The Influence of Dam-Induced Conditions on the Spatiotemporal Distribution and Size Structure of Rainbow Trout at Lower Putah Creek

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ABSTRACT

Dams exist throughout much of California's watersheds to regulate freshwater resources for various societal functions. Although dams offer a number of benefits to carry out these services, they can act as physical barriers restricting fish dispersal and body development of important salmonids like rainbow trout. Using long-term fish monitoring and stream condition datasets, I investigated how the Putah Diversion Dam and a pivotal management act called the Putah Creek Accord have impacted the spatial distribution and size structure of two rainbow trout populations at lower Putah Creek from 1993 to 2018. I performed linear regressions to estimate the rate at which rainbow trout abundance, body characteristics (fork length and weight), and their corresponding stream conditions (discharge and temperature) have changed over time. I conducted a series of ANOVA tests to determine if site, time period, and stream conditions influenced differences in rainbow trout abundance and body characteristics. I found that the number of rainbow trout at site 1 (upstream) have increased at a 7 times faster rate than at site 2 (downstream). Rainbow trout at site 1 and 2 were significantly larger on average after 2000, but their body characteristics were not statistically different between sites. Stream temperature, rather than discharge, appeared to contribute to significant differences in both rainbow trout populations. I conclude that rainbow trout abundance and body composition has largely improved in more recent years. Findings from this study will help inform future dam operations to best serve societal water needs, while promoting rainbow trout recruitment.

KEYWORDS

abundance, body condition, discharge, salmonid, temperature

INTRODUCTION

In California, dam projects have altered stream networks from connecting to their traditional reaches (Januchowski-Hartley et al. 2013). Streams provide key habitats for aquatic organisms across expansive areas and at different sections with variable microclimates. Prior to dam construction, streams used to extend throughout the central and northern parts of the state with natural flow regimes (Carlisle et al. 2011) forming continuous networks of freshwater habitats (Hanak et al. 2011). Natural flow regimes refer to stream conditions that exhibit heterogeneity in factors like magnitude, frequency, duration, and timing of high and low flows throughout the year (Poff et al. 2007). In dammed sites, flows are often homogenized with minimal variation in these stream conditions because dams largely regulate the release of water to downstream reaches (Poff et al. 2007). With the widespread presence of these structures in stream systems, many people think that dams are normal and essential infrastructure components for society to function. To their credit, dams have certainly provided useful services, including flood mitigation, hydroelectric power, transportation, and supplying water to urban communities (Magilligan and Nislow 2005). The continued expansion of urban development and growing communities have only increased societal water needs (Bunn and Arthington 2002) and have pressured municipalities to maintain dam operations for greater control of California watersheds. However, dams have simultaneously created unintended consequences on freshwater ecosystems and have increasingly threatened the existence of various salmonid fish populations.

California salmonids are increasingly at risk of long-term population declines from dam disturbances. Dams have blocked off key migration routes for anadromous fish species to travel upstream during important times in their life histories (Caudill et al. 2013), with more than 80% of historical spawning areas out of reach throughout the Central Valley (Yoshiyama et al. 1998). Fragmentation of stream connectivity prevents anadromous salmonids from reaching critical spawning and rearing habitats (Quiñones et al. 2015), which limits their ability to expand their population sizes. The altered environmental conditions in dammed streams can have detrimental health effects on salmonid respiratory organs (Newcombe and McDonald 1991) through reduced levels of dissolved oxygen (Stanford et al. 2011). Additionally, dams can cause fine sediment to smother eggs, clog fish habitats, and cluster closer to dams instead of being transported along a more even longitudinal gradient downstream (Kondolf et al. 2014). In the western US, man-made stream barriers have contributed to the decimation of nearly 45% historical habitats for Pacific salmon and rainbow trout (steelhead) populations (Anderson et al. 2014). And in California alone, approximately 83% of native fish species have been directly and indirectly threatened in dammed stream systems (Moyle et al. 2011).

Putah Creek was one of the many California streams chosen for dam construction in the mid-20th century during the heightened development of dam projects. In 1957, the Monticello Dam and the Putah Diversion Dam were constructed in the stream to primarily store water for agriculture and urban use (Marchetti and Moyle 2001). Like many of the freshwater streams subjected to dam projects throughout the state, the Monticello Dam and Putah Diversion Dam have prevented fish populations from traveling to historically accessible upstream habitats. But unlike other dammed stream sites throughout the state, Putah Creek represents a special case for exploring dam impacts on fish populations because the stream experienced a major transformation in improved habitat quality through community restoration efforts and local government actions.

Salmonid fish populations, including Chinook salmon and rainbow trout (steelhead), have historically occupied Putah Creek during wet years when stream conditions provided sufficient flows for migration (Shapovalov 1940, Shapovalov 1947). In early management efforts during the 1970s, pulse flows were released at scheduled times from the bottom of the Putah Diversion Dam in order to provide enough water for human activities such as agriculture, municipal services, and flood control mitigation (Moyle et al. 1998). However, an extreme five-year-long drought from 1987-1991 caused more than 32 km of lower Putah Creek to go dry and resulted in massive fish kills (Moyle et al. 1998). This environmental disaster triggered a lawsuit against the Solano County Water Agency and the Solano County Irrigation District in 2000 to distribute more water to Putah Creek as a way to restore healthy levels of biological activity (Kiernan et al. 2012). Following this lawsuit, the Sacramento Superior Court ultimately authorized a 50% increase in scheduled flows so that water could flow from the Putah Diversion Dam to the opening of the Yolo Bypass continuously throughout the year (Moyle et al. 1998).

Although the Putah Creek Accord was successful at restoring a more natural flow regime (Yarnell et al. 2015) and was associated with an increasing return of adult fall-run Chinook salmon and rainbow trout (Willmes et al. 2021, Jacinto et al. 2023), there is need to further understand the conditions that specifically promote rainbow trout recruitment. Like salmon, rainbow trout have been considered a popular economic fishery (Moyle et al. 2011) for recreational fishing. These salmonids also share similar habitat preferences as salmon, such as living in cold-water habitats less than 22ºC (Moyle et al. 2013) and in stream conditions with high flows like during winter months (Wenger et al. 2011). Under natural conditions, rainbow trout would presumably be able to swim to sites with greater freedom and flexibility to reach their preferred habitats. The reality is that the Putah Diversion Dam has existed at Putah Creek for more than half a century and has substantially altered the stream characteristics with different stages of local intervention over time. Thus, detailing the effects of dam-induced stream conditions on rainbow trout at Putah Creek will help improve management operations of the Putah Diversion Dam that best maximize benefits for societal needs and the fish community structure.

In this study, I explored how the Putah Diversion Dam has influenced the presence and growth of rainbow trout populations throughout lower Putah Creek. Specifically, I asked the following question: In what ways have dam-induced conditions affected the spatial distribution and size structure of rainbow trout below the Putah Diversion Dam? To unpack this question, I investigated (i) how rainbow trout population abundance has changed from 1993 to 2018, (ii) how rainbow trout size structure has changed throughout this time period, and (iii) whether altered stream conditions from the Putah Diversion Dam have promoted rainbow trout recruitment over time. For the first subtopic, I analyzed annual records of rainbow trout fish counts to observe temporal trends in their population sizes at two sites downstream of the Putah Diversion Dam. This facet was important to establish a baseline understanding of whether rainbow trout have increased, decreased, or relatively stabilized in population size from 1993 to 2018. Examining changes in rainbow trout populations at the two downstream sites during this time period was also important because it helped shed light on the Putah Creek Accord's role in restructuring rainbow trout presence at lower Putah Creek. For the second subtopic, I expanded on the abundance investigation and analyzed rainbow trout size structure by looking at changes to their fork lengths and weights at each site. Tracking changes to these body characteristics provided a more nuanced understanding of the Putah Diversion Dam's impacts on rainbow trout because it used these metrics as a way to represent their physical health, rather than simply relying on the number of fish present at each site over time. For the third subtopic, I analyzed changes in annual stream flow and temperature measurements across the same time period. These two stream conditions represented key habitat conditions that influence the presence and health of rainbow trout. Associating these stream factors with the rainbow trout abundance helped reveal the underlying mechanisms driving rainbow trout assemblage below the Putah Diversion Dam, which established better insight of the dam's disturbances on the wider freshwater ecosystem. All of these subtopics worked to address the main investigation of assessing whether the Putah Diversion Dam has promoted or undermined conditions that are conducive to sustaining rainbow trout at ecologically healthy and recreationally viable levels throughout lower Putah Creek.

METHODS

Study area

For this investigation, I selected Putah Creek as the study site because it represents a unique stream system that has undergone significant transformations since the arrival of dam structures. The creek starts from the Mayacamas Mountains as part of the larger Coast Range in the California-Great Basin Region. The creek travels eastward for approximately 130 km until it meets the Monticello Dam and forms Lake Berryessa (Moyle et al. 1998, Marchetti and Moyle 2001, Kiernan et al. 2012). From here, the Monticello Dam releases water that continues to flow eastward for approximately 13 km until it meets the Putah Diversion Dam and forms Lake Solano (Marchetti and Moyle 2001, Kiernan et al. 2012). The Putah Diversion Dam is a 29-foot high gated concrete weir structure designed with an earthfill embankment wing and a crest length of 910 feet (Solano County Water Agency 2015). Below the Putah Diversion Dam, water can be diverted south through the Putah South Canal for municipal and agricultural uses in Solano County (Miner 2022). Alternatively, water can be directed through an approximately 40 km stretch known as lower Putah Creek (Jacinto et al. 2023), which is the focal area of this study (Figure 1).

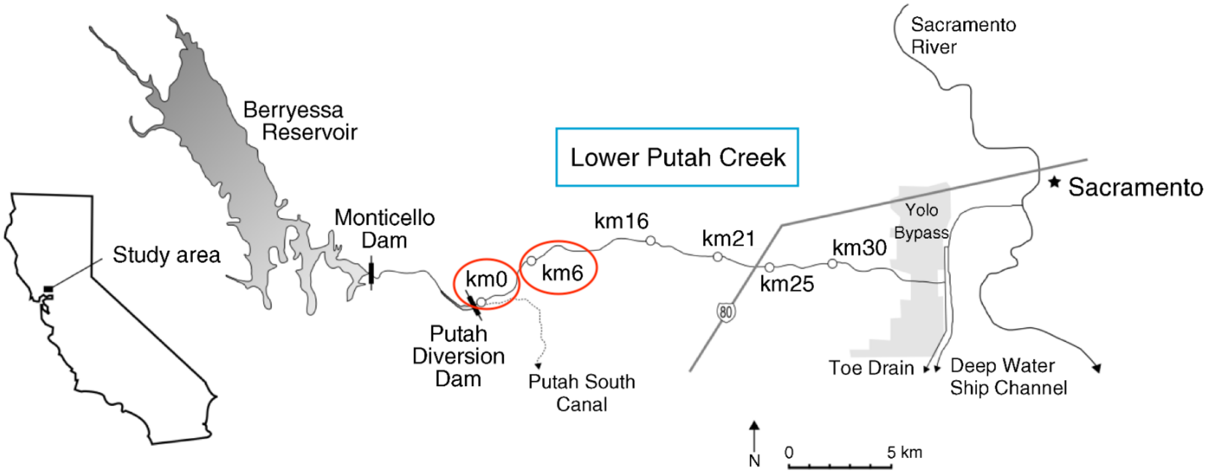

Figure 1. Map of lower Putah Creek, Yolo County, California, USA (Kiernan et al. 2012). The small open circles along the meandering line represent sample sites throughout lower Putah Creek. Sample sites are labeled with their approximate distances downstream of the Putah Diversion Dam. The two sites (km0 ≈ 0.1km, km6 ≈ 6.3km) circled in red represent the areas examined in this study.

Putah Creek has a Mediterranean climate with high flows during the winter and spring season, while it has low base flows during the summer season (Jacinto et al. 2023). Given that lower Putah Creek is situated below the Putah Diversion Dam, the volume and temperature of water it receives depends on the upstream conditions. Years with high precipitation events can cause Lake Berryessa to overflow and contribute to unplanned high flows, but stream flows in lower Putah Creek are more often controlled throughout the year because the Putah Diversion Dam regulates the source of water entering the stream (Kiernan et al. 2012).

There are 6 different sample sites located throughout lower Putah Creek labeled as km0, km6, km16, km21, km25, and km30 to represent their approximate distances downstream from the base of the Putah Diversion Dam (Kiernan et al. 2012). The California Department of Fish and Game owns these site locations, and the Yolo County Parks Department have managed field sampling projects since the 1990s at these public access points. In this study, I only focus on the first two sites (km0 and km6) in order to examine whether there are significant differences in rainbow trout population abundance and size structure between these relatively cooler-water upstream sites (Figure 1). These sites are the only two sampling locations closest to the Putah Diversion Dam with collections of rainbow trout data recorded across multiple years, as well as stream discharge and temperature measurements recorded daily. In addition to the availability of data, focusing on these two upstream sites helps better understand the immediate impacts of the Putah Diversion Dam on rainbow trout abundance and body condition across time because the dam-released water interacts with these two sampling locations first. As the creek progresses further downstream, it eventually flows into the Yolo Bypass floodplain and connects to the wider Sacramento River of the Central Valley region (Kiernan et al. 2012).

Rainbow trout life history characteristics and habitat preferences

California rainbow trout (*Oncorhynchus mykiss*) can tolerate a broad range of environmental stream conditions, but they have certain preferences that best support their growth and survival. One of the reasons that rainbow trout are well-adapted to varied stream conditions is that they can diverge into two subspecies characterized by slight differences in phenotypic behavior and development. Anadromous rainbow trout, otherwise known as steelhead, are one of the rainbow trout subspecies that migrate between freshwater and marine environments (Pavlov and Savvaitova 2008). Resident rainbow trout, on the other hand, are the subspecies of interest in this study that spend their entire life cycle in the same origin spawning ground as their freshwater habitat. Steelhead tend to mature slightly later than resident rainbow trout, at around 2-7 years (Kendall et al. 2015) compared to 1-8 years (Schill et al. 2010). Although resident rainbow trout get an early start to their development at maturation, they are usually smaller than steelhead, at around 100-350 mm compared to 500-1100 mm in body length (Kendall et al. 2015). Despite these subtle differences, both forms of rainbow trout share the life history characteristic of being iteroparous, meaning that they can reproduce multiple times throughout their lifetime (Sogard et al. 2012, Ohms et al. 2014). Both types of rainbow trout typically prefer higher flow velocities because these stream conditions have been associated with enhanced growth and body size (Vondracek and Longanecker 1993, Harvey et al. 2005). Higher flows facilitate the availability of drift prey as a food source (Sogard et al. 2012) because they suspend more stream content throughout the water column, which likely makes foraging easier for rainbow trout. Moreover, both anadromous and resident rainbow trout are generally constrained by the temperature range of 10ºC and 25ºC (Myrick and Cech 2000). Even though both forms of rainbow trout can tolerate conditions within these thermal bounds, they do not perform well as stream temperatures approach these limits. Rainbow trout have exhibited healthy body sizes nearing temperatures around 22ºC, but feeding and overall growth rates declined at temperatures starting at 19ºC (Myrick and Cech 2000). For the most part, rainbow trout at their mature and adult age ranges tend to prefer habitats on the lower end of the thermal spectrum with cooler temperature water (Vondracek and Longanecker 1993), even in situations where dissolved oxygen levels were relatively low (Matthews and Berg 1997).

Table 1. Summary of life history characteristics and habitat preferences for rainbow trout.

Forms of Rainbow Trout	Maturing Environment	Maturing Age Range (years)	Mature Body Size Range (mm)	Stream Temperature Range (ºC)
Steelhead	Marine	2-7	500-1100	10-25
Resident	Freshwater	1-8	100-350	

Data collection

Fish surveys

Every October from 1993 to 2018, two teams of fish biologists from Normandeau Associates and TRPA (Jacinto et al. 2023) sampled rainbow trout fish at the two sites (km0 and km6). Data is missing from both sites in 1995, 2009, 2011, and only site km0 in 2013 because fish sampling did not occur in these areas during these times. To sample the fish, the research teams performed single-pass electrofishing at each site using a SmithRoot model 2.5 Generator Powered Pulsator electrofisher operated from a tote barge (Jacinto et al. 2023). The electrofishing surveys temporarily stunned the fish at different temporal durations ranging from 1222 to 2820 seconds along both the left and right banks of the creek, and at various spatial lengths ranging from 342 m to 622 m. The teams then captured the stunned fish with dip nets, buckets, or placed them into net pens until they recorded their fork length and weight body measurements.

Stream conditions

To monitor stream conditions below the Putah Diversion Dam, the Solano County Water Agency recorded daily discharge measurements from 1975 to 2021 (Baruch et al. 2023). Under the supervision of the US Bureau of Reclamation, the Solano County Water Agency took these measurements using a stream gauge instrument set up at the Putah Diversion Dam to track the values throughout this time period (Jacinto et al. 2023). In addition to observations of flow data, the Solano County Water Agency collected temperature measurements from 1992 to 2019 at each of the two downstream sites. Flow and temperature measurements are key metrics for understanding the habitat suitability for rainbow trout populations because they can only tolerate certain thresholds of these environmental conditions. Examining these parameters and relating them back to the numbers of rainbow trout can further help explain the underlying abiotic factors driving spatiotemporal trends in rainbow trout abundance throughout lower Putah Creek.

Data analysis

Spatiotemporal fish abundance trends

To understand how rainbow trout populations have changed in lower Putah Creek from 1993 to 2018, I compared their annual abundance across the first two sites (km0 = site 1, km6 = site 2) downstream of the Putah Diversion Dam. To start this process, I accessed the fish monitoring dataset for all of the fish species recorded at Putah Creek from 1993 to 2018 (Baruch et al. 2023). Using Excel (Microsoft Corporation 2018), I filtered the list of fish species and selected only the records with rainbow trout since these were the species of interest in this study. Within each year, the dataset had individual entries for every fish because there was supplementary data on other body measurements, including their fork length and weight. To get the total sum of their abundance within each year, I added all of the individual rainbow trout entries and separated them by their respective sites. Next, I created a new table with four columns for year, period, site, and the number of rainbow trout to organize and store all of this newly filtered data. The period column contained entries with either "pre" or "post" labels to indicate the time period in which there were rainbow trout present at each site either before or after the Putah Creek Accord. I assigned entries between the years 1993 and 1999 as "pre" to denote that these records occurred prior to the Putah Creek Accord. Conversely, I assigned entries between the years 2000 and 2018 as "post" to denote that these records occurred after the Putah Creek Accord. I downloaded this table as a csv (comma-separated values) file and exported it into R Studio (R Core Team 2023) to generate a bar chart displaying temporal changes in rainbow trout abundance at each site.

Using the "lm" package in R, I performed linear regressions on the numbers of rainbow trout at each site to estimate the rate at which rainbow trout abundance has changed across the observed time period from 1993 to 2018. Then, I performed a series of analysis of variance (ANOVA) tests using the "aov" package in R to observe the influence of various conditions on patterns of rainbow trout abundance. I first conducted a single-factor ANOVA test only using period as the independent variable to see whether there was a statistically significant difference in the number of rainbow trout in years before and after the Putah Creek Accord. My second single-factor ANOVA test only used site as the independent variable to examine whether there was a statistically significant difference in the number of rainbow trout at site 1 compared to site 2 across the entire time period. Lastly, I conducted a two-factor ANOVA test using both period and site as paired conditions to see whether these combined factors contributed to a statistically significant difference in the two rainbow trout populations at site 1 and site 2 before and after the Putah Creek Accord. For all of these ANOVA tests, I calculated the average number of rainbow trout in every year to compare their annual mean abundance. Given that the fish monitoring dataset had one entry for each fish, the total number of rainbow trout each year also represented their annual average. Thus, I used the sum of rainbow trout from each year as the annual mean abundance when performing these ANOVA tests.

Spatiotemporal fish size structure trends

To understand how rainbow trout size structure has changed in lower Putah Creek, I followed a similar approach as the abundance analysis of showing temporal trends in fork length and weight (Baruch et al. 2023). Using the same fish monitoring database from the abundance analysis, I filtered the years from 1993 to 2018 to stay consistent with the observed time period. I selected only the fork length and weight values from the corresponding fish records to examine changes to these body measurements over time. Then, I created two new tables, each with four columns specifying values for the year, period, site, and size structure characteristics as either fork length or weight. I downloaded these two new tables as csv files and exported them into R Studio to generate four box and whisker plots displaying temporal changes in these body characteristics at each site. For the fork length data visualizations, I created two separate box and whisker plots to show changes in rainbow trout fork length at site 1 and at site 2. For the weight data visualizations, I also generated two separate box and whisker plots to show changes in rainbow trout weight at site 1 and site 2.

Similarly to the abundance analysis, I used the "lm" package to perform linear regressions on both rainbow trout fork length and weight at each site to estimate the rate at which these body characteristics changed across the observed time period. To assess whether there were statistically significant differences in rainbow trout fork length, I ran two different single-factor ANOVA tests. The first single-factor ANOVA test used data from site 1 to test the effects of the period condition influencing differences in annual mean fork length because site 1 had records in years before and after the Putah Creek Accord. I did not use site 2 in this ANOVA test because there were no rainbow trout observed until 2003, meaning there were no fork length measurements before the Putah Creek Accord. However, I used both site 1 and site 2 data to conduct the second single-factor ANOVA test in examining whether there were statistically significant differences in annual mean fork length with respect to site as the condition. I only focused on fork length data in years after the Putah Creek Accord for this ANOVA test because both site 1 and site 2 had fork length measurements after 2003.

To assess whether there were statistically significant differences in rainbow trout weight, I ran two different single-factor ANOVA tests following the same approach as the fork length ANOVA tests. The first single-factor ANOVA test used data from site 1 to test the effects of the period condition influencing differences in annual mean weight because only site 1 had recorded values in years before and after the Putah Creek Accord. However, I used both site 1 and site 2 data to conduct the second single-factor ANOVA test in examining whether there were statistically significant differences in annual mean weight with respect to site as the condition because there were weight measurements at both sample sites after 2003.

Stream flow variations

To examine how stream flow has changed over time, I analyzed a dataset containing daily discharge measurements (Baruch et al. 2023). I trimmed the original length of data entries in Excel so that November 1, 1992 was the start date and October 31, 2018 was the end date. Discharge measurements from November 1, 1992 through December 31, 1992 technically occurred before this study's observed time period between 1993 and 2018. However, I included these values in examining changes to stream flow at lower Putah Creek because they represented flow conditions starting a year before research teams conducted the first fish sampling survey in October 1993. Streams can experience large flow variability throughout a year due to seasonal shifts in weather conditions. Especially in dammed streams, water released from a dam can alter flow patterns and significantly disrupt aquatic and riparian organisms during important stages in their life cycle (Richter and Thomas 2007). Thus, I looked at discharge measurements recorded a year before the first fish sampling survey because these values likely played a role in shaping rainbow trout abundance and size structure at each site by the time research teams sampled fish in October 1993.

Using all of this filtered flow data, I created a table with three columns for date, year, and stream discharge. I downloaded and exported this new table as a csv file into R Studio. The date entries in my table were originally formatted as text characters in the format "MM/DD/YY", so I used the "lubridate" package in R to convert these into numbers and assigned them to a new column. Then, I plotted these new numerical date values with their corresponding discharge values to generate a time series hydrograph across the time period. Using the "lm" package in R, I performed a linear regression on the daily discharge measurements to estimate the rate at which flows have changed between November 1, 1992 and October 31, 2018. Then, I performed a two-factor ANOVA test using both discharge and period as the two conditions to see whether these combined factors contributed to a statistically significant difference in the annual means of the two rainbow trout populations before and after the Putah Creek Accord. For this ANOVA test, I calculated the mean annual discharge values, so I could compare these with the mean annual rainbow trout abundance at site 1. I did not perform an ANOVA test involving site as the condition because the Solano County Water Agency positioned the stream gauge at the Putah Diversion Dam, which recorded discharge measurements that were likely representative of conditions only below the dam at site 1.

Stream temperature variations

To examine how stream temperatures have changed over time, I analyzed a dataset containing daily stream temperature measurements (Baruch et al. 2023). Following the same logic as the discharge measurements, I trimmed the original length of data entries in Excel so that November 1, 1992 was the start date and October 31, 2018 was the end date. Similar to the discharge, I started the temperature analysis a year before the first fish sampling survey because stream temperatures fluctuate inter-annually from changing air temperatures and precipitation events across seasons (Zaidel et al. 2021), which can influence the distribution and development of rainbow trout at each site leading up to the sample date.

Using all of this filtered stream temperature data, I created a table with five columns for date, year, period, site, and temperature. I downloaded and exported this new table as a csv file into R Studio. Unlike the stream discharge analysis, I added the column for site because the Solano County Water Agency recorded stream temperatures at both site 1 and site 2. However, I still used the same “lubridate” package in R to convert the original dates from a text character format to numbers, where I assigned them to a new column. Then, I plotted these numerical date values with their corresponding temperature values to generate a time series graph across the time period. Using the “lm” package in R, I performed a linear regression on the daily temperature measurements to estimate the rate at which temperatures have changed between November 1, 1992 and October 31, 2018. Then, I performed a two-factor ANOVA test using both temperature and period as the two conditions to see whether these combined factors contributed to a statistically significant difference in the annual means of the two rainbow trout populations before and after the Putah Creek Accord. For this ANOVA test, I calculated the mean annual temperature values, so I could compare these with the mean annual rainbow trout abundance at site 2. I did not perform an ANOVA test involving site as the condition because there were large gaps in missing stream temperature data between 2000 to 2017 at site 1. Both site 1 and site 2 recorded stream temperatures before the Putah Creek Accord from the end of 1992 to 2000, but there were no rainbow trout recorded at site 2 until 2003 after the Putah Creek Accord. Hence, I only focused on the stream temperature effects on rainbow trout at site 2 because there was more stream temperature data spanning from 2011 to 2018, as well as recorded observations of rainbow trout.

RESULTS

Spatiotemporal fish abundance analysis

Between the years 1993 and 2018, I found that there were significantly more rainbow trout at site 1 directly below the Putah Diversion Dam compared to site 2 further downstream. Throughout this time period, I found that rainbow trout occupied site 1 in almost every year, except in 2009, 2011, and 2013 when fish sampling did not take place at site 1. On the other hand, site 2 seemed to provide a suitable habitat for rainbow trout only after the Putah Creek Accord between 2003 and 2018, while excluding the years 2009 and 2011 when fish sampling also did not occur at site 2. In the years leading up to the implementation of the Putah Creek Accord in 2000, I observed an upward trend in rainbow trout population abundance at site 1. Rainbow trout reached a maximum count of 94 fish at site 1 in 2002 (Appendix A) a few years after the Putah Creek Accord, until the abundance decreased and oscillated between relatively low and high fish counts all the way through 2018 (Figure 2). Despite reaching low fish count numbers throughout this fluctuating pattern, the rainbow trout abundance at site 1 never matched or fell below the abundance levels at site 2. In all the years that rainbow trout were observed at site 2, the population abundance maintained a relatively consistent level of low fish counts (Figure 2). The missing bars in the years 1995, 2009, 2011, and 2013 for site 1 reflect the times when there were no fish sampling surveys conducted.

From the linear regression analysis, I found that the number of rainbow trout at site 1 increased at a rate approximately 7 times faster than the number of rainbow trout at site 2. Specifically, the rate at which rainbow trout increased at site 1 across this time period was 1.701, whereas the rate at which rainbow trout increased at site 2 was only 0.243. From the ANOVA tests, I found that there were statistically significant differences in the two populations of rainbow trout for all of the conditions I tested. For the first single-factor ANOVA test using period as the condition, I found that there was a statistically significant difference ($p < 0.001$) in both rainbow trout populations during years before and after the Putah Creek Accord. For the second single-factor ANOVA test using site as the condition, I found that there was a statistically significant difference ($p < 0.001$) in both rainbow trout populations between site 1 and site 2. For the last two-factor ANOVA test combining both the period and site conditions to see their interaction effect, I found that there was a statistically significant difference ($p < 0.001$) in both rainbow trout populations resulting from these two factors.

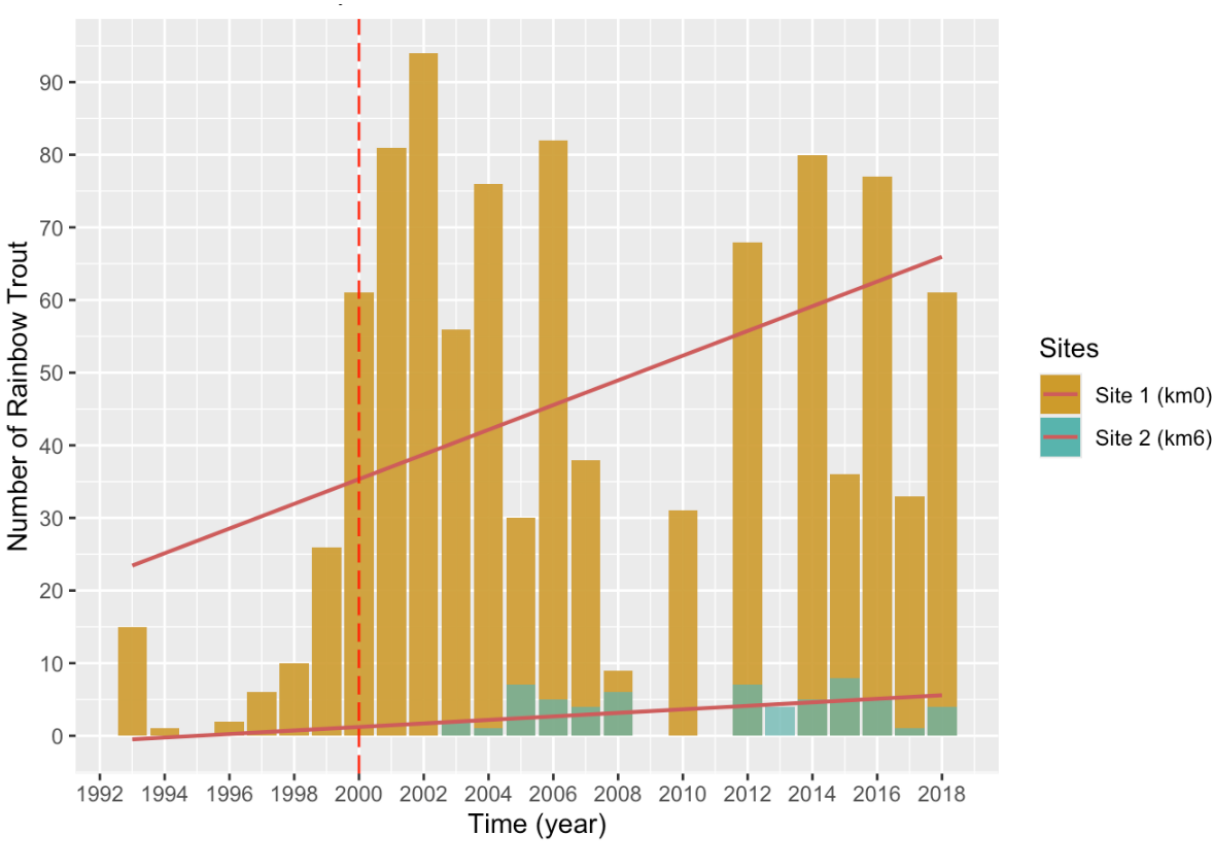

Figure 2. Rainbow trout population abundance at lower Putah Creek. The brown bars represent the number of rainbow trout at site 1 (km0), whereas the teal bars represent the number of rainbow trout at site 2 (km6). The vertical red perforated line intersecting through the year 2000 represents the year of the Putah Creek Accord. The two solid red lines cutting through the bars represent the linear regressions for each site. The steeper regression line represents the rate at which rainbow trout abundance changes at site 1, whereas the flatter regression line represents the rate at which rainbow trout abundance changes at site 2.

Table 3. Summary of rainbow trout abundance statistical test results. Site 1 and site 2 have individual linear regression rates because these models estimated the average expected changes in rainbow trout abundance for each of the two populations. The p-values for the ANOVA tests analyzing period, site, and the interaction between the period and site conditions apply to both site 1 and site 2 because these tests examined how these treatments affected both rainbow trout populations.

	Linear Regression Rates	Period Condition (p-value)	Site Condition (p-value)	Period and Site Interaction Conditions (p-value)
Site 1 Rainbow Trout Population	1.701	2.71e-05	1.79e-11	0.000136
Site 2 Rainbow Trout Population	0.243			

Spatiotemporal fish size structure analysis

Site 1 rainbow trout fork length and weight

Comparing body measurements across this time period, I found that both rainbow trout fork length and weight increased on average at site 1. Specifically, rainbow trout fork length increased at a rate of 0.912 mm per year on average, while rainbow trout weight increased at a rate of 2.867 grams per year on average (Table 4). Prior to the Putah Creek Accord, I observed that there was a marginal decrease in both the values of rainbow trout fork length (Figure 3) and weight (Figure 4) between 1993 to 2000. After the Putah Creek Accord in 2000 and all the way till the end of the fish sampling in 2018, the average values of rainbow trout fork length and weight slightly increased across each year. Rainbow trout fork length and weight measurements appeared to have greater variation in most of the years after the Putah Creek Accord compared to years before the implementation of this management policy. Especially between the more recent years in the observed time period from 2012 to 2018, rainbow trout fork length and weight measurements tended to be higher, where the maximum fork length value was 562 mm and the maximum weight value was 2535 grams in 2012 (Appendix B).

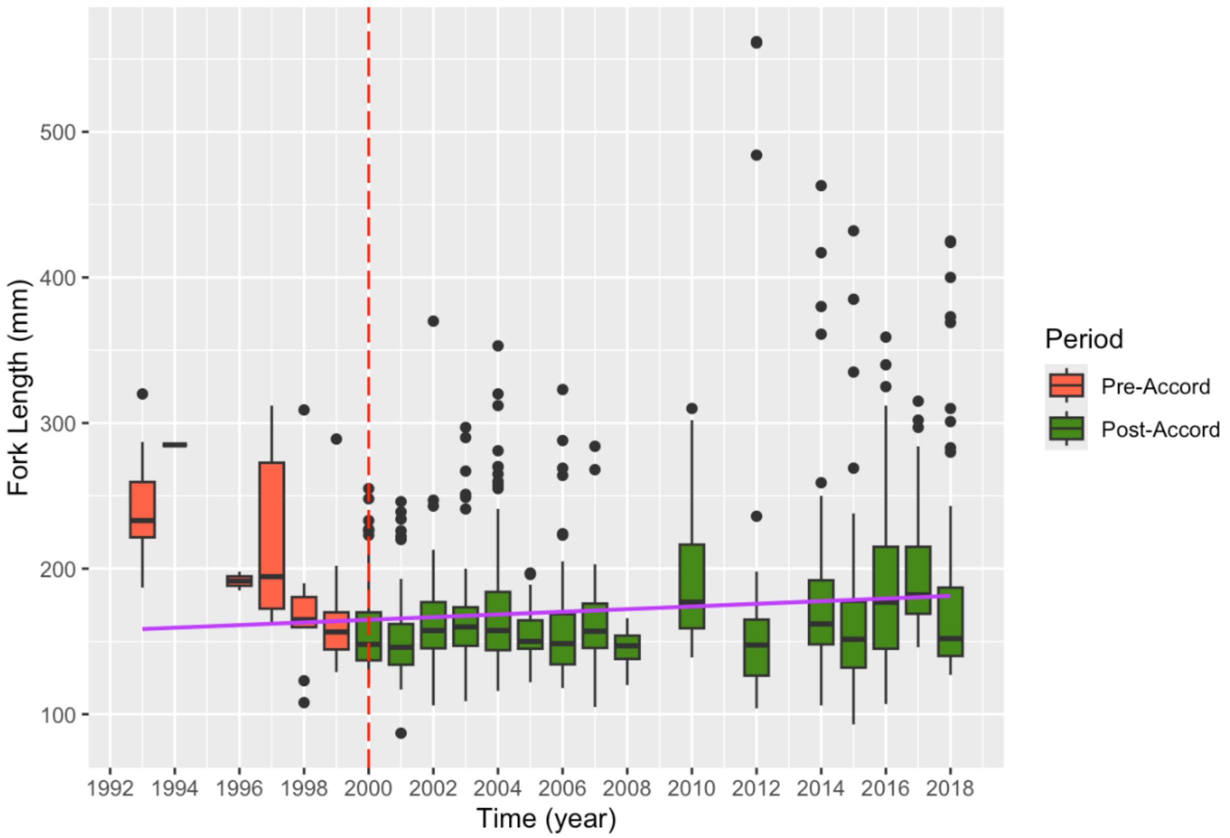

Figure 3. Rainbow trout fork length at site 1. The red boxes represent fork length measurements recorded before the Putah Creek Accord between 1993 to 1999. The green boxes represent fork length measurements recorded after the Putah Creek Accord between 2000 to 2018. The vertical red perforated line intersecting through the year 2000 represents the year of the Putah Creek Accord. The solid purple line cutting through the boxes represents the linear regression estimating the rate of change in rainbow trout fork length over time.

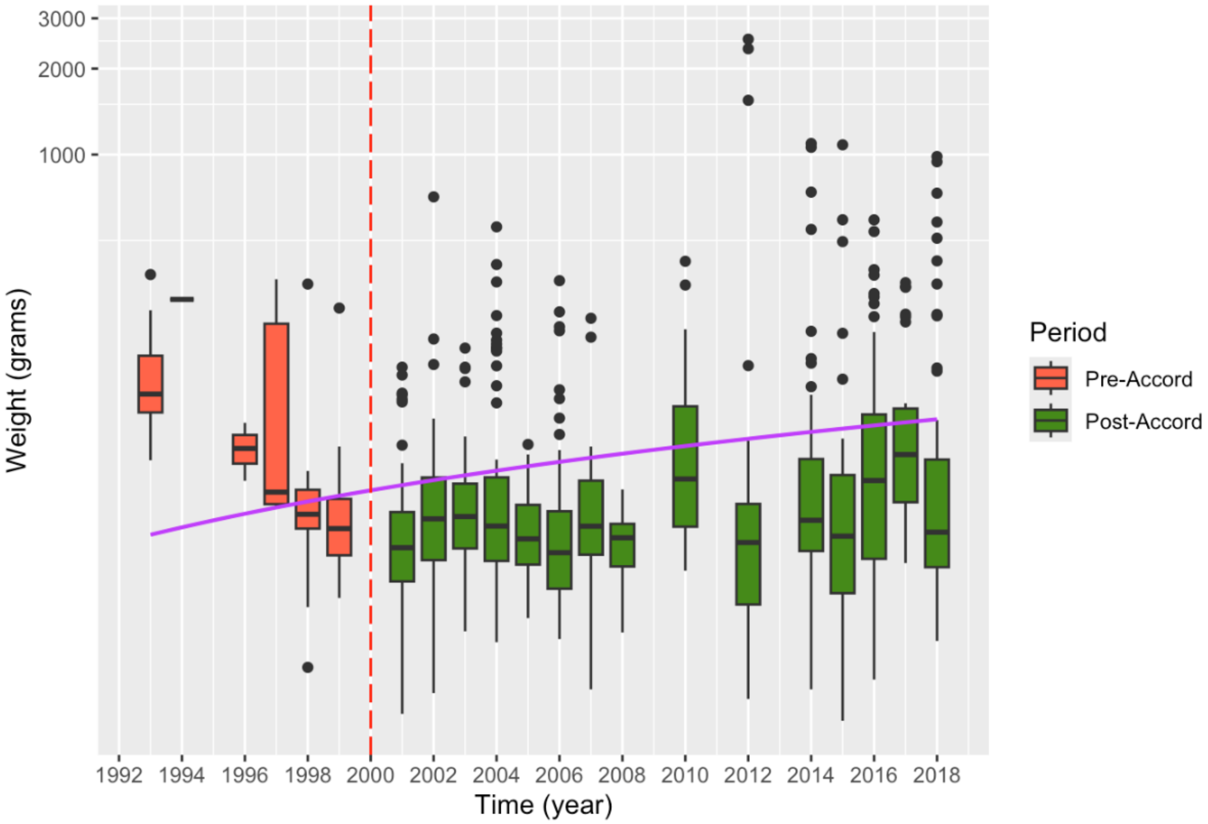

Figure 4. Rainbow trout weight at site 1. The red boxes represent weight measurements recorded before the Putah Creek Accord between 1993 to 1999. The green boxes represent weight measurements recorded after the Putah Creek Accord between 2000 to 2018. The vertical red perforated line intersecting through the year 2000 represents the year of the Putah Creek Accord. The y-axis is log-transformed to better visualize all of the relatively large and small weight measurements. The solid purple line cutting through the boxes represents the linear regression estimating the rate of change in rainbow trout weight over time. The linear regression is slightly curved due to the log transformation on the y-axis fitting the weight measurements.

Site 2 rainbow trout fork length and weight

In contrast to the body condition patterns at site 1, I found that both rainbow trout fork length and weight decreased on average at site 2. More specifically, rainbow trout fork length decreased at a rate of -1.719 mm per year on average, while rainbow trout weight decreased at a rate of -2.608 grams per year on average. Unlike site 1, I only analyzed changes in rainbow trout fork length and weight after the Putah Creek Accord because the fish sampling surveys did not observe rainbow trout at site 2 until 2003. During this post-Accord period, rainbow trout fork length measurements tended to have larger variation (Figure 5) across most of the years compared to weight (Figure 6). Still, rainbow trout body measurements were much smaller than site 1, where the maximum fork length value was 286 mm and the maximum weight value was 321 grams in 2004 (Appendix B). From the ANOVA tests, I found that there were statistically significant differences in the average fork length measurements and the average weight measurements for the rainbow trout population at site 1 across the observed time period. For the first single-factor ANOVA test using period as the condition, I found that there was a statistically significant difference ($p < 0.001$) in average fork length measurements during years before and after the Putah Creek Accord. For the second single-factor ANOVA test also using period as the condition, I found that there was a statistically significant difference ($p < 0.001$) in average weight measurements during years before and after the Putah Creek Accord.

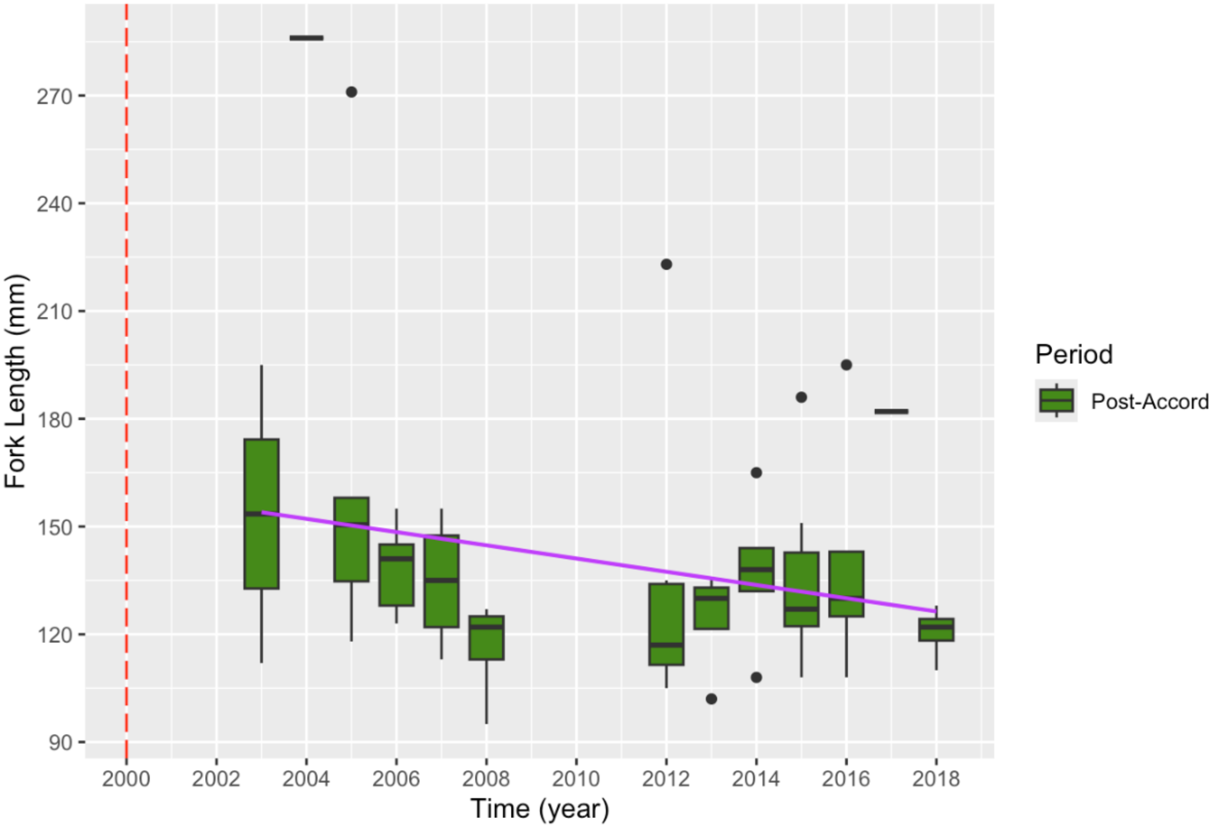

Figure 5. Rainbow trout fork length at site 2. The green boxes represent fork length measurements recorded after the Putah Creek Accord between 2000 to 2018. The vertical red perforated line intersecting through the year 2000 represents the year of the Putah Creek Accord. Fork length measurements only start in 2003 because this is when rainbow trout were first observed at site 2. The solid purple line cutting through the boxes represents the linear regression estimating the rate of change in rainbow trout fork length over time.

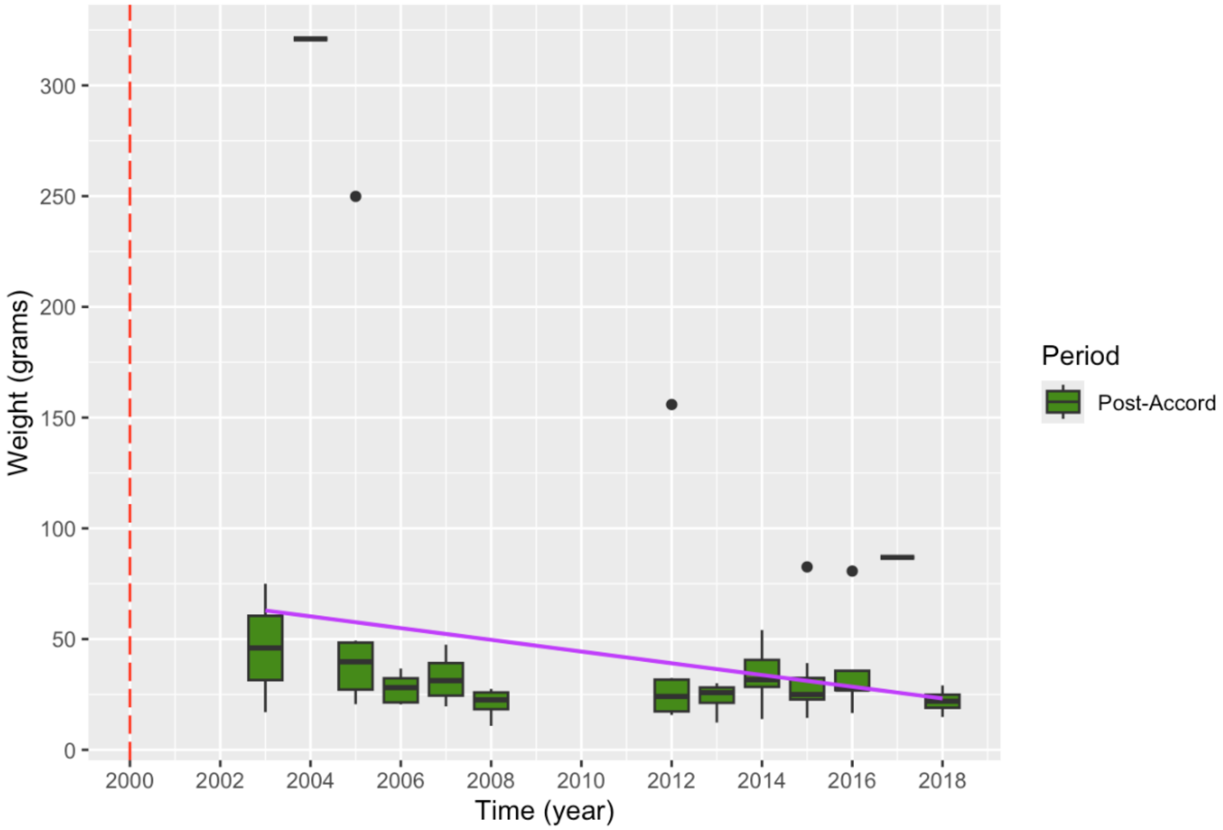

Figure 6. Rainbow trout weight at site 2. The green boxes represent fork length measurements recorded after the Putah Creek Accord between 2000 to 2018. The vertical red perforated line intersecting through the year 2000 represents the year of the Putah Creek Accord. Weight measurements only start in 2003 because this is when rainbow trout were first observed at site 2. The solid purple line cutting through the boxes represents the linear regression estimating the rate of change in rainbow trout weight over time.

Temporal differences in rainbow trout size structure

From the ANOVA tests, I found that there were statistically significant differences in the average fork length measurements and the average weight measurements for the rainbow trout population at site 1 across the observed time period. For the first single-factor ANOVA test using period as the condition, I found that there was a statistically significant difference ($p < 0.001$) in average fork length measurements during years before and after the Putah Creek Accord (Table 4). For the second single-factor ANOVA test also using period as the condition, I found that there was a statistically significant difference ($p = 0.038$) in average weight measurements during years before and after the Putah Creek Accord (Table 4).

Spatial differences in rainbow trout size structure

From the ANOVA tests, I found that there were statistically significant differences in the average fork length measurements and the average weight measurements for rainbow trout populations at site 1 and site 2 during the post-Accord period. For the first single-factor ANOVA test using site as the condition, I found that there was no statistically significant difference (p = 0.117) in average fork length measurements between both rainbow trout populations after the Putah Creek Accord (Table 4). For the second single-factor ANOVA test also using site as the condition, I found that there was no statistically significant difference (p = 0.339) in average weight measurements during years after the Putah Creek Accord (Table 4).

Table 4. Summary of rainbow trout size structure statistical test results. Site 1 and site 2 have individual linear regression rates for fork length and weight measurements because these models estimated the average expected changes in rainbow trout size structure for each of the two populations. The p-values for the ANOVA tests analyzing the period condition only apply to site 1 because this was the only site that had rainbow trout fork length and weight measurements recorded before and after the Putah Creek Accord. ANOVA tests analyzing the period condition could not be applied to site 2 because there were no rainbow trout observed until after the Putah Creek Accord in 2003, meaning there were no fork length or weight measurements sampled from this population to examine the temporal changes across periods. The p-values for the ANOVA tests analyzing the site condition apply to both site 1 and site 2 because these tests examined whether the rainbow trout body characteristics differed significantly when both populations were present after the Putah Creek Accord in 2003.

	Size Structure Body Characteristics	**Linear Regression Rates**	**Period Condition (p-value)**	**Site Condition (p-value)**
Site 1 Rainbow Trout Population	Fork Length (mm)	0.912	0.00389	0.117
Site 2 Rainbow Trout Population	Fork Length (mm)	-1.719	N/A	
Site 1 Rainbow Trout Population	Weight (grams)	2.867	0.0383	0.339
Site 2 Rainbow Trout Population	Weight (grams)	-2.608	N/A	

Stream flow analysis

Discharge measurements at the Putah Diversion Dam had large interannual variation with a slightly negative rate between the end of 1992 to 2018. Based on the linear regression, I found that stream discharge decreased at a rate of -0.018 ft sec^{-1} per year on average. After 1995, stream flow steadily increased to reach peak velocities like 11,485 ft sec^{-1} in 1997 and 11,423 ft sec^{-1} in 1998, before tapering off through 2002 (Figure 7). Stream discharge again started increasing in 2003 with fluctuations of low and high values for the next three years. Stream discharge reached its maximum value of 12,462 ft sec^{-1} in 2006 during the post-Accord period before substantially decreasing at much lower peak values for the next decade (Appendix C). In 2017, stream discharge sharply rose to a maximum value of 9,295 ft sec^{-1} before quickly dropping to low values through 2018 (Figure 7). Despite a marginally small decreasing rate across this time period, I observed that the minimum amount of discharge (base flows) tended to increase in magnitude in the years after the Putah Creek Accord (Figure 7). For the two-factor ANOVA test, I analyzed both the period and discharge conditions to see whether these two factors contributed to a statistically significant difference in the two rainbow trout populations at site 1 and site 2 before and after the Putah Creek Accord. I found that there was no statistically significant difference ($p = 0.548$) in the number of rainbow trout across this time period with respect to stream discharge.

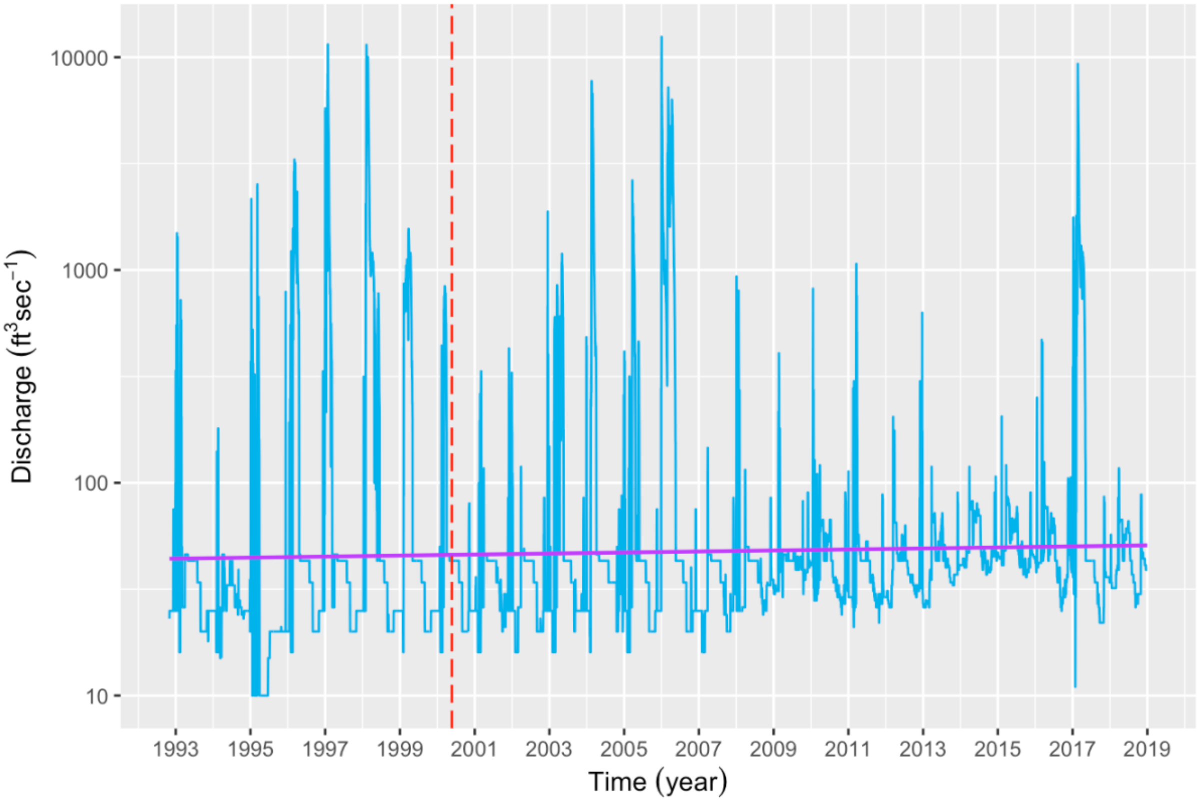

Figure 7. Stream discharge at lower Putah Creek. This time series hydrograph displays daily stream discharge measurements at site 1 from the beginning of November 1992 to the end of October 2018. The vertical red perforated line intersecting through the year 2000 represents the year of the Putah Creek Accord. The y-axis is log-transformed to better visualize all of the relatively large and small discharge measurements. The solid purple line cutting through the boxes represents the linear regression estimating the rate of change in stream discharge over time.

Stream temperature analysis

Stream temperatures at both site 1 and site 2 had large interannual variation, but each site experienced different shifts in thermal conditions over time (Figure 8). For site 1, I found that stream temperature increased at a slightly positive rate of < 0.001 ºC per year on average. On the other hand, I found that stream temperature decreased at a slightly negative rate of < 0 ºC per year on average at site 2. The minimum temperature was approximately 3 ºC at site 1 before the Putah Creek Accord, but the minimum temperature increased to around 9 ºC in 2018 during the post-Accord period (Appendix C) . At site 2, the minimum temperature was approximately 7 ºC before the Putah Creek Accord, but the minimum decreased to around 5 ºC during the post-Accord period (Appendix C). For the two-factor ANOVA test, I analyzed both the period and temperature conditions to see whether these two factors contributed to a statistically significant difference in the two rainbow trout populations at site 1 and site 2 before and after the Putah Creek Accord. I found that there was a statistically significant difference (p = 0.041) in the number of rainbow trout across this time period with respect to stream temperature.

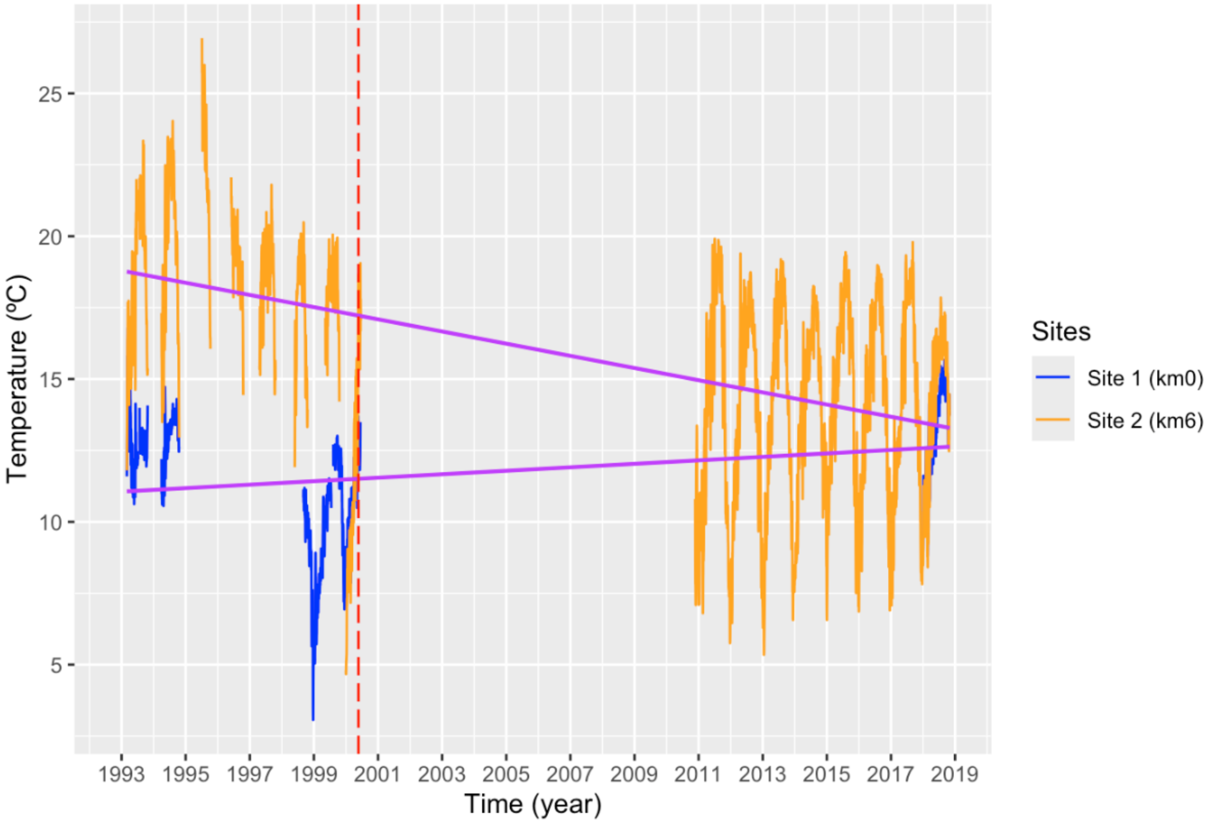

Figure 8. Stream temperature at lower Putah Creek. This time series displays daily stream temperature measurements at site 1 and site 2 from the beginning of November 1992 to the end of October 2018. The blue lines represent stream temperature measurements recorded at site 1. The orange lines represent stream temperature measurements recorded at site 2. The vertical red perforated line intersecting through the year 2000 represents the year of the Putah Creek Accord. The two solid purple lines cutting through the line graphs represent the linear regressions for each site. The upward-sloping regression line represents the marginally increasing rate of stream temperature at site 1, whereas the downward-sloping regression line represents the marginally decreasing rate of stream temperature at site 2.

Table 5. Summary of stream condition statistical test results. Site 1 and site 2 have individual linear regression rates because these models estimated the average expected changes in stream discharge and temperature at each site. Site 2 doesn't have a linear regression for discharge because the stream gauge was located at the Putah Diversion Dam

and most accurately represented the flow at site 1. The p-values for the ANOVA tests analyzing period, site, and the interaction between the period and site conditions apply to both site 1 and site 2 because these tests examined how these treatments affected both rainbow trout populations.

	Stream Conditions	**Linear Regression Rates**	**Period and Discharge Interaction Conditions (p-value)**	**Period and Temperature Interaction Conditions (p-value)**
Site 1 Rainbow Trout Population	Discharge (ft sec^{-1})	-0.018	0.548	N/A
Site 2 Rainbow Trout Population	Discharge (ft sec^{-1})	N/A		
Site 1 Rainbow Trout Population	Temperature (ºC)	0.000166	N/A	0.041
Site 2 Rainbow Trout Population	Temperature (ºC)	-0.000584		

DISCUSSION

Over the course of the observed time period (1993 to 2018), rainbow trout populations exhibited considerable differences between site 1 (directly below the Putah Diversion Dam) and site 2 (further downstream) in terms of abundance and size structure characteristics. Although both rainbow trout populations increased throughout this time period, the number of rainbow trout at site 1 increased at a much faster rate than the number of rainbow trout at site 2. Rainbow trout fork length and weight measurements grew at site 1 over time, while these size structure characteristics shrunk at site 2. Differences in fork length and weight measurements between site 1 and site 2 were not statistically significant, but these size structure characteristics were significantly different across both time periods before and after the Putah Creek Accord. Stream flow and temperature both experienced marginal changes between years in this time period, with each essentially rounding to zero. However, both stream conditions exhibited large fluctuating patterns within each year. Of these two stream conditions, I found that only temperature contributed to statistically significant differences in rainbow trout abundance before and after the Putah Creek Accord. The findings from this suggest that the Putah Creek Accord had mostly positive impacts of restoring and enhancing rainbow trout population abundance and body condition characteristics over time.

Spatiotemporal fish abundance

The number of rainbow trout at site 1 and site 2 both increased on average over time, but each population experienced significantly different rates of change. Rainbow trout at site 1 increased in population size at a 7 times faster rate than rainbow trout at site 2 on average, which suggests that the habitat conditions at site 1 were much more favorable to support a greater number of rainbow trout than at site 2. The positive rate of change continued to increase greatly at site 1 compared to site 2 after the Putah Creek Accord all the way through 2018, which also suggests that the management changes to the stream conditions below the Putah Diversion Dam helped promote higher rainbow trout fish assemblage closer to the dam. I postulate that there were significantly more rainbow trout at site 1 compared to site 2 because the site 1 population experienced the immediate effects of the modified stream conditions from the Putah Creek Accord, thereby allowing them to benefit from the suitable habitat conditions at this location more directly. This finding corroborates a recent study conducted at lower Putah Creek, which found that the number of native fish, including rainbow trout, have increased in abundance at the uppermost sites in years following the Putah Creek Accord (Jacinto et al. 2023). Another recent study also observed the return of adult fall-run Chinook salmon following the Putah Creek Accord (Willmes et al. 2021), which is significant because rainbow trout share similar habitat preferences as salmonids, including colder water habitats (Moyle et al. 2013) and relatively higher stream flows (Wenger et al. 2011). Thus, the statistically significant difference in rainbow trout at each site across both time periods in my study supports past research, which argued that there was a significant increase in native fish assemblage for species like rainbow trout after the instatement of the Putah Creek Accord.

Although I drew similar conclusions as some of the most recent research projects at lower Putah Creek (Willmes et al. 2021, Jacinto et al. 2023), my findings require greater availability and consistency in the fish sampling data in order to more accurately represent changes to rainbow trout population size and spatial distribution. Across the observed time period, there were no fish sampling surveys in 1995, 2009, 2011, and at site 1 in 2013. The lack of fish sampling during these years resulted in several gaps, which limited the linear regression model from more accurately estimating the rate at which rainbow trout populations have changed at each site over time. I treated years without fish sampling as null values in order to exclude them from the linear regression analysis, but knowing the number of rainbow trout at each site during these years could have strengthened the accuracy of the linear regression estimates and provided a more complete representation of changes to rainbow trout abundance throughout this time period. Moreover, fish sampling surveys only occurred every October, which limited the scope of determining the true rainbow trout population size throughout each year. Rainbow trout observations only recorded in one month represent a snapshot of the population size because there can be different numbers of rainbow trout throughout the year depending on their life stages. Thus, having greater consistency in data with a more complete coverage across time will reinforce past research and the findings in my study.

Spatiotemporal fish size structure

Rainbow trout fork length and weight measurements were larger on average at site 1, whereas these body characteristics were smaller on average at site 2 over time. Similar to the abundance observations, the increasing body growth rates at site 1 suggests that the habitat conditions directly below the dam were more suitable to promote rainbow trout physical health. Additionally, the continued increase in both fork length and weight measurements at site 1 after 2000 suggests that the Putah Creek Accord played a role in enhancing these body characteristics. These findings align with the Putah Creek Accord's intention of restoring native fish assemblage below the Putah Diversion Dam with a 50% increase in scheduled flows (Moyle et al. 1998). Past studies have also observed enhanced rainbow trout growth and body size in habitats with higher flows (Vondracek and Longanecker 1993, Harvey et al. 2005), likely due to an increase in drift prey as fast-flowing water moves stream sediment (Sogard et al. 2012). Despite having statistically significant differences across time, these fork length and weight measurements were not significantly different between sites when comparing both rainbow trout populations. Overall fork length and weight measurements increased at site 1 and decreased at site 2, but these changes were not large enough to be considered significantly different. This finding demonstrates that there was no considerable spatial variation in rainbow trout body composition between the two sites after the Putah Creek Accord. One reason for the lack of significant difference in body characteristics at each site could be that the dam-induced conditions from the Putah Creek Accord were not extreme enough to cause major harm to rainbow trout body health further downstream at site 2. A literature review evaluating the impacts of small impoundments on thermal regimes found that dam structures caused no change in downstream temperatures in 73% of their observed studies (Mbaka and Wanjiru Mwaniki 2015). Minimal to no changes in downstream temperatures could be an underlying factor resulting in no significant difference in body measurements for rainbow trout at site 1 and site 2. In any case, rainbow trout fork length and weight still experienced decreasing rates at site 2, which means that other stream conditions other than temperature and discharge are likely shifting growth rates in opposite directions between both sites. I conclude that there was a significant difference in rainbow trout size structure with respect to time period, but there was no significant difference in comparing populations across sites.

The general patterns in fork length and weight suggest that the Putah Creek Accord helped boost rainbow trout body size at site 1 rather than site 2. However, the lack of data in some of the years limited the full accuracy of these findings. All of the body measurement data were contingent on the number of rainbow trout observed during the fish sampling surveys. Years without fish sampling surveys in 1995, 2009, 2011, and at site 1 in 2013 meant that there were no rainbow trout to record body measurements. Similar to the missing values in rainbow trout abundance, I excluded these null values from the linear regression analysis so that only the known body measurements in other years represented changes to rainbow trout size structure over time. However, knowing the fork length and weight measurements of rainbow trout in these years would have strengthened the accuracy of size structure changes at each site. Additionally, there were several weight measurements missing in the years 2000, 2002, 2003, and 2004 at site 1 when fish sampling surveys occurred. The missing weight values during these years means that the linear regression was not fully representative of changes to rainbow trout weight at site 1. Thus, the rates at which rainbow trout fork length and weight changed at both sites over time could be much different than my findings due to the inconsistency in available data.

Another important limitation to consider is the lack of observed rainbow trout at site 2 before the Putah Creek Accord. The statistical results of my ANOVA tests indicated that there were statistically significant differences in rainbow trout fork length and weight across both time periods, but these body characteristics were not significantly different across both sites. The first ANOVA test examining temporal changes to these body characteristics only utilized data from site 1 because this was the only location that had observed records of rainbow trout in years before and after the Putah Creek Accord. The second ANOVA test examining spatial changes to these body characteristics only utilized data from both sites after the Putah Creek Accord because the post-Accord period was the only time when both sites had rainbow trout. The absence of rainbow trout, and hence the absence of their body measurements, during the pre-Accord period at site 2 meant that I could not use site 2 in determining the effect of time period on rainbow trout size structure across the entire time period. The availability of rainbow trout body measurements at site 2 only after the Putah Creek Accord also meant that I could not look at the pre-Accord period in determining the effect of site on rainbow trout size structure across the entire time period. Thus, knowing the fork length and weight measurements of rainbow trout at site 2 before the Putah Creek Accord would have revealed a more representative understanding of the time period and site effects on rainbow trout size structure in my findings. Despite the limitations in the data, I was still able to perform the statistical analysis and determine the spatial and temporal differences in rainbow trout size structure with the available data.

Stream conditions

Stream discharge and temperature did not experience large annual changes on average across the entire time period, but stream temperature was the only stream condition that contributed to a statistically significant difference in rainbow trout abundance over time. The Putah Diversion Dam regulated all of the water released to the downstream sites, which meant that both the discharge and temperature followed prescribed hydrologic patterns. Especially after the 50% increase in scheduled flows from the Putah Creek Accord (Moyle et al. 1998), dam operators strategically managed pulse flows with the goal of restoring native fish assemblage throughout lower Putah Creek (Kiernan et al. 2012). Hence, my findings align with the planned modifications to dam operations, where the overall stream discharge and temperature were managed to stabilize and remain relatively the same across years. The statistical analysis revealed that stream temperature influenced significant differences in the number of rainbow trout before and after the Putah Creek Accord. Given that my analysis on abundance found that rainbow trout increased at a 7 times faster rate at site 1 compared to site 2, I postulate that stream temperature was the dominant factor driving these trends. Higher abundance of rainbow trout at site 1 aligns with past research because this habitat provides cooler temperatures that are optimal for rainbow trout survival, whereas sites further downstream from the Putah Diversion Dam experience warmer temperatures (Jacinto et al. 2023). From this understanding, site 2 likely did not have as much rainbow trout as site 1 because it was 6 km further downstream from the Putah Diversion Dam. Areas further downstream from dam structures can generally have higher temperatures due to other external factors like sunlight and air temperature warming the water as it continues to travel away from the point source. In a study evaluating the impact of 11 dams on the thermal regime across several lowland streams, minimum stream temperatures increased at values greater than 0.5ºC and stream temperatures increased by 1ºC on average in areas downstream from the dam (Chandesris et al. 2019). Still, many studies (Vondracek and Longanecker 1993, Myrick and Cech 2000, Wenger et al. 2011, Moyle et al. 2013) explain how both stream discharge and temperature are critical factors influencing rainbow trout abundance and size structure. Thus, stream discharge should not be disregarded as an insignificant habitat condition.

The results from this analysis yield some insight on stream temperature and discharge relationships with rainbow trout abundance, but they are not fully representative of the true occurrences at lower Putah Creek. For one, all of the daily stream temperature measurements were missing from 2000 to 2010, which limited me to focus only on site 2 in examining the impact of stream temperature on rainbow trout abundance. I could not assess the relationship between stream temperature and rainbow trout abundance at site 1 because there was a paucity of temperature data at site 1 in the post-Accord period, where measurements were recorded only in 2018. The relatively low number of rainbow trout at site 2 compared to site 1 also limited my analysis on assessing the relationship between stream discharge and rainbow trout abundance. Thus, I used the relatively higher number of rainbow trout at site 1 to assess this relationship instead because it coincided better with the discharge measurements. Taking the results from one site and generalizing the findings to the rest of the creek is extremely inaccurate. These findings are largely incomplete from a spatial and temporal standpoint due to the extensive gaps in missing data, which highlights the need for improved monitoring practices to create more consistency in the data records so that other individuals can conduct further statistical analyses. The lack of data for both discharge and temperature measurements undermined my ability to conduct a thorough analysis to determine true associations between rainbow trout abundance and these tested stream conditions. Therefore, dam operators and management officials should still consider both stream temperature and discharge as important determinants for rainbow trout survival since these have affected rainbow trout differently at certain ranges and thresholds. Additionally, examining these results highlights the need to consider other stream conditions and environmental variables throughout lower Putah Creek, such as depth, canopy cover, sediment concentrations, dissolved oxygen levels, and pH values for the water quality.

Future directions

As a whole, my findings contributed to the limited knowledge of the Putah Diversion Dam's impacts on rainbow trout spatial abundance and size structure at lower Putah Creek. My first analysis on rainbow trout abundance concluded that there were higher counts of rainbow trout on average at site 1 compared to site 2, and that the rainbow trout population at site 1 have been increasing at a much faster rate. My second analysis on rainbow trout size structure concluded that rainbow trout fork length and weight were also larger on average at site 1 over time, while both of these body characteristics were smaller on average at site 2. My final analysis exploring the relationship between stream conditions and rainbow trout abundance concluded that only stream temperature contributed to significant changes in the number of rainbow trout over time. All of these results consider the Putah Creek Accord to be a critical factor due to its modification of stream conditions below the Putah Diversion Dam in 2000, but it is equally important to recognize that gaps in the underlying datasets, as well as other unaccounted variables, limit the full understanding of rainbow trout responses to dam conditions at lower Putah Creek.

Based on the current findings from my study, future projects should consider conducting longer-range fish sampling of rainbow trout to provide a more representative scope of fish counts for trend evaluation. Future dam operators should consider maintaining similar stream conditions at site 1 and at other sites further downstream of the dam to promote growth and larger body lengths of rainbow trout all throughout lower Putah Creek. Lastly, projects should investigate the intersections of climate change with respect to dam impacts on rainbow trout population abundance and size structure because climate change will continue to modify landscapes and influence stakeholder decisions of managing water resources, which can present greater challenges for rainbow trout in the near future.

Broader implications

Rainbow trout represent only one of the many fish species in lower Putah Creek. These fish have existed in the creek for many decades as a major resource spurring economic activity through fishing and contributing to the biodiversity in the wider fish community. In addition to rainbow trout, there are other vital native fish species like Chinook salmon that bring similar advantages to lower Putah Creek. Still, many of these fish species have declined as a result of dam activity at lower Putah Creek and throughout California, largely because these structures act as migration barriers to expand population distribution (Willmes et al. 2021, Hitt 2023, Jacinto et al. 2023). This study aimed to address the issue of dam effects on rainbow trout, and the findings showed that the dams can promote both rainbow trout fish abundance and size structure through colder water availability and potentially higher discharge. Other stream systems vary widely in environmental conditions and societal water needs from nearby communities, so these findings might not play out the same as in my study. Thus, the question becomes a matter of assessing trade-offs in prioritizing certain actions concerning both societal desires and ecosystem health. The main takeaway from this study demonstrates that dams have the capability to promote the development of fish that prefer cold water and high discharge, so it is up to local governments, scientists, and community members to collaborate together on coming up with decisions that provide the most benefits to all stakeholders involved in water allocation discussions.

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APPENDIX A: Summarized data of rainbow trout abundance

Table A1. The number of rainbow trout at each site from 1993 to 2018. Rainbow trout sampled between the years 1993 to 1999 represent records before the Putah Creek Accord, whereas rainbow trout sampled between the years 2000 to 2018 represent records after the Putah Creek Accord.

Year	Period	Number of Rainbow Trout at Site 1 (km0)	Number of Rainbow Trout at Site 2 (km6)
1993	pre	15	0
1994	pre	1	0
1995	pre	N/A	N/A
1996	pre	2	0
1997	pre	6	0

1998	pre	10	0
1999	pre	26	0
2000	post	61	0
2001	post	81	0
2002	post	94	0
2003	post	56	2
2004	post	76	1
2005	post	30	7
2006	post	82	5
2007	post	38	4
2008	post	9	6
2009	post	N/A	N/A
2010	post	31	0
2011	post	N/A	N/A
2012	post	68	7
2013	post	N/A	4
2014	post	80	5
2015	post	36	8
2016	post	77	5
2017	post	33	1
2018	post	61	4

APPENDIX B: Summarized data of rainbow trout size structure

Table B1: Descriptive statistics of rainbow trout fork length at site 1.

Year	Site	Period	Fork Length Minimum (mm)	Fork Length Maximum (mm)	Fork Length Mean (mm)	Fork Length Standard Deviation (mm)
1993	site 1	pre	187	320	241.067	35.107
1994	site 1	pre	285	285	285	N/A
1995	site 1	pre	N/A	N/A	N/A	N/A
1996	site 1	pre	185	198	191.5	9.192
1997	site 1	pre	163	312	221.333	65.317

1998	site 1	pre	108	309	173.3	53.895
1999	site 1	pre	129	289	160.962	31.909
2000	site 1	post	121	255	159.066	33.184
2001	site 1	post	87	246	153.815	29.172
2002	site 1	post	106	370	162.67	32.949
2003	site 1	post	109	297	168.018	39.487
2004	site 1	post	116	353	175.132	50.52
2005	site 1	post	122	197	155.233	18.234
2006	site 1	post	118	323	157.89	37.535
2007	site 1	post	105	284	164.079	33.783
2008	site 1	post	120	166	146.556	13.857
2009	site 1	post	N/A	N/A	N/A	N/A
2010	site 1	post	139	310	191.129	45.446
2011	site 1	post	N/A	N/A	N/A	N/A
2012	site 1	post	104	562	163.868	84.62
2013	site 1	post	N/A	N/A	N/A	N/A
2014	site 1	post	106	463	178.55	61.456
2015	site 1	post	93	432	173.333	73.517
2016	site 1	post	107	359	189.948	57.306
2017	site 1	post	146	315	200.909	48.809
2018	site 1	post	127	425	185.311	76.706

Table B2: Descriptive statistics of rainbow trout weight at site 1.

Year	Site	Period	Weight Minimum (grams)	Weight Maximum (grams)	Weight Mean (grams)	Weight Standard Deviation (grams)
1993	site 1	pre	85	380	171.667	77.912
1994	site 1	pre	311	311	311	N/A
1995	site 1	pre	N/A	N/A	N/A	N/A
1996	site 1	pre	72	115	93.5	30.406
1997	site 1	pre	58.1	365.9	155.333	145.358
1998	site 1	pre	N/A	N/A	N/A	N/A
1999	site 1	pre	28	290	59.462	49.72

2000	site 1	post	N/A	N/A	N/A	N/A
2001	site 1	post	11	180	52.099	33.631
2002	site 1	post	N/A	N/A	N/A	N/A
2003	site 1	post	N/A	N/A	N/A	N/A
2004	site 1	post	N/A	N/A	N/A	N/A
2005	site 1	post	23.8	96.6	50.78	19.045
2006	site 1	post	20.1	361.7	58.111	58.201
2007	site 1	post	13.4	267.1	63.371	48.623
2008	site 1	post	21.2	67.2	44.322	13.816
2009	site 1	post	N/A	N/A	N/A	N/A
2010	site 1	post	34.9	422.9	109.765	91.679
2011	site 1	post	N/A	N/A	N/A	N/A
2012	site 1	post	12.4	2535	138.629	444.162
2013	site 1	post	N/A	N/A	N/A	N/A
2014	site 1	post	13.4	1093.3	104.814	186.074
2015	site 1	post	10.4	1081.7	110.728	206.065
2016	site 1	post	14.5	590.7	110.64	115.229
2017	site 1	post	37.1	355.9	121.752	94.836
2018	site 1	post	19.8	984.4	129.072	209.59

Table B3: Descriptive statistics of rainbow trout fork length at site 2.

Year	**Site**	**Period**	**Fork Length Minimum (mm)**	**Fork Length Maximum (mm)**	**Fork Length Mean (mm)**	**Fork Length Standard Deviation (mm)**
2003	site 2	post	112	195	153.5	58.69
2004	site 2	post	286	286	286	N/A
2005	site 2	post	118	271	163.333	54.953
2006	site 2	post	123	155	138.4	12.954
2007	site 2	post	113	155	134.5	19
2008	site 2	post	95	127	117	12.264

2009	site 2	post	N/A	N/A	N/A	N/A
2010	site 2	post	N/A	N/A	N/A	N/A
2011	site 2	post	N/A	N/A	N/A	N/A
2012	site 2	post	105	223	133.714	40.983
2013	site 2	post	102	136	124.5	15.351
2014	site 2	post	108	165	137.4	20.611
2015	site 2	post	108	186	135	24.501
2016	site 2	post	108	195	140.2	33.101
2017	site 2	post	182	182	182	N/A
2018	site 2	post	110	128	120.5	7.594

Table B4: Descriptive statistics of rainbow trout weight at site 2.

Year	**Site**	**Period**	**Weight Minimum (grams)**	**Weight Maximum (grams)**	**Weight Mean (grams)**	**Weight Standard Deviation (grams)**
2003	site 2	post	17	75	46	41.012
2004	site 2	post	321	321	321	N/A
2005	site 2	post	20.6	249.9	70.717	88.494
2006	site 2	post	20.5	36.7	27.8	6.961
2007	site 2	post	19.6	47.5	32.4	12.214
2008	site 2	post	10.8	27.5	21.233	6.324
2009	site 2	post	N/A	N/A	N/A	N/A
2010	site 2	post	N/A	N/A	N/A	N/A
2011	site 2	post	N/A	N/A	N/A	N/A
2012	site 2	post	15.7	155.9	41.971	50.689
2013	site 2	post	12.3	30.1	23.525	7.863
2014	site 2	post	13.9	54.1	33.74	14.899
2015	site 2	post	14.4	82.6	32.55	21.48
2016	site 2	post	16.6	80.7	37.48	25.093
2017	site 2	post	86.9	86.9	86.9	N/A
2018	site 2	post	14.8	29.1	21.95	5.974

APPENDIX C: Summarized data of stream conditions

Table C1: Descriptive statistics of stream discharge at site 1. The values for 1992 do not represent the full year because I only included daily discharge measurements starting on November 1, 1992, which was a full year before the first fish sampling survey in October 1993.

Year	Site	Period	Discharge Minimum (ft sec^{-1})	Discharge Maximum (ft sec^{-1})	Discharge Mean (ft sec^{-1})	Discharge Standard Deviation (ft sec^{-1})
1992	site 1	pre	23	100	30.623	16.89
1993	site 1	pre	16	1489	59.619	134.098
1994	site 1	pre	15	180	28.011	12.022
1995	site 1	pre	10	2527	73.022	261.092
1996	site 1	pre	16	3304	289.831	630.609
1997	site 1	pre	20	11485	494.597	1480.621
1998	site 1	pre	20	11423	818.877	2018.81
1999	site 1	pre	16	1560	227.427	384.51
2000	site 1	post	16	839	83.178	168.472
2001	site 1	post	16	428	42.288	41.717
2002	site 1	post	16	1882	45.249	107.341
2003	site 1	post	16	1191	129.907	234.937
2004	site 1	post	16	7723	363.369	1169.263
2005	site 1	post	16	3058	156.17	406.099
2006	site 1	post	20	12462	969.31	1764.639
2007	site 1	post	16	146	32.915	13.796
2008	site 1	post	24	932	44.951	71.269
2009	site 1	post	29	406	45.137	28.409
2010	site 1	post	24	817	47.351	51.919
2011	site 1	post	21	1068	49.63	81.759
2012	site 1	post	26	630	45.399	41.513
2013	site 1	post	26	119	43.362	14.657
2014	site 1	post	37	119	53.416	15.486
2015	site 1	post	36	205	53.077	16.313
2016	site 1	post	25	470	55.101	48.879
2017	site 1	post	11	9295	455.395	1113.753
2018	site 1	post	26	117	44.332	14.865

Table C2: Descriptive statistics of stream temperature at site 1. The values for 1992 do not represent the full year because I only included daily temperature measurements starting on November 1, 1992, which was a full year before the first fish sampling survey in October 1993.

Year	Site	Period	Temperature Minimum (ºC)	Temperature Maximum (ºC)	Temperature Mean (ºC)	Temperature Standard Deviation (ºC)
1992	site 1	pre	N/A	N/A	N/A	N/A
1993	site 1	pre	10.625	16.785	12.825	1.118
1994	site 1	pre	10.558	14.721	13.028	0.869
1995	site 1	pre	N/A	N/A	N/A	N/A
1996	site 1	pre	N/A	N/A	N/A	N/A
1997	site 1	pre	N/A	N/A	N/A	N/A
1998	site 1	pre	3.066	11.186	8.93	1.894
1999	site 1	pre	5.04	13.01	9.83	2.103
2000	site 1	post	7.075	13.696	10.797	1.529
2001	site 1	post	N/A	N/A	N/A	N/A
2002	site 1	post	N/A	N/A	N/A	N/A
2003	site 1	post	N/A	N/A	N/A	N/A
2004	site 1	post	N/A	N/A	N/A	N/A
2005	site 1	post	N/A	N/A	N/A	N/A
2006	site 1	post	N/A	N/A	N/A	N/A
2007	site 1	post	N/A	N/A	N/A	N/A
2008	site 1	post	N/A	N/A	N/A	N/A
2009	site 1	post	N/A	N/A	N/A	N/A
2010	site 1	post	N/A	N/A	N/A	N/A
2011	site 1	post	N/A	N/A	N/A	N/A
2012	site 1	post	N/A	N/A	N/A	N/A
2013	site 1	post	N/A	N/A	N/A	N/A
2014	site 1	post	N/A	N/A	N/A	N/A
2015	site 1	post	N/A	N/A	N/A	N/A
2016	site 1	post	N/A	N/A	N/A	N/A
2017	site 1	post	N/A	N/A	N/A	N/A
2018	site 1	post	8.817	15.662	13.278	1.713

Table C3: Descriptive statistics of stream temperature at site 2. The values for 1992 do not represent the full year because I only included daily temperature measurements starting on November 1, 1992, which was a full year before the first fish sampling survey in October 1993.

Year	**Site**	**Period**	**Temperature Minimum (ºC)**	**Temperature Maximum (ºC)**	**Temperature Mean (ºC)**	**Temperature Standard Deviation (ºC)**
1992	site 2	pre	N/A	N/A	N/A	N/A
1993	site 2	pre	11.8	23.34	18.393	2.467
1994	site 2	pre	12.95	24.033	19.933	2.724
1995	site 2	pre	16.058	26.935	22.348	2.445
1996	site 2	pre	14.439	22.062	19.24	1.205
1997	site 2	pre	14.469	21.798	18.583	1.529
1998	site 2	pre	11.914	20.486	17.506	1.998
1999	site 2	pre	14.211	20.053	18.169	1.12
2000	site 2	post	4.671	19.058	11.603	3.682
2001	site 2	post	N/A	N/A	N/A	N/A
2002	site 2	post	N/A	N/A	N/A	N/A
2003	site 2	post	N/A	N/A	N/A	N/A
2004	site 2	post	N/A	N/A	N/A	N/A
2005	site 2	post	N/A	N/A	N/A	N/A
2006	site 2	post	N/A	N/A	N/A	N/A
2007	site 2	post	N/A	N/A	N/A	N/A
2008	site 2	post	N/A	N/A	N/A	N/A
2009	site 2	post	N/A	N/A	N/A	N/A
2010	site 2	post	7.091	13.366	10.294	1.749
2011	site 2	post	5.754	19.909	14.034	4.059
2012	site 2	post	6.458	19.393	14.058	3.349
2013	site 2	post	5.346	19.192	13.721	3.774
2014	site 2	post	7.1	18.254	14.211	2.751
2015	site 2	post	6.567	19.442	14.677	3.199
2016	site 2	post	6.862	18.988	14.402	3.142
2017	site 2	post	7.075	19.792	14.028	3.466
2018	site 2	post	8.412	17.85	14.185	2.455