



RMP
REGIONAL MONITORING
PROGRAM FOR WATER QUALITY
IN SAN FRANCISCO BAY

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Suspended Sediment Loads Analysis of Four Creeks in the San Francisco Bay Area

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Executive Summary

The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) and the permitted stormwater dischargers are undertaking extensive efforts to employ dynamic simulation models to assess the impact of management actions on water quality over time. The calibration of these models is hindered by the scarcity of urban stormwater flow and suspended sediment data. The primary objective of this study was to address these data gaps by implementing a monitoring program to estimate discharge and loads of suspended sediment from select tributaries to San Francisco Bay. With input from stakeholders to define the region's data needs and design the monitoring network, four sediment sampling stations representing diverse landscape and climatic characteristics in the Bay Area were selected to add spatial heterogeneity to the current modeling calibration dataset. The creeks selected were Walnut Creek, Novato Creek, Arroyo Corte Madera del Presidio, and Belmont Creek.

Five datasets were collected and/or evaluated at each site to estimate discharge and suspended sediment loads for the monitoring period as well as for long-term, climatically-averaged loads. These datasets included rainfall, stage, discharge, turbidity, and suspended sediment. Monitoring was conducted from Water Year (WY) 2020 to 2023. WYs 2020 and 2021 were among the driest two consecutive WYs on record in the Bay Area. These years were followed by an approximately average WY in 2022, and then a historic wet year in WY 2023. Very large storm events occurred on October 24th, 2021 and December 31st, 2022. The period between December 27, 2022 and January 17, 2023 was the second wettest consecutive 3-week period in recorded history in San Francisco. This extreme climatic variation during the monitoring period presents a good scenario from which to estimate loads using just a few years of data.

For all sites, we elected to produce estimates of sediment loads and yields using the discharge-SSC relationship. These relationships provided logical results of sediment loads and yields from the channels. Walnut Creek had the highest load and yield. Novato Creek had moderately high loads and yields. While the average SSC at Novato and Belmont creeks were the same, because Belmont is much smaller and on the drier peninsula region, it had lower discharges and sediment loads.

For most watersheds, sediment loads are transported disproportionately during large storm events with high flows. This is due to the compounding factors of high discharges and higher SSC as discharge increases. All four monitored creeks experienced disproportionately high sediment load transport during either the large storm events on October 24, 2021 (ACMdp; storm centered on North Bay) or December 31, 2022 (Belmont and Walnut Creek; storm centered in Central and South Bay), or during a moderate storm event that fell on highly saturated soils at the end of a prolonged two-week rainy period and produced significant runoff (Novato Creek). In all four watersheds, these single-day events transported significantly greater sediment loads than the entire WYs 2020 and 2021 combined, highlighting the importance of monitoring during wet years in order to more accurately estimate suspended sediment loads.

During analysis of the study results, some key data gaps were identified that increased the uncertainty of the results. At Arroyo Corte Madera del Presidio, two distinct discharge-SSC relationships were evident in the data. The two relationships were so distinct and so different from one another that we did not find it acceptable to simply average the relationships but instead, presented the sediment loads results for both relationships and concluded that the actual load is likely somewhere between the two extreme estimates. Therefore, we recommend collecting additional SSC monitoring data over the course of a season to try to identify the underlying factors that result in each distinct discharge-SSC relationship. At Novato Creek, SSC sample collection was focused during lower and moderate flow events, and we recommend additional SSC sample collection, focusing only on flows greater than 350 cfs. At Walnut Creek, there is significant uncertainty in the discharge rating curve above flows greater than 2400 cfs, resulting in uncertainty in the total estimated sediment load during seasons with high flows. Therefore, we recommend improving the discharge rating curve with measurements greater than 2400 cfs. At Belmont Creek the dataset is relatively strong due to the acceptable continuous data and discretely collected SSC samples at the full range of discharges for the creek, and no key data gaps are identified for this creek.

Ultimately, the findings of this study will enhance the calibration and accuracy of existing simulation models and will also contribute to a better understanding of the complex interactions between urban stormwater flows and sediment transport in the region.

Table of Contents

Executive Summary	4
Table of Contents	6
1. Introduction	7
2. Methods and Site Description	7
2.1. Study Area	7
2.2. Turbidity	12
2.3. Suspended Sediment	13
2.4. Continuous Data: Stage, Discharge, Rainfall and Turbidity	13
2.5.2 Resampling	17
2.5.3 Loads Estimation Methods	17
3. Results	17
3.1. Belmont Creek	18
3.1.1. Data completeness assessment for Belmont Creek	18
3.1.2. Continuous data for Belmont Creek	18
3.1.3. Sediment load estimates for Belmont Creek	20
3.2. ACMdP	23
3.2.1. Data completeness assessment for ACMdP	23
3.2.2. Continuous data for ACMdP	24
3.2.3. Sediment load estimates for ACMdP	26
3.3. Novato Creek	30
3.3.1. Data completeness assessment for Novato Creek	30
3.3.2. Continuous data for Novato Creek	30
3.3.3. Sediment load estimates for Novato Creek	32
3.4. Walnut Creek Results	35
3.4.1. Data completeness assessment for Walnut Creek	35
3.4.2. Continuous data for Walnut Creek	36
3.4.3. Sediment load estimates for Walnut Creek	38
4. Long-term average suspended sediment yields	42
5. Conclusions	43
6. References	45

1. Introduction

Urban runoff has been identified as the most significant controllable pathway for various pollutants that adversely affect the beneficial uses of San Francisco Bay. Permitted stormwater dischargers in the region are currently undertaking extensive efforts to identify pollution sources, evaluate their relative importance, choose and optimize the location of management practices, and employ dynamic simulation models to assess the impact of management actions on water quality over time. Despite these efforts, the calibration of these models is hindered by the scarcity of urban stormwater flow and suspended sediment data that span a full range of episodic flow conditions when the majority of sediment transport occurs. In addition, existing datasets do not cover the full diversity of microclimates and sedimentary provinces of the Bay Area.

This project aimed to help build out a more robust and comprehensive dataset on flow and sediment concentrations and loads that can be used to support modeling that informs and improves the management of urban stormwater pollution in the San Francisco Bay Area. The primary objective of this study was to address these data gaps by implementing a comprehensive approach that encompassed three main technical elements. The first element involved a planning phase. The team followed a systematic approach that incorporated input from various stakeholders to define the region's data needs and design the monitoring network. The second element involved the actual monitoring process, where data were gathered from selected Bay Area creeks to generate an accurate representation of the urban stormwater flow and sediment concentration and loads. Lastly, the third element concentrated on reporting and communicating the results obtained from the study, ensuring that relevant stakeholders have access to this vital new information. Ultimately, the findings of this study will not only enhance the calibration and accuracy of existing simulation models but will also contribute to a better understanding of the complex interactions between urban stormwater flows and sediment transport in the region.

2. Methods and Site Description

2.1. Study Area

We established four sediment sampling stations in four local San Francisco Bay Area watersheds (Table 1; Figure 1). These small tributaries – Belmont Creek, Arroyo Corte Madera del Presidio (ACMdP), Novato Creek, and Walnut Creek, encompass a wide range of geographic, topographic, microclimatic, and land use conditions. This range of landscape and climatic characteristics were selected intentionally in order to provide a more diverse calibration dataset for modeling purposes with a focus on choosing watersheds with large portions of urban land use (Table 2).

ACMdP (Figure 2) is a relatively steep, 12 km² watershed in Marin County of the North Bay, which drains the eastern side of Mount Tamalpais East Peak. It is less developed than the other watersheds (7.6% imperviousness) and also has the highest annual rainfall (Table 3). Most of the watershed is either open space or low-density residential.

Table 1. Sampling location information.

Watershed Name	County	City	Nearest Cross Streets	Latitude (WGS 1984)	Longitude (WGS 1984)
Arroyo Corte Madera del Presidio	Marin	Mill Valley	Miller Ave and La Goma St	37.897339	-122.535550
Novato Creek	Marin	Novato	Novato Blvd and 7th St	38.106927	-122.578717
Belmont Creek	San Mateo	Belmont	Harbor Blvd and Old County Rd	37.517187	-122.271180
Walnut Creek	Contra Costa	Concord	Diamond Blvd and Willow Pass Rd	37.969485	-122.053825

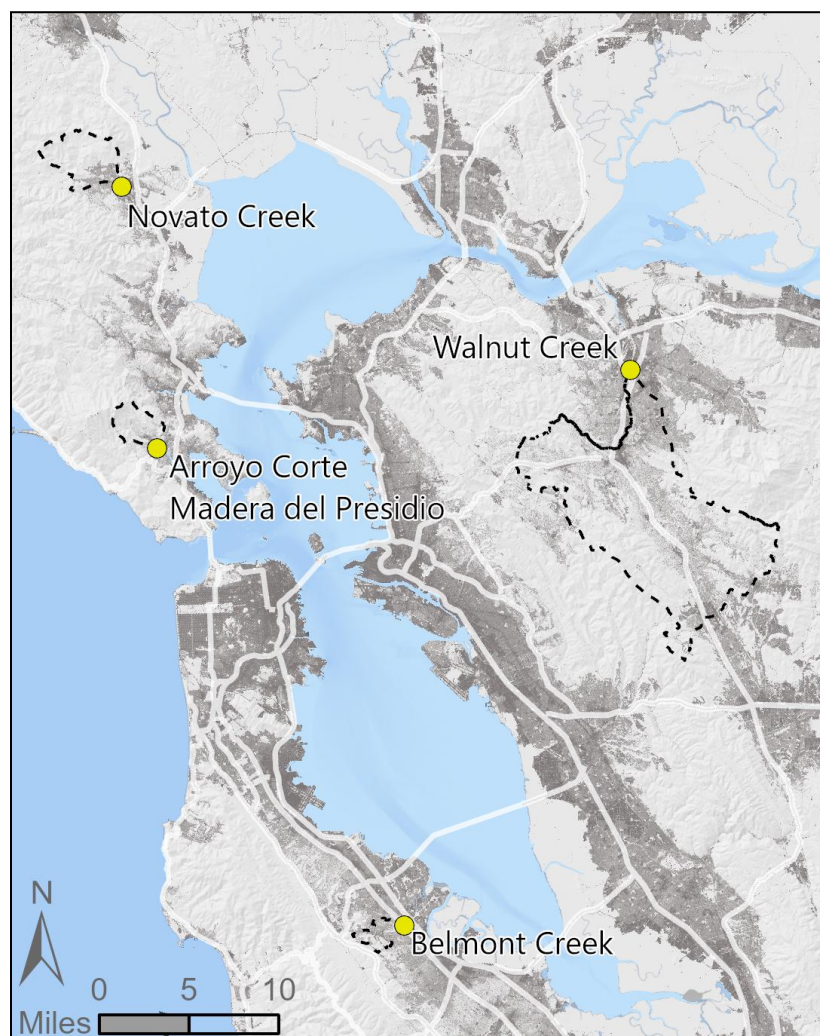


Figure 1. Sampled watersheds and sampling locations. Gray shading indicates degrees of imperviousness (very light gray (0% imperviousness to very dark gray (100% imperviousness) (NLCD, 2019).

Table 2. Land use characteristics of the monitored watersheds (imperviousness data from NLCD, 2019, and land use data from Metropolitan Transportation Commission, unpublished).

Watershed Name	Watershed Area (sq. km)	Imperviousness	Open Space (%)	Residential (%)	Commercial (%)	Industrial (%)	Transportation (%)
Arroyo Corte Madera del Presidio	12.0	7.6%	47.4%	39.2%	4.5%	0.0%	8.9%
Novato Creek	25.6	7.9%	78.3%	17.5%	0.5%	0.0%	3.7%
Belmont Creek	7.6	29.0%	22.3%	56.1%	8.0%	0.2%	13.4%
Walnut Creek	232	15.2%	40.9%	45.9%	4.8%	0.4%	8.0%

Table 3. Climatic and landscape characteristics of the monitored watersheds. Average weighted precipitation is derived using the PRISM 30-year normals for 1991-2020 (PRISM Climate Group, 2022).

Watershed Name	Watershed Area (sq. km)	Average Weighted Precipitation (mm)	Average Weighted Slope (%)	Soil Type B	Soil Type C	Soil Type D	Soil Type Undefined
Arroyo Corte Madera del Presidio	12.0	1014	41.4%	35%	18%	34%	13%
Novato Creek	25.6	1010	27.2%	4%	75%	5%	16%
Belmont Creek	7.6	594	23.4%	3%	16%	81%	0%
Walnut Creek	232	603	22.9%	9%	25%	62%	5%

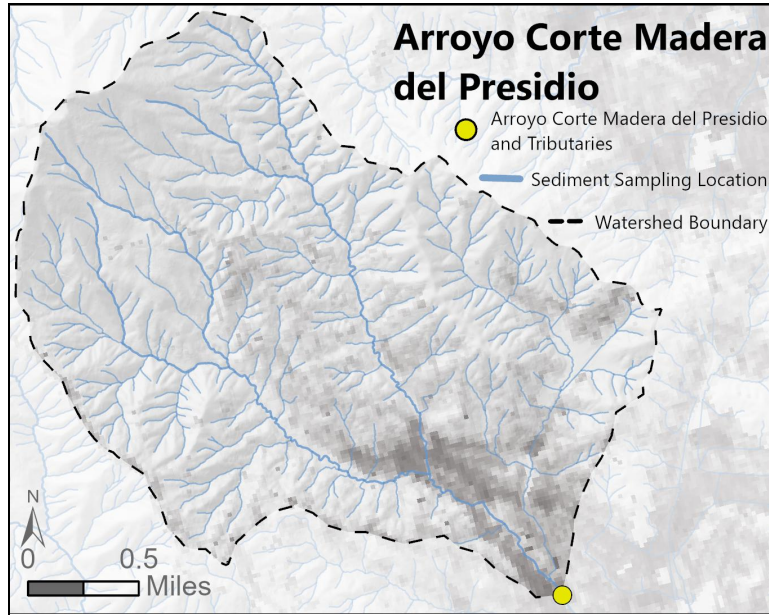


Figure 2. Arroyo Corte Madera del Presidio watershed and sampling location.

Novato Creek (Figure 3), also in Marin County, is a larger watershed (25.6 km²) than ACMdP, and lower average slope. Similar in imperviousness to ACMdP, almost 80% of Novato Creek is open space. The upper portion of this watershed is cut off by the dammed Stafford Lake.

Belmont Creek (Figure 4) is located in San Mateo County. It is the smallest watershed monitored (7.6 km²) and also the most urbanized of the four watersheds (29% imperviousness). Medium-density residential land use comprises over half of the watershed, which also has the greatest degree of commercial land use (8%) and transportation (13.4%) land use. The watershed receives the lowest average annual rainfall in the group, but when it does rain, this channel represents watersheds with high, fast-moving hydrographs, where much of the channel has been modified by human use.

Walnut Creek (Figure 5) is the largest undammed watershed in the Bay Area (232 km²). On the eastern side of Contra Costa County, Walnut Creek receives lower average annual rainfall than the Marin watersheds and about the same as Belmont Creek. Land use composition is similar to ACMdP although lower in general urban density and imperviousness, and a lower average weighted slope profile more similar to Novato and Belmont creeks.

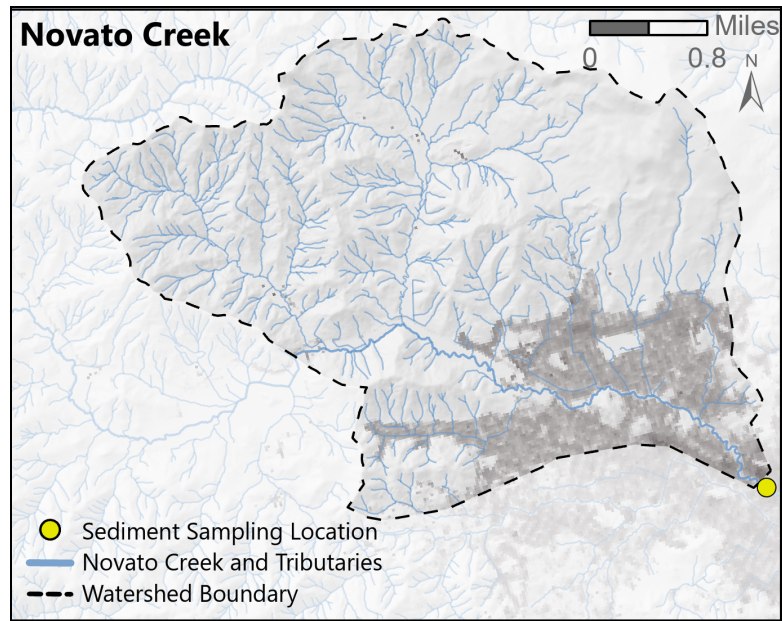


Figure 3. Novato Creek watershed and sampling location.

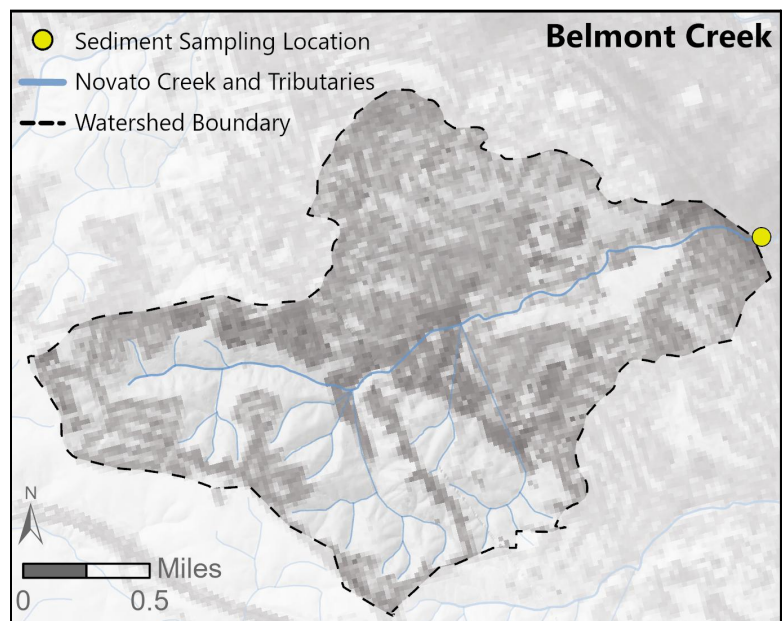


Figure 4. Belmont Creek watershed and sampling location.

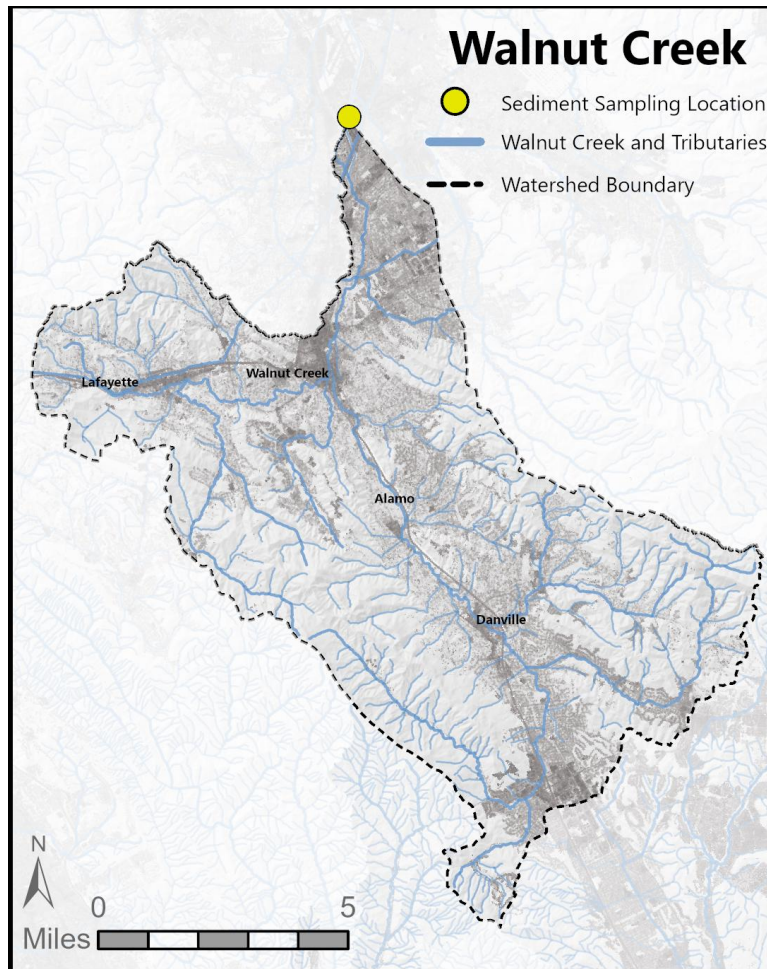


Figure 5. Walnut Creek watershed and sampling location.

2.2. Turbidity

Turbidity and suspended sediment concentration (SSC) are closely related parameters that describe a basic characteristic of water bodies; the water clarity and presence of particulate matter. Turbidity is a measure of the light-scattering properties of water, which is affected by the presence of suspended particles such as clay, silt, organic matter, and microorganisms (Davies-Colley & Smith, 2001). Suspended sediment concentration refers to the mass of suspended particles per unit volume of water, typically expressed in milligrams per liter (mg/L). The relationship between turbidity and SSC is positive; as suspended particles in the water increase, so does the turbidity (Gray & Gartner, 2009). This relationship is not always linear, and it can be influenced by several factors, including the size, shape, and composition of the suspended particles, as well as the wavelength of the incident light (Lewis, 1996).

Several studies have established empirical relationships between turbidity and SSC (e.g., Gippel, 1995; Landers & Sturm, 2013); local studies include Gilbreath et al. (2012, 2015a,b) and McKee et al. (2010). These relationships can be used to estimate SSC from continuous turbidity

measurements, which are often readily available due to the ease of collecting turbidity data using in-situ sensors at short time intervals. However, the relationship between turbidity and SSC is site-specific and may vary depending on the characteristics of the water body and suspended particles (Rasmussen et al., 2009).

Turbidity was collected at Belmont Creek, ACMdP, and Novato Creek. A [Campbell Scientific OBS 500 and 501](#) antifouling turbidity sensor was used. Measurements were taken every 5 - 15 min and data were recorded on a Campbell Scientific [CR800](#) or [CR1000](#) datalogger. At each site in the creek, the turbidity probe was mounted in the thalweg on an articulating boom that placed the sensors at approximately mid-depth under most flow conditions (McKee et al., 2004). Data are reported in units of Formazin Nephelometric Units (FNU). The FNU unit is based on the comparison of the light scattered by the water sample to that scattered by a standard solution of formazin following the ISO 7027 method for turbidity measurement. A turbidity sensor was installed at Walnut Creek but was found to be inoperable after installation. Due to time delays associated with backorders on manufacture during the Covid-19 pandemic, a new sensor could not be delivered and installed during the year that USGS maintained the site. The only continuous data available for Walnut Creek are stage and discharge.

2.3. Suspended Sediment

The four creeks were all equipped with a peristaltic automated pumping sampler ([Teledyne ISCO 6712 full size portable sampler](#)). The intake for the sampler was attached to the turbidity probe boom, thus allowing sample draw from roughly mid-depth in the thalweg of the channel. When turbidity data were available, the samplers were activated by a turbidity threshold; once a predetermined threshold was exceeded, the sampler was triggered and a new discrete grab sample was collected. Because Walnut Creek lacked a functioning turbidity sensor, automated samples were collected via stage and time triggers.

These automated samples were augmented with manually collected, depth-integrated samples collected over the rising, peak, and falling stages of the hydrograph during two to three storm events at each location. To manually collect samples, field crews used a separate automated pumping sampler (Belmont Creek, ACMdP, and Novato Creek) or a Federal Interagency Sediment Program (FISP) D-95 depth-integrating water quality sampler (used at Walnut Creek due to the large distance between the overhead structure [a road bridge] and the water surface). The intake for each sampler was manually integrated up and down through the water column using an even pace until the sample container was full. Depth-integrating samples avoids biases that others have reported with samples collected at a single point in the water column (Groten and Johnson, 2018), and therefore the automatically collected samples were adjusted based on the relationship with the depth-integrated samples.

2.4. Continuous Data: Stage, Discharge, Rainfall and Turbidity

Creek stage and rainfall were collected at each site by local municipalities or the USGS (Tables 4 and 5). These data were publicly available, which greatly aided sampling in real-time as well

as data interpretation. We retrieved the raw datasets and performed quality assurance review prior to data processing.

River stage was measured using automated pressure transducers. The setup was generally the same across locations:

1. A pressure transducer was set at a fixed location above the channel bed.
2. Data were collected every ~12 hours until a high rate of change was observed. When water depth was changing quickly, the rate of data collection increased to as often as every 5 minutes.
3. Water pressure was converted to a depth assuming hydrostatic conditions.

Discharge data were reported by the USGS for Novato Creek (station 11459500) and for Walnut Creek (station 11183670) during WY 2022. Site-specific stream-discharge rating curves were provided or developed for the other channels and then applied to the continuous stage data to estimate continuous discharge. Marin County provided the discharge rating curve for ACMdP. At Belmont Creek, SFEI collected discrete velocity measurements over a broad range of stages during multiple storm events in WY 2023 to generate a discharge rating curve. The Walnut Creek rating curve was created using the stage and discharge data available on the USGS website for station 11183670 during WY 2022. Then we applied that curve to the continuous stage record also available on the USGS website for the remainder of the period of record. Local rainfall rates were collected using tipping bucket rain gauges with a depth size of 0.04 inches. Tips were recorded and therefore data collection times varied based on rainfall intensity.

Table 4. Stage data operators and websites, and methods used to derive discharge data.

Watershed Name	Discharge or Stage Gauge & Operator	Stage Data Website	Discharge Calculation Method
Arroyo Corte Madera del Presidio	Mill Valley, Lower; Marin County	https://marin.onerain.com/site/?site_id=1550&site=302aae83-30d8-4d4a-b042-70638dfeaf2b	Rating curve provided by Marin County, then applied to the stage record to calculate discharge.
Novato Creek	Novato C at Novato CA - 11459500; USGS	https://waterdata.usgs.gov/monitoring-location/11459500/#parameterCode=00065&period=P7D	Discharge data reported on USGS website.
Belmont Creek	Belmont Creek; San Mateo County	https://smcearlywarning.onerain.com/site/?site_id=2&site=25fd9d56-e3ea-4ff9-a067-b3e99cc5c1fe	Rating curve developed by SFEI during WY 2023, then applied to the stage record to calculate discharge.
Walnut Creek (2019-10-01 to 2023-04-04)	Walnut Creek at Diamond (WDB); Contra Costa County	https://cdec.water.ca.gov/dynamicapp/staMeta?station_id=WDB	Rating curve developed using USGS discharge and stage data from WY 2022, then applied to the stage record to calculate discharge.
Walnut Creek (2021-11-01 to 2022-06-01)	Walnut C at Diamond Blvd Bridge NR Concord CA - 11183670; USGS	https://waterdata.usgs.gov/monitoring-location/11183670/?agency_cd=usgs#parameterCode=00060&period=P7D	Discharge data reported on USGS website.

Table 5. Rainfall data operators and websites.

Watershed Name	Rainfall Gage & Operator	Rainfall Website
Arroyo Corte Madera del Presidio	Mill Valley, Lower; Marin County	https://marin.onerain.com/site/?site_id=1550&site=302aae83-30d8-4d4a-b042-70638dfeaf2b
Novato Creek	Novato Library Rain; Marin County	https://marin.onerain.com/site/?site_id=16790&site=31fb73bd-d861-4c76-98a6-ae3816880cba
Arroyo Corte Madera del Presidio & Novato Creek	Kentfield	https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca4500
Belmont Creek	Belmont Creek; San Mateo County	https://smcearlywarning.onerain.com/site/?site_id=2&site=25fd9d56-e3ea-4ff9-a067-b3e99cc5c1fe
Belmont Creek (long-term gauge)	Redwood City, CA	https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca7339
Walnut Creek (2019-10-01 to 2023-04-04)	Ygnacio Valley Fire; Contra Costa County	https://cdec.water.ca.gov/dynamicapp/staMeta?station_id=YGF
Walnut Creek (long-term gauge)	Mt Diablo Junction, CA	https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca5915

Marin County provided two different discharge rating curves for Arroyo Corte Madera del Presidio. One curve resulted in flows that were roughly three-quarters the magnitude of the other curve. We calculated flows using both curves and decided to use the lower flow curve because it yielded a runoff coefficient that was conceptually more representative of watersheds with similar land use profiles. Stage records for Belmont and ACMdP were measured by pressure transducers and were typically very good, but were also validated relative to rainfall and the presence of illogical spikes were corrected via interpolation between the bounding measurements or deleted from the record and flagged. The stage record offsets were adjusted so that discharge equaled zero when the channel was dry.

Turbidity was the most challenging of the datasets to QA. There are ample opportunities for debris to catch on or near the sensor during flow events and cause turbidity spikes. At the same time, there are real, rapid changes in turbidity in flashy urban creek systems, so it was a large effort to identify false spikes in the dataset. In cases where false spikes were surrounded by most likely sound measurements, the false spike datapoint was replaced via interpolation. During sustained periods of the record that appeared suspect, the record was deleted and flagged that the sensor was not functioning correctly. The corrected continuous datasets are available in the supplementary materials.

2.5.2 Resampling

Due to the variability in dataset sampling rates, we chose to resample all of our data to 15-minute sampling intervals. This follows the standard established by the USGS and allows our data to be directly compared to other regional datasets, when available. Stage resampling was accomplished using a linear approximation: a simple line was calculated between the two data points bounding the regular interval; stage was estimated based on where the regular interval fell on that line. Rainfall resampling was conducted using a simple summation. Raw rainfall rates were recorded on a per-tip basis so any recorded tips within the interval were summed. The resampling process was automated using a script written in the R programming language.

2.5.3 Loads Estimation Methods

Sediment loads (reported in metric tonnes [t]) were estimated using the continuous discharge data combined with an estimated continuous SSC record. A regression estimator was developed for each site. This method involves developing relationships between limited SSC sample concentration data and an unlimited surrogate measure (e.g., turbidity or flow). These relationships were then applied to the unlimited surrogate measure record (e.g., the short time interval records of flow or turbidity) to calculate short time interval estimates of SSC. This load calculation method has been widely applied to estimating suspended sediment loads throughout the world (e.g., Walling and Webb, 1985; Lewis, 1996).

We discuss the completeness of the turbidity record for each site in the results section below, but overall, there were significant turbidity data collection challenges at most sites. Although a statistically significant relationship between SSC and turbidity existed for Belmont Creek, none of the other sites had robust datasets to evaluate this relationship. Therefore, at all sites, SSC sample data were regressed with discharge data measured simultaneously and then applied to the continuous discharge record to estimate continuous SSC. The relationships between discharge and SSC are shown in the results section for each site below.

Long-term, climatically-averaged loads were estimated also using a regression estimator method. The relationship between total monthly loads during the monitoring period and either total monthly discharge from the same gauge or nearby gauge, or total monthly rainfall for a nearby rain gauge, was developed. Detailed methods are reported in the results for each site below. Then that relationship was applied to the long-term monthly record (for either the discharge or rain gauge) over a 30-year time span - WYs 1991-2020. The average estimated sediment load over this time period is reported as the climatically-averaged load.

3. Results

Stage, rainfall, and turbidity data were regularly sampled and adjusted based on the data processing workflows described in Section 2.5. Rainfall and discharge data were generally complete for the data collection period at most sites. Turbidity data collection challenges throughout the monitoring period were significant. Overarching challenges included the

Covid-19 pandemic, during which initially staff were unable to complete field visits; historic dry years in the first two years of the study and large portions of the third year, during which the channels sat largely dry and therefore no turbidity was recorded; all followed by a historic wet season in WY 2023, during which the channels experienced very high flows and resulted in equipment failures. Continued moderate and high flows following the equipment failures during the largest events in WY 2023 limited access back into the channels to restore equipment function. Additional site-specific challenges leading to incomplete datasets are discussed within each site section below.

Results for each site are presented individually. Each results section begins with a data completeness description which highlights the data available for the site, any issues or inconsistencies with each dataset, and any other important information for data interpretation. Time series, divided into water years, are presented next, and finally, sediment rating curves developed with these data are presented along with the resulting loads and yields results.

3.1. Belmont Creek

3.1.1. *Data completeness assessment for Belmont Creek*

Rainfall data for WY2020 were not available and much of the turbidity data were rejected because of data quality issues. The discharge data also appeared to have significant data quality issues. Therefore, we rejected the entire WY and only reported results for WYs 2021-2023. A total of 59 samples were collected and analyzed for SSC. The Belmont Creek site is unique in that a rating curve equating stage and discharge did not exist prior to this field investigation. Team members constructed a discharge rating curve by sampling velocity across the channel at varying stages, according to USGS protocols (Turnipseed, 2010). The discharge rating curve applied to the continuous stage record to estimate discharge is available as supplementary material. During WY 2022, the station rainfall and stage data were not available, therefore, to estimate sediment loads during this time, a relationship between total monthly rainfall (from the Redwood City Rain Gauge) and total monthly sediment loads was applied, enabling us to estimate and report the total annual load and yield for that year.

3.1.2. *Continuous data for Belmont Creek*

Rainfall and discharge were extremely low for WY2021 and WY2022 during the period with acceptable data (missing Oct-Dec 2021, including the large storm event on October 24, 2021). The creek was dry during much of the period and the turbidity sensor was not installed to prevent vandalism, therefore only minimal turbidity data is available during these years. Conversely, a robust dataset is available for WY 2023. The highest flows from WY 2023 were observed in January and March. Multiple storm events exceeded bankfull and flooded nearby streets. Three storms were sampled with personnel on site (including one of the storms exceeding bankfull) and an additional four storms were sampled automatically. The majority of the turbidity observations also came from this rainfall season.

Belmont Creek - WY2021

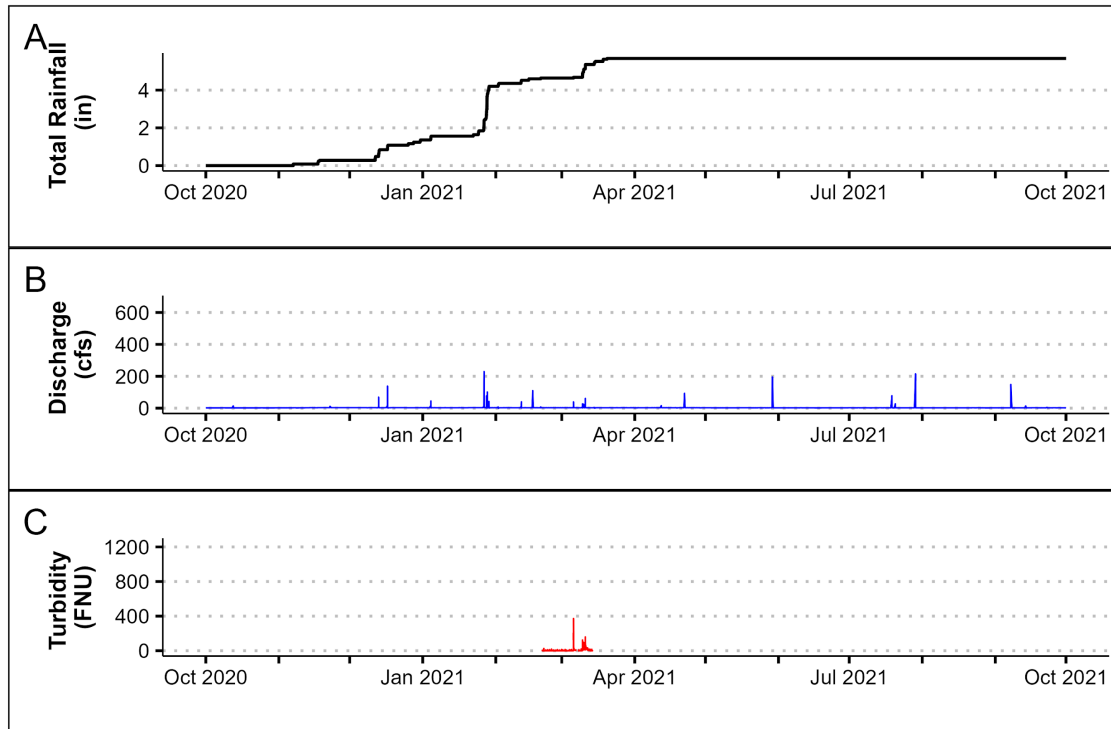


Figure 7: Belmont Creek time series of WY2021.

Belmont Creek - WY2022

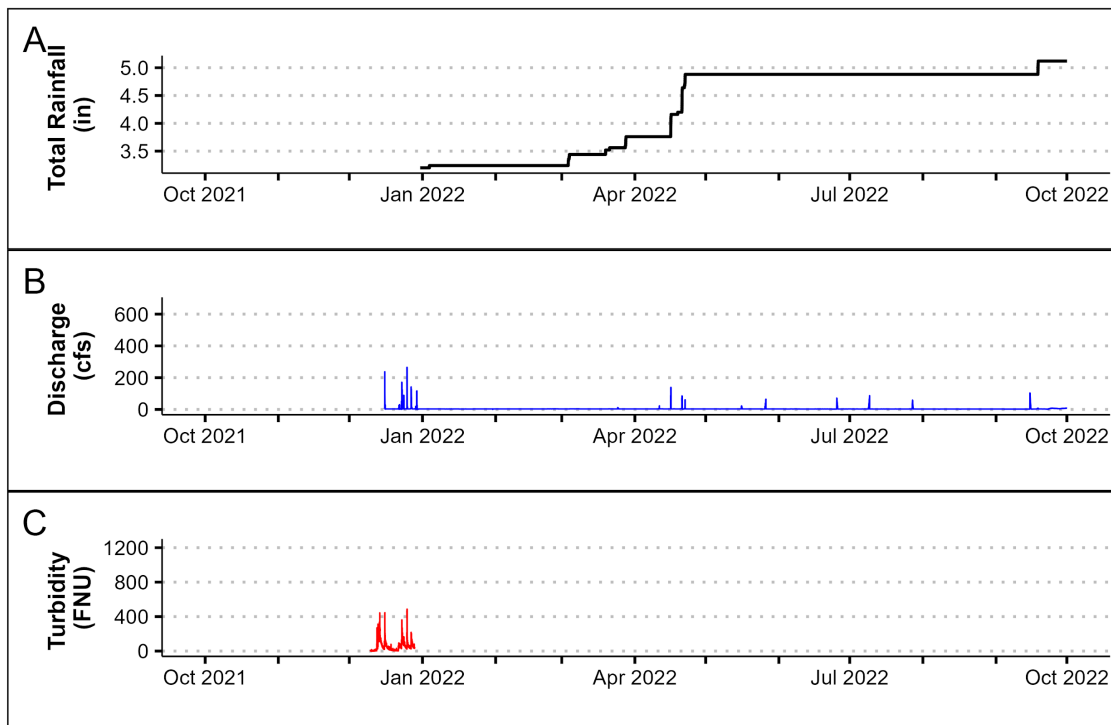


Figure 8: Belmont Creek time series of WY2022.

Belmont Creek - WY2023

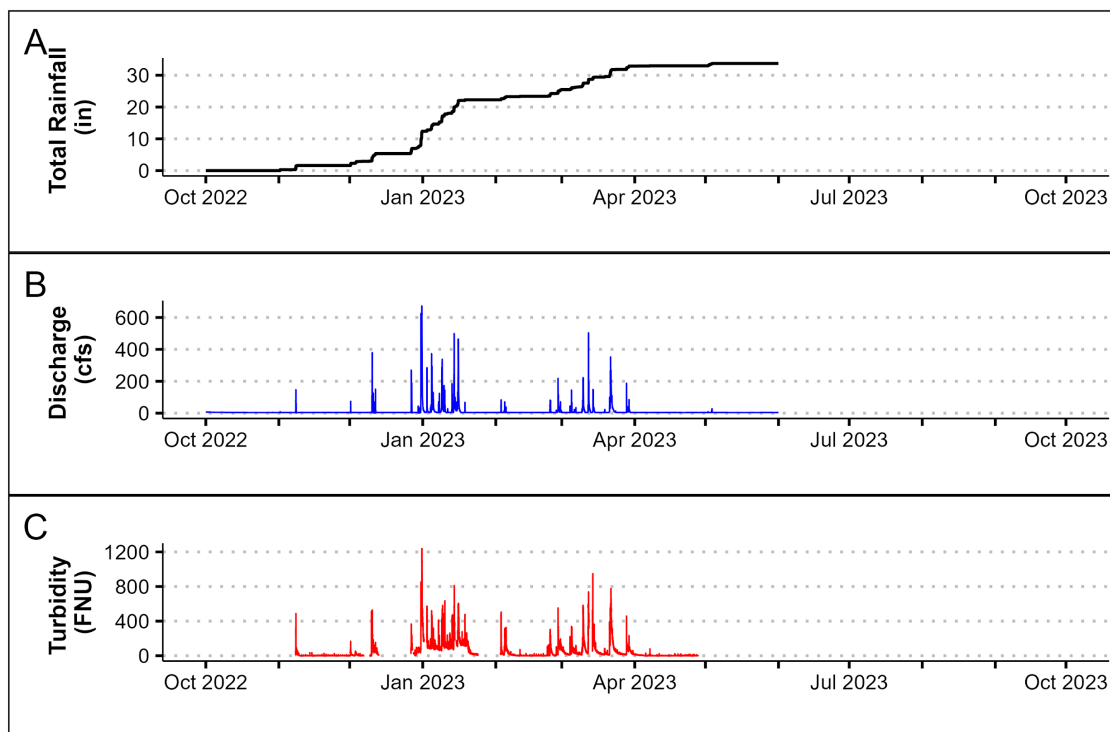


Figure 9: Belmont Creek time series of WY2023.

3.1.3. *Sediment load estimates for Belmont Creek*

SSC was sampled over a broad range of discharges and the discharge-SSC relationship was relatively strong ($R^2 = 0.82$, Figure 10). Multiple years of data collection provide confidence that the trends observed hold true across changes in weather and channel conditions. There were no statistical differences between water years, so data were compiled and analyzed as one dataset. Most storm events had a linear relationship while two had counter-clockwise hysteresis, resulting in some scatter about the best-fit line at flows below 300 cfs. The two highest discharge samples collected manually 35 minutes apart at over 600 cfs were both greater than 2600 mg/L. These are very high concentrations for a largely urban watershed and suggest high sediment inputs from the 22% open space areas.

The turbidity-SSC relationship was also strong ($R^2 = 0.79$, Figure 11). Again, there were no statistical differences between water years, so data were compiled and analyzed together. A power fit worked best for these data; concentration appeared to grow exponentially with increasing turbidity. Although this relationship was nearly as strong as the discharge-SSC relationship, we did not use it to estimate continuous sediment loads because the continuous turbidity dataset was more limited than the continuous discharge record, especially during the drier years when the turbidity sensor was not in place in order to prevent vandalism while the channel was dry.

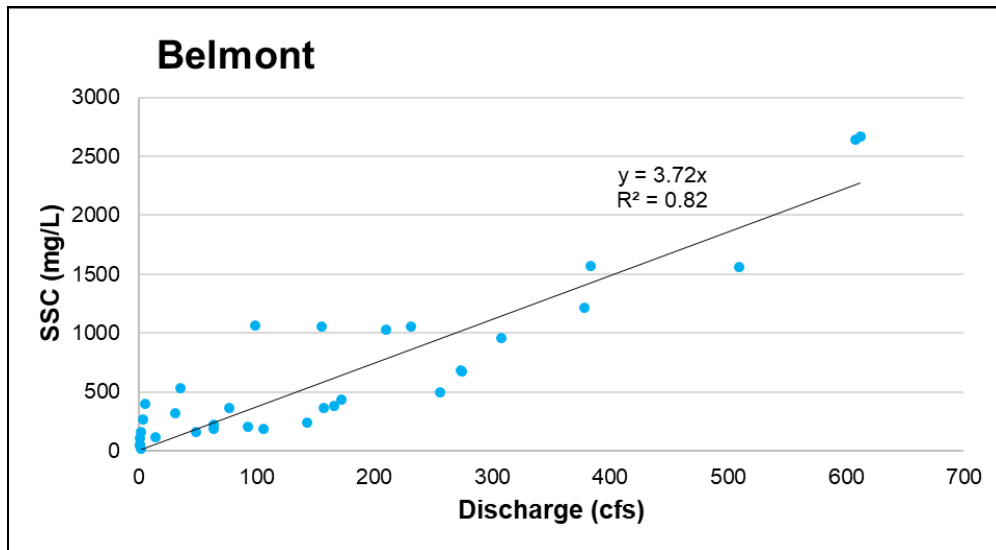


Figure 10: Discharge-SSC relationship at Belmont Creek.

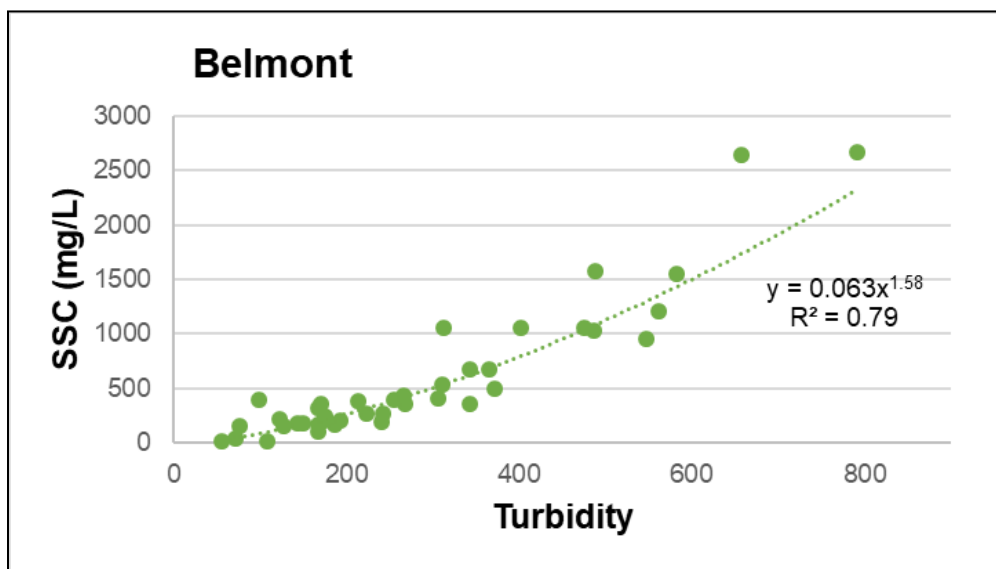


Figure 11: Turbidity-SSC relationship at Belmont Creek.

Continuous sediment loads at Belmont Creek were therefore estimated based on the relationship between discharge and SSC. Continuous loads were summed at the 15-minute, daily, monthly, and annual time steps and are reported in the supplementary materials. Total annual discharge and sediment loads at Belmont Creek for WYs 2021-2023 are reported in Table 6.

The monthly sediment load was evaluated as a function of monthly total discharge for a nearby watershed (San Francisquito Creek) gauged by the USGS, as well as the monthly total rainfall

for the nearby rainfall gauge (Redwood City, <https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca7339>). Since Belmont Creek is a relatively urban watershed, runoff processes in Belmont Creek are better correlated with the monthly rainfall data rather than the monthly discharge in the less urban San Francisquito Creek. Therefore, the relationship between the monthly rainfall at Redwood City and the monthly discharge in Belmont Creek (Figure 12) was combined with the long-term (1991-2020) rainfall record from Redwood City to estimate the long-term monthly sediment loads. This monthly sediment loads record was used to estimate long-term average (or “climatically-averaged”) loads and yields (reported in Table 6).

The monitored period was notably dry during WYs 2020 and 2021, average for WY 2022, and well above normal for WY 2023 (192% of normal at the Redwood City rainfall gauge). Discharge totals between the driest and wettest monitored seasons varied over 7-fold, whereas the higher and lower estimates of sediment load were separated by over 60-fold.

The largest storm event at Belmont Creek occurred on December 31, 2022, when an atmospheric river stalled over the Peninsula region of San Francisco Bay (Table 7). The 24-hour rainfall total for the site was 4.56 inches, which was approximately a 10-year event. Total discharge that day was 0.69 million cubic meters (Mm³) or approximately 40% of the climatically-averaged total annual discharge. This storm event had very high flows and transported a disproportionate amount of sediment load in just a single day - 1,100 metric tonnes (t), or almost double the long-term average load for an entire year.

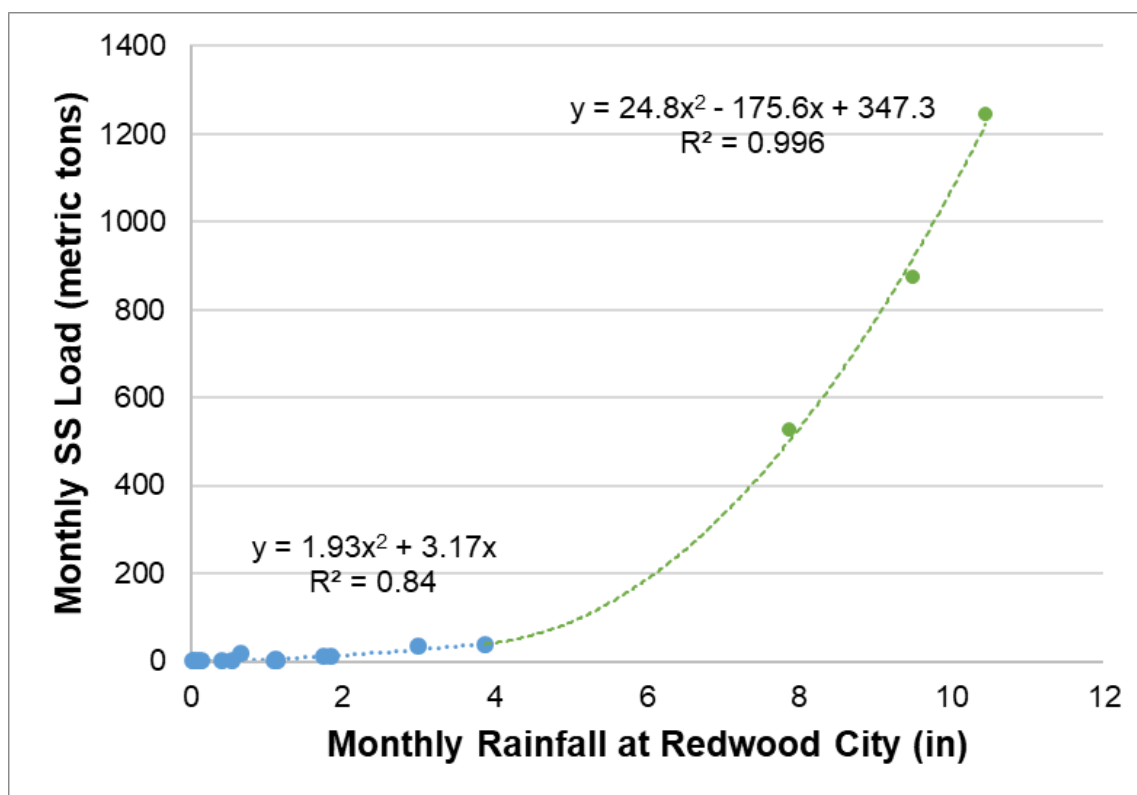


Figure 12. Relationship(s) used to estimate long-term yields from a long-term rainfall record.

Table 6. Total annual rainfall, discharge and sediment loads at Belmont Creek for WYs 2020-2023 and the long-term climatic averages.

Water Year	Redwood City Rainfall (in)	Discharge (10 ⁶ m ³)	Sediment Load (metric tons)	Sediment Yield (metric tons/sq km)
WY 2020 Total	NA	NA	NA	NA
WY 2021 Total	6.3	0.52	43	5.7
WY 2022 Total*	18	1.9	1000	132
WY 2023 Total**	35	3.8	2700	360
Climatic Average***	18	1.7	630	83

* October-December 2021 were missing and therefore values are estimated based on relationships with rainfall at the Redwood City rain gauge.

** Record ends May 31, 2023; missing June-September 2023.

*** Based on the 30 year record between WYs1991-2020.

Table 7. Largest single day totals in monitored period and climatically adjusted annual averages for comparison.

	12/31/2022 storm	Climatically Adjusted Annual Average
Total Rainfall (in)	4.56	18
Return Frequency of Storm	~10 yr, 24-hour event	–
Total Discharge (10 ⁶ m ³)	0.69	1.7
Total Sediment Load (metric tonnes)	1,100	630

3.1.4. Future monitoring recommendations

This Belmont Creek dataset is relatively strong due to the acceptable continuous data and discretely collected SSC samples at the full range of discharges for the Creek. Dynamic simulation modeling using this dataset could reveal weaknesses that could be addressed in the future, and additional future monitoring could improve certainty of the estimates, however no additional monitoring is recommended at this time.

3.2. ACMdP

3.2.1. Data completeness assessment for ACMdP

Stage, discharge, and rainfall data were regularly sampled and adjusted based on the data processing workflows described in Section 2.5. The turbidity record was mostly complete and acceptable for most storms during WY2020 and WY2021, but was completely rejected for WY2022 and WY2023 due to sensor malfunctioning that could not be corrected. A total of 84 SSC samples were collected during WY2022 and WY2023. As such, a discharge-SSC

relationship was developed but a turbidity-SSC relationship was not possible due to no overlapping turbidity record during SSC sample collection.

3.2.2. Continuous data for ACMdP

Rainfall in WY2020 was approximately 60% of normal with most falling in December and January, during which two floods reaching stages above 5 feet occurred. Virtually no rainfall or flows were observed for the rest of the water year. WY2021 was even drier at approximately 33% of normal. Small amounts of regular rainfall occurred from December to March but none of the storms produced significant runoff. Turbidity data for this year were limited and had numerous blackout periods due to the solar panel being blocked by trees and the battery going down. WY2022 saw discrete periods of rainfall in October and December. A heavy rain event caused a large and sustained flow event in October 2021 (described in more detail below). No significant flows were observed after early January 2022. Historically high rainfall and discharge were observed in WY2023.

ACMdP - WY2020

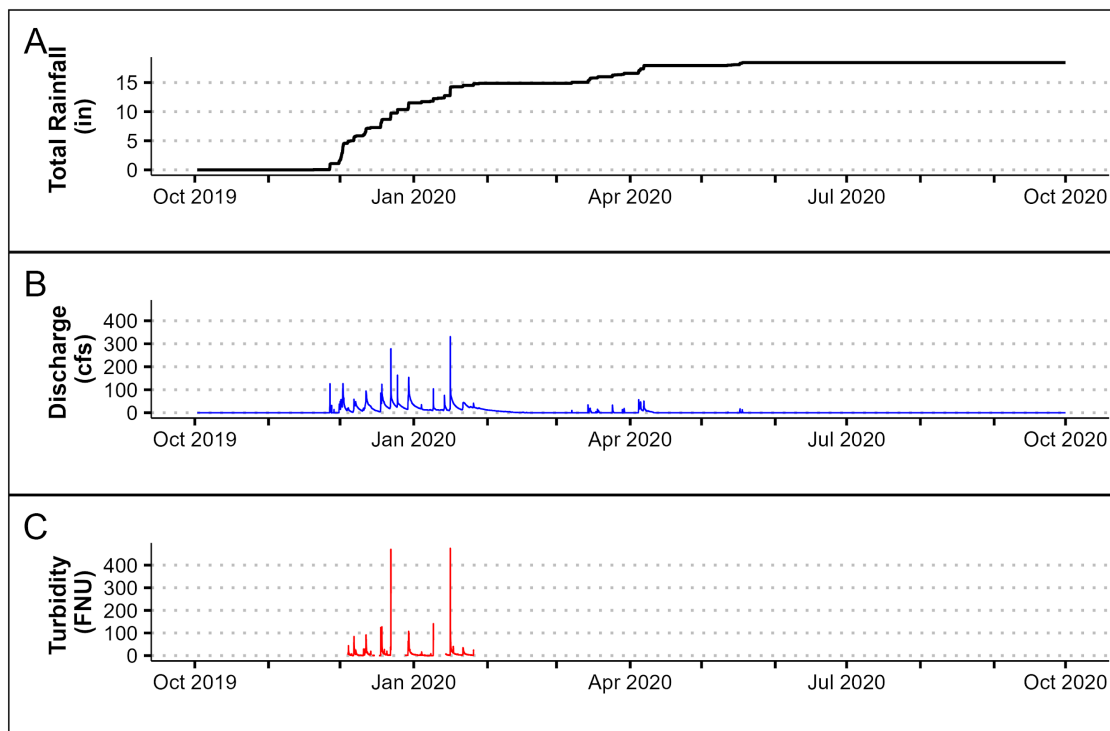


Figure 13: ACMdP time series of WY2020.

ACMdP - WY2021

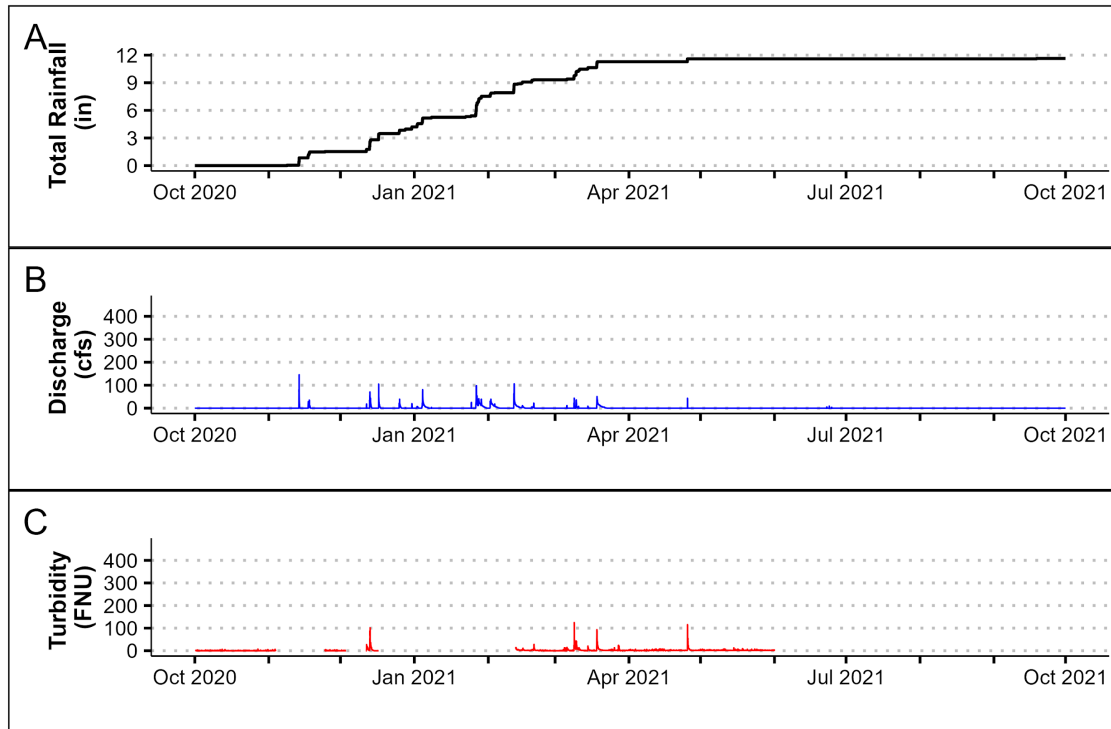


Figure 14: ACMdP time series of WY2021.

ACMdP - WY2022

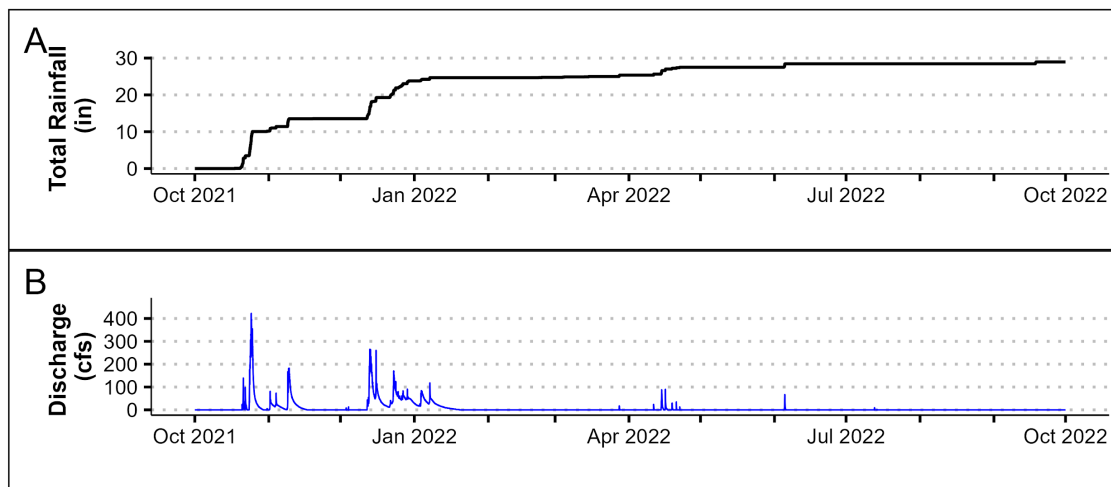


Figure 15: ACMdP time series of WY2022.

ACMdP - WY2023

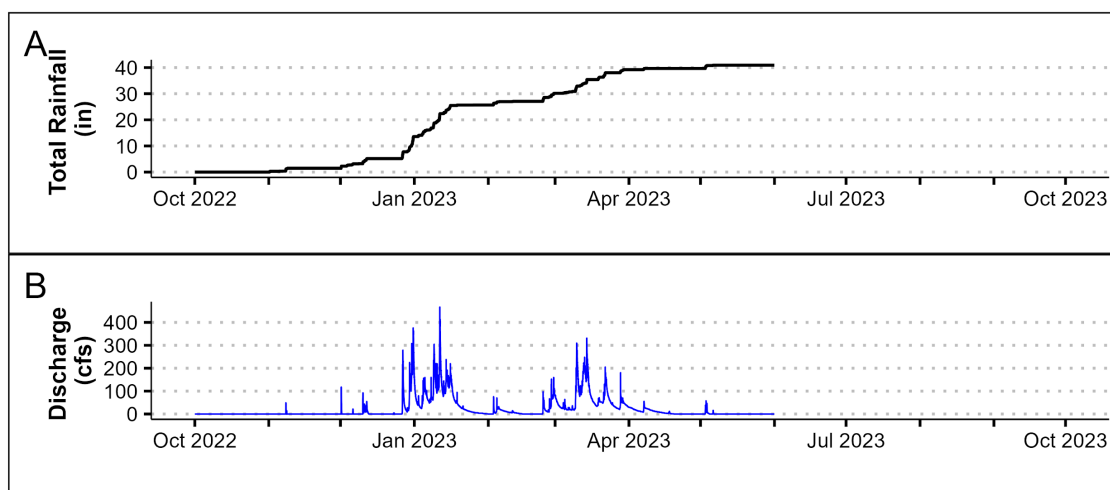


Figure 16: ACMdP time series of WY2023.

3.2.3. *Sediment load estimates for ACMdP*

SSC samples were collected in six storm events over a broad range of discharges (Figure 17). However, all of these samples were collected in WY 2023. The discharge-SSC relationship was stratified into two distinct groups of data - an early-season grouping (blue data) and a late-season grouping (green data). This divergence could be the result of a strong first flush effect, where higher rates of sediment transport off the urban landscape are associated with flows earlier in the season. Or there may be a strong dilution effect during the heavier flows in late December and early-to-mid January. Increases in baseflow contributions later in the season could lead to lower SSC per unit discharge. Because the dataset is limited to a single WY, we were not able to confirm this hypothesis and will report in the supplementary datasets both groupings to estimate a higher- and lower-bound for suspended sediment yield at the ACMdP site.

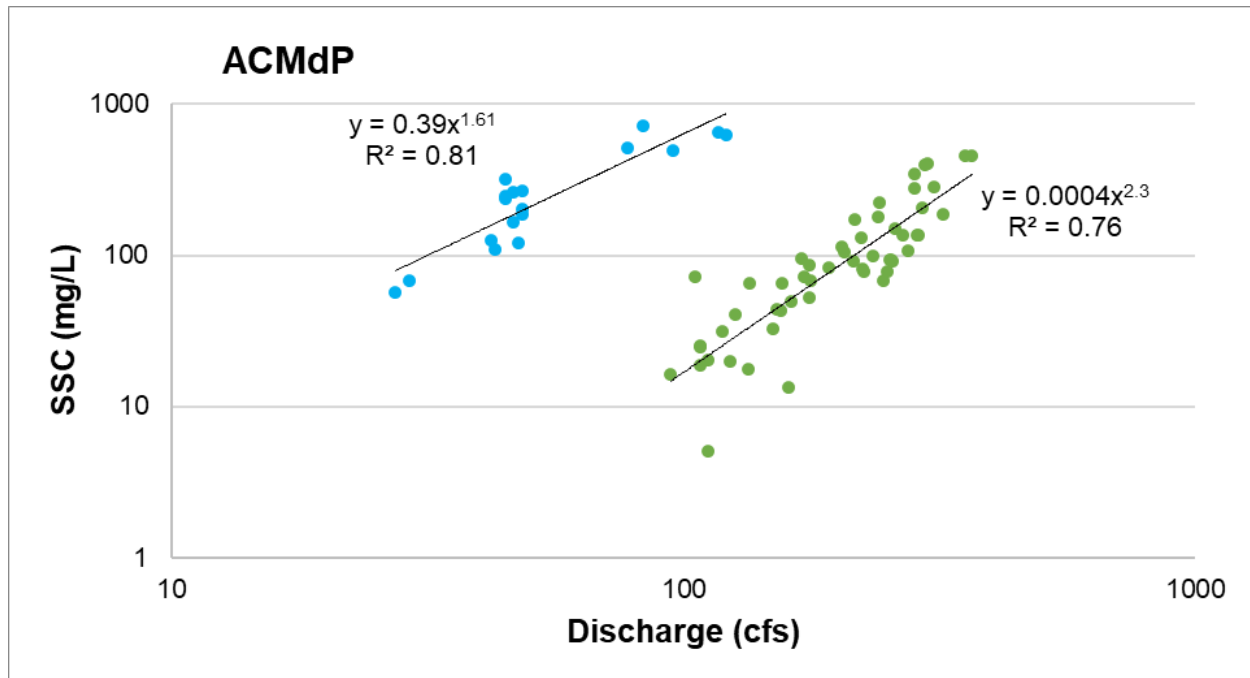


Figure 17: SSC-discharge relationship at ACMdP. Two trends were evident at ACMdP and both were used to estimate annualized sediment yields for the channel.

Continuous sediment loads at ACMdP were estimated based on the relationship between discharge and SSC. Continuous loads were summed at the 15-minute, daily, monthly, and annual time steps and are reported in the supplementary materials. Total annual discharge and sediment loads at ACMdP for WYs 2020-2023 are reported in Table 8.

Total annual discharge spanned three orders of magnitude (between 0.86 and 13.3 Mm³) during the monitoring period (Table 8). Estimates of annual suspended sediment loads for the monitored period ranged between 100 and 14,000 metric tonnes based on the higher discharge-SSC relationship, and between 2.0 and 680 metric tonnes for the lower discharge-SSC relationship.

The monthly sediment load was evaluated as a function of monthly total discharge at the nearby USGS gauge on Corte Madera Creek at Ross (note, although similar in name, this is actually a different creek). The relationship between these factors (Figure 18) was combined with the long-term discharge record from the USGS Corte Madera Creek at Ross gauge to estimate the long-term monthly sediment loads. Where there were gaps in the USGS discharge record, a relationship between monthly sediment load and total monthly rainfall at the ACMdP site was substituted (Figure 19). A full estimated long-term record from WY 1991-2020 was developed using these methods. This long-term monthly sediment loads record was used to estimate long-term average loads and yields (Table 8).

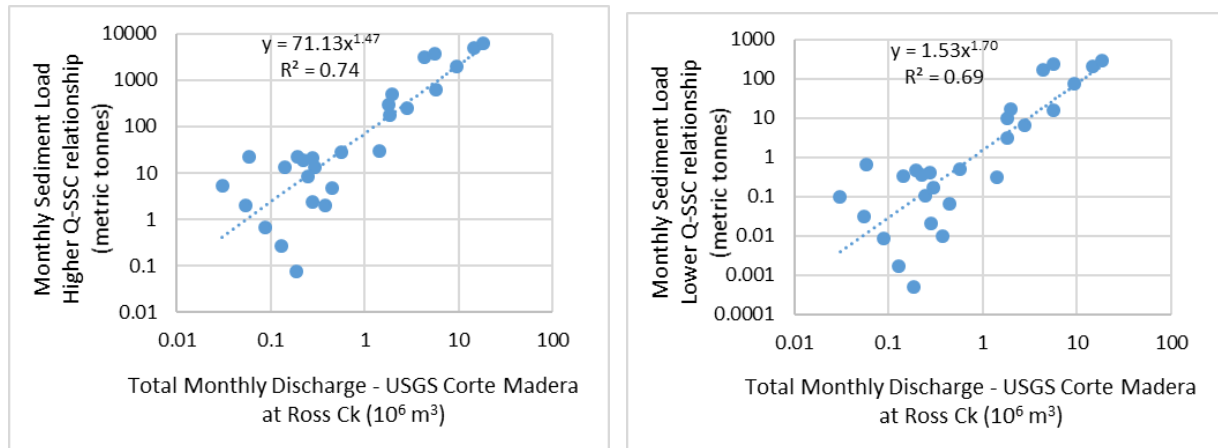


Figure 18. Relationships used to estimate long-term yields from a long-term discharge at the USGS gauge on Corte Madera Creek at Ross (USGS gauge11460000).

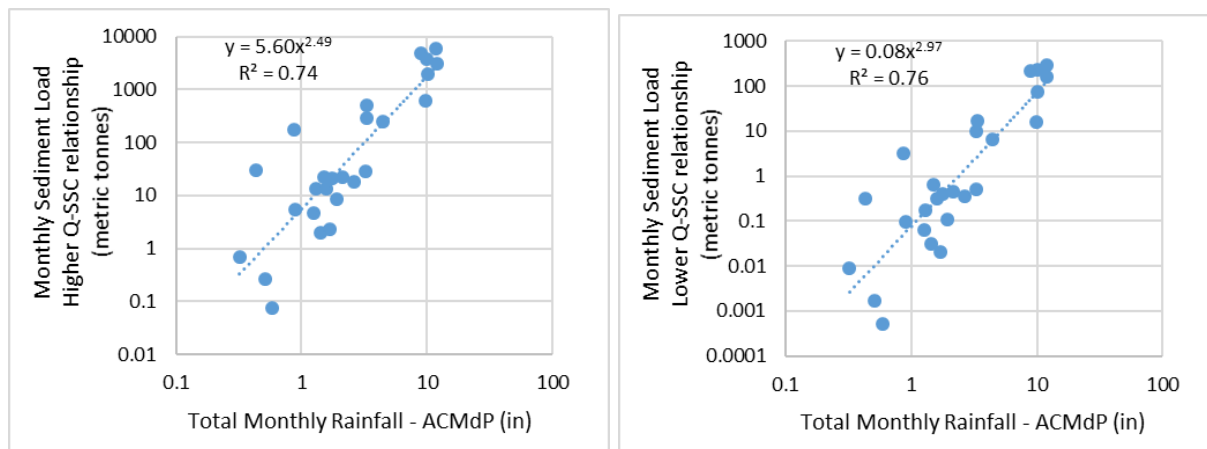


Figure 19. Relationships used to estimate long-term yields from long-term rainfall at the rainfall gauge on site at ACMdP.

Similar to Belmont Creek and although the North Bay region generally receives more rainfall than the Peninsula, rainfall at ACMdP during the monitored period was dry during WYs 2020 and 2021, and average for WY 2022. Whereas rainfall in WY 2023 was 192% of normal at Belmont, it was wet but less dramatic in the North Bay - 143% of normal at the ACMdP rain gauge. WY 2021 was on the other extreme at just 41% of normal rainfall for this site.

The higher and lower estimates of sediment load are separated by two orders of magnitude. Neither the upper or lower bounding estimates fit the conceptual model of sediment yields for this watershed. The long-term, climatically-averaged yield for the lower estimate is just 16 metric tonnes per square kilometer, which would be on the low end of even almost entirely urban watersheds previously studied in the Bay Area (Gilbreath et al., 2015a). On the other hand, the

360 metric tonnes using the higher estimate is much higher than any other watershed studied in the Bay Area and is likely too high.

The historic rain event for parts of the Bay Area on December 31, 2022, was not as large in the North Bay - that atmospheric river on that day stalled to the south of the Golden Gate Bridge. Instead, the largest storm event at ACMdP occurred during the atmospheric river on October 24, 2021, when 5 inches of rain fell at the on-site rain gauge (Table 9). The 24-hour rainfall total for the site was between a 1 in 5 and 1 in 10-year event. During this single day, more sediment was transported than during all of WYs 2020 and 2021 combined.

Table 8. Total annual rainfall, discharge and sediment loads at ACMdP for WYs 2020-2023 and the long-term climatic averages.

Water Year	ACMdP Station Rainfall (in)	Discharge (10 ⁶ m ³)	Sediment Load (metric tons)	Sediment Yield (metric tons/sq km)
WY 2020 Total	18.2	4.6	27-940	2.2-80
WY 2021 Total	11.5	0.86	2.0-100	0.17-8.4
WY 2022 Total	28.5	6.6	330-6,400	27-540
WY 2023 Total*	40.3	13.3	680-14,000	57-1,200
Climatic Average**	28.2	6.5	190-4,300	16-360

* Record ends May 31, 2023; missing June-September 2023.

** Based on the 30 year record between WYs1991-2020.

Table 9. Largest single day totals in monitored period and climatically adjusted annual averages for comparison.

	10/24/2021 storm	Climatically Adjusted Annual Average
Total Rainfall (in)	5.0	28.2
Return Frequency of Storm	Between a 1:5 and 1:10 yr, 24-hour event	—
Total Discharge (10 ⁶ m ³)	0.71	6.5
Total Sediment Load - Lower Estimate (metric tonnes)	180	190
Total Sediment Load - Higher Estimate (metric tonnes)	2,700	4,300

3.2.4. Future monitoring recommendations

Two major areas for future monitoring are recommended. The first is to verify the discharge rating curve used in this analysis. As mentioned previously, two curves were provided by Marin County and we chose to use the rating curve that produced lower total discharge because it was aligned with our conceptual model of runoff per unit area for watersheds with similar

characteristics to ACMdP. This should be verified with updated discharge measurements. The second recommendation is with regards to the two distinct relationships between discharge and SSC. The two relationships result in such a high degree of uncertainty that we present the sediment loads results for both relationships and conclude that the actual load is likely somewhere between the two extreme estimates. Therefore, we recommend collecting additional SSC monitoring data over the course of a season to verify the underlying factors that result in each distinct discharge-SSC relationship.

3.3. Novato Creek

3.3.1. *Data completeness assessment for Novato Creek*

Stage, discharge, and rainfall data were regularly sampled and adjusted based on the data processing workflows described in Section 2.5 for WY2020 - WY2023. The turbidity record was mostly acceptable for WY 2020 and during the two main flow events of WY 2022, but rejected for all of WYs 2021 (due to sensor fouling and malfunction) and 2023. During WY 2023, the articulating boom was ripped from the channel bottom during the high December flows, and continued high flows throughout the rest of the season prevented reinstallation. A total of 37 SSC samples were collected and analyzed by SFEI staff.

3.3.2. *Continuous data for Novato Creek*

Rainfall in WY2020 was just above 15 inches at the rain gauge on site and occurred mostly in December. Turbidity reached between 300-400 FNU on multiple occasions. Novato Creek received very little rainfall in WY 2021 and no significant flows. Turbidity data was also limited during the winter months and is excluded from the dataset because of a sensor malfunction. More significant rain fell in WY2022, concentrated during October and December with relatively dry inter-periods. There was a particularly large event in October 2021 (discussed previously for ACMdP), during which the turbidity record was acceptable and reached approximately 800 FNU. WY 2023 was very wet during the winter months. Consistent rainfall was observed in December, January, and March, resulting in repeated high flows.

Novato Creek - WY2020

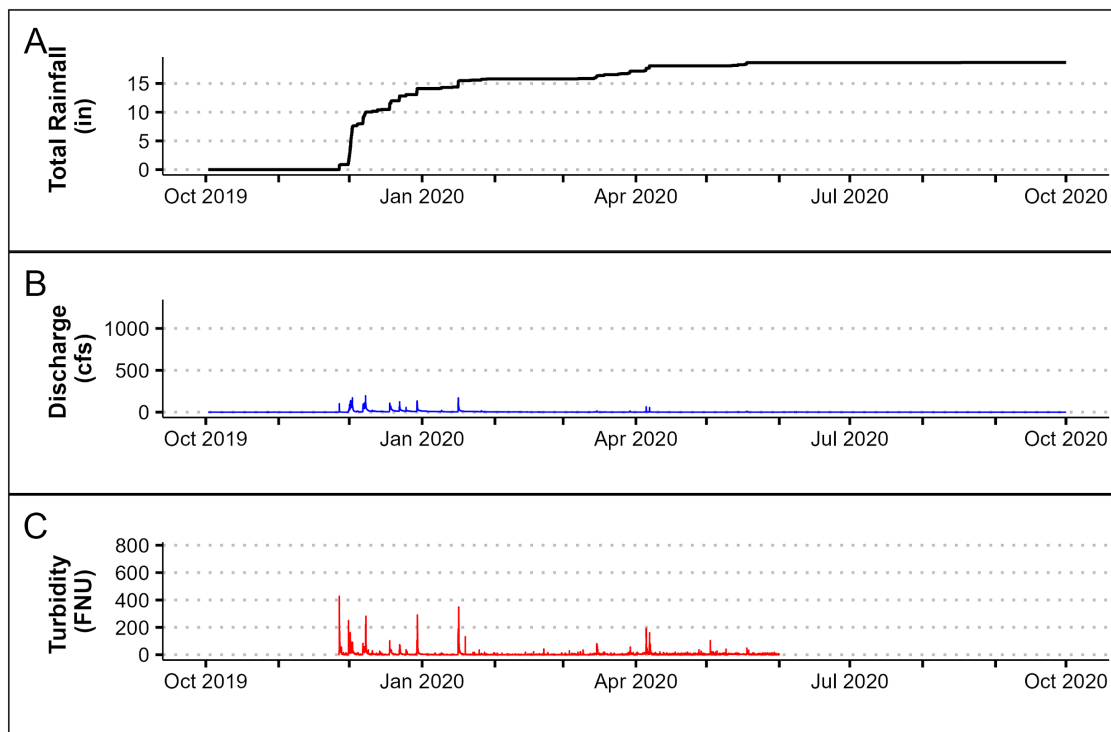


Figure 17: Novato Creek time series of WY2020.

Novato Creek - WY2021

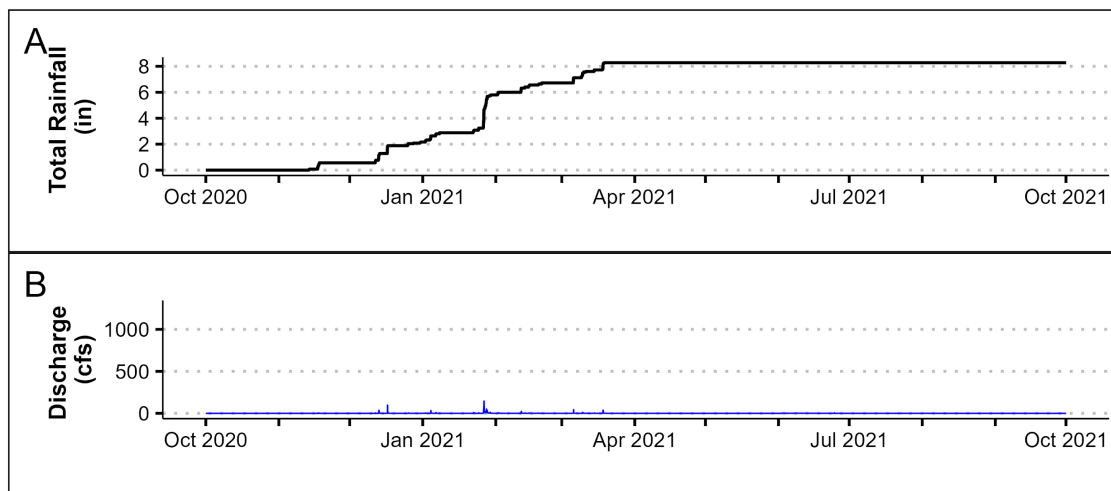


Figure 18: Novato Creek time series of WY2021.

Novato Creek - WY2022

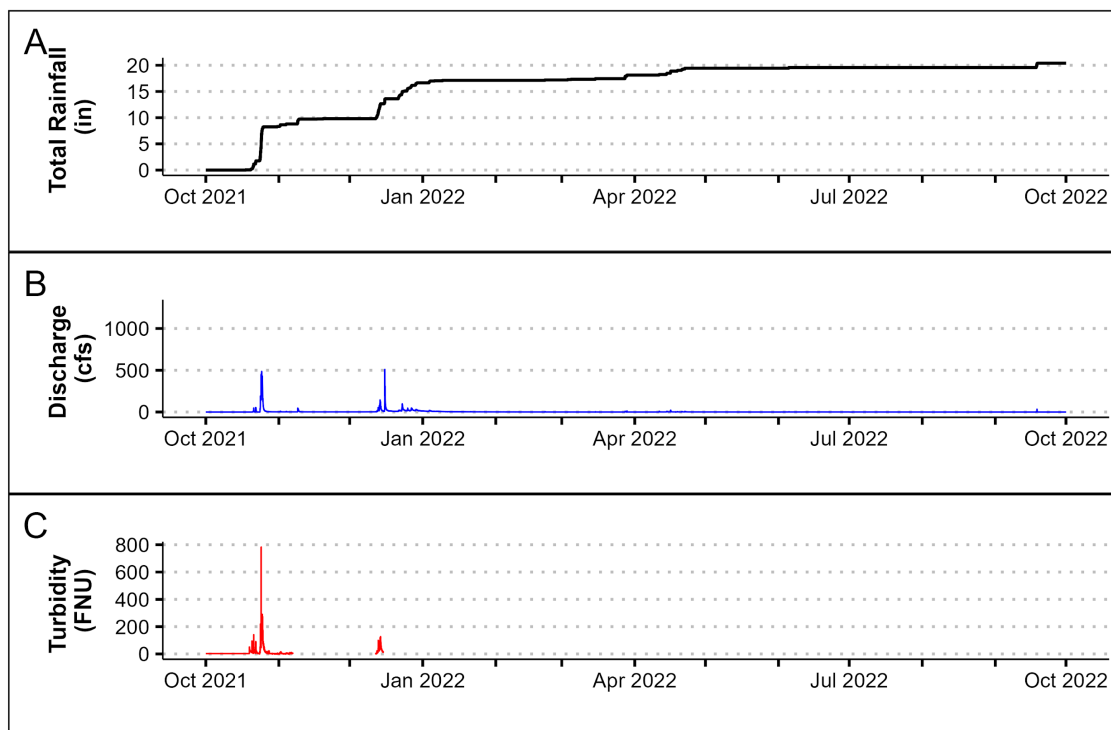


Figure 19: Novato Creek time series of WY2022.

Novato Creek - WY2023

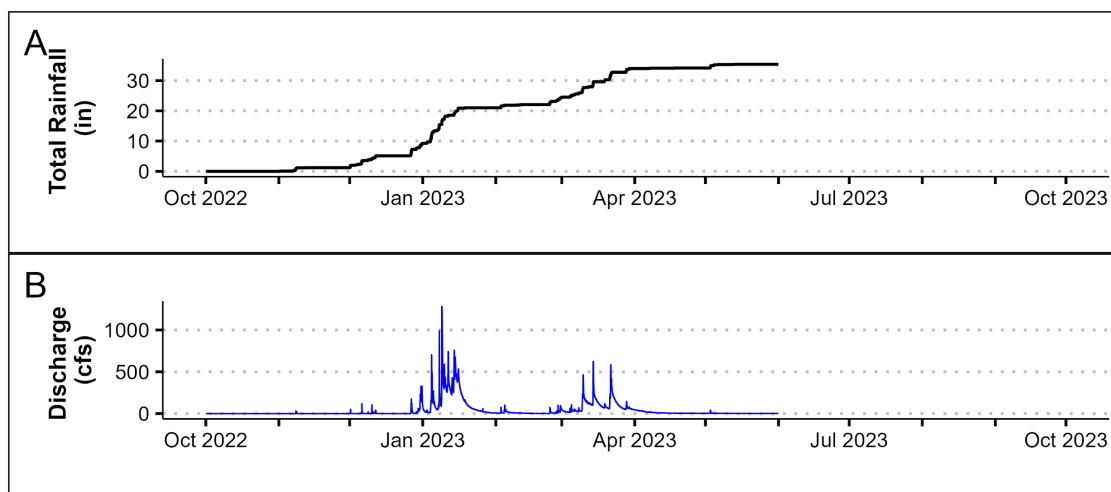


Figure 20: Novato Creek time series of WY2023.

3.3.3. Sediment load estimates for Novato Creek

Forty-one SSC samples were collected during three storm events (Figure 21). The discharge-SSC relationship has an R^2 value of 0.75. The articulating boom was ripped from the

channel bed in December, 2022, and all of the manual sampling was completed before the highest flows in January 2023. Consequently, the range of discharge associated with the SSC samples is somewhat limited - all samples collected were at flows <350 cfs, whereas the highest flow reached 1280 cfs. Therefore, confidence in the discharge-SSC relationship in flows greater than 350 cfs is low.

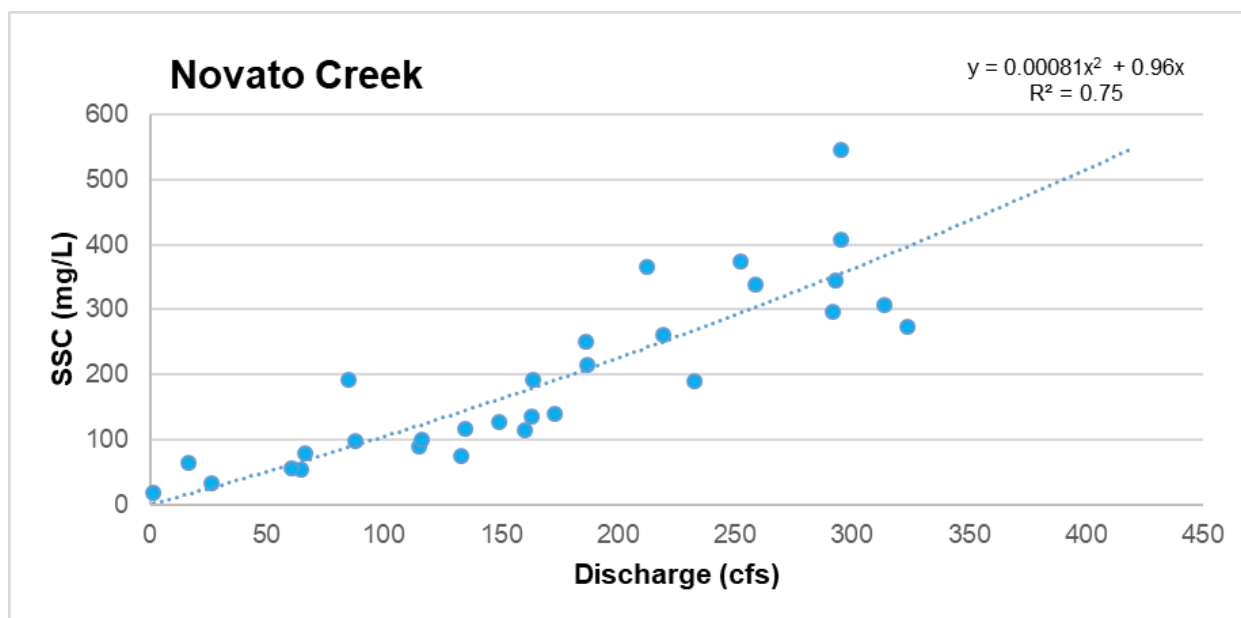


Figure 21: SSC-discharge relationship for Novato Creek.

Continuous sediment loads at Novato Creek were estimated based on the relationship between discharge and SSC. Continuous loads were summed at the 15-minute, daily, monthly, and annual time steps and are reported in the supplementary materials. Total annual discharge and sediment loads at Novato Creek for WYs 2020-2023 are reported in Table 10.

Total annual discharge, as measured by the USGS, spanned two orders of magnitude (between 0.5 and 23 Mm³) during the monitoring period (Table 10). Estimates of annual suspended sediment loads for the monitored period range three orders of magnitude, between 9 and 7,500 metric tonnes.

The monthly sediment load was evaluated as a function of monthly discharge, and the relationship between these factors (Figure 22) was combined with the long-term record of monthly discharge to estimate the long-term monthly sediment loads. This long-term monthly sediment loads record was used to estimate long-term, climatically averaged loads and yields (Table 10).

Long-term average annual discharge was two orders of magnitude greater than the driest year of the study, and the wettest year during the study was about 2.5 times greater than the climatic average. Sediment loads varied even more greatly between the wet and dry years, and the

climatic average. This greater variation is expected because both discharge and SSC are greater during a wet season and both are lower during the dry season, compounding the sediment load totals versus just discharge totals.

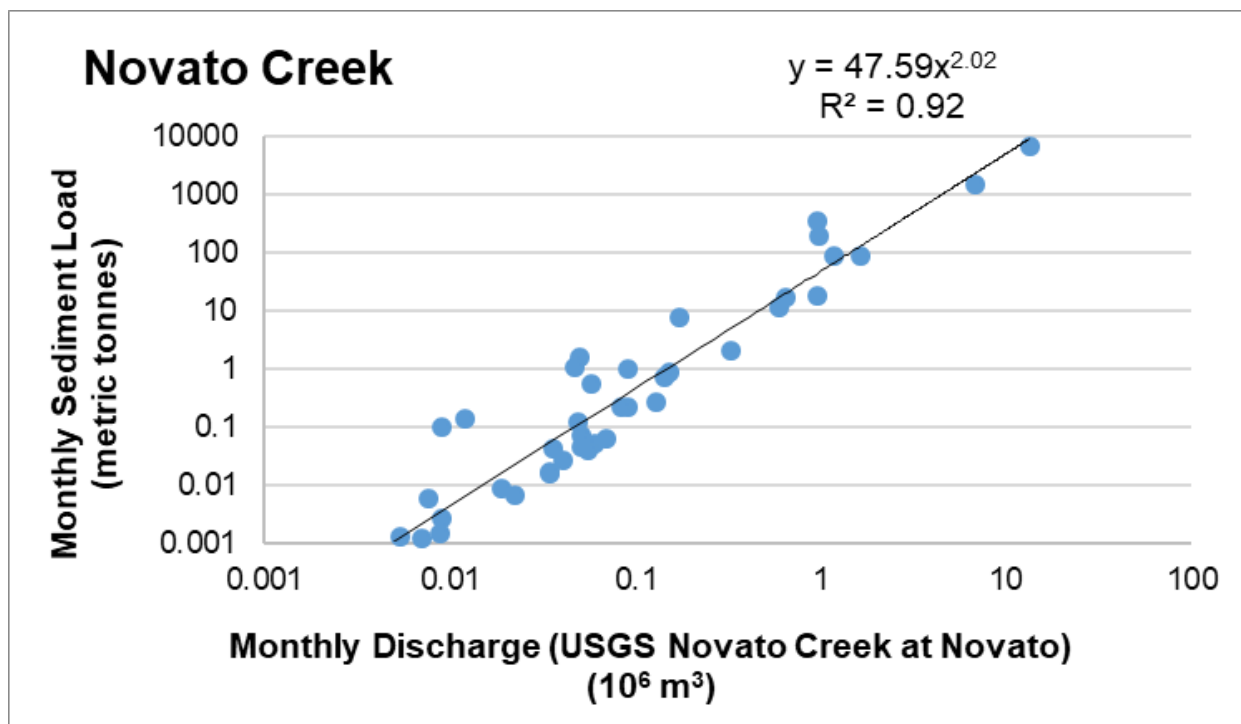


Figure 22. Relationship used to estimate long-term yields from a long-term discharge record.

Table 10. Total annual rainfall, discharge and sediment loads at Novato Creek for WYs 2020-2023 and the long-term climatic averages.

Water Year	Novato Library Rainfall (in)	Discharge (10 ⁶ m ³)	Sediment Load (metric tons)	Sediment Yield (metric tons/sq km)
WY 2020 Total	18.4	2.8	100	3.9
WY 2021 Total	8.2	0.44	9.2	0.36
WY 2022 Total	20.1	3.0	450	18
WY 2023 Total*	34.9	24	8,600	340
Climatic Average**	27.5	11.2	4,500	180

* Record ends May 31, 2023; missing June-September 2023

** Based on the 30 year record between WYs1991-2020 at the site gauge.

As opposed to the largest rainfall events of October 24, 2021 (for ACMdP) and December 31, 2022 (for Belmont Creek) leading to the greatest single day of sediment transport in each of those respective watersheds, at Novato Creek it was the January 9, 2023 event that moved the greatest sediment load. Although the rainfall in the storm event was only moderate (less than a 1-year recurrence interval storm), it occurred at the end of a historic wet period for the Bay Area. Therefore, the watershed was well-saturated and primed to erode and transport sediment. Novato Creek transported over 40% of the climatically averaged sediment load for the watershed during just this single day.

Table 11. Largest single day totals in monitored period and climatically adjusted annual averages for comparison.

	1/9/2023 Storm	Climatically Adjusted Annual Average
Total Rainfall (in)	1.71*	28.6
Return Frequency of Storm	<1:1 yr, 24-hour event	–
Total Discharge (10 ⁶ m ³)	1.46	11.2
Total Sediment Load (metric tonnes)	1,900	4,500

*This was not a particularly large storm but it was preceded by two weeks of heavy rainfall, thus the soils were fully saturated and therefore resulted in large amounts of runoff and sediment load.

3.3.4. *Future monitoring recommendations*

As discussed above, SSC sample collection was focused during lower and moderate flow events. We recommend additional SSC sample collection, focusing only on flows greater than 350 cfs.

3.4. Walnut Creek Results

3.4.1. *Data completeness assessment for Walnut Creek*

Stage, discharge, and suspended sediment data were collected at the Walnut Creek site during the study period. Rainfall data from Ygnacio Valley Fire rain gauge (Contra Costa County) was used to QA and verify the acceptability of the USGS discharge data, which was accepted entirely. However, the discharge rating curve for the site has only been rated for flows up to about 2400 cfs (shown as the red horizontal line on each of the continuous graphs (Figures 22-25)). The USGS extended this curve to estimate the few flows that exceeded this rating in WY 2022. However, there were several flows peaking significantly higher than 2400 cfs in WY 2023. Using a simple extension of the rating curve to estimate those higher flows, we found that loads estimates for WY 2023 were likely biased low relative to a review of historical USGS data for sediment loading at previously monitored sites on Walnut Creek. We do report estimated loads for this WY, but recommend using caution as there is high uncertainty. Additional monitoring is recommended, especially including flow measurement to extend the measured

data for the discharge rating curve. To estimate sediment loads for WYs 2020-2022, 49 SSC samples were collected at the site by USGS (WY 2022) and SFEI staff (WY 2023).

3.4.2. Continuous data for Walnut Creek

Rainfall at the nearby Ygnacio Valley Fire rain gauge ranged between 6.5 inches in WY 2021 and 34.9 inches in the wet WY 2023. As with other sites, discharge in WY2020 and WY2021 was very low, with only relatively low flows in December and January. WY2022 had high flows in October and December and WY2023 saw the highest rainfall and discharge throughout winter, with peaks in January and March.

Walnut Creek - WY2020

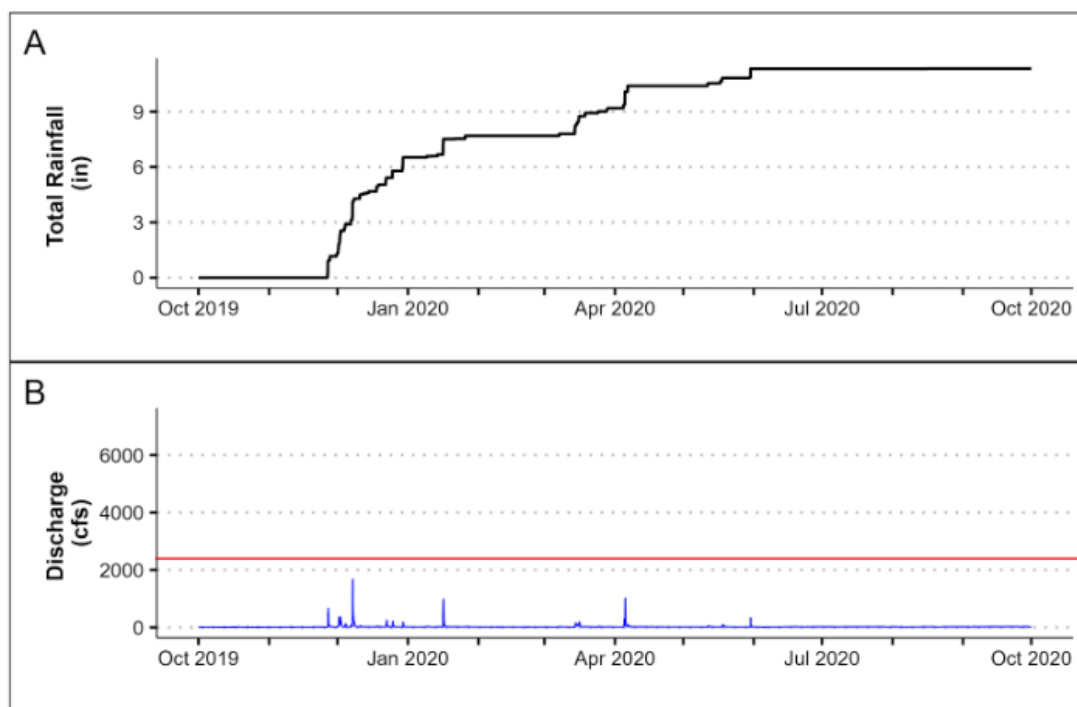


Figure 22: Walnut Creek time series of WY2020. The red horizontal line at 2400 cfs indicates the upper end of the measured discharge rating curve.

Walnut Creek - WY2021

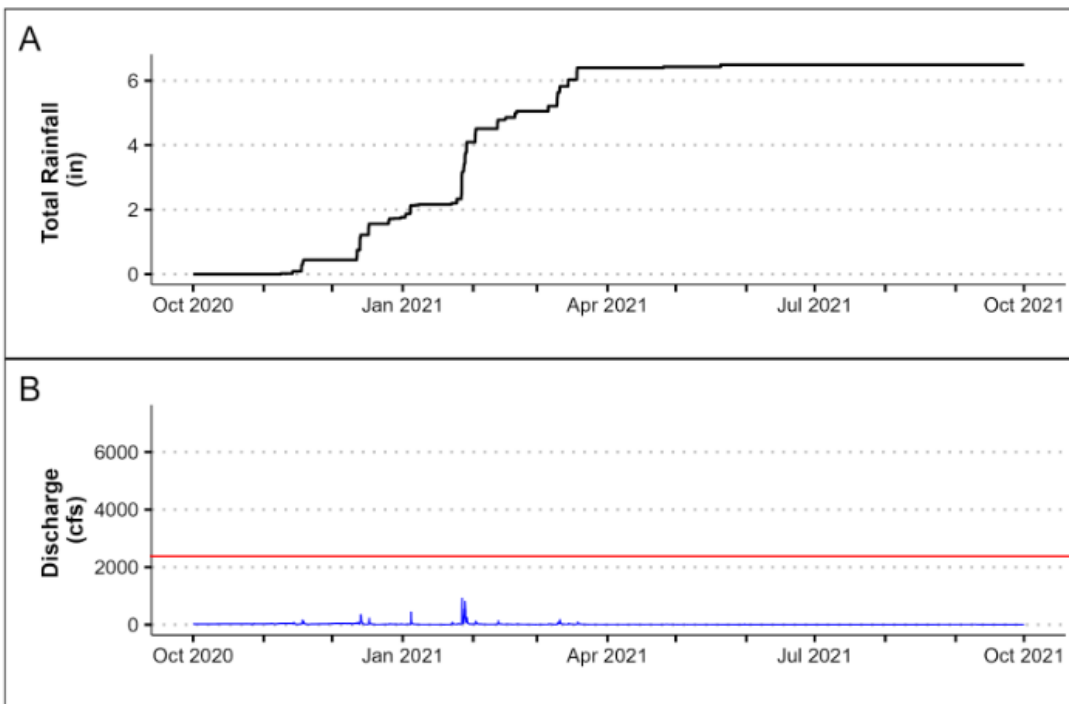


Figure 23: Walnut Creek time series of WY2021. The red horizontal line at 2400 cfs indicates the upper end of the measured discharge rating curve.

Walnut Creek - WY2022

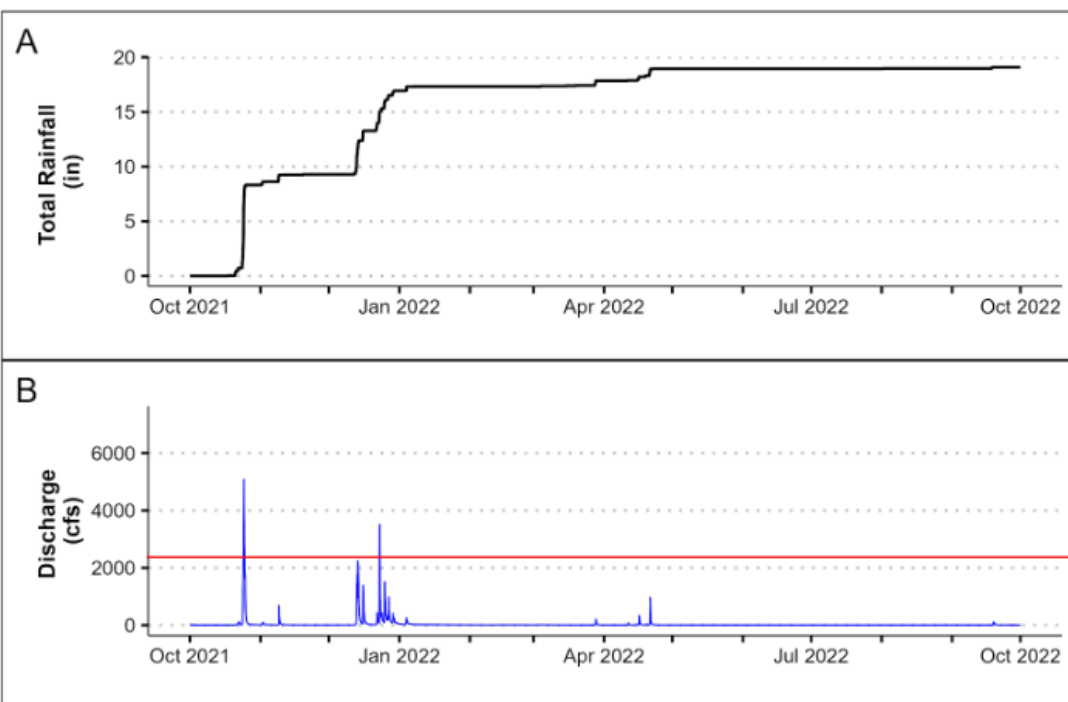


Figure 24: Walnut Creek time series of WY2022. The red horizontal line at 2400 cfs indicates the upper end of the measured discharge rating curve.

Walnut Creek - WY2023

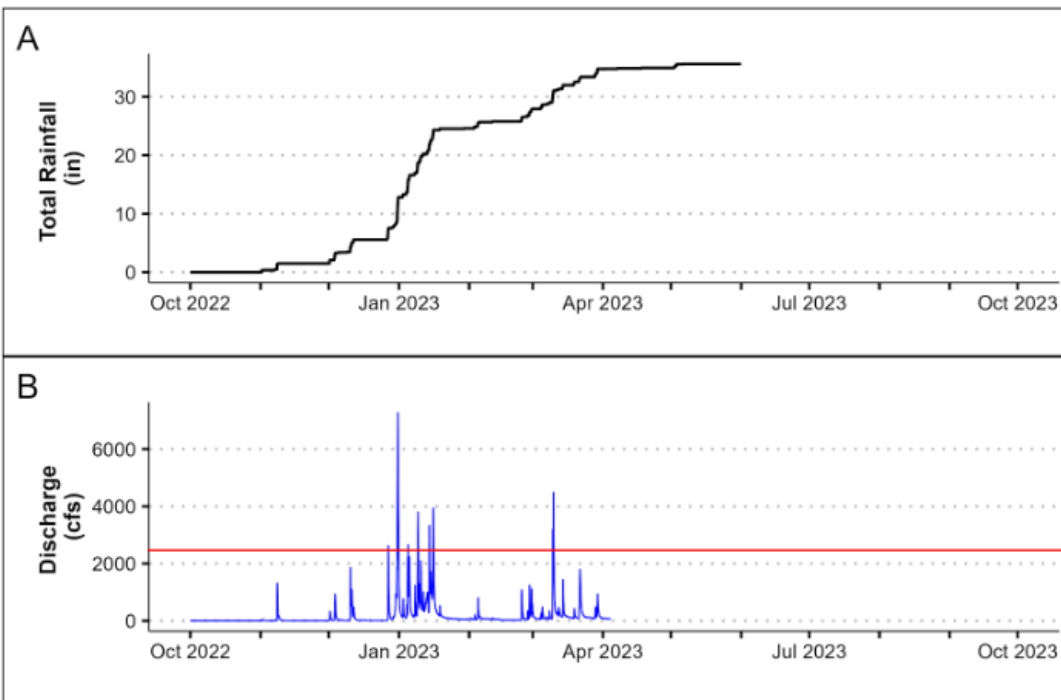


Figure 25: Walnut Creek time series of WY2023. The red horizontal line at 2400 cfs indicates the upper end of the measured discharge rating curve.

3.4.3. Sediment load estimates for Walnut Creek

Because turbidity was not collected at the Walnut Creek site, only a discharge-SSC sediment rating curve is available (Figure 26). The relationship for the dataset as a whole is weaker compared to the other sites. Walnut Creek SSC had notable counter-clockwise hysteresis, in which SSC was greater on the falling limb of the hydrograph. An example of this in one well-sampled storm event is shown in Figure 27. This is potentially because suspended sediment transport on the rising limb is more dominated by urban runoff, whereas rural runoff with higher suspended sediment loads dominates the falling limb.

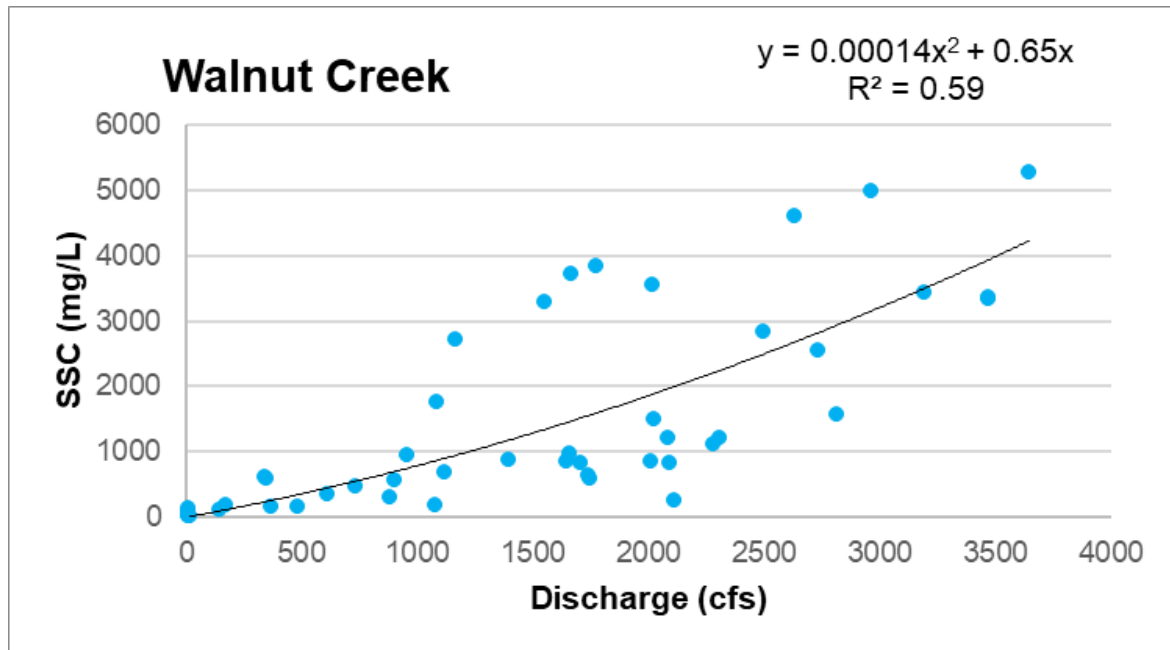


Figure 26: SSC-discharge relationship for Walnut Creek.

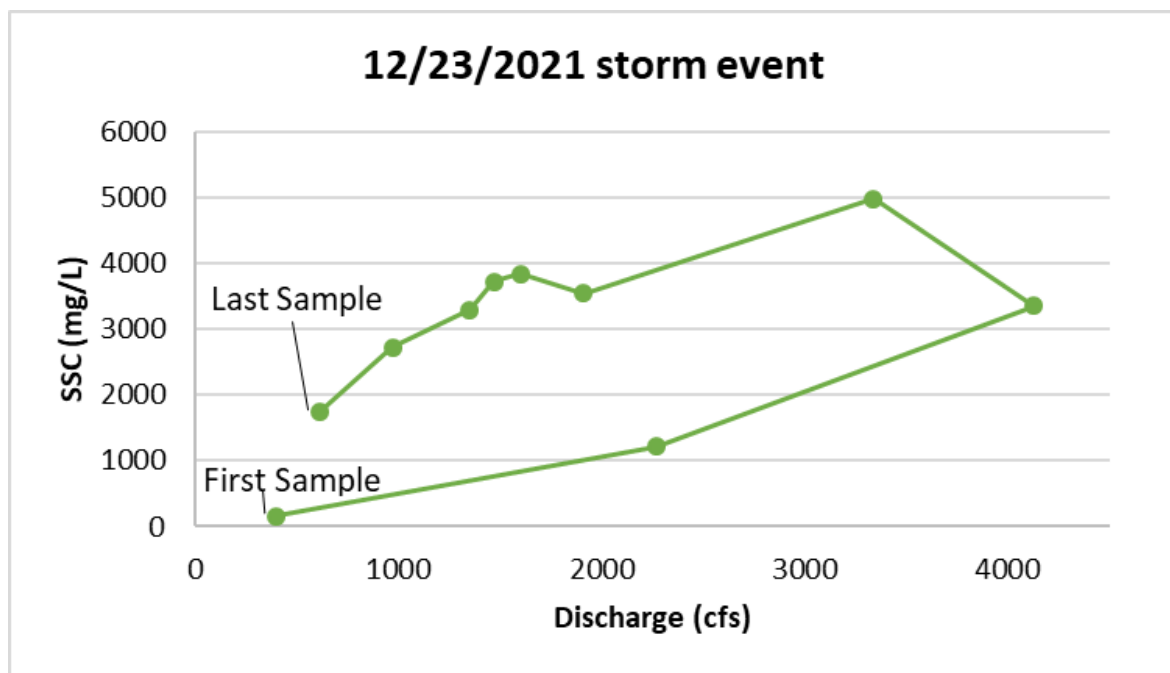


Figure 27: Example of counter-clockwise hysteresis of SSC in Walnut Creek.

Continuous sediment loads at Walnut Creek were estimated based on the relationship between discharge and SSC. The USGS data was reported on the 15-minute interval, and therefore continuous loads were summed at the 15-minute, daily, monthly, and annual time steps and are

reported in the supplementary materials. Total annual discharge and sediment loads at Walnut Creek for WYs 2020-2023 are reported in Table 12 below.

Total annual discharge, as measured by the USGS, ranged between 15.5 and 84.8 Mm³ during the monitoring period (Table 12). Estimates of annual suspended sediment loads for the monitored period varied by multiple orders of magnitude, between 1,100 and 270,000 metric tonnes.

The monthly sediment load was evaluated as a function of monthly total discharge, and the relationship between these factors (Figure 28) was combined with the long-term rainfall record from a nearby rainfall gauge (Mount Diablo Junction) to estimate the long-term monthly sediment loads. This long-term monthly sediment loads record was used to estimate long-term climatically-averaged loads and yields (Table 12).

Long-term, climatically averaged annual discharge was 2.5 times greater than the driest year of the study, and the wettest year during the study was a little more than two times greater than the climatic average. This variability is not as great as in the other watersheds studied, likely because of the greater baseflow influence and generally lower runoff coefficient due to the lower overall rainfall, low slope and largely rural area. As with the other sites, sediment loads varied more greatly between the wet and dry years (over 200 times difference). This greater variation is expected because both discharge and SSC are greater during a wet season and both are lower during the dry season, compounding the sediment load totals versus just discharge totals.

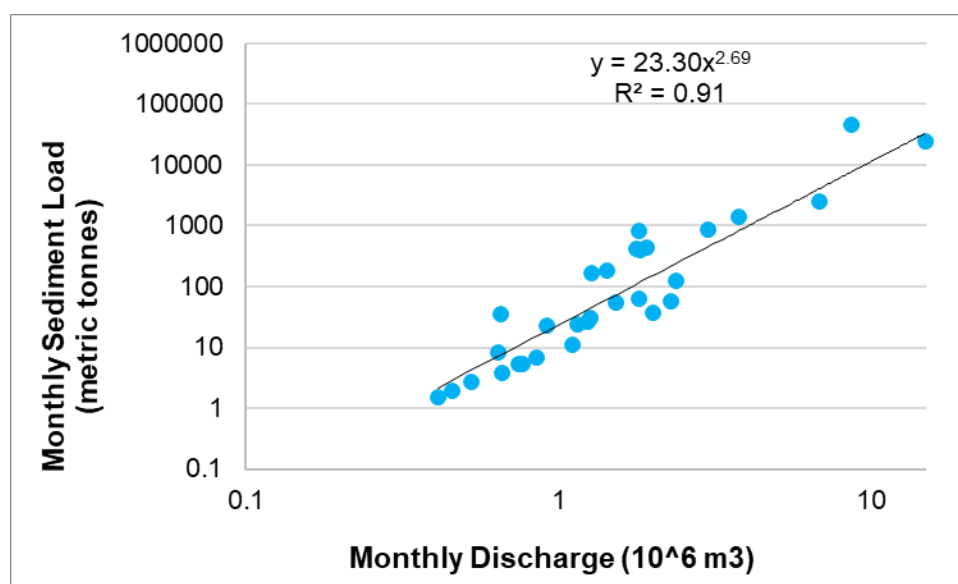


Figure 28. Relationship used to estimate long-term yields from a long-term monthly discharge record.

Table 12. Total annual rainfall, discharge, and sediment loads at Walnut Creek for WYs 2020-2023 and the long-term climatic averages.[Note: Discharge and sediment numbers for Walnut Creek are potentially biased low because the discharge rating curve only measured to 2400 cfs. The most uncertain numbers are italicized.]

Water Year	Ygnacio Valley Fire Rainfall (in)	Discharge (10 ⁶ m ³)	Sediment Load (metric tons)	Sediment Yield (metric tons/sq km)
WY 2020 Total	9.3	18.0	2,600	11
WY 2021 Total	6.0	15.5	1,100	4.7
WY 2022 Total	14.1	32.8	<i>70,000</i>	<i>300</i>
WY 2023 Total*	29.3	<i>84.8</i>	<i>270,000</i>	<i>1200</i>
Climatic Average**	16.5	<i>40.8</i>	<i>57,000</i>	<i>250</i>

* Record ends April 30, 2023; missing May-September 2023.

**Based on the 30 year record between WYs1991-2020.

Like at Belmont Creek, Walnut Creek had the most significant rainfall and sediment transport event on December 31, 2022. At Walnut Creek, this storm was about a 1:20-year event. Total discharge in this single day was nearly one-quarter the climatically averaged discharge and more than double the climatically averaged total annual sediment load.

Table 13. Largest single day totals in monitored period and climatically adjusted annual averages for comparison.

	12/31/2022 Storm	Climatically Adjusted Annual Average
Total Rainfall (in)	3.23	16.5
Return Frequency of Storm	~20 yr, 24-hour event	–
Total Discharge (10 ⁶ m ³)	9.71	40.8
Total Sediment Load (metric tonnes)	140,000	57,000

3.4.4. Future monitoring recommendations

SSC samples were collected over a large stage range, however there is significant uncertainty in the discharge rating curve above flows greater than 2400 cfs, resulting in uncertainty in the total estimated sediment load. Therefore, we recommend improving the discharge rating curve with measurements greater than 2400 cfs.

4. Long-term average suspended sediment yields

In this analysis, we estimated long-term climatically-averaged suspended sediment yields for the four monitored creeks (Table 14). These annual yield estimates are in line with our conceptual

model compared to other Bay Area watersheds (Gilbreath et al., 2015a), but extend the existing regional dataset on the upper end of climatically-averaged loads. Walnut Creek adds information to the high end of the regional dataset for watershed size and sediment loads, and even so, the reported discharge and sediment yields may be biased low given the limitations of the current discharge rating curve. The drainage area for Walnut Creek (which is undammed) is approximately the same size as Guadalupe River (downstream of five dams). Both watersheds are in areas of the region that receive lower rainfall, though Guadalupe has more total annual discharge due to a larger percentage of imperviousness in the watershed. Yet Walnut Creek has substantially greater average suspended sediment concentrations and yields than Guadalupe River due to geological differences. Novato and Belmont Creeks are the next highest. Although equal in average suspended sediment concentration, Novato Creek yields more sediment due to its larger watershed area and greater annual rainfall. For ACMdP, due to the two distinct relationships between discharge and SSC that were sampled during the study period, more sampling is required to tease out the sediment loads and yields. Upper and lower ranges are reported in Table 14, but we believe, based on other data collected in the region, that the actual annual average load and yield is somewhere within the reported possible range.

Table 14. Climatically-averaged discharge and sediment loads and yields for the four monitored watersheds of this study (highlighted in gray) as well as other watersheds previously monitored around the Bay Area (Gilbreath et al., 2015a). Walnut Creek data are italicized to denote that it has a higher degree of uncertainty due to the limitations of the discharge rating curve for higher flows. The table is sorted from highest to lowest sediment yield, and ACMdP is placed at the bottom due to the uncertainty of the results.

Watershed Name	Watershed Area (sq. km)	Discharge (10⁶ m³)	Sediment Load (metric tons)	Sediment Yield (metric tons/sq. km)	Average SSC (mg/L)
Walnut Creek	232	41	57,000	250	1400
Novato Creek	25.6	11	4,500	180	400
Belmont Creek	8	1.7	680	90	400
Marsh Creek	99	11	6,700	68	610
San Leandro Creek	9	8.5	590	66	70
Guadalupe River	236	57	11,000	47	200
Pulgas Creek Pump Station	0.6	0.4	24	40	60
Sunnyvale East Channel	15	2.5	380	25	150
North Richmond Pump Station	2	1.1	42	21	40
Arroyo Corte Madera del Presidio	12	6.5	190-4,300	16-360	30-660

* Climate-averages were calculated with all available data. The periods over which each small tributary was averaged varied but was generally more than 30 years.

5. Conclusions

The period monitored in this study included both ends of climatic extremes, resulting in very little sampling during the first few drier years, followed by the bulk of sampling during the very wet season of WY 2023. Despite efforts by the project team, turbidity data collection was limited due to a variety of complications including Covid-19 and damage to the equipment during the very high flows of WY 2023. Even when SSC estimates were possible using turbidity (Belmont Creek), the relationship between discharge and SSC was generally better. Issues with turbidity sampling included sensor fouling, battery failure, equipment displacement during high flows, and debris blocking the sensor.

For all sites, we elected to produce estimates of sediment yield using the discharge-SSC relationship. These relationships provided logical results of sediment loads and yields from the tributaries. Walnut Creek had the highest load and yield. Novato Creek had moderately high

loads and yields. While the average SSC at Novato and Belmont creeks were the same, because Belmont is much smaller and on the drier peninsula region, it had lower discharges and sediment loads.

For most watersheds, sediment loads are transported disproportionately during large storm events with high flows. This is due to the compounding factors of high discharges and higher SSC as discharge increases. All four sites experienced disproportionately high sediment load transport during either the large storm events on October 24, 2021 (ACMdp; storm centered on North Bay) or December 31, 2022 (Belmont and Walnut Creek; storm centered in Central and South Bay), or during a moderate storm event that fell on highly saturated soils at the end of a prolonged two-week rainy period and produced significant runoff (Novato Creek). In all four watersheds, these single-day events transported significantly greater sediment loads than the entire WYs 2020 and 2021 combined, highlighting the importance of monitoring during wet water years in order to more accurately estimate suspended sediment loads.

These four additional sediment loads datasets will add to the breadth of monitoring data that can be used for calibrating the regional dynamic simulation loads models for Bay Area watersheds.

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