



# Thermal Suitability of the Los Angeles River for Cold Water Resident and Migrating Fish Under Physical Restoration Alternatives

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Anthropogenic development has adversely affected river habitat and species diversity in urban rivers, and existing habitats are jeopardized by future uncertainties in water resources management and climate. The Los Angeles River (LAR), for example, is a highly modified system that has been mostly channelized for flood control purposes, has altered hydrologic and hydraulic conditions, and is thermally altered (warmed), which severely limits the habitat suitability for cold water fish species. Efforts are currently underway to provide suitable environmental flows and improve channel hydraulic conditions, such as depth and velocity, for *adult* fish migration from the Pacific Ocean to upstream spawning areas. However, the thermal responses of restoration alternatives for resident and migrating cold water fish have not been fully investigated. Using a mechanistic model, we simulated the LAR's water temperature under baseline conditions and future alternative restoration scenarios for migration of the native, anadromous steelhead trout in Southern California and the historically resident Santa Ana sucker. We considered three scenarios: 1) increasing roughness of the low-flow channel, 2) increasing the depth and width of the low-flow channel, and 3) allowing subsurface inflow to the river at a soft bottom reach in the LA downtown area. Our analysis indicates that the maximum weekly average temperature (MaxWAT) in the baseline condition was 28.9°C, suggesting that the current river temperatures would act as a limiting factor during the steelhead migration season and habitat for Santa Ana sucker. The MaxWAT dropped about 3%–28°C after applying all the considered scenarios at the study site, which is 3°C higher than the determined steelhead survival threshold. Our simulations suggest that without consideration of thermal restoration, restoring hydraulic conditions may be insufficient to support cold water fish migration or year-round resident native fish populations, particularly with potential river temperature increases due to climate change.

**Keywords:** river temperature, environmental flows, mechanistic modeling, multilayer linear regression, restoration, Los Angeles River, fish migration, climate change

## 1 INTRODUCTION

Like many urban rivers, the Los Angeles River (LAR) is experiencing a renaissance and is now viewed as a valuable ecosystem to be restored as a community amenity as opposed to the old paradigm where it was considered a source of flooding to be controlled and a conveyance for treated wastewater to the ocean (Beach, 2001; Everard and Moggridge, 2012). Given that the LAR flows through one of the largest and most urbanized cities in the United States, complete restoration to an undisturbed condition is not achievable through reclamation efforts. Instead, the overall goal is to improve ecological function through targeted remediation efforts to provide a more ecologically dynamic state (Bernhardt and Palmer, 2007). This aligns with similar projects across the world where there is an integrated and pragmatic approach to urban river restoration to improve biodiversity and achieve overall ecosystem function and resilience (Palmer et al., 2005; Smith et al., 2014; Chou, 2016).

Identifying an ecological endpoint is one of the standards for successful river restoration (Palmer et al., 2005; Zhang et al., 2018; O'Brien et al., 2020). The anadromous steelhead trout (*Oncorhynchus mykiss*) is classified as endangered in southern California (U.S. Department of Commerce, 1997). For the LAR, improving river connectivity for steelhead from the sea to their native spawning grounds in southern California is a priority ecological endpoint (City of Los Angeles, 2007). Connecting urban rivers to healthy reaches can be successful as flow and sediment are more likely to be in balance and the fish can exploit new areas (Findley and Taylor, 2006). In addition to meeting the trout's physical habitat requirements, because fish are ectotherms, water temperature must be within a defined thermal range for migrating fish to survive. Stream temperature influences the distribution of fish, food availability, body growth, movement, fecundity, and spawning success (Caissie, 2006).

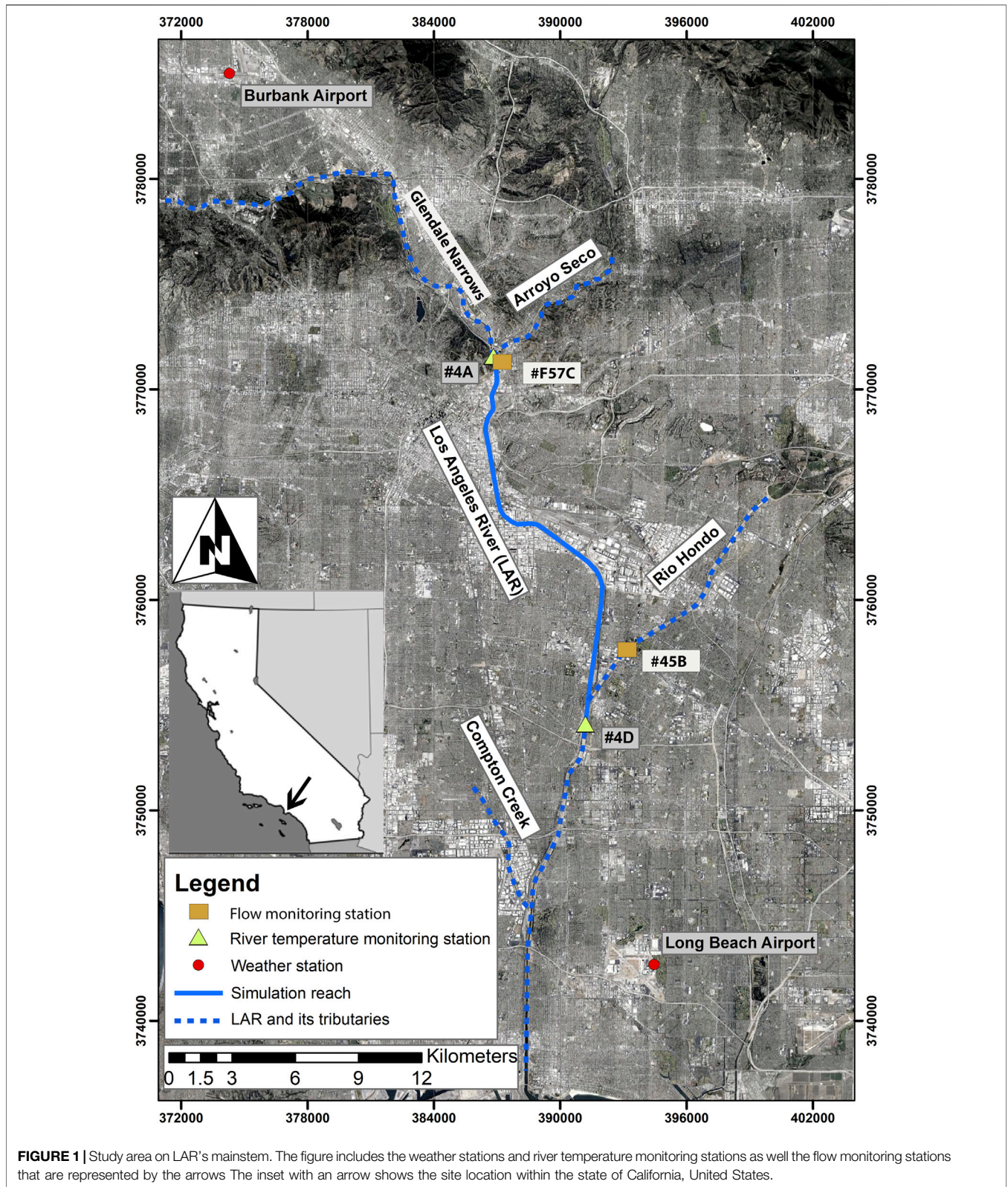
In this study, we assessed how physical restoration scenarios focused on improving connectivity will alter stream temperatures to better support migrating steelhead. To do so, we evaluated how restoration measures within the LAR may improve stream temperature during steelhead migration and support other native fish habitat from January through June which is primarily the migration season in southern California (Moyle et al., 2008). Stream temperature is a function of flow, depth, velocity, and substrate connections, all of which may be altered during the LAR stream restoration. Gu and Li (2002) found that the sensitivity of stream temperature to river flow rate is as significant as that to weather. Therefore, the other physical parameters that are controlled by flow (i.e., depth and velocity) also affect water temperature. Furthermore, water temperature in riverine systems within highly urbanized areas can be elevated through modifications in riparian landcover (by affecting the shading on the water surface), as well as surface and subsurface inflows (LeBlanc et al., 1997; Chen et al., 1998; Van Buren et al., 2000; Sridhar et al., 2004; Herb et al., 2009; Sun et al., 2015; Abdi and Endreny, 2019). Like other similar projects, remediation of the LAR has the best chance of success if efforts improve ecological function and the river can support self-sustaining populations (Palmer et al., 2005).

Fixing hydrologic and hydraulic conditions of urban rivers through physical modification is often the focus of river restoration projects (Barber and Gleason, 2017), yet seldom do restoration efforts look at how stream temperature can be improved for native fish. River temperature is a critical factor in riverine networks, as it controls the saturation of dissolved oxygen (Sand-Jensen and Pedersen, 2005; Null et al., 2017). In addition, while many rehabilitation projects do concentrate on improving water quality to address water contamination, stream temperature is often overlooked (Purcell et al., 2002; Walsh et al., 2005; Pander and Geist 2013). Rivers are often highly thermally polluted due to industrial discharges (e.g., thermoelectric power plants return flows; Madden et al., 2013) or due to associated land-use change e.g., deforestation and urbanization; (Parker and Krenkel, 1969; Wunderlich, 1972; Walsh et al., 2005; Poshtiri and Pal, 2016; Rogers et al., 2021). Increasing air temperatures from climate change are expected to increase river temperatures as well (Eaton and Scheller, 1996).

In addition to air temperature, substrate inflow as groundwater and hyporheic exchange regulates river water temperature during wet and dry weather (Risley et al., 2010; Kurylyk et al., 2016), which depending on site conditions (e.g., hard or soft bottom, and urbanized or forested area) and seasonality may vary (Poole and Berman, 2001). The upwelling in the LAR is important due to the condition of the river however, the hyporheic exchange inflow is negligible due to hardening of the floodplain (Paulinski et al., 2021). Further, riparian zone shade effects from tree canopy, hillslope, and buildings are also factors reducing river water temperature by providing terrestrial-based reduction in direct and diffuse solar radiation and the view-to-sky factor for the river, which influences longwave radiation (Boyd and Kasper, 2003). Recent advances in temperature modeling now provide the tools to explore how managing flows and riparian shading can influence thermal conditions within desired migration corridors.

This study aims to assess the river temperature condition for steelhead migration on the LAR mainstem and evaluate the cooling or warming effects of potential restoration scenarios. The applied restoration scenarios are suggested by the United States Bureau of Reclamation (U.S. Bureau of Reclamation, 2019): 1) increasing roughness of the low-flow channel (see **Supplementary Figure S1**<sup>1</sup> for an example of a low-flow channel) to reduce velocity, 2) increasing the depth and width of the low-flow channel in addition to increasing the roughness, and 3) applying additional subsurface upwelling to Scenario 2. Our central research questions are: 1) to what degree does river temperature limit steelhead migration in LAR mainstem from the Pacific Ocean to the soft bottom section of the LAR (Glendale Narrows)? 2) how does river temperature respond to restoration scenarios to facilitate steelhead migration? and 3) how would simulated thermal changes limit the year-round resident native fish in alternative restoration scenarios? Modeling results could provide a better understanding of the role of water temperature as a limiting factor for steelhead migration in the LAR. Our study had two hypotheses: 1) that warm water

<sup>1</sup>Figures and tables with "S" are presented in the supplementary materials.



**FIGURE 1** | Study area on LAR’s mainstem. The figure includes the weather stations and river temperature monitoring stations as well the flow monitoring stations that are represented by the arrows. The inset with an arrow shows the site location within the state of California, United States.

temperature is a limiting factor for cold water migrating fish in LAR and 2) the proposed USBR restoration actions cannot address the temperature problems for both species. Findings from this

work will provide the LAR water managers with a more holistic understanding of the capabilities and consequences of river restoration alternatives.

## 2 METHODS

We estimated the optimum thermal suitability ranges in the determined river reach of the LAR based on the desirable thermal condition for steelhead (see **section 2.3**). We then simulated the water temperature for current conditions and under the restoration alternatives for the LAR based on the considered thermal metrics.

### 2.1 Study Area

We evaluated the thermal impacts of the alternative scenarios that were originally proposed by the United States Department of the Interior Bureau of Reclamation (U.S. Bureau of Reclamation, 2019) for steelhead migration on the LAR. The study area is an approximately 19.6 km reach of the LAR, from the confluence with Arroyo Seco tributary to the confluence with the Rio Hondo (**Figure 1**). The selected study reach overlaps with the domain considered in other restoration analyses of the river system (U.S. Bureau of Reclamation, 2019; Reaches 7 and 8 in; U.S. Army Corps of Engineers, 2016).

The study reach drains a 1,270 km<sup>2</sup> area located entirely within the alluvial, coastal LAR watershed. The LAR watershed has a mild semi-arid Mediterranean climate with seasonal precipitation occurring primarily in the winter months (October through March). The study reach includes the physical and thermal contributions of the Arroyo Seco tributary and effluent from three water reclamation plants that discharge to the LAR upstream of the channel. Flows within the river are primarily wastewater-dominated, particularly in the summer months, when the three water reclamation plants collectively contribute over 70% of the total river flow (Stein, et al., 2021b). The water reclamation plants are upstream of the study reach and their influence on the water temperature is already captured by the upstream river temperature boundary condition. The mainstem of the LAR is primarily concrete-lined for flood control purposes (Mika et al., 2017; Read et al., 2019) except for a 17.7 km reach in the Glendale Narrows, a 3.9 km reach upstream of Sepulveda Dam, and the estuary (**Figure 1**). The hard-bottom section of the river is armored with uniform geometry to expedite stormwater removal and provide flood protection. The area under study is notable for its channelized and mostly trapezoidal cross-section form, gray concrete armoring, lack of subsurface inflows due to groundwater upwelling, and absence of riffle-pool bedform morphology that could provide thermal refugia, and lack of riparian vegetation.

Discharge within the LAR mainstem and tributaries is heavily managed through dams and reservoirs, distributed stormwater capture systems, spreading grounds, and water reclamation facilities. The hydrology within the watershed is constantly changing due to the complexity of the system, the need to balance existing water supplies, and the uncertainty of climate change impacts. For example, municipalities within Los Angeles are seeking to reuse wastewater for water supply, which would have significant impacts on hydrologic and hydraulic conditions in the effluent-dominated LAR. Since wastewater effluent is

typically warm, an increase in discharge may elevate river temperatures outside the thermal tolerance range for some fish; a decrease in discharge may also have temperature effects. In the study herein, however, we focus on the impacts of restoration alternatives on river temperature under existing hydrologic conditions to isolate their effects.

Migrating steelhead were present in the LAR until 1940 when urbanization began to rapidly increase. Changes to velocity, depth, temperature, and refuge habitat are all considered to be contributing factors to migration no longer occurring. Although migration has not been observed since then, resident populations still exist in the upper watershed tributaries (Stein et al., 2020). Current restoration efforts are aimed at creating conditions along the mainstem that would once again allow migration to occur between the ocean and the extant upper watershed populations. High temperatures are considered one of the key limiting factors for steelhead migration under current conditions (Stillwater Sciences, 2020). Exposure to high temperatures can result in acute and chronic stress for migrating adults, which can lead to secondary stress effects such as increased energy use, immunosuppression, depressed reproductive maturation, and overall could reduce growth and reproductive fitness and lead to mortality if exposure is prolonged i.e., 7 days; (Myrick and Cech, 2000; A. Myrick and Cech, 2005; Boughton et al., 2015; Stillwater Sciences, 2020).

### 2.2 Model Setup

We used a one-dimensional hydraulic model, HEC-RAS (U.S. Army Corps of Engineers, 2016), under steady-state conditions to calculate water surface profile data coupled with the i-Tree Cool River model (Abdi and Endreny, 2019; Abdi et al., 2020b) to simulate water temperature. The HEC-RAS model was a previously-created hydraulic model of the LAR, as documented in Stein et al. (2021a.) Briefly, the model was compiled from various sources and channel geometry was validated with LiDAR data, as-builts, and Google Earth, to confirm that low-flow channel geometry was correct (U.S. Army Corps of Engineers, 2004; Environmental Science Associates, 2018; HDR CDM, 2011; U.S. Army Corps of Engineers, 2005). The final hydraulic model used in this study was from station #4A through station #4D (**Figure 1**) with a length of almost 19.6 km and 440 cross sections.

We applied the Arroyo Seco tributary inflows to the main channel in HEC-RAS to generate depth and velocity data to evaluate migration feasibility (i.e., minimum depth and max velocity to support migration) as well as seven other hydraulic parameters including cross-sectional distances, flow, minimum channel elevation, and water surface elevation to calculate the water column depth, top width, flow area, and wetted perimeter. These hydraulic parameters were used as inputs to the i-Tree Cool River model. The one-dimensional steady flow component in HEC-RAS uses the standard step method for the solution of steady gradually varied flow (Chow, 1959). The i-Tree Cool River model applies the standard advection, dispersion, reaction equation to the water surface profile outputs, generated by HEC-RAS, to simulate river water temperature (Abdi et al., 2020a).

## 2.3 Ecological Metrics

Our focus was to evaluate the thermal impacts of alternative restoration scenarios on native year-round resident fish populations and steelhead migration from the estuary to the soft bottom habitat in the Glendale Narrows. From the Glendale Narrows the anadromous trout can reach potential spawning grounds in upper tributaries. The restoration scenarios will also improve physical habitat for other native fish that could be reintroduced such as the endangered Santa Ana sucker (*Catostomus santanae*; U.S. Fish and Wildlife Service, 2000; U.S. Fish and Wildlife Service, 2011).

Steelhead are anadromous and migrate into freshwater to spawn between the middle of January to the middle of June each year in California (Santa Ynez River Technical Advisory Committee (SYRTAC), 2000), which generally coincides with high flows in the LAR. The steelhead are a large-bodied fish; adults average 721 mm in length across their native range (Quinn, 2018). A minimum depth of 0.3 m (1 ft) of water is needed for the adult migrating trout to swim up the river, while greater depths closer to 0.6 m (2 ft) are required for adults to rest periodically during migration (U.S. Bureau of Reclamation, 2019). They are strong swimmers, capable of swimming 1.5–3 m/s for prolonged distances and 4–8 m/s for burst speed (U.S. Bureau of Reclamation, 2019). When migrating to spawning grounds, the trout also need locations to rest and recover at speeds below 1.5 m/s. The goal of the planned river restoration is to provide habitat and hydraulic conditions that are passable by migrating adult trout to return to spawning grounds upstream of the study reach. While the planned river restoration considers stream velocities and depths appropriate for steelhead, it overlooks temperature as a limiting factor. Steelhead are cold water stenotherms that cannot survive in water above 25–30°C (Hokanson et al., 1977; Myrick and Cech, 2000; A. Myrick and Cech, 2005).

Other smaller-bodied native fish species remain in freshwater year-round, inhabiting the LAR during the high flows when steelhead are migrating and during the low-flows in the summer. Other native fish considered in this analysis include the threatened Santa Ana sucker, a small (16 cm) fish that prefers low to mid gradient streams with coarse substrate, a minimum depth of 40 cm, and temperatures below 22°C (U.S. Fish and Wildlife Service, 2011; Haglund et al., 2001; Haglund and Baskin, 2003). Different studies have observed mortality of Santa Ana sucker at temperatures between 22 and 32.8°C, we therefore used 22°C as their critical thermal maximum (Moyle, 2002; U.S. Fish and Wildlife Service, 2011).

The temperature threshold for Steelhead ranges from 24–32°C (Lee and Rinne, 1980; Myrick and Cech, 2000; Sloat and Osterback, 2013; Spina, 2007 and references therein) under lab conditions, where loss of equilibrium or death occurs within 7 days, through direct mortality, or indirect mortality from impairment of function. Steelhead temperature preference has been reported between 17.8–24.6°C (Verhille et al., 2016), however, optimum swimming speed has been documented as 14–15°C (Myrick and Cech, 2000), temperatures higher than the optimum may hinder swimming ability making it more challenging for fish to swim against the velocities considered

in restoration. A barrier to migration has been estimated at 21–24°C (Stabler, 1981; Washington State Department of Ecology (WDOE), 2002), at which point individuals will start expressing avoidance behavior by sheltering in cooler tributaries, refusing to migrate, or migrating back downstream (McCullough et al., 2001). The critical thermal maxima for Steelhead, wherein fish lose equilibria after 24 h of exposure, has been observed to be 25°C (Myrick and Cech, 2000). While prolonged exposure, i.e., 7 days at 21°C, however, can lead to mortality, therefore the U.S. Environmental Protection Agency (USEPA) (2003) recommends a maximum weekly maximum temperature (MWMT) of 20°C for migratory corridors.

Santa Ana Sucker have been documented in large temperature ranges from 8 to 26°C (Saiki et al., 2007) but are typically found in temperatures below 22°C (Moyle, 2002). Limited information describing tolerances to water temperature is available, however, mortality has occurred at elevated water temperatures, i.e., 27–33°C (San Marino Environmental Associates (SMEA), 2010; U.S. Fish and Wildlife Service, 2014), and their physical condition has been noted to worsen in average temperatures of 19.3°C (range 14.4 – 25.9°C, Saiki et al., 2007).

To evaluate whether the proposed restoration scenarios would provide thermal habitat to support the native fish species in the migration season, we used observed and modeled data to calculate thermal metrics to compare to fishes critical thermal maxima. Temperatures can be limiting to fish in two ways, exceeding maximums over short term exposures can lead to death while exceeding optimal weekly average temperatures can reduce survivability by inducing avoidance behavior that could impact migration success (McCullough et al., 2001), increasing metabolic costs that can impact viability of eggs (Sauter et al., 2001), and causing impairment. The first metric, the Maximum Weekly Maximum Temperature (MaxWMT) is the 7 days moving average of daily maximum temperatures. The second is the Maximum Weekly Average Temperature (MaxWAT), defined as the 7 days moving average of daily mean temperatures (Table 1). The third thermal metric is the Minimum Weekly Minimum Temperature (MinWMT), which is the 7-days moving minimum of daily minimum temperatures. We compared these calculated metrics from the observed and modeled data to the critical thermal maxima of each of the fishes of interest in this study.

## 2.4 Input Data and Scenarios

### 2.4.1 Station #4A: Upstream Boundary Condition

River temperature monitoring station #4A, immediately downstream of the LAR and Arroyo Seco tributary confluence, was the boundary condition for the simulations (Figure 1). hourly observed water temperature data at this station was provided by Mongolo et al. (2017) for the dry season (i.e., with no storm event) in June 10–July 18, 2016 but not the migration season (February 1–May 31). Continuous river temperature data is rare on the LAR; however, single layer or multilayer regression relationships have been used to estimate water temperatures (Mohseni et al., 1998; Caissie, 2006; Neitsch et al., 2011). To get the river temperature at the upstream boundary condition for the desired migration season

**TABLE 1** | River temperature metrics used to evaluate the model results from different restoration scenarios in terms of fish thermal habitat suitability.

Metric	Definition	Description
Min 7 days min (MinWMT)	The minimum weekly minimum value of a continuous 7 day period (°C)	Temperatures that may be below fish survival threshold (11°C)
Max 7 days max (MaxWMT)	The maximum value of a continuous 7 day period (°C)	Temperatures that may exceed fish survival thresholds (25°C)
Mean 7 days max (MaxWAT)	The maximum average over a 7 day period (°C)	Average conditions

(February 1–May 31, 2016), we trained a multilayer linear regression machine learning (ML) algorithm (Murtagh, 1991; Pedregosa et al., 2011) on Google's TensorFlow model version 2.3.1 (Abadi et al., 2015) using Keras artificial neural network (ANN) library (Chollet et al., 2015) on Python 3. We used the observed hourly river temperature data at LAR station #4A 936 observations, (Mongolo et al., 2017) as the dependent variable for the model training and testing. We used hourly weather data, including air temperature, wind speed, station pressure, and relative humidity as the independent variables as the predictive features. We obtained the weather data for training the model for station #4A from Burbank Airport weather station for the same time window (**Supplementary Table S1**).

After data gathering, cleaning<sup>2</sup> and organizing, we used the available observed river temperature data for June 10–July 18, 2016 for our ML algorithm and used 0.6, 0.2, and 0.2 ratios for the training, validating, and testing phases, respectively. Mean absolute error (MAE) was used as the target error optimization parameter. The MAE decreased to 1.1°C after 100 iterations. The  $R^2$  for the testing process was 0.78 with a  $p$ -value of 0.202 ( $>\alpha = 0.05$ ) for a two-sample  $t$ -test, showing that there was no significant difference between the observed and predicted river temperatures.

By applying the observed weather data in the migration season (February 1–May 31, 2016; see **Supplementary Table S2** for more statistical details) on the trained ML algorithm, we predicted the upstream water temperature boundary condition for the i-Tree Cool River model. **Supplementary Table S3** shows the statistical properties of the prediction and **Supplementary Figure S2A** demonstrates the scatter plot between the observed air temperatures and predicted river water temperatures. Based on the predictions from our trained algorithm, the water temperature in migration season had an average of 23.7°C with 25th and 75th percentiles of 22.0°C and 25.4°C respectively, and a standard deviation of 2.5°C (**Supplementary Table S3**).

#### 2.4.2 Station #4D: Downstream Control Point

We used the observed water temperature data provided by Mongolo et al. (2017) to determine river water temperature at the downstream boundary, station #4D (**Figure 1**). We trained a separate multilayer linear regression ML algorithm for station #4D to predict water temperature in the migration season (February 1–May 31, 2016). We used the observed hourly river temperature data on LAR stations #4D (Mongolo et al.,

2017) as the dependent variables for the ML algorithm and similar independent features (air temperature, wind speed, station pressure, and relative humidity) obtained from Long Beach Airport weather station (**Supplementary Table S1**).

After data cleaning, for June 10–July 18, 2016, the ML algorithm with 0.6, 0.2, and 0.2 ratios for the training, validating, and testing phases respectively was applied to the station #4D dataset. The MAE was 2.5°C after 100 iterations (**Supplementary Table S1**). The  $R^2$  for the testing process was 0.68 with a  $p$ -value of 0.16 ( $>\alpha = 0.05$ ) for a two-sample  $t$ -test, showing that there was no significant difference between the observed and predicted river temperatures.

Using the trained ML algorithm, we predicted water temperature at station #4D in the migration season (February 1–May 31, 2016) using weather data from the Long Beach Airport weather station (see **Supplementary Table S2**) as the independent variables. The observed air temperature and predicted water temperature showed a similar pattern on variations in the migration season (**Supplementary Figure S2B**) and as shown in **Supplementary Table S3**, the predicted water temperature, had an average of 21.2°C with a 25th and 75th percentiles of 17.6°C and 24.7°C respectively, and a standard deviation of 5.2°C. As seen in **Supplementary Tables S1, S2, S3**, the observed air and water temperatures support the variation of predicted water temperature in stations #4A and #4D.

#### 2.4.3 Input Data for Simulations

To check the accuracy of the simulated river temperatures along the LAR in the study reach, we calibrated and validated the i-Tree Cool River model for the migration season (February 1–May 31, 2016). For this study, we simulated hourly water temperatures using the i-Tree Cool River model. We used hourly weather data obtained from the Burbank Airport weather station as was used in the ML model training procedure. For the direct and diffuse shortwave radiations, we used hourly data from National Renewable Energy Laboratory's National Solar Radiation Database NREL NSRDB; (Sengupta et al., 2018) for the station location on the LAR. We obtained solar radiation data from NREL's NSRDB (station ID #83948 located at 34.09N, 118.22 W). In the simulation period, the average air temperature was 17.1°C and the average relative humidity was 53.9% (**Supplementary Table S2**).

According to Risley et al. (2010), we considered the long-term observed flow data for the flow gaging stations in the study area during the simulation time frame (February to May from 1985 to present). We used the observed flow data from the LA County stations #F57C for the LAR mainstem and #45B for the Rio Hondo tributary (**Figure 1**). Based on the assumption of 50% exceedance probability and assuming steady state for the simulations (Stein et al., 2021a), we assumed a constant flow

<sup>2</sup>Process of preparing the data for the ML algorithms by removing or modifying inaccurate, corrupted, or improperly formatted data (<https://www.sisense.com/glossary/data-cleaning/>).

of 3.74 m<sup>3</sup>/s (132 ft<sup>3</sup>/s) in the LAR mainstem and 0.03 m<sup>3</sup>/s (0.9 ft<sup>3</sup>/s) in the Rio Hondo tributary.

Using the calculated flow values from the observed data, we ran the HEC-RAS (U.S. Army Corps of Engineers, 2011) model in steady-state to get the water profile data for the cross-sections, including cross-sectional distances, flow, minimum channel elevation, and water surface elevation to calculate the water column depth, velocity in the channel, top width, flow area, and wetted perimeter. The average river water depth for the LAR in the study period was about 26 cm, the average water velocity was 0.8 m/s, and the average cross-sectional water level area was 5.9 m<sup>2</sup>. The i-Tree Cool River model uses an internal linear interpolation function to resample the HEC-RAS cross-sectional outputs to refine the spacing of cross-sections to 100 m and applies the spatial variation channel data and riparian features to simulate the river temperature (Abdi and Endreny, 2019; Abdi R. et al., 2021). Due to the bare concrete bed and lack of riparian shading in the river reach, we considered no subsurface inflow and no shading effect in the simulations.

#### 2.4.4 Restoration Scenarios

Based on Manning's equation, at low-flow values (less than about 5.7 m<sup>3</sup>/s (200 ft<sup>3</sup>/s)) a deepened and roughened low-flow channel could provide the minimum depth requirements and velocities suitable for resting and migration of steelhead in the LAR (U.S. Bureau of Reclamation, 2019). To do so, the underpinning concept of the fish passage design for the LAR is to increase the depth, width, and roughness of a low-flow channel that would fit within the larger concrete flood control channel and could accommodate the large-bodied trout (Fryirs and Brierley, 2000; U.S. Bureau of Reclamation, 2019).

Even low flows in the LAR tend to occur near critical depth (U.S. Bureau of Reclamation, 2019), meaning that increasing Manning's roughness within the low-flow channel could increase the depth and reduce velocity to provide a passable condition without exhausting the trout during migration and allow the sucker viable habitat. For the first management scenario, we increased the roughness without changing the channel geometry. The Manning's roughness coefficient in the baseline condition within the concrete bed material was 0.017 and as suggested by the U.S. Bureau of Reclamation (2019), we assumed that the low-flow channel roughness of the design concepts would be equivalent to that of a natural gravel or cobble bed stream with a Manning's n-value of 0.035 (two times larger).

For the second scenario, in addition to changing the roughness, we modified the channel geometry to reach the desired ranges of depth and velocity. Based on the U.S. Bureau of Reclamation (2019), we applied a design flow of 8.5 m<sup>3</sup>/s (300 ft<sup>3</sup>/s) for the low-flow channel capacity, which corresponds to the 10 percentile of the annual exceedance for mean daily flows during the 1985 to 2017 period. Increasing flows in the low-flow channel area would improve habitat conditions but when the low-flow channel capacity is exceeded, habitat conditions decline (U.S. Bureau of Reclamation, 2019). As a result, we selected 8.5 m<sup>3</sup>/s (300 ft<sup>3</sup>/s) as the optimal design flow to balance habitat at base flow and higher flows. For the design flow, assuming a uniform trapezoidal low-flow channel,

we used the top width of 20 m (65 ft) and the depth of 0.6 m (2 ft). We considered the cross-sectional design as the starting point for the design of the alternative management scenario and adjusted the mentioned values for the HEC-RAS cross-sections. We also assumed that the top elevation of the designed low-flow channel designs matches the elevation of the existing concrete near the channel center and excavating a wider and deeper.

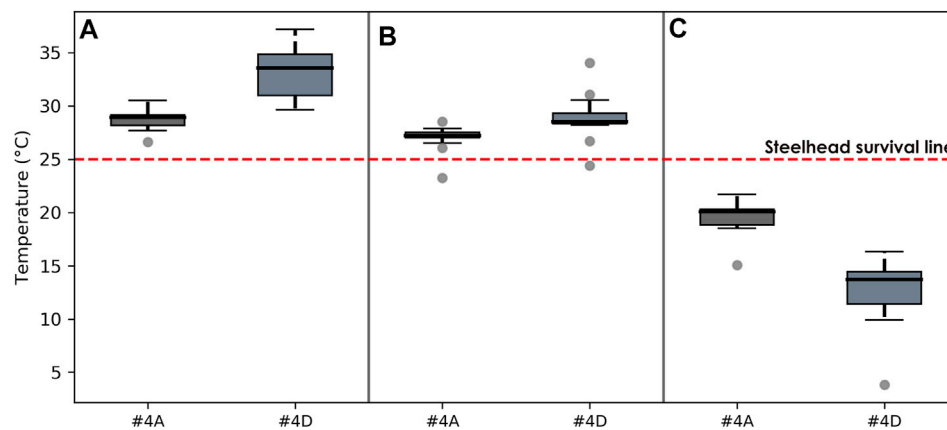
The alternative design of the low-flow channel would require demolishing a portion of the existing concrete near the channel center and excavating a wider and deeper low-flow channel, which would also allow for subsurface upwelling. Groundwater in the basin is intensively managed for water supply and subsurface water quality reasons (Upper Los Angeles River Area Wastewater (ULARA), 2019). An estimate of groundwater upwelling was provided by the Los Angeles Department of Water and Power (LADWP) at a constant rate of 3,000 acre-ft/yr, or approximately 0.117 m<sup>3</sup>/s (4.14 ft<sup>3</sup>/s). We distributed the estimated upwelling over the simulation reach with a constant temperature, slightly adjusted, based on annual average air temperature at the Burbank Airport weather station (18.7°C) as suggested by Glose et al. (2017) and Abdi et al. (2020a).

To simulate the thermal impacts of the alternative restoration scenarios for the LAR downstream of the Glendale Narrows permeable soft bottom reach, we calibrated and validated the mechanistic river temperature model for the migration season under baseline conditions using the considered control point (station #4D). In the baseline condition thermal simulations, we used the HEC-RAS modeling's outputs for steady-state conditions in the migration season. Applying values for the 440 cross-sections from the HEC-RAS model setup, we calibrated the temperature model based on solar radiation data and substrate temperature. In the calibration period (February 1–April 30, 2016), the coefficient of determination was 0.75 with and Nash Sutcliffe Efficiency (NSE) of 0.69 (Supplementary Figure S3A). In the validation period (May 1–31, 2016), the coefficient of determination was 0.66 and the NSE was 0.59 (Supplementary Figure S3B).

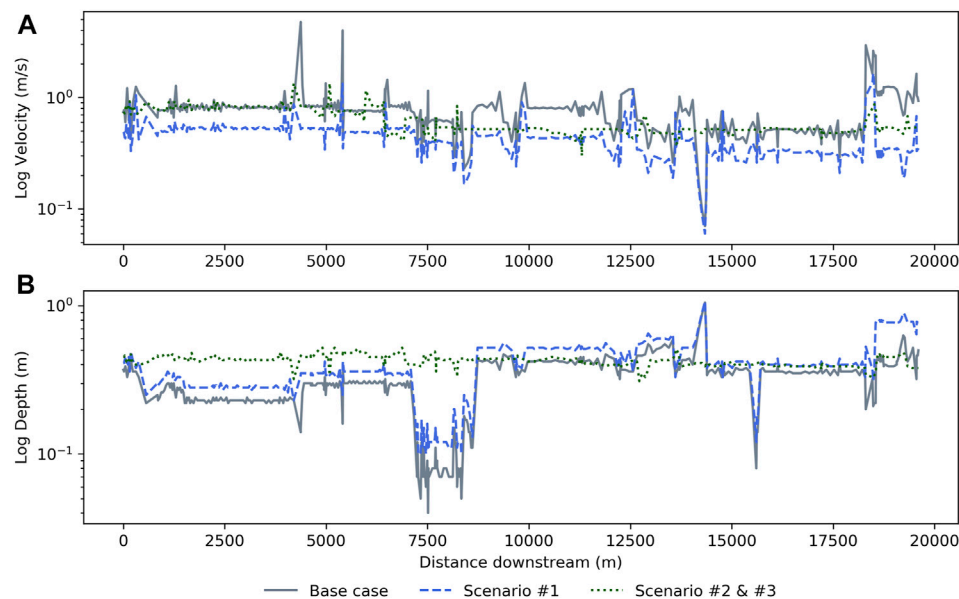
### 3 RESULTS AND DISCUSSION

Results from baseline condition simulations, and under potential restoration scenarios, showed that during migration season, baseline thermal conditions would not support the steelhead or resident Santa Ana sucker. Even with restoration of hydraulic conditions, temperatures would exceed their optimal thermal maxima. Water temperature should therefore be considered a limiting factor in facilitating steelhead migration on the LAR or establishing Santa Ana sucker populations. On average, water temperature was about 4°C higher than the fish's threshold (25°C). Even though management scenarios could improve physical conditions, other plans should be considered to reach the desired temperature thresholds.

The ML-based predictions of river temperature in the migration season for upstream and downstream of the study area showed that the calculated thermal metrics, MaxWMT and



**FIGURE 2** | Boxplots show the variation of the calculated thermal metrics: MaxWMT (A), MaxWAT (B), and MinWMT (C) for the predicted water temperatures during the migration season in 2016 (February 1–May 31, 2016) for the upstream at station #4A and downstream at station #4D. The red dashed line shows the maximum temperature a steelhead could tolerate.



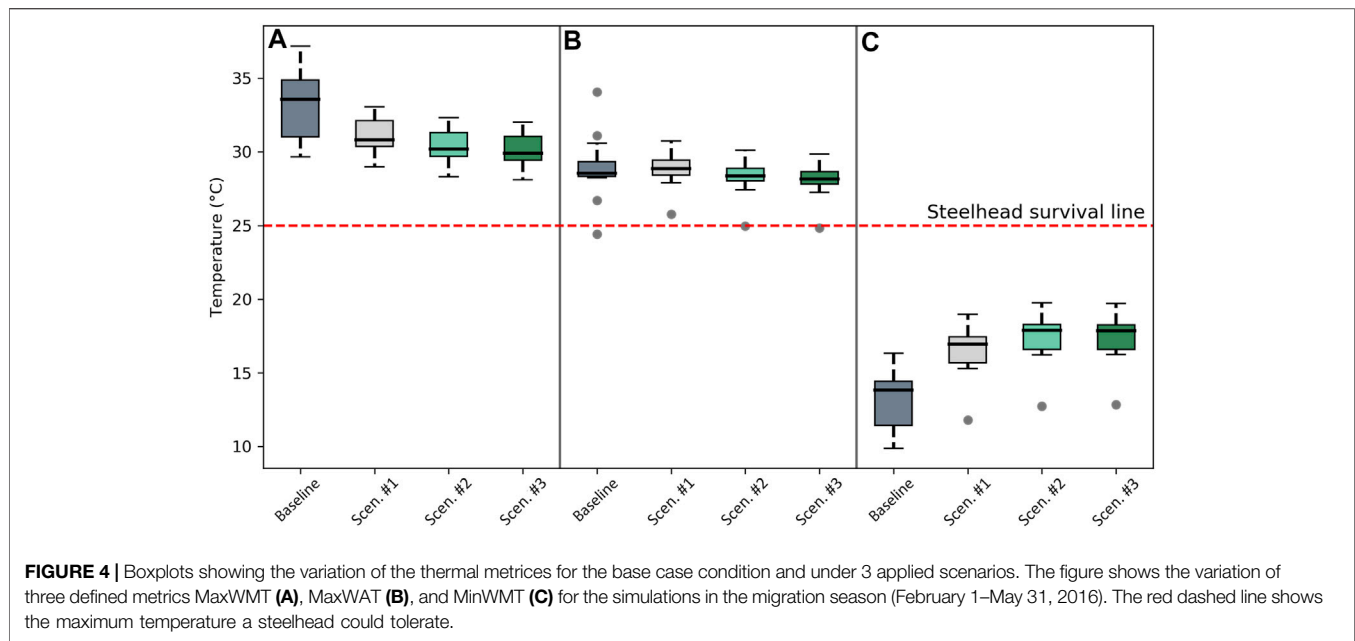
**FIGURE 3** | Variation of the cross-sectional velocity (A) and depth (B) in the base case condition and under determined management scenarios. The y-axis in both panels is in log format.

MaxWAT, exceeded the recommended 20°C MaxWMT for fish corridors and critical maxima survival threshold of 25°C for the steelhead, which is also above the 22°C maxima for the sucker (Figure 2). The median of MaxWMTs was 28.9°C at station #4A and reached 33.6°C at station #4D, an increase of 16% over baseline condition. The median of MaxWATs was 27.2°C at station #4A and reached 28.2°C at station #4D, an increase of 4%. We observed a 30% decrease in the median of the calculated MinWMTs from 20.1°C to 13.7°C. The 16% increase and a 30% decrease in the median of MaxWMTs and MinWMTs metrics respectively, showed that the diel variations of the water

temperature at the downstream station were broader compared to at the upstream station. One explanation could be that the upstream station is in a soft bottom portion of the river while the downstream station is after 20 km of bare concrete channel, which can increase water temperature (Sun et al., 2016).

By increasing the Manning's roughness in the low-flow channel from 0.017 to 0.035 (Scenario 1), the average cross-sectional water column depth increased by 50% to 39 cm and the average flow velocity decreased by 55% to 0.44 m/s (see Figure 3; Supplementary Table S4 for more details). Under this scenario, the water profile in the river channel was elevated due to the





**TABLE 2** | Average thermal metrics of the river temperature (°C) in the downstream control station #4D for the baseline condition and under the alternative scenarios during the migration season (February 1–May 31, 2016).

	ML algorithm		HEC-RAS/iTree cool river modeling	
	Baseline condition	Scenario #1 (Manning's coefficient increase)	Scenario #2 (Scenario #1 + geometry increase)	Scenario #3 (Scenario #2 + subsurface inflow)
MaxWMT	33.4	31.1	30.4	30.1
MaxWAT	28.9	28.8	28.3	28.0
MinWMT	12.8	16.6	17.5	17.5

increased Manning's roughness coefficient, and the estimated average diel change in the river temperature, based on the defined thermal metrics (MaxWMT–MinWMT), decreased by 30% from 20.6°C to 14.5°C. The average MaxWMT in the simulated migration season for Scenario 1 decreased by 2.3°C–31.1°C (7% compared to the baseline condition) and the average MinWMT increased by 3.8°C–16.6°C (29% compared to the baseline condition; **Figure 4**). The average MaxWAT didn't change significantly compared to the other two metrics and decreased by only 0.1°C–28.8°C (0.3% compared to the baseline condition) and it was 3.8°C higher than the determined steelhead survival line (**Table 2**). As reported by Smith and Lavis (1975) and Ahmadi-Nedushan et al. (2007), the decrease and increase in the average MaxWMT and MinWMT, respectively, demonstrates that the relative change on water temperature occurs primarily through the associated impact of increase/decrease of the water column depth, which is also connected to the increased/decreased thermal inertia of the river.

Updating the cross-sections in the study area, in addition to increasing the Manning's roughness (Scenario 2), caused an increase of 17 cm in the average flow depth compared to the baseline case (from 26 to 43 cm), and a 20% decrease in the average velocity (from 0.79 m/s cm to 0.63 m/s cm; **Figure 3**; **Supplementary Table S4**). The increase of flow depth starting at

station 7,500 m for the next 1 km was more pronounced by about 40 cm. This increase has the potential to provide thermal refuge for the steelhead or sucker, however, the average MaxWAT in this reach was 28.1°C so we were not able to support this claim. Executing Scenario 2 demonstrated the same pattern of changes in the average MaxWMT and MinWMT that was noted for Scenario 1 (**Table 2**). The difference between the average MaxWMT and MinWMT for Scenario 2 was 12.9°C, which was 37% lower than the same difference for the base case and 11% lower than Scenario 1. A smaller difference between these thermal factors under Scenario 2 indicates that deeper in the water column caused fewer fluctuations in the diel river water temperatures as reported by Gu et al. (1999). The average MaxWMT for Scenario 2 dropped to 30.4°C, demonstrating a 9 and 2.2% decrease compared to the baseline case and Scenario 1, respectively. The average MinWMT for Scenario 2 increased to 17.5°C which was 36.7 and 5.4% higher than the base case and Scenario 1, respectively (see **Figure 4**). The average MaxWAT also was 28.3°C which, even though it was 0.6°C lower than the base case condition similar to Scenario 1, was higher than the considered steelhead survival line (by 3.3°C; **Table 2**).

Under Scenario 3, including groundwater upwelling in the study area, the average MaxWMT and MaxWAT values for the simulation period were 30.1°C and 28°C (**Table 2**). Although

Scenario 3 provided the lowest values for the higher ranges of the determined thermal metrics, they were still higher than the desired temperature range for the steelhead migration and resident sucker (**Figure 4**; **Table 2**). Subsurface inflow temperature and volume parameters are typically sensitive parameters that affect river water temperature significantly (Abdi and Endreny, 2019; Abdi et al., 2020b). By studying the Shasta River tributary in northern California, Nichols et al. (2014) showed that subsurface upwelling inflows could act as reservoir releases to decrease water temperature. Loheide and Gorelick (2006) noted the importance of hyporheic exchange, as an important form of subsurface inflows in Cottonwood Creek in northern California during summer dry weather. They demonstrated that the absence of the subsurface inflows could lead to river temperatures warming in the downstream direction. In winter, Risley et al. (2010) and Kurylyk et al. (2016) documented that groundwater temperature could also contribute a warming effect where the river water temperature is typically below subsurface water temperatures. During the summer, in the LAR, Abdi et al. (2020a) simulated a similar phenomenon of groundwater cooling by redirecting warm surface inflows to infiltration via constructed riffles and pools, which then entered the river as cooler groundwater inflows. These findings indicate how pronounced the subsurface inflows are for reaching determined thermal thresholds for steelhead migration feasibility.

Other studies have demonstrated the impact of flow change on water temperature due to the hydraulics of river flow (Gu et al., 1999; Sinokrat and Gulliver, 2010; Abdi B. et al., 2021). Gu and Li (2002) showed that river water temperature's sensitivity to flow and its properties (in first 20% flow change) is as significant as that to climate data such as air temperature, humidity, and solar radiation. Hockey et al. (1982) studied the variation of water temperature in the Hurunui River in New Zealand and found that for every  $1 \text{ m}^3/\text{s}$  reduction in river flow, water temperature increased by  $0.1^\circ\text{C}$ . Garner et al. (2017) studied a 1,050 m reach of Gironck Burn River basin in east Scotland and found that for the scenarios with low gradient velocities ( $0.023 \text{ m/s}$ ), the water stayed longer within the reach, causing higher maximum and lower minimum temperatures. The findings from Garner et al. (2017) support our results showing the effect of lower water velocities on simulated water temperature due to enhanced heat accumulation and dissipation. However, since we didn't increase the canopy density in our scenarios, we didn't get significant changes in water temperatures (**Figure 2**). Flow velocities in even lower gradients could cause a warming effect in the water temperatures as well, where the residence time would be too high which allows water more time to heat up from solar radiation. Therefore, depending on other factors (riparian shading, upwelling, and inflows), a threshold should be considered for the residence time in the rivers to avoid unwanted warming of the water. Comparing the findings of other studies and our results shows a mixed, sensitive, and uncertain response of water temperature to variation of flow depth and velocity. Therefore, water temperature needs to be considered as a limiting factor based on the results from our

simulations and the overall uncertainty of water temperature's response to changes in depth and velocity.

Ecological restoration scenarios such as riparian shading from tree canopy, cooler substrate temperature (Trimmel et al., 2018; Abdi R. et al., 2021), as well as additional groundwater recharge and hyporheic exchange inflow could be considered to decrease water temperatures (Saha et al., 2017). Sun et al. (2015) simulated river temperature along six separate reaches of Mercer Creek in Washington State and found that tree and hillslope shading reduced the annual maximum temperatures by  $4^\circ\text{C}$ . Further, Dbouk (2017) noted that conductive heat transfer approaches and embedding conduit materials with a high thermal conductivity into substrate materials that have a much lower thermal conductivity could be used to act as cooling channels. For subsurface inflows, as suggested by Abdi and Endreny (2019), the relative contribution of groundwater and hyporheic exchange inflow with river water varies by site conditions and seasonality. For the LAR, Abdi et al. (2020a) showed that an 18% groundwater inflow contribution during dry weather in only a 0.5 km reach decreased LAR water temperature by  $0.3^\circ\text{C}$ . The need for additional restoration actions will only be exacerbated by climate change (Justice et al., 2017; Merriam and Petty, 2019), which is projected to increase river temperatures in the West (Risley et al., 2010; Rheinheimer et al., 2015).

The baseline temperature conditions of the LAR are not cool enough to support the native Santa Ana sucker nor migrating steelhead. The trout have a thermal maxima of  $25^\circ\text{C}$  (Myrick and Cech, 2000; A. Myrick and Cech, 2005) and the sucker's maxima has been observed to be  $22^\circ\text{C}$  (Moyle, 2002). Temperatures at or near the steelhead's maxima have been observed to be a source of chronic stress in other southern California streams, which may make them vulnerable to other poor water quality conditions and physiological stress (Materna, 2001; Dagit et al., 2009). Warm stream temperatures will also block the migration of salmonids, temperatures above  $23^\circ\text{C}$  have prevented steelhead migration in the Northwestern United States (McCullough et al., 2001). The results of our temperature modeling demonstrate that the three restoration scenarios selected for this study do not improve thermal conditions enough in the LAR to support the return of these fishes.

Despite a generally thermally inhospitable environment, thermal refugia can occur in association with cold water patches created from tributaries, groundwater seeps and springs, and shade. Trout have been observed to occupy thermal refugia in streams that exceeded their thermal tolerance where the refugia were  $3\text{--}8^\circ\text{C}$  colder than ambient stream temperatures (Ebersole et al., 2001). Thermal refugia could be present throughout the LAR, providing a reprieve from warm stream temperatures which would allow trout and sucker populations to survive. However, areas for thermal refugia may be limited due to the primarily engineered nature of the channel. The temperature modeling conducted here did not evaluate fine-scale micro-habitats, instead, the stream temperature was modeled on a reach-scale. Our modeling results suggest that overall, the stream temperatures are not hospitable to the steelhead and Santa Ana sucker even in consideration of proposed restoration alternatives. Support of suitable habitat for resident and migratory fish will require

additional measures to ameliorate thermal conditions and allow fish to reach upstream areas with more suitable physical and thermal habitats.

This work may be indicative of other urban rivers, in which restoration alternatives have been proposed to restore physical river parameters but water quality is not explicitly modeled or considered (Wohl et al., 2015). In addition to temperature, cold water fish are sensitive to other pollutants, like metals (Ingersoll and Mebane, 2014; Naddy et al., 2015) and trace organics contaminants (Petrovic et al., 2002), such as those from tire wear (Tian et al., 2021). Water quality stressors, in addition to changing water management regimes and the effects of climate change, should be studied in tandem with optimal hydraulic and temperature parameters for target species. Our work suggests that future studies and management recommendations should consider environmental conditions that are holistically needed to support target species. Further, this work serves as an illustration of the challenge of habitat restoration in urban rivers, given the uncertain climate future.

## 4 CONCLUSION

Like most other urban rivers, the LAR is severely impacted by anthropogenic development and urban activities and since it has been channelized and confined, it suffers from a decline in biological habitat and species diversity. Hydraulic conditions in the LAR channel are not suitable for many of the native fish fauna because of shallow depths and high velocities. Several restoration scenarios have been suggested to provide increased flow complexity and habitat heterogeneity within this confined urban stream, such as increasing the roughness of the channel substrate and redesigning the cross-sectional channel area (USBR, 2019). Restoration scenarios could facilitate the migration of the steelhead in the river, specifically targeting the passage from the Pacific Ocean to the upstream Glendale Narrows soft bottom area and upper tributaries. However, previous work focused on improving the depth and velocity for the fish habitat suitability while the thermal condition of the river in the migration season was overlooked.

Our simulations of the baseline condition showed the river temperature was about 4°C higher than the determined threshold for fishes, therefore river temperature in the migration season would not support sustainable migrating steelhead or resident sucker populations despite suitable water column depths and average velocities. Hence, river temperature should be considered as a limiting factor for habitat suitability in facilitating steelhead migration plans in the LAR. Further, after applying the developed restoration scenarios in the study area, our simulations showed that even though the restoration scenarios decreased the 4°C thermal gap, they were still higher than the desired temperature range for the steelhead migration and the resident Santa Ana sucker (about 3°C after applying three considered scenarios combined). This indicates that additional ecological restoration actions, such as shading, should be considered and applied to further decrease the water temperature in the river passage during the migration season and to support year-round resident native fish such as the Santa Ana sucker.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

Conceptualization, RA, AR, JW, KQ., and KI; methodology, RA and DP; software, RA; validation, RA and JR; formal analysis, RA; investigation, RA, and AR; resources, RA, AR, JW, KQ, and KI, ES; data curation, RA, KQ; writing original draft preparation, RA; writing review and editing, RA, AR, JW, KQ, KI, ES, TH; visualization, RA; supervision, ES, TH; project administration, ES, TH; funding acquisition, ES, TH.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2021.749085/full#supplementary-material>

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