

VIDEO MEASUREMENTS OF FLOCCULATED SEDIMENT IN LAKES AND ESTUARIES IN THE USA

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Abstract The flocculation of suspended cohesive matter has a direct effect on water quality and related environmental issues. This paper primarily describes a recently developed low intrusive INSSEV_LF: IN-Situ Settling Velocity system, which permits the direct, in situ measurement of both floc size (D) and settling velocity (Ws), simultaneously. The measurement process comprises initially capturing a suspension containing a floc population from the water column (usually with a van Dorn bottle) and this is returned to the surface vessel. Flocs are then extracted from the sampling unit and carefully transferred to the LabSFLOC - Laboratory Spectral Flocculation Characteristics - apparatus where the flocs are viewed as silhouettes, during settling, by a high resolution imaging system. By measuring a floc population within a controlled volume, floc properties such as porosity, dry mass and mass settling flux can be calculated. Floc population examples were presented for three locations. The first was the turbidity maximum zone in San Francisco Bay, where the suspended solids concentration (SSC) was 170 mg.l⁻¹ and many low density macroflocs up to 400 μm in diameter, settling at speeds of 4-8 mm.s⁻¹ were observed. The second location was the shallow (1.7 m mean depth), freshwater environment of Lake Apopka in Florida. It which is highly eutrophic, and demonstrating a turbid SSC of 750 mg.l⁻¹ within a benthic suspension layer, resulted in D from 45 μm up to 1,875 μm; 80% of the floc were > 160 μm (i.e. macroflocs). Present theories for the settling of flocs rely on fractal theory of self-similarity, but this does not appear to be applicable to the Lake Apopka flocs because they do not possess any basic geometric unit that is the building block of higher order fractal structures. Bioflocculation is deemed extremely important in freshwater environments such as lakes. The Lake Apopka macroflocs (D > 160 μm) encompassed 92% of the floc mass, and demonstrating a Wsmacro of 1.7 mm.s⁻¹ (twice as fast as the Wsmicro), this translated into the macroflocs contributing 96.4% of the total mass settling flux (1.5 g.m⁻²s⁻¹). Lake Tahoe, which crosses into both California and Nevada, was the final study location. With a maximum depth of 501 m, it is the second deepest freshwater lake in the USA. However it less turbid than Lake Apopka, with SSC rarely exceeding 10 mg.l⁻¹ during the floc surveys. At depths of both 5 m and 450 m, the SSC was 9.6 and 3 mg.l⁻¹, respectively. Flocs at both depths exhibited Ws of 2-5 mm.s⁻¹. Whereas at a depth of 35 m, the SCC was 6.8 mg.l⁻¹ and the flocs fell comparatively slowly (Ws of 0.03-2.4 mm s⁻¹) which suggest that the floc population at 35 m will have a long residence time in the water column, thus impairing long term light penetration. Interestingly, the MSF at 450 m was 10.8 mg.m⁻²s⁻¹, which was double the flux measured at 35 m, even though the deep water was only half as turbid.

INTRODUCTION

In aquatic environments, fine cohesive particles (clays and fine silts) have a much greater propensity to adsorb contaminants and nutrients than purely coarse particles (Ackroyd et al., 1986; Stewart and Thomson, 1997). This in turn has a direct effect on water quality and related environmental issues (e.g. Uncles et al., 1998). Fine particle suspended mass also makes a greater contribution to water column turbidity than the identical mass of coarser non-cohesive particles. Thus accurately predicting the movement of these muddy sediments is highly desirable in both estuarial and lake environments. When predicting sediment mass settling fluxes, the settling speed of the suspended matter is a key parameter.

In contrast to purely non-cohesive sandy sediments, cohesive muds can flocculate (e.g. Manning, 2001; Lick et al., 1993; Winterwerp and van Kesteren, 2004,) and this poses a serious complication to the modelling of sediment pathways. The resultant aggregates, called flocs, are larger and settle faster than the individual mud particles from which they are composed. An individual floc may comprise up to 10⁶ individual particles. As flocs grow in size they become more porous and significantly less dense (Tambo and Watanabe, 1979; Droppo et al., 2000), but typically

their settling speeds continue to rise due to the Stokes' Law relationship (Dyer and Manning, 1998). In electrochemistry of clay suspensions, a stable suspension contains dispersed particles. Coagulation occurs when the suspension is destabilised. Thus the degree of flocculation, often referred to as the *instability* (van Leussen, 1994), is highly dependent upon a number of parameters, in particular suspended solids concentration (SSC) and turbulence (e.g. Krone, 1962; Burban et al. 1989; van Leussen, 1994; Winterwerp, 1998; Manning, 2004a). A conceptual model which attempts to explain the linkage between floc structure and floc transport in the aquatic environment is provided by Droppo (2001).

Early theories on flocculation regarded the variations in salinity as the main enabler of cohesive sediment flocculation, because when pure clay minerals are immersed in an electrolytic fluid such as saline water, an electrical double layer forms around the clay particles and has the effect of neutralising the negative charge of the clay particle (e.g. van Olphen, 1977). Through laboratory flume studies, Krone (1963) found that flocculation quickly reaches an equilibrium situation at a salinity of about 5-10, which is much less saline than most sea water (~35). However the relevance of salt flocculation in estuaries has increasingly been questioned because of the potential greater influence of sticky organic material present, in particular extracellular polymeric substances (EPS). Electrostatic bonds are very weak, and the presence of large estuarine macroflocs in relatively fresh waters has been confirmed by in-situ photography (Eisma et al., 1983, 1990; Wells, 1989). Enhanced flocculation through biological process (e.g. diatom blooms, algal growth, secretion of mucus) has been reported by numerous researchers (Cadee, 1985; Kranck and Milligan, 1988; Jackson, 1990).

Much research has been conducted on the flocculation characteristics of suspended muddy sediments in saline/brackish tidal conditions, where electrostatic particle bonding can occur. However, very little is known about freshwater floc dynamics. This is primarily due to flocs being extremely delicate entities and thus very difficult to observe in situ. This paper primarily describes recently developed a low intrusive technique which permits in situ measurement of both floc size and settling velocity, simultaneously. Examples of floc spectra observed from three different environments within the USA are then presented.

FLOC SAMPLING INSTRUMENTATION

Overview Although flocs are integral units in flowing turbulent water, they easily break apart when sampled in response to additional shear created during acquisition (Eisma et al. 1997). Therefore flocculation data was measured using the INSSEV_LF: IN-Situ Settling Velocity instrument. The LF (LabSFLOC) version of INSSEV was developed between 2004-2006 and is a hybrid system which combines an in situ floc acquisition unit (usually a 2.2L Van Dorn horizontal sampling tube) and the low intrusive LabSFLOC – Laboratory Spectral Flocculation Characteristics – system (Manning, 2006). In summary, a suspension containing a floc population is initially captured from the water column and this is returned to the surface vessel. Flocs are then extracted from the sampling unit and carefully transferred to the LabSFLOC apparatus where the flocs are examined.

LabSFLOC Instrumentation The LabSFLOC was the instrument chosen to measure the floc population characteristics. LabSFLOC utilises a low-intrusive video camera (Manning and Dyer, 2002) to observe flocs as they settle in a 190mm high by 100mm square Perspex settling column. The video camera, positioned 75mm above the base of the column, views all particles in the centre of the column that pass within a 1 mm depth of field, 45mm from the lens. The complete LabSFLOC configuration is illustrated in Fig. 1.

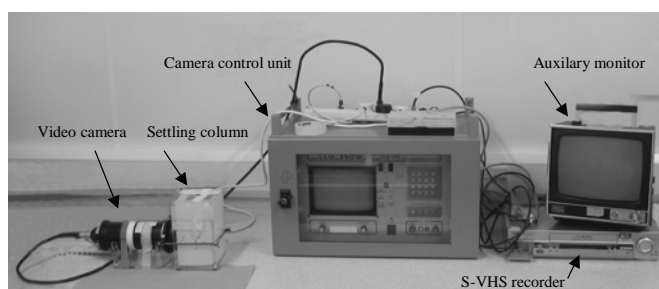


Figure 1 LabSFLOC set-up.

Once a water sample is collected from the desired location in the water column, a volume of suspended sediment is carefully extracted by a 0.4m long glass pipette (4 mm internal diameter). This sub-sample is rapidly transferred to the settling column to minimise any flocculation occurring within the pipette. The aperture of the pipette is brought into contact with the settling column water surface and held in place (vertically) allowing the captured flocs to undergo settling through the still water column. Extensive testing of this sampling protocol during the EC COSINUS project (e.g. Gratiot and Manning, 2004) revealed that this technique created minimal floc disruption during acquisition. The settling column was filled with clear water of similar temperature (and salinity where appropriate) as the sampling location; this reduced the risk of a negative density contrast. The vacuum created in the upper section of the tube retained the suspension in the pipette during the brief transferral operation.

To maintain consistency between the laboratory derived floc data and flocs assessed in situ, the operational protocols of INSSEV_LF were kept as close to those of laboratory LabSFLOC measurements as was practically possible. For example during floc sampling, a pipette is filled to produce a fluid head of 100 mm, which results in a video image control sample volume nominally of 400 mm³ (1 mm image depth and 4 mm video image width). This controlled volume permits the calculated floc mass to be compared directly to ambient concentration. Also the number of flocs entering the settling column were controlled in order to prevent settling column saturation. This was achieved by holding the pipette in contact with the settling column water surface for a duration P_t (in seconds) predetermined by the ambient SSC (in mg.l⁻¹). The contact time was estimated by the following empirical algorithm derived by Fennessy (1994): $P_t = 1860 \cdot \text{SPM}^{-0.8}$

The LabSFLOC instrument is based around a high resolution imaging system, which enables the detailed examination of the flocs as they settle in the settling column (Fig. 2a). All the flocs settling within the Perspex column were viewed by a Puffin model UTC 341 high resolution monochrome all-magnetic Pasecon tube video camera (originally supplied by Custom Camera Designs Ltd of Wells, Somerset, UK). It has a 35 mm, F4, macro lens fitted behind a 12 mm thick opal glass faceplate with an anti-reflective coating.

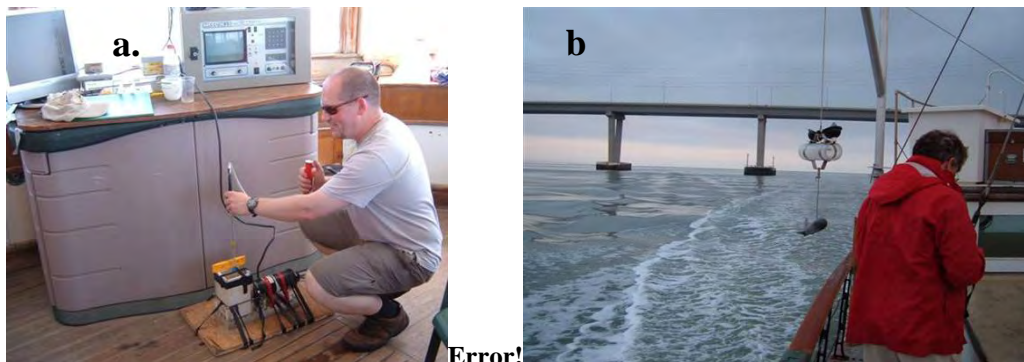


Figure 2 a) Settling an extracted floc sample in the LabSFLOC column situated in the fan-tail laboratory on RV Polaris; b) van Dorn sampler awaiting deployment.

The complete camera unit was modified for marine use by containing all the electrical circuitry within an aluminium outer casing, approximately 260 mm in length and 95 mm in diameter. The camera views through an aperture in the settling column wall at a depth of 115 mm below the column surface. It records all settling flocs/particles in the centre of the column which pass within a 1 mm focal depth of field, 45mm (focal length) from the camera lens. The total image size is nominally 3 mm high and 4 mm wide.

The analogue video camera is connected to a CCU350WA electronic Camera Control Unit (CCU) interface by a 20-core STC type 7-2-20C marine cable. The present version of LabSFLOC digitises the analogue floc images in real-time via a Zarbeco USB-2.0 Videolink PC card linking the CCU and a laptop PC. The images were digitised, at a frame rate of 25 Hz (one frame = 0.04 s) and a resolution of 640 x 480 pixels, with an individual pixel representing 6.3 μm (determined from calibration). Each floc video image time series is converted into separate AVI format files (one for each floc sample). The AVI files were not Codec compressed, so they could be analysed with MatLab

software routines during post-processing. This meant that each 360 second AVI file was approximately 4.2 GB in size, therefore all AVI files were recorded to a USB-2.0 portable 1 TB hard drive.

To render the particle/floc structure more visible and reduce image smearing, the video camera floc images are silhouettes. To achieve this the video camera utilises an integral low heat back-illumination system whereby floc images are viewed as silhouettes i.e. flocs appear dark on a light background. This back-illumination is provided by an annulus of six high intensity red 130 mW LED's positioned around the camera lens. The camera's electronic circuitry senses the scene reflectivity and adjusts the voltage to the LED's accordingly.

Floc Data Processing The HR Wallingford Ltd *DigiFloc* software - version 1.0 (Benson and Manning, 2010) was then used to semi-automatically process the digital AVI floc recordings to obtain spherical equivalent floc size (D) and settling velocity (W_s) spectra. When the flocs had low particle Reynolds numbers (i.e. $R_e = W_s D / \nu < 0.5$, where ν is kinematic viscosity), the effective density (ρ_e) for each floc could be calculated by applying Stokes' Law:

$$\rho_e = (\rho_f - \rho_w) = \frac{W_s 18\mu}{D^2 g} \quad (1)$$

where ρ is the dynamic molecular viscosity and g is gravitational acceleration. The effective density, also referred to as density contrast or excess density, is the difference between the floc bulk density (ρ_f) and the water density (ρ_w). For instances where the R_e exceeded 0.5, the Oseen modification (Oseen, 1927; Schlichting, 1968), as advocated by Brun-Cottan (1986) and ten Brinke (1994), was applied in order to account for inertial drag on the settling particles/flocs.

As a result of measuring all visible flocs within an individual LabSFLOC sample and assuming the flocs originated from a constant sample volume of water (i.e. 400 mm³), it is possible to transform the observed floc population into accurate estimates of SSC and settling flux spectra. Using specially derived algorithms (Fennessy et al., 1997; Manning, 2004b), it was possible to accurately calculate other physical characteristics for each individual floc, including: porosity and dry mass. Where practically possible, the floc mass was referenced to the ambient SSC via gravimetric analysis of a 2.2L water sample (Fig. 2b).

The mass settling flux (MSF) is generically defined as the product of the SSC and the settling velocity. It becomes the depositional flux in quiescent waters. The MSF can be calculated from LabSFLOC data by multiplying the SSC represented by an individual floc, by its respective settling velocity. If all individual floc settling fluxes are summed for a single population, the sample total MSF can be calculated. Similarly the MSF for a specific size-fraction can be calculated. Thus spectral estimates of mass settling flux can be made. This type of flux computational technique has also been applied successfully by Syvitski et al (1995), Hill et al (1998), and Sternberg et al (1999).

RESULTS

San Francisco Bay The first study location we consider is San Francisco Bay (SFB) in northern California, as most flocculation research has traditionally focused on estuarial processes. This area has a long history with flocculation research, dating back to the classic work of Krone (1962). SFB is a predominantly shallow, drowned river valley type estuary, with an ebb dominant tidal regime. The complete Bay system covers a surface area of approximately 4000 km². The estuary receives riverine inputs from both the Sacramento and San Joaquin rivers, which originate from the Sierra Nevada mountains. The San Francisco Bay catchment comprises approximately 40% of the water in California, which eventually drains in the Pacific Ocean. Geographically, San Francisco Bay comprises a number of interconnected smaller bays.

During the last 160 years, the bathymetry and sedimentation within the Bay has undergone many changes, primarily due to anthropogenic input. These included vast amounts of mud and gravel sediments released initially into the upper reaches of the Sacramento River during hydraulic mining activities in the 1850's (Gilbert, 1917), followed by the reclamation of wetlands which were carried out from the mid 1800's through to the late 1900's. This activity has had the net effect of reducing San Francisco Bay's original size by about one third. The cohesive sediments can act

as transport mechanisms for pollutants and sediment contaminants in San Francisco Bay and have been examined by Schoellhamer et al. (2007).

In order to track long term changes in water quality and morphological, the USGS has regularly monitored SFB since 1968 using the *RV Polaris* (<http://sfbay.wr.usgs.gov/access/wqdata/>). The *RV Polaris* stations are illustrated in Fig. 3. During June 2008, a series of floc measurements were conducted which included observations of floc dynamics within the predominantly freshwater region of the Sacramento-San Joaquin River Delta.



Figure 3 USGS water sampling stations in San Francisco Bay.

The scatter-plot (Fig. 4a) illustrates spherical-equivalent dry mass weighted floc size (D) plotted against settling velocity (W_s) for the floc population SFB-TMZ. It was captured by the INSSEV_LF instrument from within the turbidity maximum zone (TMZ), where the near-bed SSC was 170 mg.l^{-1} . The TMZ was situated landward of Carquinez Strait (near Benicia and Martinez), 98 km from the estuary mouth and is a feature of this region of San Francisco Bay (Schoellhamer, 2001). The observations indicate a mean floc size of $144 \text{ }\mu\text{m}$ within the TMZ, with many low density macroflocs up to $400 \text{ }\mu\text{m}$ in diameter, settling at speeds of $4\text{-}8 \text{ mm.s}^{-1}$. These D and W_s values were generally larger and quicker than those observed previously by Kineke and Sternberg (1989) in the more saline San Pablo Bay.

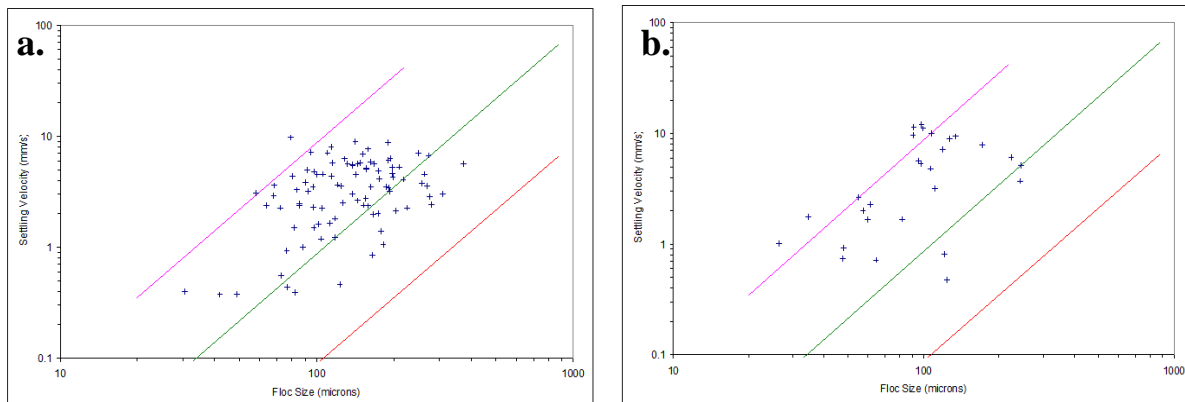


Figure 4 Floc W_s vs. D for San Francisco Bay floc samples: a) SFB-TMZ and b) SFB-CB. Diagonal lines on the W_s vs. D scatter-plot represent contours of constant Stokes equivalent effective density: pink = $1,600 \text{ kg.m}^{-3}$, green = 160 kg.m^{-3} and red = 16 kg.m^{-3} .

The diagonal lines on Figure 4a represent contours of constant floc effective density (units = kg.m^{-3}). One can see that there are many flocs of different sizes, but exhibiting a similar floc density. Also there are flocs present with similar settling velocities, but demonstrating a wide range of sizes and effective densities.

When generalising floc populations, two size classes called macroflocs and microflocs are commonly used (Eisma, 1986) and Manning (2001) suggests a demarcation value of $160 \text{ }\mu\text{m}$ to define between the macro- and microfloc

fractions. Over half the mass of the TMZ macroflocs were ($D > 160 \mu\text{m}$) and this was only a third of the total floc population. In contrast, 48 of the 56 floc observed within the more saline Central Bay (sample SFB-CB; Fig. 4b) were dense, microflocs and these comprised 70% of floc mass. The maximum floc size was $130 \mu\text{m}$ smaller within Central Bay than in the TMZ. The INSSEV_LF data can be used to assess the floc mechanics and resultant property variability through the entire SFB system (e.g. Ganju et al., 2007).

Previous research conducted in San Francisco Bay by Kranck and Milligan (1992) concluded that, except in highly turbulent conditions, most of the SFB fine cohesive suspended sediment occurs as flocs. Furthermore, Kranck and Milligan (1992) found that the population of small flocs remained fairly constant through a tidal cycle in San Pablo Bay, but the number of large flocs increased as the SSC rose. The large flocs observed in the low saline TMZ were most likely a result of biological processes which can assist floc growth and subsequently greatly enhanced the settling velocity of the flocs. This biological flocculation aspect will be explored further in the next Section.

Lake Apopka The second location considered is the Lake Apopka; the first of two lake environments. Located west of Orlando and exhibiting a surface area of 125 km^2 , Lake Apopka is the fourth largest freshwater lake in Florida (Fig. 5). This lake has a history of more than 100 years of anthropogenic interference, which originally started with the construction of the Apopka-Beauclair Canal in 1888. In 1941, a levee was constructed along the northern shore to allow 80 km^2 of shallow marsh to drain for farming purposes. The discharge of water, rich in nutrients (e.g. phosphates, nitrates) from agricultural sources, produced conditions that created a chronic algal bloom and resulted in loss of the lake's recreational value and game fish population. Thus, for nearly half a century, LA has been highly eutrophic and considered an example of cultural eutrophication (Bachmann et al., 2005).

In an attempt to reoligophy the lake, farm lands adjacent to the lake were purchased by the State of Florida. It was intended that this land would be used to develop an artificial marsh which would facilitate the removal of phosphorus from the lake, plus deploy netting to remove gizzard shad (Lowe et al., 2001). However, a major obstacle to a reversal to a more trophic state are the thick, dense muddy deposits which covers approximately 90% of the Lake Apopka bed. The lake has an average water depth of just 1.7 m, and it is therefore possible for wind-generated surface waves to regularly entrain the surface of the fluid mud layer (Mehta, 1996), together with a layer of meroplankton which grows on the fluid mud surface (Carrick et al., 1993), into the shallow water column. Bachmann et al. (1999) demonstrated that the net result was extremely high levels of suspended particulate matter, chlorophyll a, and total phosphorus continually being entrained into the lake's water column. During July 2008, a study of the Lake Apopka floc dynamics was conducted for the St. Johns River Water Management District by the University of Florida's Coastal and Oceanographic Engineering Laboratory.



Figure 5 Lake Apopka location map.

Floc sample BB_04 (Fig. 6) was collected within the benthic suspension layer (BSL), where it interfaces with a nepheloid fluid mud layer. The ambient SSC observed in the Lake Apopka BSL (at Site B) was 750 mg.l^{-1} . The floc size range of sample BB_04 extended from $45 \mu\text{m}$ up to $1,875 \mu\text{m}$. Over half of the 855 individual flocs were larger than $240 \mu\text{m}$ in diameter and 80% classified as macroflocs. Thus the BSL was a very efficient environment

where matter could be contained in a significantly lower number of very large flocs, when compared to the more dilute conditions of LT and SFB.

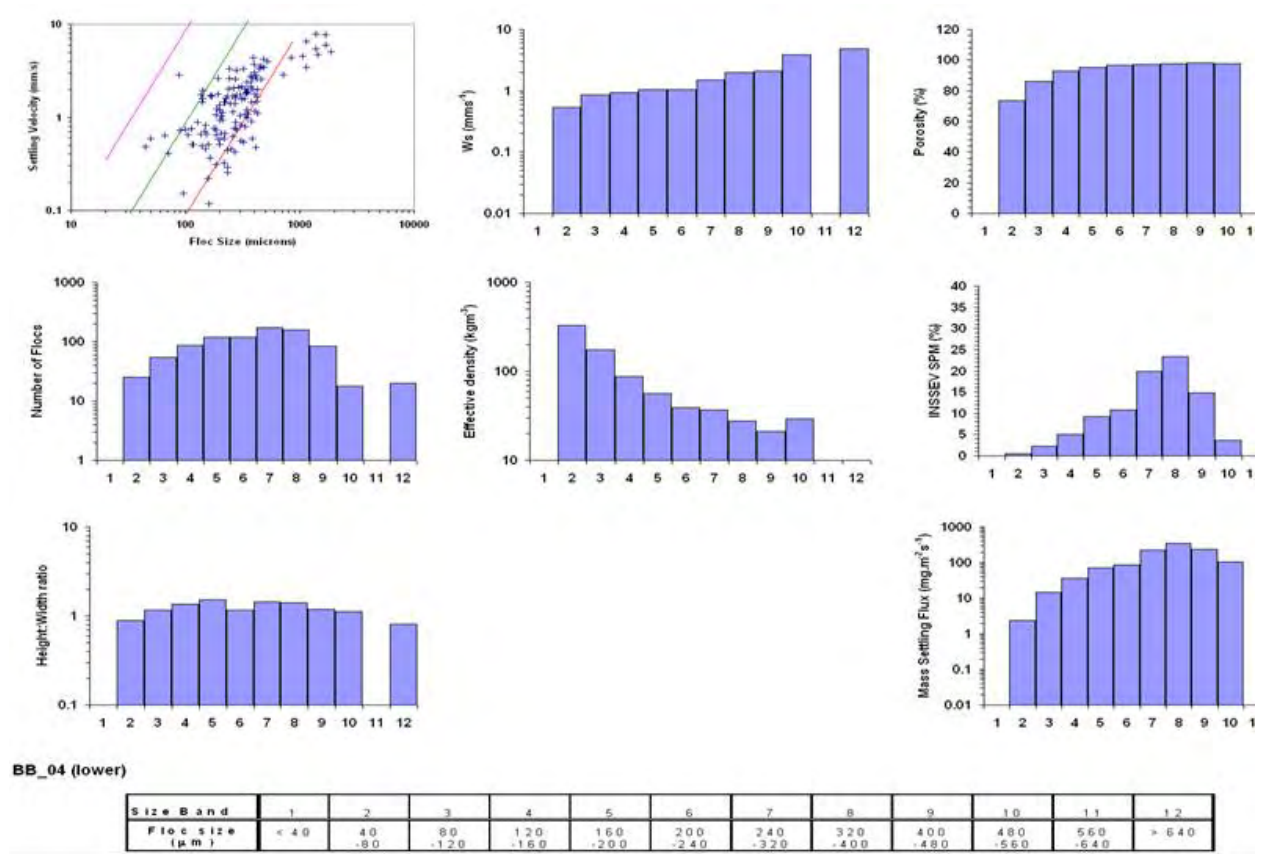


Figure 6 Size banded distributed floc properties for Lake Apopka Sample BB_04 captured within a benthic suspension layer. SSC = 750 mg.l⁻¹ suspension. Diagonal lines on the Ws vs. D scatter-plot (top-left) represent contours of constant Stokes equivalent effective density: pink = 1,600 kg.m⁻³, green = 160 kg.m⁻³ and red = 16 kg.m⁻³

Present theories for the settling of fine sediment rely on fractal theory of self-similarity (e.g. Hill, 1996; Winterwerp et al., 2006), which appears not to be applicable to the Lake Apopka flocs because they do not possess any basic geometric unit that is the building block of the higher order fractal structures. Fig. 7 illustrates large macroflocs which were extremely organic in structure, depicting either an irregular cluster shape or a stringer-type configuration. The large, very porous (over 97% porous), BB_04 macroflocs exhibited very low effective densities ($\rho_e < 60 \text{ kg.m}^{-3}$). These macroflocs consisted of a fluffy (transparent) coating wrapper around a solid (opaque) core. At times the core of these macroflocs was a single silt particle or non-decomposed (or refractory) plant matter.

The abundance of so many macroflocs larger than 640 µm present in Lake Apopka is a result of organically enhanced "bioflocculation." Extra-cellular polymeric substances (EPS; Underwood and Paterson, 2003; Tolhurst et al., 2002) which are excreted by mud-dwelling micro-organisms, such as diatoms and bacteria, as they move within the sediments, significantly enhance the inter-particle cohesion. The significant role biology plays in flocculation is further demonstrated by the findings of Gratiot and Manning (2007) from the Gironde Estuary (France). When sheared, high SSC of natural Gironde Estuary mud (i.e. mineral and organic matter) floc sizes ranged from 44 to 406 µm, but when a 5 g.l⁻¹ suspension of pure Gironde Estuary clay minerals (i.e. devoid of organic matter) was sheared in the lab, the suspension did not form aggregates larger than 140 µm.

The BB_04 flocs represented a total MSF of 1.5 g.m⁻².s⁻¹. With the macroflocs encompassing 92% of the floc mass, this translated into the fast settling macroflocs contributing 96.4% of the mass settling flux. This was a product of a

macrofloc $W_{s_{macro}}$ of $1.7 \text{ mm}\cdot\text{s}^{-1}$, which was twice as fast as the $W_{s_{micro}}$. To put this all into context, this total MSF was more than 4 times greater than the settling flux computed by a settling velocity of $0.5 \text{ mm}\cdot\text{s}^{-1}$; a typical parameterised W_s value (based on gravimetric data) used in numerical model simulations of sediment transport (e.g. Baugh and Manning, 2007).

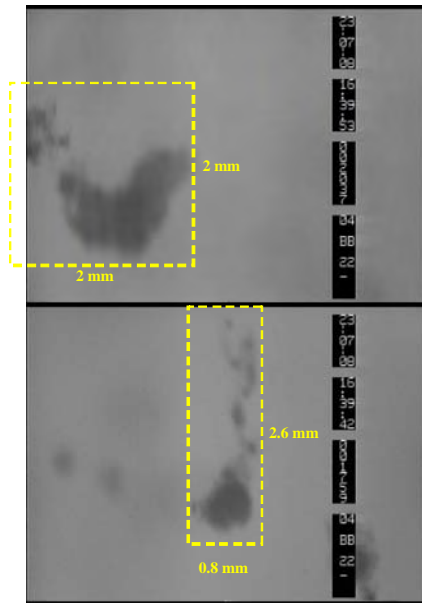


Figure 7 Examples of Lake Apopka benthic suspension layer macrofloc images observed during settling by the LabSFLOC video camera. A large clustered floc structure (top) and a long stringer-type configuration (below). Dotted rectangles indicate actual floc dimensions

Lake Tahoe The second freshwater lake location we consider is Lake Tahoe (LT), which straddles the boundary between the states of California and Nevada (see Fig. 8). In stark contrast to the extremely shallow Lake Apopka (mean depth of about 1.7 m), LT exhibits a maximum depth of 501 m. LT is the tenth deepest lake in the world and the second deepest lake in the USA (after Crater Lake in Oregon). Geologically, the LT Basin was formed by block (normal) faulting about 2 to 3 million years ago. Down-dropped blocks created the LT Basin, resulting in LT being situated in between two mountain ranges (i.e. the product of uplift blocks): the Sierra Nevada Range to the west and Carson Range to the east. Bathymetrically, LT has an average depth of 305 m and exhibits a surface area 495 km^2 ; the lake surface is 1,897 m above mean sea level.



Figure 8 Lake Tahoe Location Map.

LT is a popular tourist location and is internationally known for its water clarity. During the late 1960's the UC Davis Secchi Disc turbidity depth reading were greater than 30.5 m. However, long term monitoring has indicated that the lake's water clarity is progressively reducing. The Secchi depth was found to be only 20.6 m in 2006. This growing turbidity is a product of increased eutrophication arising from a nutrient excess in the lake. It is speculated that primary production within LT is rising at a rate of 5% per annum.

It is important for the long term environmental management of LT to establish the dynamical properties of the particulates suspended in different regions of the water column. Therefore during June 2008, a series of INSSEV_LF surveys were conducted in LT, in collaboration with UC Davis and the Tahoe Environmental Research Centre. Fig. 9a shows an example of an INSSEV_LF floc sample (LT06-35) which was obtained at a depth of 35 m. In contrast to the moderately turbid water of the San Francisco TMZ (SSC of 170 mg.l⁻¹), and the extremely turbid waters of Lake Apopka (SSC > 750 mg.l⁻¹), the ambient SSC (at 35 m) was 6.8 mg.l⁻¹, which is high for LT.

The eighteen flocs which comprised the LT06-35 population ranged in size from 45 μ m up to 284 μ m, and they settled at velocities spanning three orders of magnitude from 0.03-2.4 mm s⁻¹. The floc effective densities ranged between 2-208 kg m⁻³. Half the population was less than 75 μ m and this represented one quarter of the total mass. The $W_{s_{macro}}$ for LT06-35 was only 1 mm.s⁻¹, with the $W_{s_{micro}}$ settling at one-fifth of the macrofloc speed (0.2 mm.s⁻¹). These slow fall velocities for both fractions suggest that this floc population at 35 m will have a long residence time in the water column, thus impairing light penetration.

If we move higher in the water column to a point 5 m from the lake surface, the SSC rises by 42% to 9.6 mg.l⁻¹. However, the LT06-05 (Fig. 9b) population now only comprises fourteen flocs; four less than LT06-35. The D_{max} of sample LT06-05 is also 89 μ m larger, at 373 μ m. In terms of settling dynamics, all the LT06-35 flocs were falling at velocities faster than 1.7 mm.s⁻¹, with a $W_{s_{MAX}}$ of 5.3 mm.s⁻¹; this was double the speed of LT06-35. Both macro- and microfloc fractions were settling at over 3 mm.s⁻¹. With 84% of the floc mass present as macroflocs, the MSF results in the macroflocs representing 29.6 (86%) of the 35.4 mg.m⁻²s⁻¹ total flux. The MSF distribution was similar for LT06-35, but the total MSF was only 5 mg.m⁻²s⁻¹; a seven-fold difference when compared to the more turbid conditions.

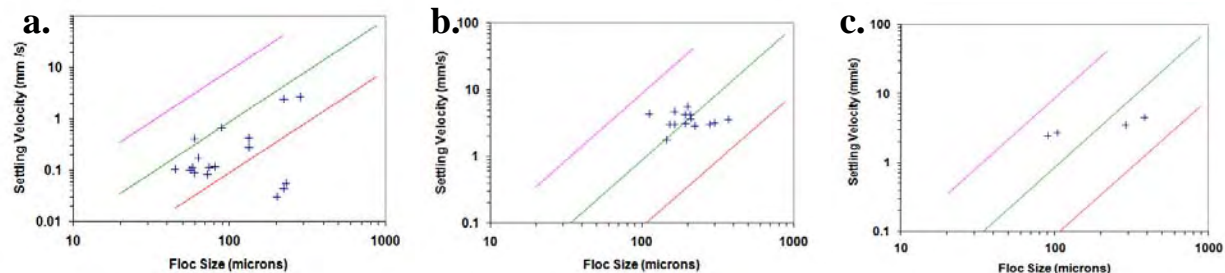


Figure 9 Floc W_s vs. D for Lake Tahoe floc samples: a) LT06-35; b) LT06-05; and c) LT06-450. Diagonal lines on the W_s vs. D scatter-plot represent contours of constant Stokes equivalent effective density: pink = 1,600 kg.m⁻³, green = 160 kg.m⁻³ and red = 16 kg.m⁻³.

In contrast to the relatively turbid surface layers of the lake, at a depth of 450 m the SSC was only 3 mg.l⁻¹. The LabSFLOC camera only viewed five flocs (Fig. 9c), but all were settling at speeds of 2-5 mm.s⁻¹. It is possible that the largest floc ($D=383 \mu$ m) was a product of particle-particle collisions due to differential settling through the water column (Lick et al., 1993). Although previous research does suggest that differential settling mainly happens at much higher SSC (hundreds to thousands of mg.l⁻¹). The total MSF was 10.8 mg.m⁻²s⁻¹, which was double the flux measured at 35 m, even though the deep water was only half as turbid. It is anticipated that this type of particle and settling flux data will provide greater insights into the long term clarity in LT.

SUMMARY

The diameter and settling velocity of individual flocs can be measured simultaneously with the video INSSEV_LF instrument within SSC of several g.l⁻¹. The video camera views all particles in the centre of the column as they settle from within a known sampling volume. These floc values can then be used to calculate the floc dry mass and mass

settling flux distribution of the floc population. This is of great importance for accurate numerical sediment transport and water quality simulation model calibration. Floc properties have traditionally been studied in estuaries such as San Francisco Bay, but information on floc properties is also valuable for addressing environmental problems in freshwater environments such as Lake Tahoe and Lake Apopka.

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