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Effect of a Small Southern California Lagoon Entrance on Adjacent Beaches

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ABSTRACT: This paper considers the effects of natural and artificial openings of a typical, small, southern California coastal estuarine lagoon on the adjacent barrier beach. A detailed history of beach profiles and lagoon entrance transects before and after flood-induced and artificial openings of San Dieguito Lagoon in Del Mar, California, has been analyzed. The results suggest that there is no statistically significant erosional effect on the adjacent beach when the lagoon inlet is artificially opened to tidal flow.

Introduction

Southern California lagoons and beaches are both valuable coastal resources. The remnants of the once-pristine lagoons of southern California continue to provide important habitats as fish nurseries, food sources for migrating birds, and living space for a number of rare and endangered species. Southern California lagoons have been extensively modified by human activity, including filling and diking, as well as inlet stabilization and dredging. The beaches of southern California are central to the state's $14 billion economic activity related to coastal recreation and tourism (King and Potepan 1997). Beaches also provide some measure of protection to adjacent public and private infrastructure and development, as well as to the sea cliffs that back most of the California coast.

Southern California lagoons are generally small and shallow, especially in comparison to the large systems on the east coast of the United States or to those in Mexico and North Africa. They are usually oriented perpendicular to the shoreline, typically extend only a few kilometers inland, and are only about 1 m deep (Elwany et al. 1998). They are usually fronted by a barrier spit and beach up to a few kilometers long, yet generally have limited coastal exposure since the inlet is prevented from migrating by jetties or by the presence of headlands and adjacent development.

Beach and lagoon inlet processes are closely tied since all southern California coastal lagoon entrances cross sandy beaches of various widths. Tidal outflow and freshwater runoff tend to keep inlets open, while tidal inflow and wave-induced sand transport act to clog entrances with littoral sand (Bruun 1978; Kjerfve and Magill 1989). Where river discharge is an important factor, the lagoon inlet also serves as the river outlet, and inlet dynamics are strongly influenced by intermittent but sometimes massive flood events. When flooding occurs, the inlet channel is scoured open, and substantial loss of sand volume on the adjacent beach may occur. Between floods, inlet behavior depends on the complex interplay between tidal in-and-out flow and wave-driven littoral sand transport, with inlet substrate type (sand or cobble) also playing a role.

Tidal flow and natural flooding at coastal lagoons that form the outlets of controlled rivers may be insufficient to keep unmodified lagoon inlets continually open across beaches with active longshore and on-offshore sand transport. Inlet maintenance in the form of excavation is then needed to restore tidal flushing, ensuring adequate water quality within the lagoon, and to drain super-elevated stagnant waters, relieving flooding problems. Typical artificial openings involve removing littoral sediments from the inlet and entrance channel with earth-moving equipment. This allows ocean water tidal exchange to resume, at least for a time.

It has been suggested that lagoons open to tidal flow cause the beach downstream of the inlet to erode. Stone (2001) claims that artificial openings at San Dieguito have a negative impact on the width of the adjacent beach. Downstream erosion patterns have been observed for large lagoon sys-

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tems, such as those found on the east coast of the United States (Inman and Dolan 1989). It is the purpose of this paper to evaluate whether significant beach erosion is attributable to artificial openings of San Dieguito Lagoon. This result is presumably valid at other small southern California lagoon inlets. This study presents the quantitative relationship between the inlet configuration at San Dieguito and the condition of the adjacent beach. We compare the effects of natural, storm flood flow inlet scour events with those of artificial, engineered openings on inlet configuration and adjacent beach sand volume and width. These comparisons demonstrate that there are no statistically significant adverse effects on the beach attributable to artificial lagoon openings.

The inlet of San Dieguito Lagoon and the adjacent beach (Fig. 1) both have long histories of monitoring, making them uniquely suited to addressing the inlet's influence on the beach (Elwany et al. 1994, 1997; Elwany 1998). Consideration of this long-term monitoring data leads to the following conclusions: seasonal beach variability at Del Mar is large compared to other local beaches; the beach just south of the inlet is eroded during floods to a greater degree than the beach 600 m away; outflow from the lagoon during ebb tide loses its momentum near the shoreline and does not significantly affect longshore sand transport; the volume of longshore sand transport is far greater than the volume of sand that the lagoon can trap; the lagoon does not add sand to or subtract sand from the local long-term sand budget; and the effects of artificial openings on the beach are small and not statistically significant.

San Dieguito Lagoon

San Dieguito (32°58′27.48″N, 117°16′7.46″W) is a typical southern California estuarine lagoon, located on the northern edge of the City of Del Mar in San Diego County, California. The lagoon forms the lower part of the San Dieguito River Valley (Mudie et al. 1976). San Dieguito River drains an area of 842 km^2, of which only 117 km^2 lie below Lake Hodges Dam. Most of the river discharge occurs when there is sufficient rainfall for Lake Hodges to spill over; otherwise river discharge is very small.

The present-day lagoon is a 0.7 km^2 wetland when referenced to its upper elevation of 1.5 m above mean sea level (msl). The lagoon consists of three main channels including one inlet channel and channels to the north and south of it. The average water depth in the lagoon is about 90 cm below msl. The lagoon has been extensively filled and diked for construction of roads, Interstate Freeway 5, and a railroad. This has reduced the tidal prism to about 3×10^6 m^3, which is well below the values that existed under more natural conditions.

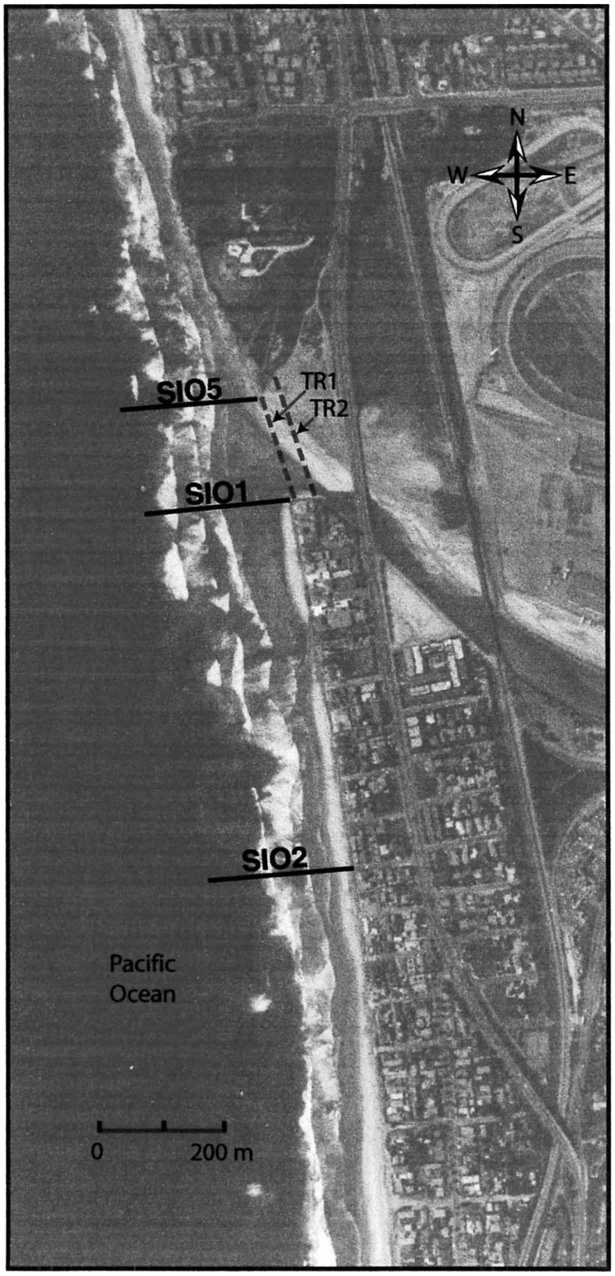

Fig. 1. Aerial photograph of San Dieguito Lagoon inlet showing the locations of ranges SIO5, SIO1, and SIO2, and transects TR1 and TR2.

The typical inlet opening and closing sequence observed at San Dieguito Lagoon, as detailed by Elwany et al. (1998), begins when a major flood scours the lagoon channels. In most cases, this below-equilibrium depth cannot be sustained by the limited maximum available tidal prism. Littoral sand, washed into the inlet by tidal flow and wave surge, rapidly fills the entrance and exterior portions of the channels. The interior channels fill more slowly over a period of 2 to 5 yr, decreasing the tidal prism and eventually leading to a relatively sudden closure of the lagoon. If there are no floods, and river flow is insufficient to fill Lake Hodges and spill over the dam, the lagoon remains closed. Exceptions may occur during unusually high tide events, during periods of heavy rains, or when the lagoon has been artificially opened.

How long the inlet stays open depends upon the condition of the main interior lagoon channel and several side channels. If these channels are shallow and narrow, the inlet will remain open for only a period of days or weeks. If the lagoon channels are still relatively free of sand, tidal flushing will reestablish the inlet, and the lagoon will remain open for 1 to 3 yr. This suggests that as long as sufficiently strong river flow occurs every 3 to 5 yr, San Dieguito Lagoon will remain open most of the time. Without occasional flood flow, the lagoon will be closed most of the time.

Methods

BEACH PROFILE SURVEYS

Beach profile data from Del Mar Beach span a 23-yr period from 1978 to 2000. We consider data from three profile ranges: SIO5, SIO1, and SIO2 (north to south). Ranges SIO5 and SIO1 are located immediately north and south of San Dieguito Lagoon inlet, respectively. Range SIO2 is located approximately 600 m south of SIO1 and serves as a control range. The locations of these ranges and several alongshore transects, TR1 and TR2, are shown on the aerial photo of the region in Fig. 1.

Del Mar Beach has been surveyed more intensively than any other beach in San Diego County (Flick et al. 1986; USACE 1991; Pisarew 1998). Data were collected from 1978 to 1982 and from 1992 to 2000 by Scripps Institution of Oceanography, and at other times by the U.S. Army Corps of Engineers (USACE), the San Diego Association of Governments, and private firms, including Coastal Environments (Elwany 1998).

The beach profile data were used to calculate beach width and the subaerial beach sand volume per unit length of beach above the 0 NGVD elevation. NGVD is the National Geodetic Vertical Datum (Mean Sea Level Datum of 1929) and lies about 6 cm below msl. Beach width and subaerial sand volume are closely related and useful for describing the condition of the exposed portion of a beach. Beach width is a measure of the offshore extent of the exposed beach and is herein defined as the distance from a fixed benchmark location at the back of the beach to the intersection of the profile with the reference plane of the NGVD. Subaerial sand volume is a measure of the width and elevation of the beach and is indicative of its health and stability. Sand volume losses may be caused by wave-induced offshore transport, by divergence of longshore transport, and by scouring.

FLOODS

Flood data are available for the San Dieguito River for 1922 to 2000 (Elwany et al. 1998; Coastal Environments 1998). Storm events in southern California occur almost exclusively during the winter. The major floods that occurred during the study period were in 1980, 1983, 1993, 1995, and 1998. Beach profile data exist that cover conditions before and after all the floods except that of 1983. Useful results for the 1983 beach width and sand volume appear in Flick et al. (1986) and Flick and Waldorf (1984).

LAGOON INLET STATUS

An inventory of the open or closed status of San Dieguito Lagoon from 1978 to 1998 was compiled by Elwany et al. (1998) from various sources, including lifeguard observations and aerial photos. Table 1 shows whether the San Dieguito Lagoon was open or closed to tidal flushing between 1978 and 2001 (modified from Elwany et al. 1998); the lagoon was open 77% of the time and closed 23% of the time. In addition to the 5 major flood events already mentioned, there were 17 artificial openings.

Results and Discussion

SEASONAL CHANGES IN BEACH WIDTH

Figure 2 shows the beach width histories at ranges SIO5, SIO1, and SIO2 (top to bottom and north to south). Times of major floods are shown by vertical lines. Table 2 presents the summary statistics for beach widths at these three ranges. Results are shown for the year as a whole, and for the summer and winter seasons separately. Ranges SIO5 and SIO1, located adjacent to the inlet, show the largest seasonal fluctuations in beach width. Range SIO2, located away from the inlet, shows slightly smaller seasonal fluctuations. The seasonal cycle at Del Mar Beach is large compared to other nearby beaches. To the north, Encinitas and Carlsbad Beaches have seasonal cycles of about 15 m in beach width, whereas at Del Mar, width can vary seasonally by up to 43 m, a factor almost three times larger.

FLOOD EFFECTS ON BEACH SAND VOLUME AND WIDTH

Typical flood discharge velocities across the beach can reach 3.7 m s^{-1}, but decline rapidly over

TABLE 1. Inlet status (open or closed) at San Dieguito Lagoon, 1978–2001. O = open inlet, C = closed inlet, c = artificially opened inlet, and I = intermittent inlet.

Month	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
January	O	O	O	c	c	O	O	O	O	O	I	O	c	C	O	O	O	c	C	O	O	O	C	I
February	O	O	O	O	c	O	O	O	O	O	O	O	c	C	O	O	O	O	c	O	O	I	C	O
March	O	O	O	O	O	O	O	O	O	c	O	C	I	c	I	O	O	O	c	O	O	I	C	O
April	O	O	O	O	O	O	C	O	O	I	I	C	c		I	O	O	O	O	O	O	I	C	O
May	O	O	O	C	O			O	O	c	O	C			C	O	O	O	I	O	O	C	C	O
June	O	O	O	C	O	O	C	O	O	O	O	I	C	C	C	O	O	O	O	O	O	C	C	O
July	O	O	O	C	O	O		O	O	O	O	C	C	C	C	O	O	O	O	O	O	C	C	O
August	O		O	C	O	O	O	O	O	O	O	O	C		C	O	O	O	O	O	O	C	C	O
September		O			O	O	O	O	O	O	O	c	C	C	C	O	O	O	I	O	O	C	c	O
October		C	C	C	O	O		O	O	O	I	O	C	C	C	O	O	O	O	I	O	C	O	O
November		I	C	C	O	I	c	O	O	I	I	C	C		C	O	O	O	O	I	I	C	O	I
December	O	c	C	c	O	O	O	O	O	I	0	C	C	C	C	I	I	C	O	I	O	C	C	C

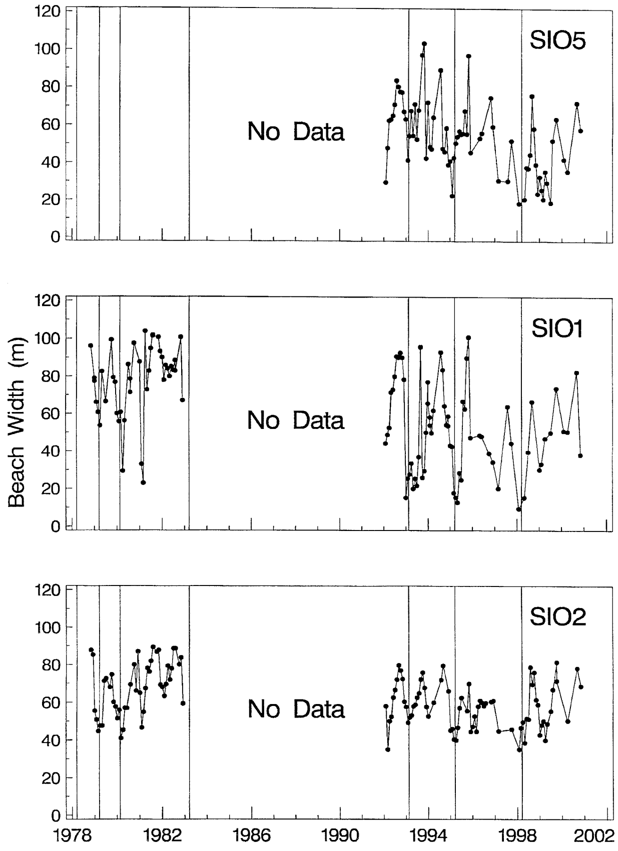

Fig. 2. Beach width history from 1978 through 2000 for ranges SIO5, SIO1, and SIO2.

short distances from the lagoon inlet. It can be anticipated that floods will cause subaerial beach sand loss and a decrease in width near the inlet to greater degrees than at locations farther away. Inspection of historical aerial photos indicates that Del Mar Beach behaves in a manner consistent with this assumption. Range SIO1 at the southern edge of the lagoon inlet is most heavily and consistently influenced by flood flows. Range SIO5 at the northern edge is affected by some events, but not others.

TABLE 2. Statistics on Del Mar Beach widths.

Station	Season	Maximum Width (m)	Minimum Width (m)	Mean Width (SD) (m)	Number of Profiles
SIO1	All	103.9	9.5	60.5 (26.2)	102
	Summer	101.1	21.7	70.3 (25.3)	47
	Winter	103.9	9.5	52.2 (24.1)	55
SIO2	All	89.3	35.1	61.7 (13.7)	117
	Summer	89.3	45.7	70.3 (10.9)	54
	Winter	87.1	35.1	54.3 (11.4)	63
SIO5	All	103.6	18.3	53.6 (19.5)	71
	Summer	103.6	18.7	62.4 (19.1)	36
	Winter	72.2	18.3	44.3 (15.3)	35

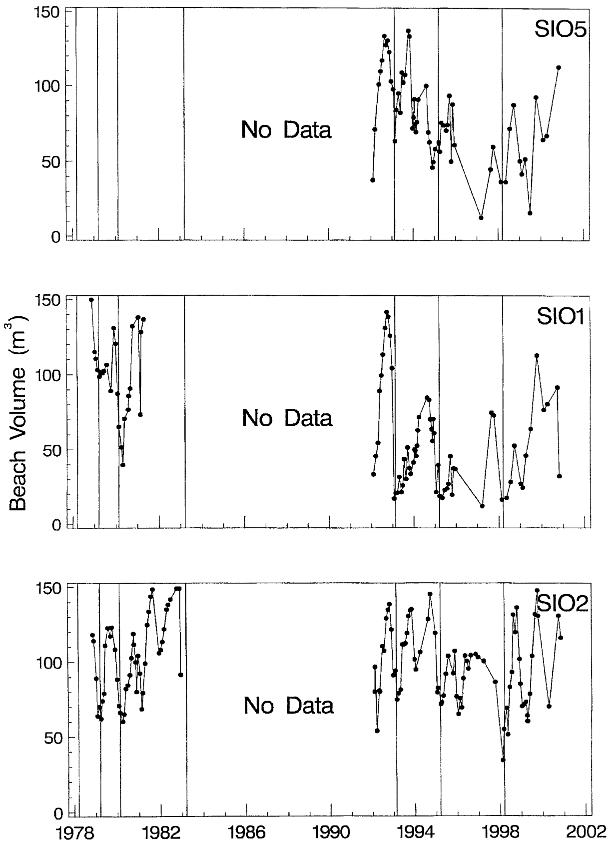

Fig. 3. Beach sand volume above the reference plane of National Geodetic Vertical Datum (NGVD) from 1978 through 2000 for ranges SIO5, SIO1, and SIO2.

Figure 3 shows the time history of changes of beach volume above 0 NGVD for ranges SIO5, SIO1, and SIO2. Times of major floods are shown by vertical lines. There was noticeable beach sand volume loss during winter at all ranges, but beach retreat coinciding with flood events was clearly more pronounced at range SIO1 than at SIO2 or SIO5.

To estimate the effects of winter floods on beach sand volume at SIO1 and SIO5, we assumed that flooding has no effect on the beach at SIO2. We further assumed that the impact of wave-induced beach retreat at the 3 ranges is the same, since this is a uniform, straight section of beach, and wave characteristics are not expected to change over such a short distance. Subtracting the subaerial sand volume change observed at SIO2 from that at SIO1 and SIO5 eliminates the storm-wave effect on these impact ranges. The respective differences before and after each flood then represent the effects of the floods on beach sand volume and width adjacent to the inlet. Beach changes during the winter of 1992–1993 are used to illustrate this technique. Profiles bracketing the flood time were selected to study the effects of the flood on the beach. Summer profiles before and after the flood were used to address beach recovery at ranges SIO1 and SIO2, as shown in Figs. 4 and 5, respectively.

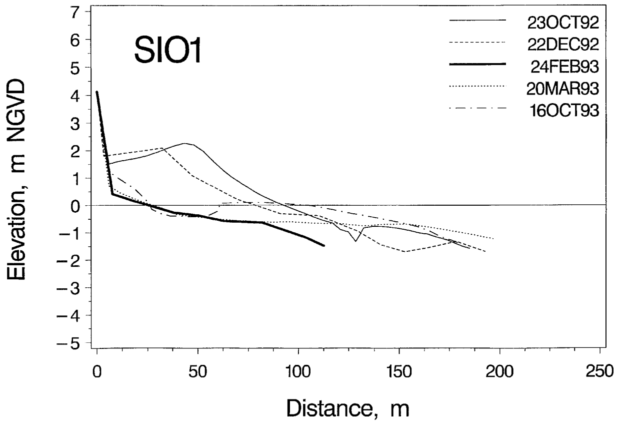

Fig. 4. Beach profiles showing the response of the beach at SIO1 to the floods of January 16 and February 20, 1993. End-of-summer season beach profiles prior to and after the flood are presented to address beach recovery.

In October 1992, the lagoon inlet was closed, and the beach had a typical end-of-summer profile, with a berm over 2 m high and 130 m wide at range SIO1 (Fig. 4). By December 1992, the seaward portion of the berm had eroded due to early winter storm waves. Floods occurred on January 16 and February 20, 1993. The February and March 1993 profiles at range SIO1 show a substantial scouring of the beach and a beach width reduction of 91 m from the previous October. This portion of the beach was slow to recover, as shown by the October 1993 profile (Fig. 4). The changes at

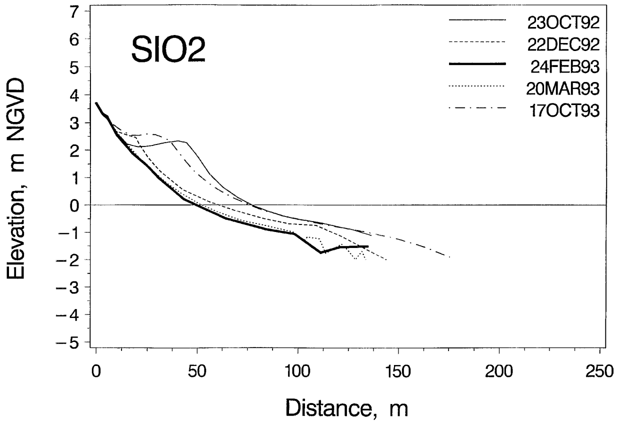

Fig. 5. Beach profiles showing the response of the beach at SIO2 to the floods of January 16 and February 20, 1993. End-of-summer season beach profiles prior to and after the flood are presented to address beach recovery.

TABLE 3. Beach sand volume before and after flooding. 1983 data are based upon sand volume to wading depth relative to arbitrary datum (Flick et al. 1986).

			Volume Above 0 NGVD (m^3 m^{-1})		
Flood Year	Period	Survey Date	SIO5	SIO1	SIO2
1980	Before	January 27, 1980	—	87.7	70.9
	After	March 30, 1980	—	51.7	60.4
1983	Before	December 1982	—	120.0	120.0
	After	March 1983	—	−25.0	−15.0
1993	Before	December 22, 1992	103.6	105.1	91.3
	After	March 20, 1993	85.5	21.0	79.1
1995	Before	February 4, 1995	48.0	63.1	82.6
	After	March 24, 1995	62.9	19.0	72.6
1998	Before	October 11, 1997	59.7	73.1	86.6
	After	May 14, 1998	36.4	17.7	51.7

range SIO2 were not as dramatic (Fig. 5). A berm was present in October 1992, but by December 1992, it had disappeared, and beach width was reduced by 46 m. There were some changes in the profile due to high winter waves, as evidenced by the February and March 1993 beach profiles. The beach width recovered to its pre-storm state by October 1993.

As shown in Table 3, the 1992–1993 winter loss of beach sand volume was -12.2 m^3 m^{-1} at SIO2 and -84.1 m^3 m^{-1} at SIO1. The difference, or -71.9 m^3 m^{-1}, is attributable to flood-flow effects (Table 4). Similar analyses were applied to the 1980, 1983, 1995, and 1998 data, and the results are summarized in Table 3. Table 4 presents the storm-wave effects at SIO2 and the residual flood effects at SIO5 and SIO1 for each flood winter for which data were available. The average loss of subaerial sand volume due to floods was -37.3 m^3 m^{-1} at SIO1, but essentially zero (+ 0.3 m^3 m^{-1}) at SIO5.

It should be noted that the effect of the flood on the beach at SIO1 extends farther offshore than elevation 0 NGVD, resulting in an additional loss of sand volume along the profile (note the loss of sand below 0 NGVD in the profiles illustrated in Fig. 4). For large floods, river outflow effects extend up to 100 m offshore. This may be the reason for the observed delay of beach recovery at range SIO1 as compared to SIO2.

TABLE 4. Net effects of flood events on SIO1 and SIO5. 1983 data are based upon sand volume to wading depth relative to arbitrary datum (Flick et al. 1986). Averages exclude 1983 data.

			Flood Effect (m^3 m^{-1})	
Flood Year	Peak Flow (m^3 s^{-1})	Storm-Wave Effect (m^3 m^{-1}) SIO2	SIO5 (north of inlet)	SIO1 (south of inlet)
1980	552	−10.5	—	−25.5
1983	182	−135.0	—	−10.0
1993	196	−12.3	−5.9	−71.9
1995	256	−10.0	−4.8	−34.0
1998	75	−34.9	11.6	−20.5
Average		−16.9	0.3	−37.3

Artificial Opening Effects on the Beach

Sometimes it is necessary to open San Dieguito Lagoon (and other southern California lagoons) in order to improve water quality by re-establishing tidal exchange or to prevent flooding of land and developments located on the lagoon banks. These engineered openings are designed to minimize the rate at which sand is subsequently trapped in the lagoon (Elwany et al. 1994). The volume of sand dredged at San Dieguito Lagoon can range from less than 4,000 m^3 up to 12,000 m^3. Sand dredged from the lagoon is usually placed south of the inlet so that the predominant southward longshore current direction does not immediately return it to the inlet.

Artificial openings at San Dieguito Lagoon were performed 17 times in the 24-yr period from January 1978 to December 2001 (Table 1), mostly to drain the lagoon and prevent or reduce flooding of property. The opening on September 23, 2000, was initiated by the City of Del Mar to restart tidal flushing and relieve stress on the wetland ecosystem. About 11,500 m^3 of sand were removed from the lagoon inlet and west channels. A comparison of inlet cross sections for the natural 1993 flood and this artificial inlet opening (based on a quasi-stable inlet cross section) is shown in Fig. 6. Transect TR1 is located at the west end of the inlet, and transect TR2 is east of it (Fig. 1). The erosion caused by the 1993 flood at TR1 and TR2 shows the significant volume of sand that can be scoured by large flood velocities.

Profile data suitable for examining beach configuration changes related to earlier artificial openings were available for 7 of the 17 openings. The beach subaerial volume differences before and after each opening were calculated from the 7 pairs of profiles taken at SIO1. A *t*-test was applied to

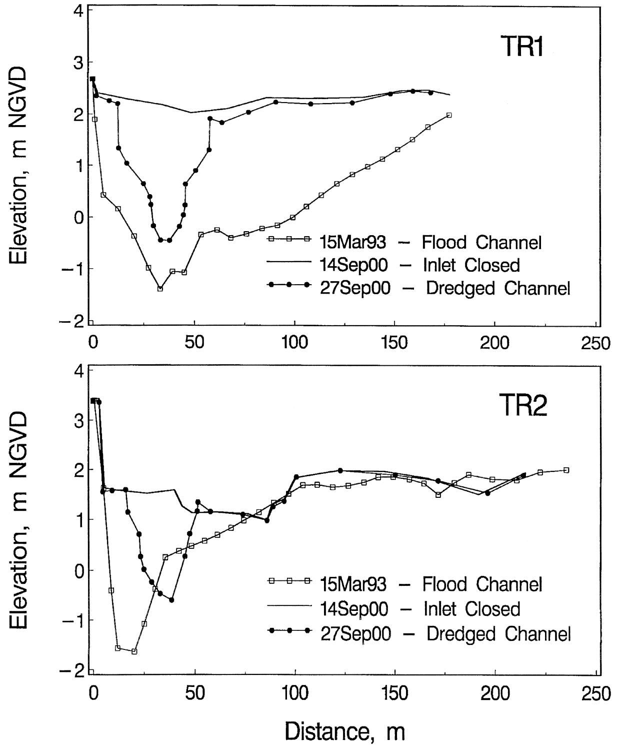

Fig. 6. Cross sections at the west end of the San Dieguito Lagoon inlet (TR1) and approximately 25 m east (TR2). Labeled curves show inlet configuration after the flood of January–February 1993: March 15, 1993, during a time of inlet closure: September 14, 2000, and after the inlet excavation: September 27, 2000.

their mean value to determine whether the result was different from zero. The difference was not statistically significant ($p = 0.5$, $n = 7$). When we performed the *t*-test on beach width instead of on subaerial volume, the mean difference of beach width change was likewise not statistically different from zero ($p = 0.2$, $n = 7$). There were insufficient data to test differences at range SIO5. Results of a *t*-test on SIO2 for beach subaerial volume differences and beach width change were also insignificant ($p > 0.05$, $n = 9$).

Tables 5 and 6 give the subaerial beach volume and beach width before and after artificial openings for SIO1 and SIO2, respectively. On average at SIO1, there were insignificant reductions in subaerial beach volume (-17.7 m^3 m^{-1}) and beach width (-15.9 m) before and after artificial openings. The observed differences were sometimes negative (erosion), but at other times positive (accretion). The negative and positive signs of the differences for profiles SIO1 and SIO2 correspond. This confirms that other reasons exist besides lagoon inlet openings for changes of beach width and subaerial sand volume.

Table 7 shows the means and standard deviations of the subaerial sand volume and beach width at profiles SIO1 and SIO2. All 102 profiles measured at SIO1 and 117 profiles at SIO2 were used to calculate these quantities (Table 2), providing a measure of the natural variability of the mean of the subaerial volume and beach width. Note that at SIO1, the standard deviation of volume is actually greater than the mean value, while the standard deviation of the width is about 40% of the mean. The mean values of subaerial sand volume and beach width before and after artificial openings are also included in Table 7. All mean values before and after artificial openings fall well within one standard deviation of the overall mean values. This shows that any effects of artificial openings on beach volume and width are smaller than the natural variability of volume and width and are insignificant.

EFFECT OF SAN DIEGUITO LAGOON ON LONGSHORE TRANSPORT

Longshore sand transport is the rate of movement of sand in the surf zone along the coast as the result of currents generated by waves breaking at an angle to the shoreline. It may be characterized by the gross transport, which represents the total rate of movement both up coast and down coast. A comprehensive review of longshore transport rates within the Oceanside littoral cell (which

TABLE 5. Volume (m^3 m^{-1}) before and after artificial openings.

	SIO1			SIO2		
Date	Before	After	Difference	Before	After	Difference
December 1979–January 1980	120.5	87.1	−33.3	88.4	70.7	−17.7
January 1981–February 1981	138.0	73.3	−64.7	92.3	68.5	−23.8
December 1981–January 1982	388.8	397.6	8.8	105.8	107.9	2.0
January 1982–February 1982	397.6	406.5	8.9	107.9	113.2	5.3
February 1982–March 1982	406.5	416.8	10.3	113.2	121.8	8.7
January 1995–February 1995	21.3	39.5	18.2	79.6	82.6	2.9
February 1996–March 1996	—	—	—	75.6	69.5	−6.1
March 1996–April 1996	—	—	—	69.5	88.9	19.5
September 2000–November 2000	91.2	32.0	−59.3	130.9	115.9	−15.0
Average (SD)			−15.9 (35.6)			−2.7 (14.0)

TABLE 6. Beach width (m) before and after artificial openings.

	SIO1			SIO2		
Date	Before	Afer	Difference	Before	After	Difference
December 1979–January 1980	76.8	60.1	−16.7	57.7	51.5	−6.2
January 1981–February 1981	87.7	33.0	−54.7	65.0	46.6	−18.4
December 1981–January 1982	93.3	90.1	−3.2	69.2	68.1	−1.1
January 1982–February 1982	90.1	78.0	−12.1	68.1	63.3	−4.8
February 1982–March 1982	78.0	85.8	7.8	63.3	69.6	6.3
January 1995–February 1995	43.1	42.5	−0.6	45.2	46.0	0.8
February 1996–March 1996	—	—	—	52.6	44.6	−8.0
March 1996–April 1996	—	—	—	44.6	57.9	13.3
September 2000–November 2000	82.5	38.2	−44.3	78.1	68.6	−9.5
Average (SD)			−17.7 (23.3)			−3.1 (9.3)

includes Del Mar) from numerous studies is presented in USACE (1991). On average, the gross longshore transport is estimated to be over 900,000 m^3 yr^{-1}. Tidal inflow in southern California lagoons is known to intercept some percentage of the gross longshore transport. Tidal outflow does not appear to significantly affect the natural longshore flow.

Elwany et al. (1994, 1998) estimated that 9,000 to 15,000 m^3 yr^{-1} of littoral sand accumulates in the entrance channel of San Dieguito Lagoon during the closure process. Monitoring of other lagoons in the San Diego area has resulted in similar estimates (Elwany et al. 1997). This volume represents less than 5% of the annual gross longshore transport volume and is negligible.

During a flood event, or when the lagoon is dredged for maintenance, sand that has accumulated in the inlet is returned to the littoral system. In the long term, there is no net change to the sediment budget due to the presence of the lagoon. The San Dieguito River may provide an intermittent source of sand for the beach at Del Mar, although the amount has been greatly reduced since the river flow has been restricted by Lake Hodges Dam. The 200 × 200 m back-beach area adjacent to the inlet (Fig. 1, landward, between SIO5 and SIO1) acts as a capacitor by storing a small fraction of the littoral longshore sand transport that accumulates over time between severe winters. During heavy winters, when the beaches are cut back by high waves, flooding re-introduces this stored material back into the shallow portion of the littoral zone, just when and where it is needed most to buffer erosion effects. In this way, the lagoon inlet area moderates the effect of storm erosion on Del Mar Beach. This may be an important factor in explaining why Del Mar has experienced much less of the chronic erosion that other San Diego County beaches to the north have suffered since 1982–1983.

The outflow velocities of approximately 1 m s^{-1} generated by the tidal flow out of a lagoon and across the beach are much smaller than the discharge velocities during a river flood. Furthermore, visual inspection confirms that the outflow loses its momentum about 30 m from the shoreline. During large wave events, when the rate of longshore sand transport is high, the surf zone may be up to 180 m wide, with most of the transport occurring near the wave breaking point. It is virtually impossible for the tidal outflow to significantly interfere with or interrupt the natural longshore sand transport in the surf zone.

Conclusions

An extensive beach profile database shows a large natural seasonal variability at Del Mar Beach compared with other San Diego County beaches. In addition to the normal erosion that occurs due to high winter waves, high outflow velocities during flood periods cause beach sand removal and loss of beach width at the southern edge of the outlet channel. This loss is larger than at a control range 600 m south of the lagoon inlet where no direct effects related to the inlet are felt. The sand volume and mean beach width at the inlet channel before and after an artificial opening indicate no

TABLE 7. Means and standard deviations of beach width and subaerial beach volume.

	Beach Width (m)					Beach Subaerial Volume (m^3)				
	All Data		Excavation Data			All Data		Excavation Data		
Profile	Mean (SD)	n	Mean Before	Mean After	n	Mean (SD)	n	Mean Before	Mean After	n
SIO1	61.4 (25.7)	102	78.8	61.1	7	123.4 (134.0)	102	119.5	207.6	7
SIO2	62.2 (13.8)	117	60.4	57.4	9	100.5 (27.3)	117	97.9	93.2	9

statistically significant difference. The effect on Del Mar Beach of an open inlet is small and insignificant when compared to natural seasonal changes and flood effects.

Ebb tidal outflow from the lagoon loses its momentum near the shoreline and does not significantly affect the longshore transport of littoral sand. The rate at which the lagoon can trap sand is only about 3% of the longshore transport rate and is negligible. Natural trapping of sand by the lagoon does not add sand to or subtract sand from the local long-term littoral cell sand budget, since eventual flushing by floods or engineered openings returns the material to the littoral system. Sand stored in the inlet and surrounding back-beach area provides material that buffers the effects of erosion during severe winters.

Southern California lagoons and beaches are both valuable coastal resources. Since all of the area's lagoon entrances cross sandy beaches of various widths, beach condition and lagoon inlet processes are closely related. Southern California's coastal lagoons are small and shallow, and their inlet dynamics depend mainly on river flooding, wave-driven littoral sand transport, and tidal flow, with secondary influences from inlet substrate type.

Since these lagoons are small and shallow, they tend to trap littoral sand until they close. Accumulations of sand range from 9,000 to 15,000 m^3 yr^{-1} prior to closure. This amount of sand is small compared to the rate of longshore sand transport and therefore is negligible. Flooding and maintenance dredging of lagoons return any accumulated sand to the littoral cell, resulting in no net change to the sediment budget in the long term. The result of no statistically significant erosional effect on the adjacent beach when the San Dieguito Lagoon inlet is artificially opened to tidal flow may be applicable to other small, estuarine coastal lagoons.

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