substantially lower flows in August and September than these flow releases provide.

Several USFWS annual monitoring reports used graphical analyses to evaluate effects of Boat Dance releases on river temperatures (Zedonis and Turner 2006, 2008; Scheiff and Zedonis 2010, 2012). A 2,650 cfs release from Lewiston in late-August 2011 dropped temperatures at the mouth of the Trinity River by approximately 4 °C, downstream of the Klamath/Trinity confluence by 1.9 °C, and by 1.3 °C in the Klamath River near Klamath (river mile 5.7) (Scheiff and Zedonis 2012). Similar results were found for the 2009 release (Scheiff and Zedonis 2010). Three-day long Boat Dance releases that peaked at 1,610 cfs in late August 2005 and 1,760 cfs in late August 2007 decreased Trinity River temperatures at the mouth of the Trinity River by approximately 1–2 °C (Zedonis and Turner 2006, 2008). The 2005 release cooled temperatures downstream of the Klamath-Trinity confluence by 0.8 °C, with effects further downstream not readily apparent (Zedonis and Turner 2006).

Table 9. Occurrence of Hoopa Boat Dance flows on the Trinity River since water year 2001.

Water year	Water year type	Start date	End date	Peak flow (cfs)	Volume (AF)[1]
2001	Dry	8/26/2001	8/28/2001	1,760	6,795
2005	Normal	8/27/2005	8/30/2005	1,610	6,319
2007	Dry	8/26/2007	8/28/2007	1,760	3,433
2009	Dry	8/23/2009	8/27/2009	2,750	15,588
2011	Wet	8/28/2011	9/1/2011	2,650	15,279
2013	Dry	8/25/2013	8/28/2013	2,630	13,587
2015	Dry	8/16/2015	8/19/2015	2,420	12,428
2017	Ext wet	8/20/2017	8/24/2017	2,380	13,295
2019	Wet	9/1/2019	9/5/2019	2,360	12,877

[1] Volume released in excess of scheduled summer baseflows (450 cfs).

Thermal effects of Boat Dance releases were evaluated using RBM10 model predictions at Douglas City, Pear Tree upstream of the NF Trinity River, Weitchpec, Klamath River near the confluence with the Trinity River and in the Klamath River 5.9 miles upstream of the Pacific Ocean as done for Safety of Dams releases (Figure 52, Figure 53). Because they occur in the hottest time of year when tributary discharges are near annual lows, Boat Dance flows have a strong cooling effect on water temperatures in the Trinity and Klamath Rivers (Table 10). Cooling that resulted from Boat Dance flows increased with downstream distance on the Trinity River and was as low as -6.7 °C at Weitchpec, -3.4 °C at Pear Tree, and -1.8 °C at Douglas City compared to temperatures modeled under summer baseflow conditions. Temperature decreases resulting from Boat Dance flows were greatest at Weitchpec and decreases in Klamath River temperatures were similar to those modeled at Pear Tree (Figure 52, Table 10).

Comparison of measured and modeled temperatures indicates that measured temperature declines were not as large as was predicted by RBM10 (Figure 53). There are two likely reasons for this. The first reason is the short duration of these releases. RBM10 instantaneously (i.e., same day) routes Lewiston releases downstream, whereas in reality, flow at Hoopa does not rise for at least a day and mixing causes further delays in the time it takes for the full temperature effects to arrive (Section C.2 in Appendix C). A second reason is that RBM10 systematically underestimates Klamath River flows, leading to an overestimation of the cooling effect of Lewiston releases at the Klamath River sites (Section 2.3.3.3).

Table 10. RBM10 estimates of daily average temperature (°C) differences between Hoopa Boat Dance flow releases and summer baseflows had they been released the same time of year. Negative values indicate the additional releases cooled river temperatures. Minimum is the day with the most negative difference and total is the degree-days of difference.

Water year	Trinity R at Douglas City		Trinity R at Pear Tree		Trinity R at Weitchpec		Klamath R nr Trinity River (rm 43.1)		Klamath R nr Pacific Ocean (rm 5.9)	
	Total	Min.	Total	Min.	Total	Min.	Total	Min	Total	Min.
2001	-2.8	-1.4	-5.0	-2.6	-11.3	-4.2	-5.5	-1.6	-4.4	-1.4
2005	-2.6	-1.2	-4.1	-2.0	-8.1	-3.4	-3.8	-1.5	-3.0	-1.3
2007	-3.1	-1.4	-5.8	-2.8	-12.5	-4.7	-5.2	-1.8	-4.1	-1.5
2009	-5.7	-1.5	-11.4	-3.3	-24.5	-6.7	-11.8	-3.8	-10.2	-3.3
2011	-6.3	-1.7	-9.9	-3.1	-21.3	-5.9	-11.7	-3.5	-11.0	-3.3
2013	-4.0	-1.3	-7.5	-2.6	-22.1	-5.5	-11.5	-3.7	-10.0	-3.5
2015	-5.0	-1.7	-9.9	-3.4	-19.6	-6.2	-9.2	-3.6	-7.6	-2.8
2017	-6.2	-1.8	-10.0	-3.4	-20.3	-6.4	-10.0	-3.6	-8.5	-3.3

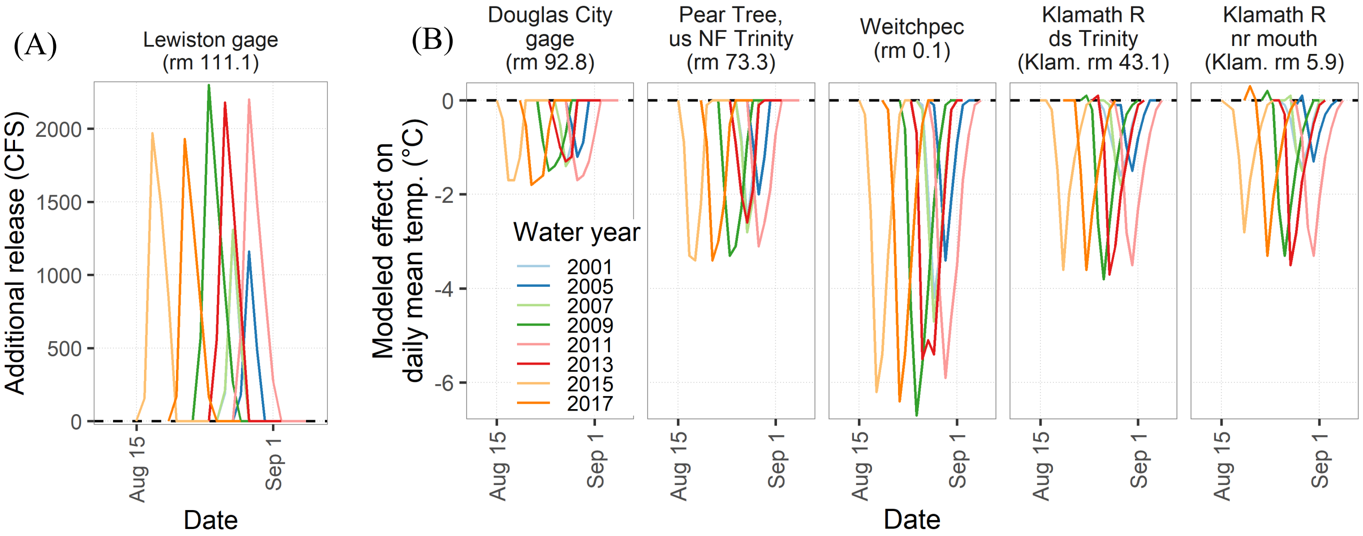


Figure 52. Summary of RBM10-modeled (A) flow and (B) temperature effects of the 2001 and 2005–2017 releases from Lewiston Reservoir for the Hoopa Valley Tribe's Boat Dance ceremony. Flow and temperatures for 2001 are mostly obscured by 2007.

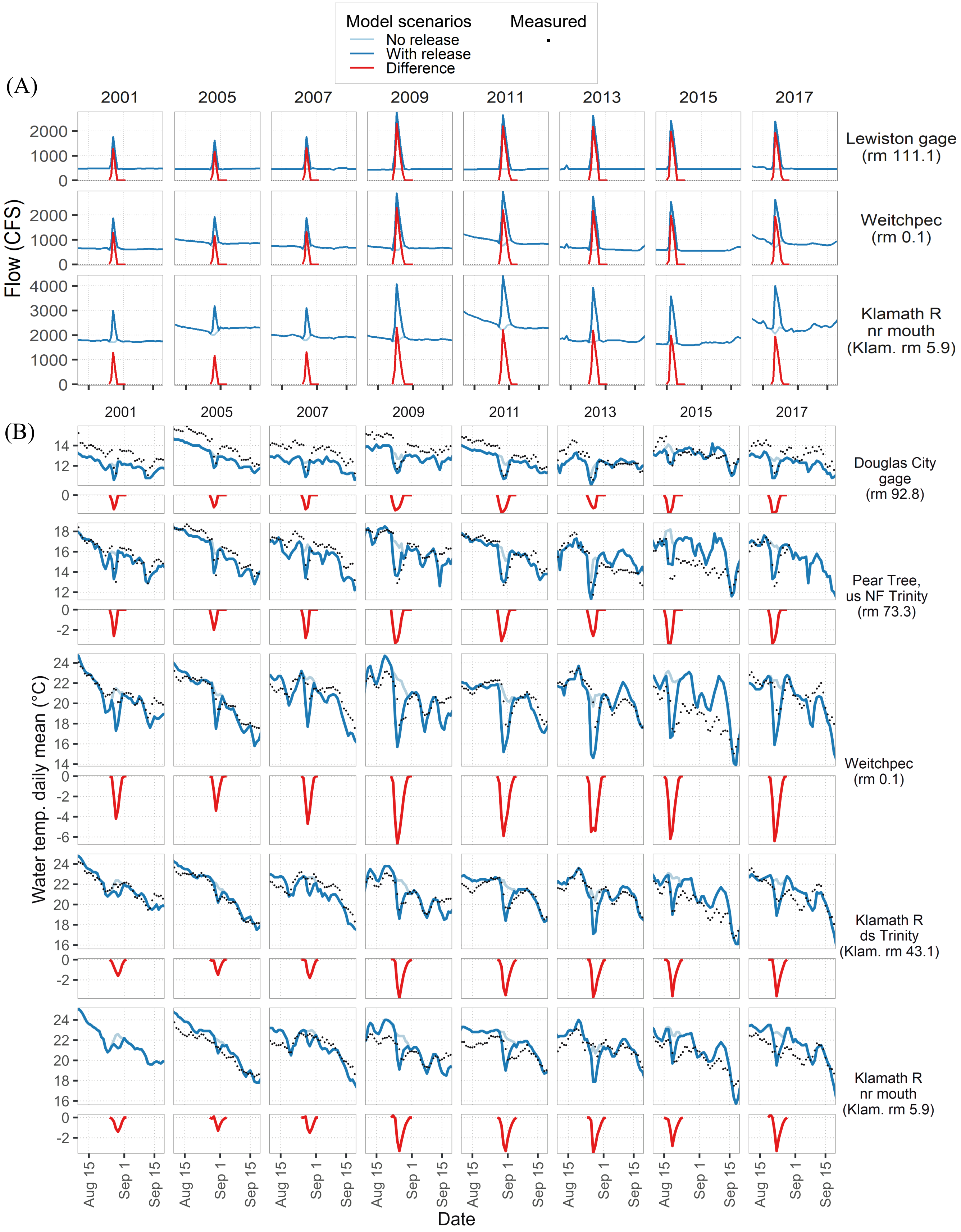


Figure 53. Daily time series of RBM10-modeled (A) flow and (B) temperature effects of the 2001–2017 releases from Lewiston Reservoir into the Trinity River for the Hoopa Valley Tribe's Boat Dance ceremony. Measured temperatures are also included, shown as points.

3.4.6.4 SUMMER/FALL RELEASES TO INCREASE FLOW IN THE LOWER KLAMATH RIVER

In eight years since the 2002 Lower Klamath River fish kill (Belchik et al. 2004, Guillen 2003, Turek et al. 2004), Trinity River flow releases have been used in late summer to improve water quality and reduce transmission of diseases affecting adult salmon in the Lower Klamath River (Table 11; USBR 2017; Buxton 2019). As with flow releases to accommodate the Hoopa Boat Dance, Trinity River flow releases to augment Klamath River flows are wholly apart from the natural flow regime of the Trinity River and observations have suggested they impart a thermal shock to the Trinity River ecosystem. For example, Indian Rhubarb (*Darmera peltata*) that provides cover along stream margins for rearing juvenile salmonids is often browned and wilted following Boat Dance and Klamath River augmentation flows (K. De Juilio, pers. obs.).

Several previous reports have evaluated the effect of these releases on water temperatures in the lower Trinity River and Lower Klamath River. David and Goodman (2017) used daily statistical models of stream temperatures observed during the 2003, 2004, and 2012–2016 flow releases and concluded releases reduced Klamath River water temperatures downstream of the Klamath/Trinity confluence by 0.9 °C per 1,000 cfs increase in Trinity River flow. At the mouth of the Klamath River, water temperatures were reduced by 0.4 °C per 1,000 cfs increase in Trinity River flows. Moreover, Zedonis (2004) found that increasing Lewiston releases from 450 cfs to 1,800 cfs in late August through mid-September 2003 decreased temperatures in the Klamath River by as much as 2 °C and at the mouth of the Trinity River by up to approximately 3 °C, with smaller decreases on days with cooler air temperatures. Zedonis (2005a) found that pulse flows from Lewiston and Iron Gate Dams in late August through mid-September 2004 also had a cooling effect, but by a lesser amount than in 2003. Magneson (2013) found that the 2012 mid-August through mid-September Lewiston release cooled temperatures at the mouth of the Trinity River by 2 °C (relative to the Klamath River upstream) and the Klamath River downstream of the Klamath/Trinity confluence by 1 °C.

Table 11. Occurrence of flows released from Lewiston Dam to the Trinity River to improve water quality and decrease water temperatures on the Lower Klamath River.

Water year	Water year type	Start date	End date	Peak flow (cfs)	Volume (AF)[1]
2003	Wet	8/24/2003	9/16/2003	1,810	60,137
2004	Wet	8/22/2004	9/13/2004	1,700	37,134
2012	Normal	8/13/2012	9/19/2012	1,380	39,032
2013	Dry	8/31/2013	9/20/2013	973	16,637
2014	Crit dry	8/23/2014	9/24/2014	3,410	64,883
2015	Dry	8/20/2015	9/19/2015	2,900	47,937
2016	Wet	8/25/2016	9/26/2016	1,250	39,176
2018	Crit dry	8/21/2018	9/20/2018	816	16,413

[1] Volume released in excess of scheduled summer baseflows (450 cfs).

Modeling with RBM10 indicates that Klamath River augmentation flows released to the Trinity River were slightly less effective at lowering daily average water temperatures at Douglas City, Pear Tree upstream of the NF Trinity River, Weitchpec, Klamath River near the confluence with the Trinity River and the Klamath River 5.9 miles upstream of the Pacific Ocean (Table 12, Figure 55, Figure 54) than Hoopa Boat Dance flows likely due to their slightly later occurrence in Fall (Table 10, Figure 52). The total degree-days of temperature declines for the duration of augmentation flows were nonetheless substantially greater than for Hoopa Boat Dance flows owing primarily to the longer duration and higher volume of release for the former (Table 10, Table 12). Comparison of measured and modeled flows indicates that measured temperature declines were not as large as predicted by RBM10 (Figure 55), likely in part because RBM10 underestimates Klamath River flows (Section 2.3.3.3).

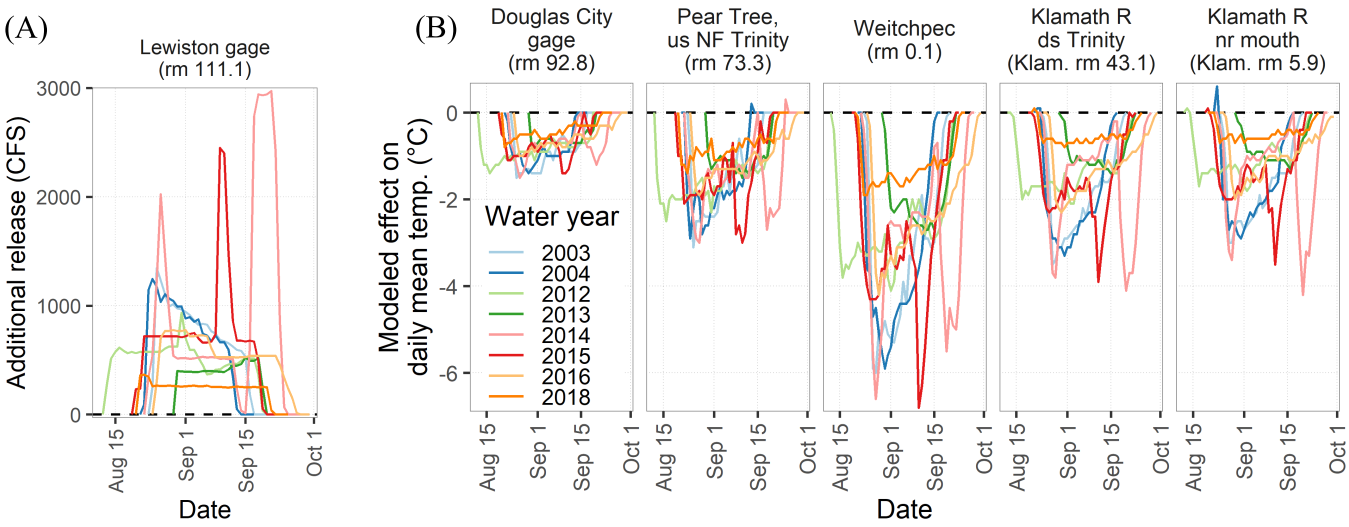


Figure 54. Summary of RBM10-modeled (A) flow and (B) temperature effects of 2003–2004, 2012–2016, and 2018 fall releases from Lewiston Reservoir into the Trinity River intended to improve conditions in the Lower Klamath River.

Table 12. RBM10 estimates of daily average temperature (°C) differences between Klamath River augmentation flows and summer baseflows had they been released the same time of year. Negative values indicate the additional releases cooled river temperatures. Minimum is the day with the most negative difference and total is the degree-days of difference.

Water year	Trinity R Douglas City		Trinity R Pear Tree		Trinity R Weitchpec		Klamath R nr Trinity R (rm 43.1)		Klamath R nr Pacific Ocean (rm 5.9)	
	Total	Min.	Total	Min.	Total	Min.	Total	Min.	Total	Min.
2003	-24.3	-1.5	-41.2	-3.1	-92.5	-6.0	-52.3	-3.5	-46.6	-3.0
2004	-21.6	-1.4	-41.4	-2.9	-92.1	-5.9	-52.8	-3.3	-44.3	-2.9
2012	-33.9	-1.4	-61.9	-2.5	-110.3	-4.1	-54.9	-2.1	-44.0	-1.8
2013	-13.7	-0.8	-24.1	-1.5	-47.8	-2.7	-23.7	-1.4	-21.1	-1.3
2014	-25.2	-1.5	-51.8	-3.0	-106.0	-6.6	-56.7	-4.1	-50.4	-4.2
2015	-24.0	-1.4	-48.3	-3.0	-101.8	-6.8	-54.8	-3.9	-48.0	-3.5
2016	-21.2	-1.0	-38.0	-1.9	-85.2	-4.2	-45.2	-2.3	-36.2	-2.0
2018	-14.4	-0.8	-26.9	-1.4	-45.0	-1.9	-19.2	-0.8	-16.7	-0.7

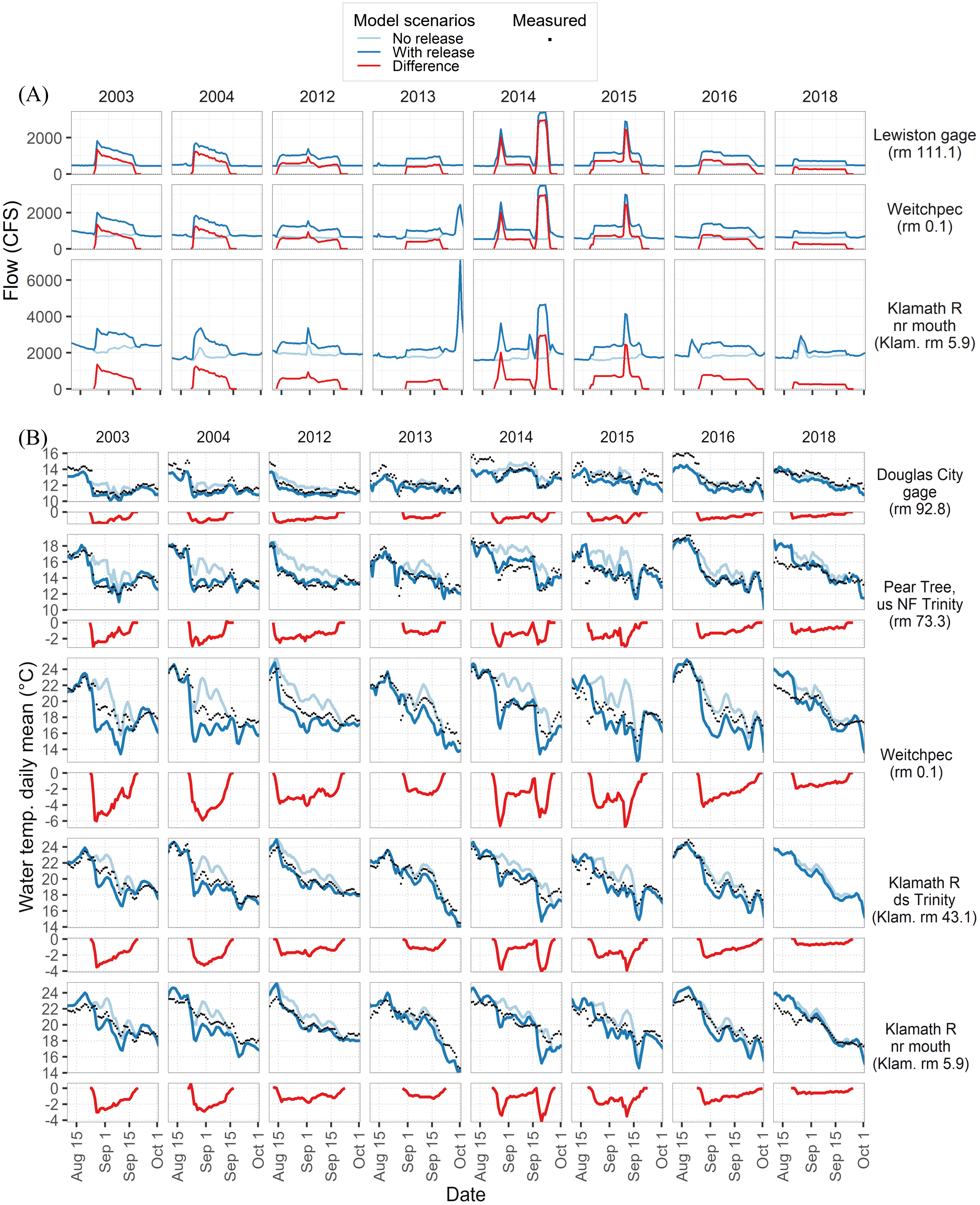


Figure 55. Daily time series of RBM10-modeled (A) flow and (B) temperature effects of 2003–2004, 2012–2016, and 2018 fall releases from Lewiston Reservoir to improve water quality and lower temperatures in the Lower Klamath River. Measured temperatures are also included, shown as points.

Relative to summer baseflow, higher release rates from Lewiston Reservoir are predicted to result in greater cooling of water temperatures in both the Trinity and Klamath Rivers until Lewiston releases reach approximately 1,450 cfs (1,000 cfs above the 450 cfs summer baseflows), above which the cooling effect appears to level off rather than continuing to intensify; however, this may be partially because the highest flows occurred in late September when air temperatures were cooler (Figure 56). As a simple comparison of RBM10 results to David and Goodman's (2017) linear statistical models discussed above, we fit a linear trend line across the entire range of flows, although as noted in the previous sentence the effect is actually not linear. The magnitude of cooling predicted with RBM10 (Figure 65) is 1.9 °C/1000 cfs and 1.7 °C/1000 cfs in the Klamath River downstream of the Klamath/Trinity confluence and the mouth of the Klamath River, respectively, more than twice that predicted by David and Goodman (2017). In principle, the process-based RBM10 model should be able to isolate the effect of the flow releases from other factors (e.g., the ratio of Klamath River flow to Trinity River flow) better than a statistical model could; however, RBM10's underestimation of Klamath River flow (Section 2.3.3.3) seems to cause overestimation of the cooling effect of Lewiston releases on the Klamath River.

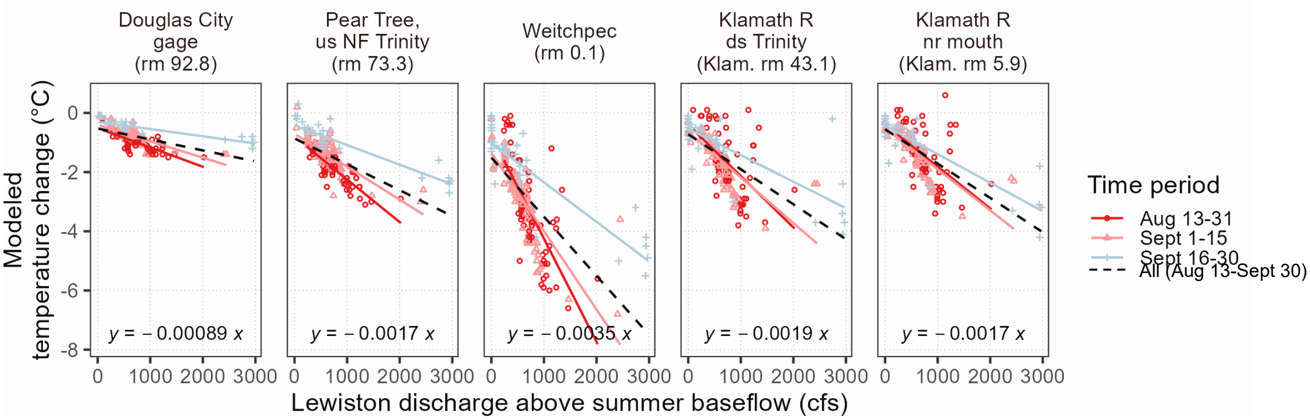


Figure 56. Relationship between Lewiston Reservoir releases above 450 cfs summer baseflows and RBM10 estimates of daily average temperature (°C) changes resulting from the additional flow releases. Each point represents a day in Mid-August through late September in 2003–2004, 2012–2016, and 2018 when releases were made from Lewiston Reservoir into the Trinity River intended to improve Lower Klamath River conditions. Temperature changes are computed as the temperature of augmentation release scenario minus temperature of summer baseflow scenario.

3.4.6.5 EMERGENCY RELEASES

Outside of flow releases from Trinity and Lewiston Reservoir for Safety of Dams (Section 3.4.6.1) and to augment flows in the Lower Klamath River (Section 3.4.6.4), emergency releases are possible for what can be unforeseen circumstances. In Summer 2018, wildfire impacts to water and power generating infrastructure required that diversions via Carr tunnel be decreased starting July 24. As a result, flow through Lewiston reservoir slowed and the reservoir warmed enough to cause water temperatures at Douglas City to exceed targets by as much as 1.3 °C (2.4 °F) (Buxton, 2018). Emergency flows were released to the Trinity River above the 450 cfs summer baseflow starting July 26 and lasting until Klamath River augmentation flows began on August 23. The volume of flow for this emergency release was 17,554 AF above the 450 cfs baseflow.

4 TRINITY RIVER MAINSTEM TEMPERATURE CRITERIA

4.1 EXISTING TEMPERATURE CRITERIA

4.1.1 SUMMARY OF NUMERIC TEMPERATURE CRITERIA

The first temperature criteria for the Trinity River were established in 1990 by California State Water Resources Control Board Water Order 90-5. To protect adult salmonids, eggs, and embryos, this order mandated Reclamation operations not cause average daily temperatures in the Trinity River to exceed 56 °F (13.3 °C) at Douglas City from Sept 15 through Sept 30 and at the confluence of the North Fork Trinity River from Oct 1 through Dec 31 (Table 1 bottom two rows). In 1993, these two thresholds and a new threshold of 60 °F (15.5 °C) at Douglas City for July 1 – Sept 14 were incorporated into the North Coast Regional Water Quality Control Board Plan for the North Coast Region where they have remained unchanged through June of 2018 (CRWQCB-NCR 1993 and 2018). These criteria were also included in the Public Draft of the 2000 Trinity River Mainstem Fishery Restoration EIS (USFWS et al. 1999), in accordance with recommendations of The Trinity River Flow Evaluation Study (USFWS and HVT 1999).

HVT has adopted its own temperature criteria for the Trinity River, first approved by U.S. EPA in 2002 (Table 13; HVTEPA 2020). These criteria span the entire year, varying by date and water year type. For April through June 15 in all water year types, and for June 16 to July 9 in extremely wet, wet, and normal water year types, the HVT criteria match the outmigration threshold values (although outmigration thresholds are typically interpreted as single-day averages while the HVT criteria are 7-day averages), but on June 16 to July 9 of dry and critically dry years the HVT criteria is 23.5 °C which is warmer than the outmigration criteria. The HVT criteria for July 10 through March are unique (i.e., not identical to any other Trinity River criteria). HVTEPA (2020) states that “the temperature standards do not require additional flows over and above those required by the TRFE” (i.e., HVT and USFS 1999) and that violations occur when 10% of days within a period exceed criteria. Given that TRRP does not typically consider these criteria, we do not calculate exceedances in this report.

Table 13. Temperature criteria for the Hoopa Valley Indian Reservation (HVT 2020). Table values are running 7-day average temperatures not to be exceeded.

Water-Year Type	May 23 to June 4	June 5 to July 9	July 10 to Sept. 14	June 5 to June 15	June 16 to Sept. 9	Sept. 15 to Oct. 31	Nov. 1 to May 22
Extremely Wet, Wet and Normal	≤ 59 °F (15.0 °C)	≤62.6 °F (17.0°C)	≤ 72.0 °F (22.1°C)			≤ 66.0 °F (19.0 °C)	≤ 55.4°F or (13.0 °C)
Dry and Critically Dry	≤ 62.6 °F (17.0 °C)			≤ 68 °F (20.0 °C)	≤ 74.0°F (23.5 °C)	≤ 66.0 °F (19.0°C)	≤ 59.0 °F (15.0 °C)

The 2000 Trinity River Mainstem Fishery Restoration EIS (USFWS et al. 1999) also adopted additional temperature thresholds from the Trinity River Flow Evaluation (USFWS and HVT 1999) for juvenile salmonid emigrants at Trinity River in Weitchpec (Table 2, Figure 57). Temperature objectives vary annually based on water year type (extremely wet, wet, normal, dry, and critically dry), and target different salmonid species at different times of year (Table 2). However, the temperature thresholds for outmigration in the lower Trinity River (Table 2) are not known to have any regulatory nexus and are not known to be enforced by regulatory agencies. The end dates for emigration targets were clearly defined by USFWS et al. (1999) and USFWS and HVT (1999) (Table 2) and the targets apply sequentially (i.e., first steelhead, then Coho Salmon, then Chinook Salmon), but the start date for the first species (steelhead) was not defined and has thus been interpreted differently over time. USFWS annual temperature compliance reports (see citations in Section A.3.4 of Appendix A) used April 15 as a start date in the reports for 2003–2007 while the 2009–2016 reports use April 22 and the 2016–2017 reports used April 1. There are two versions of the 2008 report, one of which used April 15 and the other used April 22. Recent annual flow implementation reports use April 22 (Buxton 2020). In our analyses (Section 4.3), we choose to apply an inclusive date of March 1, based on the earliest date of steelhead smolt outmigration listed in USFWS and HVT (1999).

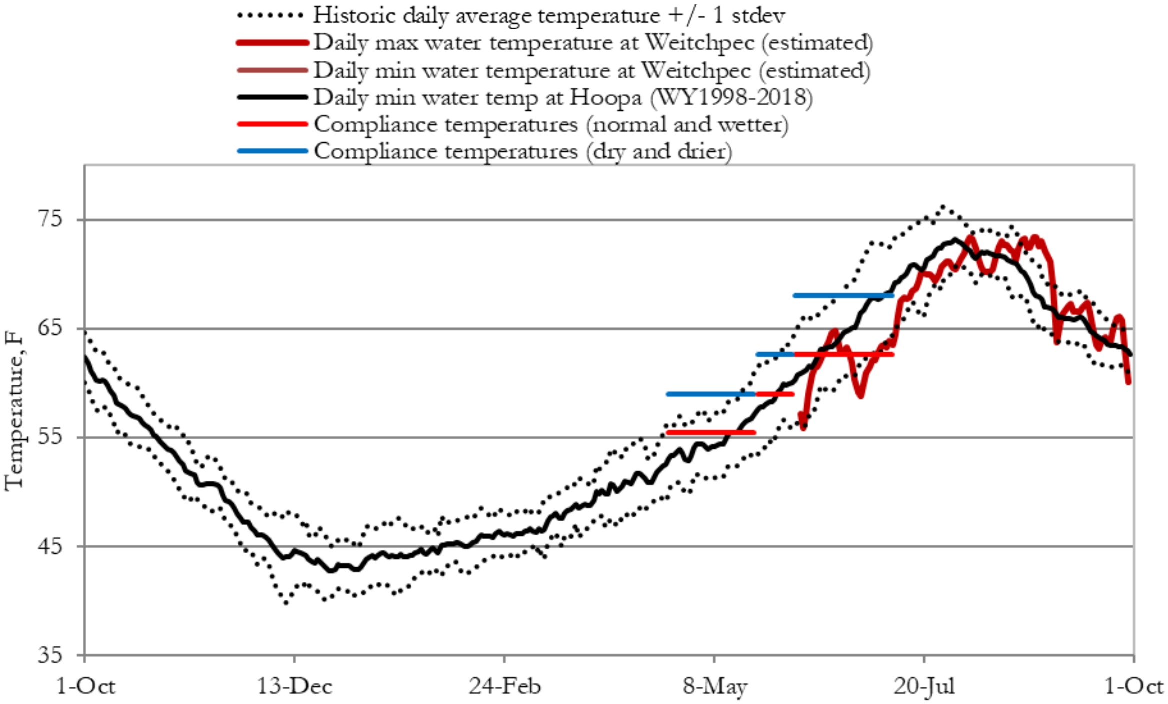


Figure 57. Temperature thresholds (horizontal red lines) for juvenile salmonid outmigration in the Trinity River at Weitchpec for Extremely Wet, Wet, and Normal years compared with estimated daily average water temperatures for an example hydrologic year (10/1/2018–9/30/2019) and daily statistics for the recent period of record. Figure adapted from Buxton (2020).

4.1.2 WHAT WAS CONSIDERED IN DEVELOPMENT OF CRITERIA

4.1.2.1 ADULT CRITERIA

Major considerations during development of adult salmon temperature thresholds were protection of holding habitat, in vivo eggs, and incubation. Temperature thresholds first recommended in State Water Resources Control Board Water Order 90-5 were developed to meet the needs of adult salmonids, particularly for Chinook Salmon in the Sacramento River Basin. These thresholds were expanded to include the July 1st – September 14th 60 °F (15.6 °C) threshold for holding adult spring Chinook Salmon (CRWQCB-NCR 1993). While the Trinity and Sacramento watersheds neighbor each other, there are significant differences. These differences include elevation of existing spawning and holding habitat and presence of different runs of salmonids, such as ESA listed Sacramento River Winter-run Chinook Salmon.

The incubation period for salmonid eggs has the most restrictive thermal requirements of all life stages and is the limiting factor for temperature management during times when eggs are in gravels. Intragravel water temperatures can differ from surface water temperatures, especially where hyporheic upwelling occurs. Monitoring of known Chinook Salmon spawning areas in the Trinity River by USFWS showed high variability among sites during the Chinook salmon incubation period, with some sites having intragravel temperatures up to 3°C warmer that surface water while gravel at other sites closely reflected surface water temperatures (David 2017, Magneson 2016). In the Trinity River Stream Salmonid Simulator (S3) model, intragravel temperatures are set as 1 °C warmer than surface temperatures (Perry et al. 2018).

4.1.2.2 OUTMIGRATION AND SMOLTIFICATION CRITERIA

The Trinity River Flow Evaluation (USFWS and HVT 1999) established temperature objectives for outmigrants at Weitchpec (Table 2) by determining water temperature requirements for the smoltification process of each salmonid species grouped together by optimal, marginal, and unsuitable thermal tolerances based on literature reviews by Zedonis and Newcomb (1997). Dates for temperature objectives for each species were determined by calculating 80 percent emigration at the Willow Creek rotary screw trap site based on data from 1992 to 1995. Zedonis and Newcomb (1997) concentrated on the smoltification process and timing of outmigration under hydrologic and atmospheric conditions observed from 1989 to 1995. Literature review focused on laboratory and hatchery studies for physiological measure of smoltification under different thermal regimes and field experiments for evaluation of emigrant timing. There was no evaluation of critical rearing area or where in the system smoltification should be prioritized. Instead, the identified criteria were applied at the terminus of the Trinity River, assuming that upstream would be colder and in compliance with threshold management.

4.1.2.3 COLD TEMPERATURES WERE GENERALLY NOT CONSIDERED A PROBLEM

Water temperatures in Table 1 and Table 2 are often called "objectives" in various TRRP documents such as USFWS and HVT (1999), they are more accurately thought of as thresholds because any water temperature below those in the tables would comply. This type of criteria contributes to biologist and managers approaching water temperature management from the perspective of "colder is better" because any water temperatures colder than the objectives are thought of as either sufficient or beneficial. This is an overly simplistic management scheme which does not account for the range of temperatures at which a particular stock of salmonids grows at a maximum rate, for a given amount of ration resulting in temperatures that regularly fall below the optimal growth range (Section 4.1.3.1).

The seasonal temperature differences between Trinity Dam releases and the river pre-dam/diversion are well established (Rowell 1979, Zedonis and Newcomb 1997, USFWS and HVT 1999, Section 3.4.1.3), but review of Trinity River temperature literature indicates cold dam releases have primarily been considered beneficial, or at least not harmful, to growth of salmonids in the Trinity River. One of the few mentions of an optimal range for river temperatures which includes both a lower and upper bound is Rowell (1979), who used target temperature criteria of 50–62 °F (10.0–16.7˚C), citing personal communication from Paul Hubbell of the California Department of Fish Game as the source. Interestingly, many hatchery reports do mention adverse effects of cold winter temperatures during egg incubation and juvenile growth (Kramer, Chin and Mayo, Inc. 1977, CDWR 1978, Turner 1978). Another example is USFWS and HVT (1999) presentation of Table 5.13 on page 187 and Figure 5.56 on page 202 which show lower bounds of optimal temperatures for steelhead, coho salmon, and Chinook Salmon, but these were not emphasized in the setting of temperature criteria that drove flow management.

An additional potentially detrimental effect of cold temperatures that has not yet been evaluated in the Trinity River is cold shock if fish experience a sudden drop in temperature (Donaldson et al. 2008), such as might occur when high flows, in the absence of selective withdrawal from Trinity Reservoir, are suddenly released from Lewiston Dam in the summer.

4.1.3 SCIENTIFIC UNDERSTANDING HAS EVOLVED SINCE CRITERIA WERE DEVELOPED

Despite not receiving much of attention locally in the Trinity River in the 1990s, the detrimental effects of excessively cold water on juvenile salmon growth had been established in the wider scientific literature for several decades (e.g., Brett 1971, Brett et al. 1982) (Section 4.1.3.1). In addition, in the time since criteria were developed, much new information has become available on how water temperatures affect salmonids. In this section, we summarize some of those studies and discuss the implications for Trinity River temperature management.

4.1.3.1 IMPORTANCE OF JUVENILE SALMON GROWTH CRITERIA

Temperature thresholds developed in the 1990s for adult salmonids were thought to be sufficient for rearing juvenile salmonids (USFWS and HVT 1999; Table 5.13) based on Brett (1952), a lab study finding that when given a choice of different water temperatures, salmon preferred (i.e., moved to) 12–14 ˚C; however, these are lower than optimal growth temperatures. These adult salmonid thresholds do not take effect until July, well after most ocean-type salmonid juveniles have emigrated from the upper Trinity River (Perry et al. 2018). Currently, there are no water temperature objectives for the upper Trinity River developed specifically for rearing salmonids.

Smoltification is a vital and impressive development in the life cycle of an anadromous salmonid, but the most vulnerable period of salmonid life history is the time between emergence and smoltification (Beauchamp 2009). This period is referred to as juvenile rearing and was hypothesized by the Trinity River Flow Evaluation Study to limit production of anadromous fish (USFWS and HVT 1999). Juvenile Salmon experience strong size-selective mortality, so periods of weight loss or reduced growth rate can translate into higher risk of mortality during subsequent life stages as they migrate downstream and enter the ocean. Smaller salmonids have been found to have a higher potential scope of benefit from both optimal temperature and ration than larger salmonids due to allometric relationships for maximum consumption, metabolism, and waste (Beauchamp 2009). During the critical rearing life stage, a salmonid can grow from 25 mm to 90 mm, over tripling in length and increasing up to 43 times in weight, over a few months. Empirical studies on the Trinity River have documented a decrease in the size of outmigration juvenile salmon since 2004 for weeks occurring after the ROD spring flow releases, beginning near the end of April, compared to the same week of the year prior to ROD releases (Pinnix et al. 2022).

During the time USFWS and HVT (1999) authored the Flow Study, limited data were available on growth of salmonids under a range of rations for various stocks throughout the range of Pacific salmon. In general, colder water temperatures were thought to be beneficial, or at least not detrimental, to salmonid growth. Lab studies by Brett et al. (1982) found juvenile Chinook salmon growth peaked at 19 ˚C at maximum daily ration or 14.8 ˚C at 60% ration. Several studies from the years 1982–1997 reviewed by Richter and Kolmes (2005) found optimum growth temperatures for juvenile Chinook salmon at maximum rations ranged from 14.8˚C to 20 ˚C. A recent laboratory study found that juvenile Chinook Salmon from Trinity River Hatchery grew faster at 20°C than 16°C (Zillig et al. 2023). In the decades since development of the Trinity River temperature criteria and flow studies, there has been new research on optimal thermal regimes for salmonids. For example, Elsner and Shrimpton (2019) found a mean temperature preference of Fraser River B.C. Coho Salmon of 16.5°C for parr, and 15.5°C for smolts. Comparing Coho salmon growth inside enclosures with a range of temperatures and prey densities in the Shasta River, Lusardi et al. (2019) found that absolute growth rates were highest in the reach with highest prey densities and 16.6 °C mean daily average water temperature. Results of water temperatures on salmonid growth in studies reviewed by Carter et al. (2005) are provided in Table 14. Sullivan et al. (2000) found that an MWMT of 13°C to 16.5°C would result in no more than a 10% reduction in maximum growth. Railsback and Rose (1999) found for rainbow trout that predicted growth varies with fish size and food consumption, but in general, their model predicted growth to be high between 10°C and 22°C, peaking at about 15°C (59°F). Recent research indicates that optimal growth temperatures differ between salmonid populations due to genetic differences (Zillig et al. 2021, 2022, 2023). In summary, many decades of accumulating evidence clearly indicate that colder water temperatures do not translate into faster juvenile salmonid growth, and in most cases can slow their growth when compared to warmer temperatures for a given ration.

Establishment of a temperature target for juvenile salmonid growth has been explored by TRRP for over a decade, until a recommendation from the Fish Workgroup was recently finalized (Naman et al. 2020). For example, it was proposed in a 2008 workshop as part of developing the Integrated Assessment Plan:

> “The Program would develop system and reach scale indices of the suitability of the annual temperature regime (e.g., total degree days deviation from the optimum temperature for juvenile salmonid growth), to use as covariates in explaining annual variations in biological responses. Similarly, the Program would need a system wide annual index of the area of suitable habitat, or number of days with sufficient habitat area and appropriate temperatures given the number of fry present in that year (see Appendix C).” (p. 101, TRRP and ESSA 2009).

Degree-days deviation provides a convenient and concise statistic; however, it underweights the true impact of higher temperatures because the relationship between temperature and fitness of ectothermic organisms is an asymmetric dome in which warming past the optimum has sudden and severe impacts, whereas cooling below the optimum has only gradual impacts (Martin and Huey 2008).

Other sections of TRRP and ESSA (2009) discuss thermal effects on juvenile growth, including: 1) a graph in Appendix C illustrating the relationship between water temperature and specific growth rate, and 2) Appendix L reviews of existing sampling designs and monitoring protocols and includes "Uncertainties / Limitations: Water temperature objectives for the Trinity River Flow Evaluation study are literature based. Will these temperatures be maintained every year, or deliberately varied (i.e., with associated monitoring of fish health, growth, etc.) to provide long-term feedback regarding the effectiveness of these targets?"

4.1.3.2 IMPROVEMENT IN UNDERSTANDING DAM/DIVERSION EFFECTS ON LOWER TRINITY RIVER TEMPERATURES

As we discussed above in Section 3.4.1.4, our modeling indicates previous evaluations by Rowell (1979) and Zedonis and Newcomb (1997) overestimated the amount of warming in the lower Trinity River in spring caused by dams/diversion. These analyses provided the impetus to establish temperature criteria to protect smolts and increase dam release flows in an attempt to remediate the perceived problem.

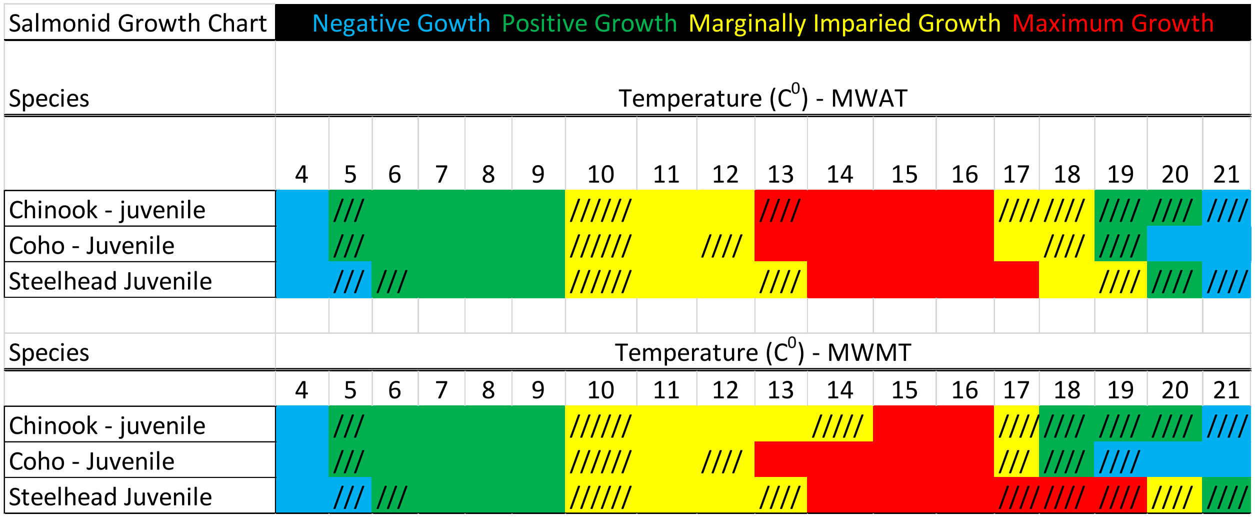
4.2 NEW PROPOSED TEMPERATURE TARGETS

4.2.1 TARGET FOR JUVENILE SALMONID GROWTH

In light of increased understandings of the altered thermal regime and importance of optimal growth conditions during juvenile rearing relative to survival, a new juvenile salmonid temperature objective has been proposed by the TRRP Fish Workgroup. The proposed target uses bioenergetics relationships and thermal tolerances to disease, for all native salmonid species (Steelhead, Chinook Salmon, and Coho Salmon), to reach a balanced target for the core rearing area of the Trinity River to provide optimal conditions for growth from April 1 through July 31. During juvenile rearing, temperatures between 13 °C and 16.5 °C generally allow all three species to experience growth rates within 10% of maximum (Carter 2005). The fish work group has suggested that this 13.0–16.5 °C range be adopted as a target for 7-day average of daily average (7DADA) water temperature above the confluence with the North Fork Trinity River from April 1 through July 31 (Naman et al. 2020). We acknowledge that there is uncertainty in the temperatures that provide optimal growth, in part due to genetic differences (Zillig et al. 2021, 2022), and that some researchers have found much higher temperatures optimal for salmonid growth (Plumb and Moffitt 2015). This proposed target is intended to provide temperatures warm enough to promote growth, yet cool enough to avoid disease risk (Schaaf et al. 2017, 2018) and the precipitous drops in fitness that occur when temperatures are too high (Martin and Huey 2008). We also note that the study by Plumb and Moffit (2015) was focused on reviewing and establishing temperature dependence on maximum consumption (Cmax). The study was performed in a laboratory with fish feed pellets. Juvenile salmonids in a stream are under much different conditions, and rarely if ever feed until satiation. For these reasons, the temperatures that produce optimal growth in a river are likely less than those in the function of temperature dependence in maximum consumption.

As temperatures in spring and summer are generally a continuum from cold upstream to warm downstream there are inherent issues with using a single compliance point as temperatures vary both upstream and downstream. This continuum is an issue when attempting to reconcile current targets with the proposed. Achieving 13 °C above the North Fork Trinity River would almost certainly result in exceeding existing temperature criteria at Weitchpec. Conversely, achieving existing criteria of 13 °C or 15 °C at Weitchpec would certainly result in suppressed growth rates in nearly the entirety of the Trinity River upstream. This conflict begs whether meeting smolt outmigration temperatures (USFWS 1999) are more important than achieving optimal growth for salmonids during the periods these criteria overlap, such as the month of May. It also highlights the importance of fish having access to off-channel habitats that warm sooner in the spring than the mainstem river does. In other river systems, such habitats have been shown to provide juvenile salmon with important growth opportunities (Baldock et al. 2016).

Table 14. Growth chart based on literature reviewed by Carter (2005). Figure from Naman et al. (2020).



Salmonid Growth Chart — 🟦 Negative Gowth 🟩 Positive Growth 🟨 Marginally Imparied Growth 🟥 Maximum Growth

Species	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Temperature (C^0) - MWAT																		
Chinook - juvenile	🟦	🟩 ///	🟩	🟩	🟩	🟩	🟨 //////	🟨	🟨	🟥 ////	🟥	🟥	🟥	🟨 ////	🟨 ////	🟩 ////	🟩 ////	🟦 ////
Coho - Juvenile	🟦	🟩 ///	🟩	🟩	🟩	🟩	🟨 //////	🟨	🟨 ////	🟥	🟥	🟥	🟥	🟨	🟨 ////	🟩 ////	🟦	🟦
Steelhead Juvenile	🟦	🟦 ///	🟩 ///	🟩	🟩	🟩	🟨 //////	🟨	🟨	🟨 ////	🟥	🟥	🟥	🟥	🟨	🟨 ////	🟩 ////	🟦 ////

Species	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Temperature (C^0) - MWMT																		
Chinook - juvenile	🟦	🟩 ///	🟩	🟩	🟩	🟩	🟨 //////	🟨	🟨	🟨	🟨 /////	🟥	🟥	🟨 ////	🟩 ////	🟩 ////	🟩 ////	🟦 ////
Coho - Juvenile	🟦	🟩 ///	🟩	🟩	🟩	🟩	🟨 //////	🟨	🟨 ////	🟥	🟥	🟥	🟥	🟨 ///	🟩 ////	🟦 ////	🟦	🟦
Steelhead Juvenile	🟦	🟦 ///	🟩 ///	🟩	🟩	🟩	🟨 //////	🟨	🟨	🟨 ////	🟥	🟥	🟥	🟥 ////	🟥 ////	🟥 ////	🟨 ////	🟩 ////

4.2.2 TARGET FOR ADULT SPAWNING AND EGG INCUBATION

The temperature objectives for the Trinity River were thought to be protective of Chinook Salmon spawning adults and their eggs in the 1990s (Table 1). More recent studies have found that even the temperatures in Table 15 are inadequate for the survival of Chinook Salmon eggs (Martin et al. 2017; Anderson et al. 2022), which decreases rapidly with temperature increases greater than 20.0 °C (53.5 °F) under natural spawning conditions. This discrepancy is due to lower water velocity in natural redds than in laboratory experiments, causing less oxygen to be available to eggs for any given water temperature (Martin et al. 2017; Martin et al. 2020). The temperature objectives for the Trinity River (Table 1) were not explicitly developed for the protection of Coho Salmon adults or embryos, which have a lower thermal tolerance than Chinook Salmon (Murray and McPhail 1988; Beacham and Murray 1990). The existing water temperature objectives also did not establish the need for normal seasonal and longitudinal water temperature patterns, to which salmonids are adapted. They were largely developed for Chinook Salmon and thought to be sufficient for the needs of Coho Salmon. The objectives in Table 15 also did not establish criteria for water temperature released from Lewiston Dam, thereby tacitly implying water temperatures released from Lewiston Dam would always be colder than water at downstream compliance points (longitudinal warming).

In unregulated waters of the Trinity River watershed, annual thermal maxima occur near the end of July, with stream temperatures responding to shortened daylength, lower air temperatures, and changes in cloud cover (Section 1.2.1). When salmon return to spawn in the fall, water temperatures have already begun to cool, and continue to cool so that salmonid eggs experience some of the coldest temperatures of the year. In many regions throughout the US, a positive relationship between stream order and water temperature has been reported, unless the stream has a high baseflow index (Segura et al. 2015), with temperatures decreasing as salmon swim upstream as described by the river continuum concept (Doretto et al. 2020; Section 1.2.1). At low reservoir storage levels (e.g., less than 750 TAF), warm water from the surface of the reservoir is entrained into the Trinity Dam outlet works (USBR 2012), disrupting both the natural seasonal and longitudinal water temperature patterns for the Trinity River at Lewiston. Under such scenarios, temperature of the water released from Lewiston Dam can be warmer or the same temperature as at downstream compliance locations (De Juilio et al. 2022). This can lead to the seasonal thermal maxima of water released from Lewiston Dam occurring as late as November (e.g., 2021; De Juilio et al. 2022), creating harmful impacts to spawning salmonids and their eggs.

De Juilio et al. (2022) recommended that the TRRP adopt the water temperature targets for Lewiston Dam presented in Table 15 to be protective of the preservation and propagation of native salmonids. These release temperature targets are compatible with the targets established by Water Order 90-05 and are intend to ensure that an adequate portion of the 40-mile Trinity River restoration reach is providing ideal conditions for reproduction of native salmonids (Table 3).

Table 15. Recommended water temperature objectives for daily-average water temperature for Trinity River, at Lewiston Dam, Douglas City, and at the confluence with the North Fork Trinity River, CA.

Date	New Objective	Existing Objective (also shown in Table 1)	
	Lewiston Dam (RM 112.1)	Douglas City (RM 93.8)	North Fork Trinity River (RM 72.4)
July 1 through Sept 14	-	60 °F (15.6 °C)	-
Sept 15 through Sept 30	53.5 °F (12.0 °C)	56 °F (13.3 °C)	-
Oct 1 through Oct 31	53.5 °F (12.0 °C)	-	56 °F (13.3 °C)
Nov 1 through Dec 31	50 °F (10.0 °C)	-	56 °F (13.3 °C)
Jan 1 through Mar 1	48 °F (8.9 °C)	-	-

4.3 MULTI-YEAR EVALUATION OF TEMPERATURE CRITERIA EXCEEDANCE

In this section, we evaluate measured Trinity River temperatures against the established criteria for adult salmonid holding, spawning, and juvenile outmigration (Section 4.1 above), and the proposed target for juvenile salmon growth (Section 4.2 above). Including data estimated from nearby sites (Section in B.7 in Appendix B), Weitchpec temperature records span back as far as 1964 while the Douglas City and Above North Fork records begin in 1987 (Figure 58). We calculated annual summaries of exceedance duration (i.e., percent of days) and magnitude (i.e., degree-days) for years in which data were available for at least 80% of the target period. We use degree-days exceedance as a simple metric to compare exceedance severity and magnitude among years, not to assess the biological significance. For most criteria, the annual degree days exceedance was calculated by subtracting the criteria threshold from each measured daily average temperature and then summing all positive values within each year. The only exception was that for the 13 °C lower bound of the juvenile growth criteria, negative (instead of positive) values were summed.

Previous assessments of compliance with temperature criteria include annual USFWS temperature monitoring reports (e.g., Zedonis 2003, David and Goodman 2017, Romberger and Gwozdz 2018, Section A.3.4) and modeling of expected exceedances with varying Lewiston releases (Sogutlugil 2012; Buxton 2019, 2020). Relative to those previous assessments, our analysis examines temperatures across a much longer period of record including the full diversion and transitional eras, although Buffington et al. (2014) assessed compliance of adult temperature criteria for 1993–2011 including some pre-ROD years.

4.3.1 EXCEEDANCE OF EXISTING CRITERIA FOR ADULTS AND JUVENILE OUTMIGRATION

At Douglas City, the percent of days exceeding the adult salmonid criteria was greater in July 1 – September 14th than September 15–30th (Figure 62). Compliance with the adult salmonid criteria at Douglas City is highly variable between years, with some years having no exceedances but other years having up to 50% of days exceeding (Figure 62). There appear to be more exceedances in years with lower flows (Figure 43), although we did not conduct analyses to quantify this pattern.

Relative to other targets, the October 1 – December 31 adult target of 13.3 °C at Above North Fork was exceeded less frequently (no year having more than 25% of days exceeded), and by a lesser magnitude (no year having more than 8 °C degree-days of exceedance) (Figure 62). Frequency of exceedance and degree-days of exceedance were greatest during 2014 and 2015, likely caused by Lewiston Reservoir releases that were warmer than normal due to drawdown of Trinity Reservoir (Figure 11, Figure 20). Without extensive releases from the auxiliary outlet during late summer and fall of 2014 and 2015, temperatures at Above North Fork would have been even higher, because temperatures of the primary outlet reached 16 °C in both years whereas auxiliary outlet temperatures did not exceed 9 °C (Figure 11, Figure 20). Above North Fork temperatures were not measured during the 1977 drought when Trinity Reservoir reached record low levels but may have been similarly high as 2014 and 2015 because daily mean Trinity River temperatures at Lewiston reached nearly 14 °C in early October 1977 (Figure 25).

Juvenile outmigration targets at Weitchpec were exceeded for a portion of almost every year (Figure 58), with a magnitude of up to 130 degree-days (Figure 62). The only exception is 2008, when several large wildfires started in late June and burned through the entire summer, providing smoke that reduced solar radiation and water temperatures across much of the Klamath Basin

(David et al. 2017; Asarian et al. 2020). Since juvenile outmigration targets are 2–3 °C higher in Dry and Critically Dry years than other water year types, the link between exceedances and flow does not appear to be as strong for juvenile outmigration as it is for the adult (Figure 58). The earliest exceedance of juvenile outmigration criteria was April 19 for a Dry or Critically Dry year (>15 °C) and April 12 for a Normal, Wet, or Extremely Wet year (>13 0°C), suggesting that analyzing target compliance with a start date of April 22 (e.g., Magneson and Chamberlain 2015, Buxton 2020) could miss early exceedances.

4.3.2 EXCEEDANCES OF PROPOSED JUVENILE GROWTH TARGET

The TRRP Fish Workgroup has proposed a new juvenile salmonid growth temperature target of 13–16.5 °C 7-day average daily average (7DADA) in the Trinity River Above North Fork for April 1 through July 31 or June 30 (Naman et al. 2020, Section 4.2). In our analyses here, we also apply that target to Douglas City and Weitchpec to characterize thermal conditions for juvenile growth across a wider extent of the Trinity River.

At Douglas City, measurements in the transitional era and ROD era indicated that temperatures in the April–July period have only exceeded the 16.5 °C upper bound of the optimal range in a few Dry and Critically Dry years, but are often colder than the 13 °C lower bound (Figure 59, Figure 60, Figure 61). In the ROD era, temperature rarely rises above 13 °C until June in Normal, Dry, and Critically Dry years or until July in Wet and Extremely Wet years (Figure 60), corresponding with the timing of flows reaching the 450 cfs ROD summer baseflows. In the 1978–1999 transitional era, temperatures reached 13 °C at Douglas City approximately a month earlier and were within 13–16.5 °C optimum range for a larger portion of April–July, although temperatures did exceed 16.5 °C more often than in the ROD era.

At Above North Fork, the site to which the proposed growth target is intended to apply, temperatures in the ROD era show markedly different temperatures in Normal, Dry, and Critically Dry years compared to Wet and Extremely Wet years (Figure 60). Temperatures in Wet and Extremely Wet years are similar to those upstream at Douglas City until flows drop in July and temperatures climb higher. In Normal, Dry, and Critically Dry years, seasonal warming starts sooner Above North Fork than at Douglas City. In the 1978–1999 transitional era, seasonal warming began earlier in the year than in the ROD era (Figure 60).

At Weitchpec, temperatures in the April–July period in the ROD era are relatively similar to the transitional era, in contrast to Douglas City and Above North Fork where there were major differences between the two eras as discussed in the previous paragraphs (Figure 60).

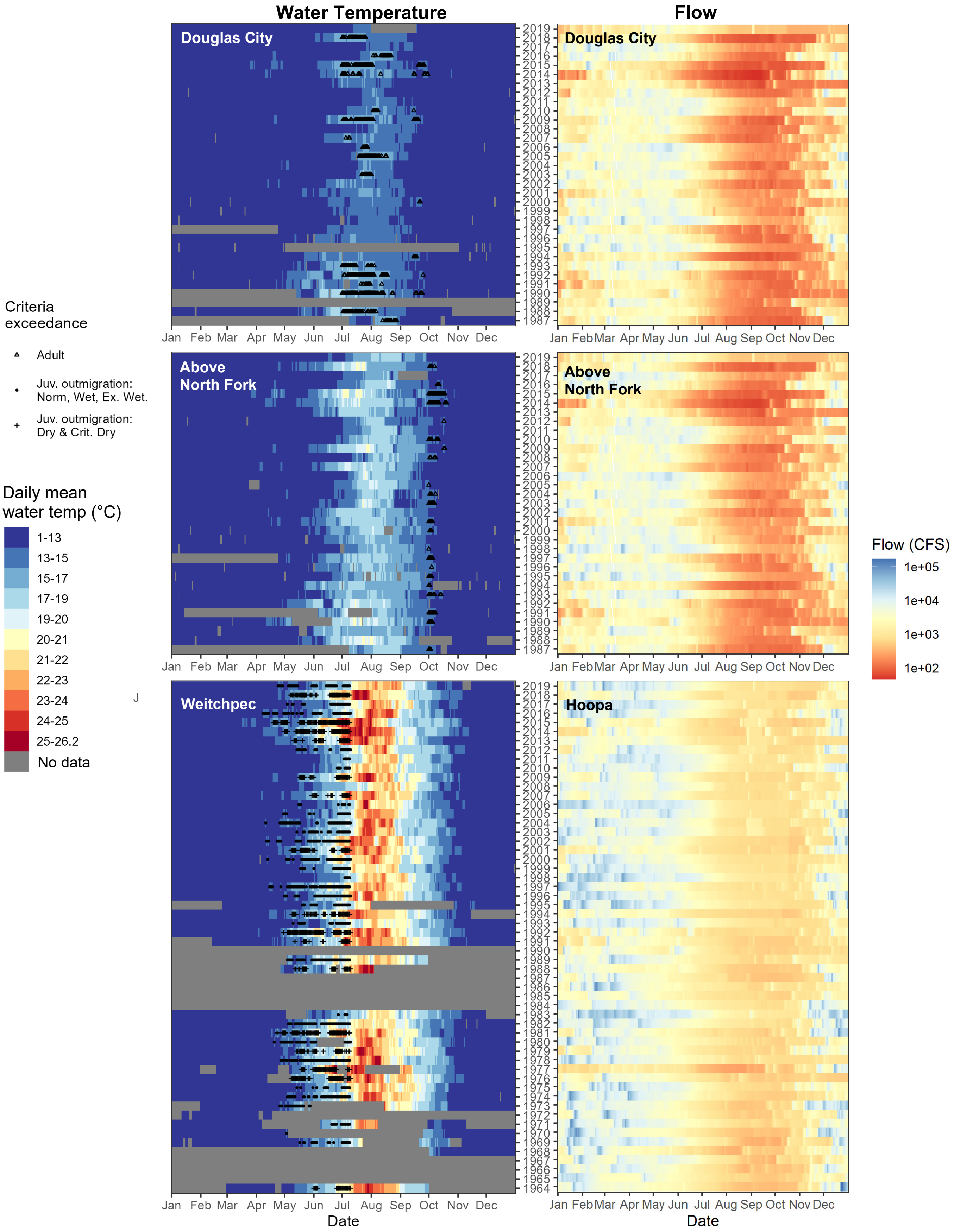


Figure 58. Time series of (A) daily mean water temperatures (colored tiles) and exceedances of juvenile and adult salmonid thresholds (black symbols) and (B) flows in the Trinity River at Douglas City, Above North Fork, and Weitchpec/Hoopa. Some temperatures are estimated by regression with adjacent stations (Section 2.3). Flow data sources: USGS (Hoopa and 2019 at other sites) and RBM10 (other sites).

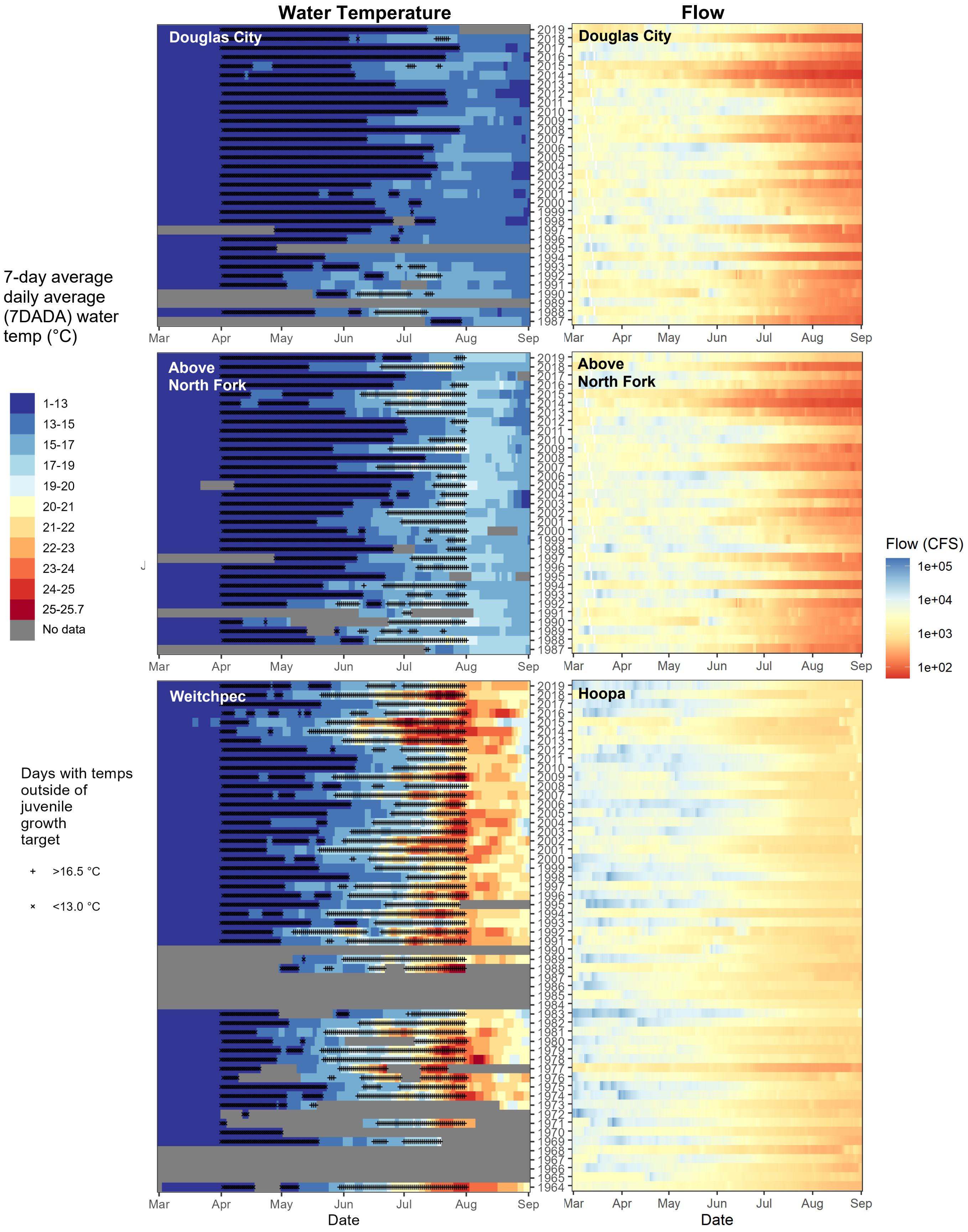


Figure 59. Time series of (A) 7-day average daily mean (7DADA) measured water temperatures (colored tiles) and days with temperatures outside of proposed juvenile salmonid growth targets (black symbols) and (B) flows in the Trinity River at Douglas City, Above North Fork, and Weitchpec/Hoopa. Some temperatures are estimated by regression with adjacent stations (Section B.7 in Appendix B). Flow data sources: USGS (Hoopa and 2019 at other sites) and RBM10 (other sites).

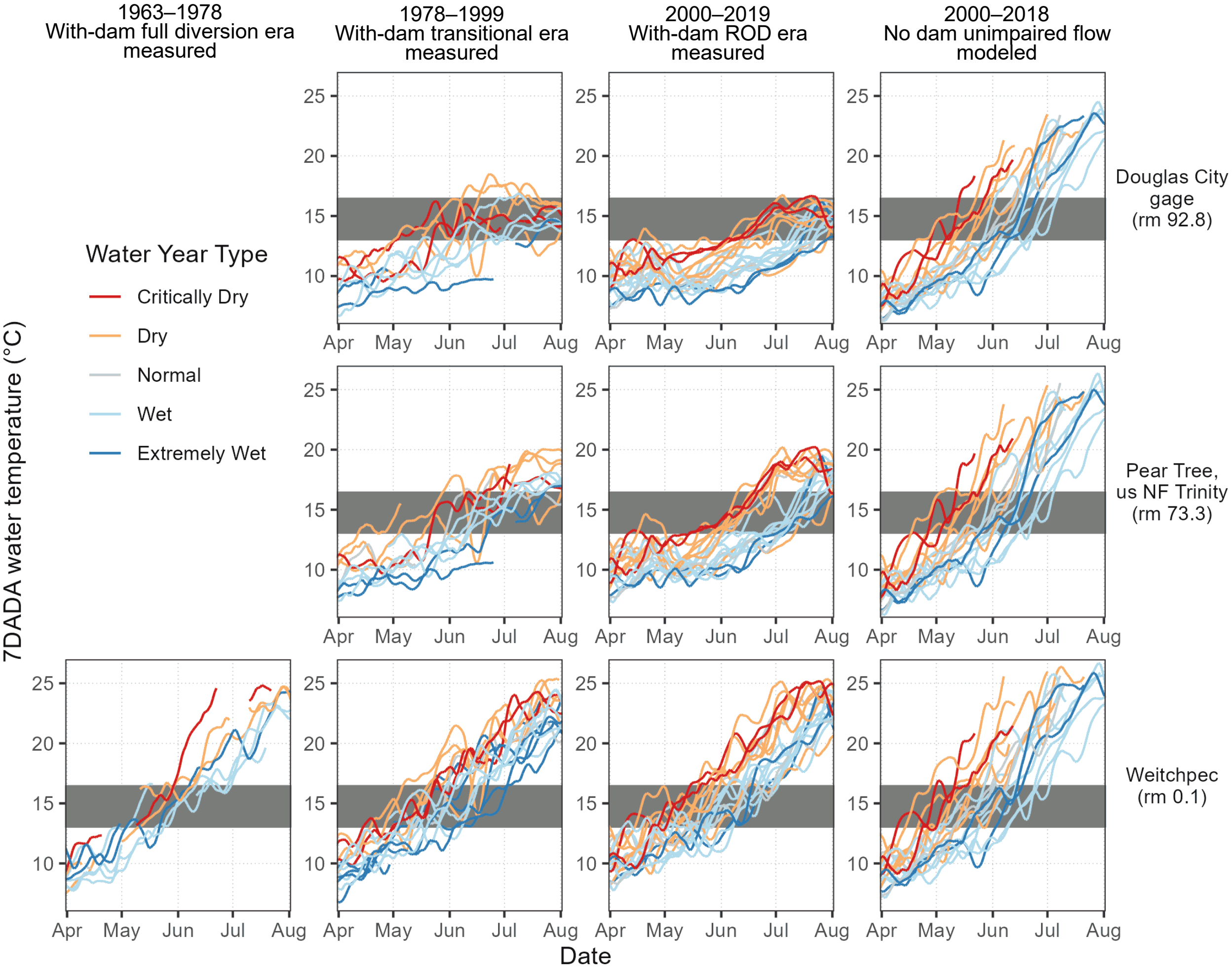


Figure 60. Measured and modeled 7-day average daily average (7DADA) water temperatures and proposed juvenile salmonid growth targets (13–16.5 °C shaded box) in the Trinity River Above North Fork where the target is proposed for April–July, arranged by actual water year type and era. Douglas City and Weitchpec are shown for comparison. Some measured temperatures are estimated by regression with adjacent stations (Section B.7 in Appendix B). For modeled unimpaired scenario, only days with Lewiston flows >350 cfs are included.

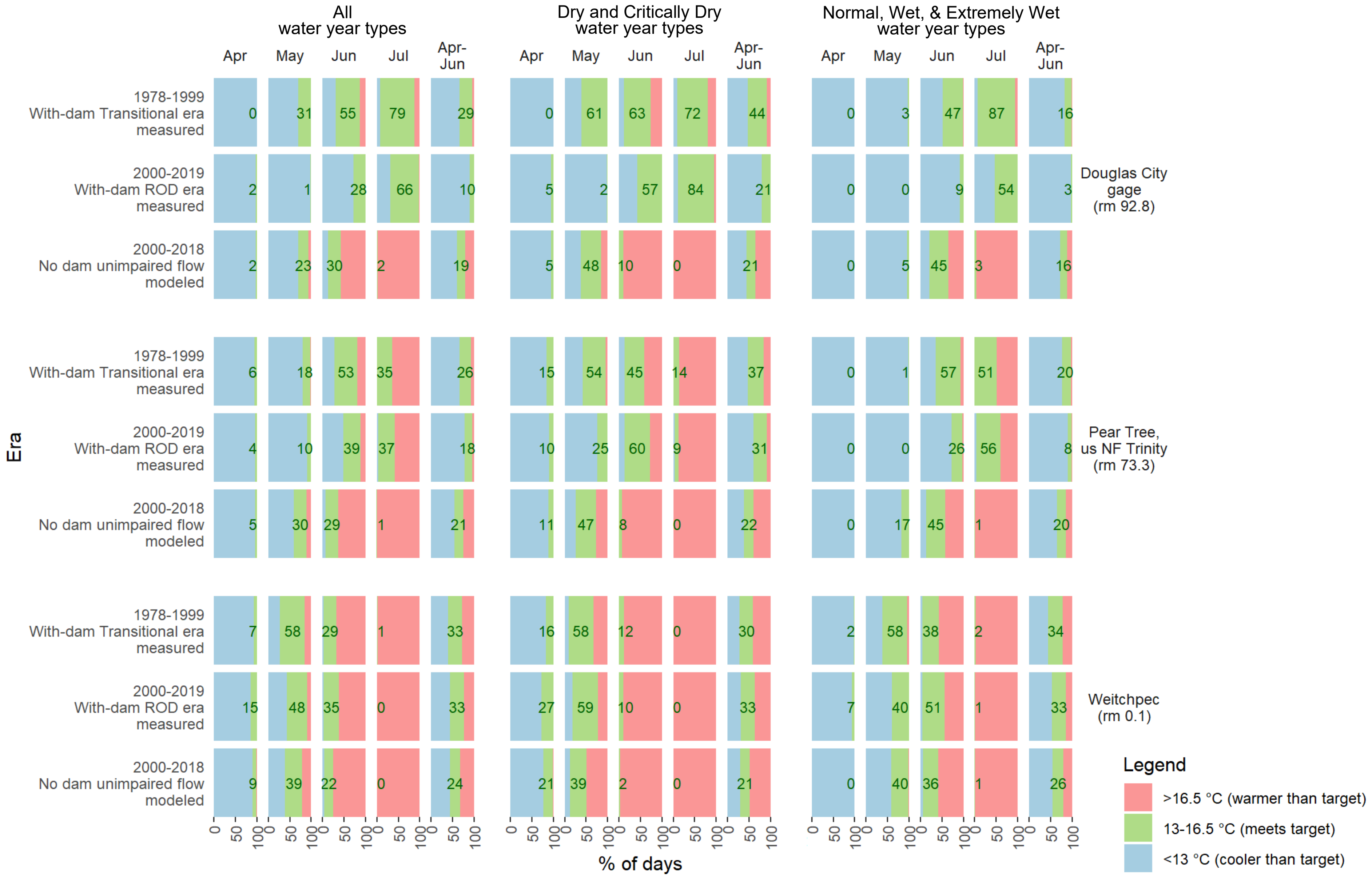


Figure 61. Percent of days meeting proposed juvenile salmonid growth temperature targets, summarized by site, month, era, and actual water year type, for measured and modeled 7-day average daily average (7DADA) water temperatures at Trinity River Above North Fork, Douglas City, and Weitchpec. Data labels are percent of days meeting targets. See Figure 60 for additional notes. Days with Lewiston flows <350 cfs in modeled unimpaired scenario are included because temperatures had already surpassed 16.5 °C prior to flows dropping below 350 cfs (see Figure 60).

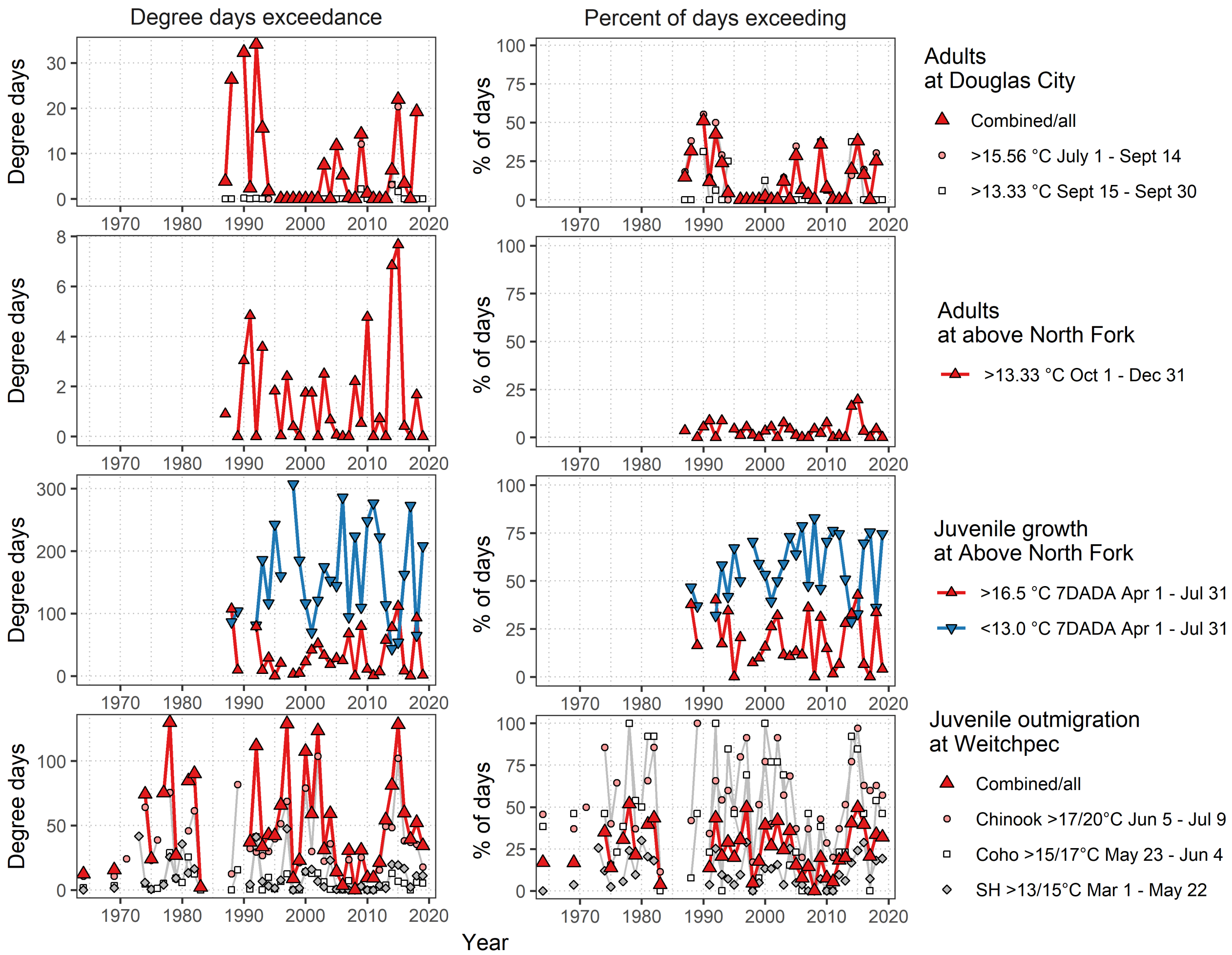


Figure 62. Annual summaries of exceedances of established (adults and juvenile outmigration) and proposed (juvenile growth) temperature targets for the Trinity River at Douglas City, Above North Fork, and Weitchpec in the years 1964–2019. Juvenile outmigration targets vary by water year type (Table 2). Key to abbreviations: 7DADA = 7-day average daily average, SH = steelhead. Degree-days exceedance is defined in the first paragraph of Section 4.3 above.

5 IMPORTANCE OF THERMAL DIVERSITY

A defining characteristic of ectothermic organisms, which includes stream invertebrates, amphibians, reptiles, and fish, is their core temperature conforms to ambient temperature. For this reason, ability to choose the temperature of their surroundings is of particular importance. This ability is referred to as behavioral thermoregulation and impacts the organism's effectiveness to capture and metabolize food (Cairns et al. 2008; Armstrong and Schindler 2013; Watz and Piccolo 2010), reproduce and develop (Railsback et al. 2016), and evade predation (EPA 2001). For example, well-fed salmonids tend to behaviorally thermoregulate in slightly warmer water than conspecifics consuming lesser ration; the combination of feeding opportunities and warmer water tends to maximize growth. When food is scarce, salmonids will select cooler water to lower their metabolic rate and conserve energy (EPA 2001). Cold temperatures can reduce foraging salmonids' ability to capture prey, one study found the percent of drifting prey captured by Brown Trout fell from 96% to 53% when temperatures reduced from 14 ˚C to 5.7 ˚C (Watz and Piccolo 2010).

5.1 4-DIMENSIONS OF THE LOTIC THERMAL LANDSCAPE

The 4-dimensional framework (i.e., temporal, longitudinal, vertical, and lateral) of lotic systems presented by Ward (1989) and discussed in Section 1.2.2 provides a conceptual model for how riverine ecosystems provide thermal diversity required by mobile ectothermic biota with differing thermal requirements. Steel et al. (2017) applies these concepts to the thermal landscape of a watershed and considers how current and historical land and water resource management have altered thermal regimes in all four dimensions. Applying those ideas, in context of the Trinity River's contemporary condition and management, we first explore how findings in previous sections of this report increase understanding of the current thermal landscape in the longitudinal and temporal dimensions by using models and novel metrics suited to that purpose. We further explore the vertical and lateral dimensions, which are not captured by data previously presented in this report, through literature review, and use of 2-D hydrodynamic and temperature models.

5.1.1 TEMPORAL THERMAL DIVERSITY

The most obvious and well documented thermal effect from construction and operation of the TRD of the CVP is to the temporal dimension. The reduced seasonal variability of water temperatures below Lewiston Dam, described in detail in sections 3.4.1.3, 3.4.1.4, 5.1.2.2, has been recognized by fisheries managers for decades (Zedonis and Newcomb 1997), but has generally been dismissed. This is because water temperatures directly downstream of the dams rarely exceed thermal tolerances of salmonids. However, the change in seasonal pattern of water temperature that has occurred below Lewiston Dam cannot be overstated. Typical annual range of daily mean water temperature was 19 °C (i.e., mean daily temperatures of 4 °C in early January and 23 °C in late August) prior to dam regulation but is now only 3 °C (i.e., mean daily temperatures of 7 °C in early January and 10 °C in late August), a decline of approximately 16 °C (Figure 26). In addition, while there are still seasonal temperature differences between water year types after damming and diversion (i.e., in March-June, Lewiston temperatures are warmer in Dry and Critically Dry water year types than in Normal and Wetter water years), these inter-year differences are more compressed than during the pre-dam era, except under exceptional circumstances, such as those that occurred in fall of 1977, when cold-water pool in Trinity Reservoir was depleted (Figure 12). The impact of flow regulation on seasonal temperature range attenuates in the downstream direction and was negligible at the confluence with the Klamath River through the 1990s.

The reduction in seasonal temperature range has consequences for aquatic species and life stages. For juvenile salmonids rearing in the Trinity River the diminished seasonal variability results in cooler water in the upper river during spring and summer, which increases availability of thermally suitable habitat for adult salmonid holding but suppresses water temperatures that could achieve higher growth rates for juveniles and increased food production (Lusardi et al. 2019). In the winter, water temperatures are warmer than under the unimpaired scenario, which could alter salmonid egg hatching success, emergence timing, and body condition during early life stages and migration (McCullough 1999).

Flow management changes from implementation of the 2000 ROD (Section 3.4.5.3) have subsequently delayed already diminished seasonal warming by roughly two months through high magnitude spring flow releases, further exacerbating departure from historical seasonal temperature patterns. This delay in warming attenuates downstream. However, the thermal mass of high-volume release results in a detectable delay in warming through the entire length of the Trinity River in years with wet hydrology. These changes have potentially altered phenology and behavior of all ectothermic species who are obligate to the aquatic environment. For example, the onset of Foothill Yellow-legged Frog breeding and oviposition is sensitive to water temperatures and the date when these events occur controls metamorphosis date and frog size, which strongly affect survival in the first winter (Wheeler et al. 2015 and 2018; Catenazzi and Kupferberg 2013). Growth, maturation, life stage transition, and food production for other aquatic obligate ectothermic organisms are likely impacted in similar ways. Studies since the implementation of the Trinity River ROD have documented demographic and behavioral changes in western pond turtles, which exhibit increased frequency and duration of basking, lower rates of gravidity, and smaller size at age (Ashton et al. 2015). In addition, the average size of outmigrating juvenile Chinook Salmon is smaller for specific dates since implementation of the ROD (Pinnix et al. 2022). Effects of temperature suppression have also been documented on the Trinity River for the timing of Foothill Yellow-legged Frog oviposition (Catenazzi and Kupferberg 2013 and 2017; Wheeler et al. 2015) a (Ashton et al. 2015; Snover et al. 2015) but most species have not been studied.

An additional impact to both the temporal and longitudinal thermal dimension results from relatively constant release temperature from Lewiston Dam over a 24-hour period, causing nodes of minimum diel temperature range and anti-nodes of maximum diel range, described in Section 3.4.4. This pattern is a deviation from the natural pattern of diel temperature variability depicted in Figure 3, and is common to regulated river systems with hypolimnetic dam releases. Consistent diel temperatures that lack variability can have significant impacts to timing and development of salmonids at early life stages (Steel et al. 2012). In the Trinity River at Lewiston, diel range is much lower since damming and diversion (Figure 40, Figure 41). For example, average July diel range was 4.3 °C in pre-dam era but is now only 1.2 °C (Figure 41). Pre-dam, these diel fluctuations could provide fish with a window of time that is thermally suitable for migration even if daily maximum temperatures were quite warm. During construction of Trinity Dam, adult Chinook Salmon arrived at Lewiston on days with daily maximum river temperatures as high as 25.6 °C (78 °F) and daily minimum river temperatures as high as 21.1 °C (70 °F), although counts were higher when temperatures were lower (Murray 1961, 1962). These observations of adult migration are reflective of research conducted since that indicates that temperatures in excess of 23 °C create a thermal barrier to adult Chinook Salmon migration

(Strange 2010), and highlight the importance of night-time cooling in aiding Chinook to continue upstream migration to more suitable holding and spawning habitat even under relatively hostile conditions. Localized diel thermal diversity can also be provided by hyporheic flow through gravel bars and floodplains that can follow a diel cycle that lags hours behind mainstem temperature patterns such that the timing of daily minimum temperatures in hyporheic water can occur when mainstem water temperatures are at daily maximums (Ock et al. 2015, Steel et al. 2017). Thermal stress is cumulative (Carter 2005) and periods of the day which offer reprieve from cold or warm temperatures can greatly influence body condition and survival.

5.1.2 LONGITUDINAL THERMAL DIVERSITY

Impacts to water temperature from hypolimnetic release from Trinity Reservoir propagates downstream during months when the reservoir is stratified, as discussed above and described in detail in section 3.4.3.2. With increasing distance from Lewiston Dam and dilution from tributary accretions, impacts are attenuated and approach historical thermal norms near the terminus of the Trinity River (Figure 28, Figure 29, Figure 34, Figure 35). This results in water temperatures increasing at a faster rate per mile compared to the unimpaired scenario during times of year when Trinity Reservoir is strongly thermally stratified (Figure 34), when compared to modeled unimpaired temperatures (Figure 35). During winter, the Trinity River actually cools in a downstream direction due to release of unseasonably warm water from the depths of Trinity Reservoir. In this altered state during summer, relatively warm tributaries enter a cold mainstem (Figure ES-1), and in winter water cools as it travels downstream (Figure 34). Both changes interrupt the natural warming trend that exists from a river's high elevation head waters to larger order, lower elevation reaches. It is important to provide a thermal regime that includes cooling nights and cooling events in the fall, in accordance with the monthly thermal patterns of streams in the geographic region. During years of low end-of-September Trinity Reservoir storage (e.g., 2021; 710 TAF), the latent heat effect created by the thermal mass of Trinity Reservoir become acutely problematic and releases to the Trinity River can continue to warm throughout the fall into November as adults are spawning, when other streams in the region began cooling in late August or September. These unnatural thermal patterns in space and time can pose threats to spawning adult salmonids when the temperatures fall outside of safe thresholds.

These alterations to longitudinal gradient of temperatures could result in changes to both upstream and downstream migration of adult and juvenile life stages of anadromous fish (Sykes et al. 2009, Keefer et al. 2008). Migration rates of juvenile Chinook Salmon have been found to be both positively influenced by increased accumulated thermal units (ATU) and negatively influenced, or even terminated, by increases in flow (Sykes et al. 2009). Adult migration timing of spring Chinook Salmon has been found to be more influenced by in-river conditions than ocean conditions or air temperature (Keefer et al. 2008). Migration timing is of key concern for both juvenile and adult salmonids because of disease issues in the Klamath River, as discussed in Section 3.4.6.4, and because of thermal barriers to migration that form in the lower river during the hot, dry, low flow period.

The changes that have resulted from historical management and a range of hypothetical constant flows are assessed below using novel metrics to compare modeled seasonal and longitudinal temperature profiles to a modeled temperature profile from the unimpaired scenario presented in Section 3.4.1.2. This analysis is put forward to assess divergence from evolutionary thermal life history cues. We convert temperature and temperature difference to metrics of biological processes, specifically development and growth. This was done for several species to investigate the effects of historical and hypothetical management on growth and life stage duration.

5.1.2.1 TEMPERATURE MODELING METHODS - LONGITUDINAL AND SEASONAL DIMENSIONS

With a focus on the critical rearing period for juvenile salmonids, defined here as February through June, we conducted a sensitivity analysis on effect of Lewiston Dam release discharge magnitude on longitudinal and seasonal temperature patterns. Metrics were developed to assess the effectiveness of a range of discharges to provide both desirable temperatures for salmonid growth, and approximate the natural thermal regime as represented by the unimpaired flow scenario, which acts as a surrogate for evolutionary life history cues. We also use relationships from literature to investigate temperature impacts on the time required to complete a generation or develop to a life stage transition for two benthic macro invertebrate species and the Foothill Yellow-legged Frog (FYLF). The evaluation was limited to the ROD era (2000–2018). RBM10 was used to predict daily average temperatures at 31 locations distributed throughout the length of the Trinity River for the unimpaired and historical scenarios, as well as constant flow scenarios using Lewiston Dam release discharges of 300, 500, 1000, 1500, 2000, 3000, and 4000 cfs (Table 4), which were then converted to monthly average temperature. Results for the month of June are not presented for Dry and Critically Dry water year types, as flows in these years for the unimpaired scenario often dropped below the range where RBM10 can accurately predict water temperature (~350 cfs, Section 2.3.3.3) and comparisons could not be made. When referring to the suite of constant flow scenarios and the historical scenario, we will use the term ‘dams-in’ to differentiate these scenarios from the unimpaired.

Constant flow scenarios are not presented as a viable alternative for management, but instead are intended to investigate a range of monthly ‘baseflows’ which could be targeted to achieve the desired thermal regime. Brief departures from this range of flows to accomplish non-temperature related objectives would not compromise the thermal regime and are present when the natural thermal regime is examined at finer resolution. The longitudinal temperature profiles for all scenarios in each month for every water year type are provided in Figure 64.

Modeling of all regulated flow scenarios use historical Lewiston Dam release water temperatures as inputs. In reality, release temperature is influenced by storage and stratification in Trinity Reservoir (Section 3.3.1.2), discharge magnitude of Trinity Dam and hydraulic residence time in Lewiston Reservoir, which are in turn affected by factors including the power market, out of basin water transfers, weather, and hydrology (Section 3.3.2.2). These factors can influence release temperature by as much as 2 °C during certain times of year, including an observed decrease in Lewiston release temperatures with onset of ROD releases, shown in Figure 26, and by far more in extenuating circumstances such as the conditions encountered in the fall of 1977. These factors are difficult to model and predict. However, should all other factors remain the same, changes in the magnitude of Lewiston releases are almost certain to change water temperatures of releases in times of year where there is significant difference between water temperature and air temperature. Reservoir modeling was beyond the scope of this project, but in the future sensitivity analysis of release temperature under several scenarios should be completed, and assessments in this report should be revisited with improved release temperature inputs to RBM10.

The relative differences between monthly averaged temperatures for the unimpaired scenario and each dams-in scenario were compared for the five months of February through June at 31 model output nodes for all 8 dams-in scenarios, which are symbolized by $T_{i,j,k}$, where the i, j, and k are indices corresponding to model output node, month, and specific dams-in scenario respectively. The difference between $T_{i,j,k}$ and mean temperature for the unimpaired flow scenario for each node and month ($U_{i,j}$) was weighted by the river distance represented by each node (L_i), and summed across i, yielding the mean monthly temperature difference over the longitudinal profile of the river from the unimpaired scenario (ΔT) for each dams-in scenario. ΔT quantifies the temperature deviation from the unimpaired scenario for each dams-in scenario, k, for each month, j. The full calculation is:

$$\Delta T_{j,k} = \sum_{i} \left| T_{i,j,k} - U_{i,j} \right| * \frac{L_i}{112.2} \qquad (1)$$

We then applied a threshold of <1.3 °C for $\Delta T_{,k,j,}$ to determine if the relative difference was significant or not. This threshold was selected in part because RBM10 is accurate to 1.1 °C.

To assess juvenile salmonid growing conditions, $T_{,j,j,k}$ and $U_{,i,j}$ were converted to relative growth rates for the dams-in ($F_{j,j,k}$) and unimpaired ($f_{i,j}$) scenarios using a polynomial equation from the Wisconsin bioenergetics model Version3, parameterized for a three gram Chinook Salmon juvenile (Stewart and Ibarra 1991; Plumb and Moffitt 2015), consuming 66% of maximum consumption, related to temperature (Figure B87 in Appendix B). The output growth rates were then weighted by L_i and summed across model nodes for each month to yield mean monthly growth rates for the entire length of the river. To calculate a metric quantifying the deviation in growth rates from the unimpaired scenario the sum of river kilometer weighted F_i was differenced from f_i for each constant flow scenario, k, for each month, j. That metric, $\Delta F_{j,k}$, is given by:

$$\Delta F_{j,k} = \sum_{i} \left(F_{i,j,k} * \frac{L_i}{112.2}\right) - \left(f_{i,j} \frac{L_i}{112.2}\right) \qquad (2)$$

We then assessed $\Delta F_{j,k}$ for each month across dams-in scenarios to identify relative increases and decreases in daily fish growth as a proportion of body weight. Relatively small changes in $\Delta F_{j,k}$, on the order of a fraction of a percent, can have a big impact over the course of a month, as growth is compounded daily. $\Delta F_{j,k}$ is presented as a daily growth rate for each month, it is not compounded daily, due to the complication of growth changing fish size daily, altering the relationship of growth to temperature. Instead, it is presented here as % body mass growth/day, and relative monthly differences can be thought of in a similar manner to an annual percentage rate for a 30-year mortgage which is compounded annually and changes relative to the size of existing debt. Δ F is intended to be an index that indicates the general effect of temperature on growth. In reality there are complexities associated with variable consumption and temperature influenced by abiotic and biotic factors. Future efforts should employ bioenergetics models and sensitivity analysis to better describe mechanistic controls on growth and explore how they can be affected by changes in management.

Pursuing metrics to assess the effects of temperature on development and productivity of native species other than salmonids, we turned to literature to find established relationships for species of interest. Species known to be sensitive to temperature and known to be important indicators or focal species prey items were selected for further evaluation. Relationships of development to temperature were modified from literature as necessary to meet the needs of the envisioned analysis.

Since publication of the Trinity River Flow Evaluation Study (USFWS and HVT 1999), the Foothill Yellow-legged Frog (FYLF) has served as an indicator species for various ecosystem services, particularly under drier hydrology. For this reason, we sought to include an assessment of FYLF in this report. One life stage that can be particularly impacted by temperature is the tadpole or polliwog phase. The time that an individual spends in this transitional aquatic obligate life stage is highly correlated to water temperature, and the size and date at which metamorphosis occurs is highly correlated to survival during the first winter (Kupferberg 1996; Wheeler et al. 2015). The importance of this period of development to recruitment and overall productivity of the species is why it was chosen for evaluation.

Because of early recognition of the importance of the FYLF as an indicator species, there has been extensive research around its life history requirements (Kupferberg 1996; Wheeler et al. 2015; Kupferberg et al. 2009; Lind et al. 1996). This research led to the development of the Foothill Yellow-legged Frog Assessment Model, Version 2 (Railsback and Harvey 2015). This model uses the following linear equation for FYLF polliwog development:

$$\textit{tadpole-daily-development} = (m\mathrm{T}+b^*)$$

where m is the slope of the relationship between temperature and development time, defined as -8.38 days/°C, T is in °C, and b^* is 240 days under conditions of natural food supply. This equation was used to calculate the number of days required for metamorphosis for each month (j) at each output node (i) in the RBM10 model for the unimpaired (p) and dams-in (P) scenarios (k). Values of development time for p and P were then weighted by L_i, summed across i, and divided by $p_{i,j}$ summed across i, to give the proportion change in development time relative to the unimpaired scenario, or $\Delta P_{j,k}$ calculated by:

$$\Delta P_{j,k} = \frac{\sum_i (P_{i,j,k} * \frac{L_i}{112.2}) - (p_{i,j}\,\frac{L_i}{112.2})}{\sum_i (p_{i,j}\,\frac{L_i}{112.2})} \qquad (3)$$

Baetidae mayflies and Chironomid midges were also chosen for evaluation of developmental rate for different temperature management scenarios. These taxa represent the most abundant macroinvertebrates in the benthos, drift, and juvenile Chinook Salmon diet on the Trinity River (Starkey-Owens 2020). The developmental stage chosen for evaluation of these taxa was egg-to-adult, referred to hereafter as generation time. For this term, and the two that follow, positive values represent accelerated development and negative values represent delayed or retarded development.

For Chironomids we used results from Gresens (1997) to calculate generation time. From mesocosm experiments with mean temperatures (T) ranging from 12–29 °C, Gresens (1997) developed two separate linear relationships for development rate (DEV, days^{-1} to pupation) based on two different diets, as follows:

For a diatom diet:

$$\text{DEV} = -0.00145 + 0.003814\ (T)$$

For a detritus diet:

$$\text{DEV} = -0.01592 + 0.003673\ (T)$$

Because neither diet could be assumed, we applied both equations to calculate DEV for the unimpaired *(c)* and dams-in *(C)* scenarios (*k*) for each month (*j*) and output node *(i)* in the RBM10 model. The diet-based and detritus-based DEV values were then averaged to obtain a single DEV value for each scenario, month, and node, which was then inverted to calculate *chironomid-generation-time*:

$$\textit{chironomid-generation-time} = 1/\text{DEV}$$

Values for *c* and *C* then replace the polliwog development terms (*p* and *P*) in Equation (3), to give ΔC, the proportion change in Chironomid generation time relative to the unimpaired scenario.

For Baetidae, we used results from Sweeney and Vannote (1984), to develop an equation for generation time. Like Gresens (1997), two different diets were studied. However, in this instance we selected the results associated with an algal diet over that of Hickory leaves, because algae are more abundant in large-order main channel rivers. Sweeney and Vannote present a table of average days from first hatch to adult Baetidae mayflies with an algal diet from 10 °C to 30 °C. We selected a polynomial equation to fit these data, because a linear equation predicted development that was much faster than the observed range for the high range of temperatures. We believe that the selection of a polynomial relationship is justified, as it is known that bioenergetic relationships involving metabolism are often polynomials as physiological thresholds of efficiency are surpassed and relationships invert. Power functions and exponential functions also provided a good fit, but because the biological processes likely invert at some threshold, we believe polynomial was the best choice and could mean that equations used for FYLF and Chironomidae underestimate the effect of temperature at the intermediate range. The following relationship was used to predict Baetidae mayfly generation time:

$$\textit{Baetidae-generation-time} = 0.6533\ (T)^2 - 33\ (T) + 443.67$$

The *Baetidae-generation-time* was solved for each month (*j*) and output node (*i*) in the RBM10 model for the unimpaired (*b*) and dams-in (*B*) scenarios (*k*). Values for *b* and *B* then replace polliwog development terms (*p* and *P*) in Equation (3), to give ΔB, the proportion change in Baetidae generation time relative to the unimpaired scenario.

After carefully considering other possibilities (i.e., evaluating each reach separately and weighting reaches according to their perceived importance), we evaluated all response variables at the scale of the entire Trinity River because: 1) it is simpler to calculate, interpret and explain results, and 2) all response variables are present throughout the river system and the relative importance of particular reaches is either poorly understood or highly variable. Readers interested in the relative impacts for a particular location should refer to the longitudinal profiles of temperature and salmonid growth provided in Figure 64 and Figure 65, respectively. The example of salmonid growth highlights the difficulty of selecting and weighting locations along the longitudinal profile. Steelhead and Coho Salmon generally exhibit an extended freshwater rearing life history and occupy large portions of the Trinity River watershed during the critical rearing period. One-year-old outmigrants generally move through the lower river while most young of the year rear near the upper limits of anadromy (USFWS and HVT 1999). This is an oversimplification as spawning occurs throughout the mainstem down to the Hoopa Valley and Coho and steelhead outmigration can occur any time from October – June. Given the complexity, it would be difficult to decide how to weight one reach of the river higher than another during this important period for so many species and life stages.

Our primary analysis aggregates to a monthly temporal scale, but as a secondary check to see if this aggregation introduced undue coarseness, we also calculated temperature (ΔT) and salmonid daily growth (ΔF) metrics on the daily basis. The daily analysis provided more resolution but did not change conclusions, so for ease of explanation we chose to focus on the monthly data while providing daily figures for ΔT and ΔF in Section C.3 of Appendix C. The following equation was used to graph the average monthly differences from the unimpaired scenario for ΔT_k:

$$\textit{average monthly difference } \Delta T_k = (\Delta T_k - U)/U$$

ΔTk is replace with ΔFk, ΔCk, ΔBk, or ΔPk as appropriate for other variables and the units of difference change from degrees Celsius to percent grams per day or percent development time.

We recognize that salmonids, Foothill Yellow-legged Frogs, and Baetidae mayflies have generation times much longer than one month. For simplicity, we analyze flow effects on biota in each month separately. These are preliminary analyses to assess flow effects on rates, not evaluation of effects on specific individuals or populations. It would have been more enlightening to run simulations over an entire year to evaluate effects of phenology and simulate transitions from one life stage to the next (i.e., egg development, naiad to nymph, polliwog to adult frog development) so it could be determined under what flow conditions life stage transitions can be successful (e.g., if polliwogs have sufficient time to metamorphose). However, such analyses were beyond the scope of this project. Available Trinity River models that could be applied to such analyses in the future include the Stream Salmonid Simulator (S3, Perry et al. 2018) and the Foothill Yellow-legged Frog Assessment Model (FYFAM, Railsback and Harvey 2015).

5.1.2.2 TEMPERATURE MODELING RESULTS - LONGITUDINAL AND SEASONAL DIMENSIONS

The analysis presented in this section limited comparisons to within water year type and within month. This is because the gradient of seasonal warming is strong over this period and shifts later in the year with wetter hydrologic conditions. From this point forward, all terms used to assess effects to temperature, growth, and development will drop their associated index, as all comparisons will be integrated over the length of the river and the specific month and scenario of comparisons will be described in text or figures. Additionally, the values for the unimpaired scenario's river kilometer weighted mean monthly temperature (*U*), juvenile Chinook Salmon growth (*f*), FYLF polliwog development time (*p*), and Chironomidae (*c*) and Baetidae (*b*) generation time are an important basis for comparison by water year type and month (Figure 63).

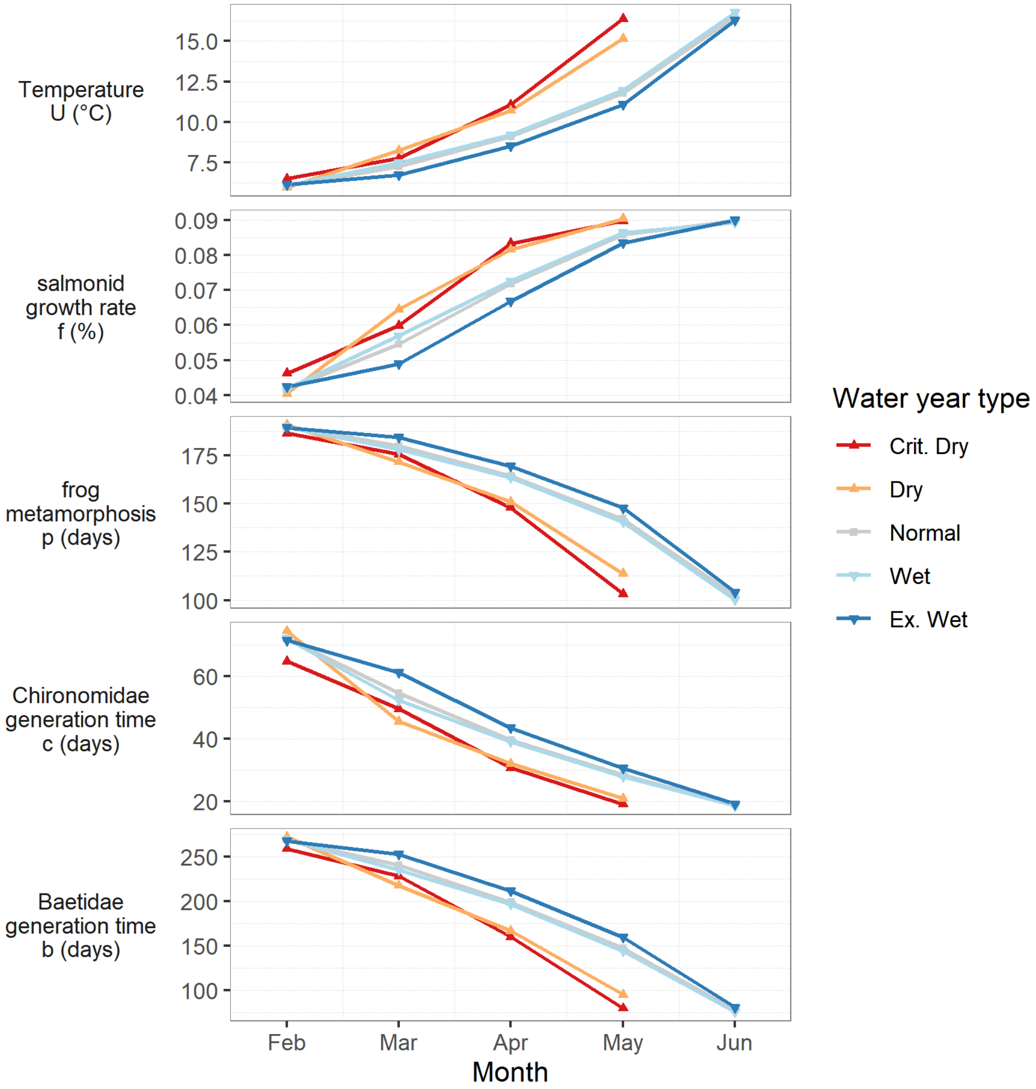


Figure 63. Display of seasonal trend, from February–June, for five metrics for the unimpaired scenario used to evaluate longitudinal and seasonal dimensions of the thermal landscape of the Trinity River, for FYLF metamorphosis time (*p*), Chironomidae generation time (*c*), Baetidae generation time (*b*), Temperature (*U*), and salmonid growth (*f*).

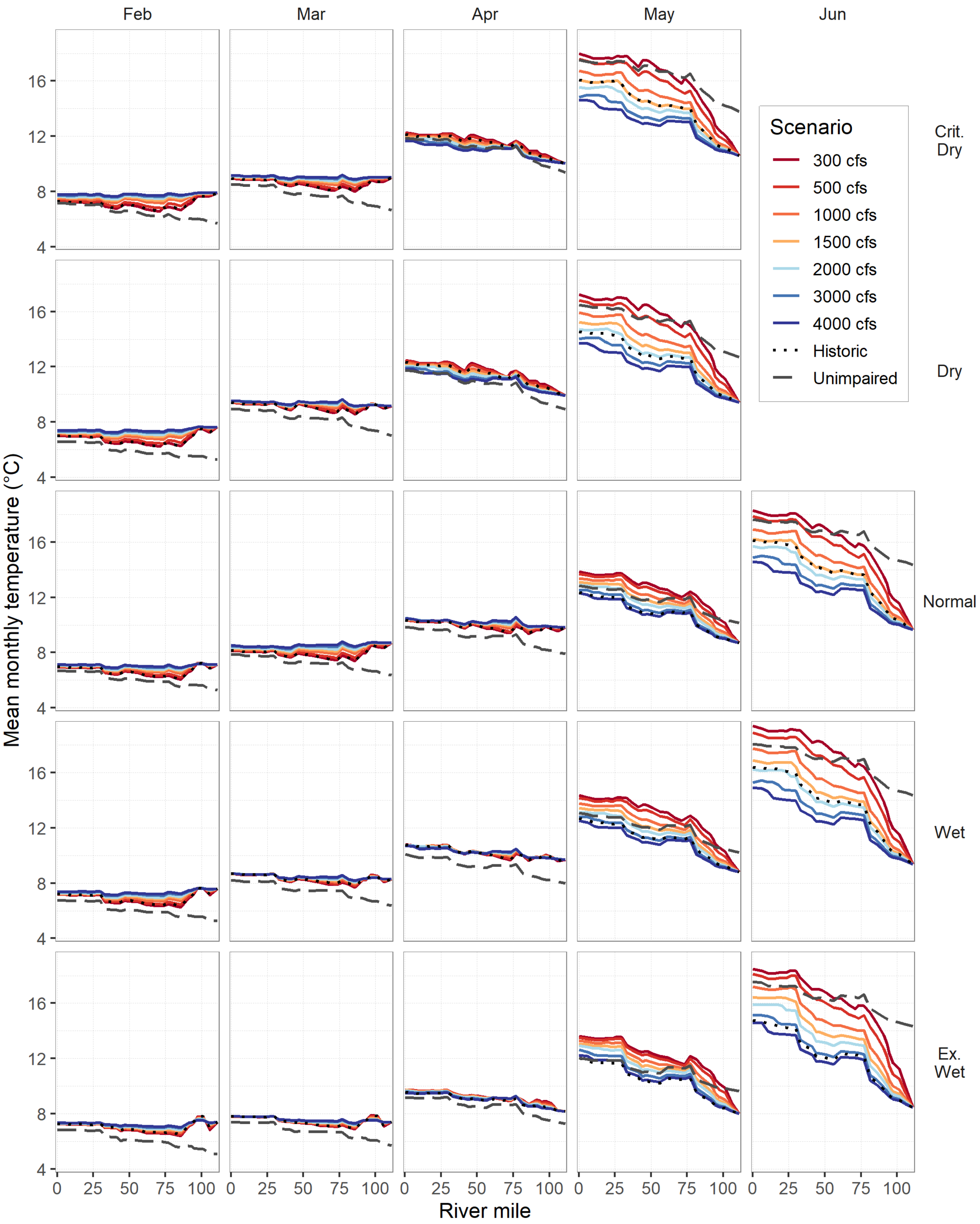


Figure 64. Longitudinal temperature profiles of mean monthly water temperature (°C) by water year type for the unimpaired and historical scenarios, and 7 constant flow scenarios ranging from 300 cfs to 4000 cfs.

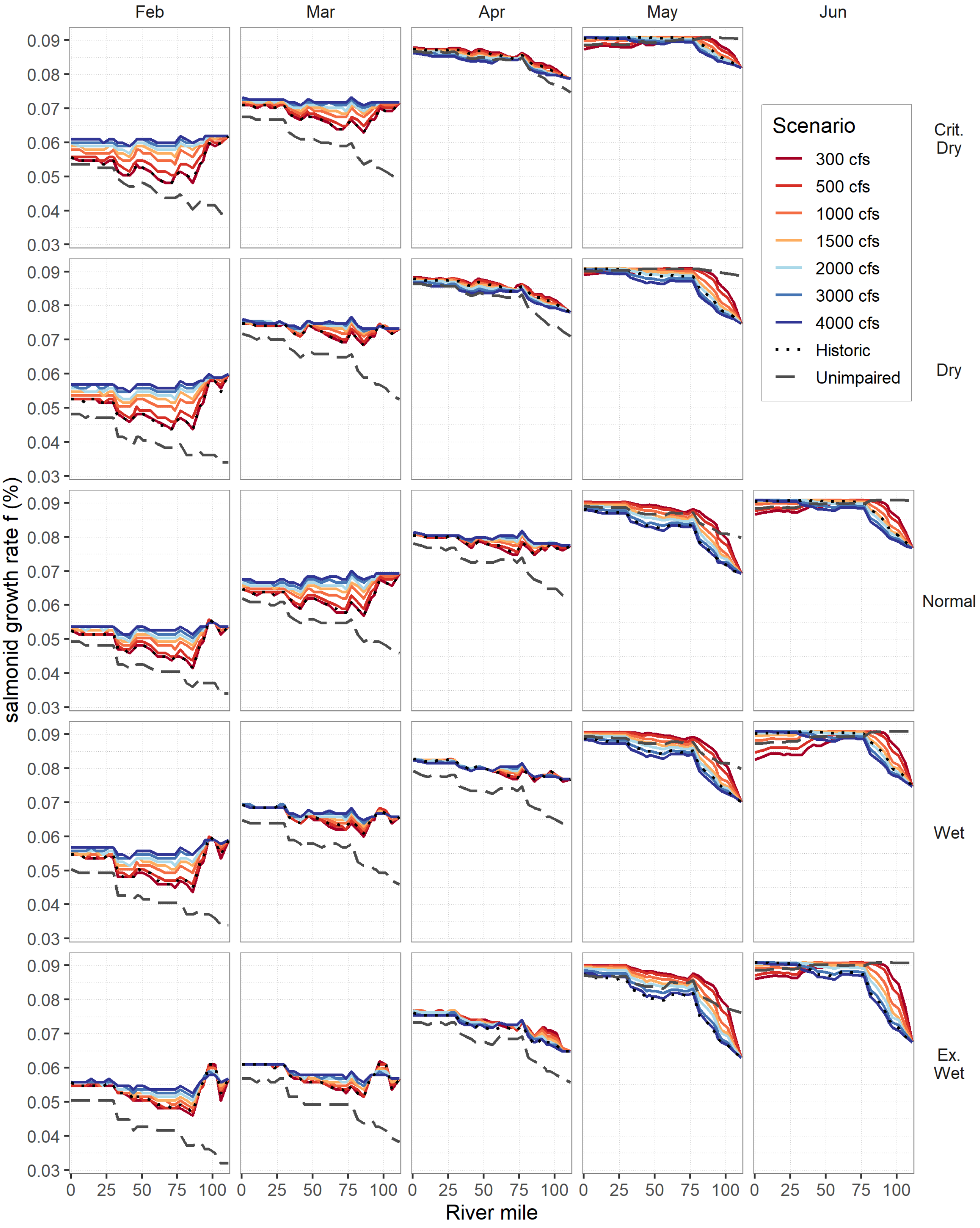


Figure 65. Longitudinal profiles of juvenile salmonid growth calculated from mean monthly water temperature (°C) by water year type for the unimpaired and historical scenarios, and 7 constant flow scenarios ranging from 300 cfs to 4000 cfs.

A common theme among all water year types for all scenarios is that longitudinal temperature profiles are, in general, warmer than the natural thermal regime in the months of February, March, and April. In February and March there is a cooling trend in a downstream direction for all dams-in scenarios, to approximately the confluence with the North Fork Trinity River. This is followed by a warming trend below the North Fork Trinity River, causing a 'belly' in the longitudinal profile (Figure 64). This is compared to the relatively constant warming trend exhibited by the unimpaired scenario in all months of all water year types. This unnatural longitudinal pattern diminishes as Lewiston discharge increases. In April, elevated water temperatures exist down the length of the river for all dams-in scenarios in Dry and wetter water years and all but the highest discharge scenarios in Critically Dry water years. However, unlike February and March, temperatures warm nearly continuously in a downstream direction during April for all scenarios in all water year types.

The life stage requiring the narrowest range of water temperature for salmonids in the months of February and March is incubating eggs. Optimal temperatures for incubation of salmonid eggs are between 6 and 10 °C (Carter 2005), which are not exceeded in any water year type for any scenario during February and March (Figure 64). Temperatures can be above optimal for incubation in April downstream of the North Fork in Normal and wetter water years and for nearly the entire length of the river in Dry and Critically Dry water years. Few salmonid eggs should remain in gravels within the mainstem river during the month of April. Those that remain would primarily be limited to steelhead and non-native Brown Trout. Steelhead mostly spawn in tributaries and their eggs are tolerant of temperatures up to 15 °C and temperatures below 13 °C are considered protective (Carter 2005), which is never exceeded in April for any water year type in any scenario.

In general, lower discharges more closely approximate the unimpaired scenario temperatures for February and March (Figure 64), and as a result ΔT performs better (Figure 66). However, low discharge exaggerates the unnatural 'belly' caused by longitudinal cooling followed by warming trend described above (Figure 64). All dams-in scenarios are generally within the threshold of <1.3 °C for ΔT in February and March, the exception are scenarios >2000 cfs in February for Dry water years (Figure 66). All scenarios in February and March achieve desirable temperatures for incubation of salmonid eggs and there is a positive relationship between ΔF and increasing discharge (Figure 66). Correspondingly, there is a reduction in development time with increasing discharge reflected for other species represented by ΔC, ΔB, and ΔP (Figure 67).

In April, ΔT remains relatively insensitive to release magnitude (Figure 66). Significantly higher dam release discharge is required to best approximate the unimpaired scenario in drier than Normal water years and Extremely Wet water years, with 3000 cfs performing best in Critically Dry and 4000 cfs for Dry and Extremely Wet (Figure 66). However, in Normal and Wet water years lower discharges perform best. When our metric of <1.3 °C for ΔT is applied, all discharges performed well for all water years. While improved juvenile growth (ΔF) is achieved in all scenarios, there is relatively low sensitivity in all water year types during April. In Critically Dry, Dry, and Extremely Wet water years the lowest discharges perform best for ΔF (Figure 66). Interestingly, the highest discharges perform best in Normal water years, while ΔF in Wet water years is nearly the same for all scenarios, with the moderate discharges (1,000 – 2,000 cfs) perform best (Figure 66). Across other species (ΔC, ΔB, and ΔP), lower discharges reduce the time required for development (Figure 67).

The relationship of dams-in scenario release temperatures relative to the unimpaired scenario inverts in May and water temperatures at Lewiston remain much colder in June for dams-in scenarios (Figure 64). The distance that temperature suppression propagates downstream increases with release discharge. For many low discharge scenarios (up to 2000 cfs in Ex Wet water year types) water warms quickly in a downstream direction and eventually exceeds the temperatures present in the unimpaired scenario in the lower reaches of the Trinity River. This phenomenon is also observed in the lowest discharge (300 and 500 cfs) scenarios in June for Normal and wetter years.

In May, water temperature as measured by ΔT becomes much more sensitive to release discharge in Critically Dry and Dry Water years, with 300 and 500 cfs performing best respectively (Figure 66). During Critically Dry and Dry water years, no dams-in scenarios can mimic the unimpaired scenario for long lengths of the upper river due to cold release temperatures (Figure 64), while ΔT remains relatively insensitive for Normal and wetter water years. Discharge of 3000 cfs performs best for ΔT in Normal and wetter water years (Figure 61). Impacts to ΔF are negative for all scenarios except those under 1000 cfs in Normal and Wet water years and under 1500 cfs in Extremely Wet water years (Figure 66). Later in the year (April and May of Dry and dryer years and May and June of Normal and wetter years) salmonid growth rates are generally higher (Figure 63), rising from rates of below 5% in February to above 8%, and average juvenile salmonid size is larger. As a result, proportional growth rate reductions later in the rearing period have greater overall impact on biomass production. The same general trend is present for other species (ΔC, ΔB, and ΔP), with much longer development times occurring in Dry and critically dry water years with increasing discharge with nearly the same discharges observed for ΔF in Normal and wetter years separating reduced from increased development time (Figure 67).

In June, no assessment of our metrics is provided for Dry and Critically Dry water year types due to the limitation of the RBM10 model to make predictions for low flows that would exist in the unimpaired scenario at this time of year. This is an indication that the spring would be giving way to the hot dry summer in these water years, as is observed in un-dammed tributaries around the basin (Figure 7), and the window for successful outmigration would begin to close in the unimpaired scenario. In Normal and wetter years, sensitivity of ΔF to discharge decreases from May to June while the opposite is true for ΔT (Figure 66). For Normal and wetter water years flows below 1000 cfs meet <1.3 °C for ΔT. The highest discharge scenarios cause negative impacts to ΔF, but these are minimized at or below discharge of 1000 cfs in Normal and Wet water years and 1500 cfs in Extremely Wet water years, and growth benefits rise as discharge decreases (Figure 66). Increases in development time from temperature suppression for other species (ΔC, ΔB, and ΔP) are more severe and diminish with reductions in flow (Figure 67).

When compared to the range of constant flow scenarios, historical management in all months and water year types performs moderate to poor for juvenile salmonid growth and development metrics for all species (Figure 66, Figure 67). The same is true of the approximation of the unimpaired temperature for May and June in all water year types and April in Dry and Critically Dry water years (Figure 66). However, the historical management performs relatively well at approximating unimpaired temperatures for February and March for all water year types and April of Normal and wetter water years (Figure 66).

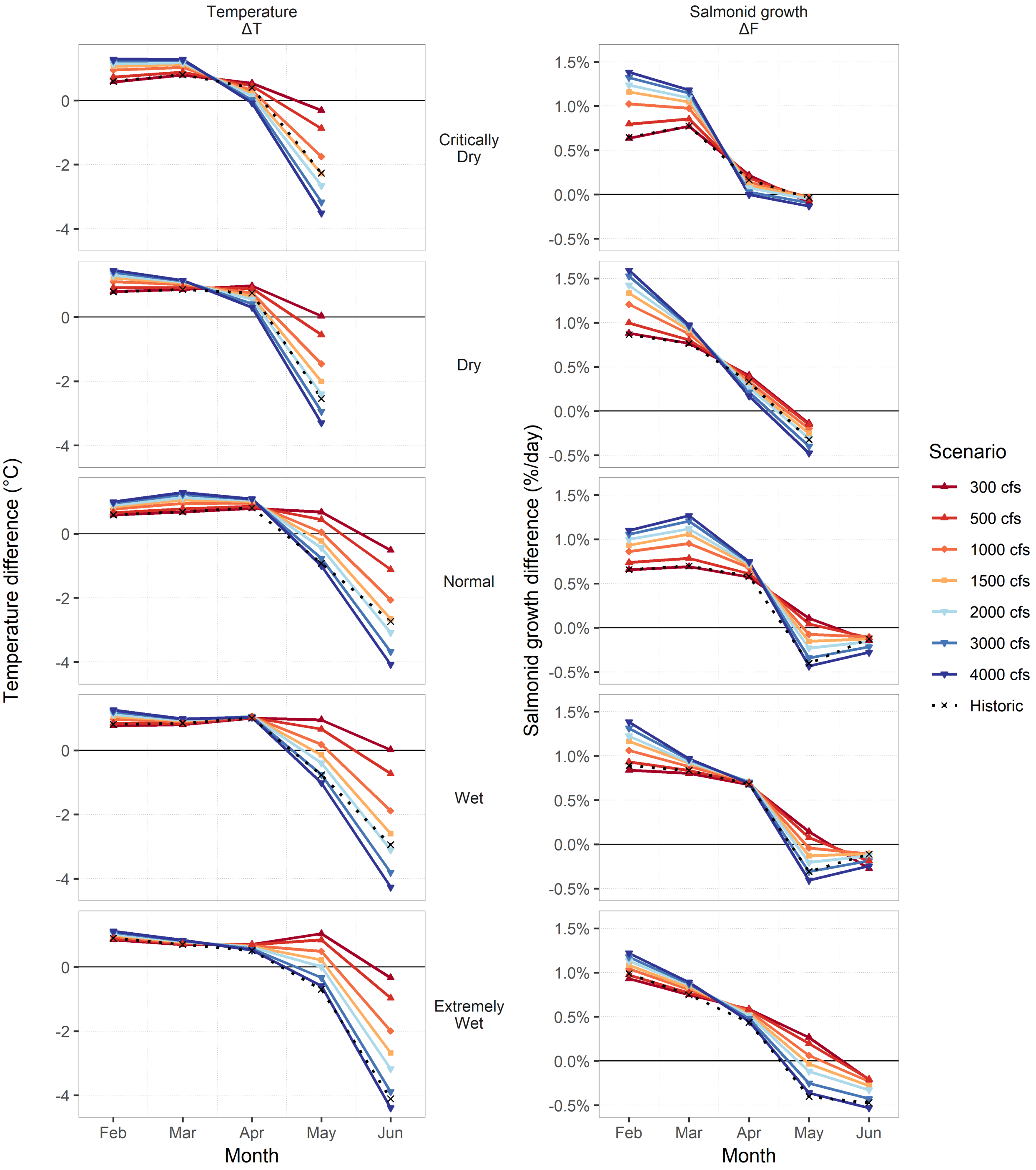


Figure 66. The average monthly difference from unimpaired for dams-in scenarios from February–June for temperature (ΔT) and salmonid daily growth (ΔF).

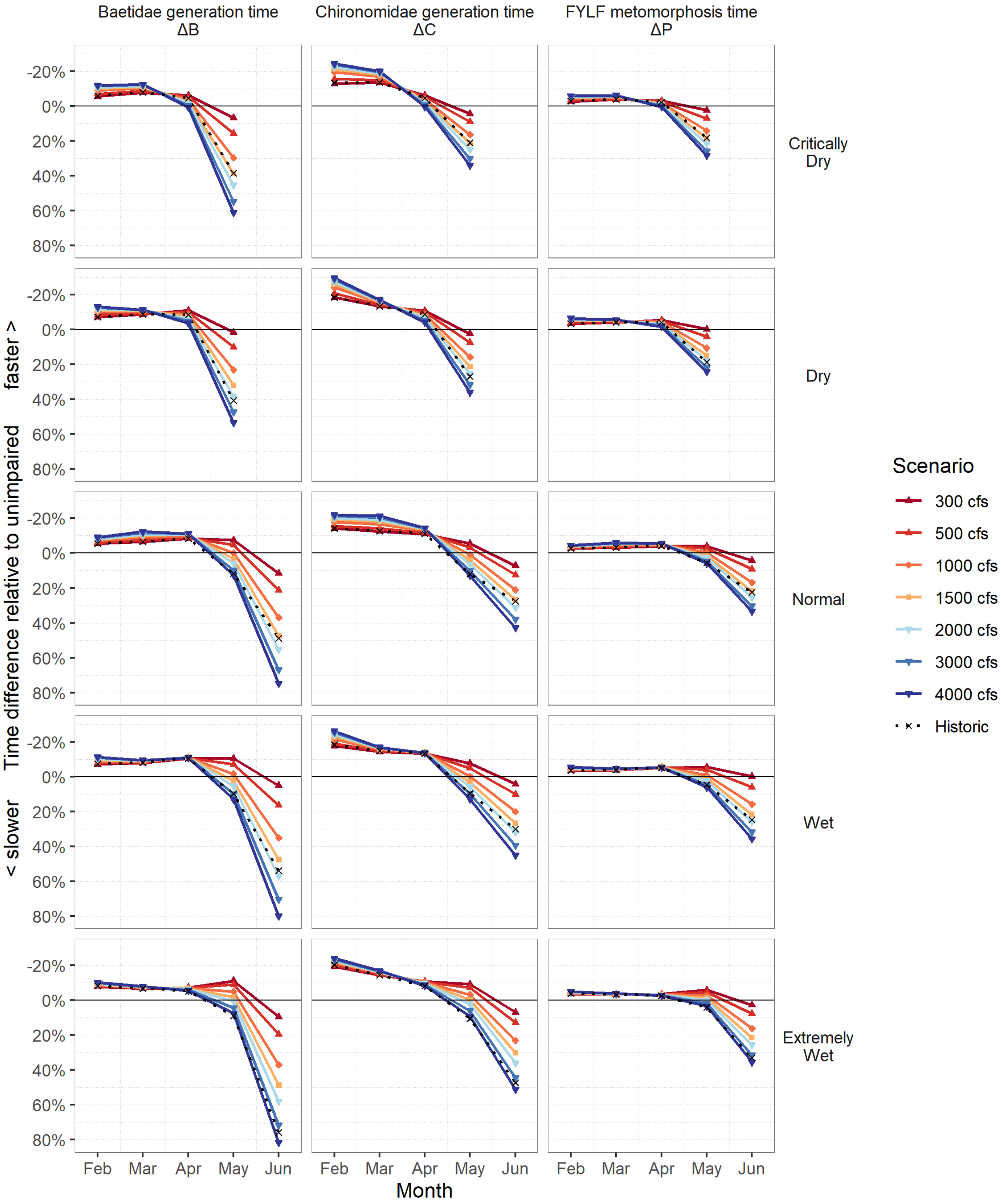


Figure 67. The average monthly difference in development time from unimpaired for dams-in scenarios from February–June for Baetidae generation time (Δ*B*), Chironomidae generation time (Δ*B*), and FYLF polliwog metamorphosis time (Δ*P*).

5.1.3 VERTICAL THERMAL DIVERSITY

While species distribution and range are primarily driven by the broadscale temperature patterns described by the seasonal and longitudinal gradients, the lateral and vertical dimensions of thermal diversity offer the most potential for behavioral thermal regulation for ectothermic species on a daily basis. These dimensions offer access to a wide range of temperatures over relatively small distances and short periods of time. The instantaneous range of temperatures available over relatively small areas in these dimensions can exceed the range available over a river's length or an entire year (Tockner and Ward 2000).

The gradient of water temperature between ground water and surface water occurs in only a few feet in the vertical dimension and is buffered by the hyporheic zone, an important and highly productive ecotone where ground water and surface water mix (Hayashi and Rosenberry 2002). Because the hyporheic zone is influenced by groundwater, it tends to exhibit a more muted temperature range than adjacent surface waters. Monitoring water temperature in the hyporheic zone on the Trinity River at Sheridan Creek spawning riffle (RM 82.5) indicated a pattern of generally higher intra-gravel water temperatures between September and March when most salmonid eggs are incubating and generally lower water temperatures from April through August, compared to surface water temperatures in the same location at the same time of year (David 2017). This pattern was also observed at several sites on the Klamath River. However, in other locations on the Trinity River temperatures did not differ between hyporheic and surface waters (David 2017). A study of the Lowden Ranch channel rehabilitation site in summer 2012 found spatial and temporal temperature differences between the mainstem Trinity River, side-channels, and alcoves, in part due to hyporheic flow through naturally formed gravel bars (Ock et al. 2015). In the Willamette River in Oregon, thermal stratification is common in alcoves and ponds, but turbulent mixing prevents the mainstem and side-channels from stratifying (Gombert et al. 2022).

The life history strategy of spring Chinook Salmon and summer steelhead puts adults in circumstances where their thermal tolerances are exceeded in many parts of the stream they occupy (Nielsen et al. 1994). Pool stratification that causes warmer surface water to reside on top of pooled, dense, cool water offers thermal refuge for returning spawners (Nielsen et al. 1994). This vertical thermal gradient has been documented in many California streams and rivers (Nielsen et al. 1994, Tate et al. 2006, Boughton et al. 2015, Lucas et al. 2016, Georgakakos 2020). In the Eel and Russian rivers, elevated summer base flows from dam releases cause mixing in pools that breaks down the thermal stratification that naturally sets up under low flow conditions (Kubicek 1977, NMFS 2002, Yoshiyama and Moyle 2010). This same effect of summer releases from Lewiston Dam has been measured on the Trinity River (Buxton et al. 2022).

Lack of mixing during low stream flows can also allow for ground water upwelling, side slope inputs, or tributary flows to reside in pools within the main channel, offering thermal refugia in the form of colder water in summer or warmer water in winter when flows decrease as surface waters freeze (Armstrong and Schindler 2013). In summer months, juvenile salmonids in the Klamath River have been observed to move seasonally and diurnally between food-rich mainstem habitats and cooler tributary habitats (Benson and Holt 2005, Sutton 2007, Sutton et al. 2007, Brewitt 2014, Brewitt and Danner 2014, Chiaramonte et al. 2016, Brewitt et al. 2017), while over-wintering juvenile salmonids in other systems have been known to seek warmer groundwater upwelling to aid in digestion (Armstrong and Schindler 2013). Important thermal refugia in the lower Trinity River is provided during summer by streams that drain higher elevations including Horse Linto Creek and Willow Creek (Naman 2005). NCRWQCB (2010) provides maps of known thermal refugia at Lower Klamath River tributary confluences. The Yurok Tribe Fisheries Program also monitors thermal refugia at many locations in the Klamath-Trinity Basin (Belchik 1997, Sutton et al. 2002, Belchik 2003, Benson and Holt 2005, Naman 2005, Strange 2011b). One study has indicated that high flow dam releases in the Klamath River may diminish the size of tributary refugia by increasing mixing (Sutton et al. 2007).

5.1.4 LATERAL THERMAL DIMENSION

The littoral zone, areas of low relief adjacent to a body of water, plays an important role in providing thermal diversity in the lateral dimension of lotic systems and forms a ‘perirheic zone’, introduced by Mertes (1997), where river waters mix with local sources. The littoral is a highly productive transitional ecotone between the aquatic and terrestrial environment (Tockner and Ward 2000; Junk 1989; Ahearn et al. 2006). Littoral zones and floodplains maintain high productivity through periodic drying resulting in routine recycling of organic materials and nutrients. Thermal diversity of side-channels, backwaters, and edge habitats from reduced mixing and pooling of side slope and tributary inputs also provide for the diverse needs of aquatic biota (Gallagher 1999; Hayashi and Rosenberry 2002). Thermal heterogeneity in the lateral and vertical dimensions can provide resolution to perceived conflict between management for salmonids and other species (e.g., Northwestern Pond Turtles, Foothill Yellow-legged Frogs; Railsback et al. 2016) by providing a greater range of temperature conditions (TRRP and ESSA 2009). Calm floodplain habitats can provide salmonids with valuable and unique prey items not available in flowing waters, including damselflies (Zygoptera) (Krall et al. 2016), even if water temperatures in those habitats regularly exceed the thermal tolerances of salmonids.

These mechanisms for water to differentiate through reduced mixing and pooling of side slope and tributary inputs allow for local variability beyond the larger temporal and longitudinal dimensions captured by most of the data summarized in this report. This local variability can be exploited by motile ectothermic biota moving laterally and vertically to thermoregulate. We explore how management actions can impact these localized thermal gradients through a review of relevant literature and numerical modeling. Thermal stratification in the vertical dimension is a 3-dimensional (D) problem, which will be addressed by a study currently being conducted by the TRRP. We instead focus on the lateral dimension using 2-D modeling tools that are currently available.

5.1.4.1 HYDRAULIC/TEMPERATURE MODELING METHODS - LATERAL DIMENSION

We applied hydraulic models that support 2-dimensional temperature modeling to demonstrate how differences in stream and floodplain morphology can alter the range of water temperatures available to ectothermic species. All modeling was performed with SRH-2D, a 2-dimensional hydraulic model developed at the Bureau of Reclamation’s Technical Services Center (Lai 2010).

For this demonstration, we chose to model the Oregon Gulch reach of the Trinity River, selected for two reasons: First, a channel rehabilitation design was recently completed for the reach so two sets of contrasting reach topography (pre-project and designed) are available for comparison. Secondly, the pre-project morphology of the reach consists of a simple canal-like channel incised into a terrace composed of tailings piles (a common impaired condition on the Trinity River), whereas the design morphology consists of a large floodplain that permits extensive floodplain inundation (Figure 68).

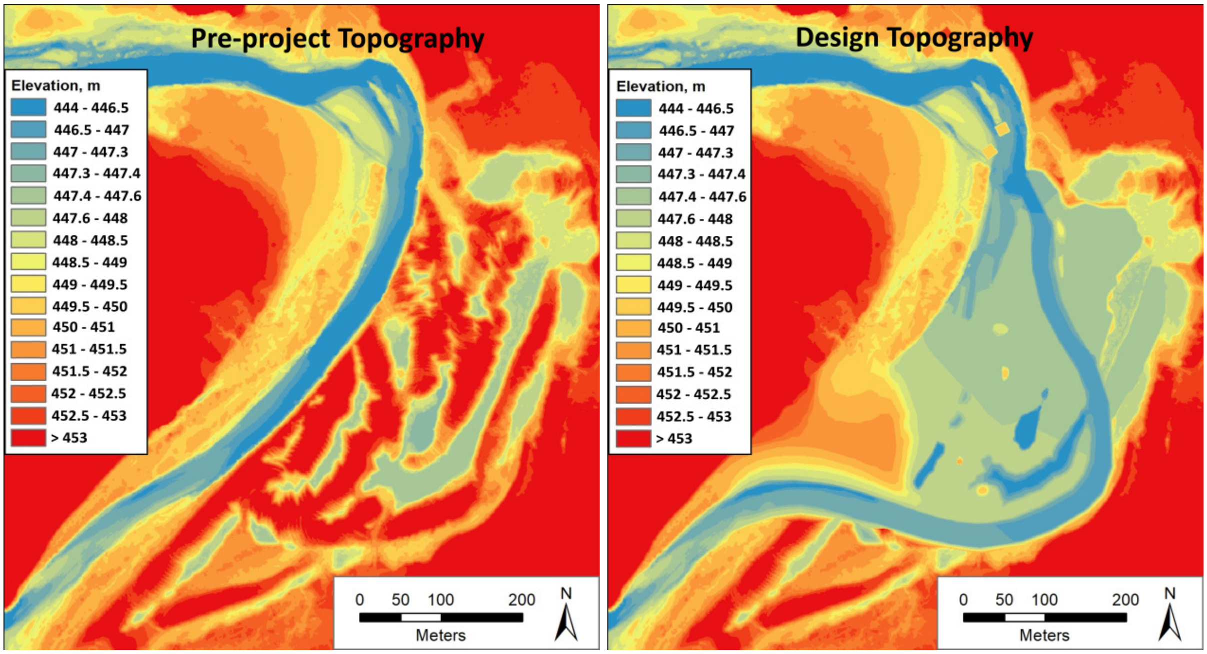


Figure 68. Pre-project (left) and design (right) topography at Oregon Gulch. Flow is from bottom toward the top.

We created a model mesh consisting of about 25,000 elements that, in areas that convey flow, typically cover around 54 to 65 ft^2 (5 to 6 m^2), and is quite dense within the region of interest (Figure B88 in Appendix B). We created pre-project and theoretical as-built hydraulic models by mapping the pre-project and design topography to the mesh. Materials defining hydraulic roughness that were mapped to the mesh for pre-project conditions were taken from the 40-mile hydraulic model developed by the Bureau of Reclamation's Technical Services Center (Bradley 2018), and the materials used in constructed portions of the design mesh were those used by the Oregon Gulch designers (Yurok Tribe 2020).

Model input data consists of an input hydrograph drawn from the Junction City stream gage, located 1.5 miles (2.5 km) downstream, plus hourly meteorological data and hourly water temperatures entering the upstream boundary of the model. Hourly measurements of air temperature, wind speed, and solar radiation inputs to the model were obtained from the U.S. Forest Service weather station at Big Bar, CA.[6] Dew point temperatures were computed from air temperatures and relative humidity according to the Magnus method (Parish and Putnam 1977). Model inputs also included barometric pressure and percent cloud cover, but these parameters were not available, so pressure was set to a constant value of 1014 mb and percent cloud cover was set to zero, as per reference. Sensitivity analyses showed that modeled water temperatures are insensitive to barometric pressure. Water temperatures entering the Oregon Gulch reach were assigned temperatures from the Douglas City stream gage, located about 11 miles (18 km) upstream, so are likely colder than the water that actually arrived at the reach and the diel temperature fluctuations may be out of phase (Section 3.4.4.1) compared to the true timing of

---

[6] https://wrcc.dri.edu/cgi-bin/rawMAIN.pl?caCBBR

daily temperature maxima and minima. Modeled temperature distributions computed within the Oregon Gulch reach are therefore not expected to match the actual temperatures that existed in the reach on model days, but nonetheless demonstrate the degree to which differences in reach morphology can alter temperature conditions in the Trinity River above its' confluence with the North Fork.

Six scenarios representing a range of flow and meteorological conditions encountered during spring and mid-summer in a critically dry and extremely wet water year were modeled at the Oregon Gulch site. Conditions prior to the spring high flow release period were modeled using flow and meteorological data from April 14, 2018 (a critically dry year) and April 13, 2019 (a wet year). Conditions during the spring release when flows were relatively high were modeled for April 19 in both 2018 and 2019. Mid-summer conditions were modeled using flow and meteorological data from July 25 in both years. Each scenario was modeled for pre-project and design conditions, for a total of 12 model runs. Each run spanned 48 hours, with a single 24-hour record of river discharge, meteorological data, and upstream boundary temperatures being repeated twice. The first 24-hour period in the model run serves to overcome thermal inertia so that water temperatures at the end of the period represent realistic initial conditions for modeling the second 24-hour period. All model results are drawn from the second 24-hour period.

The model outputs contain spatially distributed temperatures throughout the reach on an hourly interval, but we focused our attention on three times of day (0600, 1100, and 1600 hours) that were chosen assuming 0600 hours approximates minimum temperatures, 1600 approximates maximum temperatures, and 1100 hours to represent intermediate temperatures. We summarize temperature variability within these 36 sets of outputs in terms of the range of temperatures present in the reach (T_{r}) and the area-weighted standard deviation of temperatures, computed as:

$$T_{\sigma} = \Sigma([(T_b - T_{\mu})^2]/\Sigma A_b)^2$$

where T_b is the temperature of bins spanning 0.5 °C, A_b is the area of each temperature bin, and T_{μ} is the area-weighted average temperature within the reach, given by:

$$T_{\mu} = \Sigma[A_b T]/\Sigma[A_b]$$

Model elements with water depths less than 0.26 ft (0.08 m) were excluded, as model uncertainty is high for both the hydraulics and temperature results in these shallow marginal areas.

5.1.4.2 HYDRAULIC/TEMPERATURE MODELING RESULTS - LATERAL DIMENSION

In all cases but one, modeling results indicate that values of T_σ and T_r are substantially larger under design conditions than pre-project conditions (Table 16), indicating increased thermal variability from a restored valley bottom. These results are also presented as histograms in Figure 70 and Figure 71. The x-axis was allowed to vary to show the full range of available temperatures under design conditions, due to very small areas present at temperature extremes being undetectable otherwise. The greater spread of temperatures modeled for the design topography is evident in frequency histograms of modeled temperatures, which for pre-project conditions are generally limited to just one or two temperature bins (Figure 69, Figure 70, Figure 71). The only exception is for April 19, 2019, for which values of T_r are similar for pre-project and design conditions and values of T_σ for pre-project conditions slightly exceed those for design conditions. As shown by Figure 70, however, the mid-day and afternoon temperature distributions for pre-project conditions on that date are respectively above and below the optimal range for salmonid growth (Table 14), whereas the design conditions provide a more continues distribution of moderate temperatures throughout the day (Figure 70). For the case of the April 19, 2019 model output, the total areas of moderate temperatures (10 to 19 °C) at 1100 and 1600 hours under design conditions exceeds those of pre-project conditions by factors of 7 and 84, respectively. Differences in area-weighted average temperatures (T_μ) between pre-project and design conditions are comparatively small for all dates modeled.

Table 16. Results from SRH-2D temperature modeling at the Oregon Gulch rehabilitation site for pre-project and design conditions under extremely wet and critically dry hydrology for three different times of day and times of year. T_μ = area-weighted average temperature, T_σ = standard deviation of temperatures, and T_r = range of temperatures.

Year	Date	Q ft^3/s	Time	Pre-project			Design		
				T_μ °C	T_σ °C	T_r °C	T_μ °C	T_σ °C	T_r °C
2018 - Critically Dry WY	14-Apr	600	6:00	10.00	0.024	1.0	10.00	0.057	4.0
			11:00	11.00	0.000	0.5	11.39	0.478	9.0
			16:00	13.50	0.031	1.0	13.58	0.425	14.0
	19-Apr	1270	6:00	8.50	0.011	1.0	8.50	0.064	5.0
			11:00	9.50	0.029	1.0	10.10	0.689	13.5
			16:00	12.49	0.054	1.0	12.63	0.606	15.5
	25-Jul	425	6:00	15.51	0.071	1.0	16.48	1.812	8.5
			11:00	15.88	0.221	1.5	17.82	3.930	19.5
			16:00	17.36	0.225	1.0	19.93	5.368	22.5
2019 - Wet WT	13-Apr	1410	6:00	9.00	0.000	0.5	9.00	0.092	5.5
			11:00	9.50	0.000	0.5	10.20	0.880	13.0
			16:00	12.00	0.000	0.5	12.31	0.951	17.5
	19-Apr	6570	6:00	7.51	0.200	3.5	7.51	0.188	5.0
			11:00	8.73	1.601	18.5	8.69	0.988	17.5
			16:00	9.85	2.423	20.5	9.92	1.822	20.5
	25-Jul	700	6:00	12.00	0.000	0.5	12.45	1.256	9.5
			11:00	12.50	0.037	1.0	13.95	2.929	20.5
			16:00	14.51	0.057	1.0	16.10	3.456	23.0

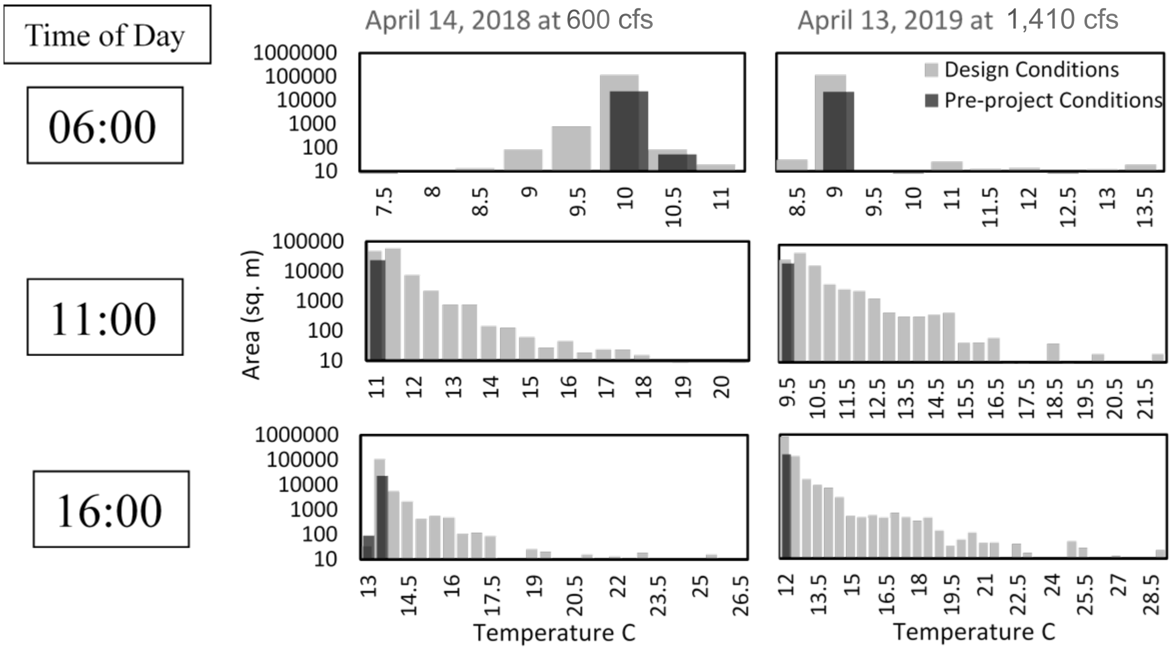


Figure 69. Summary of SRH 2-D temperature results for 3 times of day at the Oregon Gulch Rehabilitation site for design and pre-project conditions in April prior to spring releases under critically dry hydrology (left; 2018) and extremely wet hydrology (right; 2019). This figure, as well as Figure 70 and Figure 71, demonstrates that this project would dramatically increase the range of temperatures available.

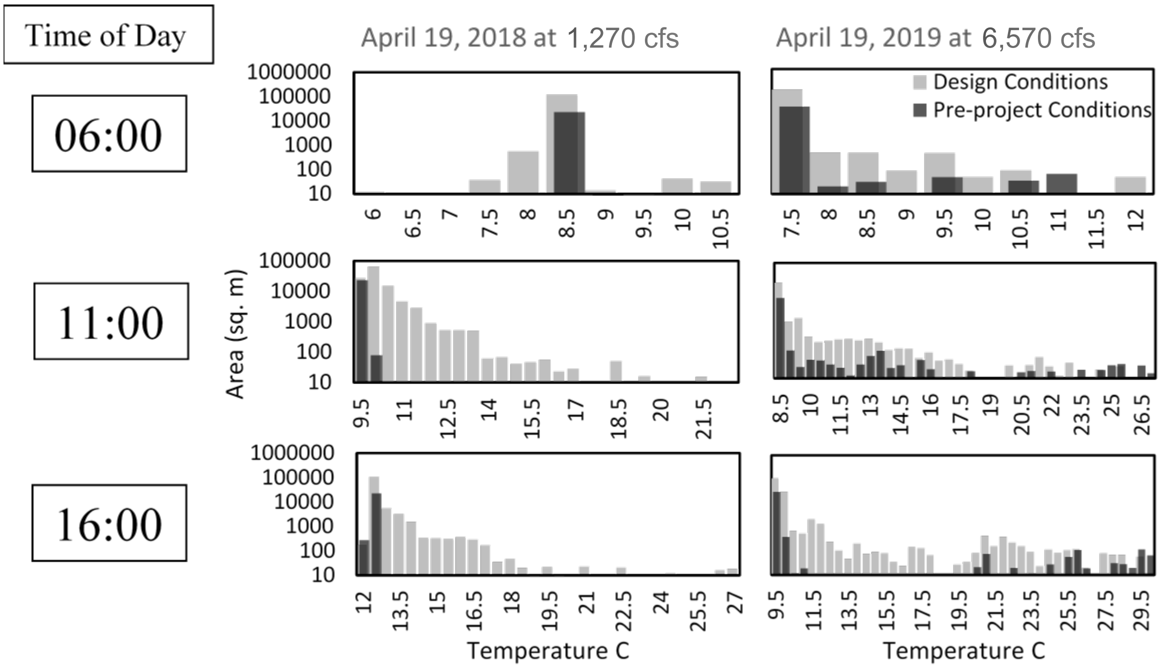


Figure 70. Summary of SRH 2-D temperature results for 3 times of day at the Oregon Gulch Rehabilitation site for design and pre-project conditions in April during spring releases under critically dry hydrology (left; 2018) and extremely wet hydrology (right; 2019).

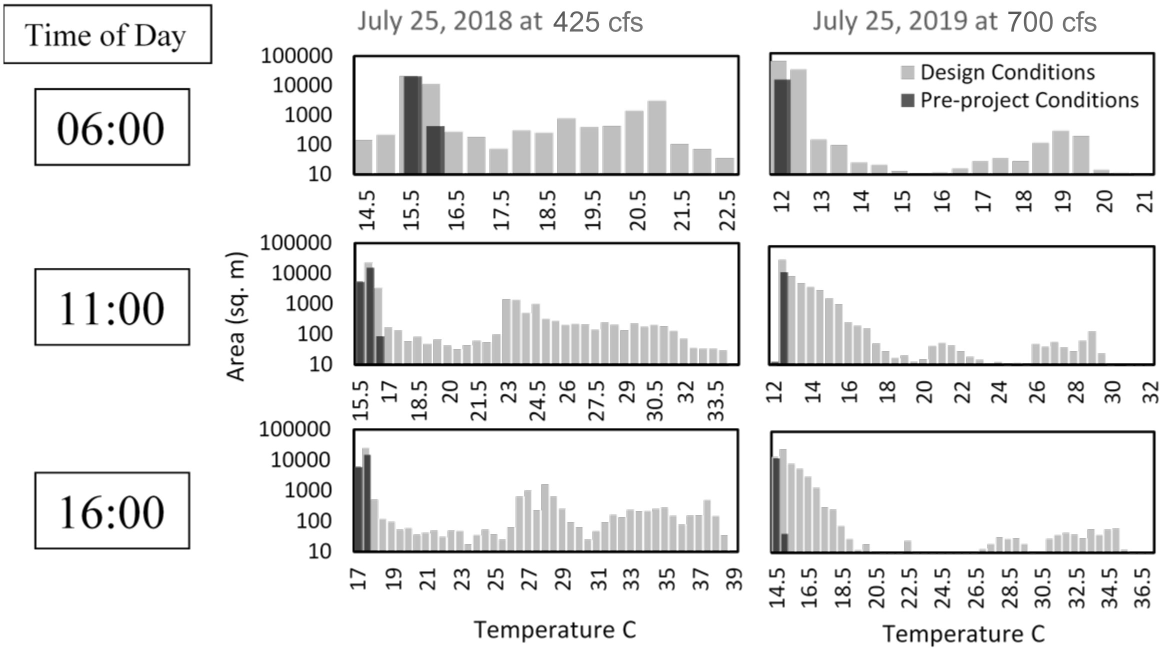


Figure 71. Summary of SRH 2-D temperature results for 3 times of day at the Oregon Gulch site for design and pre-project conditions in late July under critically dry hydrology (left; 2018) and extremely wet hydrology (right; 2019).

5.2 DISCUSSION OF THERMAL DIVERSITY MODELING RESULTS

5.2.1 LONGITUDINAL AND SEASONAL DIMENSIONS

A clear take away from this exercise is that magnitude of release discharge has relatively little effect on temperature prior to May in Dry and drier water years and prior to June in Normal and wetter water years. However, it appears that there is potential for substantial benefits to growth and development for salmonids and other ectothermic species from elevated discharge and temperatures in all years during February and March, and in April during Normal and wetter years. Slightly warmer winter temperatures are associated with spring fed systems with high base flow index (Isaak et al. 2020, Steel et al. 2017) and floodplains, channel margins, and off-channel habitat, all of which are known to be productive habitats salmonids are known to seek during rearing (Armstrong and Schindler 2013; Jeffres et al. 2008). While there are some unconfined reaches in the river where floodplains can function under high flow conditions, these have been significantly reduced by human land use and diversions. These months offer opportunity to conduct high magnitude dam releases for purposes of ROD objectives associated with geomorphic and riparian disturbance, while providing growth and development benefit to ectothermic species of the Trinity River. This is possible because reservoir release temperatures are relatively similar to temperatures of the unimpaired flow scenario and are in fact more desirable for growth during these times. With increasing discharge, temperatures throughout the system approach the release temperature due to thermal inertia of larger volume of water. This also minimizes or removes the unnatural cooling trend that can occur down to the North Fork Trinity River confluence.

However, starting in April of Critically Dry and dry years and May of Normal and wetter years moderate flow scenarios begin to perform best. During this month of transition from spring to summer, in respective water year types, a “Goldilocks” situation occurs as release temperatures and seasonal warming can be approximated within 1 °C through nearly the entire length of the river. After this time some of the metrics evaluated begin to conflict with one another and in some cases sensitivity increases dramatically. Reducing discharge decreases the longitudinal impacts of temperature suppression from hypolimnetic releases, but with reduced volume comes increased effects of atmospheric warming, causing temperatures to warm much faster longitudinally and overshoot the historical thermal regime at some point along the river’s length, in lower discharge scenarios. This month marks a transition from the pleasant conditions of spring in a Mediterranean climate, to the harsh hot and dry summer.

In May of Dry and drier years and June of Normal and wetter years temperature management becomes increasingly difficult with no exceptions to increasingly negative growth and development impacts from cold release temperatures and huge differences in the longitudinal extent and amount of thermal suppression with discharge. Small changes to discharge can have relatively dramatic effect compared to months previously discussed. During this month, in their respective water years, higher magnitude discharge increases both the departure from historical thermal norms and negative impacts to growth and development. Conversely, lower discharges reduce the longitudinal impacts to growth and development and better approximate the unimpaired temperature profile associated with outmigration and life history cues, over longer reaches of river.

This assessment clearly shows that all objectives are not met simultaneously by the same action and priorities must be set. These priorities likely need to switch at the point where certain metrics drastically increase in sensitivity to release discharge. The realistic temperature control of the river, using discharge magnitude from a single release point, has limits to the length downstream that effects can reach and the duration of the summer season that they can persist, due to water volume required to sustain discharge that can resist atmospheric warming and the impacts to temperature that occur upstream. Suppressing temperatures late in the outmigration season in favor of promoting growth, and in lieu of mimicking the natural thermal regime to send appropriate outmigration cues, could setup an ecological trap as temperatures is inevitably no longer able to be maintained in a desirable range downstream and conditions in the Trinity River or Lower Klamath River have already deteriorated. A similar type of ecological trap has been documented for FYLF, whereby suppressing temperature, and delaying the onset of breeding results in insufficient time and temperatures later in the season for polliwogs to metamorphosis and reach appropriate size necessary to successfully overwinter (Catenazzi and Kuperberg 2013).

5.2.2 LATERAL DIMENSION

Within impaired sections of unrestored Trinity River channel, results from the modeling exercise indicate that the thermal environment is nearly always entirely mixed under current management, except during flows high enough to engage floodplains, which only occurs during brief high flow peaks under pre-project channel morphology. In late spring and summer when discharges are at moderate or low levels, temperatures suitable for salmonid growth may be present, but warmer, productive habitats that generate abundant food resources and promote rapid growth, as observed by Lusardi et al. (2019), are absent.

Model outputs for July 25, 2019, for example, indicate mean temperatures of 12 to ~14.5 °C for pre-project conditions and ~12.5 to 16 °C for design conditions (Table 16). The range of temperatures for pre-project conditions at any time of day, however, is only 1 degree or less, whereas the range for design conditions varies from a low of 9.5 °C at 0600 hours to a high of 23 °C at 1600 hours.

Maps of spatial distribution of temperatures in the reach show that water temperatures in the pre-project channel are nearly uniform throughout the reach at all modeled times (Figure 72). Under design conditions, however, water temperatures in the 13.5 to 16 °C range that promotes maximum fish growth (Carter 2005) persist in areas sheltered from the main flow even at 0600 hours. By 1100 hours, water in that temperature range is present in more than a third of the wetted area. In the late afternoon, when temperatures exceed 13.5 degrees through the reach for both the pre-project and design conditions, roughly 80% of the wetted area under design conditions remain in the 13.5 to 16 °C range, whereas the remaining 20% offers warmer water that supports organisms with different temperature requirements, such as Foothill Yellow-legged Frogs, Northwestern Pond Turtles; and other ecosystem services, such as primary and secondary production. Our 2-dimensional modeling approach is not capable of predicting vertical thermal stratification, but results from other rivers suggest that structural complexity, especially alcoves, promotes such stratification (Gombert et al. 2022).

In early spring, water temperatures upstream of the North Fork Trinity River are typically cold enough to inhibit growth of juvenile salmon, especially during spring flow releases from Lewiston Dam. Model results for April 19, 2019 provide an example in which average temperature in the Oregon Gulch reach remains below 10 °C throughout the full 24-hour modeling period (Table 16). Average temperatures are also ≤10 °C in all the remaining April model outputs for 0600 hours, as well as in two more of the April outputs for 1100 hours. The persistence of cold water in the April 19, 2019 output is the result of relatively high discharge in the river on that date, which ranged from 221 m^3/s (~7800 cfs) at the beginning of the 24 hr period modeled to 151 m^3/s (~5330 cfs) at the end. These large discharges, approaching the range of the mean annual flood downstream from Lewiston Dam, are also responsible for the anomalously large range of temperature values already noted for the pre-project model output for April 19, 2019. As shown in Figure 73, water temperatures remained below 10 °C over virtually the entire wetted area under pre-project conditions. Much warmer water appears only where water is ponded in shallow floodplain areas that filled in the first hours of early morning when discharge was at its maximum. By 1600 hours that water, which had been disconnected from the channel for hours, had reached temperatures approaching 30 °C. Temperatures intermediate between cold main flow and hot water stranded in floodplain areas are virtually absent.

Somewhat similar conditions exist in the design model output for this date, in that the majority of wetted area is occupied by cold water. Comparatively large regions of intermediate water temperature nonetheless exist in the design output due to the greater inundation and edge complexity of the design topography.

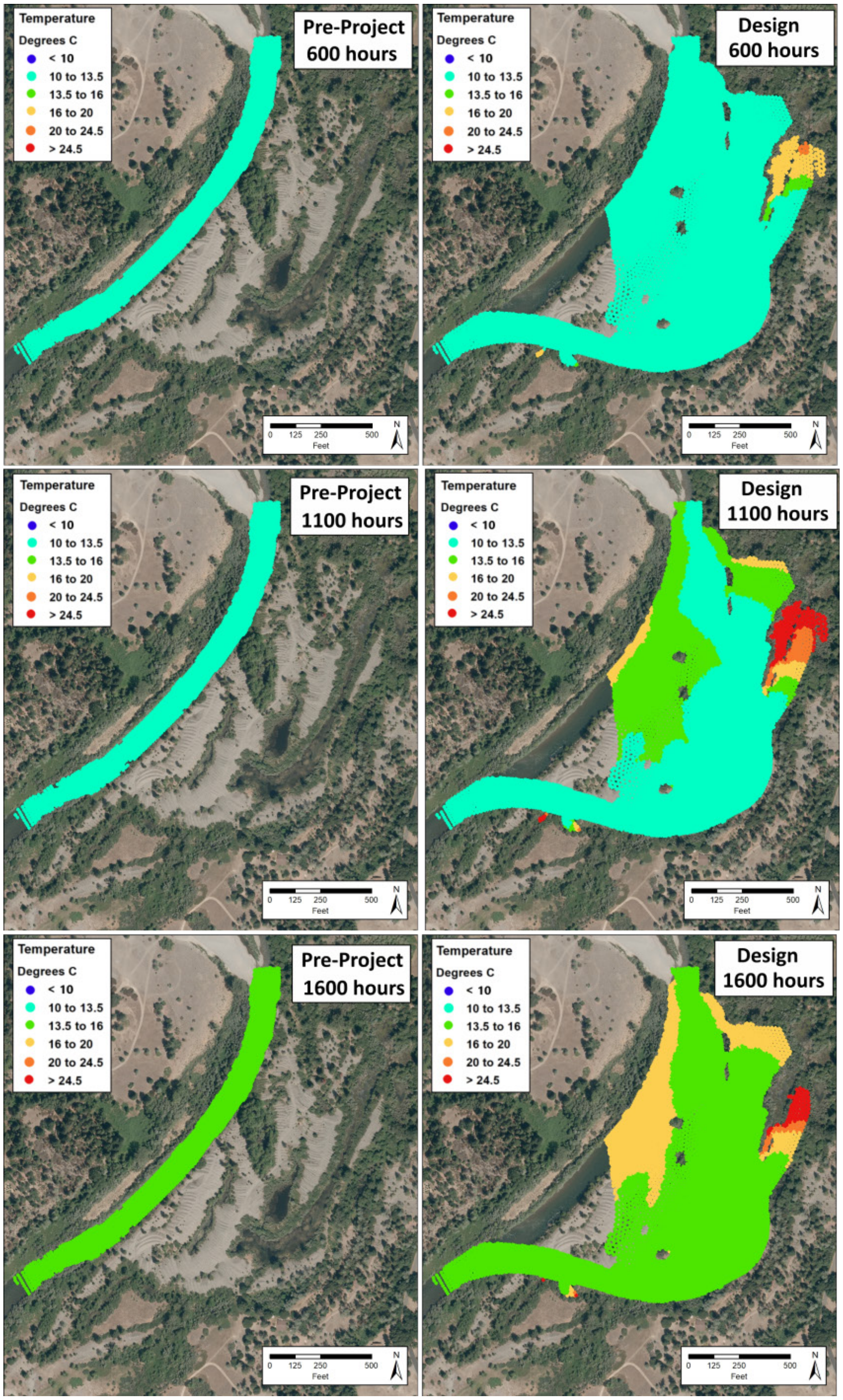


Figure 72. Map of modeled temperature output for pre-project (left) and design (right) conditions in the Oregon Gulch reach computed with meteorology and hydrology inputs for extremely wet hydrology on July 25th, 2019, and a modeled flow of 700 cfs. Flow direction is from the bottom of the image to the top. Temperature categories are based on thresholds for juvenile salmonid growth from Carter (2005), where growth ceases at <5 °C, growth reduced by >20% at 5–10 °C, growth reduced by 10–20% at 10–13.5 °C, growth reduced by <10% at 13.5–16 °C, maximum growth range and increased prevalence of disease at 16–20 °C, growth reduced <20% and high prevalence of disease at 20–24.5 °C, and >24.5 °C is unsuitable for salmonids.

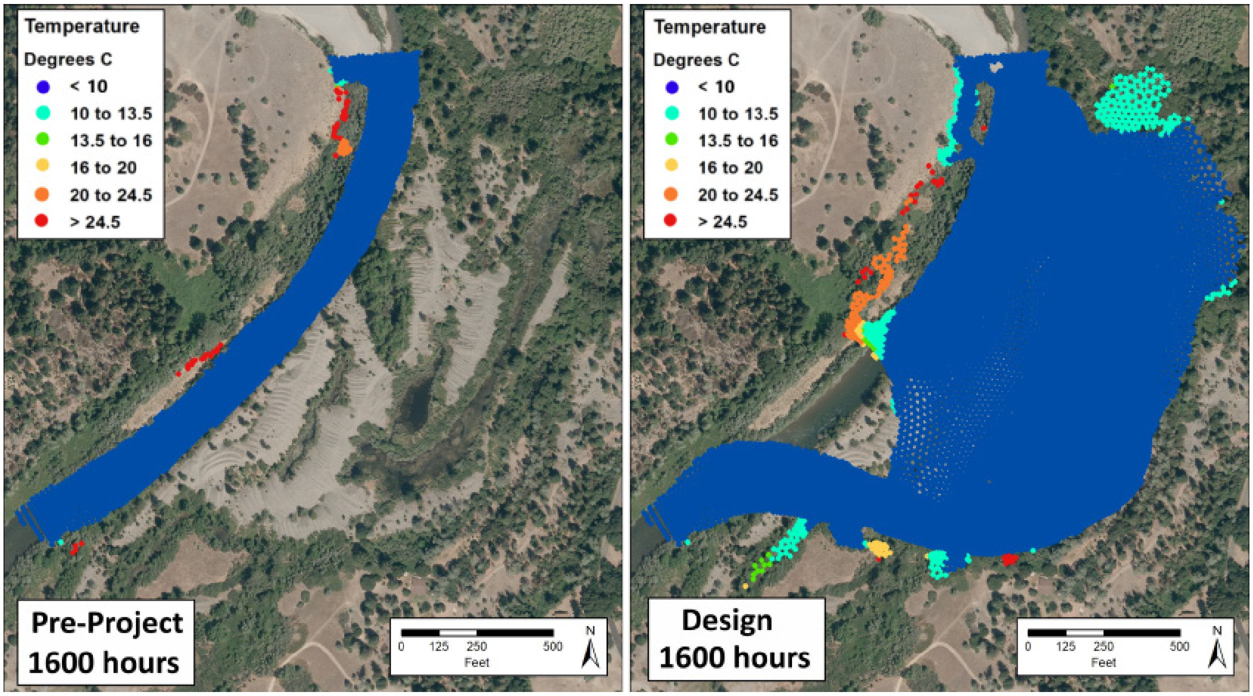


Figure 73. Map of modeled temperature output for pre-project and design conditions in the Oregon Gulch reach computed with meteorology and hydrology inputs for 1600 hours on April 19th, 2019 and a modeled flow of ~6,570 cfs. Flow direction is from the bottom of the image to the top. See caption of Figure 72 for an explanation of legend temperature categories.

5.3 RECOMMENDATIONS

5.3.1 LONGITUDINAL AND SEASONAL DIMENSIONS

In general, for all metrics that were evaluated, increases in sensitivity to dam discharge for a given month indicate the relative importance of management actions at that time for that variable. Those management actions can either have beneficial or negative temperature impacts for species. When metrics are insensitive to discharge in a given month, it is an indication that the associated species or biological process is resilient to flow-driven thermal impacts and that time can be used to release discharges for other desired effects without risk of negatively influencing thermal habitats. The recommendation provided in this section are made for temperature related objectives. We recognize that there are competing objectives and species not examined that have requirements that will have to be considered and balanced with the temperature needs of the species represented here.

We recommend that salmonid growth be the temperature priority through April in Dry and Critically Dry years and that mimicking the natural thermal regime take priority in May and June to send appropriate outmigration cues and ensure fish are not stuck in the lurch as the low flow summer season takes hold. For Normal and wetter years growth should continue to be the priority through May, then mimicking the natural thermal regime in June. This is supported by findings from other syntheses reports. Benefits to juvenile Chinook Salmon consumption rates were indicated for increased discharge in February, March, and April by TGAEC (2021), while consumption rates were negatively correlated with discharge in May. TGAEC (2021) also found that the number of redds observed prior to rearing was negatively correlated to consumption rate, indicating density dependence, which may also be alleviated by increased habitat provided by higher flows during the early rearing period prior to dispersal from the spawning grounds. The time where growth is the priority also offers opportunity to accomplish objectives associated with high discharge such as, providing physical rearing habitat for salmonids, geomorphic work, riparian scour, and bed load transport. All other species assessed herein would share in benefits through increased developmental rates throughout the season.

Recommendations for flows to meet temperature needs of the species assemblage analyzed are summarized in Figure 74 and begin with flows >1,000 cfs during February for all water year types, due to potential for benefit to growth and development of several species. This recommendation extends into March for Critically Dry and Normal water years, whereas no specific recommendations are provided for other water years in March. During April, mean monthly flows of ≤1,000 cfs in Critically Dry water years and ≤2000 cfs in Dry water years are recommended to provide optimal salmonid growing conditions. In May of Critically Dry and Dry years, flows should decrease to ~500 cfs to send outmigration cues to salmonids moving downstream while improving growing conditions in the upper river for salmonids that over-summer in the Trinity River. There are no bounds on discharge range for recommendations in April for Normal and wetter water years. In May, flows should decrease to ≤1,000 cfs in Normal and Wet water years and drop below 1500 cfs in Extremely Wet years. In Normal and wetter water years it is recommended that flows diminish to ~500 cfs in June where they should remain until base flow is reached. We believe that these guidelines would provide increased growth and development opportunity for ectothermic species while minimizing the likelihood of setting up any ecological traps for outmigrating salmonid juveniles late in the season in the lower river when temperature control is unfeasible, or for FYLFs from eggmass scour by delaying breeding until after major peak flow releases (Section 7.1.1).

Through this extensive look at longitudinal and seasonal impacts to temperature from hypothetical management alternatives after damming and diversion, we have determined that with current infrastructure only one month per year can offer a reasonable approximation of the natural thermal regime throughout the length of the river. This is the month of April in Dry and Critically Dry water years and the Month of May in Normal and wetter water years (Figure 64). With modification of infrastructure at Trinity Dam to have selective withdraw elevation relative to the thermocline in Trinity Reservoir, as recommended in Bender (2012), it is likely that a much more natural thermal regime could be achieved over a larger portion of the year by releasing higher discharges with more thermal inertia of a more desirable temperature. However, under current infrastructure constraints the natural thermal regime is an inadequate guide for managers. Instead, we recommend that managers should look to provide the ecological services that management actions can affect. The dynamics around release temperature also make the natural flow regime an inadequate guide, as attempting to approximate unimpaired flows have exacerbated temperature differences during months of the year that are critical for biological development and migration. As the lateral habit modeling exercise demonstrates (Section 5.2.2), if the valley bottom is restored, there could be sufficient complexity and inundation to provide the range of temperature that stream biota require, and which would have been present in an unimpaired river valley. Until such a time that vast areas of the valley bottom have been rehabilitate and hydrologic conditions are provided where they are inundated regularly and for long periods of time, or a selective withdrawal device is installed in Trinity Reservoir, it will be important for managers to balance the impacts and benefits of flow and temperature as management changes are made in the future.

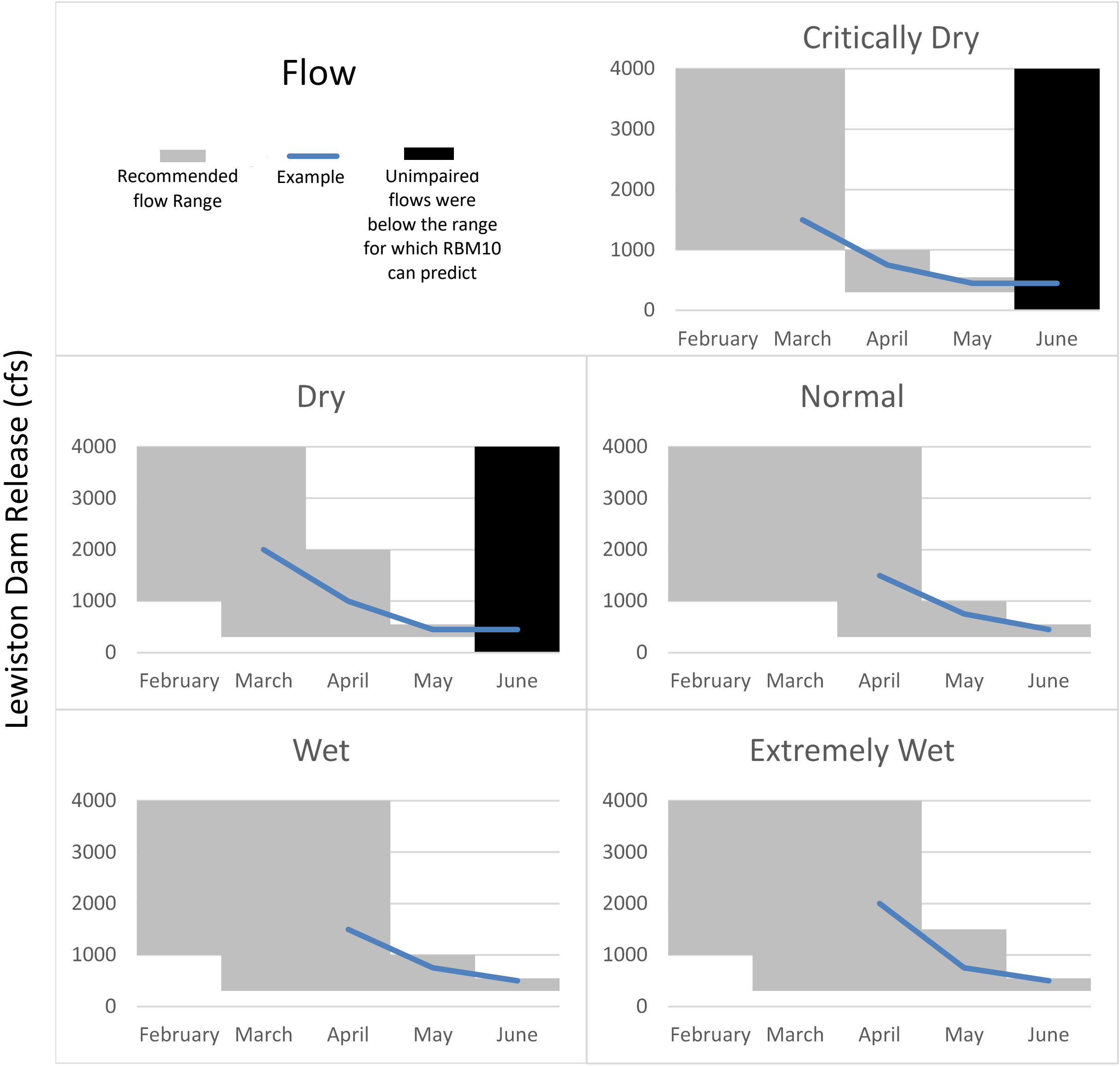


Figure 74. Recommended range of baseflows (cfs) in gray, and an example in blue, based on evaluation of departure of longitudinal temperature profile from unimpaired scenario, juvenile Chinook Salmon growth, FYLF polliwog development time, Baetidae generation time, and Chironomidae generation time. Recommendations are not provided (black) for June for Dry and Critically Dry water years because limitations of RBM10 prevented accurate predictions for the unimpaired flow/temperature scenario.

5.3.2 LATERAL DIMENSION

The TRRP has had a strong focus on defining and measuring physical characteristics (i.e., depth and velocity) of juvenile salmonid rearing habitat, but has undertaken less effort to understand and measure the other components of habitat, including temperature. The Program has recently begun to study temperature phenomenon important to salmonid life history strategies more in depth, including an ongoing investigation of the potential impacts of providing thermally stratified habitat for holding adult salmonid during summer in the Trinity River. This and other studies like it are critical for understanding how to provide diverse thermal habitats so that organisms can exploit variability to provide what they needed at a given time through behavioral thermoregulation. These types of studies will allow managers to move away from single species management, as was initially envisioned by the Trinity River Flow Evaluation Study and employ management techniques that focus on providing the range of habitats necessary to support a healthy riverine ecosystem. We have demonstrated that the unrestored channel exhibits nearly entirely mixed conditions leading to almost no variability in temperature. This highlights the importance of longitudinal and seasonal temperature management in the unrestored channel, due to the lack of thermal diversity and therefore ability of organisms to behaviorally thermoregulate. The tools to follow the recommendation of the IAP (TRRP and ESSA 2009) to develop thermal heterogeneity metrics are available, as demonstrated in this exercise, and should be used to develop better inputs to the Stream Salmonid Simulator fish production model (Perry et al. 2018) and the Foothill Yellow-legged Frog Assessment Model (Railsback and Harvey 2015), as well as being incorporated into both site design and hydrograph development.

We provide four points in summary. First, to fully address temperature issues associated with cold water hypolimnetic releases during times of year when Trinity Reservoir is strongly thermal stratified would require installation of infrastructure capable of releasing water from specific elevations, such as has been implemented at Cougar Dam on the South Fork McKenzie River (Murphy et al. 2021) and Pelton Dam on the Deschutes River (DRA 2017). Second, extensive floodplain restoration throughout the river’s length could offer diverse thermal conditions readily accessible to riverine inhabitants if frequently inundated. Third, in the absence of the two more robust solutions listed above, attempting to meet current outmigration temperature targets at the river’s terminus results in deleterious temperature impacts throughout much of the river’s length. Thus, temperature compliance should move away from point compliance and begin to consider the totality of impacts from releases on water temperature throughout the length of the Trinity River. Fourth, to best meet the temperature requirements of ectothermic stream biota under current constraints, we recommend that all sustained release discharges 1500 cfs or higher should occur prior to June in Normal and wetter water years and prior to May in Dry and drier water years (Figure 74). This will have the synergistic benefit of providing overbank flows in cooler months of the rearing period, allowing shallow lateral habitats to warm during the heat of the day offering a reprieve from cooler than optimal conditions within the main flow of the river, and better mimicking the thermal regime which life history cues and outmigration evolved with. The more detailed recommendations provided in Figure 74 offer the most opportunity for salmonid growth while maintaining levels of warming downstream that give appropriate outmigration cues for conditions that will be encountered by juvenile salmonids later in the season. These changes would also allow warming that would benefit over summering juvenile salmonids and other aquatic ectothermic organisms upstream.

6 CLIMATE CHANGE

Climate change is a critically important issue for the future of Trinity River hydrology and water temperatures. A rigorous assessment would involve a multitude of linked steps including emissions scenarios, deriving climate time series, watershed hydrology, reservoir operations, reservoir thermal dynamics, river temperatures, and biological responses. Such complex modeling of climate change effects was outside the scope of this project. Instead, we summarize previous assessments. Previous efforts to assess how climate change may affect stream temperatures in the Trinity River watershed have been conducted as part of larger regional efforts rather than intensive Trinity-specific studies. Therefore, in addition to reviewing studies that provide stream temperature predictions for the Trinity River, we also present relevant information from scientific literature for other geographic areas as well as present a brief summary of predictions for air temperature, precipitation, snowpack, and streamflow.

The first step in making climate change predictions is to adopt assumptions about future concentrations of greenhouse gases. Most of the discussions below reference two commonly used Representative Concentration Pathways (RCPs). RCP 8.5 is a high emissions scenario where greenhouse gas concentrations continue their current rapidly rising trajectory, with carbon dioxide (CO_2) concentrations reaching approximately 950 parts per million (ppm) by 2100 while RCP 4.5 is a medium emissions scenario in which considerable greenhouse gas mitigation efforts stabilize CO_2 concentrations at approximately 540 ppm by the middle of the 21st century (van Vuuren 2011). As of February 2021, CO_2 concentrations were 416 ppm[7].

6.1 PROJECTIONS FOR AIR TEMPERATURE, PRECIPITATION, SNOWPACK, STREAMFLOW, AND RESERVOIR STORAGE

Recent reviews of climate change literature are provided by Grantham (2018) for the North Coast of California and Butz et al. (2015) for Shasta-Trinity National Forest, from which we draw upon to provide a very brief summary here.

Relative to the 1950–2005 historical baseline, annually averaged maximum daily temperatures in Trinity County are predicted to rise by 8.4 °F (4.7 °C) by the late 20th century (2070–2099) if emissions are not reduced (Grantham 2018). Model predictions indicate that annual precipitation for the North Coast Region will likely continue to fall within the range of historical variability but are expected to increase slightly on average (Grantham 2018). At multiple spatial scales including California, the North-Central Region of California, and the Weaverville climate station, in the 1918–2006 period the rate of warming is greater for minimum air temperatures than for maximum air temperatures (Cordero et al. 2011). Precipitation intensity in the North Coast Region is likely to increase substantially (Cayan et al. 2018, Swain et al. 2018). Under a high-emissions scenario, the percent of the Trinity River watershed with April 1 snowpack is predicted to decline from 80% in 1981–2010 to 56% in 2040–2069 and 22% in 2070–2099 (Figure 75), and the average snow water equivalent of areas above 3,000 ft elevation is predicted to decline from 11.6 inches in 1981–2010 to 4.3 inches in 2040–2069 and 1.6 inches in 2070–2099 (Micheli et al. 2018). This shift from snow to rain will have dramatic consequences for runoff timing in the Trinity River watershed. For example, under a high-emissions scenario, inflows to Trinity Reservoir are predicted to shift from the current April–May snowmelt-dominated peak to a rain-dominated peak in January–February by the end of the 21st century (Figure 76) (Mote et al. 2014).

The USBR (2016) Klamath River Basin Study evaluated historical water demand and supply, projected effects of future climate change, and explored adaptation strategies to reduce climate change impacts. Water demand and adaptation analyses were focused on the upper Klamath Basin, but climate and hydrologic modeling spanned the entire Klamath Basin including the Trinity River watershed. For hydrologic unit code 18010211 (Trinity River watershed excluding the South Fork Trinity River), from a 1950–1999 historical baseline of 54.5 °F (12.5 °C), annual average

---

[7] https://climate.nasa.gov/vital-signs/carbon-dioxide/

temperatures are expected to increase to 55.5–57.0 °F (13.1–13.9 °C) in the 2030s and to 56.5–59.6 °F (13.6–15.3 °C) in the 2070s. Expected changes in annual average precipitation for hydrologic unit code 18010211from the historical 1950–1999 baseline of 35.6 inches vary by scenario, with a range of 33.5–40.6 inches for 2030s and a range of 31.5–42.1 inches for the 2070s. The VIC hydrologic model results did not match well with the observed seasonal peak flows, so USBR (2016) advised interpreting results in terms of change in water balance parameters (rather than projections of absolute values). Relative to the 1950–1999 baseline, USBR (2016) models predict the annual centroid of runoff (i.e., the date by which 50% of the hydrologic year's runoff has occurred) will occur 18–42 days (varies by scenario) earlier in the 2070s in the Trinity River above Coffee Creek and 9–30 days earlier the Trinity River at Hoopa. From a 1950–1999 historical baseline of 45.0 inches, evaporation from Trinity Reservoir is expected to increase to 45.7–47.0 inches by the 2030s and 46.4–49.6 inches by the 2070s.

The California Water Fix/Bay Delta Conservation Plan evaluated climate change effects on Trinity Reservoir inflow and water storage (CDWR and USBR 2016). The timing of peak inflow was predicted to shift from May under historical conditions (1922–2003, labeled as 2010) to April in 2025 and 2060. On average, annual inflows are expected to increase 2% under a 2060 climate. The largest proportional declines are in May, June, and July, when 2060 flows are predicted to be only 78, 61%, and 56% of their historical averages, respectively (Figure 77). CDWR and USBR (2016) predicted that climate change is predicted to strongly decrease annual minimum reservoir water storage (Figure 78). Modeling studies conducted for California's Fourth Climate Change Assessment also predicted future reductions in Trinity Reservoir storage resulting from increased water demand, earlier runoff, and the need to maintain greater flood control capacity (Schwarz et al. 2018, Wang et al. 2018). Trinity Reservoir was recently ranked as one of the most vulnerable major reservoirs in California to increased flood hazard from climate change (Mallakpour 2019).

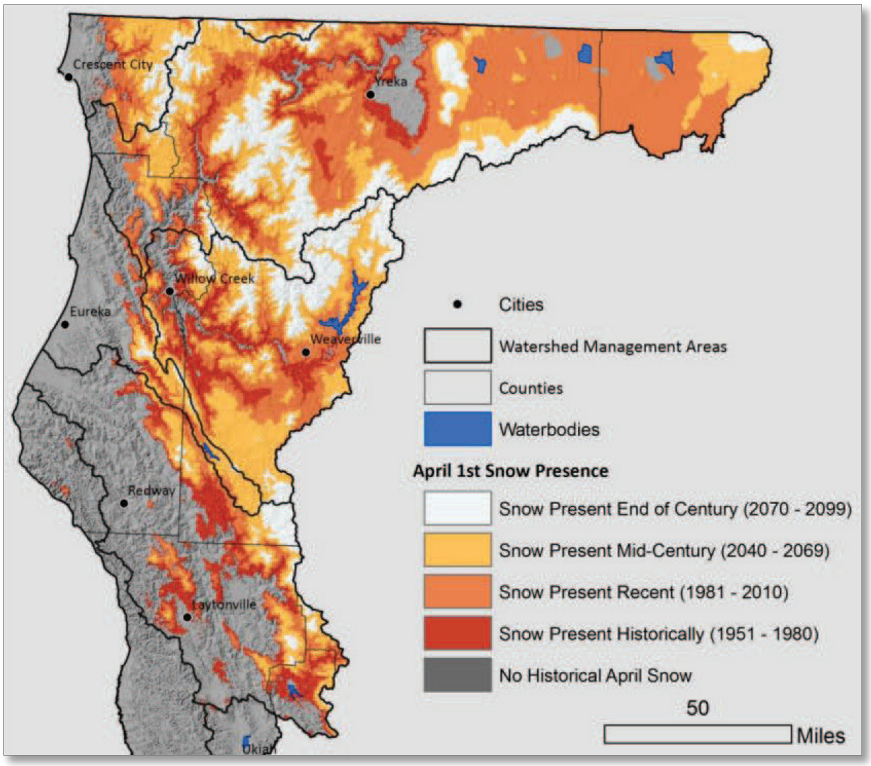


Figure 75. April 1 snow presence in the North Coast Region predicted by the USGS Basin Characterization Model under a high-emissions scenario (Flint and Flint 2014). Figure adapted from Micheli et al. (2018).

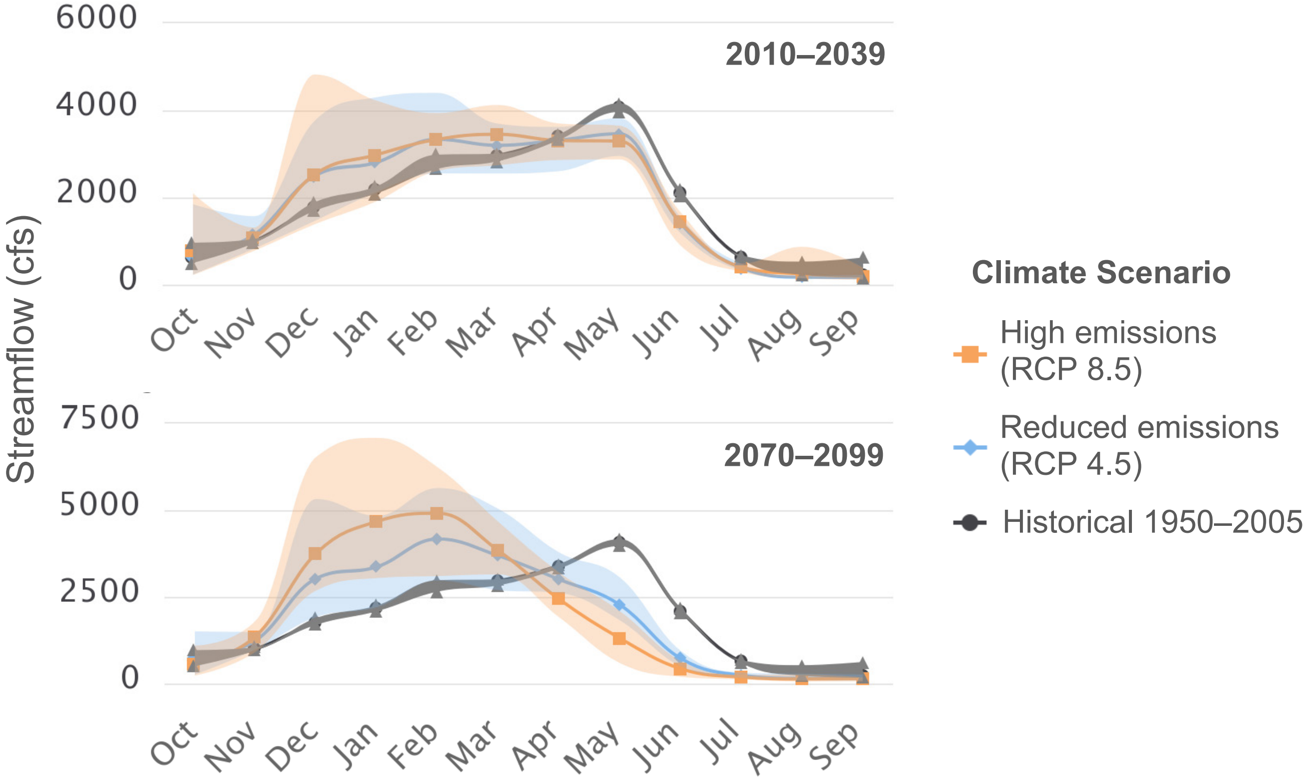


Figure 76. Bias-corrected monthly mean Trinity Reservoir Inflow predicted by the Variable Infiltration Capacity (VIC) model with meteorological inputs from the historical climate (1950–2005) and projected climates for the early 21st century (2010–2039) and late 21st century (2070–2099) under two climate change scenarios (RCP 4.5 and RCP 8.5), using ten general circulation models (GCMs). Points are means of ten GCMs while shaded regions show the range between the GCMs (not the range between years). Data from the Integrated Scenarios of Climate, Hydrology, and Vegetation for the Northwest project (Mote et al. 2014).

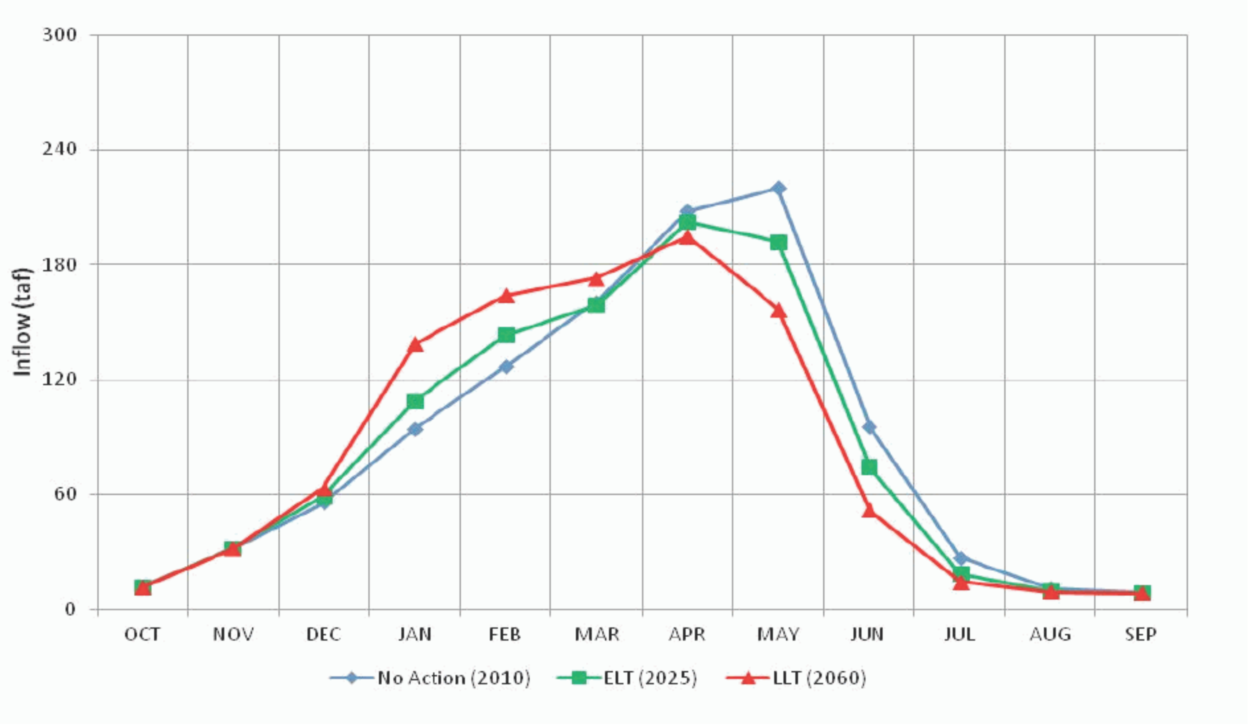


Figure 77. Projected monthly average inflow into Trinity Reservoir for 1922–2003 (labeled as 2010), 2025, and 2060 from the California Water Fix/Bay Delta Conservation Plan (CDWR and USBR 2016). taf = thousand acre-feet.

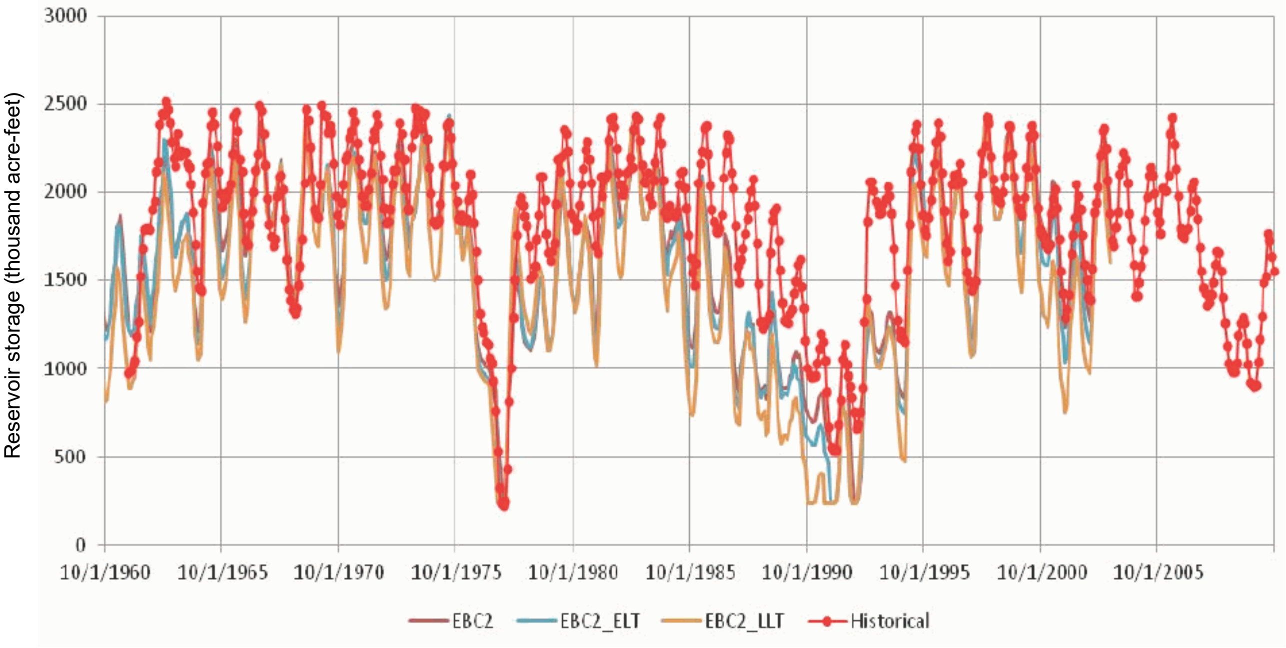


Figure 78. Historical Trinity Reservoir water storage for 1961–2010 compared with three projected scenarios: EBC2 is the 2010 timeframe, EBC2_ELT is the 2025 timeframe, EBC2_LLT is the 2060 timeframe (and the NEPA No Action Alternative). Figure adapted from the California Water Fix/Bay Delta Conservation Plan (CDWR and USBR 2016).

6.2 PROJECTIONS FOR STREAM TEMPERATURE

There are several available projections of future climate-driven increases to Trinity River water temperatures. Due to multiple interacting mechanisms and inherent uncertainties, it is difficult to quantify response of water temperatures to climate change. For reasons described below, none of the previous estimates are comprehensive and all likely underestimate the magnitude of the increases that are likely to occur.

NorWeST provides mean August stream temperature predictions for several climate change scenarios for the Northern California/Coastal Klamath unit which includes the Trinity River (Isaak et al. 2017). In NorWeST's primary climate change scenario (S32), mean August stream temperatures are predicted to rise by only 0.44–0.77 °C from the 1993–2011 baseline period to 2080 under the A1B high-emission scenario. The relatively small predicted increase in the NorWeST model is driven in large part by the low sensitivity to the 3.6°C increase in air temperature predicted by global climate models (Isaak et al. 2017). The air temperature sensitivity for the Northern California/Coastal Klamath NorWeST unit is 0.14 °C/°C (i.e., stream temperatures are predicted to increase by 0.14 °C for each 1 °C increase in air temperature), which is the second lowest of 23 NorWeST geographic units in the Western U.S. (Isaak et al. 2017). For comparison, air temperature sensitivities from previous studies in other areas include: 0.44 °C/°C for the Salmon River (Asarian et al. 2019), 0.22 °C/°C for the Lower Klamath River and adjacent coastal tributaries (Asarian et al. 2017), 0.47 °C/°C for 104 Pacific Northwest streams (Mayer et al. 2012), and 0.51 °C/°C for 246 Pacific Northwest streams (Luce et al. 2014). The NorWeST air temperature sensitivity might be skewed low due to complex spatial patterns of interannual air temperatures in northwest California that are not represented in the NorWeST model which uses a single air temperature within a year for all sites regardless of whether they are in the interior or coastal fog zone.

Spatial stream network modeling in the Salmon River watershed (Asarian et al. 2019) predicted that in the 2070–2099 period, mean daily maximum August stream temperatures will be warmer than the 1990–2017 baseline by 0.9–2.0°C under the reduced-emission RCP4.5 scenario or 1.7–3.3°C under the high-emission RCP8.5 scenario, depending on reach. Increases were predicted to be greater in Salmon River's South Fork, North Fork, and mainstem, with the smallest predicted increases in upper reaches of small tributaries (Asarian et al. 2019).

Flint and Flint (2012) developed statistical models of daily stream temperature for 24 Klamath Basin streams using air temperature, solar radiation, and vapor pressure deficit as predictors, with the latter two variables derived from air temperature. The models were calibrated for 1999–2008 and then applied to predict stream temperatures under five climate change scenarios based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) A1B and A2 emissions trajectories (Meehl et al. 2007). Averaging from the 1950–2000 climate baseline to a 2070–2099 future climate, mean and maximum daily stream temperatures were predicted to rise 0.6 °C in the Trinity River at Weitchpec, 1.2–1.3 °C in the South Fork Trinity River, and 1.3 °C in the North Fork Trinity River. These projected stream temperature increases only took into account changes expected to occur due to rising air temperatures, not changes in streamflow, so actual changes are likely to be greater.

RBM10 simulation modeling conducted as part of Klamath River dam removal studies predicted that mean water temperatures in the mainstem Klamath River would rise approximately 1–2.3 °C over the 50-year period 2012–2061, depending on the global climate model (Perry et al. 2011). In Perry et al.'s (2011) analyses, Trinity River temperatures were not simulated within RBM10 but instead were a boundary condition (i.e., input the Klamath River RBM10 model). Trinity River flows were assigned based on climate change outputs from a hydrologic model. Trinity River water temperatures increases only took into account changes expected to occur due to rising air temperatures, not changes in streamflow, so likely underestimate the total magnitude of future climate-driven water temperature increases. We acquired Perry et al.'s (2011) Trinity River flow and temperature model files but did not have time to summarize them for presentation in this report.

The California Water Fix/Bay Delta Conservation Plan used USBR's monthly temperature model (Section A.2.1) to evaluate climate change effects on Trinity Reservoir release temperatures and Trinity River temperatures at Douglas City and North Fork (CDWR and USBR 2016). Trinity reservoir inflow temperatures were fixed values for each month, and therefore did not take into account any climate-driven changes. CDWR and USBR (2016) do not summarize the differences between climate scenarios, but figures provided indicate a greater amount of warming in September (Figure 79) than October or November, and a greater amount of warming at Douglas City than Lewiston or North Fork.

6.3 LONG-TERM TRENDS FOR RESERVOIR AND STREAM TEMPERATURES

Graphical analyses in Section 3.3.1.2 above (including Figure 11, Figure 13) suggest that temperatures in the deeper portions of the Trinity Reservoir appear to be generally warmer in the years 1998–2019 than in 1972–1990. In addition, excluding periods of very low reservoir storage (i.e., <1,250,000 AF), our exploratory statistical analysis of data from the years 1972–2019 indicates that for every 1°C increase in the 12-month trailing average of air temperature, the water temperature at the depth of the main outlet of Trinity Reservoir rose by 0.49 °C (Table C20).

We did not do any original analyses of long-term stream temperature trends for this report, so instead we summarize previous research on the topic. From the early 1960s through 2001, stream temperatures at 18 long-term monitoring stations in the Klamath Basin, including some sites in the Trinity River at tributaries, increased by approximately 0.5 °C/decade (Bartholow 2005). For the period 1995–2017, an analysis aggregating 87 long-term sites in the Klamath Basin, not including any in the Trinity River, found increases in seven of nine summer stream temperature metrics, with the largest increases in mean temperature occurring in July (0.65 °C/decade) and less rapid increases in August and September (Asarian et al. 2020). The sites where temperatures rose most rapidly over the 1995–2017 study period were those where flow had the strongest effect on temperatures (i.e., cool temperatures in high flow years, warm temperatures in low-flow years) (Asarian et al. 2020). An analysis of monthly stream temperature trends for 1996–2015 at long-term monitoring sites across the Pacific Northwest found that increases of >0.3 °C were widespread at Klamath-Trinity basin in May through August, with less pronounced increases occurring in the longer period 1976–2015 (Isaak et al. 2018).

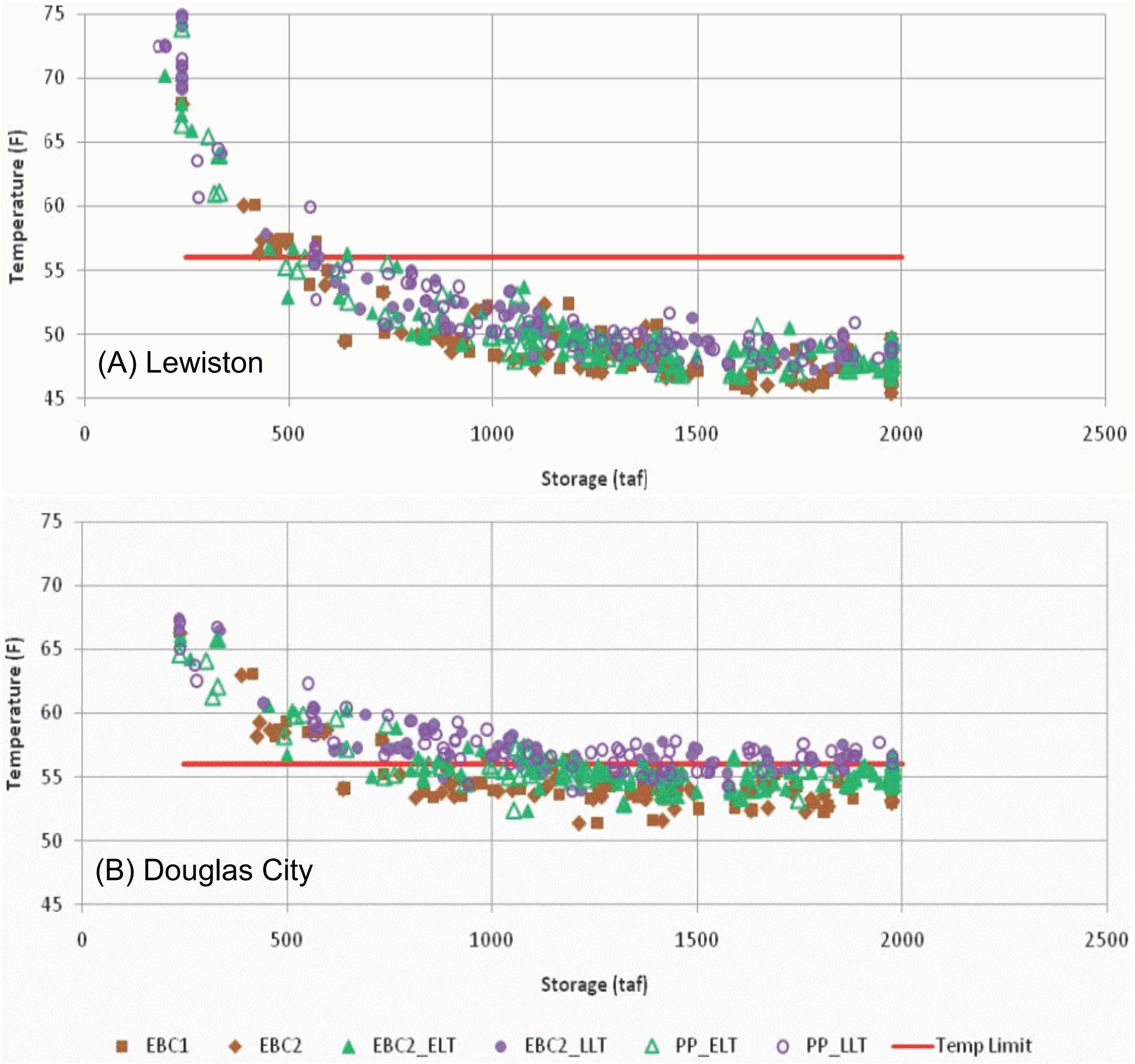


Figure 79. Mean September modeled Trinity Reservoir water storage for water years 1922–2010 and Trinity River water temperatures at (A) Lewison and (B) Douglas City for six scenarios evaluated in the California Water Fix/Bay Delta Conservation Plan. Figure adapted from CDWR and USBR (2016). EBC1 is the Existing Conditions CEQA baseline; EBC2 is the 2010 timeframe, EBC2_ELT is the 2025 timeframe, EBC2_LLT is the 2060 timeframe (and the NEPA No Action Alternative); PP_ELT is Alternative 1 for 2025; and PP_LLT is Alternative 1 for 2060. The three time frames are color coded: brown symbols for existing (2010) timeframe, green symbols for 2025 timeframe and purple symbols for 2060 timeframe.

7 DISCUSSION

The work presented in this synthesis report represents a detailed analysis of available and modeled data for the natural setting and effects from dam and reservoir features, management, weather, and climate on water temperatures in the Trinity River basin. Synthesizing this information is a necessary step in the adaptive management process to consolidate lessons learned, formulate new hypotheses, and prepare for future changes in climate, ecology, and human consumptive use. As has been established in this report and others, hydrology is a major driver of water temperature, and under current infrastructure constraints release magnitude and reservoir storage are the only tools available to manage Trinity River water temperature.

Trinity River hydrology has been fundamentally changed by dam operations since 1963 and the river's thermal landscape has been altered as a result (Figure 27, Figure 28, Figure 29). The lack of thermal range over seasons and decreased interannual variability at the release point (Sections 3.4.1.4 and 3.4.5.1) coupled with an impaired channel form likely limit productivity of salmonids in the restoration reach. The flow regime during the ROD era marked a vast improvement in reliable water quantity from the transitional and full diversion eras, helping to create and maintain physical habitat through geomorphic work and allowing predictable access to floodplain and off channel habitats, which would not have occurred in the absence of elevated ROD flows in spring. However, recommendations for water temperature were framed only to control warming and did not address issues surrounding release temperature and resulting temperature suppression.

At the time the ROD was being developed certain legal and administrative hurdles constrained technical expert's recommendations, such that management of the majority of water volume was limited to times of year with reduced uncertainty (J. Polos. Pers. Comm.). The authors of U.S Fish and Wildlife Service and Hoopa Valley Tribe (1999) recognized the importance of the timing of flows (e.g., Appendix O) and pushed to have adaptive management play a large role in determination of future management actions including environmental flow release. The ROD states that "*Based on subsequent monitoring and studies guided by the Trinity Management Council, the schedule for releasing water on a daily basis, according to that year's hydrology, may be adjusted but the annual flow volumes established in [the ROD] may not be changed*." However, Appendix C of the Trinity River Mainstem Fishery EIS specified a very structured approach to the annual dates and steps required to determine the water year type and resulting water volume required to schedule spring environmental flow releases, such that variable and elevated flow releases prior to April 22nd were not possible, other than for safety of dams.

As such, management implemented over the past 20 years resulted not only in an annual hydrograph that bore little resemblance to the historical flow regime, but it also resulted in further departure from the historical temperature regime (Figure 27). Focus was placed on meeting smolt outmigration temperatures at Weitchpec in spring, which resulted in significant cooling of the upper Trinity River (Figure 60). The high flows in spring months of May and June speed the movement of water from the cold depths of Trinity Reservoir through Lewiston Reservoir decreasing Lewiston Dam release temperatures, and as a result water temperature all the way down the Trinity River's full length. Decreases are most pronounced between Lewiston Dam and Burnt Ranch, attenuating in a downstream direction as ambient air temperatures and solar radiation warm the river longitudinally, and seasonally as flow releases from Lewiston Dam decline (Figure 29; Figure 41). This sharp decline in water temperatures, at a time when water temperatures in the Trinity River should naturally be increasing, and when water temperatures on all tributaries are increasing, likely created a suite of ecological problems throughout the Trinity River for salmonids, invertebrates, and wildlife (Sykes et al. 2009; Cairns et al. 2008; Armstrong and Schindler 2013; Watz and Piccolo 2010; Railsback et al. 2016 EPA 2001; McCullough 1999; Lusardi et al. 2019; Wheeler et al. 2015 and 2018; Catenazzi and Kupferberg 2013 and 2017; Ashton et al. 2015; Snover et al. 2015; Gresens 1997; Sweeney and Vannote 1984).

The alterations to the temperature regime of the Trinity River longitudinally and seasonally due to release temperature and flow management are exacerbated by the severely degraded river channel below Lewiston Dam. As we describe in Section 5, thermal heterogeneity allows ectothermic organisms like juvenile salmonids to choose water temperatures that maximize digestion rates and growth given their food intake (Brewitt and Danner 2014; Brewitt et al. 2017) or to seek refuge from warm summer temperatures where cold water pools (Nielsen et al. 1994; Brewitt and Danner 2014; and others). The exploration of the thermal heterogeneity in the lateral thermal dimension in Section 5.2.2 highlights how historical land use (i.e., mining) and damming and diversion have severely limited the range of temperatures present in the unrestored channel during spring when flows are elevated but cannot spread out on floodplains. Literature review also found observations in another Northern California watershed where elevated summer dam releases increased mixing and reduced the influence of cold-water sources (Yoshiyama and Moyle 2010). It is a plausible hypothesis that the ROD era flow regime diminished heterogeneity of water temperature further on seasonal and daily time scales (Section 5). If the river channel was restored and water temperatures varied more spatially, some negative impacts of temperature suppression may be able to be avoided by fish and wildlife. Juvenile salmonids could grow faster from April to July by seeking areas that maximize their growth, which could have significant survival benefits for smolts emigrating into the Lower Klamath River and Pacific Ocean. Larger size has been shown to convey survival advantages in juvenile salmonids (Irvine et al. 2013; Roni et al. 2012; Wilson et al. 2021). However, in the unrestored condition stream inhabitants are largely subjected to the mixed water temperatures provided by flow management and behavioral thermoregulation is limited.

7.1 CURRENT TRINITY RIVER WATER TEMPERATURE REGIME

After 20 years of management influenced by the 2000 ROD, we have sufficient data to evaluate the hypotheses that management recommendations were based on. The temperature related hypotheses from the Trinity River Flow Evaluation (Sections 1.4.2.1, 1.4.2.2, and 1.4.2.3) were associated with different components of the hydrograph (e.g., ascending limb). We evaluate hypothesis associated with each component for which they were presented.

7.1.1 ASCENDING LIMB OF SNOWMELT PEAK (APRIL 22 – MAY 24)

We reject the hypotheses that the timing of the ascending limb of the ROD spring hydrograph has no negative biological impacts and that it is ideal for salmonids, and instead support the alternative hypothesis that the timing and rate of increase of releases has negative impacts for salmonids and other wildlife (Section 1.4.2.1).

When environmental flows are released in spring in accordance with the ROD, natural warming of mainstem water temperatures are reduced by 3 to 4°C (Figure 45), depending on water year type (Figure 41; Figure 46). One of the most significant biological impacts occurs in salmonid rearing habitat upstream of Douglas City, where ROD-era spring temperatures are so cold they are rarely within the optimal range for juvenile salmonid growth (Section 4.2.1). In the 1978–1999 transitional era, temperatures reached the optimal temperature range in Douglas City approximately a month earlier and remained in the optimum range for a larger portion of April–July, although temperatures did exceed optimal more often than in the ROD era. That is, following implementation of the ROD, water temperatures in the upper Trinity River are far more frequently colder than the optimal growth range for salmonids during the spring juvenile rearing period than prior to the ROD. The reduction in temporal thermal variability, especially above the North Fork Trinity River, is likely at least problematic, if not growth limiting for all ectothermic species.

In general, rivers typically warm continuously in a downstream direction, with higher elevation smaller tributaries being cooler and a lower elevation higher order mainstem streams being warmer (Segura et al. 2015). The delay of warming in the seasonal dimension and change in rate of warming in the longitudinal dimensions compared to historical conditions likely send misleading thermal cues to migratory species about conditions downstream or in the tributaries (Figure 34 and Figure 35, and Section 5.1.2 and 5.2.1). Phenology and migration of temperate species are inextricably linked to day length in many instances and moderated by water temperature and other local factors (Helm et al. 2013). The potential negative effects on migrating juvenile salmonids from keeping the mainstem Trinity River colder than it would be otherwise, while temperatures increase in tributaries and the Lower Klamath River, are not well understood but raise concern about the possibility of setting up an ecological trap for downstream migrants.

The timing and rate of increase of releases also pose hazards to species and life stages susceptible to scour or inundation. For example, FYLF begin to breed and deposit egg masses after water temperatures reach 10 °C in the spring (Kupferberg 1996, Wheeler et al. 2015). During the ROD era, river temperatures frequently reach 10 °C (Figure 44, Figure 45) prior to spring releases that have magnitudes great enough to scour egg masses (Railsback et al. 2016). Delaying spring ROD releases until after spring warming has already occurred sends behavioral cues that promote an ecological trap because flow then unexpectedly (from the organism's perspective) increases at a later date, scouring FYLF egg masses and causing reproductive failure.

7.1.2 DESCENDING LIMB OF SNOWMELT PEAK (MAY 5 TO JULY 22)

We reject the hypothesis that the descending limb of the ROD spring releases maintains temperature in the optimal range for salmonids between Lewiston and Weitchpec. Instead, we find that it suppresses growth throughout much of the length of the river, isolating optimal temperatures to only near Weitchpec. In May of all water year types except for Critically Day and June of Extremely Wet water years growth potential is diminished (Figure 66). By increasing flows in earlier months and releasing lower magnitude in April and May of Dry and Critically Dry years and May and June of Normal and wetter years, growth potential could be improved (Figure 66). However, optimal temperatures are not present under normal reservoir storage levels in the upper most reaches near Lewiston Dam in any water year type at any time of year (Figure 64). The Trinity River Flow Evaluation hypothesized that an ability to adjust release temperatures (i.e., a multi-level outlet structure) would not appreciably change the amount of water needed to meet temperature requirements (e.g., provide cool water at Weitchpec for smolt outmigration) (Section 1.4.2.2), but did not recognize the detrimental effects of cold water on juvenile growth. To the contrary, based on current understanding, we suggest that large volume releases of warmer water made possible by selective withdrawal from Trinity Reservoir could maximize growth potential from Lewiston to Weitchpec during the primary rearing and outmigration period.

While hypotheses about gradual warming due to decreases in flow were correct, we find that this warming is delayed and out of sync with the rest of the basin. We hypothesize that this results in delayed life history cues, life stage transition, and/or reduced growth potential for fish and wildlife. Appendix O, Chapter 5 of USFWS and HVT (1999) claimed “spring and early summer water temperatures have become warmer throughout the Trinity River” but did not provide documentation to support that the Trinity River has become warmer in spring and early summer since construction of the TRD. Our new modeling suggests that previous evaluations by Rowell (1979) and Zedonis and Newcomb (1997) overestimated the amount of warming in the lower Trinity River in the spring caused by the dams/diversion, as shown in Section 3.4.1.4. The reach immediately below Lewiston Dam is substantially colder with the dam than it was pre-dam (Figure 30B), and that the increased spring releases since ROD implementation have expanded the length of the Trinity River that is now substantially colder than it was pre-dam (Figure 46, Figure 47, and Figure 64).

Many of the unknowns presented in Appendix O of the Trinity River Flow Evaluation, including “what are the thermal tolerances of Trinity River smolts?”, are still unknown or not clearly understood over 20 years later. A recent study conducted at the University of California, Davis may have found differences in disease resistance and temperature and salinity tolerance and smoltification between Chinook Salmon stocks within the Klamath Basin (Leah Mellinger, pers. comm.). More work is needed to understand how Klamath River conditions are affected by or align with Trinity River conditions during the outmigration period of different stocks and their thermal requirements and tolerances.

7.1.3 SUMMER/FALL BASEFLOW (JUNE 26 TO OCTOBER 15)

Most of the hypotheses associated with summer/fall baseflow should be assessed through evaluation of fish and fish population metrics and are therefore outside the scope of this report. At the time of this report’s drafting the adult, juvenile, and cohort reconstruction salmonid syntheses are being prepared. We did evaluate the ability of the 450 cfs baseflow to achieve the temperature criteria at Douglas City and the North Fork (Section 4.3.1). Since the 450 cfs summer baseflow was initiated in 1993 and continued under ROD implementation, exceedances of the Douglas City targets appear to have decreased but still occur (Figure 62). In recent drought years (2014 and 2015), exceedances of the North Fork targets were greater than were observed prior to ROD implementation (Figure 62). The benefit that 450 cfs provides adult salmon over 300 cfs at this time of year remains unquantified.

Unfortunately, the realization that the modeling tools currently available do not produce believable predictions of temperatures downstream from Lewiston Dam for flows below what they were calibrated to during summer months inhibited our ability to evaluate the Summer and Fall baseflow period. Additionally, the availability and familiarity with 3-D temperature modeling was not mature enough to include evaluation of alternative hypothesis associated with thermal stratification in this report. We reviewed literature and found evidence from another Northern California river system that elevated release from dams have the potential to discourage stratification (Section 5.1.3). A study currently being conducted will use 3-D hydrodynamic and water temperature models to estimate what flows would promote pool stratification in the Trinity River. Daily temperature range (i.e., the difference between daily minimum and daily maximum) of pool inflow is a key driver of pool stratification when there is not another source of cool water such as a tributary, hyporheic flow, or groundwater (Nielsen et al. 1994, Lucas et al. 2016), so a model such as RBM10 that only predicts daily mean temperature cannot be directly used as input for a 3-D pool stratification model. However, it may be possible to combine RBM10 predictions of daily mean with statistical estimates of daily range. This and similar efforts would benefit from recalibration of the RBM10 model to give more realistic predictions of longitudinal temperature under low discharge dam release scenarios.

The most important temperature issues associated with this hydrograph component are release temperatures from Trinity Reservoir and atmospheric warming in Lewiston Reservoir, neither of which received much attention in the Trinity River Flow Evaluation. These two factors pose significant risk to salmonid eggs present in the mainstem river during this period and extending into November (Figure 12 and Figure 14). The lack of ability to control release temperature at the main outlet works when Trinity River storage is below 1.25 MAF, and the exacerbation of this by atmospheric warming in Lewiston combine to create risk that persistent drought will result in water in excess of the thermal tolerance of salmonid eggs being released down the length of the Trinity River during Chinook and Coho Salmon spawning and incubation.

7.2 TRINITY RESERVOIR

7.2.1 STORAGE

The analyses presented in 3.3.1.2 and 6.3 illustrate how vulnerable the fisheries resources of the Trinity River are to multi-year drought under current management and infrastructure constraints. As draw down to storage of less than 1.25 MAF occurs, water temperatures in summer and fall at the main outlet works begin to increase rapidly (Figure 14). At storage less than approximately 0.75 MAF, meeting current temperature objectives becomes problematic (Figure 79). At storages less than 0.75 MAF, reliance on the auxiliary outlet at Trinity Dam becomes necessary to meet temperature objectives in fall to protect returning adult salmonids and their eggs. As recommended by Bender (2012), and as detailed in our Section 3.3.1.2 on carryover storage, 0.75 MAF end of September carryover storage should be considered a minimum storage level, below which the ability of Reclamation to protect returning adult salmonids in the Trinity River and Lower Klamath River comes into question. In 1976 and 1977, as well as 2014 and 2015, reservoir levels were low enough to make meeting temperature criteria problematic (Section 3.3.1.2). Had these droughts persisted for longer periods, providing cold water resources for the Trinity River and Lower Klamath River in subsequent summers would not have been possible, imperiling salmonids and other cold-water organisms.

Even the deepest, coldest parts of Trinity Reservoir have been warming over time (Section 3.3.1.2; Figure 11). This trend is expected to continue (Figure 79). Future human consumptive demands on Trinity Reservoir, combined with changes in climate including warming and increased evaporation will lead to lower end of September reservoir storage in the future (Figure 78). Without robust protections on minimum end of September storage levels, combined with hedging against the inevitability of multi-year droughts, the cold-water resources in Trinity Reservoir could be completely exhausted in the future. If reconfiguration of Lewiston Reservoir utilizing one or more of the methods outlined in Reclamation (2012) were pursued, the heat gain in Lewiston Reservoir (Section 3.3.2.2) could be eliminated or minimized which would reduce temperatures released from Lewiston Reservoir in late summer and fall. This would help ameliorate the effects of climate change in the future and have substantial biological benefits not just to the Trinity River but also the Trinity and Sacramento rivers because the Trinity River water diverted to Clear Creek and the Sacramento River is often warmer than desired.

7.2.2 INFRASTRUCTURE

The infrastructure of the Trinity River Division is approximately 60 years old and was not designed with the knowledge or intent to meet the complex needs of the Trinity River downstream. Natural aging of dam, conveyance, and reservoir machinery has created difficulties in meeting some objectives at certain times of the year or necessitated higher or lower flows than desired. Additionally, daily flow fluctuations used to mimic natural snowmelt and hydrologic patterns stressed mechanical components of the TRD like electrical motors and hydraulic valves. In April of 2019, a leak in a hollow jet valve in Trinity Dam resulted in hydraulic fluid being released to Lewiston Reservoir, requiring containment booms and oil spill response. Diel flow variability was also discontinued due to the failure of electrical motors that lift radial release gates at Lewiston Dam. Maintenance of the Carr tunnels has at times limited the capacity to divert water to the central valley, which can impact temperatures in the Trinity River by slowing flow through Lewiston Reservoir. Significant resources are needed to repair and upgrade aging infrastructure so that the TRD can meet all the requirements of its authorizations and permits to have an ecologically intact and productive ecosystem in the Trinity River.

Selective withdrawal was hypothesized to have limited benefit at the time of the Trinity River Flow Evaluation, but as science has progressed in the past two decades the importance of seasonally warm habitats to the growth of juvenile salmonids has become more recognized (Armstrong et al. 2021, Lusardi et al. 2019). In Section 5.1.2.2 we demonstrate how no hypothetical water management using current infrastructure can result in the entire length of the Trinity River below Lewiston Dam being at or near optimal temperatures for salmonid growth in May of Dry and Critically Dry years and June of Normal and wetter years, as would have been present prior to the dam and diversion (i.e., our no-dam unimpaired flow scenario). Selective withdrawal could allow for large volumes of water at or near the optimal range for growth to be released at this critical time of year. The volume of water would resist atmospheric warming and provide optimal temperatures between Lewiston Dam and Weitchpec.

7.3 CLIMATE CHANGE

In the face of climate change, it is possible that Spring Chinook Salmon, steelhead, and Coho Salmon could be extirpated from the mainstem Trinity River without the cold-water resources of Trinity Reservoir or increased access to their historical high elevation habitats above the Dam. Climate change severity is affected by the amount of greenhouse gas buildup in the Earth’s atmosphere. Snowpack is likely to decline substantially as air temperatures rise (Micheli et al. 2018). For example, under a high-emissions scenario, average snow water equivalent in areas above 3,000 ft elevation is predicted to decline from 11.6 inches in 1981–2010 to 4.3 inches in 2040–2069 and 1.6 inches in 2070–2099 (Micheli et al. 2018). The combination of more rain, less snow, and earlier snowmelt will cause earlier runoff and lower flows in spring and summer (CDWR and USBR 2016, Mote et al. 2014) (Figure 76, Figure 77, Section 6.1). The date by which 50% of annual runoff has occurred is predicted to shift 9–42 days (varies by site scenario) earlier in the 2070s (USBR 2016). In the mainstem Trinity River, but not the tributaries, these changes will be somewhat ameliorated by capturing runoff in Trinity Reservoir.

Water temperatures in the Trinity River and its tributaries are highly affected by river flow in the spring and summer (Figure 7, Figure 27) so are likely to rise substantially. Based solely on rising air temperatures, not including hydrologic effects (which as noted in the previous sentence are likely to be strong), water temperatures at several sites in the Trinity River Basin are predicted to increase 0.6–1.3°C (Flint and Flint 2012). In the adjacent Salmon River watershed, mean daily maximum August stream temperatures are predicted to be warmer than the 1990–2017 baseline by 0.9–2.0°C under the reduced-emission RCP4.5 scenario or 1.7–3.3°C under the high-emission

RCP8.5 scenario, depending on the reach, with larger rivers warming more than small streams (Asarian et al. 2019).

Storage in Trinity Reservoir is expected to be substantially impacted by climate change in the future with both lower end of September storage volumes (Figure 78; Section 6.1) and warmer release temperatures (Figure 79; Section 3.3.1.2). Greater emphasis will need to be placed on conserving the cold-water pool in Trinity Reservoir, much like is currently adopted in Shasta Reservoir management. A temperature control device could help maximize the conservation of the cold-water pool within Trinity Reservoir by utilizing surface waters during the times of the year when cold releases from the reservoir hypolimnion are not required. The increased flexibility and control provided by selective withdrawal would reduce mixing of stratified waters, and aid in a more nuanced approach to temperature management that could allow water temperatures to increase naturally in the spring to benefit juvenile salmonid growth, and then provide access to colder water in the fall to protect returning adult salmonids.

8 RECOMMENDATIONS

In order to have the greatest chances of meeting the goals of the TRRP, particularly with current and future effects of climate change, a much more nuanced approach to temperature management needs to be employed. The era of point compliance by simply not exceeding a water temperature threshold can serve the needs of each life stage of highly complex animals (e.g., salmonids, FYLF, etc.) in a dynamic river ecosystem should be over. As discussed above, this is an overly simplistic approach to river management which may make assessing the regulatory compliance easy but has resulted in protecting returning adults largely at the expense of juvenile salmonid growth and the productivity of their food. Temperature objectives for juvenile growth in the spring should be considered as being within a range or band of optimal, not just as being “less than” some maximum, and methods for assessing the prevalence of these temperatures over stream length should be pursued rather than point compliance. In the short term, we recommend shifting a large percentage of ROD water from May and June into the winter months to address the immediate concern of suppressed growth within current infrastructure constraints. In the pre-dam dataset from 1912 to 1960, the average date at which 50% of the flow of the Trinity River passed Lewiston was April 7. From 2001 to 2022, the average date at which 50% of the flow of the Trinity River passed Lewiston was May 15, five weeks later in the calendar year. Management should aspire to bring this apportionment of annual water volume into a more natural distribution to aid in the riverine ecological process, and consider the impacts of release temperatures in the absence of selective withdrawal from Trinity Reservoir.

In order for Trinity Reservoir to better meet all the varied requirements of water temperature for river health, including juvenile growth in the spring, while maximizing the preservation of the cold-water pool in the face of not only climate change, but also extended periods of drought, significant resources need to be focused on improving infrastructure of the Trinity River Division. Specifically, we recommend installing a temperature control device in Trinity Reservoir, so that water can be utilized from various elevations within the reservoir, combined with a new conveyance system in, or around Lewiston Reservoir, or removal of Lewiston Reservoir as described in (Bender 2012). This would also have water temperature benefits to the Sacramento River systems allowing more control over the water temperature conveyed to Whiskeytown Reservoir, Keswick Reservoir and Clear Creek.

While the 450 cfs released from Lewiston Dam in summer provides habitat for spring Chinook Salmon adults, it is possible that a lesser flow level could provide a similar amount of deep, cold water habitat. This is possible because lower discharges decrease turbulent mixing in pools that may stratify with colder water held in the bottom of pools for spring Chinook Salmon holding. This possibility is currently being evaluated by the TRRP and would allow a more natural flow level in the summer months of drought years in the Trinity River, allowing more water allocation for environmental flows to meet other unmet needs. Restoring the structural complexity of channel and floodplain habitats would also promote processes such as hyporheic flow that provide cold water sources and opportunities for stratification. Even without pool stratification, cold dam releases will always provide some length of river downstream of Lewiston where temperatures are suitable for spring-run Chinook Salmon adults, regardless of discharge magnitude (i.e., lower summer flows may reduce that length but not to zero).

The Trinity River downstream of Lewiston Dam must now serve all of the ecological functions that it has done since time immemorial, plus all those served by the 109 miles of habitat upstream of Lewiston dam prior 1963. We do not recommend a return to pre-dam water temperature levels downstream of Lewiston Dam as this does not necessarily serve the latter. Instead, we recommend a more nuanced approach to water temperature objectives where temperatures are allowed to warm more naturally in the spring and stay within the recommended band of optimal juvenile growth during the time that juvenile rearing is of utmost importance, and when the Trinity River should be warming, May to July. Beginning in July, the focus for water temperature objectives would then be placed on protection of returning adults (including spawning and incubation), and managers could use tools at their disposal to help manage water temperatures, prioritizing adult returns at that time of year.

A summary of specific recommendations are as follows:

1. Monitor temperatures in the Trinity River upstream of Trinity Reservoir to better understand the natural temperature regime and its effects on water temperatures in Trinity Reservoir.
2. Flows in spring should recede beginning in April of Dry and Critically Dry water years and May of Normal and wetter water years to provide water temperatures in the Trinity River upstream of the North Fork Trinity River within the range that provides optimal juvenile salmonid growth at outmigration (13–16.5 °C).
3. Reduced emphasis on meeting ROD temperature targets for smoltification at Weitchpec. Instead, the goal should be a balance between growth, encouraging timely outmigration, and mitigating temperatures in the lower river that approach the thermal limits of juvenile salmonids.
4. Infrastructure of the TRD should be modified to enable finer flow and temperature management to be implemented for the benefit of the river ecosystem, including:
   a. Installation of a multi-level temperature control device in Trinity Reservoir;
   b. Removal of Lewiston Dam or construction of a new type of conveyance through or around Lewiston.
5. For Trinity Reservoir, an end of September storage minimum of 0.75 million acre-feet (MAF) should be adhered to following the recommendations of Bender (2012). This should be coupled with a multi-year drought contingency plan that specifies steps taken

when reservoir storage is predicted to be less than 1.25 MAF in any year, assuming a multi-year drought is possible at any time.

6. An assessment of multiyear drought effects on Trinity Reservoir storage levels, water temperatures, and the resulting ability to meet temperature criteria in the Trinity River should be conducted.
7. Development of a modeling tool for accurately predicting Trinity River water in summer at flows lower than RBM10's current lower limit of around 350 cfs.
    a. Given that RBM10 is the tool currently used by TRRP to evaluate the thermal performance of potential annual hydrographs, a logical choice would be to re-calibrate RBM10 to make plausible predictions at lower flows. Based on our recommendations, USBR and USGS have begun updating RBM10 to provide this functionality, scheduled for completion in 2023.
    b. An alternative approach would be to develop a statistical model, but the existing temperature records between Lewiston Dam and the North Fork may not have enough days of low flows for sufficient calibration.
8. Channel rehabilitation efforts should include promotion of thermal diversity as an explicit goal. Thermally complex features such as floodplain ponds, alcoves, side channels, and beaver-influenced habitats increase the range of temperatures available to aquatic biota and may increase resiliency to climate change.

9 REFERENCES

Note: some references listed here are only cited in the appendices. A separate reference list is not provided for the appendices.

Ahearn, D.S., J.H. Viers, J.F. Mount, and R.A. Dahlgren. 2006. Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across a restored floodplain. Freshwater Biology. 51: 1417-1433.

Alvarez, J., A. Hilton, J. Bair, G. Hales, S. McBain, D. Goodman, J. Polos, and A. Martin. 2011. Integrated Habitat Assessment of the Upper Trinity River, 2009, Draft Report. Hoopa Valley Tribe, United States Fish and Wildlife Service, Arcata Fish and Wildlife Office, and Yurok Tribe.

Anderson, T. 2008. Inferring bedrock uplift in the Klamath Mountains Province from river profile analysis and digital topography. Master's Thesis. Texas Tech University, Lubbock, TX.

Anderson, J.J., Beer, W.N., Israel, J.A. and Greene, S., 2022. Targeting river operations to the critical thermal window of fish incubation: Model and case study on Sacramento River winter-run Chinook salmon. River Research and Applications, 38(5), pp.895-905. https://doi.org/10.1002/rra.3965

Armour, C.C. 1991. Guidance for evaluating and recommending temperature regimes to protect fish. U.S. Fish and Wildlife Service Biological Report 90(22). 13pp.

Asarian, J.E. 2016. Stream Temperatures in the South Fork Trinity River Watershed 1989-2015. Prepared by Riverbend Sciences for The Watershed Research and Training Center, Hayfork, CA. 61p. + appendices. http://www.trrp.net/library/document/?id=2302

Asarian, J.E. 2017. GIS Stream Temperature Modeling of Yurok Ancestral Territory. Prepared by Riverbend Sciences for the Yurok Tribe Environmental Program, Klamath, CA. 39 p. https://drive.google.com/open?id=0B2p7GuVSL4OXUEQ4Q0xjTno2bGc

Asarian, E., J. Kann, and W. Walker, 2009. Multi-year Nutrient Budget Dynamics for Iron Gate and Copco Reservoirs, California. Prepared by Riverbend Sciences, Kier Associates, Aquatic Ecosystem Sciences, and William Walker for the Karuk Tribe Department of Natural Resources, Orleans, CA. 55pp + appendices. https://klamathwaterquality.com/documents.html

Asarian, E. and J. Kann. 2013. Synthesis of Continuous Water Quality Data for the Lower and Middle Klamath River, 2001-2011. Prepared by Kier Associates and Aquatic Ecosystem Sciences for the Klamath Basin Tribal Water Quality Work Group. 50p. + appendices. http://www.trrp.net/library/document/?id=2302

Asarian, J.E., L. Cressey, B. Bennett, J. Grunbaum, L. Cyr, T. Soto. 2019. Evidence of Climate-Driven Increases in Salmon River Water Temperatures. Prepared for the Salmon River Restoration Council by Riverbend Sciences with assistance from the Salmon River Restoration Council, Klamath National Forest, Six Rivers National Forest, and Karuk Tribe Department of Natural Resources. 53 p. + appendices

Asarian, J.E., L. Cressey, B. Bennett, J. Grunbaum, L. Cyr, T. Soto, C. Robinson. 2020. Influence of Snowpack, Streamflow, Air Temperature, and Wildfire Smoke on Klamath Basin Stream Temperatures Including Long-Term Trends, 1995-2017. Prepared for the Klamath Tribal Water Quality Consortium by Riverbend Sciences with assistance from the Salmon River Restoration Council, Klamath National Forest, Six Rivers National Forest, Karuk Tribe Department of Natural Resources, and Quartz Valley Indian Reservation. 44 p. + appendices.

Asarian, J. E., C. Robinson, C., and L. Genzoli. 2023. Modeling Seasonal Effects of River Flow on Water Temperatures in an Agriculturally Dominated California River. Water Resources Research, 59(3), e2022WR032915. https://doi.org/10.1029/2022WR032915

Ashton, D.T., J.B. Bettaso, and H.H. Welsh Jr. 2015. Changes across a decade in size, growth, and body condition of Western Pond Turtle (*Actinemys marmorata*) populations on free-flowing and regulated forks of the Trinity River in northwest California. Copeia 103(3): 621-633. Doi 10.1643/CP-15-253. http://www.trrp.net/library/document/?id=2247

Armstrong, J.B. and D.E. Schindler. 2013. Going with the Flow: Spatial Distributions of Juvenile Coho Salmon Track an Annually Shifting Mosaic of Water Temperature. Ecosystems. 16: 1429-1441

Armstrong, J.B., A.H. Fullerton, C.E. Jordan, J.L Ebersole, J.R. Bellmore, I. Arismendi, B.E. Penaluna, and G.H. Reeves. 2021. The Importance of warm habitat to the growth regime of cold-water fishes. Nature Climate Change. https://doi.org/10.1038/s41558-021-00994-y

Baldock, J.R., J.B. Armstrong, D.E. Schindler, and J.L. Carter. 2016. Juvenile coho salmon track a seasonally shifting thermal mosaic across a river floodplain. Freshwater Biology, 61(9), 1454–1465. https://doi.org/10.1111/fwb.12784

Barajas, F. (2016) Letter to David Murillo (Bureau of Reclamation) dated March 24, 2016 about carryover storage for Trinity Reservoir. Trinity River Restoration Program, Trinity Management Council, Weaverville, California.

Bartholomew, J. 2011. Long-Term Fish Disease Monitoring Program in The Lower Klamath River: Final 3-Year Report on Cooperative Agreement R09AC20022, Cooperative Ecosystems Study Unit 3FC810873 (Federal Fiscal Years 2009-2011). Department of Microbiology, Oregon State University.

Bartholow, J.M. 2005. Recent Water Temperature Trends in the Lower Klamath River, California. North American Journal of Fisheries Management 25:152–162.

Bartholow, J.M., J. Heasley, B. Hanna, J. Sandelin, M. Flug, S. Campbell, J. Henriksen, and A. Douglas. 2005. Evaluating Water Management Strategies with the Systems Impact Assessment Model: SIAM Version 4. Revised October 2005. U.S. Geological Survey, Fort Collins Science Center Open File Report 03-82. Fort Collins, Colorado. 133 pp. http://pubs.er.usgs.gov/publication/ofr0382.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software, 67(1), 1-48. Doi:10.18637/jss.v067.i01.

Beauchamp, D. 2009. Bioenergetic Ontogeny: Linking Climate and Mass-Specific Feeding to Life-Cycle Growth and Survival of Salmon. American Fisheries Society Symposium 70.

Beacham, T.D., and Murray, C.B. 1990. Temperature, Egg Size, and Development of Embryos and Alevins of Five Species of Pacific Salmon: A Comparative Analysis. Transactions of the American Fisheries Society, 119(6), 927–945. https://doi.org/10.1577/1548-8659(1990)119<0927:TESADO>2.3.CO;2

Bedell, G.W. 1969. Annual report, Trinity River salmon and steelhead hatchery eleventh year of operation, 1968-69. Anadromous Fisheries Administrative Report No. 70-5.

Bedell, G.W. 1991. Annual report, Trinity River salmon and steelhead hatchery, 1990-91. Inland Fisheries Administrative Report No. 91-17.

Beesley S. and R. Fiori. 2007. Lower Klamath River Tributary Delta and Subsurface Flow Study, Lower Klamath River Sub-basin, California. Yurok Tribal Fisheries Program, Klamath, CA. http://www.trrp.net/library/document/?id=2123

Belchik, M. 1997. Summer Locations and Salmonid Use of Cool Water Areas in the Klamath River: Iron Gate Dam to Seiad Creek, 1996. Yurok Tribal Fisheries Program. Klamath, CA. http://www.krisweb.com/biblio/klamath_ytfp_belchik_1997_refugia.pdf

Belchik, M. 2003. Use of Thermal Refugial Areas on the Klamath River by Juvenile Salmonids; Summer 1998. Yurok Tribal Fisheries Program Technical Report.

Belchik, M., D. Hillemeier, and R. M. Pierce. 2004. The Klamath River fish kill of 2002; analysis of contributing factors. Final Report, Yurok Tribal Fisheries Program.

Bender M.D. 2012. Trinity Reservoir Carryover Storage Cold Water Pool Sensitivity Analysis. Technical Memorandum No. 86-68220-12-06, U.S. Bureau of Reclamation, Technical Service Center, Denver, CO. http://www.trrp.net/library/document/?id=1813

Benyahya, L., D. Caissie, A. St-Hilaire, T.B.M.J. Ouarda, and B. Bobée. 2007. A Review of Statistical Water Temperature Models. Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques 32:179–192. Doi: 10.4296/cwrj3203179.

Benson R. and J. Holt. 2005. Daytime use of the Red Cap Creek thermal refuge by juvenile steelhead and Chinook salmon in the Klamath River, August 2005. Technical report KR-06-01. Yurok Tribal Fisheries Program, Hoopa, CA. http://www.trrp.net/library/document/?id=2125

Bodeker, G.E., I.S. Boyd, and W.A. Matthews. 1998. Trends and Variability in Vertical Ozone and Temperature Profiles Measured by Ozonesondes at Lauder, New Zealand: 1986–1996. Journal of Geophysical Research: Atmospheres 103:28661–28681. Doi: 10.1029/98JD02581.

Boles, G.L. (1979) Macroinvertebrate Colonization of Replacement Substrate Below a Hypolimnial Release Reservoir. Report from the Department of Water Resources Northern District. http://www.trrp.net/library/document/?id=1589

Boles, G.L. 1981. Macroinvertebrate Colonization of Replacement Substrate below a Hypolimnial Release Reservoir. Hydrobiologia 78:133–146. Doi: 10.1007/BF00007587. http://www.trrp.net/library/document/?id=1739

Boles, G. L. 1985 Water Temperature Control in Lewiston Reservoir for Fishery Enhancement at the Trinity River Hatchery in Northern California. Report from the California Department of Water Resources. http://www.trrp.net/library/document/?id=1638

Boles, G. L. 1987 Results of Further Monitoring of Water Temperature Control for Fishery Enhancement at Lewiston Reservoir and Hatchery. Report from the California Department of Water Resources Northern District. http://www.trrp.net/library/document/?id=1590

Boles, G.L. 1988. Water temperature effects on Chinook salmon (*Oncorhynchus tshawytscha*) with an emphasis on the Sacramento River – A literature review. California department of Water Resources publication, Northern District.

Boles, G L 1990. Food habits of juvenile wild and hatchery steelhead trout, *Oncorhynchus mykiss*, in the Trinity River, California. Inland Fisheries Administrative Report No. 90-10. Department of Water Resources, Red Bluff, California. https://www.trrp.net/library/document/?id=589

Boughton, D. A., L.R. Harrison, A.S. Pike, J.L. Arriaza, and M. Mangel. 2015. Thermal Potential for Steelhead Life History Expression in a Southern California Alluvial River. Transactions of the American Fisheries Society, 144(2), 258–273. https://doi.org/10.1080/00028487.2014.986338

Bradley, D.N. 2018. Trinity River 40 mile hydraulic model: update with 2016 Topography. USBR Technical Services Center, Technical Report SRH-2018-11, Denver, CO, http://www.trrp.net/library/document/?id=2359.

Brewitt, K.S. and E.M. Danner. 2014. Spatio-Temporal Temperature Variation Influences Juvenile Steelhead (*Oncorhynchus mykiss*) Use of Thermal Refuges. Ecosphere 5: art 92. Doi: 10.1890/ES14-00036.1.

Brewitt, K.S. 2014. Environmental Heterogeneity Mediates Juvenile Salmonid Use of Thermal Refuges. PhD Dissertation in Ecology and Evolutionary Biology, University of California, Santa Cruz, CA. http://escholarship.org/uc/item/46c3h0zz

Brewitt, K.S., E.M. Danner, and J.W. Moore. 2017. Hot Eats and Cool Creeks: Juvenile Pacific Salmonids Use Mainstem Prey While in Thermal Refuges. Canadian Journal of Fisheries and Aquatic Sciences 74:1588–1602. Doi: 10.1139/cjfas-2016-0395.

Brett, J.R. 1952. Temperature Tolerance in Young Pacific Salmon, Genus *Oncorhynchus*. Journal of the Fisheries Research Board of Canada, 9(6), 265–323. https://doi.org/10.1139/f52-016

Brett, J. R. 1971. Energetic Responses of Salmon to Temperature. A Study of Some Thermal Relations in the Physiology and Freshwater Ecology of Sockeye Salmon (Oncorhynchus nerka). American Zoologist, 11(1), 99–113. https://doi.org/10.1093/icb/11.1.99

Brett, J. R., W.C. Clarke, and J.E. Shelbourn. 1982. Experiments on thermal requirements for growth and food conversion efficiency of juvenile chinook salmon *Oncorhynchus tshawytscha*. Can. J. Tech. Rep. Fish. Aquat. Sci., 1127, 29.

Buffington, J., C. Jordan, M. Merigliano, J. Peterson, and C. Stalnaker. 2014. Review of the Trinity River Restoration Program following Phase 1, with emphasis on the Program's channel rehabilitation strategy. Prepared by the Trinity River Restoration Program's Science Advisory Board for the Trinity River Restoration Program with assistance from Anchor QEA, LLC, Stillwater Sciences, BioAnalysts, Inc., and Hinrichsen Environmental Services. http://www.trrp.net/library/document/?id=2172

Butz, R.J., S. Sawyer, and H. Safford. 2015. A Summary of Current Trends and Probable Future Trends in Climate and Climate-Driven Processes for the Shasta-Trinity National Forests and Surrounding Lands. US Department of Agriculture. USFS Pacific Southwest Region. https://www.researchgate.net/profile/Ramona_Butz/publication/274960800_A_summary_of_current_trends_and_probable_future_trends_in_climate_and_climate-driven_processes_for_the_Shasta-Trinity_National_Forest_and_surrounding_lands/links/552d86fc0cf21acb09217757.pdf

Buxton, T.H. 2019. Trinity River water allocation, temperatures, and model results for the implemented flows and proposed hydrographs for water year 2018. Report TR-TRRP-2019-1 for the Trinity River Restoration Program (TRRP). TRRP, Weaverville, California. Available: http://www.trrp.net/library/document?id=2438.

Buxton, T.H. 2020. Trinity River water allocation, temperatures, and model results for implemented flows and proposed hydrographs for water year 2019. Technical Report TR-TRRP-2019-2. Trinity River Restoration Program, Weaverville, CA. Available at http://www.trrp.net/library/document/?id=2459.

Buxton, T.H., Y. Lai, N.A. Som, E. Peterson, and B. Abban. 2022. The Mechanics of Diurnal Thermal Stratification in River Pools: Implications for Water Management and Species Conservation [Preprint]. Preprints. https://doi.org/10.22541/au.165713225.50653364/v1

Caissie, D. 2006. The Thermal Regime of Rivers: A Review. Freshwater Biology 51:1389–1406. Doi: 10.1111/j.1365-2427.2006.01597.x.

California Department of Water Resources. 1965. Bulletin No. 130-63. Hydrologic Data: 1963, Volume 1: North Coastal Area. California Department of Water Resources, Sacramento, CA. https://archive.org/details/hydrologicdata19113063calirich

California Department of Water Resources. 1957. Bulletin No. 65. Quality of Surface Waters in California 1955-1956. California Department of Water Resources, Sacramento, CA. https://cadwr.app.box.com/v/wdl-historical-publications/file/675028994833

California Department of Fish and Game (CDFG). 1992a. Annual report, Trinity River basin salmon and steelhead monitoring project, 1989 - 1990 season. Report to the U.S. Bureau of Reclamation. http://www.trrp.net/library/document/?id=1267

California Department of Fish and Game (CDFG). 1992b. Annual report, Trinity River basin salmon and steelhead monitoring project, 1990 - 1991 season. Report to the U.S. Bureau of Reclamation. http://www.trrp.net/library/document/?id=1268

California Department of Fish and Game (CDFG). 1994. Annual report, Trinity River basin salmon and steelhead monitoring project, 1991 - 1992 season. Report to the U.S. Bureau of Reclamation. http://www.trrp.net/library/document/?id=1269

California Department of Fish and Game (CDFG). 1995. Annual report, Trinity River basin salmon and steelhead monitoring project, 1992 - 1993 season. http://www.trrp.net/library/document/?id=1279

California Department of Fish and Game (CDFG). 1996a. Annual report, Trinity River basin salmon and steelhead monitoring project, 1993 - 1994 season. http://www.trrp.net/library/document/?id=1278

California Department of Fish and Game (CDFG). 1996b. Annual report, Trinity River basin salmon and steelhead monitoring project, 1994 - 1995 season. Report to the U.S. Bureau of Reclamation. http://www.trrp.net/library/document/?id=1280

CRWQCB-NCR. 1994. Water Quality Control Plan for the North Coast Region. Santa Rosa, CA. http://www.krisweb.com/biblio/ncc_swrcb_ncrwqcb_1994_wqcontrolplan.pdf

California Water Regional Quality Control Board. 1991. Public Report on Proposed Action to Amend the Water Quality Control Plan for the North Coast Region to Include a Site-Specific Temperature Objective and an Interim Action Plan for the Trinity River. http://www.trrp.net/library/document/?id=1587

California Department of Water Resources (CDWR) and U.S. Bureau of Reclamation (USBR). 2016. Final Environmental Impact Report/Environmental Impact Statement for the Bay Delta Conservation Plan/California WaterFix— Chapter 29 – Climate Change. Final EIR/EIS for the BDCP/California WaterFix. December. (DOE/EIS-0515.) (ICF 00139.14.) Prepared by ICF International, Sacramento, CA. https://web.archive.org/web/20190425043442/http://baydeltaconservationplan.com/FinalEIREIS/FinalEIR-EIS_VolumeI.aspx

California Department of Water Resources. .1978. Trinity River Hatchery Water Temperature Structure Operation (September 1975-May 1978). http://www.trrp.net/library/document/?id=1621

Carter, K. 2005. The effects of temperature on Steelhead Trout, Coho Salmon, and Chinook Salmon biology and function by life stage, implications for Klamath Basin TMDLs. California Regional Water Quality Control Board – North Coast Region (CRWQCB-NCR), Santa Rosa, CA. https://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls/shasta_river/060707/28appendixaetheeffectsoftemperatureonsteelheadtroutcohosalmonandchinooksalmonbiologyandfunction.pdf

Cai, H., S. Piccolroaz, J. Huang, Z. Liu, F. Liu, and M. Toffolon. 2018. Quantifying the impact of the Three Gorges Dam on the thermal dynamics of the Yangtze River. Environmental Research Letters, 13(5), 054016. https://doi.org/10.1088/1748-9326/aab9e0

Cairns, D.K., A.J. Gaston, and F. Huettmann. 2008. Endothermy, ectothermy and the global structure of marine vertebrate communities. Marin Ecology Progress Series. 365:239-250. https://doi.org/10.3354/meps07286

Catenazzi, A. and S.J. Kuperberg. 2013. The importance of thermal conditions to recruitment success in stream-breeding frog populations distributed across a productivity gradient. Biological Conservation. 168: 40-48. http://dx.doi.org/10.1016/j.biocon.2013.09.010

Catenazzi, A. and S.J. Kuperberg. 2017. Variation in thermal niche of a declining river-breeding frog: From counter-gradient responses to population distribution patterns. Freshwater Biology. 2017; 1-11. http://doi.org/10.1111/fwb.12942

Cayan, D.R., D.W. Pierce, J.F. Kalansky. 2018. Climate, Drought, and Sea-level Rise Scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment, California Energy Commission. Report number: CCCA4-CEC-2018-006.

Chan, J.R. and M. Longenbaugh. 1994. Progress Report for Investigations on Blue Creek, FY 1992. US Fish and Wildlife Service, Coastal California Fishery Resource Office, Arcata, California. http://cahatcheryreview.com/wp-content/uploads/2012/08/Blue-Cr-salmonid-assess_1992.pdf.

Chandler, G.L., S.P. Wollrab, D.L. Horan, D.E. Nagel, S.L. Parkes, D.J. Isaak, S.J. Wenger, E.E. Peterson, J.M. Ver Hoef, S.W. Hostetler, C.H. Luce, J.B. Dunham, J.L., Kershner, B.B. Roper. 2016. NorWeST stream temperature data summaries for the western U.S. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0032.

Chiaramonte, L.V., R.A. Ray, R.A. Corum, T. Soto, S.L. Hallett, and J.L. Bartholomew. 2016. Klamath River Thermal Refuge Provides Juvenile Salmon Reduced Exposure to the Parasite Ceratonova shasta. Transactions of the American Fisheries Society, 145(4), 810–820. https://doi.org/10.1080/00028487.2016.1159612

Clinton, P.L., S.J. Ricker, C.R. Shaughnessy and B. Jong. 1998a. 1998 field sampling, Beaver Creek (Siskiyou County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 7 p.

Clinton, P.L., S.J. Ricker, C.R. Shaughnessy and B. Jong. 1998b. 1998 field sampling, Horse Creek (Siskiyou County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 9 p.

Clinton, P.L., S.J. Ricker, C.R. Shaughnessy and B. Jong. 1998c. 1998 field sampling, Horse Linto Creek (Humboldt County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 5 p.

Clinton, P.L., S.J. Ricker, C.R. Shaughnessy and B. Jong. 1998d. 1998 field sampling, Humbug Creek (Siskiyou County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 6 p.

Clinton, P.L., S.J. Ricker, C.R. Shaughnessy and B. Jong. 1998e. 1998 field sampling, Indian Creek (Trinity County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 8 p.

Clinton, P.L., S.J. Ricker, C.R. Shaughnessy and B. Jong. 1998f. 1998 field sampling, Madden Creek (Humboldt County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 9 p.

Clinton, P.L., S.J. Ricker, C.R. Shaughnessy and B. Jong. 1998g. 1998 field sampling, Sharber Creek (Trinity County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 20 p.

Connell-Buck, C.R., J. Medellín-Azuara, J.R. Lund, and K. Madani. 2011. Adapting California's Water System to Warm vs. Dry Climates. Climatic Change 109:133–149. Doi: 10.1007/s10584-011-0302-7.

Cordero, E.C., W. Kessomkiat, J. Abatzoglou, and S.A. Mauget. 2011. The Identification of Distinct Patterns in California Temperature Trends. Climatic Change 108:357–382. Doi: 10.1007/s10584-011-0023-y.

Cox, N.J. 2006. Speaking Stata: In Praise of Trigonometric Predictors. The Stata Journal: Promoting Communications on Statistics and Stata 6:561–579. Doi: 10.1177/1536867X0600600408.

Craig, J. 1991. Annual report, Klamath River fisheries assessment program, Klamath River basin juvenile salmonid fisheries investigation, 1989. Report No. AFF-1 FRO 91-3, U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1497

Craig, J. L. 1992. Annual report, Klamath River fisheries assessment program juvenile salmonid trapping on the mainstem Trinity River at Willow Creek and on the Klamath River at Big Bar, 1990. Report No. AFF-1-FRO-92-13, U.S. Fish and Wildlife Service, Arcata, CA http://www.trrp.net/library/document/?id=1496

Cross, W.F., C.V. Baxter, K.C. Donner, E.J. Rosi-Marshall, T.A Kennedy, R.O. Hall, Jr., H.A. Wellard Kelly, and R.S. Rogers. 2011. Ecosystem ecology meets adaptive management: food web response to a controlled flood on the Colorado River, Glen Canyon. Ecological Applications. 21(6):2016-2033

Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.P. Pasteris. 2008. Physiographically Sensitive Mapping of Climatological Temperature and Precipitation across the Conterminous United States. International Journal of Climatology. 28:2031–2064. Doi: 10.1002/joc.1688.

Daniels, M. E., and E.M. Danner. 2020. The Drivers of River Temperatures Below a Large Dam. Water Resources Research, 56(5), e2019WR026751. https://doi.org/10.1029/2019WR026751

David, A.T. 2017. Klamath and Trinity River intra-gravel water temperatures, 2015 and 2016. Report. U.S. Fish and Wildlife Service, Arcata, California. Arcata Fisheries Data Series Report Number DS 2017-49. http://www.trrp.net/library/document/?id=2350

David, A.T., J.E. Asarian, and F.K. Lake. 2018. Wildfire smoke cools summer river and stream water temperatures. Water Resources Research, 54(10), 7273–7290. https://doi.org/10.1029/2018WR022964

David, A.T. and D. H Goodman. 2017. Performance of water temperature management on the Klamath and Trinity rivers, 2016. Report. U.S. Fish and Wildlife Service, Arcata, California. Available: http://www.trrp.net/library/document?id=2349. http://www.trrp.net/library/document?id=2349

Deas, M.L., Meyer, G.K, Lowney, C.L., Orlob, G.T., and King, I.P. 1997. Sacramento River Temperature Modeling Project Report. Center for Environmental and Water Resources Engineering University of California, Davis, Report Number 97-01. http://www.krisweb.com/biblio/sactorvrtempmodel/ccv_ucd_cewre_1997_sactorvrtempmodel.htm [only executive summary is available online]

Deas, M.L. 1998a. Trinity Reservoir carryover analysis. Report. Davis, California. Available: http://www.trrp.net/library/document?id=2341

Deas, M.L. 1998b. Trinity Reservoir Water Temperature Simulation Model. Report. Michael Deas, Davis, California. http://www.trrp.net/library/document/?id=2340

Deas, M.L. and C.L. Lowney. 2000. Water Temperature Modeling Review: Central Valley. California Water Modeling Forum, p. 113p. http://cwemf.org/Pubs/BDMFTempReview.pdf

Deas, M.L. and G.T. Orlob. 1999. Klamath River Modeling Project. Project #96-HP-01. Assessment of alternatives for flow and water quality control in the Klamath River below Iron Gate Dam. University of California Davis Center for Environmental and Water Resources Engineering. Report No. 99-04. 379 pp. http://www.krisweb.com/biblio/klamath_ucd_deasetal_1999_rpt.pdf

De Juilio, K, K. Seitz, and S. Naman. 2022. Adult salmonid temperature objective recommendations. Memorandum to the Trinity River Restoration Program Fish Work Group. 12 pp. Available from the Trinity River Restoration Program, Weaverville, CA.

Deschutes River Alliance (DRA). 2017. 2016 Lower Deschutes Water Quality Study Results. Deschutes River Alliance, Portland, OR. https://deschutesriveralliance.org/s/1-2016-DRA-Lower-Deschutes-River-Water-Quality-Report-hdgd.pdf

Denning, M.H. 2010. Memorandum, To: Acting Executive Director, Trinity River Restoration Program, From: Michelle H. Denning, Regional Planning Officer, Subject: Request for Approval and Funding to Perform Appraisal Study for Lewiston Temperature Control. U.S. Bureau of Reclamation, Mid-Pacific Region, Sacramento, California.

Donaldson, M.R., S.J. Cooke, D.A. Patterson, and J.S. Macdonald. 2008. Cold shock and fish. Journal of Fish Biology, 73(7), 1491–1530. https://doi.org/10.1111/j.1095-8649.2008.02061.x

Doretto, A., E. Piano, and C.E. Larson. 2020. The River Continuum Concept: lessons from the past and perspectives for the future. Canadian Journal of Fisheries and Aquatic Sciences, 77(11), pp.1853-1864.

Dugdale, S.J., D.M. Hannah, and I.A. Malcolm. 2017. River Temperature Modelling: A Review of Process-Based Approaches and Future Directions. Earth-Science Reviews 175:97–113. Doi: 10.1016/j.earscirev.2017.10.009.

Elsner, RA, Shrimpton, JM. 2019. Behavioural changes during the parr–smolt transformation in coho salmon *Oncorhynchus kisutch*: is it better to be cool? Journal of Fish Biology. 95: 793–801. https://doi.org/10.1111/jfb.14069

Farber, S; D. Rankin, and T. Viel. 1998 Water temperatures in the South Fork Trinity River watershed in Northern California. http://www.trrp.net/library/document/?id=289

Faux, R. 2010. Application of airborne thermal infrared (TIR) imagery to the understanding of spatial temperature patterns in the Trinity River. Oral presentation provided at the Trinity River Restoration Program’s 2010 Trinity River Science Symposium. Watershed Sciences, Corvallis, Oregon. http://www.trrp.net/library/document/?id=406

Finnerty, A. and B. Hecht. 1992. The Need for Standards for Minimum Carryover Storage in Trinity Reservoir. Testimony of Trinity County, Submitted June 26, 1992, Before the State Water Resources Control Board Water Right Phase of The Bay-Delta Estuary Proceedings, Consideration of Interim Water Rights Actions pursuant to Water Code Sections 100 and 275 and the Public Trust Doctrine to Protect the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. Exhibit WRINT-TRICO-4. http://www.tcrcd.net/archive/trl-stor.htm

FitzGerald, A.M., S.N. John, T.M. Apgar, N.J. Mantua, and B.T. Martin. 2021. Quantifying thermal exposure for migratory riverine species: Phenology of Chinook salmon populations predicts thermal stress. Global Change Biology, 27(3), 536–549. https://doi.org/10.1111/gcb.15450

Flint, L.E., and Flint, A.L. 2012, Estimation of stream temperature in support of fish production modeling under future climates in the Klamath River Basin: U.S. Geological Survey Scientific Investigations Report 2011–5171, 31 p. https://pubs.er.usgs.gov/publication/sir20115171

Flint, L.E. and Flint, A.L. 2014, California Basin Characterization Model: A Dataset of Historical and Future Hydrologic Response to Climate Change, (ver. 1.1, May 2017): U.S. Geological Survey Data Release, https://doi.org/10.5066/F76T0JPB.

Flow/Temperature Work Group. 2016. Memorandum, To: Science Coordinator, Subject: Lewiston Feasibility Study Needed, Date: February 17, 2016. Trinity River Restoration Program, Trinity Management Council, Weaverville, California.

Folmar, L.C., and W.W. Dickhoff. 1980. The parr-smolt transformation (Smoltification) and seawater adaptation in salmonids: A review of selected literature. Aquaculture 21:1-37.

Frederiksen, Kamine, and Associates. 1980. Proposed Trinity River Basin Fish and Wildlife Management Program, Main report. Report prepared for the Bureau of Reclamation by the Trinity River Basin Fish and Wildlife Task Force, Sacramento, CA.

Fullerton, A.H., C.E. Torgersen, J.J. Lawler, R.N. Faux, E.A. Steel, T.J. Beechie, J.L. Ebersole, and S.G. Leibowitz. 2015. Rethinking the Longitudinal Stream Temperature Paradigm: Region-Wide Comparison of Thermal Infrared Imagery Reveals Unexpected Complexity of River Temperatures. Hydrological Processes 29:4719–4737. Doi: 10.1002/hyp.10506.

Fullerton, A.H., C.E. Torgersen, J.J. Lawler, E.A. Steel, J.L. Ebersole, and S.Y. Lee. 2018. Longitudinal Thermal Heterogeneity in Rivers and Refugia for Coldwater Species: Effects of Scale and Climate Change. Aquatic Sciences 80. Doi: 10.1007/s00027-017-0557-9. Doi:10.1007/s00027-017-0557-9.

Gaeuman, D., R. Stewart, and T. Buxton. 2016. First steps toward a river corridor management strategy. Trinity River Restoration Program (TRRP) Technical Report TR-TRRP-2016-1. TRRP, Weaverville, California. http://www.trrp.net/library/document/?id=2294

Gaeuman, D. and R.L. Stewart. 2017. Sediment transport in the Trinity River, CA: Data synthesis 2004-2015. Trinity River Restoration Program Technical Report. TR-TRRP-2017-1, Weaverville, CA, http://www.trrp.net/library/document/?id=2357

Gale, D. B. 1998. Memo to: Bessie Lee, from: Dan Gale, Sr. Fisheries Biologist, subject: Lower Klamath Water Quality Data. Dated September 22, 1998. Yurok Tribal Fisheries Program, Klamath, CA. 5p.

Gale, D. B. 2003. Assessment of anadromous fish stocks in Blue Creek, Lower Klamath River, California, 1997-1998. Yurok Tribal Fisheries Program, Habitat Assessment and Biological Monitoring Division. Technical Report No. 11. Klamath, CA.

Gale, D.B., T.R. Hayden, L.S. Harris, and H.N. Voight. 1998. Assessment of anadromous fish stocks in Blue Creek, Lower Klamath River, California, 1994-1996. Yurok Tribal Fisheries Program, Habitat Assessment and Biological Monitoring Division. Technical Report No. 4. Klamath, CA. 101 pp. http://www.krisweb.com/biblio/klamath_yuroktfp_galeetal_1998_4.pdf

Gale, D.B., and D.B. Randolph. 2000. Lower Klamath River sub-basin watershed restoration plan. Yurok Tribal Fisheries Program, Klamath California. 78 pp. http://www.yuroktribe.org/departments/fisheries/documents/LowerKlamathRestorationPlanFINAL2000_000.pdf

Gallagher, S.P. 1999. A note on observations of thermal habitat diversity at channel rehabilitation and control sites in the Trinity River during April 1998. Report by U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1478

Garrison, P. 2002. Annual report Trinity River tributary juvenile steelhead index research project, 2000-2001, Project 2c2. http://www.trrp.net/library/document/?id=265

Garrison, P. 2003 Annual report: Trinity River tributary juvenile steelhead index reach project, 2002, project 2c2. http://www.trrp.net/library/document/?id=270

Garwood, J. 2012. Historic and Recent Occurrence of Coho Salmon (*Oncorhynchus Kisutch*) in California Streams within the Southern Oregon/ Northern California Evolutionarily Significant Unit. https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=56769. Accessed 31 Aug 2015.

Gaeuman, D. 2013. Monitoring the Effectiveness of Gravel Augmentations for Salmonid Habitat Improvement Downstream from Dams. U.S. Bureau of Reclamation, Science and Technology Program, Project 0295 Completion Report. U.S. Bureau of Reclamation, Trinity River Restoration Program, Weaverville, California. https://www.trrp.net/library/document/?id=2210

Gilroy, I.B., M.H. Longenbaugh, and J.C. Polos. 1992. Progress Report for Investigations on Blue Creek, FY 1990-1991. Coastal California Fishery Resource Office, Region 1. http://cahatcheryreview.com/wp-content/uploads/2012/08/Blue-Cr-salmonid-assess_1990.pdf

Goldsmith, G.H. 1994. Juvenile salmonid monitoring on the Trinity and Klamath Rivers. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1492

GMA (Graham Matthews and Associates). 2001. Sediment Source Analysis for the Mainstem Trinity River, Report to Trinity County, CA.

GMA (GMA Hydrology). 2017. 2016 Trinity River focal reach survey report. Report to the Trinity River Restoration Program, Weaverville, CA, http://www.trrp.net/library/document?id=2389.

Georgakakos, P.B. 2020. Impacts of Native and Introduced Species on Native Vertebrates in a Salmon-Bearing River Under Contrasting Thermal and Hydrologic Regimes. PhD dissertation. University of California, Berkeley, CA. https://escholarship.org/uc/item/0wf2q0pk

Gombert, C. E., S.T. Lancaster, G.E. Grant, and R.L. Flitcroft. 2022. Novel dimensionless index for physically based assessment of thermal refugia characterizes off-channel habitat on gravel bed river. JAWRA Journal of the American Water Resources Association. https://doi.org/10.1111/1752-1688.13096

Grantham, T.E. 2018. North Coast Summary Report. California's Fourth Climate Change Assessment. Publication Number: SUM-CCC4A-2018-001. https://web.archive.org/web/20191221030750/https://www.energy.ca.gov/sites/default/files/2019-11/Reg_Report-SUM-CCCA4-2018-001_NorthCoast_ADA.pdf

Gresens, S.E. 1997. Interactive effects of diet and thermal regime on growth of the midge *Pseudochironomus richardsoni* Malloch. Freshwater Biology. 38: 365-373

Guillen, G. 2003. Klamath River fish die-off, September 2002: causative factors of mortality. U.S. Fish and Wildlife Service. Arcata Fish and Wildlife Office, Report Number AFWO-F-02-03.

Halstead, B.G. 1997. Memorandum to Bruce Gwynne of the California North Coast Regional Water Quality Control Board concerning water quality in the Klamath River. Unpublished letter of 23 September 1997. US Fish and Wildlife Service. Coastal California Fish and Wildlife Office. Arcata, CA. 14 p. http://www.krisweb.com/biblio/klamath_usfws_halstead_1997.pdf

Hanington, M. and K. Ellien. 2013a. Final 2012 Klamath River Continuous Water Quality Monitoring Summary Report. 2013. Yurok Tribe Environmental Program, Water Division, Klamath, CA. 63 p. http://www.yuroktribe.org/departments/ytep/documents/2013_Sonde.pdf

Hanington, M. and K. Ellien. 2013b. Final 2013 Klamath River Continuous Water Quality Monitoring Summary Report. 2013. Yurok Tribe Environmental Program, Water Division, Klamath, CA. 59 p. http://www.yuroktribe.org/departments/ytep/documents/2013_Sonde.pdf

Hannah, D.M., I.A. Malcolm, C. Soulsby, and A.F. Youngson. 2008. A comparison of forest and moorland stream microclimate, heat exchanges and thermal dynamics. Hydrological Processes, 22, 919-940.

Hanson, P.C., T.B. Johnson, D.E. Schindler, and J.F. Kitchell. 1997. Fish Bioenergetics 3.0 users manual. University of Wisconsin-Madison Center for Limnology, University of Wisconsin, Madison, Wisconsin. https://publications.aqua.wisc.edu/download/fish-bioenergetics-3-0-manual/

Harvey, B.C., J.L. White, R.J. Nakamoto, and S.F. Railsback. 2014. Effects of Streamflow Diversion on a Fish Population: Combining Empirical Data and Individual-Based Models in a Site-Specific Evaluation. North American Journal of Fisheries Management 34:247–257. Doi: 10.1080/02755947.2013.860062.

Hayashi, M. and D.O. Rosenberry. 2002. Effects of Ground Water Exchange on the Hydrology and Ecology of Surface Water. Groundwater. 40(3): 309-316. https://doi.org/10.1111/j.1745-6584.2002.tb02659.x

Hayden, T.; S.W. Naman, S. Turo. 2004. Juvenile Salmonid Monitoring on the Lower Trinity River, California, 2001. Report from the Yurok Tribal Fisheries Program, Trinity River Division, Technical Report Number TR-04-1. http://www.trrp.net/library/document/?id=2084"

Helm, B., R. Ben-Shlomo, M.J. Sheriff, R.A. Hut, R. Foster, B.M. Barnes, and D. Dominoni. 2013. Annual rhythms that underlie phenology: biological time-keeping meets environmental change. Proc. R. Soc. B. 280: 20130016. 20130016. http://doi.org/10.1098/rspb.2013.0016

Helsel, D.R., R.M. Hirsch, K.R. Ryberg, S.A. Archfield, and E.J. Gilroy. 2020. Statistical methods in water resources: U.S. Geological Survey Techniques and Methods, book 4, chapter A3, 458 p., https://doi.org/10.3133/tm4a3.

Hill, A. 2016. South Fork Trinity River 2015 Summer Temperature Profile. California Department of Fish and Wildlife, Weaverville, CA.

Hoar, W.S. 1988. The physiology of smolting salmonids. Pages 275-323 in W.S. Hoar (editor). Fish Physiology, Vol IXB. Academic Press, New York.

Hoopa Tribal Fisheries Department. 2016. Powerpoint presentation on climate change presented to the Flow Work Group, October 12, 2016.

Hoopa Valley Tribal Fisheries Department and McBain Associates. 2016. Water year 2015 Trinity River Restoration Program riparian monitoring report. Report to the Trinity River Restoration Program (TRRP). Hoopa Valley Tribal Fisheries Department, Hoopa, California.

Howell, C.K., S.D. Atkinson, J.L. Bartholomew, and S.L. Hallett. 2019. Development and Application of a QPCR Assay Targeting *Ichthyophthirius Multifiliis* in Environmental Water Samples. Diseases of Aquatic Organisms 134:43–55. Doi: 10.3354/dao03351.

HVT and McBain & Trush (Hoopa Valley Tribe and McBain & Trush, Inc.), 2006. Riparian Monitoring at Four Proposed Bank Rehabilitation Sites and One Bank Rehabilitation Site. Final report submitted to the Trinity River Restoration Program, July 2006.

HVT and McBain & Trush, 2007. Water Year 2007 Riparian Monitoring at Proposed and Constructed Bank Rehabilitation Sites. Final report submitted to the Trinity River Restoration Program, April 2007.

Irvine J.R., M. O'Neill, L. Godbout, and J. Schnute. 2013. Effects of smolt release timing and size on the survival of hatchery-origin coho salmon in the Strait of Georgia. Prog. Oceanogr. 115: 111–118.

Isaak, D.J. S.J. Wenger, E.E. Peterson, J.M. Ver Hoef, S.W. Hostetler, C.H. Luce, J.B. Dunham, J.L. Kershner, B.B. Roper, D.E. Nagel, G.L. Chandler, S.P. Wollrab, S.L. Parkes, D.L. Horan. 2016. NorWeST modeled summer stream temperature scenarios for the western U.S. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0033.

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, N. David, C.H Luce, S. Hostetler, J. Dunham, B.B Roper, S.P Wollrab, G.L Chandler, D.L Horan, and S. Parkes-Payne. 2017. The NorWeST Summer Stream Temperature Model and Scenarios for the Western U.S.: A Crowd-Sourced Database and New Geospatial Tools Foster a User-Community and Predict Broad Climate Warming of Rivers and Streams. Water Resources Research. Doi: 10.1002/2017WR020969. Doi:10.1002/2017WR020969.

Isaak, D.J., C.H. Luce, D.L. Horan, G.L. Chandler, S.P. Wollrab, and D.E. Nagel. 2018. Global Warming of Salmon and Trout Rivers in the Northwestern U.S.: Road to Ruin or Path Through Purgatory? Transactions of the American Fisheries Society. Doi: 10.1002/tafs.10059. doi:10.1002/tafs.10059.

Isaak, D.J., C.H. Luce, D.L. Horan, G.L. Chandler, S.P. Wollrab, W.B. Dubois, and D. E. Nagel. 2020. Thermal Regimes of Perennial Rivers and Streams in the Western United States. JAWRA Journal of the American Water Resources Association, 1752-1688.12864. https://doi.org/10.1111/1752-1688.12864

Jackson D.A., P.R. Peres-Neto, and J.D. Olden. 2001. What controls who is where in freshwater fish communities – the roles of biotic, abiotic, and spatial factors. *Canadian Journal of Fisheries and Aquatic Sciences.* 58: 157-170

Javaheri, A., M. Babbar-Sebens, J. Alexander, J. Bartholomew, and S. Hallett. 2018. Global Sensitivity Analysis of Water Age and Temperature for Informing Salmonid Disease Management. Journal of Hydrology 561:89–97. Doi: 10.1016/j.jhydrol.2018.02.053.

Jeffres, C.A., J.J. Opperman, and P.B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook Salmon in California river. *Environmental Biology of Fishes*. 10.1007/s10641-008-9367-1

Johnson, S.L. 2003. Stream temperature: scaling of observations and issues for modelling. Hydrol. Process. 17 (2), 497–499.

Johnson S.L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries and Aquatic Sciences, 61, 913–923.

Johnson, Z.C., B.G. Johnson, M.A. Briggs, W.D. Devine, C.D. Snyder, N.P. Hitt, D.K. Hare, and T.V. Minkova. 2020. Paired Air-Water Annual Temperature Patterns Reveal Hydrogeological Controls on Stream Thermal Regimes at Watershed to Continental Scales. Journal of Hydrology 587:124929. Doi: 10.1016/j.jhydrol.2020.124929.

Johnson, P.L., T.B. Vermeyen, and G.G. Ohaver. 1995. Managing Water Temperatures Below Hydroelectric Facilities. Hydro Review 14.

Jokikokko, E., I. Kallio-Nyberg, I. Saloniemi and E. Jutila. 2006. The survival of semi-wild, wild and hatchery reared Atlantic salmon smolts of the Simojoki River in the Baltic Sea. J. Fish Biol. 68: 430-442.

Jones & Stokes Associates, Inc. (JSA). 1992. Temperature Modeling of Lewiston Lake with the BETTER Two-Dimensional Reservoir Flow Mixing and Heat Exchange Model. Report prepared for the County of Trinity Department of Transportation and Planning. http://www.trrp.net/library/document/?id=1720

Jones, E.C., R.W. Perry, J.C. Risley, N.A. Som, and N.J. Hetrick. 2016. Construction, calibration, and validation of the RBM10 water temperature model for the Trinity River, Northern California. U.S. Geological Survey Open-File Report 2016-1056 for the Trinity River Restoration Program (TRRP). U.S. Geological Survey, Reston, Virginia. DOI: 10.3133/ofr20161056. http://www.trrp.net/library/document/?id=2352

Jong, B. 1998a. 1998 field sampling, Big French Creek (Trinity County). Memo to Files. California Department of Fish and Game, Northcoast California Anadromous Salmonid Project, Arcata. 13 p.

Jong, B. 1998b. 1998 field sampling, Dutch Creek (Trinity County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 12 p.

Jong, H.W. and T.J. Mills. 1992. Anadromous salmonid escapement studies, South Fork Trinity River, 1984 through 1990. California Department of Fish and Game, Klamath-Trinity Program, Inland Fisheries Division. Unpublished Administrative Report No. 92-XX. http://www.krisweb.com/biblio/sft_cdfg_jong_1992_escapment/jong.htm, http://www.trrp.net/library/document/?id=584

Junk, W.J. 1989. The Flood Pulse Concept in River-Floodplain Systems, p. 110-127. *In* D.P. Doge {ed.} Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences. 106.

Kamman, G. 1999a. Model Input, Output, and Code Files for: Temperature Analysis of Proposed Trinity River Fish and Wildlife Restoration Flow Alternatives Using the Better Model. Kamman Hydrology & Engineering, El Cerrito, CA. Data package online at: https://www.trrp.net/library/data/?id=150

Kamman, G. 1999b. Temperature Analysis of Proposed Trinity River Fish and Wildlife Restoration Flow Alternatives Using the BETTER Model. Prepared for Trinity County Planning Department by Kamman Hydrology & Engineering, El Cerrito, CA. Attachment to Water Resources/Water Quality Appendix A of the Trinity River Mainstem Fishery Restoration Environmental Impact Statement and Report.

Karuk Tribe. 2019. Karuk Climate Adaptation Plan. Karuk Tribe Department of Natural Resources, Orleans, CA. https://www.karuk.us/index.php/departments/natural-resources/525-climate-adaptation

Keefer, M.L., C.A. Peery, and C.C. Caudill. 2008. Migration timing of Columbia River spring Chinook salmon: effects of temperature, river discharge and ocean environment. *Transactions of the American Fisheries Society*. 137:1120-1133

Kerstetter, T.H. and M. Keeler. 1976. Smolting in steelhead trout (*Salmo gairdneri*): a comparative study of populations in two hatcheries and the Trinity River, northern California, using gill Na, K, ATPase assays. http://www.trrp.net/library/document/?id=280

Knabe, A. Fisheries technician. California Department of Fish and Wildlife. Personal communication.

Kochanski, A.K., D.V. Mallia, M.G. Fearon, J. Mandel, A.H. Souri, and T. Brown. 2019. Modeling Wildfire Smoke Feedback Mechanisms Using a Coupled Fire-Atmosphere Model With a Radiatively Active Aerosol Scheme. Journal of Geophysical Research: Atmospheres 124:9099–9116. Doi: 10.1029/2019JD030558.

Kothandaraman, V. 1971. Analysis of water temperature variations in large river. J. Sanit. Eng. Div. 97, 19–31.

Kramer, Chin and Mayo, Inc. 1977. Facilities and Operations Study: Trinity River Salmon and Steelhead Hatchery. Report prepared for the U.S. Bureau of Reclamation. Contract No. 7-07-20-V0014. http://www.trrp.net/library/document/?id=1875

Kubicek, P. F. 1977. Summer water temperature conditions in the Eel River system, with reference to trout and salmon. Master's Thesis, Humboldt State University, Arcata, CA. http://humboldt-dspace.calstate.edu/handle/2148/1011

Kurylyk, B.L., K.T. MacQuarrie, D. Caissie, and J.M. McKenzie. 2015. Shallow groundwater thermal sensitivity to climate change and land cover disturbances: Derivation of analytical expressions and implications for stream temperature modeling. Hydrology and Earth System Sciences, 19(5), 2469–2489.

Laanaya, F., A. St-Hilaire, and E. Gloaguen. 2017. Water Temperature Modelling: Comparison between the Generalized Additive Model, Logistic, Residuals Regression and Linear Regression Models. Hydrological Sciences Journal 62:1078–1093. Doi: 10.1080/02626667.2016.1246799.

Lai, Y.G. 2010. Two-dimensional depth-averaged flow modeling with an unstructured hybrid mesh. *Journal of Hydraulic Engineering* 136(1):12-23.

Lang, J.S., A.E. Gray, C.L. Jackson, R.F. Mcleod, and G.G. Phalen. 1998. Juvenile salmonid monitoring on the mainstem Klamath River at Big Bar and mainstem Trinity River at Willow Creek, 1992-1995. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1483

Lang, J.S., C.D. Chamberlain, and M.D. Magneson. 1999 Trinity River Fisheries Assessment Program: Investigations on the New River. Fiscal Year 1996-1998. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1479

Lewis, T.E., D.R. Lamphear, D.R. McCanne, A.S. Webb, J.P. Krieter, and W.D. Conroy. 2000. Regional Assessment of Stream Temperatures across Northern California and Their Relationship to Various Landscape-Level and Site-Specific Attributes. Humboldt State University Foundation Arcata, California, USA. http://wvvvv.krisweb.com/biblio/ncc_hsu_lewisetal_2000_fspregass.pdf

Lenz, J.L., S.J. Ricker, and B. Jong. 2000a. 2000 field sampling, Dutch Creek (Trinity County). Memo to Files. California Department of Fish and Game, North Coast California Coho Salmon Investigation, Arcata. 17 p.

Lenz, J.L., S.J. Ricker, and B. Jong. 2000b. 2000 field sampling, Humbug Creek (Siskiyou County). Memo to Files. California Department of Fish and Game, North Coast California Coho Salmon Investigation, Arcata. 14 p.

Lenz, J.L., S.J. Ricker, and B. Jong. 2001a. 2000 field sampling, Seiad Creek (Siskiyou County). Memo to Files. California Department of Fish and Game, North Coast California Coho Salmon Investigation, Arcata. 13 p.

Lenz, J.L., S.J. Ricker, and B. Jong. 2001b. 2000 field sampling, Sharber-Peckham Creek (Trinity County). Memo to Files. California Department of Fish and Game, North Coast California Coho Salmon Investigation, Arcata. 23 p.

Limerinos, J.T. 1967. Time-of-travel study of Trinity River, California. U.S. Geological Survey, Water Resource Division. Open-file report. Menlo Park, California. 24 pp. https://www.trrp.net/DataPort/doc.php?id=386

Lind, A.J., H.H. Welsh, Jr., and R.A. Wilson. 1996. The Effects of a Dam on Breeding Habitat and Egg Survival of the Foothill Yellow-legged Frog (Rana boylii) in Northwestern California. Herpetological Review. 27(2): 62-67

Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K.M. Andreadis, E.P. Maurer, and D.P. Lettenmaier. 2013. A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions. Journal of Climate 26:9384–9392. Doi: 10.1175/JCLI-D-12-00508.1.

Longenbaugh, M. and J.R. Chan. 1994. Investigations on Blue Creek, Final Progress Report FY 1993. US Fish and Wildlife Service, Coastal California Fishery Resource Office, Arcata, California. https://digitallib.oit.edu/digital/collection/kwl/id/3481.

Longenbaugh, M.H. and C.A. Wolfe. 1995. Progress report: fisheries investigations in New River, tributary to Trinity River, northern California, FY 1993. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1490

Lowney, C.L. 2000. Stream Temperature Variation in Regulated Rivers: Evidence for a Spatial Pattern in Daily Minimum and Maximum Magnitudes. Water Resources Research 36:2947–2955. Doi: 10.1029/2000WR900142.

Lucas, R.G., F. Suárez, S.W. Tyler, J.E. Moran, and M.H. Conklin. 2016. Polymictic pool behaviour in a montane meadow, Sierra Nevada, CA. Hydrological Processes, 30(18), 3274–3288. https://doi.org/10.1002/hyp.10834

Luce, C., B. Staab, M. Kramer, S. Wenger, D. Isaak, and C. McConnell. 2014. Sensitivity of Summer Stream Temperatures to Climate Variability in the Pacific Northwest. Water Resources Research 50:3428–3443. Doi: 10.1002/2013WR014329.

Lusardi, R.A., B.G. Hammock, C.A. Jeffres, R.A. Dahlgren, and J.D. Kiernan. 2019. Oversummer growth and survival of juvenile coho salmon (*Oncorhynchus kisutch*) across a natural gradient of stream water temperature and prey availability: an in situ enclosure experiment. Canadian Journal of Fisheries and Aquatic Sciences 77: 413–424. https://doi.org/10.1139/cjfas-2018-0484

Lyapustin, A., Y. Wang, S. Korkin, and D. Huang. 2018. MODIS Collection 6 MAIAC Algorithm. Atmospheric Measurement Techniques Discussions:1–50. Doi: 10.5194/amt-2018-141.

Lyons, J., K.R. Marine. 2004. Temperature Effects on Trinity River Salmon Reproductive Physiology. Phase I: Radio Telemetry Study of Migration and Behavioral Thermoregulation of the Spring-Run Chinook Salmon in the Upper Trinity River. Report prepared by North State Resources, Inc. for the USBR Trinity River Restoration Program. http://www.trrp.net/library/document/?id=2096

Macedo, R.A. 1992. Evaluation of Side Channels for Increasing Rearing Habitat of Juvenile Salmonids, Trinity River, California. M.S. Thesis presented to the Faculty of Humboldt State University. http://www.trrp.net/library/document/?id=1681

Magneson, M.D. 1996. Progress report: fisheries investigations in the New River, tributary to Trinity River, northern California, FY 1994 and 1995. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1487

Magneson, M. 2013. The Influence of Lewiston Dam Releases on Water Temperatures of the Trinity River and Lower Klamath River, CA. April to October, 2012. Report to the Trinity River Restoration Program, Arcata Fisheries Data Series Report Number DS 2013-30. U. S. Fish and Wildlife Service, Arcata, California. http://www.trrp.net/library/document/?id=2244

Magneson, M. 2014. The Influence of Lewiston Dam Releases on Water Temperatures of the Trinity River and Lower Klamath River, CA. April to October, 2013. Arcata Fisheries Data Series Report Number DS 2014-36. U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata, CA. http://www.trrp.net/library/document/?id=2178

Magneson, M.D. 2016. Klamath and Trinity River intra-gravel water temperatures, 2014 and 2015. Report. U.S. Fish and Wildlife Service, Arcata, California. http://www.trrp.net/library/document/?id=2346

Magneson, M.D. and C.D. Chamberlain. 2015. The influence of Lewiston dam releases on water temperatures of the Trinity River and lower Klamath River, CA, April to October 2014. U. S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata Fisheries Data Series Report Number DS 2015-41, Arcata, California. http://www.trrp.net/library/document/?id=2211

Mallakpour, I., A. AghaKouchak, and M. Sadegh. 2019. Climate-Induced Changes in the Risk of Hydrological Failure of Major Dams in California. Geophysical Research Letters, 46(4), 2130–2139. https://doi.org/10.1029/2018GL081888

Manhard, C.V., N.A Som, E.C Jones, and R.W Perry. 2018. Estimation of stream conditions in tributaries of the Klamath River, northern California. Report TR 2018-32. Arcata, California. http://www.trrp.net/library/document/?id=2401

Martin, T.L. and R.B. Huey. 2008. Why "Suboptimal" Is Optimal: Jensen's Inequality and Ectotherm Thermal Preferences. The American Naturalist, 171(3), E102–E118. https://doi.org/10.1086/527502

Martin, B.T., A. Pike, S.N. John, N. Hamda, J. Roberts, S.T. Lindley, E.M. Danner. 2017. Phenomenological vs. biophysical models of thermal stress in aquatic eggs. Ecol. Lett., 20: 50-59. https://doi.org/10.1111/ele.12705

Martin B.T., P.N. Dudley, N.S. Kashef, D.M. Stafford, W.J. Reeder, D. Tonina, A.M. Del Rio, J.S. Foott, and E.M. Danner. 2020. The biophysical basis of thermal tolerance in fish eggs. Proc Royal Soc B. 287: 20201550. https://doi.org/10.1098/rspb.2020.1550

Mayer, T.D. 2012. Controls of Summer Stream Temperature in the Pacific Northwest. Journal of Hydrology 475:323–335. Doi: 10.1016/j.jhydrol.2012.10.012.

McCarthy, S.G., J.J. Duda, J.M. Emlen, G.R. Hodgson, and D.A. Beauchamp. 2009. Linking Habitat Quality with Trophic Performance of Steelhead along Forest Gradients in the South Fork Trinity River Watershed, California. Transactions of the American Fisheries Society 138:506–521. http://www.trrp.net/library/document/?id=1260

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook Salmon. Prepared for the U.S. Environmental Protection Agency. EPA 910-R-99-010. http://wvvvv.krisweb.com/biblio/gen_usepa_mccullough_1999.pdf

McKernan, K., L. McKinnon, K. Fetcho, and E. Brunton. 2004a. Yurok Tribe Water Year 2002 (WY02) Report October 1, 2001 – September 30, 2002. Yurok Tribe Environmental Program (YTEP), Klamath, CA. 160 pp. http://www.yuroktribe.org/departments/ytep/documents/WY02.pdf

McKernan, K., L. McKinnon, K. Fetcho, E. Brunton, L. Mayo. 2004b. Yurok Tribe Water Year 2003 (WY03) Report October 1, 2002 – September 30, 2003. Prepared by Kevin McKernan, Lori McKinnon, Ken Fetcho, Eric Brunton, and Laura Mayo. Yurok Tribe Environmental Program, Klamath, CA. 538 pp. <http://www.yuroktribe.org/departments/ytep/documents/FinalWY03Report.pdf>

McKernan, K., L. McKinnon, K. Fetcho, E. Brunton, L. Mayo, J. Hackman, M. Hiner, M. Gibson, and S. Blount. 2004. Yurok Tribe Environmental Program. 2005. Yurok Tribe Water Year 2004 (WY04) Report October 1, 2003 – September 30, 2004. Yurok Tribe Environmental Program, Klamath, CA. 207 pp. <http://www.yuroktribe.org/departments/ytep/documents/WY04.pdf>

McCovey, B.W. Jr. 2003. Klamath River Basin Water Temperature Monitoring Project 2003. Yurok Tribal Fisheries Program, Water Management and Rights Protection Division, Hoopa, CA 95546, USA.

McCovey B.W. Jr. 2009a. Klamath River Green Sturgeon Acoustic Biotelemetry Monitoring 2008 Final Technical Memorandum. Yurok Tribal Fisheries Program Report. http://www.yuroktribe.org/departments/fisheries/documents/YTFPGreenSturgeonFINALTechMemo2008.pdf.

McCovey, B.W. Jr. 2009b. Lower Klamath River Adult Chinook Salmon Pathology Monitoring, 2008. Final Technical Memorandum. Yurok Tribal Fisheries Program, Klamath River Division. http://w.yuroktribe.nsn.us/departments/fisheries/documents/2008_adult_chinook_pathology_tech_memo_FINAL_000.pdf.

McCovey, B.W. Jr and J.S. Strange. 2011. Lower Klamath River Adult Chinook Salmon Pathology Monitoring, 2010. Report to the U.S. Bureau of Reclamation, Trinity River Restoration Program. http://www.trrp.net/library/document/?id=1223

Meehl, G.A., C. Covey, T. Delsworth, M Latif., B McAvaney., J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor. 2007. The WCRIP CMIP3 multimodel dataset—A new era in climate change research: Bulletin of the American Meteorological Society, p. 1383–1394 (DOI:10.1175/BAMS-88-9-1383).

Mertes, L.A.K. 1997. Documentation and significance of the perirheic zone on inundated floodplains. Water Resources Research. 33(7): 1749-1762

Metcalfe, K.Z., S.J. Ricker and B. Jong. 2000a. 1999 field sampling, Dutch Creek (Trinity County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 22 p.

Metcalfe, K.Z., S.J. Ricker and B. Jong. 2000b. 1999 field sampling, Humbug Creek (Siskiyou County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 21 p.

Metcalfe, K.Z., S.J. Ricker and B. Jong. 2000c. 1999 field sampling, Seiad Creek (Siskiyou County). Memo to Files. California Department of Fish and Game, North Coast California Anadromous Salmonid Project, Arcata. 21 p.

Moffett, J.W. and S.H. Smith. 1950. Biological Investigations of the Fishery Resources of Trinity River, California. Special Scientific Report – Fisher No. 12 from the U.S. Fish and Wildlife Service. http://www.trrp.net/library/document/?id=211

Mohseni, O. and H.G. Stefan. 1999. Stream Temperature/Air Temperature Relationship: A Physical Interpretation. Journal of Hydrology 218:128–141. Doi: 10.1016/S0022-1694(99)00034-7.

Mohseni, O., H.G. Stefan, and T.R. Erickson. 1998. A Nonlinear Regression Model for Weekly Stream Temperatures. Water Resources Research 34:2685–2692. Doi: 10.1029/98WR01877.

Mote, P., D. Turner, D.P. Lettenmaier, D. Bachelet, and J. Abatzoglou. 2014. Integrated Scenarios of Climate, Hydrology, and Vegetation for the Northwest, Final Report. https://climate.northwestknowledge.net/IntegratedScenarios/pages/publicationsreports/IntegratedScenariosFinalReport2014-10-07.pdf.

Mott, J.A., P. Meyer, D. Mannino, S.C. Redd, E.M. Smith, C. Gotway-Crawford, and E. Chase. 2002. Wildland Forest Fire Smoke: Health Effects and Intervention Evaluation, Hoopa, California, 1999. Western Journal of Medicine 176:157.

Murillo, D. 2015. Letter to Seth Naman, dated July 31, 2015, Subject: Response to Trinity Management Council (TMC) Letter of June 16, 2015. U.S. Bureau of Reclamation, Northern California Office, Shasta Lake, California.

Murphy, C. A., S.L. Johnson, W. Gerth, T. Pierce, and G. Taylor. 2021. Unintended Consequences of Selective Water Withdrawals From Reservoirs Alter Downstream Macroinvertebrate Communities. Water Resources Research, 57(6), e2020WR029169. https://doi.org/10.1029/2020WR029169

Murray, R. 1960. The Lewiston fish trapping facilities: first year of operation, 1958-1959. Inland Fisheries Administrative Report No. 59-13. https://www.trrp.net/library/document/?id=539 (missing pages) or https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=32223 (complete)

Murray, R. 1961. The Lewiston fish trapping facilities: second year of operation, 1959-1960. Inland Fisheries Administrative Report No. 61-16. https://www.trrp.net/library/document/?id=540

Murray, R. 1962. Trinity River Salmon and Steelhead Hatchery: Third Year of Operation, 1960-1961. Inland Fisheries Administrative Report No. 62-2. https://www.trrp.net/library/document/?id=541

Murray, C.B. and J.D. McPhail. 1988. Effect of incubation temperature on the development of five species of Pacific salmon (*Oncorhynchus*) embryos and alevins. Canadian Journal of Zoology, 66, 266–273. https://doi.org/10.1139/z88-038

Nakamoto, R.J. 1994. Characteristics of Pools Used by Adult Summer Steelhead Oversummering in the New River, California. Transactions of the American Fisheries Society 123: 757-765. http://www.trrp.net/library/document/?id=1129

Naman S. 2005. Thermal Refugia Use by Salmonids in Response to an Experimental Release of Water on the Trinity River, California 2004. Yurok Tribal Fisheries Program, Hoopa, CA. http://www.trrp.net/library/document/?id=2141

Naman, S. 2015. Letter to David Murillo (Bureau of Reclamation) dated June 16, 2015 about carryover storage for Trinity Reservoir and Lewiston Reservoir temperatures. Trinity River Restoration Program, Trinity Management Council, Weaverville, California.

Naman, S., K. De Juilio, and K. Osborne. 2020. Juvenile Salmonid Temperature Target Recommendations, memo to Ken Lindke, TRRP Fish Workgroup Coordinator.

National Marine Fisheries Service (NMFS). 2000. Biological Opinion, Trinity River Mainstem Fishery Restoration. Endangered Species Act - Section 7 Consultation. NMFS, Southwest Region, Long Beach, CA. https://www.trrp.net/library/document/?id=1240

National Marine Fisheries Service (NMFS). 2002. Biological opinion for the proposed license amendment for the Potter Valley Project (Federal Energy Regulatory Commission Project Number 77-110). NMFS, Southwest Region, Long Beach, CA. https://www.krisweb.com/biblio/russian_ferc_xxxx_2002_potterba.pdf

National Marine Fisheries Service (NMFS). 2014. Final Recovery Plan for the Southern Oregon/Northern California Coast Evolutionarily Significant Unit of Coho Salmon (*Oncorhynchus kisutch*). National Marine Fisheries Service. Arcata, CA.

United States Geological Survey (USGS). 2020. NHDplus. High Resolution Hydrography Framework. Available: https://www.usgs.gov/core-science-systems/ngp/national-hydrography. Accessed March 2021.

Nielsen, J.L., T.E. Lisle, and V. Ozaki. 1994. Thermally Stratified Pools and Their Use by Steelhead in Northern California Streams. Transactions of the American Fisheries Society 123:613–626.

North Coast Regional Water Quality Control Board (NCRWQCB). 2010. Final Staff Report for the Klamath River Total Maximum Daily Loads (TMDLs) Addressing Temperature, Dissolved Oxygen, Nutrient and Microcystin Impairments in California, the Proposed Site Specific Dissolved Oxygen Objectives for the Klamath River and California, and the Klamath River and Lost River Implementation Plans -Appendix 9 Maps of the Klamath River Basin in California Showing the Locations of Known Thermal Refugia. NCRWQCB, Santa Rosa, CA. https://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls/klamath_river/100927/staff_report/21_Appendix9_ThermalRefugiaLocations.pdf

Ock, G. and G.M. Kondolf. 2012. Assessment of Ecological Roles of Gravel Bar Features Restored by Gravel Augmentation and Channel Rehabilitation Activities below Lewiston Dam in the Trinity River, California. U.S. Bureau of Reclamation, Science and Technology Program Scoping Report. University of California, Berkeley, California. http://www.trrp.net/library/document/?id=1898

Ock, G., D. Gaeuman, J. McSloy, and G.M. Kondolf. 2015. Ecological Functions of Restored Gravel Bars, the Trinity River, California. Ecological Engineering 83:49–60. Doi: 10.1016/j.ecoleng.2015.06.005.

Olden, J.D. and R.J. Naiman. 2010. Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity. Freshwater Biol., 55 (1) (2010), pp. 86-107.

Oppenheim, N. 2016. Letter TO: Katrina Harrison, RE: Trinity River Alternative for the Reinitiation of Consultation on the CVP nonjeopardy Biological Opinion. Pacific Coast Federation of Fishermen’s Associations, San Francisco, California.

Oregon Water Resources Department and California Department of Water Resources. 2010. Klamath Basin Study Proposal.

Ouellet, V., A. St-Hilaire, S.J. Dugdale, D.M. Hannah, S. Krause, and S. Proulx-Ouellet. 2020. River Temperature Research and Practice: Recent Challenges and Emerging Opportunities for Managing Thermal Habitat Conditions in Stream Ecosystems. Science of The Total Environment 736:139679. Doi: 10.1016/j.scitotenv.2020.139679.

P. L. 98-541. 1984. An Act to Provide for the restoration of the fish and wildlife of the Trinity River Basin California, and for other purposes. https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/PCFFA&IGFR/part2/pcffa_92.pdf

PacifiCorp. 2004. Final License Application for the Klamath River Hydroelectric Project (FERC Project No. 2082). Portland, OR.

Parish, O.O. and T.W. Putnam. 1977. Equations for the determination of humidity from dewpoint and psychrometric data. NASA Technical Note TN D-8401. National Aeronautics and Space Administration, Washington, D.C. https://www.nasa.gov/centers/dryden/pdf/87878main_H-937.pdf

Patterson, W. and S. Beesley. 2011. Klamath River Estuary Wetlands 2010 Water Quality Monitoring Report - Investing Relationships with CRAM, Water Quality and Juvenile Salmonid Habitat Function. Yurok Tribe Environmental Program and Yurok Tribal Fisheries Program, Klamath, CA. 88p.

Pedersen, E. J., D.L. Miller, G.L. Simpson, and N. Ross. 2019. Hierarchical generalized additive models in ecology: An introduction with mgcv. PeerJ, 7, e6876. https://doi.org/10.7717/peerj.6876

Perry, R.W., J.C. Risley, S.J. Brewer, E.C. Jones, and D.W. Rondorf. 2011. Simulating Daily Water Temperatures of the Klamath River under Dam Removal and Climate Change Scenarios. U.S. Geological Survey Open-File Report 2011-1243:78pp.

Perry, R.W., J.M. Plumb, E.C. Jones, N.A. Som, N.J. Hetrick, and T.B. Hardy. 2018. Model structure of the Stream Salmonid Simulator (S3) – a dynamic model for simulating growth, movement, and survival of juvenile salmonids. Report 2018-1056 for the Trinity River Restoration Program (TRRP). U.S. Geological Survey, Reston, Virginia. DOI: 10.3133/ofr20181056. http://www.trrp.net/library/document/?id=2400

Pinnix, W. D., S. P. Boyle, T. Wallin, T. Daley, and N. A. Som. 2022. Long-Term Analyses of Estimates of Abundance of Juvenile Chinook Salmon on the Trinity River, 1989-2018. Arcata Fisheries Technical Series Report TS 2022-40, report for the Trinity River Restoration Program (TRRP). U.S. Fish and Wildlife Service, Arcata, California. Available: https://www.trrp.net/library/document?id=2571.

Plumb, J. and C. Moffitt. 2015. Re-Estimating Temperature-Dependent Consumption Parameters in Bioenergetics Models for Juvenile Chinook Salmon. Transactions of the American Fisheries Society. 10.1080/00028487.2014.986336

Polos, J. 2016. Adult salmon water temperature targets. Trinity River Restoration Program (TRRP) Performance Measure. TRRP, Weaverville, California. http://www.trrp.net/library/document/?id=2288

Poole, G.C., and C.H. Berman. 2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human caused thermal degradation. Environmental Management, 27(6), 787–802. https://doi.org/10.1007/s002670010188

Preece, R.M., and H.A. Jones. 2002. The effect of Keepit Dam on the temperature regime of the Namoi River, Australia. River Research and Applications, 18(4), 397–414. https://doi.org/10.1002/rra.686

Railsback, S.F., and B.C. Harvey. 2015. Foothill Yellow-legged Frog Assessment Model (FYFAM) Description, Version 2. https://ecomodel.humboldt.edu/sites/default/files/ecomodel/fyfam_v2_2015-12-07.pdf

Railsback, S.F. and K.A. Rose. 1999. Bioenergetics Modeling of Stream Trout Growth: Temperature and Food Consumption Effects. Transactions of the American Fisheries Society, 128:2, 241-256, https://doi.org/10.1577/1548-8659(1999)128%3C0241:BMOSTG%3E2.0.CO;2

Railsback, S.F., B.C. Harvey, S.J. Kupferberg, M.M. Lang, S. McBain, and H.H. Welsh. 2016. Modeling Potential River Management Conflicts between Frogs and Salmonids. Canadian Journal of Fisheries and Aquatic Sciences 73:773–784. Doi: 10.1139/cjfas-2015-0267.

Ray, R.A., R.A. Holt, and J.L. Bartholomew. 2012. Relationship Between Temperature and *Ceratomyxa Shasta*–Induced Mortality In Klamath River Salmonids. Journal of Parasitology 98:520–526. Doi: 10.1645/JP-GE-2737.1.

Resource Management Associates, Inc. (RMA). 2003. Draft Upper Sacramento River Water Quality Modeling with HEC-5Q: Model Calibration and Validation. December 2003. http://deltacouncil.ca.gov/docs/upper-sacramento-river-water-quality-modeling-hec-5q-model-calibration-and-validation

Rich, A.A. 1987. Report on studies conducted by Sacramento County to determine the temperatures which optimize growth and survival in juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Prepared for McDonough, 35 Holland & Allen, 555 Capital Mall, Sacramento, CA 95814.

Richter, A., and S.A. Kolmes. 2005. Maximum Temperature Limits for Chinook, Coho, and Chum Salmon, and Steelhead Trout in the Pacific Northwest. Reviews in Fisheries Science, 13(1), 23–49. https://doi.org/10.1080/10641260590885861

Romberger, C.Z. and S. Gwozdz. 2018. Performance of water temperature management on the Klamath and Trinity Rivers, 2017. U.S. Fish and Wildlife Service. Arcata Fish and Wildlife Office, Arcata Fisheries Data Series Number DS 2018-59, Arcata, California.

Roni P., T. Bennett, R. Holland, G. Pess, K. Hanson, R. Moses, M. McHenry, W. Ehinger, and J. Walter. 2012. Factors affecting migration timing, growth, and survival of juvenile coho salmon in two coastal Washington watersheds. Trans. Am. Fish. Soc. 141: 890–906

Roundy, P.E. 2017. Diagnosis of Seasonally Varying Regression Slope Coefficients and Application to the MJO: Linear Regression, Seasonal Cycle, Madden-Julian Oscillation. Quarterly Journal of the Royal Meteorological Society 143:1946–1952. Doi: 10.1002/qj.3054.

Rowell, J.H. 1979. Mathematical Model Investigations: Trinity Dam Multilevel Outlet Evaluation and Trinity River Temperature Prediction Study. Report by the U.S. Bureau of Reclamation to the Trinity River Basin Fish and Wildlife Task Force. U.S. Bureau of Reclamation, Sacramento, CA. http://www.trrp.net/library/document/?id=1386

Rowell, J.H. 1990. U.S. Bureau of Reclamation Monthly Temperature Model Sacramento River Basin: Draft Report. U.S. Bureau of Reclamation, Mid-Pacific Region., Sacramento, CA. https://catalog.hathitrust.org/Record/102212655. Accessed 28 Feb 2019.

Rowell, J.H. 1998. "A history of temperature modeling in the Central Valley." Presentation at the Bay Delta Modeling Forum, Temperature Modeling Workshop, October 22, Sacramento.

Schaaf, C.J., S.J. Kelson, S.C. Nusslé, and S.M. Carlson. 2017. Black Spot Infection in Juvenile Steelhead Trout Increases with Stream Temperature in Northern California. Environmental Biology of Fishes 100:733–744. Doi: 10.1007/s10641-017-0599-9.

Schaaf, C.J., S.J. Kelson, S.C. Nusslé, and S.M. Carlson. 2018. Correction to: Black Spot Infection in Juvenile Steelhead Trout Increases with Stream Temperature in Northern California. Environmental Biology of Fishes 101:865–866. Doi: 10.1007/s10641-018-0753-z.

Scheiff, A J, J.S. Lang, and W.D. Pinnix. 2001. Juvenile Salmonid Monitoring on the Mainstem Klamath River at Big Bar and Mainstem Trinity River at Willow Creek 1997-2000. Annual report of the Klamath River Fisheries Assessment Program. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1476

Scheiff, T and .P Zedonis. .2010. The influence of Lewiston Dam releases on water temperatures of the Trinity and Klamath Rivers, CA. April to October, 2009. http://www.trrp.net/library/document/?id=446

Scheiff, T and P. Zedonis. 2012. The influence of Lewiston Dam releases on water temperatures of the Trinity and Klamath Rivers, CA April to October 2011. U.S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata Fisheries Data Series Report Number DS 2012-24, Arcata, California. http://www.trrp.net/library/document/?id=1408

Scheiff, T, and P. Zedonis. 2011. The Influence of Lewiston Dam Releases on Water Temperatures of the Trinity and Klamath Rivers, CA. April to October, 2010. U. S. Fish and Wildlife Service, Arcata Fish and Wildlife Office, Arcata Fisheries Data Series Report Number DS 2011-22, Arcata, California. http://www.trrp.net/library/document/?id=1215

Schwarz, A., P. Ray, S. Wi, C. Brown, M. He, and M. Correa. (2018). Climate change risks faced by the California Central Valley water resource system. California's Fourth Climate Change Assessment. Publication Number: CCCA4-EXT-2018-001. https://www.energy.ca.gov/sites/default/files/2019-12/Water_CCCA4-EXT-2018-001_ada.pdf.

Segura, C., P. Caldwell, G. Sun, S. McNulty, and Y. Zhang. 2015. A model to predict stream water temperatures across the conterminous USA, Hydrol. Processes, 29, 2178– 2195, doi:10.1002/hyp.10357

Shaw, T.A., S.M. Noble, and M.M. Griffin. 1991. Progress report for investigations on New River. Report AFF 1-FRO-91-4, U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1495

Shaw, T.A., B.C. Cates, and M.M. Griffin. 1992. Progress report for investigations on New River [marked as draft]. U.S. Fish and Wildlife Service report AFF1-FRO-92-04, Arcata, CA. http://www.trrp.net/library/document/?id=1494

Siegel, J.E. and C.J. Volk. 2019. Accurate Spatiotemporal Predictions of Daily Stream Temperature from Statistical Models Accounting for Interactions between Climate and Landscape. PeerJ 7:e7892. Doi: 10.7717/peerj.7892.

Silvey, W.D. 1966. Water Quality Related to Fish Kill at Trinity River Fish Hatchery, Lewiston, Trinity County, California. Report prepared by USGS Water Resources Division in cooperation with the CDFG, Inland Fisheries. http://www.trrp.net/library/document/?id=1621

Sinnen, W., M. Currier, M. Knechtle, and S. Borok. 2006. Annual report Trinity River basin salmonid and steelhead monitoring project, 2004-2005 season. California Department of Fish and Game, Northern California – North Coast Region. http://www.trrp.net/library/document/?id=297

Sinnen, W.; A. Hill, J. Hileman, S. Borok, and M.C. Kier. 2010. Final annual report, Trinity River salmon and steelhead monitoring project, 2008-2009 season. California Department of Fish and Game, Northern California – North Coast Region, Klamath and Trinity River Projects. http://www.trrp.net/library/document/?id=629

Sinnott, S. 2010. Final 2009 Klamath River Continuous Water Quality Monitoring Summary Report. Yurok Tribe Environmental Program, Water Division, Klamath, CA. 65 p. http://www.yuroktribe.org/departments/ytep/documents/2009SondeReport122710_Final.pdf

Sinnott, S. 2011. Final 2010 Klamath River Continuous Water Quality Monitoring Summary Report. Yurok Tribe Environmental Program, Water Division, Klamath, CA. 54 p. http://www.yuroktribe.org/departments/ytep/documents/FINAL2010SondeReport032311_000.pdf

Sinnott, S. 2012. Final 2011 Klamath River Continuous Water Quality Monitoring Summary Report. Yurok Tribe Environmental Program, Water Division, Klamath, CA. 57 p. http://www.yuroktribe.org/departments/ytep/documents/FINAL2011SondeReport042012.pdf

Sloan, L.M. 2010. Population structure, life history, and terrestrial movements of western pond turtles (Actinemys marmorata) in lentic habitats along the Trinity River, California. Masters Thesis, Humboldt State University, California. http://www.trrp.net/library/document/?id=1613

Sloan L. and S. Marks. 2012 Summary of Management Implications for the Project on Western Pond Turtles (Actinemys marmorata) in Lentic Habitats Along the Trinity River, California. Report to the U.S. Bureau of Reclamation, Trinity River Restoration Program, from Humboldt State University, Department of Biological Sciences, Arcata, CA. http://www.trrp.net/library/document/?id=1819

Smith, J.G. 1991. Water temperature monitoring in Lewiston and Trinity Reservoirs (1990 through 1991). Memorandum of October 28,1991 to Project Coordinator, Trinity River Fishery Resource Office, 1 page + attachments.

Smith, C. D., S.A. Rounds, L.L. Orzol. 2018. Klamath River Basin water-quality data. (USGS Numbered Series Fact Sheet 2018–3031). https://doi.org/10.3133/fs20183031

Snover, L.M., M. J. Adams, D. T. Ashton, J. B. Bettaso, and H. H. Welsh Jr. 2015. Evidence of counter-gradient growth in western pond turtles (Actinemys marmorata) across thermal gradients. Freshwater Biology 60(9): 1944-1963. http://www.trrp.net/library/document/?id=2248

Sogutlugil, I.E. 2012. Summary of Trinity River flow and temperature model 2003 & 2005 initial simulations with regard to Trinity River water temperature targets. Technical Memorandum to the U.S. Bureau of Reclamation by Watercourse Engineering Inc. http://www.trrp.net/library/document/?id=1805

Sogutlugil, I.E., M. Deas. 2012. Conceptual Real-Time Management of Trinity River Summer Water Temperatures. Powerpoint presentation. Watercourse Engineering, Davis, CA. https://www.trrp.net/library/document/?id=1805

Staff of the Trinity River Flow Evaluation. 1988. Annual Report Trinity River Flow Evaluation 1988. Report from the USFWS. http://www.trrp.net/library/document/?id=1952

Staff of the Trinity River Flow Evaluation. 1989. Annual Report Trinity River Flow Evaluation 1989. Report from the USFWS. http://www.trrp.net/library/document/?id=1953

Staff of the Trinity River Flow Evaluation Study. 1987. Annual Report Trinity River Flow Evaluation Study 1987. http://www.trrp.net/library/document/?id=1333

Starkey-Owens, T. 2020. Impacts of Flow Releases on Invertebrate Drift and Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) Diet on the Trinity River Below Lewiston Dam. Thesis presented to the faculty of Humboldt State University.

Steel, E.A., A. Tillotson, D.A. Larsen, A.H. Fullerton, K.P. Denton, and B.R. Beckman. 2012. Beyond the Mean: The Role of Variability in Predicting Ecological Effects of Stream Temperature on Salmon. Ecosphere 3:art104. Doi: 10.1890/ES12-00255.1.

Steel, E.A., M.C. Kennedy, P.G. Cunningham, and J.S. Stanovick. 2013. Applied Statistics in Ecology: Common Pitfalls and Simple Solutions. Ecosphere 4:art115. Doi: 10.1890/ES13-00160.1.

Steel, E.A., T.J. Beechie, C.E. Torgersen, and A.H. Fullerton. 2017. Envisioning, Quantifying, and Managing Thermal Regimes on River Networks. BioScience 67:506–522. Doi: 10.1093/biosci/bix047.

Steel, E.A., A. Marsha, A.H. Fullerton, J.D. Olden, N.K. Larkin, S.-Y. Lee, and A. Ferguson. 2018. Thermal Landscapes in a Changing Climate: Biological Implications of Water Temperature Patterns in an Extreme Year. Canadian Journal of Fisheries and Aquatic Sciences. Doi: 10.1139/cjfas-2018-0244. Doi:10.1139/cjfas-2018-0244.

Stephens, S.L., A.L. Westerling, M.D. Hurteau, M.Z. Peery, C.A. Schultz, and S. Thompson. 2020. Fire and Climate Change: Conserving Seasonally Dry Forests Is Still Possible. Frontiers in Ecology and the Environment 18:354–360. Doi: 10.1002/fee.2218.

Stern, G.R. and S.M. Noble. 1990. Progress Report for Investigations on Blue Creek: FY 1989: First Year of Investigations. US Fish & Wildlife Service, Arcata, CA. https://www.fws.gov/yreka/Final-Reports/rmaap/1989-FP-2.23-AFWO.pdf.

Stewart, D.J. and M. Ibarra. 1991. Predation and Production by Salomine Fishes in Lake Michigan, 1978-88. Canadian Journal of Fisheries and Aquatic Sciences. 48: 909-922

Stokely, T. 2016. Trinity River Temperature Issues: Historical Analysis and Future Outlook. Presentation to Trinity Collaborative, July 15, 2016.

Strange, J. 2003. Adult Chinook Salmon Migration in the Klamath River Basin: 2003 Telemetry Study Final Report. Yurok Tribal Fisheries Program; School of Aquatic and Fishery Sciences – University of Washington. https://www.researchgate.net/publication/240626691_Adult_Chinook_Migration_in_the_Klamath_River_Basin_2003_Radio_Telemetry_Study_Final_Report.

Strange J. 2005. Adult Chinook Salmon Migration in the Klamath River Basin: 2005 Sonic Telemetry Study Final Report. Yurok Tribal Fisheries Program, Hoopa, CA; School of Aquatic Sciences, University of Washington; Hoopa Valley Tribal Fisheries, Hoopa, CA. http://www.trrp.net/library/document/?id=2144

Strange, J. 2006. Adult Chinook Salmon Migration in the Klamath River Basin: 2004 Telemetry Study Final Report. Yurok Tribal Fisheries Program; School of Aquatic and Fishery Sciences – University of Washington. http://www.yuroktribe.org/departments/fisheries/documents/ADULTCHINOOKTELEMETRYREPORT2004FINAL.pdf

Strange, J. 2007. Adult chinook salmon migration in the Klamath River Basin: 2006 telemetry study final report. Yurok Tribal Fisheries Program, and School of Aquatic and Fishery Sciences – University of Washington; in collaboration with Hoopa Valley Tribal Fisheries. http://www.trrp.net/library/document/?id=1808

Strange, J. 2008. Adult chinook salmon migration in the Klamath River Basin: 2007 biotelemetry monitoring study final report. Yurok Tribal Fisheries Program in collaboration with Hoopa Valley Tribal Fisheries. http://www.trrp.net/library/document/?id=1809

Strange, J. 2010. Summary of scientific evidence to guide special flow releases to reduce the risk of adult fall chinook salmon mass disease mortality in the lower Klamath River. Yurok Tribal Fisheries Program. http://www.trrp.net/library/document/?id=1609

Strange, J.S. 2011a. Behavioral Adaptations of Chinook Salmon to Adverse Riverine Conditions during Their Spawning Migration in the Klamath River Basin. PhD dissertation, University of Washington. https://www.proquest.com/openview/2f763fe42a5374a0f164e0df13d26dc5/1

Strange, J. S. 2011b. Salmonid use of thermal refuges in the Klamath River: 2010 annual monitoring study. Report for the Trinity River Restoration Program (TRRP). Yurok Tribal Fisheries Program, Hoopa, California. http://www.trrp.net/library/document/?id=2384

Sullivan K., D.J. Martin, R.D. Cardwell, J.E. Toll, and S. Duke. 2000. An analysis of the effects of temperature on salmonids of the Pacific Northwest with implications for selecting temperature criteria. Sustainable Ecosystems Institute. Portland, OR. 147 pp. Available at: < http://ww.w.krisweb.com/biblio/gen_sei_sullivanetal_2000_tempfinal.pdf>. Website accessed October 2019.

Sutton, 2007. Klamath River Thermal Refugia Study, 2006. Technical Memorandum No. 86-68290-01-07. https://www.waterboards.ca.gov/waterrights/water_issues/programs/hearings/marblemountain/exhibits/nat_marine_fs_exhibits/nmfs_18.pdf

Sutton, R. and T. Soto. 2012. Juvenile Coho Salmon Behavioural Characteristics in Klamath River Summer Thermal Refugia. River Research and Applications. Doi: 10.1002/rra.1459.

Sutton, R., M. Deas, M.R. Belchik, and S.M. Turo. 2002. Klamath River Thermal Refugia Study Report. U.S. Bureau of Reclamation. Available: http://www.trrp.net/library/document?id=2070.

Sutton, R.J., M.L. Deas, S.K. Tanaka, T. Soto, and R.A. Corum. 2007. Salmonid Observations at a Klamath River Thermal Refuge under Various Hydrological and Meteorological Conditions. River Research and Applications 23:775–785.

Swain, D.L., B. Langenbrunner, J.D. Neelin, and A. Hall. 2018. Increasing Precipitation Volatility in Twenty-First-Century California. Nature Climate Change 8:427–433. Doi: 10.1038/s41558-018-0140-y.

Sweeney, BW. And R.L. Vannote. 1984. Influence of Food Quality and Temperature on Life History Characteristics of the Parthenogenetic Mayfly, *Cloeon Triangulifer*. Freshwater Biology 14:621–630. Doi: 10.1111/j.1365-2427.1984.tb00181.x.

SWRCB Order WR 90-5. 1990. https://www.waterboards.ca.gov/waterrights/board_decisions/adopted_orders/orders/1991/wro91-01.pdf

Sykes, G.E., C.J. Johnson, and J.M. Shrimpton. 2009. Temperature and Flow Effects on Migration Timing of Chinook Salmon Smolts. Transactions of the American Fisheries Society. 138: 1252-1265

Tate, K.W., D.L. Lancaster, and D.F. Lile. 2006. Assessment of thermal stratification within stream pools as a mechanism to provide refugia for native trout in hot, arid rangelands. Environmental Monitoring and Assessment, 124(1–3), 289–300. https://doi.org/10.1007/s10661-006-9226-5

Tetra Tech, Inc. 2004. Description of the Klamath and Lost Rivers Water Quality Databases. Draft July 16, 2004. Prepared for U.S. Environmental Protection Agency Region 10, U.S. Environmental Protection Agency Region 9, Oregon Department of Environmental Quality, and the North Coast Regional Water Quality Control Board. Tetra Tech, Inc.

Thomas Gast & Associates Environmental Consultants (TGAEC). 2021. Analysis and model evaluation of long-term data collected at the Willow Creek outmigrant trap. Report 20190910YTFP for the Trinity River Restoration Program (TRRP). https://www.trrp.net/library/document?id=2492.

Tipping, J.M., R.V. Cooper, J.B. Byrne, and T.H. Johnson. 1995. Length and condition factor of migrating and nonmigrating hatchery-reared winter steelhead smolts. The Progressive Fish-Culturist 57:120-123.

Tockner, K., F. Malard, and J.V. Ward. 2000. An extension of the flood pulse concept. Hydrological Processes. 14: 2861-2883

Trinity River Restoration Program (TRRP). 2012. Trinity River Restoration Program Performance Measure: Temperature Target Performance. Performance Measure Report. TRRP, Weaverville, CA. http://www.trrp.net/library/document/?id=1381

Trinity River Restoration Program (TRRP). 2013. Trinity River restoration flow release schedule design, water year 2013. Workgroup Report WG-TRRP-Flow-2013-1. TRRP, Weaverville, California. http://odp.trrp.net/library/document/?id=2164

Trinity River Restoration Program (TRRP). 2015. Trinity River Restoration Flow Release Schedule Design for Water Year 2015. Technical Memorandum WG-TRRP-Flow-2015-1. TRRP, Weaverville, California. http://www.trrp.net/library/document/?id=2251

Trinity River Restoration Program (TRRP) and ESSA Technologies Ltd. 2009. Integrated assessment plan. TRRP, Weaverville, California. https://www.trrp.net/library/document/?id=400

Turek, S., M. Rode, B. Cox, G. Heise, W. Sinnen, C. Reese, S. Borok, M. Hampton, and C. Chun. 2004. September 2002 Klamath River fish-kill: Final analysis of contributing factors and impacts. California Department of Fish and Game.

Turner, R. L. 1978. Memorandum to the Technical Files. Subject: Evaluation of Ground Water as a Potential Heating Source for Lewiston Dam Fish Hatchery Waters–Trinity River Division–Central Valley Project, California. Memorandum from the Regional Geology Branch, Sacramento, California. http://www.trrp.net/library/document/?id=2054

Tzeng, S. and H.C. Huang. 2018. Resolution Adaptive Fixed Rank Kriging. Technometrics 60:198–208. Doi: 10.1080/00401706.2017.1345701.

Unwin, M.J. and G.J. Glova. 1997. Changes in life history parameters in a naturally spawning population of chinook salmon (*Oncorhynchus tshawytscha*) associated with releases of hatchery-reared fish. Can. J. Fish. Aquat. Sci. 54: 1235-1245.

U.S. Bureau of Land Management. 1995. Mainstem Trinity River Watershed Analysis. http://www.trrp.net/library/document/?id=1390

U.S. Bureau of Reclamation (USBR). 1978. Speed-team cost estimates for two temperature control alternatives. U.S. Bureau of Reclamation cost analyses with design notes. http://www.trrp.net/library/document/?id=1722

U.S. Bureau of Reclamation (USBR). 1988. Technical Appendix B for the Water Contracting EISs, Assumptions and Criteria Utilized in the Operations, Power, Temperature, and Water Quality Models. http://www.trrp.net/library/document/?id=1343

U.S. Bureau of Reclamation (USBR). 1992. Biological Assessment for U.S. Bureau of Reclamation Long-Term Central Valley Project Operations Criteria and Plan. http://www.trrp.net/library/document/?id=1816

U.S. Bureau of Reclamation (USBR).1997. Central Valley Project Improvement Act Programmatic Environmental Impact Statement. Attachment B, Fish Habitat Water Quality Technical Information. U.S. Department of the Interior, Bureau of Reclamation, Sacramento, California. https://web.archive.org/web/20170126090150/http://www.calwater.ca.gov/Admin_Record/C-081862.pdf

U.S. Bureau of Reclamation (USBR). 2008. Biological Assessment on the Continued Long-Term Operations of the Central Valley Project and the State Water Project, Appendix H: Reclamation Temperature Model and SRWQM Temperature Model. U.S. Department of the Interior, Bureau of Reclamation Mid-Pacific Region Sacramento, California. https://www.usbr.gov/mp/cvo/ocap_page.html.

U.S. Bureau of Reclamation (USBR). 2010. Temperature management of the CVP northern system, Shasta & Trinity Divisions. Powerpoint presentation "Temperature Mgmt of the CVP Northern System - Abbreviated 10 Nov 10.ppt" with 27 slides.

U.S. Bureau of Reclamation (USBR). 2012. Lewiston Temperature Management Intermediate Technical Memorandum, Lewiston Reservoir, Trinity County, California. Report by U. S. Bureau of Reclamation, Mid-Pacific Region, Sacramento, CA. http://www.trrp.net/library/document/?id=1814

U.S. Bureau of Reclamation (USBR). 2016. Klamath River Basin, Study Final Report, Technical Memorandum 86-68210-2016-06. Prepared by the Klamath River Basin Study Technical Working Group. https://www.usbr.gov/watersmart/bsp/completed.html

U.S. Bureau of Reclamation (USBR). 2017. U.S. Department of Interior, Record of Decision, Long-Term Plan to Protect Adult Salmon in the Lower Klamath River, Final Environmental Impact Statement. Report. U.S. Bureau of Reclamation. Available: https://www.trrp.net/library/document?id=2465.

U.S. Bureau of Reclamation (USBR). 2020. Historical Trinity Lake Temperature Profiles. Shasta Lake, California: Northern California Area Office.

U.S. Bureau of Reclamation (USBR) and CDFW. 2017. Hatchery and Genetics Management Plan for Trinity River Hatchery Coho Salmon. Available from the Reclamation Northern California Area Office. Shasta Lake, CA. 117 p.

U.S. Department of Interior. 2000. Record of decision, Trinity River mainstem fishery restoration final environmental impact statement/environmental impact report. Decision by the U.S. Department of Interior, December 2000. http://www.trrp.net/library/document/?id=227

U.S. Forest Service (USFS). 1990. Annual progress report for South Fork Trinity River watershed and fisheries monitoring plan. http://www.trrp.net/library/document/?id=1263

U.S. Forest Service (USFS). 2000. Horse Linto, Mill and Tish Tang Creek Watershed Analysis. Six Rivers National Forest. March. 380 p. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsm9_027585.pdf

U.S. Fish and Wildlife Service (USFWS). 1979. Final report: Hoopa Valley Indian Reservation - Inventory of Reservation Waters Fish Rearing Feasibility Study and a Review of the History and Status of Anadromous Fishery Resources of the Klamath River Basin. USFWS, Arcata Field Station. Arcata, CA. 143 p. https://www.krisweb.com/biblio/trinity_usfws_xxxx_1979_hoopainventory.pdf

USFWS (U.S. Fish and Wildlife Service), USBR (U.S. Bureau of Reclamation), Hoopa Valley Tribe, and Trinity County. 2000. Trinity River Mainstem Fishery Restoration EIS/EIR [Public Draft and Final]. Report. U.S. Fish and Wildlife Service, Sacramento, California. Available: http://www.trrp.net/library/document?id=1238.

U.S. Fish and Wildlife Service (USFWS). 1987. Trinity River Flow Evaluation Study Annual Report - 1987. Report from the USFWS Division of Ecological Services, prepared by the staff of the Trinity River Flow Evaluation Study. http://www.trrp.net/library/document/?id=2034

U.S. Fish and Wildlife Service (USFWS). 1990. Trinity River Restoration Program Mid-Program Review 1986-1990. http://www.trrp.net/library/document/?id=1942

USFWS (U.S. Fish and Wildlife Service) and HVT (Hoopa Valley Tribe). 1999. Trinity River flow evaluation final report. USFWS, Arcata, California and HVT, Hoopa, California. http://www.trrp.net/library/document/?id=226

Van Rij, J., P. Hendriks, H. van Rijn, R.H. Baayen, and S.N. Wood. 2019. Analyzing the Time Course of Pupillometric Data. Trends in Hearing 23:233121651983248. doi: 10.1177/2331216519832483.

Van V., D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose. 2011. The Representative Concentration Pathways: An Overview. Climatic Change 109:5. doi: 10.1007/s10584-011-0148-z.

Vannote R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, C.E. Cushing. 1980. River Continuum Concept. Canadian Journal of Fisheries and Aquatic Sciences 37: 130–137.

Vermeyen, T. 1997. Use of temperature control curtains to control reservoir release water temperatures. http://www.trrp.net/library/document/?id=504

Vermeyen, T. 2000. Application of Flexible Curtains to Control Mixing and Enable Selective Withdrawal in Reservoirs. Presented to the 5th International Symposium on Stratified Flows, IAHR, July 10-13, Vancouver, Canada. 6pp. http://www.project2105.org/TC/PAP-0847.pdf

Vogel, D.A. 2002. Assessment of Klamath River water temperatures downstream of Iron Gate Dam during September and October 2002. http://www.trrp.net/library/document/?id=306

Voight, H.N. and D.B. Gale. 1998. Distribution of fish species in tributaries of the lower Klamath river: An interim report, FY 1996. Technical Report No. 3. Yurok Tribal Fisheries Program, Habitat Assessment and Biological Monitoring Division. Klamath, CA. 80 pp. http://www.krisweb.com/biblio/klamath_yuroktfp_voightetal_1998_3.pdf

Wahl, T.L. and E.A. Cohen. 1999. Determination of Controlled Release Capacity from Trinity Dam. https://www.trrp.net/library/document/?id=224. Accessed April, 2020.

Wang, J., H. Yin, E. Reyes, T. Smith, and F. Chung. (2018). Mean and Extreme Climate Change Impacts on the State Water Project. California's Fourth Climate Change Assessment. Publication Number: CCCA4-EXT-2018-004. https://www.energy.ca.gov/sites/default/files/2019-12/Water_CCCA4-EXT-2018-004_ada.pdf

Wapner, M. 2015. Wetlands Species and Water Temperature Analysis October 1, 2013 through September 30, 2015. Yurok Tribe Environmental Program, Klamath, CA. http://www.yuroktribe.org/departments/ytep/documents/Wetlands_web1.pdf

Ward G.H. and N.E. Armstrong. 2010. Assessment of Community Metabolism and Associated Kinetic Parameters in the Klamath River. Prepared for the U.S. Fish and Wildlife Service, Arcata Office. <http://www.fws.gov/arcata/fisheries/activities/waterQuality/reports/KlamathRiver/KlamathProductionFinal_08062010.pdf>

Watercourse Engineering, Inc. 2002. Trinity Reservoir Temperature Monitoring Study. Report. Watercourse Engineering, Inc., Davis, California. http://www.trrp.net/library/document/?id=2342

Watercourse Engineering, Inc. 2003. Klamath River Water Quality 2000 Monitoring Program – Project Report. Sponsored by U.S. Bureau of Reclamation Klamath Falls Area Office with support from PacifiCorp. Watercourse Engineering, Inc. Napa, CA. 92p.

Watercourse Engineering, Inc. 2007. Trinity River flow and temperature modeling project. http://www.trrp.net/library/document/?id=338

Watershed Research and Training Center (WRTC). 2008. Big Creek Watershed Assessment Report. Contributing consulting firms: Graham Matthews & Associates, North State Resources, Inc., and Lee Benda and Associates, Inc. Prepared for the North Coast Regional Water Quality Control Board by The Watershed Research and Training Center, Hayfork, CA.

Watershed Sciences. 2009a. Airborne thermal infrared remote sensing, middle Trinity River, California. http://www.trrp.net/library/document/?id=370

Watershed Sciences. 2009b. Thermal Infrared Imagery, July 21, 2009. Trinity River Restoration Program Data Package. https://www.trrp.net/library/data/?id=36

Watz, J. and J.J. Piccolo. 2010. The role of temperature in the prey capture probability of drift-feeding juvenile brown trout (*Salmo trutta*). Ecology of Freshwater Fish 20(3):393-399. .https://dx.doi.org/10.1111/j.1600-0633.2010.00470.x

Webb, B.W., D. M. Hannah, R. D. Moore, L. E. Brown, and F. Nobilis. 2008. Recent advances in stream and river temperature research. Hydrological Processes, 22(7), 902–918. https://doi.org/10.1002/hyp.6994

Wedemeyer, G.A., R.L. Saunders, and W.C. Clarke. 1980. Environmental factors affecting smoltification and early marine survival of anadromous salmonids. Marine Fisheries Review 42(6):1-14.

Weidlein, W.D. 1971. Temperature Approximations for the Sacramento and Trinity Rivers Under Year 2020 Water Demand Conditions. Report from the California Department of Fish and Game. http://www.trrp.net/library/document/?id=1508

Weskamp, D.R. 2003. Juvenile Salmonid Emigration Monitoring on the Lower Trinity River, California, 1999-2000. Habitat Assessment and Biological Monitoring Division Technical Report No. 10. Yurok Tribe Fisheries Program, Klamath, CA. http://www.yuroktribe.org/departments/fisheries/documents/1999_00LowerTrinityScrewTrapFINAL_000.pdf

Wheeler, C.A., J.B. Bettaso, D.T. Ashton, and H.H. Welsh Jr. 2015. Effects of water temperature on breeding phenology, growth, and metamorphosis of Foothill Yellow-legged Frogs (*Rana boylii*): a case study of the regulated mainstem and unregulated tributaries of California's Trinity River. River Research and Applications 31:1276–1286. doi: 10.1002/rra.2820. http://www.trrp.net/library/document/?id=2195

Wheeler, C.A., A.J. Lind, H.H. Welsh, and A.K. Cummings. 2018. Factors That Influence the Timing of Calling and Oviposition of a Lotic Frog in Northwestern California. Journal of Herpetology 52:289–298. doi: 10.1670/17-103.

Wilson, S.M., T.W. Buehrens, J. L. Fisher, K.L. Wilson, and J.W. Moore. 2021. Phenological mismatch, carryover effects, and marine survival in a wild steelhead trout Oncorhynchus mykiss population. Progress in Oceanography, 193, 102533. https://doi.org/10.1016/j.pocean.2021.102533

Wistrom, T.V. 1991. Public Hearing to Consider Amending the Water Quality Control Plan for the North Coast Region to Include a Site-Specific Temperature Objective and an Interim Action Plan for the Trinity River. Report from the California Regional Water Quality Control Board. http://www.trrp.net/library/document/?id=1600

Wittler, R., R. Yaworsky, and P. Manza. 2010. Temperature management of the CVP northern system. Oral presentation provided at the 2010 Trinity River Science Symposium. Trinity River Restoration Program, Weaverville, California. http://www.trrp.net/library/document/?id=405

Wood, S.N. 2017. Generalized Additive Models: An Introduction with R (2nd edition). Chapman and Hall/CRC.

Yoshiyama, R.M. and P.B. Moyle. 2010. Historical review of Eel River anadromous salmonids, with emphasis on Chinook salmon, coho salmon and steelhead. University of California, Davis. https://watershed.ucdavis.edu/pdf/Yoshiyama-Moyle_Eel%20River%20Final%20Report%202010.pdf

Yurok Tribe. 2020. 90% design report, Trinity River rehabilitation site at Oregon Gulch. Report to the Trinity River Restoration Program, Weaverville, CA.

Zedonis, P.A. 1994. Estimated influences of feather edge and side-channel projects on water temperatures of the upper Trinity River. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1488

Zedonis, P. 1996. A water temperature model for the Trinity River. U.S. Fish and Wildlife Service, Arcata, CA. http://www.trrp.net/library/document/?id=1486

Zedonis, P. 2001. Empirical and Theoretical Influences of a Pulse Flow from Lewiston Dam on Water Temperature and Dissolved Oxygen of the Lower Klamath River. DRAFT Report # AFWO F2001-01 from the USFWS presented to the Trinity River Management Council. http://www.trrp.net/library/document/?id=2069

Zedonis, P. 2003. Lewiston Dam releases and their influence on water temperatures of the Trinity and Klamath Rivers, California, WY 2002. https://www.fws.gov/arcata/fisheries/reports/technical/Lewiston_Dam_Releases_and_Their_Influence_on_Water_Temperatures_of_the_Trinity_River,_California.pdf

Zedonis, P. 2003. Pulse Flows in the Trinity River in August and September, Thoughts of P. Zedonis July 2, 2003.

Zedonis, P. 2004. Lewiston Dam releases and their influence on water temperatures of the Trinity and Klamath Rivers, California, April to October 2003. Report Number AFWO-F-01-04. http://www.trrp.net/library/document/?id=221

Zedonis, P. 2005a. Lewiston Dam releases and their influence on water temperatures of the Trinity and Klamath Rivers, California, April to October 2004. Report Number AFWO-F-01-05, Arcata, California. http://www.trrp.net/library/document/?id=222

Zedonis, P. 2005b. The Influence of Lewiston Dam Releases on Water Temperatures of the Trinity and Klamath Rivers, CA., April to October, 2004. Arcata Fisheries Technical Report Number TR2005-03 from the USFWS. http://www.trrp.net/library/document/?id=2068

Zedonis, P. 2009. The influence of Lewiston Dam releases on water temperatures of the Trinity and Klamath Rivers, CA. April to October, 2008. Arcata Fisheries Data Series Report Number DS2009-15, Arcata, California. http://www.trrp.net/library/document/?id=445

Zedonis, P. and T. Newcomb. 1997. An evaluation of flow and water temperatures during the spring for protection of salmon and steelhead smolts in the Trinity River, California. http://www.trrp.net/library/document/?id=233

Zedonis, P. and R Turner. 2006. The influence of Lewiston Dam releases on water temperatures of the Trinity and Klamath Rivers, CA., April to October, 2005. Arcata Fisheries Data Series Report Number DS2006-08, Arcata, California. http://www.trrp.net/library/document/?id=223

Zedonis, P. and R Turner. 2008. The influence of Lewiston Dam releases on water temperatures of the Trinity and Klamath Rivers, CA., April to October, 2007. Arcata Fisheries Data Series Report Number DS2008-01, Arcata, California. http://www.trrp.net/library/document/?id=343

Zillig, K.W., A.M. FitzGerald, R.A. Lusardi, D.E. Cocherell and N.A. Fangue. (2023). Intraspecific variation among Chinook Salmon populations indicates physiological adaptation to local environmental conditions. Conservation Physiology, 11(1), coad044. https://doi.org/10.1093/conphys/coad044

Zillig, K.W., R.A. Lusardi, D.E. Cocherell, and N.A. Fangue. 2022. Interpopulation variation in thermal physiology among seasonal runs of Chinook salmon. Canadian Journal of Fisheries and Aquatic Sciences. https://doi.org/10.1139/cjfas-2022-0133

Zillig, K.W., R.A. Lusardi, P.B. Moyle, and N.A. Fangue. 2021. One size does not fit all: Variation in thermal eco-physiology among Pacific salmonids. Reviews in Fish Biology and Fisheries, 31(1), 95–114. https://doi.org/10.1007/s11160-020-09632-w

APPENDIX A DETAILS ON AVAILABLE REPORTS, MODELS, AND DATA

A.1 SUMMARY OF PREVIOUS REPORTS

In the process of preparing this document, we reviewed a large number of previous reports relevant to Trinity River temperature dynamics. These reports are discussed and cited in relevant sections of this report, but here we highlight a few of those we relied on most heavily. Moffett and Smith (1950) provide a unique description of the Trinity River water temperatures prior to dam construction. JSA (1992) modeled temperatures in Lewiston Reservoir and provided a detailed description of its dynamics as well as available historical temperature datasets. Rowell (1979) and Deas (1998a, 1998b) described the thermal dynamics of Trinity River Reservoir, with Rowell (1979) also providing estimates of pre-dam temperatures in the lower Trinity River. Zedonis (1996) and Zedonis and Newcomb (1997) modeled effects of varying dam releases on downstream river temperatures. Jones et al. (2016) describes the readily accessible RBM10 modeling tool for simulating river temperatures under various flow scenarios. The Trinity River Flow Evaluation Study (USFWS and HVT 1999) is a foundational document encapsulating a decade of assessments and proposing a new flow regime for the Trinity River which was analyzed in the Trinity River Mainstem Fishery Restoration EIS/EIR (USFWS et al. 2000) and ultimately adopted in the Trinity River Record of Decision (ROD; USDOI 2000). The River Corridor Management Strategy (Gaeuman et al. 2016) and Juvenile Salmonid Temperature Target Recommendations (Naman et al. 2020) contrast the Trinity River's current dam-affected ROD-based flow and temperature regime with that of unregulated tributaries and the pre-dam river. USFWS annual temperature reports (Section A.3.4, e.g., David and Goodman 2017) and TRRP implementation reports (e.g., Buxton 2020) provide a discussion of temperature dynamics and compliance with temperature criteria in individual years. The Integrated Assessment Plan (TRRP and ESSA 2009) provided a structured framework for assessing TRRP's progress toward objectives including temperature management. The Phase 1 Review from TRRP's Science Advisory Board (Buffington et al. 2014) provided a review of temperature models, temperature criteria exceedance, and recommendations.

A.2 ADDITIONAL INFORMATION ON TEMPERATURE MODELS

A.2.1 RESERVOIR

USBR Central Valley Operations (CVO) currently simulates water temperatures in Trinity and Lewiston reservoirs using numerical models (Wittler 2010, CDWR and USBR 2016). Reclamation's Temperature Model (RTM) simulates monthly mean vertical temperature profiles and release temperatures for Trinity Reservoir and other Central Valley Project (CVP) reservoirs (USBR 2008). The model divides Trinity Reservoir into horizontal layers of identical thickness, each of which is assumed to have the same temperature throughout its volume, and uses monthly data inputs of initial storage and temperature conditions, inflow, outflow, evaporation, precipitation, radiation, and average air temperature (USBR 2008). The upper Sacramento River Water Quality Model (RMA 2003) is an implementation of the HEC-5Q model that simulates mean daily water temperatures for Trinity Reservoir, Lewiston Reservoir, the Trinity River, and the other CVP water bodies (USBR 2008). These two models are adaptions of previous models (Table 1), which include the WQRRS model that is no longer used (Table B17; Deas 1999).

The Box Exchange Transport Temperature and Ecology of Reservoirs (BETTER) model, developed by Dr. Russ Brown (JSA 1992), simulates daily temperatures in Lewiston Reservoir and was used in the Trinity River Mainstem Fishery Restoration FEIR/FEIS (Kamman 1999b, USFWS et al. 2000).

Table B17. Historical modeling applications in the Trinity River Basin (from Deas and Lowney 2000, adapted from Rowell 1998).

River System	Model	System Representation		Simulation Time Step	Reference/ Analyst
		River	Reservoir		
Trinity[1]					
Trinity Reservoir	HEC/USBR[2] (1972/1990)		1-D (V)	Monthly	Rowell, 1990
	WQRRS (1986)		1-D (V)	Hourly	Meyer et al. 1993, Deas et al. 1997, Deas 1999
Lewiston Reservoir	BETTER (1990)		2-D (V/L)	Daily	JSA 1992
	HEC/USBR[2] (1972/1990)		1-D (V)	Monthly	Rowell, 1990
Trinity River	SNTEMP (1984)	1-D (L)		7-day avg	Zedonis, 1997

[1] The Trinity River is included as part of the USBR Central Valley Project

[2] HEC (1972) was modified and adapted by J. Rowell to provide temperature simulation capability throughout the Sacramento River basin. This collection of sub-models that was ultimately referred to as the "Sacramento River Basin Model" and included Trinity, Whiskeytown, Shasta, Oroville, and Folsom Reservoirs; Lewiston, Keswick, Thermalito, and Natoma re-regulating reservoirs; and the Sacramento, Feather, and American Rivers. See also Rowell (1990).

A.2.2 RIVER

TRRP currently uses the River Basin Model-10 (RBM10) model to simulate daily average river temperatures downstream from Lewiston Dam to the confluence of the Klamath and Trinity Rivers, and from Iron Gate Dam on the Klamath River downstream to the mouth of the Klamath River (Perry et al. 2011, Jones et al. 2016). See Sections 2.2 and 2.3.3 for additional details on RBM10.

Previous Trinity River models no longer in use include the weekly average Stream Network Temperature Model (SNTEMP) (Zedonis 1996, Zedonis and Newcomb 1997) and hourly RMA-2/RMA-11 (Watercourse Engineering 2007, Sogutlugil 2012, Sogutlugil and Deas 2012). The Trinity River Flow Evaluation Study (USFWS and HVT 1999) used SNTEMP. Stream Temp is a derivative of SNTEMP that is similar but has different data entry and output presentation (TRRP 2013, 2015).

The Trinity River Mainstem Fishery Restoration FEIR/FEIS (USFWS et al. 2000) used Lewiston Reservoir outflow temperatures predicted by the BETTER model for each of five specific years (1983 extremely wet, 1986 wet, 1989 normal, 1990 dry, and 1977 critically dry) and SNTEMP to predict the percent of time that NCRWQCB temperature objectives would be met under median hydrometeorological conditions. USFWS et al. (2000) also used SNTEMP to predict temperatures downstream at Douglas City and the North Fork Confluence under various combinations of flow (150, 300, 450, 600, 900, and 1,200 cfs) and outlet release temperatures (46 to 60 °C), from which the flow needed to avoid violating water quality standards were calculated.

Previous models of Klamath River water temperature include System Impact Assessment Model (SIAM; Bartholow et al. 2005) and RMA-11 (Watercourse Engineering, Inc. 2003, PacifiCorp

2004, NCRWQCB 2010). These Klamath River models all represent the Trinity River as a boundary condition and do not simulate its temperatures. A three-dimensional model that simulates temperature and other water quality parameters in the Klamath River from Iron Gate Dam to Seiad Valley was recently developed by Javaheri et al. (2018), but this model does not extend downstream to the Trinity River.

A.3 STREAM TEMPERATURE DATA (CONTINUOUS AND/OR DAILY)

We compiled continuous and daily stream temperature data from a multitude of sources for the mainstem Trinity River (Figure 5), Klamath River (Figure A80), and tributaries (Figure A81, Figure A82). We targeted data for acquisition and compilation only if there was more than a week of data, and data were collected with continuous recording equipment. If datasets included sites for both the Klamath and Trinity Basins, we generally compiled data for all sites, particularly for older datasets that were in danger of being lost. However, for large, well organized, currently maintained, and easily accessible datasets (e.g., USFWS's MS Access database, USFWS AqS, and USGS NWIS), we did not compile sites in the middle/upper Klamath basins. If datasets only included sites in the Klamath Basin upstream of Orleans, then we did not compile the data. We prioritized acquisition of older data at risk of being permanently lost.

A.3.1 YUROK TRIBE FISHERIES PROGRAM

The Yurok Tribe Fisheries Program (YTFP) collects temperature data on the lower mainstem Klamath River (McCovey 2003) and its tributaries (Gale 1998, Gale et al. 1998, Voight and Gale 1998, Gale and Randolph 2000, Gale et al. 2003, Beesley and Fiori 2007) including the lower Trinity River. Several different divisions and projects of YTFP are involved in the temperature monitoring, and the names of those divisions have changed since consistent temperature monitoring began in the mid-1990s. Associated projects included thermal refugia (Belchik 1997, Sutton et al. 2002, Belchik 2003, Benson and Holt 2005, Naman 2005, Strange 2011b) and telemetry of adult chinook salmon (Strange 2003, 2005, 2006, 2007, 2008, 2011a) and sturgeon (McCovey 2009a), and pathology of adult chinook salmon (McCovey 2009b, McCovey and Strange 2011). We attempted to obtain all of YTFP's data through the year 2016, and received data from YTFP biologist Jamie Holt, YTFP biologist Sarah Beesley, and USFWS biologist Dan Gale (previously with YTFP). Much of these data were compiled during previous projects (Asarian 2017, Asarian et al. 2020), but additional data were compiled for this project. We were not able to acquire the YTFP's 1999 Klamath River at Omagaar Creek data (Guillen 2003, Belchik et al. 2004).

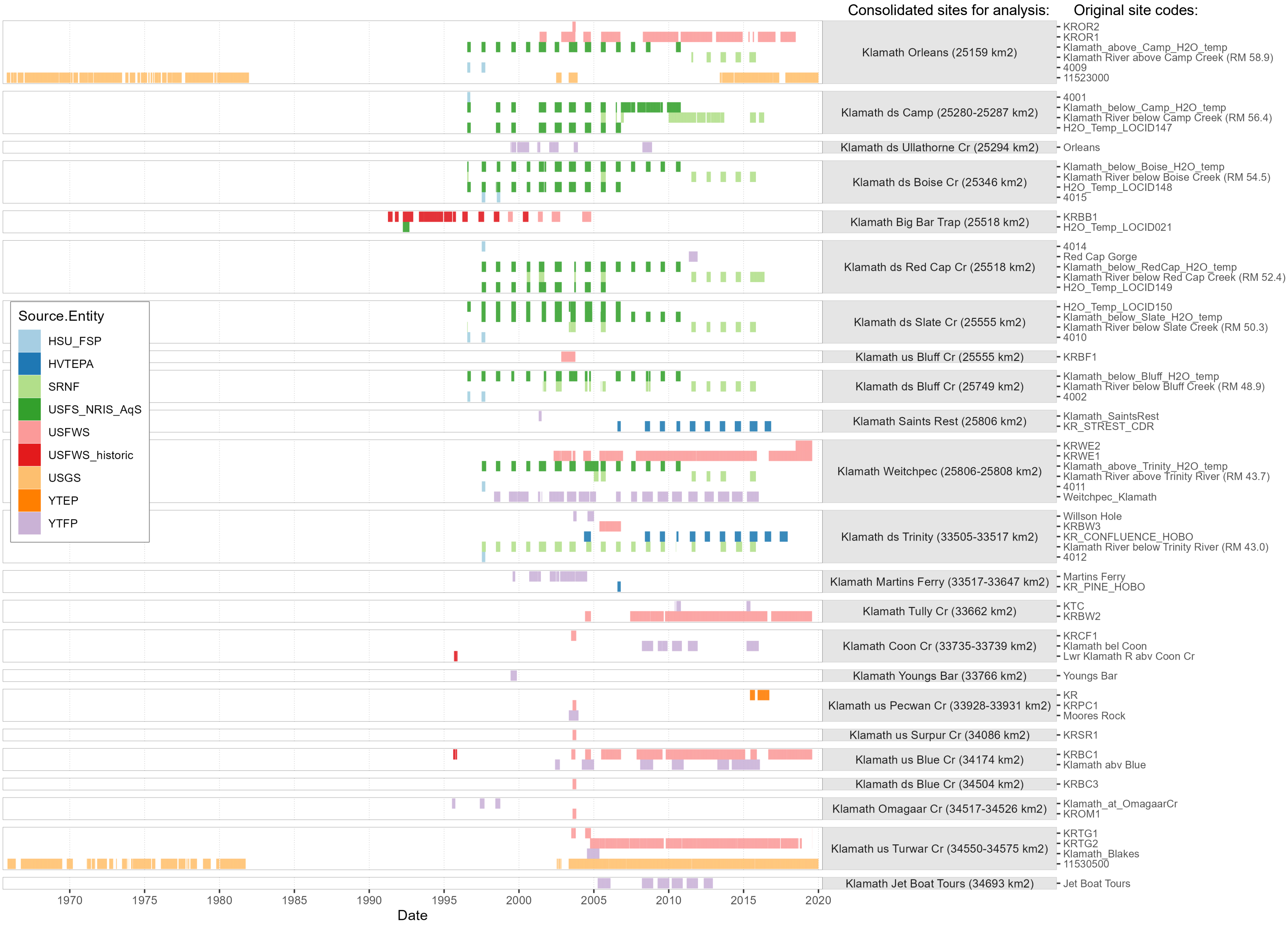


Figure A80. Sources, sites, and dates of Klamath River water temperature data compiled, 1965–2019. us = upstream, rm = river mile, km2 = drainage area in square kilometers.

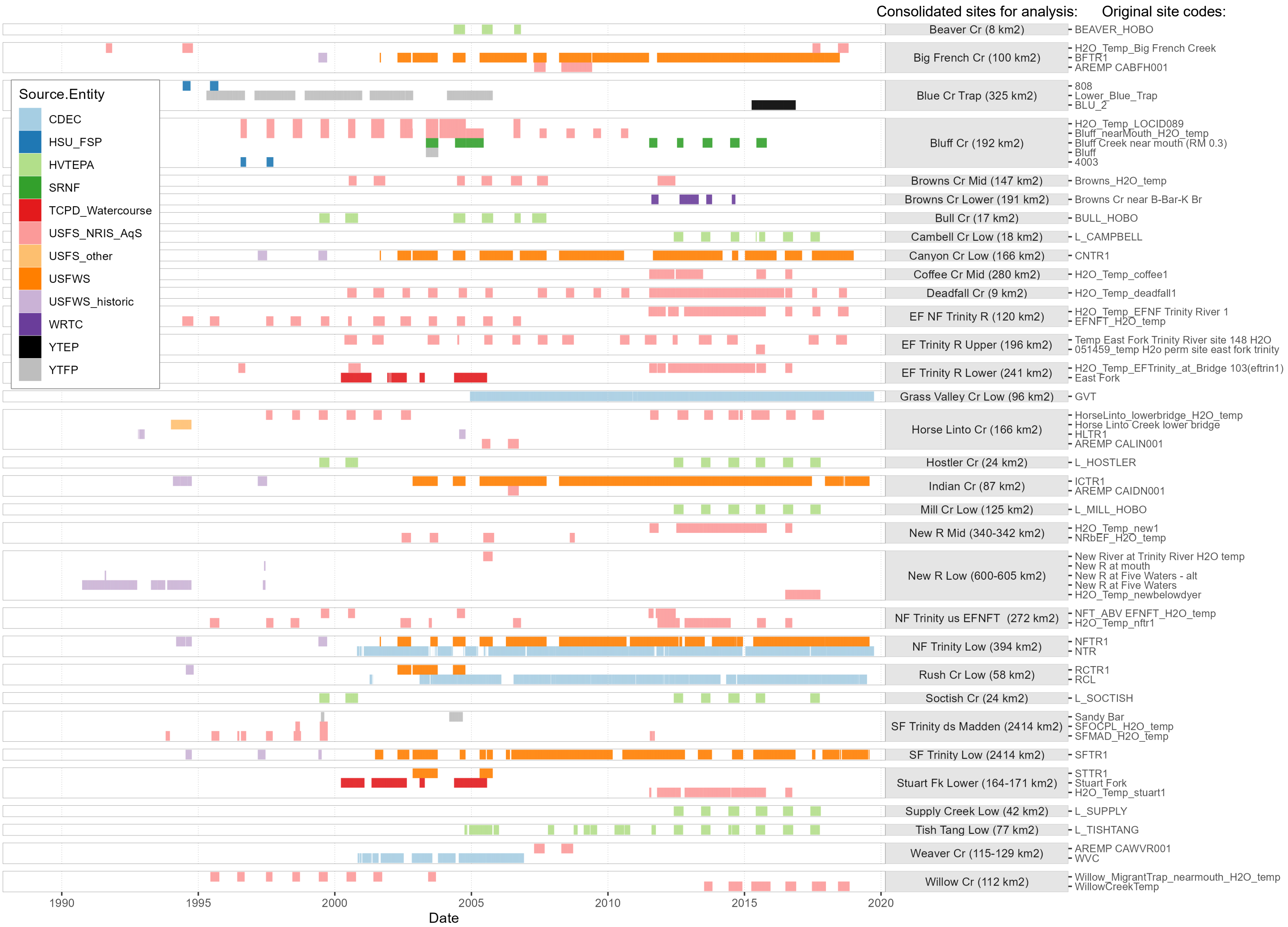


Figure A81. Sources, sites, and dates of long-term tributary water temperature data compiled, 1991–2019. This report analyzes data for only a subset of these sites (i.e., see Figure 7). us = upstream, rm = river mile, km2 = drainage area in square kilometers.

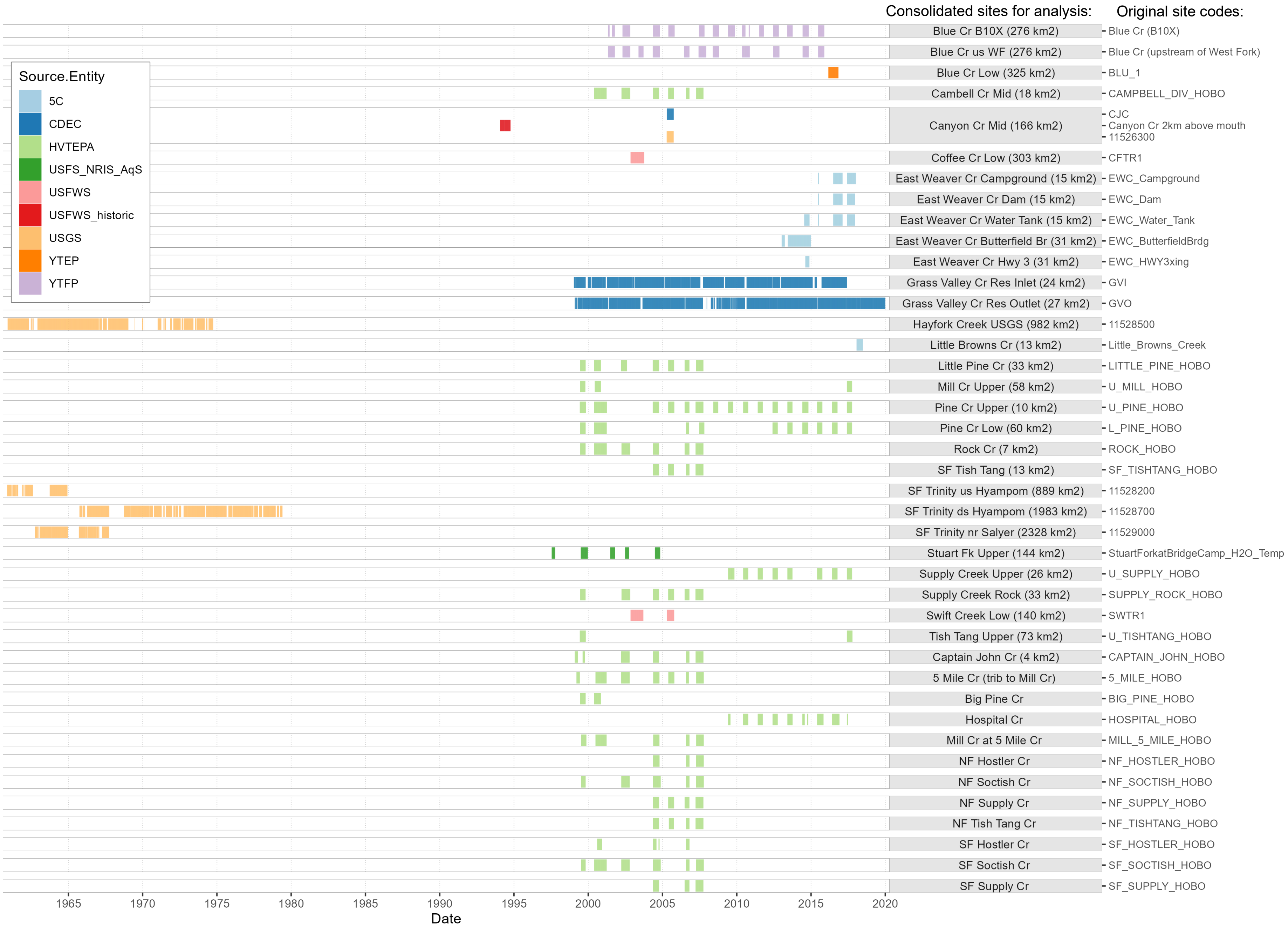


Figure A82. Sources, sites, and dates of other supplemental tributary water temperature data compiled but not used for analyses, 1961–2019. us = upstream, rm = river mile, km2 = drainage area in square kilometers. Drainage area not shown for some streams because they are not in NHDplus GIS layer.

A.3.2 YUROK TRIBE ENVIRONMENTAL PROGRAM

The Yurok Tribe Environmental Program (YTEP[8]) collects stream temperature data at long-term monitoring sites on the Klamath River and tributaries, primarily during the summer season. In addition, from spring 2015 through spring 2017, YTEP installed a network of more than 100 temperature monitoring sites on Lower Klamath tributaries and springs. Nearly all of YTEP's data through spring 2017 were compiled by Asarian (2017) and are available for use in this project.

YTEP also uses multi-parameter sondes to monitor water quality including water temperature at the mouth of the Trinity River and three sites on the Klamath River (McKernan et al. 2004a, 2004b, 2005; Sinnott 2009, 2010, 2011; Ward and Armstrong 2010, Asarian and Kann 2013), although we did not compile or use those data because they largely overlap with the USFWS data and maintained in a database and are not at risk of being lost. Towards the end of our analysis, we realized that these data would have filled some important gaps in our temperature records, including 2001 Klamath River at Turwar.

YTEP has also monitored water temperatures in wetlands around the Klamath River Estuary as part of wetland assessments (Patterson and Beesley 2011, Wapner 2015).

A.3.3 U.S. FOREST SERVICE

Most water temperature data collected by U.S. Forest Service (USFS) within the study area are input into the national Natural Resource Information System (NRIS) Aquatic Surveys (AqS) database. We received the NRIS AqS data for the entire study area from hydrologist Callie McConnell of the USFS office in Corvallis in March 2019 but compiled only the subset useful for our analyses.

USFS data collected within the Six Rivers National Forest's Lower Trinity Ranger District for years after 2010 have not yet been entered into NRIS AqS but are available by request from USFS biologist Leroy Cyr. The main sites of interest for this project (Trinity River mouth, Klamath River above Trinity confluence, and Klamath River below Trinity confluence) were compiled for the Asarian et al. (2020) Klamath Basin analysis and are also monitored by the USFWS (see below).

We acquired and compiled two additional small stream temperature datasets from Six Rivers National Forest datasets that are not in NRIS AqS. These are 1) hourly stream temperature data at a flow monitoring gate on lower Horse Linto Creek for October 1992 to January 1993 (Zedonis 1996, USFS 2000), and 2) daily data for the same site for January–September 1994. We also acquired water temperature, discharge, and turbidity data for the same site for parts of 1999–2000, but did not have time to compile it. Additional years of data were collected at this site but appear to have been lost.

---

[8] http://www.yuroktribe.org/departments/ytep/water_reports.htm

A.3.4 U.S FISH AND WILDLIFE SERVICE

A.3.4.1 MICROSOFT ACCESS DATABASE OF CURRENT DATA

The U.S. Fish and Wildlife Service[9] (USFWS) office in Arcata, California collects stream temperature data at a network of monitoring sites within the Klamath and Trinity River basins and maintains the data in a Microsoft Access database. Data were received from USFWS fisheries biologist Christian Romberger in October 2018. Most of the data span from 2001 to 2017, but there are few sites with data in 1998 and 1999. Annual reports are available for 2002–2016 (Zedonis 2003, Zedonis 2004, Zedonis 2005a, Zedonis 2005b, Zedonis and Turner 2006, Zedonis and Turner 2008, Zedonis and Turner 2009, Scheiff and Zedonis 2010, Scheiff and Zedonis 2011, Scheiff and Zedonis 2012, Magneson 2013, Magneson 2014, Magneson and Chamberlain 2015, David and Goodman 2017, Romberger and Gwozdz 2018).

A.3.4.2 KLAMATH/TRINITY DATA NOT IN CURRENT VERSION OF USFWS DATABASE (1997–2005)

Riverbend Sciences has an archived 2007 version of the USFWS Arcata's Microsoft Access database that contains additional data for the years 1997–2005 that has been removed from the current version of the database. These include a variety of Klamath/Trinity mainstem and tributary sites. No current and former USFWS staff we contacted knew why these data had been deleted, so we conducted a thorough review to determine what unique high-quality datasets should be salvaged from the old database. We concluded that some data were likely intentionally deleted because they were exact copies of datasets from other entities (CDEC and USFS). Some of the deleted data appeared to be erroneous (i.e., inconsistent with later years), suggesting it was intentionally deleted. Most of the data we salvaged were collected from 1999, but there were also one or two sites each from 1998, 2000, 2001, and 2004. We sent the results of our review, including a copy of all apparently good and unique data, to USFWS Arcata for them to consider adding to the current MS Access database.

A.3.4.3 TRINITY RIVER AT LEWISTON FROM MOFFETT AND SMITH (1942–1946)

Moffett and Smith (1950) monitored water temperatures in the Trinity River prior to construction of Trinity and Lewiston dams. Daily Trinity River at Lewiston temperatures for November 1942 – August 1946 presented in report tables were transcribed into spreadsheets for the 1999 Trinity River Flow Evaluation Study (USFWS and HVT 1999), and Paul Zedonis (formerly USFWS, now UBSR) provided us with the spreadsheets. The 1942–1944 temperature measurements are from 8am and 4pm, intended to approximate daily minimum and maximum. For our analyses, we treat them as daily minimum and maximum, and average them together to approximate a daily mean. Moffett and Smith (1950) also included tables with daily temperatures of Trinity River at Junction City for July 1945–July 1946, but we did not transcribe these.

A.3.4.4 TRINITY RIVER MAINSTEM DATA FROM ANNUAL FLOW EVALUATION REPORTS (1987–1989)

Annual Trinity River flow evaluation reports from the late 1980s show graphs and tables of mainstem Trinity River water temperatures (Staff of the Trinity River Flow Evaluation 1987, 1988, 1989). We were able to acquire most of these data from Paul Zedonis and transcribe most of the remaining 1988 (Trinity River at Willow Creek) and 1989 data (Trinity River at Hoopa

---

[9] http://www.fws.gov/arcata/fisheries/activities/waterQuality/klamathWQ.html

and Steelbridge) from the tables in the report appendices. Upon further evaluation, the Steelbridge data for 1989 appear to be erroneous[10] so we excluded them from our compilation. Unfortunately, for the remaining 1989 site, Trinity River at Lewiston, the data in the appendix table appear to be corrupted so we did not compile them because we were not confident that the temperature values were attached to the correct dates[11]. On the other hand, the report graphs of the Lewiston 1989 data do appear coherent, so with considerable effort including matching Lewiston water temperatures to flow, air temperature, and water temperature at other sites, it might be possible for future users to salvage the data. For 1987, we were only able to obtain the electronic data for three mainstem Trinity River sites. Future users could digitize the remaining 1987 mainstem (Evans Bar) and tributary (Browns, Canyon, Grass Valley, Indian, Reading, Rush, and Weaver creeks) daily average data from report graphs (Staff of the Trinity River Flow Evaluation 1987).

A.3.4.5 TRINITY RIVER MAINSTEM AND TRIBUTARY DATA FROM ZEDONIS (1988–1994)

Zedonis (1996) includes graphs of data for mainstem Trinity River data for 1988–1994 that are not available in other historical sources such as CDEC or USGS. These include but are not limited to: 5/1990-9/1990 at Douglas City; 10/1987-9/1988 and 8/1991 - 9/1994 at Steelbridge; 10/1987-9/1994 at Trinity Canyon Lodge; 10/1989-12/1989 and 10/1990 - 9/1994 at Burnt Ranch[12]; 2/1991 - 9/1994 at Willow Creek; and 7/1991-9/1994 at Weitchpec Falls[13]. Some of these data are also shown in the 1987–1989 annual flow evaluation reports (see previous section above). There are also some additional early 1990s data for tributaries which are shown on pages 57 to 65 (Rush, Indian, Canyon, NF Trinity, Big French, New River, SF Trinity, and Horse Linto). We were able to obtain electronic versions of all these data. There is uncertainty regarding the location and representativeness of the 1994 Rush Creek data (Zedonis, pers. comm.), so we compiled only the second deployment (late July through October) not the first deployment which contained some very high temperatures.

A.3.4.6 TRIBUTARIES OF THE LOWER KLAMATH RIVER AND TRINITY RIVER (1977–1978)

USFWS (1979) includes graphs (and/or tables) of water temperatures in the Hoopa Valley Indian Reservation, prior to the Yurok Indian Reservation being split from the Hoopa Valley Indian Reservation. Tributary data includes 1977–1978 temperatures at Pine Creek Supply Creek, Terwer Creek, Pecwan, Ah Pah Creek, and Hostler Creek, and 1974–1978 data at Tish-Tang Creek. Mainstem data include the top of bottom of water column in Klamath River near Requa and Klamath River near Sportsman's Camper Park. Since these data are primarily presented as graphs rather than tables, we did not take the time to digitize, but that could potentially be done in the future.

---

[10] Three lines of evidence suggest that the 1989 Steelbridge temperatures are not reliable. First, Steelbridge temperatures should be intermediate between upstream (Lewiston) and downstream (North Fork) temperatures but this was not the case in 1989. Second, Steelbridge winter temperatures were many degrees warmer in 1989 than any other year. Third, Paul Zedonis did not include them in his master compilation of Trinity River temperature data.

[11] the 12th of every month is missing, and there is a value listed for April 31 even though that month has only 30 days

[12] Trinity River at Burnt Ranch data for May-Oct 1992 are available at http://www.krisweb.com/krisklamathtrinity/krisdb/webbuilder/mt_cst11.htm

[13] Trinity above Weitchpec for July-Oct 1991 are available at: http://www.krisweb.com/krisklamathtrinity/krisdb/webbuilder/mt_cst19.htm

A.3.4.7 NEW RIVER (1989–1998)

USFWS deployed a Ryan TempMentor probe at river kilometer 3.5 in the New River to collect year-round temperatures from 1988 until at least 1998. Graphs are shown in Shaw et al. (1992), Longenbaugh et al. (1995), Magneson et al. (1996), Zedonis and Newcomb (1997), and Lang et al. (1999), but we the only electronic versions of these data we were able to acquire were daily averages for 10/1/1990–9/30/1994 and 5/15/1997–6/15/1997 , and daily minimum, maximum, and average for 7/31/1991–8/16/1991. USFWS also monitored temperatures at 11 additional sites in the New River sub-basin in May-September of 1997 using Optic StowAway probes. Lang et al. (1999) graphed some of the 1997 data but we were not able to locate the electronic data. Appendices in Lang et al. (1999) provide a table of daily flow data for May–July 1996–1998. If these data still exist anywhere, it would likely be on a floppy disc somewhere in the USFWS Arcata office.

A.3.4.8 BLUE CREEK (1988–1993)

Gale (1998) noted that USFWS monitored temperatures data in lower Blue Creek in 1988–1992. These data are shown in graphs in Longenbaugh and Chan (1994), Chan and Longenbaugh (1994), Gilroy et al. (1992), and Stern and Noble (1990) but we were unable to acquire electronic versions of these data. If these data still exist anywhere, it would likely be on a floppy disc somewhere in the USFWS Arcata office.

A.3.4.9 LOWER KLAMATH RIVER (1995)

USFWS deployed multi-parameter Hydrolab water quality sensors at two locations on the mainstem Klamath River in 1995 (Guillen 2003): above Blue Creek and above Coon Creek. We downloaded these data from the Klamath Resource Information System (KRIS)[14].

A.3.4.10 KLAMATH RIVER AT BIG BAR TRAP (1991–2000)

In the early 2000s, USFWS Arcata compiled a file of water temperature data collected in the Klamath River at the Big Bar Trap for 1991–2000. Only daily summaries were available for August–December 1992[15] and January–December 1995, while the remainder of the data are every two hours. The 1998–2000 data overlap with the contents of the USFWS 1997–2005 Access database (see above), so we only used the 1991–1997 data. Data were also collected in 1989 (Craig 1991) and 1990 (Craig 1992), but these data have been lost. Data for 1991–1996 were collected with Ryan TempMentors (Goldsmith 1994, Lang et al. 1998) while Onset Stow Away Tidbits were used starting in 1997 (Scheiff et al. 2001).

A.3.4.11 TRINITY RIVER AND TRIBUTARIES (1999)

USFWS Arcata did two rounds of temperature deployments in 1999. For most sites, the first round never made it into a database but we were able to acquire spreadsheets from Paul Zedonis and compile them. The data appear to be high quality. The second round was loaded into the MS Access database, but later deleted for unknown reasons (see above).

---

[14] http://w.krisweb.com/krisklamathtrinity/krisdb/webbuilder/lk_cst8.htm

[15] Note: a separate dataset of Big Bar daily summary (minimum, maximum, average) water temperatures for 4/1/1992 – 9/8/1992 was compiled by the North Coast Regional Water Quality Control Board and is available online at: http://www.krisweb.com/krisklamathtrinity/krisdb/webbuilder/mk_cst27.htm

A.3.4.12 MAINSTEM KLAMATH AND TRINITY RIVER SONDE DATA (2001–2005)

Continuous water quality data collected in the mainstem Klamath and Trinity Rivers in 2001–2006 with multi-parameter datasondes by the USFWS, Yurok Tribe, Karuk Tribe were corrected and compiled into a database by USFWS and contractors (Ward and Armstrong 2010). The data largely overlap with other datasets so we did not compile them, although towards the end of our analysis, we realized that these data would have filled some important gaps in our temperature records, including 2001 Klamath River at Turwar.

A.3.5 U.S. GEOLOGICAL SURVEY

The U.S. Geological Survey's (USGS) National Water Information System (NWIS) has historical daily summary water temperature data for several gage sites on the Trinity River (Lewiston, Limekiln, Burnt Ranch, and Hoopa), tributaries (South Fork Trinity and North Fork Trinity), and Klamath River (Klamath and Orleans). We have downloaded and compiled all available daily data within the Trinity and Lower Klamath basins. When true daily averages were not available, as was common in previous decades, we calculated them as the average of the daily minimum and maximum. For recent years (approximately 2007, but varies by site), USGS NWIS also includes continuous (15-minute) data from which the daily summaries are derived, but we did not download these data because there are few additional days beyond what is available as daily summaries. USGS NWIS also includes some "instantaneous" measurements, particularly in past decades (data at Hoopa start in July 1959), but these data are not necessarily representative of entire days so we did not use them, although future users would be justified to use them during high-flow portions of the year when there is little temperature variability at sub-daily time scales.

A.3.6 CALIFORNIA DATA EXCHANGE CENTER (CDEC)

The California Data Exchange Center (CDEC) includes water temperature data for the Trinity River at Hatchery, at Lewiston, below Limekiln Gulch, at Douglas City, above NF Trinity River, and at Hoopa. Tributary sites with relatively long water temperature records in CDEC are the NF Trinity River, Rush Creek, and two sites on upper Grass Valley Creek. There are also some early/mid 2000s water temperature data for lower Grass Valley Creek, Weaver Creek, and Canyon Creek.

A.3.7 CALIFORNIA DEPARTMENT OF WATER RESOURCES

The California Department of Water Resources (CDWR) Water Data Library includes continuous water for the Trinity River at Hoopa[16] for 2001–2019 and Trinity River at Weitchpec[17] for 2002–2018. We are unclear if these data are unique or if they overlap with other datasets and have not compiled them due to abundant data already available at these sites from other sources.

A.3.8 U.S. BUREAU OF RECLAMATION

Most of the temperature data collected by the U.S. Bureau of Reclamation (USBR) in the Trinity Basin are distributed through CDEC (see CDEC section above); however, USBR does collect some additional data, primarily short-term deployments (from a few weeks up to a few years) at

---

[16] https://wdl.water.ca.gov/ContinuousData.aspx?site2=F4108000

[17] https://wdl.water.ca.gov/ContinuousData.aspx?site2=F4100000

channel rehabilitation sites. We requested and received these data from TRRP data steward Eric Peterson. We did not use these data because our focus in this report was on long-term analyses and these data are not at risk of being lost; however, there are a few sites such as Weaver Creek which in the future could be combined with other datasets to extend their periods of record.

In 2000, USBR and PacifiCorp funded Watercourse Engineering (2003) to collect water temperature and other continuous water quality data across many sites in the Klamath Basin. In our study area, these data include March–November at Young's Bar in the Klamath River and May–November in the Trinity River at Hoopa. We did not compile or use these data. These continuous water quality data, including water temperature, are also now available in the USGS Data Grapher[18] and USGS Klamath River Basin Water-Quality Mapper [19](Smith et al. 2018). We are unclear on if the grab sample data have been included in the USGS NWIS database[20]. All of the Watercourse (2003) data were compiled into a Microsoft Access database by TetraTech (2004) along with other datasets as part of the Klamath River TMDL.

A.3.9 HOOPA VALLEY TRIBAL ENVIRONMENTAL PROTECTION AGENCY (HVTEPA)

The Hoopa Valley Tribal Environmental Protection Agency (HVTEPA) has monitored water temperatures within the Hoopa Valley Indian Reservation since 1998. The number of sites varies annually, but typically includes two sites on the Trinity River, one site on the Klamath, and five to 15 tributary sites. We obtained the 1998–2017 data from HVTEPA database coordinator Brian McCaughey and compiled them. Except for lower Tish Tang Creek which was already compiled for use in the RBM10 model (Jones et al. 2016), we did not compile HVTEPA's multi-parameter (e.g., stage, turbidity, air temperature, water temperature, etc.) continuous data from the 1990s and early/mid 2000s because those data were primarily stored as individual files for each multi-week deployment which would have been labor-intensive to compile. Due to staff turnover, we were unable to determine exact locations and spatial coordinates for 10 sites monitored during the years 1999–2007.

A.3.10 CALIFORNIA DEPARTMENT OF FISH AND WILDLIFE

California Department of Fish and Wildlife's (CDFW, formerly known as California Department of Fish and Game, CDFG) Weaverville Office deployed water temperature probes longitudinally along the South Fork Trinity River in 2015 as a one-season study to capture the unique drought-year conditions (Hill 2016). These data were provided for use in Asarian (2016) and were also used for this project.

CDFW annual monitoring reports for some years (e.g., Sinnen et al. 2006, 2010) show temperature data for the mainstem Trinity River at the Willow Creek and Junction City weirs that are not available from other sources. We did not seek to acquire these data because they only cover only a relatively short period of the year and other nearby sites are usually available. Annual reports show graphs of data collected in 1989 (Craig 1991, graphs are only weekly averages), 1990 (Craig 1992, graph shows daily data), and 1991 (Goldsmith 1994). We obtained the 1991 Willow Creek data from Paul Zedonis, but electronic versions of the 1989 and 1990

---

[18] https://or.water.usgs.gov/cgi-bin/grapher/graph_setup.pl?basin_id=klamath
[19] https://or.water.usgs.gov/projs_dir/klamath_wq_mapper/#
[20] https://waterdata.usgs.gov/nwis

data have been lost and future users wishing to access the data will have to digitize from report graphs. Documentation for the 1992–1995 data is available in Lang et al. (1998).

CDFG also monitored temperatures at 21 sites in 2001 and 2002 in Trinity River tributaries as part of a steelhead monitoring project (Garrison 2002, 2003). We requested these data from CDFW but they were unable to locate them. The reports include tables with spatial coordinates and annual maximum temperatures.

In the years 1998–2000, CDFG deployed probes to monitor summer temperatures in streams across the California's North Coast associated with coho presence/absence surveys. Justin Garwood from CDFW's Arcata office provide us with these data as well as copies of field maps from survey reports (Clinton et al. 1998a, 1998b, 1998c, 1998d, 1998e, 1998f, 1998g; Jong 1998a, 1998b; Lenz et al. 2000a, 2000b, 2001a, 2001b; Metcalfe 2000a, 2000b, 2000c) included in CDFW's coho document library (Garwood 2012). We only compiled the data for Klamath/Trinity tributaries but retained copies of the data for other geographic areas.

CDFG operated thermographs associated with fish weirs on Hayfork Creek and on the South Fork Trinity River at Forest Glen Campground, Gates, and Sandy Bar in the early 1990s (Jong and Mills 1992; CDFG 1992a, 1992b, 1994, 1995,1996a, 1996b). We acquired the trap databases which appear to include the daily minimum and maximum water temperatures on days when the trap was operating; however, the files are not thoroughly documented and temperature values do not match those in the report graphs, so we did not compile them. Future users wishing to obtain those data could digitize them from report graphs. There may be additional days of data in paper files in the CDFW Arcata office (Wade Sinnen, pers. comm).

A.3.11 MURRAY REPORTS ON LEWISTON FISH TRAPPING FACILITIES (1958–1961)

During construction of Trinity and Lewiston dam, adult salmon and steelhead were trapped at Lewiston and transported either upstream of the dam or downstream. Associated reports by Murray (1960, 1961, 1962) provide tables with daily maximum and minimum water temperatures for the Trinity River at Lewiston for most days beginning September 29, 1958 through June 30, 1961. The dams began retaining water in late January 1961, so these 1958–1961 data are valuable record of an unregulated Trinity River. We transcribed the data from September 29, 1958 through June 30, 1960 data (Murray 1960, 1961), but not the July 1, 1960 through June 30, 1961 data because the USGS started recording daily Trinity River temperatures nearby at gage 11525500 in July 1959.

A.3.12 TRINITY COUNTY PLANNING DEPARTMENT AND WATERCOURSE ENGINEERING

Watercourse Engineering and the Trinity County Planning Department (TCPD) collected stream temperature data from March 2000 to June 2002 for three sites upstream of Trinity Reservoir: Stuart Fork, East Fork Trinity, and upper Trinity River (Watercourse Engineering 2002). The executive summary of the report notes that a data CD was produced containing all data, but we were unable to locate a copy of the CD. We were able to compile a version of the data by combining files obtained from Mike Deas of Watercourse Engineering and Tom Stokely, formerly with TCPD.

A.3.13 FIVE COUNTIES SALMONID CONSERVATION PROGRAM

As part of the East Weaver Creek dam removal project, the Five Counties Salmonid Conservation Program[21] (5C) has monitored stream temperatures at several sites on East Weaver Creek from 2013 to present. It also monitored temperatures in upper Little Browns Creek in 2018. We obtained the 2013–2017 data and part of the 2018 data from 5C assistant engineer Oliver Rogers.

A.3.14 ADDITIONAL STREAM TEMPERATURE DATASETS ACQUIRED BUT NOT COMPILED OR NOT USED IN ANALYSIS

Due to time and budget constraints, we acquired some datasets that either we did not have time to finish compiling or were in small tributaries (or tributaries of tributaries) so we did not prioritize for use in analysis. These datasets are available upon request, but likely will not be merged into the master database or uploaded to the TRRP DataPort. Some of these data are mentioned above in Sections A.3.1 through A.3.14 while the remainder are described in the subsections below:

A.3.14.1 U.S. FOREST SERVICE, REDWOOD SCIENCES LAB

The U.S. Forest Service’s Pacific Southwest Research Station in Arcata, California (aka Redwood Sciences Lab, RSL) has collected stream temperature data as part of several research projects in the Trinity Basin. Some of these data have already been entered into NRIS AqS. Asarian (2016) compiled data for Hayfork Creek above Shiell Gulch. We obtained upper West Weaver Creek temperature data for hydrologic years 2007–2018 from RSL biologist Rodney Nakamoto, collected during studies of a major water diversion (Harvey et al. 2014). Other RSL datasets that we obtained but did not compile are stream temperature data on the South Fork and mainstem of the Trinity River from Ashton et al. (2015) turtle studies in 2005 and 2006 (2007 data were collected but could not be found) and Wheeler et al. (2018) frog studies in 1994. We also obtained temperature data collected by Wheeler et al. (2015) in shallow water at the edge of several Trinity River tributaries in 2008 and 2009, but these data do not necessary represent well-mixed stream temperatures.

A.3.14.2 HUMBOLDT STATE UNIVERSITY'S FOREST SCIENCE PROJECT

Humboldt State University’s (HSU) (now known as CalPoly Humboldt) Forest Science Project (FSP) compiled data from the North Coast of California for 1990–1998 from a multitude of entities, including private timber companies, state and federal agencies, non-profit organizations, and consultants (Lewis et al. 2000). The FSP was later renamed the Institute for Forest and Watershed Management and is now dissolved. The data are extremely well organized and were rigorously reviewed during the Lewis et al. (2000) analysis, but one deficiency of the version of the publicly shared version of the database is that there is no way to ascertain which entity collected any particular piece of data, which inhibits transparency and made it difficult to determine potential overlap with other datasets. FSP data for the South Fork Trinity River sub-basin were compiled by Asarian (2016) while data for the remainder of the Trinity River basin were compiled by NorWeST (Isaak et al. 2017).

A.3.14.3 RIVERBEND SCIENCES

Riverbend Sciences monitored stream temperatures at ten sites near Weaverville in summer 2015, primarily in West Weaver Creek but also in Weaver Creek and Sidney Gulch. We acquired

---

[21] https://www.5counties.org/

but did not compile these data.

A.3.14.4 THE WATERSHED RESEARCH AND TRAINING CENTER

The Watershed Research and Training Center[22] (WRTC) is a community-based non-profit organization located in Hayfork, California. Since 2010, the WRTC has been collecting water temperature data in the South Fork Trinity River watershed as well as some streams in the adjacent mainstem Trinity River watershed. WRTC's 2010–2015 data were compiled by Asarian (2016), from which we used only a single site: Browns Creek near B-Bar-K Bridge. We have acquired WRTC's 2016–2021 data but did not compile them.

A.3.14.5 GREEN DIAMOND RESOURCE COMPANY

Green Diamond Resource Company[23] (GDRC) is a private, family-owned forest products company that owns and manages forest land in California, Oregon, and Washington. GDRC used to own land on South Fork Mountain near Hyampom, including a large portion of the Pelletreau Creek watershed, and collected stream temperature data at several sites on the property from 1998 until 2012, when the land was sold to a new owner (New Island Capital). GDRC shared annual data summaries for use in Asarian (2016).

A.3.14.6 GRAHAM MATTHEWS AND ASSOCIATES

Graham Matthews and Associates monitored temperatures at two sites on Big Creek near Hayfork during 2007 and 2008 (WRTC 2008). Asarian (2016) was only able to obtain a subset of the data at both sites (May-December at Hwy 3 and May-September at Road 324). The graphs in the appendices to WRTC (2008) show additional data were also collected in January-May 2007 and December 2007 through June 2008, but the original electronic files appear to be lost (Asarian 2016).

A.3.14.7 OREGON STATE UNIVERSITY

The Bartholomew Lab at Oregon State University has monitored year-round temperatures in the Klamath River as part of fish health research since 2008 (Bartholomew 2011). Sites include Klamath River at Interstate 5, Beaver Creek, Seiad Valley, Orleans, and Tully Creek. We acquired the 2008–2014 data from OSU's Julie Alexander, but did not have time/budget to compile them.

A.3.14.8 ADDITIONAL STREAM TEMPERATURE DATASETS NOT ACQUIRED OR COMPILED, OR ARE NO LONGER AVAILABLE

In addition to portions of the data sources listed above, we are aware of additional datasets that we did not acquire or compile because they are no longer, or are not yet, available:

- Asarian (2016) attempted to acquire several other South Fork Trinity River datasets but was unable to obtain the original electronic data. These include portions of the Graham Matthews and Associates data from Big Creek in 2007–2008; and CDFW data from 2015 (see Asarian 2016 for details).
- The original North Fork Trinity River temperature data collected by Nakamoto (1994), including pool stratification, has been lost and is no longer available.

---

[22] http://www.thewatershedcenter.com/?page_id=645

[23] https://greendiamond.com/responsible-forestry/research/fisheries/

- During the late 1990s, the Timber Products Company[24] (TPC) collected temperature data in some streams in the SFTR watershed. Most of those data were likely included in the HSU FSP database, however, a map in Farber et al. (1998) shows some sites on western tributaries to the SFTR that were not included in the HSU FSP database. Former TPC employee Stuart Farber provided annual summaries for these sites from the year 1997 for use in Asarian (2016). TPC subsequently requested that these data not be used in future analyses.
- Green Diamond Resource Company (GDRC) monitors stream temperatures data at large number of streams on its timber lands along the Lower Klamath River as part of their Aquatic Habitat Conservation Plan (AHCP) (GDRC 2006). The company declined requests to share the data with Asarian (2017) so we did not contact this for this project, but some portions of older data (1990–1998) might be included in the HSU FSP compilation (Section A.3.14.2 above).
- Oregon State University doctoral student David Roon is intensively monitoring temperatures (tens of probes per creek) associated with a riparian thinning experiment in the West Forks Tectah Creek and East Forks Tectah Creek on Green Diamond Resource Company Land (Roon 2017, GDRC 2017). The project runs for at least the years 2016–2017.

A.4 TRINITY RESERVOIR TEMPERATURES

Since the year 2000, USBR has measured temperature depth profiles in Trinity Reservoir approximately once per month. We acquired these data for January 2000–March 2020 from USBR's Randi Field (USBR 2020). USBR was also able to provide a supplemental archival spreadsheet of 155 additional temperature depth profiles spanning the years 1972–1989 and 1998–1999 (USBR 2020). We compiled the 1972–2020 data for this report (although Oct. 2019–Mar. 2020 were accidentally excluded from analyses), available as Electronic Appendix 6.

The 1972–1989 profiles, in addition to six profiles from 1990 and 1991, are also available in U.S. EPA's legacy version of the STORET database, although we did not use them because we had already completed our Trinity Reservoir analysis prior to discovering these data. Some temperature depth profiles from earlier years are graphed in previous reports, including 1961–1968 (Weidlein 1971), 1964 (Rowell 1979), 1974–1976 (Rowell 1979), 1987 (Rowell 1990), 1986–1994 (Deas et al. 1997, Deas 1998b, Watercourse Engineering 2002), 1991 (Smith 1991, Bender 2012), 1967–1991 (USBR 1997), 1999 (RMA 2003). Users wishing to compile a fully complete record of depth profiles could download the 1990–1991 data from STORET and digitize additional data from graphs for the years 1961–1968, 1987, 1993, and 1994 in the reports cited above from which we were not able to obtain data in tabular electronic form. USBR collected relatively few temperature profiles in the 1990s due to lack of equipment (Gregory Gotham, pers. comm.). Water temperatures of Trinity Reservoir's outlets are typically inferred from the depth profiles rather than directly measured, although USBR has monitored temperatures on the outside of the penstocks in at least some years (JSA 1992).

A.5 OTHER WATER TEMPERATURE DATA

A.5.1 LEWISTON RESERVOIR TEMPERATURES

USBR has also measured Lewiston Reservoir temperature depth profiles in some years. For the years 1978–1991, 108 of these profiles are available in U.S. EPA's legacy version of the STORET database. We did not attempt to determine if more recent data exists, nor attempt to

---

[24] http://www.timberproducts.com/About_Us/

obtain it, although Watercourse Engineering 2007 noted that profile data collection continued. The JSA (1992) BETTER model includes a 1960–1990 data atlas of hydrological, meteorological, and water temperature data including daily data at the Lewiston Hatchery intake, daily data for various depths of Lewiston Reservoir, and Lewiston Reservoir profiles. Kamman (1999b) added 1991–1993 to the BETTER model package. We obtained the entire 1960–1993 package from Greg Kamman and uploaded it to the TRRP DataPort (Kamman 1999a). Beyond the USBR Lewiston Reservoir profiles available in STORET, the BETTER package includes many additional Lewiston Reservoir profiles collected by DWR (Boles 1985, 1987), CDFW, and USFWS (JSA 1992), as well as possibly additional USBR data.

Annual reports with tables and/or graphs of daily Trinity River Hatchery temperatures for 1968–1992 are available on TRRP ODP[25] (e.g., Bedell 1969 and 1991). Trinity River Hatchery temperatures for 1996 to present are available on CDEC as station LFH. Since 1958, Trinity River Hatchery managers have manually recorded morning and afternoon (typically 7 am and 3 pm) hatchery intake water temperatures, air temperature, and weather, maintained in paper log books of which the years 1960–1993 were digitized for the BETTER model (JSA 1992, Kamman 1999b). We obtained scanned copies of log book pages for 1997–1998 and 2014–2017 from CDFW's Amy Knabe, for use in verifying and filling gaps in the LFH temperature records (Knabe 2019); pre-1997 log books could not be located. Shane Quinn of the Yurok Tribe Fisheries Program transcribed the 1997 and 2014–2017 log book temperatures.

A.5.2 THERMAL INFRARED

Watershed Sciences collected thermal infrared (TIR) imagery for approximately forty miles of the Trinity River in July 2009 (Watershed Sciences 2009a, 2009b; Faux 2010). We have acquired these data but were not used in the analysis. Fullerton et al.'s (2015) TIR-based analysis of longitudinal patterns 53 Pacific Northwest rivers.

A.5.3 NORWEST STREAM TEMPERATURE MODEL

The NorWeST stream temperature model uses observed temperature data (Chandler et al. 2016), Geographic Information Systems (GIS) data, and a multivariate spatial statistical model to produce spatially continuous predictions of mean August temperature throughout the entire stream network (Isaak et al. 2017). NorWeST's model structure was later applied to all months by FitzGerald et al. (2021). The Klamath/Trinity Basin was included in the "Northern California Coastal Klamath processing unit" which was last updated in 2017 (Isaak et al. 2016, 2017). The outputs include climate change scenarios. NorWeST provides a nicely organized database with daily summaries of the observed temperature data (Chandler et al. 2016) but for this project we did not use NorWeST's summaries but instead created our own compilation with additional years, sites, and data sources (much of the NorWeST compilation stops in 2013).

A.5.4 HISTORICAL FIELD MEASUREMENTS ASSOCIATED WITH WATER QUALITY SAMPLE COLLECTION

Continuous water temperature data were relatively uncommon in the Trinity River prior to construction of Trinity Dam (Rowell 1979), but individual field measurements of water temperature were made during collection of water quality samples. As early as 1950, the California Department of Water Resources began collecting water samples approximately monthly at several sites on the Trinity River including Lewiston, Burnt Ranch, Hoopa, and

---

[25] https://www.trrp.net/library/?search=bedell&abstract=1&sort=citation

Weitchpec (e.g., CDWR 1957, CDWR 1965) which we downloaded from the California Water Data Library but did not analyze. Temperature follows a diel (i.e., 24-hour) cycle, so it is difficult to analyze and interpret discrete temperature measurements given they could represent either the daily minimum, maximum, or average, except during high-flow periods when diel ranges are low. The historical CDWR data could potentially be used to assess pre-dam longitudinal (i.e., upstream to downstream) temperature patterns during the important spring outmigration period to see if they match those in our model predictions for the no-dam/unimpaired flow scenario (i.e., see figures in sections 3.4.1.3 and 3.4.3.2).

A.6 HYDROLOGY DATA

Trinity Reservoir storage, river and creeks flows, and Carr Powerhouse diversion data were downloaded from USGS NWIS. NWIS lacks Carr Powerhouse diversion data for hydrologic year 2018, so we filled that gap using CDEC JCR which left three missing days July 27, 28, and 29 which we assumed to be zeroes since those days coincided with the Carr Fire during which the plant shut down for a few days. Trinity Reservoir elevation data were downloaded from CDEC (station CLE). This elevation dataset contained missing values and outliers which we overwrote with estimated values generated from the USGS Trinity Reservoir storage data and a rating curve[26].

USBR's Randi Field provided Trinity Reservoir hourly flow release data which include generation releases QG1 and QG2, hollow jet river outlets QU1 and QU2, and auxiliary outlet QU3. We summarized each of these five releases into daily average time series. For a few days in May 2005 with many missing hourly measurements, we set total daily Trinity Reservoir releases equal to the sum of USGS Carr Powerhouse (station 11525430) and USGS Trinity River at Lewiston (station 11525500). Since water in the generation and hollow jet outlets is withdrawn from the same intake (i.e., reservoir depth), we summed them for analysis.

A.7 METEOROLOGICAL DATA

We use several different air temperature datasets for our statistical models of stream temperature. When possible, we use the PRISM Climate Group at Oregon State University's (Daly et al. 2008) AN81d daily 1981–2019 gridded dataset that utilizes data from the major weather station networks within our study area, including federally operated remote automated weather stations (RAWS) and the NOAA Global Historical Climatology Network Daily (GHCN-D). For analyses when daily data prior to 1981 are required, we use Livneh (2013) which is a gridded dataset for 1915–2011 using GHCN-D data. The Livneh and PRISM datasets both provide daily minimum and maximum air temperatures which we averaged into daily means.

---

[26] We plotted the USGS 11525400 daily storage data against the CDEC CLE daily elevation data. From that plot we noted outliers and missing values in the years 1963, 1967, 1983, 1985, 1986, 1988, 1989, 1990, 1993, 1995, 1996, and 2011. We then fit a loess rating curve to the stage/elevation data (excluding the above-mentioned years), which we then applied to the entire USGS storage time series to obtain a daily elevation time series. For days with missing CDEC elevation values, and for 59 days in the above-mentioned years when the CDEC elevation value differed from the USGS-estimated elevation by more than one foot, we overwrote the CDEC value with the USGS-estimated value.

APPENDIX B ANALYTICAL METHODS

In this appendix, we provide an overview of the analytical tools used in this report. In addition, we describe some specific applications, such as filling gaps and extending a period of record, that are not very instructive for their own sake but are used in support of other analyses. In other sections of the report (e.g., Sections 3 and 4), we include descriptions of methods "of interest", immediately followed by the results of that analysis. For example, developing the unimpaired flow scenario for the Trinity River at Lewiston is a key piece of the report so is described in Section 3 rather than in this generic methods section. All statistical models were developed in R version 4.01 (R Core Team 2020) using various packages, as described below.

B.1 LINEAR REGRESSION

For some simple analyses, we use linear regression to model one variable as a linear function of another variable. Examples include filling temporal gaps in mainstem Trinity River temperature records using adjacent stations (Section B.7). We typically assessed the adequacy of these models using: 1) the coefficient of determination (R^2) which indicates the correlation between the two variables, with a value of 1 indicating a perfect fit and value of 0 indicating no relationship between the variables, and 2) the root mean squared error (RMSE), which is a measure of average error. To implement linear regressions, we used the *lm* function in R (R Core Team 2020) to fit the model using Ordinary Least Squares (OLS).

B.2 LOESS REGRESSION

LOESS (LOcally Estimated Scatterplot Smoothing, also known as LOcal regrESSion or Local Polynomial Regression Fitting) regression is an alternative to linear regression, useful when the relationships between variables are not linear (Helsel et al. 2020). LOESS regression fits a smooth flexible curve using polynomials that are locally fitted. Observations are weighted so that the local curve is most affected by nearby observations. A span parameter (ranging from 0 to 1) specifies a maximum distance of the observations to be included in the local weighting. Relative to GAMs (Section B.4) or regular (i.e., not locally-weighted) polynomials, loess curves generally allow changes in the slope of the curve to be more abrupt. We used loess regression to estimate Lewiston flows under an unimpaired no-dam flow scenario (Section 3.4.1.1) and as a graphical aid to show overall trends in many scatterplots throughout the report. We used the *loess* function in R (R Core Team 2020) to implement loess regressions.

B.3 LINEAR MIXED-EFFECTS MODELS

Linear mixed-effects models are an extension of linear regression that allows both fixed and random effects, used when observations are not independent such as when they are in a hierarchal structure (e.g., observations grouped by site or time period). Random effects account for variation between groups. We used the *lme4* package version 1.1-19 (Bates et al. 2015) to develop linear mixed effects models in R (R Core Team 2020) to model Trinity Reservoir temperatures (Section 3.3.1.2), using month as a grouping variable with a random intercept so temperatures can vary by month.

B.4 GENERALIZED ADDITIVE [MIXED] MODELS (GAM AND GAMM)

High-frequency time series such as daily stream temperatures are often highly correlated with the values on adjacent days, a phenomenon referred to as autocorrelation (Benyahya et al. 2007). These correlations violate the assumption in regression analysis that measurements are independent. For measurements such as these that are not likely independent, it is best to use a model that can explicitly include the autocorrelation structure (Steel et al. 2013), a feature possible with GAMs.

GAMs are an extension of Generalize Linear Models (GLMs) that allow relationships between variables to be non-linear rather than forcing them to be linear. GAMs have been previously shown to work well for modeling stream temperatures (Siegel and Volk 2019, Laanaya et al. 2017) including in the Trinity River watershed (Asarian et al. 2023). By using non-linear interaction between day of the year (ranging from 1–365 in most years or 1–366 in leap years) and another predictor variable such as flow, we can allow the relationship between that predictor and stream temperature to vary smoothly over the year. Generalized additive mixed models (GAMMs), also referred to as hierarchical generalized additive models (HGAMs), are an extension of GAMs that can include autocorrelation and random effects, which allows construction of models for non-independent data such as repeated measurements at multiple sites (Pedersen et al. 2019). We use the *bam* function in *mgcv* package version 1.8-31 (Wood 2017) to implement generalized additive models (GAMs) in R (R Core Team 2020). Following guidance from Baayen et al. (2018), we initially fit models without an autocorrelation term, and then re-run the model with an autocorrelation term, assigning a rho value based on the lag 1 autocorrelation from the residuals of the initial model.

Rather than slavishly follow a pre-specified procedure such as forward-selection or backward selection, we take a more holistic approach to model selection. For each analysis, we chose a final model after considering multiple models using a variety of methods including Akaike information criterion (AIC), goodness of fit metrics (RMSE and R^2), and graphical review of outputs including residual plots, plots of predictions across sites and times of year, and auto correlation function (ACF) plots. For GAMs, we use the *compareML* function in the *itsadug* package to compare models' AIC scores.

B.5 SUPPLEMENTAL METHOD FOR MODELING UNIMPAIRED LEWISTON FLOWS

Methods for estimating unimpaired (i.e., no dams or diversion) flows for the Trinity River at Lewiston are described in Section 3.4.1.1. As a supplemental "reality-check" on those estimates during the low-flow season, we used the three-year pre-dam period of overlapping record (10/1/1957–11/23/1960) to develop a regression between the Trinity River above Coffee Creek (USGS gage 11523200) and at Lewiston (USGS gage 11525500), as described in Section 3.4.1.1. To reduce the length of Section 3.4.1.1, we provide Figure B83 and Figure B84 as supplemental figures here to illustrate the regressions from that supplemental method:

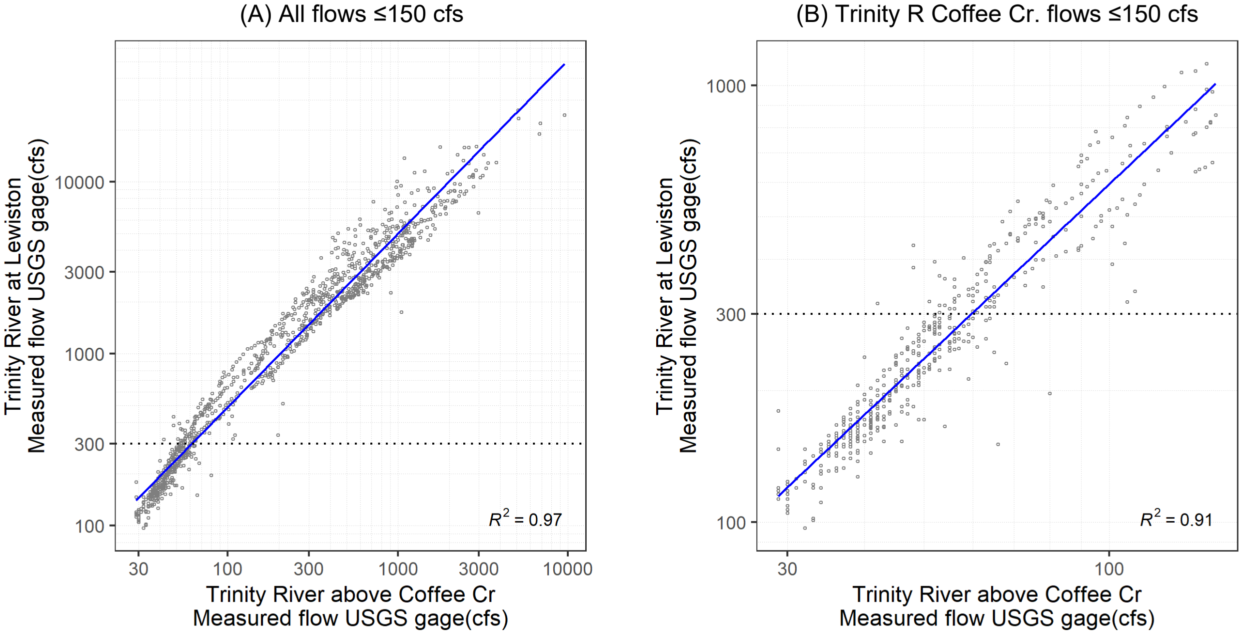


Figure B83. Linear regression of daily gaged flow in the Trinity River above Coffee Creek (USGS gage 11523200) and at Lewiston (USGS gage 11525500) for the 10/1/1957–11/23/1960 pre-dam period on (A) all dates, and (B) only dates when Trinity River above Coffee Creek flows were ≤150 cfs.

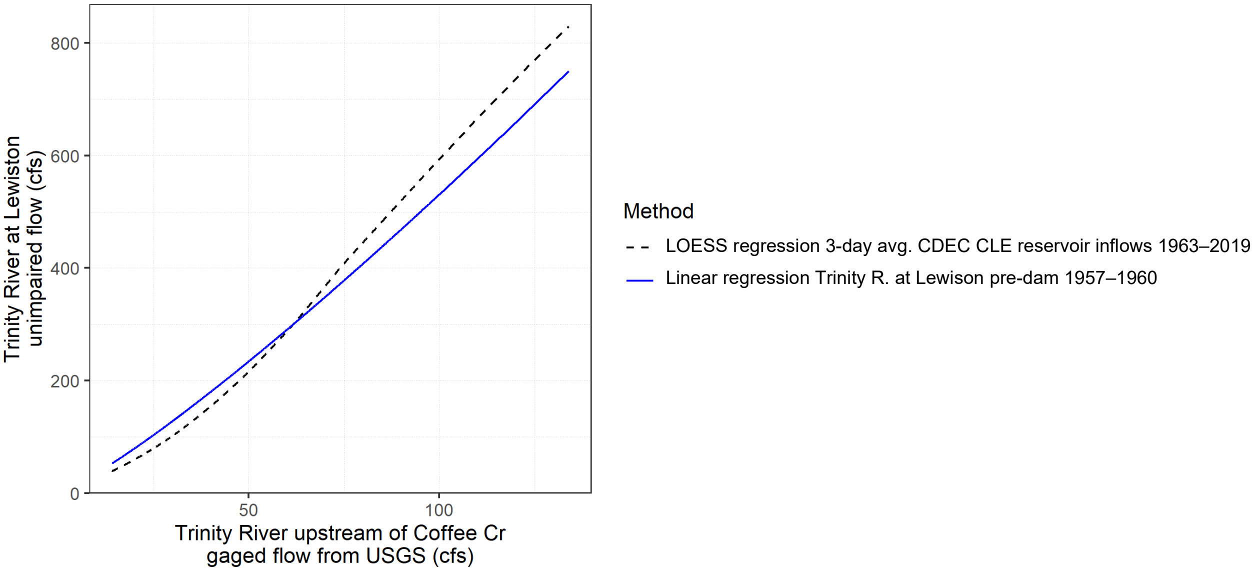


Figure B84. Comparison of two methods for estimating daily unimpaired flow in the Trinity River at Lewiston using gaged daily flows from the Trinity River above Coffee Creek (USGS gage 11523200): 1) LOESS regression with 3-day average CDEC CLE reservoir inflows from 1963–2019 (i.e., Figure 21), and 2) linear regression with Trinity River at Lewiston pre-dam data from 10/1/1957–11/23/1960 (i.e., Figure B83b).

B.6 FILLING GAPS IN LEWISTON WATER TEMPERATURE RECORD

Methods for filling gaps in the Lewiston water temperature record are described in Section 2.3.2, but to reduce the length of that section we provide the supplemental Table B18 and Figure B85 here:

Table B18. Root mean squared error (RMSE) in degrees C for validation of predicted water temperatures in the Trinity River at Lewiston. Generalized additive models (GAMs) were fit using data from 1997–2011, applied to predict 1996–2019 (primarily for use in filling the 2011–2017 gap), and validated with data from 2017–2019. See Figure 6 for key to site names.

Metric	Predicted from CDEC LFH	Predicted from CDFW logs of hatchery temperature
Maximum	0.18	0.28
Mean	0.11	0.30
Minimum	0.13	0.33

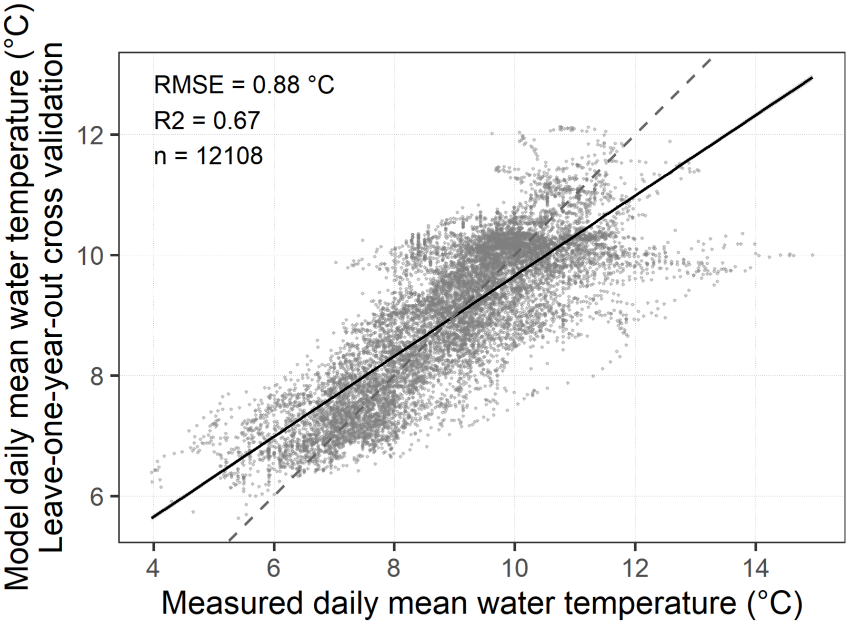


Figure B85. Comparison of measured daily mean water temperatures and leave-one-year-out cross-validated predictions for the Trinity River at Lewiston for 1981–2019. RMSE = root mean squared error (a measure of prediction accuracy), R^2 = coefficient of determination ranging from 1 (perfect correlation) to 0 (complete lack of relationship between the variables), and n = number of days with temperature data.

B.7 EXTENDING WATER TEMPERATURE PERIOD OF RECORD AND FILLING GAPS AT OTHER TRINITY RIVER SITES

At a few key mainstem Trinity River sites used to assess compliance for temperature criteria, we filled periods of missing daily mean water temperature data to extended the period of record by applying linear regression to nearby sites (Table B19). Since we only used nearby sites (range approximately 2–20 miles) without major tributaries between them, model fits were excellent, with R^2 values ranging from 0.987–0.998 and RMSE ranging from 0.24–0.40 °C (Table B19). For future use, we provide these gap-filled temperature data in Electronic Appendix 4

Table B19. Datasets and regression models used to fill gaps and extend records at key mainstem Trinity River sites.

Key target site	Site used to fill gaps and extend record	Dates of overlapping records for model fitting		Model fit		Dates gap-filled	
		n	Date range	R^2	RMSE (°C)	n	Date range
Douglas City gage	Douglas City Bridge	608	1992-10-03 - 2001-09-08	0.994	0.24	901	1990-05-14 - 1994-10-01
Douglas City gage	Limekiln/ Steelbridge	6918	1992-10-03 - 2019-06-19	0.987	0.34	790	1987-07-09 - 2019-06-27
North Fork/ Pear Tree	Upstream of Canyon Creek	4113	2001-08-25 - 2016-11-08	0.990	0.40	35	2002-07-11 - 2011-10-04
Weitchpec	Hoopa	6913	1998-07-30 - 2019-07-31	0.998	0.24	5603	1964-02-28 - 2019-12-30
Weitchpec	Willow Creek	3087	1991-07-24 - 2012-07-01	0.994	0.37	559	1988-04-26 - 2008-03-26

B.8 EXTENDING WATER TEMPERATURE PERIOD OF RECORD AND FILLING GAPS AT TRIBUTARY SITES

The relationship between water temperature and flow varies over the course of the year as a result of numerous other variables which follow their own seasonal cycles. For example, the source and flow paths of river water varies seasonally according to precipitation form (i.e., snow or rain), groundwater dynamics of hillslope and alluvial aquifers, and irrigation management (i.e., water withdrawals and subsequent return flows back the river via surface or groundwater). In addition, the effects of flow on water temperature could be seasonally mediated by variables that affect the intensity and duration of solar radiation striking the water, such as day length, solar angle, cloud cover, wildfire smoke, and leaf out and leaf fall of deciduous riparian vegetation. Some of these variables follow a nearly identical seasonal trajectory each year while the timing of others fluctuates within ranges, but all have an annual cycle. It is not possible to include all these individual factors in a statistical model, so instead we use a modeling approach that allows the implicit aggregation of all these factors to vary smoothly over the course of the year.

To fill gaps in the daily mean water temperature records at major tributaries, we used a generalized additive mixed model (GAMM). We experimented with several configurations of model variables and structures before selecting a final model that uses two air temperature variables, day of year (DOY), an interaction between DOY and daily log-transformed stream flow per watershed area, and random effects including site-level smoothers and a random intercept for year. To account for air temperature effects at two different time scales, we used two separate air temperature variables, following Siegel and Volk (2019): 1) the mean of the 5-day period before the predicted day, and 2) the difference between mean air temperature for the predicted day and the mean of the 5-day period before the predicted day. The predicted day's air temperature is expressed as a difference to reduce multicollinearity and concurvity (multicollinearity's non-linear analogue). Air temperatures were assigned values from the PRISM pixel closest to each site. Flows for each site were assigned based on one of three sources: 1) sites upstream of Trinity Reservoir as well as selected tributaries downstream of Lewiston Dam that drain the highest elevation watersheds (Rush Creek, Weaver Creek, Canyon Creek, and NF Trinity River) were assigned to the Trinity River above Coffee Creek USGS gage, 2) the SF Trinity River was assigned to the SF Trinity River USGS gage, and 3) all other sites were assigned to the accretions between the Lewiston and Hoopa USGS gage, minus the SF Trinity USGS gage, as described in Section 2.3.3 above.

Prior to assigning flows to sites, flows were divided by watershed area to yield units of mm/day (so that flows emphasized temporal changes rather than location differences) and log-transformed to improve normality and prevent infrequent high flows from having undue influence. For all variables, we used a global smoother plus site-level group smoothers that have the same "wiggliness", which Pedersen et al. (2019) referred to as a "GS" model (Global smoother with individual effects that have a shared penalty). The global smoother represents the overall relationship (i.e., lumping all sites) while the group smoothers allow the relationship at each site to deviate from the overall relationship. The interaction between DOY and stream flow was fit using the "by" function in the R package *mgcv*, allowing the linear slope between stream flow and water temperature to vary smoothly by DOY. We used thin-plate spline smoothers for all model variables except DOY for which we used a cyclic cubic regression spline to force a smooth transition between December and January.

To avoid overfitting, all smoothers were limited to five knots and visually reviewed to confirm their shapes matched the hypothesized direction of effects (e.g., warmer air temperatures were not associated with cooler water temperatures) and did not appear overly wiggly. Following guidance from Baayen et al. (2018), we initially fit a model without the autocorrelation term, then re-ran the model with an autocorrelation term, assigning a rho value based on the lag 1 autocorrelation (0.819) from the residuals of the initial model. After including the autocorrelation term, there was no residual autocorrelation in the model.

We validated the model using leave-one-year-out cross-validation, yielding an overall (i.e., lumping all sites together) RMSE of 1.05 °C and R^2 of 0.96, indicating excellent model fit. At individual sites, cross-validated RMSE ranged from 0.80–1.28°C and R^2 ranged from 0.89–0.98 (Figure B86). Model performance was weakest at Grass Valley Creek (Figure B86), which we attribute to the effects of Buckhorn Dam, located approximately 10 miles upstream from creek's mouth. The dam's outlet works releases a near-constant 6 cfs, plus additional high-flow releases from the spillway during winter and spring when the reservoir is full (Gaeuman 2013). The dam-influenced hydrology is not well represented by the flows we assigned based on the accretion from Lewiston to Hoopa. Potential future refinements include generating a new continuous time series of Grass Valley Creek flows by combining the records of that stream's current USGS gage with the historical USGS gage upstream.

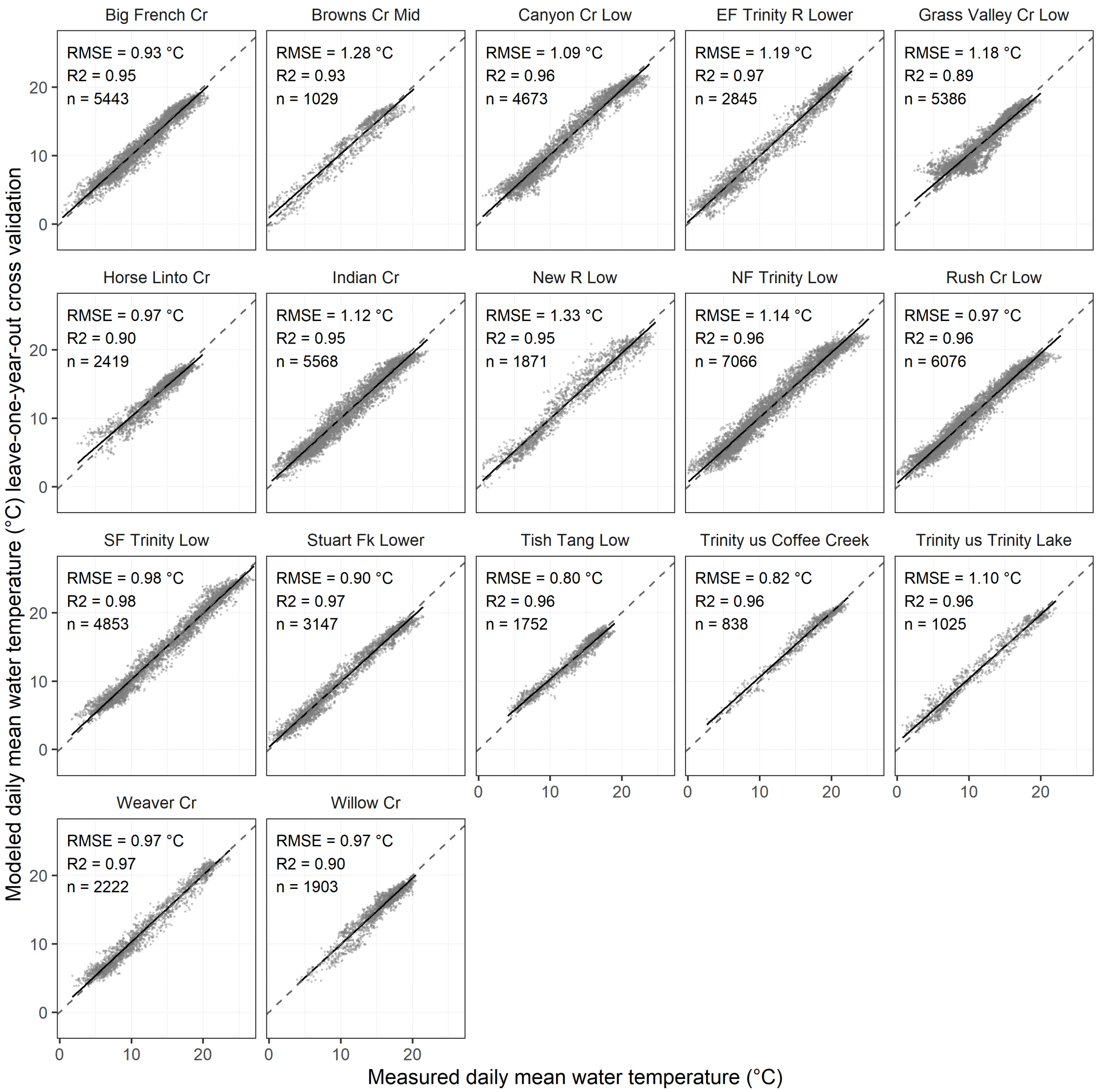


Figure B86. Comparison of measured daily mean water temperatures and leave-one-year-out cross-validated predictions for sites on major tributaries as well as the Trinity River upstream of Trinity Reservoir. RMSE = root mean squared error (a measure of prediction accuracy), R^2 = coefficient of determination ranging from 1 (perfect correlation) to 0 (complete lack of relationship between the variables), and n = number of days with measured temperature data.

B.9 SPATIOTEMPORAL INTERPOLATION OF TRINITY RESERVOIR TEMPERATURE PROFILES

USBR (2020) has measured temperature depth profiles in Trinity Reservoir approximately once per month since 2000, with 155 additional temperature depth profiles available in 1972–1989 (Section A.4). Since temperatures were measured at 25-foot depth intervals and there are temporal gaps, for visualization purposes we used fixed rank kriging to spatiotemporally interpolate these profiles to a daily temporal resolution and 2-ft depth resolution in R (R Core Team 2020) using the *autoFRK* package (Tzeng and Huang 2018). We ran the spatiotemporal interpolation separately on the 1972–1987 and 1998–2019 periods due differences in the number of depths sampled between the two periods. Results are shown in Sections 3.3.1.2 and 3.3.2.2.

B.10 TEMPERATURE MODELING METHODS – LONGITUDINAL AND SEASONAL DIMENSIONS

Methods for the modeling of the longitudinal and seasonal dimensions of Trinity River thermal diversity are described in Section 5.1.2.1, but to reduce the length of that section we provide Figure B87 as a supplemental figure here:

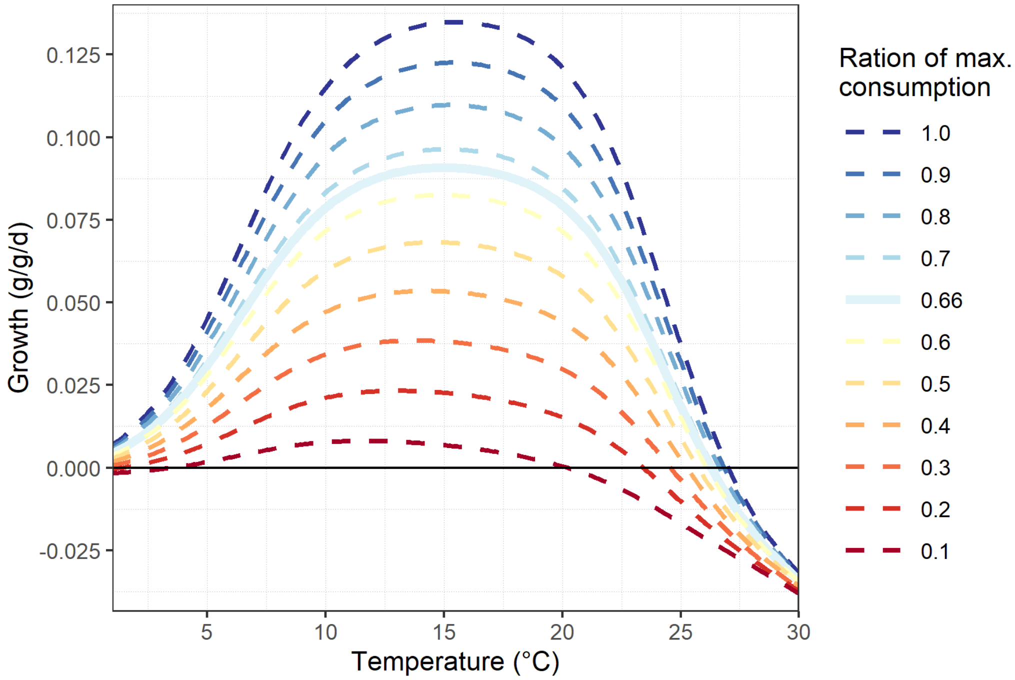


Figure B87. Graph of growth rate of a 3-gram Chinook Salmon (Stewart and Ibarra 1991; Plumb and Moffitt 2015) in percent body weight per day at 66% ration of maximum consumption over a range of temperatures using equations from the Fish Bioenergetics Manual 3.0 (Hanson et al. 1997).

B.11 HYDRAULIC/TEMPERATURE MODELING METHODS -LATERAL DIMENSION

Methods for the hydraulic/temperature modeling of the lateral dimension of the Trinity River thermal diversity are described in Section 5.1.4.1, but to reduce the length of that section we provide Figure B88 as a supplemental figure here:

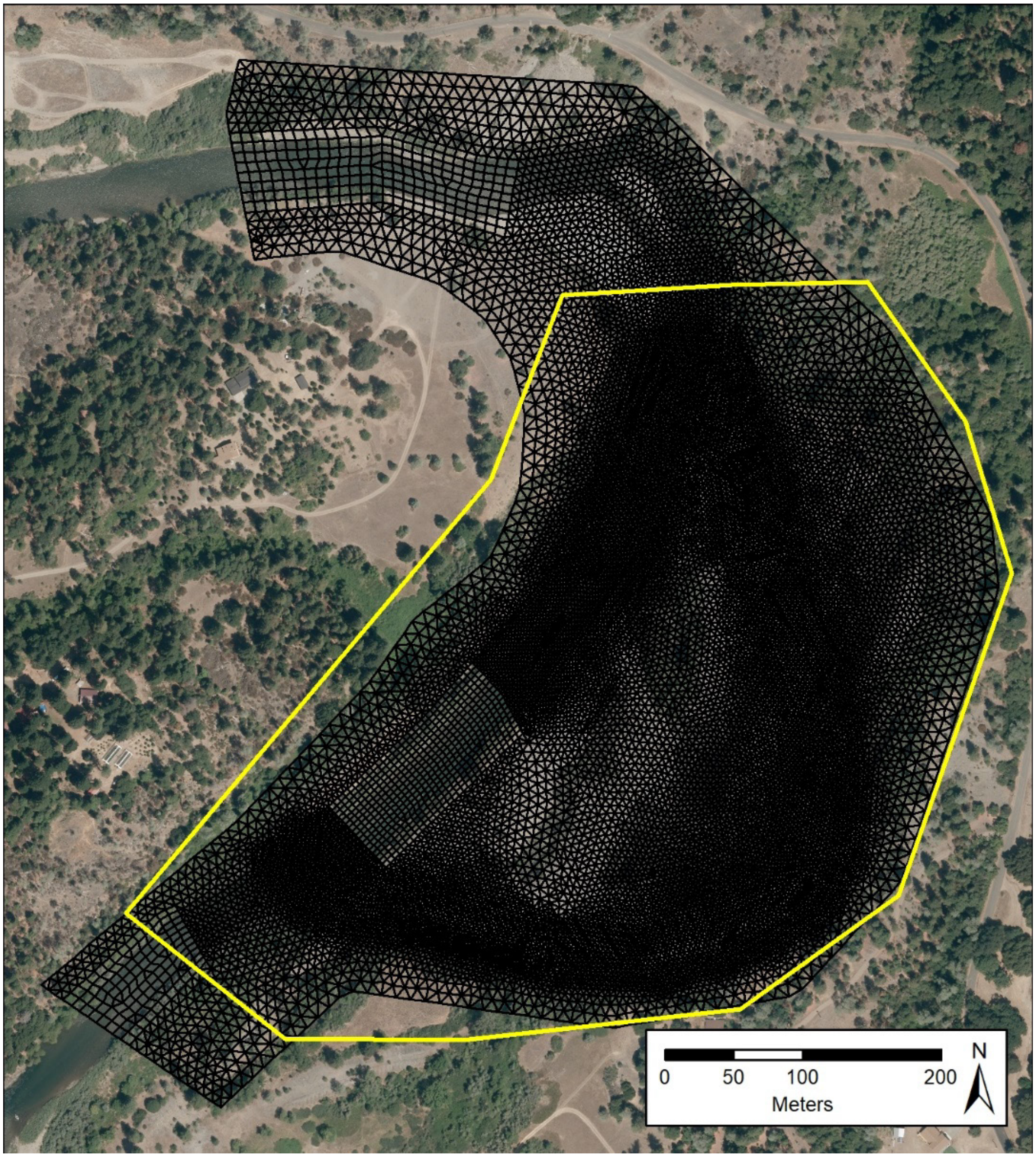


Figure B88. The model mesh used for temperature modeling at Oregon Gulch. The region of interest from where temperature statistics were drawn is outlined in yellow.

APPENDIX C SUPLEMENTAL RESULTS AND LITERATURE SUMMARIES

C.1 TRINITY RESERVOIR THERMAL DYNAMICS

Trinity Reservoir thermal dynamics are described in Section 3.3.1.2, but to reduce the length of that section we provide Table C20 as a supplemental table here:

Table C20. Comparison of linear mixed-effects models for predicting reservoir water temperatures (°C) at the main outlet elevation. T_{air} = 12-month trailing average of air temperature (°C); Storage = reservoir storage (thousand acre-feet); RMSE = root mean squared prediction error, ΔAIC = delta Akaike information criterion. Lower RMSE and AIC generally indicate better models; *b* = coefficient (i.e., change in reservoir temperature per unit change in the variable) provided in the original units and standardized units; 95% CI = 95 percent confidence intervals (i.e., uncertainty in estimate of coefficient) provided in the original units; t = coefficient divided by standard error. The greater the absolute value (i.e., how far it is from zero in either a positive or negative direction) of the t statistic, the less uncertainty in the coefficient and the greater the influence of the variable on the predicted stream temperatures.

Model structure			Model comparison		Parameter estimates for T_{air}	
Model	**Fixed effects**	**Random effects**	**ΔAIC**	**RMSE**	***b* (95% CI)**	**t-value**
1	T_{air}	Month	0	0.65 °C	0.49 (0.36–0.67)	7.9
2	T_{air} + Storage	Month	2.0	0.65 °C	0.49 (0.36–0.62)	7.2
3	Storage	Month	47.8	0.70 °C	-	-
4	[none]	Month	55.6	0.71 °C	-	-

C.2 TRAVEL TIME

As river flows and velocities increase, the amount of time it takes for water to transit a reach decreases; however, it is difficult to precisely quantify the travel durations between different reaches and flows. In this section, we present several sources of information regarding river travel time, including a 1966 dye release study (Limerinos 1967), comparisons of flow gages during pulse flow releases (Zedonis 2004, 2005a), and outputs from the sub-daily Trinity River model (Watercourse Engineering 2007). We also discuss the presence of thermally stable river nodes with minimal daily temperature range occurring 24-hour travel time downstream of Lewiston Dam and corresponding anti-nodes of maximal daily temperature range occurring 12-hour travel time downstream of the dam Watercourse Engineering 2007). The issue of travel time, and how it affects water temperatures, is relatively complex and our treatment of it here is relatively brief.

Rivers are not pipes through which water flows downstream without mixing. When upstream inputs change, the “new” water mixes with “old” water in each habitat unit and it takes time for the “new” water to completely flush out the “old.” This concept is nicely illustrated by the concentrations of upstream-injected dye which arrives at a downstream monitoring station (Figure C89). Rather than arriving suddenly and leaving abruptly as would occur in a pipe, the dye is detected over many hours, with concentrations exhibiting a bell-shaped curve with an extended descending limb.

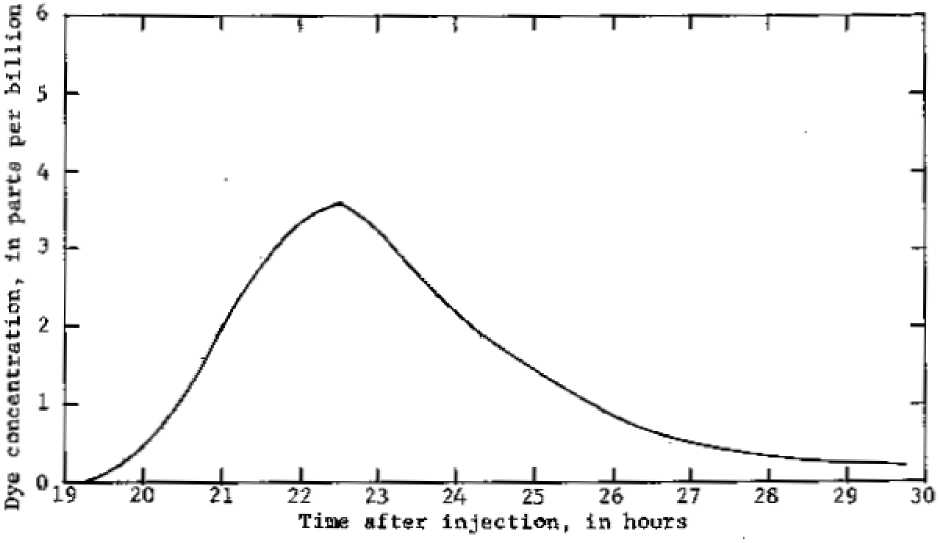


Figure C89. Concentration of fluorescent dye measured in the Trinity River at Douglas City on October 27–28, 1966, plotted as a function of the length of time since the dye was injected 17.4 miles upstream near Lewiston Dam. Figure from Limerinos (1967).

When dam releases increase such as during a pulse flow, a kinematic wave forms which pushes “old” water in front of the “new” water. The counter-intuitive result is the “old” water speeds its downstream transit, and thus stage and discharge may rise downstream before the “new” water arrives. This has been documented on the Klamath River above Copco reservoir, where hydropower peaking (i.e., 5–10x difference between daily minimum and daily maximum flows) and high-volume natural springs combine to cause dramatic sub-daily fluctuations in river flow and water quality (Appendix A2 in Asarian et al. 2009). During extended periods (i.e., 12–18 hours) in which the algae-laden Klamath River’s flow is almost entirely retained upstream in J.C. Boyle Reservoir, water downstream in the Klamath River above Copco Reservoir is dominated by clean spring water. Then when algae-laden river water is released from the powerhouse as a daily flood pulse, it pushes the spring water rapidly downstream and for the first few hours that stage and discharge rise dramatically downstream in the river above Copco Reservoir (14 miles downstream of the powerhouse), water quality measurements (especially specific conductance) still reflect clean spring water. Only after several hours of elevated stage and discharge does the algal-laden water finally arrive.

In contrast to fluorescent dye and specific conductivity, water temperature is not a conserved parameter (i.e., does not pass downstream unchanged) but instead rises and falls in response to energy fluxes including solar radiation, conduction, and evaporative cooling (Section 1.2.1 above), adding to the difficulty of evaluating travel time and its effect on water temperature.

C.2.1 LIMERINOS (1967) DYE RELEASE STUDY

Limerinos (1967) used dye releases to assess travel time through ten contiguous Trinity River reaches from Lewiston to Weitchpec. River flows on September 6–9, 1966 ranged from 163 cfs at Douglas City to 482 cfs at Weitchpec. Flows were higher on October 26–28, ranging from 279 at Douglas City to 560 at Weitchpec. Data were summarized by the timing of the peak dye concentrations and the leading edge of dye. The leading edge of the dye is useful for understanding the downstream rate of contaminants such as a chemical spill while the timing of peak dye concentrations was considered most relevant to water temperature and assumed representative of average water velocity. Limerinos (1967) divided travel time by reach length to obtain velocities which were then plotted against discharge (Figure C90A). The reach-specific relationships of discharge to velocity were then used to interpolate or extrapolate travel time at a design discharge of 200 cfs for Lewiston to Salyer (upstream of the South Fork Trinity River) and 300 cfs for Salyer to Weitchpec (Figure C90 A, B). Total travel time for peak dye concentration from Lewiston to Weitchpec at the 200–300 cfs design flows was approximately 158 hours (6.6 days) (Figure C90 B). Zedonis and Newcomb 1994 cite the Limerinos (1967) as "Results of this study indicated that approximately 8 days were required for peak dye concentrations to travel from Lewiston to Weitchpec." However, we were unable to find that statement in the Limerinos (1967) report. As expected, the higher October flows had shorter travel times and higher velocities than the lower September flows (Figure C90 A). Velocities were generally higher in lower Trinity River reaches than upper Trinity River reaches, except for Douglas City to Junction City which has high velocities relative to its discharge (Figure C90 A). Velocities range from 0.54 to 1.55 miles per hour (0.79-2.28 feet per second) (Figure C90 A).

As suggested by Limerinos (1967), velocities for lower flows could be obtained by extending the velocity/discharge curves (Figure C90 A) downward assuming zero velocity as zero discharge. The velocity/discharge curves could also likely be extrapolated upward to somewhat higher flows. A modern statistical approach would be to fit a linear mixed effects model to these data using a random intercept (and/or slope) for reach, but we did not take the time to do that. The average velocity predicted by the Limerinos (1967) dye study (Figure C90 A) for 300 cfs ROD winter baseflow is approximately 1.2 miles per hour, which equates to a 12-hour travel distance of approximately 14 miles (near Limekiln Gulch), 24-hour travel distance of 29 miles (near Deep Gulch several miles upstream of Junction City), 36-hour travel distance of 43 miles (near Eagle Creek several miles downstream of the North Fork Trinity River).

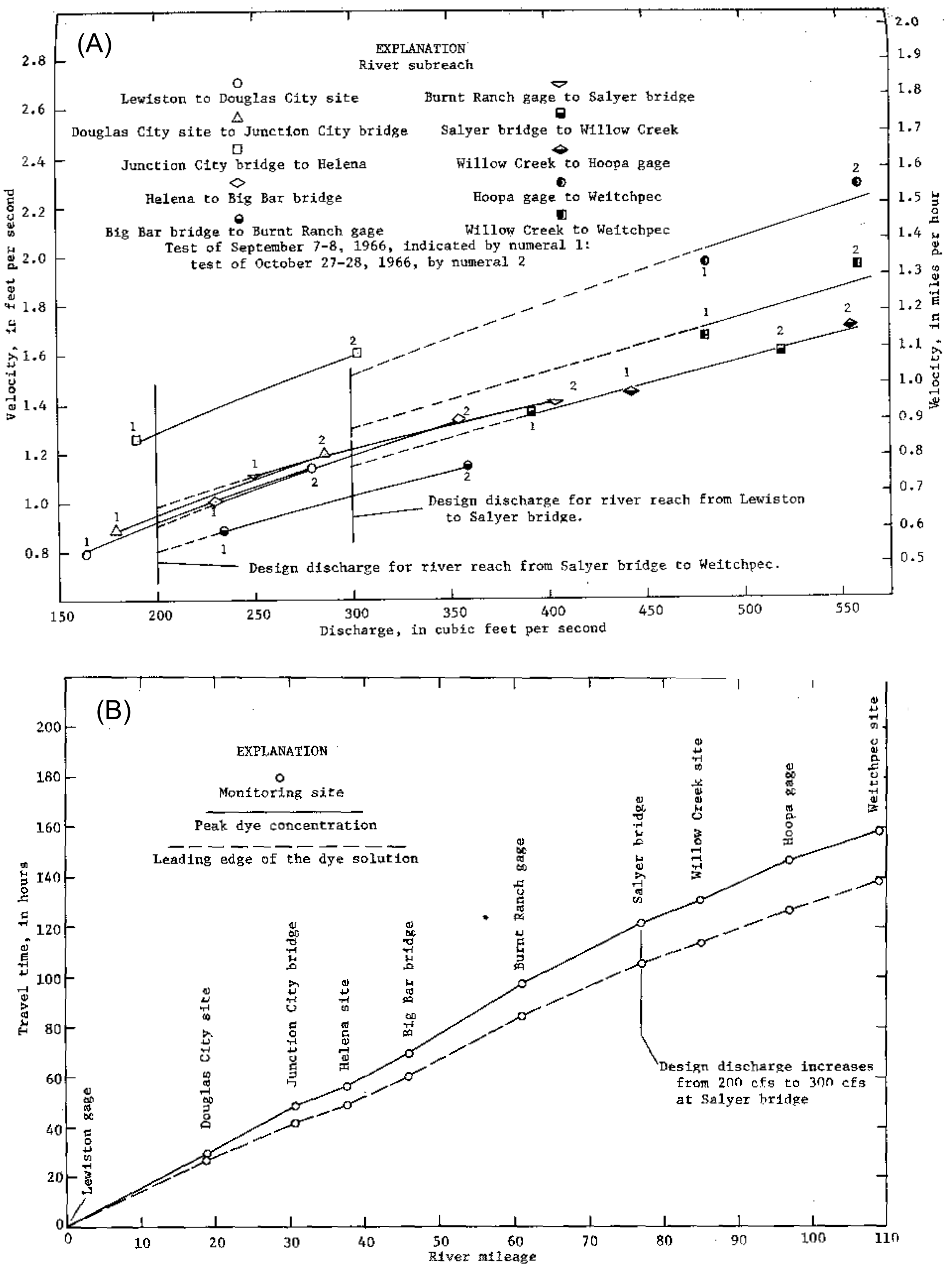


Figure C90. (A) Relationship of the velocity of the peak dye concentration to river discharge in 10 subreaches of the Trinity River. (B) Travel time of peak dye concentration and leading edge of dye solution for the Trinity River from Lewiston gage to Weitchpec, calculated for a design discharge of 200–300 cfs. Figures from Limerinos (1967) study which released fluorescent dye to track downstream movement of water.

C.2.2 TRINITY RIVER SUB-DAILY MODEL (WATERCOURSE ENGINEERING 2007)

According to the Trinity River sub-daily temperature model, travel times from Lewiston to Hoopa for selected days in 2005 ranged from 40 hours (with Lewiston flows of 2,450 cfs; Figure C91) to 90 hours (with Lewiston flows of 467 cfs) (Watercourse Engineering 2007; Table C21). Watercourse Engineering (2007) states that the sub-daily model's representation of travel time from Lewiston Dam to Douglas City is good, but at low flow the travel time is overestimated (i.e., too slow) between Douglas City and Burnt Ranch, likely due to the trapezoidal representation of channel geometry.

Table C21. Approximate Trinity River travel times from Lewiston to Hoopa, from the sub-daily Trinity River temperature model. Table adapted from Watercourse Engineering (2007).

Date	Approx. Travel Time (hours)	Flow at Lewiston (cfs)	Flow at Hoopa (cfs)
May 1, 2005	40	2,450	17,800
June 1, 2005	50	2,020	6,090
July 1, 2005	56	1,990	3,300
August 1, 2005	90	467	1,060
September 1, 2005	68	1,410	1,660
October 1, 2005	98	445	707

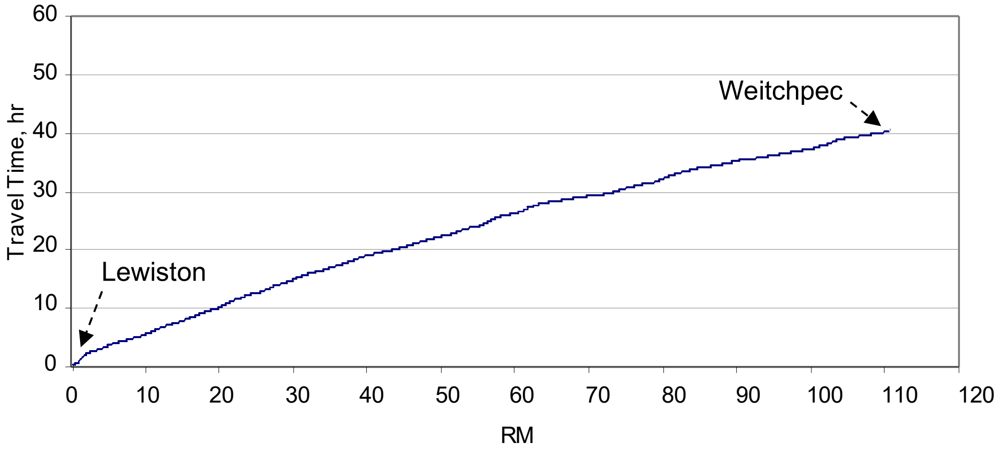


Figure C91. Trinity River travel time from Lewiston to confluence with the Klamath River on May 1, 2005, from the sub-daily Trinity River temperature model. Figure adapted from Watercourse Engineering (2007).

C.2.3 COMPARISON OF GAGED FLOWS DURING CHANGES IN DAM RELEASES

Travel time can be estimated by comparing flow gages to see how long it takes for changes in dam releases to arrive at downstream gages, though as described above these gage-based travel times will be different (likely faster) than dye-based estimates that take into account mixing. To our knowledge, gage-based Trinity River travel times have not been comprehensively analyzed previously, and we did not prioritize such an analysis for this report. In addition, we are not aware of any previous efforts to review changes in water temperature from pulse flows on an hourly basis, and we did not conduct such an analysis ourselves.

Here we briefly summarize results from previous analyses. Late summer pulse flows from Lewiston take approximately 30 hours to first be observed at the Hoopa gage and 43 hours to reach the Klamath gage (Table C22) (Zedonis 2004, 2005a). Changes in Lewiston releases take approximately 3.5–5.5 hours to reach the Limekiln gage (Chris Laskodi, unpublished analyses) from which Buxton (2020) estimated a Lewiston to Rush Creek travel time of approximately 1-1.7 hours. Mid-August pulse flows of 1,200 cfs in odd-numbered years for the Hoopa Valley Tribe's ceremonial purposes are released from Lewiston Dam approximately 1.5 days prior to the time at which the higher flows are needed (Zedonis and Newcomb 1994).

Table C22. Estimates of travel time for late summer Lewiston pulse flow to arrive at several gages along the Trinity River and the Lower Klamath River in August 2003 and August 2004. Lewiston flows prior to releases were 467 cfs on 8/23/2003 and 462 cfs on 8/22/2004. Gaged flow values in table are preliminary (not approved). Table adapted from Zedonis (2004, 2005a).

			Initial Release			Peak Release		
Year	Gage Location	River KM	Date and Time of Initial Release	Flow estimate (cfs)	Travel time (hours)	Date and Time of Peak Release	Flow estimate (cfs)	Travel time (hours)
2003	Trinity R. at Lewiston	248.7	8/24 @ 15:00		0	8/25 @ 01:00	1800	0
2003	Trinity R. at Burnt Ranch	148.7	8/25 @ 11:00		20	8/25 @ 17:00		16
2003	Trinity R. at Hoopa	95.2	8/25 @ 22:00		31	8/26 @ 04:00		27
2003	Klamath R. at Klamath	10.8	8/26 @ 11:00		44	8/26 @ 18:00		41
2004	Trinity R. at Lewiston	248.7	8/22 @ 20:00	503	0	8/23 @ 6:00	1660	0
2004	Trinity R. at Burnt Ranch	148.7	8/23 @ 15:00	647	19	8/24 @ 0:00	1610	18
2004	Trinity R. at Hoopa	95.2	8/24 @ 2:00	821	30	8/24 @ 9:00	1850	27
2004	Klamath R. at Klamath	10.8	8/24 @ 14:00	2,720	42	8/25 @ 2:00	3800	44

C.3 LONGITUDINAL AND SEASONAL TEMPERATURE MODELING OF DAILY THERMAL EFFECTS OF DAM RELEASE MAGNITUDE

The modeling methods and development of terms for describing the longitudinal profile of temperature (ΔT) and salmonid growth (ΔF) for the historical, unimpaired and seven constant flow scenarios are presented in Section 5.1.2.1. Here we offer supplemental figures of ΔT and ΔF on a daily time step over the critical rearing period (Feb – June)(Figure C92, Figure C93 and Figure C94), examined to ensure that the monthly time step discussed in section 5.1.2.2 and 5.2.1 was not so coarse that it masked or misrepresented patterns found on a shorter time step. No results are presented for June in Dry and Critically Dry water year types, since estimated unimpaired flows reach levels below what could accurately be modeled for temperature during the summer months by RBM10 (350 cfs). Flows below the threshold for modeling purposes were not reached until July of Normal and wetter water years for the unimpaired scenario.

With one exception, the monthly time step captured the essential information in a format that was easier to describe and interpret. The lone exception was at the very end of the rearing period examined for ΔF in all water year types. There is a second inversion point near the middle of the last month where temperatures could be modeled for each water year type (May in Dry and Critically Dry years, and June in Normal and wetter years). This inversion occurs as flows approach summer lows and results in higher discharges providing increased growth opportunity. However, it appears that growth opportunity at this time of year, for respective water types, is an unnatural phenomenon made possible by the cold hypolimnetic dam release and would not have occurred under the unimpaired scenario and is not present in the tributaries (including those upstream of Trinity Dam) or the Lower Klamath River. At this point it becomes increasing likely that recession from high magnitude releases will set up an ecological trap for outmigrating salmonids in the lower Trinity and Lower Klamath Rivers because elevated releases delay outmigration (Sykes et al. 2009; Zedonis and Newcomb 1997). When flows are inevitably reduced, water temperatures will rise quickly due to the high air temperatures and abundant solar radiation present at that time of year (Section 1.2.1). Thus, we recommend prioritizing outmigration cues prior to this time.

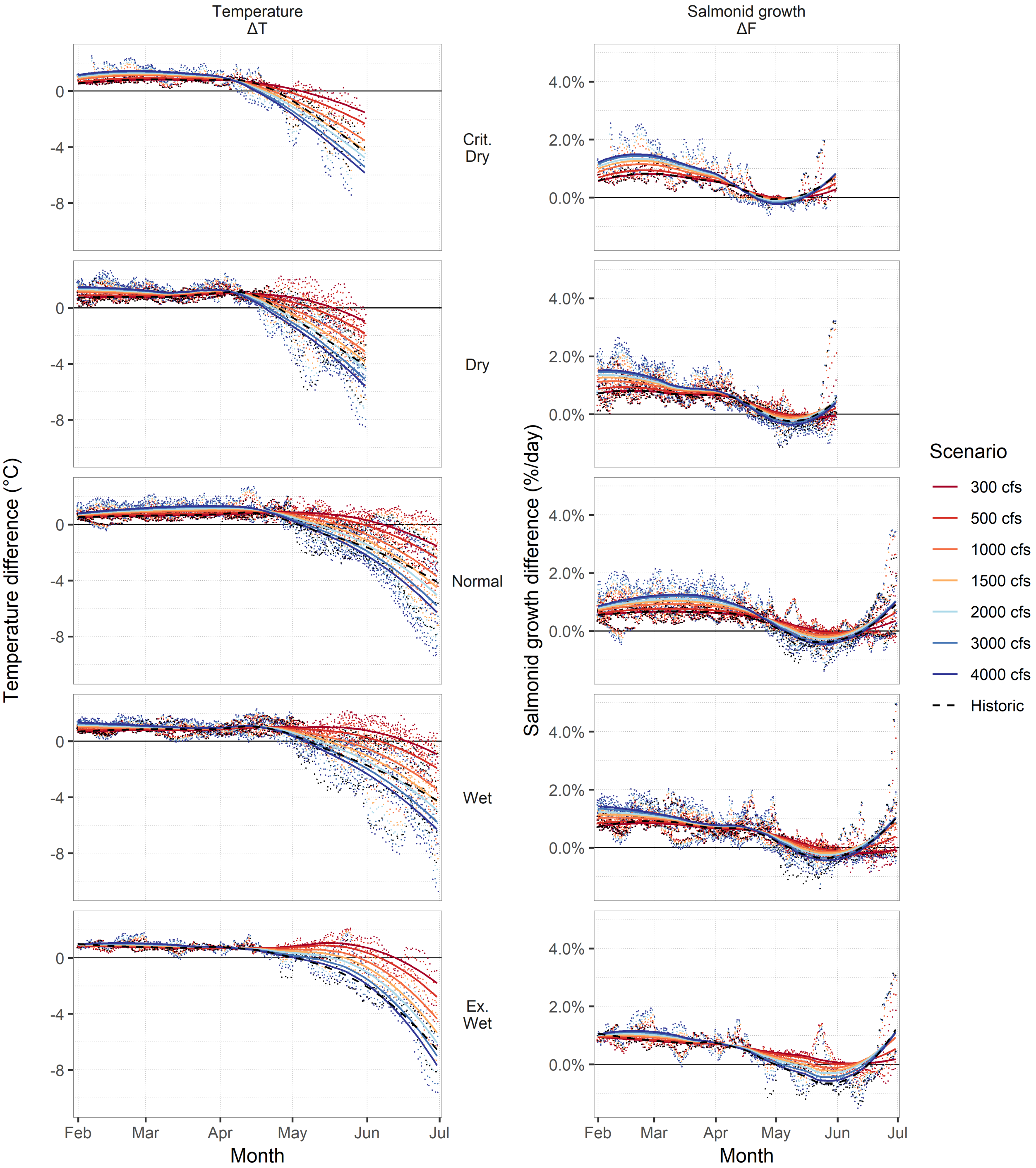


Figure C92. Daily differences in temperature (Δ*T*) and salmonid daily growth (Δ*F*) between the no-dam unimpaired flow scenario and eight dams-in flow scenarios in the February–June period of 2000–2018. Each dot is a single date. Lines are LOESS (LOcally Estimated Scatterplot Smoothing) smoothers fit with all data within each scenario and water year type.

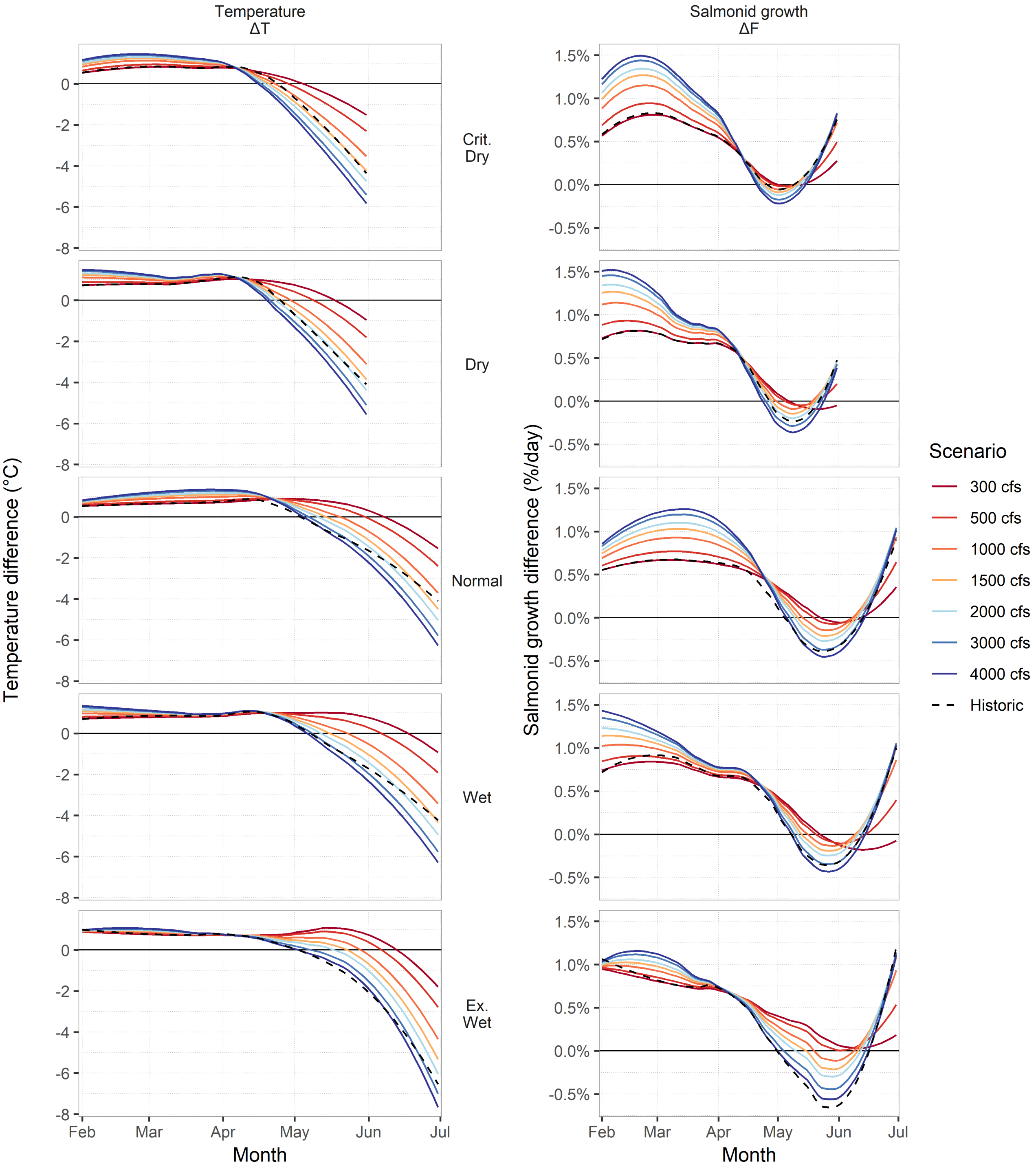


Figure C93. Smoothed daily differences in temperature (Δ*T*) and salmonid daily growth (Δ*F*) between the no-dam unimpaired flow scenario and eight dams-in flow scenarios in the February–June period of 2000–2018. Lines are the same LOESS (LOcally Estimated Scatterplot Smoothing) smoothers shown in Figure C92 above, but this figure does not show the individual points and thus it is easier to see the smoothers.

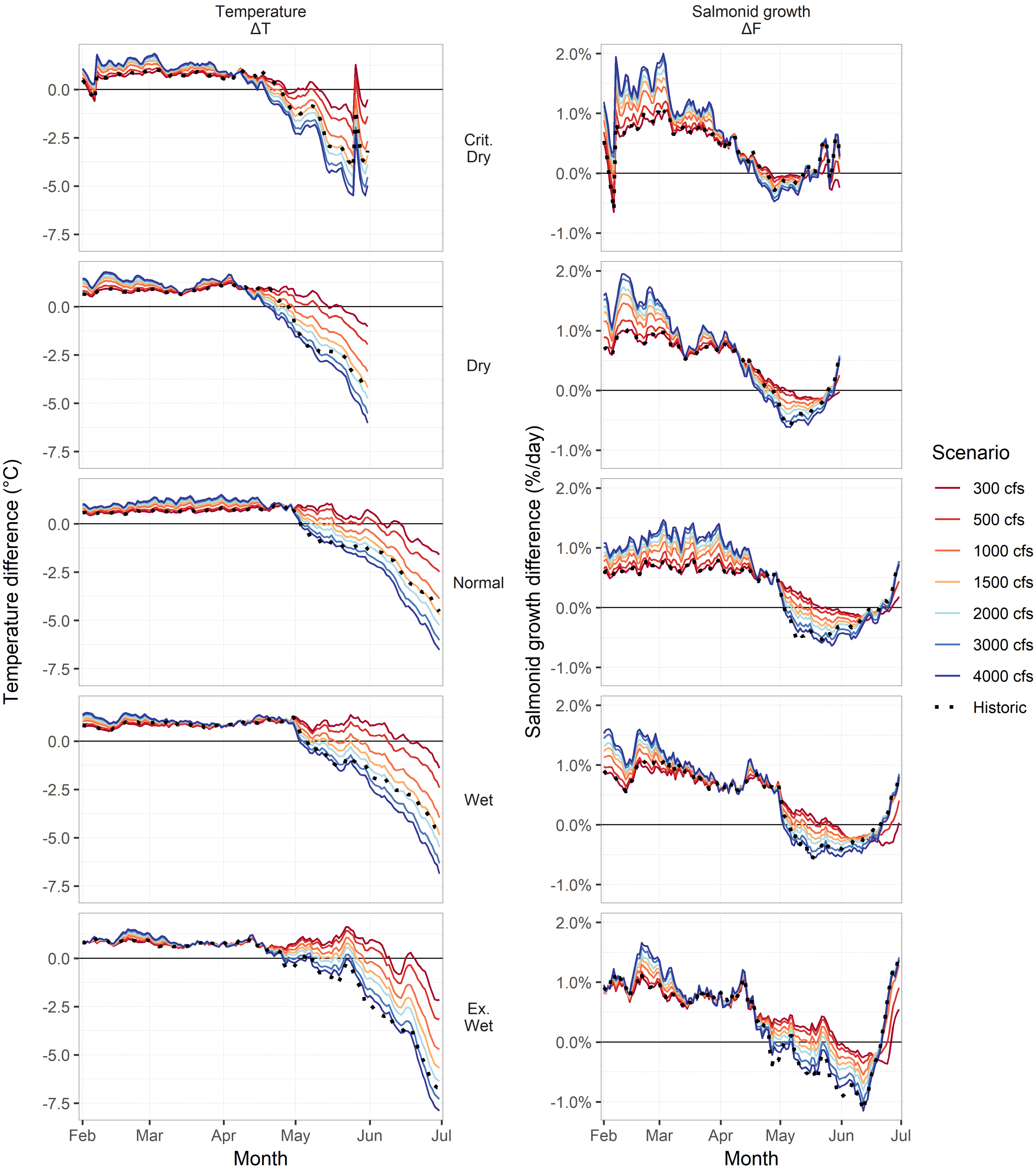


Figure C94. Daily average differences in temperature (Δ*T*) and salmonid daily growth (Δ*F*) between the no-dam unimpaired flow scenario and eight dams-in flow scenarios in the February–June period of 2000–2018. Lines are daily averages, summarized from the same individual dots shown in Figure C92 above.