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

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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 main objectives of our FY12 effort were to: 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

Our approach is to collect field observations to evaluate the sensitivity of Delft3D and to test the hypothesis that a dynamic front originates at New River Inlet, NC that extends from Stones Bay, NC out to the inner shelf and is strongly influenced by the morphology, tidal, wind, and wave forcing, which induce varying material exchange rates that affect visibility, temperature, and sediment transport.

WORK COMPLETED

We (MacMahan, Reniers, Weltmer, Rynne, Brown, Thornton, and van de Kreeke) collected various field observations at New River Inlet, NC in May 2012. We are in the midst of analyzing the field data and evaluating Delft3D. We are actively collaborating with Feddersen, Guza, Raubenheimer, Elgar, Lippmann, Gallagher, Milligan, Boss, amongst others involved with RIVET.

During RIVET we used Delft3D to make approximately 5-day predictions of the wave and tidal conditions. To that end the Delft3D model was coupled to WWIII to obtain the predicted frequency-directional wave spectra at the offshore. The boundary conditions for the flow modeling were obtained from local tidal predictions. The results were subsequently posted on the web for easy access by all PIs and used for planning purposes, including dye releases. MATLAB scripts were provided to generate

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plots of instantaneous velocity maps (see left panel of Figure 1), residual flows, wave height distributions (right panel of Figure 1), etc.

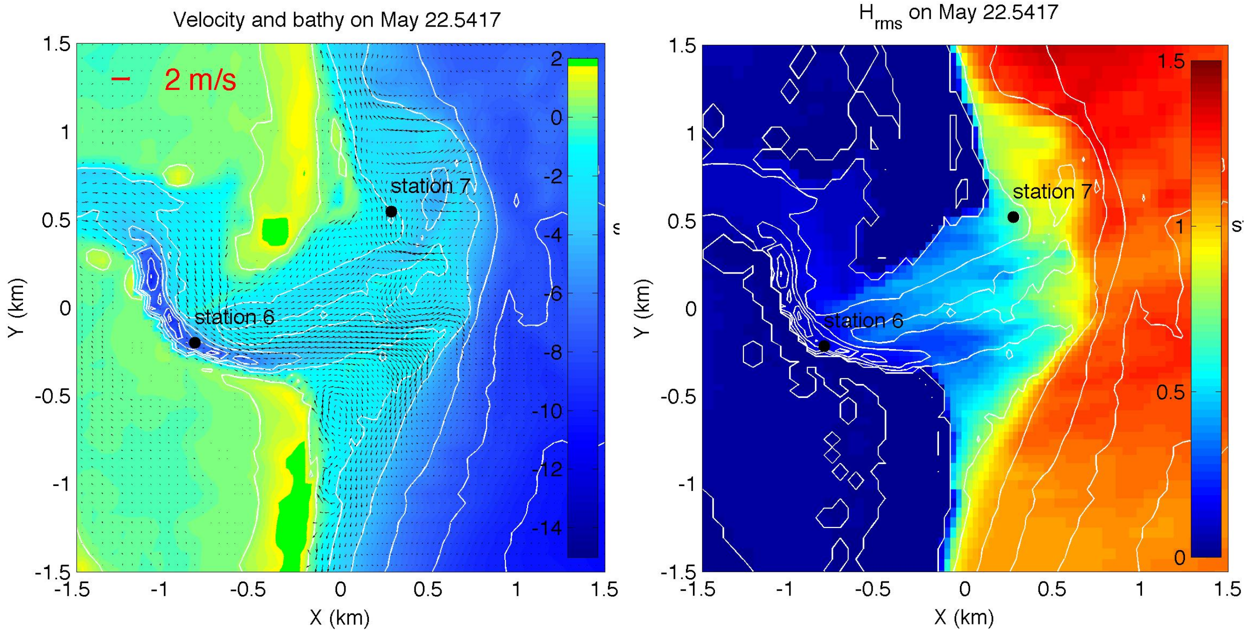

Figure 1. Left panel; Snapshot of Delft3D predicted ebbing surface-velocity field. Right panel: Corresponding root mean square wave height (color bars in meters).

Below are various topics of interest related tides, estuarine processes, and inlets that we are pursuing with ONR support. Most of these topics are associated with theses and dissertations by NPS Naval officers or civilian students at RSMAS.

i) Tidal wave propagation throughout New River estuary

Six mini-catamarans with downward-facing ADCPs, CTDs (surface), optical sensors (surface), and pressure sensors mounted on the anchors were deployed at various locations around New River Inlet. Each location represents approximately 25hrs of measurements, such that tidal analysis (T_tides) could be performed. There is significant attenuation of the semi-diurnal M2 tidal constituent from the ocean to the bay (Figure 2). NRI is a shallow-water, frictional estuary that connects to the ocean via a 5 km long, narrow channel to the back bay. NRI is considered a “choked” inlet due to the small cross-sectional area, long channel, and large storage of the back bay (Hill, 1994).

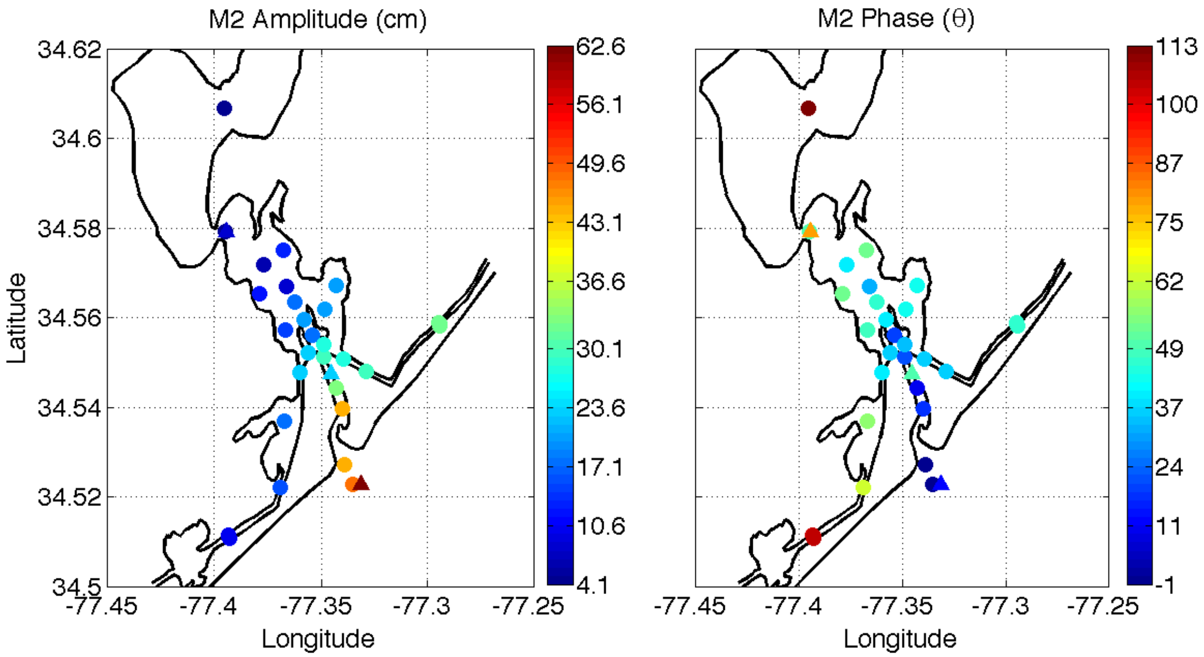

Figure 2. Spatial map of M2 tidal amplitudes (left) and phase (right) for New River Inlet, NC.

ii) Tidal Exchange

As a conduit between the ocean and inland bodies of water such as bays, lagoons and rivers, a tidal inlet plays a significant role in the dynamics of much of the world's coastline (Cromwell, 1973). Of practical importance for the health of ecosystems that exist in these regions is the exchange of inland water with offshore seawater. Because the physical scale of many inlet systems is so large, tidal prisms of 10^7 cubic meters are common (Powell *et al* 2006), and quantifying the dominant processes that influence exchange through *in situ* measurements is logistically complicated. By implementing numerical models to simulate inlet dynamics, a broader scale of processes can be examined.

Following the technique outlined by van de Kreeke (1984) for measuring exchange in small boat basins, virtual dye releases are used to quantify the tidally averaged residence times for locations of interest within an inlet system. Although this study is focused on New River Inlet (NRI), the technique can be applied to any inlet. Residence time can be thought of as the average time a volume of water will remain entrained inland, or conversely as the time it takes it to reach the ocean. To calculate the residence time, numerous virtual dye releases are introduced to a three-dimensional numerical model using Delft3D. As illustrated in Figure 3, a continuously discharging dye source will slowly fill the estuary. Eventually the tidally averaged advection of dye from the estuary into the ocean will equal the flux of dye introduced by the source (Q). At this point the system is said to be at a tidally averaged steady state, and the volume of dye that remains in the estuary (V) remains constant from one tidal cycle to the next. Once steady state is reached, the residence time is calculated as,

$$Resi\ \ ence\ Time = \frac{\mathrm{V}}{Q}.$$

By calibrating the model with *in situ* measurements from NRI, this approach will provide a baseline with which to examine the importance of various physical processes on tidal exchange and residence time. Such information could prove to be insightful and promote a better understanding of water quality in coastal regions influenced by inlets.

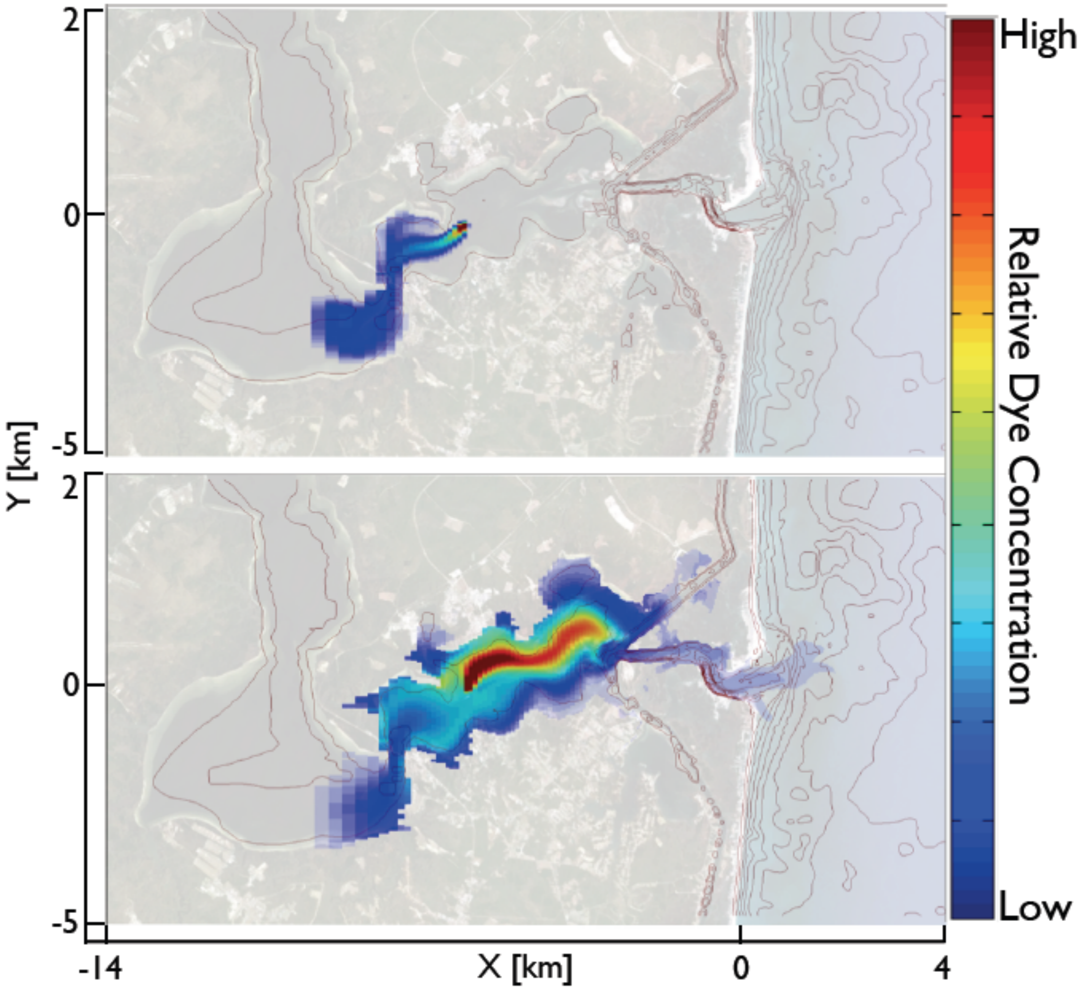

Figure 3. The top image illustrates the spatial coverage extent early after a continuous dye release has begun in the NRI Delft3D model. The lower image illustrates that over time, the advection of dye reaches the inlet mouth and begins to ñleakò into the ocean.

iii) Tidal Fronts

Tidal intrusion fronts, where the dense seawater flooding into an estuary arrests and subducts beneath the buoyant ouflow (Largier, 1992), are commonly found and have been extensively studied in partially mixed or salt wedge estuaries (Marmorino and Trump, 1996; Thain et al., 2004; McDonald and Geyer, 2005; Ralston et al., 2010; Talke et al., 2010), but not in well-mixed environments such as the New River Estuary (NRE). Remotely sensed imagery of the NRE, however, shows the distinct "V"-shaped foam lines associated with tidal intrusion fronts on multiple occasions. To investigate this phenomenon, RIVET included detailed field measurements to verify the appearance of frontal signatures at the surface and describe their subsurface structure and evolution. High resolution CTD casts were made by hand from a small inflatable boat to capture the subsurface T-S structure and evolution, surface features were measured by GPS traces of the fronts and dragging a CTD slowly near the surface, GPS drifters were released to evaluate surface currents, and persistent subsurface observations were made using the NPS-built Mini-Cats, anchored but relocatable non-powered catamarans that were each outfitted with a downward-looking ADCP from the frame, a CTD and optical sensor ~50cm down on the anchor line, and a pressure sensor mounted to the anchor. Coverage was extended at lower resolution through the deployment of an Ocean Server IVER II UUV.

Preliminary results show a surface front consistently located to the lee of a shoal that extends obliquely inward from the end of the most inland of the flood delta islands. Associated with this surface feature is a distinct 2-layer salinity and temperature stratification extending from the front down and away from the dominant central flood, with corresponding enhanced subsurface flow in stark contrast to the surrounding friction-dominated profiles (Figure 4). These features persist through the tidal flood and are consistent with the characteristics of a tidal intrusion front. This front highlights the limitation of bulk estuary characterizations and emphasizes the importance of detailed local measurements in determining the spatiotemporal variability of such characterizations.

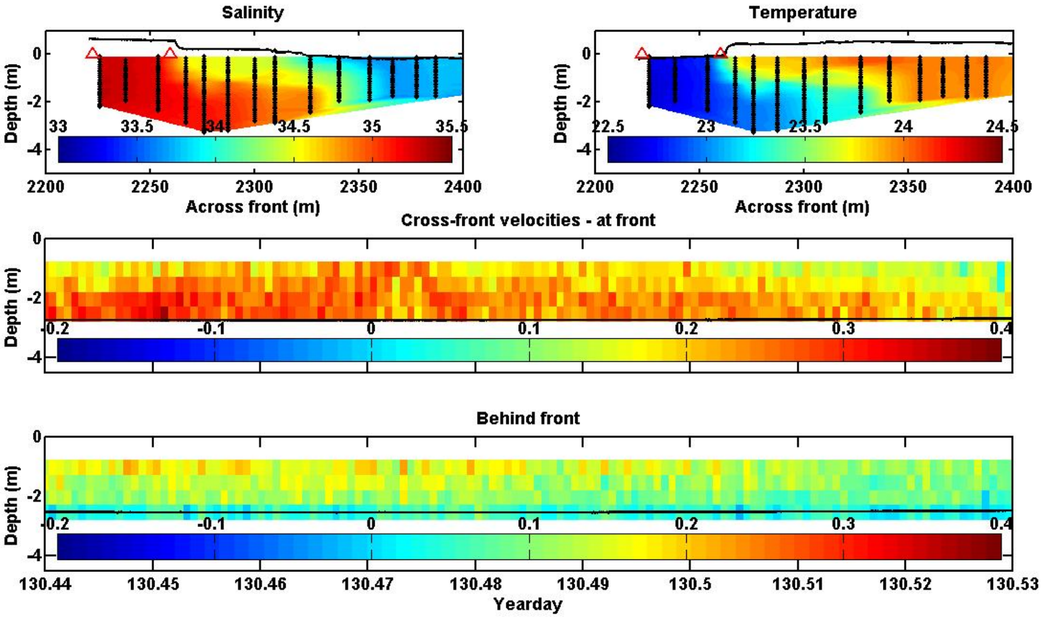

Figure 4. Cross-front measurements of salinity (top left) and temperature (top right), and velocity profiles at the front (middle) and behind the front within the main flood flow (bottom). Relative locations are shown as (Δ) in the top profiles.

iv) Tidal wave reflection and non-linearity in Elkhorn Slough, CA

Elkhorn Slough is a shallow, tidally- forced estuary connected to Monterey Bay, which is highly reflective (96%) creating a standing wave pattern. The literature has shown that non-linearity of a tidal wave associated strictly with the evaluation of the pressure signal increases with distance up the channel. To better understand the non-linearity of the tidal wave, four longitudinally placed acoustic doppler current profilers (ADCPs) were deployed for 60 days in September–October, 2011. Collocated sea surface elevation and depth-averaged velocity are estimated from the ADCPs. Harmonic analysis using the T_Tide program (Pawlowicz et al., 2002) resolved the tidal constituents at the four tidal stations. The non-linearity of the tidal wave is estimated by summing the tidal amplitudes with frequencies >0.085 cph, which are not astronomically forced. The non-linearity increases with increasing distance up the slough, which is consistent with the literature. However, the velocity-derived elevation shows a steady decrease in non-linearity with distance up the slough (Figure 5). Instead of examining the non-linearity of a standing wave using solely the potential and kinetic signal, the standing wave was separated into a shoreward and seaward elevation using the collocated pressure and velocity. Surprisingly, the non-linearity of the shoreward elevation signal decays as it propagates upstream. The seaward elevation signal shows a slight increase in non-linearity as it propagates out to sea. Currently, reasons for the decrease in the non-linearity of the shoreward wave and increases in the non-linearity of the seaward wave are unknown.

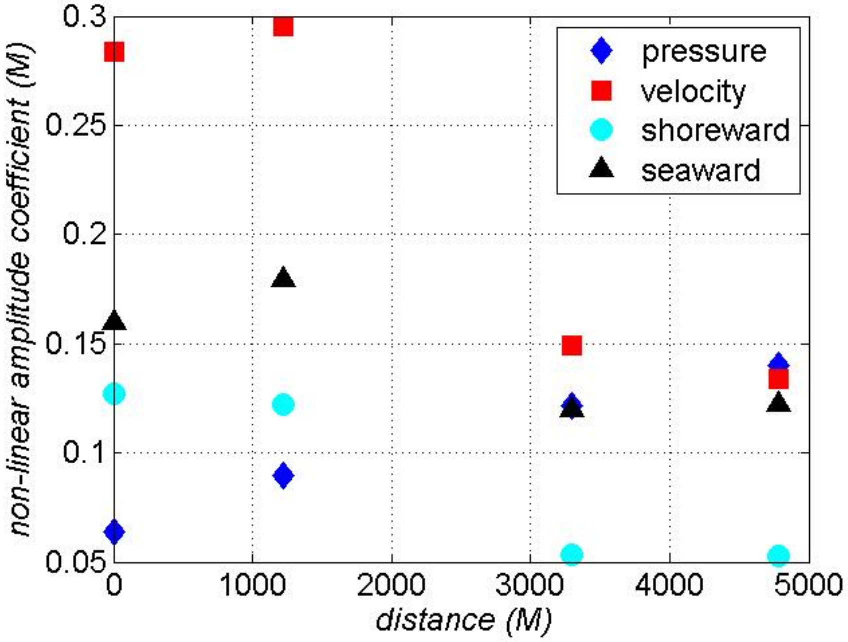

Figure 5. Non-linear amplitude (f>0.085cph) of pressure, velocity and shoreward/seaward surface elevation at four ADCP locations in Elkhorn Slough, CA.

v) Numerical evaluation of wave-current interaction

Areas of turbulent wave-current interactions are of great concern to the Navy because of the hazards to navigation that they present. Both small boat operations and war ship movement evolutions must be conducted with a mind towards the safety of personnel and equipment. Blocking flows at river inlets pose a significant hazard to navigation and the inability to detect and predict these turbulent areas is detrimental to our Naval forces.

Refractive and shoaling effects contribute to the enhancement of wave field energy, causing instabilities and breaking, resulting in energy dissipation and transfer at the blocking point. The non-linearity of wave-current interactions and wave-breaking makes the dynamics of blocking flows difficult to model. In this study, wave-blocking in river inlets is examined using the SWASH (Simulating Waves till Shore) and NHWAVE (Non-Hydrostatic Wave) models. SWASH implements nonlinear shallow water equations with non-hydrostatic pressure to include the effects of vertical accelerations. This is important for describing rapidly evolving waves on a current up to the wave-breaking and wave-blocking point. NHWAVE uses the non-hydrostatic incompressible Navier-Stokes equations to model fully dispersive wave processes. The model is capable of simulating wave refraction, diffraction, shoaling, breaking, landslide tsunami generation, and long shore current. Both monochromatic and random wave cases are explored and compared with Chawla and Kirby (2002) laboratory data in which a series of experiments were conducted to study energy dissipation due to wave-breaking under conditions of strong opposing current.

Current efforts compare SWASH and NHWAVE to the Chawla and Kirby lab data. The objective is to see if the models can provide a useful prediction of the turbulent processes that occur in wave fields on opposing currents. The extension will then be towards the processes at river inlets, in particular, in wave-blocking cases. Ultimately progress towards a reliable prediction of wave-blocking will be of future benefit to the Navy.

vi) NPS-RSMAS Delft3D-UUV short course

In 2011, Reniers and MacMahan in collaboration with Mike Incze and Scott Sideleu developed a Delft3D-UUV short course for NPS Navy Officers and RSMAS students. We continued this course in 2012 and expanded participation to NRL and Oceanserver collaborators. The teaching effort parallels ONR Littoral Geosciences and Optics research themes. Measuring the bathymetry, boundary conditions, and tidal flows with a UUV at Bear Cut Inlet, Miami were the objectives for 2011 and 2012. Additional travel support was provided by CNMOC.

vii) NPS-NRL assistance with UUV in Atchafalaya

Dr. Allen Reed participated in the 2012 short-course and this led to a collaborative research venture in the Atchafalaya. Jenna Brown of NPS teamed up with NRL-SSC (Seafloor Sciences Branch), members of the NAVO Fleet Survey Team, LSU-Geotechnical Engineering and a USNA professor and two midshipmen to address clay-aggregate (“flocs”) transport processes in the Atchafalaya Basin of Southern LA during a cruise this past June. Brown in her first “offshore” trip brought an IVER2 EcoMapper (Figure 6) aboard the RV Pelican. Working from Pelican’s small boat, Brown released the UUV throughout the area of interest to collect current, chemistry and bathymetric data, all of which are essential in understanding environmental controls on floc formation, transport and deposition. Brown’s data are being used to bridge-the-gap between the fixed sample stations where data on water chemistry, currents, bed shear strength (in situ flume) and samples of suspended and bottoms were collected. The combined data sets will increase understanding in the relationship between suspended sediment concentrations, floc properties, nearshore chemistry and currents. Therefore, this data set will facilitate the development of forecasting capabilities for mud depositional patterns (and organic matter and contaminant sequestration) in a littoral environment where optical properties are poor, seafloor shear strengths are low, wave damping is prevalent and current energy is damped.

viii) NPS-RSMAS Kootenai River Research: Riverine flow observations and modeling: sensitivity of Delft3D river model to bathymetric variability (UM no-cost extension).

The key element of this effort is to establish the sensitivity of river flow to (changes) in the bathymetry. All the relevant data has been collected in 2010 and two papers have been published (Brown et al., 2011 and MacMahan et al., 2012, see results section). At present we are working on finalizing three manuscripts: 1) *Spatially Variability of Natural River Mixing* by Swick et al., 2012. 2) *Numerical Model Comparisons of Transverse Mixing in a Natural River* by Swick et al., 2012 and 3) *Modeling shear instabilities in river flow* by Reniers et al., 2012.

Figure 6. A picture of the Ecomapper (Iver2) UUV performing a transect in Atchafayala waters.

RESULTS

MacMahan, J., A. Reniers, W. Ashley*, E. Thornton (2012) Frequency-Wavenumber Velocity Spectra, Taylor's Hypothesis and Length-Scales in a Natural Gravel-Bed River, *Water Resources Research* doi:10.1029/2011WR011709

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

Macro-scale turbulent coherent flow structures in a natural fast-flowing river were examined with a combination of a novel 2 MHz Acoustic Doppler Beam (ADB) and a Maximum Likelihood Estimator (MLE) to characterize the stream-wise horizontal length scales and persistence of coherent flow structures by measuring the frequency (f)- streamwise-wavenumber (k_s) energy density velocity spectrum, $E(f, k_s)$, for the first time in natural rivers. The ADB was deployed under a range of Froude numbers (0.1-0.6) at high Reynolds Numbers ($\sim 10^6$) based on depth and velocity conditions within a gravel-bed reach of the Kootenai River, ID. The MLE employed on the ADB data increased our ability to describe river motions with relatively long (>10 m) length scales in ~1 m water depths. The $E(f, k_s)$ fall along a ridge described by $V = f/k_s$, where V is the mean velocity over depth, verifying Taylor's hypothesis. New, consistent length scale measures are defined based on averaged wave lengths of the low frequency $E(f, k_s)$ and coherence spectra. Energetic (~50% of the total spectral energy), low-frequency (f<0.05Hz) stream-wise motions were found. Mean length scales, L_m, compared with the depth, h, are significantly larger than previously suggested for macro-turbulence with $L_m/h \sim 28$ –

118 (Figure 6). Although the energy appears as low-pass white noise, it is stream-wise coherent along the length of the array. In fast flows with velocities >1 m/s, L_m were found to be significantly longer than their corresponding coherence lengths suggesting that the turbulent structures evolve rapidly under these conditions (Figure 6). This is attributed to the stretching and concomitant deformation of pre-existing macro-turbulent motions by the ubiquitous bathymetry-induced spatial flow accelerations present in a natural gravel-bed river.

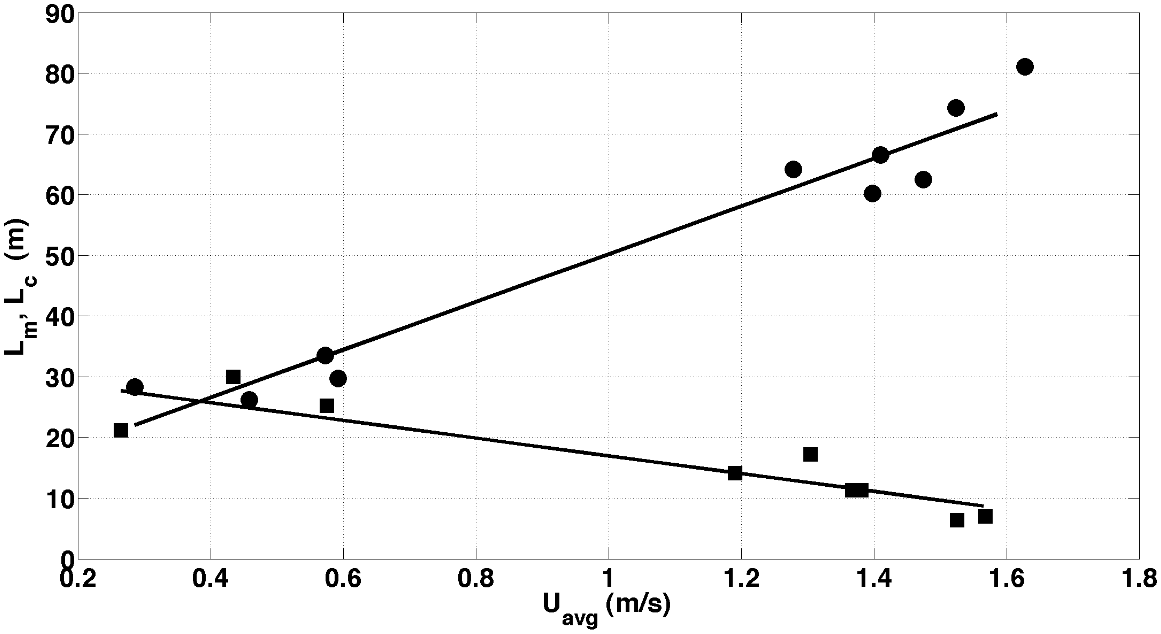

Figure 6. Mean motion lengths, L_m, (circles) and coherence lengths, L_c, (squares) as a function of the mean streamwise velocity at various locations in gravel river bed of the Kootenai River, ID.

IMPACT/APPLICATIONS

The observations are important for understanding riverine and estuarine processes by providing high-quality data for numerical model validation. We found that portable catamarans are useful platforms that can easily be deployed from small vessels.

PUBLICATIONS (2011-2012) acknowledging ONR support

MacMahan, J., A. Reniers, W. Ashley*, E. Thornton (2012) Frequency-Wavenumber Velocity Spectra, Taylor's Hypothesis and Length-Scales in a Natural Gravel-Bed River, *Water Resources Research* doi:10.1029/2011WR011709

Herbers, T., P.F. Jessen, T.T. Janssen, D.B. Colbert, J.H. MacMahan (2012) Observing ocean surface waves with GPS-tracked buoys, *Journal of Atmospheric and Oceanic Technology,* doi 10.1175/JTECH-D-11-00128.1.

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