Characterizing the circulation and dispersive nature of the Passaic River and its dependence on river discharge and tidal range: elucidation of major processes that determine the impact of the proposed Passaic River dredging project.

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Overview

To assess the impact of a proposed dredging project to remove contaminated sediment from the Harrison reach of the Passaic River the New Jersey Department of Transportation will undertake a small-scale pilot dredging project scheduled for the summer of 2005. To aid in the planning of and in the interpretation of results from the pilot study we propose to characterize the aspects of the circulation and dispersive nature of the Passaic and describe how these processes change with tidal range and river discharge. This characterization permits placing results from the one-week dredging project in context with the natural variability of the system and thus enabling planners to extrapolate from the pilot study to the full-scale dredging operation. The work proposed here will also provide the requisite date needed to assess the skill of the hydrodynamic simulations that will be a central tool used to assess the impact of the full-scale dredging operation. Moreover, the proposed work will facilitate plans to monitor the sediment plume from the pilot dredging program.

The work proposed here involves long-term moorings in the Passaic River, shipboard surveys to characterize the salinity and sediment structure of the River over a range of river flow conditions. We will also conduct a detailed tidal cycle surveys in the Harrison Reach to characterize the spatial structure of currents, total suspended sediment, stratification and bottom shear stress in the vicinity of the pilot dredging study. Finally, we will conduct a dye study to quantify the dispersive nature of material released into the water column in this reach of the river.

Objectives:

The three primary objective of the propose work are:

1) To characterize the structure of the estuary as a function of river flow and tidal forcing. Included in this characterization will be salt intrusion length, stratification in the Harrison Reach, the structure of the suspended sediment load and the strength and variability of the two-layer estuarine flow.

2) To provide a detailed description of spatial structure of tidal period variability of tidal currents, suspended sediment and stratification in the Harrison reach.

3) To quantify rates of dispersion and vertical mixing in the Harrison reach by conducting a series of dye studies in conjunction with Doppler current meter deployments designed to measure vertical profiles of stress.

Rationale – Objective 1

The rationale of objective 1 is to place conditions of the Passaic River Estuary during the pilot study in context with the natural variability of this system over a range of tidal forcing and river discharge. This is critical because processes that drive the transport of suspended sediment differ radically both seasonally and over the spring/neap cycle (Woodruff et al. 2000). Estuarine systems are known to trap sediments in the landward flowing lower layer (Chant and Stoner, 2000; plus older stuff). However, the three major trapping mechanisms -- flocculation, landward flow in lower layer and the suppression of turbulence by stratification --are largely absent upstream of the salt wedge (Geyer, 1992; Schubel, 1962, Krank and Milligan, 1985). Subsequently, the fate and transport of material released into the Passaic River is highly dependent on its location relative to the salt wedge. For example, high river discharge events are likely to push the salt field down stream of the Harrison reach and result in fresh and non-stratified conditions. Under these conditions flocculation is reduced and sediments are carried down stream with the river flow. In contrast during low flow conditions, the Harrison reach will stratify and promote flocculation and rapid settling of sediment into the lower layer where the tidally mean flow is directed up river. Yet under times of extended drought the two layer flow may vanish and material discharged into the water column will disperse both upstream and downstream due to the oscillatory tidal motion.

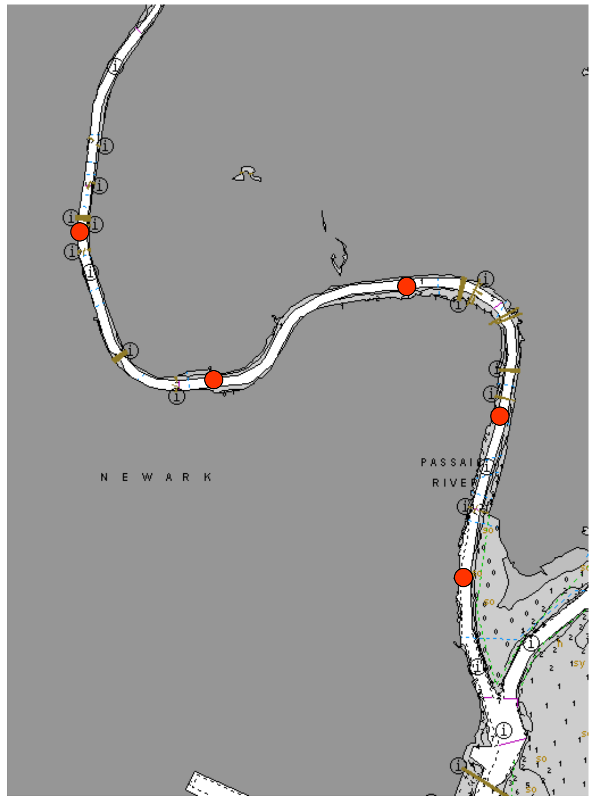

Figure 1. Study site. Red dots show approximate locations of proposed moorings. Central dot represents the two moorings in the Harrison Reach.

However, the relationship between the circulation and salinity structure of the Passaic River and river discharge have yet to be determined. (Note that the recent NJDEP/CARP study of the Newark Bay/Kills system did not involve any mooring deployments in the Passaic River) Back-of-the-envelop calculations, based on an internal Froude Number (Chant and Wilson, 2002; Armi and Farmer, 1985) and given the observed stratification in the reach, suggests that a river flow of approximately 100 m^3/s would push the salt field south of the Harrison Reach. Based on the historic discharge data in the Passiac River this occurs approximately 10% of the time. However, frictional effects in shallow depths and sineous channel are likely to cause the salt wedge to move seaward of the

Harrison reach at discharge rates less then 100 m^3/s. Thus it is likely that the Harrison reach is fresh more often then 10% of the time.

Results obtained with objective 1 would empirically characterize the location of the salt wedge and stratification of the Harrison Reach as a function of river discharge. Moreover, salt-intrusion length defines the estuarine portion of the river and will provide a critical data set to test the skill of numerical simulations of Passaic River.

Field Work- Objective 1.

The field-work includes both moored instrumentation and shipboard surveys of the estuarine reach of the River. We propose to run approximately 12 CTD sections beginning in Newark Bay and ending either at the head of salt or as far as the river is navigable. We will make all attempts to utilize a low-clearance vessel and operate at low tide in the upper reaches of the river where bridge clearance can be less then 8 feet. These sections would take place from June 2004 through June 2005. Dates would be selected to cover a range of river discharges—with emphasis on high discharge conditions. Salinity would be measured with an OS-200 Conductivity, Temperature Depth probe (CTD) that obtains estimates of salinity, temperature and pressure at a rate of 6 Hz. CTD casts would be made approximately every km in the river. The CTD will be mated with an Optical Backscatter Sensor (OBS) to characterize the suspended sediment concentration. During each CTD section we would collect ~ 10-1 liter bottle samples to calibrate the OBS sensor.

In conjunction with the 12 CTD surveys to be conducted, the USGS will sample the river water to determine the suspended sediment and salinity distribution in detail. At approximately 1 km intervals, 1 vertical profile will be sampled at four depths to characterize the particulate and salt distribution across the river. Samples will be collected at 1 meter below the surface, 1 meter above the bottom, and 2 through the mid-range depth. The mid-river vertical profile will be made in the vicinity of the CTD tow, allowing the data to be used for instrument calibration as well as river characterization. Samples will be measured for suspended sediment, total dissolved salts, and conductivity.

The total number of sampling locations for this objective is 960. A subsection of these samples will also be measured for density in the USGS District Laboratory.

A mooring array will be deployed to obtain fixed-point time series of currents, salinity, temperature and suspended sediment (Figure 1). The array will consist of 6 moorings. Two of these moorings will be deployed in the Harrison reach, one located in the deep channel, and the second on the shoaling southern flank. Each of these two moorings will contain an Acoustic Doppler Current Profiler and surface and bottom Conductivity and Temperature (CT) sensors, and a bottom OBS sensor. The other four moorings will contain surface and bottom mounted CT sensors. The moorings will be separated by approximately 2 km. In addition the most upstream and downstream moorings will each contain OBS sensors and paroscientific pressure sensors that are accurate to a few millimeters. The pressure sensors will provide estimates of along-river pressure gradients that together with time-series of velocity measurements from the central array, can be used to provide bulk estimates of bottom shear stress (Trowbridge et al, 1999; Geyer et al. 2000)—a critical parameter to quantify for modeling efforts. We propose two mooring deployments. The first will run from late summer to late fall to capture both circulation during the low flow summer conditions and the increased river discharge rates that occur in the fall. The second deployment will cover the late winter/early spring to catch the spring freshet. Several of the moorings will need to be removed by mid March 2005 for a scheduled deployment associated with another project in the New York Bight. However the 4 C-T sensors to be purchased with funding from this project will remain moored in the estuary for the duration of the 2005 spring freshet.

The Doppler profilers will obtain estimates of current velocity in 25 cm bins at a temporal resolution of 15-30 minutes. The Doppler also records the acoustic backscatter that can be calibrated against the measured suspended sediment from bottle samples to provide high-resolution estimates of total suspended sediment. The moored data would definitively characterize the strength of the two-layer flow in the Passaic River and its dependence on River Flow, and provide an estimate of the natural flux of sediment in the system.

In conjunction with these moorings, the USGS proposes to collect a single vertical profile of suspended sediment, total dissolved salt, conductivity, and water density in the vicinity of each mooring, once when the moorings are deployed and again when retrieved. Up to 10 samples will be collected at 1 meter intervals. The data provided by these samples will document the calibration of the instrumentation. The maximum total number of samples collected for the mooring work is estimated at 240.

Rationale: Objective 2

Objective 2 will aid in the design of the pilot-dredging project by generating a detailed map of current structure. This data will also be useful to assess the model's capability to simulate observed vertical and cross-channel shears in the flow. This assessment is critical because it has long been recognized that it is vertical and horizontal shears the drive dispersion in riverine and estuarine systems (Taylor, 1951; Wilson and Okubo, 1975; Smith, 1976; Fischer, 1978). Furthermore, these detailed surveys will aid in the interpretation of the dye release studies outlined in objective 3 and place the larger spatial scale variability characterized by objective 1 in context with details of the circulation in the vicinity of the pilot dredging study.

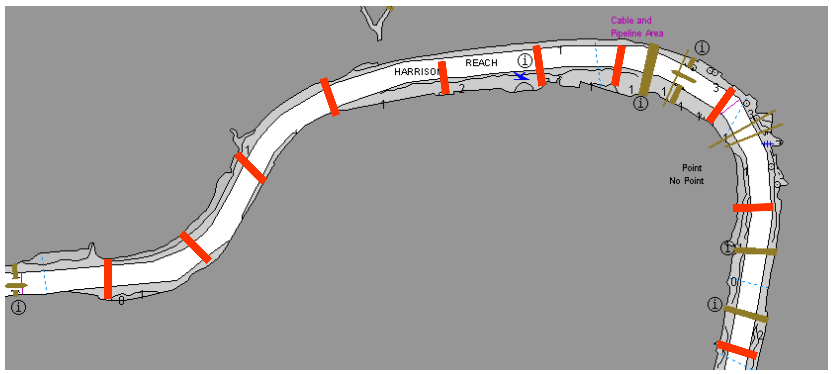

Figure 2 Proposed ship track for detailed tidal current survey of Harrison Reach. Red lines depict cross-river sections. Bridges are shown in brown.

Work Plan Objective 2

This project involves running repeat surveys across the river in the vicinity of Harrison Reach. We propose a total of 4 days of ship-board surveys to characterize the tidal currents. This field-work would occur in the late summer/early fall of 2004. We would conduct 2 of the shipboard surveys during neap tide conditions and 2 surveys during spring tide conditions. We would complete the sections shown in figure 2 once approximately once each hour over an 8-12 hour period. By fitting tidal period harmonics to time series of currents observed at grids along this track we would generate a detailed model of tidal currents in this reach during neap tide and spring tide conditions. We anticipate spending approximately 3 minutes surveying each 100-meter section to generate currents with resolution of approximately 10 meters in the cross-stream direction and 25-cm in the vertical. This would provide a more spatially detailed view of the tidal and subtidal motion in this reach than provided by the moorings. It would also assess the strength of the cross –channel circulation in the river bends in the vicinity of the Harrison Reach that can be an important process driving dispersion in the system (Chant, 2002; Chant and Wilson, 1997; Geyer 1993).

In conjunction with the hydrodynamic evaluation of the Harrison Reach, the USGS proposes to characterize the cross sectional distribution of suspended sediment and dissolved salt in this reach of the river. Twice during neap and twice during the spring tide, the USGS will collect samples at each cross section in a grid of three verticals at three depths (1 meter below surface, one meter above bottom, and mid section, 9 samples total per cross section). These samples will be analyzed for suspended sediment, dissolved salt, and conductivity. This data will be combined with the hydrodynamic view of tidal and subtidal motion and cross-sectional circulation in the river section. Approximately 470 samples will be collected in this objective.

Rationale - Objective 3

The two dominate processes that will determine the spatial extent of the dredge-plume are the dispersive nature of the system and the fall-rate of the suspended sediment. The dispersive process is driven by a shear dispersion whose rate is determined by the structure of the vertical and horizontal current shear and the intensity of vertical and horizontal mixing (Wilson and Okubo, 1975; Smith, 1976). The structure of the currents shear will be obtained by objective 2 and the intensity of mixing and dispersion will be determined in objective 3. To make estimates of the spatial extent of the dredge plume we then need to determine the fall velocity of dredged material released in the water column, and this will be determined with data from the pilot dredging project in conjunction with the estimates of mixing obtained with objective 3. Particle fall velocities will be primarily determined by the rate that flocculation occurs. Observations in a dredge plume in Danish waters by Mikkelson and Pejrup (2000) indicate that the flocculation time-scale is approximately 50 minutes. While conditions in the Passaic will likely differ a flocculation time-scale on the order of one hour is probably relevant in the Passaic River. Consequently it is the dispersion that occurs at time-scales on the order of one hour that are important to quantify. Note that the rate of dispersion in Marine systems is well known to increase with increasing time (Okubo, 1971).

Unlike the wide Oresund Sound, however, the Passaic is a narrow sinuous channel and likely possesses radically different dispersive characteristics. Consequently, we propose to conduct a series of short-term dye experiments to characterize the 1-3 hour time-scale dispersive nature of the Passaic River in the vicinity of the Harrison reach. In addition we will deploy a third Doppler current meter and a fixed point Sontek Acoustic Doppler Velocimeter to obtain estimates of strength of vertical mixing and bottom shear stress. Results from the dye study will aid in the design of plans to monitor the pilot-dredging project because they will help predict the along-channel and cross-channel extent of dredged plume. Secondly, with knowledge of the vertical mixing rates and vertical profiles of sediment concentrations inverse methods could be used to back out sediment fall velocities (Fugate and Friedrichs, 2002). Moreover, quantification of and characterization of dispersion and mixing rates in the Passaic provides an important and extremely relevant dataset to test the model’s skill. For example, if modeling efforts poorly characterize the observed structure of the sediment plume—it could be due to the model’s inability to accurately predict dispersion or due to inaccuracies in parameterizing particle fall velocities (i.e. the flocculation algorithm). By testing the model against the evolving structure of the passive dye tracer modelers will isolate the dispersive process and can refine the model until dispersion is well represented by model simulations. Once the model can accurately predict dispersion efforts to simulate a sediment plume can focus on the details of the parameterization of settling velocity and flocculation (Winterwerp, 2002; Fugate and Friedrich, 2003).

Work Plan- Objective 3

Chant and colleagues have successfully used dye tracers in the Hudson River Estuary in 2001 and 2002 and will be conducting a series of dye studies on the inner shelf scheduled for the spring of 2004,2005 and 2006. In the Hudson the dye patch was tracked even in the presence of tidal currents as large as 1 m/s, and with the data estimates of dispersion and vertical mixing were obtained.

Each study will commence with a release of dye from an anchor station by pumping dye through a hose attached to a rapidly undulating package containing a CTD and OBS sensor. This will result in a dye release distributed throughout the water column and similar to the vertical structure of the sediment released by the dredging operation. We can control the length of time it will take to release the dye, but anticipate a release taking approximately 15 minutes. We will use a fluorescent dye as a tracer. This technique has a number of attributes essential for our investigation-- foremost is its ability to measure 3-dimensional dispersion processes. After injection the boat will run a series of cross-channel sections to map out the dye-patch followed by an along-channel section down the middle of the patch. This will continue for approximately 8 hours after injection.

Dye will be tracked with a Chelsea Aqua-track fluorometer that will be mated with the CTD and affixed to a frame that will be tow-yo'd while underway at ~ 3 knots. Details of the survey plan will be adaptive based on real-time displays of currents, dye and salinity distribution. The dye can be detected down to levels of 1 part per 10 billion—a limit that is typically set by background fluorescence in the environment. Therefore a release of just a few kilograms of dye will easily detectable even when mixed completely along a 5 km reach of the 100-meter wide 5-meter deep Passaic River channel. Because we expect the dispersive properties of the estuary to vary between neap and spring tides we propose to conduct dye experiments over a range of tidal forcing.

Dye studies will take place during the weeks that we conduct the detailed tidal-current surveys proposed in objective 2. We propose 4 one-day dye studies that would bracket the days of the detailed tidal current surveys. Dye releases would occur at slack before flood and slack before ebb for each neap tide and spring tide conditions. Dye would be traced for ~8 hours after injection with a series of cross-channel and along channel sections. In the past we have used both Rhodamine-WT and Fluorescein dye. Both have low toxicity and comparable detectability. While Fluorescein is photo-sensitive and its fluorescence will diminish when exposed to light, since we are conducting short term experiment in turbid waters photo-degradation will not be a problem.

Dye will be injected by pumping 5 kg of Fluorescein in a 5% water solution through a hose attached to a CTD suspended from the ship. The dye solution is mixed with propanol to achieve the anticipated *in situ* density. Use of this mixture together with the rapid 1000 to 1 dilution as the dye solution is injected through a diffusing nozzle, has precluded any subsequent anomalous density driven flow in past experiments.

In addition we will recover and re-deploy one of the 1200 kHz RDI Acoustic Doppler Current Profiler operating in mode 12. The ADCP will collect vertical profiles at 1 Hz with 25 cm resolution. Since we are operating in mode 12 these 1-second ensembles have very small errors—on the order of a few cm/s—and the ping-to-ping variability in the along-beam current speeds can be used to estimate the turbulent Reynolds stresses (Stacey and Monismith, 1999). Dividing the stresses by the mean vertical shear provides estimates of the vertical eddy viscosity. Due to intensive memory requirements and power requirement of operating the ADCP in this mode mooring deployments are limited to several weeks. After the recovery of this ADCP the instrument will be re-programmed and re-deployed for the duration of the fall mooring deployment. In addition we will deploy a single Sontek ADV that will provides estimates of horizontal and vertical current speeds obtained in a 1 cm cube at a rate up to 25 Hz. With this data we can make direct estimates of the Reynolds stress via the eddy correlation method (Trowbridge et al. 1999) or via the dissipation method via spectral analysis (Voulgaris and Trowbridge, 1998).

The USGS-NJ will assist in monitoring the distribution of the dye during the 8-12 hours after the Fluorescein dye is released. In addition, the USGS will collect a single vertical transect consisting of 10 samples immediately preceding the release of the dye, to document the conditions of the river in the area of dye release. These samples will be measured for SS, dissolved solids, conductivity. These samples will also be measured for particle grain size using a Sedigraph III laser analyzer, available at the USGS Cascades Volcano Observatory in Vancouver, Washington. A total of 40 samples will be analyzed for this work.

Summary

In summary the proposed work would provide the necessary data to characterize the physical environment of the Passaic River estuary with particular emphasis on the strength of the estuarine circulation, details of the current structure in the vicinity of the Harrison reach and quantification of the rates of vertical mixing horizontal dispersion. The proposed work would also characterize the relationship between river discharge and the salinity structure and river's 2-layer circulation. This data will facilitate planning of the pilot-dredging operation, interpretation of the results from the pilot study and provide critical data to assess the skill of the numerical model that will be used to determine the impact of the proposed full-scale Passaic River dredging project.

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