SAN FRANCISCO BAY NUTRIENT MANAGEMENT STRATEGY

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

## Year One Report for 2022

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

[1]San Francisco Estuary Institute

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## Summary

Suspended sediment concentration (SSC) is of critical importance to the management of San Francisco Bay (SFB), yet has not been a focus of sustained high frequency monitoring efforts in shallow shoal and slough habitats that make up a majority of the area of the South Bay (SB) and Lower South Bay (LSB). In this report, we provide a status update for year one of a three year collaboration between the San Francisco Bay Nutrient Management Strategy (NMS) and Regional Monitoring Program (RMP) with the South Bay Salt Pond Restoration Project (SBSPRP) to estimate high frequency SSC throughout the SB and LSB. As a part of this effort, 15-minute turbidity data from seven locations, collected as part of the NMS Moored Sensor Program (MSP), was paired with monthly discrete SSC sampling, with the goal of creating a robust turbidity-SSC calibration. An additional turbidity-specific sensor was also deployed and paired with discrete SSC sampling on the shoal near the Eden Landing Whale’s Tail. Here we present preliminary results from turbidity-SSC calibrations at these eight sites, which together span a range of environments (deep channel, shoal, slough) representative of SFB. Following completion of this calibration, resource managers will be able to convert continuous high-frequency turbidity data to SSC at locations throughout SB and LSB, greatly aiding future sediment-focused efforts.

## Acknowledgements

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## 1. Introduction

Spatiotemporal variance of suspended sediment concentration (SSC) in San Francisco Bay (SFB) is of key interest to regional water quality, wetland, and fisheries managers. Accurate measurements of SSC are critical for quantifying sediment delivery to shorelines, migration of particle-associated contaminants, light attenuation for phytoplankton growth, and habitat suitability for marine wildlife (Cloern, 1987; Cloern and Jassby, 2012; Newcombre and Jensen, 1996). SSC and sediment transport processes are especially relevant to the South Bay (SB) and Lower South Bay (LSB) regions of SFB due to historical mercury loading, significant nutrient enrichment from publicly owned treatment works (POTWs), and adjacent large-scale marsh and wetland restoration projects around the Bay's perimeter (Marvin-DiPasquale et al., 2022; SFEI, 2016; Shellenbarger et al., 2013; Valoppi, 2018). Due to the value of SSC data to the region, continuous high-frequency monitoring of SSC is of high importance in SFB.

The USGS has conducted SSC monitoring at several deep channel locations in SFB. Continuous SSC estimates are generated through the calibration of moored sensor turbidity measurements with discrete SSC samples via site-specific linear regressions (Rasmussen et al. 2009). Currently, the only publicly available USGS continuous SSC data are from their Dumbarton Bridge station, though summaries of USGS SSC monitoring efforts at other stations for specific water years are described in public reports (Livsey et al., 2020).

With SSC monitoring limited to the deep channel, a critical monitoring gap exists for shallow margin shoal and slough habitats in SB and LSB. To address this gap, a collaboration was formed in January 2022 between the San Francisco Estuary Institute's (SFEI's) Nutrient Management Strategy (NMS) and Regional Monitoring Program (RMP), along with the South Bay Salt Pond Restoration Project (SBSPRP). The goal of this project is to augment high-frequency turbidity data from seven NMS water quality monitoring stations in SB and LSB by collecting discrete SSC samples, and developing a turbidity-SSC calibration to determine estimates of continuous SSC. This project also establishes an eighth turbidity monitoring station that also includes discrete SSC sample collection. Together these eight locations span a range of channel, shoal, and slough sites across SB and LSB. The project is set to run for three years (2022-2024).

The purpose of this year one report is to:

1. Describe the approach for SSC monitoring
2. Present preliminary turbidity-SSC calibrations
3. Report preliminary SSC results and trends
4. Discuss upcoming work in the second and third year of the sediment monitoring project

## 2. Data collection

### 2.1 Turbidity monitoring stations

Continuous high-frequency (15-min) turbidity data is currently collected using YSI EXO2 multiparameter sondes at seven sites in SB and LSB as part of the NMS moored sensor program (MSP), which conducts routine water quality monitoring of SFB (Figure 1, Table 1). The NMS MSP sites are: San Mateo Bridge (SM), San Leandro Marina (SLM), Hayward (HAY), Shoal (SHL), Newark Slough (NW), Guadalupe Slough (GL), and Alviso Slough (ALV). Turbidity at SM was recorded with a Seabird HydroCat prior to August 2022, and with an EXO2 from August 2022-present. As a part of this project, an additional turbidity monitoring station with a PME C7 turbidity sensor was established on the SB shoal offshore of the Eden Landing Whale's Tail (EDL). Of these eight total stations, one is located in the SB deep channel, four are located on the SB shoal, and three are located in the LSB sloughs (Table 1). An additional high frequency RBR Solo3 pressure sensor was deployed at the Hayward station to measure wave height and period at 5-minute resolution. This serves as a complementary dataset informing wave-driven resuspension of SSC on the SB shoal.

Turbidity stations were serviced every three to five weeks. During each servicing trip, instruments were either swapped for lab-cleaned and calibrated instruments, or else field-serviced consisting of cleaning, calibration checks, and battery replacement. Following retrieval, all data was run through a multistep QA/QC process in accordance with NMS MSP procedures.

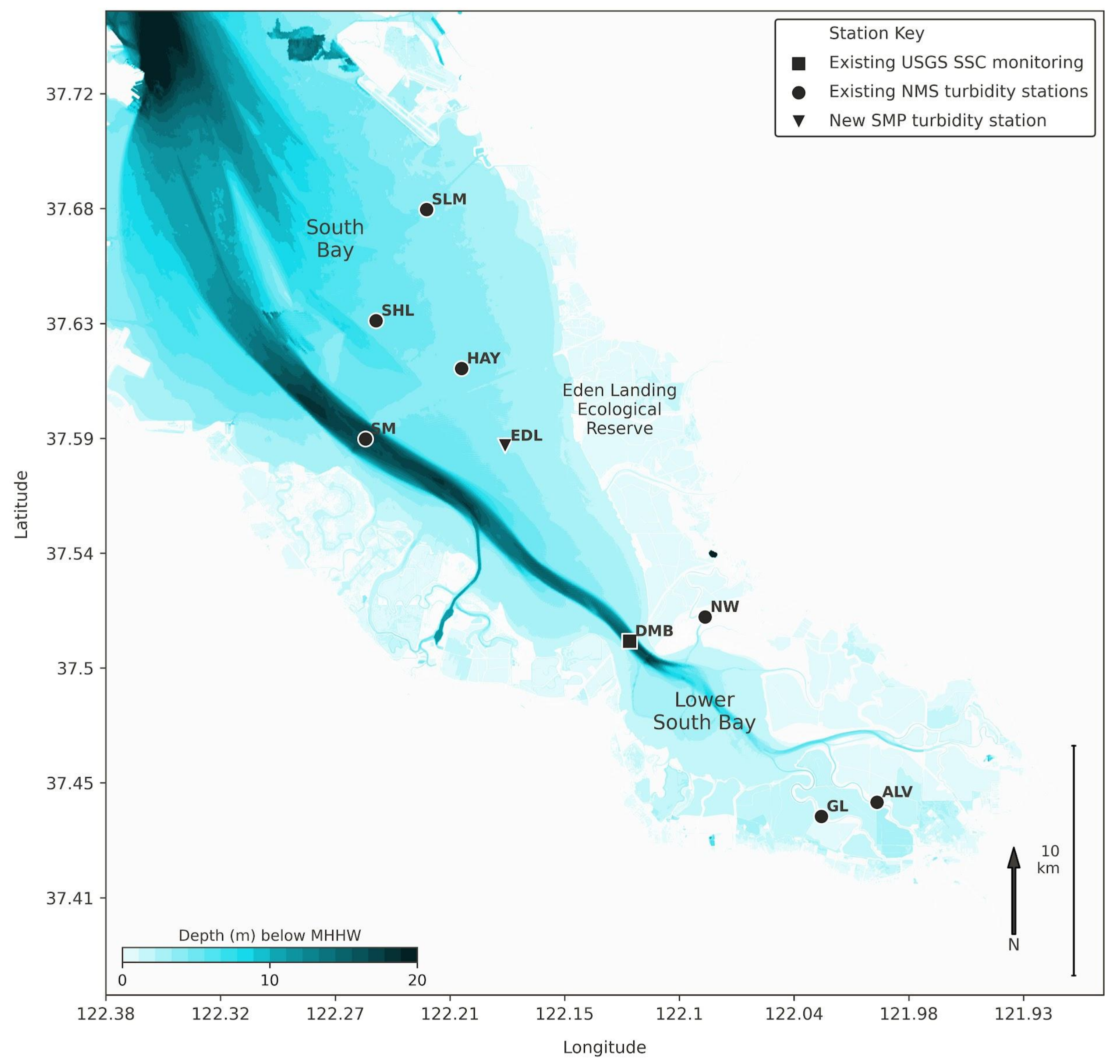


Figure 1. Map of the SB and LSB turbidity monitoring stations. SM - San Mateo Bridge, SLM - San Leandro Marina, HAY - Hayward, SHL - Shoal, EDL - Eden Landing, NW - Newark Slough, GL - Guadalupe Slough, and ALV - Alviso Slough. See Table 1 for station details.

Table 1. Site details for the SB and LSB turbidity monitoring stations. Monitoring instruments include: EXO2 - YSI EXO2 multiparameter water quality sonde, C7- PME Turner Cyclops7 turbidity logger, RBR - RBR Solo3 pressure sensor, HCEP - SeaBird Hydrocat multiparameter water quality sonde.

| Station | Lat | Long | Dist above bed (m) | Date installed | Habitat type | Equipment |
|---|---|---|---|---|---|---|
| San Mateo Bridge (SMB) | 37.584 | -122.248 | 10 | July 2014 | Main channel | EXO2, HCEP |
| San Leandro Marina (SLM) | 37.674 | -122.217 | 1.3 | Nov 2020 | Shoal | EXO2 |
| Hayward (HAY) | 37.611 | -122.201 | 1 | Aug 2021 | Shoal | EXO2, RBR |
| Shoal (SHL) | 37.630 | -122.243 | 0.8 | April 2015 | Shoal | EXO2 |
| Eden Landing (EDL) | 37.581 | -122.180 | 0.5 | Jan 2022 | Shoal | C7 |
| Newark Slough (NW) | 37.513 | -122.082 | 1.3 | April 2015 | Slough | EXO2 |
| Guadalupe Slough (GL) | 37.435 | -122.026 | 0.5 | June 2015 | Slough | EXO2 |
| Alviso Slough (ALV) | 37.44 | -121.998 | 0.5 | Sept 2013 | Slough | EXO2 |

## 2.2 Discrete sampling

Discrete SSC samples were collected every three to five weeks at each site. As part of the NMS MSP, discrete SSC samples have been collected at SM, SLM, HAY, and SHL since 2020. Beginning January 2022, monthly discrete SSC sampling was expanded to EDL, NW, GL, and ALV. All discrete samples were collected at the approximate instrument depth (± 1 m) following standard USGS procedures (Rasmussen et al. 2009). At SM, SLM, HAY, and SHL, samples were collected using a submersible centrifugal pump while at EDL, NW, GL, and ALV samples were collected using a Van Dorn sampler. Discrete samples were analyzed for total sediment concentration and percent fines at the USGS Santa Cruz Sediments Laboratory. Total sediment concentration results were used for the calibrations of turbidity to SSC. Per USGS guidelines, we plan to collect >30 discrete SSC samples for each site by the end of year three of the project. At the time of this report, the number of discrete samples that have been processed for each site are: ALV = 14, GL = 14,  NW = 14, EDL = 13, SM = 17 (only 4 SM samples were used - see section 3 below), SHL = 51, HAY = 17, SLM = 18.

## 3. Model calibration development

Two calibration models were tested for developing the turbidity to SSC relationship. The first was a series of site-specific least squares linear regressions between discrete SSC and turbidity, similar to the approach commonly used by the USGS for SSC monitoring (Rasmussen et al., 2009). This methodology has the advantage of being applicable to the different instruments (EXO2, HydroCat, C7) that have been used as part of this study. However, the primary downside to a site-specific approach is the limited number of discrete samples that have been collected at each site.

One solution to a small sample size is a linear mixed effect model (LMM) - a powerful tool that assumes similarity in x-y relationships across a range of sample groups. For example, in our case the turbidity-SSC relationship is likely to be similar across all sites in SB and LSB. LMMs are similar to the linear regression models described above, but have the advantage of more efficiently utilizing a limited number of datapoints. LMMs combine fixed effects (FE) shared across all sites with site-specific random effects (RE). For our turbidity-SSC calibration model, the LMM for each site takes the form:

$$SSC = (a_{FE} + a_{RE}) * turb + (b_{FE} + b_{RE}) \tag{1}$$

where $a_{FE}$ and $a_{RE}$ are the fixed and random effects slopes, respectively, and $b_{FE}$ and $b_{RE}$ are the y-intercepts. This LMM is our working model for the turbidity-SSC calibration in this project, and was applied to all sites with EXO data (ALV, GL, NW, SHL, HAY, SLM, SM). As EDL used a different turbidity sensor (PME C7), this data was excluded from the LMM and a least-squares linear fit between turbidity and SSC was performed, as described above. Additionally, data at SM was recorded with a HydroCat prior to August 2022, and an EXO from August 2022 to present. The NMS MSP is in the process of recalibrating all historical SM data, including turbidity, using results from a side-by-side field deployment of a HydroCat with an EXO2. This calibration is ongoing, and for now SM data collected prior to August 2022 was excluded from the LMM.

Three data transformations were considered for the turbidity-SSC LMM: linear (untransformed), semi-$\log_{10}$x (turbidity), and $\log_{10}$-$\log_{10}$.

## 4. Year one project results

### 4.1 Turbidity data

Turbidity at the sites tended to be substantially higher and more variable in the sloughs (ALV, NW, GL) than on the shoal (SHL, HAY, EDL, SLM) or in the channel (SM) (Figure 4). The sloughs in LSB drain a complex network of former salt ponds, several of which are in the process of restoration (SFEI, 2016). High sediment persisted throughout the year at these sites, showing little seasonality. Although levels were lower, there was a stronger seasonal turbidity signal on the shoal and in the deep channel.  On the shoal, turbidity was elevated in late winter and spring compared to the rest of the year, possibly from wave-driven resuspension of sediments due to strong spring winds and elevated freshwater inflow.

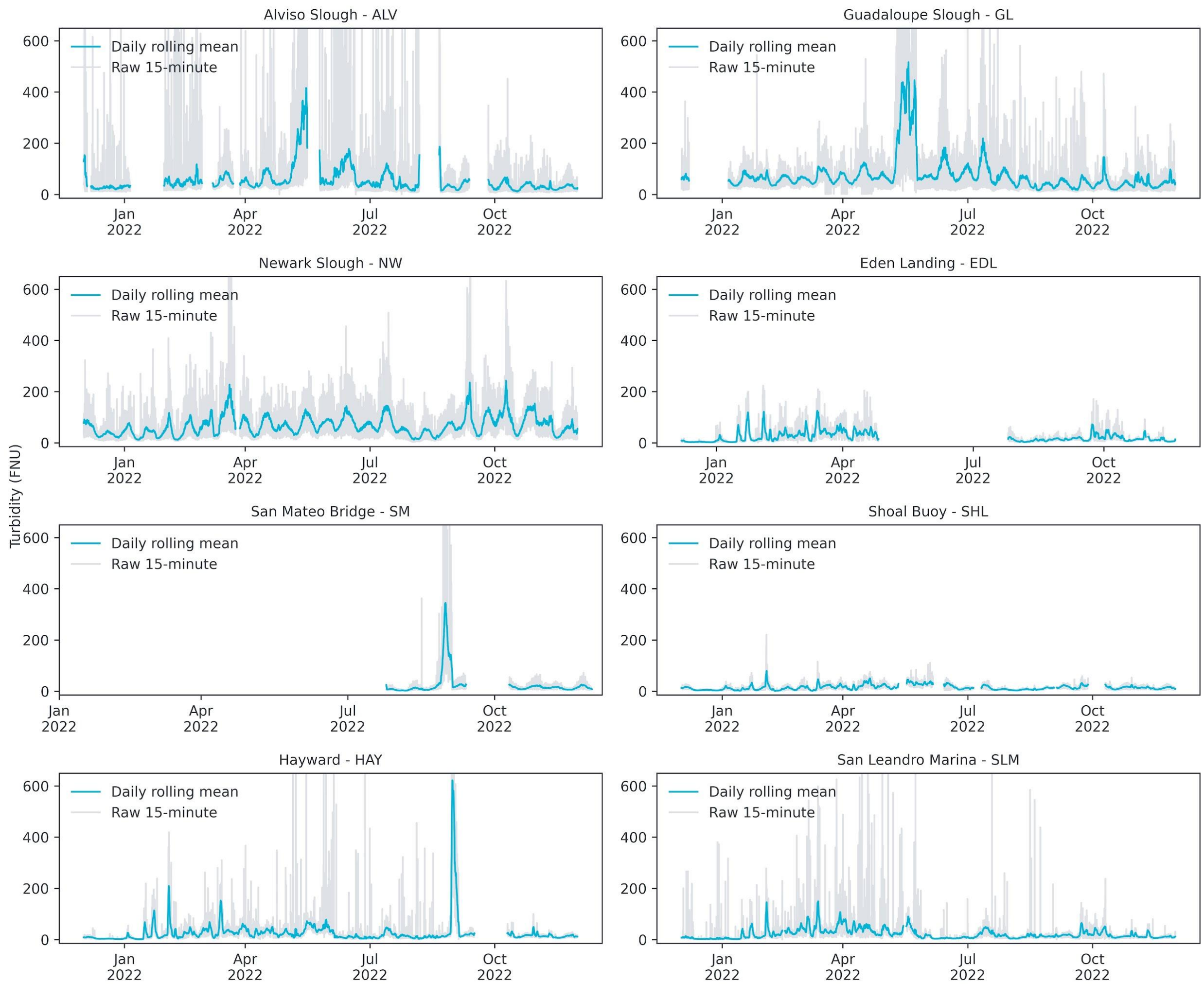


Figure 4. Turbidity data at the eight monitoring stations from Jan-Dec 2022.

## 4.2 Model Results

### 4.2a Heteroskedasticity

The LMM was run for the seven NMS MSP sites with linear, semi-log, and log-log data transformations. Substantial heteroskedasticity, defined as a change in standard deviation with x, was present in residual plots from the LMMs run with both linear and semi-log transformed data. It was not present in the residual plots from the LMM with log-log transformed data. Heteroskedasticity violates the assumptions of linear regression and LMMs and is a sign of poor model fit. Thus, log-log transformed data was used for the LMM. For consistency with our LMM, log-log transformations were also used for the least-squares linear regression for EDL.

### 4.2b Model results

Results from the log-log LMM and log-log EDL turbidity-SSC regression are presented in Figures 3 and 4, respectively, with model coefficients presented in Table 4. One strength of the LMM is it allows for the direct comparison of model coefficients. We are still evaluating the model for potentially significant differences between RE coefficients. These differences would imply that the contribution of SSC to overall turbidity compared to other constituents (e.g. organic matter), differs between sites in SB and LSB.

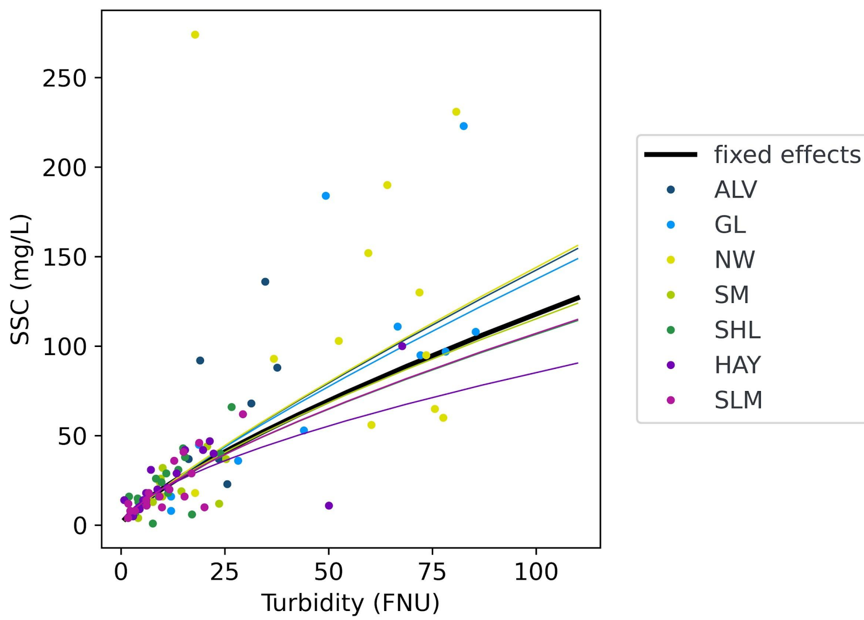


Figure 3. Turbidity vs. SSC at the seven NMS MSP sites used for calibration. Site-specific and global (fixed effect) relationships were modeled using an LMM to $\log_{10}$-$\log_{10}$ transformed data.

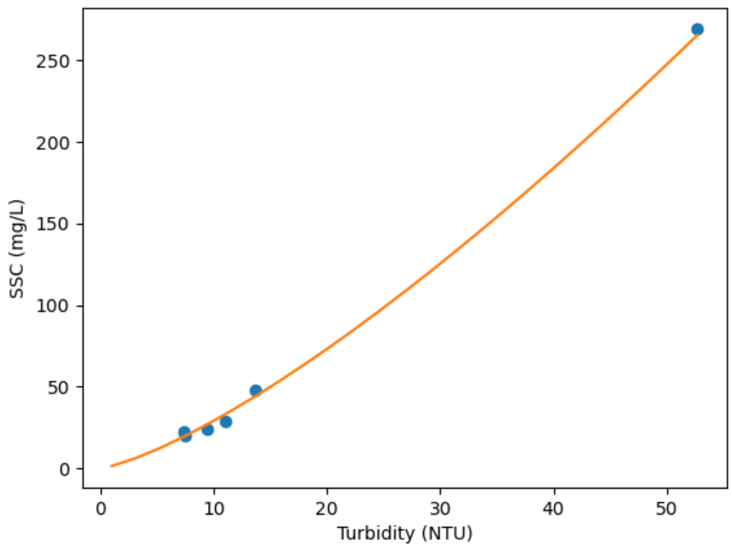


Figure 4. Turbidity vs. SSC at the Eden Landing station used for calibration. The best fit line was modeled to a $\log_{10}$-$\log_{10}$ transformation of the data.

Table 4. Station specific relationships between turbidity and SSC for each station.

| Station | Regression | Equation |
|---|---|---|
| Alviso Slough | LMM | $log_{10}(SSC) = 0.84 * log_{10}(turb) + 0.46$ |
| Guadalupe Slough | LMM | $log_{10}(SSC) = 0.82 * log_{10}(turb) + 0.48$ |
| Newark Slough | LMM | $log_{10}(SSC) = 0.84 * log_{10}(turb) + 0.46$ |
| Eden Landing | Least-squares linear regression | $log_{10}(SSC) = 1.33 * log_{10}(turb) + 0.13$ |
| San Mateo Bridge | LMM | $log_{10}(SSC) = 0.75 * log_{10}(turb) + 0.53$ |
| Shoal | LMM | $log_{10}(SSC) = 0.71 * log_{10}(turb) + 0.59$ |
| Hayward | LMM | $log_{10}(SSC) = 0.62 * log_{10}(turb) + 0.68$ |
| San Leandro Marina | LMM | $log_{10}(SSC) = 0.72 * log_{10}(turb) + 0.58$ |

These regression equations are preliminary and will continue to be refined as more turbidity and SSC data become available. USGS protocol dictates that continuous SSC should not be extrapolated to turbidity >110% of the highest value used for SSC calibration (Conlen and Morgan-King, 2023). Due to the nature of the LMM, all NMS MSP calibrations share the same turbidity threshold of approximately 90 FNU. Turbidity tended to be below this threshold, and thus be in the acceptable range for SSC conversion, far more often in the channel and on the shoal (SM = 96.4%, SHL = 99.5%, HAY = 96.7%, SLM = 97.8%), than in the sloughs (ALV = 80.0%, GL = 72.4%%, NW = 57.8%). EDL had a site-specific turbidity threshold of 58 NTU, of which values fell below 57.1% of the time.

### 4.3 Preliminary Continuous SSC data

Using the equations in Table 4, we generated preliminary continuous SSC estimates for all eight stations (Figure 5), with comparisons across sites revealing differences in SSC based on habitat type (Figure 6). Slough stations exhibited the greatest SSC while the channel stations exhibited the lowest SSC (Figure 6B). Of the slough sites, GL and NW appeared to have the highest median SSC, followed by ALV (Figure 6A). SSC at EDL is more comparable to the three slough stations and notably higher than other three shoal stations.

Time series plots of SSC from each site capture trends across a wide range of timescales (Figure 5). These high resolution data are able to capture short events like floods and storms, which is a level of detail that discrete sampling cannot capture.  Once SSC calibrations are finalized we will also be able to evaluate longer term trends in SSC, ranging from seasonal to interannual, averaged over tidal cycles. The NMS MSP has been recording turbidity in SB and LSB since 2014, allowing for a multi-year analysis of SSC trends in the region.

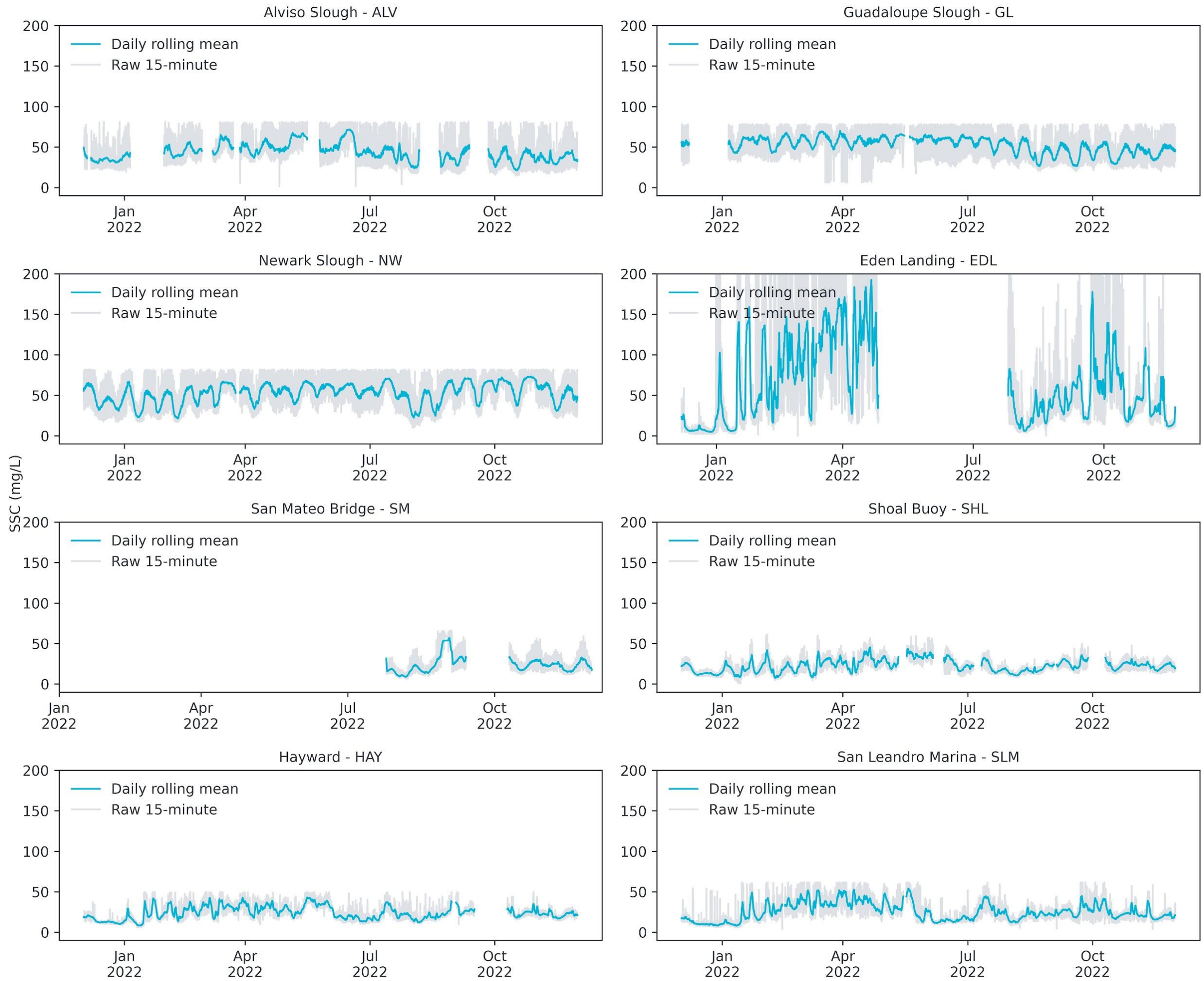


Figure 5. Time series plots of continuous SSC data from 2022 at each station. Large gaps in the daily rolling mean are due to data loss from turbidity sensors (section 4.3). Data where turbidity values are out of range for the calibration to SSC are not plotted (90 FNU at EXO stations, 58 NTU at EDL; section 4.2b).

6.A 6.B

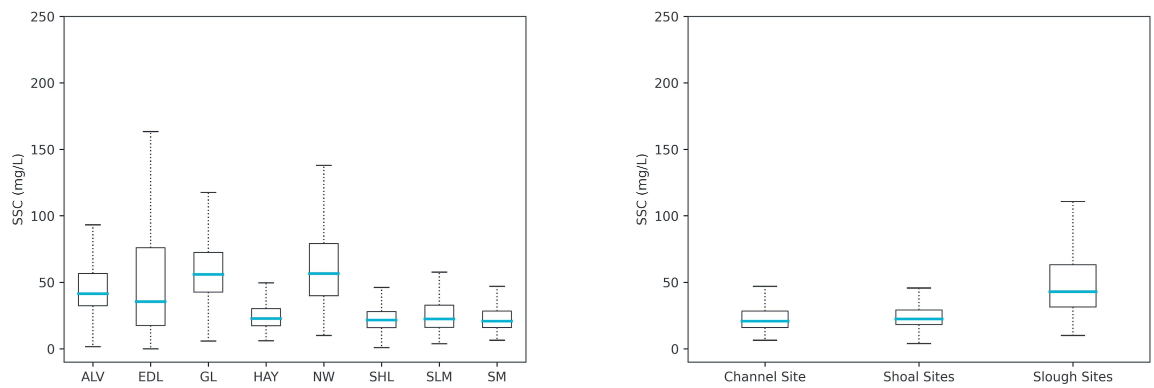


Figure 6. Box plot comparisons of continuous SSC data from 2022 by project station (6A) and by distinct SB and LSB habitat types (6B).

## 5. Data gaps and future solutions

Our dataset contains gaps and limitations that we are working to address during year two and three of the project. In particular, our turbidity-SSC calibration can only be applied when turbidity is <110% of the maximum turbidity used during calibration, resulting in significant SSC gaps as described above. Higher turbidity events are, by definition, associated with significant sediment transport events such as storms. Without higher value calibration points these infrequent but management-relevant values will not be represented in the continuous SSC data. We hope to better align SSC sampling with higher turbidity events during year two and year three of the project.

Additional gaps in our turbidity dataset are due to the challenging nature of water quality monitoring in SFB. Strong afternoon winds, narrow tide-windows, fast-growing biofouling, high sediment loading, and frequent boat traffic can limit safe access to sites, cause wear and tear on the instruments, and reduce data quality. Listed below are selected gaps in the turbidity dataset and planned remediation efforts for the future:

- The EDL sensor mooring was lost in June 2022 and replaced in August 2022, resulting in turbidity data loss during June, July, and part of August 2022. Given that the shoal offshore of EDL has high boat traffic, a ship most likely struck the mooring and removed it from the water. This mooring was replaced with an updated design intended to be more visible to boaters.
- Instrument malfunction resulted in turbidity data loss for January at Guadalupe Slough station, February for Alviso Slough station, and April for San Mateo Bridge station. The NMS MSP has augmented its backup sensor inventory and refined its sensor maintenance schedule to ameliorate this issue moving forward.
- Several times throughout the year, significant biofouling accumulated on sensors between station servicing trips which resulted in data being removed during the QAQC process. To minimize this type of data loss moving forward, sensor housings will be wrapped with antifouling copper tape and stations will be serviced at a higher frequency during high biofouling months.

## 6. Future Work

As monitoring and in-depth calibration testing continue in year two and three of the project, the strength of the turbidity-SSC calibrations and the size of the continuous SSC dataset will continue to grow. As in year one, the focus of year two monitoring efforts is on data gathering, in particular expanding the breadth of calibration points. Additionally, we will address whether separate calibration methods are necessary for different applications of SSC data (e.g. minimizing error in a sediment transport model vs minimizing error when estimating light attenuation). When calibrations are finalized, discrete SSC, wave data, and predicted continuous SSC data will be curated and shared with managers.

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