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# Fluid Mud Sondes & Acoustic Imaging Methods for Coastal Dredging

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## ABSTRACT

A new method or protocol for measuring fluid mud and muck using passive sondes and an acoustic imaging method is described. Results made during two recent dredging projects are reported. The desired result in terms of environmental remediation dredging was to reduce the movement of fluid mud and muck. The movement of fluid mud and muck is measured quantitatively in terms of a flux density (mass $L^{-2}$ $T^{-1}$) using in-situ direct sondes. The muck management goal was to measure fluid mud and muck movement reduction (MMR) in coastal Indian River Lagoon. Prior fluid mud methods rely upon surrogate or indirect methods and have limitations because they sample a point in space at an instant in time. The use of vertical and horizontal sondes deployed for 12-48 hours represent a monitoring protocol for measuring fluid mud and muck movement. In conjunction with the vertical and horizontal placements of sondes, stationary acoustic fanbeam imaging was conducted. The fan beam imaging shows the presence of moving nephelometric layers and a moving bottom lutocline. This near bottom deformable fluid mud layer is thus measured with the sondes to directly estimate directional fluxes of dense particulate fluidized material in the coastal bottom boundary layer. Results of measuring deposition and resuspended fluxes of total particulate matter fluxes in the bottom boundary layer is also presented at a transect and at individual stations.

KEY WORDS: Fluid mud, muck, imaging, sondes, passive sensing, sediment transport, cohesive sediment, flocs, colloidal aggregates, mass flux density.

## INTRODUCTION

Improving our scientific understanding of estuaries occurs through research. This improved understanding occurs through advances in techniques, instrumentation and methods used by scientists (Schubel, 1986). The research reported in this paper concerns direct observations of the movement of muck and fluidized mud. The method was developed in response to recommendations made by the American Society of Civil Engineers, Task Committee on Management of Fluid Mud (McAnally, et al. (2007, I,II). Fluid mud is most often associated with a lutocline and forms in near-bottom waters. This mud is a high concentration aqueous suspension of fine sediment and flocs. This fluff and fluidized muck has been defined using site specific density. It is defined as to flow as a density current and is most often associated with navigation and related dredging activities. However, fluid mud is now described as being “ubiquitous” in inland waterways. The fluidization and liquefaction of muck and mud occurs through pore water pressure oscillations associated with amplitude changes of water surface waves. Individual particles are then entrained (Kato and Philips, 1969) within moving lutoclines, and nephelometric water layers. The ASCE Task Force, indicated measurement techniques are indirect or surrogate measures, extremely unreliable, not universally applicable, slow, and limited by calibration requirements. They reported new field instruments, techniques and methods are needed (Waters, 1987; Hydraulics Research Ltd., 1990). Specifically needed is the characterization of fluid mud by temporally averaging the fluid mud sediment fluxes in channels and ports (McAnally, et al., 2007, I). The research reported below addresses the above recommendations. The approach makes use of newly developed passive probes or sondes. By definition a sonde is a device that measures a physical property. The conceptual framework for this research was previously developed by Mehta, Lee and Li (1994) and used during a Florida Inland Navigation District dredging project. The use of vertical sondes for settling flux measurements to estimate nutrients associated with sediment fluxes was discussed by DiToro (2001). The concepts behind directional sediment measurements used in this research has also been described by Anderson (1992). He discussed using short or long time interval, directional sediment monitoring arrays. These utilize positioning collecting tubes, orifices, funnels, and baffles (that help minimize the effects of turbulence) while measuring large volumes, rate, and the vector (direction & magnitude) of sediment movement carried by currents in remote and inaccessible locations such as in the bottom boundary layer. Sediment flux methods and fluid-mud interactions with water surface wave energy dissipation has been the topic of research sponsored by the US Office of Naval Research, Coastal Geosciences (Hsu, 2016; Dalrymple, 2006). A recent review of methodologies and comparisons of reported sediment sampling (Gray and Gartner, 2009; Bostater and Rotkiske, 2015) describes the types of methods, benefits, and limitations of various techniques. Indirect methods have been developed for measuring concentrations of particulate matter and colloidal aggregates, but none were developed for directly measuring the vertical and horizontal fluxes (g cm $^{-2}$ sec$^{-1}$) of fluid mud and muck useful for dredging efficacy evaluations.

Surrogate methods do not conserve mass flux within a control volume since they are typically instantaneous point measurements. High concentrations of suspended matter estimated from optical backscatter sensors yield noisy calibrations when compared to filtration techniques. Bianchi (2007) discusses in-situ investigations of this mobile fluid and reported accurate results are not possible with conventional equipment using submersible pumps, samplers, CTD (conductivity, temperature, depth (CTD) systems, OBS (optical backscattering sensors) and ADPs (acoustic Doppler profilers). These systems sample waters too coarsely in time and space and do not allow the reliable calculations of volume mass flux in a mass conservation form. Fluid mud definitions are shown in Table 1.

Table 1. Definitions of coastal fluid mud & muck collected by sondes.

| Trefry, et al. (1987) definition of muck. | Fluidized muck collected by sondes (Bostater, 2016) |
|---|---|
| 1. Water Content >75% by weight<br>2. Organic Matter >10% by weight<br>3. >60% silt + clay by weight<br>4. >50% particles with <4 um dia. by wt. | 1. Water content >75% by weight (80-90 %)<br>2. Organic matter ~ (10-20 %) by weight<br>3. > 60% silt +clay by weight (~ 70-90 %)<br>4. ~ 80-90% particles << number 04 sieve (500 micron, 0.0197 in., # 35 mesh) by wt. |
| Teeter, 1994 definition of fluid mud. Teeter, et al.(1992) used the term *"fluff"* synonymously as fluid mud. | |
| 1. Solids 50 to 350 dry wt. g/L.<br>2. Density 1.05 to 1.25 g/cc.<br>3. Settling occurs within 5-6 hours<br>4. Fluid mud is a high concentration aqueous suspension of fine grained sediment in which settling is substantially hindered by the proximity of sediment grains and flocs.... leading to a persistent suspension (McAnally, et. al., 2008). | 1. Solids ~ 53 to 264 dry wt. g/L.<br>2. Density ~ 1.03 to > 1. 9<br>3. Settling and surface interface visible within 5 hours<br>4. An upper or surface sediment layer or solids that is not well consolidated, and may occur due to residual sediment erosion and resulting solids resuspension. Its movement is a result of disturbance to surface sediment solids, e.g. wind wave dissipation resuspension and is measured as a dense fluid of particulates, flocs and colloidal aggregates (Bostater, 2016) |

During 2015, two dredging projects in the coastal waters of the Indian River Lagoon, Florida were instrumented with a suite of sensing systems. These projects were completed during 2015 at the Sebastian Inlet area and Palm Bay, Florida. Pre-dredge, during dredging and post-dredging research included the deployment of horizontal and vertical sondes for the measurement of fluid mud flux (g $m^2$ $t^{-1}$). Measurements were made within the bottom moving fluid mud layer and moving lutocline. The sondes sampled the lower 0.5 water column. Restoration dredging is involved with removal of fluid mud and fluff in this mud bottom. In order to evaluate the efficacy of this dredging it is essential to understand the movement or "flux" (mg $cm^{-2}$ $sec^{-1}$) of the material before, during and after dredging activities. This moving material is a "carrier" of nutrients and is needed in order to understand water quality improvement associated with remediation dredging. The goal of using the sondes was to quantify muck movement reduction (MMR) by comparing before, during and after dredging. Acoustic imagery was used to image the moving lutocline and nephelometric layers. In summary, this paper builds upon previous results, but does not duplicate the results reported in Bostater and Rotkiske (2015).

## METHODOLOGY

This section describes in detail the methods used to measure fluid mud movement using the passive sondes in greater detail than published previously by the authors and includes references to the methods used.

The sondes have been shown in Bostater and Yang (2014) and Bostater and Rotkiske (2015). They measure total particulate matter: fine sand 500-62 μm, silts 62-4 μm and clays 4-0.24 μm as reported in Newcombe, 1997. At stations in the Indian River Lagoon, sample analyses indicated collected particles were ~80-90% << number 04 sieve (500 micron, 0.0197 in., # 35 mesh) by wt.

After rinsing material captured during 12-48 hour sonde deployments, and final settling (~ 5 to 24 hr.) the moving fluid particulate matter is typically > 75 % water content and approximately 10-20% organic matter by weight based upon loss on ignition analysis (105° C drying followed by placement in a muffle furnace at 550° C). The sondes collect moving particles and small floc aggregates with estimated settling velocities ranging from <26 to 53 mm $sec^{-1}$ for fine sands and 3 to 0.044 mm $sec^{-1}$ for silts and less than 0.011 mm $sec^{-1}$ for clays. The measurement technique yields a measurement of the mean flux (g $m^{-2}$ $t^{-1}$) during a deployment period. The area ($m^{-2}$) is based upon the crossectional area of the sonde wherein particles enter a fixed control volume. Particulates moving into the volume of the sonde have momentum and after entrainment, particle momentum decays due to turbulent dissipation. Hence the particulate matter falls to the lower portion of the sonde control volume. The horizontal sondes are made of PVC fittings anchored into consolidated sediment. The vertical sondes are a particle settling trap that measure vertical fluxes of marine particulates, marine snow, and floc aggregates. The unit of measurement calculated from these sondes is also a time and space averaged mean mass flux density. The sondes essentially measure the total particulate deposition within their respective control volumes and is a standard method used in modeling fate and transport of chemicals and materials described in Bostater, Ambrose and Bell (1981). The sondes passively collect the moving fluid mud and muck as a flux of particulate matter during a deployment period $\Delta t$.

After retrieving the sondes, the total solids (fluid mud) in a sonde is collected in one gallon plastic containers. The water and solids removed from the sondes are allowed to settle in the laboratory for 24 hrs. The settled particulates are rinsed with deionized water to remove dissolved salts. Sample preservation is not practical according to EPA (1983) in method 160.3 Total Residue (STORET NO. 00500). The residue is placed into pre-weighed porcelain dishes. Particulates settle and water is then decanted using a vacuum tube and/or a syringe or similar device. The residue wet volume and wet weight is then recorded. Wet density (mg $ml^{-1}$) is calculated. The porcelain dishes are heated to 105 degrees C until water is evaporated (at least 24 hours is required due to the large quantity of fluid mud captured). Final dried residue is weighed and this dry weight of residue (mg) recorded for each sample. Dry weight flux (mg $m^{-2}$ $time^{-1}$) is calculated using the sonde deployment time and crossectional area of the sonde. The dried residue and dish is placed in a muffle furnace at 550° C +/- 50° C for one hour. The evaporating dish is immediately covered, cooled to just above room temperature and re-weighed. The result is used in the calculation of % loss on ignition (LOI) in order to provide an estimate of organic matter fluid mud flux. Linear relations between % LOI and nutrients in the particulate matter (TPN, TPN, and TPC) are then calculated as proposed by DiToro (2001) using the relations obtained by Trefry (2015). Sonde nutrient fluxes are then calculated using % LOI and the organic weight for each sample. Additional information concerning the above procedures are described in Greenberg, et al., (1980) as method 209,A,D,E and in ASTM (2016) methods C1603-10, STP148E-EB, STP148D-EB and D5907-13) regarding standard test methods for particulate, nonfilterable solids or residue in water. Triplicate horizontal and duplicate vertical sonde deployments provide estimates of precision using recommendations published by EPA (1984). A review of direct and indirect fluid mud movement and flux methods in Bostater and Rotkiske (2015) indicates that this technique is the only published direct method available for in-situ analysis of fluid mud mass flux density.

Directional fluxes of moving fluid mud are obtained by deploying the horizontal sondes in different directions (E, W, N, S) at ~15 cm above the bottom. Vertical fluxes (depositional and re-suspended) are deployed ~10-20 cm off the bottom and 35-50 cm above the bottom. The vertical depositional (settling) and resuspension (upwelling) sondes are placed in pairs. Thus the lower 0.5 meter of the bottom region is sampled. The deployment procedure results in 8 flux measurements at a station. The heights used are based upon the Hillsboro Bay, Florida, fluidization depths, lutocline and moving fluid heights and model predictions reported by Mehta, et al. (1994) under the influence of water surface wave amplitudes of 2-4 cm. These heights also coincide with waves on lutoclines imaged by acoustic sensors reported by Traykovski, et al. (2000).

The sonde deployment period is on the order of 12-48 hours although longer periods (such as over the duration of a wind and/or rainstorm event) can be made. The size of the horizontal systems is scalable in size. Precision estimates for horizontal sonde measurements used to estimate organic matter content of the moving fluid mud are shown in Table 2.

Acoustic imaging was conducted to investigate moving fluid mud and muck. Fixed location, time continuous acoustic fan beam imaging or echograms were conducted at station TCB1. A five channel system was operated in a down scan mode using an Airmar 455 KHz transducer. The surface of the moving lutocline is thus imaged as water and bottom particulates move through the "acoustically illuminated" area. Similar acoustic backscatter imaging results have been used by Traykovski, Geyer, Irish and Lynch (2000) above fluid mud flows and above moving lutoclines. Using this approach, waves in resuspended sediment and nepheloid layers induced by internal solitary waves have been reported in acoustic echograms and models by Bourgault, et al. (2014).

Fig. 1 shows the station location where measurements were conducted from February thru October, 2015.


Fig. 1 Stations locations in Palm Bay, Florida during 2015. The satellite image is courtesy of Digital Globe. The image and stations are georeferenced.

## RESULTS

Table 1 shows results of triplicate horizontal sonde deployments used to estimate the precision of horizontal sondes to obtain the % loss on ignition of the fluid mud. This measurement is used to calculate the organic matter content of the moving fluid mud flux. Station TCB3 results may have been influenced by a nearby island. It is believed that the other stations are more representative of the precision to be expected from the sonde protocol. Thus precision within 5 to 10 % is considered typical of the fluid mud flux method.

Figure 2 utilizes station sonde data to develop a gridded subsurface flux map of organic matter flux. A spatial grid of ~25 $m^2$ is overlaid on gridded image data of 6.5 cm. The subsurface characterization is based upon utilizing Bayesian kriging power semivariogram methods by Nobre and Sykes (1992). Fig. 3 shows the dry weight flux of moving fluid mud in Palm Bay for use in sediment and water quality model calibration.

Table 2. Triplicate deployment results at three stations for % loss of ignition (organic matter) within sonde moving fluid mud.

Horizontal Sonde Precision Estimates ( % Loss on Ignition - Organic Matter Content )

| | Station TCB1 | Station TCB2 | Station TCB3 |
|---|---|---|---|
| Standard Error Mean | 0.91 | 1.28 | 5.63 |
| Standard Deviation | 1.58 | 2.21 | 9.76 |
| Coefficient of Deviation | 0.05 | 0.09 | 0.39 |

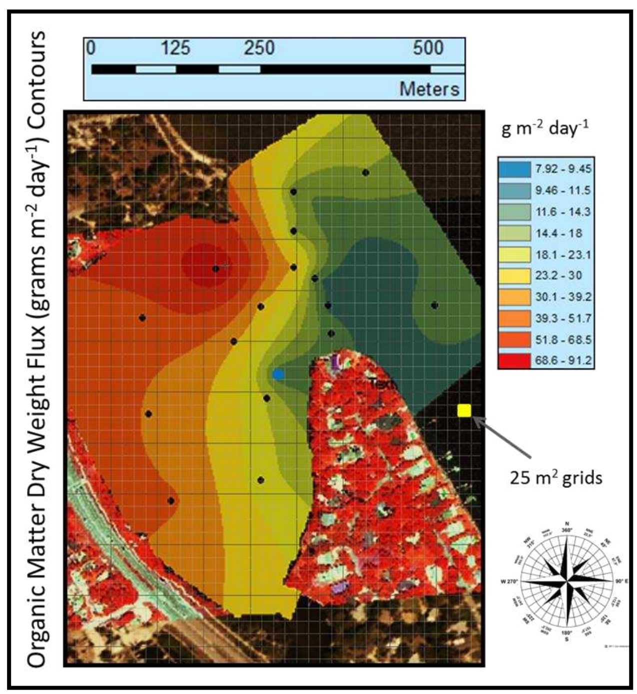


Fig. 2 Gridded and color contoured map of the moving (total particulate organic matter) dry weight flux (g $m^{-2}$ $day^{-1}$) in the lower 0.5 meter water column based upon horizontal and vertical sonde data from stations east of US 1 and at the mouth of Palm Bay

Combining organic matter and particulate organic carbon fluxes with Redfield ratios one can obtain particulate organic phosphorus and nitrogen fluxes measured using the sonde data seen in Fig. 4 and Fig. 5.

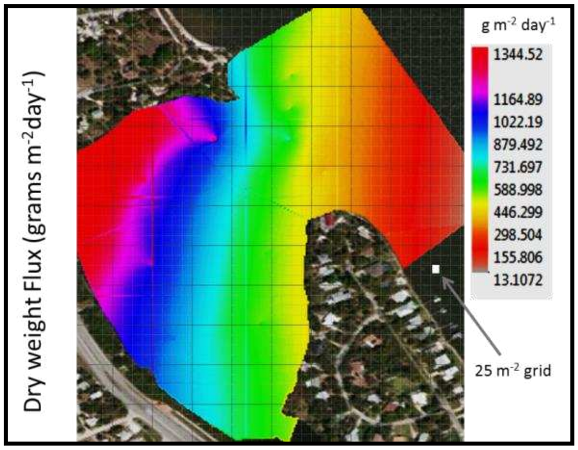


Fig. 3 Gridded and color contoured map of the moving (total particulate organic matter) dry weight flux (g $m^{-2}$ $day^{-1}$) in the lower 0.5 meter water column based upon horizontal and vertical sonde data from stations east of US 1 and at the mouth of Palm Bay.

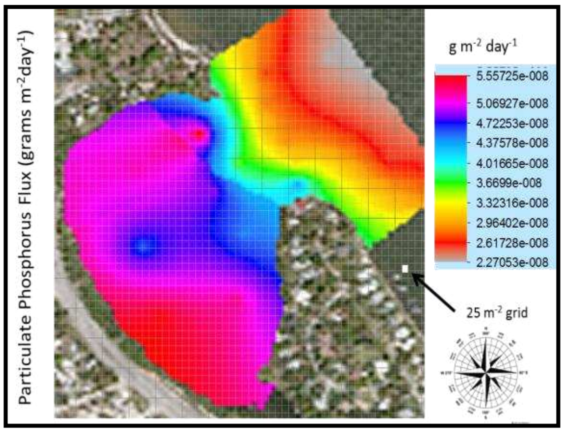


Fig. 4 Gridded and color contoured map of the moving total particulate organic phosphorus flux (g $m^{-2}$ $day^{-1}$) in the lower 0.5 meter water column based upon horizontal and vertical sonde data from stations east of US 1 and at the mouth of Palm Bay

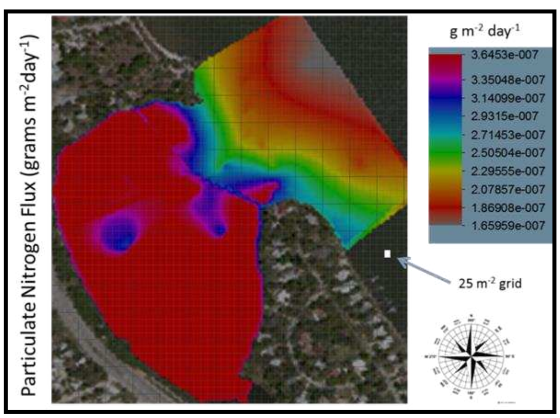


Fig. 5 Georeferenced map of estimated total organic nitrogen in the fluid mud flux (g $m^{-2}$ $day^{-1}$) moving in the lower 0.5 meter water column based upon horizontal and vertical sonde A spatial grid of ~25 $m^2$ is overlaid on the 6.2 $cm^2$ gridded image. Subsurface characterizations utilize Bayesian kriging power semivariogram methods due to Nobre and Sykes (1992).

The horizontal directional sondes (Fig. 6) can be used to estimate the mass flux of fluid mud going into and out of the estuary at a transect and at stations located across the mouth of the bay. Stations TC1 thru TC6 were deployed simultaneously to estimate the net flux of dry weight flux based upon the net fluxes between the east and west directions. The net flux was into the Bay from the lagoon based upon pre-dredging data. The fluxes nearly doubled during dredging. On a dry weight basis, the sonde results suggest that 0.75 million lbs. $m^{-2}$ $yr^{-1}$ or approximately 2 million lbs. $m^{-3}$ $yr^{-1}$ of dry weight fluid mud and muck moves at the mouth of Palm Bay in the lower 0.5 m depth bottom layer

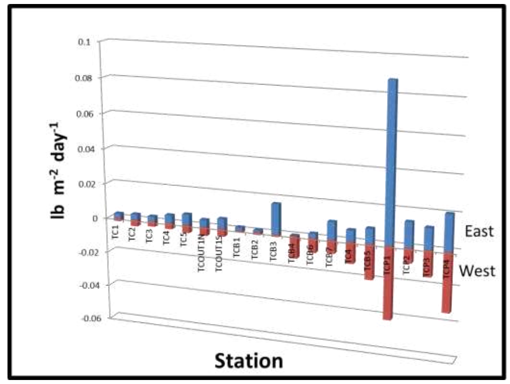


Fig. 6 Horizontal directional moving fluid mud fluxes measured at stations in the east and west directions at a coastal dredge site in Palm Bay, a sub estuary of the Indian River Lagoon, Florida. Net fluxes were from the lagoon to the bay during pre-dredge monitoring.

The vertical sonde measurements (Fig. 7) suggested a greater resuspension or upwelling of the fluid mud at most stations as shown in Figure 3. However the magnitude of the depositional fluxes from the water column to the bottom water column cannot be disregarded when one extrapolates the depositional or downwelling fluxes to a hypothetical sediment transport or water quality model grid cell as shown in Fig. 8. One can estimate the nutrient depositional fluxes using the vertical sonde data depicted in Fig. 8 for a 100 x 100 meter model grid cell.

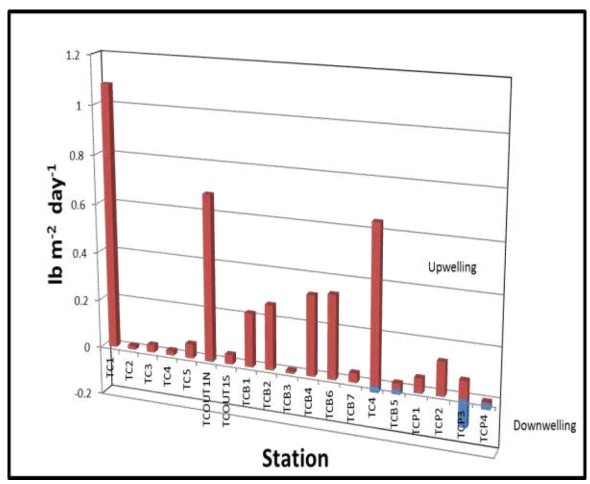


Fig. 7 Example of vertical directional moving fluid mud fluxes measured at stations at a coastal dredging site in Palm Bay, Florida.

The vertical fluxes shown in Fig. 8 are from station TCP1 located along the northern shore of Palm Bay. The upper vertical sonde calculations represent an upper layer lutocline and the lower sonde layer is assumed to represent the moving fluid mud layer deposition at this location. One notes that the pre-dredge depositional fluxes are much greater within the region of the moving fluid mud layer at this station.

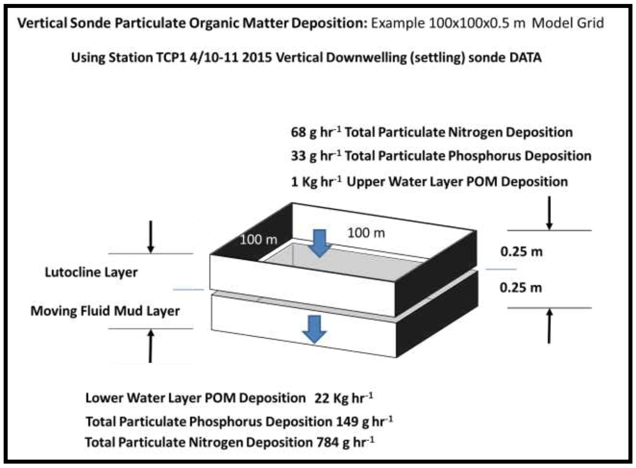


Fig. 8. Schematic showing results of combining sonde depositional mass flux and % loss on ignition data using % LOI and nutrient relations due to Trefry (2015) for two layers within the bottom boundary 0.5 meter water column.

As indicated earlier a unique method of acoustic fan beam imaging was conducted. Results for station TCB1 is shown in Fig. 9.

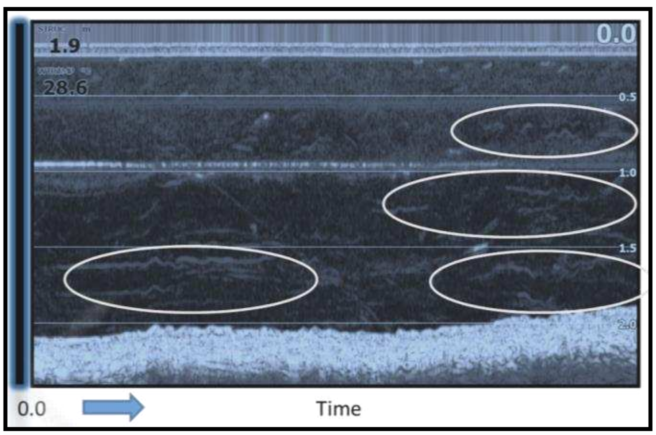


Fig. 9. A fixed location acoustic fan beam echogram image indicating internal nephelometric layers passing through the stationary fan beam. Oscillations at the top of the lutocline indicates the presence of the moving fluid mud using a 455 MHz acoustic imaging system.

The bottom 1 m water layer shown in Fig. 9 indicates high concentrations of flocs and colloidal aggregates. Sludge judge (push pole) measurements made before and after deployments at this station indicated muck thickness of 0.5 meters. This bottom fluid mud layer is also indicated in the acoustic echogram image above. Flocs and colloidal assemblages settled on the sonde and just inside the sonde during the deployment period October 3 to 5, 2015. At TCB1, Lagrangian movement of the water was measured. Triplicate measurements indicated water movement between 30-31 cm $sec^{-1}$. Flocs were observed in the PVC sludge judge settling tube. Dominate floc diameter sizes were in the 2,000-3,000 µ range or the equivalent size range of US Screen Mesh numbers ≈ 6-12. Visual inspection by a diver and imagery indicated the fluidized muck and mud being captured by the sondes was predominantly in the form of flocs and colloidal assemblages. These assemblages enter the sondes, settle and break within the sonde control volume. After breaking, they are indistinguishable from bottom muck and muds.

Fig. 10 shows that muck movement reduction (MMR) occurred at transect 4 when pre-dredge; during dredging and post dredging sonde fluxes are compared. This analysis shows the use of sonde data for remediation dredging analysis, where dredging operations are considered the environmental intervention.. The fluxes were lower before dredging, increased during dredging and then decreased after dredging was completed.

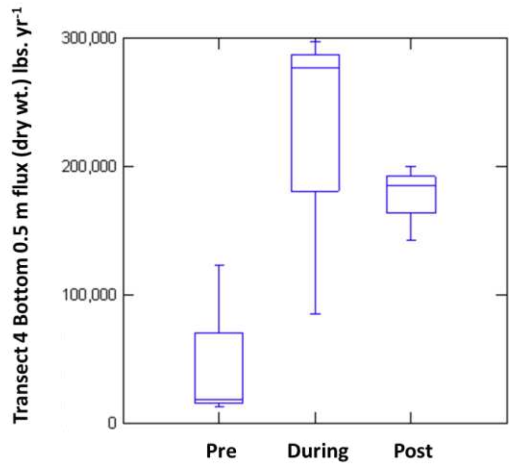


Fig. 10 Results of pre-dredge, during dredging and post dredging transect monitoring in Indian River lagoon at transect 4 near Sebastian, Florida (modified after Bostater and Rotkiske (2015). Dredging efficacy in terms of muck movement reduction (MMR) was observed.

## CONCLUSIONS

In this paper the concept of muck movement reduction is presented and in-situ results presented showing reduction of fluid mud and muck by comparing before and after dredging data as indicated in Fig. 10. New in-situ methods and protocol method using passive sediment sampling of moving fluid mud is presented and discussed in the methodology section. The passive sonde measurement method is one of the only reported in-situ & direct method for measuring horizontal fluid mud fluxes in coastal and estuarine systems.

The acoustic imaging approach (fixed location echogram recordings) as shown in Fig. 9, used in conjunction with the sonde deployments provides useful characterizations of flocs and colloidal aggregates moving in lutoclines and fluid mud flows. These particulate assemblages are ubiquitous in the Indian River Lagoon bottom boundary layer.

In-situ imaging of large underwater flocs has also been reported by Eisma et al. (1990) and Manning et al. (2011). The presence of these fragile mineral and biogenic aggregates are not typically seen in samples taken by Niskin bottles and pumps, and thus are not recognized in typical water sampling as described by Gibbs and Konwar (1983) during dredging projects. Similar images have been obtained using a multispectral submerged camera system deployed in Florida coastal waters reported in Bostater and Rotkiske (2015).

Data derived from the sondes include total particulate matter, dry weight fluxes, organic matter fluxes, inorganic matter fluxes as well as nutrient fluxes in the fluid mud as shown in Figs. 2~5.

The use of the horizontal sonde methods and protocol reported in this paper represent a new and novel direct method & protocol for measuring horizontal particulate fluxes in estuarine and coastal bottom boundary layers. The technique integrates spatial and temporal averaging that was recommended by McAnally, et al. (2009) and Bianchi (2007). The results also compare well with the previous conceptual model, observations and modeling of horizontal particulate fluxes reported by Mehta, Lee and Li (1994), as shown below in Fig. 11. The grey area represents the range of fluxes measured during the two dredging studies discussed in this paper. The sondes also measure fluid mud according to the definitions of fluid mud by Teeter, et al. (1992) and Teeter (1994). By using the sonde protocol methods as described and demonstrated in this paper, sediment flux modeling as described by DiToro (2001), can be extended to estimate horizontal nutrient fluxes useful in water quality modeling in estuaries and coastal waters.

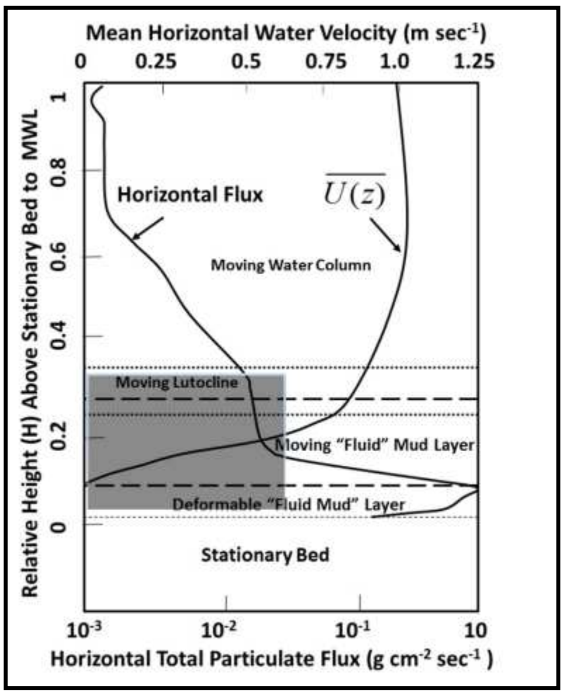


Fig. 11. A conceptual diagram of the bottom water column, fluid mud and lutocline based upon previous observations and mathematical models (modified after Mehta, Lee and Li (1994) and Bostater and Rotkiske (2015).

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