Understanding particle-mediated contaminant transport through real-time monitoring

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Abstract*- Aquatic particles represent a significant sink for hydrophobic contaminants including Poly-Chlorinated Biphenyls (PCB). The riverbed of the Hudson River near Ft. Edward, New York is contaminated with PCBs due to the discharge of these chemicals from two General Electric Company (GE) capacitor manufacturing plants into the river from approximately 1947 to 1977. The contaminated sediments continue to be an active PCB source to the water column and biota. GE initiated remedial dredging operations in 2009 to remove the contaminated sediments and subsequently reduce PCB concentrations in fish, river water and sediment, and to minimize downstream transport. To meet these objectives, Environmental Protection Agency (EPA) required GE to follow three engineering performance standards (production, re-suspension and residual) during the dredging operation. Data collected from the River and Estuary Observation Network (REON) are presented in this paper to provide evidence of the capability of the observation network in characterizing particle dynamics which can guide in adaptive dredging operation to meet the objectives, and to track the improvements of water quality due to this remediation action. In this study, the particle dynamics at the Thompson Island Pool (TIP), where high PCB concentrations are found in the sediment and biota, were characterized with respect to stream velocity profiles, suspended sediment concentration and particle size distribution during a flood event. This characterization presented sediment resuspension and advection as potential mechanisms for sediment and sediment bound PCBs transport during a flood event. Moreover, integration of the monitoring datasets with the PCB fate and transport model can serve as a valuable diagnostic tool for investigating the impacts of PCB on the ecosystem of the Hudson River.

Keywords- Observation network; PCBs; sediment re-suspension; dredging; Hudson River.

I. INTRODUCTION

Suspended particles play a significant role in maintaining the balance and health of natural aquatic systems. They exist in different forms, and affect water quality of the system in various ways depending on their types, origins, sizes, shapes, density, etc. They can act as a carrier for transport of hydrophobic contaminants such as in Polychlorinated biphenyls (PCBs). General Electric (GE) Company discharged wastewater containing these pollutants into the Upper Hudson River from two of its capacitor manufacturing facilities in Hudson Falls and Fort Edward, NY over for approximately 30-years until 1977. Much of the contamination was initially sequestered in the sediments upstream of the Fort Edward Dam located approximately two miles downstream of the Hudson Fall capacitor plants [1]. The removal of this dam in 1973 and subsequent high flow events in the mid-1970s transported PCB-containing sediments further downstream. Between 1976 and 1978, the New York State Department of Environmental Conservation (NYSDEC) identified 40 sediment PCB "hot spots" over a 40 mile stretch of the river between Fort Edward and Troy [2]. This site was designated as a U.S. EPA Superfund site in 1983. Thomann et al. (1991) conducted mass balance calculations and found that long-term, chronic releases of PCBs from the sediments can account for the PCB inventory in the water column [3]. To curtail the potential for continued release of buried PCB-containing sediments into the water column, the United States Environmental Protection Agency (EPA) has recommended dredging of the contaminant sediments as a remediation.

GE has been conducting dredging activities under EPA oversight with four human health and environmental objectives as described in the 2002 Record of Decision (ROD): i) reduce PCB concentrations in fish, ii) reduce PCB concentrations in river water, iii) reduce the bioavailable inventory (mass) of PCBs in sediments and iv) minimize the long-term downstream transport of PCBs in the river. GE conducted the initial phase of dredging operations from May 15 to October 27, 2009. During this test phase, dredging occurred at a reduced rate while extensive monitoring was conducted. EPA established three engineering performance standards to realize the objectives of the dredging activities: 1) the rate at which dredging is conducted (productivity), 2) re-suspension of PCBs in the water during dredging (re-suspension) and 3) the level of PCBs left on the river bottom after dredging (residuals). These three standards were not achieved consistently and simultaneously as these requirements often proved to conflict with each other [4]. For example, maintaining a dredging rate consistent with the productivity standard resulted in sediment and PCB re-suspension that exceeded the limit defined by the re-suspension standard. Also, the standard for removing PCBs residues required repeated attempts to scrape small amounts of sediment from difficult, uneven areas that eventually required capping. The delays encountered while attempting to comply with the standards reduced productivity and led to increased re-suspension due to the increased time interval during which the contaminated areas were left open and exposed to the water column. The experiences gathered from the first phase of the dredging activities were considered during the subsequent evaluation period, resulting in revised standards for the full-scale dredging implementation [5]. This second, final phase was initiated in 2011 and is anticipated to continue for five to seven years.

Collecting data from in-situ sensors in near real time can assist in evaluating how well dredging activities achieve the objectives of the remediation. Real-time monitoring data can also guide in implementing adaptive dredging operation. For example, dredging activities could be slowed down or temporarily shut down during the strong current and re-suspension events, which can be detected by real-time in-situ sensors. In addition, real-time data can be used to monitor if the three engineering performance standards are achieved during dredging activities, allowing activities to be adjusted accordingly. Moreover, high-frequency real-time monitoring data can drive PCB fate and transport modeling which can be used as a diagnostic tool to track the progress of remediation activities in improving the water column condition over short and long term. Data collected from our River and Estuary Observatory Network (REON) can be used for these purposes. REON is being developed through a joint venture of the Beacon Institute, Clarkson University, General Electric Inc. and IBM Inc. to monitor New York's Hudson and St. Lawrence Rivers via an integrated network of sensors, robotics and computational technology distributed throughout the watersheds. In this paper, we present datasets collected from our observation network which illustrate the capability of REON in characterizing particle dynamics with respect to stream velocity profiles, suspended sediment concentration, and particle size distribution. This characterization demonstrates the effects of a flood event on sediment re-suspension as a potential mechanism for PCB mobilization into the water column.

II. DESCRIPTION OF THE OBSERVATION NETWORK

REON has deployed three different types of sensor platforms with multiple nodes within the network. The three platform types are: 1) fixed robotic vertical profiler (FRVP); 2) mobile robotic undulating platform (MRUP); 3) fixed acoustic Doppler current profiler (FADCP) (Fig. 1). On the first platform type, an automated profiler system moves a suite of water quality sensors vertically within the water column for periodic measurements at various depths. Two additional in-situ sensors are installed on the platform which record data continuously; a meteorological station, which monitors atmospheric conditions, and an ADCP, which measures the vertical water velocity profiles. This platform is self-powered by photovoltaic panels. An on-board computer receives

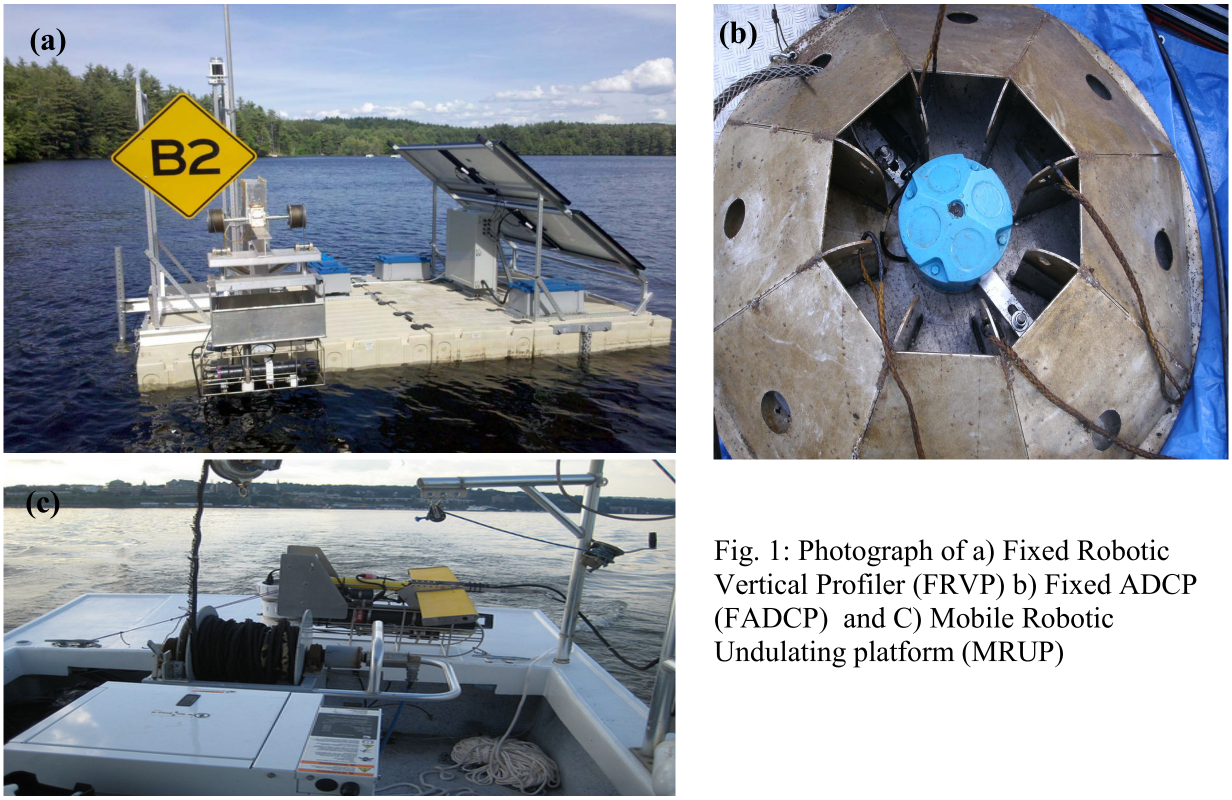

Fig. 1: Photograph of a) Fixed Robotic Vertical Profiler (FRVP) b) Fixed ADCP (FADCP) and C) Mobile Robotic Undulating platform (MRUP)

information from the instruments and serves as a data logger and telemetry control. Remote programming allows for autonomous and cyber control of the sensor array and real time data streaming. The MRUP utilizes an undulating tow-body tethered behind a research vessel to measure the same set of water parameters as the FRVP, but does so 'synchronically' over a highly-resolved spatial regime. The MRUP displays the relative variation of measured parameters in real-time, and thereby guides in selecting the transect route to detect the event of interest. Collectively, the sensors installed on these platforms measure a wide variety of environmental parameters, including waterborne particle size distribution, optical back scatter, currents/ shear/ turbulence, conductivity, temperature, depth, chlorophyll "a", fluorescein, colored dissolved organic matter, dissolved oxygen, wind speed and direction, barometric pressure and air temperature. The third platform type is the fixed ADCP, which is installed in a fixed location in the water body to continuously monitor the water current profile. This platform is cabled to an onshore control station, which provides power to and communication with the sensor unit.

Fig. 2 displays the location of deployed REON continuous monitoring platforms (i.e., FRVP and FADCP) in 2010 on an interactive Google map. Each location of the REON monitoring platforms are represented as "push-pin" marker in the figure and these markers are linked with color-coded contour plot of measurements for a specified time (e.g., the last 24 hours, last 7 days, or last 30 days of measurement). These measurements are made available to the users in near real time through our developed cyber infrastructure [6]. This real-

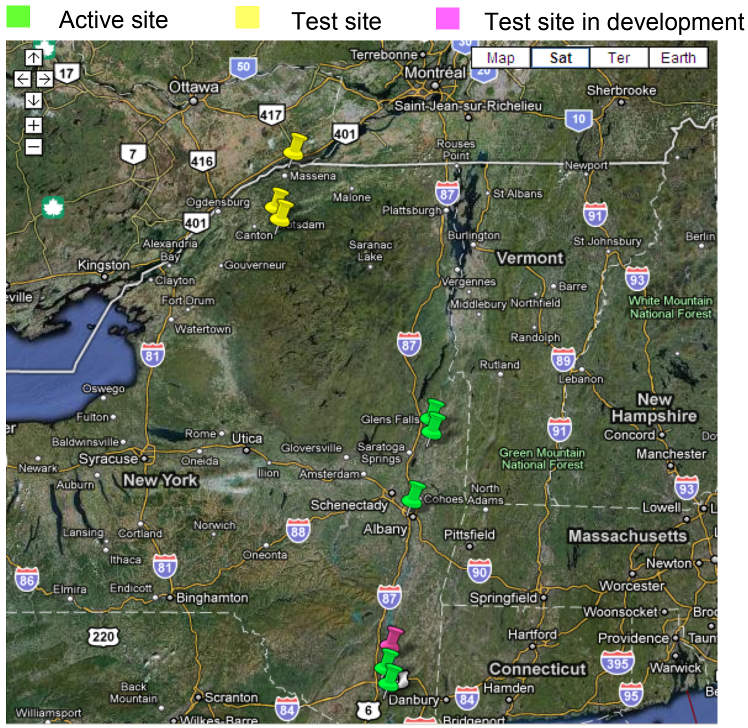

Fig. 2: Location of REON monitoring platforms in 2010

time availability of measured data will help to implement adaptive management strategies in restoring and maintaining health of the natural aquatic system.

We have also implemented a data visualization system that displays transect routes of surveys conducted with the MRUP on a Google-interactive map. Fig. 3 shows the transect route of one such survey made during 2010. This color-coded line is placed along the top and bottom of figures displaying contour plots of the various measured parameters, visually matching the observed data with the location of measurements. These representations provide opportunities to understand the spatial variation of measured parameters and to explore the dynamics controlling various important environmental phenomena. Example datasets from the MRUP are presented in the results and discussion section. This mobile system will be deployed in the upstream of the river during the dredging activities in 2011. The large spatial datasets collected from this monitoring platform will assist in tracking particle movement during the dredging operation. Moreover, data can be used in initialization and verification of PCB fate and transport model.

III. MATERIALS AND METHODS

A FRVP was installed in the Upper Hudson River in the Thompson Island Pool (TIP) (Latitude: 43° 11'44" N, Longitude: 73° 35' 06” W) near Fort Edward, NY from June 22 - October 20, 2010. The highest PCB concentration in the sediment bed and biota in the region has been found to be located in the TIP [7]. The platform was located about 750 m above the Thompson Island Dam, and was moored using six 100 lb mushroom anchors (four upstream for anchoring and two downstream for stabilization). The computer-controlled autonomous robotic profiler recorded measurements at five evenly spaced depths once per hour. The water quality sensors included in the profiler system are a particle size analyzer (LISST-100X; Sequoia Sciences, Inc.), a dissolved oxygen sensor (Optode; Aanderaa), a conductivity, temperature and depth (CTD) sensor (SBE 37 SIP ‘‘Microcat’’; Sea-Bird Electronics, Inc.), and a fluorosensor (Eco-FL3; WET Labs Inc). A 1200 KHz downward-looking ADCP is mounted on the platform to

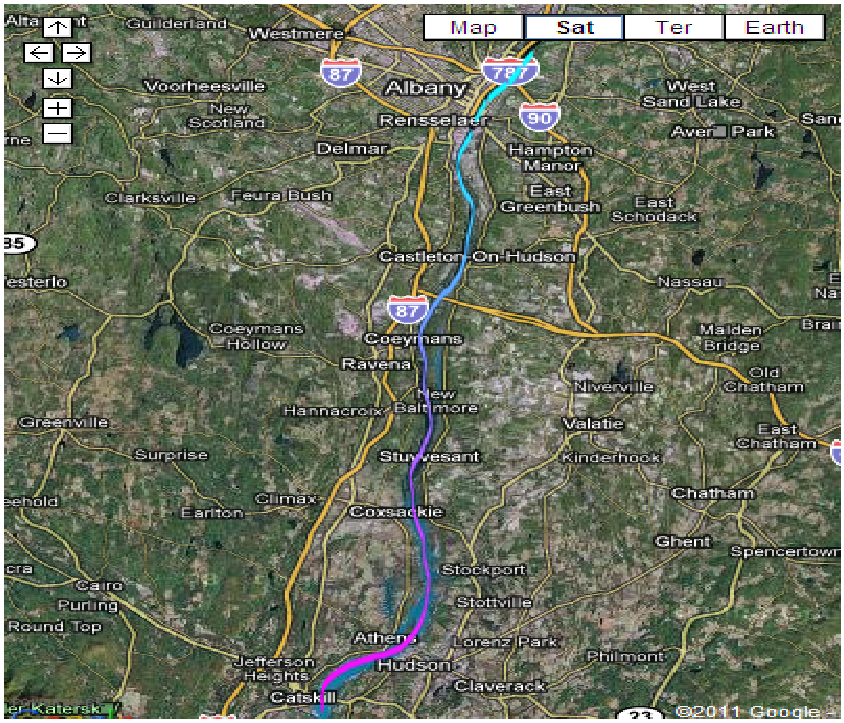

Fig. 3: Transect route of the cruise made on July 21, 2010 on Google interactive map.

provide continuous water velocity and acoustic backscatter intensity at one-minute intervals. All sensors were calibrated prior to deployment, and the accuracy of the sensors was tested following the retrieval of the platform. In this paper, we have also used stream flow measurements from the USGS gauging station at Fort Edward, NY (Latitude 43°16'10", Longitude 73°35'47) in the analysis. Data from this site was imported using CUAHSI Hydrodesktop toolbox [8], and MATLAB software (The MathWorks, Inc.) was used in the post-processing and analysis of datasets.

IV. RESULTS AND DISCUSSIONS

Data collected from a FRVP monitoring station in the Thompson Island Pool is presented here to illustrate the capability of our monitoring network to characterize how a flood event contributed to particle-mediated contaminant transport in the river. This characterization also provides evidence of the capability of our system in resolving particle dynamics during dredging operation which may re-suspend sediment as was observed during flood event. A precipitation event at the end of June, 2010 resulted in a significantly elevated stream discharge. Figure 4 displays the variation of river discharge at the USGS Fort Edward gauging station which is located a few kilometers upstream of the TIP monitoring site. Storm discharge levels began to increase on June 28, reached a peak on July 1, and gradually receded thereafter. The ADCP sensor installed on the FRVP captured the vertical profile of the water current during this high-flow event. Vertical profiles of the northerly and vertical components of water current are displayed in color-coded plots in fig. 5 (a) and fig. 5(b), respectively. The negative magnitude of the northerly current component indicates that current is moving southward (downstream). The southerly water current increased considerably during the occurrence of the high flood event (June 28 to July 3) as shown in Fig. 5(a). This strong southward current can be expected to expedite the transport of particulate matter downstream. Negative magnitude of vertical current component, reflected by the blue colors in Fig. 5(b), represents downward movement

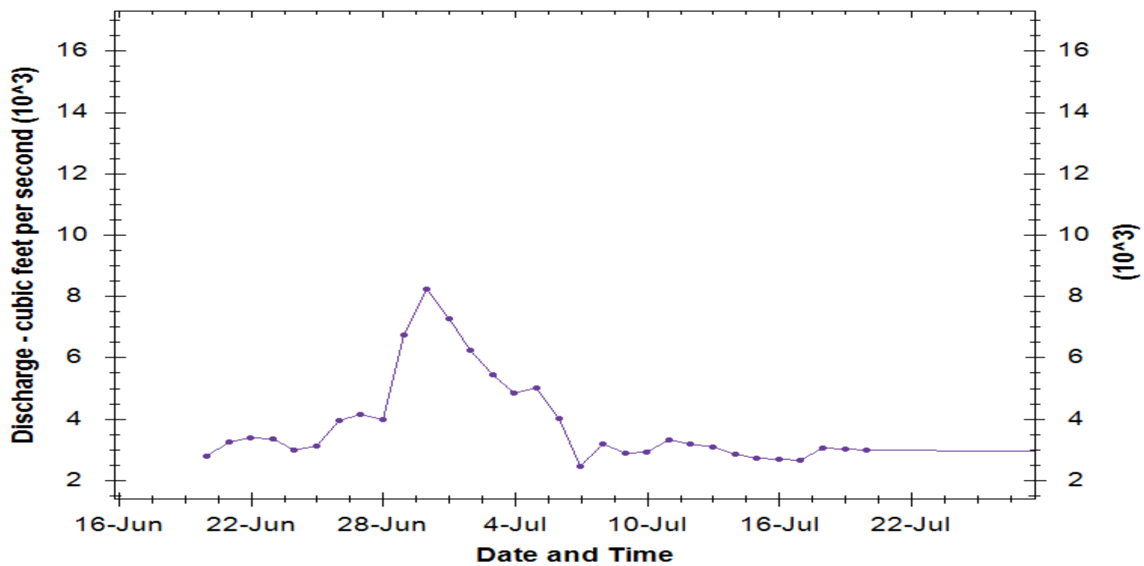

Fig. 4: Storm discharge variation at USGS gauging station at Fort Edward which is close to the monitoring site

of water (i.e. , into the river bottom), whereas positive values mean water is moving upward. The magnitude of this vertical component of water current displays a strong vertical gradient within the water column. The dark blue color at the upper level of the water column suggests strong downward movement of water current during the occurrence of high flood event. This downward movement of water might result from the high outflow over the dam, 750 m to the south. The occurrence of upward movement of water current at the lower level of water column during the early stages of each intermittent current spike suggests that sediment might re-suspend under these conditions. Moreover, the vertical gradient in the northerly component of water current near the bed at the beginning of the storm provides evidence of shear stress within the water column which is strong enough to overcome the critical bed stress necessary to re-suspend the bottom sediments.

Data collected from the LISST particle size measurements shows the sediment re-suspension associated with the high-flow event. Figure 6 presents the variation of the vertical profile of particle concentration during the same time period as that shown in Figure 5. Blue color denotes low particle concentration whereas red color represents higher concentration. By comparing figures 5(b) and 6, it is clear that particle concentration was very high at all water column depths after the initial occurrence of upward current at the later part of June 29. However, particle concentration decreased after a matter of hours, while strong southward current persisted for over two days. This observed particle concentration reduction was likely due to the removal of re-suspendable particles from the surface sediment layer by the initial flood current, after which bed-armoring prevented further erosion of sediment bed [9]. Moreover, high bed stress resulting from the persistent strong southward current prevented particle deposition, indicating that the particle load was being transported downstream. The absence of vertical gradient in the particle concentration data also supports the hypothesis of downstream movement of sediment instead of deposition around the monitoring site.

Particle size spectra captured by the sensor at the monitoring site can shed further light on particle-mediated contaminant transport in the water column. Smaller particles pose a greater risk of exposing contaminant in the water column than larger particles, for two reasons. One, smaller particles have larger surface area/ particle volume ratio than larger particles. This translates to a larger adsorptive surface for

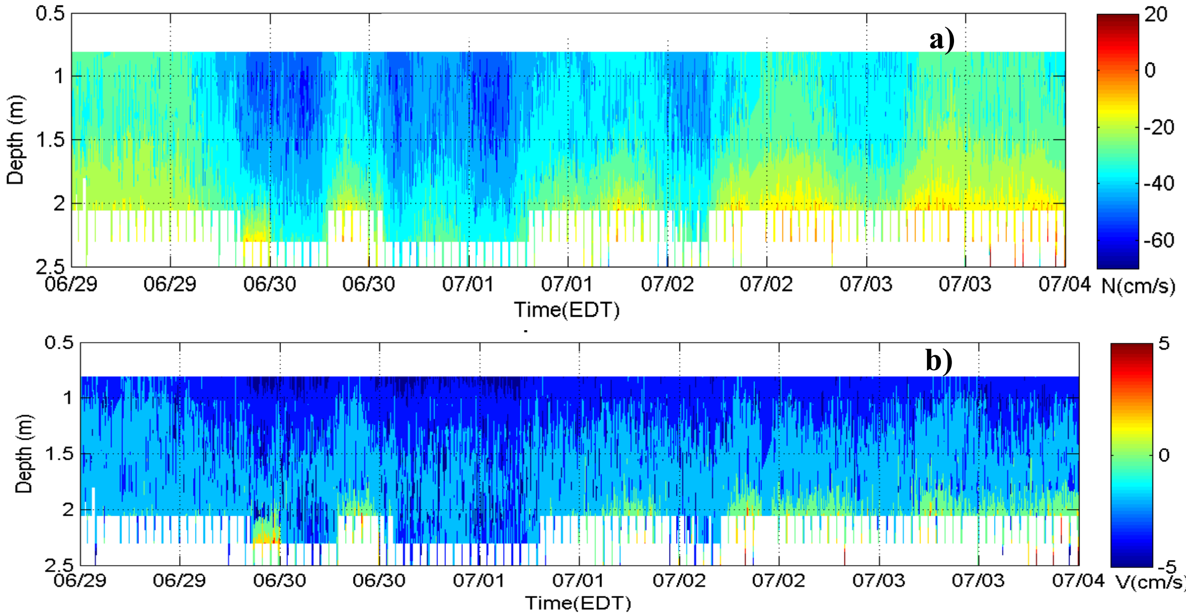

Fig. 5: Vertical profile of a) North component and b) vertical component of water current at the TIP monitoring site from June 29 to July 04, 2010

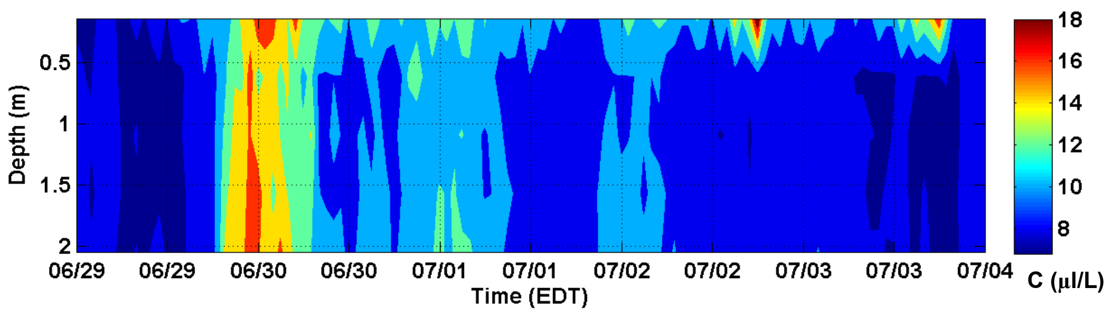

Fig. 6: Vertical profile of particle concentration variation at the TIP monitoring site from June 29 to July 04, 2010

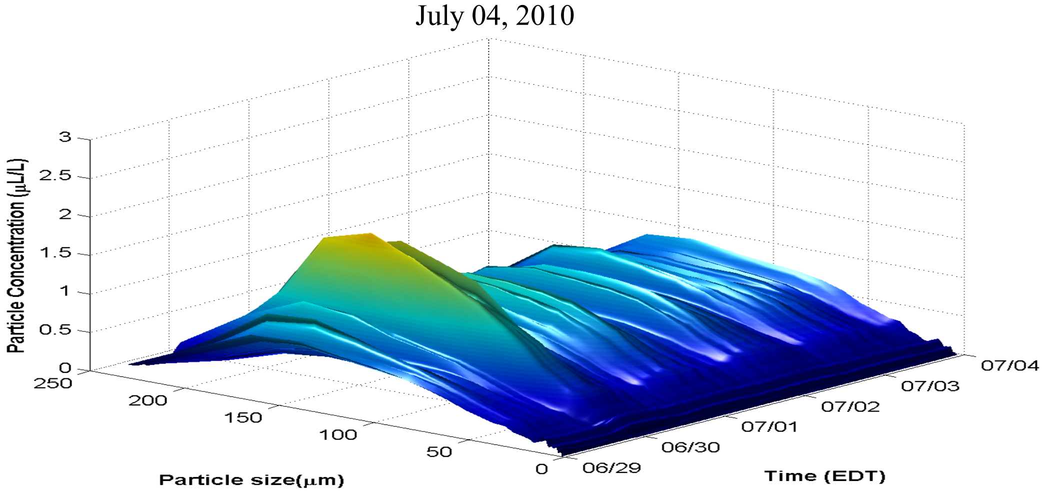

Fig. 7: Particle size spectrum variation at a depth of 1m at the TIP monitoring site from June 29 to July 04, 2010

contaminants per unit mass than larger particles. Second, smaller particles can remain suspended in the water column for longer period of time, as defined by Stoke's settling velocity. Particle size variations with time at one depth level of measurements are shown in Figure 7 where the x-axis represents the time, the y-axis represents the particle size, and the vertical axis shows particle concentration at each size category. Particle concentration at all measured size categories (1-250 µm) increased following the re-suspension event (Fig. 7). However, particle concentration peaked at sizes near 180 µm suggesting that re-suspendable particles (silt, clay, fine to medium sand and particulate organic matter) are aggregated due to the strong flow caused by precipitation event. This aggregation can change the porosity and density of the particles and therefore flocculation process might play a critical role in transport of particles within the water column. Presence of smaller particles at elevated concentrations during the re-suspension event and stronger southward current suggest that these smaller particles might move further downstream before deposition in the bed.

Simultaneous measurement of water current and particle concentration through our real-time monitoring system provides a unique opportunity to determine the critical bed shear stress, which is an important parameter in characterizing particle dynamics during a re-suspension event. Moreover, shear stress combined with particle concentration provide critical information to adjust dredging activities to meet sediment re-suspension and residue criteria established by the EPA. Fig. 8 shows the depth-averaged measured particle concentration and north component of water current at the TIP site for the same time period discussed in the previous figures as blue and green lines, respectively. Fig. 8 provides further evidence of the bed erosion due to the storm-induced water current. Particle concentration in the water column dramatically increased toward the end of June 29 when strong flow significantly raised the magnitude of the water current. Also, the particle concentration in the water column never returned to the level of this initial re-suspension during the time period presented, even as the water current later returns to the same high magnitude associated with the initial re-suspension. This suggests that most of the re-suspendable particles from the surface sediment might enter into the water column during the initial stages of the high-flow event. Much stronger shear stress would thus have been needed to further erode the sediment bottom. Although it is possible that the precipitation event might have transported considerable amount of sediment from upstream of the monitoring site, the simultaneous increase in water current and particle concentration suggests that re-suspension was also a critical factor in increasing sediment load in the water column. Sediment transport modeling could be used to investigate the relative importance of these two transport mechanisms in controlling particle dynamics within this portion of the river.

A flocculent transport model developed in our laboratory to understand the fate and transport of particles in the natural system [9-14] can be applied to understand particle dynamics in the contaminated sites of the upper Hudson River. Data collected from MRUP can be used to initialize and validate the flocculent model as this system can measure the spatial variation of the particle size spectrum along with other hydrodynamic and water quality parameters. Figure 9 displays example datasets that were collected in the estuarine Lower Hudson River on June 01, 2010. This figure shows the variation of particle size spectrum along the transect route of the survey at a depth of 2m. The inset plot of the figure shows the transect route. This color-coded line is presented along the Y-axis of the figure to allow visual correlation of the measured datasets with the location of measurements. The vertical axis denotes the concentration of particles. As the MRUP moves the sensor suite through water column, it provides the three-dimensional (latitude, longitude and depth) variation of the particle size spectrum. This platform will be deployed in the Upper Hudson River during the second phase of dredging activities. The measured datasets from this platform, along with the continuous monitoring datasets at the TIP site, will provide valuable information to drive the flocculent transport model.

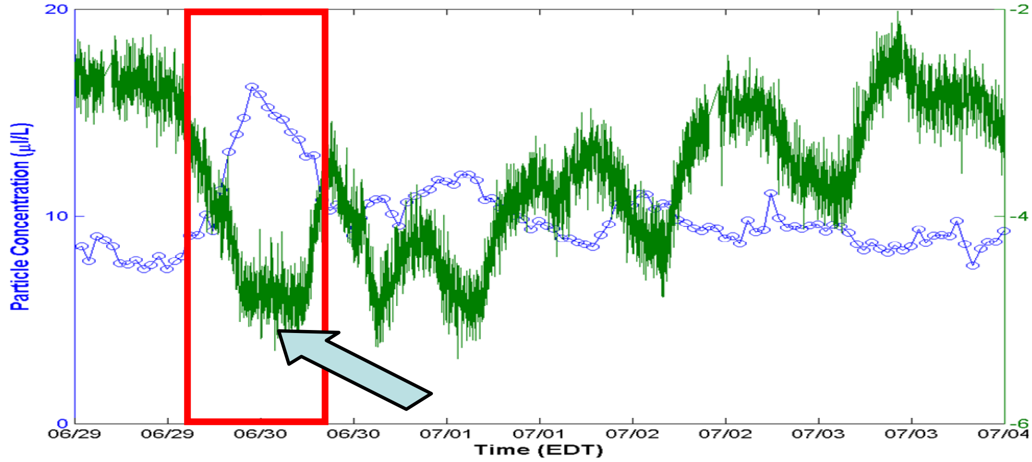

Fig. 8: Depth-averaged water current (green-colored line) and particle concentration (blue-colored line) variation at the TIP monitoring site from June 29 to July 04, 2010.

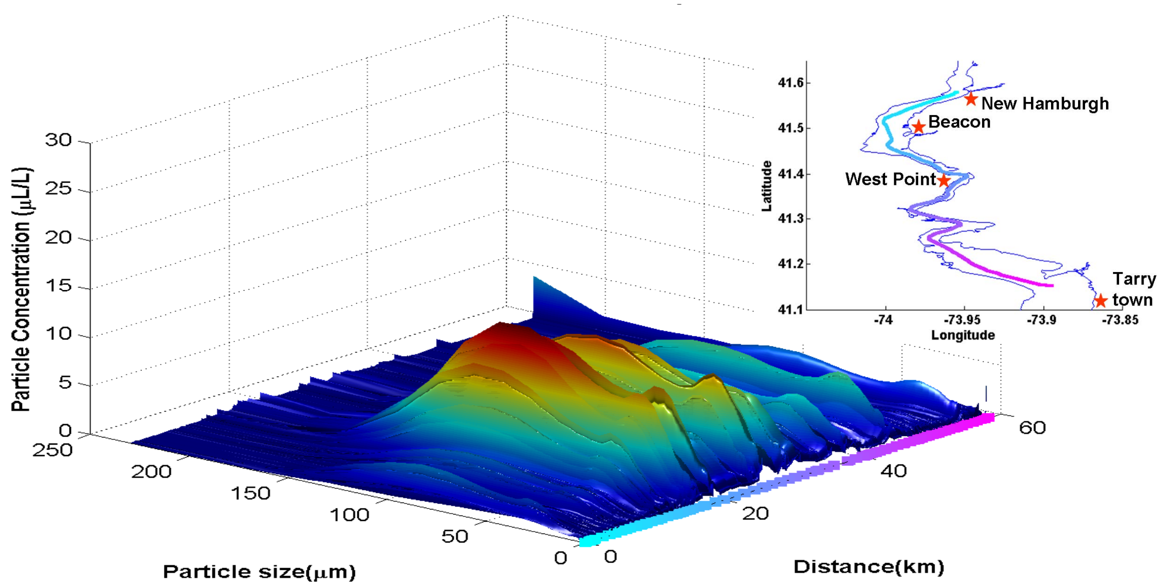

Fig. 9: Example dataset from MRUP: Particle size variation at a depth of 2m along the transect route of the cruise which is shown as color-coded line in the inset plot.

The flocculent transport model can be linked with the toxicant sub module of Water Quality Analysis Simulation Program (WASP) which has been used for a variety of contaminant fate and transport, and water quality applications over the past several decades [15,16]. WASP provides a dynamic, mass-balance framework for modeling the fate and transport of a variety of contaminants in surface water systems. The output of the linkage model will guide in understanding the impact of dredging and could aid in tracking the improvement of water quality following the remediation activities over a short and long time period.

V. CONCLUSION

Real-time monitoring data from REON can assist in understanding contaminant transport in the water column. Hydrodynamic and water quality data measured during the flood event suggests that sediment re-suspension and advection are the potential mechanisms for PCB mobilization into the water column during this event. Characterization of particle size distribution shows that aggregation kinetics is an important mechanism affecting particle dynamics during a flood event. The real-time monitoring data from our observational network could guide in implementing adaptive dredging operations to achieve remediation goals. Integration of these monitoring datasets with the PCB fate and transport model can serve as a valuable tool to track the improvement of water quality due to this remedial action over a short and long term.

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