Publication No. WI-2011-05

The Watershed Institute

Division of Science and
Environmental Policy

California State University Monterey Bay

http://watershed.csumb.edu

100 Campus Center, Seaside, CA, 93955

Central
Coast
Watershed
Studies

CCoWS

Assessment of a photometric analysis technique for monitoring beach nourishment: An example from Del Monte Beach, Monterey, California

Fall 2011

CSUMB Class ENVS 660:

Kyle Stoner (Team Leader)
Doug Smith (Instructor, Editor)
Patty Cubanski
Kathy Pugh
Natalie Jacuzzi
Roger Arenas
AJ Purdy
Ryan Bassett
Jacob Smith
Shaelyn Hession

Acknowledgements

Thanks to:

- Dr. Jon Warrick, USGS Pacific Coastal and Marine Science Center
- Dr. Daniel Buscombe, University of Plymouth
- Brad Damitz, Monterey Bay National Marine Sanctuary
- Dr. Steve Moore and Cortlen Hernandez, Cal State Monterey Bay

Disclaimer:

This report primarily represents student work completed within the constraints of a fixed-duration (four week), limited-verification college class setting.

This report may be cited as:

CSUMB Class ENVS 660: Stoner K, Pugh K, Arenas R, Cubanski P, Purdy A, Bassett R, Smith J, Hession S, Jacuzzi N, Smith D. 2011. Assessment of a photometric analysis technique for monitoring beach nourishment: An example from Del Monte Beach, Monterey, California. The Watershed Institute, California State Monterey Bay, Publication No. WI-2011-05, 21 pp.

Executive Summary

This report describes research conducted as part of a class project by students in the Advanced Watershed Science and Policy (ENVS 660) course at California State University Monterey Bay.

In late 2010, the City of Monterey Harbor Department submitted an application for a beach nourishment project to reduce beach erosion in front of the Del Monte Beach Townhouses. To assist the city in assessing the impact and success of this project, we have conducted a study to characterize the mean grain size of the sand present on Del Monte Beach and in the Monterey Harbor, which is a potential source of sand for the project. The specific goals of this project were to: 1) develop a repeatable, rapid, efficient method for conducting a photometric analysis for mean grain size on Del Monte Beach, Monterey, CA, 2) establish a bias correction model for the analysis of mean grain size at Del Monte Beach, 3) establish the pre-project, mean grain size of the beach, and 4) perform a reconnaissance-level evaluation of Monterey Harbor substrate as a donor of nourishment material for Del Monte Beach.

This project usee the photometric analysis software, designed by Buscombe et al. 2010. The results of 137 individual grain size estimates distributed in several transects through two potential nourishment sites indicated that the pre-project mean grain size of the beach is very uniform, ranging from 0.220 mm to 0.280 mm. One sample from Monterey Harbor had mean grain size of 0.260, indicating that the material is a good candidate for beach nourishment. When compared to other standard methods, photometric analysis is inexpensive, efficient, accurate, and can be performed on site with a camera and laptop computer. If a full grain-size distribution is required, other methods must be used.

Table of Contents

1 Introduction

1.1 Background

Coastal erosion is driven by a variety of natural processes and anthropogenic activities. Under current conditions of stable or gradually-rising sea level, coastal erosion and deposition are natural and necessary processes that serve to maintain beaches. In certain areas, anthropogenic alterations to the beach system have exacerbated coastal retreat. The loss of coastal wetlands, mining of beach sand, and the damming of rivers that would naturally deposit terrestrially-sourced sediments onto coastlines, can accelerate this retreat. For coastal communities, potential loss of coastline poses a major economic and environmental problem (Griggs et al., 2005).

Coastal areas are popular, with many highly valued properties now threatened by coastal retreat. In the United States, approximately 53% of the population lives within the coastal zone (Crossett et al. 2004). In sandy beach areas, the development and urbanization of coastal areas has resulted in permanent structures being threatened by coastal erosion. In response to coastal retreat, and in an effort to maintain these coastal structures, communities commonly use coastal armoring to protect their seaside developments. Sea walls, bulkheads, and revetments are all armoring structures used to control coastal erosion and maintain coastal developments. However, studies have identified that such armoring techniques can disrupt littoral zone processes and ecosystems (Dugan et al. 2008; Pope 1997). In addition, armoring creates potential for drowning of seaward beaches by flanking erosion around the protected structure (Dugan et al. 2008).

Other techniques to protect coastal developments that mimic natural beach processes have been explored and found to have mixed success. Beach nourishment is one such technique that operates by replenishing shoreline sediment in areas experiencing excessive coastal erosion. In some cases, this type of shoreline stabilization may require additional nourishment treatments. The source of the sediment for beach nourishment may be terrestrial or from an offshore dredge site depending on the project and surrounding available sources. While this form of erosion prevention aims to reduce the environmental impact the coastline experiences from "hard" erosion prevention measures, in some settings beach nourishment does not appear to successfully restore the area and may have negative effects on the adjacent terrestrial, littoral zone, and/or marine ecosystems. On the Eastern Coast of the United States, Trembanis et al. (1998)

documented that necessary re-nourishment frequencies and sediment quantities varied substantially depending on the characteristics of the location. In addition, the assessment noted that sand requirements for each nourishment episode did not decrease with time as originally thought based on the shoreface-profile-of-equilibrium concept (Dean 1984).

1.2 Grain Size Estimation Techniques

Grain size is an important consideration when determining source material for a beach nourishment project. Successful beach nourishment treatments that have minimal negative environmental effects, including aesthetic differences, require a similar color and grain size distribution to that of the beach targeted for restoration (Stauble 2005). Typical grain size analytical techniques are sieving and laser-scattering particle counters. These techniques have relatively well known differences in benefits, costs and constraints that must be weighed when choosing analytical methods for a particular project. The costs and benefits of in-situ photometric analysis of beach sand will be investigated in this report.

Particle sieving, a standardized method of grain size estimation, is a multistep approach which produces a particle size distribution. Sieving analysis consists of passing a sediment sample through a series of consecutively smaller stacked wire-mesh sieves, capturing grains in each sieve that are too large to pass through. Each sieve's sample portion represents a range in particle size that larger than that sieve's mesh diameter and smaller than the above sieve's mesh diameter. Each sieved portion of the sample is then individually weighed to determine the percentage of the sample by mass. These values are then typically plotted on log linear graphs to visually estimate the distribution percentiles, or software can estimate the percentiles automatically.

More recently, the use of laser instruments to estimate grain size has provided another technique to analyze sediment samples. This approach examines laser light scattering by particles in the forward direction which also can be estimated as laser diffraction. There are many variations of laser diffraction that produce a particle size distribution. The accuracy of those variations depends on the detectors and the analytical methods that estimate spatial light scattering patterns (Ma et al. 2000). Laser diffraction assumes particles are spherically shaped and thus have uniform diffraction patterns. If the particles are irregularly shaped, the scattering patterns may introduce systematic error into the distribution (Muhlenweg and Hirleman 1998). The output of this technique produces percentiles, as in sieving, but the measured quantity is volume (via area and assumed sphericity) rather than mass. Transforming the volume data into mass can be problematic in sediment with a high proportion of non-silicate minerals such as seashells (Calcite) or low density rock fragments.

Photometric analysis provides two-dimensional information concerning grain size. This technique can operate with statistical methods to distinguish mean grain size in a digital image. Appropriate statistically based models contrast the light and shaded regions of a digital image using local semivariance (Verdu et al. 2005), particle fractal dimensions (Buscombe and Masselink 2009), power spectral density (Buscombe and Masselink 2009), and autocorrelation (Barnard et al. 2006; Buscombe et al. 2010). An autocorrelation approach computes the number of pixel shifts needed to decrease the rate of autocorrelation between pixels light values (Warrick et al. 2009). Buscombe et al. (2010) provides an autocorrelation method by which mean grain size may be estimated over a wide size range (0.1-150 mm), by establishing calibration curves. This method only requires information concerning image spatial resolution, but has a reported accuracy of 11% to 20%. This technique can be implemented using a high resolution handheld camera, but greatly improved results in the sand fraction can be obtained using a specialized camera mount in a waterproof housing with a ring of LEDs around the lens. The LEDs evenly illuminate all areas of the frame (Barnard et al. 2006). This specialized camera setup is known as the “beachball.” Analysis of this instrument indicated that it accurately estimated 96% of the mean grain size of sediment samples ranging fine sand to cobbles (Barnard et al. 2006).

1.3 Application of photometric grain size analysis in southern Monterey Bay, Ca

Southern Monterey Bay describes the region from the mouth of the Salinas River, to Point Pinos in the south (Brew et al. 2011). This coastline is one of the most rapidly eroding reaches of shoreline in California (Hapke et al. 2006). The primary natural source of sand for beaches in Southern Monterey Bay is the erosion of coastal dunes and weak seacliffs. Coastal erosion rates here have been estimated at approximately 0.4 to 4.7 feet per year, which is equivalent to roughly 200,000 cubic yards of sand annually. Another small source of sediment is the Salinas River. On average, the Salinas River supplies 65,000 cubic yards of sand per year. However, 55,000 cubic yards of the sediment from the

Salinas River is lost from the regional sand budget as it is transported northward to the Monterey submarine canyon (Brew et al. 2011). Other losses to the South Monterey Bay beach sediment budget includes sand transported by rip currents to the continental shelf and sand extracted by the CEMEX sand mine located in Marina. In the past two decades, the sand mine has removed approximately 200,000 cubic yards of sand per year (Brew et al. 2011).

In order to address the sediment supply and erosion issues of southern Monterey Bay, a collaborative workgroup known as the "Coastal Sediment Management Workgroup" has created the Regional Sediment Management (RSM) plan. This plan seeks to minimize the impacts of coastal retreat by focusing on options that protect or restore coastal habitat by reducing disturbances to the natural sedimentary processes (PWA et al. 2008). Shoreline armoring has been employed along a small portion of the coastline in Southern Monterey Bay to prevent the loss of beachfront property to erosion. However, this armoring has led to beach loss around these structures as they interrupt natural beach formation processes (ESA PWA 2011). Additionally, such armoring practices have been demonstrated to result in ecological problems for shorebirds by reducing and prey availability (Dugan et al. 2008). As an alternative to structural armoring, the RSM plan proposes to implement and investigate the feasibility of beach nourishment as a sediment management approach to slow erosion rates. Beach nourishment is especially feasible within the southernmost portion of the Monterey bay where low wave energy and low sand transport predominate (PWA et al. 2008).

One prospective source of sediment for beach nourishment in the region is material dredged from the Monterey Harbor and Marina. The City of Monterey periodically dredges the harbor and marina to mitigate the navigational hazards of the areas experiencing shoaling (CCC 2011). To be considered suitable for the application of beach nourishment, the dredge material must be free of hazardous contamination, and must be have a mean grain size similar to the pre-existing beach. Del Monte Beach, located east of the Monterey Harbor and Marina, has been identified as a potential area to dispose of dredge material from the Monterey Harbor and Marina for the purpose of beach nourishment (Fig. 1; CCC 2011).

1.4 Goal

Section 30233(b) of the Coastal Act requires that the method of disposal of dredged material avoid disruption of habitat (CCC 2011). As there are potential ecological impacts associated with change in beach particle size, grain size monitoring is an important aspect of beach nourishment projects. Further, sand color is part of the aesthetic quality of beaches, so beach nourishment material will be better suited to a site if the color does not markedly contrast with the pre-existing sand. The purpose of this study was to assess photometric analysis as a potentially rapid and repeatable methodology for obtaining accurate mean grain size data for the proposed beach nourishment sites at Del Monte Beach, and to compare a potential donor site in terms of both grain size and coloration. This information can be used to match the potential nourishment donor sites, and to monitor changes from the baseline conditions following sand placement.

1.5 Study Area

Our study focused on two areas of Del Monte Beach in Southern Monterey Bay (Fig. 1). Del Monte Beach is located in an urban area, directly east of the Monterey Municipal Wharf II. Del Monte Beach is heavily used by the public for recreational purposes and is groomed regularly (CCC 2011).

The study areas are located within the proposed placement sites for dredge material from the Monterey harbor and marina as part of a sediment management plan for the region. The proposed management plan calls for the deposition of up to 10,000 cubic yards of dredged material from the harbor and marina annually onto Del Monte Beach, within designated areas (CCC 2011).

Study site A was a 200-meter stretch of Del Monte Beach adjacent to Municipal Wharf II. Study site B was a 400-meter stretch of beach located north of the Del Monte Beach Townhouses.

Figure 1. Survey areas on Del Monte beach in Southern Monterey Bay. Both sites have been designated as possible sites for beach re-nourishment projects. Site A is located adjacent to the municipal wharf, and site B is located in front of the Del Monte Townhouses. Municipal Wharf II is located at the left end of the beach.

2 Methods

2.1 Field and Lab Methods

We photographed sand at multiple locations within two sites on Del Monte Beach in order to conduct a photometric analysis of mean grain size. Ten transects from the backshore to the mean high tide line perpendicular to the shoreline at approximately 60 meter intervals were completed (Fig. 2). Digital photographs were obtained every two meters along each transect. We used the USGS “beachball” camera to obtain minimally distorted images of sand at a close proximity. The “beachball” camera consists of a Canon Powershot G12 camera in a customized water housing (Fig. 3 and Fig. 4). We placed the camera in the macro setting, with the flash turned off. LEDs mounted to the inside of a stainless steel attachment blocked ambient light from the picture extent. This attachment ensures uniform lighting for each image. The “beachball” camera was set directly on top of the sand to maintain a 5 cm distance from lens to substrate.

Figure 2: Map of transects sampled, showing the distribution of sampling locations within the potential nourishment areas of Del Monte Beach.

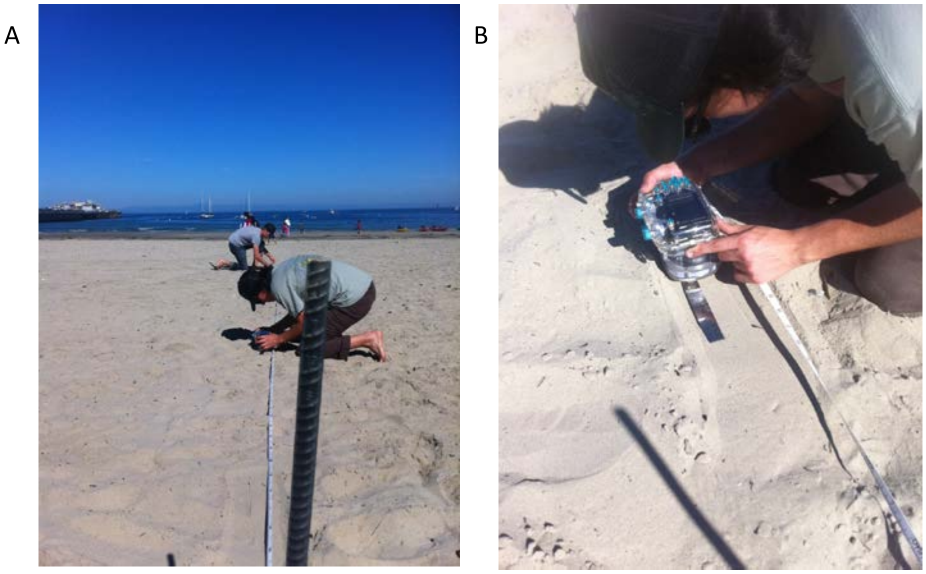


Figure 3. Photo acquisition transects (A and B). An image was acquired every two meters (B) with a camera in a waterproof housing and a ruler for scale in the image.

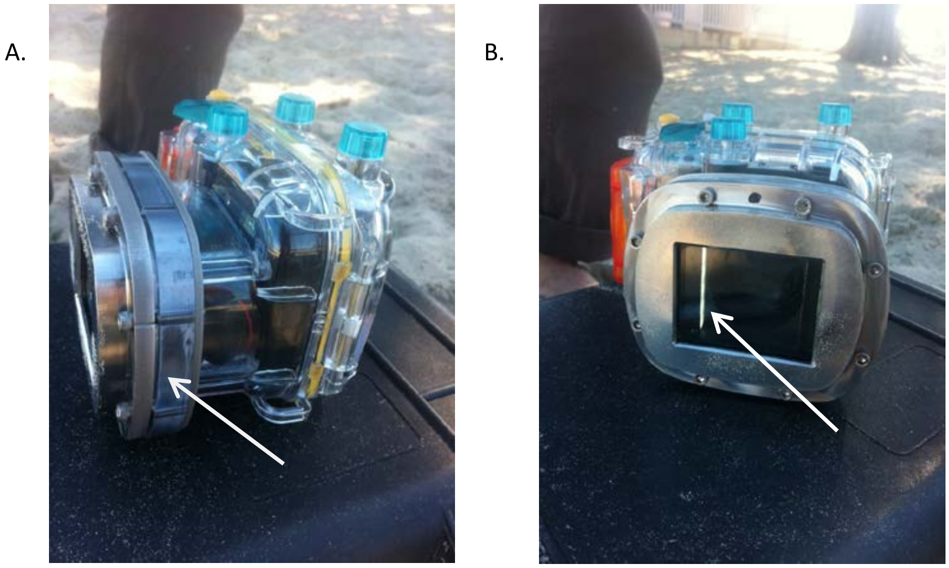


Figure 4: Camera in waterproof housing (A and B) used to obtain beach sediment images. The camera was placed directly on the substrate, a stainless steel barrier (A) in the front of the housing blocked ambient lighting. LED lighting (B) in the housing provided illumination for images of sediment.

A 2 kg sample of sediment collected from Monterey harbor (36° 36’ 28.53” N, 121° 53’ 36.62” W) was compared to the Del Monte Beach sand in terms of mean grain size and both wet and dry coloration. The sample was collected by digging down below the organic-rich surface, and scooping material from a depth of approximately 10 cm below the sea floor. The sample was dried in an oven for 24 hours at 70C. The dried sample included peds of sand that were disaggregated by hand. Small pieces of organic debris greater than 1 mm in diameter were removed by passing the sample through a 1 mm sieve screen. No inorganic material was caught by the sieve. The mean grain size was determined by averaging three photometric images using the “beachball” camera in the laboratory. Coloration was determined by comparing both dry and moistened samples to color chips of the Munsell Soil Color Charts (Kollmorgen Instruments Inc. 1994).

2.2 Photometric Analysis

Our analysis was conducted using the Grain-size toolbox (Buscombe et al. 2010) in MATLAB (MathWorks Inc 2011). We used the Grain-size toolbox to estimate the mean grain size in individual images of sand. The toolbox uses autocorrelation of pixel brightness values at 150 pixel shifts in the images to estimate the mean grain size of the image based on previously established calibration curves by Buscombe et al (2010).

2.3 Bias Correction

When using an automated grain size analysis, a bias correction must be calculated to convert photometric grain size estimates to real grain sizes (Barnard et al. 2007, Rubin et al. 2004, Warrick et al. 2009, Buscombe et al. 2010). The bias correction consists of a manual count of grain size dimensions, to be compared to the automated estimation of the same images. In order to eliminate operator bias during the manual count process, a grid composed of 100 intersections was overlaid on the cropped image that was used in the MATLAB analysis. The intermediate axis of each grain was measured in pixel units at every line intersection in the image. In the event where a grain is partially covered or indistinguishable, the operator measured the closest grain to the upper left diagonal center square.

A total of 137 images were processed in this study, of which 15 were included in the bias correction analysis. The manual calculations were then plotted versus the grain-size toolbox generated estimates. The manual measurements were regressed against the automated measurements to calculate the systematic bias, and the photometric data were then corrected using the regression equation.

2.4 Data Analysis

All images from each transect were analyzed using the grain-size toolbox, and sections of Cobble Cam (Warrick et al. 2009). The Cobble Cam Matlab code is available from the following US Geological Survey web site http://walrus.wr.usgs.gov/seds/grainsize/. The JPEG files were cropped using the cropping tool in Cobble Cam, this function crops the image and then converts the cropped file to a .TIF format. The cropped images were then analyzed using the batch_magic.m file in the Grain-size toolbox, with the filter function turned on. The filter function was used due to the quality of the images and the shading of this sand type. The tool produces a value for mean grain size for each image in pixel units. The pixel units were converted into millimeters using a conversion calculated from the measure_mm2pix.m file in Cobble Cam. The mm values were then adjusted according to the regression equation calculated in the bias correction.

A Welch's t-test was used to test for differences in mean grain size between the two nourishment sites.

3 Results

Data collection for Del Monte Beach was completed in approximately four hours in one continuous field period. Lab analysis, including bias correction and main analysis were completed in approximately 3 hours. Picture quality from each sample location was adequate and all data points were included in the photometric analysis.

3.1 Bias Correction

The bias correction plot (Fig. 5) compares manual grain size measurements with photometric grain size estimates using the grain size toolbox in MatLab (Buscombe et al. 2010). While there is a significant relationship between the manual measurement and the photometric estimate, there is not a one-to-one relationship, indicating the presence of a systematic bias. The linear model equation provides a way to correct the systematic bias (Fig. 5). The model assumptions are assessed in Appendix A.

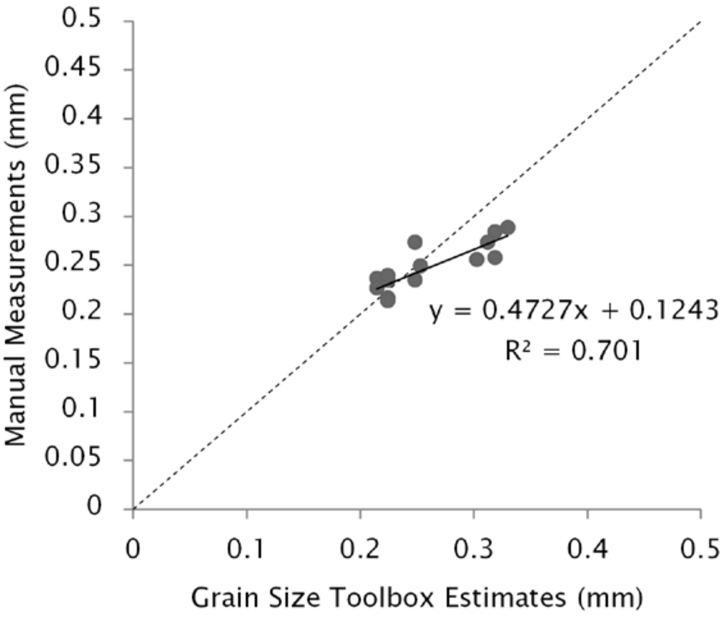


Figure 5. Results of bias correction showing manual grain size measurements versus photometric estimates. The relationship is significant ($p < 0.001$), but does not follow a one-to-one relationship (dashed line).

Figure 6 shows the results of manual grain size measurements plotted against the corrected photometric estimates. The photometric estimates were corrected using the linear regression equation from the bias correction model (Figure 5). The relationship in Figure 6 follows a one-to-one correlation indicating that the bias-corrected photometric estimates accurately represent manual measured mean grain sizes. The correction was applied to all photometric mean grain sizes in the analyses.

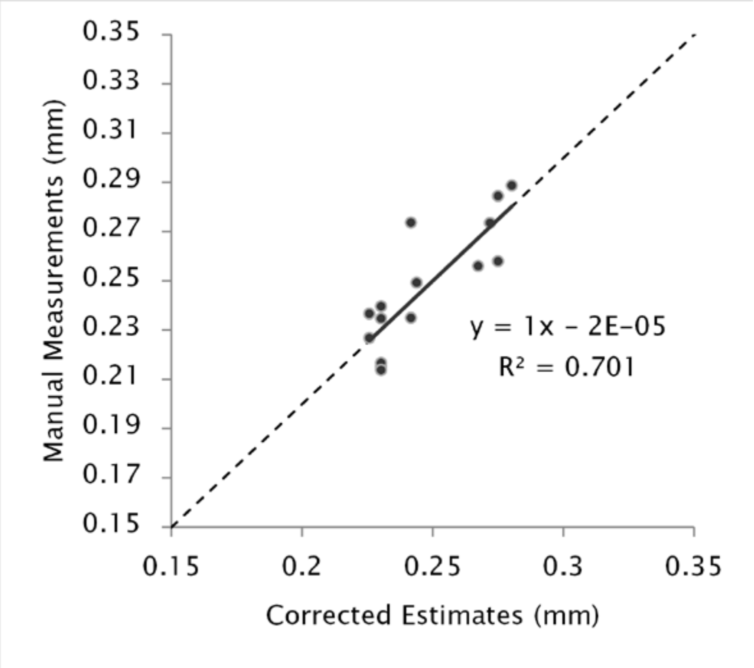


Figure 6. Manual measurements compared with the corrected estimates. The results follow a one-to-one pattern (dashed line) showing that the corrected estimates of grain size were accurate estimates of manual measurements.

3.2 Grain Size Analysis

The mean grain site for site A was approximately 0.230 mm with a standard deviation of 0.005 mm (95% confidence interval = 0.002 mm). The mean grain size of site B was approximately 0.246 mm with a standard deviation of 0.016 mm (95% confidence interval = 0.003 mm). Grain size data are provided in Appendix B. A Welch's T-test comparing grain size at each disposal site indicates that there is a small, but significant, difference between mean grain sizes ($p < 0.001$) (Table 1).

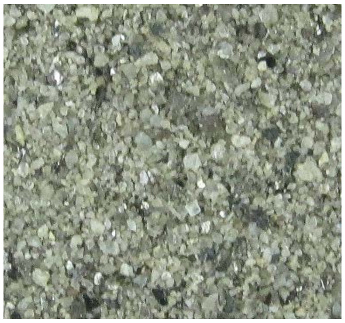
Table 1. Results of photometric analysis averaged for each transect in sites A and B, and for total samples within sites A and B.

Transect	samples (n)	mean (mm)	95% CI (mm)
A1	21	0.229	0.001
A2	16	0.228	0.003
A3	14	0.232	0.004
Site A	51	0.230	0.002
B1	12	0.237	0.008
B2	12	0.235	0.005
B3	11	0.237	0.006
B4	11	0.252	0.012
B5	12	0.257	0.012
B6	14	0.254	0.008
B7	14	0.248	0.009
Site B	86	0.246	0.003

3.3 Harbor Sediment

A single sample of substrate collected from Monterey Harbor had a photometric mean grain size of 0.260 mm (Table 2) and a greener coloration than Del Monte Beach sand.

Table 2. Visual comparison between Del Monte Bech sand and a sand sample from Monterey Harbor. Colors are hue (H), value (V) and chroma (C) were from comparison with a Munsell soil color chart (Kollmorgen Instruments Inc. 1994).

Location	Del Monte Beach	Monterey Harbor
Photo		
Grain size	0.240 mm (grand average)	0.260 mm
Dry color	H = 2.5Y V = 7 C = 1	H = 5Y V = 5 C = 2
Moist color	H = 5Y V = 5 C = 3	H = 5Y V = 3 C = 1

4 Discussion

This study assessed photometric analysis as a rapid methodology for obtaining baseline data of mean grain size using Grain-size toolbox in MATLAB (Buscombe et al. 2010, Mathworks 2011). Three methods of grain size analysis are compared in Table 3. If the sand samples are to to be spatially explicit, then the same technology is assumed for each grain-size technique (e.g., GPS, total station, etc.). While this element is not further considered here, the choice of survey method might raise the man-hour estimate.

Table 3 Comparison of grain-size sampling techniques, showing required materials, time needed, advantages, and disadvantages.

	Grain-size Sampling Technique		
	Photometric Analysis	**Sieve**	**Electronic Laser Instrument**
Equipment Requirements	digital camera "beachball" camera housing measuring tape MATLAB software	Collection buckets soil oven sieve stacks sieve shaker scale	Collection buckets Laser Instrument corresponding software
Manhours/sample n=137	0.1	2	0.1
In-situ application	yes	no	no
Potential Advantages	Speed of analysis, Cost of analysis	Minimal equipment cost, size distribution	high precision at small grainsize, sediment distribution
Potential Disadvantages	surface analysis only, Mean grainsize statistics only	time consuming	High cost initial investment (>$10,000), sample preparation time

To calculate the man-hours per sample value for photometric analysis, we assessed that two people could collect 137 images over ten transects and process the images in a total of seven hours. Man-hour calculations for other methods were approximated from Grout et al. (1998), and Poppe et al. (2003). There are advantages and disadvantages to each method of grain size analysis (Table 3). Technology selection will be based upon the project goal data requirements, precision, and temporal and fiscal constraints. The results of this study indicated that photometric analysis can provide an accurate, rapid estimate of mean grain size for monitoring beach nourishment at both proposed sites. The ability to rapidly assess grain size on-site, in real time, as nourishment material is placed, sets photometric analysis apart from other methods. If a full grain size distribution is required, the photometric analysis described here cannot be used.

The photometric data collected for this study provide a baseline of mean grain size for two proposed beach nourishment pilot project areas of Del Monte Beach. The uniformity of grain size shown in this study suggests that future grain-size monitoring could utilize fewer transects or individual samples. The reconnaissance-level comparison of Monterey Harbor sand with Del Monte Beach sand indicates that the Harbor offers a reasonable sand source based upon grain size. The color differences will lead to initial aesthetic differences between placed and native sand, but that difference will diminish as the sands mix. Only one sample of Harbor material was assessed, so it is unclear if the sample is generally representative of the harbor substrate. Additional application of the photometric methods may include immediate in-situ measurement and analysis of recently placed dredged material.

5 References

Brew DS, Battalio RT, Thornton EB, Davenport C, Damitz B. 2011. Coastal regional management planning in southern Monterey Bay, California. [Internet] [Accessed 26 October 2011]. Available from: http://coastnet-littoral2010.edpsciences.org/index.php?option=com_article&access=standard&Itemid=129&url=/articles/litt/abs/2011/01/litt-05009/litt-05009.html

Buscombe D and Masselink G. 2009. Grain-size information from the statistical properties of digital images of sediment. Sedimentology 56: 421-438.

Buscombe D, Rubin DM, Warrick JA. 2010. A universal approximation of grain size from images of noncohesive sediment. Journal of Geophysical Research 115: 1-17.

[CCC] California Coastal Commission. 2011. Coastal development permit application. [Internet]. [Cited 26 October 2011]. Available from: http://documents.coastal.ca.gov/reports/2011/2/F12a-2-2011.pdf

Crossett KM, Culliton TJ, Wiley PC, Goodspeed TR. 2004. Population trends along the Coastal United States: 1980-2008.National Oceanic and Atmospheric Administration Coastal Trends Report Series.

Dean RG. 1984. Principles of beach nourishment. In: Komar PD, ed. CRC Handbook of coastal processes and erosion. Boca Raton, FL.: CRC Press.

Dugan JE, Hubbard DM, Rodil IF, Revell DL, Schroeter S. 2008. Ecological effects of coastal armoring on sandy beaches. Marine Ecology 29:160-170.

Griggs GB, Savoy L. and Patsch (eds). 2005. Living with the California Coast. University of California Press,

Grout H, Tarquis AM, Wiesner MR. 1998. Multifractal analysis of particle size distributions in soil. Environmental Science and Technology. 32:1176-1182.

[ESA PWA] ESA Philip Williams & Associates, Ltd, Thornton E, Caldwell M, King P. 2011. Southern Monterey Bay: evaluation of erosion mitigation alternatives.

Hapke CJ, Reid D, Richmond BM, Ruggiero P, List J. 2006. National Assessment of Shoreline Change Part 3: Historical Shoreline Change and Associated coastal land loss along sandy shorelines of the California coast [Internet]. [cited: 2011 October 24]. Available from: http://pubs.usgs.gov/of/2006/1219/of2006-1219.pdf.

Kollmorgen Instruments Incorporated. 1994. Munsell Soil Color Charts. Macbeth Division of Kollmorgen Instruments Incorporated. 405 Little Britain Road, New Windsor, New York.

Ma Z, Merkus HG, de Smet JGAE, Heffels C, Scarlett B. 2000. New developments in particle characterization by laser diffraction: shape and size. Power Technology 111:66-78.

MathWorks Inc. 2011. Matlab Version 7.12.0.635. Natick, MA

Muhlenweg H and Hirleman ED. 1998. Laser diffraction spectroscopy: Influence of particle shape and a shape adaptation technique. Particle & Particle Systems Characterization 15(4): 163-169.

Orzech MD, Thornton EB, MacMahan JH, O'reily WC, Stanton TP. 2010. Alongshore rip migration and sediment transport in southern Monterey Bay. Journal of Geophysical Research 271(3-4):278-291.

Poppe LJ, Eliason AH, Fredericks JJ, Rendigs RR, Blackwood D, Polloni CF. 2003. Chapter 1: Grain-size analysis of marine sediments: methodology and data processing. USGS report 00-358. Available at: http://pubs.usgs.gov/of/2000/of00-358/text/chapter1.htm

[PWA] Philip Williams & Associates, Ltd, Thornton E, Dugan J, Halcrow Group. 2008. Coastal Regional Sediment Management Plan for Southern Monterey Bay [Draft]. Prepared for Association of Monterey Bay Area Governments and the Coastal Sediment Management Workgroup. [Internet] [Accessed 26 October 2011] Available from: http://www.dbw.ca.gov/csmw/pdf/SMontereyBay_CRSMP_3Nov2008_ALL_rev_040411.pdf

Sokal RS and Rolhf FJ. 2012. Biometry, 4th Ed. W.H. Freeman and Co., New York, 937 pp.

Stauble SK. 2005. A review of the role of grain size in beach nourishment projects. National Conference on Beach Preservation Technology 2004 February 2-4, Destin, FL. [Internet]. [cited 2011 October 27]. Available from: http://www.fsbpa.com/05Proceedings/02-Don%20Stauble.pdf

Trembanis AC, Pilkey OH, Valverde HR. 1999. Comparison of beach nourishment along the U.S. Atlantic, Great Lakes, Gulf of Mexico, and New England shorelines. Coastal Management 27: 329-340.

[USGS] U.S. Geological Survey. [17 Jun 2011]. Grain size from digital images of sediment. [Internet]. [cited 2011 Oct 20]. Available from: http://walrus.wr.usgs.gov/seds/grainsize/code.html

Verdu JM, Batalla RJ, Martinez-Casasnovas JA. 2005. High-resolution grain-size characterization of gravel bars using imagery analysis and geo-statistics. Geomorphology 72:73-93.

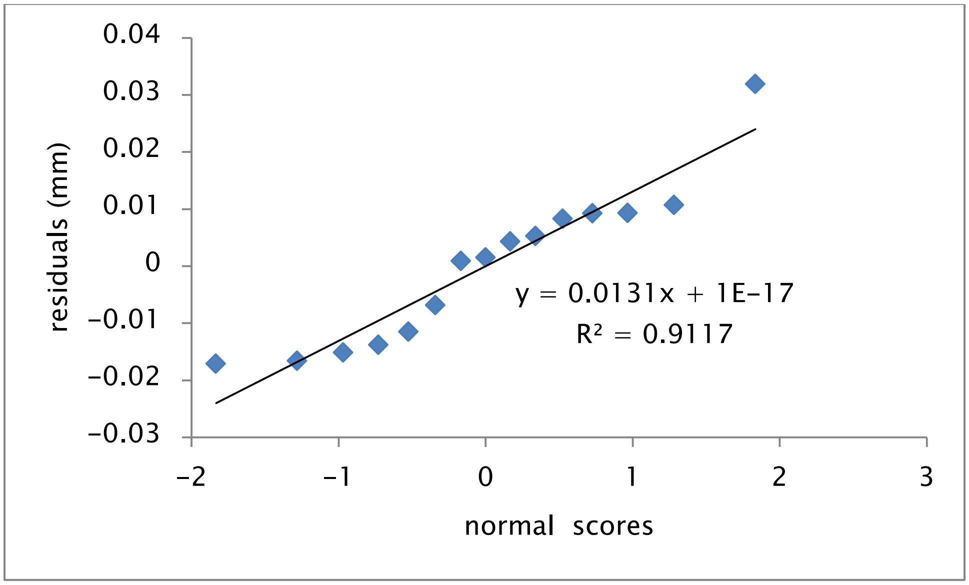
6 Appendix A – Model Assumptions

Linear regression analysis was used to create a bias correction between photometric and manual estimates of grain size. The resulting linear model (Fig. 5) carries the assumption that model residuals are random, normally distributed, independent values (e.g., Sokal and Rohlf 2012). The residuals have a mean of 2 X 10^{-17} mm (95% confidence interval = 0.008 mm) and a skew of 0.6. A normal score plot (Fig. A1) indicates an approximately linear relation between raw data (residuals) and their calculated normal scores. Further, there is a significant relation between residuals and normal scores ($p<0.001$ on regression slope), and the Y intercept value equals the mean residual value, thus the residuals do not markedly diverge from a normal distribution. Furthermore a normal distribution is supported by a high p value from a Shapiro-Wilk test on model residuals (w=0.91, p=0.14).

Regression analysis indicates no relationship between model residuals and estimated grain size (p=1 on regression slope) or sampling order (p=0.33 on regression slope), partially satisfying the requirement of residual independence.

The model residuals appear to be random, normally-distributed, independent values, thereby validating the assumptions for linear regression to develop the bias-correction model.

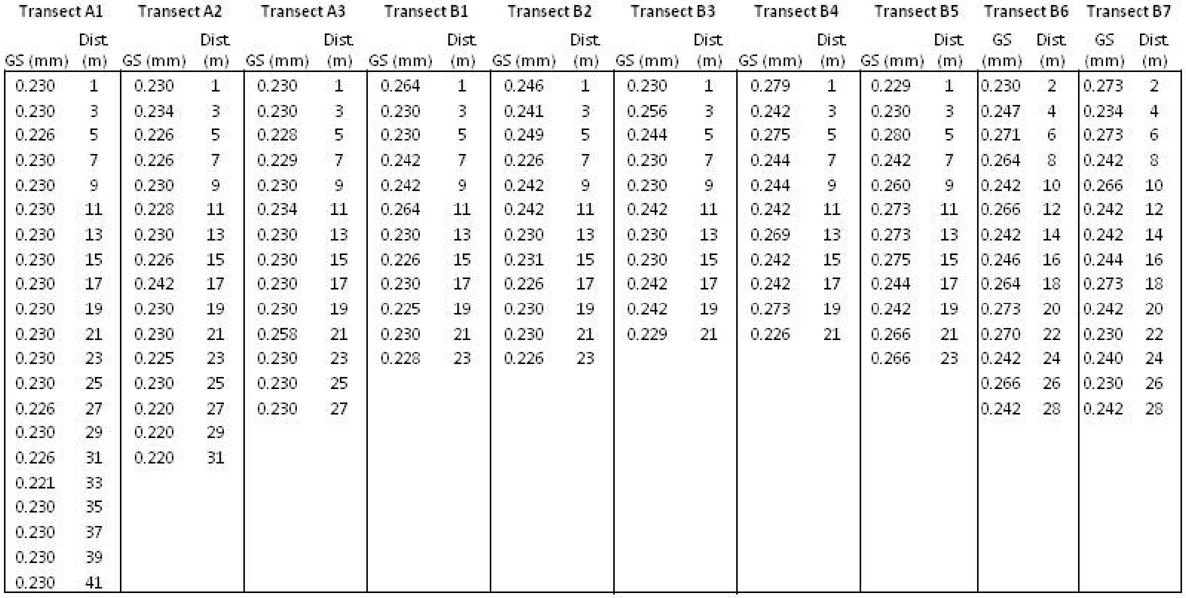
Figure A1. Normal score plot of model residuals.



7 Appendix B – Mean Grain Sizes

Table B1. Mean grain size values for each image along the survey transects.

GS is mean grain size in each image, and Dist. is the distance along the transect.



Transect A1		Transect A2		Transect A3		Transect B1		Transect B2		Transect B3		Transect B4		Transect B5		Transect B6		Transect B7	
GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)	GS (mm)	Dist. (m)
0.230	1	0.230	1	0.230	1	0.264	1	0.246	1	0.230	1	0.279	1	0.229	1	0.230	2	0.273	2
0.230	3	0.234	3	0.230	3	0.230	3	0.241	3	0.256	3	0.242	3	0.230	3	0.247	4	0.234	4
0.226	5	0.226	5	0.228	5	0.230	5	0.249	5	0.244	5	0.275	5	0.280	5	0.271	6	0.273	6
0.230	7	0.226	7	0.229	7	0.242	7	0.226	7	0.230	7	0.244	7	0.242	7	0.264	8	0.242	8
0.230	9	0.230	9	0.230	9	0.242	9	0.242	9	0.230	9	0.244	9	0.260	9	0.242	10	0.266	10
0.230	11	0.228	11	0.234	11	0.264	11	0.242	11	0.242	11	0.242	11	0.273	11	0.266	12	0.242	12
0.230	13	0.230	13	0.230	13	0.230	13	0.230	13	0.230	13	0.269	13	0.273	13	0.242	14	0.242	14
0.230	15	0.226	15	0.230	15	0.226	15	0.231	15	0.230	15	0.242	15	0.275	15	0.246	16	0.244	16
0.230	17	0.242	17	0.230	17	0.230	17	0.226	17	0.242	17	0.242	17	0.244	17	0.264	18	0.273	18
0.230	19	0.230	19	0.230	19	0.225	19	0.230	19	0.242	19	0.273	19	0.242	19	0.273	20	0.242	20
0.230	21	0.230	21	0.258	21	0.230	21	0.230	21	0.229	21	0.226	21	0.266	21	0.270	22	0.230	22
0.230	23	0.225	23	0.230	23	0.228	23	0.226	23					0.266	23	0.242	24	0.240	24
0.230	25	0.230	25	0.230	25											0.266	26	0.230	26
0.226	27	0.220	27	0.230	27											0.242	28	0.242	28
0.230	29	0.220	29																
0.226	31	0.220	31																
0.221	33																		
0.230	35																		
0.230	37																		
0.230	39																		
0.230	41																		