**MIXED SEDIMENT BEACH PROCESSES: KACHEMAK BAY, ALASKA**

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**Abstract:** Mixed sediment beaches are morphologically distinct from and more complex than either sand or gravel only beaches. Three digital imaging techniques are employed to quantify surficial grain size and bedload sediment transport rates along the mixed sediment beaches of Kachemak Bay, Alaska. Applying digital imaging procedures originally developed for quickly and efficiently quantifying grain sizes of sand to coarse sediment classes gives promising results. Hundreds of grain size estimates lead to a quantitative characterization of the region’s sediment at a significant reduction in cost and time as compared to traditional techniques. Both the sand and coarse fractions on this megatidal beach mobilize into self-organized bedforms that migrate alongshore with a seasonality reflecting the temporal pattern of the alongshore component of wave power. In contrast, the gravel bedforms also migrate in the cross-shore without significant seasonality suggesting that swash asymmetry is sufficient to mobilize the gravel even during low energy summer conditions.

**INTRODUCTION**

The majority of our knowledge of nearshore sediment transport and associated beach morphodynamics is derived from studies of beaches dominated by a single sediment type. Typically that sediment type is sand, and numerous studies have documented the rates of sediment transport along well-sorted, sand-rich beaches resulting in correlations (and models) relating sediment transport to forcing by waves and currents. To a lesser extent, gravel (shingle) beaches have also been the focus of numerous coastal studies but predictions of coarse-grained transport are often unreliable (Osborne, 2005). The
dynamics of mixed-grain size beaches, however, have received relatively little attention in the scientific literature (Mason and Coates, 2001) in spite of the fact that heterogeneous sedimentary environments comprise approximately 80% of the worlds’ non-rocky coastal regions (Holland et al., 2004). Mixed sediment beaches occur on shores where glaciation has provided significant sources of sands and gravels and are recognized as being morphologically distinct from and more complex than either sand only or gravel only beaches (Kirk, 1980). Two recent studies of mixed-sediment beaches, Osborne (2005) and Allan et al. (2006), reveal interesting relationships between transport rates and coarse-grained material size and shape. Unfortunately, a detailed understanding of the processes governing mixed-sediment transport remains elusive.

![Study location. Kachemak Bay is located on the Eastern shore of Cook Inlet in south central Alaska. The star marks the location of the Argus cameras used in this study.](image1)

The tectonically active, megatidal (spring tide range greater than 8m), and sea dominated beaches of Kachemak Bay, AK (Figure 1) exhibit a wide range of interesting characteristics and provide an ideal natural laboratory for investigating mixed sediment beach processes. The surficial sediments range from fine sand to large boulders and this broad range of sediment size is reflected in intriguing morphodynamics in which self-organized bedforms composed of fine-to-medium sand migrate as coherent packages over a coarse substrate which is also dynamic (Figure 2). Understanding sediment transport patterns and rates along the north shore of Kachemak Bay is particularly important as net southeasterly transport is primarily responsible for maintaining the
Homer Spit (Figure 1), the economic engine of the region, at engineering/planning time scales.

Our goals in this paper are to first characterize the mixed sediment environment of the north shore of Kachemak Bay, AK, then quantify the rates and modes of sediment transport. We achieve these goals through the application of three novel digital imaging techniques. Due to the general lack of detailed understanding of mixed-sediment systems as discussed above, our approach here is to build, and report on, a high quality data set which will be used to develop sediment transport and morphological evolution models for these systems in future efforts.

Fig. 2. Proto-typical mixed sediment beach along the north shore of Kachemak Bay, AK. Note the discrete sand bedform in the far field migrating over the coarse substrate and the mobile gravel berm (near field).

METHODOLOGY
Understanding the range of natural variability of mixed sediment beaches is essential to the management of these complex systems. Historically, quantitative characterization of surficial grain size variability has been difficult because standard techniques are inadequate due to the sampling and processing efforts required and because of the volumes of material that must be handled to capture the full range of variability. Quantifying sediment transport patterns at event-seasonal-interannual scales on these beaches also poses complex sampling problems. Here we apply three digital imaging techniques (beachball camera, cobble-cam, and an Argus Beach Monitoring System) to overcome these sampling issues in investigating the mixed sediment dynamics along the north shore of Kachemak Bay, AK.
Beachball Camera
Recently, Rubin et al., (2006) developed digital imaging methodologies for quickly sampling surficial bed sediments in a variety of field environments. Images of surficial sediment, either sub-aqueous (flying eyeball) or sub-aerial (beachball), sand are taken by simply pressing a watertight camera system into the bed. Grain-size analysis from the digital images requires a calibration process in which sediments from the field area are sieved at quarter-phi size intervals and digitally photographed. An autocorrelation algorithm (Rubin, 2004) between pixels in the digital images has been developed to compute the average grain size of sediment on the bed and the grain size distribution of bed sediment. This emerging technique is extremely rapid and has the potential to revolutionize our ability to quantify grain size information in heretofore inaccessible regions.

The ‘beachball’ camera is simply a grain-imaging digital still camera fitted with macro lenses and housed in a watertight plastic case. In summer 2004 we collected approximately 150 images using this system on the north shore of Kachemak Bay, AK. Images were collected at low tide and only on the self-organized sand bedforms that exist in the region. Figure 3a shows the spatial distribution of many of the beachball images (red asterisks) overlaid on a gridded topographic surface derived from GPS measurements of the beachface during the same sampling period that the images were taken.

Figure 3. a) Location of beachball camera (red asterisks) and cobble-cam (black asterisks) images overlaid on 2004 gridded topographic surface. b) Gridded surface of surficial sediment grain size.
Cobble-Cam
We are extending the methodology developed by Rubin et al. (2006) to also estimate the size distribution of the coarse component of the region’s sediments (Harney et al., in press, Warrick et al., in prep.). The ‘Cobble-Cam’ consists of a digital still camera mounted on a downward looking, vertically-telescoping tripod designed for capturing a population of coarse grained material. A bubble level on the tripod enables horizontal positioning while an adjustable, rotating extension arm allows for the camera to be mounted looking downward at the sediment surface without capturing the legs of the tripod in the field of view. Typically, the camera is mounted approximately 1.5 m above the bed and images are triggered using a remote control to minimize camera movement. Two images at each location are taken and a scale bar in one of the image’s field of view enables the development of a conversion factor defined as the number of pixels in the image equal to 1 mm ground distance. In a summer 2004 pilot effort we collected cobble-cam images at a handful of locations while in summer 2005 we collected approximately 70 images approximating a 50x50 m rectilinear grid as shown in Figure 3a (black asterisks).

For each digital photograph, a regular spaced (200-pixel) grid was overlain producing a 9-by-12 matrix for the photograph using the commercially-available Abode Photoshop computer application. The longest exposed length of each rock underlying each grid intersection was then measured in pixels using a line-drawing tool. If there was no distinguishable rock under the grid point, the rock directly up and to the left was measured. Notes were made if the rock was partly buried (<50% of rock perimeter buried), mostly buried (>50% of perimeter buried), and/or off of the photograph. A second length measurement was then made for each rock along the “short” axis, which was defined to be the longest visible distance perpendicular to the “long” axis measurement. Rocks that were too small to be measured with the resolution of the photograph (typically 3-4 pixel length, ~1.2-mm long) were defined to be “sand” and given an arbitrary grain-size equal to the mean of the beachball samples. These length measurements in pixels were then converted to actual distances using the conversion factor for each photograph.

Argus
In February 2003 we installed an Argus Beach Monitoring System (Lippmann and Holman, 1989; Holman et al., 1991; Holman et al., 1993) along the north shore of Kachemak Bay, AK to observe and quantitatively document the mixed sediment dynamics of the region (Adams et al., in press). The system consists of 8 digital cameras spanning a field of view of approximately 220°. Within this field of view, a geometry solution is computed allowing for the conversion from oblique merged panoramic views (Figure 4) to merged planform views, thereby defining true geographic coordinates to each pixel in the merged planform image. Typically snapshots and time averaged exposures (approximately 3 minutes) for each camera are taken each hour. However, since summer 2005 we sample each camera every 15 minutes during spring tides. Utilizing low tide images in which bedforms are exposed and a tidal contouring algorithm (Plant and Holman, 1997, Aarninkhof et al., 2003) we quantify the rates and
directions of sediment transport exhibited by the sand and cobble fractions of the bi-modal sediment distribution, respectively.

RESULTS

Intertidal beach sediments along the north shore of Kachemak Bay are composed of a poorly sorted coarse component (glacial till), consisting of fist-sized cobbles (5-10 cm) to Volkswagen-sized boulders (1-3 m), and a fine component, fine-to-medium, well-sorted sand. The average mean grain size of the sand bedforms estimated from the approximately 150 digital sand samples collected is 0.29 mm (medium sand), ranging from 0.15 mm (fine sand) to 0.83 mm (coarse sand). In general, the sand fraction is well sorted; however, there is a trend of coarsening toward the trailing edge of individual sand bedforms with finer sands at the leading edge (Figure 3b).

Fig. 4. Merged panoramic images from the Homer, AK ABMS site; top panel: June 2004; bottom panel: June 2005.

For two of the 70 cobble-cam samples approximately 15-20 rocks were labeled in the field and then removed following photographing to allow for physical measurements of the rock dimensions. For both samples, the size estimate of the major (long) axis derived from the photo method (pixel counting) compared extremely well with the physical measurements of the major axis of the rock. The correlation coefficient between the two techniques exceeded 0.97 (Figure 5a) indicating the point counting method is sufficiently accurate to quantify the mean grain size of each cobble-cam image. The mean grain size derived from all of the cobble-cam images was 44 mm (coarse gravel) while the estimated means ranged from 10 mm to 105 mm.

Calibration curves, similar to those developed for Rubin’s (2004) autocorrelation algorithm for sand grains, were constructed by Warrick et al., (in prep.) from coarse
samples extracted from a similar mixed sediment beach at the mouth of the Elwha River in Port Angeles, WA. Surprisingly, the Kachemak Bay images, when processed with the autocorrelation algorithm using the Elwha calibration curves, showed remarkable agreement between point count size estimates and computer derived size estimates (Figure 5b). This result suggests that estimates of coarse grain sizes may be computed with significant reduction of cost and time as compared to traditional techniques.

The beachball and cobble-cam results give us reasonably accurate estimates of mean grain size at over 220 locations within the field of view of the Homer Argus cameras. From these data we develop a gridded surface of the surficial grain size in the study area (Figure 3b). While in this example we combine data collected over a two year period to construct a composite surficial sediment surface, our goal here is to demonstrate that these relatively simple techniques can be applied to accurately and efficiently characterize the range of variability in heterogeneous environments.
Alongshore migration rates of intertidal sand bedforms, 1-2 m amplitude and ~200m wave length (Figure 2), over the coarse gravel substrate have been documented to be approximately 250 m/yr (Adams et al., in press). Strong seasonality in alongshore migration rates is evident with the majority of sand body movement, up to weekly-averaged rates of movement exceeding 6 m/day, occurring during large wave events. The seasonal signal of the alongshore bedform migration rate (proxy for bedload transport) is well correlated with seasonal variability in the alongshore component of wave power suggesting that the sand component of this mixed sediment system behaves much as most sand beaches with strong net longshore sediment transport rates.

The cobble substrate, over which the organized sand fraction is transported, is dynamic as well. Field observations (Figure 2), Argus video measurements (Figure 4), and ground surveys (Figure 6) have documented the growth and migration of a large gravel bedform over a life cycle of more than two years.

The cobble bedform was initially formed during late fall early winter 2003/2004 (note that the feature does not exist in summer 2003 in the cross-shore profile shown in Figure 6) by a now abandoned tidal slough outlet (flows typically exceed 1 m/s) immediately to the west of the Argus cameras. Human intervention may have played a role in the formation of the gravel feature in that the outlet of the slough was forced to the west in late 2003 as it had been steadily migrating toward the east and was beginning to threaten private property with erosion. The coarse material associated with the remnant stream bed was then impacted by only marine processes rather than the balance between marine
and fluvial processes that previously existed. While it is difficult to resolve the detailed processes associated with the formation of the feature with the Argus cameras (poor weather caused unusable images), the feature soon became large enough to accurately track using the cameras. By spring 2004 (Figure 4) the bedform had organized into a mobile gravel berm with a landward slipface approximately 1.5 m high and a cross-shore length of about 50 m. During the following year this feature increased in volume and migrated approximately 50 m in the cross-shore and over 100m in the alongshore direction while the berm crest gained over 1.0 m in vertical elevation (Figure 6).

By mapping the location of the gravel bedform in subsequent merged rectified Argus images we quantify the pattern and rate of migration of this feature much in the same manner as Adams et al., (in press) quantified the sand body migration rates at the same site. Figure 7 illustrates the gravel bedform’s footprint at three distinct times in its life cycle. From the initial development of the feature until late spring 2005 the primary direction of transport was in the alongshore (with some cross-shore movement). From summer 2005 until the feature’s eventual collapse, the bedform primarily moved onshore. The gravel feature also elongated during its life cycle from extending approximately 100 m in early 2004 to over 300 m in late 2005.

Fig. 7. Plan view of migrating cobble berm.

The white asterisks in Figure 7 represent the position of the easternmost tip (toward the top of the page) of the gravel bedform at approximately bi-weekly intervals, every spring
tide from early 2004 until late 2006. This data is used to estimate the migration rate of the gravel berm as illustrated in Figure 8. Similar to the transport pattern of the sand bodies (Adams et al., in press), the cobble berm migration rate experiences a significant seasonality to its movement. In early 2004, when storm waves were still frequent, the gravel berm migrated at a rate of approximately 0.7 m/day (primarily in the alongshore direction). During the relatively calm spring and summer months of 2004 the gravel berm halted only to resume its movement when waves increased in late fall/winter. During the first year of its existence the gravel berm migrated approximately 150 m resulting in an annual average migration rate of 0.4 m/day.

The megatidal nature of Kachemak Bay is ideally suited for quantifying beach changes using tidal contouring methods (Plant et al., 1997, Aarninkhof et al., 2003). Knowing the time of each merged rectified time averaged exposure and the corresponding tidal elevation (taken from the NOAA tide gage located at Seldovia, AK on the south shore of Kachemak Bay approximately 25km south-southwest of Homer) we construct monthly cross-shore beach profiles at three alongshore locations (Figure 9). Unfortunately, because ponding occurs on the landward side of the gravel berm as the tide recedes, we are not able to resolve the slip face of the gravel berm and the beach face immediately landward of the bedform (Figure 9b).

In order to accurately resolve the cross-shore migration of the gravel berm we extract the cross-shore position of the 4.5 m (MLLW) contour at monthly intervals (Figure 10). At all times when the gravel feature is present at a particular alongshore location, the 4.5 m
contour is on the seaward sloping face of the bedform. Therefore, tracking this contour serves as a reasonable proxy for the cross-shore migration of the gravel berm. Figure 10 illustrates that the migrating gravel berm reaches the transect located at alongshore position 400 m (Figure 9) in November 2004, as evidence by over 75 m of offshore migration of the contour. From February 2005 until December 2005 the 4.5 m contour migrates steadily onshore with an average rate of 0.1 m/day.

Fig. 9. top) Plan view demonstrating tidal contouring methodology. bottom) Quarterly cross-shore profiles extracted from tidal contouring method at alongshore position of 400 m.
CONCLUSIONS

New digital imaging techniques now available for quantifying grain size allow for quick, inexpensive, and relatively accurate characterization of mixed sedimentary environments. We have initiated the extension of a technique initially developed for sand (Rubin et al., 2006) to produce sufficiently accurate estimates of coarse sediment (gravel and cobble) sizes in order to resolve the cross-shore and alongshore gradients of surficial sediments in a highly heterogeneous sedimentary environment.

Along the sea-dominated, megatidal, mixed sediment environment of Kachemak Bay, AK, both the sand and gravel fractions are highly mobile with the dominant mode of sediment transport being the migration of self-organized bedforms. Employing merged rectified Argus images we estimate the annual migration rate of the sand bedforms to be approximately 0.75 m/day (Figure 8, blue circles) while the gravel bedform migrates at 0.4 m/day. Surprisingly however, the bedforms of different size components migrate in the alongshore with a similar seasonality which is well correlated with the seasonality in the alongshore component of wave power. This result suggests that simple models, similar to the “CERC formula” (Komar and Inman, 1970; U.S. Army Corps of Engineers, 2002), for alongshore bedload transport of the coarse fraction may be developed, at least for this system.

Intriguingly, the cross-shore migration rate of the gravel berm is relatively constant during most of 2005 (February to December) without exhibiting seasonality. This perhaps suggests that the asymmetric swash motions on the seaward flank of the gravel bedform are always sufficient to mobilize the coarse sediment, even during the relatively...
calm summer conditions. Presumably the permeability of the gravel bedform produces a net onshore shear stress over the swash backwash cycle leading to net onshore transport. Future experiments performed using Argus images and Argus time stacks will specifically test this hypothesis by determining whether or not swash velocities are sufficient to mobilize the gravel bedform throughout the year.

ACKNOWLEDGEMENTS
The U.S. Geological Survey supported this work through the ‘Geological Characterization and Sedimentary Processes of Nearshore Habitats in Kachemak Bay, Alaska’ project. Logistical support was provided by the Kachemak Bay Research Reserve. We thank Guy Gelfenbaum, Jodi Harney, and Jodi Eshleman for stimulating scientific discussions and excellent field support. Special thanks go to Dr. Paul Eneboe who continues to allow us to maintain our Argus cameras on his lovely property. Finally, we would like to thank Carl Schoch for his continued vision and strong support of sediment dynamics studies in Kachemak Bay.

REFERENCES


