Title

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ABSTRACT

The San Clemente Dam on the Carmel River was removed in 2015 . We analyzed the grain size distribution changes on the river on one site upstream and six sites downstream of the damsite, as part of an ongoing study monitoring a total of 10 sites since 2013 (East et al., 2023). Trends from this data indicate that the geomorphic changes observed downstream of the dam are predominantly dependent on high flows. This study contributes to field data collection and analyzes fresh pebble count data for 2023 from one control reach above the dam removal and six reaches downstream of the removal. Given that the Carmel River had a peak flow of 11,000 CFS during the 2022-2023 winter, pebble counts from 2023 offer the opportunity to continue studying the stream system's geomorphic response to high flows. To study spawning gravel availability, we applied the criteria of Smith et al (2021), who used grains within 32mm and 90mm to study spawning gravel abundance, then calculated the average percent of spawning gravel at each reach. We used the same analysis method to assess changes in fines and cobbles, where in this study cobbles are more accurately the grains that are too large to be productive spawning gravel according to Smith et al. (2021)'s analysis. Fines are classified as grains less than 2mm from Wentworth (1922) and cobbles as sediment greater than 64 mm. However, for the purpose of this study, we have considered cobbles as grain sizes too large to contribute to the spawning gravel range of 32mm to 90 mm according to Smith et al. (2021). Therefore, we have calculated cobbles as greater than 90mm, but acknowledge that cobbles are defined as sediment greater than 64mm by Wentworth (1922). Downstream of the dam, the average percent spawning gravel increased in four of the six reaches, average percent fines decreased for four of the six reaches, and average percent cobble increased in two reaches, decreased in the three, and showed no

change in two reaches. At the control reach site, the percent spawning gravel decreased slightly, the percent fines decreased, and the percent cobble increased significantly. We found that the high flows of the past year coincided with an average increase in sediment size across reaches downstream of the dam. While percent spawning gravel increased, we were not confident in drawing conclusions about the effect of this year's high flows on spawning gravel.

INTRODUCTION

THE STORY OF THE SAN CLEMENTE DAM REMOVAL

The San Clemente Dam was located 18 miles upstream of the ocean on the Carmel River in California. This 32m high, nearly 100 year old dam was removed in 2015 due to concerns about its seismic stability. As of 2013, the reservoir had lost 95% of its capacity to sediment deposition. It was no longer serving its original purpose of supplying water to the Monterey Peninsula area (PCMSC, n.d.).

The owner of the dam, California American Water Company (Cal-Am) was responsible for the upkeep of the dam, and was required by the California Public Utilities Commission (PUC) to implement the cheapest option for solving the seismic issue, for which the initial proposal was to buttress the dam. When scientists in the NOAA Fisheries office in Santa Rosa, CA, reviewed the environmental impact report generated by Cal-Am, they proposed that dam removal be seriously considered as an option because of the opportunity to improve steelhead habitat (NOAA Fisheries, 2016).

A principal concern with dam removal is the fate of the decades worth of sediment trapped behind the dam. If the dam is simply removed, the stored sediment can be transported downstream and deposited in the downstream channel, thereby reducing the capacity of the channel to convey floods and increasing flood risk to downstream developments. To avoid increasing downstream flood risk, the 1.7 million cubic meters of sediment behind the dam would have to be removed from the reservoir before the dam was taken down (Pacific Coastal and Marine Science Center). Many options for that removal were considered but all of those strategies proved were significantly more costly than buttressing the dam. But Don Lingenfelter, the dam keeper at the time, proposed a novel method that would circumvent the need for removing the sediment (NOAA Fisheries, 2016).

Instead of removing the sediment, the Carmel River was rerouted through San Clemente Creek and around the sediment deposit, which required cutting a channel through the ridge separating the river from its tributary San Clemente Creek (**Figure 1**). The sediment deposit was stabilized at both the upstream and downstream ends with the dam still in place. With the sediment stabilized, the dam could be removed safely. This strategy reduced the risk of flooding and the geomorphic volatility associated with large sediment pulses (East et. al 2021). The removal of the dam promised increased range for the dwindling steelhead populations native to the Carmel River and a number of other ecological benefits. The project was still $36 million more expensive than buttressing the dam, but because of the benefits to steelhead habitat associated with dam removal, NOAA Fisheries partnered with the California Coastal Conservancy to raise the additional funds. Through this partnership between government agencies and the private water company, the additional costs of dam removal over that of buttressing the dam could be funded (NOAA Fisheries, 2016).

In 2013, construction of the reroute began and in November of 2015, the dam removal was complete, opening up 6.8 miles of additional habitat for steelhead, lamprey and the California red legged frog while also side-stepping the flood risk posed by the sediment deposit behind the dam, and ending concerns about the dam’s seismic integrity permanently (East et al., 2023). The dam removal provides a rare opportunity to study the geomorphic changes to the river brought on by such a drastic change to the fluvial system below the former dam site as a whole.

STUDYING THE GEOMORPHIC EFFECTS OF DAM REMOVAL

Geomorphic responses to dam removals are not well understood. While there have been over 2,003 dam removals in the U.S. (American Rivers Dam Removal Database, 2023) **(Figure 2)**, under 10% have been accompanied by long-term studies (East et al., 2023). While California is home to a large number of removals, these removals have a disproportionately small number of associated monitoring efforts **(Figure 3)** (Bellmore et al., 2017). This dearth of information highlights the importance of the long-term studies associated with the San Clemente Dam. The San Clemente Dam is the second largest dam removal in U.S. history, and one of only two large dam removals with an associated Before-After-Control-Impact (BACI) study.

Harrison et al. (2018) used a BACI study design to document sedimentary and geomorphic changes in the Carmel River between 2013 and 2017 where nine impact sites downstream and a control site upstream of the San Clemente Dam were established (**Figure 4)**, with six cross-sections per reach. Harrison et al. (2018) surveyed the bed-sediment grain size via a quadrat and slag line method over this time period. This sediment information was then compared against the ideal spawning-habitat as predicted by Kondolf and Wolman (1993). Additionally, Harrison et al. (2018) used aerial photography to map planform changes before and after the dam removal.

The BACI study was extended by another four years where East et al. (2023) continued documenting fluvial response from 2018 to 2021. Topography measurements were recorded with total-station and auto-level surveys at 10 reaches **(Figure 4)** with 4 to 6 cross sections per reach. Additionally, pebble counts were conducted via Wollman pebble counts (Wolman, 1954) along nine reaches to measure bed-sediment grain size. However, the East et al. (2023) study did not compare spawning habitat against grain size. Smith et al. (2021)

defined spawning gravel abundance as grains within 32mm to 90mm and calculated averages from 2013 to 2021 using the pebble count data from the BACI studies (Harrison et al., 2018; East et al., 2023).

The goal of our study is to build off of the Smith et al. (2021) study by analyzing changes in grain size after the high flow year on the Carmel River. We contributed to this year's data collection by conducting a field study of the bed-sediment grain size with pebble counts along the DM reach. There are pebble counts for 2023 from six out of the nine study reaches (CR, DM, SR, BW, DDL, and DDU).

Geomorphic change downstream of the former dam site occurs primarily during high flow events (Harrison et. al 2018; East et al. 2021). The winter of 2023 was particularly wet due to atmospheric river events, and flows on the river peaked above 11,000 CFS (**Figure 5**). In October of 2021 there was a single high flow event of 1,250 CFS (**Figure 5)** and no pebble count data was collected for this year. We estimated that roughly eight events of equivalent or greater discharge to the October 2021 event occurred in water year (WY) 2023(**Figure 6**). However, given this limitation we cannot distinguish the effects of multiple and prolonged high flow events of WY 2023 with the single intense flow that occurred in October 2021. The roughly 40-year peak flow in WY 2023 was the second time in the course of the BACI study when flows of this magnitude affected the study area (Smith et al. 2021) so we seized the opportunity to study the changes in coverage of the river bed since 2021 across three categories: potential steelhead spawning gravels, fine sediment, and cobbles. We also contextualize our findings at the DM reach within the greater scope of the new pebble count data collected this year at other reaches in the study area, as well as the historical data from 2013 to present.

METHODS

FIELD DATA COLLECTION

We took a pebble count at each of the six cross sections of a reach known within the long-term BACI study of the river as DM. We performed our counts according to the Wolman (1954) style used by East et. al (2023) and Harrison et al. (2018). DM is located immediately downstream of the dam site as shown in **Figure 4**. To locate the pins we used a handheld GPS to approximate the location and searched for the rebar or flagging from the previous year. In situations where we could not find flagging or rebar on one side or the other, we used the recorded length and azimuth of the previous year's cross sections to determine the appropriate placement of our slag line/measuring tape. We divided the bankfull width into five equal quantiles and took 20 samples of the surficial sediment facies using a 0.5m by 0.5m quadrat at each of the five points we calculated between the pins, resulting in 100 samples per section.

While we were on the river, we also observed evidence of some recent debris flows, which appeared to have recently delivered sediment to the river. We used satellite imagery from Google Earth to locate one major debris flow just above the former dam and soil maps from the USDA Soil Survey website for contributing to the total spawning gravel available to the DM reach (**Figures 7** and **8**). Smith et. al 2021 suggests that 45% of the gravels in debris flows in this area are between 32mm to 90mm.

DATA ANALYSIS

We followed the precedents set by Smith et. al (2021) in our analysis of spawning gravel. We summed our results into three macro groups: fines (all samples with a B-axis diameter below 2mm), spawning gravel (32mm to 90mm) and cobbles, which we defined as everything larger than 90mm. We defined the spawning gravel range not to imply that this is the range of grain sizes that Carmel River steelhead use to spawn, but to follow Smith et al. (2021) in trying to analyse an appropriate range of grain sizes that may allow us to assess spawning gravel abundance. While Wentworth (1922) defines cobbles as grains between 64 and 256mm, we define cobbles as 90mm to assess grains which are too large to be considered in an analysis of spawning gravel abundance according to Smith et al. (2021)'s range of 32 to 90mm.

We averaged the amount of fines, steelhead gravel, and cobbles over each reach using historic data provided by East et al. (2023) with 2023 pebble counts for the CR, DDU, DDL, BW, SR, and CRO from Professor James Guilinger (CSUMB) and our counts for the DM reach. We then compared the changes over time to the flow data provided by the USGS gauge at Robles Del Rio.

We compared the steelhead population trends to the trends in redd-building gravel availability to determine whether the declining steelhead population could be correlated to spawning gravel quality. This dam removal was predicated in part on the expectation that the extent of gravel suitably sized for spawning might increase in the Carmel River as a result of reconnecting the lower river with its watershed (NOAA, 2016), so extent of potential spawning gravel could be used as a metric of project success. Smith et al. (2021) has observed that spawning gravel availability has not increased post dam removal. We extended that analysis incrementally into 2023.

RESULTS

SPAWNING GRAVEL

According to our first analysis in the style of Smith et. al (2021), the average spawning gravel over each of the six cross sections at the DM reach has increased since last year from 8% to 16% spawning gravel (**Figure 9**). With the exception of the most upstream cross section (DM1), each cross section increased in percent spawning gravel by 8% to 17% from 2021 to 2023 (**Figure 10**).

A majority of sites with 2023 pebble count data below the dam are on a similar trend. Sites DDL, DDU, and BW increased by roughly 5% in percent of spawning gravel since 2021. Sites SR and CRO have decreased by roughly 5% in percent spawning gravel from 2021 to 2023 (**Figure 11)**. Our 2023 data shows that average percent spawning gravel at the control reach (CR) and the average of reaches below the dam is nearly equivalent (**Figure 12**).

FINES

The average fines over each of the six cross sections at the DM reach has experienced little change between 2021 and 2023, with respective averages of 15% and 16% (**Figure 13**). DM4 and DM6 had higher percent fines this year at around 30%, whereas DM1, DM2, DM3, and DM5 had roughly 10% fines (**Figure 14**).

Sites CR, DDU, BW, SR, and CRO decreased in average percent fines from 2021 to 2023 and DDL increased (**Figure 15**). In 2023, we found CR to have 17% fines and the average of the reaches below the dam to have 32% fines (**Figure 16**). The percent fines at CR dropped by 15% from 2021 to 2023 while the average of the reaches below the dam dropped by 8%.

COBBLE

The percent cobble at the DM reach has decreased from 67% to 57% from 2021 to 2023 (**Figure 17)**. DM1, DM2, DM4, and DM6 decreased in percent cobble and DM3 and DM5 stayed the same (**Figure 18**).

The CR and DDU reaches increased in average percent cobble, the DM, DDL, and SR reaches decreased, and the CRO and BW reaches remained relatively steady (**Figure 19)**.. The percent cobble at CR jumped from 25% to 56% between 2021 and 2023 (**Figure 20**). The average percent of cobble at the reaches below the dam went from 22% to 17%.

DISCUSSION

The DM reach is a coarse grained, “armored” cobble/boulder bed, with the exception of DM4, which is a sandy pool. Fines pass quickly through these rough reaches during high flows and tend to deposit at slower moving, shallower grade reaches (Smith et al., 2021). Our analysis of the 2023 winter peak flows against the level of fines (**Figure 13)** shows little variance in fines at DM since 2017. The overall effect of the 2022-2023 flows on fines at all reaches downstream of the dam was a net decrease from 2021 (**Figure 16**). We cannot distinguish the effects of the multiple and prolonged high flows of WY 2023 from the effects of the short but intense high flow in Oct 2021. However, given the geomorphic characteristics of the Carmel River being primarily responsive to flows (East et. al 2023; Harrison et. al 2018), and that there were roughly eight flows in WY 2023 that were greater than the single high flow of October 2021 (**Figure 6**), it is possible that grain size distributions were not drastically different from 2021 to 2022.

We found that the spawning gravel available in 2023 at the DM reach was similar to levels recorded during the 2020 pebble count and increased by 8% compared to 2021. That slight increase makes DM somewhat unique within the study area. The DDU reach is the only other reach where spawning gravel has increased since dam removal. At DM, this could be due to a number of factors.

The Carmel River experienced a 40-year flow over the past winter as a result of atmospheric river precipitation events. Slope failure is likely around that area given the soil types in the valley. When precipitation spikes above 24mm/hr for a 15 minute interval, most of these slopes have a predictable failure probability between 20-50% (Smith, 2021). The steep slopes and composition of the soils on those slopes makes it very likely that salmon gravels that were recruited into DM came from debris flows into the Carmel River at some point above the dam. Our analysis of satellite imagery over the course of the last 8 years revealed that the slope just on the other side of the former dam site has failed more than once since dam removal. USDA web soil survey data tells us that the east bank of the river at the dam site consists mainly of Junipero Sur Complex, Xerorthents Rock Outcrop, and Cieneba sandy, gravelly loam (USDA, 2023). All of these soils have the potential to contribute 32 to 90mm gravels, and a cursory visual analysis of that debris flow shows that it certainly contains those diameters in abundance, but the snout of the flow does not reach the main channel of the river. Thus, high flows would be necessary, but possibly not sufficient, to recruit those gravels into the channel. Further analysis is necessary to determine if this source contributed to last winter's aggradation of salmon gravels.

Our analysis of flow peaks versus salmonid gravels at DM were inconclusive. While in 2017, the bedload responded to the greater than 11,000 CFS flows with drastic reduction of fines, slight reduction in spawning gravels, and increase in cobbles, we cannot say definitively whether this pattern was repeated over the winter of 2023 without data from 2022 (**Figure 21**). However, DM does respond differently than the rest of the study area to high flooding historically. The high flows in 2017 created a sediment pulse that increased the average fines across the entire study area including the control reach (CR). DM, however, decreased in average fines. This could be a result of a documented effect wherein fines pass quickly and easily through highly cobbled reaches during high flows (Sklar et al., 2009).

Assuming that grain size didn't change dramatically in 2022, the high flows of water year 2023 did not seem to have the same effect on grain size as the 2021 water year where there were high flows following a fire in the basin. Results for pebble counts in 2023 indicate that high flows seemed to have flushed out some of the finer material on average. Spawning gravel averages increased, and trends in percent cobble since 2021 are not very uniform throughout the reaches. This begs the question, do fires and high flows produce more fine-grained sediment versus years with only high flows where spawning gravel increased, but fines decreased? While we are unable to answer this question with the data we have, the increase in spawning gravel at the upstream reaches supports the hypothesis by Smith et al. (2021) that the system may have a lagged recovery of sediment suitably sized for salmonid spawning.

Regardless of the slight trend in spawning gravel, the steelhead populations are still on a worrisome decline in the Carmel River (**Figure 22)**. Smith et al. (2021) states that lack of spawning gravel is thought to be the major limiting factor for steelhead in this system. The 2023 data show promise that spawning gravel may be increasing, but the steady decrease of spawning gravel prior to this year has coincided with a declining steelhead population on the Carmel River.

LIMITATIONS

We recognize that the methods for quantifying spawning gravel set forth by Smith (2021), while providing a reproducible approach for repeat measurements (even by different operators over time), may not directly characterize the gravel sizes most relevant to spawning according to the criteria drawn from a wide literature review by Kondolf and Wolman (1993). Spawning gravel sizes for steelhead trout vary from population to population. Without data on gravel sizes actually used by Carmel River steelhead, it is difficult to confirm if the size range of 32-90mm accurately reflects the size of potential spawning gravels that would be used by these fish. Furthermore, the Smith et al. (2021) method uses simple averaging to quantify spawning gravel coverage, whereas Harrison et al. (2018) and Kondolf (2000) use geometric mean to assess spawning gravel quality.

The methods we used sum all pebble counts from both pools and riffles into one average. Traditionally spawning gravel counts are collected from riffles only (Harrison, 2018), and pebble counts are conducted on individual facies only, not over an area of bed that includes different geomorphic features and thus different facies..

CONCLUSION

The San Clemente Dam was removed both to solve a seismic safety issue and to open up additional habitat for steelhead trout. By rerouting the river around decades of reservoir-stored sediment, the design of the dam removal effectively prevented downstream transport of most stored sediment, thereby mitigating flood risk **(Figure 23)**. One ecological goal was to increase the availability of steelhead spawning gravels downstream of the removed dam. However, the metrics used to analyze the changes to steelhead spawning gravel availability are not enough to draw conclusions about the long term effects of dam removal. It was thought at the time of removal that regardless of the bypass, the natural inputs from debris flows into the river basin would provide ample steelhead spawning gravels (Boughton et. al 2016), and it is entirely possible that this may still come to be. The watershed around the river can provide suitably sized spawning gravels and high flow events like those in 2023 and 2017 can transport gravels into the river channel (Smith 2021). Despite its limitations, the lessons from 8 years of post-dam-removal monitoring on the Carmel River can provide a case study to inform future dam removals.

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TABLES AND FIGURES

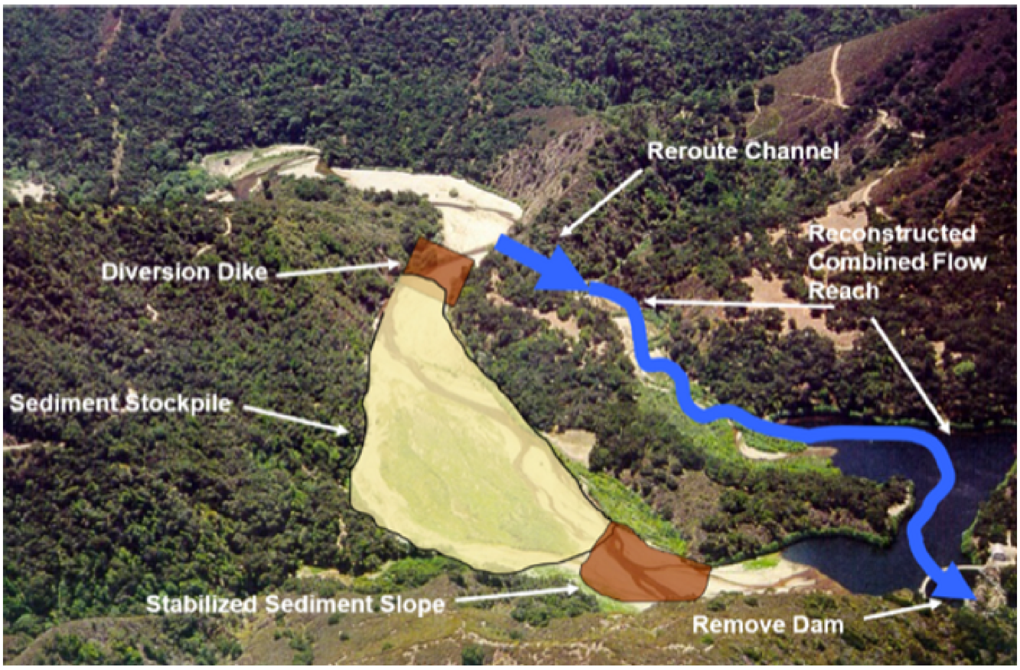
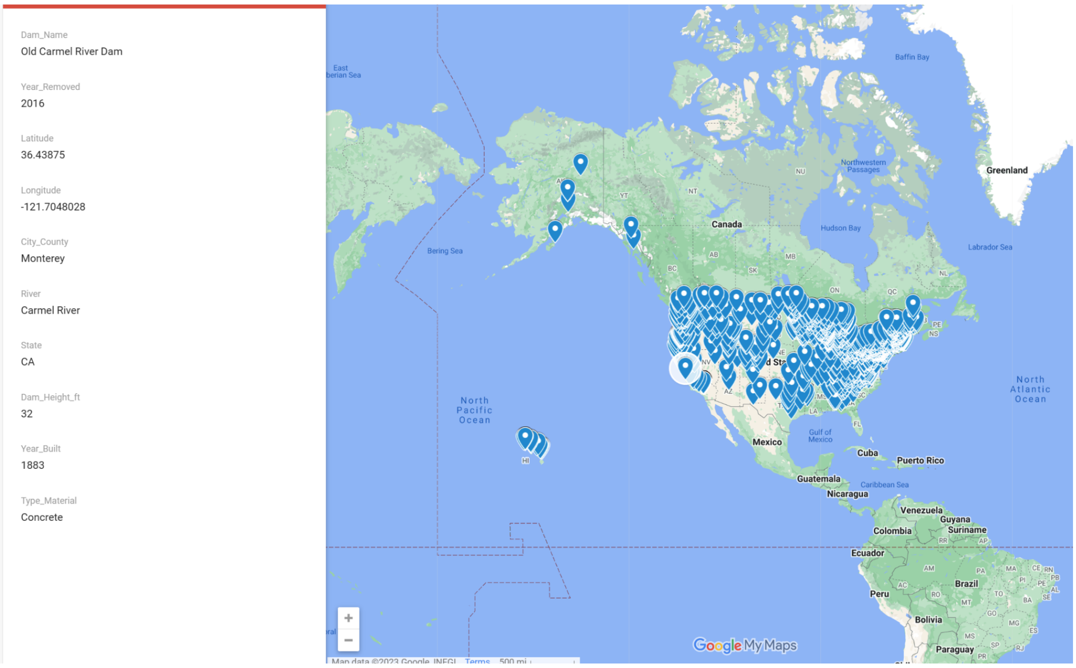


Figure 1: The diversion plan for the San Clemente Dam removal.
Retrieved from San Clemente Dam Project Overview website (PCMSC, n.d.).



Dam_Name	Old Carmel River Dam
Year_Removed	2016
Latitude	36.43875
Longitude	-121.7048028
City_County	Monterey
River	Carmel River
State	CA
Dam_Height_ft	32
Year_Built	1883
Type_Material	Concrete

Figure 2: US Dams removed between 1912 and 2022 from the American Rivers Dam Removal Database, 2023

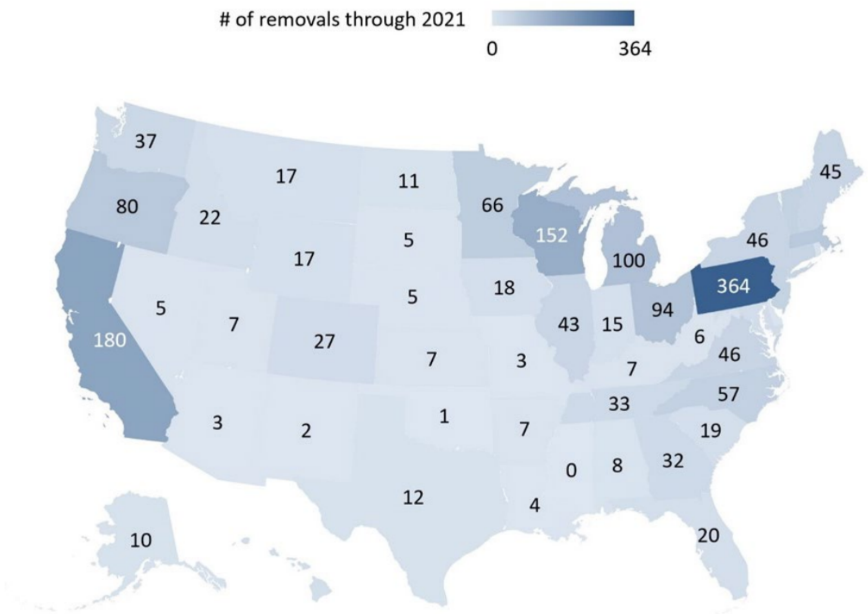
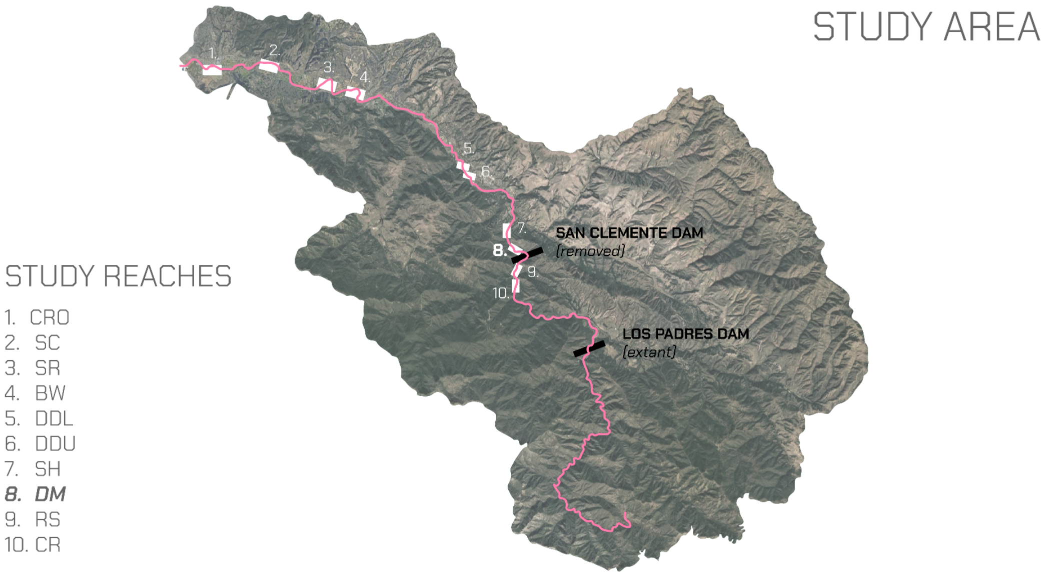


Figure 3: California has the second highest number of removals from any other state between 1912 and 2021. Retrieved from the americanrivers.org website.



***1 to 8 (including DM) are downstream and 9 and 10 are upstream of the former dam site.**

Figure 4: The Carmel River Basin with locations of each study site (East et al., 2023). The reaches are abbreviated as follows: control reach (CR), reservoir (RS), dam reach (DM), Sleepy Hollow (SH), DeDampierre upper (DDU), DeDampierre lower (DDL), Berwick

(BW), Schulte Road (SR), San Carlos (SC), and crossroads (CRO). Note that the RS reach was omitted from our analysis as it isn't included in the 2021 or 2023 field study.

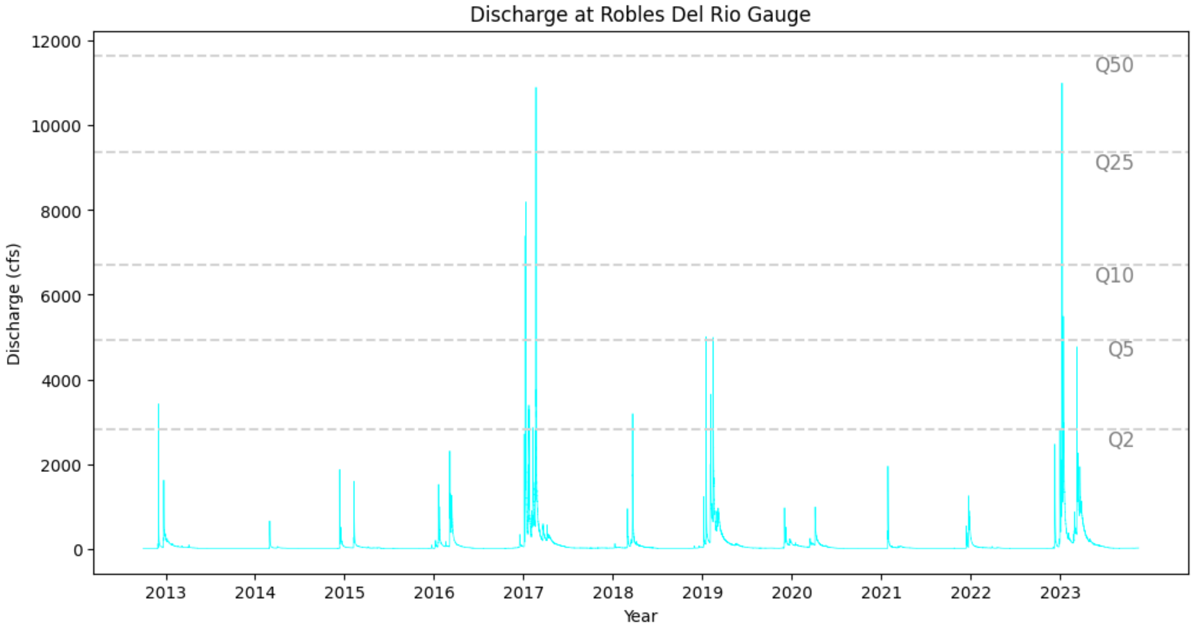


Figure 5. Carmel River discharge from USGS flow gauge at Robles Del Rio. The recurrence intervals Q2, Q5, Q10, Q25, and Q50 are estimated from the discharge plot in East et al. (2023).

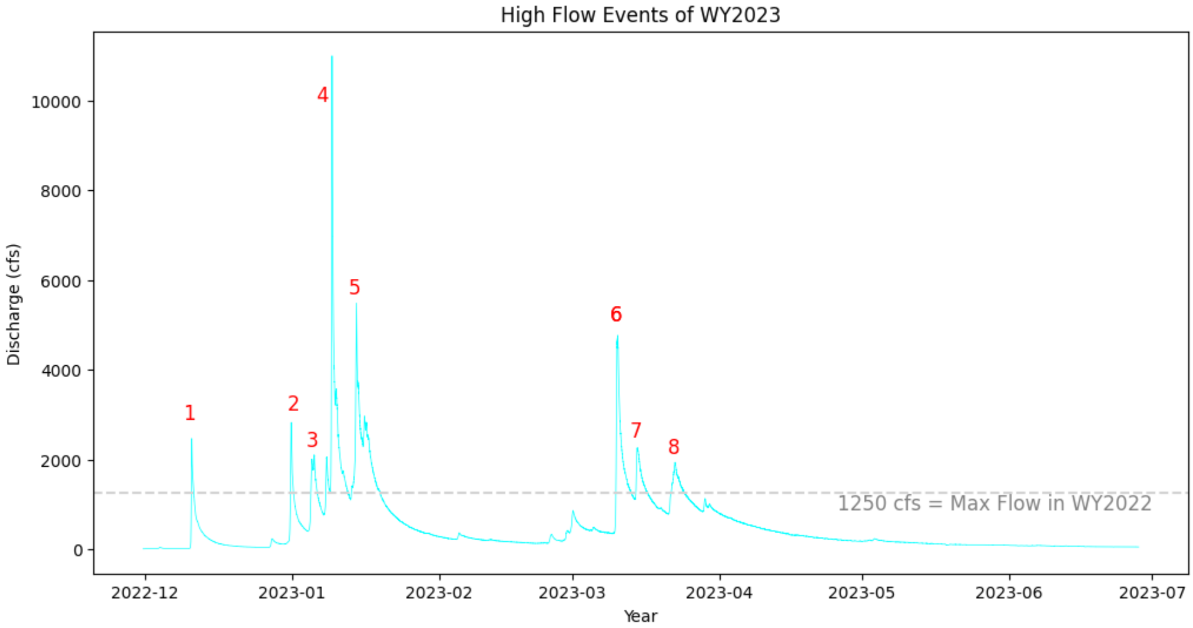


Figure 6. Carmel River high flow events during WY 2023. There was one high flow in WY 2022 and roughly 8 high flow events of equivalent or higher discharge during WY 2023.

Figure 7: Google Earth satellite image of a debris flow located just upstream of the DM reach.

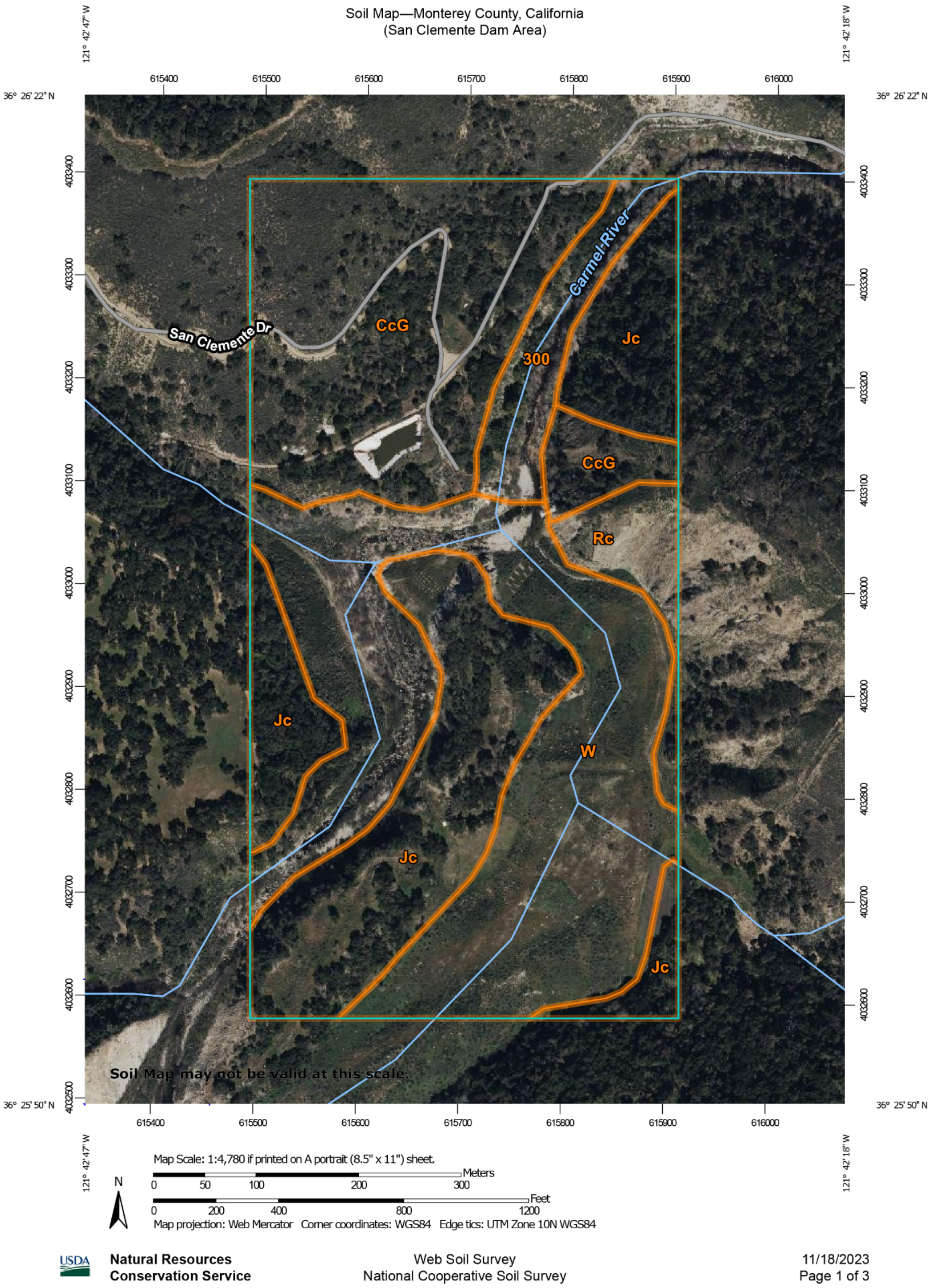


Figure 8: A soil map from the USDA Soil Survey website reveals that slopes around the dam site are generally gravelly loams with the potential to contribute steelhead spawning gravels to the river.

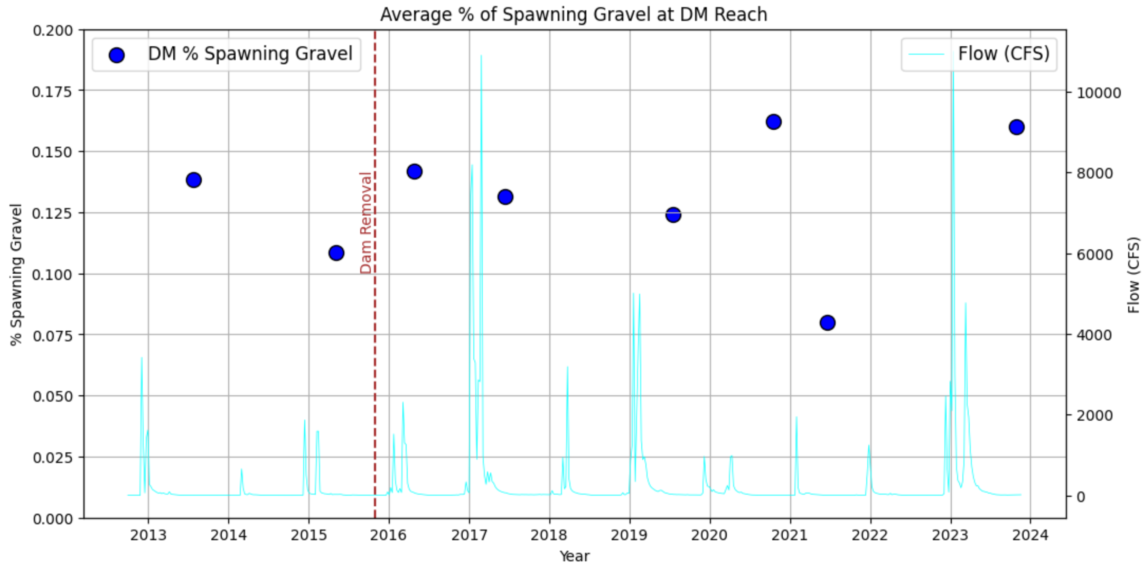


Figure 9: Average Percent Spawning Gravel at the DM reach and Carmel River flow over the years. (DM reach depicted in Figure 4)

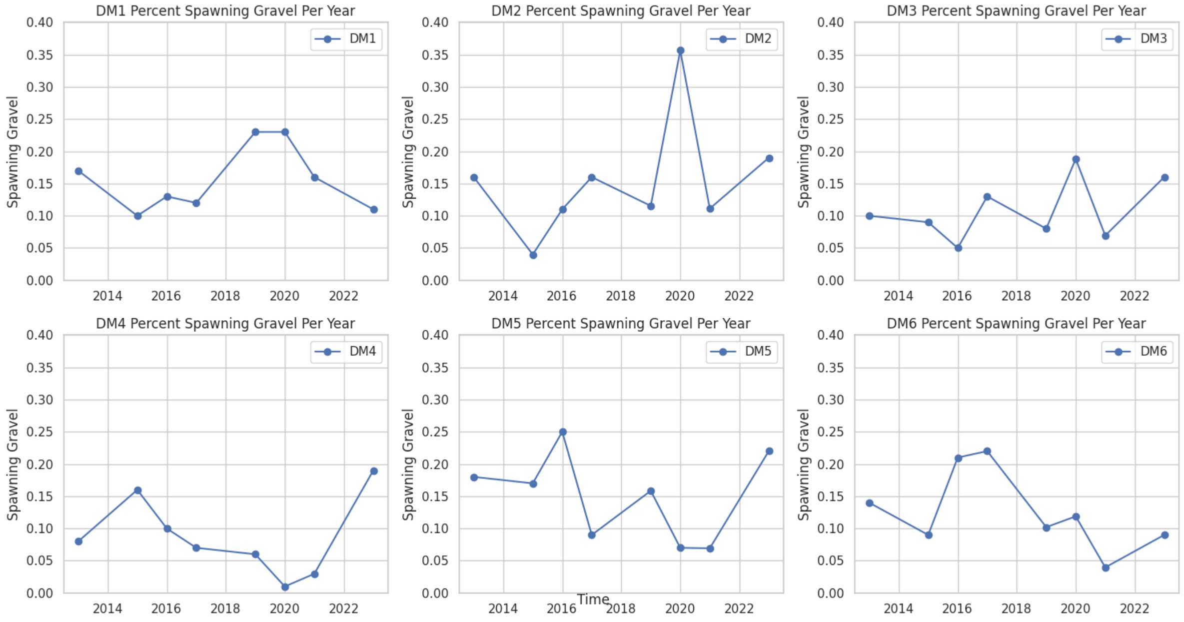


Figure 10: Percent Spawning Gravel as measured at each cross section at DM.

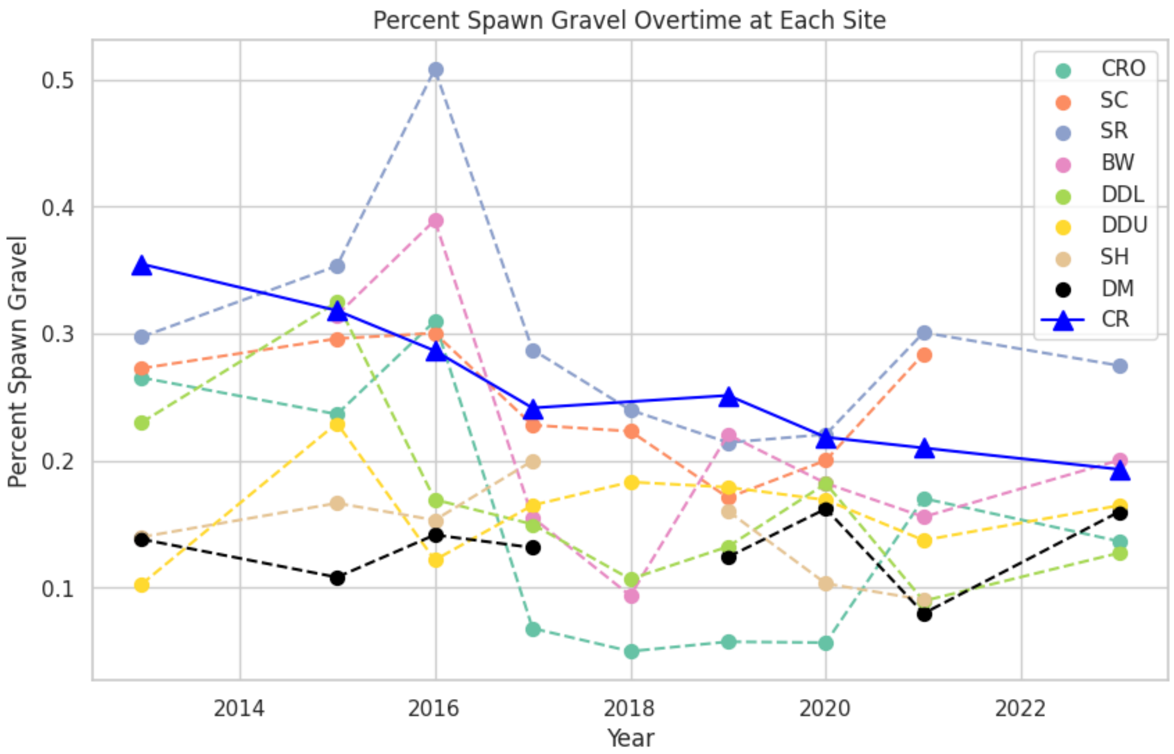


Figure 11: Average percent spawning gravel as measured at each reach over the years. The reaches listed in the legend are in order from closest to furthest from the mouth of the Carmel River.

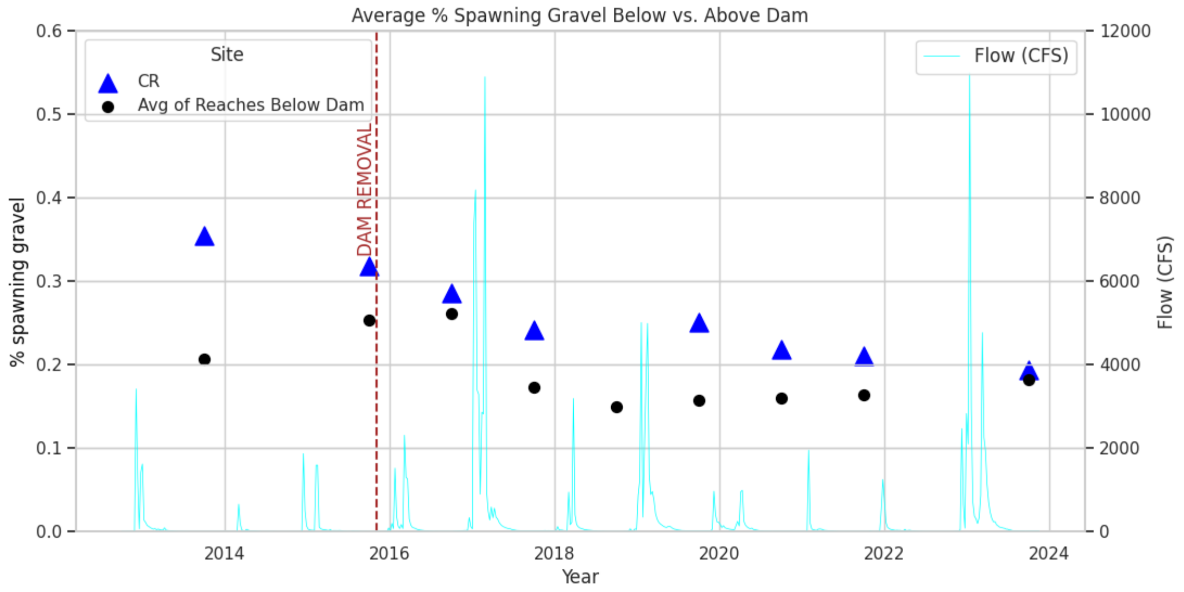


Figure 12: Average of measured percent spawning gravel at reaches downstream of the dam removal versus the control reach upstream of the dam removal, with flow superimposed.

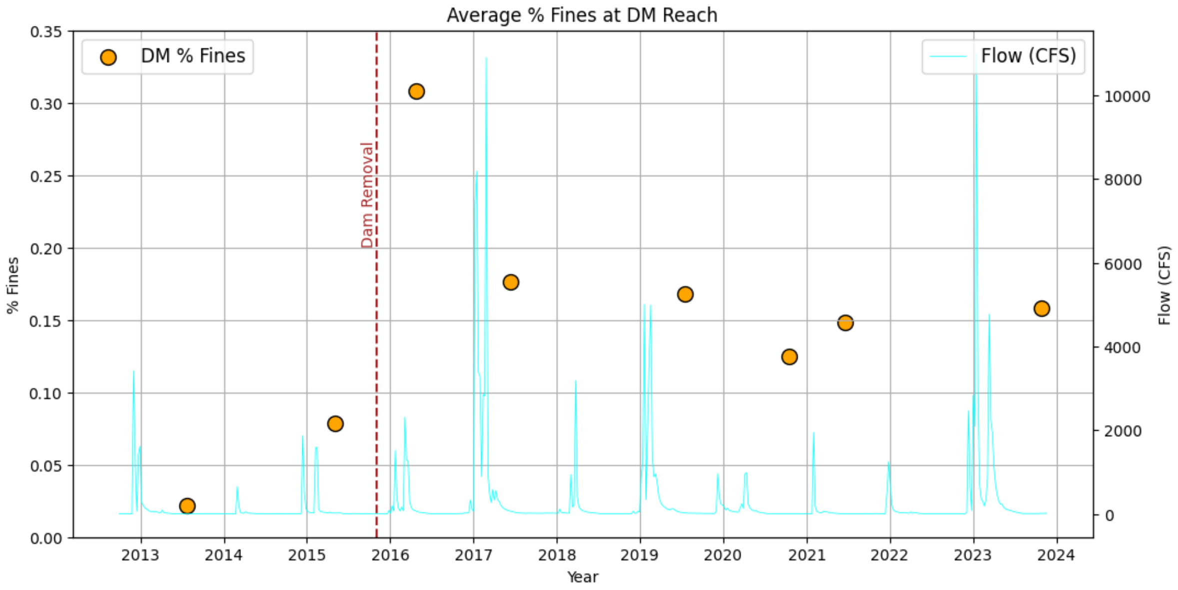


Figure 13: Average Percent Fines as measured at the DM reach and Carmel River flow over the years.

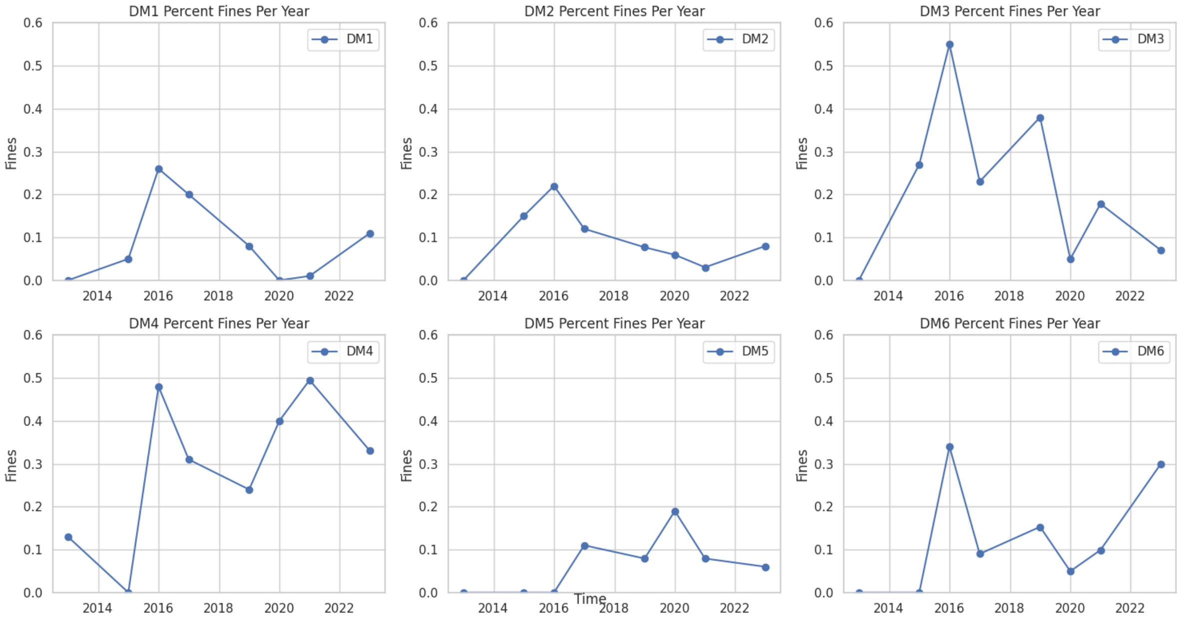


Figure 14: Percent fines as measured at each cross section at DM.

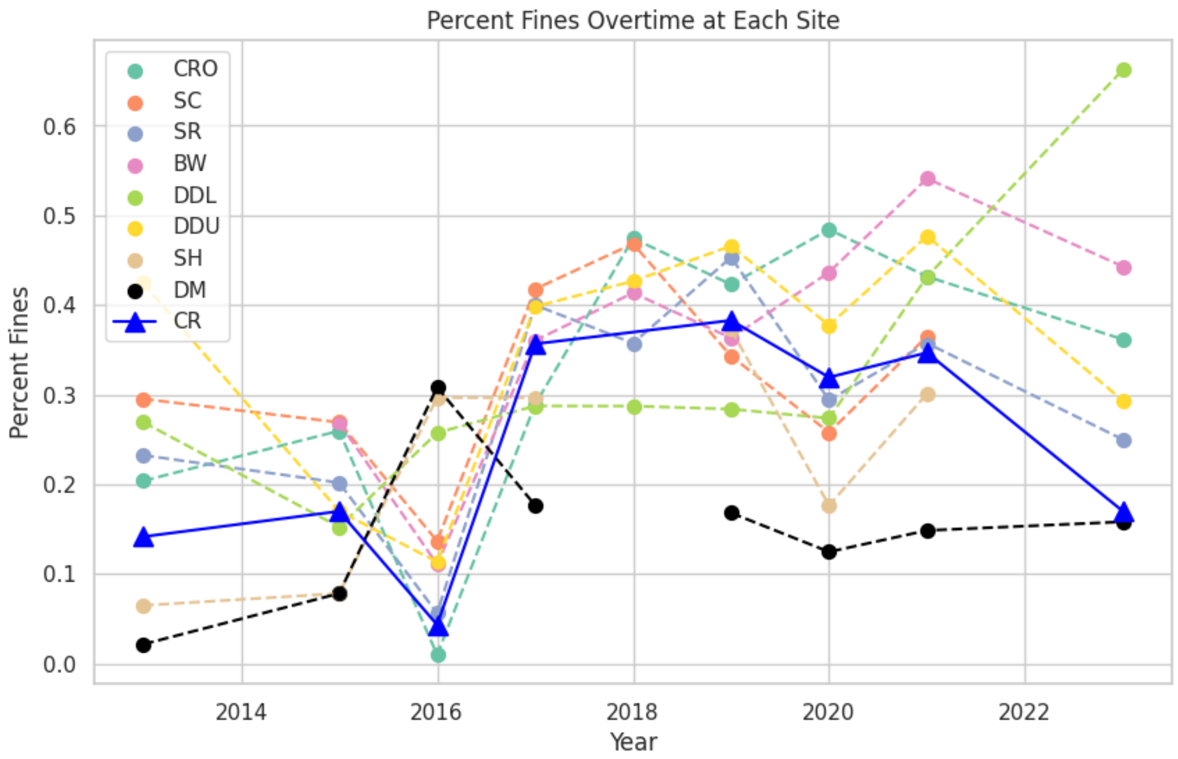


Figure 15: Average percent fines as measured at each reach over the years. The reaches listed in the legend are in order from closest to furthest from the mouth of the Carmel River.

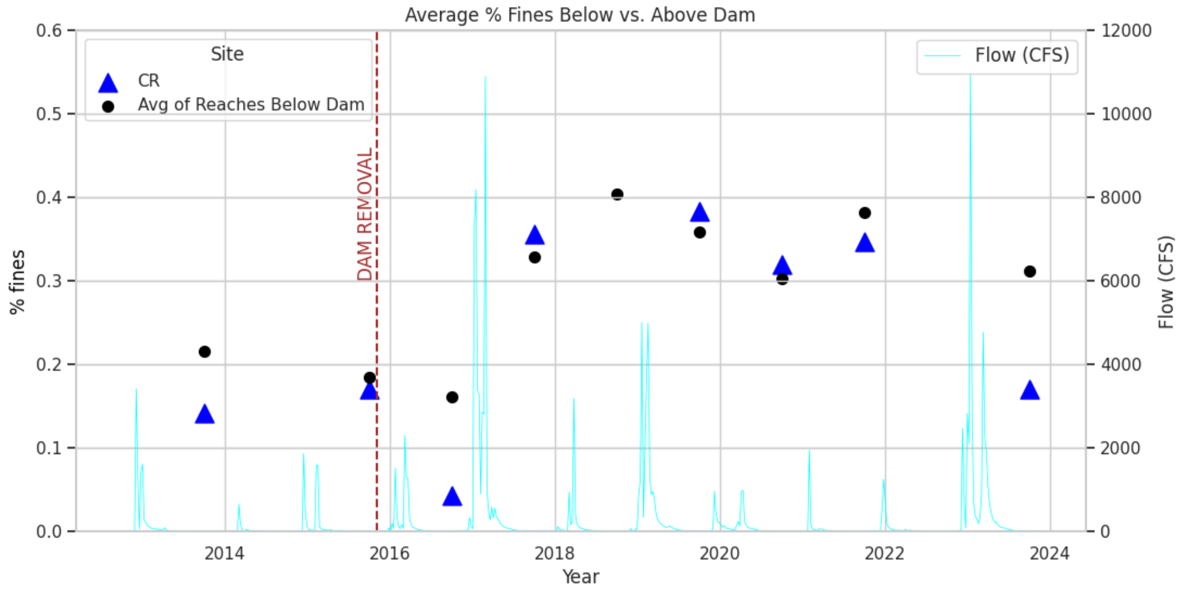


Figure 16: Average measured percent fines of reaches downstream of the dam removal versus the control reach upstream of the dam removal, with flow superimposed.

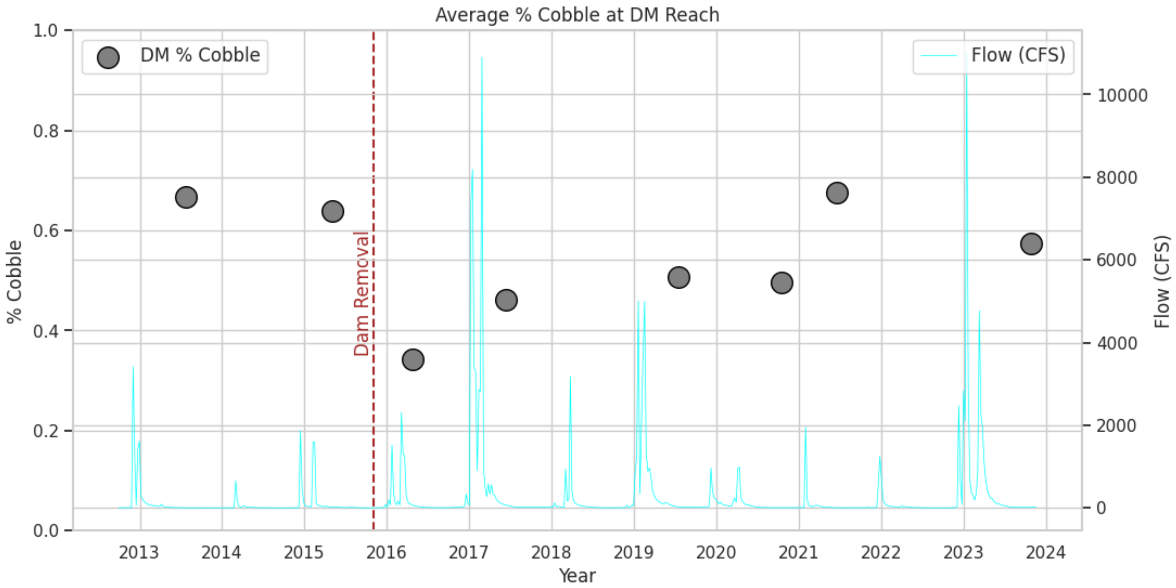


Figure 17: Average Percent Fines as measured at the DM reach and Carmel River flow over the years.

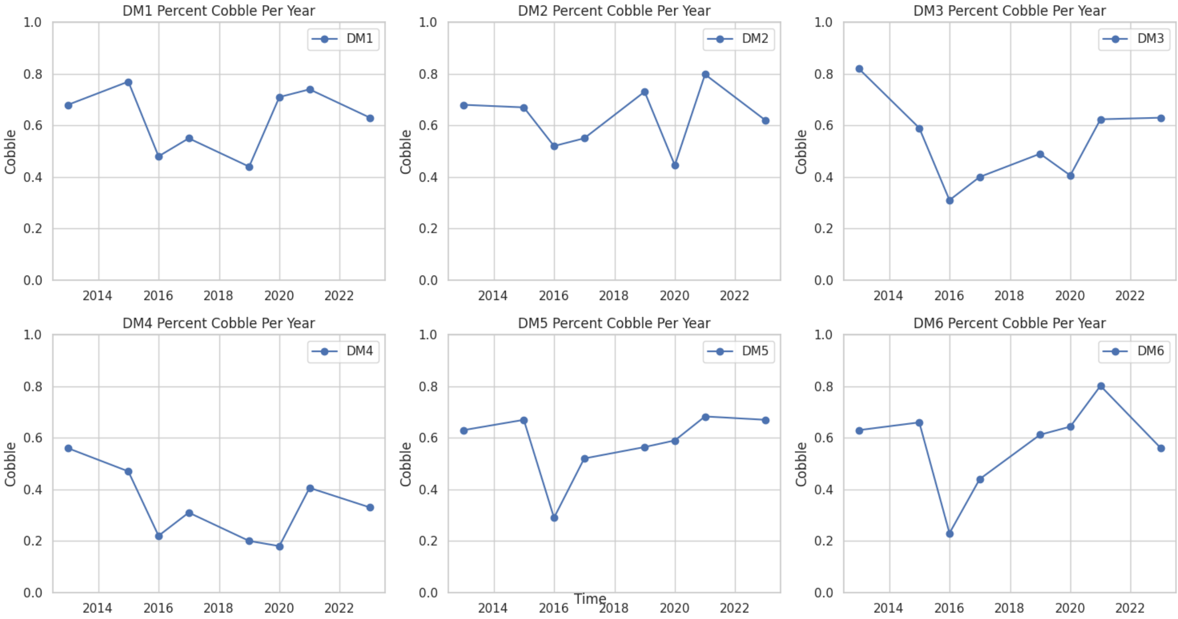


Figure 18: Percent Cobble as measured at each cross section at DM.

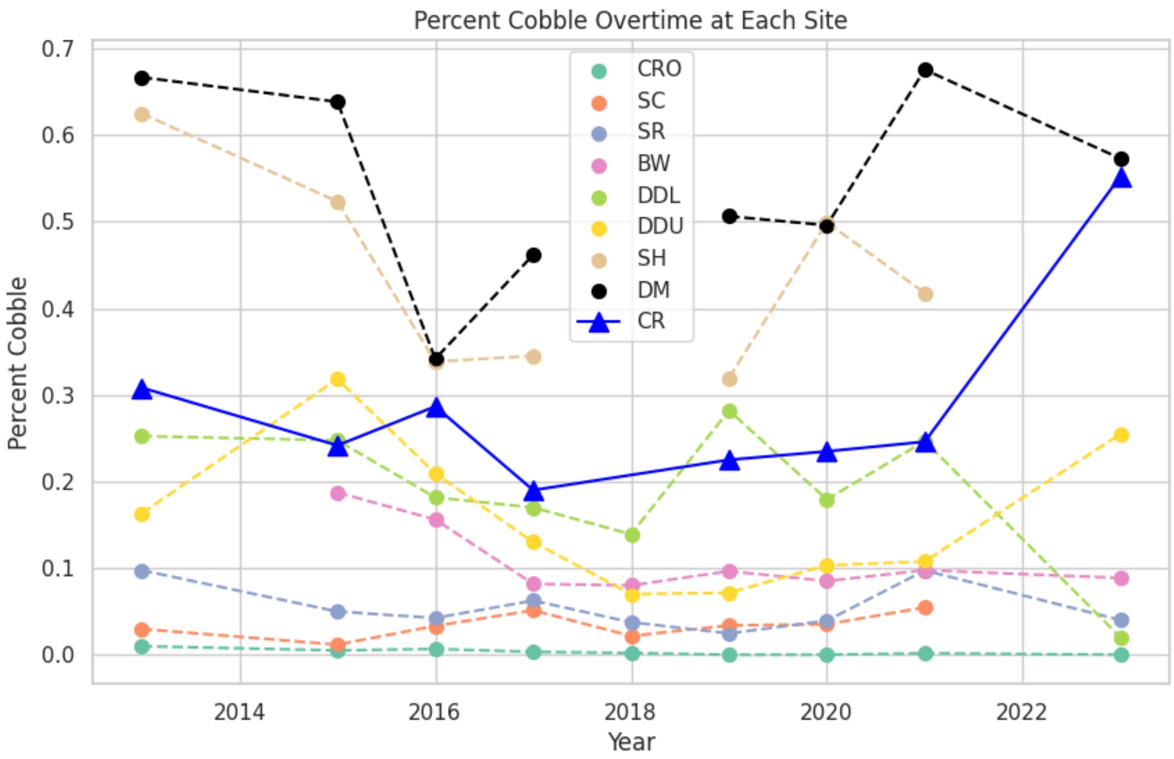


Figure 19: Average percent cobble as measured at each reach over the years. The reaches listed in the legend are in order from closest to furthest from the mouth of the Carmel River.

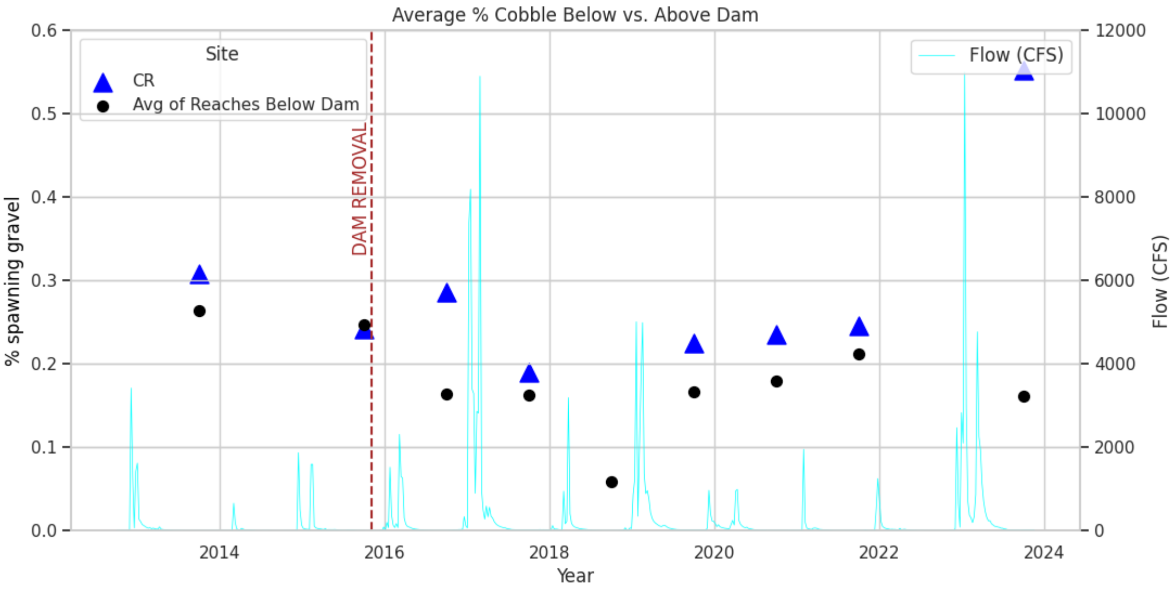


Figure 20: Average measured percent cobble of reaches downstream of the dam removal versus the control reach upstream of the dam removal, with flow superimposed.

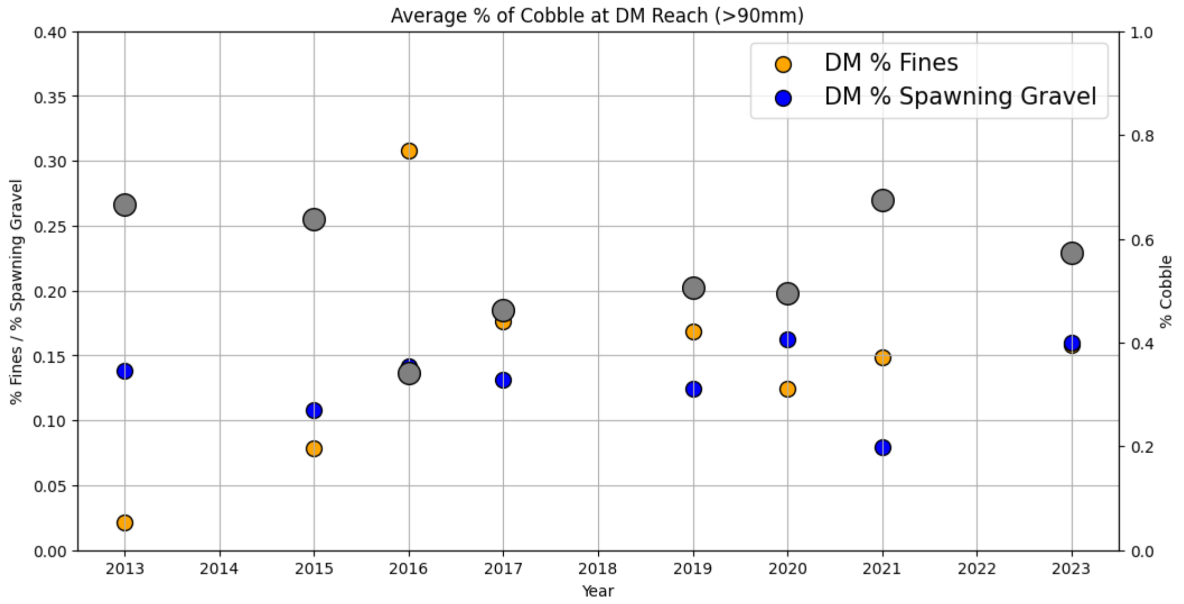


Figure 21: Average of measured fines, spawning gravel, and cobble at DM over time.

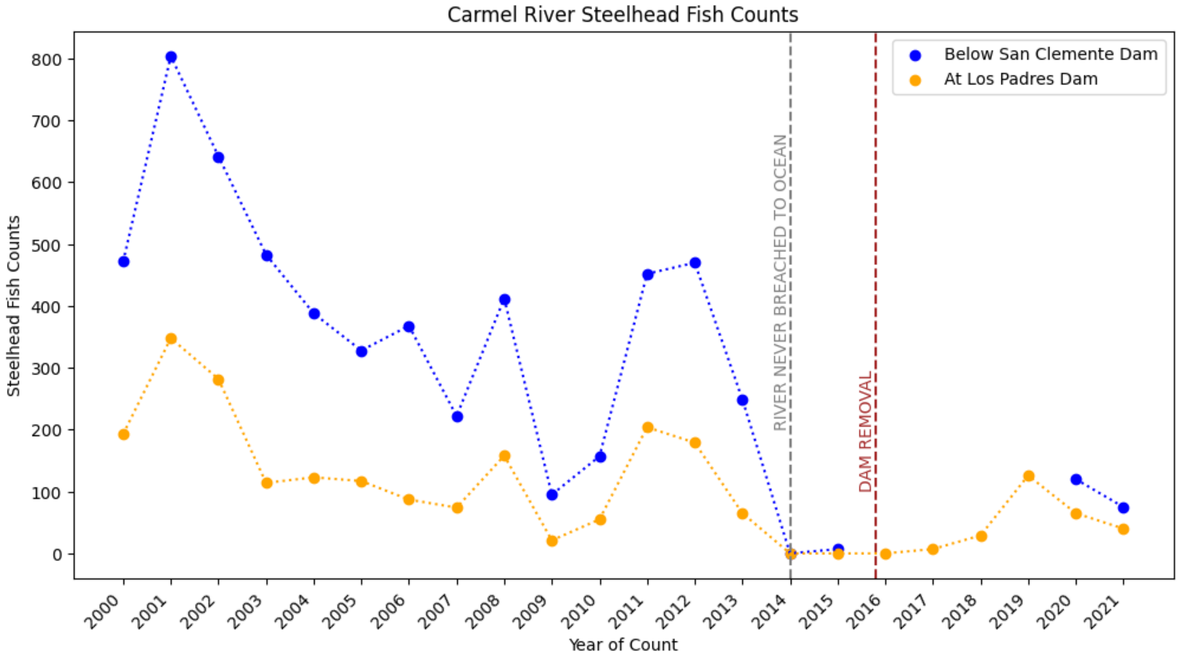


Figure 22: Steelhead counts over time, below San Clemente Dam versus below Los Padres Dam. Note that the counts for below San Clemente Dam in 2020 and 2021 were from the Carmel River Weir.

Figure 23 : Looking downstream at the former site of the San Clemente Dam. You can see remnants of it from the rock face where the walls once stood. Photograph from the field in November 2023.