Title
The Cosumnes River Watershed After the Caldor Fire: Dissolved Organic Carbon Export from 2021-2024

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The Cosumnes River Watershed After the Caldor Fire: Dissolved Organic Carbon Export from 2021-2024

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Abstract

Climate change in California is driving an increase in the duration of the wildfire season as well as severity and size of wildfires. With the increased prevalence of mega wildfires, there is a need to understand the long-term effects of wildfire on the water quality of forested watersheds. After the 2021 Caldor Fire in the Sierra Nevada mountain range, a long-term, high-frequency surface water sampling campaign was implemented in the Cosumnes River Watershed alongside the mining of historical stream water chemistry and discharge data available through National Water Quality Monitoring Council and USGS databases. Here we develop a pipeline to integrate current measurements and historical water quality data to analyze in detail the variations in dissolved organic carbon exported from the watershed. For the purposes of this study, dissolved organic carbon was defined to be any organic matter present in stream water that could pass through a 0.45 µm PVDF filter. We hypothesized dissolved organic carbon content in the Cosumnes River would be dependent upon burn severity experienced and would reach a maximum in the first-year post fire. Our work demonstrated that storm events drive increases in DOC concentration and instantaneous loads post fire, with maximum concentrations observed in the first year. Storms in subsequent years continue to drive spikes in DOC concentrations and instantaneous loads but require higher discharges to achieve the levels observed in the first-year post fire. This analysis indicates the readily available organic matter supplied by years of drought followed by fire are depleted after the first year. Maximum DOC concentrations and instantaneous loads during high discharge storm periods are higher in the first-year post fire than in available pre-fire data. Atmospheric rivers are a strong driver of DOC transport and subsequent high concentrations. During the years of this study, snowmelt was not a driver of DOC transport. Our work suggests that the Cosumnes River Watershed is resilient in the face of

wildfire, with dissolved organic carbon values returning to historical ranges in the second year after fire.

Introduction

In recent years, California has experienced the most destructive wildfire seasons on record[1]. In fact, 18 out of the 20 largest fires in recorded history have occurred between 2003 and 2021 and the top five largest fires have all occurred since 2018[1]. Of the 20 largest fires in California, four occurred in the forests of the Sierra Nevada mountain range, burning more than 1.8 million acres[2]. The Sierra Nevada is an essential part of California's water system. More than 75% of all California residents drink water originating in this region. Ten percent of all water in the Central Valley aquifers that supply the agricultural industry comes from groundwater that percolates down from the Sierra Nevada[3].In addition to the potential negative economic impact of wildfire disruptions to the residential and agricultural water supply, billions of dollars are spent on fighting fires and rebuilding burned communities[4]. Given the importance of Sierra Nevada watersheds to California's overall water system and the frequency of fire in these watersheds, field studies are needed to understand how wildfire impacts stream water quality.

The threats posed by wildfires that occur in forested watersheds begin with damage to structures and direct threats to human health but continue well beyond the spatial and temporal boundaries of the fire with smoke plumes that travel long distances. Disruptions to native ecosystems caused by wildfire can persist for up to 10 years after the fire has been extinguished[5,6]. For instance, wildfires have been found to increase soil hydrophobicity, decreasing infiltration and increasing the amount of overland flow[5]. This modifies the overall hydrology of burned areas, decreasing response times between rainfall and increase in discharge[7]. In turn, this increases the risk of flooding and erosion throughout the burned landscape during atmospheric rivers[7]. These increases in erosion and overland flow are also associated with an increase in total suspended solids concentrations, as runoff is able to make direct contact with exposed soil and ash in burned landscapes[8]. As vegetation grows back and hinders contact between runoff and the previously bare landscape, suspended solid concentrations decrease[8]. In response to these land surface perturbations, nutrient concentrations, such as nitrogen, phosphorus, and organic carbon, have been found to increase in streams in the wake of wildfires[7,9].

The forests of California's Mediterranean ecosystems are adapted to wildfire, with many types of vegetation becoming reliant on fire to continue normal healthy ecosystem functioning[10]. However, rising temperatures throughout the year, particularly in the summer and autumn, have increased the probability of severe drought in this region[11]. Climate modeling suggests that future multi-year droughts may frequently be followed by extreme wet years, leading to oscillating drought atmospheric river cycles[12]. Despite interludes of extreme wet years, rising temperatures decrease snowpack and increase forest mortality in response to moisture stress, thereby increasing available fuel load[11]. This warming and drying trend is anticipated to accelerate, expanding the duration and severity of the California fire season[11]. Already, studies of California wildfires have demonstrated increases in burn area, frequency, and fire size since the mid 1900s[5]. This is particularly true for the Sierra Nevada region, which experienced a 5-fold increase in burn area since 1910[5]. Prior to burn suppression techniques in the 1900s, wildfires burned broad swathes of the landscape regularly, though the fires had little to moderate impact on the physical and chemical properties of soil (low and moderate burn severity, respectively) rather than the high soil impact burns (high burn severity) becoming more common today[13,14]. Given the unprecedented changes to California's fire season, long-term observation-based studies of water quality parameters are needed to understand the ramifications of increased wildfire frequency and intensity on watershed hydrology and biogeochemistry.

Past research has shown that burn severity has a strong impact on the quantity of dissolved organic carbon (DOC) post fire[8]. High temperatures and readily available oxygen enable the burning of organic matter to produce pyrogenic organic matter (PyOM)[8]. PyOM on the ground surface can create a hydrophobic layer that prevents water from infiltrating and thereby causing increased streamflow and flash floods with debris flow inside burned watersheds after rainfall[8]. The PyOM on the ground surface is also capable of releasing dissolved PyOM upon contact with precipitation[18]. This dissolved organic matter can then be transported into surface or groundwater[18]. While wildfires have been widely observed to increase debris flow in forest streams, various studies of water quality after wildfires have observed both increases and decreases in DOC concentrations[7,15–17]. The conflicting results are attributed to temperature thresholds that mark the maximum DOC content produced in fire compared to unburned vegetation, and the point at which there is a net DOC loss compared to unburned vegetation[18]. Zhang et al estimated the maximum DOC generation to occur in temperatures 225-300 °C, and net DOC loss to occur at temperature 325-375 °C[18]. Low to moderate severity wildfires would fall at and below the maximum DOC generation threshold, causing an increase in DOC observed after fire, while high severity burns fall above the DOC loss threshold, causing a decrease in DOC measured in surface water after wildfire[18]. These temperature thresholds make wildfire burn severity a driver of DOC concentrations observed after fire[18].

High DOC concentrations seen after low to moderate severity wildfires are driven by precipitation events within the burn perimeter[19]. In a study of Cold Creek Watershed after the Wragg fire, the second rainy season post fire had lower DOC concentrations than the first, which indicates that the easily mobilized DOC in the wake of wildfire is rapidly removed from the burned watersheds[8,19]. In the second year post fire, DOC concentrations had decreased, as the

DOC was originating from organic matter present in soil, rather than tapping into additional DOC available in the burn scar[19]. Freshly burned ash has a greater DOC leaching potential than unburned vegetation, which itself has greater leaching potential than ash from fires two or more years previously[19,20]. These varying leaching potentials may explain why the high DOC concentrations seen directly after fire are followed by a decrease in DOC concentrations in later years. Additional multi-year field studies are needed to validate the decrease in DOC concentrations as leaving potential declines after the first-year postfire.

While a number of studies have monitored surface water constituents (refer to Table A in Appendix for a sub-sample of these studies) little data is currently available at high temporal resolution to assess the long-term changes in DOC in the wake of wildfire in forested watersheds. Infrequent sampling necessitates observations of water quality trends on a broad scale from one year to another. Higher temporal resolution through more frequent sampling enables analysis of the effect of wildfire on water quality after individual storms, better estimation of nutrient loads, and observation of trends from year to year through continued sampling. This work seeks to use monthly and weekly time series data collected in partnership with local communities to assess the effects of the Caldor Fire on DOC concentrations and instantaneous loads in the Cosumnes River Watershed. The water monitoring campaign data is augmented by discharge data from the USGS to section out periods of baseflow and storm events as well as historical data from the National Water Quality Monitoring Council for comparison pre and post fire.

Research Questions

1. How do DOC concentrations vary across the Cosumnes River Watershed in the first three years post Caldor Fire in relation to burn severity?
2. How do periods of storm, snowmelt, and baseflow affect the DOC concentration and instantaneous load exported from the watershed to lower regions of the Cosumnes River?

Hypotheses

1. DOC concentration is dependent upon watershed area burned at moderate severity. Monitoring stations with larger absolute area of moderate burn severity will have higher DOC concentrations than stations with smaller areas.
2. DOC concentration is dependent upon time since burn was extinguished. DOC concentrations will be highest in the first-year post fire.
3. DOC concentrations and instantaneous loads will be increased by the first rains of the water year and during periods of snowmelt as compared to historical data and the second- and third-years post fire.

Objectives

1. Examine changes in stream water dissolved organic carbon concentration throughout the Cosumnes River Watershed over a 3-year period after the Caldor fire.
2. Compare DOC concentrations and loads at the watershed exit post fire to historical pre-fire data.
3. Compare DOC concentrations and instantaneous loads throughout the watershed and over time in the context of the hydrograph.

Site Description and Hydrologic Context

Cosumnes River Watershed

The Cosumnes River watershed (Figure 1) falls within the western slope of the Sierra Nevada mountain range and contains the granitic rocks characteristic of the region. Soil in the area is primarily lava caps on top of granitic rocks or metasedimentary marine sediments. The soil texture is loam soil, which is prone to erosion, particularly when a fire has removed much of the soil covering[21]. Before the fire, the area contained mixed conifer vegetation, including non-native and native grasslands, and a variety of pines, chaparral, and firs[21]. This area had been subject to fire suppression techniques since the 1940s, allowing for the buildup of fuel throughout the region[22].

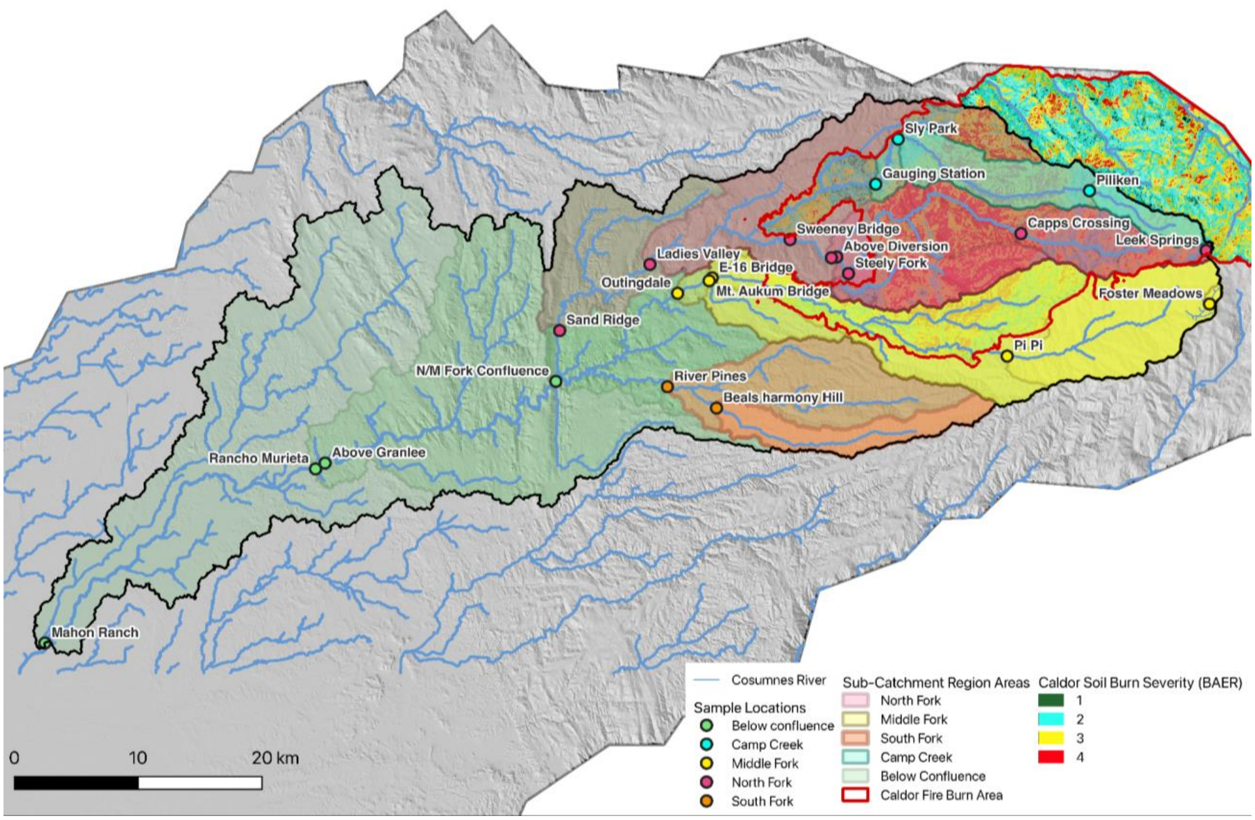

Figure 1: Map of sampling sites in the Cosumnes River Watershed. The black line outlines the perimeter of the Cosumnes River Watershed. The red line outlines the Caldor Fire burn area. Colored areas indicate sub-catchments, with circles representing sampling locations.

Despite these fire suppression techniques, the Cosumnes River Watershed experienced several fires prior to the Caldor Fire (Figure 1). Of these fires, the Caldor Fire is notable for being the largest fire recorded in the watershed and occurring in the upper regions of the watershed. Before 2021, the most recent fire occurred in July of 2014 (Figure 2), when the Sand Fire burned 4240 acres in the lower regions of the watershed[23].

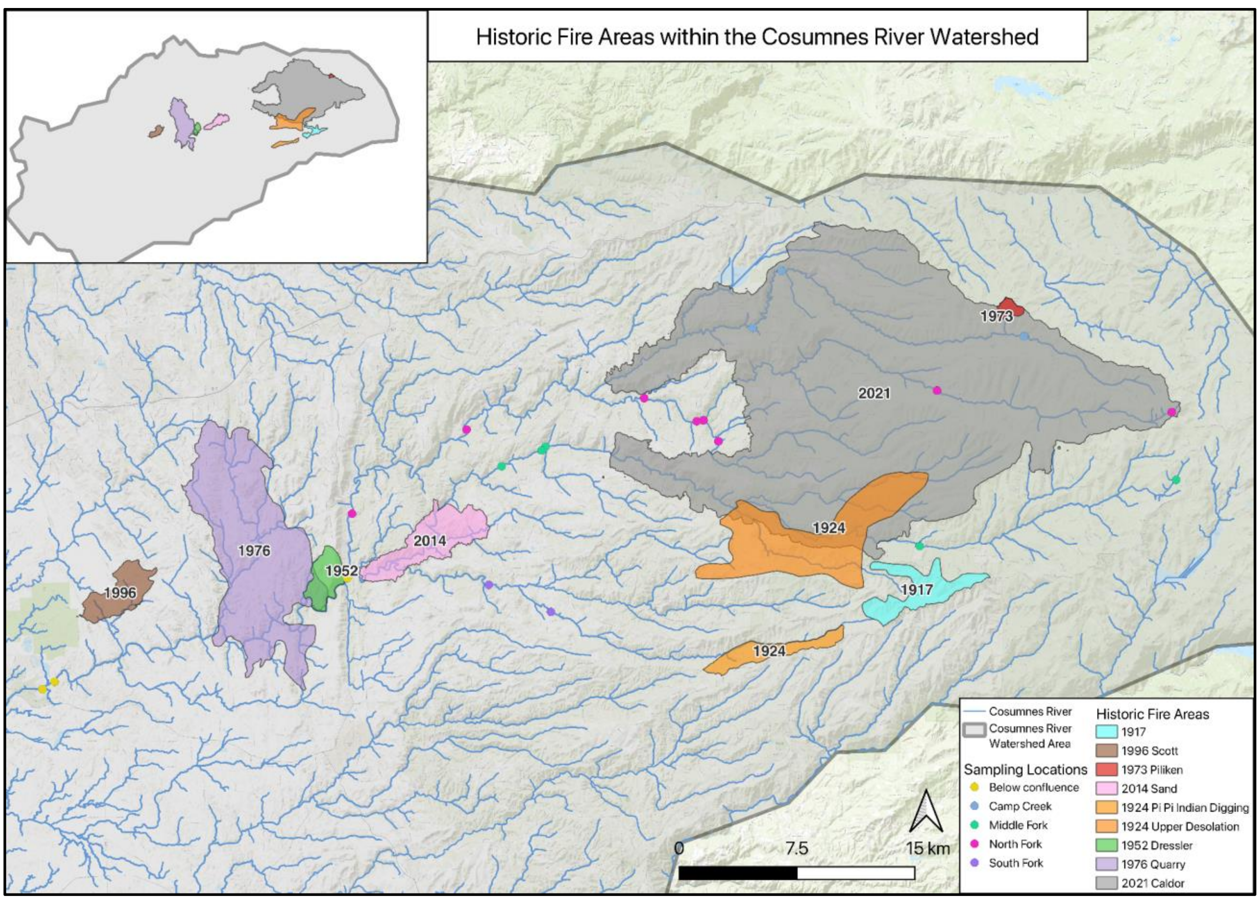

Figure 2: Map of historic fires in the Cosumnes River Watershed. The borders of the watershed are outlined in dark gray. Within the watershed, burned areas from fires that occurred in 1917 - 2021 are shaded. Locations of sampling sites for the current water monitoring campaign are shown with colored points.

Hydrologic Events in Cosumnes River Watershed

California is infamous for its highly variable weather condition from year to year[24,25]. Recent water years have been no exception (Figure 3), with a recent trend of dry hot summers in addition to fluctuating wet seasons that have been by turn unusually dry and unusually wet[25]. Water year 2020, which began on Oct 1, 2019, and ended September 30, 2020, was notable for being California's fifth driest year on record[24]. There was both little rainfall, only 62% of average statewide, and a poor snowpack, 53% of average April 1st Sierra Nevada snowpack[24]. In addition to being dry, water year 2020 experienced heat waves throughout the end of summer, leading to a catastrophic wildfire year, with more than 3.8 million acres burned throughout California[26].

Water year 2021 was an extremely dry water year[24]. The Cosumnes River Watershed experienced very little precipitation throughout the rainy season, and the statewide precipitation was only 50% of average[24]. The storms that did occur throughout the first half of the water year accumulated very little snow[24]. The April 1st Sierra-Cascades snowpack measured 60% of the average[24]. California also experienced the warmest state-wide monthly average temperatures that had yet been measured in October, June, and July, exacerbating water deficits[24]. As a result, water year 2021 was the second driest year in California to be recorded[24]. The hot and dry conditions set the stage for the Caldor Fire to break out in the last month of water year 2021 and into water year 2022[22].

Water year 2022 continued to be both hot and dry, though not to the extent seen in 2021[27]. The start of the water year brought a category 5 atmospheric river on Oct 24-25, 2021[28]. The storm was unusual for the area for both its magnitude and early occurrence[27,28]. This event was followed by two more atmospheric rivers. The first was a category 2/3 atmospheric river in Dec 10-13, 2021, which resulted in more than 5 inches of storm precipitation in the Sierra Nevada and several feet of snow[29]. The second was another category 2/3 atmospheric river occurring on Dec 22, 2021 – Jan 1, 2022, which again brought several inches of rain and feet of snow to the Sierra Nevada[30]. The rest of the rainy season was dry[27]. The final statewide precipitation was 76% of average, and the April 1st Sierra-Cascades snowpack was only 37% of average[27].

In contrast, water year 2023 experienced significant precipitation and was one of the snowiest years on record[31]. California experienced nine atmospheric rivers from December 26, 2022, to Jan 17, 2023[32]. As these atmospheric rivers swept south from the Oregon border, the Cosumnes River Watershed experienced several moderate and strong atmospheric rivers in January 1-9, 2023[32]. Another seven atmospheric rivers hit California in late February and into March[32]. Of these, the Cosumnes River Watershed experienced a strong atmospheric river on March 10 and a moderate atmospheric river on March 28, 2023[32]. All told, California received 141% of average statewide precipitation and 237% of Sierra-Cascades April 1st snowpack[33].

As of April 30th, water 2024 was a remarkably average water year[34]. Most atmospheric rivers to hit the western half of the US occurred in the Pacific North-West, with only a handful of weak atmospheric rivers making landfall over the Sierra Nevada. These atmospheric rivers occurred on Dec 22 2023, Jan 24 2024, and March 2, 2024[35]. The Sierra Nevada also experienced a late season low-pressure system from April 4-6, 2024, which brought up to an inch of rain to the Sierra Nevada, followed by another low-pressure system April 13-15, 2024 that brought another two inches[34]. Together, these storm systems brought enough rain to make up 105% of average statewide precipitation[34] and an April 1st Sierra-Cascades snowpack that was 113% of average[36].

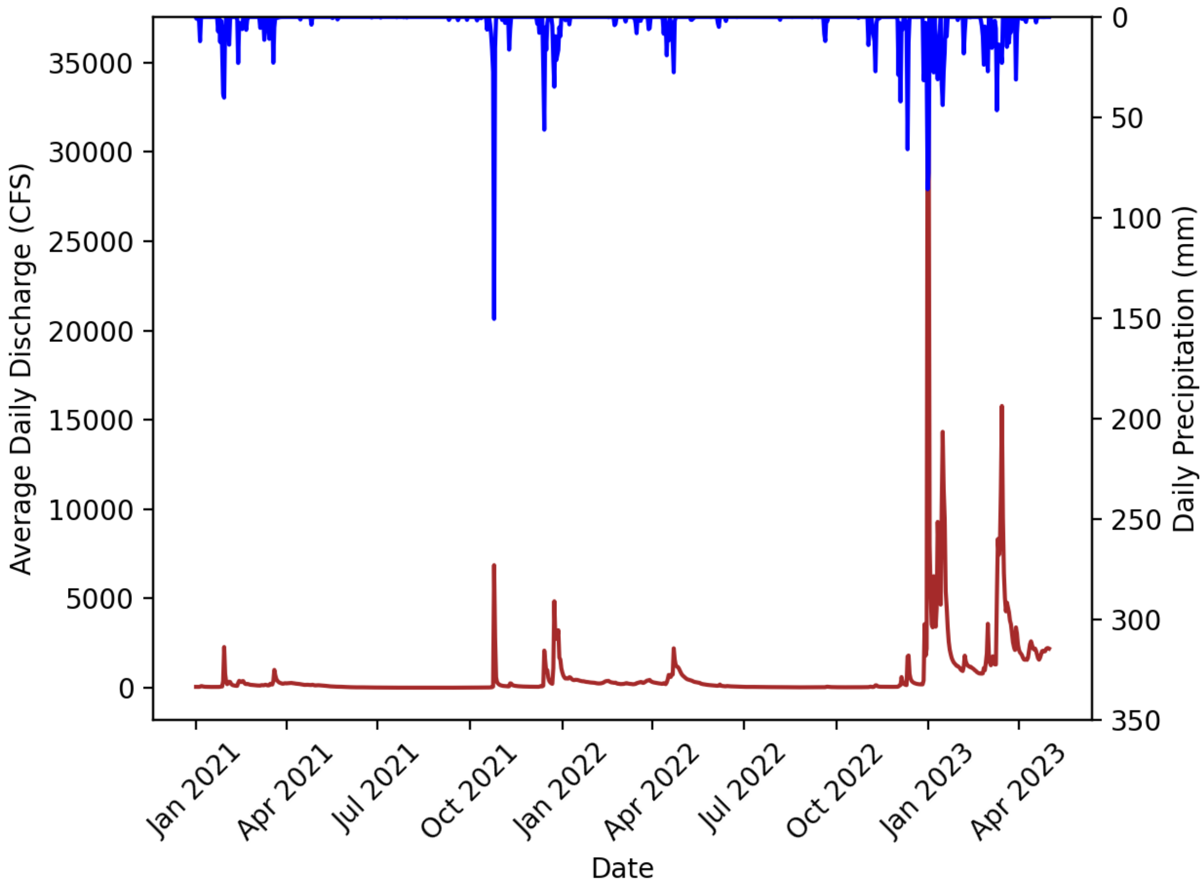

Figure 3: Graph of daily precipitation (in blue, rightmost y-axis) and average daily discharge (in brown, leftmost y-axis) at the USGS monitoring location Michigan Bar in the Cosumnes River Watershed.

Caldor Fire

In the fall of 2021, the upper regions of the Cosumnes River watershed were burned by the mega wildfire known as the Caldor Fire. The fire was ignited on August 14, 2021 due to reckless use of firearms, and burned for nearly 70 days before being fully contained on October 21, 2024[37]. During this time, 221,835 acres of land were burned[22] throughout Cosumnes River Watershed, including the El Dorado National Forest and the community of Grizzly Flats. The large size of the burn area (greater than 25000 acres) and high severity of the fire motivates its classification as a mega wildfire[38]. The days leading up to and during the fire experienced hot and dry weather as well as strong winds[21]. These conditions coupled with readily available fuel led to extreme wildfire behavior[22]. The fire grew at rates of 10,000 to 40,000 acres per day, at times becoming a crown fire with flames a hundred feet tall[22].

As a result of the fire, the Cosumnes River watershed experienced a range of soil burn severities, from very low/none (labeled as burn severity 1 on maps) to high burn severity (labeled as burn severity level 4). The burn severity in the area was assessed by the Forest Service BAER team using the USDA Forest Service's "Field Guide for Mapping Post-Fire Soil Burn Severity".[21] These levels of soil burn severity are intended to assess changes to physical and biological soil properties as the result of fire, and are not intended to describe other impacts of fire, such as the health of surrounding trees or overall ecosystem[14]. Under this classification system, burn severity is categorized by the remaining surface organic layer, soil structure aggregate stability, root charring, and overall soil appearance[14]. Table 1 describes the four levels of burn severity and their primary characteristics.

Table 1: Summary of the four levels of burn severity and their primary characteristics in terms of surface organic matter, structural aggregate stability, roots, and ground surface appearance as defined by the USDA Forest Service's field guide to burn severity.

Characteristic	**1 (very low/none)**	**2**	**3**	**4 (high)**
Surface organic matter	Untouched or very little consumed	Much of the surface organic matter remains and is easily recognizable	Up to 80% has been consumed, but some surface organic matter remains	All or nearly all surface organic matter has been consumed
Structural aggregate stability	Unchanged	Unchanged	Unchanged	Less stable
Roots	Unchanged	Unchanged	Fine roots may be scorched, but have not been completely consumed. Large roots are untouched	Both large and fine roots have been burned
Ground surface	Unchanged	Brown or black	Blackened ash	Black from

appearance		(lightly charred). Canopy and surface vegetation remains green	on the surface, which may contain gray patches. Some scorched needles and leaves on the ground. Overall, looks brown with burned vegetation	extensive charring. Bare soil and ash exposed, and may have up to several centimeters of white or gray ash. May have orange or reddish markings where large fuels were consumed.

Methods

Stream Water Sampling

Stream water was collected from a total of twenty-one sites throughout the study period. Research sites within the Cosumnes River Watershed cover the upper elevations of the watershed at 2220 meters above sea level down to a gated community near the exit of the watershed at 39 meters above sea level. Sites at upper elevations experienced the full range of burn severities and differing levels of total drainage area burned. Sites at lower elevations were completely untouched by the Caldor Fire, though the lowest regions were in the burn perimeter of a previous wildfire in 2014 (4240 acres[23])(Figure 2). Table 2 contains a list of sites with their GPS coordinates, elevations, burn severities, and total drainage area burned.

Table 2: Sub-catchment information for each of the sites monitored through partnership with the ARC. Some sites (E-16, Above Granlee, and Mahon Ranch) are part of ARC's original water monitoring program and were not sampled during partnership with UCD-LBNL.

			Total Area of BAER SBS		Severity %				Percent Burned		
Region	**Sample ID**	**Subwatershed Name**	**Area of Fire inside Drainage Basin [km^2]**	**Drainage Area [km^2]**	**1**	**2**	**3**	**4**	**Total %**	**Category 3+4**	**Sample Point Elevation [m]**
North Fork	532COS001	Leek Springs	0.4	0.4	11%	76%	14%	0%	100%	14%	2,220
	532COS002	Capps Crossing	50.5	51.2	4%	44%	43%	8%	99%	51%	1,526
	532COS015	Steely Fork	51.0	54.5	2%	16%	41%	34%	94%	76%	861
	532COS003	Above Diversion	164.5	180.0	2%	20%	40%	29%	91%	69%	741
	532COS004	Below Diversion	164.5	180.7	2%	20%	39%	29%	91%	69%	726
	532COS005	Sweeney Bridge	165.0	191.1	2%	19%	37%	28%	86%	65%	617
	532COS006	Ladies Valley	316.6	438.8	21%	2%	31%	18%	72%	49%	362
	532COS007	Sand Ridge	308.6	529.8	2%	16%	26%	15%	58%	40%	256
Middle Fork	532COS008	Foster Meadows	0.0	1.5	0%	0%	0%	0%	0%	0%	2,081
	532COS009	Pi Pi	3.2	105.7	0%	1%	1%	0%	3%	1%	1,200
	532COS010	E-16 Bridge	96.1	248.0	1%	14%	17%	6%	39%	23%	507
	532COS019	Mt. Aukum Bridge	96.2	277.7	1%	13%	15%	5%	35%	21%	503
	532COS011	Outingdale	96.2	283.4	1%	13%	15%	5%	34%	20%	485
Camp Creek	532CAM001	Piliken	19.0	19.0	4%	31%	55%	11%	100%	65%	1,673
	532CAM002	Sly Park	76.4	76.3	2%	23%	51%	24%	100%	75%	1,103
	532CAM003	Gauging Station	85.7	85.9	2%	26%	49%	22%	100%	71%	946
South Fork	532COS012	Beals harmony Hill	0.0	47.9	0%	0%	0%	0%	0%	0%	642
	532COS013	River Pines	0.0	154.2	0%	0%	0%	0%	0%	0%	562
Below Confluence	532COS014	N/M Fork Confluence	404.7	1,070.5	1%	11%	17%	9%	38%	25%	240
	532COS016	Above Granlee	404.7	1,390.6	1%	9%	13%	7%	29%	19%	51
	532COS017	Rancho Murieta	404.7	1,400.4	1%	9%	13%	7%	29%	19%	39
	531COS018	Mahon Ranch	404.7	1,864.8	2%	15%	22%	11%	22%	33%	18

Table Organization Note: The order of the Sub watersheds is from highest elevation to lowest within their respective regions on the Cosumnes River.

The sites sampled were chosen because they were part of a long-term water monitoring campaign run through the American River Conservancy (ARC). This campaign recruits volunteers from neighboring communities to monitor water quality throughout the watershed once a month during the summer. Specifically, volunteers conduct field measurements of pH, stream and air temperature, electrical conductivity and dissolved oxygen, in addition to a visual inspection of stream habitat and species observed[39]. Through collaboration with University of California, Davis (UC Davis) and Lawrence Berkeley National Laboratory (LBNL), the ARC campaign was expanded to include year-round sampling of stream water from these sites. Sampling of the upper regions began on September 17, 2021, and continues through June 2024. All the samples collected are routinely transported to UC Davis for a battery of geochemical analyses. No discharge data was collected for the ARC sampling sites.

The most downstream location considered in this analysis was monitored through a partnership with the water treatment facility that serves the local community, Rancho Murieta Community Services District (RMCSD). This location will be referred to as the exit of the watershed. Technicians at the facility collect water samples as part of their routine monitoring that are then transported to UC Davis. Sample collection started on Oct 25, 2021, and continued daily until January 2022, after which sampling was scaled back to weekly or twice weekly. Sampling at this location increased during snowmelt and storm events to improve the temporal resolution of the dataset. Discharge data is available for this site through the USGS monitoring location Michigan Bar, which is located 2 miles upstream of the RMCSD facility and 1 mile downstream from the ARC sampling site Rancho Murieta.

All field samples were collected following a standard protocol as described in the Supporting Information. Briefly, samples were collected in the field using a 50 mL plastic syringe, which was rinsed with stream water three times. Stream water was then filtered using a 0.45 μm PVDF syringe filter into a 40 mL amber vial. Vials were fully filled with less than 1 mL headspace. Sample collection typically occurred between 8 AM and noon. After collection, samples kept in a cooler on ice during transport and subsequently stored at 4°C until time for analyses.

DOC Measurements

Dissolved organic carbon was determined using a Sievers 5310C Laboratory TOC Analyzer. The instrument was calibrated using six standard solutions prepared gravimetrically using a 500 ppm sucrose stock solution acidified with ten drops of phosphoric acid and ranging in concentration from 0.25 ppm to 50 ppm. Samples were measured in triplicate with a blank and 10 ppm standard check at the beginning and end of the batch as well as every 30 samples. Concentrations are reported in molar units, though can easily be converted to common mass units by dividing the concentration by the molar mass for carbon of 12 g mol^{-1}. All concentration data were tabulated along with site name, location, date of sample collection (as mm-dd-yyyy, and day of water year), drainage area size, fraction of site that experienced the four levels of burn severity, and geology of catchment. Water samples were also analyzed for major cations and anions, trace metals, and water isotopes, though these constituents are outside the scope of this thesis.

Data Mining

Historical data on water quality constituents in the Cosumnes River Watershed was obtained from the Water Quality Portal maintained by the National Water Quality Monitoring Council. All historical data was collected from the USGS monitoring site Michigan Bar (USGS-11335000) and accessed through the R package dataRetrieval[40]. The earliest DOC concentrations available in the watershed begin in October 2001. Samples were collected once a month from

Oct 2001 until August 2004, except for January, February, and July of 2004, during which no samples were collected. After 2004, no DOC data was collected at Michigan Bar for several years. DOC data collection resumed in October of 2012 and continued every other month until June of 2015. No further DOC data was obtained until the UCD-LBNL water monitoring campaign began in September 2021.

The USGS station Michigan Bar was also used to obtain discharge data for the watershed. This discharge data was only considered for closest sampling sites, namely RMCSD (two miles downstream of Michigan Bar) and Rancho Murieta (one mile upstream of Michigan Bar). All other ARC sampling sites were considered to be too far from the USGS site for the discharge to be an accurate representation of streamflow. Discharge data was used to determine storm events within the watershed, evaluate C-Q plots, and calculate instantaneous loads.

Baseflow Separation and Identification of Storm Periods

To classify sampling dates at RMCSD and Rancho Murieta as falling within a storm period or outside a storm period, all available discharge data from the USGS site Michigan bar was used, going back to Oct 1, 1907. This dataset was used in the *high.spells* function from the Hydrostats R package[41] to find the threshold discharge for a storm event at Michigan Bar. The threshold was defined to be 36.8 m^3/s. Each discharge value was divided into its component baseflow and quickflow parts using the *BaseflowSeparation* function in the R package EcoHydrology[42]. The default filter parameter and passes were used (0.925 and 3, respectively). The storm threshold was also used to examine the quickflow portion of the hydrograph to identify periods that could be classified as storm events. This was done using the package Hydrostats *high.spell.lengths* function.

The dates of sample collection were compared against the list of storm event periods. For the purposes of this analysis, dates that fell within a storm event or the next seven days, were classified as a storm event[43]. The seven days were added as a buffer period to account for overland flow moving throughout the watershed after the end of the storm itself as well as subsurface storage. This number was selected based on the research team's previous experience with mountainous watersheds and the average age of DOC in quickflow for low elevation watersheds with loam soils[44]. Dates that did not meet these requirements were classified as falling outside of storm events. Precipitation and snowmelt were not distinguished during the classification process.

Data Analysis

Discharge values were considered with DOC concentrations measured at RMCSD and Rancho Murieta to create C-Q plots. These plots are commonly used to examine solute behavior at a single location along a stream[45]. For the purposes of this study, RMCSD and Rancho Murieta were considered to be a single location (Figure A in Appendix) C-Q plots can be used to determine seasonal behavior, make simple predictions of solute transport, and observe hysteresis patterns[45]. Several different C-Q patterns are possible and commonly observed in forested watershed (Figure B in Appendix)[45]. For the purposes of this study, we are concerned with patterns indicating clockwise and counterclockwise hysteresis. Hysteresis patterns show differences in solute concentration at a given value of discharge when measured at the beginning and end of a water year[45]. In clockwise hysteresis, concentrations are higher at the start of the water year, whereas counterclockwise hysteresis has low concentrations at the start of the water year and high concentrations at the end[45]. These patterns can be used to draw conclusions about the depletion or replenishment of sources of solute throughout the water year[45].

In addition to C-Q plots, concentrations collected from RMCSD and Rancho Murieta were used to calculate the instantaneous load of DOC. This was done by multiplying the DOC concentration by the discharge at Michigan Bar at the time the sample was collected[46]. When no time of sample collection was recorded, the average time, 10 am, was used. The R code for the instantaneous load calculations and classification of dates within storm events can be found in the Supplemental Information.

Results

Trends in DOC Concentration as a function of discharge at the Watershed Exit

A detailed analysis of the DOC time series was possible at the watershed exit given the availability of discharge data near this site. Figure 4 shows DOC values at RMCSD and Rancho Murieta plotted as a function of the discharge measured at Michigan Bar. Water year 2022 exhibits a clockwise hysteresis effect, whereby DOC concentrations at similar discharge are three times higher at the beginning of the water year than at the end of the water year. This indicates that the source of DOC in the watershed is not readily replenished throughout the year[45]. Water year 2022 had the highest DOC concentrations measured during the study period, with DOC concentrations being especially high immediately following storm events (Figure 6). This DOC may be the result of fire burning vegetation and making DOC more available during storm events. However, it is important to note that prior to water year 2022, the Cosumnes River Watershed was in the midst of a severe drought, which began in 2019[24] (Figure 3). Thus, the observed high DOC concentrations may have been the result of normal accumulation of DOC over the course of several years not being washed away during high intensity storm events.

In water year 2023 and water year 2024, we consistently observed lower DOC concentrations as compared to water year 2022. These lower DOC concentrations indicate lower mobile organic carbon in the watershed, which required higher intensity storm events to be released. No clear hysteresis patterns were observed. However, higher discharge values were needed to produce high DOC concentrations. This trend continued into water year 2023, with 10-20x higher discharge values were required to get the mid-range DOC concentrations seen during storm events in water year 2022. Overall DOC concentrations were lower in water year 2023. Less organic carbon remained in the watershed, and it required higher intensity storm events to release what remained.

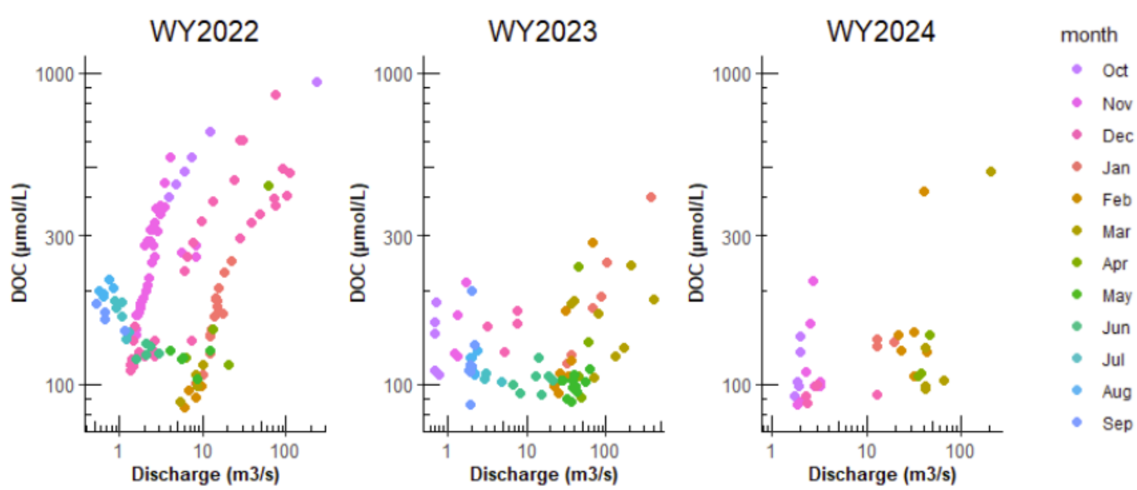

Figure 4: C-Q plots at the exit of the watershed for water years 2022, 2023, and 2024. All concentrations were measured at RMCSD and ARC sampling site Rancho Murieta.

Dissolved Organic Carbon Within Storm Events

The high intensity storm events that leached DOC from soil organic matter on hillsides and into streams can be seen in the three branching lines that radiate outward from the center of the C-Q plot. The first storm event occurred Oct 24-25, 2021, with a category 5 atmospheric river[27,28]. As the storm progressed and the stream discharge increased, more DOC entered the stream, resulting in a line of points across the C-Q plot (see arrow on Figure 5). DOC concentrations are at a maximum at the beginning of a storm event, and gradually taper off. Two more atmospheric rivers also occurred early in the water year, from Dec 10 to December 14 and from December 22 to January 1, respectively. While these atmospheric rivers resulted in similar patterns with regards to the C-Q plot, each subsequent storm required a higher discharge to produce the same in-stream DOC concentration values.

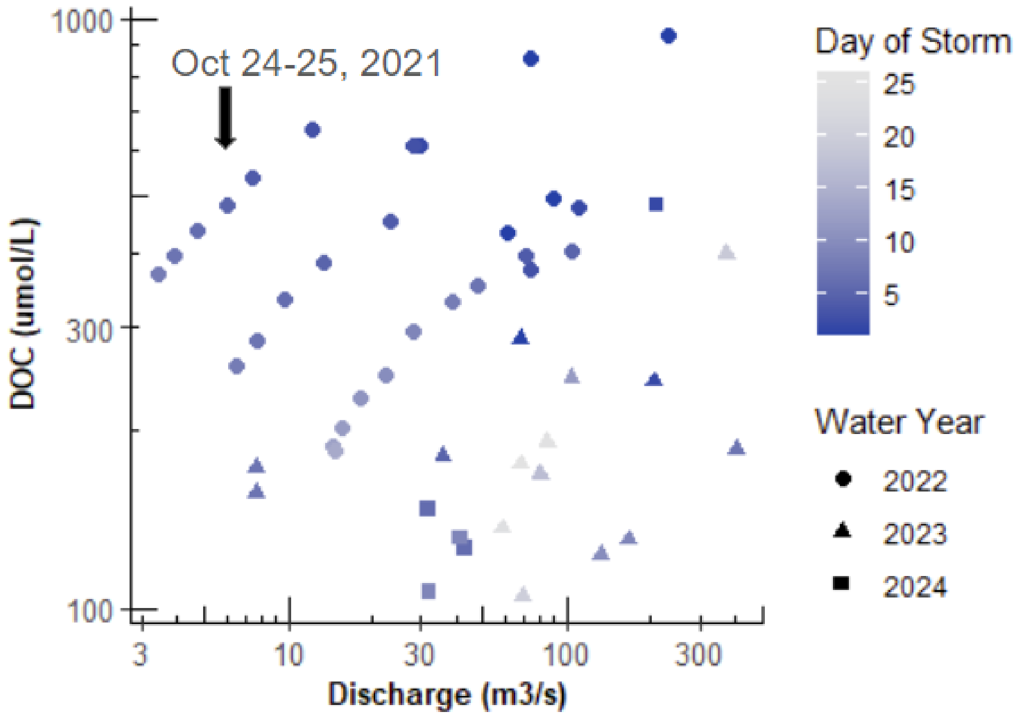

Figure 5: C-Q plot for concentrations measured at the exit of the watershed during storm events. Duration of storm events is measured as the number of days the quickflow component of hydrograph is above the storm threshold (36.8 m^3/s) plus an additional seven days. Arrow refers to points originating from October 24-25, 2021 atmospheric river.

Dissolved Organic Carbon Outside of Storm Events

In the Sierra Nevada mountain ranges, peak snowpack is considered to be April 1st[36]. From this point onwards until early summer, the streams are assumed to be fed by snowmelt[36]. Unlike with storm events, snow melt at the exit of the Cosumnes River watershed was not observed to be associated with increases in DOC concentration. Despite the high discharge values seen at Michigan Bar, DOC concentrations during snowmelt are five times lower than

DOC values observed during storm events (Figure 4). This is true for water year 2022, which experienced a short snowmelt in March and April, as well as water year 2023, which experienced a longer snowmelt from March-June. The available data for water year 2024 suggests a similar snowmelt to 2023. The low DOC concentrations suggest that the influx of water from snowmelt does not mobilize the DOC from surface ash as seen during high intensity storm events. In the September 2021 through June 2024 dataset analyzed here, snowmelt was not a significant mechanism for DOC transport post-fire.

Table 3: Average DOC concentrations at watershed exit during the months of July, August, and September. Post-fire (all time) column contains data from water years 2021, 2022, and 2023. Water year 2021 is not considered as its own year because only one data point was collected at the watershed exit during the July - September timeframe.

Time period	Average	n	Std Dev
Pre-fire	134.29 µmol/L	20	76.91
Post-fire (all time)	157.32 µmol/L	31	63.99
Water year 2022	177.84 µmol/L	15	22.46
Water year 2023	118.24 µmol/L	15	25.31

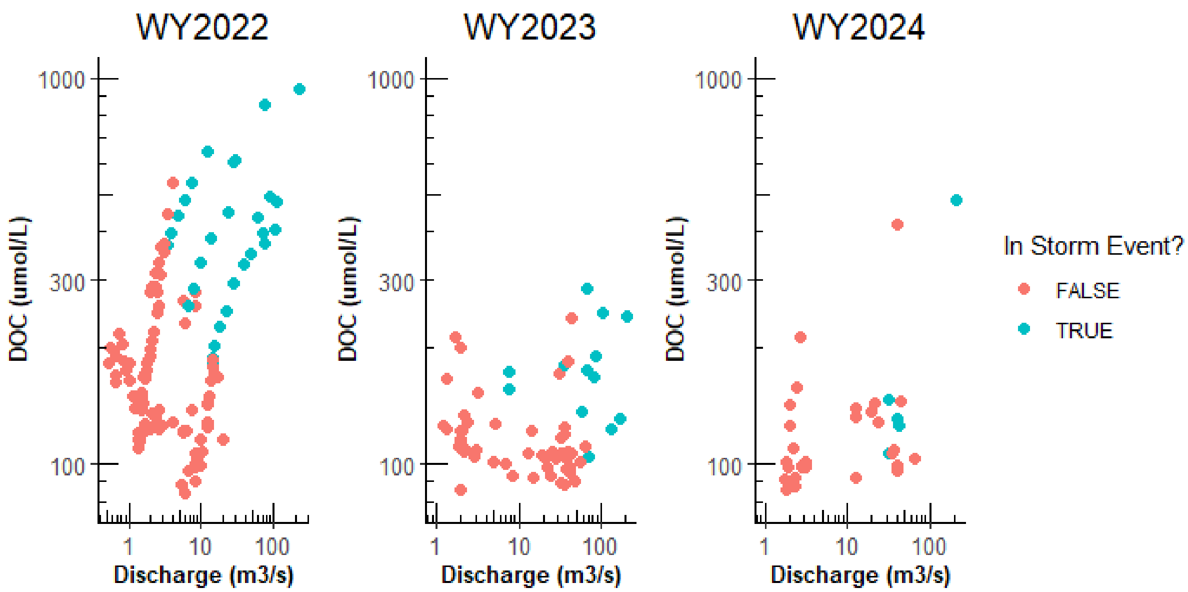

Figure 6: C-Q plots for all water years post-fire. Each point is categorized as occurring during a storm event (blue points, marked TRUE) and occurring outside of a storm event (red points, marked FALSE).

Dissolved Organic Carbon Export

The amount of carbon exiting the watershed was estimated through instantaneous load as shown in Figure 7. In water year 2022, the periods not defined as a storm event (i.e. snow melt, baseflow, and some dry periods during the rainy season), make up the bulk of the L-Q relationship. During atmospheric rivers, the loads jump above those seen during non-storm events. At a given discharge during storm events, the DOC load is considerably greater than would be expected from the same discharge during a non-storm period. The exceptions to this trend are the loads calculated from samples collected on November 10 at Rancho Murieta and November 1-30 at RMCSD, which continue to be above the L-Q non-storm points, most likely due to the category 5 atmospheric river that occurred at the end of October. Maximum loads occur during atmospheric rivers in October and December, particularly the Oct 24-25, 2021, atmospheric river event. Minimum loads occur during the baseflow period in August and September.

The water year 2023 loads also exhibit the same distribution of non-storm periods seen in 2022. However, storm events do not enhance the DOC loads in the second year after the fire. For the January and March atmospheric rivers, high values of discharge are required to produce large loads. The leaching of much of the readily mobile DOC in 2022 necessitates larger storm events in 2023 to produce similar DOC loads. The exception is the first of the atmospheric rivers in December, which was larger than subsequent atmospheric rivers, and was able to generate a small jump above the baseline for the associated value of discharge, but not to the same magnitude seen in 2022. Similar to 2022, maximum loads in 2023 occur during atmospheric river storm events, and minimum loads occur during baseflow, although in 2023, the baseflow period extended into October and November.

As of June 2024, water year 2024 follows the same non-storm load behavior as water years 2023 and 2022. Similar to water year 2023, storm events with discharge values equivalent to those seen during non-storm periods do not export enough DOC to jump above non-storm loads. These storms are not sufficiently large to transport high quantities of DOC given the smaller pool of DOC remaining after the storms in water year 2022 and 2023. It is only with larger storm events that have high values of discharge that are not seen during non-storm periods that high loads can be produced.

Both the historical pre-fire data and post-fire data collected in this study share the same general trend for instantaneous loads during non-storm periods (Figure 8). The majority of loads before and after the fire fall within a similar range and at similar discharges. Though there are a collection of loads before the fire that are lower than those seen after, and post-fire loads higher than any pre-fire loads.

The loads outside of storm periods vary from year to year. Water year 2022 loads are higher at every discharge than water year 2023. In turn, most 2023 loads are higher than 2024. High DOC loads continue for at least three years post-fire, though with each subsequent year, more precipitation and correspondingly high discharges are required to generate the high loads.

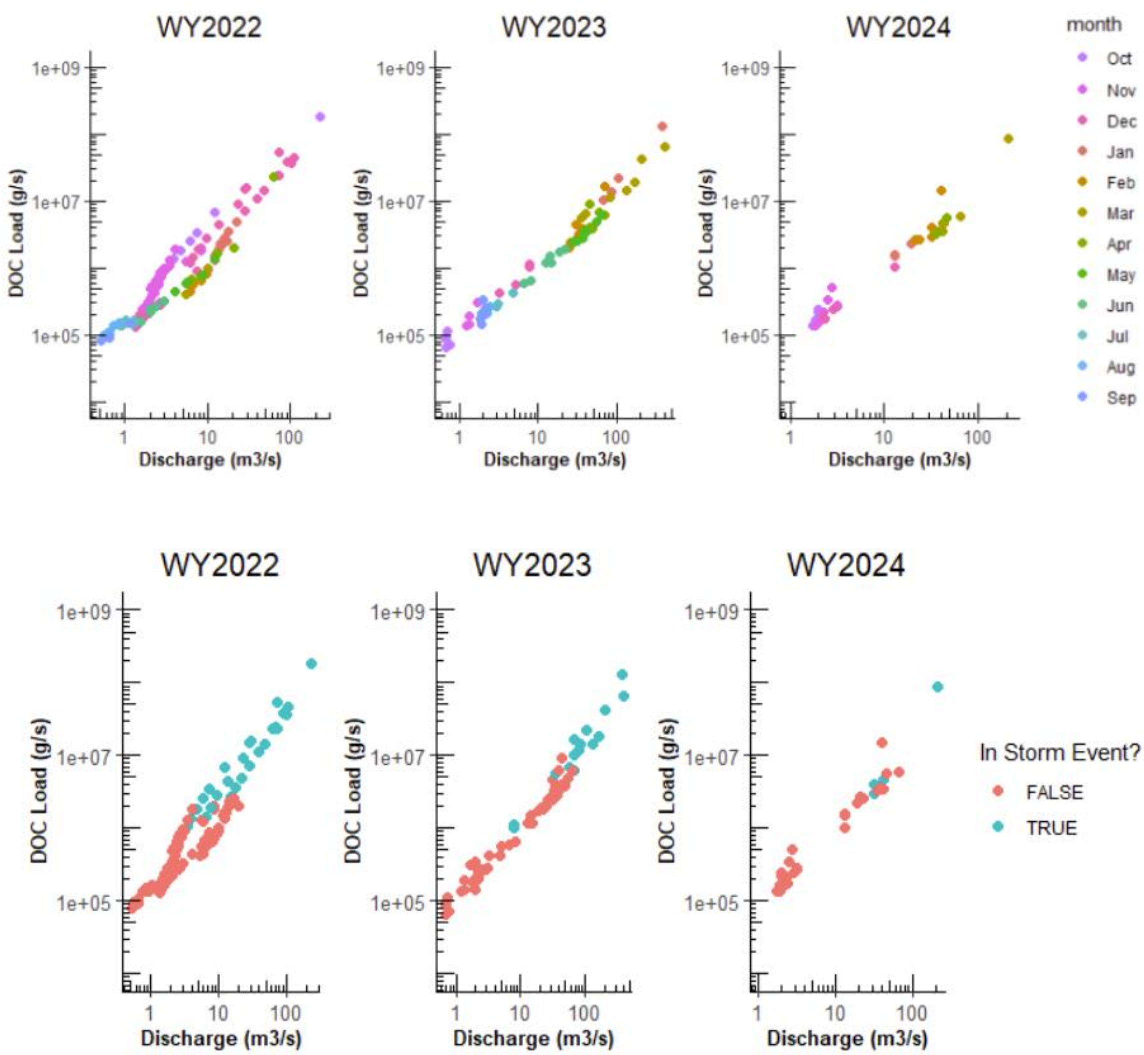

Figure 7: Instantaneous load and discharge relationships for water years 2022, 2023, and 2023 at the exit of the watershed. Loads were calculated using concentrations measured at RMCSD

and ARC site Rancho Murieta and discharge data collected from USGS monitoring station Michigan Bar. Bottom row of graphs are color coded by whether the sample was collected during a storm event (blue points labeled TRUE) or outside a storm event (red points labeled FALSE).

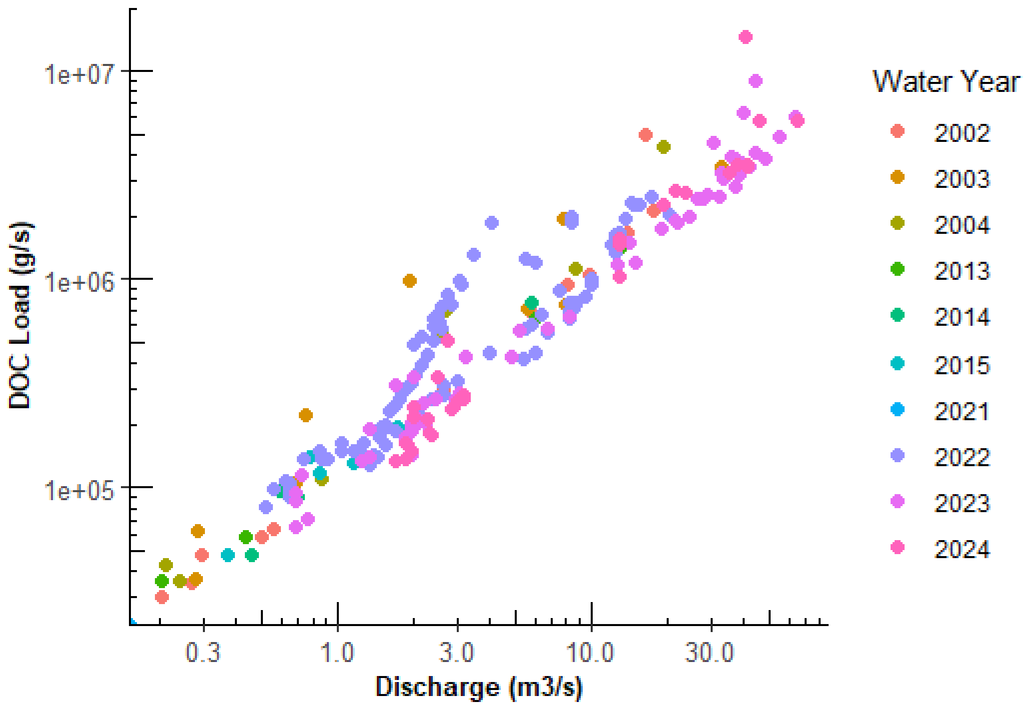

Figure 8: Instantaneous load and discharge relationships during non-storm periods at watershed exit for historic and current sampling campaigns.

Trends in Dissolved Organic Carbon Across the Watershed

Baseflow Periods

Discharge data is not available for the ARC sampling sites upstream of Rancho Murieta, and thus classifying individual sampling events as occurring during a storm event is not possible. Therefore, the storms identified at RMCSD and Rancho Murieta using Michigan Bar discharge data were used to delineate time frames for when storms, snowmelt, and baseflow likely occurred in the ARC sampling sites in upper regions of the watershed. For all years, the rainy season was defined to be October through March, snowmelt to be April through June, and baseflow to be July through September. This broad division of time periods within a water year enables us to identify relationships between DOC and sampling site characteristics.

During periods of baseflow, DOC has a negative relationship with site elevation (Figure 9, plot A). The highest DOC concentrations occur at the lowest elevation sites, namely RMCSD and Rancho Murieta. This is true for all water years for which we have baseflow data. Baseflow concentrations for water years 2022 and 2023 fall within a range of 50-200 µmol/L with no noticeable differences between these years. The limited data available for water year 2021 falls mostly within this range, with the exception of a value in the 400 µmol/L range measured on September 17, 2021 at Rancho Murieta. While this time point does fall during a time the Caldor Fire was active, it is unlikely we are seeing direct impacts of the fire, as there had not yet been storm events to wet soils and facilitate DOC transport. While there could be direct deposit of DOC from smoke or wind, it is more likely that the elevation DOC at this time point is the result of activity in the recreation areas nearby.

In addition to its relationship with elevation, DOC in water years 2022 and 2023 also varies with the total burned area within the site drainage area (Figure 9, plot B). In this case, DOC increases with increasing burn area. In sites with a large area burned, a significant portion of the vegetation became a layer of ash on the soil surface. When conducting sampling in September 2021, the UCD-LBNL research team did not see evidence of a hydrophobic soil layer, suggesting infiltration remained possible inside the burned areas of the watershed. As water percolated down, it would encounter the ash on the soil surface, leeching available DOC before becoming groundwater[18] (Figure 9, plot C).

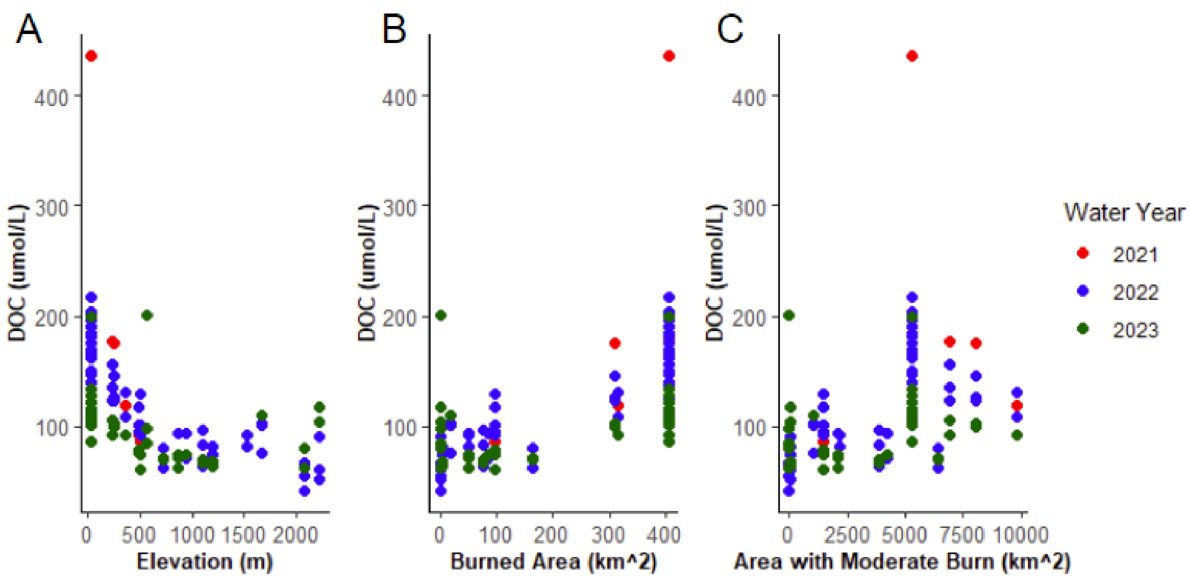

Figure 9: DOC concentrations measured at all sampling sites in July through September, which is considered to be a period of baseflow. Plot A: DOC and sampling location elevation in meters. Plot B: DOC and area of fire inside the drainage basin associated with that sampling location in square kilometers. Plot C: DOC and area of fire within the drainage area that was classified as moderate burn severity (severity 3) measured in square kilometers.

Rainy Season

Using discharge and identification of storm periods at RMCSD and Rancho Murieta demonstrated that storm events are a strong driver of DOC transport in the first-year post-fire at those locations. During the rainy season in the upper regions of the watershed, we continue to see high DOC concentrations and variations in concentration from one water year to another. Higher concentrations of DOC are measured at every elevation in water year 2022 as compared to water years 2023 and 2024. For high elevation sites, such as Foster Meadows (elevation 2081 m), this difference is very small. At lower elevations, the DOC measured at Sand Ridge (elevation 256 m) during the October 24-25 atmospheric river was six times higher than concentrations measured at the same site in October of later water years. Despite changes in the range of DOC concentrations, the negative relationship between elevation and concentration seen in baseflow holds true for the rainy season (Figure 10, plot A). This is not the case for the relationships between concentration, burn area, and moderate burn area.

Though there are some DOC concentrations measured in water year 2024 in areas of large burn area that are twice the concentration measured in areas that were completely unburned, most concentrations are similar regardless of burned area (Figure 10, plot B). A similar pattern is seen between DOC and area of moderate burn, though the few large DOC points occur in the middle of the range of areas (Figure 10, plot C). This suggests that burned vegetation's greater capacity for leaching and moderate burn severity falling within an optimal temperature range for DOC production are not the primary factor behind DOC variation in the rainy season within the Cosumnes River Watershed[18]. Instead, time since fire explains more variation in DOC concentration, as evident in the difference in DOC values measured in water year 2022 as compared to water years 2023 and 2024.

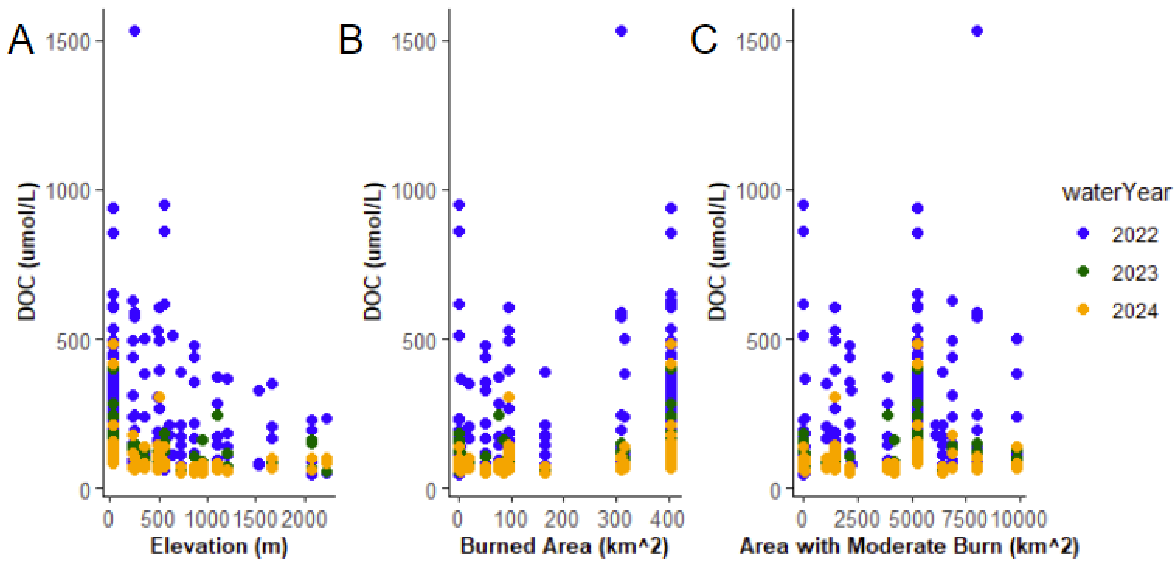

Figure 10: DOC concentrations measured at all sampling sites in October through March, which is considered to be the rainy season. Plot A: DOC and sampling location elevation in meters. Plot B: DOC and area of fire inside the drainage basin associated with that sampling location in square kilometers. Plot C: DOC and area of fire within the drainage area that was classified as moderate burn severity (severity 3) measured in square kilometers.

Snowmelt

During the snowmelt period, April through June, DOC concentration does not vary with elevation, total area burned, or area with moderate burn severity (Figure 11). In previous section of this analysis, it was found that snowmelt is not a major driver of DOC transport. As a result, site characteristics should influence variation in DOC concentration measured during this time period.

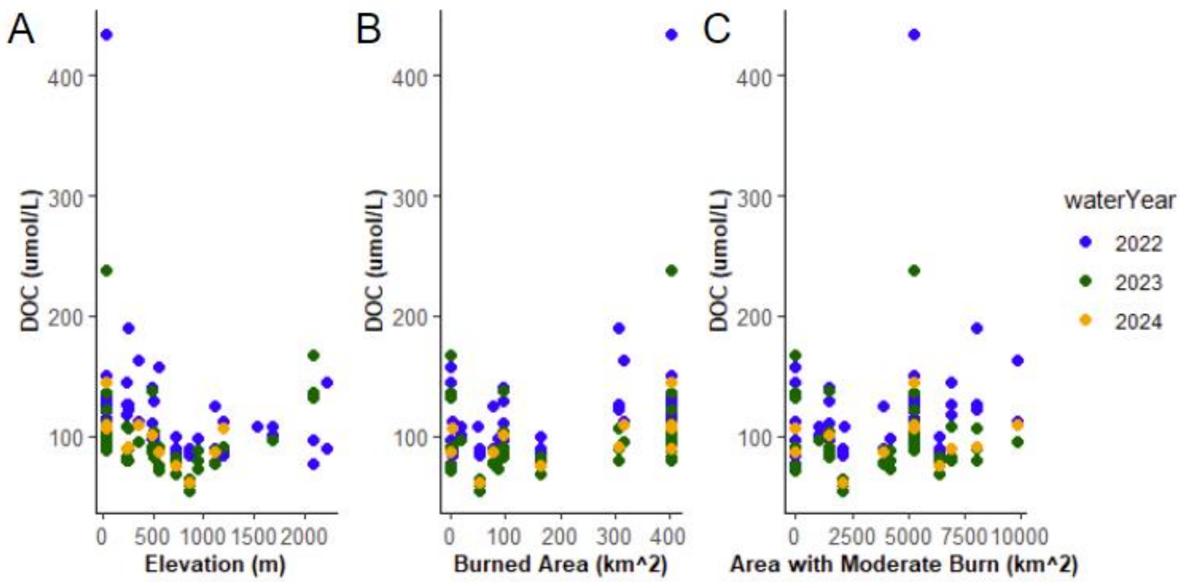

Figure 11: DOC concentrations measured at all sampling sites in April through June, which is considered to be snowmelt period. Plot A: DOC and sampling location elevation in meters. Plot B: DOC and area of fire inside the drainage basin associated with that sampling location in square kilometers. Plot C: DOC and area of fire within the drainage area that was classified as moderate burn severity (severity 3) measured in square kilometers.

Discussion

The ARC and RMCSD water monitoring campaign has provided the UCD-LBNL research team with nearly three full years of data on water quality in the Cosumnes River Watershed to use in addressing our research hypotheses. The first hypothesis, that DOC concentration would increase with area of moderate burn severity within a site area, was not supported. For all water years 2021-2024, DOC concentration did not increase with increasing moderate burn area during any part of the year. Concentration did increase with total burned area, regardless of burn severity experienced.

The second and third hypotheses, that DOC would be highest in the first-year post fire and be increased by early storm events, were supported by the data. For all water years since the fire was extinguished in October 2021, high DOC concentrations were measured during the rainy season, with maximums occurring during the first storms of the water year. The highest DOC concentrations measured during the monitoring campaign occurred directly after the fire in water year 2022. In subsequent water years, concentrations decreased, though the range of DOC concentrations did not vary from water year 2023 to 2024. Contrary to our hypothesis, snowmelt did not drive DOC transport in the Cosumnes River Watershed. The hypotheses addressed in this thesis focused on quantitative measures of water quality with regards to DOC, but it is also important to consider the resilience of the watershed in relation to the ecosystems and communities that depend upon it's healthy functioning.

The 2021 Caldor Fire had a devastating impact on the nearby communities[22]. Over the nearly seventy days of active fire, more than 50,000 residents were evacuated, 1,000 structures destroyed, and 21 fire personnel and civilians injured[22,37]. DOC concentrations measured at the local water treatment facility (RMCSD) exceeded the 2.0 mg/L limit in drinking water set by the US EPA by a factor of six during the atmospheric river event directly after the fire[47]. Measured concentrations continued to exceed this limit during high-intensity storm events for the next three years. Despite this, other California wildfires demonstrate the Caldor Fire's potential to increase the overall resilience of the Cosumnes River Watershed.

The Caples Fire burned in the Caples Creek Watershed of the El Dorado National Forest in October of 2019[48]. The fire was intended as a prescribed burn to improve watershed ecological functioning, though high winds increased fire activity and its classification was changed from prescribed burn to wildfire[48]. As a result, the Caples Fire experienced a range of low to high burn severities in an ecosystem much like the Cosumnes River Watershed[48]. Two years later, the area burned by the Caples Fire played an essential role in protecting the Caples Watershed and nearby communities from the Caldor Fire[49].

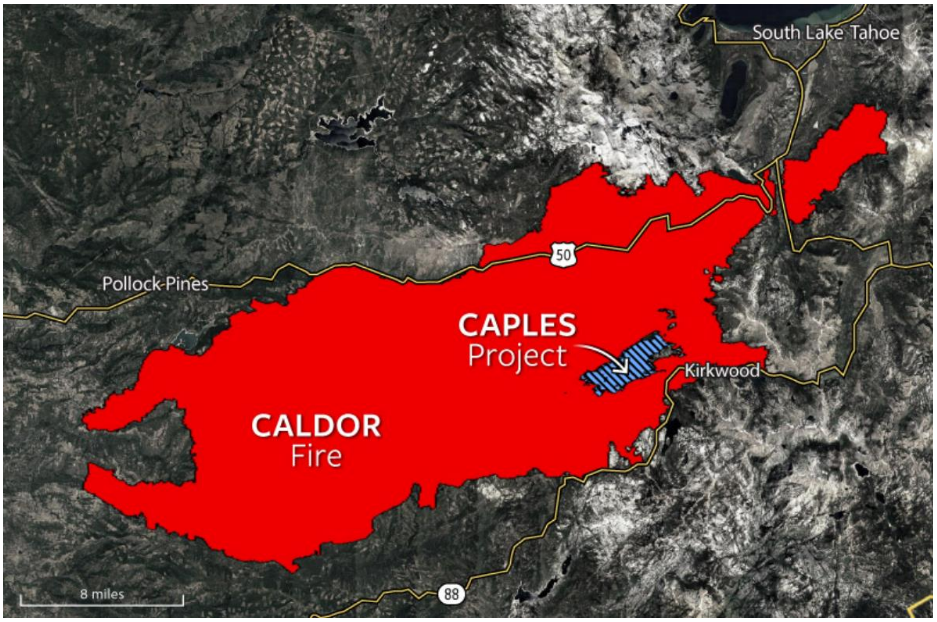

Figure 12: Burn areas of the 2021 Caldor Fire (red shading), and 2019 prescribed burn the Caples fire (blue shading). Map courtesy of Sierra Nevada Conservancy[49].

In areas burned by the Caples Fire, the Caldor Fire was slowed significantly[50]. The perimeter of the Caples burn scar did burn, but the interior did not, even given the high winds, extreme heat, and drought of the later summer and fall of 2021[49]. As the Caples Fire protected the watershed from the Caldor Fire, the Caldor Fire itself may prove a source of resilience for the Cosumnes River Watershed in the coming fire seasons.

Conclusion

Increases in the frequency and severity of California wildfires have underscored the need for information on the behavior of dissolved organic carbon during storm events and over the long-term several years post fire. In collaboration with citizen scientists from the American River Conservancy and technicians from the Rancho Murieta Community Services district, UCD and LBNL established a surface water sampling program in the Cosumnes River Watershed post Caldor Fire to obtain spatially and temporally measurements of DOC. In the first water year post fire, atmospheric rivers drive an influx of DOC into streams. The second- and third-year storms require higher discharge to produce the DOC concentrations and instantaneous loads seen in the first year. For all years post fire, snowmelt is not a significant pathway for DOC to enter streams. Total burned area and area with moderate burn severity increases DOC concentrations during baseflow periods but has little to no effect on concentration during the rainy season and snowmelt periods. Continued sampling in this watershed is necessary to determine if high intensity storm events continue to drive spikes in DOC concentrations as the watershed recovers from the mega wildfire.

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Appendix

Study	**Fire**	**Constituents(s)**	**Length of Monitoring**
Uzun et al 2020	Rocky and Wragg Fires, 2015	DOC, total dissolved nitrogen, ammonia, nitrate, nitrite, bromide, $SUVA_{254}$	2 years (16-17 samples collected per year)
Mast and Clow 2008	Glacier National Park Fires, 2003	Total nitrogen, nitrate, DOC, sulfate, chloride,	4 years
Santos et al 2019	Rim Fire, 2013	DOC, total dissolved nitrogen, dissolved organic nitrogen, calcium, magnesium, potassium, sodium, chloride, nitrate, ammonium, sulfate, phosphate	June- October 2014
Miller et al 2013	Gondola Fire, 2002	Ammonia, non-protein nitrogen,	5 years

		phosphorus	
Taylor et al, 1993	Unnamed fire upstream from Lexington Reservoir, California 1985	Dissolved oxygen, pH, specific conductance, water transparency, nitrogen, phosphorus, calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, aluminum, arsenic, boron, cadmium, chromium, cobalt, copper, iron, lad, manganese, mercury, molybdenum, nickel, selenium, vanadium, zinc	2 years

Table A: Subset of past studies monitoring stream water quality after wildfire.

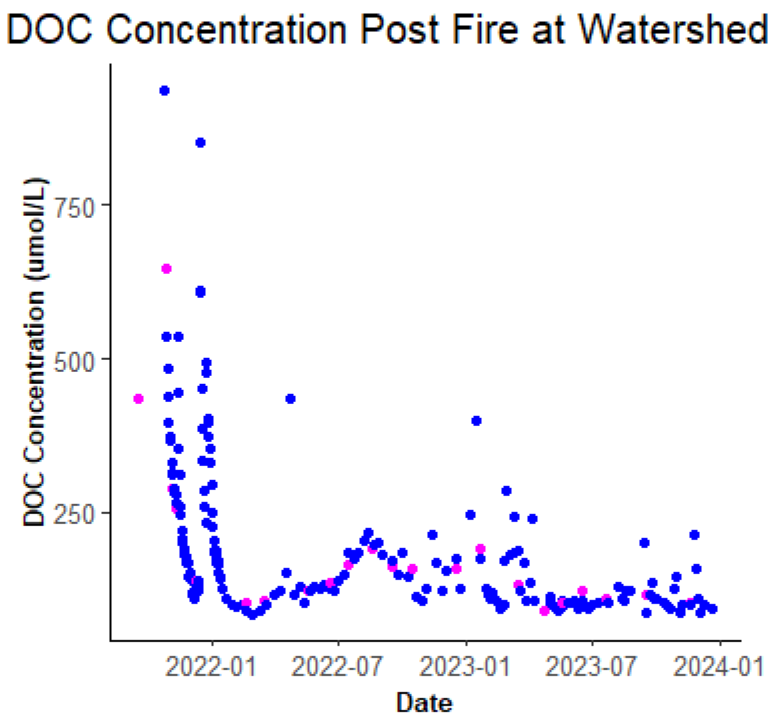

Figure A: Graph showing agreement between DOC concentrations measured at RMCSD and ARC site Rancho Murieta.

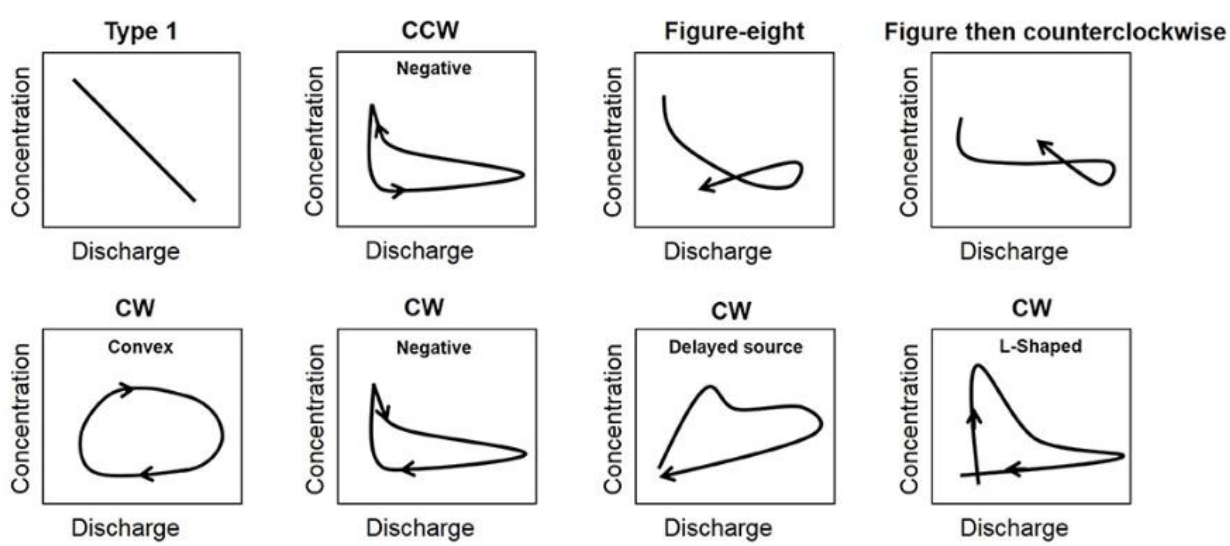

Figure B: Types of C-Q patterns commonly observed at the East River Catchment. Figure courtesy of Arora et al[45].

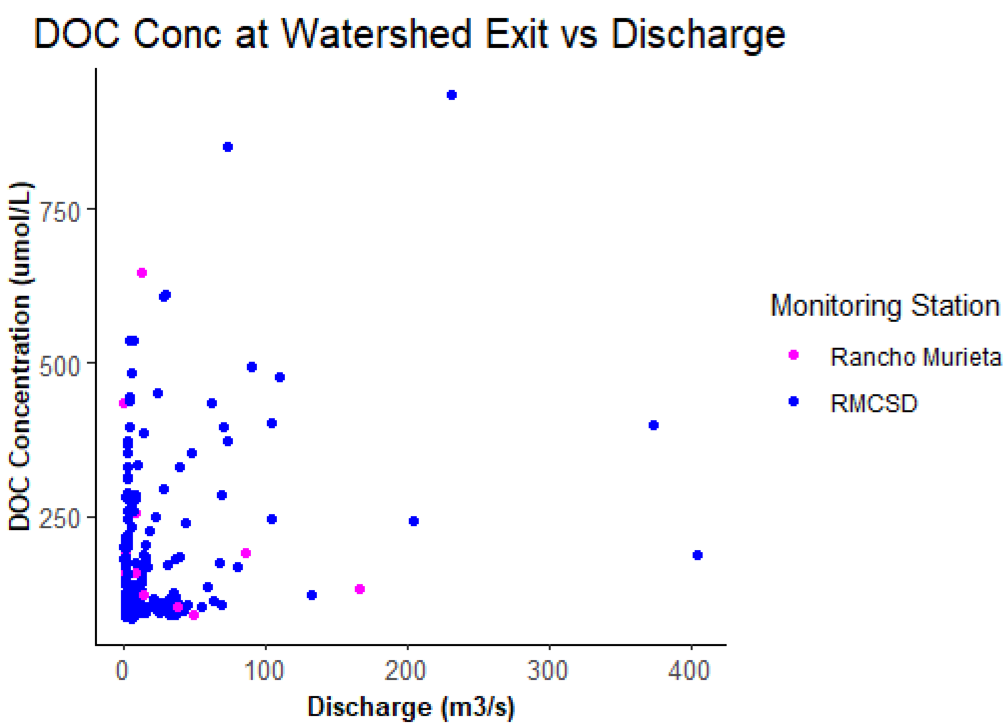

Figure C: C-Q plot of data collected from watershed exit for all time (Sept 2021 - June 2024) on linear scale.

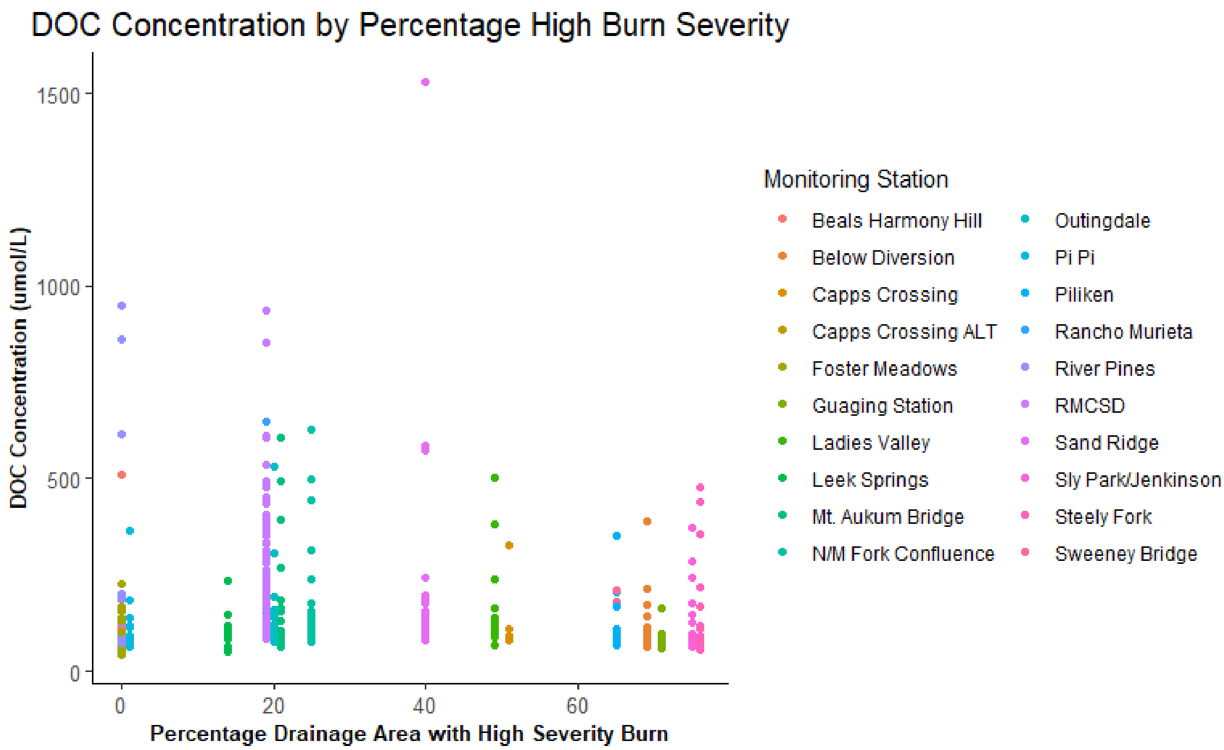

Figure D: Graph of DOC concentration and percentage of site drainage area that experience high severity burn. Points are colored based on the monitoring station name.

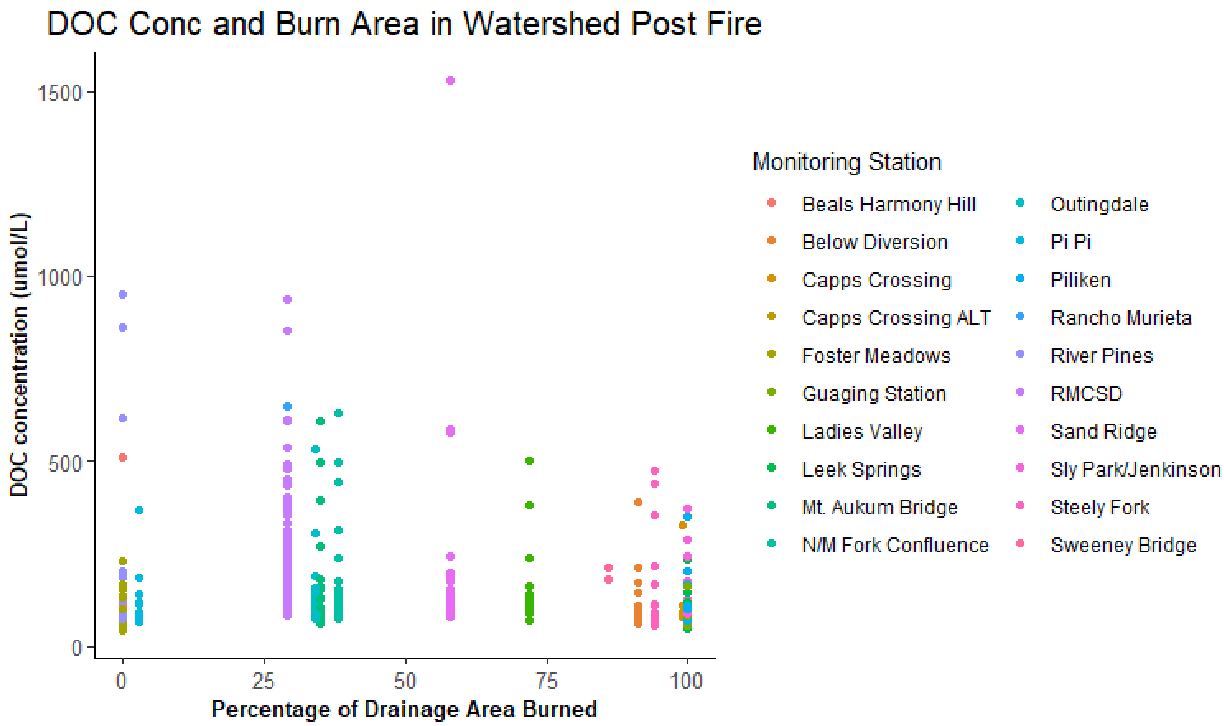

Figure E: Graph of DOC concentration and percentage of total site drainage area that experienced burn. Points are colored based on the monitoring station name.