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PREDICTIONS OF BEDFORMS IN TIDAL INLETS AND RIVER MOUTHS

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Award Number: N00014-13-1-0621

LONG-TERM GOALS

The long-term goals of this research are to model bedforms in tidal inlets and river mouths. To do this, an existing self-organization bedform model is being used. The advantages of this model are that it is relatively simple, with intuitive rules for transport and feedback, it is easily adaptable and produces realistic results. Results from this model will be used to examine bedform growth and dynamics as well as resulting bedform-induced roughness parameterizations.

OBJECTIVES

The specific objectives of this study are to

- continue to develop and adapt the present model for flows in river mouths and tidal inlets, including expanding the model to 2-D in morphology, transport and flow modules, scaling the model up for larger spatial domains and translating to FORTRAN for faster runtimes.
- test the hypothesis that bedform grow and adapt continuously and because of this multiple scales of bedform formation, growth and migration can occur simultaneously.
- continue to compare model predictions with measurements from the literature, from the Hampton River Inlet (Lippmann), from the Golden Gate (Hanes) and from the New River Inlet Experiment (Lippmann, Traykovski).
- calculate bed roughness parameterizations useable by hydro- and morpho-dynamic modelers.
- continue working with the CSDMS so that the present model can be utilized by that community modeling environment.

APPROACH

Bedforms are ubiquitous in unconsolidated sediments. Bedforms act as roughness elements, altering the flow and creating feedback between the bed and the flow. In doing so, they are intimately tied to erosion, transport and deposition of sediments (eg Parsons et al. 2005, Ernstsen et al. 2005). It has been suggested that bedforms in rivers and tidal inlets are dynamically similar to Aeolian dunes and bedforms on the continental shelf and in the surf zone (Best 2005, Frank and Kocurek 1996, Nemeth et al. 2007, Gallagher 2003). Because of this similarity, Gallagher (2011) developed a model for bedforms in the nearshore, based on the principles of work by Werner (1995), who hypothesized that Aeolian dunes were self-organized features and as such could be modeled with a relatively simple model.

It has been suggested that self-organization is responsible for the formation of many different types of morphological patterns, including river meanders (Stolum 1996), sorted-patterned ground (Kessler & Werner 2003), beach cusps (Coco et al. 2000), wind ripples (Nishimori & Ouchi 1993) and Aeolian dunes (Werner 1995, Reffet et al. 2010). In each of these pattern-forming systems, complexity arises from nonlinear interactions between the system and the environment, from dissipative processes such as friction, turbulence and sediment transport, and from being open (both material and energy are exchanged across system boundaries) and therefore the system is never in equilibrium (Werner 1999).

Werner (1995) used a 'hierarchical' approach (Ahl & Allen 1996) to modeling self-organized systems, wherein processes at different temporal and spatial scales are distinct from each other and can be separated. With this approach, grain-scale sediment transport is parameterized with simple rules to drive bedform-scale dynamics. Gallagher (2011) developed a hierarchical model to predict nearshore, combined flow megaripples. The model consists of a matrix of sediment slabs that represent a spatial domain or a region of a bed across which sediment is moving. The sand slabs are picked up and moved according to a transport model (either simple rules similar to Werner (1995) or a physics-based formulation, e.g. Bailard 1981, Ribberink 1998). Sediment transport is driven by the free stream velocity, u, which is modeled with a sinusoidal velocity, a measured velocity signal from the natural surf zone or with a Rayleigh distributed wave velocity signal. In the original model, for each time step, the flow is the same at all locations in the domain except for an imposed random spatial fluctuation representing local turbulence. However, once bedforms are created, the local flow around the bedforms is altered via feedback: flow is reduced in the lee of a bedform to simulate a velocity shadow zone and flow is accelerated over the crest of a large bedform. These spatial alterations to the flow generate gradients in transport, which alter the bed. Feedback is required for bedform growth and development (Gallagher 2011). In addition, the slope of the bed is not allowed to exceed 17°.

The long-term plan for this research has been to use the self-organization model originally developed for nearshore bedforms and adapt it for predicting bedforms in the combined flows of tidal inlets and river mouths. In these environments, oscillatory flows with wave frequencies are superimposed on the quasi-steady flows associated with tides (oscillatory but with a much longer period than the surf waves) as well as steady flows (possibly with seasonal variations) exiting river mouths. These complex, but naturally realistic, flows are being incorporated to predict the growth and migration of dunes and the evolution of multiple scales of bedforms. In addition to combined flows and multiple scales, variations owing to spatially varying water depth (morphology) and grain size are also being examined. This model lends itself to tackling these dynamically complex issues, because relatively simple changes can be implemented to test the importance of factors such as lateral flows, feedback changes, grain size and subtle 3-D morphology changes. Model results are being compared with data from the literature (eg, Hanes 2012 , Jerolmack and Mohrig 2005, Ernstsen et al. 2005) and with data collected as part of the River Mouths and Tidal Inlets DRI experiments in collaboration with Tom Lippmann (UNH), Steve Elgar (WHOI) and Peter Traykovski (WHOI).

Lastly, the model has been submitted to the Community Surface Dynamics Modeling System. CSDMS is a community of experts promoting open-source modeling of earth surface processes. They develop, support, and disseminate software modules that predict the movement of fluids and the flux of sediments and solutes in landscapes and sedimentary basins (for more information see their website at http://csdms.colorado.edu/wiki/Introduction). Here, the bedform model can be used and improved by others and integrated into larger-scale fluid and morphodynamic models with the intention of improving predictions of bedforms, bed roughness, wave and flow dissipation, and sediment transport.

WORK COMPLETED

The self-organization bedform model developed by Gallagher 2011 is being adapted for bedforms in river mouths and inlets (see Fig 1 for a development schematic). The flow model, which drives sediment transport and bedform dynamics, was extended from 1-D to 2-D (ie, directionally varying). Results suggest that this advance has improved model predictions significantly by adding complexity and slowing the bedform formation process. In addition, the inclusion of directionally varying flow in the model (using realistic measured velocities), generated bedforms that behave similarly to observed bedforms from the New River Inlet field experiment (Fig 4).

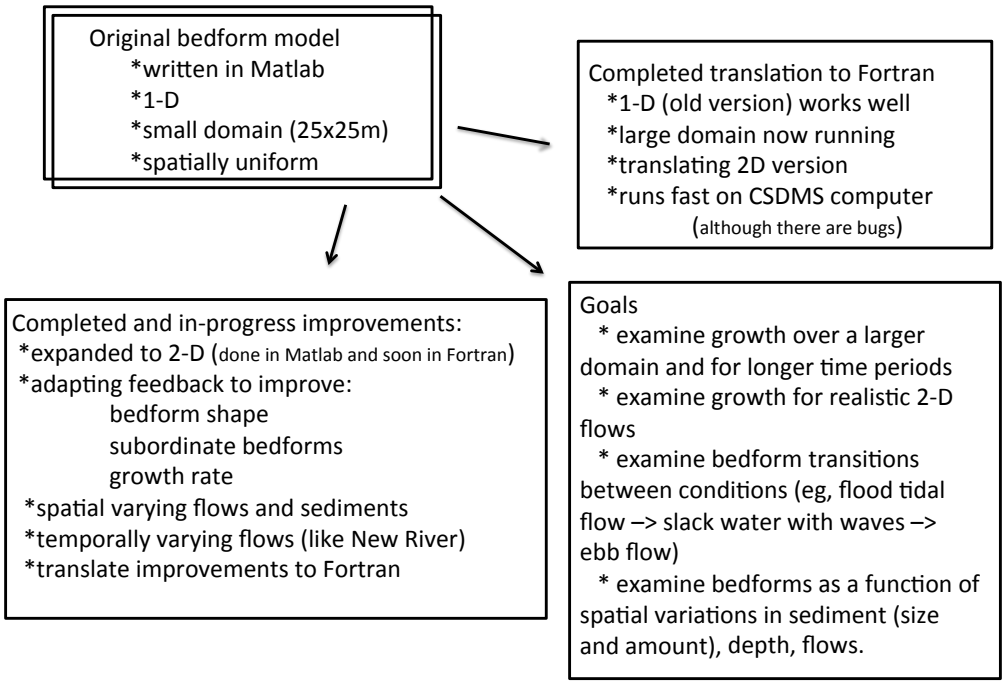

Figure 1. Flowchart of model improvement.

The original MATLAB version of the model is available on the CSDMS website (and has been for over 3 years). The model has been translated from MATLAB to Fortran to fascilitate increasing the domain size and running on the CSDMS High Performance Computing Cluster. In addition, with a final Fortran version, it will be possible to include the model as a 'component' in CSDMS making it easily integratable with other models. The Fortran version of the model is now being run successfully (and speedily) for larger domains, although a significant amount of effort (sometimes frustrating) has been invested in testing the model between running in MATLAB, Fortran on a PC and Fortran on CSDMS. Bugs are still being worked out between running the code on the different platforms. These steps are considered neccesary in the model development, although in themselves they do not produce interesting or measureable results.

In addition to these coding/computer science aspects of the model improvement, a number of model adaptations are being considered to improve the model's accuracy. With the increased domain size now possible, the model needs to have spatially varying flow and bed domains to realistically reproduce the larger scale tidal inlet regions to be modeled. This is in contrast to the smaller nearshore megaripple model domain, which represented a single patch of nearshore bed with a spatially uniform

flow. In addition, adaptation of the model feedback is being considered to create more realistically shaped bedforms and to (hopefully) improve the predicted growth dynamics. One adaptation would be to the calculation of slope, which is done locally now (on a single pair of grid points). Calculation of slope on the scale of a bedform would allow for feedback at bedform scales, rather than at "grain" or block-scales. Also, a crude mechanism for suspended load bypassing is being considered in the feedback/transport routines. These rather serious changes are in their infancy.

I presented the model at the River Coastal and Estuarine Morphodynamics Conference in July 2013. I have established a collaboration with Giovanni Coco at the University of Cantabria and with Jon Miles at the University of Plymouth. The model was also presented at the AGU 2012 Fall Meeting.

I participated in the tidal inlet experiment at New River Inlet with Tom Lippmann in May 2012 and bedform data from that experiment will be presented at the AGU 2014 Fall Meeting. Peter Traykovski also collected rotary side scan measurement and created exciting bedform movies which show multiple scales of bedforms coexisting and that these bedforms are changing constantly as the waves and tides change (Fig 4 and http://vimeo.com/44806773). Through collaboration, these data sets are being used to test the model.

RESULTS

This model was developed for nearshore flows (combined waves and currents) and sediment transport. Predicted nearshore bedforms have been shown to be similar to observed features in the surf zone (Gallagher 2003, Gallagher 2011). The model predicts that bedforms begin as random irregularities on the bed and, via feedback between the flow and the bed, coalesce into small bedforms (Fig 2). As bedforms continue to evolve, smaller, faster bedforms merge with larger, slower ones, causing crest- and wave-lengths to grow. Thus, younger bedforms tend to be short-crested, shorter in wavelength and irregular in shape, while more mature features are longer in both wavelength and crest length (Fig 2). This merging and lengthening is observed in nature (eg, Clarke and Werner 2004) and in other modeling studies (eg, Coco and Murray 2007, Werner and Kocurek 1999, Jerolmack and Mohrig 2005). Clarke and Werner (2004) observed that the growth of bedforms (wavelengths) from a flat bed to maturity occurred first linearly and then became logarithmic (Fig 3). This corresponds to the theoretical model of Werner and Kocurek (1999), which attributed the dynamics and growth of bedforms to the behavior of defects or the ends of bedform crests. The change in growth (from linear to logarithmic) was attributed to the growth and lengthening of bedform crests and the reduction in numbers of defects. The present model predicts this transition in growth rate (and the reduction in defect number), suggesting that the model captures well the bedform dynamics (Gallagher 2011). The natural megaripples in Clarke and Werner (2004) made the transition at around 12 hrs (Fig 3). The modeled megaripples grow and transition much more quickly: 25 mins for sinusoidal flows and 50 mins when natural measured velocities are used to drive the model (Fig 3).

The difference in growth rate of modeled megaripples driven with the sinusoidal versus the natural velocities may be explained by examining the velocity records. The largest amplitudes of the natural cross-shore velocity from the measured time series are over 100 cm/s and the root mean square (RMS) is 32 cm/s. The sinusoidal flows have amplitudes of 75 cm/s and a RMS of 65 cm/s. This difference is because the measured velocities are skewed (with the strongest flows having a short duration) and irregular, with the largest velocities (>75 cm/s) occurring infrequently. So, under natural flows, high transport rates are intermittent. In contrast, the sinusoidal flows reach their maximum velocity every cycle and drive high rates of sand transport consistently. Therefore, bedforms are built more quickly

under the consistent sinusoidal flows and more slowly under the variable natural flows. Neither model reproduces the natural growth rate and transition time of 12 hrs observed by Clarke and Werner (2004). The long transition time observed in the natural surf zone likely results from the even higher variability of the total flow field, including more realistic turbulence, more realistic acceleration on the bedform crest (acting to reduce amplitude growth), variation in direction, variation in tidal level, which Clarke and Werner (2004) state is the dominant controller of the magnitude of the depth-dependent, wave-driven flows in the surf zone (Raubenheimer 2002), and possibly the frequent interruption of the feedback mechanisms by turbulence from breaking waves.

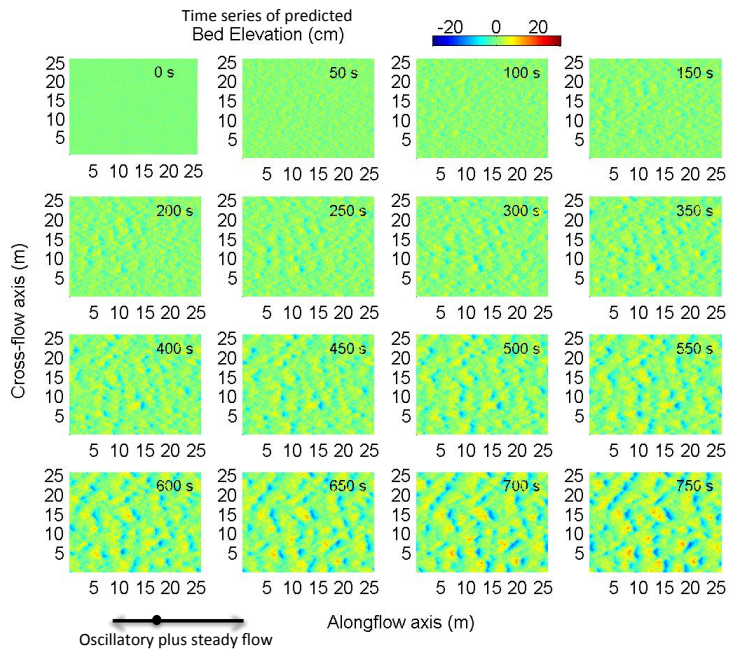

Figure 2. Time series of the bedform domain illustrating creation and development. The model begins with a flat bed, random irregularities in the flow (or the bed) alter the transport via feedback and bumps begin to grow into bedforms, which then grow in wavelength, crest length and height. In this example an oscillatory flow with an amplitude of 75 cm/sec and a steady flow of 20 cm/sec (to the right) were used to drive the model.

As part of the present study, adaptations have been made to the model to include more realistic flows and to allow the model to be scaled up. For example, by implementing 2-D flows in the calculations for Fig 3, the model was run and the model growth rate was slowed further (the magenta points fall below and to the right of the blue points in Fig 3). Note that this model run has not been completed for the long time needed to quantify this result so the transition time has not yet been determined. These preliminary results support the idea that variability of the bedform-building flows are important in understanding the growth and dynamics of the bedforms. Note that the model is also being tested now on larger domains. The asterisks in Fig 3 represent a typical model run on a larger grid to test for edge effects. As all aspects of model improvement are pulled together, model predictions will likely collapse into a sensible and realistic suite of informative results.

To examine bedforms in tidal inlets and river mouths, the upgraded (2-D, large domain, spatially variable) model will be driven by measured currents to predict spatial and temporal varying bedforms. Fig 4 shows preliminary results of a 2-D flow (small-domain) model exercise driven with currents measured at Peter Traykovski's instrument frame. The top panels show observations from his rotary scanning sonars. In those images, darker brown tones represent acoustic shadows, while lighter brown tones represent strong acoustic reflections from bedforms sloped toward the sonar. The center of the

circle is a higher resolution sensor measuring a 5m diameter area and the larger area is from a lower-resolution instrument measuring a 25m diameter area. These images are snapshots from movies that Traykovski has made from the data (see http://vimeo.com/44806773). The bottom three panels are snapshots of model predictions for similar (but not exactly the same) time periods. The model examples shown are at about the same scale (25m x 25m) and colors represent bed elevation (red is high, blue is low).

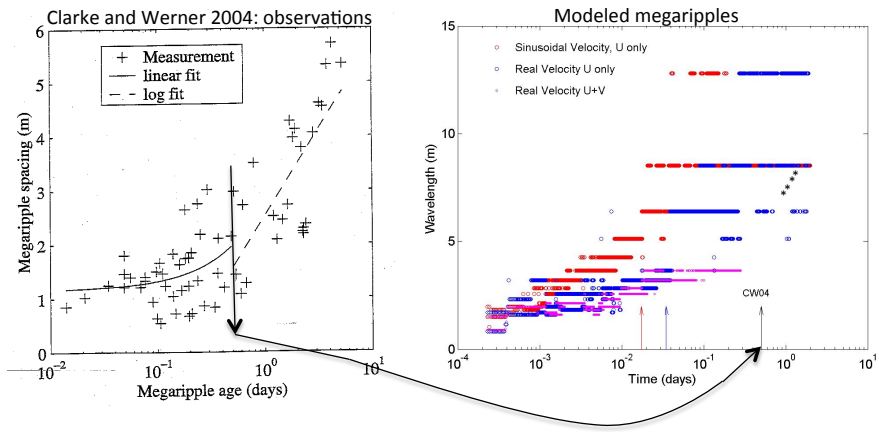

Figure 3. Bedform wavelength growth with time. Left panel is from Clarke and Werner 2004 showing their observations of natural megaripple growth in the surf zone. The arrow represents the transition from immature to mature bedforms at about 12 hrs. The right panel contains models predictions of similar bedforms. The black arrow marks the time for which Clarke and Werner (2004) found that natural growth transition. The red and blue arrows mark the transition times for sinusoidally (25 mins) and natural-flow (50 mins) driven predicted bedforms, respectively. The magenta points are for bedforms driven by a directionally varying flow with the new 2D model. There is no quantitative transition time yet for these preliminary data, but it can be seen that they are growing more slowly than their 1D counterparts (because they are below and to the right of the other examples). The black asterisks are for recent predictions on a large domain (with 1-D flow), thus testing possible edge effects in a smaller domain.

Both observations and model predictions are exciting. Observations show a bed that is highly dynamic with bedform lengths, morphologies and orientation changing with every image (approximately once every half hour). When driven with a similar velocity field, the model predictions show similar variations. In the left panels, both observations and predictions indicate relatively long crested, long wavelength, smooth dunes when the steady ebb flows are strong. When the ebb flow slows, the dunes are still visible, but smaller scale ripples begin to form on top of the dunes (middle panels). Finally, the tidal flow changes direction and begins to flood, moving with the waves propagating into the inlet. Under these conditions, the little ripples grow larger, still riding over the dunes and smoothing their profiles, while possibly an even smaller set of ripples is forming (right panels). These observations show that multiple scales of bedforms occur at the same time and that they are continually adjusting to the variable flow velocities in the inlet and preliminary model result suggest similar behaviors (albeit in a simplified, too-straight way). Results like this are encouraging and it is expected with an upgraded model, the correspondence with the observations will be better and our understanding of bedform growth, development, adaptation, sediment transport and roughness will all be informed and improved.

IMPACT/APPLICATION

This model is being adapted and applied to different environments. At this time the model is being expanded to be able to predict bedforms in larger scale more highly variable environments. For

example, the flow field and conditions varyed significantly in time and in space during the New River Inlet experiment, including the deep sediment-starved channel with very strong, quasy steady, tidal flows and the waves-plus-tidal-flow-dominated shallow, sandy shoal that included breaking and directionally varying flows. Soon, the model will be compared with observations from these varied environments. This will be the first attempt at modeling tidal inlet and river mouth bedforms with the self organization model. It is expected that a simple model of this type could be expanded to model other environments. By beginning to work with CSDMS at this time, it is hoped that this model will be easily integrated into larger-scale flow and morphology models and will help improve the predictive capabilities of hydro- and morpho-dynamics in general.

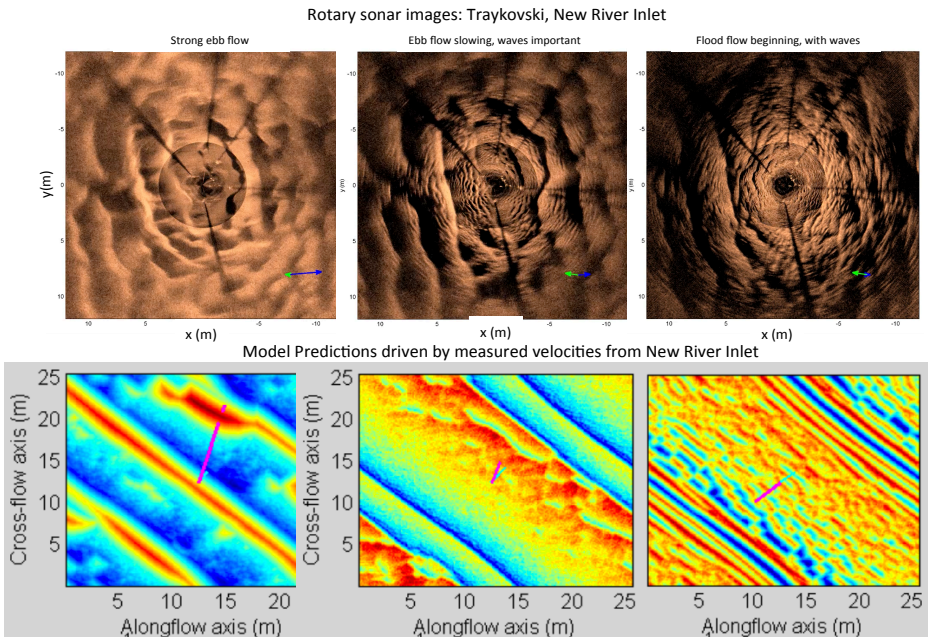

Figure 4. Snapshots of measurements of bedforms from New River Inlet (top row) and model predictions of bedforms for similar conditions (bottom row). Arrows represent the flow vectors with blue and magenta representing steady flow and green and cyan representing the wave velocity variance. Left hand panels show smooth, longer wavelength dunes that were formed during strong ebb flow conditions. Middle panels show those dunes with super-imposed ripples formed as the ebb flow diminishes and wave flows become important. Right hand panels show the dune field beginning to break up multiple scales of ripples forming as the tidal flow turns and begins to flood.

RELATED PROJECTS

This work was originally supported by an NSF ADVANCE grant. At this time, ONR is the only granting agency for this work.

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Gallagher, E.L., Computer Simulations of Megaripples in the Nearshore. Abstract and Presentation at the River Coastal Estuarine Morphodynamics conference, Santander Spain, June 2013.

Gallagher, E.L., Computer Simulations of Bedforms. Abstract and Presentation at the AGU Fall Meeting San Francisco, CA, December 2013.

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