Constancy of the relation between floc size and density in San Francisco Bay

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The size and density of fine-sediment aggregates, or flocs, govern their transport and depositional properties. While the mass and volume concentrations of flocs can be measured directly or by optical methods, they must be determined simultaneously to gain an accurate density measurement. Results are presented from a tidal cycle study in San Francisco Bay, where mass concentration was determined directly, and volume concentration was measured in 32 logarithmically spaced size bins by laser-diffraction methods. The relation between floc size and density is investigated assuming a constant primary particle size and fractal floc dimension. This relation is validated with measurements from several sites throughout San Francisco Bay. The constancy of this relation implies a uniform primary particle size throughout the Bay, as well as uniform aggregation/disaggregation mechanisms (which modify fractal dimension). The exception to the relation is identified during near-bed measurements, when advected flocs mix with recently resuspended flocs from the bed, which typically have a higher fractal dimension than suspended flocs. The constant relation for suspended flocs simplifies monitoring and numerical modeling of suspended sediment in San Francisco Bay.

1. INTRODUCTION

Measurement of in situ particle size is critical to understanding the dynamics of fine-sediment flocculation and settling. The methods used to evaluate size distribution range from video camera-based (Manning and Dyer, 2002) to laser-diffraction, *e.g.*, Laser In-Situ Scattering Transmissometer-100[1] (LISST-100; Agrawal and Pottsmith, 1994). The LISST-100 system is an autonomous unit that measures laser diffraction from suspended particles, and assigns each particle to 1 of 32 logarithmically spaced size classes (1–250 μm). The output of the LISST-100 is total volume concentration in each size class. While these results are helpful in analyzing particle-size evolution, the evolution of mass distribution can be estimated only with knowledge of the average mass density of each size class. Mass distribution is necessary to estimate mass concentration and settling flux for each size class, both of which have ramifications for numerical modeling and contaminant transport.

Converting a volume distribution to a mass distribution requires knowledge of the floc density for a given size class. Kranenburg (1994) suggests that sediment flocs aggregate in a fractal manner, requiring that a given fractal dimension and primary particle size will yield a specific density for a corresponding floc size. Varying fractal dimension and primary particle size will alter the floc density, though actual floc size may remain unchanged. If one assumes that fractal dimension and primary particle size remain unchanged over space and time for a given system, then Kranenburg's floc size–density relation also will hold. This relation then can be applied to volume-distribution data to yield the mass distribution.

This study tests the hypothesis that the floc size–density relation is constant in San Francisco Bay, California. Tidal cycle, synoptic, and continuous measurements of floc size and Suspended Sediment Concentration (SSC) will provide the means to investigate the floc size–density relation. If the relation is constant, the underlying implication is that primary particle size and fractal dimension also are constant throughout the Bay.

San Francisco Bay (Fig. 1) drains a 154,000 km^2 watershed through the confluence (Delta) of the Sacramento and San Joaquin Rivers. Downstream of the Delta are four subembayments: Suisun Bay, San Pablo Bay, Central Bay, and South Bay. The first three subembayments are affected primarily by freshwater flow from the Delta and tidal forcing from the Golden Gate, while exchange in South Bay is governed mainly by

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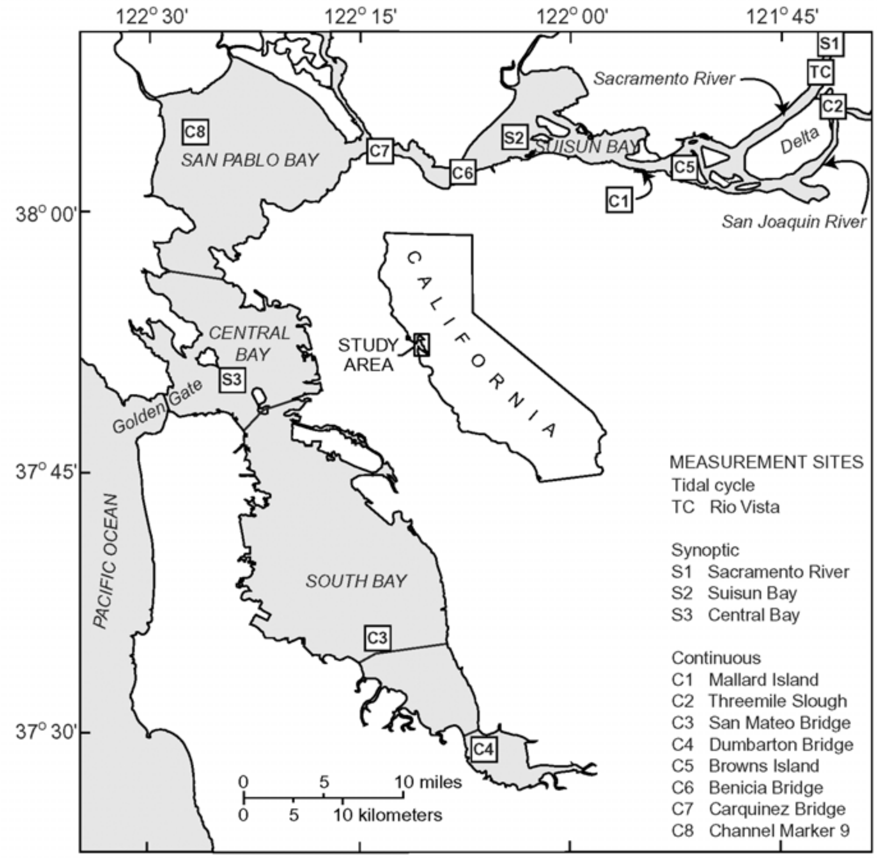

Fig. 1. Area map, showing measurement sites for tidal cycle, synoptic, and continuous studies.

tidal forcing, as freshwater flow is relatively minimal. Freshwater flow generally is low from late spring to late fall, while flow increases during winter and spring due to rainfall, snowmelt, and reservoir releases.

2. METHODS

2.1. TIDAL-CYCLE MEASUREMENT

A preliminary study of floc size (Sacramento River to Central Bay) suggested that vertical variability may be greater than longitudinal variability. Therefore, on

November 5, 2002, a fixed, vertical-profiling deployment was initiated near the freshwater-saltwater interface, at Rio Vista (Sta. TC, Fig. 1). The date was chosen to coincide with a spring tide and low freshwater input. Prior to deployment, it was confirmed that freshwater and saltwater were present during ebb and flood tides, respectively, at the site. The specific site was at the edge of the main channel in 10 m of water. Measurements were performed from an anchored vessel.

Floc identification was performed with the LISST-100, which can measure particles ranging in size from 1–250 µm, in 32 bins (logarithmically spaced). Details of the instrument can be found in Agrawal and Pottsmith (1994). Output consists of particle volume concentration in microliters per liter [µL/L] for each size class. The volume concentration for a given aggregate includes sediment particles, interstitial water, and any other material bound into the floc (*e.g.*, extracellular polymeric substances).

Suspended-sediment concentration was determined with a nephelometric turbidity sensor, which was part of a multi-probe unit (Datasonde 4, Hydrolab Corp.). Other sensors on the unit were conductivity, temperature, and depth. The turbidity output of the sensor (nephelometric turbidity units or NTU) was calibrated to SSC using water samples collected using a peristaltic pump. Water samples were analyzed gravimetrically for SSC.

The profiling package consisted of the multi-probe and LISST-100; a 10-m tube was secured to the package and delivered water samples to the peristaltic pump. The tube opening, LISST-100 optics, and multi-probe sensors were positioned as closely together as possible without interference from one another. The package was raised and lowered through the water column at 1-m intervals every 2 min. Vertical profiles ranged from 1–8-m depths, and measurements were taken every minute during a flood tide, to yield replicate measurements at every vertical location. The duration of each vertical profile was approximately 15 min, and 20 vertical profiles were collected during a flood tide from slack after ebb to slack after flood. A boat-mounted acoustic Doppler current profiler (ADCP) collected profiles of velocity continuously during the deployment. Water samples were collected at various depths and stages of the tide.

2.2. Synoptic Measurement

Surface-water samples were collected monthly from April to October 1996 at three stations in northern San Francisco Bay (Stas. S1, S2, and S3; Fig. 1) as part of a study of bacterioplankton dynamics (Murrell *et al.*, 1999); these samples were analyzed to determine mass concentration and volume concentration. Part of the sample was used to determine SSC by the traditional filtering and weighing procedures while part of the sample was used to determine floc size by filtering onto 0.45-µm filters.

Photomicrographs were taken of the filters and the effective size distribution that could be observed was 2–25 μm. The photographic slides were digitized. Particle areas were converted to equivalent circular diameters and accumulated into 1-μm-diameter bins. Particle volumes were calculated assuming that the particles were spherical.

2.3. Continuous Measurement

Primary particles: Mallard Island

In December 1996 and January 1997, water samples were collected at Mallard Island (Sta. C1; Fig. 1) and analyzed to determine primary particle size. The site is located on the edge of a wide channel, in 8 m of water. Sampling was done during a relatively large freshwater flow pulse as part of a study of sediment-associated pesticide transport. Two-hundred and four samples were collected with a peristaltic pump at a depth of 1 m below the surface. The particles were disaggregated and particle size was determined with a Coulter Counter.

LISST-100: Threemile Slough

During July 2002, the LISST-100 was deployed at Threemile Slough (Sta. C2; Fig. 1), within the Delta. Flow is bi-directional at the site, with salinity present during flood tides. Total depth at the site is 4 m, while the LISST-100 was located 2 m above bottom. The unit was situated at an existing fixed site on the levee at the edge of the channel. A peristaltic pump was deployed on the levee, with the sampling tube near the optics of the LISST-100. During a 24-hour period (July 25–26, 2002), a water sample was collected each hour, while the LISST-100 was sampling. Water samples were analyzed gravimetrically for SSC.

LISST-100: South Bay

Two locations in South Bay, near the San Mateo and Dumbarton Bridges (Stas. C3 and C4; Fig. 1), were occupied in October 1998. These experiments focused on near-bed processes; therefore, a package consisting of a LISST-100, optical backscatterance sensor, and ADCP was deployed 2 m above the bed at each site. Total depth at the San Mateo site was 16 m and 7 m at the Dumbarton site. Optical sensors were calibrated to SSC by immersing the sensor in a bucket of well-mixed surficial sediment, and withdrawing water for SSC analysis (Gartner *et al.*, 2001). The LISST-100 and optical sensors collected measurements in 15-min intervals for 4 days at the San Mateo site and 6 days at the Dumbarton site.

Turbidity and SSC: Bay-wide

The relation between turbidity and SSC will be used to postulate the constancy of the floc size–density relation. Data from turbidity sensors at four sites in San Francisco Bay will be used: Carquinez Bridge, Benicia Bridge, San Pablo Bay channel marker 9 (1998–2002; Buchanan and Ganju, 2003), and Browns Island (1-month deployments in May and November 2002 and April and November 2003; Ganju *et al.*, 2003) (Fig. 1). The first two sites have two sensors each, one at mid-depth and one at near-bottom. Water samples are collected periodically during the entire duration of each sensor's operation. These samples are analyzed for SSC and used to convert the turbidity output to SSC.

3. RESULTS

3.1. Tidal-cycle measurement

Tidal variability

Floc-size distribution at the site was controlled by mean velocity (max. 0.67 m/s) and SSC (6–83 mg/L). At slack after ebb, quiescent conditions led to a median volumetric floc diameter (D_{50}) range of 20–80 µm (increasing with depth). At maximum flood, D_{50} became more uniform with a range between 45–65 µm in the water column. Once currents subsided, higher SSC during slack after flood (as compared to slack after ebb) led to a wider D_{50} range of 40–110 µm (also increasing with depth). Salinity varied between 0 and 1.6 psu. Any possible effect of salinity on flocculation is difficult to infer, because the source of salinity and suspended sediment are the same (Suisun Bay), and increasing SSC may have a greater influence on particle size.

Floc size versus density

Volume concentration distributions from the LISST-100 were converted into mass concentration distributions, using a size-dependent floc density function given by Kranenburg (1994):

$$\rho_f = \rho_w + (\rho_p - \rho_w)[(D_p/D_f)^{3-n}] \qquad (1)$$

where ρ is density, D is diameter, n is fractal dimension, and subscripts f, p, and w indicate floc, primary particle, and water, respectively. Fractal dimension is a measure of the packing of individual particles – larger fractal dimension indicates tighter packing.

Water samples collected at different elevations in the water column and different tidal stages during the study were analyzed for SSC. The simultaneous LISST-100 volume concentration distribution was multiplied by the above density distribution, yielding a mass concentration distribution by size class. The sum of mass concentration for all classes provided a LISST-100-derived SSC. The best agreement between actual SSC and LISST-100-derived SSC was achieved with a primary particle diameter of 2.5 μm and fractal dimension of 2 (Fig. 2).

3.2. Synoptic Measurement

The median diameter, by volume, of the material on the filters was 14.0 ± 0.8 μm, 13.4 ± 1.5 μm, and 12.6 ± 0.6 μm at Stas. S3, S2, and S1, respectively. These diameters are greater than the primary particle diameter and less than the diameter of flocs. Thus, filtration appears to have broken flocs apart and into lower-order aggregates that comprise the larger floc.

The ratio of SSC to aggregate volume (Fig. 3) equals the dry density of the lower-order aggregates. Fitting a line to the data in Fig. 3, the dry density of the lower-order aggregates is 0.117 grams per cubic centimeter (g/cm^3), which equals a wet density of 1.07 g/cm^3. The constant slope indicates constant aggregate dry density for an SSC

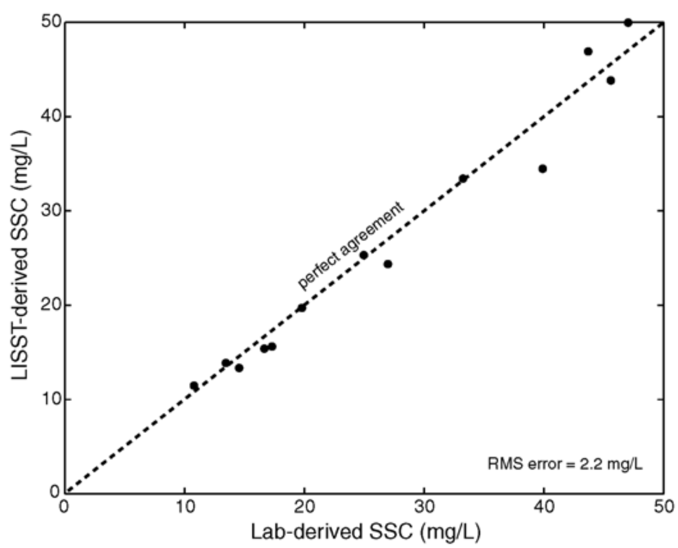

Fig. 2. Validation of floc size–density relation, from LISST-100 data and lab-analyzed water samples. Volume concentration data (LISST-100) was converted to mass concentration data via Eq. 1, with D_p = 2.5 μm and n = 2. Primary particle diameter (D_p) was varied to yield best fit between LISST-derived SSC and lab-derived SSC.

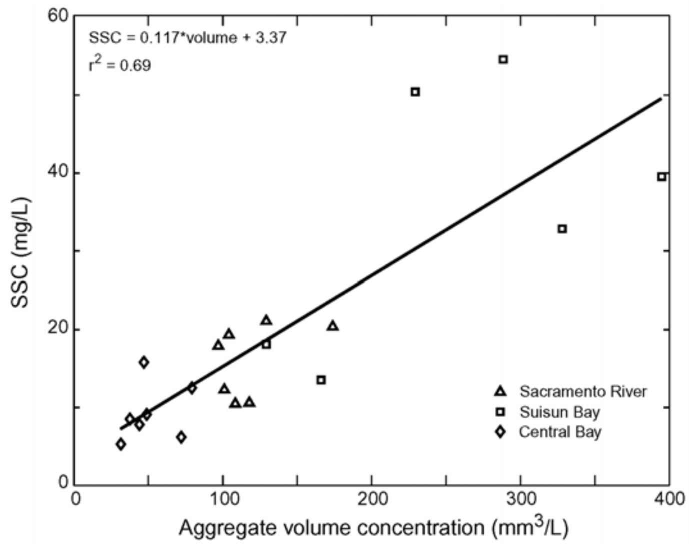

Fig. 3. Relation between SSC and aggregate volume, from synoptic measurements. Slope of the fitted equation indicates a constant aggregate dry density.

range of 35 – 400 mg/L. Thus, the size and the density of the lower-order aggregates on the filters are fairly constant, longitudinally and temporally. The density is less than expected from Eq. 1 (1.29–1.33 g/cm^3) because filtration somewhat flattened the material on the filters, but the material was assumed to be spherical to estimate particle volume, and therefore, the volume may be overestimated.

3.3. Continuous Measurements

Primary particles: Mallard Island

Median primary particle size at the landward boundary of the Bay usually was 4–6 μm and increased to 12 μm for only a few hours during a large flood (Fig. 4).

The observed primary particle size was greater than the primary particle size calculated from the Rio Vista data and found by Krone (1962) in laboratory experiments (2.5 μm). Incomplete disaggregation of flocs in the samples probably contributes to the discrepancy.

LISST-100: Threemile Slough

LISST-100-derived SSC corresponds well with actual SSC at Threemile Slough (Fig. 5). The density relation determined by the tidal cycle study was applied to the

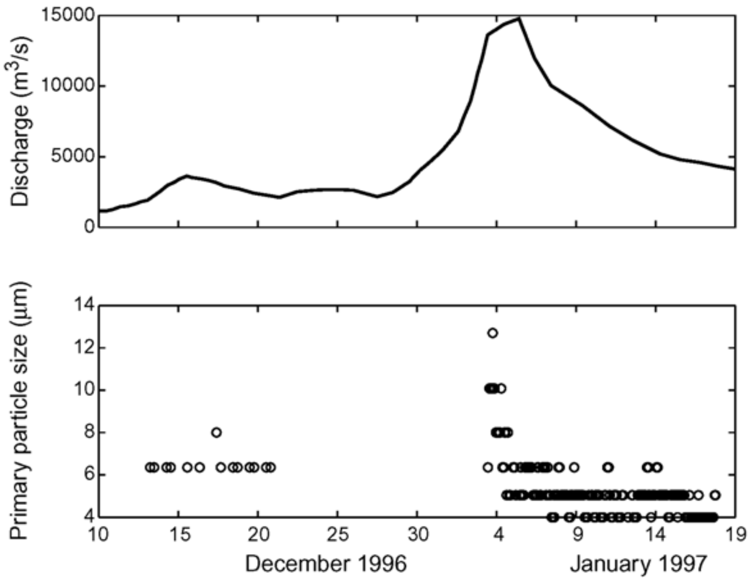

Fig. 4. Median primary particle size at Mallard Island, during freshwater flood period, December 1996 to January 1997.

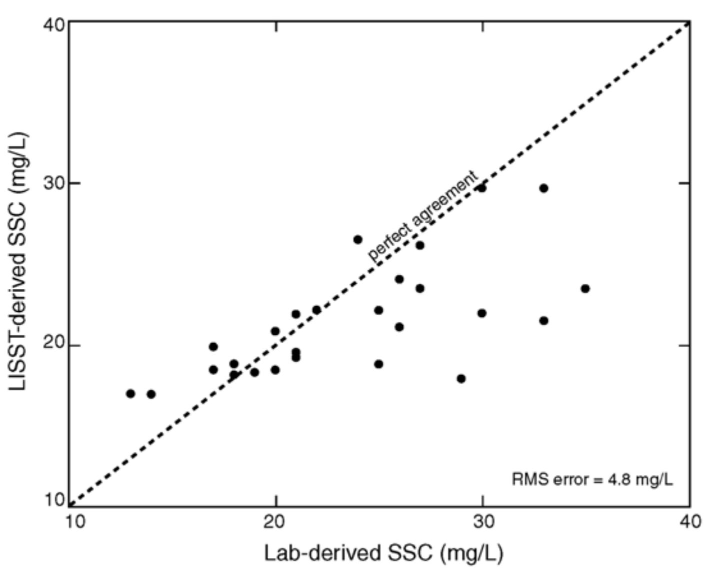

Fig. 5. Comparison of lab-derived SSC with LISST-100-derived SSC at Threemile Slough. LISST-100-derived SSC was calculated using density relation determined from data obtained at Rio Vista.

volume concentration distributions measured at Threemile Slough. The agreement between LISST-100-derived SSC and actual SSC (as determined by 24 concurrent water samples) suggests that the density relation at Rio Vista is suitable for Threemile Slough. The mean error of the LISST-100-derived SSC is 14 percent, with an RMS error of 4.8 mg/L.

LISST-100: South Bay

LISST-100-derived SSC corresponds with OBS-derived SSC at South Bay sites C3 and C4, though LISST-100-derived SSC is consistently lower than the OBS value (Figs. 6, 7). Again, the density relation from the Rio Vista study was applied to the volume concentration distributions. The best relation between OBS and LISST-100-derived SSC was achieved with larger fractal dimensions than 2 (2.3 and 2.1 for San Mateo and Dumbarton Bridges, respectively). Winterwerp (1999) noted that average fractal dimension of suspended particles is about 2, while greater fractal dimensions (> 2.6) are found within the bed. The intermediate values at the South Bay sites suggest a mixing of suspended particles and bed-derived flocs, which is plausible due to the near-bed deployment of instruments. The mean error of the LISST-100-derived SSC (with

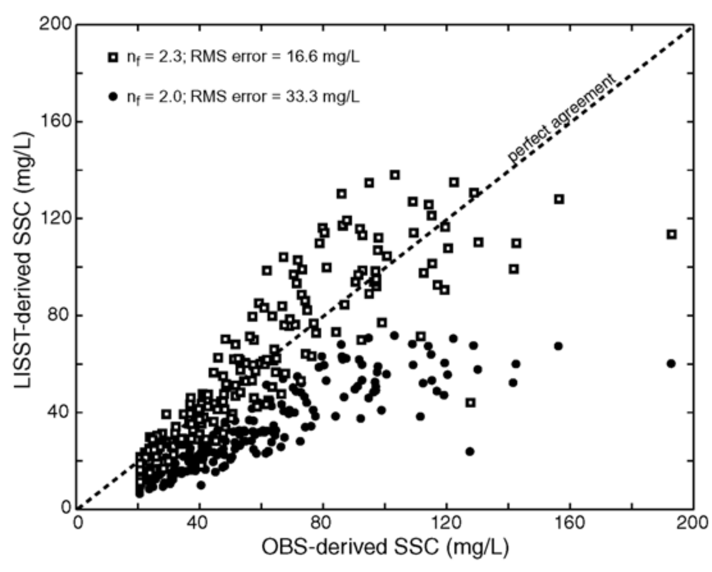

Fig. 6. Comparison of OBS-derived SSC with LISST-100-derived SSC at San Mateo Bridge. LISST-100-derived SSC was calculated using density relation determined from data obtained at Rio Vista, with fractal dimension 2. Best fit was obtained with fractal dimension 2.3.

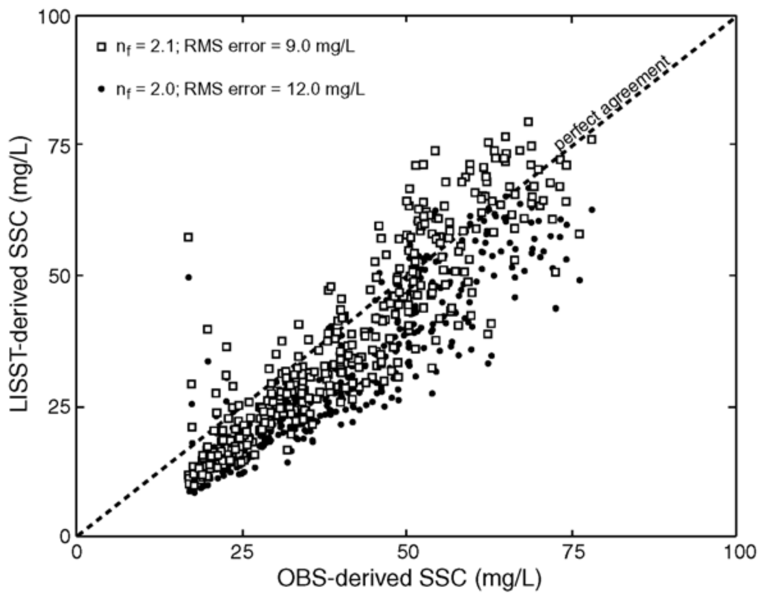

Fig. 7. Comparison of OBS-derived SSC with LISST-100-derived SSC at Dumbarton Bridge. LISST-100-derived SSC was calculated using density relation determined from data obtained at Rio Vista, with fractal dimension 2. Best fit was obtained with fractal dimension 2.1.

fractal dimension 2) is 27 percent at the Dumbarton site (RMS error of 12.0 mg/L) and 46 percent at the San Mateo site (RMS error of 33.3 mg/L). Usage of the higher fractal dimension yielded lower RMS errors of 9.0 and 16.6 mg/L for Dumbarton and San Mateo Bridge, respectively.

Turbidity and SSC: Bay-wide

Correlation between turbidity and SSC at four sites throughout the Bay is high, with an r^2 value of 0.92 (Fig. 8). One hundred and fifty-seven samples were collected at the four sites during 4 years. Individual sites have similarly good correlations by themselves (Buchanan and Ganju, 2003).

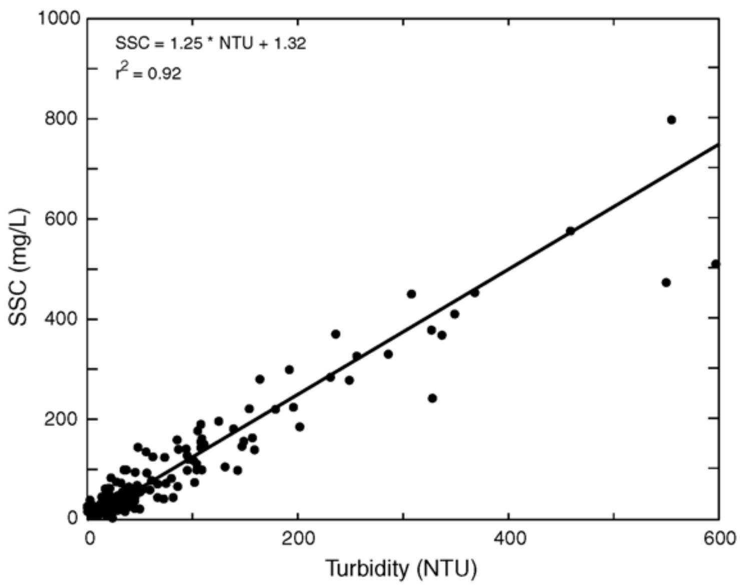

Fig. 8. Comparison of turbidity and SSC measurements, from four locations in San Francisco Bay.

4. DISCUSSION

4.1. Homogeneity of turbidity/suspended-sediment concentration and floc size/density

The homogeneous relation between turbidity and SSC can be shown to verify the floc size–density relation (Eq. 1) and its homogeneity. Turbidity is an optical measure of light scattering and is proportional to the surface area of flocs, as follows:

$$\text{Turbidity} \propto N D_f^2 \qquad (2)$$

where N is the number of flocs per unit volume of water. SSC is proportional to dry density of the floc (ρ_{fd}) multiplied by the floc volume:

$$\text{SSC} \propto N \rho_{fd} D_f^3 \qquad (3)$$

in which

$$\rho_{fd} = \rho_p (\rho_f - \rho_w)/(\rho_p - \rho_w) \quad (4)$$

By setting turbidity and SSC proportional and combining Eqs. 2–4, for turbidity and SSC to be proportional, the following condition must hold:

$$(\rho_f - \rho_w) D_f = \text{constant} \quad (5)$$

Rearranging the floc size–density relation, and setting n=2 (Eq. 1) gives

$$(\rho_f - \rho_w) D_f = (\rho_p - \rho_w) D_p \quad (6)$$

The left sides of Eqs. 5 and 6 are equal and the right side of Eq. 6 is constant if D_p is constant (and for n=2), so the floc size–density relation satisfies the condition required for turbidity to be proportional to SSC (Eq. 5). If primary particle size varied or if fractal dimension varied (or was not equal to 2), then turbidity and SSC would not be proportional throughout the Bay. Thus, the homogeneity of the turbidity and SSC relationship throughout San Francisco Bay indicates that the floc size–density relation must be constant.

4.2. Constancy of floc size–density relation

The floc size–density relation (Eq. 1) is remarkably constant in San Francisco Bay. This relation was developed from tidal cycle measurements at a fixed point. It then was used to convert volume concentration and size distribution to total mass concentration at three sites. The comparison between calculated and measured mass concentration is good (Figs. 5, 6, 7), indicating the validity of the relation for different sites and different times.

The homogeneity of lower-order aggregates confirms that the floc size–density relation is homogeneous. Photomicrographs of filtered water samples collected during low inflow showed that the median size (12.6–14.0 µm) and density (1.07 g/cm^3) of lower-order aggregates did not vary longitudinally (Fig. 3). This is an independent measure of one point on the floc size–density relation, and that relation is constant in space (sites S1, S2, S3) and time (April – October 1996). In Krone's (1986) model of aggregation, (homogeneous) lower-order aggregates combine to form larger flocs, which, in turn, have a homogeneous relation between size and density.

We hypothesize that constant primary particles and constant turbulence and flocculation mechanisms are responsible for the constancy of the floc size–density relation. Median primary particle size appears to be constant, even during large floods where it would be expected to be most variable (Fig. 4). This eliminates one source of variability that could vary the floc size–density relation (Eq. 1). In addition, constant primary particle size is required to have the observed homogeneous relation between turbidity and SSC (Fig. 8, Eq. 6).

The two primary flocculation mechanisms in San Francisco Bay, biological activity and turbulent shear, are, to some extent, spatially homogeneous. The bottom of San Francisco Bay is dominated by *Potamocorbula amurensis* (Asian clam) with densities sometimes exceeding 12,000 clams per square meter (Carlton *et al.*, 1990). Werner and Hollibaugh (1993) measured individual clam filtering rates of 45 milliliters per hour, so the water column can be filtered at rates up to 0.5 meters per hour. This grazing rate is a homogeneous bioflocculation mechanism. San Francisco Bay has an average depth of 2 m and is a partially mixed estuary with semidiurnal tides. Deeper portions of the Bay undergo repeating cycles of vertical mixing and turbulent shear followed by a brief (less than 1 hour, typically) period around slack tides when currents are small and turbulence is damped by vertical stratification (Brennan *et al.*, 2002). Thus, the general production and dissipation of turbulence is similar throughout the channels of the Bay, which leads to similar turbulent shear and flocculation mechanisms. These homogeneous flocculation mechanisms probably account for the constant fractal dimension n=2 in the floc size–density relation (Eq. 1) being homogeneous.

An exception to the homogeneous floc size–density relation is near the bed in relatively deep areas where sediment eroding from the bed may increase the fractal dimension (Figs. 6, 7). Bed sediment has a greater fractal dimension, due to consolidation processes (Winterwerp, 1999). For the near-bed measurements, a combination of recently resuspended flocs and advected flocs (subjected to turbulence and mixing) yielded a fractal dimension greater than 2, though less than the normally assumed fractal dimension of flocs in the bed (> 2.6).

4.3. Mass distribution versus volume distribution

Application of a floc size–density relation (Eq. 1) to a LISST-100 volume distribution yields a mass distribution that differs substantially in character. For example, a unimodal volumetric size distribution with high concentrations of larger flocs becomes a weakly bimodal mass-based size distribution (Fig. 9). This is due to the high density of small flocs (despite low volumetric contribution) and the low density of large flocs (despite high volumetric contribution). As a consequence, the median particle diameter by mass typically will be smaller than the median particle diameter by volume. When evaluating particle distribution data, the differences between mass and volume distributions should be considered.

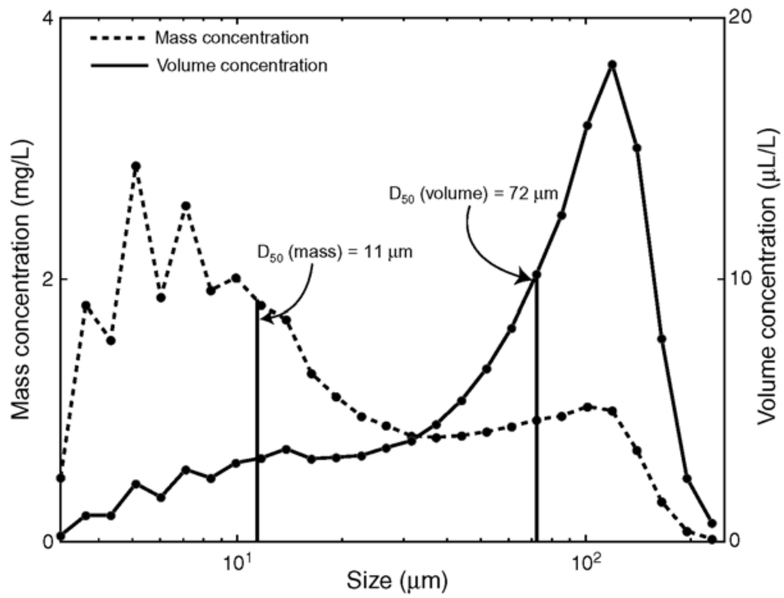

Fig. 9. Mass and volume concentration distributions for an individual 1-minute sample. Note unimodal volume concentration distribution becomes weakly bimodal mass distribution after floc size–density relation is applied to volume data.

4.4. Implications for monitoring and numerical modeling

The homogeneity of the floc size–density relation in San Francisco Bay simplifies monitoring and numerical modeling. One consequence is that turbidity and SSC are proportional throughout the Bay (Fig. 8). Thus, for monitoring SSC, optical sensors can be calibrated to turbidity and the output of the sensors can be converted to SSC without the need for detailed site-specific calibration. Samples still should be collected to verify sensor operation and the validity of the conversion to SSC. Numerical modeling of SSC in San Francisco Bay also is simplified by the existence of a homogeneous relation between floc size and density. This removes some of the potential variability that can confound model development, such as variability of settling velocity.

5. CONCLUSIONS

The floc size–density relation proposed by Kranenburg (1994) is validated, determined through tidal cycle measurements at a single site. This relation holds for other sites in San Francisco Bay. Homogeneity between turbidity and suspended-sediment concentration and homogeneity of lower-order aggregates supports the constancy of this relation. The two variables that control the relation are primary particle diameter and fractal dimension. Median primary particle size appears to be constant, even during large floods where it would be expected to be most variable and fractal dimension is constant because the mechanisms of flocculation and breakup are spatially homogenous throughout the Bay. An exception to the homogeneous floc size–density relation is near the bed in relatively deep areas where sediment eroding from the bed increases the fractal dimension. Otherwise, the floc size–density relation is constant in San Francisco Bay.

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