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Special Study on Bulk Density

Final Report
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Executive summary

Sediment bulk density is the total mass of mineral and organic sediment within a defined volume. It is a key variable in many research questions pertaining to Bay sediment studies but one that is often poorly quantified and can be misinterpreted. The motivation for this report comes from a recommendation by Schoellhamer et al. (2018) to compile more accurate estimates of bulk density of Bay sediments to convert between volume and mass with a higher level of certainty. Through funding and guidance from the Bay Regional Monitoring Program Sediment Work Group, this report is a first step towards compiling the available data on sediment bulk densities across Bay habitats and along salinity gradients to provide better information for resource managers and others working on sediment-related issues.

This report:

- discusses the need to know the bulk density of Bay soils to convert between sediment mass and soil volume;
- clarifies general definitions and common points of confusion related to sediment bulk density;
- compiles primary sources of bulk density measurements, secondary sources of bulk density estimates, and standard engineering estimates of bulk density for different habitats in San Francisco Bay; and,
- provides a database where practitioners can track, analyze, and share bulk density measurements.

Key findings:

- Limited primary data are available for sediment bulk density for intertidal and subtidal habitats in San Francisco Bay. Only four studies contain primary data on the mineral component of dry bulk density in near-surface soil samples for tidal marshes, tidal flats, and deep Bay/channel environments. These data only include samples from some subembayments and some habitat types across the Bay; there are many data gaps.
- Given the sparseness of the primary data, it is difficult to know whether bulk density varies most by subembayment (salinity), habitat type (bathymetry), site, decade, or method of sampling and analysis. In the future, a statistical analysis would be warranted to try to understand where the uncertainty lies, once there is enough data to justify such a study.
- For the most detailed bulk density values from the primary literature, see Table 2 and Figure 5 on pages 14 and 15, or access the database here. A visual (non-statistical) assessment of the data grouped by habitat type (across the bayshore profile) and subembayment (along the salinity gradient) indicates that dry mineral bulk density values for:
    - tidal marsh, tidal flats and deep bay/channel in Central, South and Lower South Bays are generally around 30 lbs/ft^3

  - tidal marsh in San Pablo Bay are variable, with some values below 30 lbs/ft^3
  - brackish tidal marsh in Suisun Bay are lower in bulk density (closer to 10 lbs/ft^3)
  - tidal flat and deep bay/channel in Suisun, San Pablo and Central Bays do not exist or are not readily available
  - shallow bay in any of the subembayments do not exist or are not readily available

- There is evidence for a gradient in dry mineral bulk density related to marsh salinity, as expected, but other patterns were not apparent in the limited data set available.

- Several secondary studies combine data from more than one primary study, but it is unclear whether the bulk density values combined from the primary literature were consistent types of bulk density and/or whether differences in study methods and design were taken into account when calculating average bulk density values. The use of bulk density data directly from the primary sources may reduce the potential for error or misinterpretation when converting between volume and mass.

- Practitioners often use higher values than the empirically measured in-situ bulk density values when estimating bulk densities of dredged sediment for reuse in restoration activities.

Recommendations for future studies:

- report dry bulk density mineral and organic matter values, and describe the collection and preparation of samples in detail;

- follow coring methods outlined in Callaway et al. (2012), as this is the most recent and detailed study reviewed in this report and the basis of the most extensive and current primary bulk density data for San Francisco Bay;

- prioritize data collection in baylands habitats with limited primary data available—namely tidal flats, shallow Bay, and deep Bay/channels; and,

- add bulk density data to the database to track, compare, and share values.

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A note about reporting units, conversion factors, and the bulk density database

The majority of bulk density values are reported in pounds per cubic foot (lbs/ft^3) because this is the unit that practitioners typically use for sediment reuse projects. The following conversions can be used to obtain bulk density values in SI units:

1 lbs/ft^3 = 0.0160185 g/cm^3 (multiply lbs/ft^3 by **0.0160185** to convert to g/cm^3)

1 lbs/ft^3 = 16.0185 kg/m^3 (multiply lbs/ft^3 by **16.0185** to convert to kg/m^3)

The database to track, compare, and share bulk density values is available at this link. The database is a first step towards compiling the available data on sediment bulk densities across Bay habitats and along salinity gradients to provide better information for resource managers and others working on sediment-related issues. To submit data, follow the instructions in the "read me" worksheet included in the database. For more information, email katiem@sfei.org.

1. Introduction

The San Francisco Estuary is the largest estuary on the west coast of North America, and plans exist to expand tidal marsh habitats in the region by tens of thousands of acres over the next several decades (Goals Project 2015). While vast and expanding, the ability of bayland habitats to persist over time in the face of rising sea levels, changing precipitation regimes, and other climate considerations is uncertain (Stralberg et al. 2011, Kirwan et al. 2010). One pathway for tidal habitats to persist over time is through vertical accretion (Brinson et al. 1995). Scientists, engineers, restoration practitioners, and policymakers recognize that sediment is a precious and necessary resource to facilitate fast-paced marsh restoration. Sediment can help raise subsided areas through natural or artificial means and support vertical accretion of bayland habitats over time. Sediment bulk density—the mass of total mineral and organic sediment within a defined volume—is a key variable in many research questions pertaining to Bay sediment, but one that is often poorly quantified and/or misinterpreted.

In a recent regional sediment supply synthesis for San Francisco Bay, Schoellhamer et al. (2018) discuss the need for more accurate estimates of bulk density of Bay sediments to convert between volume and mass with a higher level of certainty. The motivation behind the present report stems directly from this recommendation. Through funding and guidance from the Bay Regional Monitoring Program Sediment Work Group, this report is a first step toward compiling the available data on sediment bulk densities across Bay habitats and along salinity gradients to provide better information for resource managers and others working on sediment-related issues.

This report provides a definition and overview of bulk density calculations and summarizes application of bulk density values in San Francisco Bay. Bulk density estimates at different stages of the dredging-placement process (e.g., in situ Bay channel, post-dredging, post-filling) and for various Bay habitats (e.g., Bay channel, tidal flat, tidal marsh) are reported here to show the range of values within one region. Both field observations of bulk density and estimates used in engineering design are reported. In addition, this study distinguishes primary sources from secondary sources and measured from estimated data to determine which studies are directly comparable. This report also provides findings in a database to track, compare, and share values of bulk density among practitioners. Findings from this study can be used to improve accuracy in sediment calculations when converting between volume and mass, and to highlight data gaps and areas in need of further research.

2. The need for bulk density data

Bay soils are comprised of three main components: mineral sediment, organic material (e.g., detritus, roots), and pore space, which can be filled with air or water (Cohen 2008). The bulk density of Bay soils is dependent upon how well the sediment is compacted, how large the pore spaces are, how much organic material is present, and how much moisture is present. Thus, the bulk density of Bay soils can vary in space and time: across habitat types under different vegetative cover, within habitat types with changes in elevation and inundation patterns, with depth as soil conditions change, and over time with compaction.

There have been several efforts to quantify the amount of sediment supply to the Bay, and separate efforts to calculate the volume of sediment needed to sustain existing and restored planned tidal wetlands, but the estimated or measured values found in different studies are not always easily comparable. Different studies may quantify sediment by mass or volume and may not report the soil conditions. Estimates of sediment supply and transport tend to be reported in mass, based on measurements of suspended sediment in the water column. For example, Schoellhamer et al. (2018) quantified sediment supply to the Bay based on trends over a 20-year period as a mass of approximately 1.9 million metric tonnes (Mt) of sediment per year. However, estimates of erosion and deposition in the Bay tend to be reported in volume as calculated through bathymetric and surface level changes (Cohen 2008). Restoration practitioners focused on sediment demand and dredgers focused on sediment availability typically report their findings in English units of bulk volume (e.g., Perry et al. 2015, DMMO 2019, SediMatch 2019). For example, Perry et al. (2015) quantified a volume need of approximately 163 to 202 million cubic yards of sediment to raise 40,000 acres of planned or in-progress restoration to current marsh plain elevations. Sediment bulk density estimates are necessary for comparing studies like Schoellhamer et al. (2018) and Perry et al. (2015).

Bulk density estimates also vary depending on the amount of compaction, leading to spatial and temporal variation of bulk density. This variation can result in over- or under-estimations of total sediment needed to achieve a specified elevation for a certain habitat. This disconnect in reported findings for different aspects of the Bay's sediment budget can create impediments to more timely and targeted beneficial reuse of sediment, elevating the need for bulk density as a critical and often missing link between sediment observations, predictions, and on-the-ground efforts for reuse in San Francisco Bay.

The bulk density values used to calculate sediment budgets can significantly impact results. A sensitivity analysis by Brew and Williams (2010) explored the impact of varying a number of independent variables, including riverine and estuarine sediment inputs, relative sea level rise, and bulk density, among others, on a sediment budget for South San Francisco Bay. Changing the bulk density of deposited sediment from 1.3 to 1.5 metric tonne per cubic meter (t/m^3) increased marsh plain accretion, sediment demand of restored ponds, and tidal channel deposition. This resulted in a net decrease in calculated total mudflat area from 26 to 23 square kilometers in 50 years, a reduction of about 10%. Increasing the bulk density of deposited sediment by 0.2 t/m^3 had about the same impact on mudflat area as reducing estuarine sediment inflow to zero.

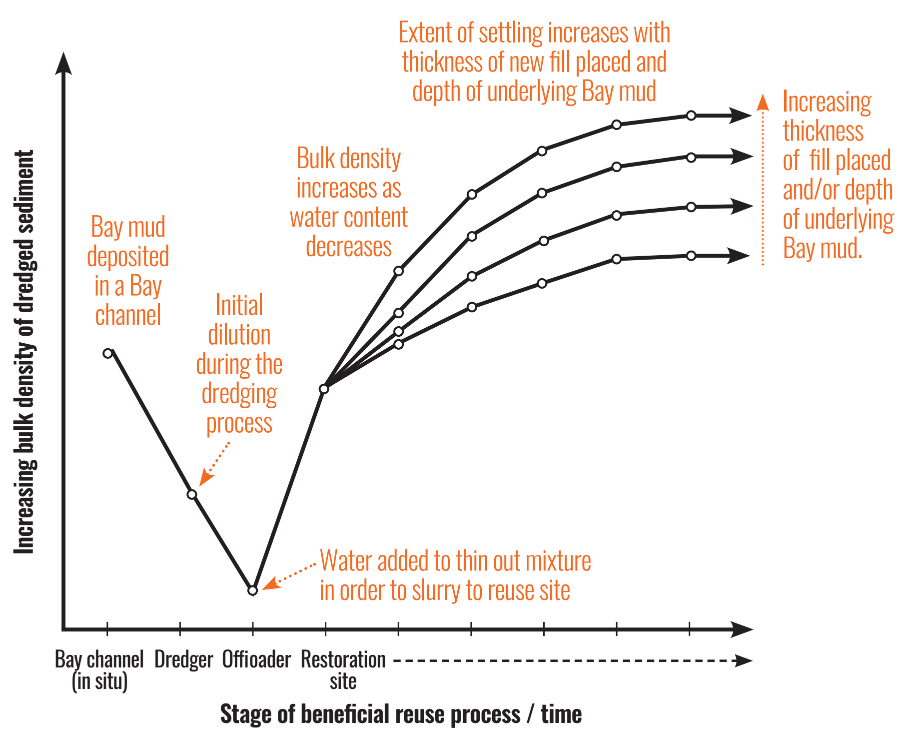
The conversion between sediment bulk mass and bulk volume is an important step for sediment beneficial reuse projects in the San Francisco Bay Area. The beneficial reuse of upland and dredged sediment to augment natural sediment supply from tributaries and support tidal marsh restoration has been discussed in the Bay Area for decades. Dredging to maintain navigational channels, harbors, refinery wharfs, small marinas, and other maritime activities has produced an average of over three million cubic yards of sediment per year since 1990 (Moffatt & Nichol 1997, DMMO 2019, SFEI 2019). The Long-Term Management Strategy (LTMS) for the Placement of Dredged Material, a multi-agency regulatory body that oversees dredging and disposal activities in San Francisco Bay, has outlined a goal of using at least 40% of dredged sediment for beneficial purposes (LTMS 1998). With increased interest in using dredged sediment in restoration projects, a better understanding of how sediment bulk density of Bay mud changes, from dredging in the Bay's navigation channels to placement at tidal marsh restoration sites, (Figures 1 and 2), will allow for more accurate estimates of the amount of sediment required.

Thus, bulk density links observations and modelling of sediment transport and morphology to dredging operations and wetland restoration projects. However, there are currently no established reference bulk density data for San Francisco Bay (regionally or for the various sub-regions).

Bulk density is used in the Bay to:

- Estimate the mass of sediment needed to raise subsided land to marsh elevations
- Estimate the volume of sediment deposited on a marsh from the water column
- Estimate how the elevation of the marsh surface changes as the soil column consolidates
- Estimate the volume of sediment entering the Bay from tributaries and from the Delta
- Estimate the mass of sediment generated by dredging to a specified depth

Figure 1. Conceptual diagram of changes in bulk density of dredged sediment at each stage of the beneficial reuse process, with the y-axis representing an increase in bulk density of dredged sediment. When dredging occurs, there is an initial dilution of the sediment being excavated. Over time the bulk density of the sediment exceeds the in situ bulk density levels, as it compacts and settles over time based on the depth of underlying Bay mud and the thickness of fill placed (Dilip Trivedi, personal comm.; Nick Malasavage, personal comm.).



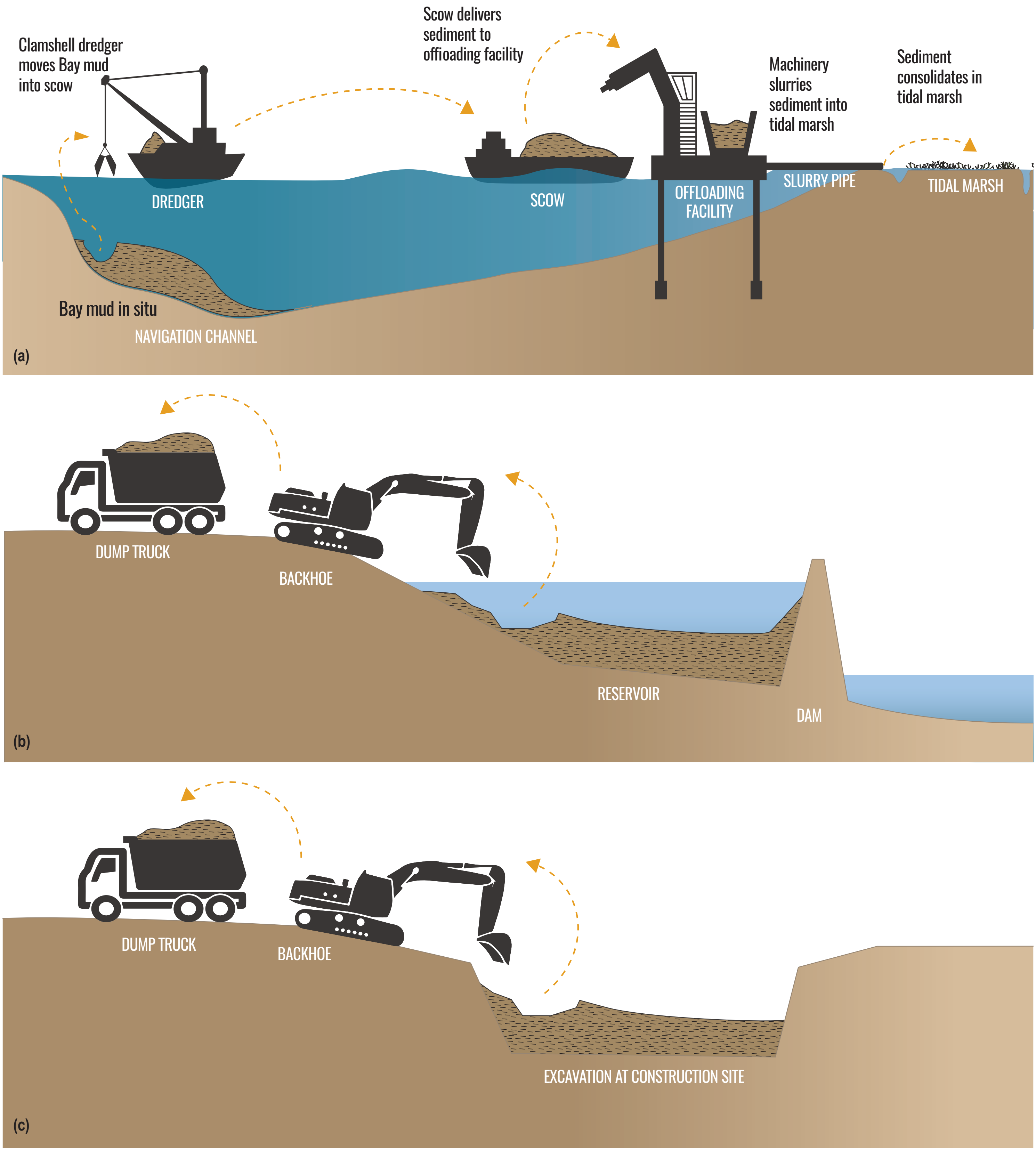


Figure 2. Conceptual diagrams of potential sources for beneficial reuse of sediment, including (a) maintenance dredging and beneficial reuse of dredged material on a tidal marsh, (b) excavation of fluvial sediment trapped behind dams, and (c) excavation of upland sediment removed during consruction.

Strategic placement of dredged sediment

Strategic placement of dredged sediments has been proposed as one method to help restore and enhance tidal marshes and mudflats in the context of sea level rise. Placement of dredged sediment onto or near marshes could augment natural accretion from suspended Bay sediment. There are several potential methods for strategically placing dredge sediment. Potential methods include: (1) marsh spraying; (2) water column seeding; and (3) shallow water placement (Figure 3).

Marsh spraying (thin layer placement), as was performed for the Seal Beach Restoration Project (see page 26), involves spraying dredged sediment directly onto the marsh. Though vegetation is initially buried, over time the marsh is recolonized by new shoots or from buried rhizomes. Water column seeding could involve releasing dredged sediment into the water column at a marsh channel entrance during a flood tide, so it is carried onto the marsh as the tide flows inland. Finally, the shallow water placement method could involve placing dredge sediment offshore, which is then resuspended and carried by tides onto the marsh. Though there are ecological benefits to each strategy, there are also detriments; for instance, marsh spraying initially buries marsh vegetation, water column seeding impacts water column communities through increased turbidity and suspended sediment concentration, and shallow water placement buries organisms in the shallow subtidal area.

The different methods change the sediment bulk density at the site over time. The placement method can affect both the rate of accretion and the rate of compaction/settling on the marsh. For example, a site restored using the marsh spraying method may initially have a higher rate of increase in bulk density compared to a site restored using water column seeding, which generally results in more gradual accretion. These different bulk density curves need to be taken into consideration because they can impact when the marsh will attain the desired elevation.

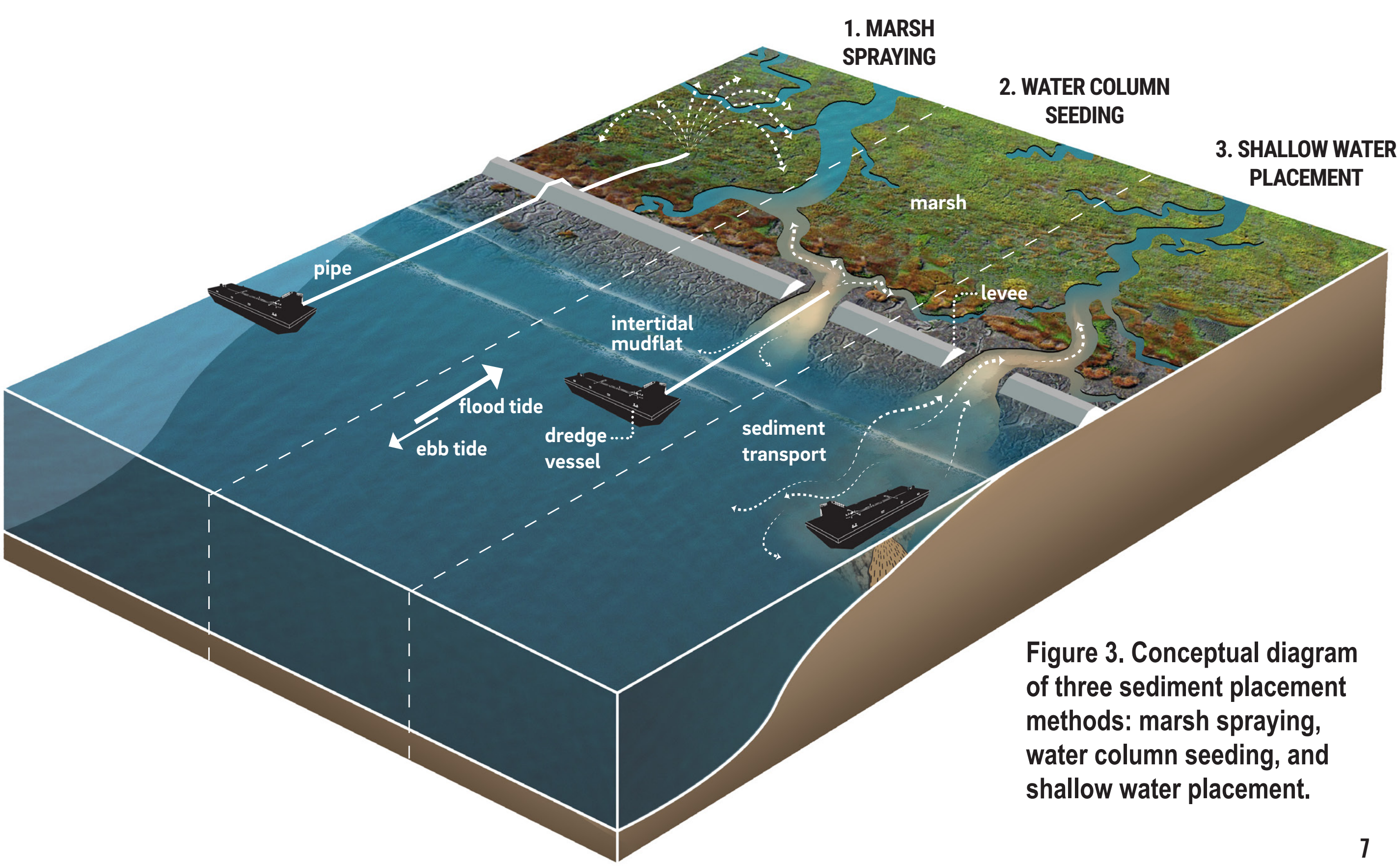


Figure 3. Conceptual diagram of three sediment placement methods: marsh spraying, water column seeding, and shallow water placement.

3. Bulk density definitions and sources of confusion

A consistent definition of bulk density is required to translate between sediment mass and volume calculations. Other issues, such as organic content and compaction rates, also factor into mass/volume calculations.

There are a number of variables used to define bulk density: partially saturated bulk density, fully saturated bulk density, dry density, bulk weight density (partially and fully saturated), and dry weight density. These all have specific uses and definitions but are not always adequately reported. The presently available conversion factors lack specificity of application and are dated, potentially leading to inconsistent or inappropriate use and the potential for large errors that may lead to less-than-optimal decision making. Confusion surrounding bulk density and related concepts has led to misapplications in various locales and contexts (Flemming and Delafontaine 2000).

This report was compiled as an attempt to reduce confusion surrounding the use of bulk density (both the term and the values) in sediment mass and volume conversions. The presently available conversion factors lack specificity of application and are outdated, potentially leading to inconsistent or inappropriate use and the potential for large errors and less-than-optimal data being used to make management decisions. Sources of confusion in application of bulk density values include:

Terminology:

Sediment bulk density is the total mass of mineral and organic sediment within a defined volume. A survey of the literature revealed that there is a good deal of crossover in terminology between “concentration” (e.g., mass of sediment divided by unit volume) and “content” (mass of sediment divided by total mass in unit volume), which leads to confusion about what these terms represent and how they can be applied (Flemming and Delafontaine 2000). Bulk density (mass of sediment divided by unit volume) represents concentration, so interpreting it as content can cause calculation errors.

The “content” versus “concentration” question is not the only terminology issue. There are many closely related terms (e.g., particle density, water density, bulk weight density, dry weight density, water weight density). Clarifications on some of the key terms related to bulk density are provided in Table 1.

Units:

Inadequate reporting of units leads to confusion and misapplication of bulk density values. Common units used to report bulk density include grams per cubic centimeter (g/cm^3), tonnes per cubic meter (t/m^3), and pounds per cubic foot (lbs/ft^3).

Wet versus dry:

Another source of confusion is inadequate reporting about whether reported bulk density values are wet (saturated) or dry (see Table 1 and Figure 4). These represent two different values, but if a value is reported as “bulk density” without further specification, it can be difficult for users of the data to interpret the meaning.

Organic versus mineral/inorganic:

There are two components of sediment: organic and mineral/inorganic. Some studies measure these components together, while others report percent organic matter and/or the mass of the mineral component of sediment separately. When this is not specified, it can be difficult to know whether reported bulk density values are for the mineral component only or for both mineral and organic sediment.

Application from other systems and time periods:

Bulk density values vary widely from place to place depending on geomorphology and habitat, so applying values from one location to another can lead to confusion and inaccuracy. This is also true of applying older values to systems that have undergone change over time and may no longer have the same sediment bulk density. Because practitioners conducting sediment mass and volume calculations come from a variety of backgrounds, the numbers they use come from a variety of sources, and may not always be the most pertinent to the local setting and current time period. In addition, established regional values may not still hold in places where construction or other rapid changes have affected sediment conditions.

Table 1. Common soil terms defined (adapted from Barnes 2016).

Term	Symbol	Expression	Meaning
Porosity	n	$\frac{(V_a + V_w)}{V_t}$	Ratio of pore space (water and air) to total volume
Bulk density (fully saturated)	ρ_{sat}	$\frac{(M_s + M_w)}{(V_s + V_w)}$	Concentration of sediment in given volume, including water in pore space
Dry bulk density	ρ_b	$\frac{M_s}{V_t}$	Concentration of sediment in given volume after removing water in pore space

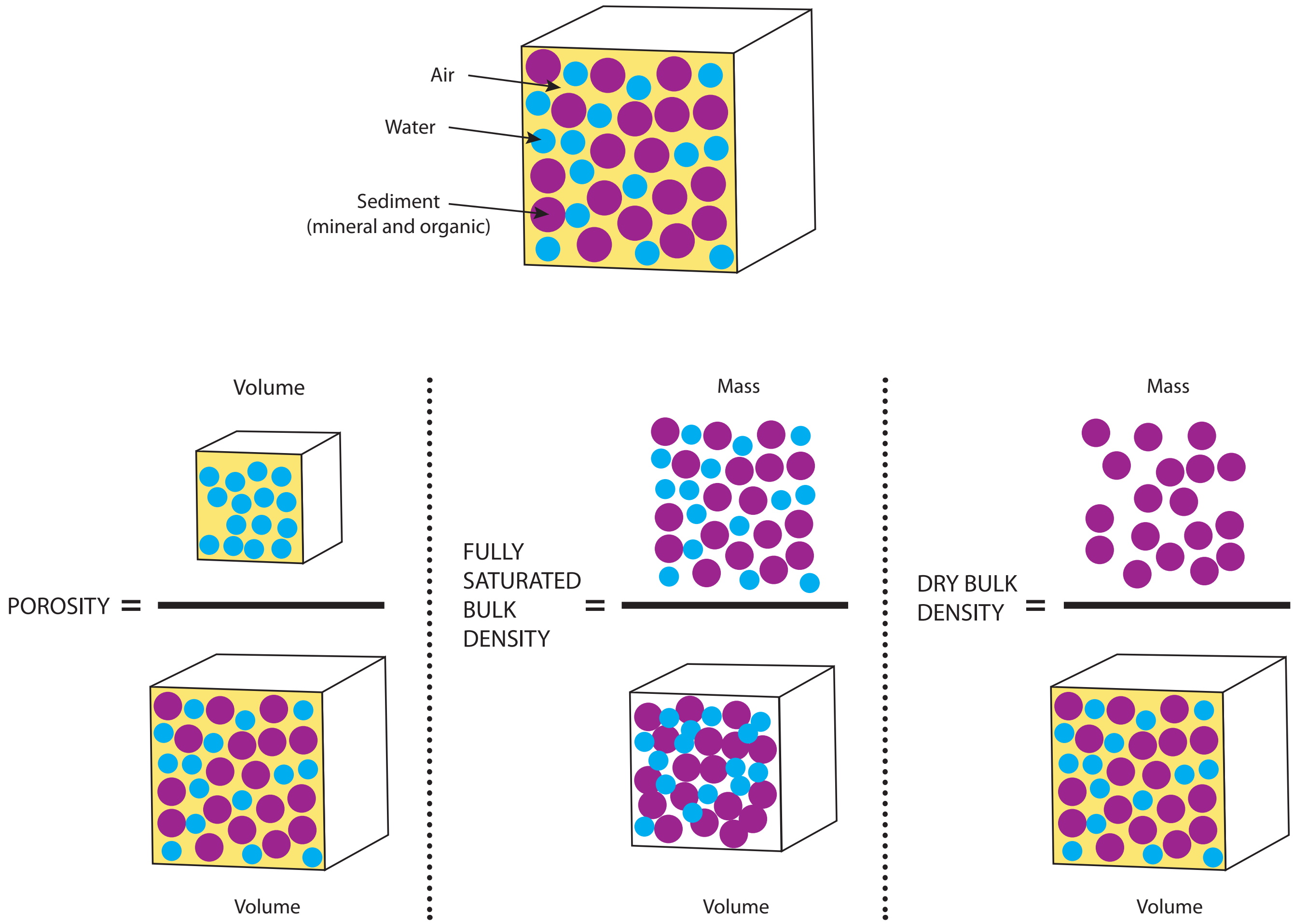


Figure 4. Visual representation of porosity, fully saturated bulk density, and dry bulk density definitions. Adapted from Flemming and Delafontaine 2016.

4. Methods

A literature review was conducted to determine the current state of knowledge on in-situ bulk density estimates for various bayland habitats throughout San Francisco Bay, including tidal marsh, tidal flat, shallow Bay, and deep Bay/channel habitats. The **primary literature** examined consisted of peer-reviewed studies that collected original measurements of bulk density. The **secondary literature** examined—studies that used bulk density values from previous studies—included both peer-reviewed journal articles and publicly available technical reports (i.e., unpublished white papers). Although this review of bulk density values for San Francisco Bay is likely not exhaustive, we reviewed the best-known secondary studies based on our own professional judgment and conversations with professionals. We then obtained and reviewed all the publicly-available primary studies referenced by the secondary studies.

Bulk density values were analyzed by location within the Bay (i.e., subembayment), habitat type, and across studies to identify potential trends. Comparisons between studies were limited, however, due to differences in methods used, the quality of data reported, and range in sample size. The published literature determined to be relevant for this study is shown in Figure 7 on pg. 19. A database was compiled to track bulk density measurements and estimates from each study reviewed, and to compare across studies when possible.

4.1 Compilation of bulk density measurements from primary literature

Bulk density values collated from the primary literature were converted to mass of the mineral component of dry bulk density of the soils sampled when sufficient data was available (i.e., dry bulk density and percent organic matter), which included Pestrong (1965, 1972), Callaway et al. (2012), and Thorne et al. (2013). All values were converted to English units of pounds per cubic foot (lbs/ft^3). Measurements were averaged by core, sample location, habitat type, and subembayment. The formula used to calculate mass of the mineral component of dry bulk density is as follows:

$$m_d = ((100 - P_{OM})/100) * \rho_b$$

where m_d = mass of mineral component of dry bulk density (lbs/ft^3)

P_{OM} = organic matter (%)

ρ_b = dry bulk density (lbs/ft^3)

Two of the primary studies reviewed, Love et al. (2003) and Patrick and DeLaune (1990), reported the dry bulk density measurements of samples analyzed. For these studies, we averaged the dry bulk density measurements of the cores sampled (i.e., the combined mineral and organic component of dry bulk density of the soils sampled since organic matter content was not readily available). Due to the small sample size in Love et al. (i.e., two cores at the same location), the average dry bulk density of the cores did not change across sample location, habitat type, or subembayment. Although Patrick and DeLaune include data on dry bulk density measurements for three cores collected at three tidal marshes, only graphs of the dry bulk density measurements versus depth of cores collected are reported. Because the tabular data were unavailable, graphs were digitized to estimate dry bulk density measurements with depth to calculate the average bulk density for each core/sample location, habitat type, and subembayment. The individual bulk density measurements as digitized from the graphs are reported in the bulk density database.

Caffrey (1995) reports the porosity for each sample as calculated from percent water in sediment, rather than the dry bulk density. Caffrey listed an assumed sediment density of 2.6 g/cm^3, so this value was used to convert porosity to dry bulk density using the formula below:

$$\rho_b = (1-\varphi) * \rho_d$$

where ρ_b *= dry bulk density (lbs/ft*^{3}*)*

φ *= porosity (non-dimensional)*

ρ_d *= sedment particle density (assumed to be 2.6 g/cm*^{3} *or 162.3 lbs/ft*^{3}*)*

Sternberg et al. (1986) did not specify whether the bulk density value published reflects wet or dry conditions and organic matter content and porosity of the sample(s) was not readily available. Because of this, we report Sternberg et al.'s bulk density estimate as is as a useful point of comparison in Appendix B.

Primary studies that reported bulk density values for locations outside of our study area (i.e., San Francisco Bay, from Golden Gate to Broad Slough) were omitted from this analysis. Studies with bulk density data beyond our study area include Pestrong (1965) and Caffrey (1995). In addition to reporting bulk density values in the bulk density database, we created a map indicating the location of sampling sites for each primary study reviewed, overlaid onto modern bayland habitat types and labeled with corresponding averaged bulk density values using the methods described above. When specified, the geographic coordinates were used to map the sampling location (e.g. Pestrong 1965, Patrick and DeLaune 1990). In some instances, geographic coordinates were not specified, so published location maps were used to estimate the sampling location (e.g., Pestrong 1972, Caffrey 1995, Sternberg et al. 1986, Love et al. 2003). For studies that collected many core samples across each marsh analyzed, we mapped the general location of that marsh to simplify the sampling location for comparison purposes (e.g., Callaway et al. 2012, Thorne et al. 2013).

4.2 Compilation of bulk density estimates from secondary literature

Bulk density values compiled from secondary studies were converted to lbs/ft^3 and are reported by habitat type. Data are also reported by subembayment when enough data was available to determine which subembayment primary data represent. We created a tree diagram of primary and secondary studies to distinguish between types of primary studies and to explain the basis of the values included in well-known secondary studies.

4.3 Compilation of bulk density estimates through informal interviews

Additional bulk density estimates were collected through informal interviews and correspondence with restoration managers, dredgers, engineers, and agency staff involved in beneficial sediment reuse projects. The aim of these interviews was two-fold: (1) to expand the database of bulk density values to include dredged and excavated sediment to compare with in situ estimates from the literature; and (2) to better understand how sediment availability and sediment demand are quantified by practitioners. Bulk density estimates obtained through these interviews range from field observations and informal measurements to engineering standards and, in most instances, are unpublished and/or the primary source(s) is not reported. Additional findings from interviews are detailed in Appendix C.

4.4 Bulk density database

All measured and estimated bulk density values are listed in a database (available for download here). Summary tables of data sets included in the inventory table are shown on pages 14 and 16, and additional tables are included in Appendix B. Findings informed recommendations to standardize bulk density measurements across disciplines. We highlight data gaps and considerations for future studies with the aim of building towards a more detailed sediment database for San Francisco Bay. For studies that do not specify the corresponding habitat types of the bulk density samples collected, tidal thresholds to distinguish between bayland habitat types were determined using guidance from the Goals Project (1999) and are described in Appendix A.

5. Results

The literature review resulted in a synthesis of bulk density measurements from eight primary studies and bulk density estimates from nine secondary studies and six informal interviews. Major differences in study design and methodology exist in the primary data reviewed, limiting the degree to which comparisons between studies are possible. In this section, we discuss results in order of the most detailed measurements (i.e., starting with measurements of mineral component of dry bulk density from the primary literature) to more general estimates or 'rules of thumb' (i.e., values from best professional judgment collected through correspondence with practitioners and others).

5.1 Primary values of bulk density by subembayment

Mineral component of dry bulk density

Only four primary studies report the mineral component of dry bulk density for near-surface cores of similar depths (i.e., samples range from the top 7.9 in to 9.8 in of soil). When averaged by subembayment, a much lower mineral component of dry bulk density of soil was observed in tidal marsh samples collected in Suisun, at approximately 10.6 lbs/ft^3 (n = 12 soil core samples), compared to other subembayments, which ranged between 28.9 lbs/ft^3 in Central Bay (n = 6 soil core samples), 30.3 lbs/ft^3 in San Pablo Bay (n = 61 soil core samples), 30.4 lbs/ft^3 in South Bay (n = 62* soil core samples), and 32.6 lbs/ft^3 in Lower South Bay (n = 81*,** soil core samples) (Table 2, Figure 5). Values for the mineral component of dry bulk density for tidal flat and deep Bay/channel in Central Bay, South and Lower South Bays are generally around 30 lbs/ft^3. We could not access readily available primary data for the mineral component of dry bulk density for tidal flat and deep bay/channel in Suisun, San Pablo and Central bays, nor for shallow bay in any of the subembayments.

Table 2. Primary published studies with sufficient data to calculate and compare the mineral component of dry bulk density samples. Values listed in this table are averaged for each study by habitat type and subembayment. For original data for each study and for standard deviations, click here to access the bulk density database. (SUI = Suisun Bay, SPB = San Pablo Bay, CB = Central Bay, SB = South Bay, LSB = Lower South Bay)

Reference	Sampling time period	Sample depth (in)	# of cores collected within study area	Core samples taken per habitat type per unique location (x)	Average mineral component of dry bulk density across all samples (lb/ft3)														
					Tidal Marsh					Tidal Flat					Deep Bay/Channel				
					SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB
Pestrong 1965	1962-1965	9.0	216*	12*				31.4	33.5				29.3	29.6				30.2	32.8
Pestrong 1972	Unspecified (1972 publication date)	Unspecified***	37**	1**					31.7					35.6					32.1
Callaway et al. 2012	December 2008 to February 2010	7.9	54	6 - 12 cores per marsh; 2-4 per low/mid/high per marsh	10.6	25.7	28.9	29.5											
Thorne et al. 2013	August 2009	9.8	44 (note: 3 replicates were collected at each site giving a total of 132 samples analyzed)	3		34.8													
Averages, by subembayment and habitat type					***10.6***	***30.3***	***28.9***	***30.4***	***32.6***				***29.3***	***32.6***				***30.2***	***32.5***

See next page under Figure 5 for footnotes referred to in Table 2.

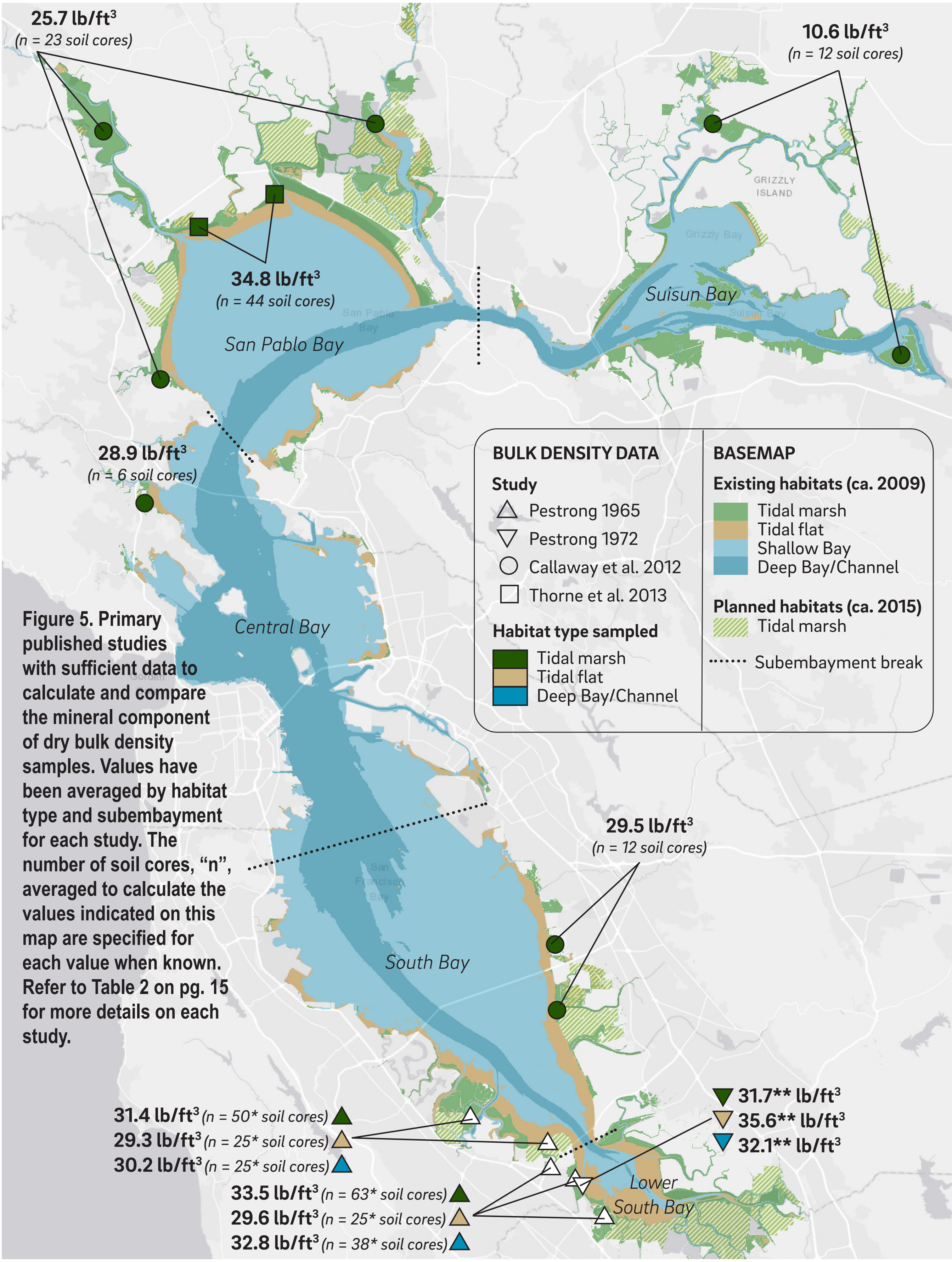


Figure 5. Primary published studies with sufficient data to calculate and compare the mineral component of dry bulk density samples. Values have been averaged by habitat type and subembayment for each study. The number of soil cores, "n", averaged to calculate the values indicated on this map are specified for each value when known. Refer to Table 2 on pg. 15 for more details on each study.

** Pestrong (1965) did not specify the number of cores collected at each site. Twenty-two individual environments within each location were sampled and a total of 275 near-surface cores were collected. Assuming equal amounts of cores were collected at each site at each environment, approximately 12.5 samples were collected for each location sampled, which we rounded down to 12.*

***The number of soil cores collected (x) per habitat type for Pestrong (1972) is unspecified. The total number of cores collected across all habitats sampled by Pestrong is ~27, as interpretted from figure 12 in Pestrong's report (1972).*

****Pestrong (1972) does not specify the depth of soil cores collected for bulk density and organic matter analyses but indicates cores are near-surface samples.*

Dry bulk density

We report the dry bulk density values listed in Table 3 below separate from the mineral component of dry bulk density values in Table 2 to underscore the differences between them. The data included in Table 3 reflect the combined mineral and organic concentration within a specified volume of soil whereas the data included in Table 2 reflect only the mineral concentration within a specified volume of soil--the organic mass has been removed.

Data on dry bulk density of soils was limited to three primary studies with variations in sample depths ranging from 3.1 in to 61.0 in (Table 3). For tidal marsh, the average dry bulk density was approximately 43.2 lbs/ft^3 in South Bay (n = 2 soil cores) and 32.2 lbs/ft^3 in Lower South Bay (n = 1), with no data obtained for Suisun, San Pablo, and Central bays. For shallow Bay, the average dry bulk density was approximately 46.0 lbs/ft^3 in South Bay (n = 3), with no data obtained for Suisun, San Pablo, Central and Lower South bays. Deep Bay/channel samples had the largest variation in averaged dry bulk density measurements, with lower values of 30.7 lbs/ft^3 in Central Bay (n = 2) and 35.1 lbs/ft^3 in South Bay (n = 2), and higher values of 65.7 lbs/ft^3 in San Pablo Bay (n = 1) and 80.2 lbs/ft^3 in Suisun Bay (n = 2). No data for dry bulk density was obtained for deep Bay/channel in Lower South Bay. No data in any of the subembayments was obtained for tidal flats (with the exception of data listed in Table 2; i.e., Pestrong 1965, 1972).

Table 3. Primary studies of dry bulk density data. This table summarizes the bulk density values from studies that reported values for dry bulk density (i.e., combined concentration of mineral and organic sediment within a specified volume of soil). Values listed in this table are averaged for each study by habitat type. Patrick and Delaune (1990) and Love et al. (2003) reflect dry bulk density values analyzed from soil cores of varying depths. Values from Caffrey (1995) were converted from published porosity values for each sample by assuming a particle density of 162 lbs/ft3 (2.6 g/cm3). For original data for each study and more information on methods, click here to access the bulk density database.

Reference	Sampling time period	Sample depth (in)	# of cores collected within study area	Core samples taken per habitat type per unique location (x)	Average dry bulk density across all samples (lb/ft3)														
					Tidal Marsh					Shallow Bay					Deep Bay/Channel				
					SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB
Patrick and Delaune 1990	1983, 1988	31.5-61.0	3	1				43.2	32.2										
Love et al. 2003	July 1997	44.4-47.6	2	2													30.7		
Caffrey 1995	1991-1993	3.1	8	1									46.0		80.2	65.7		35.1	

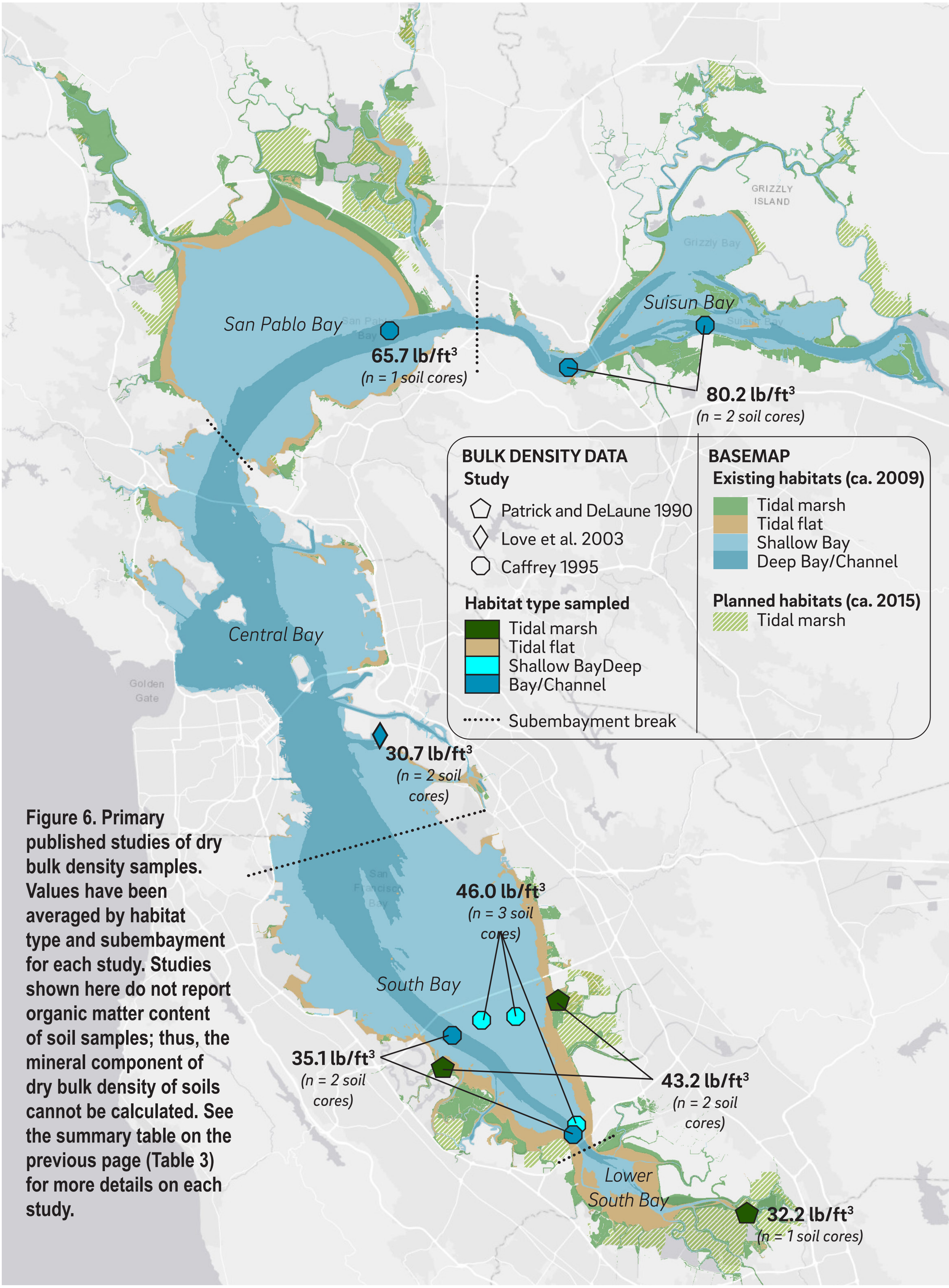


Figure 6. Primary published studies of dry bulk density samples. Values have been averaged by habitat type and subembayment for each study. Studies shown here do not report organic matter content of soil samples; thus, the mineral component of dry bulk density of soils cannot be calculated. See the summary table on the previous page (Table 3) for more details on each study.

Notable differences between primary studies

Most of the primary studies for San Francisco Bay collected soil core samples of varying depths, with the exception of Sternberg et al. (1986) and Caffrey (1995). Sternberg et al. and Caffrey collected surface samples using Van Veen grabs and analyzed the top 0.4 in (1 cm) and 3.1 in (8 cm) of soil respectively, and reported values for only one soil sample/core collected at each location. The remaining six primary studies collected soil core samples of varying depths, from 9 in (22.9 cm) near-surface cores to deeper cores up to 61 inches (155 cm) in depth. The number of soil cores collected for each sampling location within San Francisco Bay also varied greatly by study, ranging from one sample per location to an estimated twelve[1] samples per location.

Other differences between primary studies include:

- the study design (e.g., study objectives, sample size, replicates, location, depth, and environment sampled).
- the time period during which samples were collected (i.e., sampling among individual studies ranged from a single to multi-year time period).
- the type of instrument used to collect sediment samples (e.g., piston cores of varying diameters and lengths, Van Veen grab samplers).
- the range of soil parameters analyzed (e.g., porosity, dry bulk density, organic matter content).
- the length of time and temperature at which dry bulk density samples were processed.
- the granularity of bulk density results reported (i.e., some results were reported as a lump average for the cores collected while others were reported for each subsample processed).

[1] *Pestrong (1965) did not specify the number of cores collected at each site. Twenty-two individual environments within each location were sampled and a total of 275 near-surface cores were collected. Assuming equal amounts of cores were collected at each site at each environment, approximately 12 samples were collected for each location sampled.*

5.2 Secondary values of bulk density by subembayment

Comparisons between secondary values of bulk density are difficult due to differences in the type of bulk density measured, overlapping primary sources used, and, in some instances, difficulty in obtaining the primary sources from which the secondary values were derived. Thus, secondary values are not compared here as averages by subembayment for each habitat type reviewed. Rather, a summary table of bulk density values from the nine secondary studies reviewed for this report is provided in Appendix B (see Table B3 on pg. 35), organized in a similar format to the previous data comparison tables. Bulk density values from individual studies are reported by subembayment for each study based on sampling locations from the primary literature used to derive the values. For studies that combined primary data collected from multiple subembayments or when primary sources could not be reviewed, cells within the subembayment categories in Table B3 were condensed to reflect one value across all five subembayments. For relationships between primary and secondary studies, see Figure 7 below.

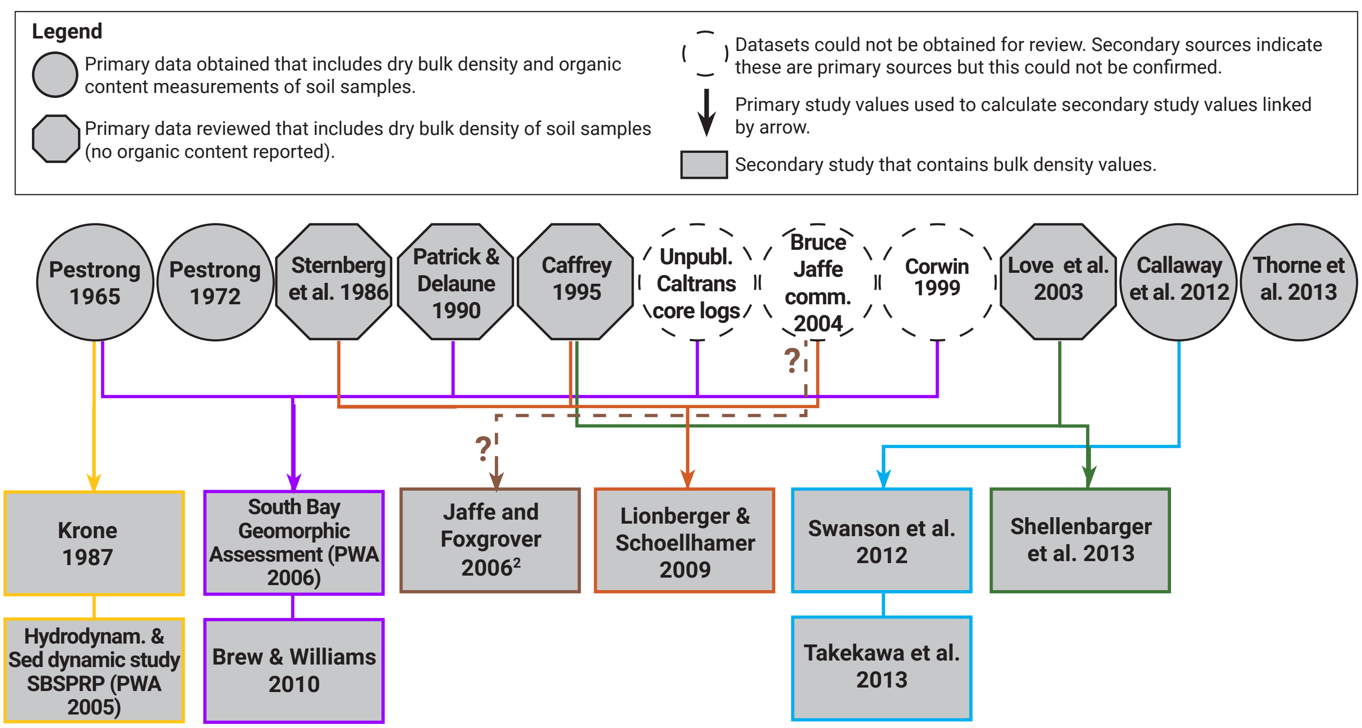


Figure 7. Relationship between studies of primary bulk density measurements and secondary bulk density values. The bulk density values compiled for this study were generated from a mix of primary research (indicated by circles) and secondary research (indicated by rectangles). The secondary research reviewed builds off of one or more primary research reports, as indicated in this tree diagram, and can be helpful to track down original bulk density values with the corresponding habitat types surveyed. We were not able to obtain three of the eleven primary research reports mapped, as indicated in white (i.e., white indicates the study was not reviewed; gray indicates the study was obtained and reviewed). Note: this is not an exhaustive list of the primary and/or secondary bulk density studies within San Francisco Bay; rather, it is solely conveying the studies we obtained and reviewed for this report, and the relationship of the studies to each other. Dashed circle signifies source could be primary but unsure because we could not obtained a copy of the data for review. The brown dashed line signifies the best guess in terms of connection between studies.

[2] *Jaffe and Foxgrover (2006) assume a bulk density value for soft mud to be 33 lbs/ft^3 in the discussion of their report (pg. 17) but no citation is given. Lionberger and Schoellhamer (2009) report references "Bruce Jaffe" communication from 2004 so we speculate that the bulk density value used by Lionberger and Schoellhamer is 33 lbs/ft^3; however, this has not been confirmed by the report authors.*

5.3 Estimates and observations from informal interviews and correspondence

Dredged Bay mud and excavated upland soils are two of the main sources of reused sediment in San Francisco Bay. The bulk densities of these materials vary considerably based on their texture (i.e., the percent sand, silt, and clay), structure, and porosity. Typical values for dredged Bay mud range from 90 lbs/ft^3 in situ to 90-120 lbs/ft^3 after placement, depending on where in the habitat continuum it is placed (Dilip Trevedi, personal comm.) (Appendix B, Table B2). Upland soils that typically have a high clay and silt content have a bulk density of approximately 135 lbs/ft^3, and those with a higher sand content typically have a bulk density of approximately 145 lbs/ft$^{3.}$

No measurements of bulk density for reused upland soils were obtained for this study, although case studies do exist (e.g. Inner Bair Island). Of the six informal interviews conducted, only one interview yielded measurements of dry bulk density of placed dredged sediment on a marsh. These values, provided by Steve Carroll (personal comm., 2019) and collected at Cullinan Ranch Marsh Restoration, ranged from around 31 lbs/ft^3 to 100 lbs/ft3 (see Appendix C for details on methods used). The low end, ~34.5 lbs/ft^3, was the dry bulk density of soils measured before dredged material was placed at the restoration site at Cullinan Ranch and falls within the range of dry bulk density estimates of in situ tidal marshes in San Francisco Bay. The measured dry bulk density of soils sampled increased over time after initial placement, from around 35.5 lbs/ft3 after one week to as high as 80 lbs/ft^3 several years after placement in ponds that remained dry. Both Carroll and Trevedi note that after sediment is placed, the bulk density increases as soil moisture decreases and soils compact.

6. Discussion

Due to the differences between the types of bulk density values reported for each study category (i.e., primary, secondary, and interviews/correspondence), we discuss and compare bulk density values separately for each study category, incorporating qualitative observations and trends discussed in the literature.

6.1 A comparison of findings on bulk density from the primary literature

Mineral component of dry bulk density from the primary literature

Tidal marsh: Tidal marsh habitats have the most robust and current primary data compared to any other intertidal habitat, and data was collected in a way that allows for some comparison within and across marshes. Thorne et al. (2013), Pestrong (1965, 1972), and Callaway et al. (2012) reported dry bulk density and organic matter content of tidal marsh samples for different tidal marsh zones. Thorne et al. sampled at a marsh in the Sonoma Baylands located in San Pablo Bay and found the highest bulk densities of marsh soils were located along the Bay's edge, with lower values located towards the middle of the marsh. Thorne et al. found an opposite trend for organic matter content: the highest organic matter was found in samples located towards the middle of the marsh while the lowest organic matter was found in samples located near the Bay's edge. Pestrong (1965, 1972) collected and analyzed separate samples for zones of ***Spartina***-dominated marsh (low marsh) and ***Salicornia-***dominated marsh (high marsh). Although Pestrong's studies were limited to the South Bay and Lower South Bay, both studies found that ***Salicornia*** marshes had higher dry bulk densities, organic matter content, and, by our calculation, mineral component of dry bulk density of near-surface soils compared to ***Spartina*** marshes.

Callaway et al. (2012) sampled low-, mid-, and high-marsh stations to collect data across elevations. Callaway et al.'s study extended through all subembayments of the Bay except Lower South Bay. Callaway et al.'s data show lower mineral components of dry bulk density of soils sampled in mid- and high-marsh stations compared to low-marsh stations for all subembayments except for Central Bay. However, it should be noted that Central Bay contained the fewest number of soil cores—6 core samples—and was limited to one marsh (Muzzi Marsh) compared to the 12 to 23 soil cores collected across two or more marshes in the other subembayments. Callaway et al. point out that the brackish sites sampled in Suisun Bay had the lowest rate of mineral sediment accumulation despite their proximity to major fluvial inputs (i.e., the San Joaquin and Sacramento Rivers) which could be attributed to lower tidal range and thus lower tidal energy to deposit sediment onto adjacent tidal marsh.

While Callaway et al. (2012) and Thorne et al. (2013) found similar trends of higher mineral content and lower organic content in low marsh soils, Pestrong's (1965, 1972) studies found a slightly different trend of higher mineral content and higher organic content in high marsh soils. It is unclear why this may be, but it is worth noting that Pestrong's 1972 study was located in the Lower South Bay, which may have different sedimentation dynamics resulting from a larger tidal range compared to the other subembayments. Although some of Pestrong's 1965 study was located in the South Bay, the marshes sampled did not overlap with those sampled in Callaway et al. (2012) nor Thorne et al. (2013). In addition, Pestrong's soil cores were collected over four decades prior to the Callaway et al. and Thorne et al. studies. Callaway et al. (2012) note that over the most recent decade the Bay has experienced a 36% decrease in suspended sediment concentration. Since Pestrong's datasets reflect different time periods the bulk densities observed could be influenced by differences in mineral sediment availability.

Tidal flat: Data on the mineral portion of dry bulk density in tidal flats was limited to Pestrong's work (1965, 1972). While robust in terms of the quality of data, Pestrong's studies were limited in geographic scope to the South Bay and Lower South Bay. When averaged by subembayment, the mineral component of dry bulk density was slightly higher in tidal flats in the Lower South Bay, 32.6 lbs/ft^3, compared to the South Bay, 29.3 lbs/ft^3. However, Pestrong's 1972 study included both tidal flat samples located on natural tidal flat levees adjacent to channels and tidal flat samples collected at lower elevations and located further from channels. Pestrong's 1965 work does not specify whether samples were collected along tidal flat levees. The intravariability of tidal flat samples is described in more detail in the "Across and within habitats" section below.

Shallow Bay*:* Caffrey (1995) was the only primary study reviewed that reported bulk densities for samples collected in shallow Bay habitat (see Appendix A for details on how sample depths were crosswalked to habitat types). Caffrey did not report organic matter content for the samples analyzed, so the mineral component of the dry bulk densities could not be calculated. Thus, no data was obtained for this habitat type for the mineral component of dry bulk density.

Deep Bay/channel*:* Data on the mineral portion of dry bulk density in channels was limited to Pestrong's work (1965, 1972). As mentioned above, Pestrong's studies were limited in geographic scope to the South Bay and Lower South Bay. When averaged by subembayment, the mineral component of dry bulk density of channel soils was slightly higher in the Lower South Bay, at 32.5 lbs/ft^3, compared to the South Bay, at 30.2 lbs/ft^3.

Across and within habitats*:* Pestrong's 1965 report found that dry bulk density was lowest on the tidal flats and highest on the ***Salicornia*** marsh in near-surface soil cores from the South Bay and Lower South Bay. Pestrong attributed this trend to the ability of the roots of the ***Salicornia*** marsh plants to bind with the soil, leading to an increase in shear strength and bulk density. Pestrong notes that although ***Spartina*** plants have less well-developed root systems compared to ***Salicornia*** and thus do not increase bulk density as effectively, ***Spartina*** plants serve as an important sediment trap for tidal flats and tidal channels. Pestrong's 1965 study also found that although the highest amounts of organic matter were found within tidal marsh habitats (an average of about 14.9% organic matter across all S.F. Bay tidal marsh samples analyzed by Pestrong 1965), he noted that surprisingly high measurements of organic matter were found within the channels and tidal flats sampled (about 2.9% and 4.6% respectively) despite the visual absence of root and plant fiber material from these habitat samples. Thus, Pestrong concludes that the tidal channel and tidal flat samples must be dominated by decomposed rather than intact forms of organic matter.

Other researchers, such as Cohen (2008), have noted that the amount of organic matter in non-marsh sediment is typically small and may be ignored, meaning the dry bulk density of in situ soils is sufficient to convert sediment mass to volume and vice versa. However, upon further inspection of data from Pestrong's 1972 report, dry bulk density and organic matter data collected at Cooley Landing in the Lower South Bay shows relatively high levels of organic matter in tidal flat and channel habitats: between 4.2 and 6.9%. For comparison, Thorne et al. (2013) found the organic matter content of tidal marsh soils sampled throughout the Sonoma Baylands ranged from 2.2% to 5.4%.

In the 1972 report, Pestrong measured bulk density and organic content across the tidal marsh-flat-channel habitat continuum with more intra-habitat specificity (i.e., habitat types were categorized into tidal flats, tidal flat channels, tidal flat levees, ***Spartina*** marsh, ***Salicornia*** marsh, tidal marsh channels) at Cooley Landing in the Lower South Bay. Interestingly, Pestrong (1972) found that tidal flat samples had both the lowest and highest mineral content of dry bulk density compared to other habitat types sampled. Tidal flat samples located further from channels (i.e., samples not considered tidal flat levees) averaged approximately 25.1 lbs/ft^3 for the mineral component of dry bulk density while the tidal flat levees (i.e., slightly elevated levees adjacent to tidal flat channels and free of marsh vegetation) averaged approximately 46.1 lbs/ft^3. This nearly 46% increase in the mineral component of dry bulk density within tidal flats highlights the potential for intra-habitat variability that may be present throughout habitat types, a concept supported by the tidal marsh work performed by Callaway et al. (2012) and Thorne et al. (2013) as discussed in the previous section.

Dry bulk density from the primary literature

Due to the low sample sizes and geographic limits of these data sets and without knowing organic content of samples reviewed, trends are challenging to discuss. It is notable, however, that the dry bulk density of deep Bay/channel habitats appears to decrease from 80.2 lbs/ft^3 in Suisun Bay to 65.7 lbs/ft^3 in San Pablo Bay and continues to decrease to below 40 lbs/ft^3 in the Central Bay (30.7 lbs/ft^3) and South Bay (35.1 lbs/ft^3) (Table 3, Figure 6). Because the sample sizes are small and organic content is unknown, it is difficult to know why dry bulk densities of deep Bay/channel soils vary in this way and whether this trend would be observed over a larger sample size using consistent methods. Additionally, the Central Bay data from Love et al. (2003) extends around fifteen times deeper compared to the near-surface (~3.1 in) samples analyzed by Caffrey (1995), whose data comprises the rest of the subembayment data for deep Bay/channel habitats.

It is worth nothing that comparisons of dry bulk density between all eight of the primary studies could be made, though this was not done in this study. To compare between all eight of the primary studies, refer to the individual worksheets listed for each study in the database to identify dry bulk density values accordingly. The differences in sampling methods, depths, and other considerations should be noted before any comparisons are made. Depending on the type of sediment study pursued, the dry bulk density of soil samples may be applicable if organic matter content is not needed, so it is important to note that all eight primary studies could be compared, with the main caveat being the differences in study design, sample collection methods, etc.

6.2 Limitations with secondary bulk density data

Several secondary studies combine data from more than one primary study, but it is unclear whether the the bulk density values combined from the primary literature were consistent types of bulk density and/or whether differences in study methods and design were clearly explained. Additionally, at least one incorrect secondary value was found in the bulk density value reported in PWA 2005, likely resulting from a unit conversion error of the primary data which was off by three orders of magnitude.

Another issue that became clear during the review of secondary literature is the difficulty in obtaining unpublished datasets for review. Three datasets shown as dashed circles in Figure 7 could not be obtained for this study, which results in unclear assumptions and raw numbers used for three of the nine secondary studies analyzed here.

6.3 Estimates and observations on bulk density during beneficial reuse

Although the estimates and observations gathered from correspondence with practitioners are not published or measured values, they demonstrate the variability of bulk density of dredged material between the dredging location and beneficial reuse site. The bulk density of typical Bay mud is roughly around 90 lbs/ft^3 in situ, but this estimate varies depending on how long a site remains undisturbed, i.e., the length of time between maintenance dredging (Dilip Trevedi, personal comm.). The frequency of maintenance dredging varies by site: some locations experience dredging as frequently as every 8 to 16 months whereas other sites may experience more infrequent dredging ranging between 1 to 3+ years. When Bay mud is excavated and placed in a scow, Bay water dilutes the material which causes the bulk density to decrease to approximately 70 lbs/ft^3. When the dredged material is deposited at the beneficial reuse site, the bulk density likely returns fairly quickly to its in-situ value, around 90 lbs/ft^3. Over time, the material consolidates and typically approaches a range of 110-120 lbs/ft^3 when placed in a marsh, 100 lbs/ft^3 when placed in a mudflat, and 90 lbs/ft^3 when placed in subtidal areas (Dilip Trevedi, personal comm.) (see Figures 1 and 2 for conceptualized diagrams of how bulk density changes during the beneficial reuse process).

The lower and upper ranges of dry bulk density for reused dredged material discussed with Trevedi and Carroll are similar, but these estimates are much higher than in situ values observed in the primary and secondary literature reviewed for this study, with the exception of PWA (2006)/Brew and Williams (2010). Because two of the four primary sources referenced by PWA (2006)/Brew and Williams (2010) could not be obtained, it is unclear which in situ datasets, if any, caused the bulk density estimates used to be as high as reported (81.2 to 93.6 lbs/ft^3). This is of particular interest considering the much lower values observed in the primary data (i.e., Pestrong 1965 and Patrick and DeLaune 1990) that were obtained and reviewed (which were on the order of ~30-50 lbs/ft^3).

There are many potential reasons for the higher bulk density estimates reported by engineers compared to in situ estimates. One possibility is that compaction and settling is baked into engineering estimates so adequate volumes of dredged sediment equate to a certain amount of elevation gain; thus, the estimates of soil bulk densities used to convert volumes to mass needed inherently account for that compaction difference. Given the history of filling low-lying areas in the Bay Area in the first half of the 20th century, engineering practice could have evolved over time to reflect the estimates reported here. Another possibility is that a conversion error occurred in the values reported by PWA (2006) and Brew and Williams (2010), and those values have been adapted as common knowledge, though this is unlikely.

Both Trevedi and Carroll mentioned soil compaction after initial sediment placement, which results in higher soil bulk densities over time. The magnitude of settling can be approximated based on the depth of fill (or in this case, reused dredged material), and the type and depth of underlying geology (e.g. depth of Bay mud; Mark Lindley, personal comm.). For more information on settling curves and compaction estimates, see Appendix C for findings from correspondence with Nick Malasavage (personal comm.).

Case study: **Seal Beach National Wildlife Refuge Thin-Layer Sediment Augementation Project**

Post-project topographic surveying at the sediment augmentation site in Seal Beach National Wildlife Refuge (Photo courtesy of USGS and USFWS)

Completed in April 2016, the Seal Beach National Wildlife Refuge Thin-Layer Sediment Augmentation Project is the first pilot study of thin-layer sediment augmentation on an existing tidal marsh in California. The aim of the project was to test thin-layer placement as a management tool to augment sediment accretion in tidal marshes in the face of rising sea levels. The study was conducted across approximately 7.9 acres in the Seal Beach National Wildlife Refuge (SBNWR) located in Southern California, and aimed to augment existing elevations by 10 inches (25.4 cm)—nearly three times the goal of most thin layer placement projects (most projects aim for an elevation increase of around 10 cm or 3.9 in) (Evyan Slone, personal comm.).

At the beginning of the project, consultants estimated that approximately 13,500 cubic yards of dredged sediment would be needed to raise 10 acres of existing marsh to target elevations (~1,350 yd^3/acre). The actual amount of sediment needed was much higher, approximately 16,875 cubic yards across 7.9 acres (~2,144 yd^3/acre)—about 58% more dredged material than anticipated, when normalized by area. After the project was completed, the placed dredged material settled and led to a reduction over time in elevation gained. According to annual repeat topographic studies conducted by Karen Thorne and others, the mean surface elevation gain at the time of project completion was approximately 8.9 inches (~225 mm) (Evyan Sloane, personal comm.; USFWS 2019). A topographic assessment by Thorne and others revealed the average elevational gain decreased to around 4.7 inches (~120 mm), with the highest rate of decrease (-46.6 mm) occuring in the period immediately following project completion (April - June 2016). The elevation change continued to gradually decrease until a near leveling-off was observed in the most recent survey available (approximately -4.51 mm between February 2019 and April 2019). The Seal Beach case study demonstrates the need to improve the methods used in calculating the amount of sediment required through the use of mass, not volume, and the need to anticipate the amount of elevation loss from dewatering and settling over time. Findings and lessons learned from this project can be used to inform similar approaches being considered for tidal marshes throughout San Francisco Bay.

Case study: **Montezuma Wetland Restoration Project**

Aerial view of project ponds at Montezuma Wetland Restoration Project (Photo courtesy of Montezuma Wetlands LLC)

Authorized in 2001, the Montezuma wetland restoration project aims to restore approximately 2,000 acres of tidal, seasonal, and managed wetlands in Suisun Marsh, on the eastern side of Montezuma Slough near the town of Collinsville, California in Solano County. The site had previously been diked and drained for agricultural use, and the current surface elevations have subsided about 4-6 feet below sea level. Sediment dredged from the San Francisco Bay-Delta is being used to raise surface elevations to conditions suitable for tidal marsh to be re-established at the site. Material is barged to the site, off-loaded, and placed in settling cells until target elevations are reached.

According to Roger Leventhal, project engineer, a great deal of additional sediment has been needed to maintain desired elevations before levees are breached, due to both consolidation of the dredge sediment itself and consolidation of the underlying sediments. At Montezuma, the underlying soil is primarily peat, which compacts when the heavy dredged sediment is placed on top. Given both continuous compaction and the varying composition of dredged material, the challenge is to determine how much non-cover material to place before beginning to place cover material. This example illustrates the importance of factoring in compaction/settling, which can greatly impact the bulk density over time of sediment placed at restoration sites.

7. Conclusions and next steps

This report and the associated database created for this study provides a compilation of primary and secondary bulk density values for habitats throughout San Francsico Bay. We do not suggest any standard values to use in the design of tidal marsh restoration projects or other sediment studies; rather, this study offers a review and consolidation of data that individuals can use to determine appropriate values. The database compiled for this report is a first attempt at synthesizing the state of bulk density knowledge and is intended to help aid studies related to the future of sediment in San Francisco Bay (e.g., sediment budgets, demand for sediment by bayland habitats, fill projections to fast-track restoration projects). The database catalogues primary and secondary bulk density measurements with various degrees of information (e.g. dry bulk density vs. mineral component of dry bulk density) and general rules of thumb used by engineers and restoration practitioners.

In total, we reviewed eight primary bulk density studies. Based on the findings of this study, four detailed comparable primary datasets of the mineral component of dry bulk density exist to compare across and within habitat types throughout San Francisco Bay. No data was readily available for shallow Bay habitats and limited data exist for tidal flat and deep Bay/channel habitats. Comparisons between subembayments, and across and within habitats, is limited by the variability of data and small sample sizes. Future sediment coring efforts should consider prioritizing tidal flat, shallow Bay, and deep Bay/channel habitats to expand empirical data inputs which can be used to support future sediment studies. Three additional primary datasets exist for dry bulk density, but these studies do not include the organic content of samples, so the applicability of these data may be more limited depending on the type of sediment study being conducted.

A review of the secondary studies on bulk density values for San Francisco Bay raised many questions, especially for the studies where primary datasets could not be obtained. Differences in study design, sample sizes, depth of cores collected, and other inconsistences between studies make comparing the secondary datasets difficult. Several of the studies calculated bulk density estimates using primary data with similar inconsistencies, which raises questions of the quality and appropriateness of some of the secondary values reviewed.

Conversations with engineers and practitioners revealed a significant difference between in situ measured bulk density values in the literature and the estimated bulk density values used by practitioners when estimating bulk densities of dredged sediment for restoration activities. Although trends are difficult to determine given the small sample size of data reviewed, possible reasons for this discrepancy are discussed in the previous section.

A standardized coring protocol when collecting bulk density measurements would be useful to allow easier comparison across studies. Of the studies reviewed, Callaway et al. (2012) provided the most detailed guidance on coring methods, which could be used as a reference for future studies. Callaway et al. (2012) also sampled to deeper depths (up to 54cm) allowing for an assessment of bulk density estimates across a longer time horizon. Additionally, most of the current data on mineral component of dry bulk density is from Callaway et al. (2012), so future studies using the same method would be expanding the regional bulk density database in a consistent way. Pestrong's studies (1965, 1972) also outline detailed methods to follow for soil coring, but best practices and coring technology has likely evolved since the 1970s.

Future studies could be improved by reporting dry bulk density values as opposed to wet bulk density values (the latter of which can change as water content changes), describing the coring and drying methods in detail to avoid confusion, and measuring and reporting organic matter content to give the option of calculating the mineral component of dry bulk density of soils sampled. Reporting organic matter content and dry bulk density can aid in the understanding of in situ rates of mineral sediment accumulation and offer conversion factors to compare sediment demand with measured Bay tributary and Delta sediment loads entering the Bay. Furthermore, by reporting organic matter content, the database can also be used to better understand mineral sediment versus organic sediment dynamics across Bay habitat types and salinities, which will likely be of increasing interest as the magnitude of natural sediment supply to the Bay could shift under future climate regimes.

The database should be maintained regularly and integrated with SediMatch (SediMatch 2020). The SediMatch platform could provide guidelines to standardize testing and/or reporting of bulk density (i.e., dry bulk density and organic matter content) for brokers of available sediment. The tool could also provide an automated translation of the volume of material needed for restoration projects based on desired elevations and existing topobathymetry using the bulk density information provided by the entity with excess sediment. The tool could go further by analyzing underlying geology characteristics (if sufficient data is available), depth of projected fill, and other simple information to approximate the magnitude of settling that may be experienced based on settling curves. The tool would not be a substitute for the feasibility or engineering design of restoration efforts but would be a useful step in refining estimates of the amount of sediment needed for a specific site.

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9. Appendices

Appendix A. Clarifications of methods used

Caffrey (1995) collected nine cores, each approximately 8 cm in length, from north and south San Francisco Bay. Water depths at the time of sample collection ranged from 2 to 12 m as recorded during mean tide. In order to determine the corresponding habitat type (i.e., shallow Bay or deep Bay/channel) of each sediment core, we calculated average mean tide level (MTL), mean low water (MLW), and mean lower low water (MLLW) estimates for each subembayment (i.e., Suisun Bay, San Pablo Bay, Central Bay, and South Bay; Table A1) using tidal data modeled by AECOM (2016). Tidal datums, described in Table A2 below, were adjusted by -2 mm/year over a 21-year time period (i.e., -0.042m between 1995 to 2016) to account for an approximate 2 mm/yr rise in sea level (Church et al. 2001) in San Francisco Bay between Caffrey's sample collections in 1995 and AECOM's modeling of tidal datums in 2016.

Table A1. Tidal thresholds to distinguish between bayland habitat types were determined using guidance from the Goals Project (1999), described below.

Habitat type	Position within the tidal frame[1]
Deep bay/channel	> 5.5m (18ft) below MLLW
Shallow bay	MLLW to 5.5m (18ft) below MLLW
Tidal flat	MLLW to MTL
Tidal marsh	MTL to MHHW

[1]Adapted from the Goals Project (1999)

Table A2. Tidal datums averaged by subembayment using data modeled by AECOM (2016).

Subembayment	MLLW (meters, NAVD88)	MLW (meters, NAVD88)	MTL (meters, NAVD88)	MSL (meters, NAVD88)	MHW (meters, NAVD88)	MHHW (meters, NAVD88)
Suisun Bay	0.3	0.5	1.1	1.1	1.7	1.9
San Pablo Bay	0.1	0.3	0.7	0.7	1.7	1.9
Central Bay	0.0	0.3	0.9	1.0	1.7	1.9
South Bay	-0.1	0.0	0.2	0.2	2.0	2.2

Appendix B. Additional data included in the bulk density database

Detailed data on bulk density for all studies reviewed in this report are available in the database located here. Summary tables of the additional data available in the database are located on Tables B1, B2, and B3. More information about each study and original values reported are available within the individual worksheets of the database. The database also includes original bulk density data that extends beyond what was summarized in Table 2 from Callaway et al. (2012) to a depth of up to 54 cm below marsh surface elevations.

Table B1. Primary published studies of bulk density measruements with insufficient data to include in meta-analysis.

Reference	Sampling time period	Sample depth (in)	# of cores collected within study area	Core samples taken per habitat type per unique location (x)	Average bulk density across all samples (lb/ft3)														
					Tidal Marsh					Shallow Bay					Deep Bay/Channel				
					SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB
Sternberg et al. 1986	Dec 1-3, 1982	0.4	Unspecified	Unspecified													79.5		

Table B2. Estimated bulk densities from informal interviews and correspondence with practitioners. For more information, click here to access the bulk density database.

Reference	Sampling time period	Subembayment(s)	Habitat type [based on primary study]	Type of bulk density reported	Sample size of soil cores/samples collected	Estimates of bulk density					Notes
						Bay Mud					
						SUI	SPB	CB	SB	LSB	
Personal comm., Steve Carroll (Ducks Unlimited, 2019)	Unknown	San Pablo Bay	Placed sediment on tidal marsh restoration project	rough measurement of dry bulk density	unknown		34.5				Estimated pre-dredge bulk density of Cullinan
					unknown		35.5				Estimated post-dredge (1 week) at Cullinan
					unknown		70				Estimated bulk density of Cullinan during dry year, ponds dry for 2-4 years. One pond was 80 lbs/cubic feet
					unknown		95				With compaction, bulk density around 90-100 lbs/ft3
Personal comm., Dilip Trevedi (Moffatt and Nichol, 2019)	n/a	n/a	Best professional judgment	estimate of dry bulk density based on best professional judgment	n/a	90					Reasonable estimated bulk density for typical Bay mud in situ; Estimate when dredged material deposited at the beneficial reuse site; Over time material consolidates and approaches 90 lbs/ft3 when placed in subtidal
					n/a	70					Reasonable estimated bulk density of Bay mud after being excavated from channel and placed in scow / after Bay mud diluted
					n/a	100					Over time, material consolidates and typically approaches 100 lbs/ft3 when placed on a mudflat
					n/a	115					Over time, material consolidates and typically approaches between 110 - 120 (avg 115) lbs/ft3 when placed on a marsh

Table B3. Secondary published studies of bulk density values. Refer to the previous tables for information on the primary studies that were used to derive these values. Values from this table may not be the best representation of the primary data, so refer to Tables 2-5 for original measurements, habitat types sampled, and methods used. For additional data for each study, click here to access the bulk density database.

Reference	Primary research this study is based on	Type of bulk density reported in primary literature	Core samples taken per habitat type per unique location (x)	Bulk density values (lb/ft3)																									Estimates of bulk density				
				Tidal Marsh					Tidal Flat					Shallow Bay					Deep Bay/Channel					Bay Mud				
				SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB	SUI	SPB	CB	SB	LSB
Krone 1987	Pestrong 1965	Mineral component of dry bulk density	n/a				35.02																					
PWA 2005 (Hydrodynamic and sediment dynamics study for SBSPRP)*	Krone 1987 (Pestrong 1965)	Mineral component of dry bulk density (note: final number incorrectly reported)	n/a				**0.035* [see note about error in this value]**																					
Lionberger and Schoellhamer 2009**	Caffrey (1995), Sternberg et al. (1986), and Bruce Jaffe (USGS, written commun., 2004)	Combination of dry bulk density and unspecified bulk density	n/a											53.9	62.2	45.6	48.3	36.3	53.9	62.2	45.6	48.3	36.3					
Jaffe and Foxgrover 2006***	Unspecified (estimate)	Unspecified	n/a																							33		
PWA 2006 (South Bay Geomorphic Assessment)****	Corwin (1999), Pestrong (1965), Patrick and DeLaune (1990), Caltrans Logs at San Mateo Bridge (unpublished)	Unclear	n/a			81.2					81.2, 93.6					93.6												
Brew and Williams 2010****	Pestrong (1965), Patrick and DeLaune (1990), Caltrans Logs at San Mateo Bridge (unpublished)	n/a	n/a			81.2					81.2, 93.6					93.6												
Takekawa et al. 2013*****	Callaway et al. 2012	Dry bulk density (converted from porosity by assuming a particle density of 2.65g/cm3)	unspecified		32.3*			43.0*																				
Swanson et al. 2013*****	Callaway et al. 2012	Dry bulk density (converted from porosity by assuming a particle density of 2.65g/cm3)	unspecified		32.3*			52.9*																				
Shellenbarger et al. 2013	Caffrey (1995), Love et al. (2003)	Unspecified bulk density	n/a															38.5										

**Note:* PWA 2005 reports that "Krone (1987) gives a dry bulk density of inorganic material of 560 mg/l for pickleweed marshes in the South Bay". This value converts to 0.035 lbs/ft^3. Krone (1987) reports an average dry density of Salicornia marsh to be value of 0.671 g/cm3 with an organic matter content of 16.4%, which yields a dry bulk density of inorganic material of 0.561 g/cm3 (35.02 lbs/ft^3, which stems from a subset of data published by Pestrong 1965). It is clear that the conversion from g/cm^3 to mg/l is off by a magnitude of 1,000, likely an error during the conversion.*

***Lionberger and Schoellhamer (2009) report a mix of deep bay and shallow bay bed sediment density estimates, so values listed for Shallow Bay and Deep Bay/ Channel habitats in this table are duplicative.*

**** Jaffe and Foxgrover (2006) refer to th sediment bulk density of 33 lbs/ft^3 in reference to "soft mud". This table assumed "soft mud" corresponds to Deep Bay/ Channel habitat.*

*****PWA 2006 categorizes core data from Caltrans at the San Mateo and Dumbarton Bridges as "eroding sweep zone sediments". Based on how this zone is described in PWA 2006, we have crosswalked the "eroding deposits" category to tidal flat and shallow habitats. PWA 2006 also gives a separate bulk density estimate for "non-eroding mudflat" which we crosswalked to tidal flat. The tidal flat data is not associated with a particular subembayment since references of the value reported point to data from Sonoma Baylands (San Pablo Bay) and samples taken in the South and Lower South Bay; thus, we merged all the subembayment cells. Brew and Williams (2010) seems to be a publication that built on / resulted from PWA 2006. While the values reported are the same, Brew and Williams (2010) left out the reference to the bulk density data by Corwin (1999) for the Sonoma Baylands. It is unclear what, if anything, changed between studies as the values stayed the same. It is also unclear how authors arrived at these high bulk densities. When compared with the primary data for tidal marshes, the bulk densities reported by PWA (2006) and Brew and Williams (2010) are significantly higher (i.e., 81 lbs/ft^3 compared to the primary data which ranges from 31-43 lbs/ft^3 for tidal marsh).*

******Takekawa et al. (2013) and Swanson et al. (2013) use porosity as an input to model sediment accretion in San Francsico Bay. Published porosity values of reference samples for the model reflect the top 5cm (surface porosity) and bottom 5cm (depth porosity) of core samples collected. Porosity values were converted to dry bulk density using an assumed particle density of 165.4 lbs/ft^3 (2.65 g/cm^3), and then surface and depth bulk density estimates were averaged by subembayment. Core data used for these studies is the same core data analyzed by Callaway et al. (2012; Karen Thorne, personal comm.).*

Appendix C. Findings from correspondence with practitioners

Steve Carroll, Engineer at Ducks Unlimited:

The estimate for required sediment volume at Cullinan Ranch was based on a simple (void space) calculation, not accounting for bulk density. The strategy has been to fill a bit at a time and collect field measurements to keep track of compaction, but now better volume estimates are needed because the site has almost reached target elevation. In general, they have seen more compaction than expected, and the site is requiring more sediment than expected as a result.

Source areas (Sears Point, Richmond, Mare Island, Foster City) typically have pre-dredge bulk densities ranging from 31-38 lbs/ft3.

Dry-density tests post-placement at Cullinan showed bulk densities of 32-39 lbs/ft3 within one week of placement. In two ponds that were dried and then re-wet after 2-4 years, bulk densities ranged from 60-85 lbs/ft3. There is more consolidation in general in areas with a lower water table; for example, they have seen more compaction at Montezuma than at Cullinan.

Steve noted some difficulties with the process: 1) timing issues - small dredging window means turnaround is quick and it can be difficult to coordinate the offloader; 2) achieving a consistent elevation - they break up the site into smaller units to address this; 3) volumes awarded are uncertain, as are volumes delivered by dredgers.

Roger Levanthal, Engineer/Private Contractor at Montezuma Wetland Restoration Project:

The filling of Montezuma Marsh to restoration elevations has been an ongoing process for about 16 years, since opening in 2003. Roger bases his estimates for required sediment volumes on the capacity needed (volume to fill) and past experience with compaction ratios. He has measured [cut yards: placed yards] ratios to determine the amount of settling, based on annual surveys. These cut:placed ratios are generally about 0.8 or 0.9.

Some difficulties in the process that Roger noted were: 1) it is challenging to estimate volumes over the long term and across units being filled; 2) often the material that arrives is not what was expected (e.g. sand instead of mud); and 3) individual barge loads can have a wide range of water content - anywhere from a ratio of 0.2 - 0.9 [barge sediment load: cut yards].

Dilip Trivedi, Vice President and Coastal Engineer at Moffatt & Nichol, Inc.:

Dilip has worked on several projects involving beneficial reuse of dredged and upland materials. Projects discussed include levee construction (in progress) at Bel Marin Keys restoration, Hamilton restoration, Treasure Island, and Inner Bair Island restoration.

The bulk density of dredged material changes dramatically between the dredging location and beneficial reuse site. The bulk density of typical Bay mud is around

90 lbs/ft^3 in situ, but this estimate varies depending on how long a site remains undisturbed, i.e., the length of time between maintenance dredging. The frequency of maintenance dredging varies by site: some locations experience dredging as frequently as every 8 to 16 months whereas other sites may experience more infrequent dredging ranging between 1 to 3+ years. When Bay mud is excavated and placed in a scow, Bay water dilutes the material which causes the bulk density to decrease—a reasonable estimate being 70 lbs/ft^3. When the dredged material is deposited at the beneficial reuse site, the bulk density probably returns fairly quickly to its in-situ value, around 90 lbs/ft^3. Over time, the material consolidates and typically approaches a range of 110-120 lbs/ft^3 when placed in a marsh, 100 lbs/ft^3 when placed in a mudflat, and 90 lbs/ft^3 when placed in subtidal areas. The Bel Marin Keys levee construction and Hamilton restoration projects are examples that utilized dredged sediment to raise areas to desired elevations.

Both Treasure Island and Inner Bair Island employed beneficial reuse of upland sediment—material that typically has high concentrations of clay and silt. A typical bulk density estimate for upland material comprised of mostly clay and silt is roughly around 135 lbs/ft^3. If the upland material has a higher sand content, the bulk density will be slightly higher, roughly around 145 lbs/ft^3.

Dilip noted that management decisions on whether to fill a restoration site to desired elevations before breaching is usually cost prohibitive unless offset by a specific effort. For example, Hamilton Wetland Restoration received around 5 million cubic yards (MCY) of material as a function of dredging activities at the Port of Oakland. Another example is the construction of a parking lot at Stanford University which generated around 1 to 1.5 MCY of material which provided between 0.7 to 0.9 MCY of material to the restoration of Inner Bair Island. Without an explicit effort to fund the cost of material removal and placement, raising restoration sites to desired elevations before breaching remains challenging due to high costs. One exception is Cullinan Ranch which has been open to accepting sediment from a variety of sources, but without a specific project specifically matched with filling it, it has taken a very long time to acquire enough sediment to hit target elevations.

Nick Malasavage, Engineer at the U.S. Army Corps of Engineers:

Nick provided a number of geotechnical considerations related to reusing Bay mud as fill for wetland restoration. Bay mud is generally normally consolidated, highly compressible and very weak clayey/silty soil. Bay mud is deposited underwater. Along the edges of the deposit, the upper few feet (approximately 1-3 feet) has been observed to have slightly less compressibility, higher strength and higher over consolidation ratios, due to some desiccation drying of the soil during tidal cycles. This upper layer is commonly identified as Bay mud “crust”.

Consolidation settlement has complex soil mechanics that depends on the soil permeability, stress history, applied loads, existing loads, load geometry and other factors.

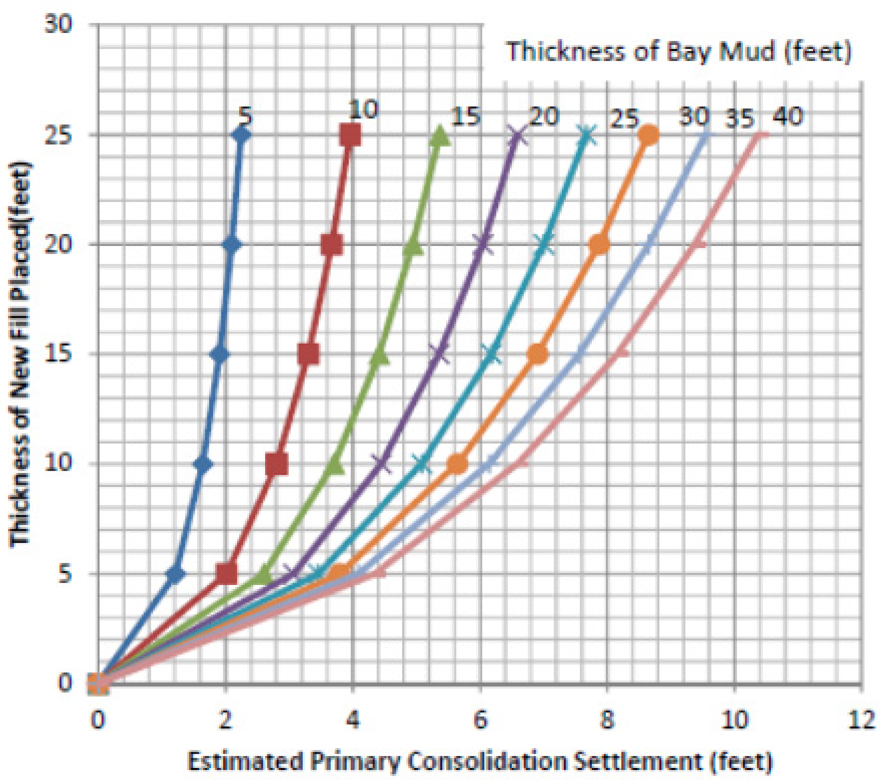
Usual assumptions include:

- New fill will have a total unit weight of 125 lbs/ft^3.
- Existing levee fills are assumed to have a total unit weight of 115 lbs/ft^3.
- Bay mud crust has a total unit weight of 100 lbs/ft^3.
- Normally consolidated Bay mud has a total unit weight of 97 lbs/ft^3.
- Bay mud is 100 percent saturated at all depths.

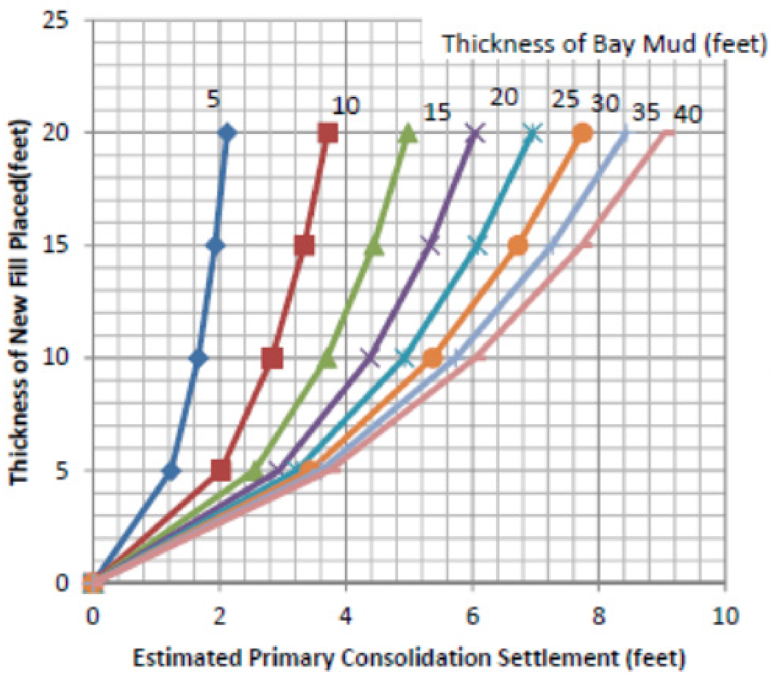
Fills not only cause settlement under the filled area, but also can cause settlement of nearby adjacent features. Environmental fills should be properly designed and constructed to minimize these effects on utilities, infrastructure, and flood damage reduction features.

Settlement estimates:

- Graph 1 below shows the estimated Bay mud consolidation settlement for a large mass fill area such as a marsh placement or horizontal levee.



- Graph 2 below shows the estimated Bay mud consolidation settlement for levees constructed directly on Bay mud (no existing fills present). Settlements will be reduced if new levees can be constructed along an existing levee fill alignments.



Consolidation rates:

- Graph 3 and Table 1, show the estimated time for 50 percent and 90 percent consolidation for various Bay mud thicknesses. Assumptions in the time rate consolidation include the assumption that double drainage will occur and that the coefficient of consolidation for the Bay mud is 8 ft^2/yr. The time for consolidation is relatively short (less that 1 year for 90 percent consolidation) for thin Bay mud thicknesses (5 feet or less).

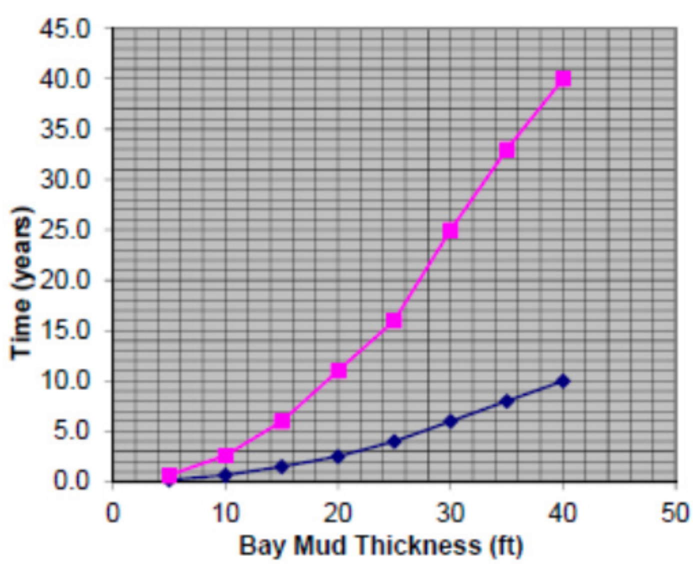


Table 1. Estimated Consolidation Rates for Bay Mud

Bay Mud Thickness (feet)	Time for 50% consolidation (years)	Time for 90% consolidation (years)
5	0.2	0.7
10	0.7	2.6
15	1.5	6.0
20	2.5	11.0
25	4.0	16.0
30	6.0	25.0
35	8.0	33.0
40	10.0	40.0

Estimated Maximum Fill Thickness that Can Be Placed at One Time

Because the underlying Bay mud for the project area is weak and slowly draining the weak Bay mud will only support limited fill thicknesses without being overstressed. Overfilling Bay mud will cause slope instability and bearing failures. Filling to design grades may be required in stages to allow for pore pressure dissipation before each new stress is applied

Table 2, below includes estimated allowable first filling thicknesses for various fill side slopes, of 3:1(H:V) to 5:1 (H:V). In areas where fills are planned where previously placed fills were/are located, allowable fill heights will be somewhat higher.

Table 2. Estimated Fill Thickness Placement Limits for first fill stage for 3:1 to 5:1 Slopes on 5 to 40 feet of Bay Mud

Bay Mud Thickness (ft)	Side Slope of Fill (H:V)		
	3:1	4:1	5:1
5	20 feet	20 feet	20 feet
10	11 feet	11 feet	16 feet
15	9 feet	10 feet	14 feet
20	9 feet	10 feet	12 feet
40	8 feet	10 feet	12 feet

Evyan Sloane, Project Manager at the California State Coastal Conservancy:

Completed in April 2016, the Seal Beach National Wildlife Refuge Thin-Layer Sediment Augmentation Project is the first pilot study of thin-layer sediment augmentation on an existing tidal marsh in California. The aim of the project was to test thin-layer placement as a management tool to augment sediment accretion in tidal marshes in the face of rising sea levels. The study was conducted across approximately 7.9 acres in the Seal Beach National Wildlife Refuge (SBNWR) located in Southern California. Findings and lessons learned from this project can be used to inform similar approaches being considered for tidal marshes throughout San Francisco Bay.

SBNWR tidal marsh complex is cut off from the contributing watershed due to surrounding landscape modifications. Prior to the SBNWR Thin-Layer Sediment Augmentation Project, refuge staff observed evidence of stunted marsh plants, increasing the need for further study and potential management interventions. Because of the vulnerability to future sea level rise and the extent of land subsidence that has taken place at SBNWR (i.e., greater than 1ft over the last century, likely due to nearby oil extraction and other activities), this project aimed to augment existing elevations by 10 inches (25.4 cm)—nearly three times the goal of most thin layer placement projects (i.e., most projects aim for an elevation increase of around 10 cm or 3.9 in).

An initial small box experiment was used to test the thin-layer placement approach before scaling efforts across the full 7.9-acre study area. The box experiment demonstrated that vegetation would be able to respond to placement of over 10 in of dredged material and provided the preliminary evidence necessary for the project to move forward; however, Evyan noted that the methods used in the box experiment were flawed and, in retrospect, the project team should have taken a few additional measures to minimize the influence of surrounding marsh vegetation on the ability of the underlying marsh plants to grow through the sediment placed on top of it (e.g. through cutting plant roots along the box perimeter). The U.S. Fish and Wildlife Service (USFWS) is working on a summary of lessons learned that should capture these considerations and other aspects of the study in more detail. Maintenance dredging conducted in Huntington Harbour, located near the placement site, generated the dredged material used. The dredged material applied to the box experiment consisted of about 10% sand, but a much higher sand content—approximately 80% and a much sandier substrate than anticipated despite being generated from the same source—was used for the rest of the study area. Evyan mentioned other challenges such as identifying the appropriate equipment to effectively spray the sediment onto the marsh from the dredge pipeline, in addition to the decision to implement hay bales to contain the sediment slurry once it was placed, which had the unexpected consequence of stifling channel development. More details on these and other lessons learned will be reported in the USFWS's upcoming report.

At the beginning of the project, consultants estimated that approximately 13,500 cubic yards of dredged sediment would be needed to raise 10 acres of existing marsh to target elevations (~1,350 yd^3/acre). The actual amount of sediment needed was much higher, approximately 16,875 cubic yards across 7.9 acres (~2,144 yd^3/acre)—an underestimation of around 58% when normalized by area. After the project was completed, the placed dredged material settled and led to a reduction over time in elevation gained. According to annual repeat topographic studies conducted by Karen Thorne and others, the mean surface elevation gain at the time of project completion was approximately 8.9 inches (~225 mm) (USFWS 2019). A topographic assessment by Thorne and others revealed the average elevational gain decreased to around 4.7 inches (~120 mm), with the highest rate of decrease (-46.6 mm) occuring in the period immediately following project completion (April - June 2016). The elevation change continued to gradually decrease until a near leveling off was observed in the most recent survey available (approximately -4.51 mm between February 2019 and April 2019). The Seal Beach case study demonstrates the need to improve the methods used in calculating the amount of sediment needed to raise a site to target elevations through the use of mass, not volume, and in anticipating a more accurate amount of elevation loss from dewatering and settling over time.

Mark Lindley, Senior Engineer at Environmental Science Associates:

Uses estimated bulk density values in design (88-110 lbs/ft3). Hasn't measured bulk density directly. Suggested using a moisture density curve to estimate bulk density (see Proctor curve). However, projects do monitor compaction, e.g., Hamilton Airfield restorations.

Hamilton Airfield:

- There was generally less sediment imported than expected which meant that elevations were generally lower than designed. More sand was imported than expected - not sure how much difference that made to consolidation.
- The upland transition zone in the Wildlife Corridor subsided considerably in the three-year period immediately following grading in 2011 and before breaching in 2014. There was as much as 0.5 to 1 foot of subsidence between 2011 and 2014. Areas with higher design grades including mounds and along the revegetation access corridor adjacent to the new levee saw the most subsidence. Nearly 1 foot of subsidence was recorded between 2011 and 2014. Little change was observed at the geotechnical test mound that was constructed in 2005 to inform the design of the NHP levee. This seems due to the considerable amount of surcharge, length of time for consolidation, and subsequent regrading. Areas closer to Ammunition Hill showed only minor amounts of subsidence since grading in 2011, and likely to have a much thinner layer of Bay mud. A lower wildlife corridor affects inundation frequency and vegetation, thus threatening the intended function of the corridor.
- The separation berm for the North Seasonal Pond complex was constructed lower than the designs, it subsided and has subsequently eroded. The separation berm now overtops more often during high tide events than intended, causing erosion that could result in complete failure of the berm. The separation berm was expected to overtop into the adjacent ponds only during the most extreme storm surge events but is now more frequent and regular overtopping
- In the South Seasonal Pond complex, all four of the pond crests experienced significant subsidence and scour between 2014 and 2015 and again between 2017 and 2018. Much of the pond crests now sit below design elevation and, as a result, drainage channels have developed through the perimeter berm crests.
- The vegetation bench on the N2 levee subsided vegetation bench can be seen subsiding 0.2 feet in places and to a maximum of approximately 1.0 feet. This may be partly due to compaction following grading and before breaching as it was used as a roadway for trucks. As a consequence of the bench lowering there is less dissipation of wave energy on the bench and scarping is occurring on the levee face due to wind-wave erosion.

Main findings have been an underestimate of the compaction of material placed above MHHW. Elevations in these areas are sensitive to compaction as they do not receive regular tidal sedimentation; mudflat and marsh will eventually accrete naturally to their design elevations. Therefore the initial grading and any surcharge is important if the desired elevations, inundation frequency, and depths are to be attained.

Design elevations for grading future tidal marshes are 1 foot below vegetation colonization elevation. Design elevations for seasonal wetlands with occasional tidal inundation at the highest tides difficult to achieve with dredged sediment due to subsidence issues. It might be worth considering different design philosophies in the future which allow for lower elevation tolerances.