Title
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Authors
Senegal, Taylor
Staiger, Stephen
Goodman, Denise
et al.

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NOTE

Clear as Mud: Considerations for Turbidity Equipment Changes for Long-Term Monitoring Programs

Taylor Senegal[1]*, Stephen Staiger[2], Denise Goodman[1], J. Ryan Cook[1]

ABSTRACT

Long-term monitoring programs may face protocol or equipment changes for various reasons, and they must determine how to implement change while maintaining the historical consistency and significance of their data. A case study on the US Fish and Wildlife Service's (USFWS's) Enhanced Delta Smelt Monitoring program (EDSM) demonstrates what factors a long-term monitoring program might consider when substituting new equipment to collect environmental data, such as turbidity. Turbidity can influence the health, survival, and habitat quality of fish and other organisms. Thus, reliable collection of turbidity data is critical. Turbidity data are commonly presented in two units: nephelometric turbidity units (NTU) and formazin nephelometric units (FNU). The EDSM historically collected turbidity data using NTU units, like other monitoring programs in the San Francisco Estuary. Changes in reported turbidity values by other agencies, and proposed criteria relevant to the protection of the federally threatened Delta Smelt, have shifted focus to FNU values. Before transitioning to only collecting FNU values, the EDSM performed side-by-side collections of both FNU and NTU values for 2 years. Multiple linear regression supported a linear relationship between FNU and NTU values when the covariates of temperature, dissolved oxygen, specific conductance, stratum, and month were included. The discrepancies in FNU and NTU values could be explained by varying light wavelengths, differences in sample collection method, or sensor fouling. The model also demonstrated predictive capabilities for future unit conversion. These findings support the EDSM collecting turbidity in a single unit while maintaining the ability to correlate with historical environmental data, if needed. Other long-term monitoring programs could make similar considerations when faced with programmatic or equipment changes to ensure minimal effect on their historical datasets.

KEY WORDS

Hypomesus transpacificus, Delta Smelt, water quality, San Francisco Estuary, FNU, NTU

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* Corresponding author: taylor_senegal@fws.gov
1 US Fish and Wildlife Service
Lodi, CA 95240 USA
2 Resource Environmental Solutions, LLC
Sacramento, CA 95818 USA

INTRODUCTION

Long-term monitoring programs routinely collect environmental data to draw relationships between a species and their habitat. Findings can elucidate previously unknown relationships (Mussen et al. 2023; Hartman et al. 2024), document changes in an ecosystem (Bosworth et al. 2024), or, in the case of endangered species, influence protective management actions (Ghalambor et al. 2021; Grimaldo et al. 2021). Long-term monitoring programs often collect environmental data for years or decades (e.g., Malinich et al. 2023; IEP et al. 2023). Long-term datasets are a powerful ecological tool, but programs may face challenges to ensure the consistency of data collection when equipment becomes faulty, new technology emerges, partner programs (e.g., California Department of Water Resources [CDWR], US Bureau of Reclamation [USBR]) use different methods or units, or policy-related changes are implemented. This case study explores how a long-term monitoring program—the US Fish and Wildlife Service's (USFWS's) Enhanced Delta Smelt Monitoring program (EDSM)—experienced an equipment substitution while also maintaining the consistency and significance of its historical environmental data.

A common characteristic measured in aquatic systems is turbidity, or the cloudy appearance of water that results from the amount of light scattered by fine particles of sediment in the water (Davies–Colley and Smith 2001). Turbidity is considered to both directly (Vogel and Beauchamp 1999) and indirectly (Kirk 1994) affect health and survival of aquatic organisms. The turbidity data collected by monitoring programs—along with physical properties of water (e.g., temperature, pH; Anderson 2005)—are often uploaded to a repository where they can be used to track water-quality trends, perform ecological research, or inform management actions. Turbidity is frequently used synonymously with—or at a least as an index of—water clarity, but these optical concepts are distinct. While water clarity was historically described by visible depth with instruments such as Secchi discs (e.g., Malinich et al. 2023; IEP et al. 2023), turbidity is the measurement of suspended particles scattering light in water (Davies–Colley and Smith 2001). Turbidity data are commonly presented in two units: nephelometric turbidity units (NTU) or formazin nephelometric units (FNU). These units are measured by emitting a light beam into a sample and detecting the scattering at a 90-degree angle to the incident light beam (Foster et al. 2021). Turbidity sensors presenting data in NTU use a white light source; those presenting data in FNU use a near-infrared light source (Anderson 2005). All turbidity measurements—including NTU and FNU—are arbitrary and are not scientific quantities (i.e., "a relative index of side scattering light referred to side scattering of an arbitrary standard" (Davies–Colley and Smith 2001). Depending on the turbidity sensor and manufacturer, differences in turbidity values may occur, even with the same turbidity units. For example, Foster et al. (2021) found that two models made by the same manufacturer produced readings that were inconsistent. However, NTU and FNU often have a linear relationship, though not typically 1:1 (Foster et al. 2021). These differences in values can be significant when considering the collection of turbidity data for long-term monitoring programs that influence natural resource management.

Multiple agencies and monitoring programs in the San Francisco Estuary (estuary) historically reported turbidity data in NTU. Then, a 2019 technical memorandum by Yellow Springs Instruments (YSI) stated that some sensors, such as the YSI 6-series multi-parameter, were incorrectly reported in NTU and should be reported in FNU (YSI 2019). That is, these instruments collected turbidity data according to an FNU-specific method (ISO 7027; International Organization for Standardization 1999) but improperly labeled as NTU. ISO 7027 is a preferred method because the near-infrared light source minimizes the negative effect of small-sized particles or particle coloration (Anderson 2005). The California Department of Water Resources (CDWR) responded to this memorandum by updating turbidity data units on the California Data Exchange Center to FNU; no conversion was necessary, only a unit labeling change (2020 email between J. Frantzich and CDWR program managers, unreferenced, see "Notes").

Since December 2016, the EDSM has collected turbidity in NTU with Hach portable turbidimeters. After the YSI memorandum, EDSM turbidity data—because they were measured in NTU rather than FNU—were considered incompatible with water-quality data provided by other agencies. Notably, Anderson (2005) stated that raw turbidity data from differently designed instruments should not be compared during any data analysis without additional work to establish a relationship between the different measurements over the range of the environmental conditions present. Newer multi-parameter water-quality sensors—often referred to as "sondes"—produced by YSI (e.g., EXO, ProDSS) report that turbidity data are recorded in FNU. Consequently, EDSM purchased YSI ProDSS meters in 2020 so FNU data could be collected and more readily compared to the turbidity data collected by other agencies.

The impetus to reconcile the differences between NTU and FNU stems from the relationship of Delta Smelt (*Hypomesus transpacificus*)—the EDSM's target species— with turbidity. The occurrence of Delta Smelt in more turbid waters is an observation documented by various field and modeling studies (Feyrer et al. 2007; Nobriga et al. 2008; Kimmerer et al. 2009; Thomson et al. 2010; Latour 2016). As visual feeders, the visual range and feeding success of Delta Smelt depends upon water clarity, and can vary among life stages (Hasenbein et al. 2013). At the same time, turbidity influences predation risk (Quist et al. 2004) so Delta Smelt feeding behavior and habitat choice are likely contingent upon turbidity levels. Feyrer et al. (2013) and Bennett and Burau (2015) documented behavioral responses in movement to turbidity, indicating that turbidity may act as a migratory cue. Thus, reliable collection of turbidity data is critical to the monitoring of an ESA-listed threatened species such as Delta Smelt.

Because of the site-specific nature of a turbidity sample and the broad geographic range the EDSM covers in the estuary, the EDSM collected NTU turbidity data concomitantly with FNU data for approximately 2 years. In addition to assessing the relationship between NTU and FNU data, the EDSM sought to determine if it could discontinue the collection of two turbidity units (i.e., discontinue NTU collection) by establishing a correlation between the units, thus preserving the long-term continuity of turbidity data. The results of this study could inform agencies about potential modification of their long-term monitoring data collection methods or equipment of key considerations.

METHODS

Data Collection

The EDSM uses trawls to collect year-round fish data as well as associated environmental data. Sampling locations within the estuary are determined via generalized random-tessellation stratified design (USFWS 2025) and grouped into regions called strata. From April 2021 through April 2023, the EDSM collected turbidity data in NTU and FNU (Figure 1). Hach 2100Q Portable Turbidimeter (hereafter, "Hach meter") measured NTU values. This involved collecting a water sample in a small bucket from the water surface. Then, we dipped a transparent cuvette into the bucket and placed the cuvette in the enclosed Hach meter for measuring. YSI ProDSS Multiparameter Digital Water Quality Meter (hereafter, "YSI ProDSS") measured FNU values. We placed the YSI ProDSS sensor approximately 1 m beneath the water surface and recorded the reading once values stabilized. A minimum depth of 2.4 m was required for trawling, and we sampled at an average depth of 3.46 m over the 2-year period.

We measured other water-quality parameters in addition to turbidity, including Secchi depth, temperature, dissolved oxygen, and specific conductance at 25 °C. We collected all parameters by YSI ProDSS except for Secchi depth, which was collected by visual observation of a Secchi disc. We collected all parameters simultaneously (typically within 1 minute) with each turbidity data point. One to two field crew members

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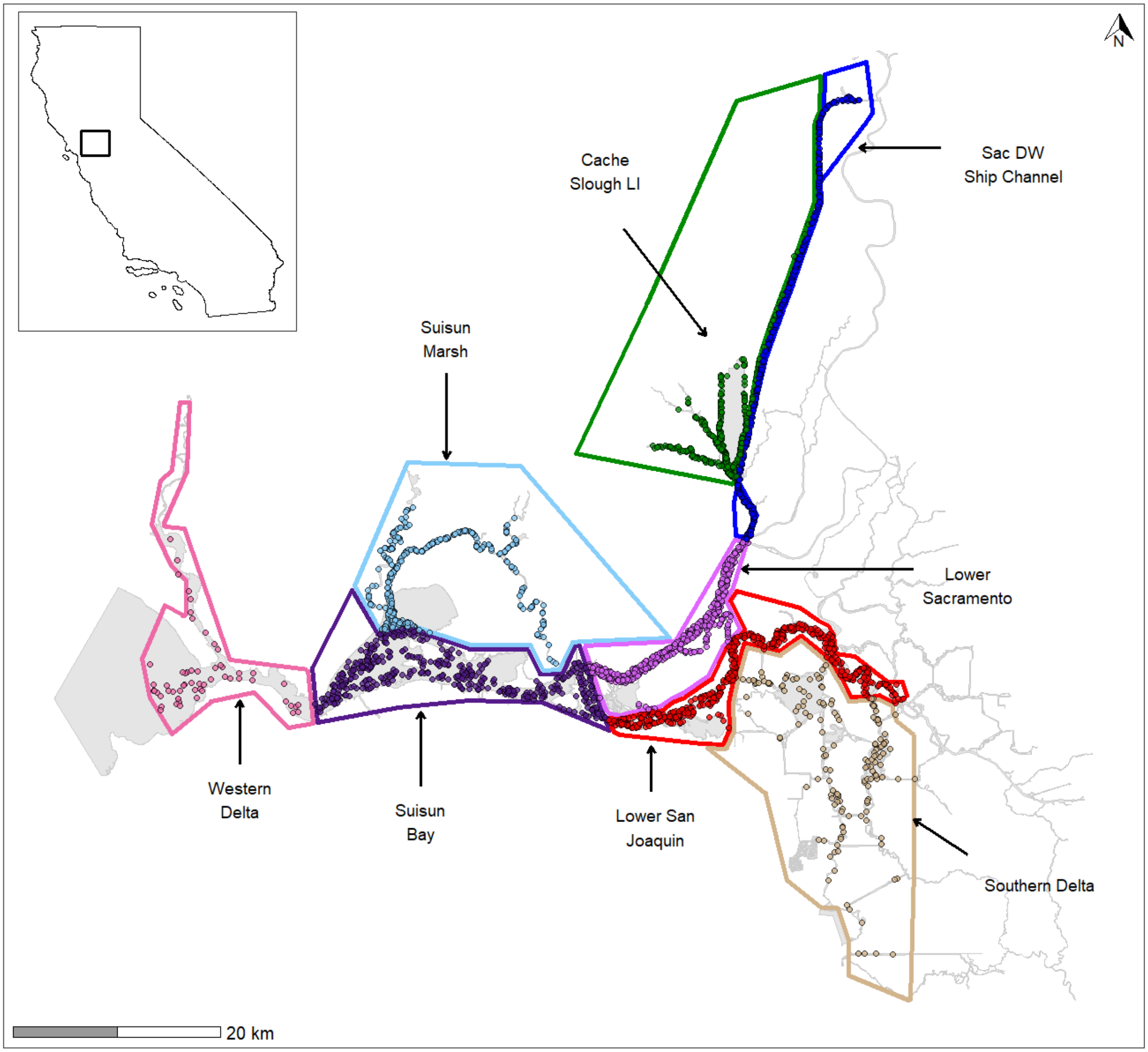

Figure 1 Map of EDSM sampling locations in the San Francisco Estuary from April 2021 through April 2023. *Thick lines* show geographic strata and represented by *different colors*. *Points* represent sampling sites.

recorded observations each day, with dozens of field crew participating over the study period.

Data Analysis

We performed multiple linear regression between FNU and NTU values with the covariates of temperature, dissolved oxygen, specific conductance, stratum, and month included. We removed observations from the dataset if values (n = 4) were an obvious transcription error compared to values from other tows at a site. We developed all statistical analyses and plots in R (R Core Team 2023).

Before model fitting, we checked for correlation among all predictors (Table 1; Figure 2). We elected to leave Secchi depth data out of the linear model because of the known inverse relationship between Secchi depth and turbidity (Tobias 2020,see "Notes"). We performed multiple linear regression to assess the relationship between NTU and FNU using a model with mean structure:

Table 1 Paired correlation of variables: turbidity FNU (Turb FNU), turbidity NTU (Turb NTU), Secchi depth, temperature, dissolved oxygen (DO), and specific conductance (SC)

	Turb FNU	Turb NTU	Secchi	Temp	DO	SC
Turb FNU	1.00	0.96	−0.63	−0.27	0.12	0.12
Turb NTU	0.96	1.00	−0.60	−0.23	0.09	0.13
Secchi	−0.63	−0.60	1.00	0.26	−0.08	−0.30
Temp	−0.27	−0.23	0.26	1.00	−0.82	0.03
DO	0.12	0.08	−0.08	−0.82	1.00	−0.25
SC	0.12	0.13	−0.30	0.03	−0.25	1.00

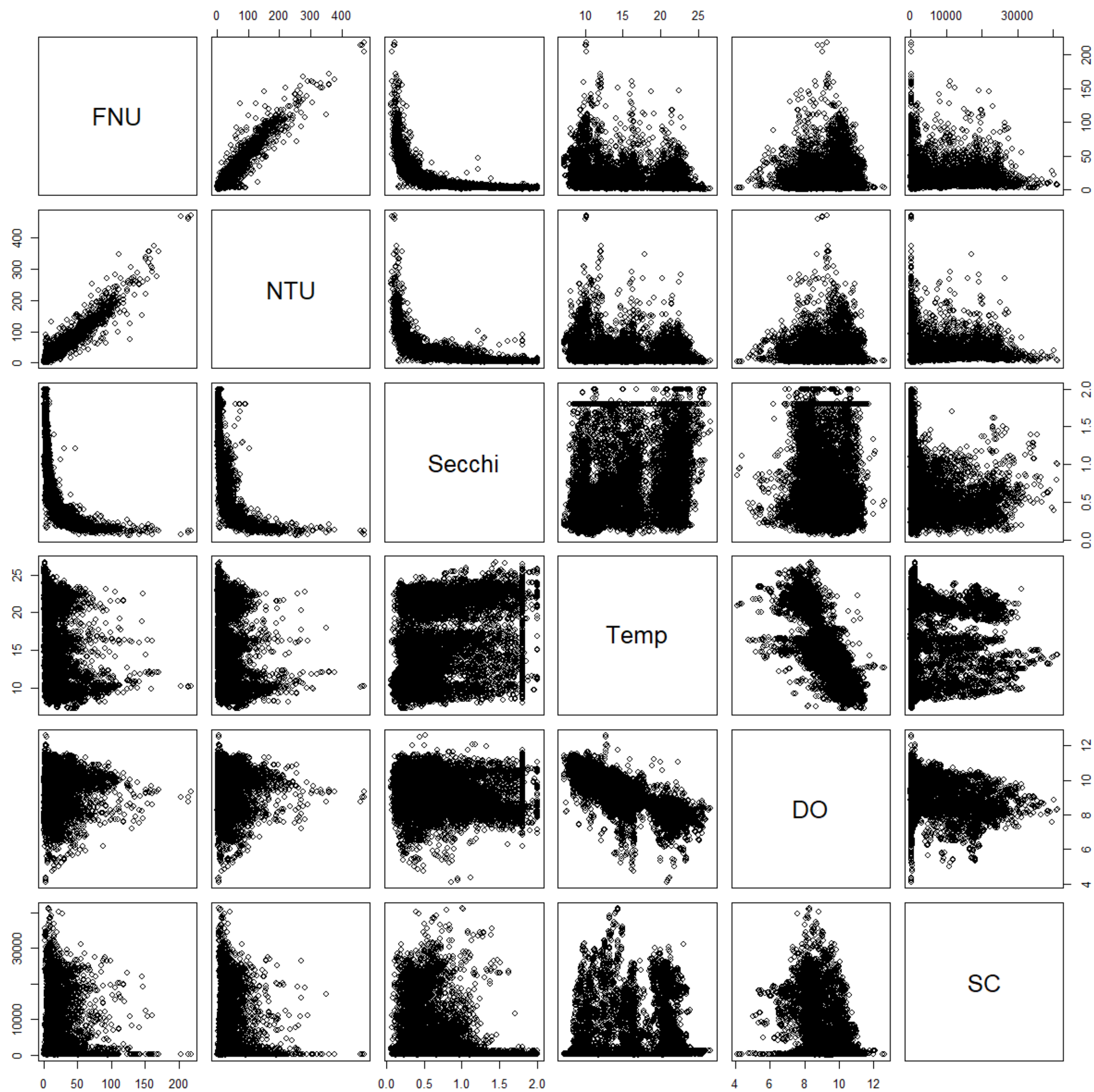

Figure 2 Correlation plot for all environmental variables collected. Secchi data included to display inverse relationship despite not being included in model.

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$$FNU = \beta_0 + \beta_1 NTU + \beta_2 Temp + \beta_3 DO + \beta_4 SC + \beta_5 Stratum + \beta_6 Month \qquad \text{Eq 1}$$

where FNU is the model response variable, given the predictor variables; β_0 is the model intercept; NTU, temperature (Temp), dissolved oxygen (DO), specific conductance (SC), stratum, and month are predictor variables; and β_1 through β_6 are the estimated regression coefficients, respectively. All predictor variables except for stratum and month were standardized (mean = 0, SD = 1) using the scale function before model fitting. The Cache Slough Liberty Island stratum was the fixed reference level for the categorical stratum variable (as a result of alphabetical order). We assessed model residuals to ensure assumptions were met (see Appendix A). We compared the full model (Equation 1) to an intercept-only model using an F test. For the full model, we examined the significance of the individual predictors as they were sequentially added into the model. Lastly, we tested for multicollinearity using the variance inflation factor (VIF).

After model-fitting, we tested the model's predictive capability. We split the data 70%:30% to create a training set and test set, respectively. We fit the linear model to the training data, then used the predict function with the test data.

RESULTS

The EDSM collected 9,492 total paired turbidity samples over 2 years (Figure 1). NTU values ranged from 1.3 to 471.0; FNU values ranged from 0.7 to 217.9 (Figure 3). NTU values were generally greater than FNU values. In general, differences between the two units (i.e., between an NTU and FNU paired sample) increased as values increased (Figure 4). However, 77% of samples had differences of fewer than 20 units (i.e., fewer than 25% of the samples accounted for "large" disparities). When looking at FNU values under 50 (94% of total samples), the percentage of samples with differences fewer than 20 units increased to 82%.

We found support for including all predictors in the model ($F_{12,\,9479} = 78.58$, $p < 0.001$). We found a linear relationship between FNU and NTU, with estimated regression coefficient for NTU = 0.99 ($p < 0.001$; Table 2). Regarding multicollinearity, all covariates had a VIF of less than 5, and therefore were treated as independent variables without correlation issues. The model demonstrated strong predictive capabilities ($R^2 = 0.93$, RMSE = 5.22, $RMSE_{normalized} = 0.02$) and—when predicted values were plotted against observed values—had a nearly 1:1 relationship with observed data (Figure 5).

DISCUSSION

Two years of paired turbidity data collected by the EDSM demonstrated the close association between NTU and FNU values. In general, as NTU values increased, FNU values also increased, though larger values (> 50 FNU) presented greater differences. While the units did not possess a true 1:1 relationship, the overall linear association was consistent with the strong linear associations of laboratory and field comparisons of three turbidity sensors by the US Geological Survey (Foster et al. 2021). Our results (Table 2, Figure 5) suggest the EDSM could continue collecting turbidity with a single unit and not lose the significance of previously collected turbidity data.

There are several reasons why NTU and FNU values could have differed. We believe the most obvious reason is the wavelength of the light source. NTU uses broad spectrum incident light in a wavelength range between 400 and 680 nm (i.e., white light); FNU uses incident light in a wavelength range between 780 and 900 nm (i.e., near-infrared; Anderson 2005). More specifically, meters that adhere to ISO 7027 (such as YSI ProDSS) have a defined light source for FNU measurements with a wavelength of 860 nm (ISO 1999). Since the interaction of wavelength and water properties, such as particle size, affects the scattering of light (Anderson 2005), it is unsurprising that NTU and FNU methods may yield different turbidity values.

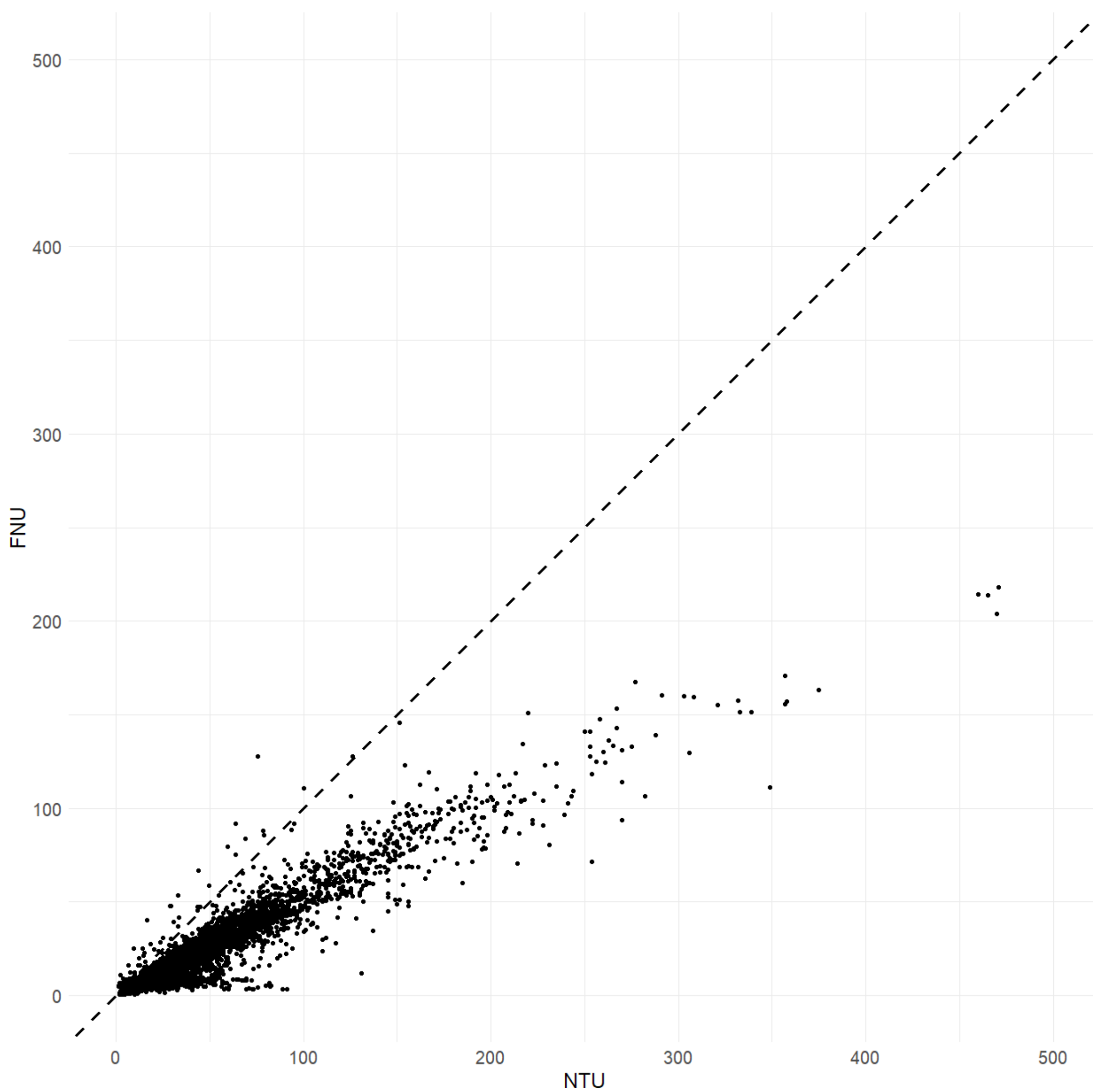

Figure 3 Turbidity data in nephelometric turbidity units (NTU) and formazin nephelometric units (FNU). *Black solid* line indicates actual fit and *black dashed line* represents 1:1 relationship.

The mechanics of how each sensor in our study collected turbidity data is another factor that influences the differences between NTU and FNU values. Turbidity sensors often have different optical designs, so even when the instruments are calibrated, readings can differ by factors of two or more for the same sample (Davies–Colley and Smith 2001; Anderson 2005). In the study dataset, nearly one-third of our paired samples had NTU values twice those of FNU values. Hach meters used a small sample of water in a cuvette that remained unchanged for the duration of the reading (i.e., static sample). The YSI ProDSS, on the other hand, utilized a submerged sensor that was constantly scanning (i.e., dynamic sample). Static measurements do not completely account for particle settling; dynamic measurements can more accurately account for particle movement within the water body. These differences are more notable when coarse silt or sand-sized particles are present (Anderson 2005). The value differences between the two sensors used in this study could reflect the differences between static and dynamic sampling.

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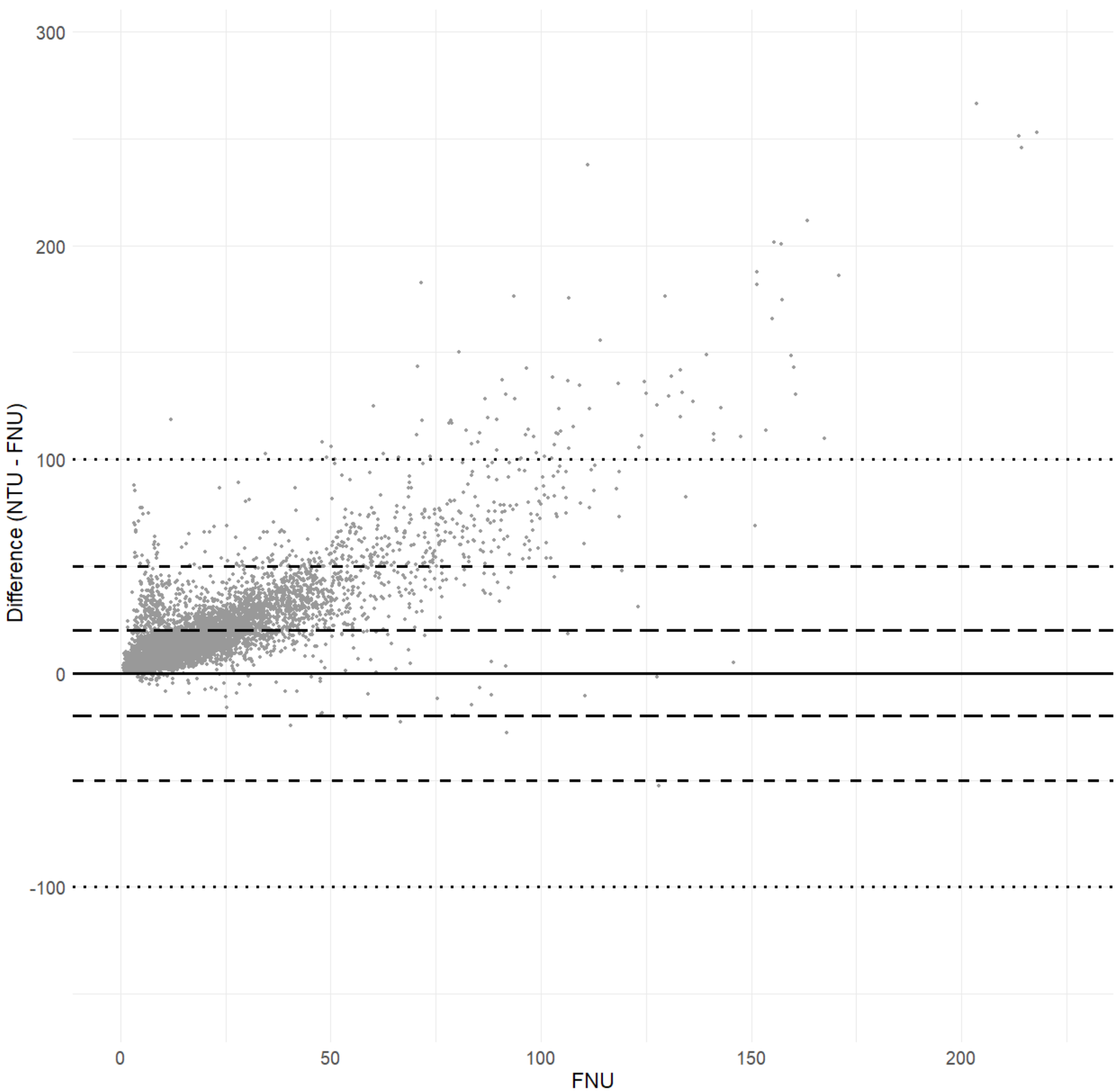

Figure 4 Absolute differences between nephelometric turbidity units (NTU) and formazin nephelometric units (FNU) as FNU increases. Positive and negative difference intervals distinguished by line type: 20 *(large dash)*, 50 (*small dash*), 100 (*dotted*).

Sensor fouling is also a consideration for the different measurements between NTU and FNU. Fouling includes biological growth or scratches on the optical surface of the instrument. Sensor fouling tends to produce a negative bias due to blocking the sensor's light beam but can produce a positive bias due to scratches increasing the scatter of the sensor's light beam (Anderson 2005). YSI ProDSS sensors are protected within metal housing and less likely to be damaged. The Hach meter cuvettes, however, are handled multiple times a day and could possibly possess scratches that are artificially inflating NTU turbidity values. Although the EDSM did not track the lifespan or changing of cuvettes, the program maintained a gear maintenance team that inspected and calibrated water-quality equipment on a regular schedule. The EDSM and other programs could benefit from recording the specifics of maintenance and equipment replacement.

The estuary is a complex water system with regional and seasonal water chemistry fluctuations (Schoellhamer et al. 2012). Our

Table 2 Linear model results including the intercept (turbidity FNU), turbidity NTU, temperature, dissolved oxygen, specific conductance, stratum, and month

	Estimate	Standard error	*t* value	Pr(>|t|)
Intercept	17.96	0.21	85.32	< 0.001
Turbidity NTU	17.70	0.07	269.22	< 0.001
Temperature	– 2.41	0.11	– 20.96	< 0.001
Dissolved Oxygen	– 1.43	0.12	– 12.11	< 0.001
Specific Conductance	– 0.46	0.10	– 4.74	< 0.001
Stratum: Lower Sacramento	– 0.41	0.20	– 2.03	0.04
Stratum: Lower San Joaquin	– 0.59	0.20	– 2.94	3.30E-3
Stratum: Sac DW Ship Channel	0.83	0.22	3.83	< 0.001
Stratum: Southern Delta	– 1.55	0.28	– 5.58	< 0.001
Stratum: Suisun Bay	0.38	0.27	1.39	0.17
Stratum: Suisun Marsh	2.14	0.28	7.67	< 0.001
Stratum: Western Delta	– 0.26	0.50	– 0.52	0.61
Month	– 0.19	0.02	– 9.84	< 0.001
R^2	0.92			
Adjusted R^2	0.92			

model included spatial and temporal covariates—stratum and month, respectively—to investigate their relationship to turbidity. While there is statistical support to include both factors, we want to note how coarse those covariates are, particularly stratum. Turbidity measurements are site-specific, as noted in the sensor mechanics paragraph, and our stratum, while based on estuary hydrology, are vast in comparison. Some broad spatial differences are apparent, such as lower maximum values in the southern Delta and lower San Joaquin River strata (see Appendix B, Figure B1). However, the linear relationship between FNU and NTU remains largely the same. Regarding a seasonal component, higher maximum values are common in winter months (see Appendix C, Figure C2), especially after high water years in 2022 and 2023 (Figure C3). Individual turbidity measurements contain geographic location (latitude and longitude), as well as a collection time. While a more complex analysis was beyond the scope of this study, data are available on the Environmental Data Initiative (USFWS 2025) to allow further investigation.

Our study supports the recommendation that researchers should avoid directly interchanging or even comparing NTU and FNU values without establishing a relationship between the units within their study system (Anderson 2005). Determining a relationship between NTU and FNU values, however, allows us to consider the biological significance of the relationship. When putting turbidity units and values in the context of the EDSM's study species (Delta Smelt), we recall that understanding the response of Delta Smelt to key abiotic factors, such as turbidity, is important to resource managers making informed decisions on Delta Smelt conservation (Hasenbein 2013). Turbidity is an important determinant for feeding behavior (Hasenbein 2013) and, as a known spawning cue, is a key habitat feature for spawning success for Delta Smelt in the estuary (Bennett and Burau 2015). Hasenbein et al. (2016) concluded late-larval Delta Smelt prefer 25–80 NTU, while Hasenbein et al. (2013) observed stable feeding rates for juvenile Delta Smelt between 12–120 NTU. Eleven of 16 Delta Smelt collected during the EDSM's larval sampling included in this study were in the preferred range, and 80 of 83 caught during the EDSM's juvenile/adult sampling were in the stable feeding range, respectively (Figure C1). Although this study did not focus on the relationship of Delta Smelt to

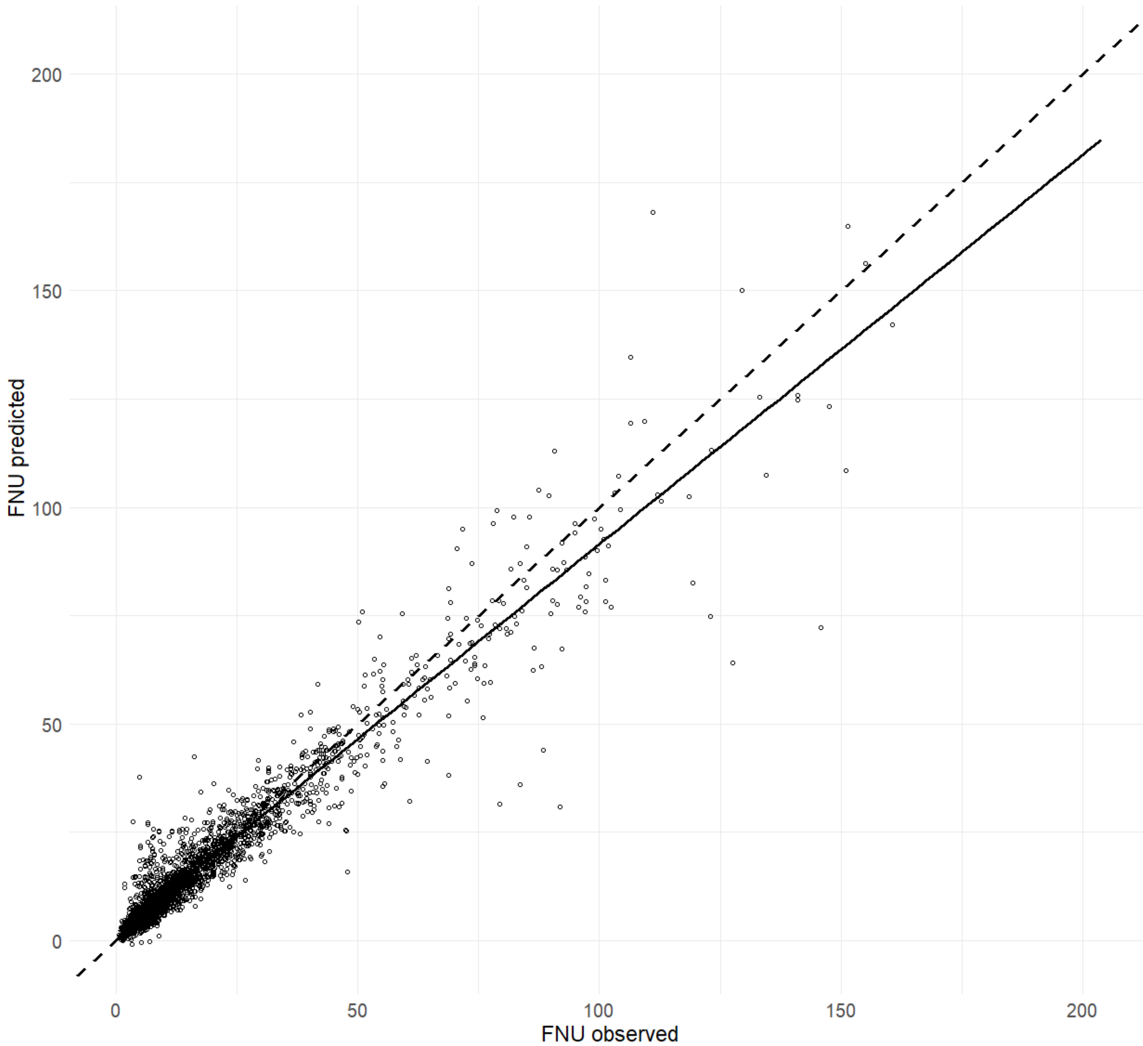

Figure 5 Plot of FNU turbidity values and predicted FNU turbidity values. *Black solid line* indicates actual fit and *black dashed line* represents 1:1 relationship.

turbidity, turbidity measurements collected by the EDSM—because it is a leading program in Delta Smelt monitoring—are relevant to the species' conservation. Water operations in the estuary (i.e., pumping by the Central Valley Project and State Water Project) account for turbidity levels at fixed sensors (USBR 2023). Documenting the site-specific turbidity where Delta Smelt are observed expands our knowledge of the conditions inhabited by the species.

CONCLUSION

The findings from this study suggest a long-term monitoring program, such as the EDSM, could discontinue collecting NTU values and only collect FNU values while maintaining the ability to correlate with historical environmental data. First, a significant linear relationship exists between NTU and FNU samples collected by the EDSM. While we used a predictive function as a form of model checking, it suggests predictive abilities and that our dataset could be used to estimate future NTU values or historic FNU values. EDSM data are publicly available on the Environmental Data Initiative (USFWS 2025) so interested parties may pursue their own model or conversion factor, as well. Second, the EDSM would begin reporting turbidity data in the same unit as other agencies in the estuary, such as the CDWR (2020 email between J. Frantzich and CDWR program managers, unreferenced, see "Notes"). In a recent Biological Assessment, turbidity values were standardized to FNU (Reclamation 2023). Since the EDSM provides data to inform water operations, reporting FNU values is more practical and beneficial. Third, the decision would complete ongoing side-by-side collections, and streamline the EDSM sampling protocol by removing an additional step and piece of equipment (i.e., the Hach meter). The YSI ProDSS collects turbidity, temperature, and dissolved oxygen in one meter, saving both time and effort for field crews. Using a dynamic submersible multi-parameter sensor, such as the ProDSS, allows for more accurate real-time water-quality data collection, which is recommended for long-term monitoring programs (Anderson 2005).

While changing equipment or reported units is less than ideal for a study, on some level long-term monitoring programs will face change. Programmatic changes could occur as a result of technological advances, logistical hurdles, or policy-related issues. Long-term monitoring programs seeking to make responsible changes can follow best practices as recommended by Jones et al. (2025). Regardless of the reason, programs must establish a relationship between current and new equipment to preserve the consistency and significance of their historical data (Foster et al. 2021). It is also imperative to document the equipment used when sharing data (Davies–Colley and Smith 2001), given that this could influence the comparison or interpretation of data. The systems studied by monitoring programs are not static and—when executed appropriately—long-term monitoring programs can adapt to continue providing valuable data.

DATA AVAILABILITY STATEMENT

Data for this study are available from the Environmental Data Initiative of the US Fish and Wildlife Service et al. (2025): *https://doi.org/10.6073/pasta/3e290f60357f34b88c42135aabeefdf7*. Appendix D contains fully reproducible code that supports the analysis and visualization provided in the study.

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