SAN FRANCISCO BAY NUTRIENT MANAGEMENT STRATEGY

Continuous Suspended Sediment Monitoring in South and Lower South San Francisco Bay

Year Two (2023) Report

Lilia Mourier[1]
Lucy Montgomery[1]
Martin Volaric[1]
Ariella Chelsky[1]
David Senn[1]

[1]San Francisco Estuary Institute

July 2024

SFEI Contribution #1188

Executive Summary

This report provides a project update for year two of a three-year collaboration between the San Francisco Bay Nutrient Management Strategy (NMS), San Francisco Bay Regional Monitoring Program, and South Bay Salt Pond Restoration Project, to estimate high frequency suspended sediment concentration (SSC) in San Francisco Bay (SFB). Through its role in monitoring water quality in SFB, the NMS maintains an array of autonomous sondes that record high frequency (15-minute) water column turbidity, amongst a suite of other environmental parameters. Turbidity data from these monitoring sites was combined with discrete SSC samples to create a bay-wide turbidity-SSC calibration, allowing for estimates of high frequency SSC. The calibration for 7 of these sites was performed using a linear mixed effect model (LMM), which leverages similarities in the turbidity-SSC relationship between sites while allowing for potential differences. An additional turbidity-only sensor was deployed at an 8th site along with discrete SSC collection, with this calibration performed via least squares linear regression. Both models showed reasonable agreement between turbidity and SSC, with R^2 = 0.62 for the LMM, and R^2 = 0.72 for the regression performed at the turbidity-only site.

Using these calibrations, we created continuous 15-min SSC datasets at all 8 locations, representing 1 channel, 4 shoal, and 3 slough sites. These calibrations are considered preliminary and will be finalized as part of the final year 3 report after SSC sample collection is completed. For these datasets, only turbidity data less than 110% of the maximum calibration value were converted to SSC. In total, SSC estimates were generated for ~90-99% of the data record at the water quality monitoring sites and 68% of the record at the turbidity-only station.

Acknowledgments

This work was funded by the South Bay Salt Pond Restoration Project, the Regional Monitoring Program for Water Quality in San Francisco Bay, and the San Francisco Bay Nutrient Management Strategy. We thank staff from USGS PCMSC Marine Facility and USGS California Water Science Center for field support. We also thank the following Watershed Stewards Program corpsmembers for assisting with fieldwork: L Partida, C Diamant, and O Hockley-Rodes.

Suggested citation:

Mourier, L.; Montgomery, L.; Volaric, M.; Chelsky, A.; Senn, D. 2024. Continuous Suspended Sediment Monitoring in South and Lower South San Francisco Bay: Year Two (2023) Report. SFEI Contribution No. 1188. San Francisco Estuary Institute: Richmond, CA

1. Introduction

High frequency continuous monitoring of suspended sediment concentration (SSC) across diverse habitats at the subembayment scale is essential for addressing regional water quality, wetland restoration, and fisheries management needs in San Francisco Bay (SFB). Despite the fact that shallow shoal and slough habitats comprise the majority of South Bay (SB) and Lower South Bay (LSB), continuous monitoring of SSC in this region is currently limited to the USGS Dumbarton Bridge deep channel station. While USGS has conducted short-term SSC studies in several shallow margin and deep channel locations in the SB, its primary focus has been long-term SSC monitoring within the deep channel. This project aims to address this monitoring gap by establishing turbidity-SSC calibrations at eight continuous, high-frequency turbidity monitoring stations located throughout the channel, shoal, and slough habitats of SB and LSB over three years (2022-2024). For a more in-depth description of this project, please see the Continuous Suspended Sediment Monitoring in South and Lower South San Francisco Bay 2022 Year 1 Report (SFEI, 2023). This year 2 summary for 2023 is an addendum to the 2022 Year 1 Report.

The purpose of the Year 2 Report is to:

- Summarize data collection for 2023
- Present updated turbidity-SSC calibrations using 2022 and 2023 data
- Report turbidity and SSC results for 2023

2. Data collection for 2023

2.1 Turbidity monitoring

High frequency turbidity monitoring was conducted at 8 locations within SB and LSB. These include one channel site: San Mateo Bridge (SM), 4 shoal sites: San Leandro Marina (SLM), Hayward (HAY), Shoal (SHL), Eden Landing (EDL), and 3 slough sites: Newark Slough (NW), Guadalupe Slough (GL), and Alviso Slough (ALV) (Figure 1). All sites except EDL utilized YSI EXO2 multiparameter sondes, which record turbidity data in Formazin Nephelometric Units (FNU). EDL utilized a PME C7 sensor, which records data using Nephelometric Turbidity Units (NTU). Please see the 2022 Year 1 Report for a detailed description of procedures for station maintenance, sensor servicing, and turbidity data review.

Due to the numerous challenges associated with continuous water quality monitoring in SB and LSB, there were sporadic gaps during 2023 data collection, with the most substantial gap occurring at the EDL station. The PME C7 turbidity sensor at this site malfunctioned in March 2023 and was under factory repair through October 2023. Redeployment of the station in November 2023 was then postponed to January 2024 due to a USGS sediment deposition and transport study in the area and concerns about the station getting damaged by the large barge that carried sediment to and from the deposition area. As a result, year 2 turbidity data for EDL station only exists for January - February 2023. Listed below are other noteworthy periods of time when stations were offline in 2023.

- NW station was offline from June 20th to August 9th. The sonde battery died on June 20th and was not able to be serviced until the August 9th servicing trip. The station was not accessible in June or July due to weak spring tides and evening high tides.
- ALV station was offline from November 8th to December 20th. Following deployment on November 8th, the battery of the sonde quickly drained due to a sensor malfunction.

- SM station was offline from November 29th through the end of 2023. The entire station had to be temporarily removed due to CalTrans renovations of the San Mateo Bridge.

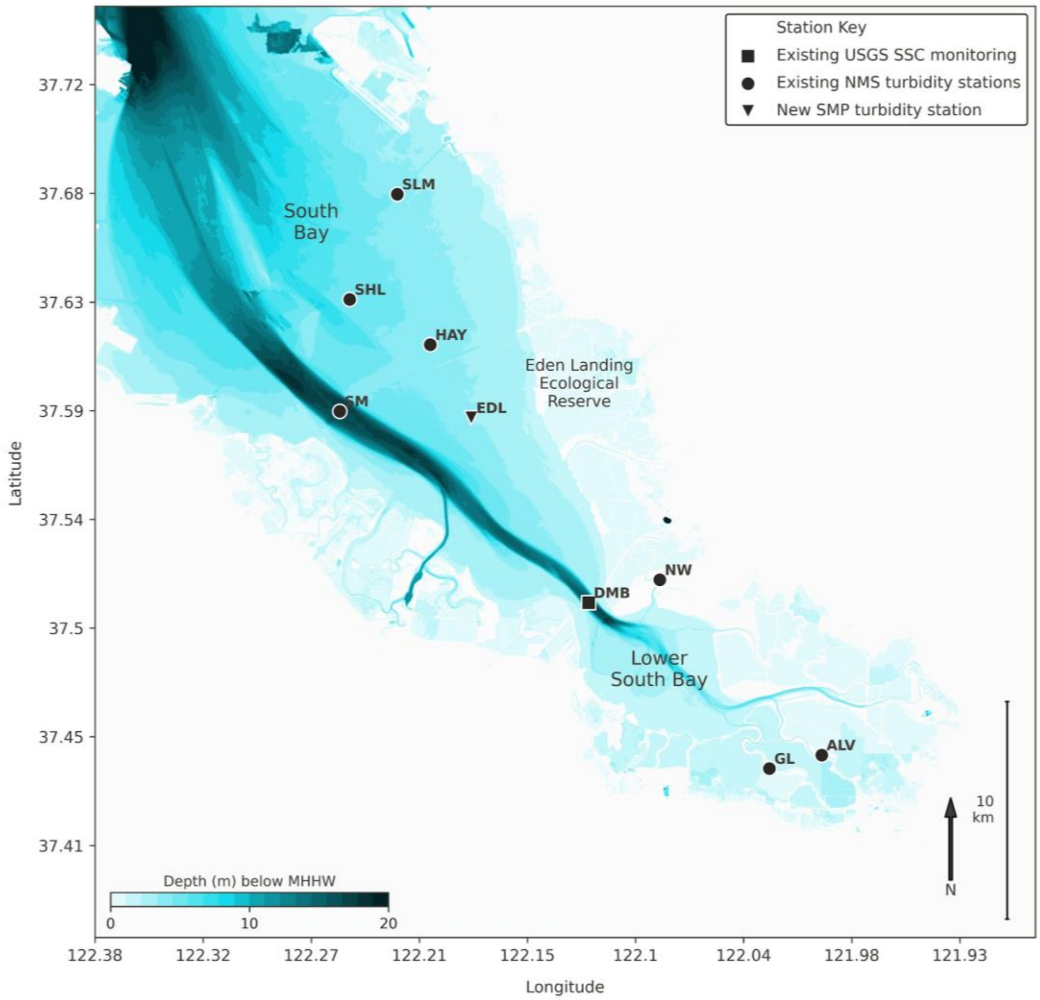

Figure 1. Map of the SB and LSB turbidity monitoring stations. SM - San Mateo Bridge, SLM - San Leandro Marina, HAY - Hayward, SHL - Shoal, EDL - Eden Landing, NW - Newark Slough, GL - Guadalupe Slough, and ALV - Alviso Slough.

2.2 Discrete sampling

Discrete SSC samples were collected in 2023 according to procedures described in the 2022 Year 1 Report. At the time of this year 2 report, the number of SSC samples processed for each site are: ALV = 22, GL = 22, NW = 18, SM = 25, SHL = 36, HAY = 28, SLM = 27, EDL = 15. Sample numbers are higher at SHL, HAY, and SLM because sample collection at those stations preceded the start of this project.

2.3 Wave monitoring

Wave characteristics were measured at the HAY station using a RBR solo high-frequency wave sensor. As with the turbidity sensors, the wave sensor was serviced every 3-6 weeks. Each servicing trip, the wave sensor was cleaned, data was offloaded and reviewed, and the battery was replaced. The sensor-specific program (Ruskin) was used to calculate significant wave height and period, 90th percentile wave height and period, maximum wave height and period, and average wave height and period. All values were calculated at 5 min resolution from 4 Hz pressure data. These results were processed through a multi-level QAQC procedure that included automated formatting, statistical filtering, and semi-automated manual review. Near-continuous monitoring of wave data for all of 2023 was accomplished, with the exception of two month-long periods when the sensor was offline:

- The sensor was offline from May 10th to May 31st. The sensor was retrieved from the field for in-depth lab servicing after being continuously deployed for a year.
- The sensor was offline from July 19th to August 16th due to an internal clock malfunction.

3. Model calibration development

As in year 1, a Linear Mixed Effect Model (LMM) was used to calculate SSC for the seven project stations equipped with a YSI EXO2 sonde (all sites other than EDL). Prior to August 2022, turbidity data at SMB was recorded using a Seabird Hydrocat instead of an YSI EXO2 sonde. As a result, only turbidity data from August 2022-December 2023 were used for SSC calibrations at this site. A Least Squared Linear Regression (LSLR) continued to be used for the EDL station, where a PME C7 turbidity logger is deployed. The turbidity data used for every calibration were the mean of sonde values recorded $\mp$ 30 min around the time of discrete SSC sample collection. Model-specific thresholds were defined to limit the turbidity data used to extrapolate continuous SSC to <110% of the highest turbidity value used in the calibration. In addition to the untransformed (linear) data, both semi-$\log_{10}$x (turbidity) and $\log_{10}$-$\log_{10}$ data transformations were considered for the LMM. The model results were strongest when using untransformed linear data (see Section 4.3 below for a full description), so no data transformation was used for the LMM. Both semi-$\log_{10}$x and $\log_{10}$-$\log_{10}$ transformations also tended to attenuate SSC at high turbidity values, a result that did not occur when using calibrations performed with untransformed data. As this represents a change from year 1 calibrations, when a $\log_{10}$-$\log_{10}$ model was used, calibration model results using $\log_{10}$-$\log_{10}$ transformed data are shown in the Appendix.

In addition to the LMM with untransformed data, two alternative models were evaluated for the EXO2 sites: a global LSLR and site-specific LSLRs. The global LSLR - a linear regression between SSC and turbidity across all sites with no weighting - performed slightly worse than the LMM based on R^2 values. All site-specific LSLRs, with the exception of San Mateo Bridge, likewise performed worse than the LMM based on R^2 values. Results from these alternative models will be presented in more detail in the final Year 3 Report.

Notable outliers in the SSC data, visually identified as extremely high SSC at low turbidity, were removed. Further outlier analysis is ongoing in the third year of the project.

4. Year 2 project results

4.1 Turbidity and discrete SSC data

Spatiotemporal trends in turbidity data recorded in 2023 showed higher and more variable turbidity in the sloughs (ALV, GL, NW) compared to the channel (SM) and shoal (SHL, HAY, SLM, EDL) stations (Table 1, Figure 2). Mean turbidity ranged from 45 to 74 FNU at the slough stations and 12 to 25 FNU/NTU at the channel and shoal stations (Table 1). Turbidity levels remained relatively consistent throughout the year at both slough and channel stations, while levels at the shoal stations appeared slightly elevated in springtime compared to the rest of the year. These trends are consistent with those identified in data recorded in 2022.

Mean SSC of discrete samples collected at each project station ranged from 26 to 106 mg/L (Table 2, Figure 2). Unfortunately, during both 2022 and 2023 we were unable to collect discrete SSC samples during periods of high turbidity. Due to site accessibility restraints and safety concerns in the field, servicing of turbidity monitoring stations necessarily occurs during floods tides when conditions are safest to access sites. As turbidity tends to be elevated during ebb tides and low during flood tides, discrete SSC samples collected each servicing trip did not often capture elevated or peak SSC (Figure 3). As a result, the current calibration thresholds for the LMM and the LSLR are 122 FNU and 20.6 NTU, respectively. For all sites but EDL, the majority of turbidity data (87% - 99%) were within the acceptable range for SSC conversion (Table 1). A notably smaller proportion (68%) of the turbidity data at EDL station were below the calibration threshold.

Table 1. Turbidity statistics for project years 2022 and 2023. SD - standard deviation and P - percentile. Mean, SD, P25th, P50th, P75th and threshold values are in FNU (ALV, GL, NW, SM, HAY, SHL, SLM) and NTU (EDL). Data ≤ Threshold values are percentages of data that meets the calibration threshold for turbidity to SSC.

Station	Mean	SD	P25th	P50th	P75th	Threshold	Data ≤ Threshold
Alviso Slough (ALV)	45.60	56.02	21.5	31.55	48.26	122	94%
Guadalupe Slough (GL)	74.00	76.26	33.94	54.13	89.18	122	89%
Newark Slough (NW)	69.10	61.11	28.11	51.02	90.96	122	87%
San Mateo Bridge (SM)	12.92	33.79	4.00	6.63	12.30	122	99%
Hayward (HAY)	25.22	77.12	4.31	9.01	20.13	122	97%
Shoal (SHL)	12.53	15.23	4.38	8.49	15.69	122	99%
San Leandro Marina (SLM)	20.46	43.76	3.77	8.62	20.71	122	98%
Eden Landing (EDL)	22.75	26.84	7.18	12.89	27.45	20.6	68%

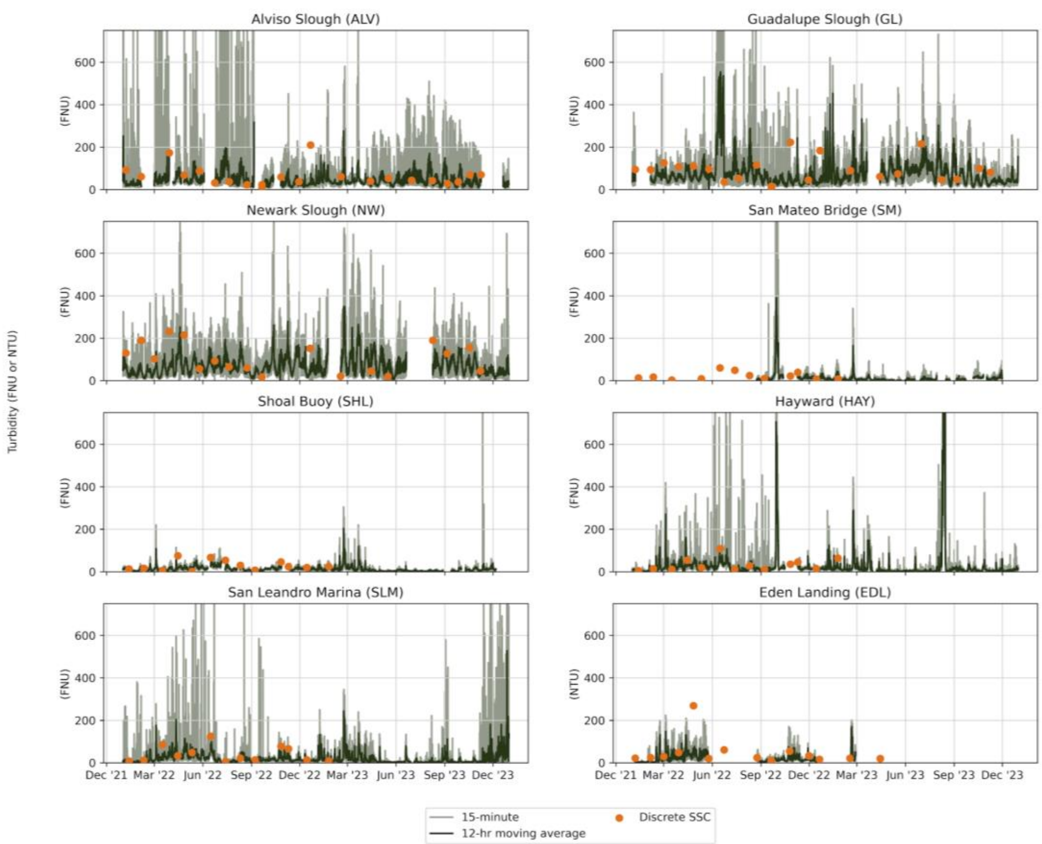

Figure 2. Time series turbidity (FNU or NTU) and discrete SSC (mg/L) data from the eight monitoring stations for project years 2022 and 2023.

Table 2. Discrete SSC distribution statistics for SMB, HAY, SHL, and SLM stations (2020 - 2023) and ALV, GUAD, NEW, and EDL (2022-2023). SD - standard deviation and P - percentile. Mean, SD, P25th, P50th, P75th and Max are in mg/L.

Station	n	Mean	SD	P25th	P50th	P75th	Max
Alviso Slough (ALV)	22	61.59	47.37	36.25	48.50	68.75	210.00
Guadalupe Slough (GL)	22	92.04	57.05	49.25	91.50	110.25	223.00
Newark Slough (NW)	18	106.56	70.02	48.50	98.00	154.25	231.00
San Mateo Bridge (SM)	25	26.68	28.70	10.00	19.00	32.00	145.00
Hayward (HAY)	28	31.03	25.91	12.75	20.50	42.00	109.00
Shoal (SHL)	36	29.16	18.37	15.75	24.50	40.50	75.00
San Leandro Marina (SLM)	27	31.77	29.23	11.50	18.00	43.50	125.00
Eden Landing (EDL)	15	44.00	64.14	20.00	24.00	40.50	269.00

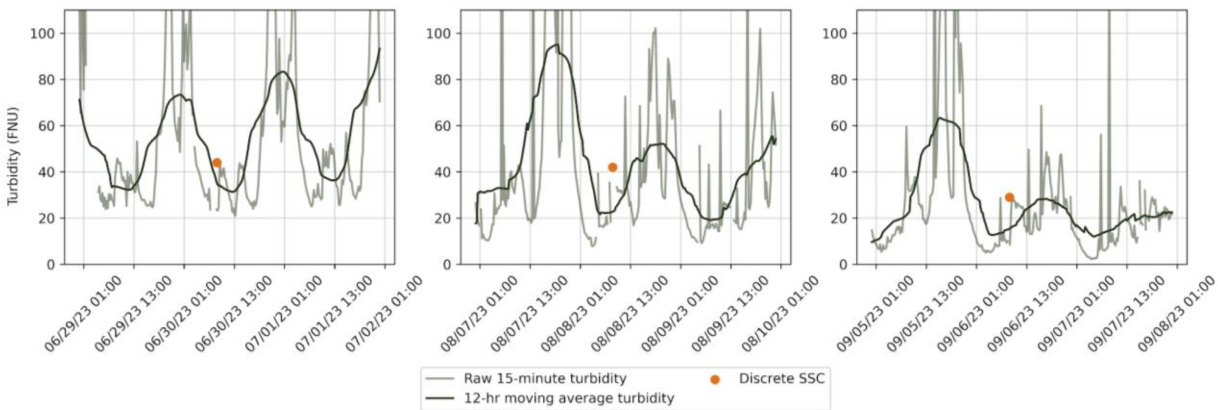

Figure 3. Example turbidity (FNU) and discrete SSC (mg/L) data collected at low turbidity flood tides at ALV, narrowly missing higher turbidity ebb tides, during servicing trips on June 30, 2023, August 8, 2023, and September 6, 2023. Times are in UTC.

4.2 Wave data

The Hayward station (HAY) is located on the exposed eastern shoal of South San Francisco Bay and experiences windy conditions marked by substantial waves (Figure 4). In 2022-2023 the mean significant wave height and period at HAY were 0.15 m and 2.95 s, respectively, with interquartile ranges of 0.02 - 1.38 m and 2.25 - 3.00 s, respectively. Elevated turbidity coincided with periods of elevated wave activity. An example of this occurrence is shown in Figure 5, where from January through March 2023 all elevated turbidity events occurred during periods of elevated wave height, particularly when wave height was >0.45 m. Turbidity likely increased during these times due to wave-driven resuspension of benthic sediments and other particulates.

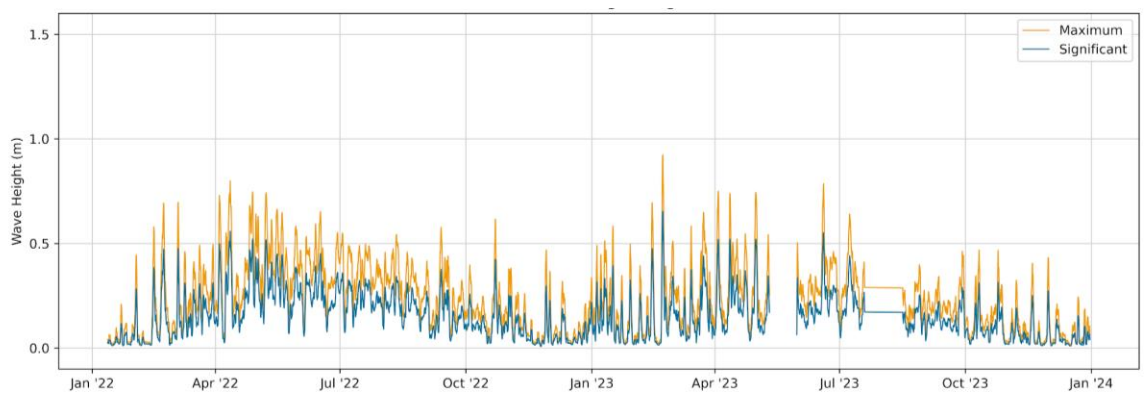

Figure 4. Time series of 24-hour moving average significant and maximum wave height (m) calculated over 5-minute intervals at Hayward station.

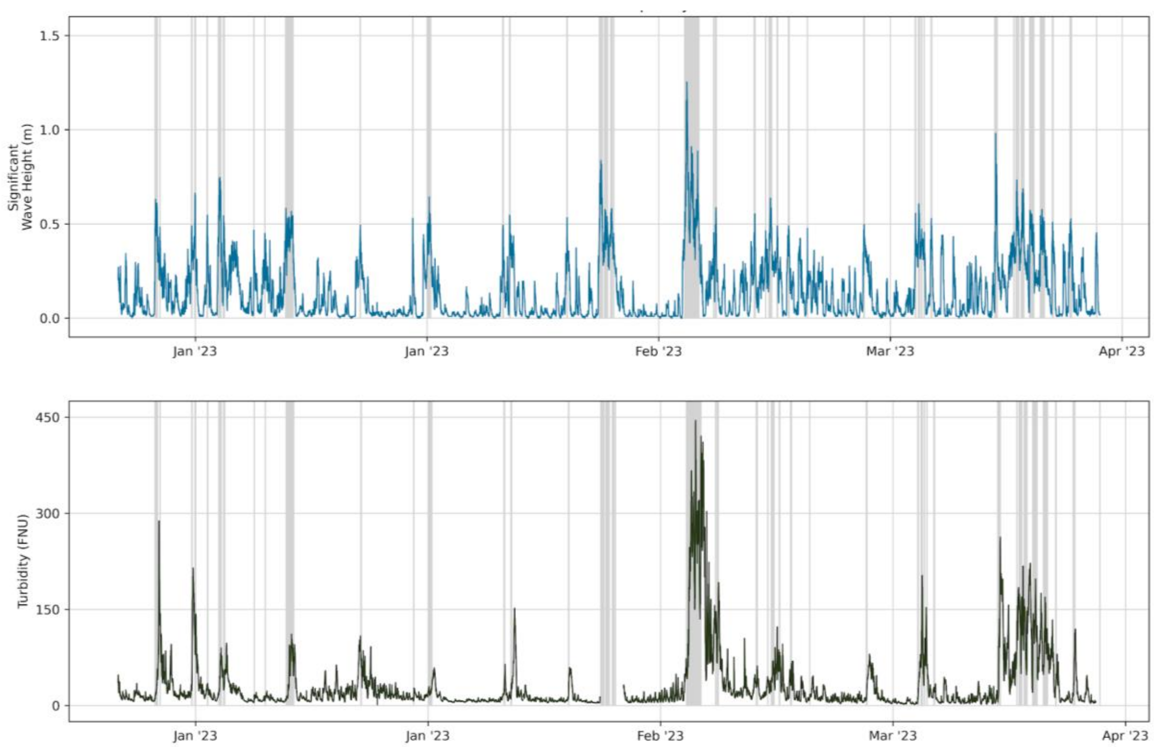

Figure 5. Elevated significant wave height (m) and turbidity (FNU) levels at Hayward station. The shaded areas indicate periods when the significant wave height reached or exceeded 0.45 m.

4.3 Calibration Model Results

Results from both the LMM and LSLR indicate a reasonably strong linear relationship between turbidity and SSC across all project stations, with R-squared values of 0.62 and 0.72, respectively (Table 3). Similarity between LMM site-specific coefficients (slope and intercept) between sites in similar habitats indicates that the LMM is well-suited for this use case (Figure 6). Slough station relationships had higher slopes compared to those for channel and shoal stations, where the slopes were relatively similar. These results suggest that SSC accounts for a higher fraction of turbidity in slough habitats compared to channel and shoal habitats.

Additionally, the R^2 value of the LMM ran with linear data was greater than the R^2 value 0.59 of the LMM ran with $\log_{10}$-$\log_{10}$ transformed data. See Appendix for calibration model results using $\log_{10}$-$\log_{10}$ transformed data.

One potential issue with the LMM is a y-intercept of ~14 mg L^{-1}, suggesting that the calibration overestimates SSC at low turbidities. Further exploration of adjustments of the y-intercept, such as forcing it to be 0, will be explored during the Year 3 final report.

Table 3. List of site specific and fixed effects relationships computed by the LMM and the site specific regression computed by the LSLR for Eden Landing station.

Station	Habitat	Model	Regression	p (α =0.05)	R^2
LMM Fixed Effects	-	LMM	$ssc = 1.25 * (turb) + 13.75$	0.00	0.62
Alviso Slough (ALV)	Slough	LMM	$ssc = 1.91 * (turb) + 13.22$	0.31	
Guadalupe Slough (GL)	Slough	LMM	$ssc = 1.77 * (turb) + 14.03$	0.17	
Newark Slough (NW)	Slough	LMM	$ssc = 1.63 * (turb) + 14.38$	0.39	
San Mateo Bridge (SM)	Channel	LMM	$ssc = 0.63 * (turb) + 13.64$	0.82	
Hayward (HAY)	Shoal	LMM	$ssc = 0.83 * (turb) + 13.68$	0.16	
Shoal (SHL)	Shoal	LMM	$ssc = 0.98 * (turb) + 13.54$	0.68	
San Leandro Marina (SLM)	Shoal	LMM	$ssc = 0.99 * (turb) + 13.51$	0.44	
Eden Landing (EDL)	Shoal	LSLR	$ssc = 3.2 * (turb) + 0.14$	0.00	0.72

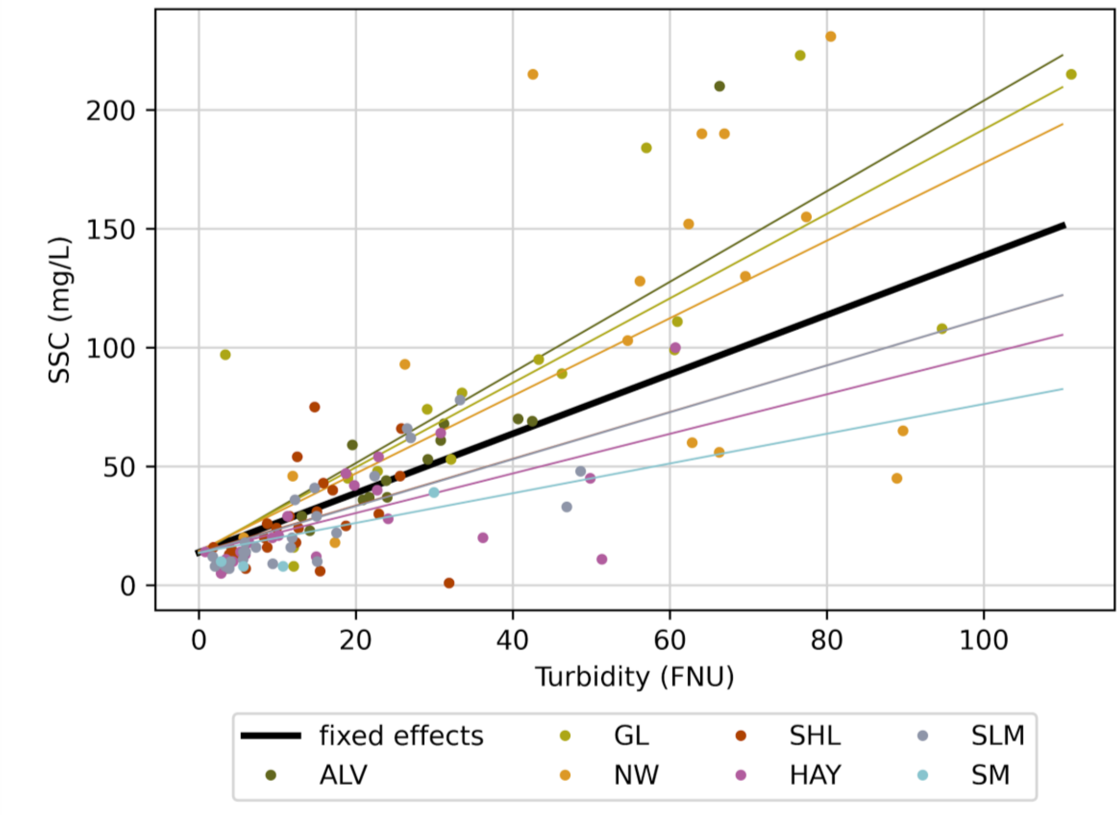

Figure 6. Turbidity vs SSC and best fit lines for HAY, SHL, and SLM stations (2020 - 2023) and ALV, GL, NW and SM (2022-2023) generated by the linear mixed model (LMM).

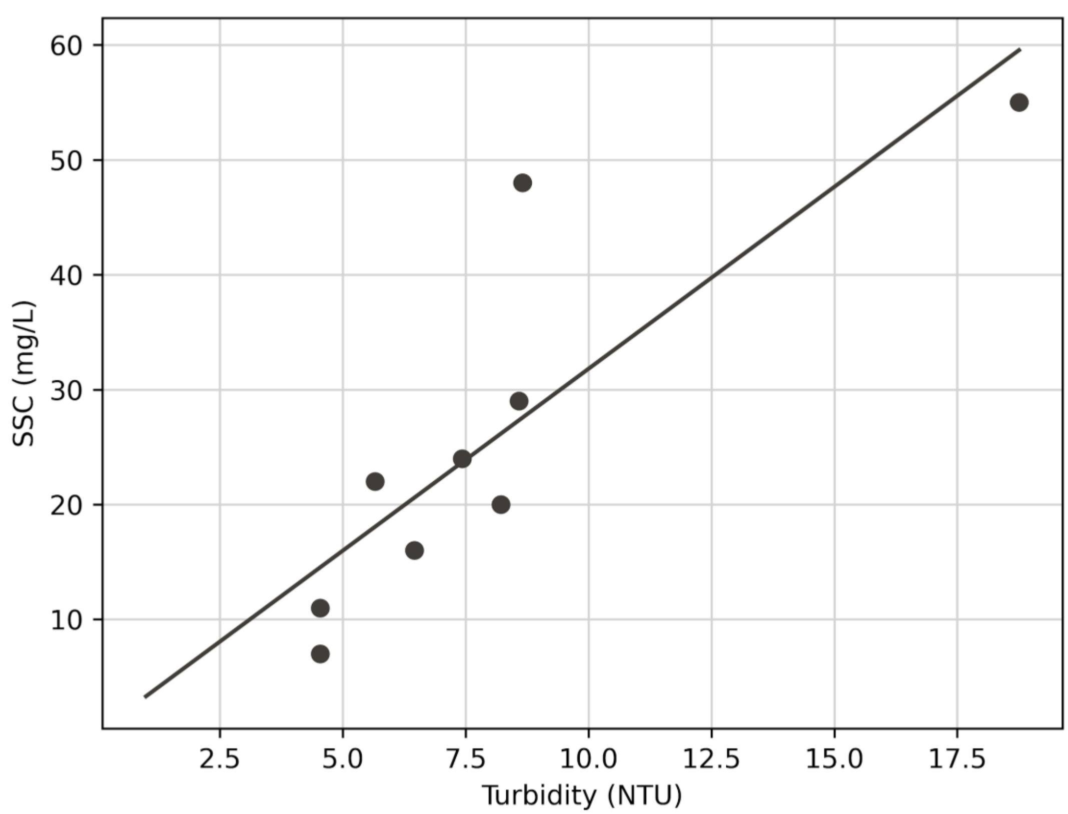

Figure 7. Turbidity vs. SSC for 2022 - 2023 at the Eden Landing station and the best fit line generated by the least-squared linear regression (LSLR).

4.4 Preliminary Continuous SSC Data

Preliminary continuous SSC estimates were generated using the site-specific relationships listed in Table 3 for all eight stations (Figure 8). Note that the range of SSC values are limited by the calibration thresholds (122 FNU for LMM stations and 20.6 NTU for Eden Landing). SSC estimates were out of range for 1-13% of data from LMM stations and for 32% of data from Eden Landing.

Despite the calibration thresholds, the provisional SSC dataset is nearly continuous and often captures short events like storms and floods. For example, SSC estimates during the atmospheric river events in the San Francisco Bay Area from late-December to mid-January 2023 fell within the model thresholds for nearly all stations (Figure 9). One exception to this was Guadalupe Slough, where peak turbidity recorded during these storms exceeded the LMM threshold during four of the five highlighted events and SSC could not be calculated. SSC at the slough (ex: ALV) and shoal (ex:SLM) stations was elevated during the atmospheric river events, whereas SSC in the channel (SM) remained low and relatively unaffected. However, the timing of the elevated SSC pulses differed. Peaks in SSC were closely aligned with the timing of storms at the shoal stations, while there was a noticeable lag between storm intensity and SSC pulses at the slough stations. This difference in the timing of the SSC response to storms suggests differences in sediment transport dynamics between shoal and slough environments.

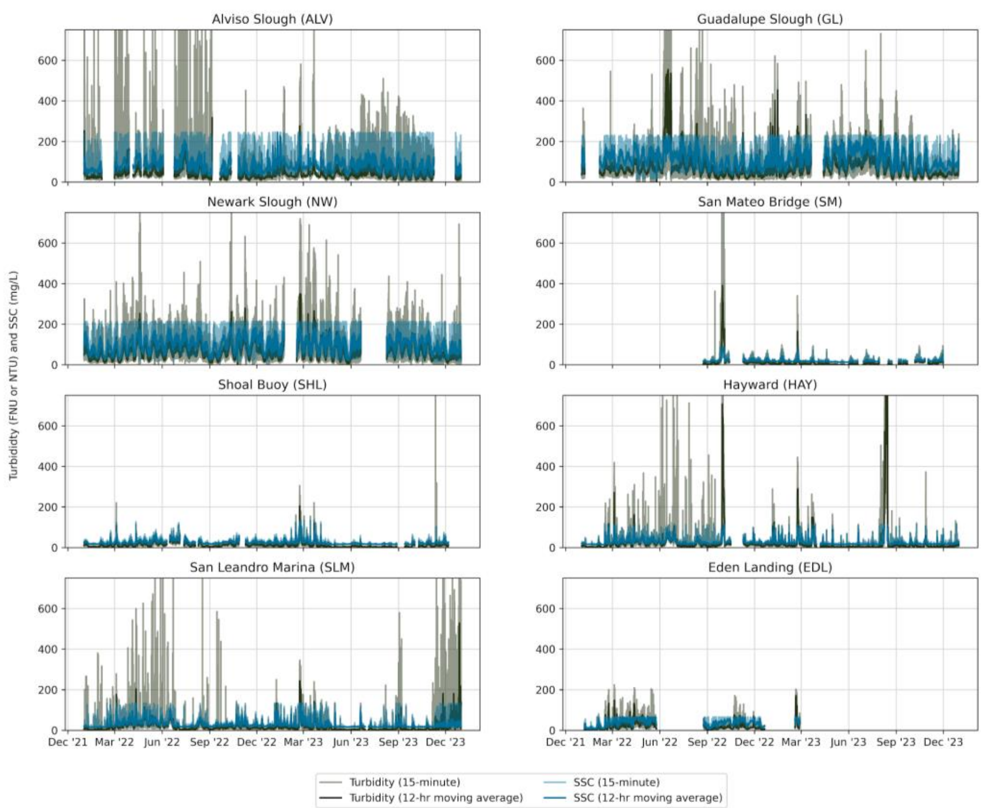

Figure 8. Time series plots of continuous SSC and turbidity data from 2022 and 2023 generated using a LMM for stations with EXO2 sondes and a LSLR for Eden Landing station. Large gaps in the time series are due to data loss from turbidity sensors (see Section 2.1). SSC data extrapolated from turbidity that was out of range for the calibration (122 FNU for LMM stations and 23 for Eden Landing station) are excluded from the timeseries.

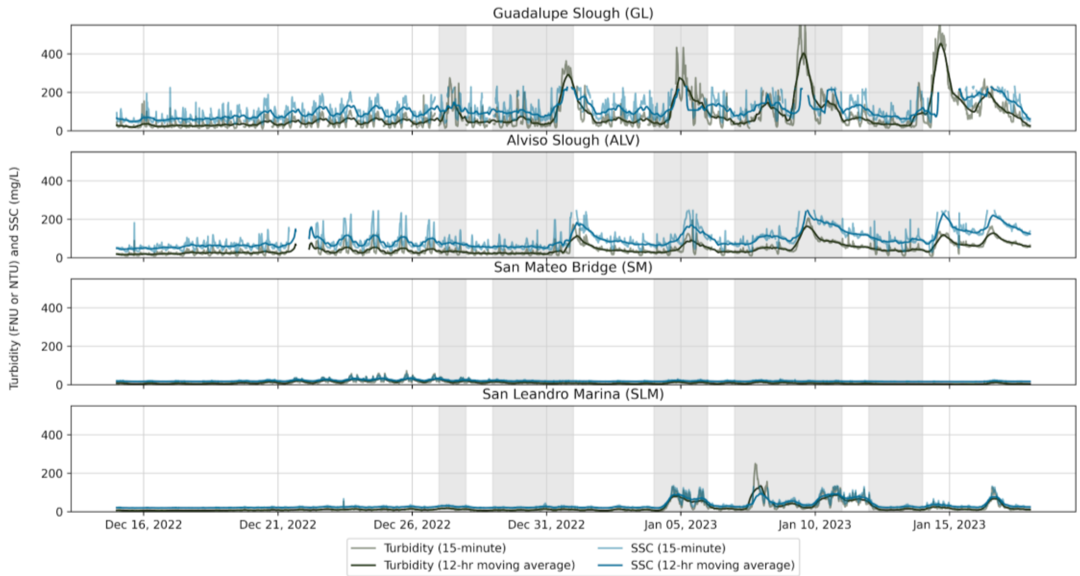

Figure 9. Time series plots of continuous SSC (mg/L) and turbidity (FNU) data at GL, ALV, SM, and SLM stations from mid-December 2022 to mid-January 2023. Grey shaded areas correspond to atmospheric river events that took place between December 26, 2022 and January 17, 2023 in the San Francisco Bay Area.

5. Project data repository

Preliminary data from project years 1 and 2 (2022-2023) are available for download on the SFEI google drive. The repository directory (Table 4) includes the file names and which parameters are included in each. While substantial efforts are made to ensure the accuracy of data and documentation contained in this dataset, complete accuracy of data cannot be guaranteed. All data are made available "as is". See the Data User Agreement in the project data repository folder for additional details and citation information.

Table 4. Directory for project data repository.

File Name	Contents	Years
discrete_sediment.csv	• Total sediment (g) • Sediment concentration (mg/L) • Total sand (g) • Total fine (g) • Percent finer (%)	2020, 2021, 2022, 2023
turbidity_ssc.csv	• Continuous turbidity (FNU or NTU) • Continuous suspended sediment concentration (mg/L)	2022, 2023
wave.csv	• Water column depth (m) • Significant wave height (m) • Significant wave period (s) • 90 percentile wave height (m) • 90 percentile wave period (s) • Maximum wave height (m) • Maximum wave period (s)	2022, 2023

	- Average wave height (m) - Average wave period (s) - Wave energy (J/m^2) - Pressure (dbar) - Sensor depth (m)

6. Next steps

The upcoming and final year of this project will concentrate on strengthening and finalizing site-specific calibrations, leveraging an additional six months of data collected in 2024. Several objectives of the calibration refinement process will be to resolve outliers in the model calibration data, assess the validity period of both models, and conduct an in-depth comparison of models. This will include testing a version of the LMM with a forced y-intercept at 0. The last phase of the project will focus on comprehensive reporting, synthesis, and interpretation of the project dataset. This project is set to end December, 2024.

7. References

Mourier, L., Volaric, M., Chelsky, A., & Senn, D. (2023). Continuous Suspended Sediment Monitoring in South and Lower South San Francisco Bay (SFEI Contribution #1135). San Francisco Estuary Institute Nutrient Management Strategy.

Appendix

Table A1. List of site specific and fixed effects relationships computed by the LMM and the site specific regression computed by the LSLR for Eden Landing station using log_{10}-log_{10} transformed data.

Station	Habitat	Model	Regression	p (α =0.05)	R^2
LMM Fixed Effects	-	LMM	$log_{10}(ssc) = 0.63 * log_{10}(turb) + 0.72$	0.00	0.59
Alviso Slough (ALV)	Slough	LMM	$log_{10}(ssc) = 0.73 * log_{10}(turb) + 0.66$	0.31	
Guadalupe Slough (GL)	Slough	LMM	$log_{10}(ssc) = 0.77 * log_{10}(turb) + 0.64$	0.11	
Newark Slough (NW)	Slough	LMM	$log_{10}(ssc) = 0.76 * log_{10}(turb) + 0.64$	0.12	
San Mateo Bridge (SM)	Channel	LMM	$log_{10}(ssc) = 0.56 * log_{10}(turb) + 0.76$	0.66	
Hayward (HAY)	Shoal	LMM	$log_{10}(ssc) = 0.52 * log_{10}(turb) + 0.78$	0.22	
Shoal (SHL)	Shoal	LMM	$log_{10}(ssc) = 0.48 * log_{10}(turb) + 0.81$	0.13	
San Leandro Marina (SLM)	Shoal	LMM	$log_{10}(ssc) = 0.59 * log_{10}(turb) + 0.74$	0.69	
Eden Landing (EDL)	Shoal	LSLR	$log_{10}(ssc) = 1.53 * log_{10}(turb) + 0.72$	0.00	0.72

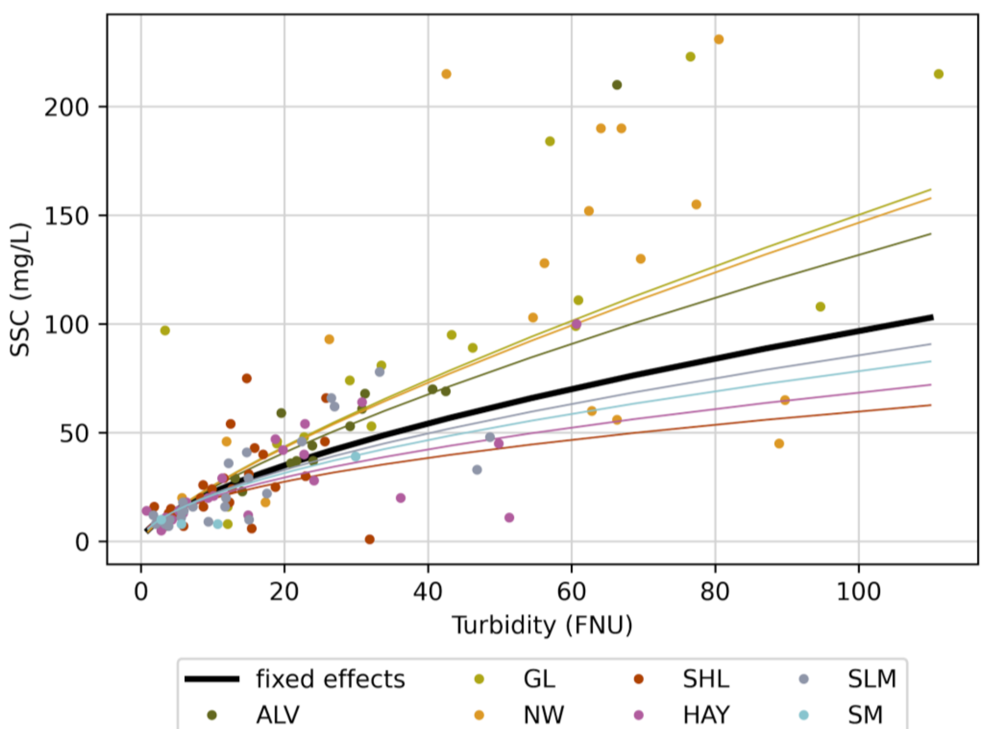

Figure A1. Turbidity vs SSC AND the best fit lines for HAY, SHL, and SLM stations (2020 - 2023) and ALV, GL, NW and SM (2022-2023) generated by the linear mixed model (LMM) using log_{10}-log_{10} transformed data.

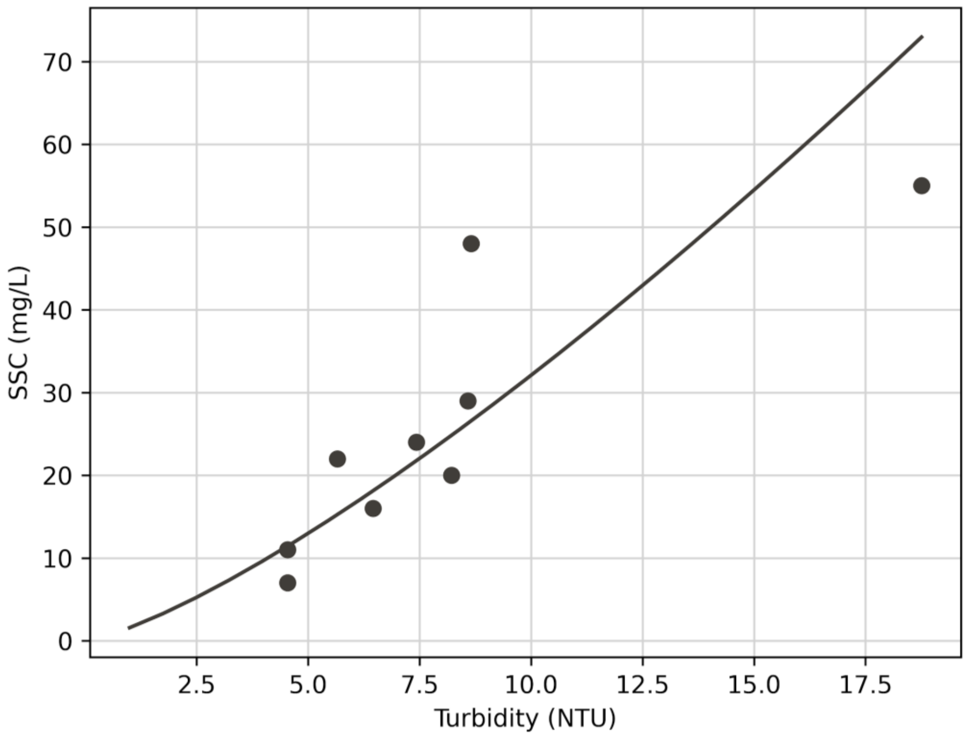

Figure A2. Turbidity vs. SSC for 2022 - 2023 at the Eden Landing station and the best fit line generated by the least-squared linear regression (LSLR) using $\log_{10}$-$\log_{10}$ transformed data.