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Assessing the Impact of an Organic Restoration Structure on Boat Wake Energy

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ABSTRACT

Erosion of unprotected levee banks decreases their structural integrity and increases the likelihood of failure. Several types of restoration structures for levee protection and stabilization have been used in the Sacramento–San Joaquin River Delta, California, to reduce erosion. The purpose of this paper is to describe the results of a field experiment designed to measure the effectiveness of organic restoration structures (brush bundles) in altering the hydrodynamic regime in the vicinity of levees, with specific focus on changes in boat wake energy. Two simple hypotheses were tested: 1) restoration structures reduce boat wake energy, and 2) energy reduction is dependent on water depth. Field work was conducted August 29-31, 2000 on Georgiana Slough, which is a tidally influenced (spring tidal range of 2 meters) distributary of the Sacramento River. Pressure sensors were deployed offshore and landward of the restoration structures. Data collection occurred with the bundles in place and with them removed. Boat wakes were generated during rising and falling tides to capture the effects of fluctuating water levels. Wakes were characterized by index wave height, period and energy. Comparing sample means of normalized energy with the bundles removed and with the bundles in place revealed a 60% reduction of energy by the bundles. It was also determined that energy reduction was tidally, or depth dependent. The reduction of energy by the structures indicates that they are an effective method to protect against boat-wake induced, levee erosion.

ADDITIONALINDEXWORDS: *Sacramento-San Joaquin River Delta, levee erosion*

INTRODUCTION

Sacramento-San Joaquin River Delta

The Sacramento-San Joaquin River Delta, east of San Francisco, is a prominent geographical feature of California (Figure 1). Formed during the Holocene sea level rise by the confluence of the Sacramento and San Joaquin Rivers, the Delta is not always classified as a ‘true’delta because of its inland location. However, the channel behavior and morphology are similar to deltas worldwide (MOUNT, 1995).

The Delta’s natural and engineered waterways and interspersed islands support agriculture, urbanization, industry, recreation and the natural environment (CADWR, 1995). An extensive network of levees is critical to protect the low-lying lands from flooding. However, land subsidence, boat wake and wind wave erosion, animal activity and tractive forces from channel and flood flows erode unprotected levee banks. Decreasing levee integrity is evidenced along unprotected banks by cut banks and scallops (arcuate embayments) in levees. A recent strategy to restore the eroding levees was developed by a consulting company, the Habitat Assessment and Restoration Team, Inc. This group constructed and emplaced a number of organic structures (brush bundles) along the eroding levee banks of north Georgiana Slough. The structures are one example of vegetative stabilization, a common response to mitigate levee erosion (BARSDALE, 1960; ALLEN and LEECH, 1997; BOUMANS *et al.*, 1997; LEE *et al.*, 1997). Brush bundles offer advantages over conventional armoring, such as rip-rap. The bundles are porous and therefore allow sedimentation during flood and normal flow conditions. They are relatively inexpensive, are designed to allow the system to repair itself and are more visually appealing than armoring.

Levee erosion in the Sacramento-San Joaquin River Delta is caused by tractive forces from the river flow, wind waves and boat-generated waves. Benchmark studies of erosion in the Delta include those by COLLINS and NODA (1971), LIMERINOS and SMITH (1975), FODA (1995), and FODA *et al*. (1999). These four studies quantified erosive potential of river flow, wind waves, and boat-generated waves by estimating the total energy from each source dissipated on levee banks. It was suggested that boat wakes in non-flow dominated channels of the Delta contribute the largest amount of erosive energy to levee banks (LIMERINOS and SMITH, 1975; FODA, 1995; FODA *et al.*, 1999).

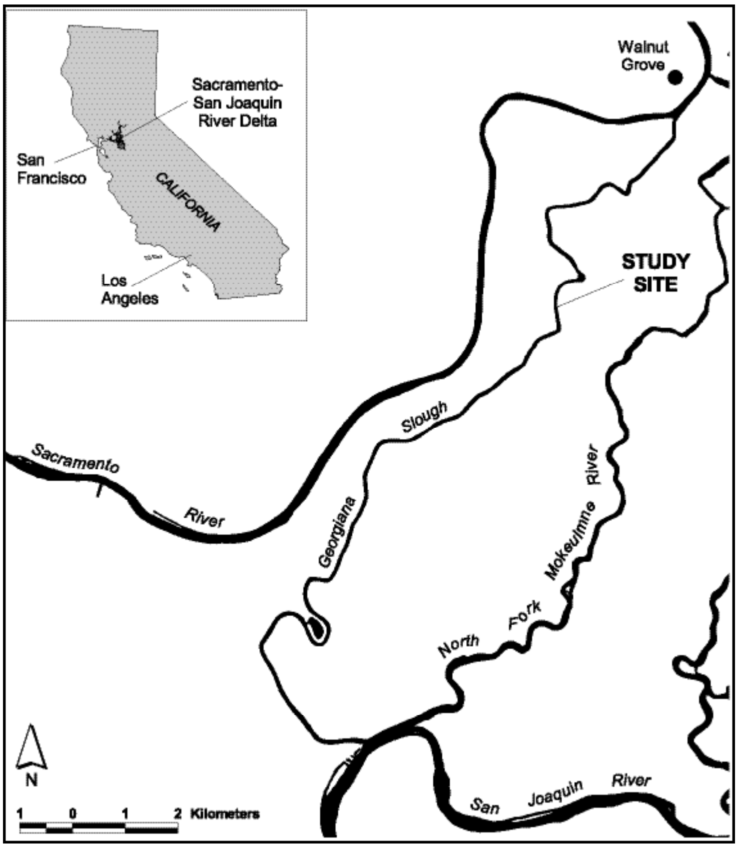

Figure 1. General location of the study site along Georgiana Slough in the Sacramento-San Joaquin River Delta (38° 12'16.630N, 121° 32'26.244W).

Energy Dissipation Through Structures

Previous work has examined energy dissipation through various coastal protective structures. WALTHER and LEE (1975) and MASSEL and BUTOWSKI (1980) examined the hydrodynamic effects of porous breakwaters. FONSECAand CAHALAN (1992) and KOBAYASHI *et al.* (1992) considered wave energy dissipation through sea grass and MASSEL *et al.* (1999) considered dissipation through mangrove forests. In addition, research has been conducted to quantify wave interaction, transformation and energy reduction over coral reefs (ROBERTS *et al.*, 1975 and 1992; ROBERTS and SUHAYDA, 1983; LUGO-FERNÁNDEZ *et al.*, 1998 and 1998a).

Several methods have been used to quantify energy reduction. ROBERTS *et al.* (1975), WALTHER and LEE (1975), and ROBERTS and SUHAYDA (1983) used spectral energy density and LUGO-FERNÁNDEZ *et al.* (1998; 1998a) and ROBERTS *et al.* (1992) calculated a wave transmission coefficient. FONSECAand CAHALAN (1992), ROBERTS *et al.* (1992), and LUGO-FERNÁNDEZ *et al.* (1998; 1998a) quantified energy reduction, Ered, using changes of wave height, and calculated a corresponding energy reduction:

$$E_{red} = \frac{E_{in} - E_{out}}{E_{in}} \text{ x } 100 \tag{1}$$

where the subscripts *in* and *out* indicate conditions onshore and offshore of the coral reefs, respectively, and H is wave height. It is assumed that H2 in Eq. 1 is equivalent to energy density:

$$E = 1/8\ pgH^2 \tag{2}$$

where p is fluid density, and g is gravity.

ROBERTS and SUHAYDA (1983) and LUGO-FERNÁNDEZ *et al.* (1998; 1998a) found that energy reduction over coral reefs is depth (tidally) dependent with 6%-20% more energy dissipated at low tide than at high tide. KOBAYASHI *et al*. (1992) and DUBI and TORUM (1996) also suggested that energy reduction was depth dependent in their studies of wave attenuation through sea grasses and kelp, respectively, but did not quantify the reduction.

Boat Wake Studies

Boat wake studies have focused on wave height differences for various vessel types (JOHNSON, 1958 and 1968; BREBNER *et al.*, 1966; SORENSEN, 1967 and 1973; HEY, 1968; PARNELL, 1996), boat-wake induced erosion (COLLINS and NODA, 1971; LIMERINOS and SMITH, 1975; OSBORNE and BOAK, 1999), and boat and wind wave comparisons (HEY, 1968; BHOWMIK *et al.*, 1982). In these studies, wave height was an important parameter in defining the characteristics of a wake event. For example, several used maximum wave height, the largest trough to crest distance in a wake train, to characterize a boat passage (SORENSEN, 1967 and 1973; HEY, 1968; JOHNSON, 1968; PARNELL, 1996). LIMERINOS and SMITH (1975), NANSON *et al*. (1994), and PARNELL(1996) calculated wave energy (Eq. 2) using maximum, or as LIMERINOS and SMITH termed it, index wave height. COLLINS and NODA (1971) and FODA (1995) also used linear wave theory to quantify energy using the energy density equation (Eq. 2).

Reduction Through Organic Structures

Several studies have previously described organic structures (ALLEN and LEECH, 1997; BOUMANS *et al*., 1997; LEE *et al*., 1997; CHEN, 1998), investigated energy dissipation through structures (WALTHER and LEE, 1975; KOBAYASHI *et al.*, 1992; LUGO-FERNÁNDEZ *et al.*, 1998), or evaluated the hydrodynamics of boat wakes (JOHNSON, 1968; SORENSEN, 1973; NANSON *et al*., 1994). Only BOUMANS *et al*. (1997) integrated the three approaches with their investigation of boat wake reduction in the presence of organic structures. Those structures, called intertidal fences, were composed of bundled Christmas trees located offshore from a bank and secured to the bed with wooden posts. BOUMANS *et al.* (1997) reported a wave energy reduction of 50% using linear regression of the incident (offshore of the fences) versus transmitted (onshore of the fences) waves.

This study investigates boat-wake energy dissipation through organic restoration structures located along eroding levee banks of the Sacramento-San Joaquin River Delta. Boat wakes are commonly perceived as causing significant levee erosion in this region. The deployment of brush bundles, strawbales wrapped in coir, is becoming a wide-spread mitigation strategy to protect the levees against the erosion. However, there has been no controlled experimentation to measure the efficacy of these structures This project investigated two hypotheses: 1) that restoration structures reduce boat wake energy substantially, and 2) that energy reduction is depth dependent.

EXPERIMENTAL DESIGN

The study location is in the northern portion of the Sacramento-San Joaquin River Delta, along the unprotected levee banks of Georgiana Slough (Figure 1). Georgiana Slough originates on the Sacramento River, south of the city of Walnut Grove, CA and extends approximately 18.5 km before merging with the San Joaquin River. The reach of the slough containing the study site is relatively straight, averages 5-7 meters in depth, and 45-75 meters in width with a 0.0003% slope (INTER-FLUVE, INC., 1999). The banks are vegetated or consist of exposed sediment.

The study site was a scallop in the eastern levee bank located approximately 7.2 kilometers downstream from Walnut Grove. The scallop was 4.2 meters wide longshore and 5.8 meters from the outer edge of the opening to its apex (Figure 2a). Two rows of bundles were placed across the opening of the scallop (Figure 2b). The outer portion of the structure was placed along the original levee bank margin. Bundles were stacked between wooden posts, with their crests 1 meter above the bed. The second, onshore portion of the restoration structure, consisted of two freestanding brush bundles.

Pressure transducers were deployed at three locations offshore and three locations onshore of the bundles in triangular configurations (Figure 2). Each pressure transducer (PT) was named to correspond with its location relative to the other PTs and the bundles (e.g., downstream inner). All instruments were mounted on PVC pipe that was driven into the bed. The inner PTs were mounted at the same height relative to each other and the outer PTs were also mounted at the same height relative to each other (Figure 3). This paper only considers data obtained from the downstream and upstream pairs of pressure transducers. The pairs were centered around the bundles at a 2.5 meter spacing.

Data collection occurred during August 29-31, 2000. To isolate the effectiveness of the bundles, the experiment was conducted with the bundles in place on 8/29 and 8/30 (AM) and again on 8/30 (PM) and 8/31 with the bundles removed to establish the control conditions. Data collection occurred during different water levels under each scenario to assess depth effects on energy reduction. A data acquisition system was configured to record signals from the instruments at a sampling interval of five hertz.

Thirty-one usable data sets were obtained. Each data set included an upstream and downstream boat passage. A 21-foot jet boat was used for data sets with the bundles in place and a 19-foot outboard motor boat was used for the control scenario. Under both scenarios the boat traveled approximately 27 km/hr. The bundles were in place for 36 boat-wake events, whereas 26 boat-wake events occurred under the control scenario.

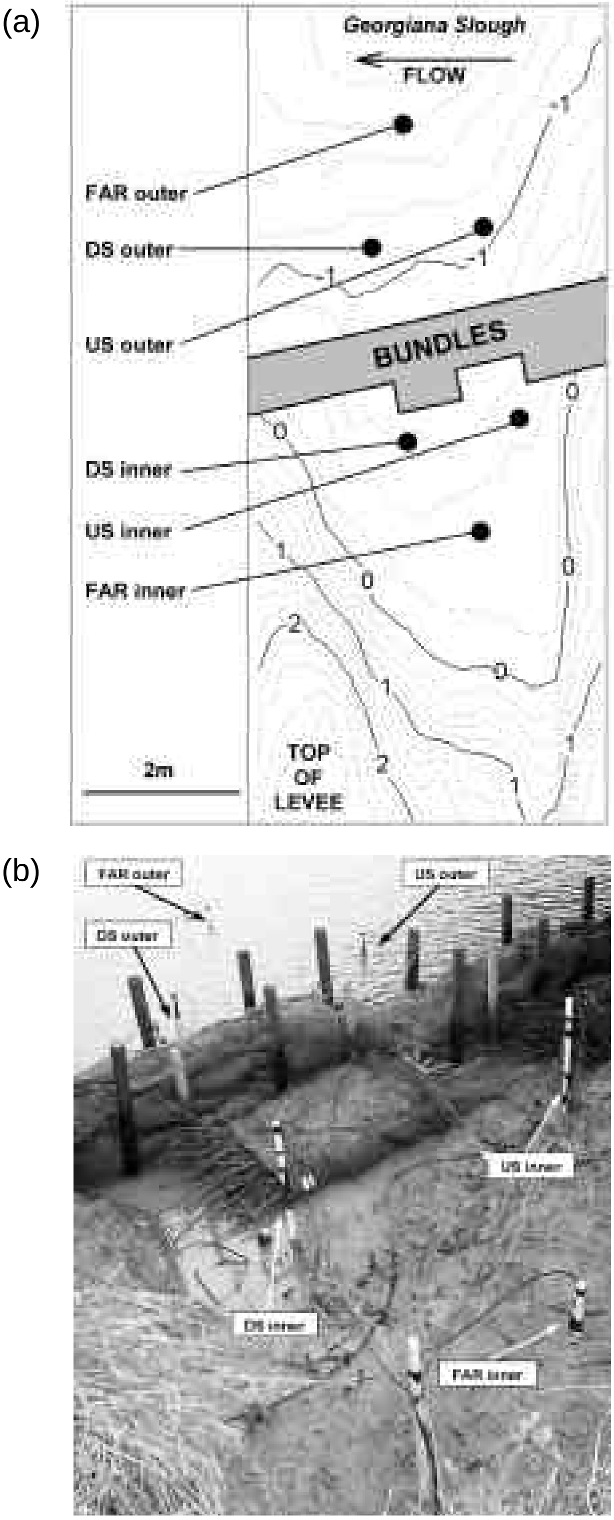

Figure 2. (a) Morphology of the study site. Contour labels are in meters. Pressure sensor locations and general bundle locations are shown. (b) The study site with the bundles in place at low tide. Note the lower bundle crest offshore from the upstream inner PT.

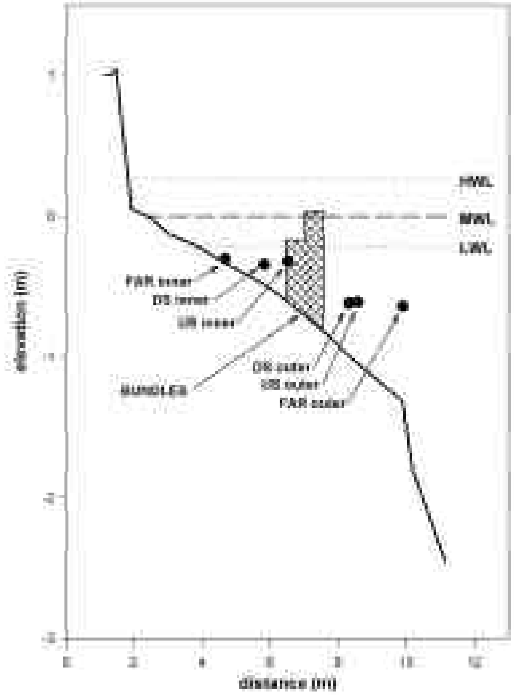

Figure 3. The profile through the study site that depicts PT elevations and mean water level (MWL). High water level (HWL), low water level (LWL), and MWL refer to levels observed during the study period.

The PT time series were reduced by characterizing each boat wake event (i.e. two per data set) by index wave height and period. Index wave height was calculated from the linear average of the largest two consecutive crest to trough differences after the arrival of the wake. This is the same method used by NANSON *et al.* (1994). Index wave period is the time over which the index wave occurred. Lastly, index wave heights were corrected for depth attenuation of the pressure signal using techniques outlined by NIELSEN (1989), DEAN and DALRYMPLE (1984) and KAMPHUIS (2000).

RESULTS

Tables 1 and 2 show the results of the experiments under the bundle and control conditions. Both tables show index wave height, Hi, index wave period, Ti, and water depth, h, for each boat passage. At the inner locations, average index wave height, , was larger for the control scenario (0.17m) than for the bundle scenario (0.11m). At the outer instruments was smaller under the control scenario (0.17m) than with the bundles in place (0.20m). The 0.03m difference between the average index wave heights at the outer stations is a result of the different boat types, speeds,

Table 1. Summary statistics for boat runs with bundles in place. Each boat passage shows index wave height, H_i, index wave period, T_i, and water depth at the instrument, h, for the DS and US outer and inner PTs.

		DS outer			**US outer**			**DS inner**			**US inner**		
Date	**Time**	**Hi (m)**	**Ti (s)**	**h (m)**	**Hi (m)**	**Ti (s)**	**h (m)**	**Hi (m)**	**Ti (s)**	**h (m)**	**Hi (m)**	**Ti (s)**	**h (m)**
8/29/00	16:07	0.22	1.8	0.85	0.17	2.4	0.85	0.09	1.8	0.49	0.07	2.4	0.21
		0.16	2.0	0.85	0.17	2.0	0.85	0.04	2.0	0.49	0.14	2.0	0.21
	16:31	0.17	2.6	0.93	0.14	2.6	0.92	0.08	2.6	0.57	0.10	2.6	0.28
		0.17	2.2	0.93	0.19	1.8	0.92	0.09	2.2	0.57	0.15	1.8	0.28
	17:05	0.24	1.8	1.00	0.18	2.2	0.99	0.13	1.8	0.65	0.11	2.2	0.35
		0.23	1.8	1.00	0.19	2.0	0.99	0.11	1.8	0.65	0.14	2.0	0.35
	17:35	0.14	2.0	1.06	0.16	2.0	1.05	0.11	2.0	0.72	0.09	2.0	0.41
		0.21	1.6	1.06	0.21	1.6	1.05	0.13	1.6	0.72	0.13	1.6	0.41
	18:01	0.14	2.0	1.10	0.14	2.2	1.09	0.12	2.0	0.76	0.10	2.2	0.44
		0.18	2.0	1.10	0.15	2.2	1.09	0.09	2.0	0.76	0.15	2.2	0.44
8/30/00	7:39	0.19	2.6	1.13	0.23	1.8	1.13	0.14	2.6	0.80	0.15	1.8	0.49
		--	--	--	0.20	1.8	1.13	0.17	1.6	0.80	0.14	1.8	0.49
	7:54	0.12	3.0	1.23	0.18	2.0	1.22	0.11	3.0	0.90	0.13	2.0	0.56
		0.30	1.8	1.23	0.24	2.0	1.22	0.24	1.8	0.90	0.15	2.0	0.56
	8:02	0.18	2.4	1.20	0.19	2.0	1.19	0.14	2.4	0.86	0.15	2.0	0.53
		0.25	2.0	1.20	0.20	2.2	1.19	0.17	2.0	0.86	0.16	2.2	0.53
	8:20	0.22	2.4	1.17	0.23	2.2	1.16	0.15	2.4	0.82	0.13	2.2	0.51
		0.24	2.0	1.17	0.26	1.8	1.16	0.16	2.0	0.82	0.18	1.8	0.51
	8:40	0.18	2.6	1.14	0.22	2.2	1.13	0.14	2.6	0.79	0.12	2.2	0.48
		0.26	1.8	1.14	0.19	2.2	1.13	0.16	1.8	0.79	0.16	2.2	0.48
	9:02	0.20	2.2	1.09	0.17	2.4	1.08	0.15	2.2	0.74	0.13	2.4	0.43
		0.20	2.0	1.09	0.20	2.0	1.08	0.16	2.0	0.74	0.17	2.0	0.43
	9:24	0.36	1.6	1.03	0.20	2.4	1.02	0.18	1.6	0.68	0.14	2.4	0.37
		0.18	2.2	1.03	0.20	2.0	1.02	0.13	2.2	0.68	0.17	2.0	0.37
	9:46	0.12	2.6	0.99	0.17	2.0	0.98	0.09	2.6	0.63	0.11	2.0	0.33
		0.19	2.0	0.99	0.20	2.0	0.98	0.12	2.0	0.63	0.15	2.0	0.33
	10:06	0.16	2.6	0.94	0.14	2.6	0.94	0.08	2.6	0.59	0.09	2.6	0.29
		0.21	1.8	0.94	0.18	2.0	0.94	0.09	1.8	0.59	0.12	2.0	0.29
	10:26	0.23	1.6	0.90	0.24	1.6	0.90	0.09	1.6	0.55	0.11	1.6	0.25
		0.26	1.8	0.90	0.20	2.0	0.90	0.07	1.8	0.55	0.16	2.0	0.25
	10:48	0.28	1.6	0.86	0.19	2.6	0.86	0.09	1.6	0.50	0.08	2.6	0.21
		0.24	1.8	0.86	0.17	2.2	0.86	0.06	1.8	0.50	0.15	2.2	0.21
	11:11	0.25	1.6	0.81	0.16	2.8	0.81	0.08	1.6	0.45	0.07	2.8	0.17
		0.17	2.2	0.81	0.16	2.4	0.81	0.05	2.2	0.45	0.13	2.4	0.17
	11:32	0.17	2.4	0.76	0.19	2.4	0.77	0.06	2.4	0.40	0.05	2.4	0.13
		0.20	2.0	0.76	0.22	1.8	0.77	0.04	2.2	0.40	0.12	1.8	0.13

and water levels. To adjust for these factors, the inner wake height measurements were normalized relative to the outer, or input, wake height.

One of the objectives of this study was to compare wake energy inside and outside of the bundles. Therefore, for each pair of PTs normalized energy density, En, was obtained using:

$$E_n = \frac{(H_i \text{ inner})^2}{(H_i \text{ outer})^2} \qquad (3).$$

Normalizing energy density compares pairs of ‘inner and outer’ PTs under the control and bundle scenarios, and provides a standardized basis for assessing potential impacts of the bundles. Using this method, normalized energy densities larger than 1.0 indicate a greater inner energy and values less than 1.0 indicate a greater outer energy. Figure 4 shows the distributions of En for the control and bundle conditions. Under the control conditions energy is frequently greater at the inner PT than at the outer PT(En>1). There is one instance at the upstream pair where the wave energy doubled from the outer to inner location

Table 2. Summary statistics for boat runs with the bundles removed. Each boat passage shows index wave height, H_i, index wave period, T_i, and water depth at the instrument, *h*, for the DS and US outer and inner PTs.

		DS outer			**US outer**			**DS inner**			**US inner**		
Date	**Time**	**Hi (m)**	**Ti (s)**	**h (m)**	**Hi (m)**	**Ti (s)**	**h (m)**	**Hi (m)**	**Ti (s)**	**h (m)**	**Hi (m)**	**Ti (s)**	**h (m)**
8/30/00	16:57	0.20	1.6	0.85	0.19	1.8	0.86	0.16	1.6	0.50	0.23	1.8	0.25
		0.23	1.8	0.85	0.19	2.0	0.86	0.18	1.8	0.50	0.24	2.0	0.25
	17:20	0.12	1.8	0.90	0.11	2.0	0.90	0.10	1.8	0.55	0.15	2.0	0.30
		0.22	1.6	0.90	0.18	1.8	0.90	0.17	1.6	0.55	0.22	1.8	0.30
	17:30	0.20	1.8	0.93	0.18	2.0	0.93	0.20	1.8	0.58	0.15	2.0	0.33
		0.20	1.8	0.93	0.17	1.8	0.93	0.15	1.8	0.58	0.23	1.8	0.33
	17:50	0.18	1.6	0.98	0.18	1.8	0.98	0.18	1.6	0.63	0.18	1.8	0.38
		0.21	1.6	0.98	0.20	1.6	0.98	0.16	1.6	0.63	0.13	1.6	0.38
	18:12	0.14	2.0	0.95	0.23	1.6	1.02	0.16	2.0	0.67	0.18	1.6	0.43
		0.24	1.6	0.95	0.22	1.6	1.02	0.20	1.6	0.67	0.22	1.6	0.43
8/31/01	8:20	0.21	2.0	1.15	0.17	2.2	1.14	0.23	2.0	0.80	0.18	2.2	0.56
		0.14	1.8	1.15	0.11	1.8	1.14	0.15	1.8	0.80	0.15	1.8	0.56
	8:50	0.19	2.0	1.09	0.24	1.8	1.09	0.18	2.0	0.75	0.18	1.8	0.51
		0.09	2.0	1.09	0.08	2.0	1.09	0.11	2.0	0.75	0.09	2.0	0.51
	8:56	0.13	2.4	1.09	0.15	2.0	1.09	0.07	2.4	0.75	0.16	2.0	0.51
		0.20	1.6	1.09	0.09	2.4	1.09	0.17	1.6	0.75	0.10	2.4	0.51
	9:27	0.12	2.2	1.04	0.17	1.8	1.04	0.12	2.2	0.70	0.15	1.8	0.46
		0.13	1.8	1.04	0.13	1.8	1.04	0.15	1.8	0.70	0.14	1.8	0.46
	10:00	0.14	1.8	0.97	0.17	2.4	0.97	0.13	1.8	0.62	0.19	2.4	0.40
		--	--	--	0.20	1.6	0.97	0.21	1.6	0.62	0.18	1.6	0.40
	10:32	0.17	1.6	0.96	0.14	2.0	0.90	0.12	1.6	0.54	0.15	2.0	0.33
		0.22	1.6	0.96	0.27	1.4	0.90	0.16	1.6	0.54	0.23	1.4	0.33
	11:00	0.14	2.4	0.89	0.16	2.2	0.83	0.15	2.4	0.48	0.19	2.2	0.26
		0.24	1.8	0.89	0.17	1.8	0.83	0.15	1.8	0.48	0.24	1.8	0.26
	11:20	0.13	2.2	0.89	0.17	2.0	0.83	0.14	2.2	0.44	0.20	2.0	0.26
		0.22	2.0	0.89	0.20	1.8	0.83	0.15	2.0	0.44	0.24	1.8	0.26

(En=2). When the bundles were in place, the outer wave energy was consistently larger than the inner wave energy (En<1). The average energy ratios under the control scenario were 0.84 for the downstream pair and 1.20 for the upstream pair. The average energy ratios with the bundles in place were 0.34 for the downstream pair and 0.48 for the upstream pair.

Finally, we averaged the inner PT records and normalized them by the averaged outer records (Eq. 3). This yielded overall ratios of 1.02 for control conditions and 0.41 with the bundles in place. Similarly, averaged data were used for subsequent analysis so that spatial comparisons could be made between inner and outer conditions.

DISCUSSION

In order to test the first hypothesis, that the brush bundles reduce energy, the sample means of the control and bundle data sets were compared using Student's t-test. A prerequisite for the t-test is that the sample is normally distributed. Normality was tested using the chi-square test, and in all cases the results suggested that this condition was met. It was assumed that the background populations of the samples had equal standard deviations. The results of the t-test indicate that the mean energy-density ratios are significantly different ($p \leq 0.01$), and therefore, it is concluded that the brush bundles reduce energy. However, this finding does not quantify the magnitude of the impact. The change in energy, ΔE, may be calculated using:

$$\Delta E = \left(1 - \frac{\bar{E}_n \text{ bundle}}{\bar{E}_n \text{ control}} \right) \text{x } 100 \tag{4}$$

where; bundle and control are calculated using the data from Eq. 3. Positive values indicate that normalized wave energy under the bundle scenario is reduced relative to control conditions. A negative ΔE indicates that wave energy is increased relative to control conditions. This

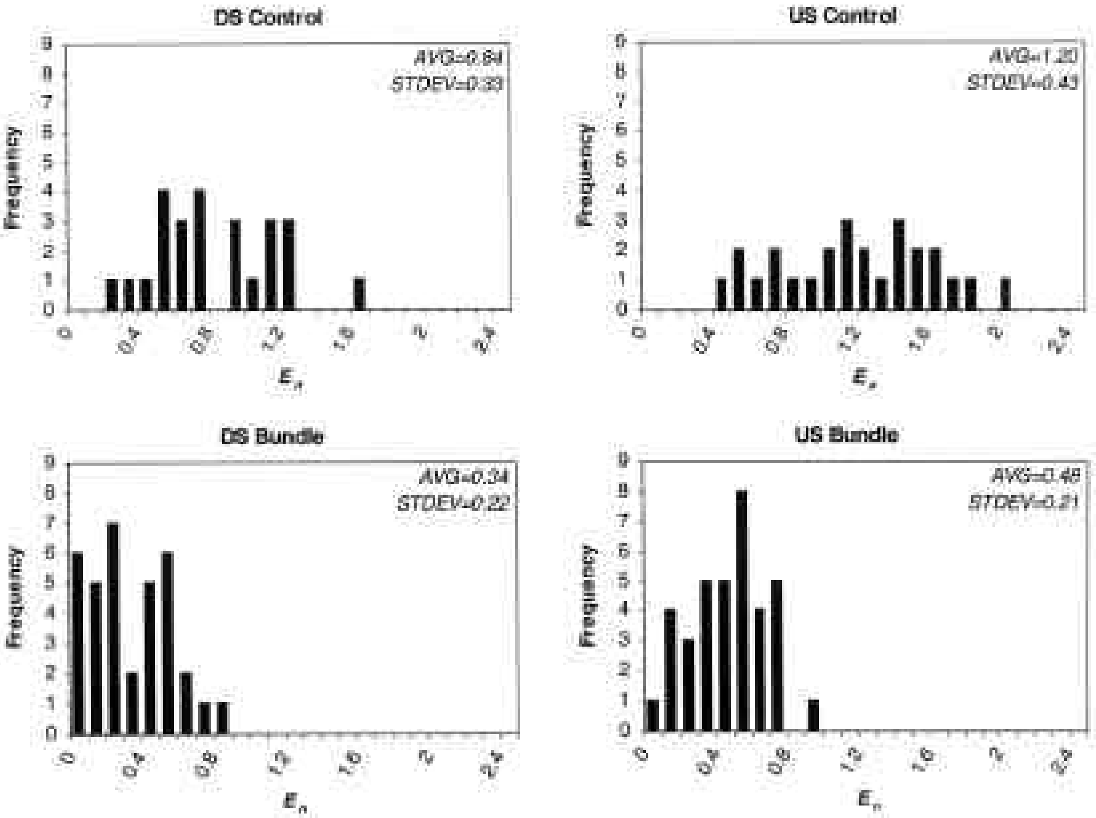

Figure 4. Energy ratio distributions for the experimental conditions. Note especially the reduced energy ratios when the bundles are in place (E_n<1.0)

experiment found an energy reduction of 59% for the downstream pair, 60% for the upstream pair, and 60% for average that combined the upstream and downstream data.

The second hypothesis is that energy reduction is depth dependent. Total water depth fluctuated by approximately 0.5 meters during sampling. During high tides the bundles were completely submerged and during low tide, the crest of an average boat wake would not reach the top. Because of their porous composition, there was always some flow through the structures. A depth dependency would indicate that bundle effectiveness fluctuates with changes in water levels caused by tides or flood flows.

In order to test for depth dependency, total water depth was normalized relative to the average elevation of the top of the bundles (0.65 meters relative to a reference elevation) and half the index wave height $(1/2H_i)$ using:

$$h_n = \frac{h_{out} - 1/2H_i}{0.65} \tag{5}$$

where hn is normalized depth, and h_{out} is outer instrument depth. Normalized depths equaling 1.0 indicate that the crest of the index wave height is flush with the top of the bundles. Normalized depths less than 1.0 indicate that the crest of an index wave is below the bundle top (i.e. low water). Values greater than 1.0 indicate the wave crest will overtop the bundles.

Regression analysis was used to test for a relationship between water depth and bundle effectiveness. The test used the data obtained from the spatial averaging of inner and outer pressure transducer pairs. Analysis used the downstream and upstream averages by regressing normalized depth versus energy. Normalized depth versus energy relationships are presented in Figure 5. A least-squares lines is plotted when regression analysis indicates statistical significance ($p \leq 0.001$).

For the control scenario, regression analysis indicated that energy is not dependent on depth. There is, however, some suggestion that with very low water (h_n=0.8), E_n increases as h_n decreases. This is likely a result of normal wave transformation in shallow water as the boat wakes begin to break. With the bundles in place, regression analysis indicated that energy is dependent on depth during low water conditions ($p \leq 0.001$).

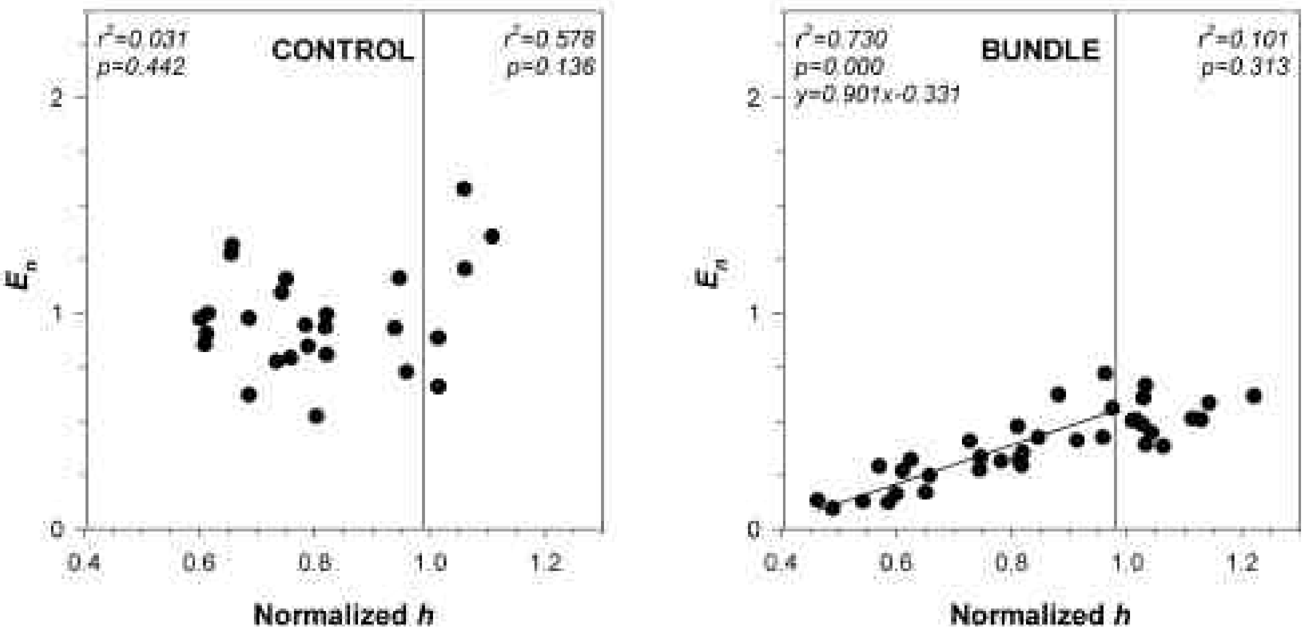

Figure 5. Normalized depth versus energy ratios (E_n) for the control (a) and bundle (b) scenarios for the DS and US average. High and low water conditions are delimited by the h_n=1 line. Only statistically significant, least-squares lines are plotted.

SUMMARY AND CONCLUSIONS

This study was designed to assess the impacts of brush bundles on boat wake energy, and to determine if the degree of effectiveness depends on water depth. Field work was conducted on Georgiana Slough, a distributary of the Sacramento River, in August 2000. Characteristics of boat wakes were measured using an array of pressure transducers with and without the brush bundles installed. Index wave heights at the inner instruments were normalized using measurements from the outer instruments to represent input wave conditions. These ratios were then used to test the hypotheses concerning brush bundle effectiveness.

This study found that brush bundles are an effective method to reduce potential boat-wake induced levee erosion. Comparing the sample means of the control and bundle scenarios revealed a 60% reduction of wake energy by the brush bundles. It was also found that wake energy reduction was strongly depth dependent. These results are comparable to previous studies that quantified energy reduction through or across other natural or anthropogenic barriers (Table 3). These results provide the first quantitative demonstration of the efficiency of brush bundles in reducing boat wake energy. It may be presumed that they would have a similar effect on wind-generated waves, also an erosion hazard in some reaches of the Delta.

Table 3. Summary of results from related studies of energy reduction by natural and anthropogenic barriers, and reduction by brush bundles (this study).

	Average Percent Energy Change
Porous Breakwater	
WALTHER and LEE (1975)	90
Coral Reefs	
ROBERTS *et al*. (1975)	75
ROBERTS and SUHAYDA (1983)	73
ROBERTS *et al*. (1992)	85
LUGO-FERNÁNDEZ *et al*. (1998)	83
LUGO-FERNÁNDEZ *et al*. (1998a)	91
Intertidal Fences	
BOUMANS *et al*. (1997)	50
Mangrove Forest - dense	
MASSEL *et al*. (1999)	99
Brush Bundles	
This Study	60

Using brush bundles to reduce boat wake energy fits well within a larger context of environmental management and policy. In the Sacramento-San Joaquin Delta, levees are a vital boundary between natural and engineered waterways and the low-lying islands. Managers are challenged to implement policies that improve levee integrity while concurrently considering economic, recreational, developmental, agricultural and environmental protection factors. Because they suit the constraints imposed by many of these factors, brush bundles appear to be a compromise solution to levee erosion. Their design, construction and installation is inexpensive and less time consuming than various forms of armoring. Additionally, they are not physically intrusive or aesthetically disturbing. For these reasons, brush bundles are a viable management alternative where such environmental issues are of concern.

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