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Key Points:

- Discharge-mediated temperature management can be used as a tool to mitigate against excessively warm temperatures in the Sacramento River

Supporting Information:

Supporting Information may be found in the online version of this article.

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Discharge-Mediated Temperature Management in a Large, Regulated River, With Implications for Management of Endangered Fish

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Abstract For large, regulated rivers, operators can impact abiotic conditions for the benefit of the ecosystem, primarily by controlling the volume of discharge from upstream reservoirs. Understanding the decision space around discharge is necessary for evaluating tradeoffs between environmental and other objectives. As a result of climate change, warming water temperatures are increasingly becoming a concern for thermally-sensitive fauna. In California's largest river, the Sacramento, extinction risk of salmon populations is linked to high water temperatures. Yet, little is known about how much water temperature in lower reaches can be affected by reservoir discharge operations, and the potential benefits to salmon. We used a process-based water temperature model to estimate the ability of reservoir discharge to mediate river temperature heating processes impacting downstream locations (discharge-mediated temperature management). To bound this analysis, we used historical forcings over a recent 29-year span. Results indicate reservoir discharge increases of up to 340 cms over the historical record could have decreased water temperature in the lower reaches by up to 3.6°C. Salmon require water below 20°C during most stages of their lifecycle, and we found that normative water operations could ensure 20°C was rarely exceeded for two potential management seasons, in late-spring and early-fall. These periods coincide with important rearing and migratory periods for salmon, during which they frequently experience excessive temperatures under the management *status-quo*. This analysis provides stakeholders tools to manage conditions for native fauna in the face of a warming climate, and a framework for developing similar tools in other large, regulated rivers.

Plain Language Summary High river water temperatures have long been known to have lethal effects on juvenile and adult salmon in California's Sacramento River. While water temperatures are managed in the upper 30 km for winter-run Chinook salmon eggs, no effort is made to manage water temperatures in the remaining 450 km of the Sacramento River. We use a water temperature model to estimate water temperatures as a result of hypothetical river flow simulations to demonstrate that reservoir discharge management can effectively reduce water temperatures throughout the non-tidal portions of the Sacramento River during key times of the year for migrating salmon. We suggest, and give examples for how, discharge-mediated temperature management can be used as a tool to mitigate against excessively warm temperatures in the Sacramento River.

1. Introduction

Increasing freshwater temperatures are an important concern for the conservation and management of fish populations worldwide. In large, regulated rivers, resource managers have the ability to make large-scale changes to abiotic conditions for the benefit of fish populations through discharge management actions. Discharge has been repeatedly demonstrated to influence water temperatures in many rivers of various sizes across the world (Gu et al., 1998; Sinokrot & Gulliver, 2000; van Vliet et al., 2011). However, resource managers often lack the information and tools necessary to predict the impacts of discharge-mediated temperature management and evaluate the costs and benefits of such actions. Using a case study in a highly constrained water management arena, we provide a framework for developing such tools.

In California, USA, significant efforts have gone into estimating the thermal tolerance and resulting climate change vulnerability of Endangered Species Act (ESA) listed fish, such as delta smelt (*Hypomesus transpacificus*) and longfin smelt (*Spirinchus thaleichthys*) (e.g., Jeffries et al., 2016; Wagner et al., 2011). Similarly, Chinook salmon (*Oncorhynchus tshawytscha*) populations are known to be sensitive to high temperatures throughout

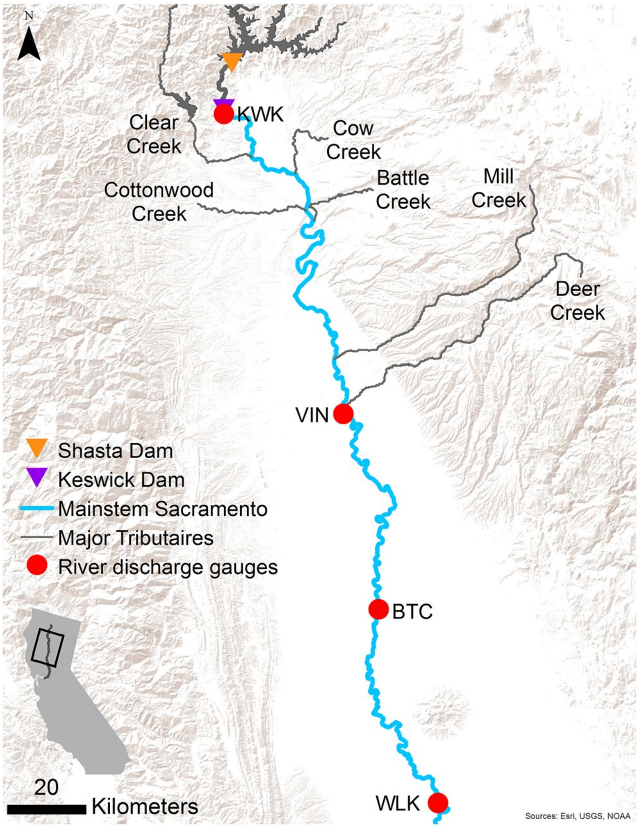

Figure 1. Map of study area, with mainstem Sacramento River outlined in blue. Major flow and temperature gauges used in the analysis are highlighted with red points: KWK—Keswick, VIN—Vina, BTC—Butte City, and WLK—Wilkins Slough.

their life cycle (Richter & Kolmes, 2005). Chinook salmon in California's Central Valley are at the southern extent of the Pacific salmon's range and are predicted to experience unfavorable temperature extremes increasingly more often than other salmon populations (Fitzgerald et al., 2021), making them more vulnerable to climate change than other populations (Crozier et al., 2019). Alterations to the California's Central Valley major watersheds (the Sacramento and San Joaquin Rivers and their tributaries), in particular the construction of low elevation dams that lack fish passage, have exacerbated the problem by blocking salmon access to colder high-elevation habitat. Moreover, dams and related infrastructure aimed at delivering water for out of stream uses (irrigated agriculture, municipal, and industrial use) has vastly altered stream flow and stream temperature regimes.

Many studies in the Central Valley have investigated the role of warming water temperatures on survival rates at different stages of the Chinook salmon life cycle, including eggs during incubation (Martin et al., 2017), juveniles during rearing (Munsch et al., 2019), juveniles during outmigration (Baker et al., 1995; Michel et al., 2021; Nobriga et al., 2021), adults during spawning migration (Martin et al., 2015), and adults during over-summer holding periods (Mosser et al., 2013). With this understanding, there are water temperature management efforts in the Central Valley, the most publicized involving managing water temperatures to provide ESA-listed winter-run Chinook salmon eggs with thermally suitable conditions during the incubation phase. This is attempted annually through multi-agency planning efforts and major infrastructure projects (such as the Lake Shasta Temperature Control Device; Hanna et al., 1999). Managing water temperatures for winter-run Chinook salmon is possible because the near entirety of the winter-run Chinook salmon population spawn in the first 30 km downstream of Shasta and Keswick Dams (Figure 1). Being so close to the release point of cold reservoir water results in little time for the discharged water to heat up during the hot Central Valley summers when winter-run Chinook salmon eggs are incubating.

Little research has explored if water temperatures could be regulated for the remaining 450 km of the Sacramento River downstream to San Francisco Bay Estuary. Daniels and Danner (2020) performed a comprehensive analysis using a process-based model to discern which factors most influence water temperatures throughout the non-tidal portions of the Sacramento River. They found that air temperatures and solar radiation were major drivers of water temperature changes in lower reaches of the Sacramento River, such that as water traveled further from its source temperature (the reservoir) it approached equilibrium with surface air temperatures. Air temperatures and solar radiation, however, are two factors that are uncontrollable. That study also found that reservoir discharge had a lesser, but significant, influence on water temperatures, largely mediated through the travel time of a parcel of water. The authors concluded that higher discharge leads to faster water travel times, which ultimately gives a parcel of water less time to come to equilibrium with air temperatures. Based on this concept, the impact of discharge, and therefore travel time, on water temperature should be especially pronounced during times of the year with a high air temperature-water temperature differential at reservoir release. Empirical data has not conclusively demonstrated if discharge alone can regulate water temperatures in the lower portions of the Sacramento river; this is largely because high flow events are typically associated with storms, during which air temperatures and solar radiation are typically lowered, thereby confounding the influence of any one of those drivers. Yet, discharge manipulations have been successfully used in other dam-regulated rivers to decrease water temperatures during summer months for the benefit of salmon (Clabough et al., 2006; Macdonald et al., 2012). There is therefore reason to believe that discharge-mediated water temperature regulation may lead to important, previously unexplored, management options for salmon conservation in the Sacramento River.

From a management perspective, assessing the value of increasing reservoir discharge to manage downstream water temperature must also consider how that value changes throughout the year. For example, an additional 100 cms (cubic meters per second) of water discharged from the reservoir during March when air temperatures are cool and water diversions are low will presumably not impact downstream water temperatures as much as an additional 100 cms of water delivered during June when surface air temperatures are much warmer and downstream river flow becomes increasingly reduced due to increased agricultural diversions and reduced tributary inflow. Furthermore, overlaying the understanding of the seasonal discharge-temperature relationship with the seasonality and locations of salmon life history events can allow managers to focus on periods and places when increased discharge can yield disproportionally high gains in maintaining cooler river temperatures and associated salmon health and survival benefits. The judicious use of additional water for salmon recovery and conservation efforts is a must in this contentious water management arena.

Here we identify and quantify the relationship between reservoir discharge and downstream water temperatures in a large, managed river using a process-based model of river temperature (RAFT; Pike et al., 2013; Daniels et al., 2018). This was done for the Sacramento River by modeling water temperatures over the historical record (1990–2020) of model forcings and only perturbing reservoir discharge levels on a daily time step. Specifically (a), we compared the RAFT model simulated temperatures to observed water temperatures to verify that it is an appropriate model for this exercise (b), we simulated water temperatures over a range of hypothetical daily reservoir discharge levels across the historical record, and (c) we summarized and contextualized the findings to facilitate consideration by resource managers and other stakeholders. We include real-world examples of how these findings could have been successfully used for both seasonally-explicit minimum flow standards and adaptive temperature management for salmon populations, as well as an online decision-support tool.

2. Methods

2.1. Study System

The Sacramento River is the largest river and home to the largest Chinook salmon runs in California (Figure 1). Historically, the Sacramento River, along with the San Joaquin River that joins it to form the San Francisco Bay Estuary, had some of the largest Chinook salmon runs in the world. A legacy of watershed deterioration, dating back to the California Gold Rush, has left this watershed with drastically reduced salmon populations (Yoshiyama et al., 1998, 2001), to the point of one population being extirpated and two others listed on the U.S. Endangered Species Act. One of the most significant alterations to the watershed was the construction of low elevation dams on all the major tributaries in the system, permanently blocking upwards of 72% of historic salmon spawning habitat (Yoshiyama et al., 2001). These dams were constructed for flood control, hydropower generation, and water storage and supply. Notably, Shasta Reservoir (capable of storing 5.6 cubic kilometers of water, the most in California) and its downstream forebay, Keswick Reservoir, block access to hundreds of kilometers of spawning habitat, and also regulate the flow through the majority of the length of the Sacramento River (Figure 1). These dams and the associated downstream water diversion infrastructure have inverted the Sacramento River hydrograph both spatially and temporally. Historically the Sacramento River was a gaining river where flow increased in the downstream direction and the majority of flow occurred in winter and spring following patterns of a Mediterranean climate. Now, during most months outside of the winter season, flow is highest in the upper watershed nearest to Keswick Dam and reduced in the downstream direction due to water diversions for agricultural, municipal and other uses, while reservoir inflow is stored in winter and spring and downstream flows are bolstered by reservoir releases in the late-spring and summer for agricultural needs (Kimmerer, 2002).

Water temperatures in the Upper Sacramento River (approximately the first 50 km downstream from Keswick) are reflective of a reservoir (i.e., Shasta) tailwater: cold and fairly stable, with temperatures suitable for juvenile salmon rearing year-round (Figure 2). Water temperatures in the Lower Sacramento River, however, fluctuate dramatically, ranging from a median monthly temperature of 10°C in the winter months to a median temperature exceeding 20°C in the summer months (Figure 2). At daily mean water temperatures above 20°C, the juvenile Chinook salmon migratory corridor essentially becomes disconnected, given that survival is estimated to be near zero under these conditions (Michel et al., 2021; Nobriga et al., 2021). In addition, Munsch et al. (2019) found that relatively lower springtime water temperatures led to longer springtime rearing seasons in the lower Sacramento River and estuary for Chinook salmon fry, and larger sizes at ocean entry (where survival is size selective; Woodson et al., 2013). Significant efforts are made annually to keep the upper 30 km of the Sacramento River cold (<11.9°C) from 15 May to 31 October in order to provide thermally suitable conditions for ESA-endangered winter-run Chinook salmon egg incubation. However, no current efforts exist to manage water temperatures in the remaining lower 350 km of non-tidal river. This is likely in part due to the uncertainty

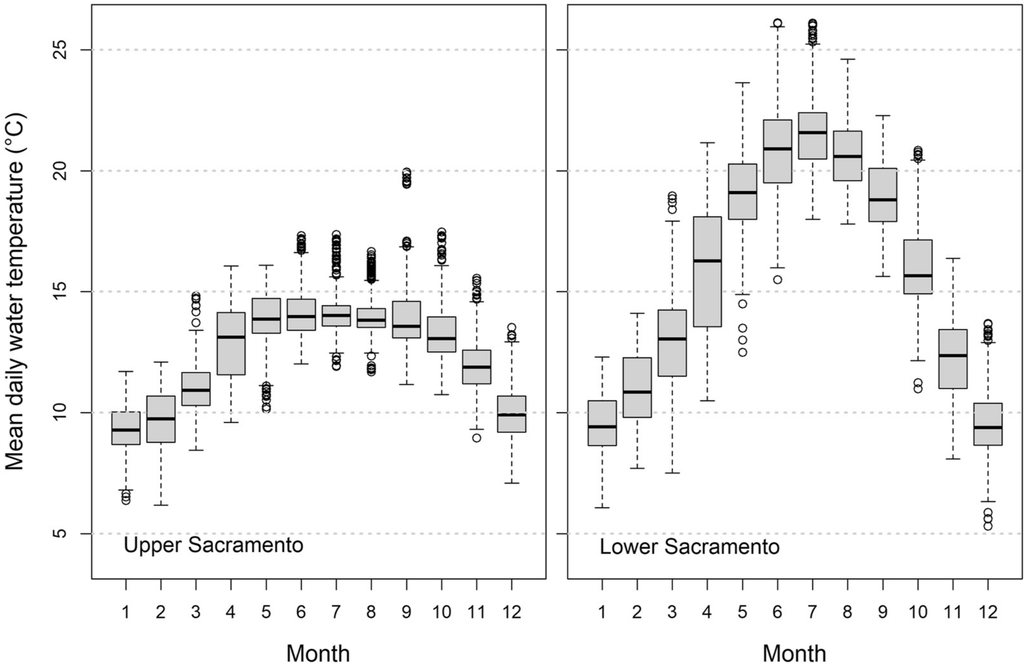

Figure 2. Mean daily water temperatures by month in the Upper Sacramento (Sacramento River at Bend Bridge, California Data Exchange Center gauge ID "BND"; Figure 1) and Lower Sacramento (USGS Sacramento River at Wilkins Slough; gauge ID 11390500; Figure 1) for the years 1994, 1995, and 2013 through 2020 (representing the years with complete temperature records at both locations).

in whether or not water temperatures can be affected by discharge regulation in the lower river and estuary (Bashevkin & Mahardja, 2022).

2.1.1. Water Temperature Model

We estimated the ability (on a daily mean scale) of discharge-mediated temperature management in the Sacramento River throughout the entire year using a region-specific model called RAFT (Daniels et al., 2018; Pike et al., 2013). RAFT simulates temperature dynamics in a one-dimensional direction longitudinally downstream, while averaging across the depth and lateral sections of a river channel. The primary processes used to estimate how different sources of heat enter and exit a given model longitudinal segment are the effects of downward solar radiation, incoming longwave radiation, outgoing longwave radiation, latent heat of evaporation, and conduction. The version of RAFT used in this analysis is further described by Daniels et al. (2018), and has a temporal resolution of ten minutes and a spatial resolution of 2 km. The upstream boundary is Keswick Dam, and the downstream boundary is near the town of Knights Landing, CA, USA (just below WLK; Figure 1).

2.2. Input Data and Discharge Perturbations

There are three major categories of input data and model forcings for the RAFT model; meteorological data, water temperature data, and flow data. For meteorological forcings, we used sub-daily historical inputs from years 1990–2020, sourced from the North American Region Reanalysis (NARR) weather product (Mesinger et al., 2006). NARR products are produced 8 times daily (i.e., 3-hr temporal resolution) and are gridded at a spatial resolution of 32 km. Prior to use in the RAFT model, NARR products were temporally downscaled to a sub-hourly time series and were bias-corrected to observed meteorological stations as outlined in Daniels et al. (2018). Our intention of running discharge perturbations over each of the historical years of meteorology was that each year would represent possible meteorological conditions that could occur on any given day of the year. Therefore, the uncertainty of meteorology in this analysis was bounded in the context of historical conditions occurring in the system. In addition to historical meteorology, we used observed water temperatures as inputs to RAFT. Specifically, water temperature inputs were used as boundary conditions in the RAFT model, with the upper boundary being reservoir release temperatures at Keswick Reservoir. In addition to an upstream input of temperature, we also simulated major tributary inputs (Clear, Cow, Cottonwood, Battle, Mill, and Deer Creeks, Figure 1) into the system, where both observed temperature and flow were used.

To explore our primary hypothesis that discharge-mediated temperature management may be a valuable management tool in the more downstream sections of the Sacramento River, we perturbed upstream discharge from Keswick Reservoir. The discharge perturbations in our modeling exercise were simulated to achieve flow targets at the most downstream river gauge in the study region, that is, at the USGS Sacramento River at Wilkins Slough gauging station (USGS gauge ID 11390500; hereafter "Wilkins" or WLK in Figure 1). We chose this location because, from a management perspective, flow targets at more downstream locations will ensure that desired flow conditions are met or exceeded throughout the Sacramento River despite the multitude of water diversions along its length. In other words, if flow targets were instead set at gauge stations in the Upper Sacramento, tributary additions and diversion removals may result in drastically different flow rates in the Lower Sacramento River, and therefore a decreased ability to achieve desired water temperature targets.

Discharge scenarios were set to range from 85 to 425 cms as measured at Wilkins, at 2.8 cms increments, for a total of 121 total simulations. The lower end [85 cms, or 3,000 cubic feet per second (cfs), the regional river flow rate unit] approximately represents the current minimum flows observed at Wilkins. We chose the upper bound of the range to approximately represent the maximum discharge released from Keswick under normative, non-emergency water operations (i.e., outside of flood control spills). To achieve a flow target at Wilkins on any given day of the historical record, we back-calculated how much water would have had to be released from Keswick Reservoir. More specifically, we estimated the net daily difference in flow along the length of the river. For this purpose, we split the river into three sections using existing gauge locations: Keswick to Vina, Vina to Butte City, and Butte City to Wilkins (Figure 1). Net flow change in each of these three sections was estimated as the net change in flow at the downstream end of the section compared to the upstream end (as measured at the gauges), and therefore approximately represents the net difference between inputs (tributaries) and exports (diversions, evaporation, groundwater recharge; Figure S1 and Text S1 in Supporting Information S1). Ultimately, the flow inputs into the RAFT model were fixed at 4 locations, at Keswick release, and at the end of each section, based on both the net flow and desired discharge perturbation. Gauge data was available from 1990 to 2020, however, due to gauge coverage gaps, 1996 and 1997 were omitted from the time series, therefore resulting in a 29-year record for all perturbation exercises.

In order to assess the strength of the relationship between simulated discharge and modeled water temperatures across space and time, we broke up the study region and year into smaller subsections, consisting of spatial-temporal cells that were each 1 week long and encompassed a river segment 8–24 km long. We then estimated the slope from a single linear regression between the discharge (in units of 100 cms) and the resulting daily mean water temperature (°C) for each cell. Within each week, data was further subset to the middle day to avoid temporal autocorrelation within the week. Each linear model estimated the effect of discharge on simulated water temperatures and included a random effect of year, so as to capture major temperature changes not due to discharge.

2.3. Validation Exercise

RAFT was developed to make water temperature predictions throughout the Sacramento River. Until now, it has largely been used to better understand the temperature exposure of incubating Chinook salmon eggs under forecast and hindcast conditions in the ~50 km of the river downstream of Keswick Dam. During hindcast simulations, RAFT uses a version of the Kalman Ensemble Filter for data-assimilation purposes to reduce model error (Evensen, 2009). To ensure RAFT would also make accurate water temperature predictions for the remaining 300 km of non-tidal Sacramento River without data-assimilation, we performed a validation exercise for the hindcast period of 1990–2020. Specifically, we used observed meteorology and observed water temperatures at Keswick Reservoir and at tributaries, as described above. Unlike the perturbation simulations, we used observed flow for the same three locations as with the perturbation simulations (Vina, Butte City, and Wilkins) and we did not alter the observed releases from Keswick Reservoir. We then compared the predicted to observed water temperatures measured at various temperature gauging stations along the river.

The validation exercise indicated high correlation between predicted and observed water temperatures at various gauging stations along the Sacramento River and across all years in the historical record (Text S2 in Supporting

Information S1). Many of the response metrics are based on predicted temperatures at the Wilkins gauge, and focusing on the accuracy of predictions at just that location, we see strong accordance between predictions and observations there ($R^2 = 0.96$; Figure S2 in Supporting Information S1). The root mean square error (RMSE) between predicted and observed water temperatures at Wilkins over the simulated time series was 1°C with a mean bias of 0.4°C, indicating that the model tended to predict slightly warmer temperatures than observed on average. We also found high correlation between predicted and observed water temperatures on a per month and per discharge level basis, with RMSE ranging from 0.8 to 1.2°C and 0.8 to 1.1°C, respectively (Figures S3 and S4 in Supporting Information S1). We conservatively adopted the per month RMSE for depicting prediction error in figures where necessary.

2.4. Non-Exceedance Probability

For the discharge perturbation exercise, water temperatures were predicted at 10-min intervals and 2-km intervals for every day in the historical record, and then averaged per day for every discharge perturbation (121 in total per day). Therefore, for every day of the 29-year historical record, we estimated the mean daily water temperature given 121 different discharge levels out of Keswick Reservoir. Because the RAFT model requires continuous inputs to run, we interpolated data in cases of river gauge data gaps. Instances where missing gauge data were interpolated represented only ∼6% of the time series and once RAFT temperature predictions were generated, we dropped any simulations that used interpolated data for further analysis. These interpolated time periods primarily occurred in the months of October, November, and December when discharge-mediated temperature management was likely to have little utility and therefore the interpolation and dropping of these values was not expected to impact the interpretation of the modeling results.

We used *probability of non-exceedance* to summarize the capability for discharge-mediated temperature management. We define non-exceedance probability as the probability that temperatures will stay below some level given the possible conditions. As an example, the stream flow at Wilkins needed to achieve 90% non-exceedance probability for 20°C on a given day during the spring period may be 225 cms. This means that if Wilkins flow is 225 cms for that day, there is a 90% chance that Wilkins water temperatures will stay below 20°C given the range of possible meteorological conditions for that day in the 29-year historical time series. We estimated non-exceedance probability using temperature predictions at Wilkins as this is one of the most downstream prediction locations, and therefore typically represents the warmest water temperatures in the study region during periods when temperatures are of concern for salmon. We also estimated *non-exceedance curves* for specific non-exceedance probabilities throughout the year. For example, the 90% non-exceedance curve represents the daily flow necessary to ensure a 90% non-exceedance probability for 20C across the year. We estimated non-exceedance curves across the study period for 19°C, 20°C, and 21°C. These temperatures represent the approximate temperature range where we begin to see lethal effects of warm water temperatures on juvenile and adult salmon (Bowerman et al., 2018; Hallock et al., 1970; Kjelson & Brandes, 1989; Michel et al., 2021), and therefore provide three potential temperature targets for resource managers to use in establishing potential future flow criteria or actions.

To smooth over stochastic sub-seasonal (daily to weekly) fluctuations in the non-exceedance curves caused by individual weather events in the historical record, we estimated non-exceedance probability for each discharge level and temperature target over a 2-week moving window (Text S3 in Supporting Information S1). Using these smoothed daily non-exceedance values, we plotted non-exceedance curves through the year for 50%–90% non-exceedance probability at 10% increments using the geom_contour function within the ggplot2 package (Wickham, 2016) in program R, version 4.2.1 (R Core Team, 2022). These non-exceedance curves were included in Table S1.

2.5. Travel Time Estimation

The primary hypothesized mechanism that allows river discharge to influence water temperatures, as also demonstrated theoretically by Monismith et al. (2009), is by impacting the water travel time and therefore time a parcel of water has to come to equilibrium with atmospheric temperature. In addition, the increased thermal mass of larger volumes of water will also increase the amount of time for a parcel of water to come to equilibrium with atmospheric temperature. However, the RAFT model in its current form cannot disentangle these two drivers of discharge-mediated temperature regulation and we chose to focus on the travel time mechanism. In order to assess the potential effect of travel time in our simulations, we calculated the total travel time for a parcel of water from Keswick Reservoir to Wilkins under all discharge perturbation scenarios. This was done in a step-wise fashion (starting at the upper boundary of the model) where the mean channel velocity was extracted from RAFT output for each simulation time-step. Mean channel velocity (m sec^{-1}) was then use to estimate the residence time (sec) a parcel of water remained in each 2 km RAFT segment. The parcel of water was then simulated to move downstream based on mean channel velocity and the cumulative residence time was calculated once the parcel arrived at Wilkins.

2.6. Seasonality in Water Cost and Salmon Relevance

When assessing the feasibility of performing discharge-mediated temperature management during a given week of the year, there are three important and related questions to consider: (a) Is the temperature target achievable with reasonable discharge levels for the time of year? (b) At what water cost? and (c) How many salmon would benefit? For estimating the first element, we tabulated the frequency of years when temperatures did exceed 20°C as well as the frequency of years when surpassing 20°C could have been avoided given the range of perturbation, per week of year. Ultimately, we hoped to identity weeks of the year when discharge-mediated temperature management was frequently both necessary and possible given our perturbations. For estimating the second element, we calculated the additional water discharge volume needed over the status quo (i.e., the actual gauge flow time series at Wilkins) to ensure temperatures do not exceed 20°C at Wilkins per week in the historical record (29 years) to assess the seasonality in water “cost” (here represented by water volume). For this exercise, we did not use the exceedance probability curves and instead identified the RAFT simulation with the lowest Wilkins flow (cms) that achieves 20°C non-exceedance given river conditions for every day in the historical record (i.e., perfect knowledge). We then converted the additional daily discharge rate to a daily additional water volume needed, then summed these daily volumes across the week. Finally, for the final element, we estimated seasonality in both juvenile and adult salmonid migrations in and out of the primary spawning and rearing reach of the Sacramento River. Juvenile Chinook salmon migration timing was represented by downstream fish passage at Red Bluff, CA as a function of date and by run acquired from B. Poytress (USFWS—Red Bluff, CA), and represents median daily passage estimates expanded from rotary screw trap counts from 2006 to 2019, with 20-day moving average smoothing applied. Adult Chinook salmon and Steelhead migration timing was represented by upstream passage data as a function of week and by run acquired from Killam and Harvey-Arrison (2004), and based on adult salmon counts at the Red Bluff Diversion Dam Counting Station during the years 1970–1988. Red Bluff represents the end of the migratory corridor for adult salmon on the Sacramento, and the beginning of the migratory corridor for juvenile salmon that are born upstream, and so exposure time to potentially warm water temperatures downstream of here is a function of migration rates. Limited adult Chinook salmon telemetry data has shown travel times of 10–45 days to transit the non-tidal lower Sacramento River before arriving to Red Bluff (Martin et al., 2015), and actively migrating juvenile Chinook salmon can take of 3–60 days to reach the tidal portions of the river after leaving Red Bluff (Hassrick et al., 2022; Michel et al., 2013).

3. Results

We found that the relationship between reservoir discharge and downstream water temperature response varies by downstream distance and season (Figure 3). Throughout the year, regression slopes in the upper approximately 58 km of the study region indicate weak relationships between flow and water temperature (regression coefficients between 0.14 and −0.339). Weak discharge-temperature relationships also exist in the late fall, winter, and early spring, with regression coefficients having an absolute value <0.4 from approximately 17 October to 7 March. Reciprocally, we see the largest regression coefficients between late May and late September, and these increase in magnitude in the downstream direction. Regression coefficients downstream of 140 km indicate a stronger relationship, with absolute values consistently >0.67 from May through September, such that a summertime increase in 100 cms in this region will decrease water temperatures by minimum of approximately 0.67°C. In other words, reservoir discharge changes have the largest impact on water temperatures in the late-spring, summer, and early-fall and in the more downstream regions.

In summer months, we saw a maximum possible temperature reduction over minimum flow conditions (i.e., 85 cms at Wilkins, or the resultant Wilkins flow if Keswick discharge is 92 cms, whichever is higher) of

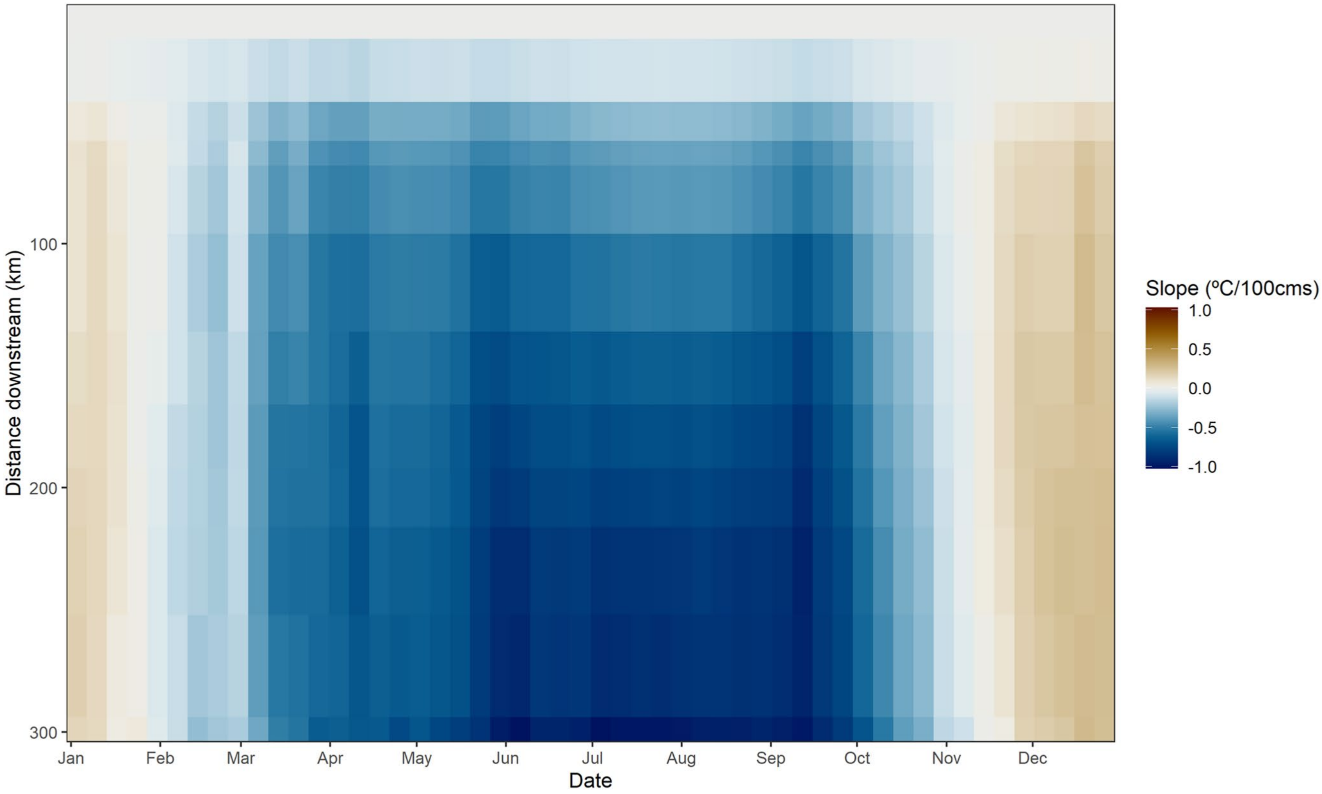

Figure 3. Heatmap of regression coefficients (i.e., slope) for the effect of flow (as measured at Wilkins, in 100 cms) on water temperatures (as predicted within each cell). Regression coefficients are represented by the color of each cell, with warmer colors representing steeper positive slopes (i.e., higher flow increases water temperatures), cooler colors representing steeper negative slopes (i.e., higher flow decreases water temperatures), and white representing near zero or zero slope (i.e., no relationship between flow and water temperatures).

approximately 3.6°C at Wilkins (Figure 4). Such reductions in temperature were only possible in the peak water temperature months of June-September. Beyond those months, the month of May had the largest possible potential reductions in water temperatures as a result of discharge perturbations, with a 2.7°C temperature reduction at 425 cms compared to minimum flow conditions. Inversely, wintertime water temperatures were predicted to warm by as much as 0.6°C over minimum flow conditions (Figure 4).

Our simulations also demonstrated that varying discharge rates affected water parcel travel time from Keswick Reservoir to Wilkins (Figure 5). Given the range of discharge-mediated flow perturbations at Wilkins, from 85 to 425 cms, we saw a reduction in water parcel travel time from approximately 4.5 to 3.5 days. During the summer months, this 1-day reduction in travel time leads to a reduced water temperature warming of ∼5°C between Keswick and Wilkins (i.e., July; Figure 5), although the larger thermal inertia of larger water volumes also likely reduced warming potential as well.

Results from the non-exceedance analysis indicated that discharge-mediated temperature management was achievable during some portions of the year for some temperature targets, but not for others (Figure 6). For example, if we had hoped to ensure that water temperatures are highly likely (i.e., 90% probability based on historic conditions) to stay below 20°C on May 1st, we would need to ensure a minimum flow at Wilkins of approximately 250 cms (Figure 6, Table S1). For 80% reliability that water temperatures do not exceed 20°C any time before May 15 (during the entire peak outmigration window for juvenile spring-run Chinook salmon, Figure 7), we would need to ensure a minimum flow of approximately 225 cms (Figure 6). However, discharge management could instead follow a desired non-exceedance curve as the outmigration season progresses, such that (using the previous example), minimum flow increased progressively from 100 to 225 cms across the mid-April to mid-May time span.

As a result of estimating the need and capacity of discharge-mediated temperature management and water cost per week for a hypothetical temperature target of 20°C, we found that two clear discharge-mediated temperature management seasons can be identified (Figure 7). Under all 29 years of observed meteorological and

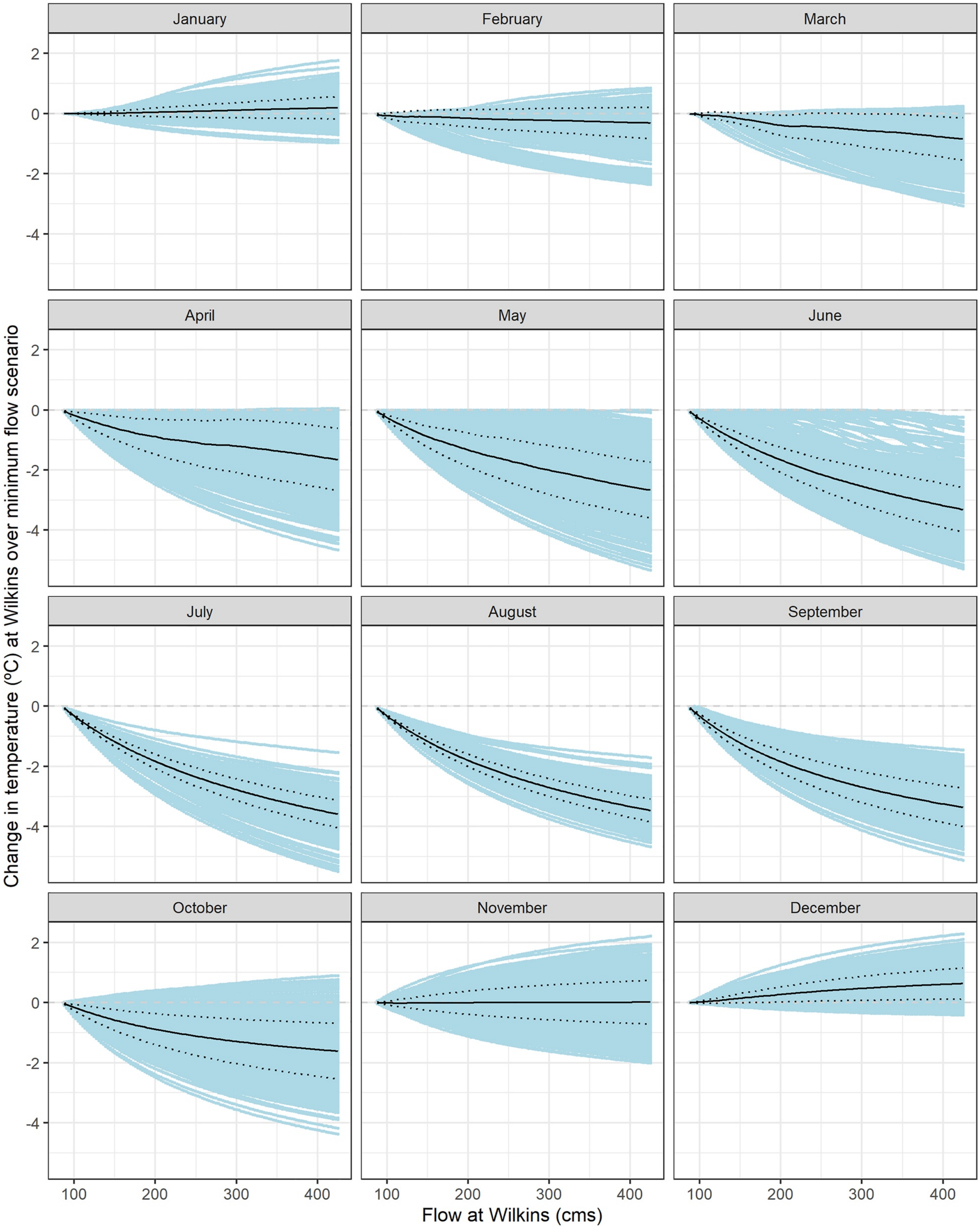

Figure 4. Estimated daily water temperature change at Wilkins across the range of Wilkins flow values, compared to the temperature at daily baseline flow, for all days in the historical record, split out by month. Minimum daily flow was set to 85 cms at Wilkins (the approximate minimum of all observed values), or the resultant Wilkins flow if Keswick discharge is 92 cms, whichever is higher. The monthly mean of all the daily temperature change values for each flow level at Wilkins is represented with a solid black line, with surrounding dotted lines representing ± 1 SD.

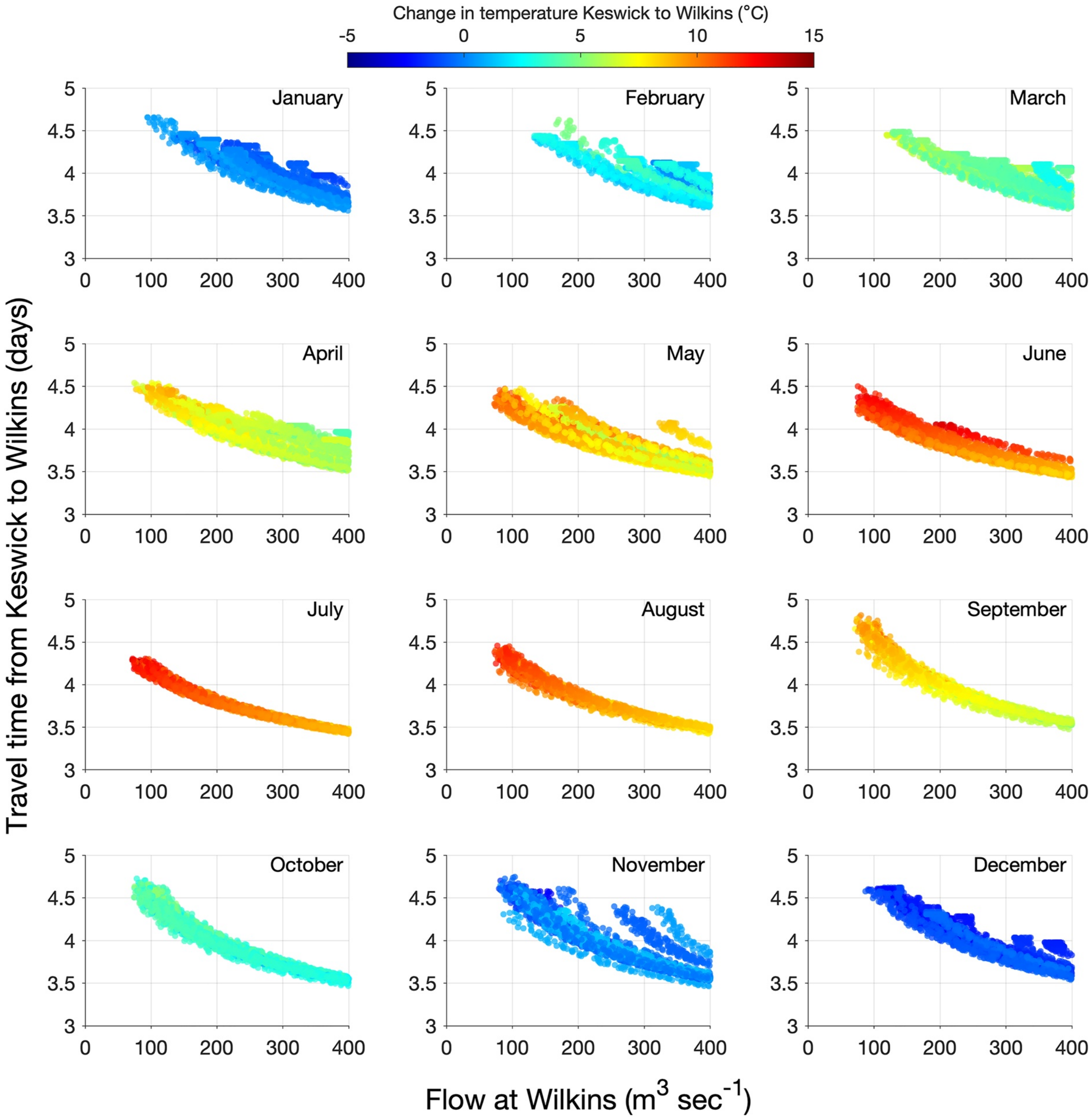

Figure 5. Predicted change in water temperature (in °C) from Keswick Reservoir to Wilkins as a function of flow (as measured at Wilkins in cms) and travel time from Keswick to Wilkins (in days), broken out by month. Each point on a given subplot represents one of the 121 discharge perturbations for a given historical year.

hydrological conditions, 20°C was never exceeded down to Wilkins for calendar weeks 1 through 14 (January 1 to ~9 April), and 43 (~25 October) through the end of the calendar year (Figure 7a). During the peak summer months, weeks 22 through 34 (~1 June–27 August), discharge perturbations of up to 425 cms at Wilkins either did not result in temperatures below 20°C at Wilkins, or if they did, the average water cost was relatively high [generally >37 million cubic meters (mcm) per week; Figures 7a and 7b]. Between these two periods, we have two discharge-mediated temperature management windows during which historical observed conditions have not always resulted in water temperatures below 20°C, yet discharge perturbations could have kept water temperatures below 20°C with a relatively lower mean water cost compared to that required for the summer period. These discharge-mediated temperature management windows coincide with important migratory periods in the salmon life-cycle, such as when the bulk of ESA-listed winter-run and ESA-listed spring-run juveniles outmigrate to the ocean, as well as when a significant portion of adult winter-run and fall-run Chinook salmon, as well as adult ESA-listed steelhead, return to spawn (Figure 7c).

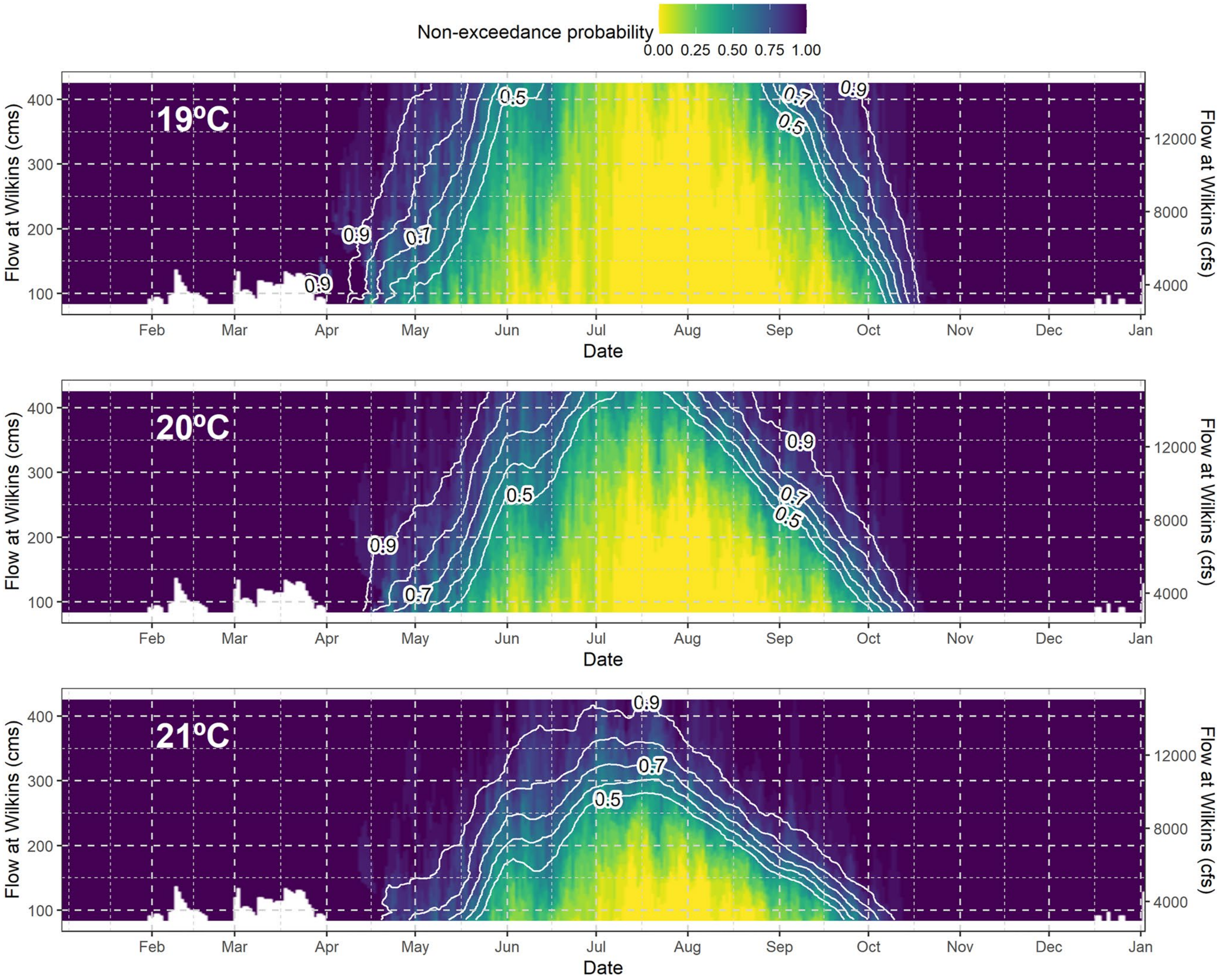

Figure 6. Heatmap representing unsmoothed non-exceedance probabilities as a function of date and flow at Wilkins (cms). Flow rates are also depicted in cubic feet per second (cfs) on the secondary *y*-axis, the unit of measurement used locally. Contour lines depict 0.5 to 0.9 non-exceedance probability at 0.1 intervals, using a 2-week moving average smoothing for the needed flow. White cells within the heatmap represents missing data.

4. Discussion

In freshwater systems where human infrastructure has altered the hydrograph and thermograph, there is a need to evaluate the range of water management actions available to maintain temperatures within the tolerance of native species, and this need becomes more urgent as a warming climate drives freshwater temperatures higher. We used a process-based water temperature model to demonstrate that discharge-mediated temperature management can regulate downstream water temperatures in a major river in California's Central Valley, and the methods we applied are relevant to many systems worldwide. In our study system, the Sacramento River, the water cost and magnitude of the impact varies substantially across the year. We have linked this variation to the impact of river flow to water travel time, as mediated through the increased warming potential of higher air temperatures and solar radiation during the late-spring, summer, and early-fall months. These findings indicate manipulating discharge can be a valuable management tool to target sufficiently cool temperatures for salmonids and other temperature-sensitive native fauna. Many Central Valley salmon populations migrate during periods of the year when temperatures regularly exceed their thermal tolerance under the management status quo (Figures 2 and 7), and yet the water cost may be too high at times to use discharge-mediated temperature management to mitigate for these lethally warm temperatures. During the hottest months of the year (June-August), the increase in flow necessary to ensure nonlethal water temperatures may require too much water, depending on reservoir storage

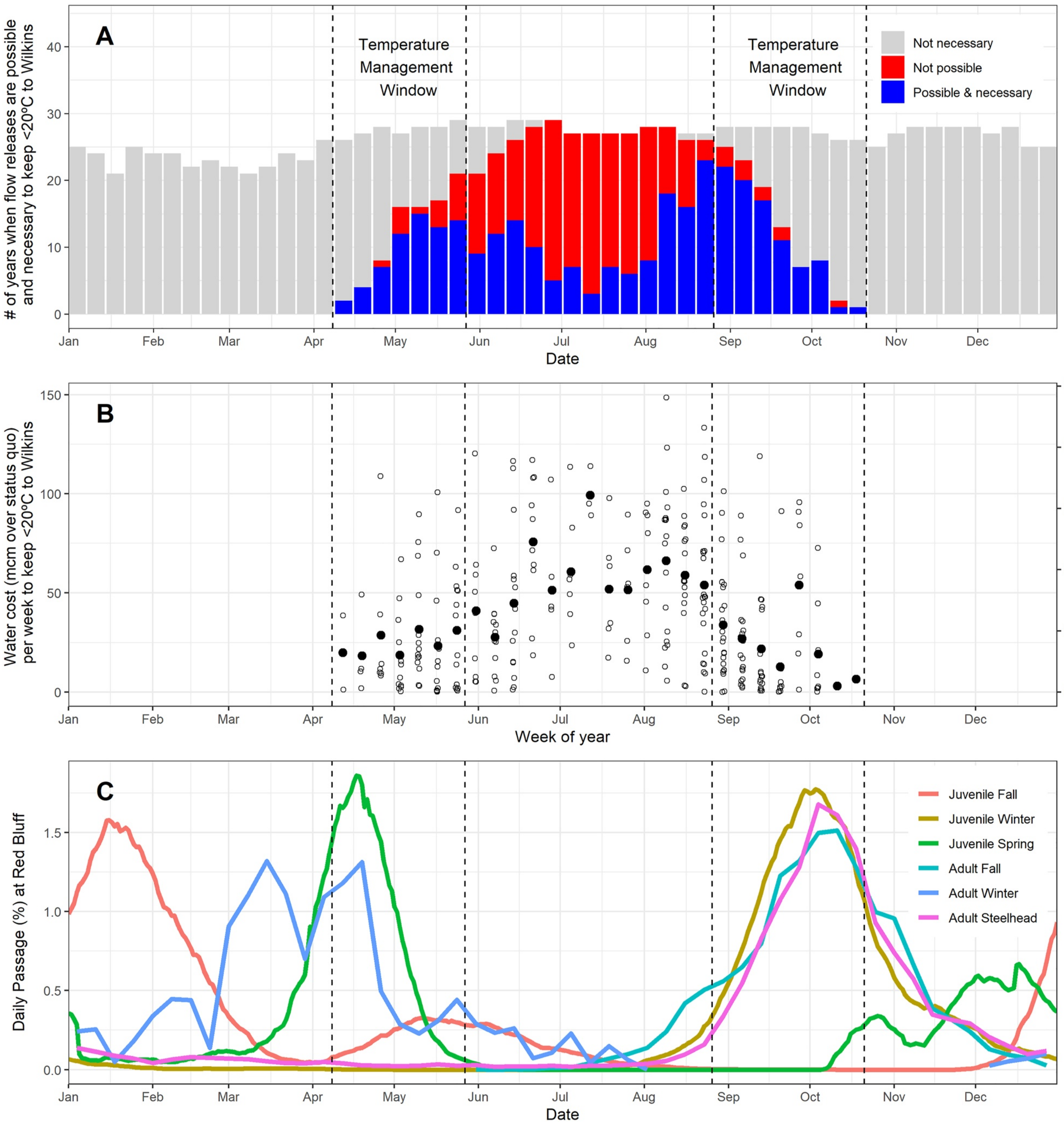

Figure 7. Weeks during which discharge levels resulting in flow of up to 425 cms at Wilkins either could have, could not have, or were unnecessary to keep temperatures below 20°C in the historical record (panel a). Water cost (measured as additional water needed over status quo in million cubic meters—mcm, open circles) to achieve water temperatures below 20°C down to Wilkins as a function of week are depicted in panel (b), with weekly mean water cost represented with a solid black point. Water cost in thousand acer-feet (TAF), the unit of water volume used locally, is also shown on the second *y*-axis of panel (b). Weekly passage rates of outmigrating juvenile salmon and returning adult salmon at Red Bluff, CA on the Sacramento River are depicted in panel (c). Based on panels (a) and (b), potential discharge-mediated temperature management windows are weeks 15–21 (~10 April–1 June), and weeks 35–42 (~27 August–25 October); weeks that are also important to migrating juvenile and adult salmonids (panel c).

levels, especially given the few migrating salmon during this time of year (Figure 7). During the cooler months of the year (early October to early April), flow had little effect on water temperatures as air temperatures were closer to, and often lower than, the reservoir discharge temperature. During this same period, water temperatures were also well below the lethal and sublethal temperature limits for juvenile salmon (Figure 7). Between these two periods, we identified two discharge-mediated temperature management seasons: one in the late-spring (~second week April through the last week of May) and one in late-summer/early-fall (~first week of September through the third week of October). These periods are also biologically important to migratory salmon and steelhead in the Sacramento River (Figure 7), and were identified as periods when salmon rearing opportunities become temporally truncated during drier years due to excessive water temperatures (Munsch et al., 2019).

The authors suggest two specific improvements to how streamflow is regulated on the Sacramento River. First, the non-exceedance curves provided here could guide the enacting of seasonally-explicit minimum flow standards at the Wilkins Slough location for the protection of thermally-sensitive fauna. Specifically, these curves can be used to inform the probability that temperatures will not exceed lethal levels when a large portion of salmon are migrating through the watershed (both juveniles migrating out and adults migrating in). Second, when a large pulse of migrating fish is detected or predicted, and/or a heat wave is forecast during peak outmigration season, the outcomes of our discharge simulations can provide managers with the information needed to temporarily increase discharge to promote safe passage of the migrants within an adaptive management framework. To further this goal, we provide an online decision-support tool for managers to use to forecast the real-time water cost and effectiveness of discharge-mediated temperature management: https://sac-temp-simuls.shinyapps.io/temp_simuls. We also provide hypothetical examples of both these management suggestions below:

- *Seasonally-explicit Minimum Flow Standards*

As an example of how seasonally-explicit minimum flow standards at Wilkins could be implemented, we performed a retrospective analysis of what the daily water temperatures would have been (based on RAFT simulations) if the flows were managed to meet or exceed the 80% non-exceedance curve for a 20°C temperature target during the temperature management seasons outlined above (15 weeks total). We only selected years for which we had daily observed flow measurements for at least 60 days of the temperature management seasons, resulting in 24 years spanning from 1990 to 2020. We then counted the number of days during which water temperatures at Wilkins exceeded 20°C under the status quo, and for the 80%–20°C minimum flow standard simulation (Figure 8). These estimates were grouped based on Water Year Hydrologic Classification Index for the Sacramento Valley (http://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST). This analysis indicated that wet and above normal water years have a relatively lower water cost to adhering to these minimum flow standards, up to approximately 250 mcm, and a 44%–85% reduction in number of days with water exceeding 20°C during the temperature management seasons. Below normal and dry years represented a second tier in terms of water cost, with cost ranging from approximately 250 to 500 mcm, and with a reduction of 37%–100% of days with water exceeding 20°C. Finally, water cost for following minimum flow standards during the temperature management seasons in critically dry water years ranged from 310 to 740 mcm, and with an 8%–76% reduction in days with water exceeding 20°C (Figure 8). Such high water cost in a drought year may be an untenable solution, but the non-exceedance probability level could also be adjusted up or down from 80% to better match the availability of water resources in any given year.

- *Adaptive Management Application Exercise*

As an example of how these temperature non-exceedance curves could also be used for *adaptive* resource management, we present an example based on actual salmon hatchery release data. On 29 April 2016, the USFWS Coleman National Fish Hatchery (Anderson, CA, USA) released 2.8 million fall-run Chinook salmon smolts into the Upper Sacramento River. The day before (hypothetical "decision point" for a management action; Figure 9), flow at Wilkins was unusually low, about 122 cms at that time. Given that flow level and the typical meteorological conditions during that time of year, our non-exceedance curves would have predicted that there would have been an approximately 30% chance water temperatures would have exceeded 20°C that day (i.e., 70% non-exceedance), with an increasing likelihood of exceeding 20°C until the end of July. For this particular release, unseasonably warm conditions did ultimately occur that resulted in temperatures exceeding 20°C in the river (Figure 9). If instead, managers on April 28th (decision point) had access to our non-exceedance curves, they could have requested that reservoir discharge be altered overnight to match flow necessary to meet the 90% non-exceedance probability for 20°C during the days fish were migrating through the river (through to approximately May 5th, which would have required approximately 240 cms at Wilkins, Figure 6, Table S1). Based on our RAFT predictions, this would have resulted in daily mean water temperatures at Wilkins varying between 16.4 and 19.6° rather than the daily mean temperatures actually experienced by these fish (up to a daily mean of 20.7°C; Figure 9). In reality, this large release group experienced exceptionally low survival (Michel et al., 2021; Zeug et al., 2020), likely in part due to the warm temperatures they experienced.

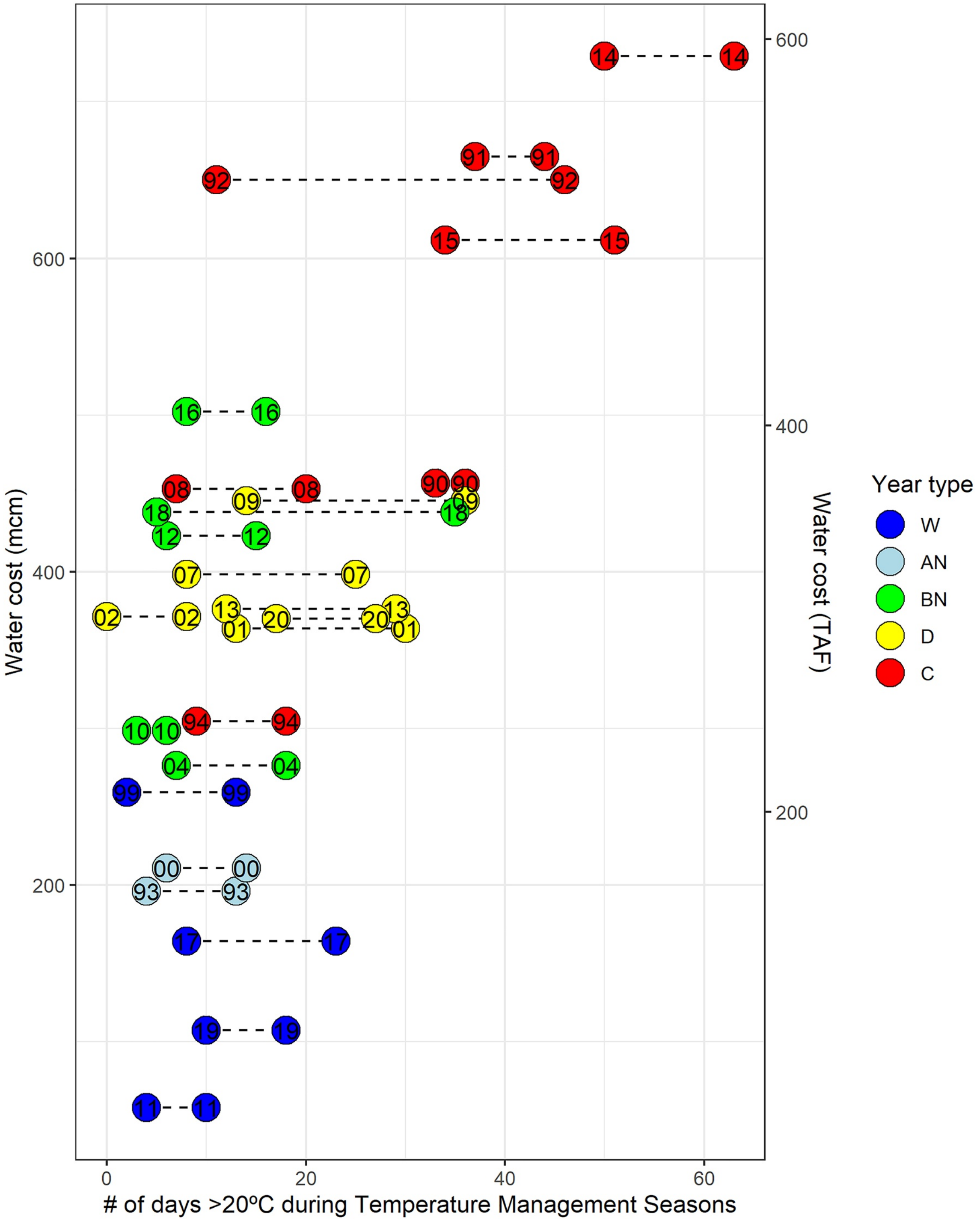

Figure 8. Reduction in number of days with a mean temperature above 20°C at Wilkins (*x*-axis) and water cost [in mcm on primary *y*-axis, in thousand acer-feet (TAF) on secondary *y*-axis] per year given increased discharge to match the 80% non-exceedance flow curve for a 20°C temperature target for the temperature management seasons. Each pair of points connected by a horizontal dashed line represents one year (point labels represent last two digits of year), with the point on the right representing the number of days over 20°C under the status quo hydrograph, and the point on the left the number of days resulting from setting minimum flow standards to the non-exceedance flow curve. Points are color coded based on annual hydrologic classification index (W—wet, AN—above normal, BN—below normal, D—dry, and C—critically dry).

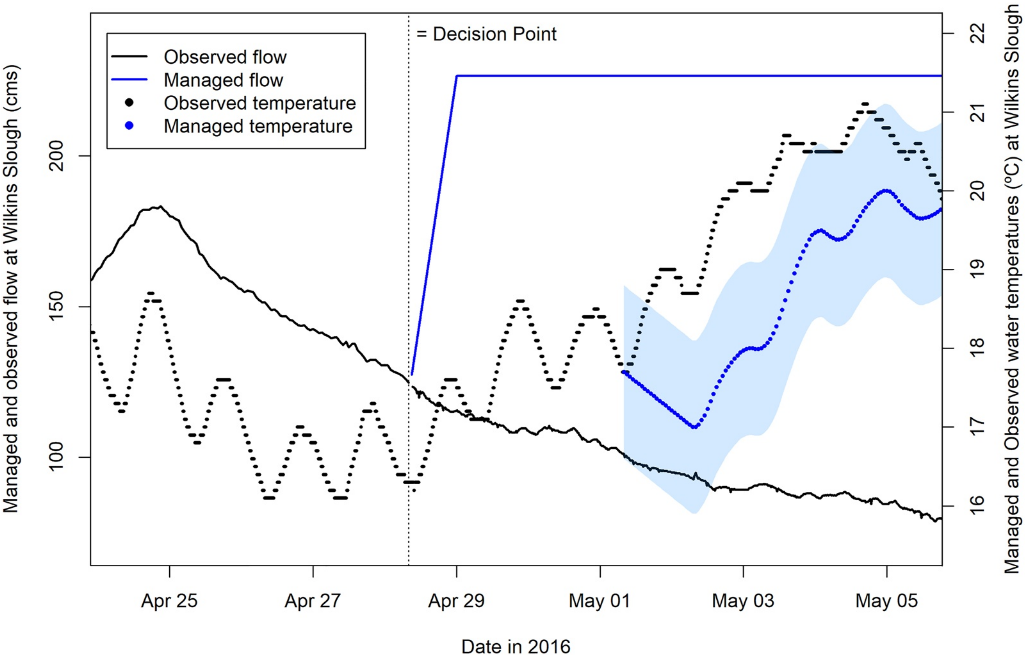

Figure 9. On 28 April 2016, the decision point before hatchery fish were released on April 29th, had reservoir discharge (blue solid line) been altered to match flow necessary to meet the 90% non-exceedance probability for 20°C during the days the majority of fish were expected to be migrating through the river, water temperatures (blue dotted line) would have been sufficiently reduced to avoid surpassing 20°C. Observed flow and temperature leading up to and after the decision point are also depicted with black solid and dotted lines, respectively. Blue ribbon around managed temperature points represents ± RMSE from validation exercise (Text S1 in Supporting Information S1).

Salmon migrating through the Lower Sacramento River during the spring and fall are most likely to be affected by lethally-high water temperatures and may benefit the most from discharge-mediated temperature management. During the spring period, winter-run Chinook, spring-run Chinook salmon, Central Valley steelhead (all ESA listed), as well as fall-run Chinook salmon juveniles (ESA species of concern) outmigrate toward the ocean through the lower watershed. Tagging studies have shown that survival of outmigrating Central Valley Chinook salmon declines dramatically when water temperatures exceeded 20°C (Kjelson & Brandes, 1989; Michel et al., 2021; Nobriga et al., 2021). Michel et al. (2021) found that fish experiencing temperatures below 20°C had a six-fold increase in survival rate through the Sacramento River compared to fish experiencing temperatures above 20°C. Applying this survival thresholds to the adaptive management example in this paper (i.e., discharge actions taken to keep water temperatures below 20°C) results in an expected survival of 529,000 fish from of the 2.8 million released through the Sacramento River, compared to the 84,000 fish that are estimated to have survived given the observed water temperatures. During the fall period, both fall-run Chinook salmon and ESA-threatened steelhead adults return to the Upper Sacramento River to spawn. Federal guidance and empirical studies have indicated temperatures should not exceed 20°C to ensure the successful completion of migration for adult Chinook salmon (Bowerman et al., 2018; Hallock et al., 1970; U.S. EPA, 2003). Ultimately, the low survival experienced by juvenile and adult salmon when water temperatures exceed 20°C in the lower river results in a functional disconnection of the migratory corridor during many months of the year. These species at the southern end of their range have already adapted their life history to take advantage of the cooler seasons of the year, and therefore any further contraction in thermally-suitable rearing and migration windows will likely lead to a truncation rather than a shift in run-timing (Munsch et al., 2019). This reduction in run-timing diversity can lead to timing mismatches with ecosystem phenology (Satterthwaite et al., 2014), and ultimately, a weakening in the portfolio effect (Schindler et al., 2010).

Some limitations of this analysis warrant discussion. Importantly, we used past historical meteorological data and suggest that the resulting guidance plots could be used for future temperature predictions. Using 29 years of historical data, however, does not give a complete picture of the full range of possible future meteorological conditions. This is not only because of the limited extent of this historical data set, but also due to increasingly extreme weather patterns that are being experienced in California (and elsewhere) due to climate change (Huang et al., 2020; Swain et al., 2018). Furthermore, warming air temperatures expected from climate change have not been incorporated into our simulations or guidance plots. This analysis is also dependent on using the observed Keswick Reservoir discharge temperatures for the historical record, which are ultimately a function of upstream conditions in Shasta Reservoir. Additional efforts should focus on simulating future weather patterns while incorporating the effects of climate change and upstream reservoir dynamics to produce similar temperature non-exceedance information with an eye to the future (e.g., Steinschneider et al., 2019).

While we have focused our analysis on the potential of discharge-mediated temperature management originating from discharge perturbations out of Keswick Reservoir, there are other water flow management actions that could increase the likelihood of maintaining target temperatures in the lower river. In particular, reductions in Sacramento River water diversions during certain key periods of the salmon migration seasons would have beneficial impacts on flow, and result in similar effects on water temperatures. Another strategy could be to shift the timing of peak water delivery to the state and federal water project pumping facilities in the south Delta to the key discharge-mediated temperature management months such that more water would be delivered through the entire length of the Sacramento River; currently, the peak of Sacramento River water deliveries to the South Delta pumping facilities occur during peak summer months (Hutton et al., 2017; Kimmerer, 2002) when they have little relevance to salmonids in the watershed. Considering the various constraints on, and connected nature of the system, both increases in discharge in concert with temporary reductions in diversion could be the best path for implementation, ensuring all stakeholders are involved in the environmental stewardship of the largest river in California.

Finding ways to manage ecosystems for both wildlife and humans within a changing climate will require adaptive management coupled with a better understanding of the relationships between resource management and habitat quality. Effective adaptive management will require a framework that will both model the temperature and flow values for full spatial extent of a system, and also allow for the evaluation of tradeoffs associated with different water management scenarios. While this study has focused on potential discharge-mediated temperature management strategies for salmon in California's Central Valley, many other cold-water native species would benefit from such management actions (e.g., Jeffries et al., 2016). The thermal tolerances of native fish in California are frequently exceeded by current water temperatures, and while California's increasingly dry and warm climate is worsening the problem, our outdated water management practices are also responsible. We believe that the information presented here could fit well into a larger environmental flows framework for the Sacramento River (e.g., Stein et al., 2021): while restoring flows on rivers to unimpaired levels during key periods of the year is likely an important step in restoring healthy river ecosystems (Poff et al., 1997), ensuring the quality of that water (including temperature) is vital to the success of such actions (Olden & Naiman, 2010). The framework presented here provides insight into the ability to update water management practices in managed rivers, and aid in making informed resource management decisions that are necessary for managing fish populations into the 21st century.

Glossary

Discharge	Defined here as the flow rate of water being released from a reservoir
Flow	The volume of water moving past a fixed point on a river over a fixed period of time, expressed as a rate, such as cubic meters per second (cms).
Moving average smoothing	Smoothing of time series data by averaging data over a time window (e.g., 1 week before to 1 week after) for each step in the time series (e.g., for each day).
Net flow change	The net change in flow between two points along a river. This value incorporates elements of both flow gains along that segment (e.g., from tributaries), and flow losses (e.g., from water diversions).
Non-exceedance probability	Probability that a value will not be exceeded during a predefined time period.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All RAFT data inputs and temperature simulations are available and preserved at Dryad, https://doi.org/10.7291/D1Q386 (Daniels & Michel, 2023).

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