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Research papers

Evaluating the effects of climate change on managed lowland rivers in the California Bay Delta Watershed

Andrés F. Rojas-Aguirre [a,*], Erin N. Bray [a], Jeff Dozier [b]

[a] School of the Environment, 1600 Holloway Avenue, San Francisco State University, San Francisco, 94132, CA, United States of America

[b] Bren School of Environmental Science and Management, University of California, 2400 Bren Hall, Santa Barbara, 93106, CA, United States of America

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ABSTRACT

Water that is released from reservoirs can affect the downstream thermal regimes of rivers. During the summer months, these flow releases can lower the river temperature downstream of dams in an extension that mainly depends on the volume and temperature of these releases and the energy exchange with the overlying atmosphere. The benefit of this cooling effect has been suggested as an approach to mitigate the effects of climate change in downstream-regulated rivers. However, anticipated climate change conditions may weaken these cooling benefits, especially in managed lowland rivers (MLRs), as they are subjected to large withdrawals, are shallow, and convey clear water. Here, we show that MLRs in the California Bay Delta Watershed are vulnerable to water temperature increases, especially during future summer months subjected to a future high-emission greenhouse scenario. Low-flow conditions exacerbate this vulnerability, especially at locations downstream of high-flow diversions. By using a physical energy balance model (FLUVIAL-EB) paired with a downscaled climate regional model (CRCM5-RCP8.5), we found that for summer months between 2030 and 2100, longwave and latent heat fluxes will contribute to water temperature increases, while absorbed solar radiation will likely decrease under future climate scenarios. Despite the warming effects of climate change on MLRs in the California Bay Delta Watershed, our findings suggest that increasing the release of hypolimnetic water from reservoirs during summer months can be a viable solution to mitigate the river temperature increase.

1. Introduction

The construction of large dams significantly impacts downstream riverine thermal regimes, leading to changes in their ecosystem services, negative effects on the riverine ecology (Olden and Naiman, 2010), and alteration of the microclimate of river valleys (Troxler and Thackston, 1977). The thermal regime changes in regulated rivers are reflected in the variations in timing, frequency, and magnitudes of water temperatures compared to non-regulated rivers (Olden and Naiman, 2010). Typically, the release of water from reservoirs located in mid/high latitudes leads to downstream river cooling in the spring and summer months and warming effects in the winter (Horlacher et al., 2012), whereas raising of minimum water temperature and the reduction of thermal seasonality is expected in reservoirs located in low latitudes (Calamita et al., 2021). The thermal regime alteration is intensified due to the flow released from thermally stratified reservoirs. As a consequence, the extent of the cool thermal front is influenced by the strength of the thermal stratification in reservoirs, as well as the volumes, temperatures, and locations of the flow releases.

Studies have found that several unregulated rivers globally are experiencing a consistent rise in water temperatures, a trend that is expected to worsen in the future due to annual warming trends caused by climate change (Stefan and Sinokrot, 1993; Punzet et al., 2012; Isaak et al., 2012). Researchers have also found that regulated rivers are sensitive to climate change (Sinokrot et al., 1995; Isaak et al., 2012). Nevertheless, there remains a relatively limited number of investigations that have modeled future river temperatures under climate change scenarios (Null et al., 2013; Rheinheimer et al., 2015) and there is limited research on the mechanisms and energy fluxes impacted by changing climate. The cooling effect of reservoir releases was shown to be slightly weakened due to the increase in air temperature associated with climate changes (Cheng et al., 2020). The cooling effects of rivers downstream of dams are impacted due to changes in their natural flow regime, especially in rivers with strong seasonal patterns (Van Vliet et al., 2013). Alteration of the natural flow regime can also result in low flow conditions over longer durations, which can make regulated rivers more vulnerable to high water temperatures (Sinokrot and Gulliver,

* Corresponding author.
E-mail address: andresrojas@sfsu.edu (A.F. Rojas-Aguirre).

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2000). Therefore, significant water withdrawals or diversions of flow from the main channel (i.e., water extractions) can reduce streamflows, leading to higher temperatures downstream of diversions and during summer months as rivers become shallower (Caissie, 2006).

Despite the negative consequences dams can have on the thermal regime in rivers, river managers have implemented temperature management strategies in an attempt to mitigate the thermal impacts of regulated rivers (Olden and Naiman, 2010). The management of flow releases has been viewed as an opportunity to mitigate the downstream warming effects due to climate change (Kędra and Wiejaczka, 2018; Null et al., 2013; Mi et al., 2019). The mitigation of the downstream warming aims to manage the timing and the water temperatures downstream of dams by optimizing flow release operations, withdrawing water at multiple depths in stratified reservoirs (Rheinheimer et al., 2015; Mi et al., 2019), modifying the dam height (Zhao et al., 2020), or implementing techniques such as temperature control devices, trunnions, bubble pump, draft tubes, flexible curtains, submerged weirs, or other techniques to destratify reservoirs (Lieberman and Horn, 2001; Olden and Naiman, 2010; Heggenes et al., 2021). Other non-structural solutions include the development of new policies for dam operation to mitigate downstream temperature alterations (Calamita et al., 2021).

There have been few studies assessing the benefits of using water cooling in rivers to mitigate the climate change effects downstream of dams, particularly during summer months (Null et al., 2013). However, the present and future effectiveness of these strategies is constrained, as releasing cold water from dams has a limited effect on the temperature downstream in regulated rivers. Even though researchers have found that the incoming shortwave and longwave radiation are the most important fluxes that drive the water temperature (Ouellet et al., 2014), the analysis conducted by Bray et al. (2024) demonstrated that the assessment of future climate change scenarios in regulated rivers must consider the influence of the flow releases in concert with the spectral irradiance because around half of the incoming shortwave radiation lies in a wavelength range where heat absorption is independent of streamflow or water depth (Bray et al., 2017). As 2023 was Earth's warmest year on record and the global ten warmest years have occurred in the last decade (NOOA, 2024), accurate prediction of future river temperatures becomes an urgent research priority.

Herein, this paper aims to evaluate the effectiveness of stream cooling downstream of stratified reservoirs as a strategy to mitigate the effects of climate change in managed lowland rivers (MLRs) within the California Bay Delta Watershed. These rivers are vulnerable to climate change as they are shallow and wide, and usually flow through valleys with highly developed industrial agriculture, where diversions and groundwater withdrawals are prominent. The benefits of river cooling in MLRs may be reduced by the large water withdrawals that lead to shallower water, making them more vulnerable to heating from heat fluxes at the air/water and streambed/water interfaces.

In order to accomplish the main objective of this paper we: (1) use a spectral physically based energy balance model that employs a detailed radiation and balance model, (2) employ two approaches of future climate data from a Regional Climate Model (RCM) to predict river heat fluxes and river temperatures under future climates between 2030–2100, (3) predict and compare driving energy heat fluxes under future climate conditions, and (4) evaluate how differences in managed flow releases influence the effects of climate change on downstream river temperatures in MLRs. Among different mechanistic water temperature models (Siviglia and Toro, 2009; Dugdale et al., 2017; Ouellet et al., 2020), the evaluation implements the Fluvial Energy Balance model, FLUVIAL-EB (Bray et al., 2017), along the San Joaquin River in California, as this is a representative MLR in the California Bay Delta Watershed. This model considers the convolution of the spectrum of sunlight and the spectral characteristics of optical water properties, which enables us to comprehend how distinct fluvial processes impact the physical processes that partition, store, and release energy. Additionally, this model allows us to assess how future climate or flow manipulation will impact river temperatures.

The paper is structured as follows: In Section 2, we present the study domain and the methodology we follow to answer our research gap. Sections 3 and 4 show the results and analysis of implementing the methodology in the study domain in the San Joaquin River (California). Finally, Section 5 presents conclusions and recommendations. This paper does not aim to predict definitive future values along the San Joaquin River or at the sub-reach spatial scale. Instead, this work aims to utilize gridded weather data from Regional Climate Model for 2030–2100 to predict the rates of change in water temperature and energy fluxes that would make MLRs more vulnerable to the effects of climate change.

2. Methods

To address this research question, we selected a 150-km reach of the San Joaquin River (California), downstream of the Friant Dam (Fig. 1). This study domain represents a typical and common case in which the hydrological and thermal regimes of a lowland river in the California Bay Delta Watershed are significantly altered by the construction of the dam itself, the construction of multiple flood control structures (e.g. levees), and multiple water diversions along its main course. Friant Dam is a 97-m high structure that induces thermal stratification in the impounded Millerton Lake. Water withdrawals are usually from the hypolimnion zone of the lake (Resource Management Associates Inc. and Bureau of Reclamation, 2007), thereby sending cool water downstream. The temperature duration curves depicted in Fig. 2(a) show evidence of this cooling effect in the San Joaquin River, especially at the temperature monitoring stations immediately downstream of Friant Dam.

The San Joaquin River flows west across much of the Central Valley of California, one of the most productive agricultural areas in the United States, before turning north to the confluence of the Merced River, and eventually the confluence with the Sacramento River where it drains to the California Bay Delta. Water withdrawals along the reach studied are used mainly for irrigation, leading to a significant alongstream-decrease in the baseflow and flow peaks in the river downstream of the Friant Dam (up to 81% decrease in the 2-year return period peak flows) (Mathias Kondolf and Batalla, 2005).

To study how river temperatures and energy fluxes change over time and along river distance for current and future climates in a high-emissions scenario for global warming, we employ the energy balance FLUVIAL-EB model (Bray et al., 2017) along the study domain, paired with downscaled RCM data for the years 2030–2100 (see Section 2.1). Unlike other similar commercial and non-commercial models of river temperature, the FLUVIAL-EB model used here specifically calculates net shortwave radiation based on an integration of the spectral solar absorption and reflectance over all wavelengths within the solar spectrum. This full-spectrum integration approach is pertinent for our study domain because it takes detailed account of the reflection and absorption of shortwave radiation by the water column and the riverbed, the flow released from the dam is generally clear, and the bed albedo varies spatially along the gravel–sand transition. Without this spectral approach applied to lowland rivers, predicting changes to climate may be accurate but attributed to the wrong mechanisms.

The FLUVIAL-EB model is a physically-based one-dimensional finite difference spectral energy balance model. The model uses a continuous Eulerian framework and explicit finite difference methods to solve the one-dimensional heat advection–diffusion equation. The heat transport equation incorporates the energy fluxes and, more specifically, a radiation balance with the turbulent heat and bed conduction fluxes (Eq. (1)).

$$\frac{\partial T_w}{\partial t} = \frac{1}{A}\frac{\partial (T_w Q)}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left[D_L A \frac{\partial T_w}{\partial x}\right] + \frac{Q_{net}}{\rho c_p D} \quad (1)$$

where T_w is the water temperature, A is the cross-sectional area, D is the water depth, Q is the flow rate, D_L is the longitudinal dispersion

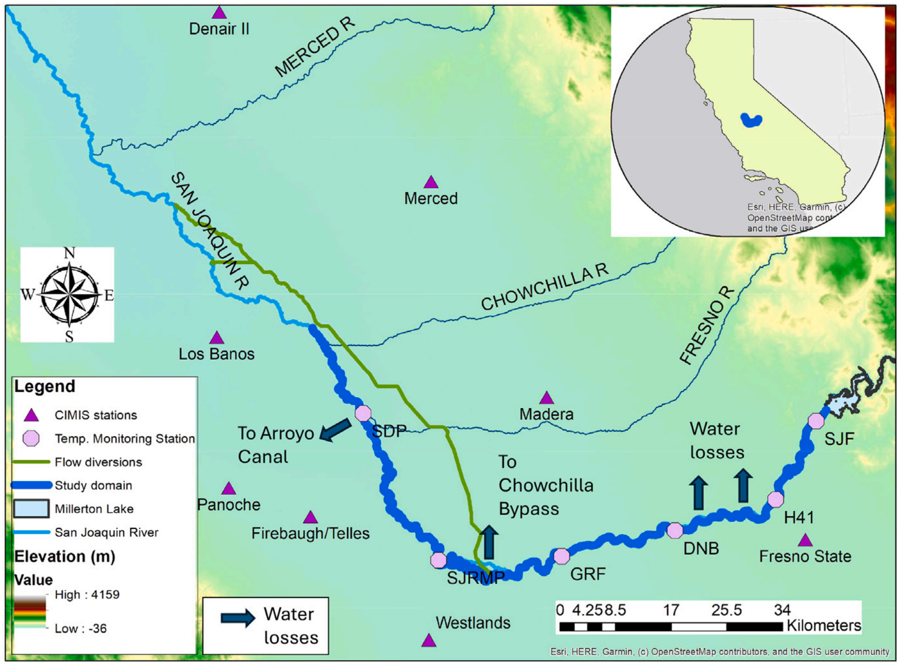

Fig. 1. San Joaquin River study domain, highlighting the locations of CIMIS weather stations and water temperature monitoring stations.

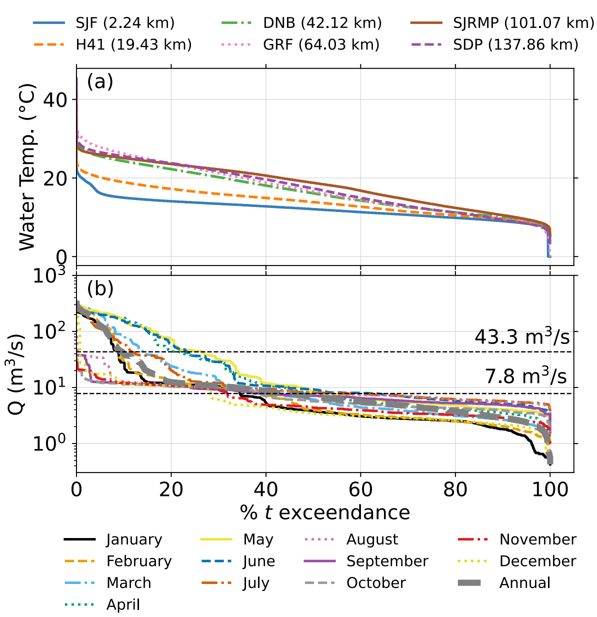

Fig. 2. (a) Water temperature duration curves at different monitoring stations along the study domain. (b) Monthly flow duration curves for the releases at Friant Dam, considering streamflow time series after January 2012. Dashed lines correspond to the two flow release values considered in this manuscript. Note: values in parentheses indicate distances downstream of the Friant Dam.

coefficient, ρ is the water density, c_p is the specific heat of water, and Q_{net} denotes the net heat fluxes,

$$Q_{net} = S_{net} + F_{net} + L + H + G, \tag{2}$$

where S_{net} is the net shortwave radiation, F_{net} is the net longwave radiation, L is the latent heat flux, H is the sensible heat flux, and G is the bed conduction flux. All these flux components are estimated based on the formulations below, where positive magnitudes refer to incoming fluxes that heat the water,

$$S_{net} = S\left[\frac{\int_{\lambda_1}^{\lambda_2} I(\lambda)(1-R_{surf})(1-R_{bed}e^{-\tau_0(\pi+sec\theta_r)})\,d\lambda}{\int_{\lambda_1}^{\lambda_2} I(\lambda)\,d\lambda}\right], \tag{3}$$

$$F_{net} = \Phi\downarrow - \zeta\sigma T_w^4, \tag{4}$$

$$L = -\frac{\zeta}{p}\rho_{air}L_v C_E U_z (VPD), \tag{5}$$

$$VPD = e_{sat}(T_w) - R_h e_{sat}(T_{air}), \tag{6}$$

$$H = -\rho_{air}C_a C_H U_z (T_w - T_{air}), \tag{7}$$

$$G = -K\frac{dT_w}{dz}|_{z=0}, \tag{8}$$

where S is the measured solar radiation from gridded data or from a weather station, λ is the wavelength, ζ ratio of molecular weight of water vapor and dry air equal to 0.622, $I(\lambda)$ is the spectral irradiance calculated based on Gueymard (2019), R_{surf} is the surface reflectivity, R_{bed} is the bed albedo, τ_0 is the optical depth, θ_r is the angle of refraction, $\Phi\downarrow$ is the downwelling long-wave radiation, ζ is the water emissivity, σ is the Stefan–Boltzmann constant, ρ_{air} is the air density, T_{air} is the atmospheric temperature of the overlying air, R_h is the relative humidity of the overlying air, p is the surface air pressure in mbar, L_v is the enthalpy of vaporization, C_E and C_H are the turbulent exchange coefficients estimated based on Verburg and Antenucci (2010), C_a is the specific heat of air, U_z is the wind speed, e_{sat} is the saturated vapor pressure at temperature T_i, K is the thermal conductivity, and z is the vertical coordinate toward the deep riverbed. Additional details of the modeling framework, equations, and description of the computational scheme can be found in Bray et al. (2017) and its corresponding Supplemental Information.

Equation (3) shows how the model integrates the spectral solar absorption and reflectance across all wavelengths within the solar spectrum (0.28 to 2.8 μm) to calculate the net shortwave radiation balance taking into consideration the individual transmissions, including the proportion of incident solar radiation that is reflected and absorbed in total, at the water surface, in the water column, on the downward path and upward path, and at the bed.

2.1. Model setup and validation

To evaluate the effects of climate change on the water temperature of the river during low flow conditions, we conducted a monthly analysis for the month of August from 2030 to 2100. This late-summer month is critical for the river and aquatic habitat, as sustained low-flow releases from Friant Dam during this timeframe create shallow river conditions, resulting in water temperature increases predominantly due to the net absorbed solar radiation. While current flow releases downstream of Friant Dam are determined by a settlement and subsequent Restoration Actions to support water users in addition to recovery of a salmon fishery (Willis et al., 2022), in this study, we selected two representative flow releases.

First, we estimated alongstream hydraulic values corresponding to a flow release (Q_0) of 7.8 m^3/s, which corresponds to the flow discharge that is equal or exceeds 50% of the time according to the annual flow duration curve (Fig. 2-a). This flow discharge also represents a flow equal to or exceeds 52% of the time (Q_{t52}) based on the flow duration curve for the month of August. Another criterion for selecting this discharge is its feasibility throughout the entire month of August, supported by past release time series (Appendix). For comparison purposes, we also selected and implemented a high-flow release of 43.3 m^3/s that corresponds to $Q_{t9.6}$ according to the annual flow duration curve. Although the case of 43.3 m^3/s is a modeling scenario, there is no implication of its feasibility in the future. The rationale behind this is that besides the dam releases to the San Joaquin River, there are two other outflows from this reservoir corresponding to irrigation canals (Friant–Kern Canal and Madera Canal). Increasing the future releases to the San Joaquin River, may require reducing discharge to these canals. The selection of 43.3 m^3/s is based on historical records indicating a sustained maximum and constant flow release that lasted nearly a month during May 2010. The hydrodynamic variables in the river for these two flow conditions were obtained by adapting and using a calibrated 1-D steady-state HEC-RAS model (US Army Corps of Engineers, 2010) of the study domain developed by Mussetter Engineering and Tetra Tech (Mussetter-Engineering, 2008; Tetra-Tech, 2015). These hydrodynamic variables are then exported into the FLUVIAL-EB model to solve the heat transfer advection–diffusion equation.

In order to assess the combined impact of changes in climate together with streamflow reductions on the river energy balance and heat fluxes, the study domain includes the representation of four streamflow reductions located at 26 km, 39 km, 82 km, and 135 km downstream of the Friant Dam. The first two reductions represent the effects of infiltration losses are mainly due to channel percolation along the first 40 km of the river (Mussetter-Engineering, 2008; Visser et al., 2018). The latter two reductions represents the flow losses and the diversion rules at the Chowchilla Bypass and Arroyo Canal diversions. The Chowchilla Bypass is a control structure bifurcation designed to manage the flows in the San Joaquin River and the Chowchilla Bypass. It operates based on specific conditions upstream and downstream of the bifurcation. The Arroyo Canal is the second bifurcation that diverts water from the San Joaquin River to this canal through a set of wooden flap gates located in a small concrete structure dam, Sack Dam (McBain and Inc, 2002). The operational rules at these bifurcations are subjected to the San Joaquin River Restoration Settlement (U.S.-Congress, 2009).

The discharge losses at the aforementioned four sites are represented using the water loss ratios defined as,

$$r_0 = \frac{Q_d}{Q_{up}} \tag{9}$$

where Q_d is the discharge losses, and Q_{up} is the streamflow in the main channel, upstream of the diversion.

The water loss ratios selected are based on the analysis performed by Bray et al. (2017) with values of 0.02 at sites that represent the effects of infiltration and 0.22 and 0.07 to represent the Chowchilla Bypass Diversion and the Arroyo Canal Diversion, respectively. These water loss ratios are based on a study conducted by Mussetter-Engineering (2008) which involved a hydraulic steady-state analysis of the entire San Joaquin River system, where discharge distribution across all reaches was estimated using historical streamflow records from 1986 to 1999. This distribution accounts for flow losses, tributary contributions, and operational rules at diversions. Although water losses due to infiltration increase under low flow releases, we decided to maintain a ratio of 0.02 for the flow release of 7.8 m^3/s due to numerical instabilities that arise from low water depths. On the other hand, the water loss ratio of 0.22 for the Chowchilla Bypass when releasing 7.8 m^3/s was based on Mussetter-Engineering (2008). However, a flow release of 43.3 m^3/s would result in a ratio of 0.12. We decided not to use this ratio because the sustained maximum flow release (43.3 m^3/s) observed throughout most of May 2010 is atypical for August. Since August is drier than May, we anticipated higher water losses due to infiltration if such a flow release occurred in August. As we do not have the elements to quantify these water losses for such flow release for August conditions, we assume a conservative and hypothetical case in which the ratio at the Chowchilla Bypass would be the same as the ones assumed for the 7.8 m^3/s case (i.e., $r_0 = 0.22$).

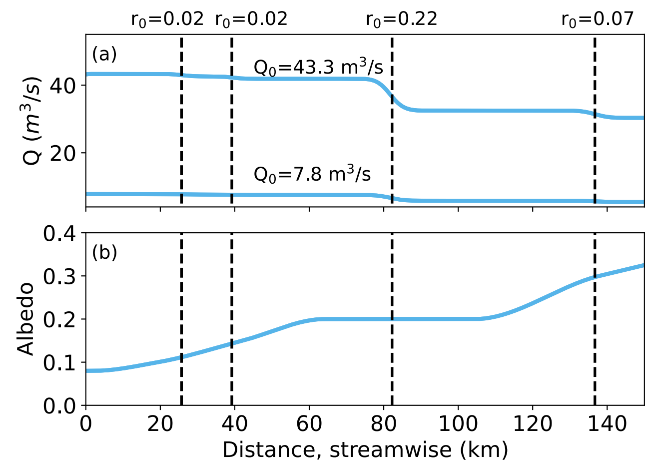

Fig. 3. (a) Flow discharge profile for flow releases $Q_0 = 43.3$ m^3/s and $Q_0 = 7.8$ m^3/s, (b) spatial distribution of Albedo in the riverbed.

The riverbed albedo values are selected based on the analysis performed by Bray et al. (2017) along the study domain. Typical values for wet gravel range from 0.03 to 0.05, while submerged sand ranges from 0.25 to 0.45 (Legleiter et al., 2004; Zhang and Voss, 2006). Based on sediment surveys, cobbles, and gravel dominate the first 20 km, transitioning thereafter to a sand-bed river (McBain and Inc, 2002). Therefore, we assigned lower albedo values to the upper part of the study domain, while higher values were applied downstream (Fig. 3-b).

To evaluate the river temperature effects due to climate change, we used two gridded weather time series to predict the energy fluxes along the study domain for the years 2030 to 2100. These gridded weather time-series data are from the fifth-generation Canadian Regional Climate Model (CRCM5) (Martynov et al., 2013) under the Representative Concentration Pathway (RCP) 8.5 (CRCM5-RCP8.5). These gridded time-series are driven by data from the second-generation Earth System Model developed by the Canadian Centre for Climate Modelling Analysis (CCCma-CanESM2) and from data from the Max–Planck Institute (MPI), Earth System Model (ESM). The specifications of these two gridded data are described in Table 1. These gridded time-series datasets are implemented within the FLUVIAL-EB model and used herein to estimate the energy fluxes described above (Eq. (2)). The selected spatial resolution in the river is 100 m, with an estimated temporal resolution based on a Courant number of 0.3.

To estimate the bed conduction fluxes (G), we assumed a 2-m thickness of the riverbed with constant sediment properties (e.g., K = 2.4 W m^{-1} deg^{-1}). The vertical profile temperatures within the riverbed

Table 1
Gridded data specifications and descriptions.

Product	Spatial resolution	Time resolution	Pathway	Variables	Description
MPI-ESM-MR	0.44 deg	3 h	RCP8.5	Wind velocity, near-surface air temp., surface air pressure, down. longwave rad., down. shortwave rad., specific humidity	The model is driven by data from the Max-Planck Institute (MPI), Earth System Model (ESM) Mixed Resolution (MR)
CCCma-CanESM2	0.44 deg	3 h	RCP8.5		The model is driven by data from the second-generation Earth System Model (ESM2) developed by the Canadian Centre for Climate Modelling Analysis (CCCma)

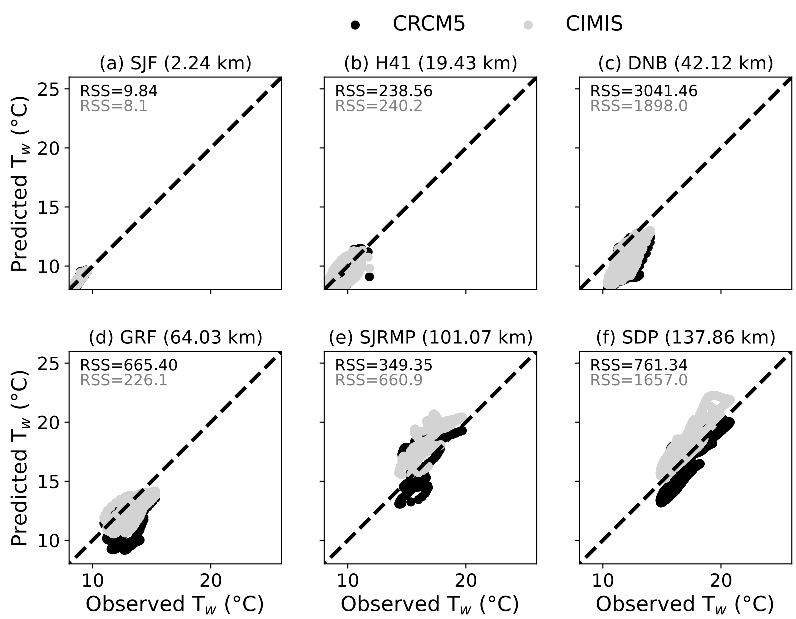

Fig. 4. Comparison between predicted and observed water temperatures at monitoring stations for May 2010 streamflow conditions using CRCM5-ERA-Intermin model and CIMIS data.

were calculated assuming a zero flux at the lower boundary condition (Hondzo and Stefan, 1994) and a 5-cm grid resolution.

For all future climate change simulations, we defined the upstream boundary condition (i.e., the temperature of the flow released from Friant Dam) using a multi-year median daily temperature based on historical records. Given the difficulty of finding a water temperature trend based on the limited water temperature records (from 2005 to 2010) at the water outlet level in the hypolimnion zone (USBR, 2011), we opted to use the global gradient of +0.15°C per decade reported by Golub et al. (2022).

Similarly, we use historical water temperature records from May 2010 as the upstream boundary condition to evaluate the accuracy of water temperature predictions in the FLUVIAL-EB model when using gridded meteorological inputs. We estimate the goodness-of-fit for predicted water temperatures using data from the California Irrigation Management Information System (CIMIS) weather station (Fig. 1) and those generated by the CRCM5 model driven by the ERA-Interim reanalysis dataset (produced by the European Centre for Medium-Range Weather Forecasts, ECMWF) at a spatial resolution of 0.11 degrees. This goodness-of-fit analysis was conducted using a constant flow release window in May 2010 when observed water temperatures were measured continuously at multiple locations along the study reach.

The FLUVIAL-EB model demonstrates reasonable accuracy in predicting water temperatures at monitoring stations when using inputs from both the 3-hourly CRCM5 ERA-Interim model and CIMIS data (Fig. 4). It shows slightly improved performance with the CIMIS data, yielding lower Residual Sum of Squares (RSS). However, the model predicts water temperatures at the monitoring stations DNB and SJRMP with some difficulties. This may arise due to the insufficient inclusion of some waterlosses and the inadequate representation of some hydraulic inline structures like the Mendota Dam in the hydrodynamic model.

3. Results

To comprehend the evolution of the river temperatures under climate change scenarios, it is crucial to analyze the evolution of the weather variables along the study domain to understand how such variables impact the water temperatures in the river. The median values for August of each year for all weather variables (Fig. 5) indicate a general trend of increasing values downstream, except for solar radiation, which remains relatively constant along the study domain (Fig. 5). The observed decreasing trend in some weather variables (e.g., air pressure, vapor pressure, air temperature) along the study domain can be partially attributed to the decreasing altitude along the river.

The weather variables are also influenced by climate change. Specifically, the median weather values for the study domain indicate that all weather variables from both gridded time series will change in future years, except for air pressure (Fig. 5-a). Future trends indicate a decrease in solar radiation and wind speed, while other variables show an increasing trend, as shown in Fig. 6. The decline in wind speed, however, is slight, with a rate of less than 0.01 m/s per year for both gridded time series. The most substantial changes are anticipated in the solar radiation and downwelling longwave radiation for both gridded data, decreasing and increasing by up to 0.81 W/m^2/year and 0.65 W/m^2/year, respectively. These effects result from the climate models predicting greater cloud cover in the future.

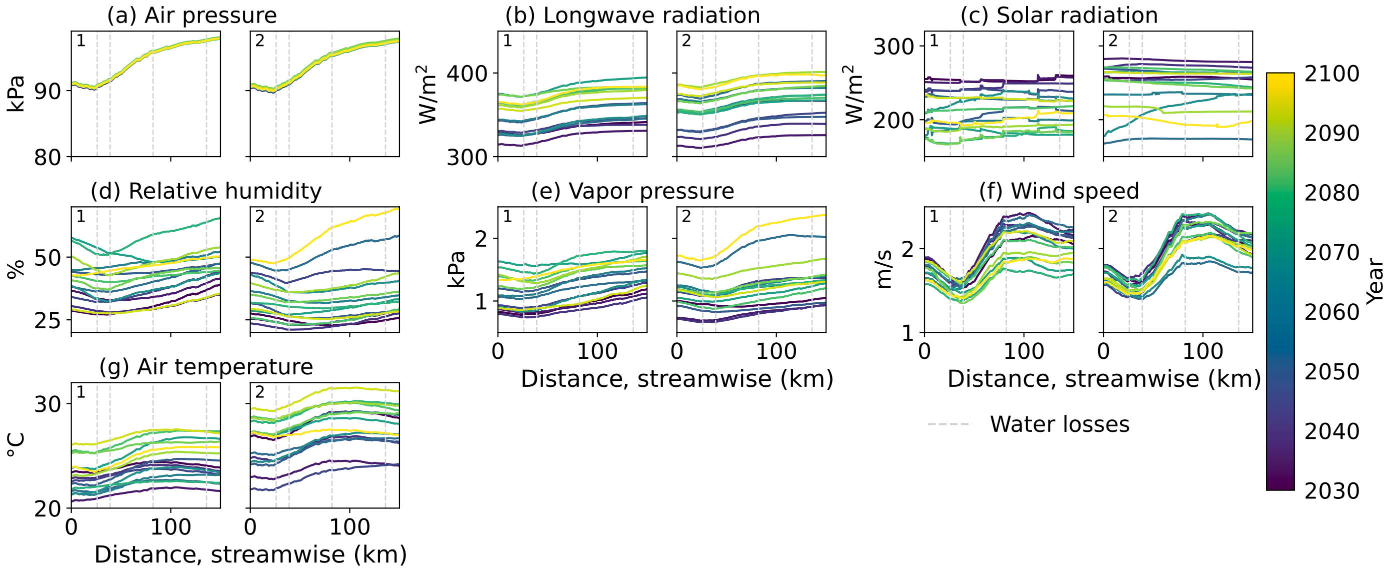

Fig. 5. Median spatiotemporal evolution of (a) air pressure, (b) longwave radiation, (c) solar radiation (only day hours), (d) relative humidity, (e) vapor pressure, (e) wind speed, (g) air temperature. Panel 1 refers to gridded data CCCma-CanESM2, while panel 2 refers to MPI-ESM-MR.

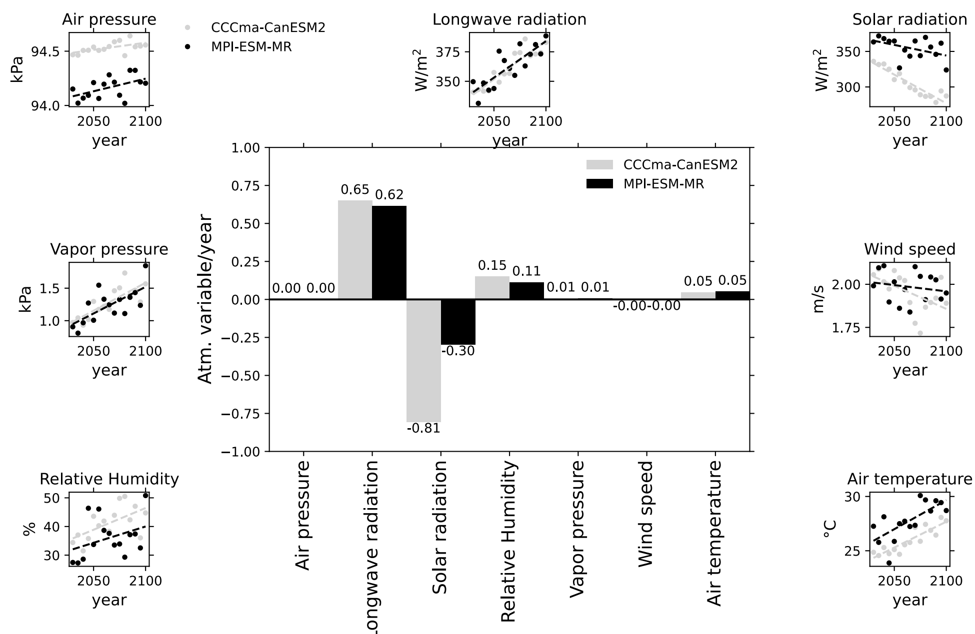

Fig. 6. Bar graph denotes the mean annual trend of the atmospheric variables along the study domain. The trends for each weather variable are represented by linear regression trend lines.

Regarding energy fluxes from and to the river, notable changes are observed in the median longitudinal profiles of net heat fluxes at sites where streamflow is reduced. These changes occur under both high and low flow conditions across all simulated years in both sets of gridded data (Fig. 7-h). These changes impact the median water temperatures downstream of sites that represent water losses, particularly on those with high r_0 values. These changes in the net heat flux (Q_{net}) can be explained by disturbances in the net longwave radiation, latent heat fluxes, and sensible heat fluxes, as shown in Fig. 7. The primary reason behind these disturbances is the decrease in flow discharge downstream of sites with high water losses r_0, particularly at Chowchilla Bypass diversion ($r_0 = 0.22$). This reduction in streamflow results in shallower river depths, making the river more vulnerable to higher temperatures and more influenced by weather conditions.

The longitudinal step-changes in the water temperature along the study reach are explained by the incremental changes of the components of the net heat fluxes over time for the two gridded data under the RCP8.5 climate change scenario. Although Fig. 8 presents the longitudinal distribution of median fluxes for August 2060, the results are representative, as the other years show similar patterns. As expected, in all these simulated years, the net shortwave radiation flux (positive) has the largest contribution to increasing the water temperature along the study domain. This contribution is followed by the latent heat and the net longwave radiation fluxes (negative magnitudes) that counteract the net shortwave radiation flux in all analyzed years. The sensible heat fluxes along the study domain do not contribute significantly to the net heat flux, Q_{net}, despite a significant temperature difference caused by flow releases from the Friant Dam. Similarly, the contribution of bed conduction is negligible when compared to the other fluxes.

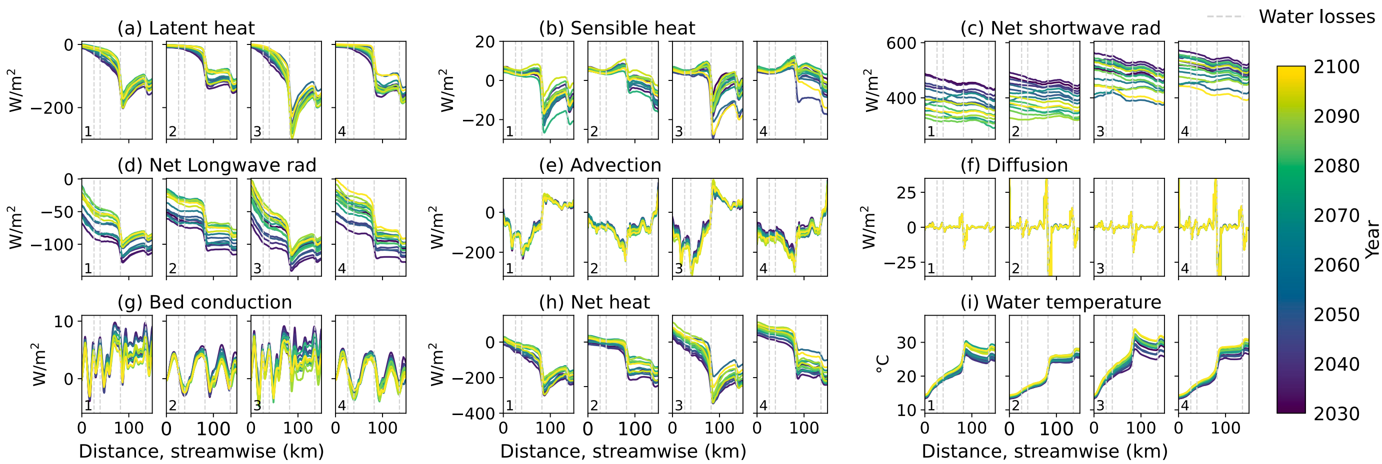

Fig. 7. Median heat fluxes along the study domain in the San Joaquin River, showing (a) latent heat, (b) sensible heat, (c) net shortwave radiation, (d) net longwave radiation, (e) advection, (f) diffusion, (g) bed conduction, (h) net energy exchange, and median (i) water temperature. Panels 1 and 2 refer to gridded data CCCma-CanESM2 and flow releases of $Q_0 = 7.8$ m^3/s and $Q_0 = 43.3$ m^3/s, respectively. Panels 3 and 4 refer to gridded data MPI-ESM-MR and flow releases of $Q_0 = 7.8$ m^3/s and $Q_0 = 43.3$ m^3/s, respectively.

The contribution of the latent heat flux (always negative) increases downstream, particularly beyond the Chowchilla Bypass Diversion, and is more relevant under low-flow conditions (Fig. 8). This is primarily due to a substantial increase in water temperatures downstream of the diversion, leading to a higher vapor pressure deficit (VPD, Eq. (5)). Nonetheless, the yearly rate of increase in latent heat flux is greater upstream of the Chowchilla Bypass Diversion (Fig. 9). This is attributed to more consistent water temperatures over time, influenced significantly by cooling effects from the dam releases. This phenomenon results in steeper VPD gradients, where the saturation vapor pressure of the overlying air remains relatively uniform due to river cooling, while air temperature increases lead to higher vapor pressures.

The time evolution of the different components of the net heat flux (Q_{net}) indicates that for both gridded time-series under the RCP8.5 scenarios, and low-flow releases ($Q_0 = 7.8$ m^3/s), a continuous increase in the net longwave radiation is projected, as well as a decline in the net shortwave flux (Fig. 9). The temporal decline in the net shortwave radiation flux can be attributed to the decrease in the incoming solar radiation, as depicted in both gridded time-series (Fig. 6). Similarly, the decreasing streamwise trend in net solar radiation, has to do with the streamwise decrease of water depths (up to the Chowchilla Bypass Diversion) and increase of riverbed albedo (Fig. 3-b). This alongstream increase in bed albedo is observed by the transition from a dark gravel bed to a brighter sand bed. Thus, the net solar radiation spatial decrease is partially explained by a larger resistance to heating of brighter sand beds compared to darker gravel beds (Bray et al., 2017).

Similarly to the net shortwave flux, the increasing trend in the net longwave fluxes over time (i.e., 0.34 W/m^2/year to 0.58 W/m^2/year) is partially explained by the increase in the downwelling longwave radiation along the study domain, shown in both gridded time-series (Fig. 5-b), attributed to the increase in greenhouse gases in a future climate scenario. It is expected that in all future years, the median upwelling longwave radiation will always be greater than the median downwelling longwave radiation, resulting in negative net longwave radiation, regardless of the flow conditions or the gridded time-series. The upwelling longwave radiation is expected to increase at a lower rate than the downwelling longwave radiation, causing an increase in net longwave radiation in future years. Specifically, the yearly increase rate of net longwave radiation is higher upstream of the Chowchilla Bypass Diversion due to the lower yearly increase rate of upwelling longwave radiation caused by low water temperatures resulting from water dam releases (Fig. 9).

Despite the overall trend of increasing river temperatures attributed to climate change, the temperature range bands of the median water temperature profiles for all analyzed years and gridded time series (Fig. 10) show that the flow releases from Friant Dam could significantly cool the San Joaquin River, especially upstream of the Chowchilla Bypass Diversion ($r_0 = 0.22$). The downstream cooling effects are more notable for high-flow releases (i.e., $Q_0 = 43.3$ m^3/s) as than for low-flow ones (i.e., $Q_0 = 7.8$ m^3/s). The lowriver temperatures and low variability in median water temperature (narrow Interquartile range, IQR) at a flow of $Q_0 = 43.3$ m^3/s, highlight influence of the flow releases in the reach upstream of the Chowchilla Bypass ($r_0 = 0.22$, Fig. 10-b). However, this water-cooling phenomenon is weakened during low-flow releases, where water temperatures tend to be higher and less uniform.

The rate of water temperature increases along the study domain for both discharges, and for both gridded time-series, demonstrate that high-flow releases are more effective in lowering the water temperature than in low-flow discharge conditions (Fig. 11-a). However, the impact of withdrawing water from the river not only significantly increases the downstream water temperatures in the river, but also rapidly increases the water temperature change over time by 1.6 to 2.2 times in comparison with the upstream conditions (Fig. 11-d). It is worth noting that the rate at which the water temperature increases downstream of the main diversion during the low-flow release (Fig. 11-a) is similar to the rate at which the air temperature is rising across the entire study area (Fig. 6). This indicates that water temperature downstream of the main diversion is strongly influenced by weather conditions and is, therefore, susceptible to changes in weather.

4. Discussion

The expected river temperature increases due to climate change agree with other findings reported in previous studies (Null et al., 2013; Ahmad et al., 2021). As the results indicate, the effects of climate change are significantly notorious in the San Joaquin River, that is representative watercourse of MLRs in the California Bay Delta Watershed where flow discharge conditions are altered by the presence of dams, water losses (e.g. withdrawals, infiltration) and low streamflows. However, the water cooling approach via flow release from a snowmelt-fed reservoir is a potential tool to mitigate water temperature increases due to climate change in MLRs, during late-summer months. This approach is especially important for these types of rivers in the California Bay Delta Watershed over downstream distances where advective fluxes dominate. We show that the most efficient path to achieving that goal is via high flow releases from the hypolimnion zone, which efficiently cools the water temperature increases for a considerable distance and mitigates the impacts of an abrupt flow discharge decrease.

Higher flow releases will make the absorption of the incoming shortwave radiation less dependent on the streambed and more on the water

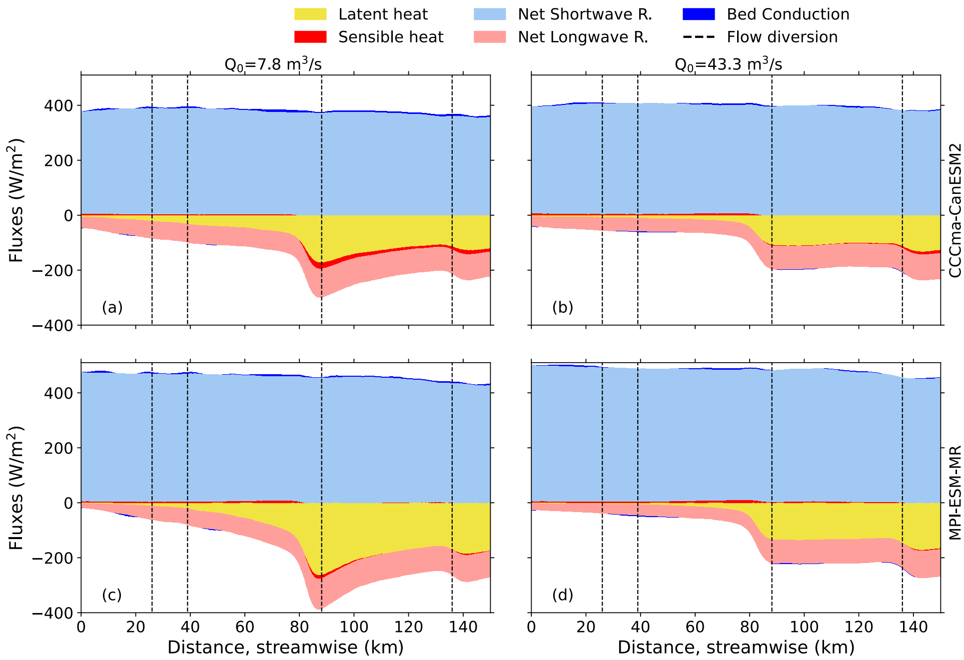

Fig. 8. Median energy fluxes for August 2060 along the study domain for (a) Q_0 = 7.8 m^3/s and CCCma-CanESM2, (b) Q_0 = 43.3 m^3/s and CCCma-CanESM2, (c) Q_0 = 7.8 m^3/s and MPI-ESM-MR, and (d) Q_0 = 43.3 m^3/s and MPI-ESM-MR. Positive fluxes refer to a water heating source while cooling processes are indicated by negative values.

column, due to spectral variations and optical properties of the river and the bed. However, across the range of reasonable water depths commonly observed in MLRs, absorption of shortwave radiation has been shown to be the dominant control of river temperatures. Likewise, high flow releases make the advective heat fluxes more relevant than atmospheric heating fluxes, which, in turn, makes the river temperature more dependent on the temperature of flow releases (i.e., upstream boundary condition) for a limited distance downstream of the dam. High flow releases can limit the net longwave radiation fluxes as the upwelling component decreases due to lower river temperatures. Additionally, latent heat fluxes are mitigated during higher flow releases primarily due to the decrease in vapor pressure deficit. The decreased trend of wind velocities also contributed to diminish the exchange fluxes at the water/air interface due to the thickening of the viscous sublayer (Leach et al., 2023).

The remaining fluxes, including sensible heat, diffusion, and bed conduction, are expected to have minimal effects on MLRs and are typically lower than radiative or latent heat fluxes (Dugdale et al., 2017). While cooling and air temperature increases create a significant difference between water and air temperatures, that is anticipated to intensify as a result of climate change, sensible heat fluxes generally remain uniform for different flow release magnitudes. Similarly, diffusion fluxes remain relatively unaffected by both climate change and the magnitude of flow releases. Although bed conduction fluxes tend to diminish under the influence of climate change, their overall impact on the net energy exchange is not significant, which is consistent with other studies conducted downstream of dams (Pike et al., 2013).

Our study was limited to analyzing two gridded time-series from a regional climate model under an RCP8.5 scenario. However, we expect that our conclusions will remain valid when other climate models and driving data are used. The consensus among climate models is that air temperature will continue to rise globally (Gao et al., 2023), so it is expected that the implementation of other models and forcings will also show that latent heat flux is a significant contributor to MLRs due to the high VPD gradients caused by high air temperatures. Likewise, regardless of the RCM, climate driving data and boundary conditions, MLRs would experience an increased trend in the net longwave radiation caused mainly by the increase of the downwelling longwave radiation at the surface (Roderick et al., 2014).

The decreasing trend in solar radiation observed in our analysis aligns with findings from Chen (2020), who investigated the impact of climate change on surface solar radiation across the United States. This study, based on multiple regional climate models following the RCP8.5 pathway, indicated that most models project a decrease in annual mean solar radiation in California from 2071 to 2100. Furthermore, the ensemble mean of 37 CMIP5 models, 14 NA-CORDEX models, and WRF models suggests a reduction in surface solar radiation specifically during June, July, and August over the period between 2071 and 2100, for our study domain area.

In light of these findings, although our study focused solely on two flow releases scenarios, it is reasonable to suggest that the ratio r_0 in MLRs should be considerably reduced to mitigate the step-change increases in water temperature, during low-flow conditions. It is important to highlight that this study does not aim to find nor propose the optimum flow release and flow diversion combination that minimizes the impact along MLRs in the California Bay Delta Watershed. The optimum flow-release and flow-diversion combination must be defined based on the water temperature limits that can be achieved in concert with different water requirements in those rivers.

Water management in MLRs must focus on reducing the vulnerability of alongstream thermal regimes to rising temperatures caused by climate change. Although management decisions must consider water rights, endangered species, aquatic habitat, and competing demands, the ultimate goal must aim to guarantee water uses along the river, which implies controlling water temperatures. For instance, the design of the future environmental flows should consider the flow releases to regulate the water temperatures in these rivers.

To consider the slight warming effects expected in deep reservoirs and deep lakes (Ahmad et al., 2021; Anderson et al., 2021), we consider a +0.15 °C/decade rate to represent the effects of climate change on the water temperature at the water intake level of Millerton Lake. However, to enhance the accuracy of the predicted water temperatures along the river, it is recommended to couple hydrodynamic and temperature models of the reservoir (e.g., 2D or 3D) with 1-D hydraulic and temperature models of the downstream river (e.g., FLUVIAL-EB model). This approach can help evaluate the influence of cooling phenomena on the downstream river caused by changes in water and temperature inflows, dam operations, and water usage within reservoirs.

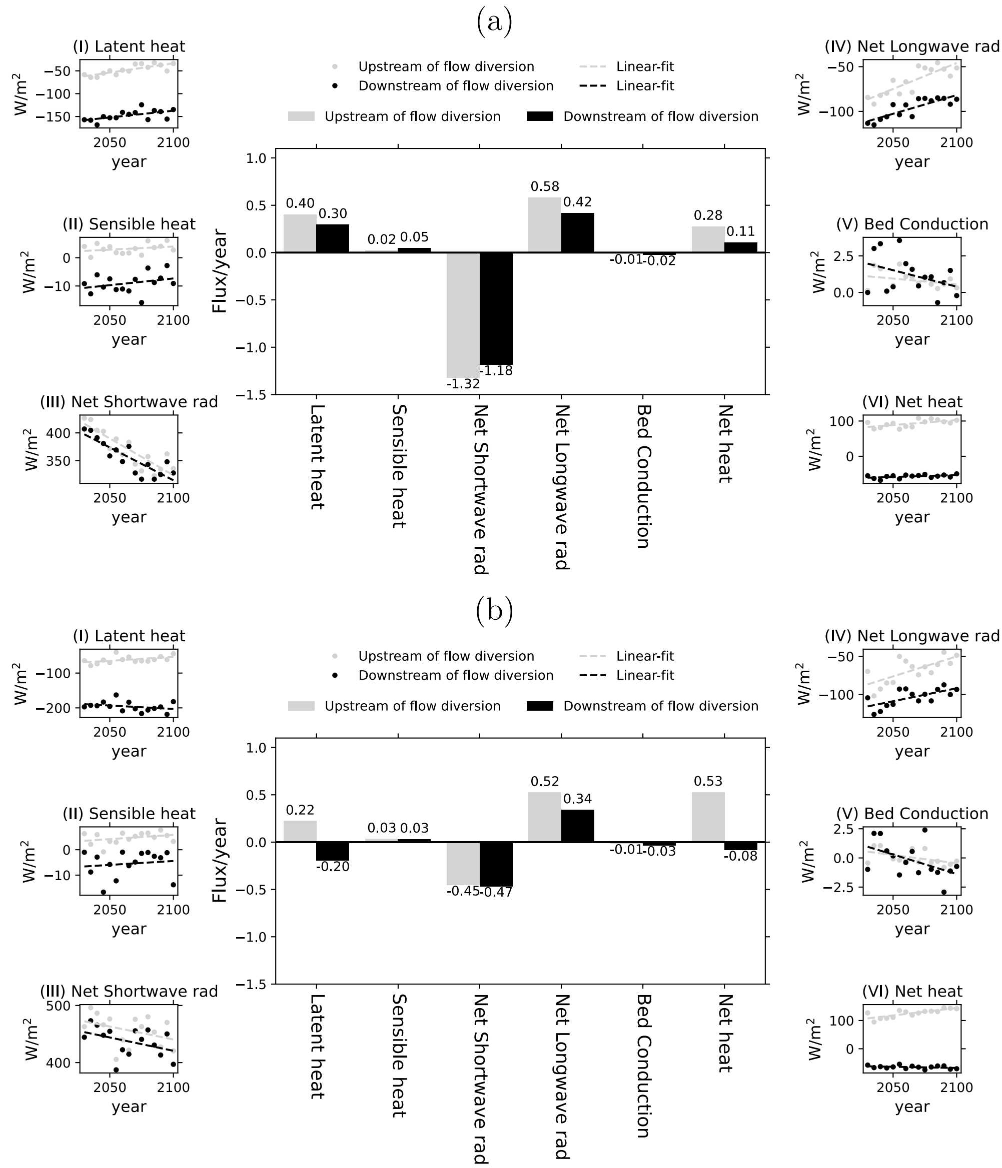

Fig. 9. Comparison of the mean annual flux changes upstream and downstream of the main river diversion (Chowchilla Bypass), alongside the mean annual trend of the net heat flux (Q_{net}) and its components, for Q_0 = 7.8 m^3/s. Weather data from (a) CCCma-CanESM2, and (b) MPI-ESM-MR. The trends for each energy flux are represented by linear regression trend lines.

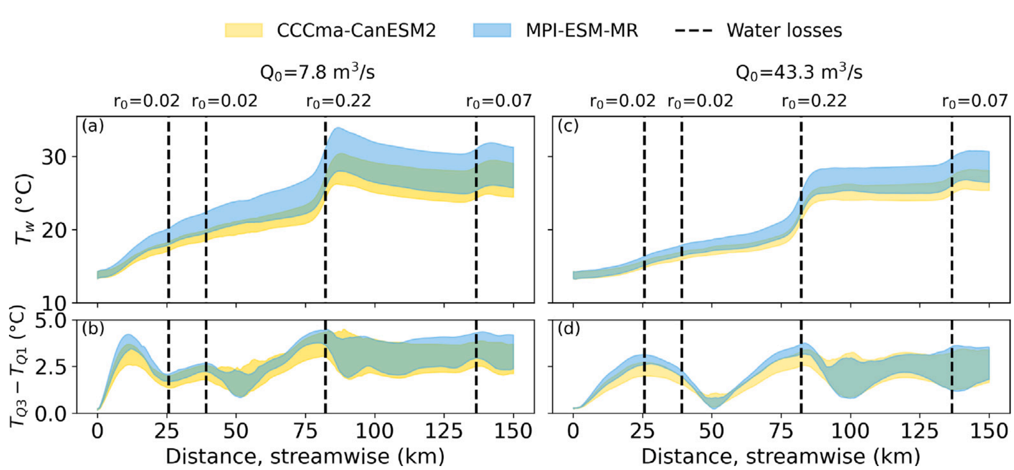

Fig. 10. (a) median water temperature range along the study domain for Q_0 = 7.8 m^3/s, (b) interquartile range (IQR) of water temperatures along the river for Q_0 = 7.8 m^3/s, (c) median water temperature range along the study domain for Q_0 = 43.3 m^3/s, and (d) interquartile range (IQR) of water temperatures along the river for Q_0 = 43.3 m^3/s. IQR is calculated as the difference between the upper quartile (T_{Q3}) and the lower one (T_{Q1}).

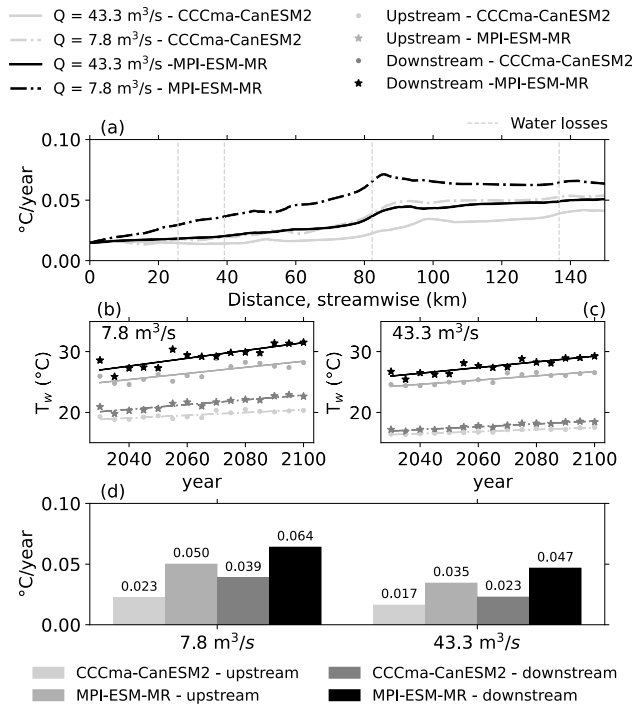

Fig. 11. (a) Spatial distribution of the yearly increase rate of water temperature for Q_0 = 7.8 m^3/s and Q_0 = 43.3 m^3/s, (b) projected mean water temperature change, upstream and downstream of the main flow diversion (Chowchilla Bypass) for Q_0 = 7.8 m^3/s, (c) projected mean water temperature change, upstream and downstream the main diversion for Q_0 = 43.3 m^3/s, and (d) mean annual temperature change, upstream and downstream of the main diversion for Q_0 = 7.8 m^3/s and Q_0 = 43.3 m^3/s.

Transitioning to sediment analysis, the assumption of clear water (i.e., low turbidity) assumed in this analysis has a valid base and extrapolates to all major rivers in the California Bay Delta Watershed, as they are regulated through reservoirs (Hutton et al., 2017). The sediment trapping upstream of large dams leads to a significant reduction in the total sediment transport loads downstream of dams. Over time, this sediment trapping phenomenon usually leads to changes in the sediment size distribution along the riverbed downstream of the dam. These changes in the riverbed composition can affect the water temperature downstream, as the alongstream changes in albedo are a primary control to the net shortwave radiation fluxes, and variations in sediment albedo have been shown to lead to 2 °C changes in water temperatures (Bray et al., 2017). For the San Joaquin River, the coarser gravel bed reach has a lower albedo, which means that the coarsening effect may increase the net absorbed solar fluxes, leading to further increases in water temperatures downstream of dams in MLRs in the California Bay Delta Watershed. On the contrary, it is noteworthy to mention that during low-flow conditions, high river albedo counteracts the effects of climate change as a large fraction of the incoming solar radiation is reflected. Thus, to assess the increase of water temperatures in such rivers, due to the changes in the riverbed composition, future research endeavors should involve a coupling of sediment transport analysis with river temperature simulations.

We also want to highlight a limitation of our model: the effects of suspended sediment on river temperatures were not considered in our analysis. However, this assumption of clear water is generally valid for MLRs in the California Bay Delta Watershed due to sediment trapping in reservoirs, especially during low-flow conditions and in downstream reaches close to dams. It is difficult to foresee what would be the effect of the river temperatures if we included the suspended sediment in the water column. The cooling or warming effect depends on the sediment type. Sediments originating from glaciers or granitic watersheds often increase reflectance, mitigating warming effects. In contrast, darker sediments like brownish-clay or -silt from watershed sources (washload) tend to absorb more heat solar radiation, thereby raising river temperatures.

5. Conclusions

The assessment of climate change effects, using two gridded weather data, under the RCP8.5 scenario suggests that future water temperatures in MLRs in the California Bay Delta Watershed will significantly increase in the summer months. This increase is exacerbated during low-flow conditions and as a consequence of large water losses. Although the two gridded data under RCP8.5 scenario predict a continuous decline in the incoming solar radiation at the surface between 2030 and 2100, the net longwave radiation and the latent heat fluxes compensate for this decline. These two energy fluxes are the primary contributors to the increase in the net heat fluxes that lead to the effects of warming water.

To counteract the potential increase in water temperature that could negatively impact aquatic habitat in MLRs in the California Bay Delta Watershed, due to the effects of climate change, we found that an increase in water releases from the hypolimnion zone in reservoirs could partially mitigate the rates of water temperature increase in these rivers over downstream distances where advective fluxes are more relevant than atmospheric heating fluxes. Over these distances, net longwave radiation is limited due to a decrease in the upwelling component, and latent heat flux is also constrained by a reduction in the vapor pressure deficit. Given that water temperature is highly sensitive to abrupt changes in discharge over these distances, it is crucial to minimize water losses during low-flow conditions. Beyond these distances, the warming of the river, primarily attributed to atmospheric effects, is not fully mitigated by the water releases.

CRediT authorship contribution statement

Andrés F. Rojas-Aguirre: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Erin N. Bray:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Jeff Dozier:** Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The opinions and findings presented in this paper are solely those of the manuscript authors and do not represent the opinions of any state or federal agencies.

Appendix

The Fig. A.12 depicts the continuous flow releases from Friant Dam for August across various years.

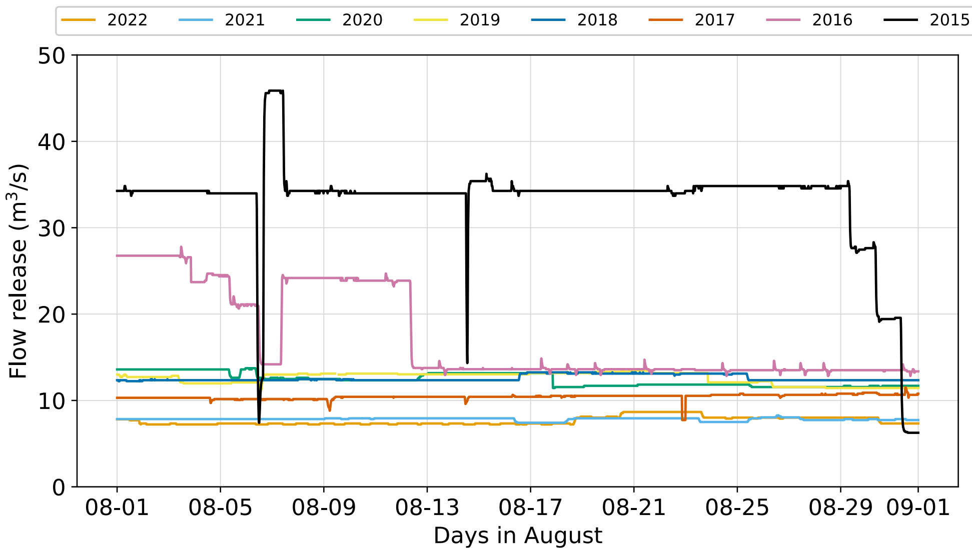

Fig. A.12. Friant Dam releases for the month of August.

Data availability

Data and codes used in this paper can be obtained from the following repository https://www.hydroshare.org/resource/0c4d1d56cc0e40109e92cab6f4519d73/.

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