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Design and Operation of Sonde Arrays to Measure Fluid Mud in the Marine Environment

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ABSTRACT

The measurement of moving fluid mud in the bottom boundary layer is important for dredging operations as well as understanding the environmental remediation aspects of dredging. During dredging operations fluid mud in the lutocline is resuspended and transported as nephelometric layers of dense suspended particulates and flocs. The measurement of the vertical profile of the fluid mud flux (g m^{-2} sec^{-1}) in the horizontal direction is accomplished using an array of eight passive sondes. The passive flux traps or sondes were designed using computer aided software and 3-D printing techniques with acrylonitrile butadiene styrene (ABS) materials or polyvinyl chloride pipes and fittings. Deployment of the sondes arrays range from days to several weeks to allow the estimation of moving mud in the bottom boundary layer. Exponential vertically increasing concentrations of mud in the moving lutocline follows the profiles of high concentrations of suspended particulate matter previously reported in scientific literature. Results presented demonstrate the use of the new vertical sonde arrays as a monitoring protocol for characterization of moving fluid mud and muck in the bottom boundary layer in marine or freshwater systems.

KEY WORDS: fluid mud; muck; mass flux; horizontal transport; lutocline; nephelometric layers; sediment transport; sediment flux; bottom boundary layer, sondes.

INTRODUCTION

The purpose of this paper is to describe the design, application, and results of passive *in-situ* arrays of sondes used to measure the vertical structure of the horizontal mass flux density of fluid mud in the bottom boundary layer. Sampling of suspended particulates using vertical arrays allows one to integrate over a collection period of hours and days to weeks. The individual sondes integrate the sampling of particulates passing through a cross-sectional area, wherein they settle into a control volume and thus perform spatial averaging of the mass flux density. Bianchi (2007) has pointed out the need for sampling of water that integrates over spatial and temporal time scales. Sondes allow sampling of fragile flocs and colloidal aggregates that cannot be effectively captured using traditional Niskin bottles as pointed out by Gibbs and Konwar (1983).

The passive sondes thus directly measures mass flux density (g m^{-2} sec^{-1}) to avoid noisy calibration problems and results associated with optical backscatter and acoustic point sensors (Gartner, 2009). The sonde technique is not a point sampling technique typically used to sample water using Niskin or Nansen bottles or "grab" samplers commonly used in water quality monitoring. This open sampling technique allows one to capture or trap flocs and colloidal aggregates that move within the near bottom moving lutocline as the particulates pass thru the sonde cross-sectional area. Previous research suggested that design and construction of smaller sondes might improve the measurement of the vertical or horizontal flux movement of fluid mud (Rotkiske and Bostater, 2016) using sonde arrays. This paper presents results demonstrating the ability of vertical sonde arrays to measure the vertical structure of horizontal particulate fluxes and thus the movement of fluid mud and muck within one approximately one meter from the consolidated mud bottom. The definition of fluid mud has been described by Teeter, et al. (1992) and more recently by McAnally, et al. (2007). The results obtained from horizontal and vertical sediment traps and sondes are used in estimating rate constants used in modeling sediment and nutrient fluxes (DiToro, 2001). An extensive review of techniques and methods previously used to sample muck and fluid mud pointed out the limitations of the previous techniques (Bostater and Rotkiske, 2015). The principle of the sampling of fluid mud using the passive sondes takes into account perturbation theory concerning estimating mass flux density (Q) by direct measurement of a time and space averaged mass flux density ($\overline{\overline{CU}}$) where U is velocity and C is concentration. This directly measured quantity Q (measured by the sondes over a time or deployment period) is composed of an instantaneous flux (CU) that is typically obtained from grab samples. In addition the sondes capture the turbulent flux ($C'U'$) that is not sampled with traditional grab water samplers and a secondary flux ($C''U''$) that occurs due to the presence of wave like structures of mass flux (See Eq. 1). These wavelike structures of mass flux are not sampled via grab sampling techniques that measure an instantaneous point in time. This flux is known to exist and can be observed through acoustic imaging showing internal waves of nephelometric particulate fluxes as shown by Bourgault et al. (2014) as well as Bostater and Rotkiske, (2015), where:

$$Q = \overline{\overline{CU}} = CU + C'U' + C''U'' \quad . \tag{1}$$

METHODS

Sonde Design

The sondes designed to be used within a vertical array are smaller than those described previously (Rotkiske and Bostater, 2016). The sondes were designed using PVC pipe components and computer aided design (CAD) software followed by 3-D printing of components using ABS (acrylonitrile butadiene styrene) plastic filaments. Figure 1 shows an image of one sonde used in an array. The horizontal flux sondes are scalable in size and can be placed in vertical and horizontal arrays as suggested by Rotkiske and Bostater (2016). Fig. 1 shows the vertical sonde array deployed in the field (left) and in the lab (center). The right image shows horizontal flux arrays on the water bottom in a 4 x 2 array configuration used to test the horizontal variation over a 4.5 x 2 meter area. The sondes shown in Fig. 3 are constructed from PVC components.

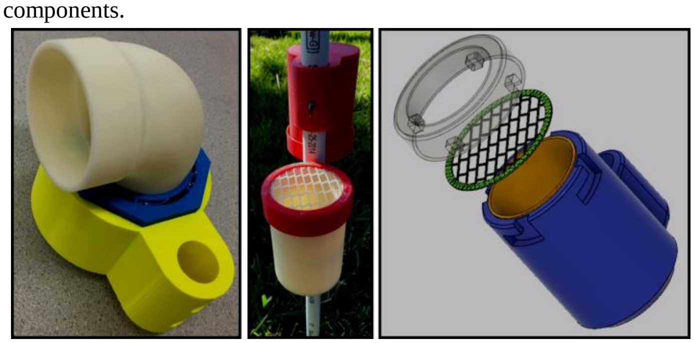

Fig. 1. Fluid mud sondes created using 3-D printers based upon computer aided designs originally described in Bostater and Yang (2014) using off-the-shelf PVC components.

Sonde Array Deployments

Multiple horizontal flux sondes can be deployed horizontally or vertically in the form of laterally spaced or vertically stacked arrays. In this paper results are presented from multiple deployments of a vertical array of eight sondes. The cross-sectional circular opening of each sonde is 84 cm^2. The vertical arrays are created by stacking the individual horizontal flux sondes using the integrated mounts created from a 3-D printer or using PVC sondes designed from readily available PVC pipe components. The sondes are stacked into vertical arrays using mounts attached via machine stainless screw. They were deployed near Palm Bay, Florida indicated in Fig. 2. Fig. 3 shows a PVC array in the lab and when deployed in the field. Six sonde flux array deployments were conducted from August 1, 2016 thru Nov. 12, 2016. Deployment periods ranged from 1 day to 56 days.

Daily rainfall during each deployment was obtained from the nearest National Weather Service (NWS) rainfall station located at Melbourne Florida airport (KMLB). Stream flow for Turkey Creek is influenced by tidal variations at the nearest United States Geological Survey (USGS) gauging station. Tidally filtered flow rates in cubic feet per second (CFS) are reported for this nearby flow gauging station (number 02250030). The watershed drainage area at this location is 272 km^2 and is approximately 182 meters from the sonde array deployment location.

The location where the vertical array was deployed is North latitude 28.018316 and West longitude -80.594706 and the area is indicated in Fig. 2. The average water depth at the deployment site is approximately 1.75 m with a cross-sectional area of 52.5 m^2.

Fig. 2. Sondes deployments location in within the Palm Bay watershed, in the Indian River Lagoon region, along the North Atlantic Ocean.

RESULTS

Total daily rainfall during the 2016 deployment periods was 27.14 inches. The results of the first six vertical array deployments are shown in Fig. 4 for August thru September 17, 2017. Hurricane Matthew passed through the study area and the movement of fluid mud and particulates in the lutocline increased as shown in Fig. 5 during the deployment period September 17 to November 12, 2017. The vertical profiles of the horizontal fluxes of fluid mud and muck follow vertical flux (g m^{-2} day^{-1}) profiles similar to previous work reported in Vanoni (1975). The profiles can be described by a form of Burger's differential equation that is similar to an advective-diffusive transport equation that is written in a time variable form given by Eq. 2.

Fig. 3. Vertical array of eight horizontal flux sondes in the field (left), the center image shows the array of sondes in the lab before field deployment. The right image shows the horizontal flux sondes located in a two dimensional array (4.5 x 2 m).

The mean horizontal moving fluxes (Q_z) of fluid mud and fine particulate matter measured as a function of depth (z) can be shown to be a function of the height above the bed (z), or:

$$\frac{dQ_z}{dt} = k_1 \frac{\partial Q_z}{\partial z} - k_2 \frac{\partial^2 Q_z}{\partial z^2} \quad , \tag{2}$$

The method used to estimate the coefficients k_1 and k_2 in Eqs. 2-3 has been outlined in Bostater, Rotkiske and Oney (2016).

A steady state solution to Eq. 3 used to describe the vertical profiles of the steady state horizontal bedload material Q(z) captured using the sondes (see Figs. 4-5) can be written as:

$$Q(z) = Q_h \exp\left[-\frac{k_1}{k_2} z \right] \quad , \qquad (3)$$

where Q_h is the mass flux value measured by a sonde at h=0 in the lutocline at or just above the bottom.

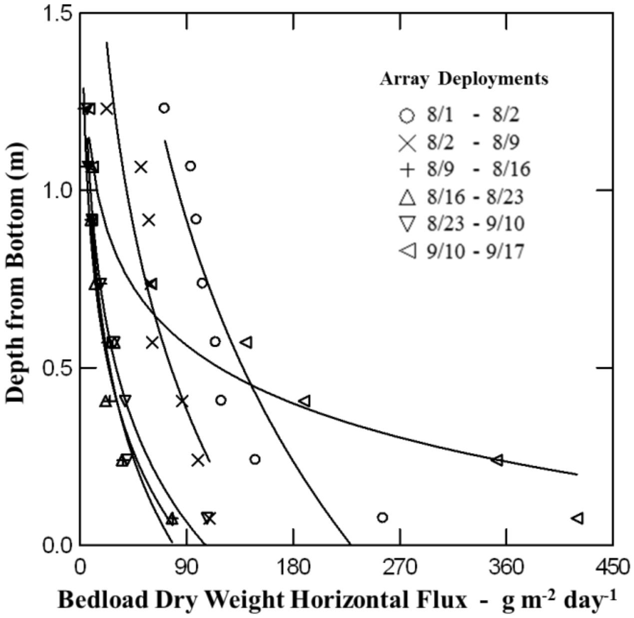

Fig. 4. Fluid mud vertical array profiles results from sonde deployments from August through September 17, 2017.

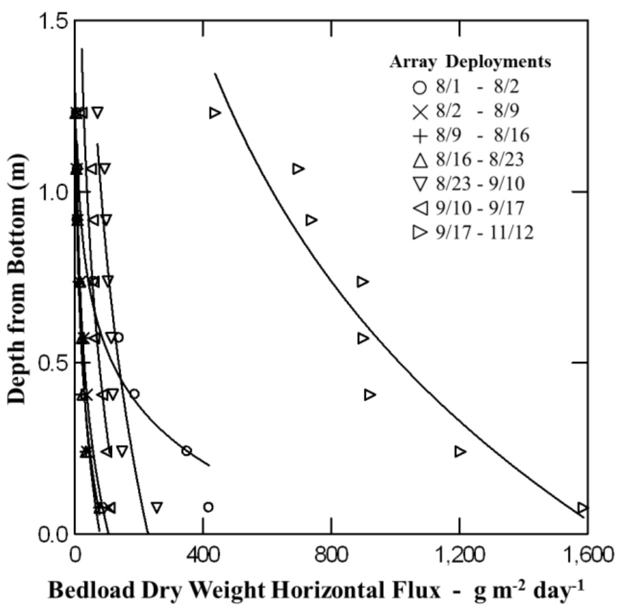

Fig. 5. Fluid mud vertical array profiles results from sonde deployments from August through November 12, 2017. The influence of hurricane Matthew caused a 4 fold increase in the movement of particulates within the lutocline at the water bottom at z=0.

The constants k_1 and k_2 are proportional to (1) the net vertical settling and resuspension flux rates of particulates and (2) to the vertical dispersion of the particulates due to turbulent kinetic energy (TKE) fluxes and cross correlation between the vertical mass fluctuating fluxes Q_z' and vertical turbulent velocities w' obtained from application of a Reynold type decomposition.

Previous analysis was performed (Bostater and Rotkiske, 2015) to indicate the precision of horizontal mass flux estimates using the sondes located in the lutocline. Triplicate deployments resulted in the coefficient of variation ranging from 0.125 to 0.147. Thus, measurement error is expected to be approximately 14 percent based upon the procedures recommended by the US Environmental Protection Agency (EPA, 1984).

Extrapolation of data to the cross-sectional of the tidally influenced stream suggests 54.98 +/- 7.69 metric tons of particulates (dry weight) moved downstream as bedload material within the lutocline from August 1 to November 12, 2016. Extrapolation to an annual basis suggests 194.84 +/ 27.8 metric tons of bedload fluid mud and muck moves downstream towards Palm Bay and the Indian River Lagoon.

Extrapolation of the above results to obtain loading rates that can be applied to the estuary, river, or stream cross-sectional area (m^2) requires knowledge of the watershed drainage area (km^2) and daily rainfall in inches (based upon the nearby Melbourne, Florida airport rain gauge). During the study period the bedload or moving lutocline mass loading rates (g km^{-2} $inch^{-1}$) are estimated. The results from the study period (August-November 12, 2016) are estimated to be 7.52 +/- 1.05 kg km^{-2} inch $rain^{-1}$.

CONCLUSIONS

The protocol for deployment and retrieval of vertical sonde arrays to measure fine bedload particulate fluxes within in the moving lutocline allows one to conduct near continuous sampling for extended time periods. In this paper the results reported are samplings occurring for a total of 104 days during 2016.

The technique to measure the mass flux or movement of particulates does not require expensive equipment or external power requirements. Shallow water deployments are accomplished by a swimmer or diver. Deep water deployments using autonomous underwater vehicle techniques are being evaluated for future research.

Previous methods to measure bedload particulate transport and movement has been published the International Standards Organization (ISO, 1997) Technical Committee ISO/TC 113. No standard methods exist to measure fine grain muds and fluid mud movement in the lutocline in streams, rivers, and marine waters as described.

A review of other techniques, including optical and acoustical techniques was described by Bostater and Rotkiske (2015). This review also indicated no method exists that samples the mass flux density over extended time periods. The need for methods that sample over space and time was pointed out by Bianchi (2007). The technique of using the vertical sonde arrays also allow for an *in-situ* method to measure the nepheloid layers with internal wave features reported by Bourgault, et al. (2014). The technique of using vertical arrays of sondes to measure fluid mud provides a needed instrument method and sampling protocol for quantitative sampling of fluid mud movements in the marine environment as discussed by Waters (1987).

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