REAL TIME SEDIMENT PLUME TRACKING FOR COMPLIANCE MONITORING DURING DREDGE AND DISPOSAL OPERATION

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ABSTRACT

Today's stringent environmental regulations require comprehensive, highly defensible monitoring and assessment of sediment resuspension during dredging and disposal operations. Monitoring the fate and transport of potential contaminant releases to the aquatic environment is a critical compliance element for clean-up, remediation, maintenance, and other activities. Increasing restrictions on offshore disposal are resulting in the use of more and more nearshore options such as Confined Aquatic Disposal (CAD) cells. Disposal operations at CAD sites are highly scrutinized by regulators and the environmental community because the material being placed into the CAD is usually relatively contaminated (otherwise it would have been placed offshore or beneficially used) and there is concern over the impacts of this material being resuspended and deposited outside of the CAD. It has become increasingly evident that high resolution sediment plume tracking studies can substantially contribute to monitoring programs and defensible environmental evaluations. A series of case-studies are presented to describe several different applications and methodologies for plume tracking. Each of the systems described employ real-time *in situ* data on water quality characteristics and plume behavior, with the ability to simultaneously obtain water samples for other contaminant measurements (PAH, PCB, metals, etc). The ability to integrate continuous water collection with *in situ* measurements in real-time provides unparalleled accuracy for spatial and temporal mapping of sediment plumes and water quality characteristics. Discrete samples enable laboratory analysis to ground-truth electronic measurements as well as link easily measurable tracers (e.g. turbidity, fluorescence) to specific contaminants. Based on the application a variety of systems may be used. These include towed arrays which cover large spatial scales in deeper waters and rigid systems which capture fine scale changes in shallow water areas at multiple depths simultaneously. Highlighted projects include resuspension tracking of dredge and disposal operations in the Northwest and Northeast. These programs have shown success at tracking plume behavior on time scales from minutes to several days. The use of these systems is transforming the way science and public agencies address compliance programs.

Keywords: Capping operations, fate and transport, high resolution turbidity mapping, water sampling, resuspension

INTRODUCTION

Estimates by US EPA (2004) indicate approximately 10% or 0.92 billion cubic meters (1.2 billion cubic yards) of the sediment underlying the country's surface water is sufficiently contaminated with toxic pollutants to pose potential risks to fish and to humans and wildlife that eat fish. Currently, the primary remedial options for contaminated sediment sites are dredging, capping and monitored natural recovery. Dredging can have adverse short-term effects due to resuspension of sediments and subsequent release of contaminants. Adverse effects can be expressed as increased toxicity/bioaccumulation due to contaminant release, enhanced downstream transport of contaminants with subsequent contamination of uncontaminated areas, and/or physical habitat disruption (Kravitz and Timberlake, 2002; Berry et al., 2003). Additionally, residual contamination due to redeposition of suspended sediments can reduce the long-term effectiveness of the remedy. The degree of resuspension and release is often site specific and is influenced by a wide variety of factors (Herbich and Brahme 1991, Collins 1995, Johnson and Parchure 2000, Pennekamp et al. 1996, Hayes and Wu 2001) including sediment type and current regimes. Dredge type, operational methods, best management practices, and operator skill also contribute to variability in the levels of resuspension. Recent analyses suggest that the mass of sediment resuspended range from less than 1% to as high as 9% (Hays and Wu 2001; NRC 2001). In addition to actual dredging operations, dredge related activities such as debris removal and sediment disposal are also associated with significant levels of sediment resuspension.

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Sediment plumes resulting from dredging and dredge material disposal show substantial temporal and spatial variability. The suspended sediment loads in the immediate vicinity of the operations are typically much higher than ambient levels and decreases rapidly away from the source (Goodwin and Michaelis, 1984). Numerous modeling approaches have been developed in an effort to characterize sediment plume behavior (Nakai, 1978; Wu and Hayes, 2000; Hayes et al. 2000). However, most of the presently available models still have a high degree of uncertainty and limitations. In many cases model applications may over or underestimate sediment resuspension rates by orders of magnitude (Israelsson and Connolly, 2001). Decoupling of contaminant concentrations from sediment loads in the water column can further underestimate environmental risk of suspended sediments (Steuer, J., 2000).

Regardless of site specific attributes, one goal is universal to every monitoring program – risk reduction. During dredging operations, risk from resuspended sediments takes a number of forms. Ecological and human health risks are associated with redistribution of contaminants at the site as well as transport away from the site. The presence of contaminates in the water column during resuspension events poses additional acute health risks to humans and other organisms. Ecological risks are present where primary production, fish predation, and seagrass health are impacted by turbidity in the water column. Financial risks to both funding agencies and contractors are present when redeposited sediments require additional dredging efforts. By fully characterizing sediment resuspension and transport events, dredge programs are able to reduce these risks through mitigation controls.

Due to the variability in sediment resuspension between sites and operations, generalizations regarding resuspension rates and volumes are challenging at best. As a result, site-specific monitoring programs are frequently warranted. The consideration and selection of the proper approach to monitoring resuspended sediments and their fate and transport are the subject of this paper. A series of case studies using different sampling approaches in a variety of sites and conditions are compared and their applicability to other sites are presented. The general conclusion is that adaptive sampling approaches which incorporate high resolution *in situ* data collection with discrete sample collections are the most effective method for fully characterizing sediment plumes. These approaches provide the highest level of defensible data support risk reduction at a number of levels.

PLUME MONITORING SYSTEMS

Plume monitoring systems consist of four major subsystems:

- **Sensor Suite** which is used to measure suspended solids resulting from dredging, capping, and resuspension operations.
- **Data Acquisition System** which collects the sensor readings, displays the data in real-time for adaptive sampling, and tracks time and location of collected water samples.
- **Water Collection System** which provides discrete samples to calibrate *in situ* readings, and for conducting analysis of contaminates of concern.
- **Deployment Subsystem** which positions the sensor suite and water collector at the desired locations.

The Sensor Suite and Data Acquisition System are described below. Three systems that combine the Water Collector and Deployment Subsystem are also described.

Sensor Suite

The typical main unit of a sensor suite is a data logger with three basic physical oceanography measurements: conductivity, temperature, and depth (CTD). These CTD units include extra analog to digital channels which allow for the connection of a variety of other sensors. For tracking dredging, capping, and resuspension operations, one or more turbidity sensors (optical back scattering [OBS]) and transmissometer (beam attenuation) are usually part of the sensor suite. Transmissometers determine turbidity over relative long path lengths and therefore provide much higher sensitivity to suspended particles relative to OBS sensors. Thus transmissometers are excellent for defining the edges of sediment plumes. However, in higher turbidity regimes these sensors are less effective with an ability to handle total suspended solids (TSS) concentrations only up to about 40 to 90 mg/L depending on the type of suspended material. Figure 1 shows a comparison of transmissometer readings to about 400 collected water samples which were analyzed for TSS. Although less sensitive at the low end, optical backscatter turbidity sensors can be configured to operate in ranges up to 2000 mg/L. Additionally, OBS sensors are fairly rugged and inexpensive compared to transmissometers and are therefore well suited to operating in the harsher environments of high turbidity areas. The lower sensitivity of a OBS sensor is about three times higher than the transmissometer, thus using a combination of these sensors can provide improved resolution over a greater range.

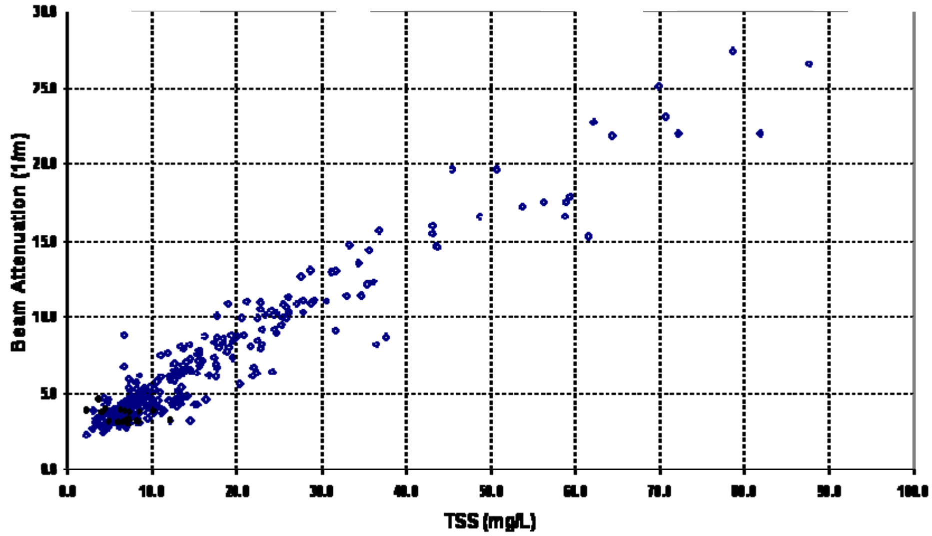

Figure 1. Results of calibrating transmissometer to measured total suspended solids.

Real-Time Data Acquisition System

Real-time data acquisition and display is a critical element of sediment plume tracking programs. The ability to react to instantaneous field data allows for adaptive sampling programs. Because sediment plume behavior is so variable on both spatial and temporal scales accurate characterization of a plume depends on the ability to modify sampling locations quickly. Additionally, a wide range of data must be captured and integrated to provide a full characterization of the plume. Data sources which contribute to plume assessment include the water column sensors (CTD, OBS, transmissometer, etc) and navigational equipment (GPS, echosounder, etc). Systems such as Battelle's internally developed software package NavSam© integrate all these data sources to support real-time field efforts and provide the capability to process the data for later interpretation. Figure 2 shows the real-time NavSam© display during a dredge material capping survey. In addition to data acquisition NavSam© provides:

- Survey Planning
- Worksheets for Station logs and sub-samples
- Electronic ledger
- Real-time generation of sample container labels with barcodes
- Generation of custody forms
- Reconciliation of COC and sample containers
- Summary Table of sampling events
- Tabular and graphic output of collected electronic data
- Easy transfer of data into program database.

Figure 2. Real-time data acquisition system in use during capping operations.

Vertical Hydrocast System

Vertical hydrocast systems are a traditional oceanographic sampling approach. These systems are often used for sediment resuspension monitoring. These systems deploy a sensor suite (as described above) to profile the water column along a single vertical cast. Real-time data is provided the shipboard crew through the use of data integration software packages (such as NavSam©) or more simple hand-held devices. Water collection systems such as pumps or discrete bottles (e.g. Niskin) are frequently added along with the sensor suite to provide water samples for analysis. Vertical hydrocast systems range from the very simple, lightweight hand-held systems which can be deployed from small vessels to complex rosette systems which operate in deep water from larger vessels. Figure 3 shows photos across the range of these systems.

Vertical hydrocast systems are generally operated in pre-planned sampling strategies. This allows for well designed sample spacing often based on modeled or expected plume behavior. Advantages of this approach include simplicity in the field and gridded sample spacing to meet specific objectives. Disadvantages include limited horizontal data coverage and reduced ability to adaptively react to plume behavior.

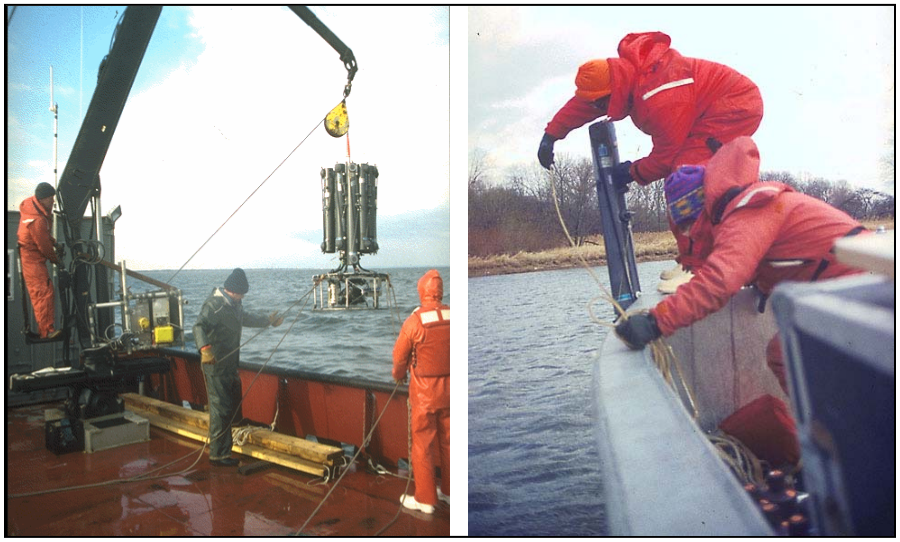

Figure 3. Views of vertical hydro-cast systems.

Towed Body System

Towed body systems or towed profilers rely on a towed body that can be profiled up and down vertically in the water column while simultaneous acquiring horizontal data by being towed by a vessel. Profiling is achieved either by winching the towed body up or down, control surfaces on the towed body, gravity free-fall, or combinations of these. The tow body serves a platform for the sensor suite and water sampling systems. Data from the sensors and water from the sampling system is brought to the surface in real-time via the tow cable. Towed profiler systems such as the Battelle Ocean Sampling System (BOSS) integrate *in situ* measurements with continuous water collection, navigation, sample tracking, and real-time display for rapid mapping of physical and chemical characteristics of waters. Figure 4 shows the BOSS towed body being deployed of the stern of survey vessel, as well as a close up of the sensor suite. The sensors in the figure include a CTD, transmissometer, and fluorometers, as well as a pump for provided discrete water samples.

The advantages of towed body systems include high resolution data acquisition in both horizontal and vertical planes, adaptability in response to real-time data, the ability to collect large volumes of water instantaneously so that any contaminant of concern can be targeted for analysis, and effectiveness in relative deep waters. Additionally, towed body system can be easily customized to carry virtually any sensor. Potential disadvantages of towed profilers is their relatively low horizontal profile spacing compared to the near-field width scale of dredge plumes in shallow waters, and difficulty in safely mapping near-bottom.

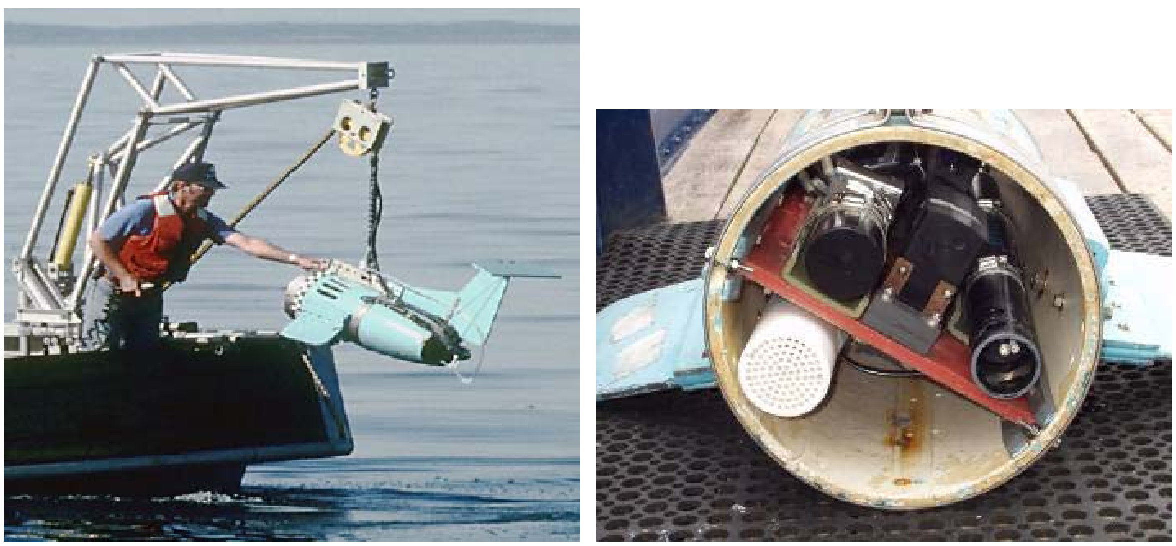

Figure 4. Views of Battelle ocean sampling system.

Multi-Depth Water Sampling System

The Multi-Depth Water Sampler (MDWS) consists of segments of aluminum piping to create a sampling wand which can be customized from 4 to 10 meters long. Two winches are used to pivot the wand up and down in the water column from a pin positioned on the side of the survey boat. At five points along the wand a turbidity/fluorometer sensor and the inlet of a Teflon® tube are attached. The tubing and wiring are protected inside the piping. A pumping system draws water independently and simultaneously from each of the five inlets at 2.5 liters per minute. A CTD located at the end of the wand collects traditional physical water column data. Other *in situ* sensors can be added to the system to customize for specific applications. While the wand is in sampling/collection mode, the survey boat can transit at speeds up to 5 knots; make sharp turns, and even backup. Figure 5 shows several views of the MDWS including: a design schematic, on shore set up, deployment on a small vessel, and a close up of a sensor/water port.

The MDWS can operate at up to 5 knots while continuously recording *in situ* data and providing water from each of the five sampling depths. With integration by the onboard NavSam© system, real-time data contouring is provided. Advantages of the MDWS include increased vertical and horizontal data resolution, increased water collection capabilities, and increased adaptability to real-time conditions. Disadvantages of the system include the limitation of sampling depths to 10 meters.

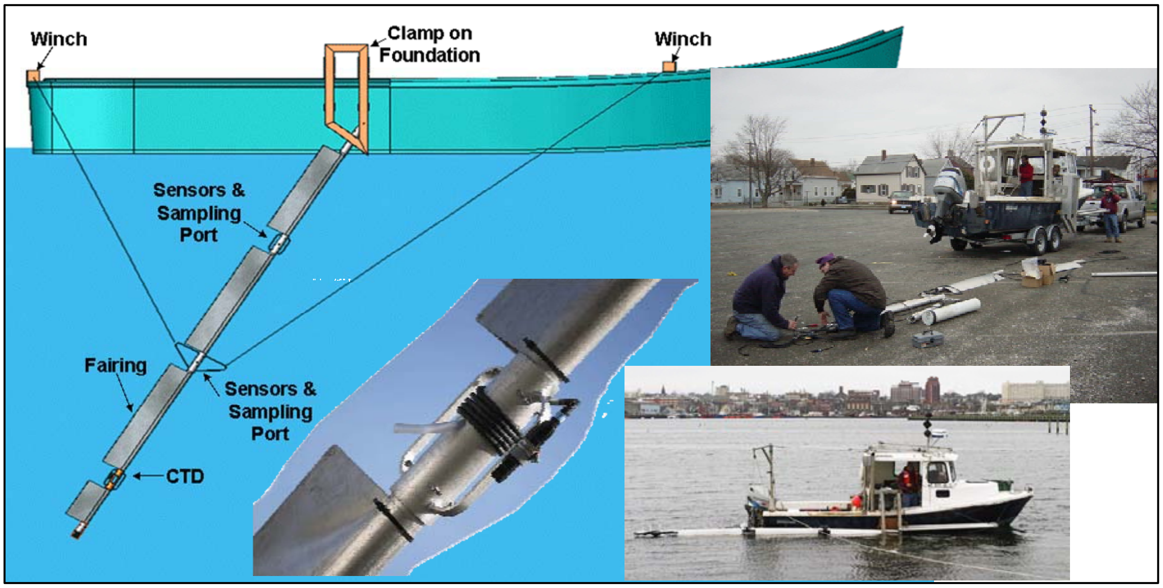

Figure 5. Views of the multi-depth water sampler.

CASE STUDIES

CASE 1 – Evaluation Of Sediment Agitation And Mixing Into The Surrounding Water Column From Capping Activities At Eagle Harbor, In Bainbridge, Washington (Lyons, 2006).

During the operation of the former Wyckoff wood treatment facility, the Eagle Harbor site sediments were contaminated with polynuclear aromatic hydrocarbons (PAH) from use of large quantities of creosote that were used to treat wood against natural pests. To remediate the contamination, the U.S. Army Corps of Engineers capped the entire area with clean sediments (primarily sand) collected from an uncontaminated area. The capping process is gentle, whereby capping sediments are gently sprinkled over the contaminated material. However, EPA was concerned that the contaminated sediments could be resuspended into the water column by these capping activities. As a result, EPA initiated an investigation into the effects of these activities on the water column at the Eagle Harbor site which included sediment collections and plume tracking and simultaneous collection of water samples for PAH, total petroleum hydrocarbons (TPH), and total suspended solids.

In October 2000, Battelle collected pre-capping reference samples by using divers. At that time, water samples were collected at each of seven reference locations for the targeted parameters. As soon as possible after capping was initiated (early November), field activities for monitoring the capping event were undertaken. The monitoring/sampling survey consisted of towing the BOSS towfish horizontally at a depth of less than 2M above bottom to collect continuous in-situ data for conductivity, temperature, transmissometry, turbidity, BOSS sensor depth, and bottom depth. In addition, water samples for the targeted analytes were also collected at locations specified in the field based on movements of the capping barge. Three days of monitoring/sampling were conducted and three events (determined arbitrarily) were monitored during each survey day during capping activities. A total of nine samples were collected during each event at a depth within 1meter of bottom to ensure collection of resuspended sediments (if present). Also during each survey day, a pre- and post-capping survey transect (predetermined) was monitored by towing the BOSS at a depth of less than 2 meters above bottom. This was done to gather background information prior to initiating and after completing daily capping activities. Water samples were collected at three locations along this transect.

Figure 6 shows an example of adaptive transects conducted during the survey. The color of the trackline was linked to turbidity values and provided a coarse contouring of the sediment plume in real-time. This helped the field researchers adapt to the plume attributes and characterize both the core and the spatial extent of the plume. Discrete water samples were collected throughout the sampling. Discrete samples were analyzed for TSS to calibrate the *in situ* turbidity data and for hydrocarbon analysis. Figure 7 shows turbidity values from the *in situ* data with superimposed PAH values from the discrete sample analysis. The upper panel of the figure shows the low turbidity and PAH values representative of the background condition prior to capping activities. In the lower panel, the sediment plume resulting from capping activities can be clearly seen in the turbidity data. Elevated PAH concentrations correlated well with turbidity values as contaminated sediments were released in to the water column. Figure 8 further demonstrates the ability of the BOSS system to characterize the resuspended sediment plume with *in situ* data. The operational day is shown from pre-capping activities, through three surveys during capping events, to a post-capping survey which shows the settling and dissipation of the plume. Again the relationship between PAH and turbidity was quite high. This relationship provided the ability to estimate total mass of PAH released and its transport away from the site.

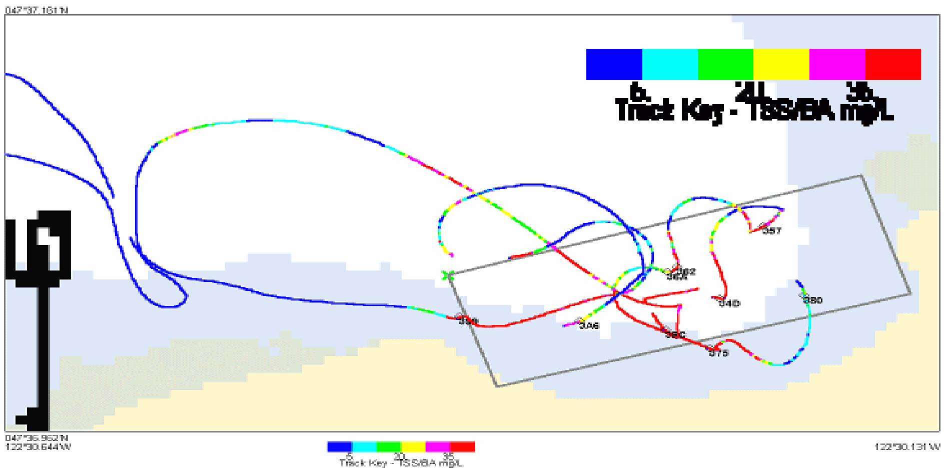

Figure 6. Typical survey transect during a sampling event.

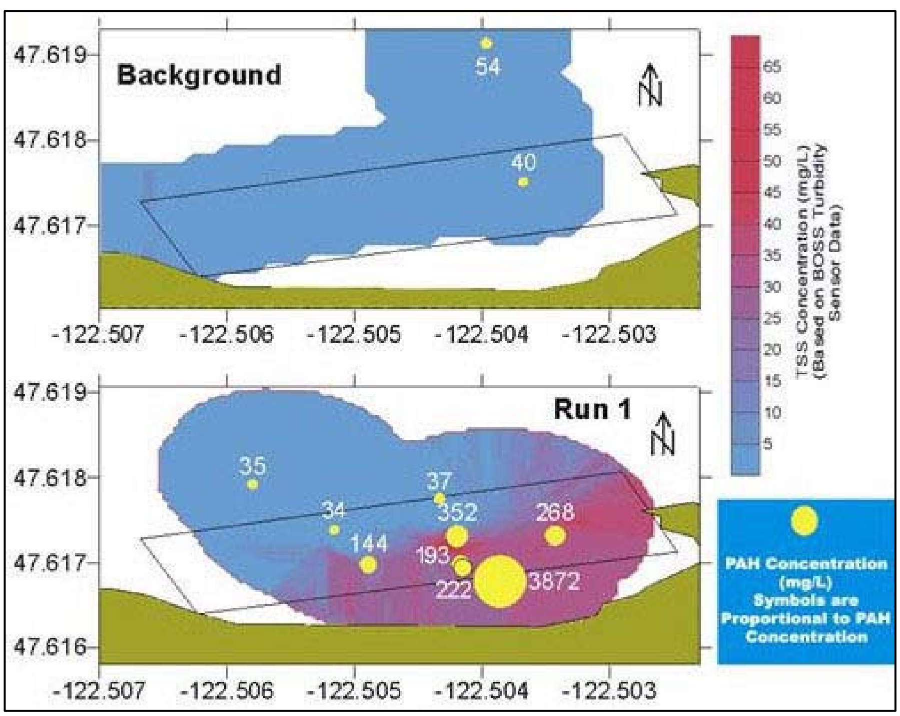

Figure 7. Concentrations of PAH during background and capping operations.

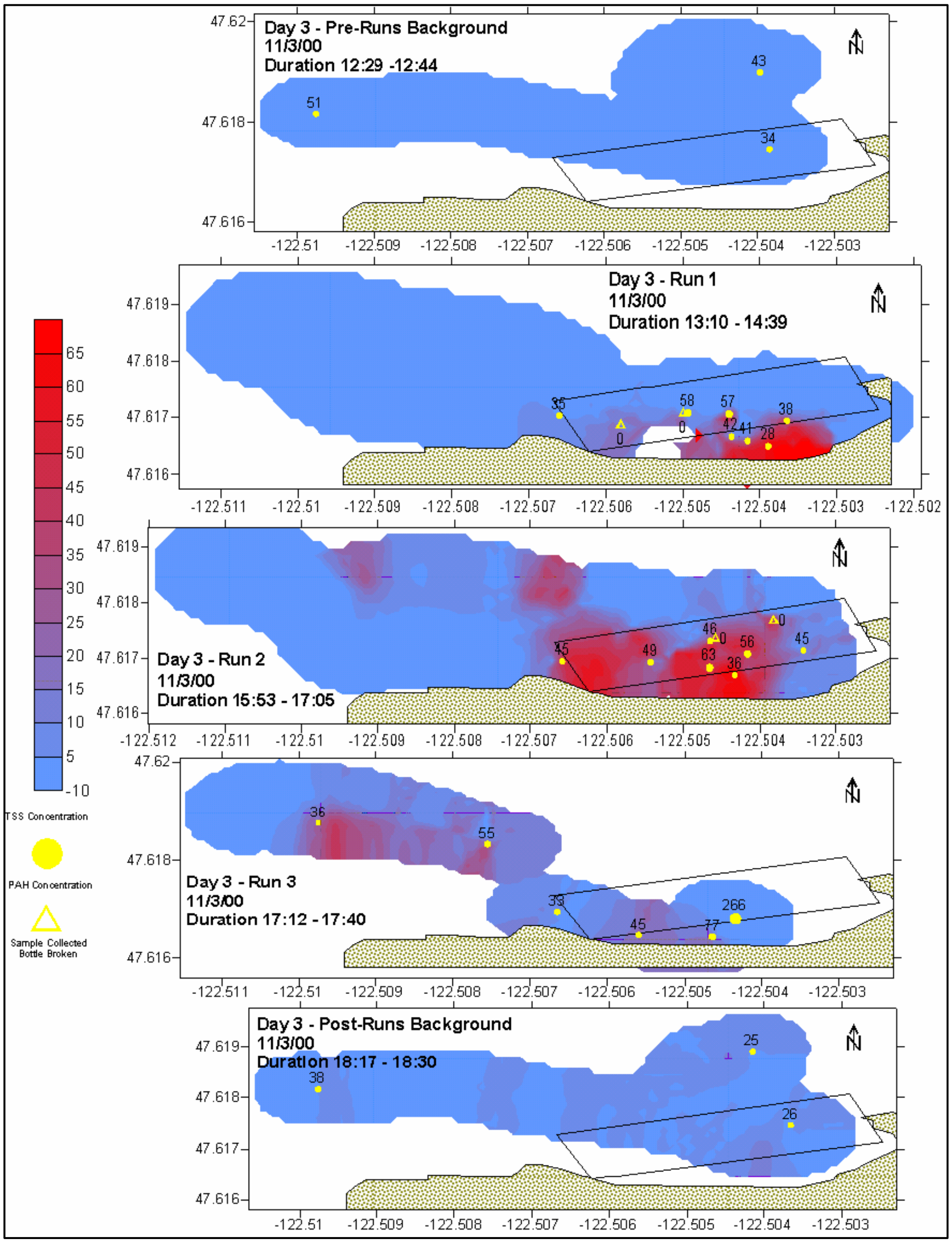

Figure 8. Full day of tracking capping operations.

Case 2 – Evaluation of Sediment Agitation and Mixing into the Surrounding Water Column from Capping Activities at Specified Contained Aquatic Disposal (CAD) Sites in Boston Harbor - Boston, Massachusetts (Lyons, 2006).

Confined aquatic disposal (CAD) cells in Boston Harbor are used as disposal sites for silty, fine grained sediments, determined unsuitable for ocean placement from the Boston Harbor Navigation Improvement Project (BHNIP). Two of the CAD cells, located in the Mystic River portion of Boston Harbor, were filled with dredged material in March 2000. The dredged material in these cells, M8 and M19 (Figure 9) was allowed to consolidate in order to reduce the amount of mixing between the dredged silt and the sand during capping of the cell. Sand dredged from the Cape Cod Canal was used to create caps for cells M8 and M19 (Fredette, 2000). The sand cap was “sprinkled” on the cells using a partially opened hopper dredge, which was maneuvered using a tug rather than utilizing the dredge's engines. This was done in order to minimize disturbance of the silt material in the disposal cells.

The primary objective of this investigation was to evaluate if capping activities in Boston Harbor resulted in the release of contaminants into the surrounding water column and onto surrounding sediments. Monitoring of the capping events was conducted using the BOSS deployed from the Battelle owned survey vessel, R/V *Aquamonitor*. The BOSS *in situ* sensor package included a CTD, OBS sensor, and a Teflon®/titanium pumping system for sample collection. An Acoustic Doppler Current Profiler (ADCP) was also deployed to obtain vertical profiles of horizontal currents.

On the day prior to the initiation of capping, a reference sampling event was conducted in the Mystic River at the CAD cells M8 or M19. The following days were dedicated to sampling at two CAD cells M8 and M19. Because the amount of resuspension was expected to diminish more with each dumping event, we sampled the first three or four capping dumps at each CAD cell. Prior to and following each dumping event, two background tows/samplings, a pre- and post-dump sampling, were conducted along a predetermined transect to assess conditions at the appropriate CAD (Figure 10). At three locations along the transect, water samples were collected using the BOSS pumping system for analysis of polychlorinated biphenyls (PCBs), polynuclear aromatic hydrocarbons (PAHs), total petroleum hydrocarbons, RCRA metals, and total suspended solids. The BOSS sensor package continuously monitored conditions at and between each station sampled. During each dumping event, water samples for the specified analytes were collected at each of nine stations within the boundaries of each CAD. The BOSS sensor package continuously monitored conditions at and between each station sampled.

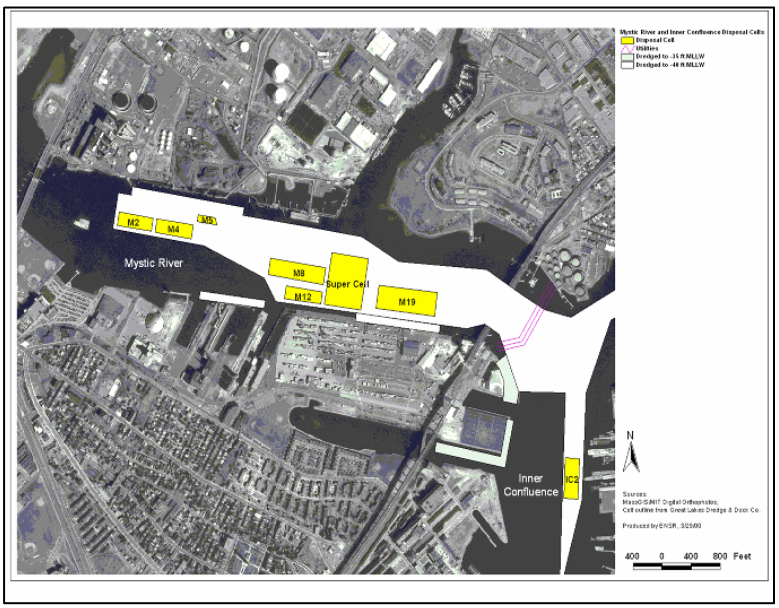

Figure 9. Boston Harbor CAD cells.

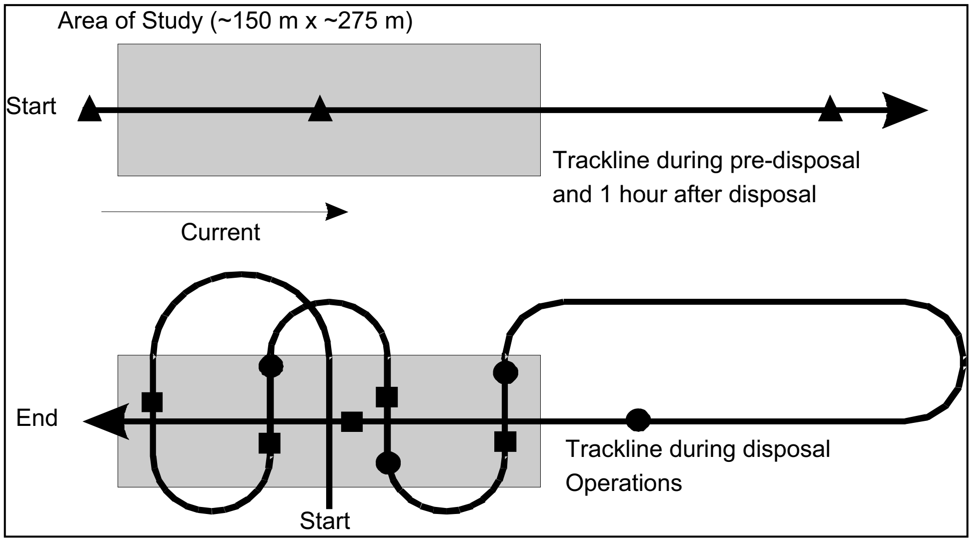

Figure 10. Preplanned survey tracklines and sampling locations.

Unlike the Case 1 survey at Eagle Harbor, this survey operated on pre-planned tracklines and sampling locations (Figure 10). However, additional adaptive tracklines were conducted where time allowed to further characterize the plume. Figure 11 shows turbidity values from the *in situ* data with superimposed chromium values from the discrete sample analysis. The upper part of the figure shows turbidity and chromium in the water column prior to capping operations. The lower part of the figure shows turbidity and chromium values during the capping event. The suspended sediment plume can clearly be seen in the *in situ* data. However, there was little correlation between chromium concentrations and turbidity in the water column.

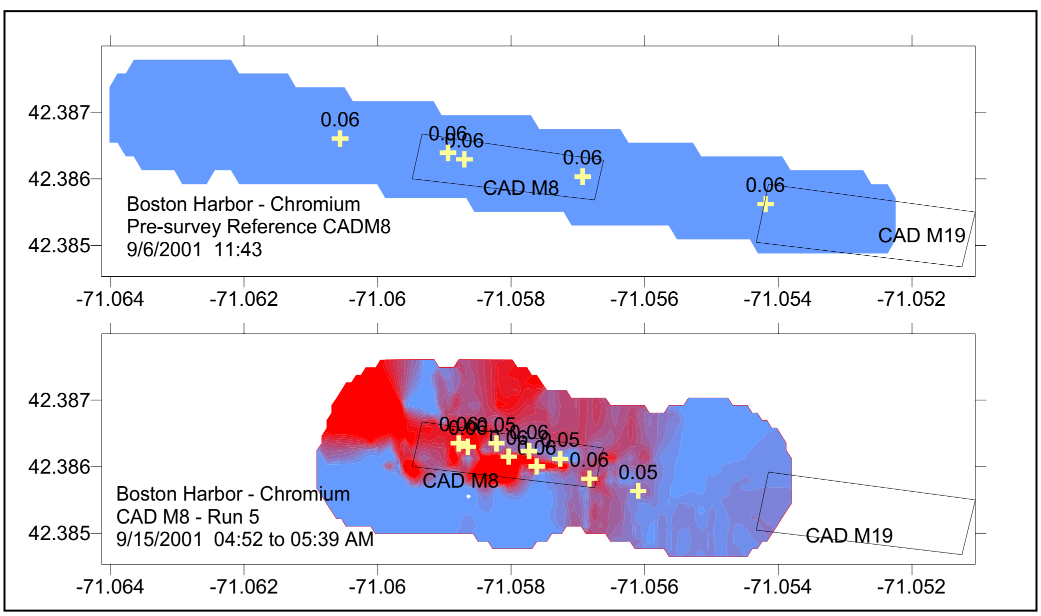

Figure 11. *In situ* turbidity values and chromium concentrations from discrete samples during background capping event surveys.

Case 3 – Water Column Monitoring Results from the June 1996 GFC Demonstration Project (SAIC, 1996)

Geosynthetic Fabric Containers (GFCs) were being considered as a means of minimizing the dispersion of dredged material that is routinely disposed at existing ocean disposal sites such as the New York Mud Dump Site located offshore Sandy Hook, NJ. The conventional method of disposing uncontaminated dredged material at the site is via split-hull scows which generally carry 2294 to 3823 m^3 (3,000 to 5,000 yd^3) of dredged material per load. Dredged material initially released at the surface descends through the water column with the result that the majority of the material reaches the seafloor in less than one minute, but a non-trivial volume of fine-grained dredged material is temporarily suspended in the water column due to its slow settling velocities. The result is a plume of suspended sediment that is rapidly and continually acted upon by waves, currents, particle dispersion, gravitational effects of particle settling and, during the first few minutes after disposal, any residual momentum from the descent of the bulk load of dredged material. The GFCs would modify the disposal method by containing the dredged material in a large sealed fabric bag and being dropped onto the seabed while remaining intact.

The U.S. Army Corps of Engineers – New York District (CENAN) and the Port Authority of New York/New Jersey (PANY/NY) contracted with Science Applications International Corporation (SAIC) to conduct the water column monitoring portion of the June 1996 GFC demonstration Project. This project was to demonstrate that GFCS could be placed into conventional split-hull scows, filled with fine-grained dredged material from New York Harbor, transported to the Mud Dump Site, and dropped at a location in 18.3 m (60 ft) of water without rupturing and/or releasing a significant quantity of dredged material into the water column.

SAIC subcontracted with Battelle to provide the BOSS make *in situ* turbidity measurements and collect water samples for determination of total suspended solids concentrations around the dropped GFCs. During the project, the BOSS was used in to modes; tow-yo and time-series vertical. Figure 12 shows a tow-yo transit starting at the GFC drop location moving down-stream from the GFC. Figure 13 shows the sediment plume evolution as function of time which was developed by conducting multiple vertical profiles with the BOSS® directly downstream of the GFC.

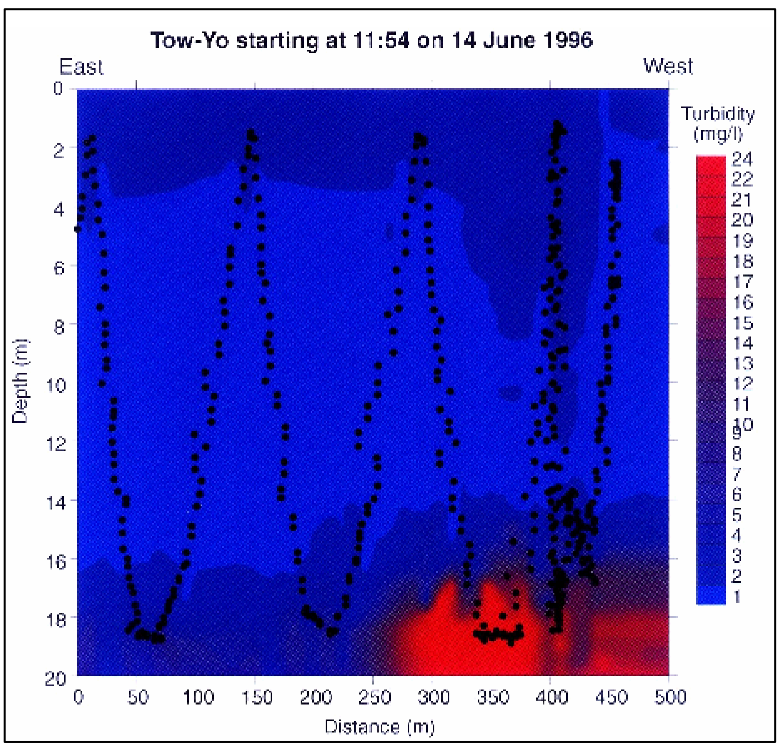

Figure 12. Tow-Yo starting at 11:54 on 14 June 1996.

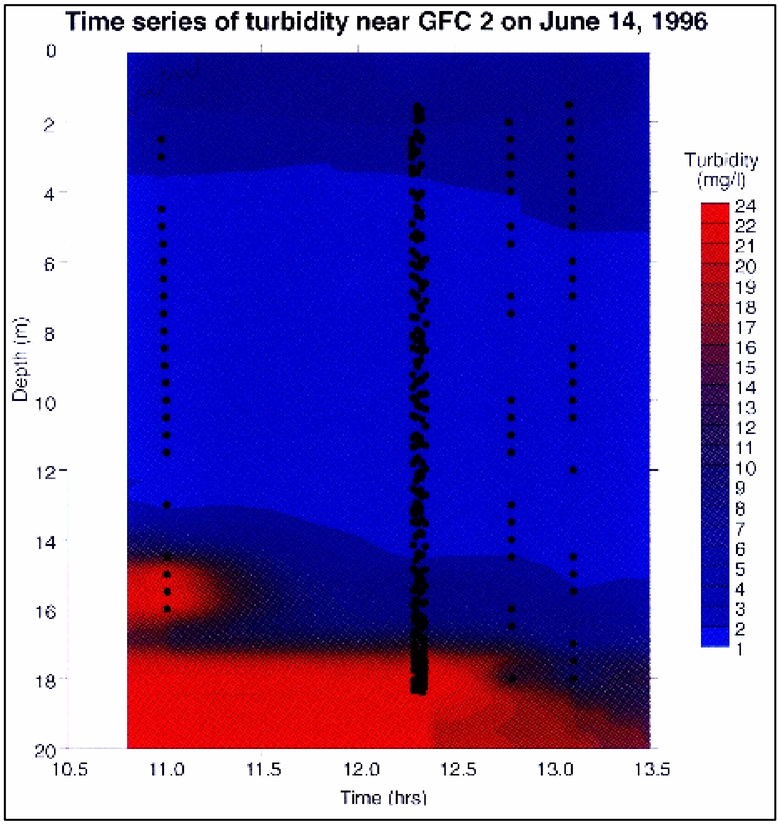

Figure 13. Time Series of turbidity near GFC 2 on June 14, 1996.

Case 4 – Demonstration of Multi-Depth Water Sampler during Dredging Operations

The MDWS system was field tested at a dredge site in Southeastern Massachusetts in January of 2006. Dredging activities included clean up of small marina slips using a small dredge bucket (Figure 14). The expectation was that sediment plumes would be fairly limited in nature and therefore serve as good test of the sensitivity of this new system. Additionally the area of operation was in the tight quarters of a small marina. This presented challenging maneuverability that added to the rigorousness of the field test. The MDWS was deployed off of a 7 meter (23 foot) privateer (Figure 14). Water depths varied from approximately 2 to 5 meters.

Resuspended sediment plumes were encountered as a result of both direct dredging activities and barge movements in shallow areas. The MDWS was used to track each type of plume using a variety of methods. In very shallow areas, where barge activity generated relatively large sediment plumes, the vessel transited into the barge area and ran a series of data collection transects. During active dredging the MDWS was used in two modes. In the first mode, the vessel was tied up along side the barge as close as safely possible to the active end. The MDWS was deployed vertically in the water column. Once dredging commenced a clear sediment plume could be seen on the real-time display from the *in situ* turbidity sensors. Turbidly levels varied over the course of the dredging and individual plumes from each bucket drop could be identified. In addition to the individual plumes, an overall cumulative increase of turbidity was identified as dredging continued. In the second dredge monitoring mode, the MDWS was deployed in the water column and the survey vessel transited in expanding arcs away from the dredge operation. The resuspended sediment plume could be seen as a decreasing turbidity signal with increasing distance from dredge operations.

A screen capture of the real-time display is presented in Figure 15. This snapshot includes: 1) the navigation overlay with a color-coded trackline linked to turbidity values (upper right of screen), 2) a real-time line plot of eight *in situ* parameters versus time (upper left of screen), 3) real-time contouring of turbidity values over time which represents horizontal movement (bottom center of screen), 4) and continuously updating navigational position and sensor readouts (bottom and right hand side respectively). As can be seen in the contouring portion of the screen, the continuous data feed back allows the field researchers to adjust the depth of deployment and operated very close to the bottom despite variability in the depth.

Figure 14. Dredge bucket and survey vessel in the marina.

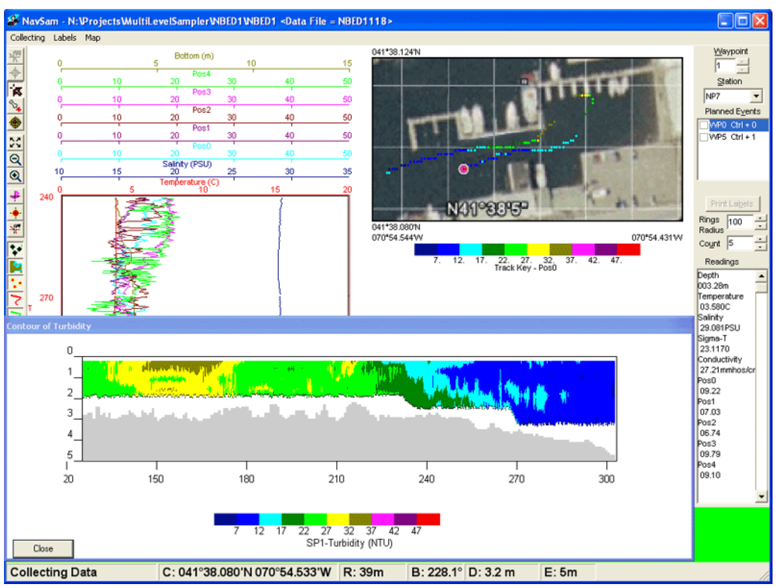

Figure 15. Real-time display during dredge monitoring survey.

Figure 16 shows the results of three plume tracking transects. The plume identified in the figure resulted when the barge pulled out of a shallow dredging area. Weight added from collection of dredge material had pushed the barge onto the bottom. As soon as the tide raised the barge enough to move, it was pulled out of the shallow area generating a relatively large sediment plume. Immediately after the barge was removed, the survey vessel transited through the area with the MDWS deployed. All three transects shown in Figure 16 are along approximately the same line. Variability in the bottom contours in the three panels represented slightly different vessel position along the transect line. However, the three panels are aligned so that horizontal position is approximately equal. The first panel shows a transect conducted approximately five minutes after the dredger departed the area. Very high turbidity values can be seen at the shallow (right hand) end of the area. Turbidity values decreased further away from where the dredge had been aground (left hand side of panel). A second transect was conducted eleven minutes after the dredge departed. A reduction in suspended sediment concentrations could already been seen at this point as a result of resettling. It appears that little of the sediment plume was transported away from the site. The third panel shows a transect conducted along the same line nearly two hours after departure of the barge. At this point turbidity values in the shallow regions where the barge had been aground were substantially lower and closer to the ambient values seen a little further out.

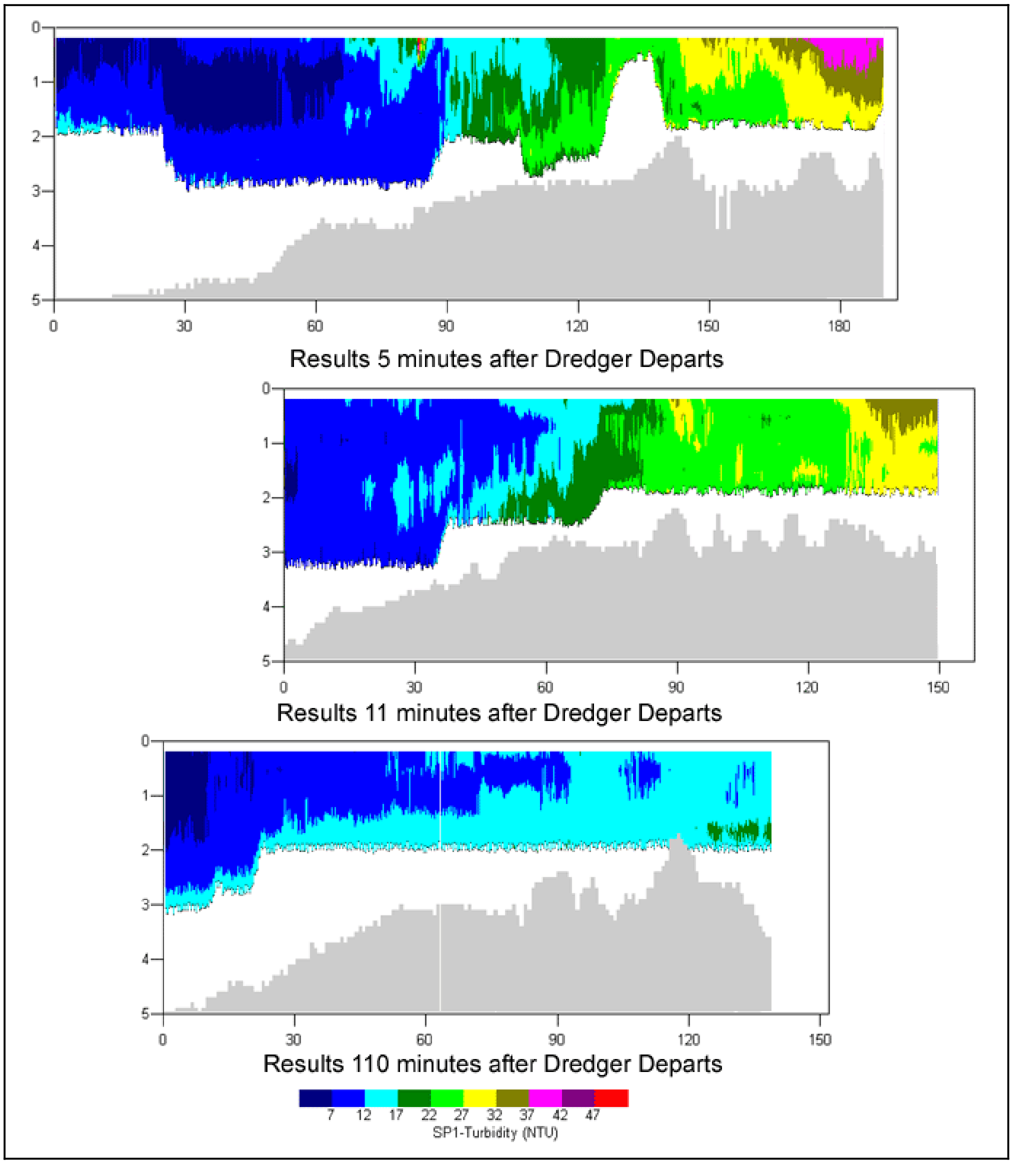

Figure 16. Three transects showing time-series of sediment plume evolution.

SUMMARY

The case studies presented above are a small representation of the variety of applications for real-time plume tracking systems. Each case presents site-specific needs which must be factored into the selection of a monitoring system, the sampling objectives, and the approach. For example, the deep waters surveyed in Case 3 would not make the use of the MDWS feasible. In Case 4 a towed profiler would not be able to operate in the tight quarters and shallow depths encountered in the marina. However, in each of the case studies high resolution *in situ* data and real-time feedback allowed for adaptive sampling approaches which helped fully characterize the extend of the plume. Single point sampling systems would most certainly have missed some portion of the turbidity field.

A comparison of the three monitoring methods is presented here for a theoretical sampling event. Figure 17 shows a hypothetical plume and the data collection points for the three methods. The assumption is that the anticipated sampling area is 1000 meters long by 10 meters deep. The desired transit rate is 3-4 knots, which will cover the area in 10 minutes. For vertical hydrocast methods the survey vessel may travel at higher speeds between individual sampling locations, but the time required for positioning results in an approximately equivalent speed to the other methods (3-4 knots). The blue lines show the vertical casts that can be conducted and in a 10 minute period will generate 576 *in situ* readings at 4 Hz. The magenta line shows the tow-yoing of the BOSS system from 1 meter to 9 meters getting four complete cycles in the 10-minute transit collecting 2,400 readings at 4 Hz. The horizontal yellow lines show the tracks of the five sensors depths on the MDWS resulting in 12,000 readings.

The number of *in situ* data points clearly improves the resolution of the method, and the rapid stream of real-time data allows for adaptability in the field providing even greater assurance the turbidity field is being fully characterized. The hypothetical plume in Figure 17 provides an example of how vertical methods can under or over estimate plume concentrations and extent be allowing for considerable data gaps. In the figure, the towed body trackline is likely an underestimation of the systems ability to fully characterize a plume. In a field setting the towed depths would likely be modified to stay where the elevated signal is seen (below 4 meters) thereby increasing the data resolution in that area.

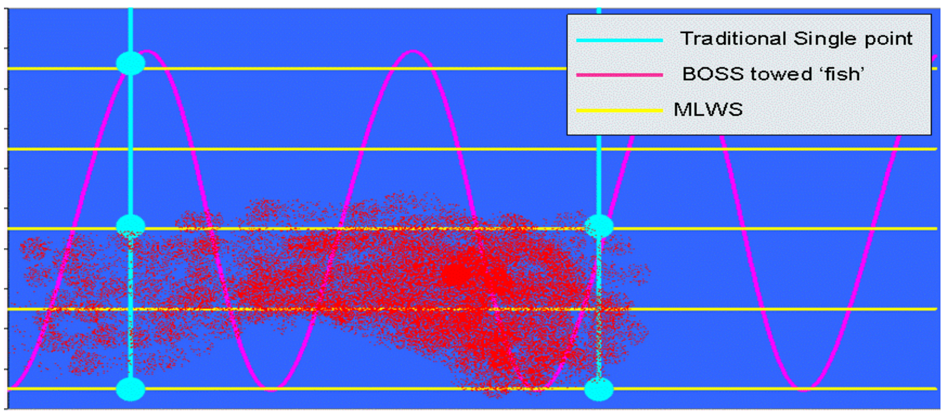

Figure 17. Theoretical plume and comparison of three methods.

The ability to collect discrete water samples during a sediment resuspension survey is also critical. Turbidity is often representative of suspended sediment concentrations; however there are a number of confounding factors that make TSS/turbidity calibrations necessary. Particle size, biogenic material, bubbles from dredge operations, and other effects can reduce the correlation of the turbidity and TSS at site-specific levels. Therefore TSS analysis is an important part of suspended sediment load and transport calculations from *in situ* data. When dealing with contaminated sediments it is even more critical to collect discrete water samples. Current technology is extremely limited in detecting contaminant levels *in situ.* Therefore, turbidity measurements are frequently used as a proxy for contaminant loading. However, contaminant and site-specific properties often result in a decoupling of contaminant loads from turbidity readings. Increased dissolved and particulate phase PCB concentrations found downstream of dredging operations contained higher levels than those predicted based solely on turbidity and TSS measurements (Steuer, J., 2000). This could be a result of exposing layers of highly contaminated sediment and porewater to relatively clean overlying waters. When these highly contaminated particulates are suspended into the relatively clean water column during dredging operations, PCBs could desorb from particulates. Once in the dissolved phase transport of PCB can become highly decoupled from transport of the sediments they were originally associated with. In general transport of the dissolved contaminants can cover far greater areas than sediments which tend to settle out fairly rapidly. Conversely, high porewater PCB concentrations, when exposed to relatively low concentration suspended particles, may cause absorption of PCBs onto the particles and result in higher than expected particulate PCB concentrations (QEA, 2000). As a result, it is not appropriate to assess PCB release during dredging strictly from *in situ* turbidity data or even TSS concentrations (Steuer, J., 2000). Both the BOSS and MDWS systems allow for instantaneous collection of relatively large volumes of water on demand. By coordinating water collections to *in situ* data, field scientists are able to capture various elements of the plume including peak concentrations and concentrations on the extreme ends of the sediment plume. Discrete sample analysis can, in turn, provide data to link contaminant concentrations to *in situ* parameters. This allows for estimations of resuspended contaminant loading which feeds to risk reduction measures.

Systems for characterizing sediment plumes are continually evolving. The descriptions provided in this paper present a summary of both traditional methods as well as emerging methods that increase the capability to fully and accurately assess sediment resuspension. As efforts continue to clean up contaminated sediments across the nation public interest and regulatory oversight is only likely to increase. All sides of dredging operations will be faced with a need to reduce risk at the financial, environmental, and public health levels. Real-time plume tracking will become an increasingly critical part of the dredge management and risk reduction process.

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