Determination of stream discharge, hydrodynamics and sediment transport variation at the estuarine section of the Hudson River and Estuary, NY

Mohammad S. Islam, James S. Bonner , Chris Fuller and William Kirkey
Department of Civil Engineering, Clarkson University, Potsdam, NY

***Abstract*— Tidal forces play a dominant role in controlling the sediment transport and water quantity and quality changes along the estuarine section of the Hudson River and Estuary (HRE), NY- a system of major ecological and economic importance. We present concurrent hydrodynamic and acoustic backscatter data collected through the River and Estuary Observatory Network (REON), with Acoustic Doppler Current Profilers (ADCP) installed on both a moored platform and research vessel to quantify tidal effects on this section of the HRE. Using index-velocity method, the concurrent datasets captured over a tidal cycle were used to develop rating curves for continuous estimation of stream discharge as a function of the current velocity and river stage height. These rating curves were used to estimate discharges during another tidal cycle which are in good agreement with those measurements with the vessel mounted ADCP. This demonstrated the applicability of using moored-ADCP datasets to generate continuous real-time estimates of stream discharges using the rating curves. In addition, concurrent determination of bed shear stress from ADCP-measured current profile and measurements of suspended solid concentration provides evidence of periodic occurrence of tidal-driven sediment re-suspension events. Significant variability in water current over each tidal cycle including strong vertical gradient in current at peak ebb tide and bi-directional movement of water at slack tide were observed. These hydrodynamic and suspended sediment variability will have significant impacts on nutrient dynamics, sediment and contaminant transport, water quantity and quality variation along the estuary and so, ecosystem managers needs to consider the tidal effects for conservation and management of this valuable ecosystem.**

Keywords*— Sediment re-suspension; stream discharge; tidal hydrodynamics; ADCP; Hudson River and Estuary.

I. INTRODUCTION

The Hudson River and Estuary (HRE), NY, a system of major ecological and economic importance, is a dynamic and energetic system. This 507-km long waterbody is hydro-dynamically divided into two sections by a federal dam at Troy, NY: the 243-km stretch of tidal-driven estuarine section and the freshwater-influx driven riverine section upstream of the dam. Tidal flows are typically an order of magnitude greater than net flows [1] and so tidal hydrodynamics play a critical role in controlling water quality along the estuarine section. Further, stream discharge variation, especially within the estuarine region of the waterbody, results in corresponding changes in salinity and suspended sediment levels. Real-time monitoring is critical to characterize these significant environmental changes which can occur rapidly, on the order of hours or minutes, due to dynamic nature of tidal forces. Measured data from vessel-based surveys and one of the monitoring nodes of the REON at the estuarine region is presented in this paper to quantify discharge, hydrodynamics variation and to evaluate their impacts on the sediment transport. REON is being implemented for near real-time monitoring of New York's Hudson, Mohawk and St. Lawrence rivers via an integrated network of sensors, robotics and computational technology distributed throughout the rivers.

Traditionally, stream discharge is derived from a stage-discharge rating curve which is developed through relating stream stage heights with periodic measurements of cross-sectional discharge under various flow conditions. However, this relationship can not be used to calculate discharge under all conditions including flow reversals, backwater effects, and hysteresis effects (different stage-discharge relations for rising and falling stages). In this study, we, therefore, evaluate applicability of the index-velocity method [2] to estimate continuous measurements of stream discharge at the mentioned monitoring site in the estuarine region. This method is based on the premise that there exists some well-defined and unique relation between the velocity within the subarea of the cross-section and the cross-sectional velocity. Estimated discharge and measured water current datasets are then analyzed to understand the hydrodynamics and sediment transport variation over a tidal cycle. This improved understanding will guide ecosystem managers in various projects including navigational and remedial dredging activities, mitigation of benthic habitat alteration for sustainable management of the ecosystem.

II. METHODOLOGY

We present concurrent hydrodynamic and acoustic backscatter data collected from one of the moored-ADCP sites of the REON in the estuarine region and the vessel-based ADCP surveys in proximity to the moored site. The moored ADCP measured water current profiles every minute from an ensemble of 45 pings whereas the vessel-mounted ADCP collected data every 30 seconds from an ensemble of 30 pings. The vessel mounted ADCP was used to perform cross-sectional surveys, in close proximity to the moored platform, to provide stream discharge measurements over a complete tidal cycle. The concurrent datasets were analyzed to develop rating curves for continuous estimation of stream discharge as a function of the current velocity and river stage height. In addition to ADCP datasets, vertical profile of particle concentration measured at the monitoring site via fixed robotic vertical profiler (FRVP) are analyzed to understand tidal effects on sediment transport mechanisms. The FRVP is an automated profiler system which moves a suite of water quality sensors vertically within the water column for hourly measurements at five different depths (~20% depth interval). The water quality sensors include a particle size analyzer which measures total volume of particle concentration and size distribution. Further, surrogate measurements of suspended solid concentrations (SSC) was estimated as a function of the ADCP echo intensity corrected for attenuation (sound absorption, beam spreading) and other instrument-specific variables [3]. Moreover, bed shear stress (τ) at the monitoring site was calculated from velocity observations to evaluate impacts of tidal hydrodynamics on river bed sediment scour. Estimates of τ were made using the "law of the wall" method on the assumption that the velocity profile in the lower portion of an open channel flow has a logarithmic structure. The logarithmic velocity profile is expressed by the von Karman-Prandtl equation (1):

$$\frac{u}{u_*} = \frac{1}{k}\ln\left(\frac{z}{z_0}\right) \tag{1}$$

where, $u_* = (\tau/\rho)^{1/2}$, ρ is fluid density, u is time-averaged streamwise velocity at height z above the bed, z_0 is bed roughness length and k is von Karman's constant (taken to be 0.40). Equation (1) applies within a near-bed region that is well below the free surface and above the local influence of individual bed roughness elements [4]. In this study, near-bed shear stress is determined through analyzing velocity datasets measured in the lower 50% of the water column where observed velocity data followed logarithmic profile. Ten vertical profiles of current velocities measured over ten minutes are used to calculate bed shear stress through fitting the least squares line. The slope of this least squares line fitted to (u, ln(z)) is seen to be u_*/k . Bed shear stress is then estimated through multiplication of u_*^2 with water density.

III. RESULTS AND DISCUSSIONS

Stream cross-sectional areas showed a linear correlation with the river stage height measured at the moored platform (Figure 1a). The relationship between index-velocity and x-sectional mean velocity follows a second order polynomial curve that varies with respect to the tidal flood and ebb currents as a loop curve, shown in Figures 1b and 1c, respectively. Real-time stream discharges are computed (Figure 1d, red circles) as the product of the x-sectional area, determined as a function of stage height and x-sectional mean velocities for the respective flood and ebb flows (Figure 1d). Also shown in Figure 1d (black dots) are the stream discharges measured with the vessel mounted

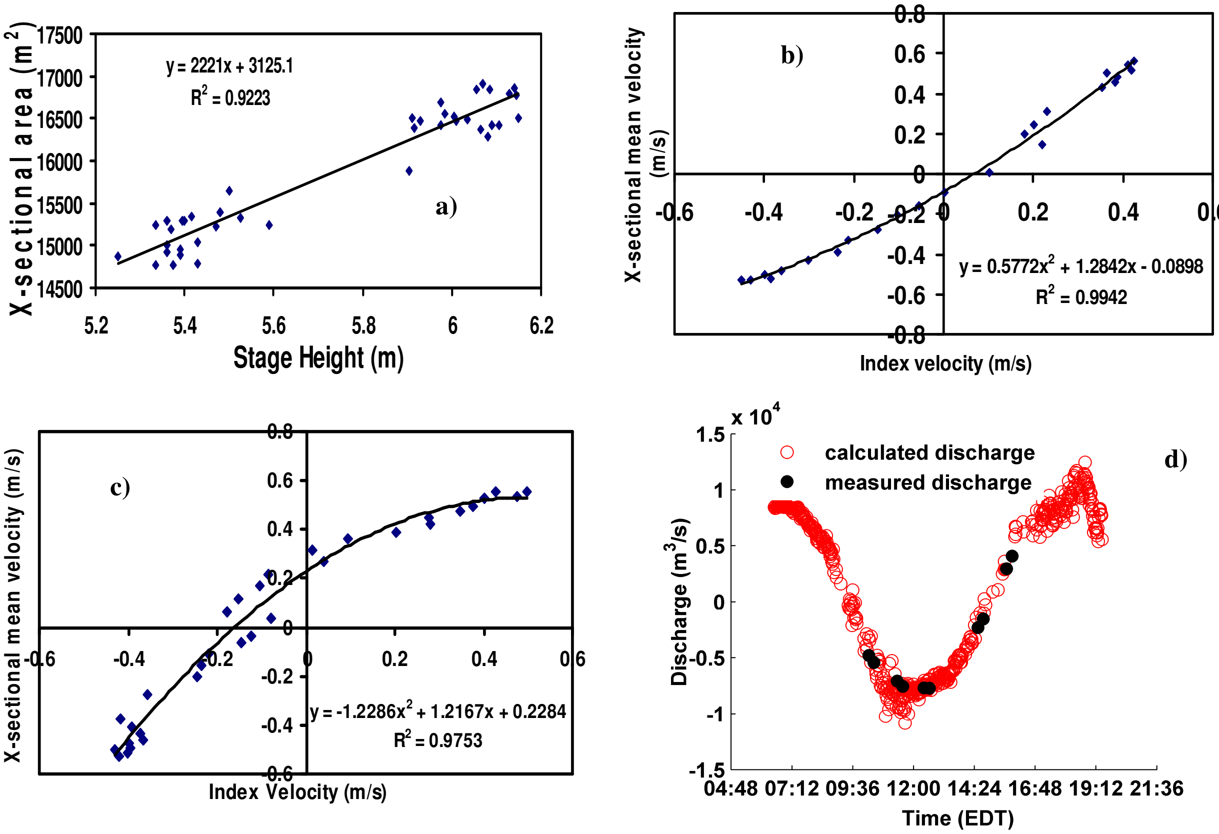

Figure 1. Calibration and validation of index-velocity method: a) Vessel-based ADCP measured x-section area vs. moored ADCP measured stage height; b) x-sectional mean velocity vs. index velocity at ebb to flood tide; c) x-sectional mean velocity vs. index velocity at flood to ebb tide and d) measured discharge (denoted as solid black circle) vs. calculated discharge (denoted as open red circles). Note: Positive discharge value represents the flood discharge whereas the negative discharge value denotes the discharge measured at ebb tide.

ADCP which are in good agreement and demonstrated the applicability of using ADCP derived index velocities to estimate stream discharges. However, periodic cross-sectional surveys are needed to calibrate and validate rating curves for the range of flow conditions expected at the monitoring site.

Concurrent measurements of water current and SSC provided information about the impacts of tidal forces on sediment dynamics. Both calculated bed shear stress and depth-averaged particle concentration at the monitoring site of the same 13-hr time period are shown in figure 2 as solid red and blue circles, respectively. From this figure, it is clear that both bed-shear stress and particle concentration changes with tide. As bed shear stress reached to approx. 0.2 N/m^2 from slack to flood/ebb tide, tide-induced turbulence was strong enough to overcome this critical bed shear stress to re-suspend the bottom sediment and so, particle concentration increased thereafter. Also, measured elevated suspended solids at the peaks of both flood and ebb tides and low particle concentrations at slack tide provides further evidence of tidally mediated suspension of bottom sediments. In addition, concurrent cross-sectional variation of water current and surrogate measurements of SSC also validates the occurrence of tidal sediment re-suspension event. Strong vertical gradient in current magnitude was also observed at peak ebb tide whereas a strong velocity gradient along the cross-section represented as bidirectional flow across the river was observed at slack tide (data not presented here). These observed hydrodynamic and suspended sediment variability provides insight

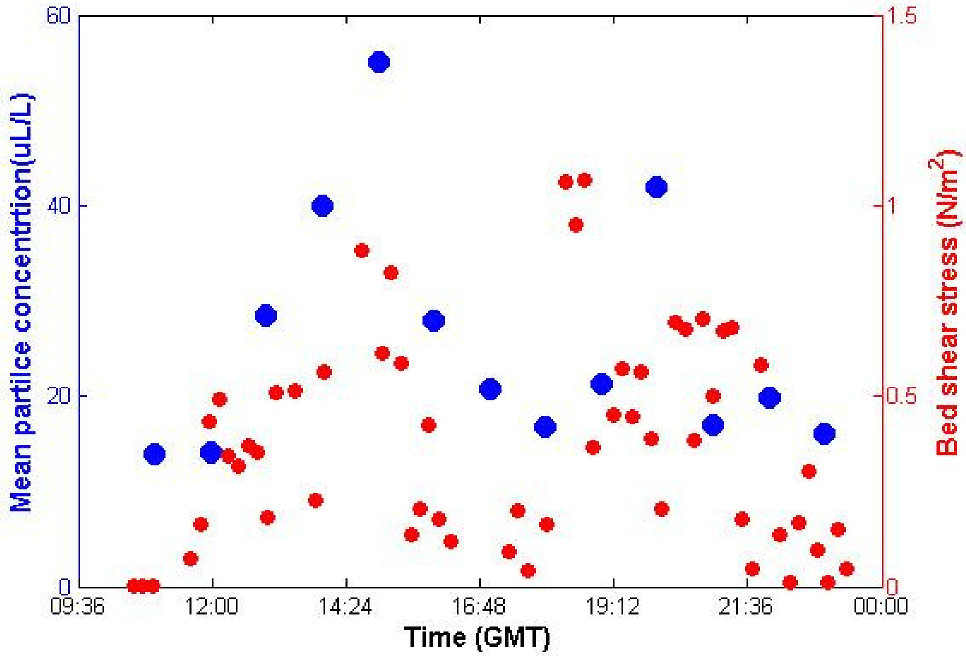

Fig. 2 Variation of depth-averaged particle concentration (solid blue circles) and bed-shear stress (solid red-circles) over a tidal cycle.

with respect to tidal influences on sediment transport mechanisms in estuarine rivers. Therefore, these tidal effects will have significant impacts on nutrient dynamics, sediment and contaminant transport along the estuary and so, ecosystem managers needs to consider their effects for conservation and management of this valuable ecosystem.

IV. CONCLUSIONS

Measured ADCP datasets at the moored platform can be utilized with the rating curves generated through application of the index-velocity method to compute real-time stream discharge variation within the estuarine section of the HRE. Also, vertical profile of water current and sediment measurements at the moored platform provide insight with respect to tidal influences on sediment transport mechanisms in the estuarine section of the river. Concurrent estimation of SSC and bed shear stress suggests that bottom sediment re-suspended at ebb and flood tide and re-settled at slack tides. Strong vertical gradient in current magnitude was also observed at peak ebb tide. During slack tide, a robust velocity gradient along the cross-section represented as bidirectional flow across the river was observed. These observed distinct tidal variability of hydrodynamics, stream discharge and sediment transport will have significant implications to the nutrient dynamics, benthic habitat conditions, navigability, water quantity and quality of the HRE.

ACKNOWLEDGMENT

Funding for this work was provided by the Beacon Institute for Rivers and Estuaries and the National Science Foundation (grant no. CBET-1058422 and CBET-0821531). Thanks also go to the REON field engineering team for their support in the data collection effort.

REFERENCES

[1] Blumberg,A.F. and Hellweger, F.L. (2006). Hydrodynamics of the Hudson River Estuary, American Fisheries society Symposium, 51, p. 9-28.

[2] Levesque, V.A., and Oberg, K.A., 2012, Computing discharge using the index velocity method: U.S. Geological Survey Techniques and Methods 3–A23, 148 p. (Also available at http://pubs.usgs.gov/tm/3a23/.)

[3] Gray, J .R. and J.W. Gartner (2009), Technological advances in suspended-sediment surrogate monitoring, Water Resources Research 45, W00D29, doi:10.1029/ 2008WR007063.

[4] Wilcock, P.R. (1996), Estimating local bed shear stress from velocity observations, Water Resources Research, 32(11), 3361-3366.