Bedform Migration and Sediment Transport Rates in the Mouth of San Francisco Bay

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Summary/Abstract:

The purpose of this study is to determine sediment transport rates and sand wave migration rates in the mouth of the San Francisco Bay west of the Golden Gate Bridge. Strong tidal currents flow through the Golden Gate, moving mud in suspension and coarser sediment (i.e. sand and gravel) as bedload transport. The United States Geological Survey (USGS) is aiming to quantify rates of bedload transport to use as a basis for their sediment transport model for the mouth of San Francisco Bay. The United States Army Corps of Engineers (USACE) is also very interested in sediment movement through the Golden Gate because they are responsible for dredging the shipping channel. The need for maritime commerce has increased with the influx of people settling in the San Francisco area. An increased need for maritime commerce has lead to larger sized ships entering and exiting the Bay. The larger hulls on these ships have created increased navigational risks and potential for an ecological disaster, thus understanding of sediment accretion patterns at the mouth of San Francisco is a benefit to all the stakeholders. Multibeam bathymetric data of approximately 60 square km were collected from September 2004 through October 2004 west of the Golden Gate Bridge. These data were analyzed in CARIS HIPS Spatial Editor and ArcGIS 9.0 to calculate sediment movement in a sand wave field within the mouth of San Francisco Bay. The question in this study is: Is there an onshore or offshore movement of sediment occurring over the 12-day study period in the mouth of San Francisco Bay? The null hypothesis was that there is no net change of sediment. Results showed 59334 x 10^4 $m^3 \pm 4m^3$ of sediment movement in the offshore direction. The results also showed a sand wave migration average over the twelve days of 1.7 m/day. Results from this study could be used as a basis for future studies in this sand wave field.

Introduction

Background

San Francisco Bay and the adjoining San Joaquin Delta, which covers approximately 1,600 square miles, is used by millions of people for such activities as research, recreation, waste disposal, aesthetic pleasure, and commerce. San Francisco Bay is one of the main ports in California for maritime commerce, annually generating over $7.5 billion. The rapidly growing population in California has led to an ever-increasing need for maritime commerce. Because of this, the first Federal navigation project, named the San Francisco Channel, began in 1868. Thus began the Federal Government's first involvement in maritime safety issues in the San Francisco estuary. The growing population also placed a number of pressures on the estuary. Large container ships and oil tankers are constantly entering and exiting the San Francisco Bay through the Golden Gate Bridge, shipping approximately 50 million tons of cargo yearly (Chin et al., 2003, Pirie and Steller, 1977). The large draft of these vessels has raised concern for navigational and ecological hazards. The deep hulls of these ships can become grounded on the seafloor, causing oil spills or other disasters. It is essential for the U.S. Army Corps of Engineers to know the depth, geomorphology, and short-term evolution of San Francisco Bay so that dredging projects can be designed appropriately.

The geomorphology of the Bay impacts not only the ship traffic, but also the terrestrial and marine wildlife in the estuary. Along with the geomorphology, it is essential for scientists to know how changes in bathymetry relate to changing biological communities, contaminant issues and future development within this estuary (Rothery, 2003). Factors such as strong tidal currents entering and exiting the Bay and the stability of substrate can greatly influence the shape it takes (Rothery, 2003). Gaining knowledge of the effects currents and substrate have of the Bay can help determine the need for potential coastal engineering projects such as dredging and development (Duffy and Hughes Clarke, 2004).

A series of studies conducted by the United States Geological Survey (USGS) using hydrographic surveys provided sediment transport data in South San Francisco Bay from 1858 to 1983 (Foxgrover et al., 2004). Between 1898 and 1983 the USGS concluded that periods of both erosion and deposition occurred. The fluctuating periods of erosion and deposition could have an effect on the geomorphology of the rest of the estuary because the sediment is either being deposited in other areas of the estuary or increasing the suspended sediment passing through the estuary.

In another study by the USGS in 1997 west-central San Francisco Bay east of the Golden Gate Bridge was surveyed using a multibeam swath bathymetric system (Chin et al., 1998). Detailed bottom features were used to determine natural and manmade influences on the geomorphology. In 1998 and 1999 cooperative surveys were conducted by the USGS and the National Oceanic and Atmospheric Administration (NOAA) to field check the previous studies done in 1997 (Chin et al., 2003). The USGS concluded that the geomorphology is greatly influenced by the increased dredging and blasting, which provides safe navigation channels. By changing bottom features, dredging has a potentially profound effect on stability of sediment in the Bay. Sediment can become loose, increasing the amount of suspended or bedload sediment.

The purpose of this study is to determine sediment transport rates and sand wave migration rates over twelve days at the mouth of San Francisco Bay in a large sand wave field west of the Golden Gate Bridge. For this study a time series of repetitive multibeam sonar surveys through the middle of the sand wave field in the mouth of San Francisco Bay were conducted. The same portion of the sand wave field was surveyed over a twelve-day period, with surveys being conducted one day after the initial survey, seven days after the initial survey, and twelve days after the initial survey.

The USGS is particularly interested in this particular study because they are aiming to create a digitized sediment transport model in the mouth of San Francisco Bay. Once the USGS creates a model they can use this to run what-if scenarios to better predict such events as dredging needs and dredge spoil placements that could affect the geomorphology of the Bay. By determining sediment movement in west San Francisco Bay through observation of sand wave movement and calculations, researchers will also be better equipped to make informed decisions about policy related issues such as coastal development. Scientists and land planners could use the sediment transport model to analyze erosion rates in conjunction with water and sediment movement through the estuary to aid in more informed land use decisions.

Deltas and Estuaries

Estuaries play a significant role in continental shelf makeup and oceanic processes due to the tidal exchange of water, contaminants, and sediment between the estuaries and the coastal sea. Estuaries serve as the routes from which sediment is transported from inland landmasses via rivers (Pye, 1994). Deltas often times have built up deposited sediment from rivers that are richly organic, fine-grained, cohesive, and prone to flocculate (Pye, 1994). Two key factors play a role in the build up of sediment. The first factor is the slowing of water flow. Just as an alluvial fan, the flow spreads out and the speed drops resulting in deposited river bed-load. Second, individual clay particles will tend to stay in suspension until the water becomes even slightly saline. This mixing of fresh and salt water causes the clay particles to stick together, or flocculate and settle (Pye, 1994, Rothery, 2003). Continual deposition, re-erosion, and transport through the estuary alter the grain-size of the sediment. Grains that are transported by dragging, rolling, or station are said to make up the bed-load, while smaller grains that are picked up by the flow and suspended for longer periods of time are said to belong to the suspended load (Pye, 1994, Rothery, 2003).

Ripples and Sand Waves

Tidal currents, fresh water discharge, tidal cycle, wind action, bottom topography, and waste water discharge move water, which in turn transports and re-suspends sediments (Pirie and Steller, 1977). Once the flow of water reaches a force strong enough to erode particles, sedimentary structures known as bedforms are produced. Formation of these bedforms depends on grain size, velocity, flow, and depth (Pirie and Steller, 1977).

Common bedforms found in the mouth of San Francisco Bay are ripples and sand waves. Sand waves, or dunes are characterized as ripple-like structures over 1m in wavelength and 0.1m in height (Pye, 1994). Ripples and sand waves are usually only found in sand or coarse silty sediments and the shape they take depends on the conditions in which they form (Pye, 1994). The surface of the bed may have small irregularities, which causes the water to be diverted up and around them. As the water flows over the obstacle it will no longer hug the bottom and separate from it at the point of separation, or crest of the sand wave. The flow will then meet the bottom again at the point of reattachment (Prothero, 2004, Rothery, 2003). Because the sand wave is being eroded on the upstream side and accreted on the downstream side, the bedforms tend to migrate in the direction of flow. A relatively slow flow in a constant direction creates transverse ripples or sand waves that are aligned at 90 degrees to the current and as the flow increases the crests become wavier, eventually braking into crescent shapes (Pye, 1994, Rothery, 2003). The cross-bedding that allows sand waves to be distinguished is associated with these different patterns (Pye, 1994, Rothery, 2003).

Tidal currents and waves play a major role in the shaping of bedforms in San Francisco Bay. Strong currents entering and exiting the Bay change in both strength and direction. These strong currents can lead to alternating directions of cross-bedding and thin layers of fine-grained suspended load that are able to settle during slack water while the tide is turning (Pye, 1994). Typically, this type of bedform has a gentle slope on the upstream side and a steeper slope on the lee side. The current pushes the sediment up the gentle upstream slope and deposits it on the lee side, causing the sand wave to migrate slowly downstream. Waves can cause bedforms to grow in the shape of symmetric ripples or sand waves, with the opposite faces having equal steepness (Rothery, 2003). When the direction of waves is completely different than that of the current, current and sand may interface to produce a criss-cross pattern of interface sand waves (Rothery, 2003).

The question in this study is: Is there an onshore or offshore movement of sediment occurring over the 12-day study period in the mouth of San Francisco Bay? The null hypothesis (H_0) is that no net movement of sediment will be detected at the mouth of San Francisco Bay. Alternative hypothesis one (H_1) is a net offshore movement of sediment will be detected and alternative hypothesis two (H_2) is a net onshore movement of sediment will be detected.

Methods

Site Description

San Francisco, California is located on the Pacific coast of the United States (Figure 1). To determine sediment transport rates and sand wave migration rates in a sand wave field west of the Golden Gate Bridge a research vessel equipped with a multibeam sonar device was used to collect bathymetry and bottom topography data. The entire surveyed area consisted of an area approximately 60 square km west of the Golden Gate Bridge (Figures 1 and 2). The entire survey area required 25 days of data collection from September 2004 through October 2004. A sand wave field within the survey area was specified as the study site (Figure 2). These data were analyzed using CARIS HIPS Spatial Editor to clean erroneous data points and ArcMap GIS 9.0 to calculate sediment movement and sand wave migration rates.

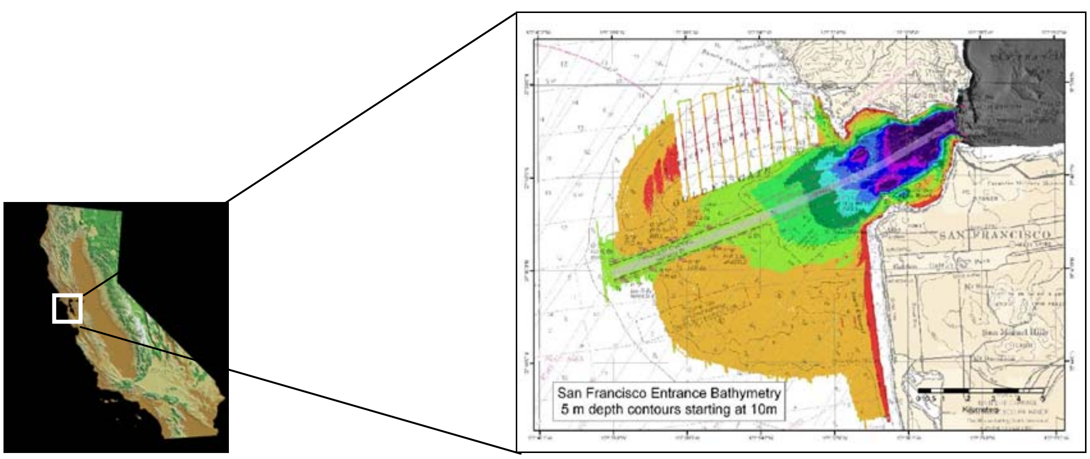

Figure 1: White box shows location of San Francisco, California. Enlarged image on right is survey area. Warmer colors indicate shallower depths while cooler colors indicate deeper depths.

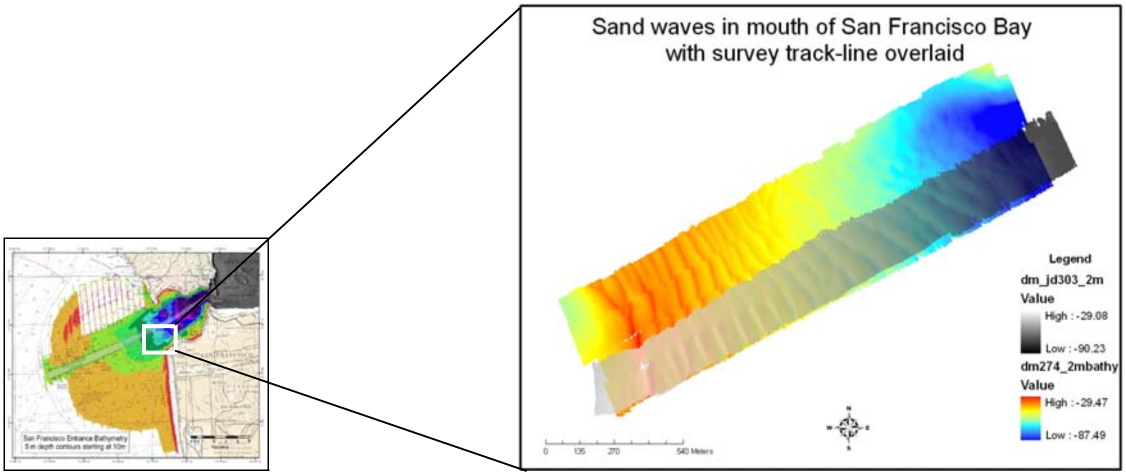

Figure 2: Left: Study site approximately 60 square kilometers, just west of the Golden Gate Bridge. Right: Sand wave field overlaid with individual survey track-line, which this study was restricted to. Warmer colors indicate shallower depths while cooler colors indicate deeper depths. (Dune crest offsets shown in figure are probably artifacts due to heading errors caused by incorrect POS leverarm values and GPS errors.)

Survey Design

The California State University at Monterey Bay Seafloor Mapping Lab conducted hydrographic surveys using its pole mounted Reson 8101 Seabat 244 kHz multibeam sonar aboard the R/V *VenTresca* to achieve multibeam bathymetric data acquisition. Prior to collecting data, a series of survey lines were created using Hypack software from Coastal Oceanographics. A total of 981 lines of data were collected during this period. For this study, only five days of surveying were used. They were between September 30, 2004 and October 29, 2004. The multibeam sonar collected data across 150° of swath coverage, utilizing 101 1.5° x 1.5° beams. A Trimble 4700 differential global positioning system (DGPS) was used to position the vessel during data collection. Predicted tides from a NOAA station were taken from a Tides and Currents program to account for tide cycle fluctuations and sound velocity profiles were acquired each survey day using an AML SV+ sound velocity profiler. All raw data were collected using a Triton-Elics International Isis Sonar data acquisition system, with real-time bathymetry DTM generation. The data were then exported into CARIS HIPS 5.4 hydrographic cleaning software (http://seafloor.csumb.edu).

Data Processing

Preliminary multibeam processing was done aboard the *R/V VenTresca* using CARIS HIPS 5.4 hydrographic data cleaning system software. Data were post-processed in the Seafloor Mapping Lab at CSUMB utilizing the same software. All data points were filtered, merged and thoroughly cleaned to eliminate erroneous data points. Once the data were cleaned, individual geotiffs of each of the five specified days were exported from CARIS HIPS Spatial Editor with 2m resolutions in sunshaded grayscale and 10-color rainbow imagery with a sun azimuth of 315°, elevation of 45°, and vertical exaggeration set at 5. The five days used for this survey were September 30, 2004, October 17, 2004, October 18, 2004, October 24, 2004, and October 29, 2004.

Data Analysis

The focus of this study is on a specific region of dunes in the mouth of San Francisco Bay. Therefore, the net volume and net transport rates for the entire mouth of the Bay were not derived. The sand wave field consisted of approximately 13 sand waves of various heights and wavelengths (Barnard et al, unpublished data). One swath of the sand wave field was mapped on four separate days throughout the study (Figure 2). Within the individual swath, the 9 most westerly sand wave crests were found to have an average wavelength of 79.59m and average amplitude of 6.45m (Table 1). The individual swath also showed a 2% slope offshore. The data were exported into ArcMap GIS 9.0 and specified areas within the mouth of San Francisco Bay were analyzed using raster subtractions to calculate total volume of sediment transport. Data collected on 10/18/04, 10/24/04, and 10/29/04 were separately raster subtracted from data collected on 10/17/2004. A mask was applied to each set of subtractions and re-calculated to ensure the calculations were only applied to similar areas within each survey day. The applied masks also served to eliminate “noise” along the outer edges of each dataset. The volume of sediment transport was calculated using the zonal analysis tool in GIS. The sediment transport rates for each day analyzed were then divided by the number of days elapsed from 10/17/04 to calculate sediment transport rates per day. The timeframe of these analyses occurred after 1 day, 7 days, and 12 days respectively.

In addition to total sediment transport per day, the 9 most westerly sand wave crests were individually analyzed to calculate sediment transport within each crest (Figure 3).

Sand Wave Wavelength (m)					
Crest	Oct 17	Oct 18	Oct 24	Oct 29	Average
1,2	115.3	110.3	114	111.1	112.68
2,3	55.9	57.6	54.8	60.1	57.1
3,4	73.1	72.6	74.1	70.1	72.48
4,5	80.2	79.7	79.1	80.7	79.93
5,6	89.5	86.1	86.9	90.6	88.28
6,7	75.2	79.7	79.8	75.7	77.6
7,8	70.2	72.6	69.8	72.2	71.2
8,9	78.8	76.1	78.4	76.2	77.38
Avg	**79.78**	**79.34**	**79.61**	**79.59**	**79.58**

Sand Wave Amplitude (m)					
Crest	Oct 17	Oct 18	Oct 24	Oct 29	Average
1	8.37	8.46	8.42	8.26	8.38
2	3.39	3.57	3.61	3.54	3.53
3	6.34	6.59	6.44	6.53	6.48
4	7.88	8.06	7.97	8.03	7.99
5	5.56	5.6	5.65	5.5	5.58
6	7.25	7.32	7.19	7.26	7.26
7	5.9	6.12	5.86	5.93	5.95
8	6.6	6.49	6.42	6.43	6.49
9	6.37	6.43	6.45	6.38	6.41
Avg	**6.41**	**6.52**	**6.45**	**6.43**	**6.45**

Table 1: Left: Wavelengths of 9 most westerly sand wave crests along individual swaths for each survey day. Right: Amplitudes of 9 most westerly sand waves along individual swaths for each survey day.

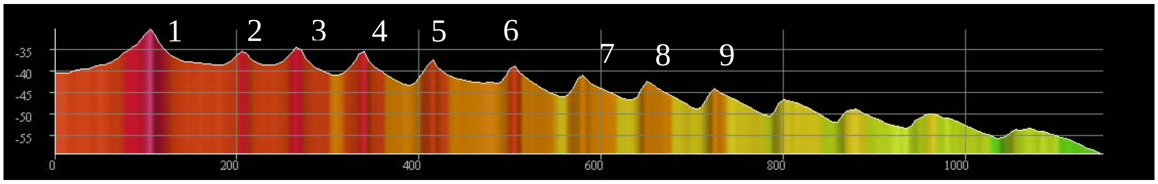

Figure 3: Profile view of sand waves showing 9 most westerly sand wave crests.

Sand wave migration rates were calculated using profile views from each survey day. ArcMap 9.0 and Hawths Tools were used to analyze the individual sand wave layers from each survey day. Output values were then graphed in Excel. The distance between each crest was measured and divided by the corresponding time difference between survey lines to determine the speed at which the sand waves migrated.

The Nobeltec Tides and Currents Lite program was used to obtain predicted current velocities and vectors (Table 2). This was done to determine if there was a possible correlation between current velocity and vectors and sediment transport rates.

	Current	
Date	**Velocity (kt)**	**Vector (flood/ebb)**
9/30/2004	3.6	Ebb
10/17/2004	0.4	Flood
10/18/2004	1.5	Flood
10/24/2004	0.1	Flood
10/29/2004	3.1	Ebb

Table 2: Predicted current velocity and current vector for study days.

Results

Sediment Transport

Total sediment transport rates were calculated for three different days (Table 3). The surveys were 1 day, 7 days, and 12 days after the initial survey day of October 17, 2004. After one day the October 18th, 2004 survey showed erosion of 3.628 x 10^4 m^3 ± $4m^3$ (Figure 4). After 7 days the October 24th, 2004 survey showed deposition of 5.595 x 10^4 m^3 ± 4m (Figure 5). Finally, 12 days after the initial survey, October 29, 2004 showed deposition of 7.901 x 10^4 m^3 ± $4m^3$ (Figure 6). The total net sediment movement over 12 days was 5.933 x 10^4 m^3 ± $4m^3$.

Sediment transport rates were also calculated between days within the survey. From October 18, 2004 to October 24, 2004 there was a deposition of 1.435 x 10^4 m^3 ± $4m^3$. From October 24, 2004 to October 29, 2004 there was a deposition of 2.705 x 10^4 m^3 ± $4m^3$ (Figure 7).

The 9 most westerly sand wave crests were analyzed to show sediment transport within each individual crest (Table 4). The results of individual sand wave crest analysis showed erosion after 1 day and deposition after 7 days and 12 days. Crest 1 showed the largest average change of 2297 m^3 ± 4 m^3, while the other 8 sand wave crests showed various sediment transport volumes ranging from –95 m^3 ± 4 m^3 to 818 m^3 ± 4 m^3.

Date	Sediment change (m^3)	# of days between surveys
10/18/2004	-36275	1
10/24/2004	55946	7
10/29/2004	79005	12

Table 3: Net sediment transport rates and the number of days since the initial survey.

Sediment Transport (m^3)				
Crest	**After 1 day**	**After 7 days**	**After 12 days**	**Average**
1	1592	2729	2571	2297
2	-586	237	976	209
3	-21	1530	945	818
4	-440	678	625	288
5	-1212	1009	295	31
6	-706	476	277	16
7	-323	519	455	217
8	-603	1062	530	330
9	-1029	470	275	-95
Average	**-370**	**968**	**772**	**457**

Table 4: Sediment transport for 9 individual sand wave crests.

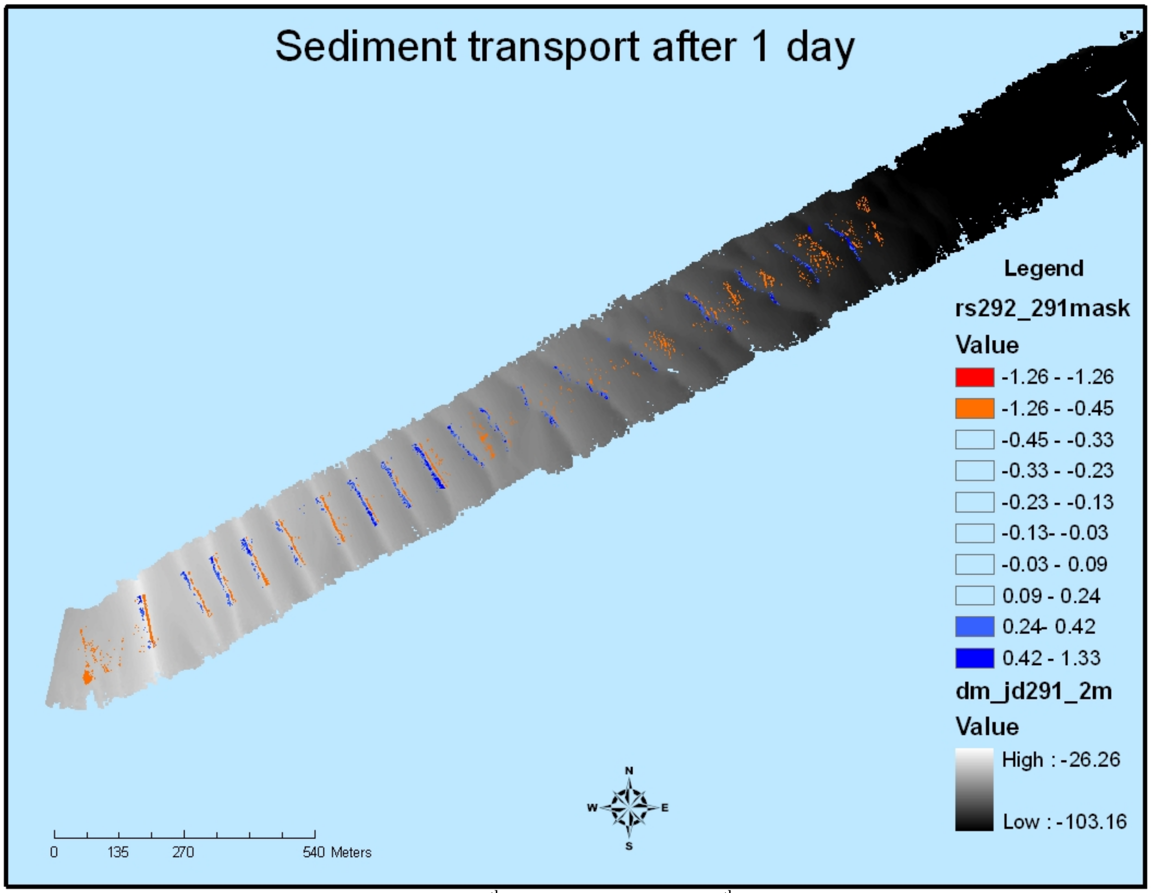

Figure 4: Sediment transport from October 17th, 2004 to October 18th, 2004 (1 day after initial sand wave survey). Warmer colors represent sediment loss and cooler colors represent sediment gain.

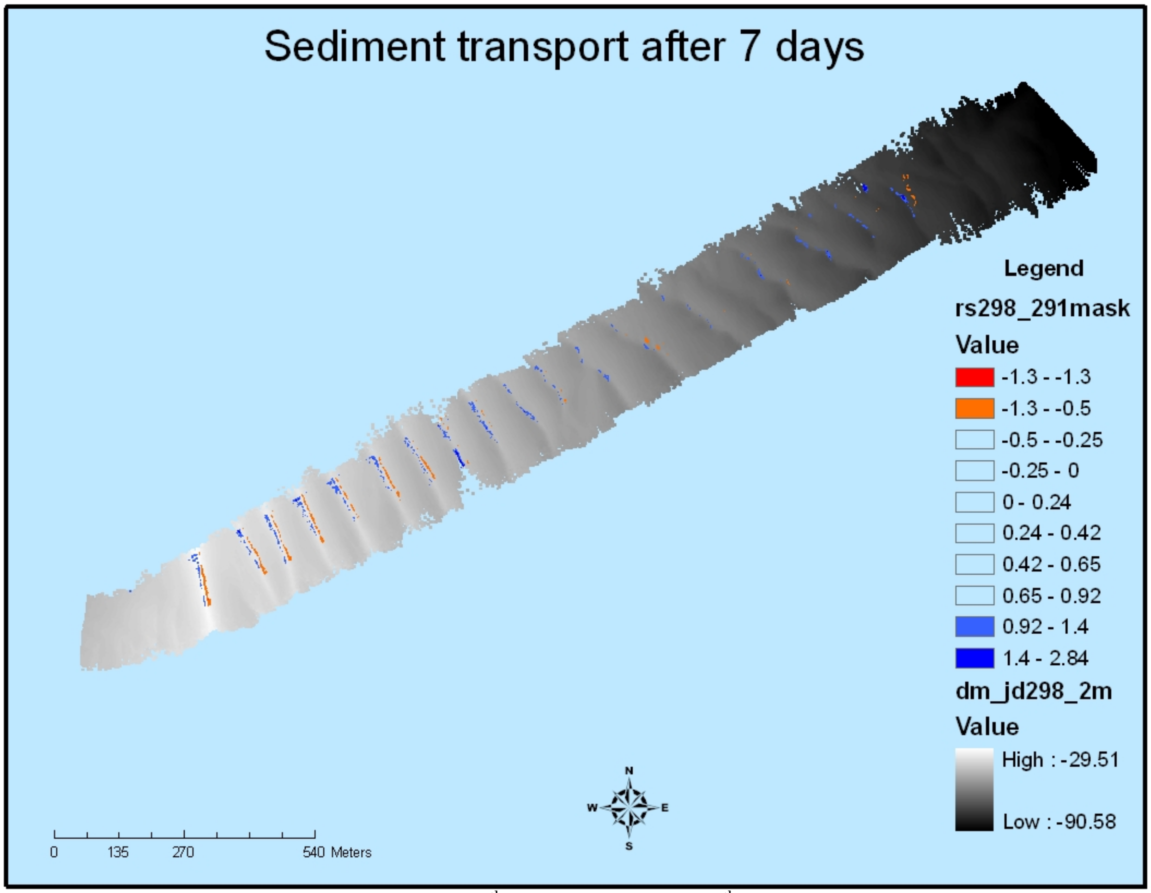

Figure 5: Sediment transport from October 17th, 2004 to October 24th, 2004 (7 days after initial sand wave survey). Warmer colors represent sediment loss and cooler colors represent sediment gain.

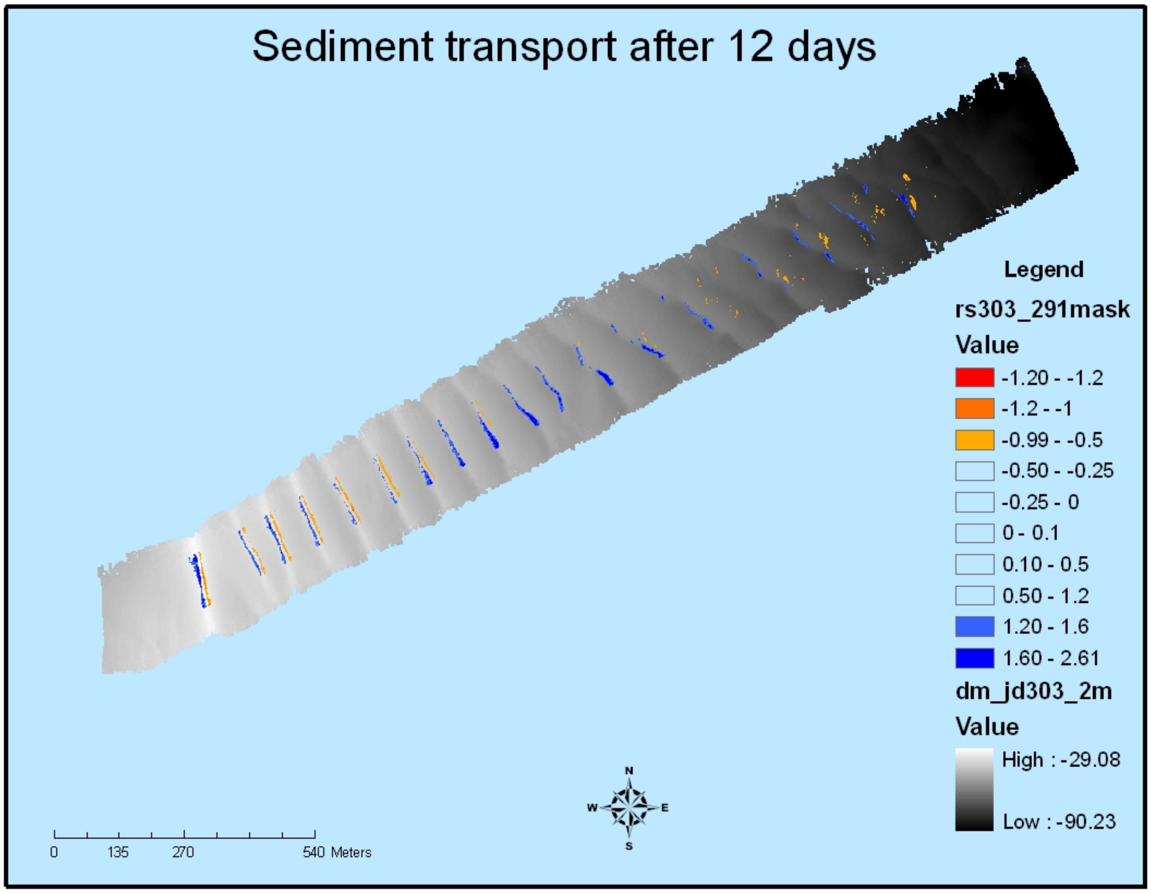

Figure 6: Sediment transport from October 29, 2004 (12 days after initial sand wave survey). Warmer colors represent sediment loss and cooler colors represent sediment gain.

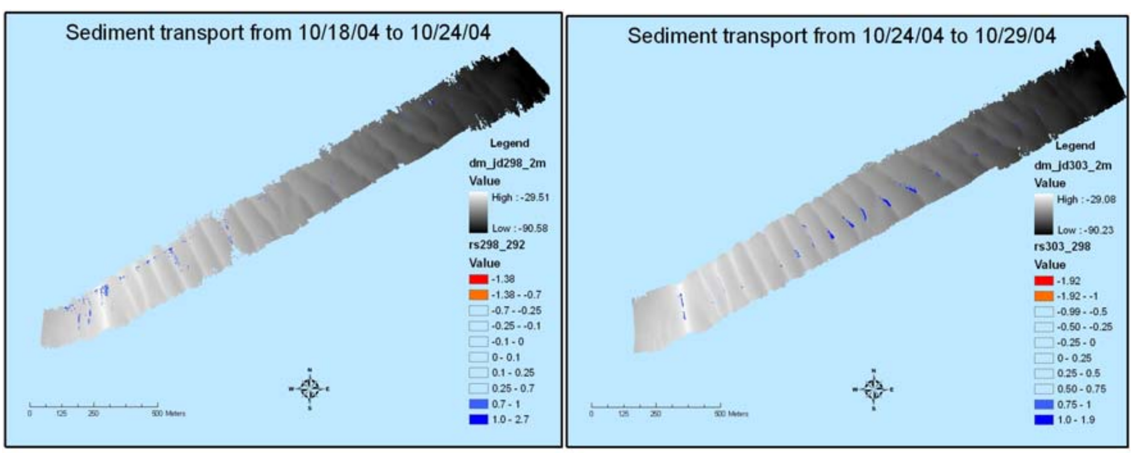

Figure 7: Left: Sediment transport from October 18th, 2004 to October 24th, 2004. Right: Sediment transport from October 24th, 2004 to October 29th, 2004. Warmer colors represent sediment loss and cooler colors represent sediment gain.

Sand Wave Migration

Sand waves showed an average migration rate of 1.7 m/day over the course of the twelve-day study period. After one day the average sand wave migration was 1.1 m. This increased to an average of 1.7 m after the seventh day and to an average of 2.2 m after 12 days (Table 5). Profile views of each survey showed the dominant transport direction to be offshore (Figures 8 and 9).

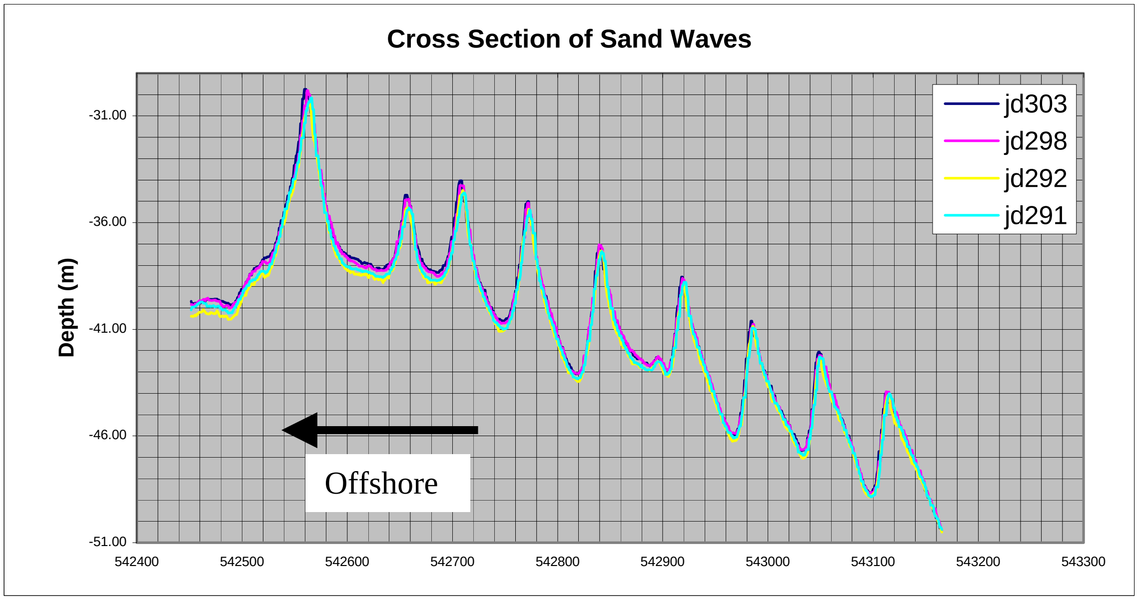

Figure 8: Cross-section of 9 most westerly sand waves from all four survey days overlaid.

Sand Wave Migration Rates				
Sand wave	**Migration-1 day (m)**	**Migration-7 days (m)**	**Migration-12 days (m)**	**Avg. m/day**
1	1	3	5	**3**
2	2	0	2	**1.3**
3	2	2	3	**2.3**
4	2	2	2	**2**
5	0	3	1	**1.3**
6	1	1	1	**1**
7	0	0	1	**0.3**
8	0	1	1	**0.7**
9	2	3	4	**3**
Average	**1.1**	**1.7**	**2.2**	**1.7**

Table 5: Sand wave migration rates for the 9 most westerly sand waves.

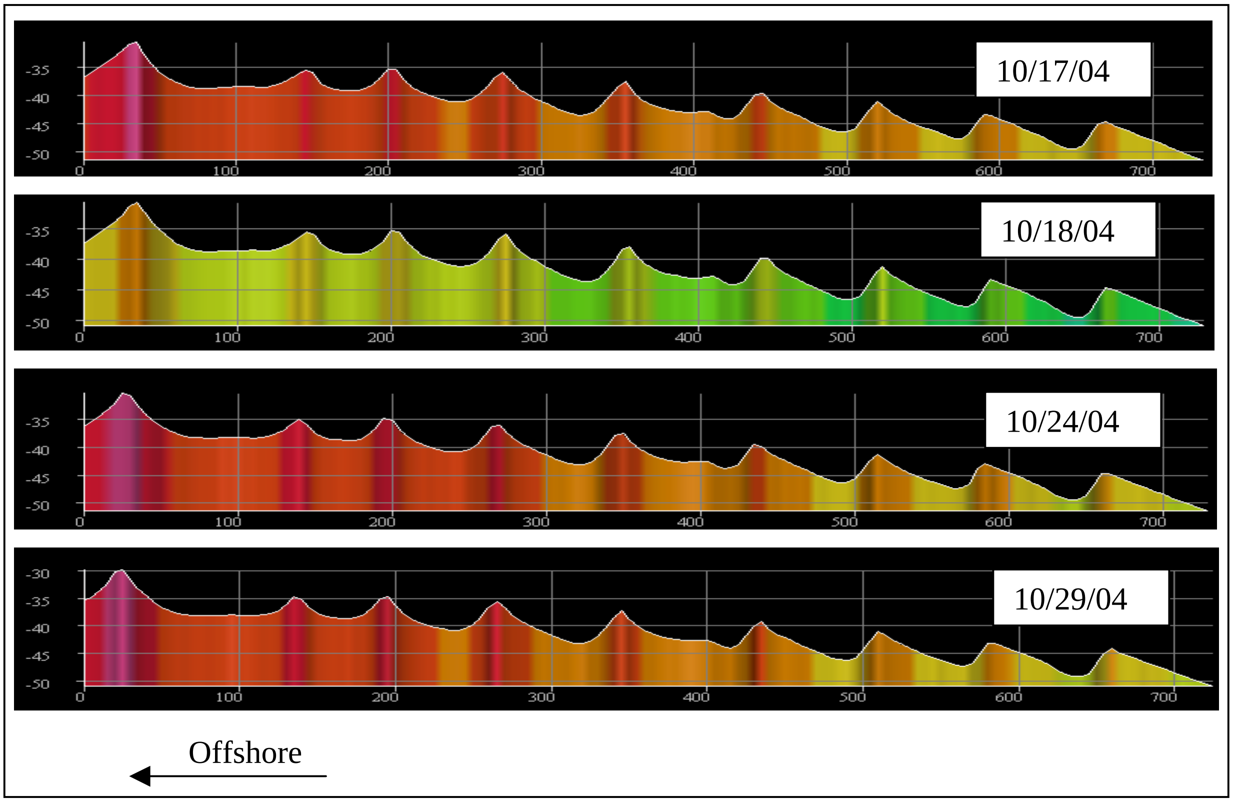

Figure 9: Profile view of each survey day, showing the offshore movement of sediment.

Discussion

The giant sand wave field present in the mouth of San Francisco Bay shows to be a dynamic environment in which sediment movement is playing a role in the geomorphology of the surroundings. In this study three days of sediment transport within this sand wave field were calculated, with a large range of sediment moving throughout the system. The largest amount of sediment movement occurred after the longest period of time (12 days) and at the time of a strong current velocity (3.1 knots, ebb). Tidal direction did not appear to influence the direct the sand waves were migrating, which could lead to further questions of how much tidal fluctuation and currents influence the bedload sediment in the sand wave field. Net sediment movement calculated and profile views of the sand waves showed an offshore accumulation of sediment. This indicates that sediment is being pushed out of the Bay and being transported up the faces of the sand waves, then moving down the lee-side. A further study of this area could determine if sediment is moving in and out of the sand wave field, or just moving back and forth within it.

When interpreting onshore and offshore sediment movement calculations it is also important to consider the effects dredging may have on the system. Rates of sediment movement may change with the location of the dredging and length of time from the last dredging event. Detecting patterns of sediment movement could assist the U.S. Army Corps of Engineers, USGS, and other interested parties to determine the effect dredging has on sediment movement in the sand wave field.

Although this study is over a short time period, it gives useful preliminary results that could be utilized for future studies to determine if there is a pattern of sediment movement occurring within the sand wave field in San Francisco Bay. This study provides a snapshot of what could possibly be happening over a longer period of time.

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