LINKING NEARSHORE PROCESSES AND MORPHOLOGY MEASUREMENTS TO UNDERSTAND LARGE SCALE COASTAL CHANGE

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Abstract:
Two field experiments on the ebb-tidal delta and adjacent beaches near Grays Harbor, Washington USA provide detailed information about bed sediments, waves, currents, suspended-sediment concentrations, and sea-bed change for the calibration and verification of numerical models of sediment transport and morphology change. For the first time, process and nearshore bottom change measurements are being coupled along the high-energy dissipative beaches typical of the U.S. Pacific Northwest. The experiments successfully capture the transition between low-energy beach-building conditions typical of summer and the high-energy erosive conditions of winter (Fall 1999 experiment), as well as the spring transition back to progradational conditions (Spring 2001 experiment). Process-based morphological models are tested with field measurements to improve our ability to predict coastal profile and shoreline change at seasonal and interannual time scales. Model simulations indicate net southerly and onshore sediment transport during the Spring 2001 experiment, agreeing with observations. The magnitude of simulated net onshore sediment transport is highly dependent on the wave-related bed roughness height, a parameter estimated to have varied by approximately 3 orders of magnitude during the experiment. Initial model results suggest that cross-shore sediment transport processes are more important than alongshore processes for seasonal scale (months) morphological change.

INTRODUCTION
We are examining the mechanisms of beach retreat and progradation at seasonal to decadal time scales via beach processes experiments, morphology measurements, and coastal modeling. Our goals are to: 1) investigate the physical mechanisms governing morphological change, 2) link short-term measurements (months) to coastal change at management scales (decades and tens of kilometers), and 3) evaluate and improve upon existing predictive models for nearshore morphodynamics and shoreline change over a continuum of socially relevant scales. Our study site includes the ebb-tidal delta complex and beaches adjacent to Grays Harbor, Washington USA (Figure 1). Studies of physical processes and nearshore bathymetric change have each been conducted in a variety of environments, however they have rarely been linked in high-energy dissipative environments such as the beaches of the U.S. Pacific Northwest.

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Figure 1. Chart of the study area near Grays Harbor, WA showing sites where tripods were deployed. Sites SD, SS, MD, MS, ND, and NS were occupied during the Fall 1999 experiment. In Spring 2001, sites SD, MD, ND, and MS were reoccupied while sites MIA and MIB replaced NS and SS. Transect lines for nearshore bathymetric surveys are shown in green.

The beaches of the Columbia River littoral cell (CRLC) are ideal locations to study these linkages because they are extremely dynamic (due to the severity of the wave climate (Tiltsen and Komar, 1997)), meso-tidal (2m – 4m tide range), and are comprised primarily of fine Columbia River sand (foreshore median grain sizes of approximately 0.20 mm). The inner shelf and beaches are mild sloping with nearshore slopes as gentle as ~1V:200H and inter-tidal slopes averaging ~1V:50H (Ruggiero et al., in review). Winter (November – February) conditions are characterized by elevated water levels, and high waves (average ~3 m) with long periods (12 s) that approach from the west-southwest. Summer (May – August) conditions are typified by smaller waves (1.2-m heights, 8-s periods), lower water levels, and wind and waves from the west-
northwest. This seasonal cycle in environmental forcing generates seasonal cycles in morphodynamics, with offshore and northerly sediment transport resulting in beach erosion during the winter and onshore and relatively weak southerly sediment transport dominating beach recovery during the summer.

The morphology of the ebb-tidal delta and adjacent beaches of the North Beach sub-cell (Figure 1) are thought to be nearly in dynamic equilibrium, but the position of the shoreline continues to experience significant seasonal through interannual variability (Buijsman et al., in press and Kaminsky et al., 1999). The shoreline retreats approximately 20-40 m each winter and subsequently recovers each summer presumably as sand from the sub-aerial beach is transported back from storage in relatively large offshore sandbars (Ruggiero et al., 1999 and Ruggiero et al., in review). The 1997/98 El Niño event resulted in the re-orientation of the North Beach sub-cell as sand from the southern end of the sub-cell was transported north due to wave directions having a more SW approach than typical. The future position of the North Beach shoreline will be governed by a delicate balance between sediment bypassing around the ebb-tidal delta from the south, cross-shore feeding from the ebb-tidal delta and inner shelf, and net northerly directed alongshore sediment transport (Kaminsky et al., 2000). The goal of this study is to test this conceptual model of seasonal response to environmental conditions by examining the relative contribution of cross-shore and alongshore sediment transport processes to seasonal scale morphological changes using both field data and process-based morphological models.

PROCESS MEASUREMENTS

Two field experiments were conducted in Fall 1999 and Spring 2001 on the Grays Harbor, WA ebb-tidal delta (Figure 1). In each of the experiments, instrumented tripods collected time series of waves, near-bottom velocities, and proxies for suspended sediment concentrations at up to 6 locations on the inner shelf (Figure 1).

Fall 1999 experiment

The Fall 1999 experiment consisted of a suite of wave, current, and suspended sediment concentration measurements between 2 October and 29 December 1999 (Gelfenbaum et al., 2000 and Sherwood et al., 2001). The experiment successfully quantified the environmental conditions occurring during the transition from beach progradation (summer southerly flows and upwelling) to beach retreat (winter northerly flows and downwelling) (Figure 2). A major winter storm occurred during the experiment interval, 28 October, with significant wave heights peaking at 7.7 m from the WSW with peak periods of 16-18 seconds. Waves remained high during much of the rest of the field campaign averaging approximately 2.8 m.

Spring 2001 experiment

The Spring experiment, from 4 May to 11 July 2001, measured conditions during the relatively mild rebuilding phase of the beaches. Four sites (ND, MD, SD, and MS) were re-occupied with the same instrument packages as deployed during the Fall 1999 experiment (Sherwood et al., 2001). Sites SS and NS were eliminated and replaced by
two stations (MIA/MIB) in shallower water (~8 m MLLW) placed approximately 50 m apart. Station MIA was instrumented with 2 acoustic Doppler velocimeter field (ADVF) Hydra systems, 3 pressure sensors, 6 D & A Instruments optical backscatter sensors (OBS), an Aquatec acoustic backscatter system (ABS), and a Sontek pulse-coherent acoustic Doppler profiler (PC-ADP) to measure bottom shear stress and bottom roughness. Station MIB held an ADVOcean acoustic Doppler velocimeter (ADVO), 1 Paroscientific digiquartz pressure sensor, 2 OBS and a rotating head sonar to measure small-scale bed morphology. Upwelling favorable winds from the NW predominated during the deployment period. The mean significant wave height was 1.7 m with waves approaching generally from the WNW (Figure 2), conditions suggesting southerly alongshore sediment transport.

![Figure 2](image_url)

**MORPHOLOGY MEASUREMENTS**

During the Fall 1999 field campaign, monthly three-dimensional topographic beach surface maps extending from the toe of the dune seaward to ~MLLW were collected along 4 km of beach immediately north of the Grays Harbor North Jetty. These data were collected using the Real Time Kinematic Global Position System (RTK DGPS)
techniques described in Ruggiero et al. (1999) and Ruggiero et al. (in review). During the Spring 2001 experiment, regular topographic and bathymetric surveys quantified both the beach and sandbar change during the transition from winter to summer conditions. Weekly topographic surface maps (10 surveys) and monthly nearshore bathymetric surveys (5 surveys, profiles spaced at 200 m) mapped the active nearshore planform from the toe of the primary dune to below the limit of measurable annual change (~12 m MLLW) within 4 km of the Grays Harbor North Jetty. Six profiles, collected monthly and spaced at 1 km, extended the region of morphology measurements to the alongshore location of station ND approximately 5 km to the north (Figure 1). Morphology measurements were initiated approximately 1 month prior to the deployment of the instrumented tripods (29 March 2001) and were continued until one month following instrument retrieval (6 August 2001).

MORPHOLOGY MODELING

The one-line shoreline change model UNIBEST-CL (WL|Delft Hydraulics, 1994) has previously been applied to simulate historical shoreline change and to predict future shoreline behaviour along much of the coast of the CRLC (Buijsman et al., 2001 and Kaminsky et al., 2000). The model uses prescribed time series of approaching wave heights, periods, and direction to calculate alongshore transport rates and uses the divergence of transport rates to update the shoreline configuration. As regions accrete or erode, shoreline angle changes, and transport rates adjust to the changed local wave approach angle. A detailed sensitivity analysis was performed utilizing a sediment budget for the entire CRLC (Buijsman et al., 2002) to determine model parameters and the model was closely calibrated to observed shoreline changes along North Beach. In this study, we apply the calibrated model to simulate the morphology change that occurred during the Spring 2001 experiment. The model was initialized with measured bathymetry and shoreline position as of 6 May 2001 and was run using a wave climate developed from the Coastal Data Information Program (CDIP) Waverider buoy in ~42 m of water (Figure 1). Waves were shoaled to the offshore extent of 7 individual profiles (~13 m MLLW) spaced at approximately 1-4 km, accounting for changes in relative shoreline angle. At each profile, sediment transport is calculated as a function of shoreline angle with the Bijker (1971) sediment transport formula. Gradients in calculated transport rates result in beach retreat or progradation.

To quantify the relative contribution of cross-shore processes to the overall morphological change that occurred during the Spring 2001 experiment we also make exploratory runs using the deterministic cross-shore sediment transport model UNIBEST-TC (WL|Delft Hydraulics, 1997). The model calculates cross-shore transport and changes in nearshore morphology using several sub-modules, including wave propagation, mean current profile, bottom orbital velocity, bed load and suspended load sediment transport, and bed level change. Bed load is calculated with the generalized formula of Ribberink (1998) with extensions accounting for slope effects on transport (Van Rijn, 1995). Suspended sediment transport is calculated from the vertical distribution of simulated fluid velocities and sediment concentrations.
A thorough calibration of wave breaking hydrodynamics is precluded by the fact that our shallowest station, MIA/MIB, is in ~8 m (MLLW), well seaward of wave breaking during the Spring 2001 experiment. However, in a recent study assessing model predictability, van Rijn et al. (2003) demonstrated that process-based profile models could successfully simulate nearshore morphological change on storm time scales of hours to days using default model parameters. Reasonable simulations on time scales of months to years required tuning using measured bed profiles.

We initialized the cross-shore model with measured bathymetry (a 1-km alongshore-averaged profile from the 6 May 2001 bathymetric survey), sediment size, and measured wave and water level conditions. Alongshore averaging reduces the influence of rhythmic and non-rhythmic features that violate a major assumption of the model, alongshore uniformity. Our alongshore-averaged profile is centered approximately 2 km north of the Grays Harbor North Jetty and more than 1 km north of a topographically bound rip current that dominates circulation near the jetty. For both model applications we simulated the period between 6 May 2001 and 6 August 2001 to include the relatively large changes of the outer bar and shoreline that occurred during the month following instrument retrieval.

RESULTS

Results from the Fall 1999 experiment can be summarized as follows: a) during typical winter storm conditions, sediment is often mobilized to depths of at least 24 m indicating that sediment frequently bypasses the Grays Harbor inlet; b) net northward flows and associated downwelling circulation during winter storms cause northward and offshore transport of suspended sediment; c) inferred onshore bedload transport rates were ~2 orders of magnitude smaller than the offshore suspended-sediment transport rates (Sherwood et al., 2001). During the experiment, storms dominated nearshore circulation patterns and forced northward and offshore sediment transport resulting in tens of meters of beach retreat (Figure 3).

During the Spring 2001 experiment, milder wave conditions (relative to Fall 1999) resulted in between 10 to 20 m of shoreline progradation (Figure 3). While wave heights were low, analyses of the grain roughness Shields parameter show that the threshold for sediment movement was exceeded throughout the experiment, at least at station MIA/MIB (Lacy et al., in review).

Onshore bar migration, trough infilling, and sub-aerial sediment accumulation dominated morphological changes during the Spring 2001 experiment as observed in profile view (Figure 4) and plan view (Figure 5). The outer bar migrated onshore approximately 100 m as sediment, scoured from the seaward flank of the initial “winter” bar, was deposited in the landward trough. This migration produced vertical profile changes of ~1 m. The overall height of the bar decreased from as high as 3 m to less than 1 m, while the shoreline prograded as much as 25 m. Nearshore planform differencing (Figure 6) between the May and August surveys reveals that virtually all morphological change occurred between the -6 m and +3 m (MLLW) contours. Alternating alongshore
regions of erosion (indicated by cool colors) and accretion (warm colors) illustrate the predominantly 2-dimensional nature of the bathymetric changes.

The relative contributions of cross-shore and alongshore sediment transport processes to the observed morphological change is examined by combining model results with a sediment budget analysis. Between 6 May and 6 August 2001 we measured a net accumulation of approximately 88,000 m$^3$ of sediment within the 1-km, alongshore control volume shown in Figure 6. The control volume extends in the cross-shore from the –8 m (MLLW) contour onshore approximately 1.5 km to the +3.0 m contour. While the estimated uncertainty of individual topographic and bathymetric elevations is approximately 0.1 m (MacMahan, 2001 and Ruggiero et al., in review) for these volume calculations we assume that the errors are without bias and are randomly distributed.

Results from the alongshore model indicate net southerly directed sediment transport with 65,000 m$^3$ of sand entering the northern boundary of the control volume and 46,000 m$^3$ leaving the southern boundary. These results suggest that 19,000 m$^3$ of
the accumulated sediment within the control volume derives from convergences in the net southerly directed sediment flux, primarily due to changes in shoreline angle (Figure 6). The modeled shoreline change is much less than the measured change of the 3.0-m (MLLW) contour, a datum-based proxy for shoreline position in the CRLC (Figure 5).

Assuming that the modeled gradients in alongshore sediment transport are accurate, an additional 69,000 m$^3$ of sediment is necessary to balance the budget. While
the cross-shore model is able to reproduce the reduction in bar height, trough infilling and landward migration in trend, the magnitudes of the simulated changes are much less than indicated by the measurements resulting in poor overall model skill (Figure 4). Both the outer and inner bar are significantly flattened during the 3-month simulations. The cross-shore model does much better at reproducing the ~20 m of progradation of the sub-aerial beach than the alongshore model, particularly between the 0.0 and +2.0 m (MLLW) contours. The qualified Brier Skill Score (BSS), as given in van Rijn et al., (2003), is provided in Table 1 for three cross-shore zones: outer bar (-700 < x < -450 m), inner bar (-450 < x < -300 m), and foreshore (-300 < x < 0 m). While the model typically does a bad job representing the observed bar changes, negative BSS, for this initial model application we are more interested in the prediction of bulk volume changes than precise bed evolution.

<table>
<thead>
<tr>
<th>Model Results</th>
</tr>
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<tbody>
<tr>
<td>05/06/01 - 08/06/01</td>
</tr>
<tr>
<td>05/30/01</td>
</tr>
<tr>
<td>07/07/01</td>
</tr>
<tr>
<td>08/06/01</td>
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</tbody>
</table>

Figure 5. Alongshore variability of bar height, bar position from the shoreline, and shoreline change (both measured and modeled) between 6 May and 7 August 2001.

The cross-shore simulations indicate that a substantial amount of sediment enters the control volume across the -8.0-m (MLLW) contour. However, the amount of net onshore directed sediment varies considerably with the user defined wave-related bed roughness parameter. Table 1 illustrates that increasing the roughness from 0.001 m to 0.05 m, a reasonable range as the hydrodynamic bed roughness is estimated to have
varied over 3 orders of magnitude during the experiment (Lacy et al., in review), increases the accumulated volume from 23,000 m$^3$ to 40,000 m$^3$. Taken together the cross-shore and alongshore modeling efforts combined do not explain between 29,000 m$^3$ (~33%) and 46,000 m$^3$ (~53%) of the measured sediment accumulation.

Table 1. Sensitivity analysis of net onshore transport to the wave related roughness parameter in the cross-shore model. Also shown are qualified Brier Skill Scores for the outer bar, inner bar and foreshore. Negative BSS scores indicate a bad agreement, 0 < BSS <0.3 is poor, 0.3 < BSS <0.6 is fair, 0.6 < BSS < 0.8 is good, and 0.8 < BSS < 1.0 is an excellent model fit.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Wave related bed roughness m</th>
<th>Accumulated Volume m$^3$</th>
<th>Brier Skill Score outer bar</th>
<th>Brier Skill Score inner bar</th>
<th>Brier Skill Score foreshore</th>
</tr>
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<tr>
<td>1</td>
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</tr>
<tr>
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</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>40,000</td>
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</tbody>
</table>

CONCLUSIONS

We have collected simultaneous data sets of morphological change and physical processes governing sediment transport over two three-month periods when significant beach change occurred. Our conceptual model of seasonal variability of environmental conditions and nearshore morphological change in the U.S. Pacific Northwest has been tested and improved. Seasonal morphological change is significant, and during the spring transition is dominated by shoreline progradation and onshore bar migration on the order of 10 m and 100 m respectively.

To investigate the physical mechanisms of morphological change we are using a combination of data analysis and numerical model simulations linking both cross-shore and alongshore sediment transport to wave energy, sediment characteristics and antecedent morphology. Simulations of process-based models indicate net southerly and onshore sediment transport during the spring transition. The magnitude of modeled onshore sediment transport varies by a factor of two and is sensitive to the wave-related roughness parameter.

Initial model results suggest that cross-shore sediment transport processes are more important than alongshore sediment transport processes in reproducing the seasonal morphological change observed during the Spring 2001 experiment. This result is similar to the conclusions of a modeling study of interannual scale wave climate variability in the CRLC. Buijsman et al. (2001) concluded that the large shoreline changes associated with the La Niña of 1998/1999 were dominated by onshore-directed sediment transport. However, model runs over decadal time scales, indicated that alongshore transport processes were responsible net trends in shoreline orientation.

Future work will first concentrate on comparing the details of modeled hydrodynamics, sediment concentrations, and transports to the measurements to improve model skill at reproducing seasonal sandbar changes. We will then scale-up our analyses by attempting to reproduce observed annual to interannual variability with the cross-shore model, particularly the morphology change associated with ENSO variability.
Ultimately, we are interested in predicting coastal change on much longer time scales, years to decades rather than the time scale over which measurements are typically made (months). To go beyond the limitations of process data sets, and to allow further investigation of the large-scale coastal behaviour, we are applying fully integrated hydrodynamically-forced sediment transport and morphological change models, like Delft 3D, to simulate coastal change over years to decades (Gelfenbaum et al., these proceedings).

![Conceptual model of summer sediment pathways overlaid on a nearshore planform difference plot between the 6 May 2001 and 6 August 2001 surveys. Measured accumulated volume and simulated volume change (run 2) are also shown.](image)

**Figure 6.** Conceptual model of summer sediment pathways overlaid on a nearshore planform difference plot between the 6 May 2001 and 6 August 2001 surveys. Measured accumulated volume and simulated volume change (run 2) are also shown.

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REFERENCES


Ruggiero, P., Kaminsky, G.M., and Gelfenbaum, G., and Voigt, B., in review, Seasonal to interannual morphodynamic variability along a high-energy dissipative littoral cell, Submitted to: Journal of Coastal Research.


