DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

Riverine Flow Observations and Modeling: Sensitivity of Delft3D River Model to Bathymetric Variability

Jamie MacMahan & Ad Reniers
Oceanography Department, Spanagel 327c
Naval Postgraduate School
Monterey, CA 93943
Phone: (831) 656-2379 Fax: (831) 656-2712 Email: jhmacmah@nps.edu

NPS Award Number: (N0001410WX21049; N0001411WX20962)

Rosenstiel School of Marine and Atmospheric Science
Miami, FL33149
Phone: (305) 421-4223 Fax: (305) 421-4701 Email: areniers@rsmas.miami.edu

UM Award Number: (N000141010379)

LONG-TERM GOALS

The goal of our effort is to understand river and inlet fluid dynamics through in situ field observations and model validation.

OBJECTIVES

The primary objects are to: 1) establish the river flow response to horizontal (e.g., river width variations, bends, groins, etc.) and vertical bathymetric variability (e.g., channels and shoals, bars and dunes) with GPS-equipped surface drifters, dye sensors, an Unmanned Surface Vehicle (USV), and an Unmanned Underwater Vehicle (UUV) in varying river reaches that are charateristically different; and 2) validate Delft3D river flow model with these unique observations and subsequently examine the sensitivity of Delft3D river flow model to bathymetric variability in general under a wide range of forcing conditions using an ensemble approach.

APPROACH

The key element of our effort is to establish the sensitivity of river flow to (changes) in the bathymetry. To that end, we propose to collect a number of unique data sets at two characteristically different reaches with the Kootenai River, ID, which will be used to study the flow dynamics of rivers and to validate the Delft3D model for river flow.

WORK COMPLETED

We (MacMahan, Reniers, Swick, Brown, Thornton, Tuggle, Ashley, Rynne, and Cowen) collected various measurements on two characteristically different reaches in the Kootenai River, ID in August

2010. During our efforts, we have collaborated with Todd Holland at NRL and Jon Nelson at the USGS and Lisa Emery at QinetiQ. The braided reach (Figure 1) is a shallow (<3m) gravel river with flow velocities up to 2 m/s. We deployed stationary catamarans with downward facing ADCPs at various locations within this reach for approximately 15 minutes to obtain the mean vertical velocity profile. We deployed a frame instrumented with a 4m lagged coherent electromagnetic current meter array, single ADV, and custom 2 MHz Acoustic Doppler Current Profiler (ADCP) head to measure coherent structures at various locations within the braided reach for a minimum duration of two hours per location. We performed an intensive steady-state dye study in a 30m x 3 m channel to evaluate transverse mixing. 10 NPS and 6 QinetiQ drifters were deployed in the same dye channel. Bathymetric surveys were performed by a person walking with a GPS-equipped backpack and with an echosounder-equipped electric kayak. The meandering reach (Figure 2) is a deep (~10m) channel with flows around 0.5m/s located downstream of the braided reach. Two autonomous vehicles were used to describe the mean velocity profiles within this reach. In addition 40 NPS drifters and 6 QinetiQ drifters were also deployed in this reach.

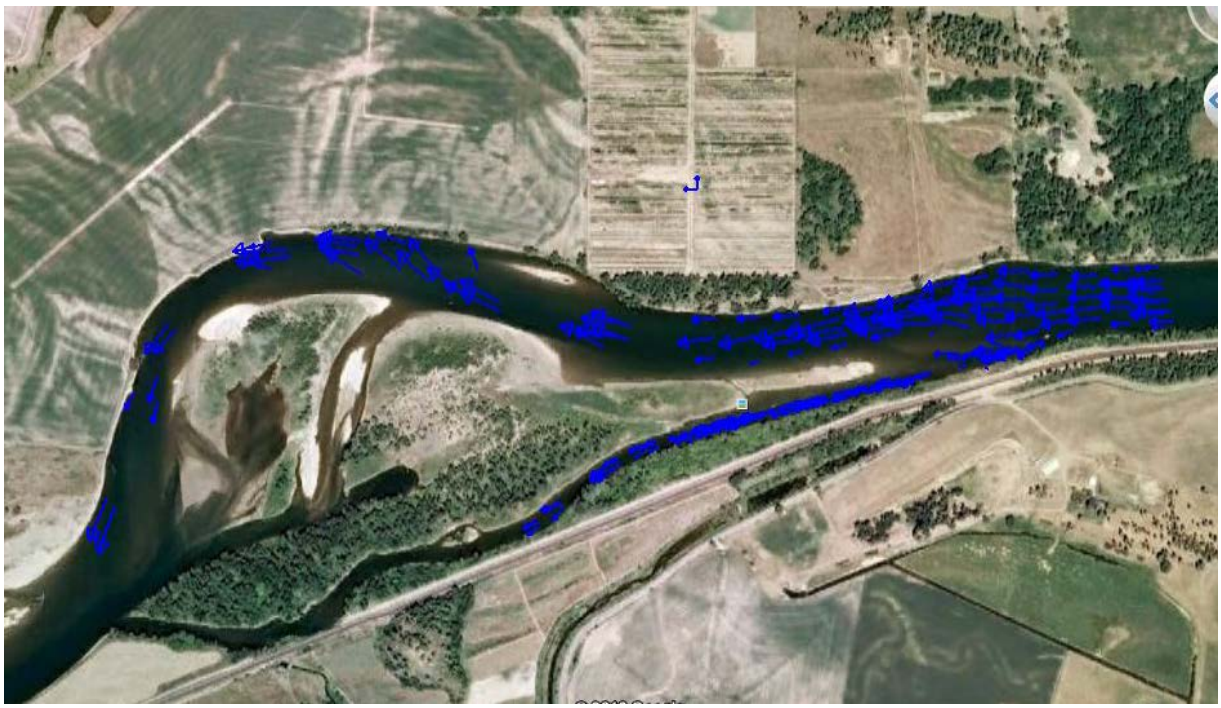

Figure 1. Surface velocity vectors from 15-minute averaged ADCP observation from stationary mini-catamarans overlaid on a Google Earth image of the meandering reach of the Kootenai River, ID. 0.5 m/s velocity scale plotted on the land north of the channel

Figure 2. Surface velocity vectors from 10-minute averaged ADCP observation when the USV was station-keeping overlaid on a Google Earth image of the meandering reach of the Kootenai River, ID. 0.5 m/s velocity scale plotted on land.

RESULTS

Data

We have provided ADCP data, bathymetry, and drifter data to Todd Holland at NRL, Tuba Okzan-Haller at OSU, and David Walker at Michigan.

Papers

MacMahan, J., W. Ashley, A. Reniers, E. Thornton (2011) Observations of Stream-wise Coherent Flow Structures in a Natural Gravel-Bed River submitted to Geophysical Research Letters.

Manuscript Abstract

Stream-wise, horizontal length scales and persistence of coherent flow structures are estimated from an Iterative Maximum Likelihood Estimator (IMLE) applied to velocities acquired by a horizontal 2 MHz Acoustic Doppler Beam (ADB) deployed at various fast-flowing locations in a gravel-bed reach of the Kootenai River, ID. The IMLE employed on the ADB data increased our ability to describe river motions with relatively long (>10 m) length scales in 1 m water depths (Figure 3). It was found that the length of river motions, L_m>20h, where h is the water depth, appear longer than previously suggested. It was found that energetic (~50% of the total spectral energy), low-frequency (f<0.05 Hz) stream-wise motions appear as low-pass white noise, but they are stream-wise coherent along the length of the array. The energetic spectral ridge in the frequency-wavenumber spectra is slightly slower (~10%) than the mean velocity differing from Taylor's frozen turbulence hypothesis (Figure 3). The low-frequency

motion lengths were found to be longer than their corresponding coherent lengths (Figure 4) suggesting that they evolve rapidly while propagating downstream.

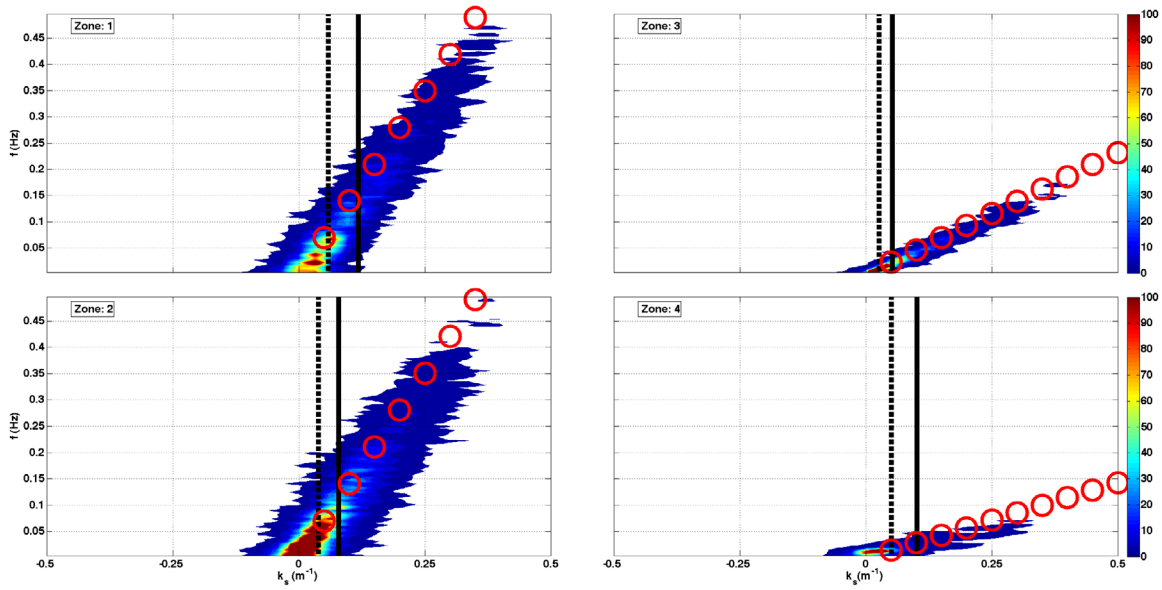

Figure 3. Frequency-wavenumber spectra for the streamwise ADB velocities measured within the four different zones. The red circles represent the mean velocity. Vertical lines represent two (solid) or four times (dashed) the maximum array length. Normalized velocity colorscales plotted to the right.

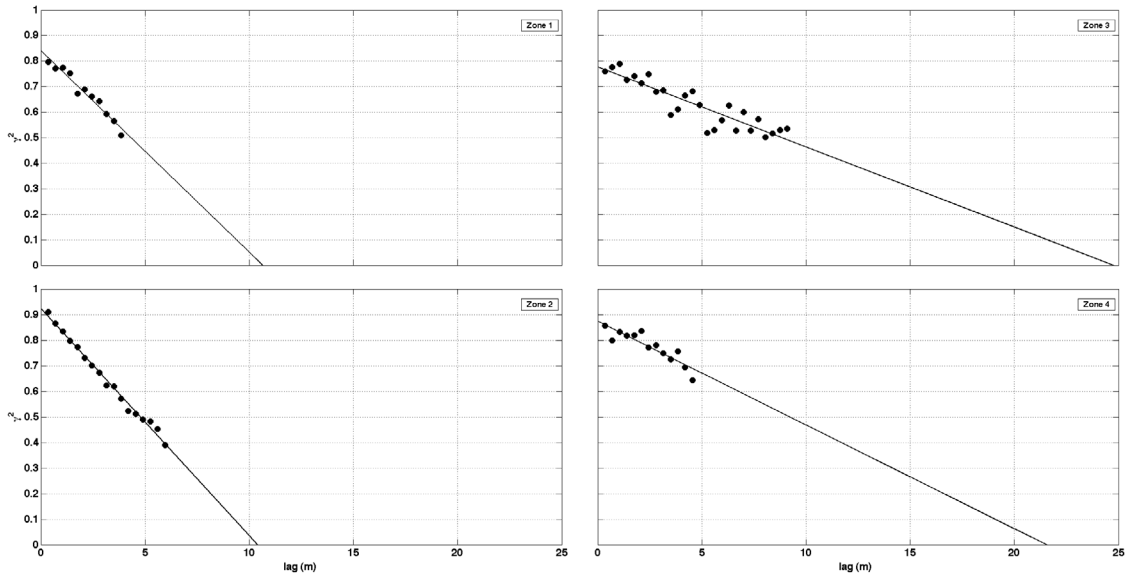

Figure 4. The mean coherency as function of lag. Solid lines represent least-square linear fit. Y-intercepts represent coherent lengths.

Brown, J.*, C. Tuggle*, J. MacMahan, A. Reniers (2011), The use of autonomous vehicles for spatially measuring mean velocity profiles in rivers and estuaries, Intelligent Service Robotics. doi: 10.1007/s11370-011-0095-6

Manuscript Abstract

Autonomous vehicles (AVs) are commonly used in oceanic and more recently estuarine and riverine environments because they are small, versatile, efficient, moving platforms equipped with a suite of instruments for measuring environmental conditions. However, moving vessel observations, particularly those associated with Acoustic Doppler Current Profiler (ADCP) measurements, can be problematic owing to instrument noise, flow fluctuations, and spatial variability. A range of ADCPs manufactured by different companies were integrated on to an Unmanned Surface Vehicle (USV), an Unmanned Underwater Vehicle (UUV), and some additional stationary platforms and were deployed in a number of natural riverine and estuarine environments to evaluate the quality of the velocity profile over the depth, minimum averaging time interval requirements, and AV mission planning considerations. Measurements were obtained at fixed locations to eliminate any spatial variations in the mean flow characteristics. The USV has the unique capability to station-keep to within 1 m owing to its dual-propeller design, providing the best setup for spatially mapping velocity profiles. Single-propeller UUVs can perform a quasi-stationkeeping (<10 m) operation, but are designed for traveling underwater at speeds >1 m/s. An appropriate averaging window, denoted as $T*$, was determined using the Kalman Algorithm with a Kalman gain equal to 1%. $T*$ was found to be independent of depth, flow velocity, and environment (Figure 5). There was no correlation ($R^2 = 0.18$) for $T*$ between flow magnitude and direction. Results from all measurements had a similar $T*$ of approximately 3 min. Based on this, an averaging window of 4 min is conservatively suggested to obtain a statistically confident measure of the mean velocity profile.

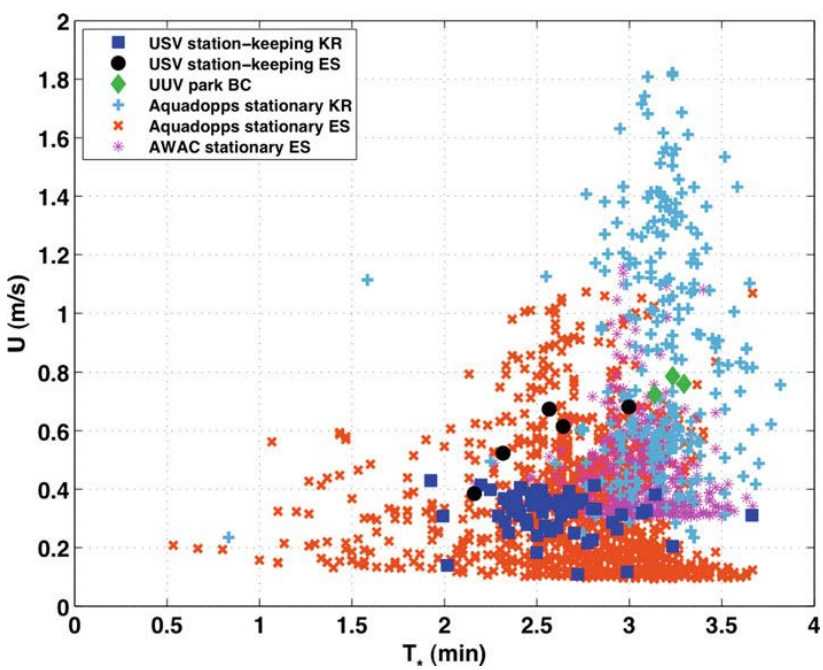

Figure 5. Depth-averaged flow velocity magnitude versus depth-averaged averaging window, T∗, measured by ADCPs mounted on various stationary platforms in differing environments

MacMahan, J., R. Vennell, R. Beatson, J. Brown*, A. Reniers (2011), Divergence-Free Spatial Velocity Flow Field Interpolator for Improving Measurements from ADCP-equipped Small Unmanned Underwater Vehicles, submitted to J. of Atmospheric & Oceanic Technology.

Manuscript Abstract

Applying a 2D divergence-free interpolation (DF) to the one-person deployable Unmanned Underwater Vehicle's (UUV) noisy Moving-Vessel Acoustic Doppler Current Profiler (MV-ADCP) measurements improves the results and increases the utility of the UUV in tidal environments. For a 3.5 hr MV-ACDP simulation that spatially and temporally varies with the M2 tide, the DF estimated velocity direction and orientation improves by approximately 85% (Figure 6). Next the 2D DF method was applied to velocity data obtained from two UUVs that repeatedly performed seven 1-hr survey tracks in Bear Cut Inlet, Miami, FL. The DF method provides a more realistic and consistent representation of the ADCP measured flow field, improving magnitude and orientation estimates by approximately 25%. However near slack tide when flow reversal occurs and the flow velocities are small, the DF estimates are invalid, because the flows are not steady state within the survey circuit and the measurements have a low signal to noise ratio.

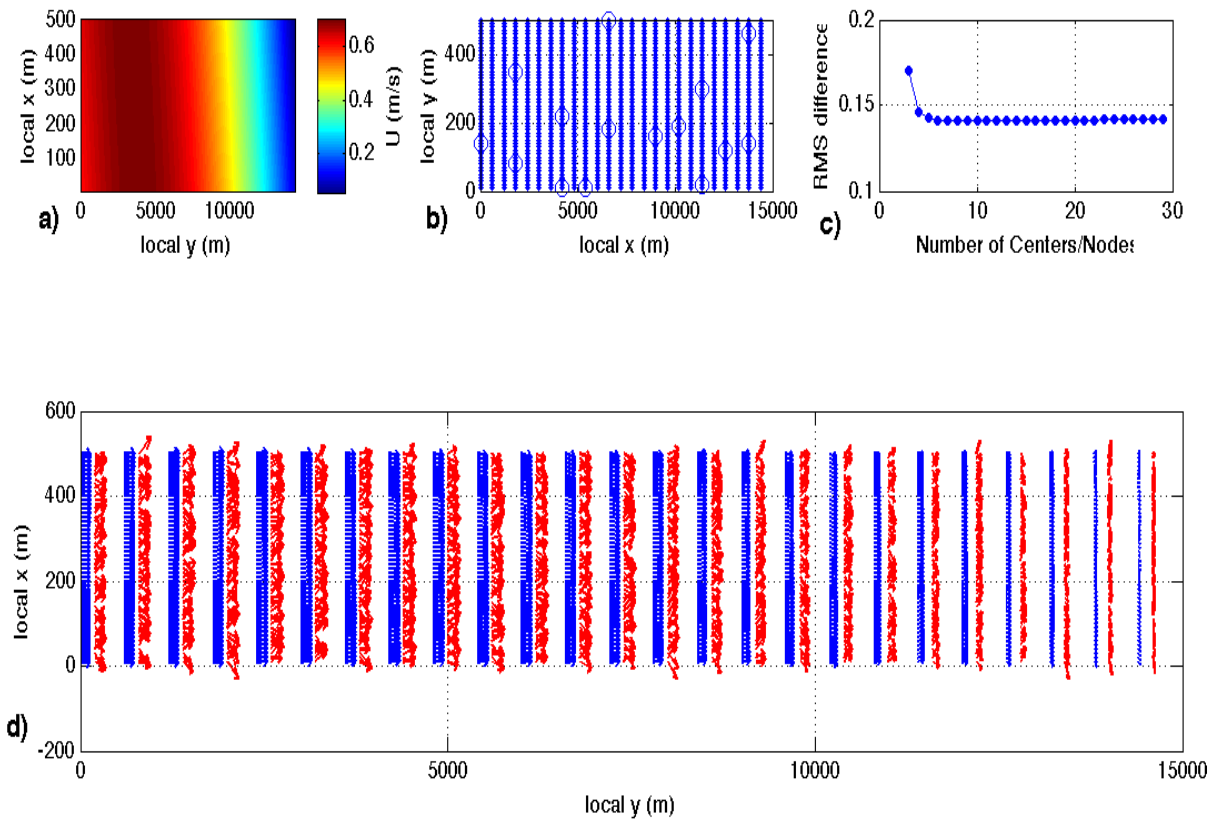

Figure 6. Synthetic tidal example. a) The representative true "non-noisy" tidal velocity for the 3.5-hour synthetic time frame, which mimics the operational duration of the UUV. b) Planform of the spatial survey, where the 10-s measurement locations of noisy ADCP observations and nodes are described as small dots and large circles respectively. c) RMS difference as a function of number of centers/nodes. d) An example of velocity output at 9 cross-sections, where red vectors represent synthetic noisy velocities (offset in the streamwise direction by 250 m) and blue vectors represent DF velocities.

River Mixing – William Swick PhD Dissertation

Spatially Variability of Natural River Mixing (Manuscript in Preparation)

Spatial variability of mixing in natural rivers is described using Lagrangian statistics computed from a fleet of GPS-equipped surface drifters released in three configurations on four hydraulically unique reaches in Skagit River, WA and Kootenai River, ID, USA. The drifters provide near-continuous estimates of mixing that are unobtainable with the historically employed riverine dye efforts. Near-field diffusivity estimates are independent of initial drifter deployment location. However, the presence of river bends influence the streamwise and transverse diffusivity. Single-particle, streamwise diffusivity increased linearly (R^2>0.92) with associated turbulent and shear velocity variances of 0.02 – 0.41 m^2/s^2. An order of magnitude differences was found between single–particle (flow translation) and two-particle (relative spreading) dispersion, suggesting that mixing is due to randomness of particle movement in a flow field with background shear. For all streamwise separation lengths, l_s, diffusivity scales as Richardson ($l^{4/3}$). Reaches with numerous bends resulted in anomalously small two particle diffusivities associated with the streamwise distances of river bends owing to surface flow convergence. Transverse length scales (l_n) are predominantly random, expect when l_n<20m. For the first time, the spatial variability of mixing is quantified, which highlights the significance of channel features in a natural river setting.

Numerical Model Comparisons of Transverse Mixing in a Natural River (Manuscript in Preparation)

Two comprehensive point-source dye experiments were performed in a 1.6 m deep, 30 m wide channel, and 550 m reach of the Kootenai River, Idaho, USA to describe natural river transport and mixing dynamics. The channel is relatively straight and uniform with significant bathymetric features (shallow-water riffle, a channel constriction, and an embayment) located toward the middle of the study reach. Eulerian and Lagrangian flow characteristics and steady state plume behavior were obtained through a combination of stationary and moving observational platforms consisting of dye sensors, GPS-equipped drifters, acoustic Doppler current profilers, and acoustic velocimeters. In the straight sections, the transverse diffusivity, k_n was ~0.02 m^2/s. The flow variability associated with bathymetric features increase k_n (0.06m^2/s) by a factor of three. Dye concentration maximum, Cmax(s), followed a 3D mixing decay as a function of downstream distance, s, as $C_{max}(s) \sim s^{-3/2}$ and then, for s>125m, $C_{max}(s) \sim s^{-1}$, indicating 2D mixing behavior. Lagrangian drifter pathways highlight separation eddies along the channel bank. Simulated results from a three-dimensional hydrodynamic model compared well with field observations for velocity (m=0.81,R^2=0.87), water level (m=0.99, R^2=0.97), and dye concentration (m=1.04,R^2=0.86). Numerical estimates of dye patterns, dispersion, integrated mean particle pathways and mean vorticity patterns for idealized, individual prominent bathymetry features reveal transport is dominated by the mean flow. The effect of combined channel features is highly non-linear, increasing mixing by 200%. Coherent flow structures associated with persistent eddies generated by channel features are important in transporting dye across the channel.

IMPACT/APPLICATIONS

The observation are important for understanding riverine processes by providing high-quality data for numerical model validation. We found that Delft3D can succesful describe mixing accurately. We determined the minimum time required for collecting high-quality ADCP velocity profiles. We improved the utility of the UUV by applying a 2D divergence-free spatial interpolator in a spatiallly and temporally varying flow environment.

New River Inlet DRI: Observations and Modeling of Flow and Material Exchange

Jamie MacMahan & Ad Reniers
Oceanography Department, Spanagel 327c, Naval Postgraduate School
Monterey, CA 93943
Phone: (831) 656-2379 Fax: (831) 656-2712 Email: jhmacmah@nps.edu

NPS Award Number: (N0001410WX21049; N0001411WX20962)

Rosenstiel School of Marine and Atmospheric Science
Miami, FL33149
Phone: (305) 421-4223 Fax: (305) 421-4701 Email: areniers@rsmas.miami.edu

UM Award Number: (N000141110376)

New River Inlet, North Carolina

The main objectives of this effort are: 1) measure the intra-tidal three dimensional flow velocity distribution; 2) measure the concurrent suspended sediment concentration (the accompanying sediment transports will be obtained by multiplying the concentration with the simultaneously measured velocity); 3) extract the tidal flow circulation with Delft 3D to retrieve the residual flow circulation associated with the forcing by waves, wind and density differences; 4) verify Delft3D in predicting the complex velocity field and concurrent sediment transports under a range of environmental conditions (i.e. waves, wind and potentially stratification)

APPROACH

Measure the 3-dimensional flow structure within the inlet area using a combination of mini-catamarans (which are deployed from a small boat) and unmanned surface. All catamarans will be equipped with a downward-looking ADCP to measure the flow velocity structure and concurrent sediment concentration (to be inferred from the acoustic backscatter). In addition, an autonomous winch will be integrated onto the USVs and equipped with a CTD and a WETLABS triplet optical sensor to measure temperature, salinity, turbidity, and CHL-A vertical profiles. The mini-catamarans will be deployed in shallow areas, whereas the USVs will operate in the deeper parts of the channel and the ebb-tidal delta. We intend to position the catamarans in such a pattern (see Figure 1) that we can extract the tidal velocity field from the measurements making use of Delft3D, throughout the domain and thereby obtain accurate estimates of the residual flow circulation. We will also deploy a sediment pumping tripod to calibrate the ADCP and optical backscatter for sediment concentrations. We will drive the model with both the offshore water elevation and the water elevation within the channel.

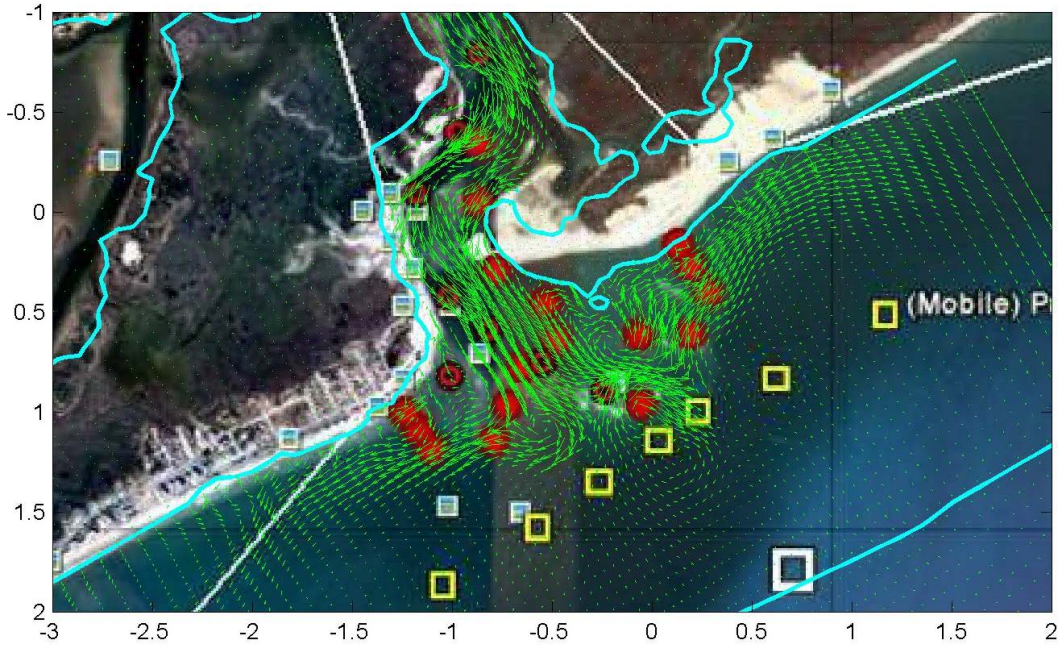

Figure 1 D3D-calculated snapshot of surface velocity field at the New River Inlet during outgoing tide with waves normally incident on the beach. The bathymetric contours are meters water depth (cyan lines). Tentative locations for instruments of various research groups involved in the project are indicated by the squares and the red dots.

With a tidal harmonic analysis (T-TIDES), we can either use the tidal elevation only (to be used in the extraction operation to retrieve the residual flow circulation) or use the measured elevations obtained from self-logging pressure sensors (see Figure 1 for approximate locations) and include forcing by waves/wind/density for model verification/validation. We will have drifters and dye available to examine interesting flow features like eddies (see Figure 1), but we feel that the focus of our efforts should be on measuring and understanding the three-dimensional velocity field and concurrent sediment transport.

WORK COMPLETED

We have incorporated and tested an autonomous winching system and extened battery capacity to the SeaRobotics Unmanned Surface Vehicle allowing the vertical water quality profiles and take measurements over 13 hours to capture the tidal signal. An initial model investigations of the hydrodynamics are being explored by two PhD students (Patrick Rynne at U of Miami and Micah Weltmer at NPS). The observations obtained during the New River Inlet experiment, planned for may 2012 will be ultilized by both students.

IMPACT/APPLICATIONS

The observation are important for understanding river and tidal inlet processes by providing high-quality data for numerical model validation.

PUBLICATIONS (2010-2011) acknowledging ONR support

Brown, J.*, C. Tuggle*, J. MacMahan, A. Reniers (2011), The use of autonomous vehicles for spatially measuring mean velocity profiles in rivers and estuaries, *Intelligent Service Robotics.* doi: 10.1007/s11370-011-0095-6

Orzech, M*, A.J.H.M. Reniers, E.B. Thornton, and J. MacMahan (2011), Megacusps on Rip Channel Bathymetry: Observations and Modeling, *Coastal Eng.* doi:10.1016/j.coastaleng.2011.05.001

MacMahan, J., A. Reniers, J. Brown*, R. Brander, E. Thornton, T. Stanton, J. Brown*, and W. Carey (2011), An introduction to rip currents based on field observations, Editorial, *J. of Coastal Research.* doi: 10.2112/JCOASTRES-D-11-00024.1

Senechal, N., S. Abadie, E. Gallagher, J.H.M. MacMahan, G. Masselink, H. Michallet, A. J.H.M. Reniers, B.G. Ruessink, P.E. Russell, D. Sous, I.L. Turner, F. Ardhuin, P. Bonneton, S. Bujan, S. Capo, R. Certain, T. Garlan, R. Pedreros (2011), The ECORS-Truc Vert'08 nearshore field experiment: Presentation of a three-dimensional morphologic system in a macro-tidal environment during consecutive extreme storm conditions, *Ocean Dynamics* doi: 10.1007/s10236-011-0472-x.
Gallagher, E. L., J. MacMahan, A. Reniers, J. Brown* and E. Thornton (2011), Grain Size Variability on Rip-Channeled Beaches Measured with a Digital Imaging System, *accepted to Marine Geology.*

Laudier, N*. E.B. Thornton and J.H. MacMahan (2011), Wave Overtopping of a Barrier Beach, *Coastal Eng.* doi:10.1016/j.coastaleng.2011.04.005

Gallagher, E.L., J.H. MacMahan, A.J.H.M. Reniers, J. Brown and E.B Thornton, Grain size variability on a rip-channeled beach (2011), Marine Geology, 287, doi:10.1016/j.margeo.2011.06.010, pp. 43-53..

Submitted

MacMahan, J., W. Ashley, A. Reniers, E. Thornton (2011) Observations of Stream-wise Coherent Flow Structures in a Natural Gravel-Bed River *submitted Geophysical Research Letters.*

MacMahan, J., R. Vennell, R. Beatson, J. Brown*, A. Reniers (2011), Divergence-Free Spatial Velocity Flow Field Interpolator for Improving Measurements from ADCP-equipped Small Unmanned Underwater Vehicles, *submitted to J. of Atmospheric & Oceanic Technology.*

Herbers, T., P.F. Jessen, T.T. Janssen, D.B. Colbert, J.H. MacMahan (2011) Observing ocean surface waves with GPS-tracked buoys, *submitted to Journal of Atmospheric and Oceanic Technology.*