Morphodynamics of Southern California Inlets

Christopher K. Webb†, Douglas A. Stow† and Howard H. Chang‡

†Department of Geography
San Diego State University
San Diego, CA 92182, USA

‡Department of Civil Engineering
San Diego State University
San Diego, CA 92182, USA

ABSTRACT ▮

WEBB, C. K., STOW, D.A., and CHANG, H. H. Morphodynamics of Southern California Inlets. *Journal of Coastal Research*, 7(1), 167–187, Fort Lauderdale (Florida), ISSN 0749-0208.

The morphology of small tidal inlets common to the coast of southern California responds dynamically to tidal, wave, and stream stormflow processes, and they often become unstable. This paper analyzes inlet morphology in relation to process and material parameters, and compares spatial and temporal patterns of morphodynamics at three small southern California tidal inlets. Topographic surveys and velocity measurements were made, and aerial photographs acquired for the inlets to the Tijuana River Estuary, Los Penasquitos Lagoon, and San Dieguito River. Analyses of these data and corresponding hydrologic data from archives showed that the morphology of these small inlets changes rapidly to variations in tidal range. Spring tidal flows and stream stormflows are effective at scouring littoral sediment from inlets and restoring inlet stability. The inlets were most unstable and occasionally closed when high waves coincided with neap tide conditions. Inlets with cobble-size bed sediment tend to be less stable than those with sandy beds due to bed armouring.

ADDITIONAL INDEX WORDS: *Estuaries, tidal inlets, river mouths, entrance channels, coastal geomorphology, coastal sediment transport, southern California coast.*

INTRODUCTION

The relatively small, unnavigable tidal inlets common to the coast of southern California exhibit dramatic morphologic dynamics in response to process/material interactions associated with tides, waves, and stream stormflows (large coastal stream discharges from winter storms). These inlets fluctuate between an unstable, closed status and equilibrium open conditions as the result of interactions between these variables. Inlet stability refers to the long-term tendency for an inlet to remain open, whereas unstable inlets experience periodic or long-term closures. The unstable nature of many small tidal inlets affects biological conditions of the adjacent lagoon/wetland system, often resulting in the implementation of coastal management practices such as dredging to maintain a functioning inlet. Systematic study of tidal inlet morphodynamics aids in the prediction of temporal and spatial patterns of inlet form. Understanding inlet morphologic response to process and material interactions can lead to more effective coastal management practices in the future, and maintenance of high quality lagoon/wetland systems.

The objectives of this study were to: (1) analyze inlet morphologic response relative to process and material parameters, and (2) compare temporal and spatial patterns of inlet morphodynamics at three small southern California tidal inlets. Inlet morphology was examined with topographic survey data, aerial photographs, and archived data pertaining to historic inlet conditions.

BACKGROUND

Previous researchers have focused attention on process/response relationships of large, navigable inlets of the Gulf and East Coasts of the U.S. (O'BRIEN, 1971; JOHNSON, 1973). These relationships do not always apply to the smaller inlets found at lagoons, or the mouths of coastal streams along the southern California coast. Tidal inlets in southern California differ from these larger inlets in that they are relatively small, unnavigable, less stable, and are significantly affected by periodic high stormflows from coastal streams. Only a few studies have focused on morphologic characteristics of southern California coastal inlets (JENKINS and SKELLEY, 1985; O'HIROK, 1985), and small inlets elsewhere (MEHTA,

1987; LIN, 1988; SMITH AND ZARILLO, 1988; FITZGERALD et. al, 1984; MEHTA and WINTON, 1981; BRUUN, 1968; BRUUN and GERRITSEN, 1974).

The dynamics of a small barrier beach-inlet system near the Santa Clara River mouth in Ventura, California were investigated by O'HIROK (1985) from 1982-83. Continual monitoring of conditions at the river mouth over one year showed that inlet morphology and stability are influenced by the interactions of tidal currents, wave energy, stream stormflows, and lagoon overtopping by waste water releases. Detailed surveying of the inlet, barrier beach and nearshore topography led to the conclusion that the inlet tended to close by shore-normal movement of sand bars within the breaker zone and onto the river mouth. This contrasted with the more generally stated process of inlet closure by longshore drifting as suggested by BRUUN (1978).

JENKINS and SKELLEY (1985) quantified the magnitude-frequency relationship of inlet closure at Batiquitos Lagoon (Carlsbad, California) relative to longshore transport and tidal scouring. They utilized historical wave and tidal data, and a modification of O'BRIEN'S (1971) stability criteria to calculate recurrence intervals of inlet closure under a range of wave and tidal conditions.

Inlet morphology in response to tidal and wave conditions has been studied extensively by BRUUN (1968, 1978), and BRUUN and GERRITSEN (1961 and 1974). They studied patterns of inlet cross-sectional geometry and flow velocity changes resultant from the influx of littoral drift. The shape and cross-sectional area change to produce flow velocities sufficient for removing excess sediment from the mouth. This process occurs until a critical point is reached, at which time any additional sedimentation results in rapid flow deceleration, sedimentation, and possible closure. Inlet stability was found to be a function of the relationship between the volume of littoral drift entering the inlet and the tidal prism.

WINTON (1979), MEHTA and WINTON (1981), and MEHTA (1987) measured and modeled the morphologic response of a small inlet to storm-generated wave activity on the Florida coast. They utilized field surveys, aerial photographs, and a numerical model to quantify inlet morphodynamics and hydraulics resulting from varying tidal and wave conditions. Small sandy inlets were found to remain in a long-term, non-silting equilibrium state, while sediment accumulated in flood and ebb-tidal shoals. These inlets became unstable during episodic winter storms.

Field data collected and analyzed as part of this study were also used by STOW et al. (in review) for verification of an inlet process model called INLET. The model was used to simulate inlet morphologic response to tidal flows, wave-related sedimentation, stream stormflows, and varying bed sediment size. Simulated inlet cross-sectional area varied in response to tidal discharge in a manner similiar to what was measured in the field ($r^2 = 0.6$). Sediment inflow rates of 100 and 500 m^3/day caused the model inlet to close after 120 and 51 hours, respectively. The inlet remained stable during a sediment influx of 10 m^3/day. The range of sediment inflow rates simulated was comparable to that occurring at the Tijuana River inlet during field observations in 1987. Simulated stormflows were found to scour sediment from the inlet channel resulting in an enlarged inlet cross-section. Flow velocities predicted by the model were similar to those recorded at the Tijuana River during high discharge events. Effects of variable bed sediment sizes comparable to those found at the Los Penasquitos Lagoon inlet on inlet morphology were also simulated. The inlet became wider and more shallow when the bed consisted of cobble-size sediment, but narrowed and deepened when composed of sand size sediment. This result was supported by field observations at the Los Penasquitos Lagoon inlet.

Sediment transport within a tidal inlet was modeled numericlaly for an inlet at the Stony Brook Harbor in Long Island, New York by ZARRILLO AND PARK (1987). They modeled an inlet-basin system and tested five different sediment transport equations to estimate net sediment transport patterns. The model predicted flood-directed net sediment transport, which agreed well with observed conditions.

STUDY INLETS

Tidal inlets analyzed in this study are located within San Diego County, California at the mouths of the Tijuana and San Dieguito Rivers, and the entrance to Los Penasquitos Lagoon

(Figure 1). Each inlet connects a lagoon or an estuary with the Pacific Ocean. These lagoon-inlet-sea systems vary in size, from the larger Tijuana River inlet to the smaller Los Penasquitos Lagoon. All locations are influenced by a mixed-tidal regime (mostly semi-durnal with an infrequent diurnal component), with a mean tidal range of approximately 1.5 and a range of 0.75 to 3.0 meters.

The Tijuana River inlet is formed at the confluence of two slough arms (inland extensions of estuarine waters) that extend north and south, with the Tijuana River toward the east (Figure 2a). The Tijuana River Estuary encompasses 1.2 hectares of subtidal habitat, 12.2 hectares of intertidal mudflat, and an intertidal marsh plain of 121.5 hectares. The tidal prism of the Tijuana Estuary is approximately 370,000 m^3 (WILLIAMS and ASSOCIATES, 1986). The wetland area is bordered on the seaward side by a 4.8 km long barrier beach which is breached by the inlet. The Tijuana River flows into the estuary about 8 km inland of the inlet. The watershed area of the Tijuana River is approximately 330 km^2, and streamflow is low most of the year, except following winter storms when it can reach 10 m^3 sec^{-1}.

The inlet at Los Penasquitos Lagoon is a short channel connecting the shallow lagoon with the sea (Figure 2b). Two slough arms reach 1.5 km inland and drain the northern and southern areas of the wetland. This lagoon system encompasses approximately 255 hectares, including 86 hectares of shrub-scrub and forested and riparian vegetation, 13 hectares of tidal channels, and 142 hectares of coastal salt marsh (CALIFORNIA STATE COASTAL CONSERVANCY, 1985). Railroad tracks and a bridge traverse the lagoon, having effectively severed connections between portions of the lagoon and sea (reducing the effective tidal prism). The 62,362 m^3 tidal prism (MUDIE and
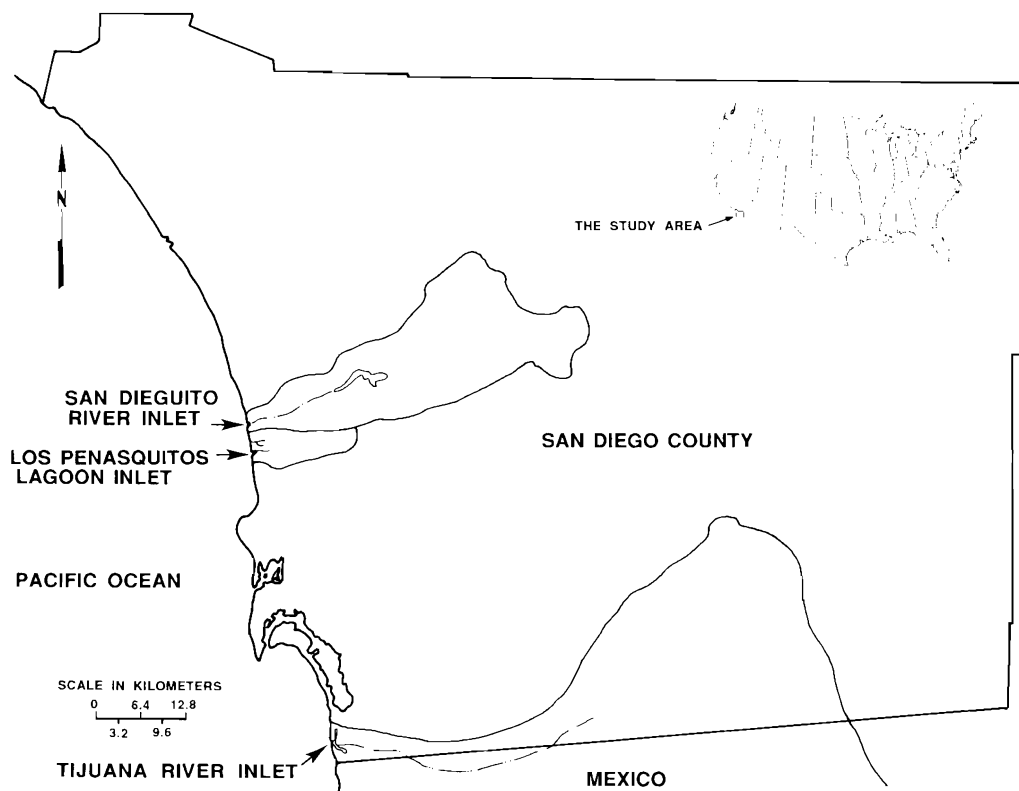

Figure 1. The locations of the study inlets and associated drainage basins are shown on a map of San Diego County.
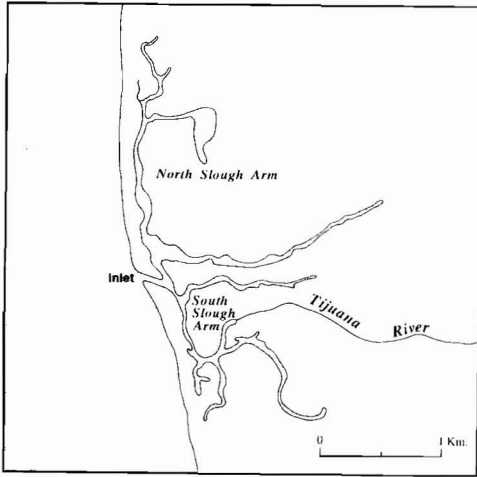
Figure 2 Cont.

Figure 2. (a) Maps showing the configuration and relative positions of the three study inlets and their associated lagoons or estuaries. The inlets shown are those at the (a) Tijuana River; (b) Los Penasquitos Lagoon, and (c) San Dieguito River.

BYRNE, 1974) passes through a bridge opening under a major road. Watershed area is approximately 250 km² (MUDIE and BYRNE, 1974), and streamflow contributions from Carmel Valley, Los Penasquitos Creek and Carroll Canyon Creek drain into the lagoon.

The San Dieguito River inlet is intermediate in size compared with the other study inlets (Figure 2c). It drains a lagoon which forks into two arms extending 2.4 km inland. The area of the lagoon has been reduced by construction of a fairgrounds, and two major highways. The tidal prism is approximately 57,272 m³ (MUDIE et al., 1976). Slough channels and marshland cover approximately 81 hectares. The lagoon channel system is surrounded by 109.4 hectares of salt marsh and maritime
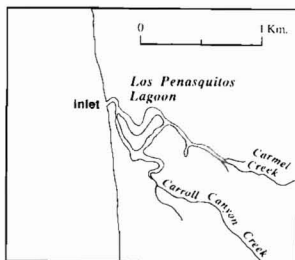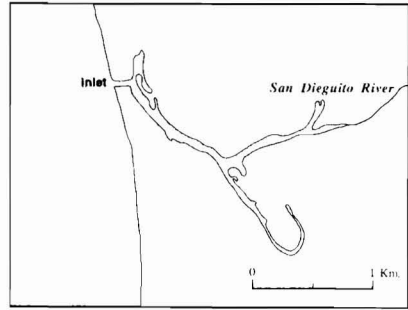

Figure 2 Cont.

grassland, with another 134 hectares of original lagoon (now floodplain) lying east of a major highway (MUDIE et al., 1976). Stream flow is typically low all year; however, large floods can occur in winter as evidenced by the flooding of 1980 and 1982-83.

METHODS

Field data were collected for the study inlets over a one year period (March 1987 to April 1988). Topographic surveys were performed at low water during neap and spring tide events, and large wave and stream stormflow events. A baseline survey point was established from which to reference measurements (Figure 3) at each study site. Cross-sectional measurements were made along transects across the inlet, with the transects spaced at regular intervals from the lagoon to the sea. Topographic measurements were surveyed by sighting on a staff secured by a person traversing the inlet. The data were recorded on a plane table and later transferred to computer files.

Surface flow velocity (meters/second) was estimated by clocking the time taken for a float to travel 25 meters. Three readings were obtained and their average calculated. This average surface flow velocity was multiplied by 0.7 (based on field measurements by Philip Williams and Associates, Consultants in Hydrology) to estimate mean channel flow velocity (Mehta, 1988). Average velocity estimates were multiplied by channel cross-sectional area to estimate discharge, and bed sediment was sampled from the thalweg at the upstream and downstream sections as conditions permitted.

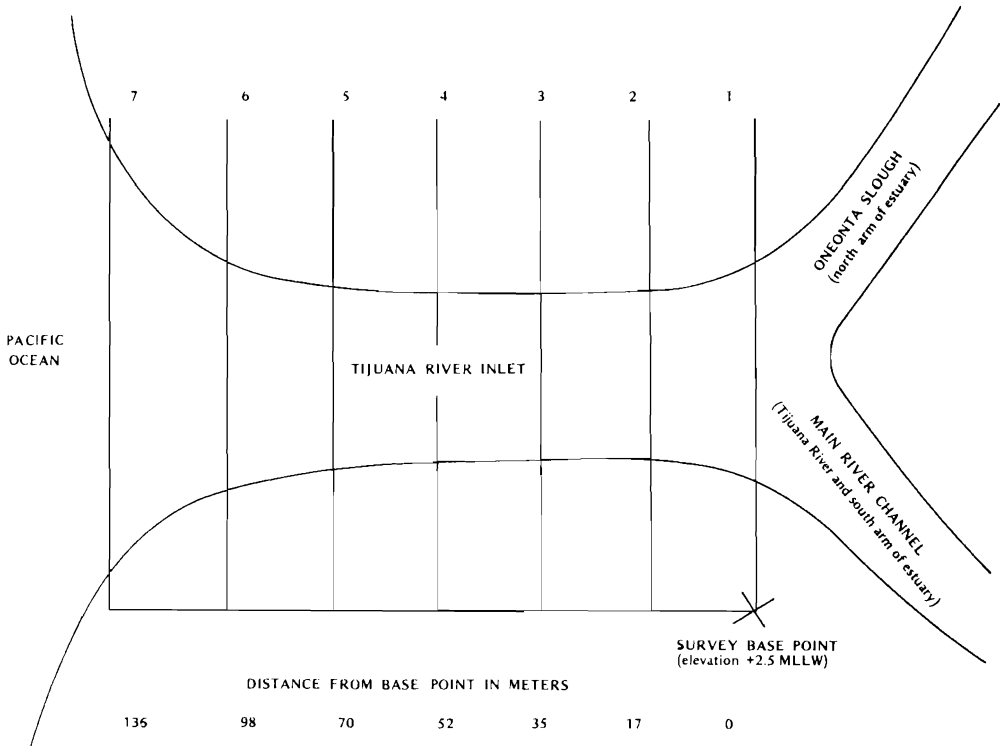Aerial photography was acquired to increase

Figure 3. The topographic survey scheme used at the Tijuana River. Fixed survey transects were oriented across the channel and were referenced to a perpendicular baseline fixed to a survey control marker.

temporal and spatial coverage of the study inlets. Overflights took place on or immediately following processes which significantly affected inlet morphology. Oblique photographs were obtained using a hand held 35 mm SLR camera and color slide film from platform altitudes of approximately 250 to 1000 meters. Photographs were also acquired on the ground during field surveys, and historical photographs were obtained from public and private sources.

Archived data of tidal elevations, tidal prism, wave characteristics, and stormflow discharge were extracted for time periods preceeding and encompassing the dates of field surveys and air photo acquisitions. National Oceanic and Atmosphere Administration (NOAA) tidal data recorded in San Diego Bay were acquired from government archives. Streamflow data for the Tijuana River as recorded by the International Boundary and Water Commission (IBWC) were also acquired. In addition, wave data obtained

as measured by the Coastal Data Information Program (CDIP) were used. The CDIP is a wave measurement program, developed and funded by the U.S. Army Corps of Engineers, the California State Department of Boating and Waterways, and Scripps Institution of Oceanography. Wave height and direction are measured by a pressure transducer wave array anchored offshore in water 10 meters deep. Wave arrays are located offshore from the Tijuana River inlet, and mid-way between the San Dieguito River and Los Penaquitos Lagoon inlets.

OBSERVATIONS

In this study, emphasis was placed on the Tijuana River inlet due to its relatively natural configuration, biological significance, and long-term stability. Seasonal patterns of inlet morphologic change resulting from interactions of

tidal, wave-generated, and stream stormflow processes were analyzed along with the morphologic effects of varying bed sediment size.

Tijuana River Inlet

Historically, the Tijuana River inlet has been more stable than the other two study inlets. The inlet is known to have closed at least once prior to 1978, and also in 1983, 1984, and 1986 (Table 1); inlet closures were short-lived.

The January 24, 1983, closure coincided with an "El Nino" event characterized by intense local storm activity with steep, high waves and heavy rainfall. Neap tides (maximum tidal range 0.7 m) preceded the first closure date by four days. High waves also occurred during this period. Low tidal flows during the neap tides were incapable of removing sediment deposited by storm wave processes. When tidal elevation increased (2.5 m) on January 26, 1983, sedimentation occurred farther into the inlet channel, and the inlet closed.

The inlet reopened on January 29, 1983, from scouring by high stream stormflows, but flow through the northern arm remained restricted. The inlet remained open from January, 1983 to April, 1984. On April 28, 1984, neap tides coincided with high waves and the inlet closed. The inlet remained closed for six months, until the mouth was dredged by the U.S. Fish and Wildlife Service.

Most recently, the Tijuana River inlet closed on February 4, 1986. Neap tide conditions occurred six days prior to inlet closure (January 27 to February 3, 1986). Extremely high waves (3.0 m) on February 2, 1986, damaged the off-shore measuring station and caused sedimentation in the mouth and inlet closure.

Tidal, wave, and stream stormflow conditions recorded before and during closures of the Tijuana River inlet suggest that instability resulted from the superposition of neap tides and high waves. In each instance, neap tides occurred just prior to, or coincident with waves of at least 1.3 m in height. It is apparent that small tidal discharges associated with neap tides were incapable of removing sediment supplied by high winter storm waves.

In the absence of high winter storm waves (spring and summer months), tidal processes most significantly affected inlet form. On June 4, 1987, the inlet constricted after having conveyed relatively low tidal flows for two months. During this period the inlet experienced moderately constructive wave activity. An experiment to record inlet morphologic change over an entire neap tide cycle was conducted on June 4–5, 1987. The inlet was surveyed initially at low tide on June 4, and tidal discharge was monitored for the following 25 hours, at which time another survey was performed. Tidal elevation varied only 0.5 m over eight hours, and waves averaging 1.25 m in significant height approached at a mean significant angle (average approach angle of significant waves) of 240 degrees (shore-normal angle of incidence is approximately 255 degrees). The channel bed slightly aggraded from -0.6 m Mean Lower Low Water (MLLW) to -0.25 m MLLW (Figure 4). The north inlet bank migrated south approximately 3–6 m between June 4 and 5, and the inlet was oriented nearly north to south with a very irregular bed gradient. Sedimentation

Table 1. *Closures and constrictions at the Tijuana River inlet.*

Date	Closure Status	Tidal* Range (meters)	Significant** Wave Height (meters)
prior to 1978—see text			
1/24/83	Closed	0.7	2.5
4/28/84	Closed	1.2	1.3
2/4/86	Closed	1.0	2.6
4/7/87	Open (14 m²)***	1.3	1.2
6/5/87	Open (12 m²)	1.1	0.9
10/13/87	Open (16 m²)	1.4	0.6
12/11/87	Open (8 m²)	2.2	1.7
1/18/88	Open (23 m²)	2.3	4.6

*Difference between highest high water and lowest low water
**Average of the highest 1/3 of waves recorded.
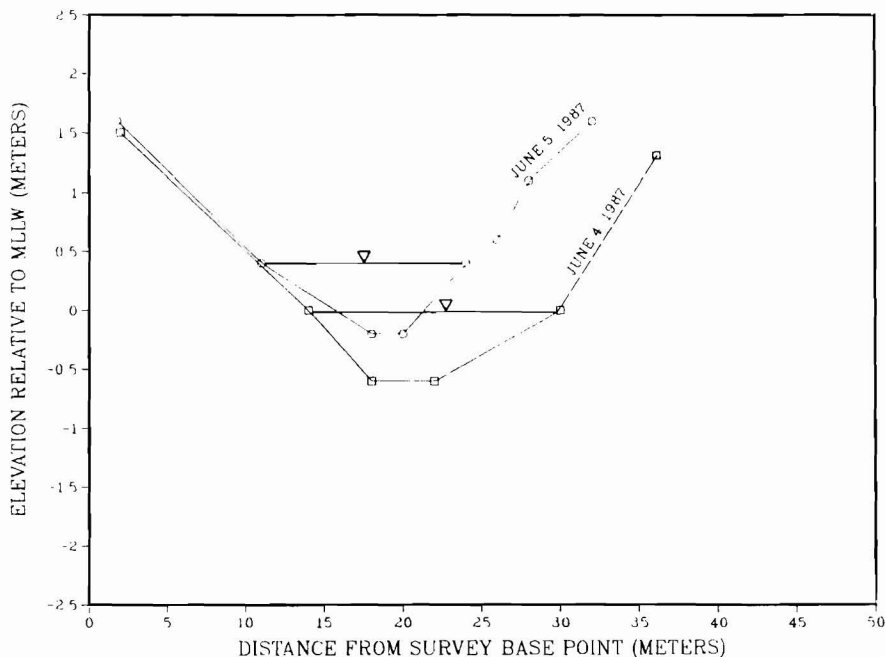***Inlet cross-sectional area in parentheses.

Figure 4. Cross-section number five (approximate midpoint) at the Tijuana River inlet surveyed on June 4 and 5, 1987. The cross-sectional area below MLLW is smaller on June 5, reflecting inlet constriction during neap tides.

occurred within a fairly narrow foreshore zone near the inlet, due to limited tidal range, flow, and increasing wave energy.

Inlet morphology changed due to large tidal discharges during a spring tide cycle in mid-July. The maximum tidal range was 2.5 m, and average significant wave height was recorded at 0.6 m approaching from a mean significant angle of 250 degrees. Little morphologic change occurred between the surveys of July 11 and July 12 (Figure 5), but morphologic changes from June 5 were evident. As the result of scouring by spring tides, the inlet enlarged and moved nearly 9–12 m farther south from its position in June, becoming aligned almost directly with Oneonta Slough. The inlet had deepened, widened and developed a smoothly sloping bed gradient.

Tidal discharges of the June 4–5 and July 11–12 events represented those associated with the minimum and maximum tidal prisms for the Tijuana Estuary in the summer of 1987. Maximum estimated tidal discharge on June 4–5 was 110 m^3 sec^{-1}, and discharge for July 11–12 reached approximately 1,230 m^3 sec^{-1}. On June

4–5 the peak average flow velocity was 0.5 m sec^{-1}, as compared to 1.4 m sec^{-1} on July 11–12. The contrast in inlet morphology between these two dates reflected the different bed scouring capabilities of neap and spring tidal flows. Bed sediment ranged from medium to coarse-size sand on June 5, and from medium-size sand to cobbles on July 12.

Processes affecting inlet form changed in November, as the wave climate shifted from summer swell to winter storm wave conditions. High waves incident at a 275 degree mean significant angle occurred from November 10 to November 15, 1987. Maximum significant wave heights reached 1.4–1.7 m with most of the wave energy delivered by steep, short period waves. Steep waves were present at peak high tide on November 10, causing large volumes of sediment entrained within the surf zone to be transported to the inlet. Smaller tidal range and high waves followed on November 14–15, and the inlet constricted and moved westward.

High tidal ranges (2.8 m on November 22) occurred throughout the next week. The inlet was scoured by larger tidal flows, deepening by
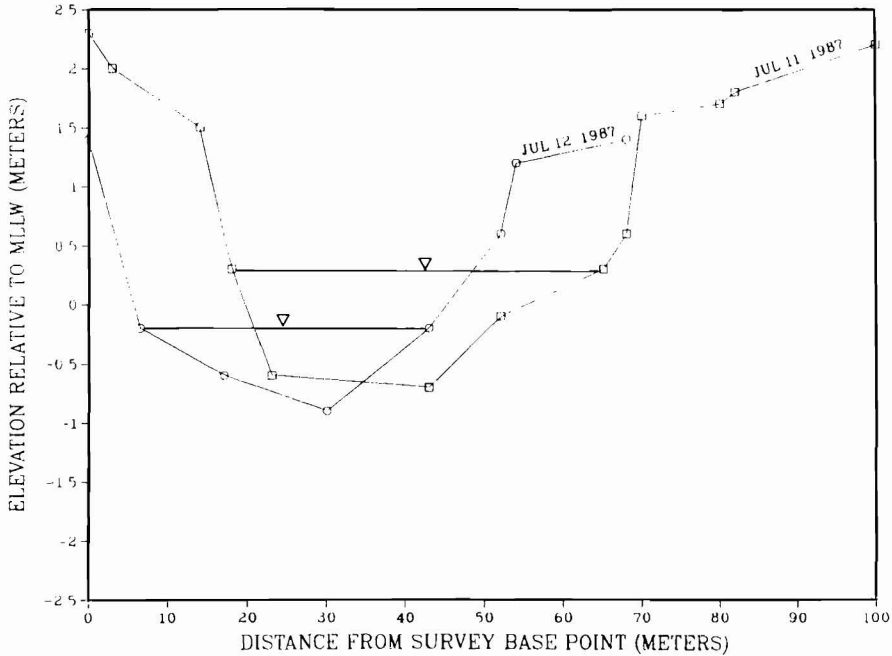
Figure 5.   Cross-section number five (approximate midpoint) at the Tijuana River inlet surveyed on July 11 and 12, 1987. The inlet migrated south and deepened during the spring tidal cycle, but cross-sectional area below MLLW remained approximately equal on both dates.

0.3 m in the thalweg, and widening by 25 m. The bed sloped gently seaward and cross-sections were more asymmetrical in shape, reflecting flow from the main river channel (east), rather than Oneonta Slough (north).

High waves occurred on December 7–8, nearly closing the inlet. The time of the recorded peak significant wave height (2.0 m) coincided with high tide on December 8. This was followed by a period of small-range mixed tides from December 11–14. Tidal flows were substantially reduced as inlet cross-sectional area decreased below MSL by 26.5 m^2 between November 22 and December 11. In addition, cross-sectional bed elevations aggraded by 1.3 m, and the inlet narrowed by 24.7 m, as seen in Figure 6a. Average flow velocities slowed to less than 0.5 m sec^{-1}.

On December 17, the inlet was scoured by high tidal discharges augmented by stream stormflow. By December 20, the inlet had widened by 25 m and deepened in the thalweg by 1.2 m from its geometry on December 14 (Figure 6b). Stormflow also eroded the southern

slough arm which had closed on December 14, and the inlet was wide and deep, and oriented with the Oneonta Slough arm (Figure 7).

The inlet remained stable throughout the remainder of 1987 and into 1988. Wave overwash caused sedimentation within the southern slough arm, the downstream section of Oneonta Slough, and the inlet on January 18, 1988 (Figure 8). The inlet remained partially open due to scouring by stream stormflows and tidal flows coinciding with the storm (WEBB et al., 1989). The inlet channel migrated progressively to the northwest during the winter storm period, in response to the augmented tidal prism and runoff from the main river channel. This northwestward migration was bolstered by high discharges from an extreme rainfall event on February 3, 1988 which deeply scoured the inlet. Cross-sections were deep, narrow and oriented east-to-west in alignment with the main river channel, and they remained in this configuration throughout the next month.

The last survey of the study period was conducted on April 1, 1988 when the inlet had

Figure 6. (a) Oblique aerial photograph of the Tijuana River inlet acquired at low tide on December 14, 1987. The inlet was narrow and nearly closed after sedimentation from high waves followed by neap tides. Note the protrusion of sediment into the lagoon from the southern barrier beach which deflected tidal flow from the southern arm.

assumed a sinuous course. The main source of flow was from the main river channel (to the east), but the mouth had migrated southeast as a result of sedimentation from littoral drift.

Los Penasquitos Lagoon Inlet

Morphologic characteristics of the Los Penasquitos Lagoon inlet contrast sharply with those of the inlets of the Tijuana and San Dieguito Rivers. Los Penasquitos Lagoon has a limited tidal prism (similar to that of the San Dieguito River inlet), which is ineffective at flushing and maintaining an open inlet. Development within the lagoon (Figure 9) has further reduced the effectiveness of scouring by tidal flows. Also, the inlet bed is composed of cobble-size sediment which requires greater shear stress than sand-size sediment to entrain and maintain in transport.

Stability and morphology at Los Penasquitos Lagoon inlet varied widely throughout the study period. The lagoon was isolated from the sea for most of the year, separated by a barrier beach which forms across the inlet as it passes under a highway bridge. Barrier breaching occurs by the build-up of lagoon levels from stream stormflow contributions or by high tidal elevations. Breaching creates an inlet opening which enlarges rapidly during ebb flow.

The opening of the inlet at Los Penasquitos Lagoon is typically short-lived, with closure reoccurring within a matter of days to weeks (Table 2). Closure has been closely documented over time by the Los Penasquitos Lagoon Foundation (LPLF) (CALIFORNIA STATE COASTAL CONSERVANCY, 1985).

A bulldozer was used by the LPLF to create an opening in the barrier early in the fall months of each year. The first opening during

Figure 6 Cont.   (b) Oblique aerial photograph of the Tijuana River inlet acquired at low tide on December 21, 1987. The inlet was wide and deep from scouring by spring tidal flow and stormflow. The sediment deposit visible in the previous photograph was eroded leaving a channel scar in the flood-tidal delta.

the study period occurred February 23, 1987, but scouring by neap tidal flows was insufficient to maintain the opening and the inlet closed after four days. The inlet was dredged on April 1, 1987, and remained open for approximately one month before closing again for the summer.

A large hydraulic head between the lagoon surface and the ocean level existed in late October of 1987 due to the cooccurrence of spring tides and rainfall-runoff contributions to the lagoon. The inlet was opened again by a bull dozer on October 24, 1987, releasing lagoon water and initiating scouring by high flows created by the large hydraulic head. The inlet remained open under high tidal discharges from October 24 to November 2. Inlet width on October 25 varied from 30 m at the gorge to 66 m at the mouth, and the thalweg depth was −0.6 m MLLW. By October 27 the inlet had moved south approximately 23 m, and a cobble

delta had been deposited at the mouth. Ebb tidal flow bifurcated around this deltaic deposit causing a reduction in flow velocity, and the depth of the thalweg decreased to −0.4 m MLLW.

Neap tide conditions followed, and by November 1 the inlet was narrower at the gorge, had moved farther south, and was draining from only one side of the forked channel. Due to insufficient scouring by tidal flows, the inlet bed continually aggraded until closure occurred on November 2 and lasted to November 24.

Extremely high tidal elevations occurred along the coast on November 24, and breached the barrier beach. The inlet remained open from scouring by tidal flows until December 6–7, when high waves reached the adjacent shore. This wave event caused a cobble bar to form, and then migrate shoreward, effectively closing the inlet. It was closed for a short time, until
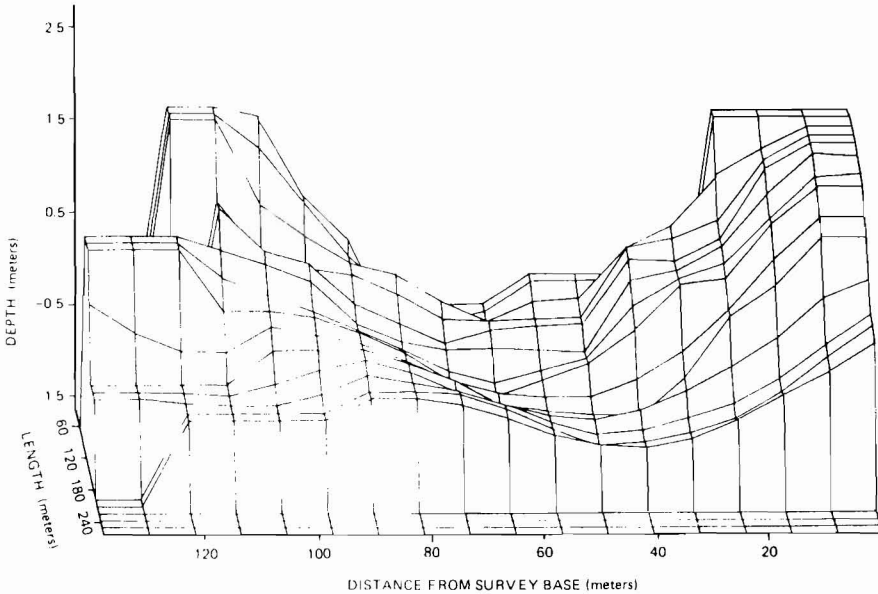
Figure 7. Three-dimensional diagram of a topographic survey of the Tijuana River Inlet on December 20, 1987. View is from the ocean (foreground) to lagoon (background). The inlet is wide and deep from scouring by spring tides and stream stormflow.

high stream stormflows and spring tidal currents scoured an opening on December 15. By December 21 the inlet was wide (62 to 110 m) and deep, with thalweg depths of -1.1 m MLLW. It remained open throughout the remainder of 1987 and into 1988 from the effects of scouring, and in the absence of high waves.

The inlet closed during a neap tide cycle on January 9, 1988. It remained closed until the massive overwash wave/tide event of January 18, 1988, when tides reached heights of $+2.3$ m and waves peaked at approximately 3.1 m. High water surface elevations from stream stormflow contributions and spring high tides breached the barrier beach. The inlet channel was subsequently scoured by stream stormflows and high tidal flows. Los Penasquitos Lagoon inlet stayed open periodically until May of 1988, at which time it closed for the duration of the summer.

Observations of the Los Penasqsuitos Lagoon inlet showed that it was less stable than either Tijuana River or San Dieguito River inlets over the study period. The seasonal pattern of stability was as follows: (1) summer conditions promoted build-up of the barrier beach which led to closure and lagoon stagnation; (2) the inlet was artificially opened by bulldozer in mid-autumn when the hydraulic head between lagoon and ocean surface was high; (3) the inlet alternated between an open/closed status throughout winter months depending on tide, storm runoff, and wave conditions; (4) constriction and eventual closure occurred during the neap tides of early spring, while storm waves moved a cobble bar onshore, and (5) the barrier beach was subsequently reestablished during the constructive wave climate of late spring/early summer.

The San Dieguito River Inlet

The inlet to the San Dieguito River mouth exhibits process and form characteristics intermediate between those of the Tijuana River and Los Penasquitos Lagoon inlets. Wave, tide and stormflow conditions at this site are comparable to those at Los Penasquitos Lagoon inlet, owing to their close proximity (8 km) and similar shoreline configuration. The San Dieguito River inlet is more stable than Los Penasquitos Lagoon inlet, even though it has a slightly smaller tidal prism (57,300 m^3 versus 62,400

Figure 8.   Oblique aerial photograph of the Tijuana River inlet acquired at low tide on January 27, 1988. High waves caused the barrier-beach to be overwashed, resulting in sedimentation of the inlet and slough arms. The inlet was aligned with the main river channel.

m³) (MUDIE *et al.*, 1976). The inlet is a nearly straight extension of the slough that it drains, and development within the slough has reduced the tidal prism and resultant tidal flushing (Figure 10).

The San Dieguito River inlet was open for several consecutive years prior to the study period of 1987–1988. During the first two months of 1987 the inlet was open, but it closed in mid-March under sea wave conditions (Table 3). A bulldozer was used to reopened the inlet,

but one week later it closed again during storm wave conditions. The inlet had been open for several years up until that time. It was reopened by a bulldozer in early April, 1987, and stayed open for more than a month under fluctuating neap and spring tidal flows. The inlet closed again on May 6 coinciding with neap tides, but spring tidal flows reopened the inlet on May 11. It remained stable over the summer under varying tidal ranges. Topo-

Figure 9. Oblique aerial photograph of Los Penasquitos Lagoon inlet acquired at low tide on January 27, 1988. West is to the bottom of the photograph. The inlet was open during spring tides and stormflow conditions. Note the influence of cobble-size sediment on the form of a braided channel cutting through the delta seaward of the bridge.

Table 2. *Closures and openings of Los Penasquitos Lagoon inlet, October 1986 to May 1988.*

Year	Date	Comments	Conditions*
1986	10/20	Bull-Dozed Open	Spring Tides, Stormflow
1987	2/23–2/26	Bull-Dozed Open	Spring Tides, Stormflow
	2/26–4/1	Closed	Neap Tides
	4/1–5/1	Bull-Dozed Open	Neap Tides
	5/1–10/24	Closed	Neap Tides
	10/24–11/1	Bull-Dozed Open	Stormflow
	11/2–11/24	Closed	Swell-Waves, Neap Tides
	11/24–12/6	Opened Naturally	Spring Tides
	12/6–12/15	Closed	Swell-Waves
	12/15–12/21	Opened Naturally	Spring Tides, Stormflow
1988	1/9–1/15	Closed	Neap Tides
	1/18–3/11	Opened Naturally	Spring Tides, Stormflow
	3/11–4/20	Closed	Neap Tides
	4/20–5/23	Opened Naturally	Stormflow
	5/23–	Closed	Neap Tides

*Generalized for time period.

graphic surveys were performed on July 4 and on September 6, representing neap and spring tides, respectively. Inlet cross-sectional area at mid-inlet was 10 m² on July 4, and 24 m² on September 6, reflecting differential scouring by associated tidal discharges. Stream stormflow

Figure 10.   Oblique aerial photograph of the San Dieguito River inlet acquired at low tide on January 27, 1988. The inlet was open and in a linear alignment with the slough. Note that the wave breakpoint was deflected offshore from the inlet as a consequence of delta formation and low spring tide conditions.

Table 3.   *Closures and Openings of San Dieguito River Inlet, March 1987 to May 1988.*

Year	Date	Comments	Conditions*
1987	3/16–3/20	Closed	Sea-Waves, Neap Tides
	3/20–3/23	Bulldozed Open	Sea-Waves, Neap Tides
	3/23–3/30	Closed	Sea-Waves, Neap Tides
	4/8–5/6	Bulldozed Open, Constricted	Neap Tides
	5/6–5/11	Closed	Sea-Waves, Neap Tides
	5/11–11/11	Open, Constricted	Spring Tides
	11/11–11/17	Closed	Swell-Waves, Neap Tides
	11/17–11/24	Open	Spring Tides
	12/10–12/17	Closed	Swell-Waves
1987-88	12/17–1/1/8	Bulldozed Open	Stormflow, Spring Tides
1988	1/1/88–1/18/88	Closed	Neap Tides
	1/18/88–	Open	

*Generalized for time period

and significant wave activity were absent during this period.

The San Dieguito River inlet remained open throughout the fall of 1987, until high, steep waves impinged upon the shore on November 11–14. Neap tide/high wave conditions closed the inlet, but it was reopened by large tidal flows on November 17. It closed again on December 10 after several days of high waves. A bulldozer reopened the inlet on December 17,

and the inlet was scoured by subsequent stream stormflows and spring tidal currents of December 20–21, 1987.

In early 1988, closure occurred during neap tidal flows. The inlet was reopened by the high stream stormflows and spring tidal flows on January 18, 1988. The San Dieguito River inlet remained open throughout the spring and summer of 1988.

DISCUSSION

Tidal and Bed Sediment Influences

In general, the three study inlets responded morphologically (in terms of cross-sectional area) in a similar manner to variations in tidal range (Figure 11), with wide scatter among data points arranged in a slight positive increasing trend. The relationship of inlet area to tidal range is slightly better defined for the Tijuana River inlet. The scatter in data points reflects the influence of other factors which affect the channel cross-sectional area, such as

sediment influx and bed material size. Tidal flow processes greatly influence the morphology of the Tijuana River inlet, where the tidal prism is greatest and bed sediment ranges between − 2 and 0 phi in size. The Tijuana River inlet scours and widens during spring tides, aligning with the northern estuary arm. The northern arm holds most of the tidal prism in the Estuary's present condition. During neap tides, the inlet constricts and becomes more susceptible to the influences of wave-related sediment transport near the mouth, which often causes it to migrate. The Tijuana River inlet remains in dynamic equilibrium in response to tidal flows, and in the absence of significant wave or stream stormflow activity throughout summer months. It reestablishes a stable configuration during high tidal discharges of winter spring tides, after constricting under winter wave sedimentation.

The inlet to Los Penasquitos Lagoon shows the least varied morphologic response to tidal range. The inlet often closes during neap tides, and remains closed until the occurrence of
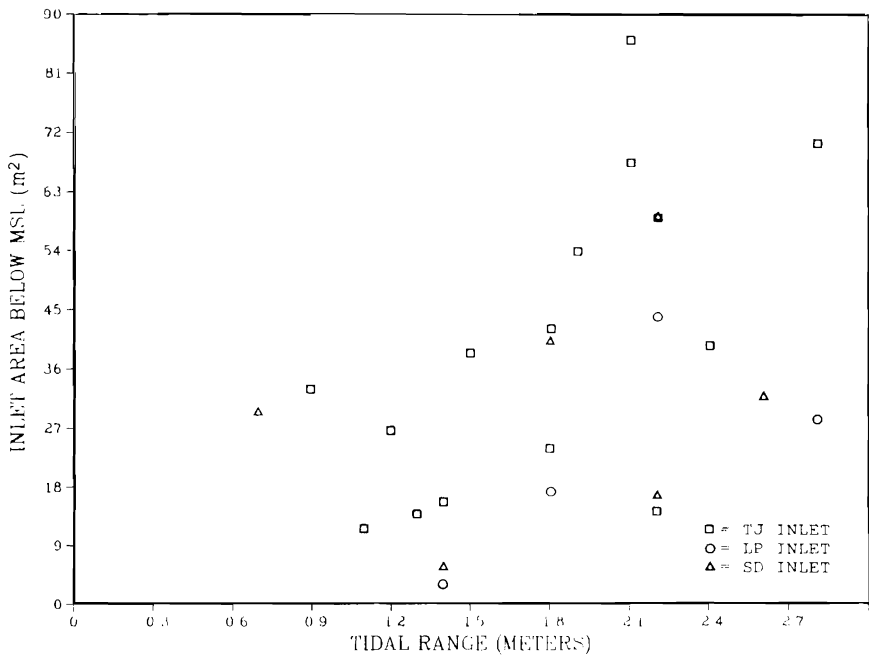

Figure 11. Plot showing the relationship between tidal range and inlet cross-sectional area below MSL measured at the three study inlets in 1987.

spring tides. Inlet geometry is less responsive to changes in tidal discharge, and more affected by its large bed sediment. Cobble-size bed sediment (− 7 phi) armours the bed, and inhibits scouring by ebb currents and stream storm-flows. Changes in cross-sectional area are limited due to bed armouring. Thus, inlet cross-sectional geometry is less variable and remains rectangular over a wide range of tidal discharges as is documented in Figure 12.

The San Dieguito River inlet also responds rapidly to changes in tidal range, although the tidal prism is much smaller than that of the Tijuana River inlet. Bed sediment also ranges in size between − 2 and 0 phi. Inlet migration and flow velocity are constrained by the highway bridge approximately 200 meters upstream from the mouth. During spring tide conditions, the inlet scours, widens and becomes more aligned with the linear trending slough arm (tidal prism storage). The inlet becomes narrower, shallower and tends to migrate during neap tides.

Wave-related Influences

Inlet morphology is affected by wave-related influences such as longshore and shore-normal currents, wave-tidal current interactions and wave set-up. The effects of sediment transport into the inlet by wave-generated currents near the mouth, and periodic wave overwash of the inlet and barrier beach were observed at all three inlets. Although waves have an indirect effect on inlet morphology throughout most of the year, high storm waves and overwash can produce episodic instability by causing sedimentation within the inlet and/or slough channels.

Historically, closures of the Tijuana River inlet have occurred only three times over the last thirty years, always during winter or early spring. Wave data collected before and during these closure dates show that waves were 1.3 m or larger, and approached the shore from significant angles (average approach angles of significant waves) of 255 degrees or greater (north-
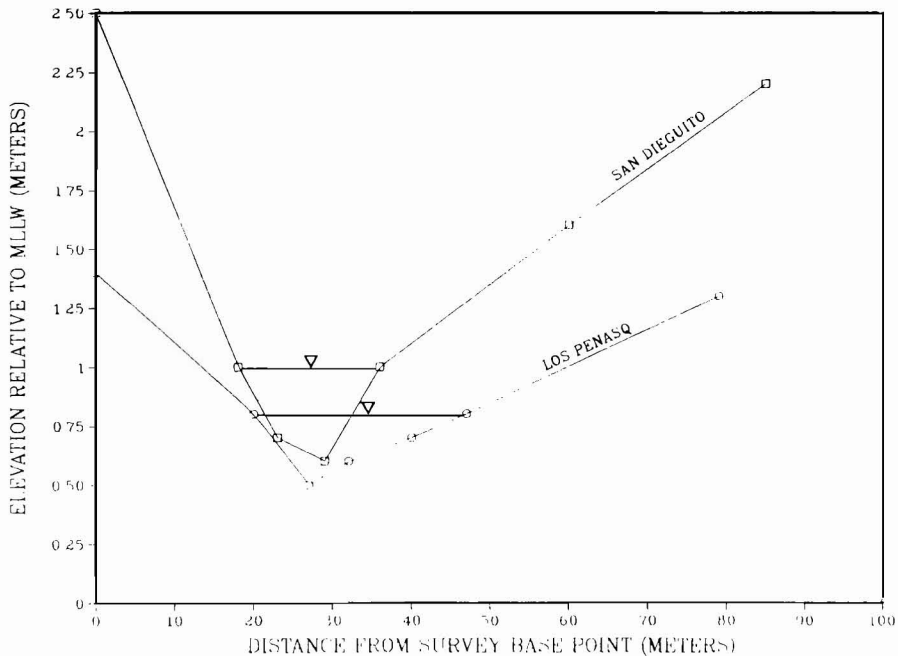

Figure 12. Cross-sections five (approximate midpoints) at the Los Penasquitos Lagoon inlet and the San Dieguito River inlet surveyed on October 27, 1987 during spring tides. Note the similarity of thalweg depths, but cross-sectional geometry and area are influenced by bed sediment sizes.

west). The Tijuana River inlet remained open during high waves (3.0 m) when other factors, such as stream stormflows and spring tides (2.5 m range January 18–19, 1988), maintained sufficient flow to remove littoral sediment (WEBB *et al.*, 1989).

The Los Penasquitos Lagoon and San Dieguito River inlets closed more frequently under a wider range of wave conditions. Instability was observed at all inlets during mid-November of 1987, which coincided with winter waves higher than 2.0 m. The shoreline appeared to have adjusted to summer swell conditions, and was in disequilibrium relative to the winter storm waves. These inlets become unstable as wave-related sedimentation can occur farther into the inlet at high tides while the shore-normal beach profile adjusts to winter wave conditions.

Field observations at the Los Penasquitos Lagoon inlet showed that cobble-size bed sediment was deposited as a delta at the conclusion of high flow events, and reworked into a barrier bar during high wave events. This was documented on April 3, 1987, when wave processes moved the bar shoreward onto the beach face (L. LaGrange, *personal communication*) This cobble bar closed the inlet for an extended period of time, similar to the process recorded in topographic surveys by O'HIROK (1985) at the Santa Clara River mouth.

Stream Stormflow Influences

Streamflow following winter storms alters inlet morphology by reopening closed inlets, enlarging existing inlets, and adjusting channel geometry and course. Inlet geometry is modified by increased scouring during high stream discharges (and resulting high bed shear stresses), and by channel migration when the major flow source shifts from slough arms to stream channels. Inlet morphologic response to stormflow varied for each of the study inlets over the study period due to differences in flood hydrographs and lagoon/estuary configurations at each location.

The course of the Tijuana River inlet has changed dramatically over the last sixty years for which aerial photographs are available (compare Figures 6 and 13). Generally, the inlet migrates southward during summer months in response to tidal flow from Oneonta

Slough, and northward in winter in response to stream stormflow from the main river channel. Stream stormflow altered the morphology of the Tijuana River inlet from a wave-dominated to a fluvial-dominated form on several occasions during the study period. In the fall of 1987, stream stormflow and high tidal flows combined to scour the inlet into a deep asymmetrical channel, after being constricted in November and early December. The inlet migrated northwestward and exhibited a sinuous channel configuration. Also, very high stormflow in mid-January and early February of 1988 eroded sediment at the inlet-lagoon confluence that had previously been deposited by wave overwash of the barrier beach.

Though stormflow discharges are much lower at the two smaller inlets, they are the major natural process for reopening these inlets once they are closed. High velocity stormflows scoured the San Dieguito and Los Penasquitos Lagoon inlets and maintained their stability during the extreme wave event of January 18, 1988. A residual effect of stormflow is that the expanded cross-sectional area of the inlets enhances subsequent tidal flow through these smaller inlets. As the sill to the lagoon is scoured deeper, the volume of seawater stored within the lagoon during a given high tide (*i.e.*, the effective tidal prism) increases.

Stability

Field observations and aerial photographic interpretations showed that the Tijuana River inlet, and to a lesser degree the San Dieguito River inlet, were relatively stable compared to the Los Penasquitos Lagoon inlet. Table 4 shows a comparison of closures at the Los Penasquitos Lagoon and San Dieguito River inlets, which were chosen for comparison because of similar tidal prisms and incident wave characteristics. The San Dieguto River inlet closed more times in 1987 than did the Los Penasquitos Lagoon inlet. In 1988 however, the inlet to Los Penasquitos closed more frequently than the San Dieguito River inlet. All closures of the San Dieguito River inlet during the study period were of shorter duration than those at the Los Penasquitos Lagoon inlet. This occurred even though the tidal prism of Los Penasquitos Lagoon is slightly larger than that at the San Dieguito River.

Figure 13.   Oblique aerial photograph of the Tijuana River inlet during flooding in 1980. The inlet experienced extreme scouring, and the barrier beach was breached from high stream stormflow discharges.

Table 4.   *Comparison of Inlet Closures from 1/87 to 5/88.*

	Los Penasquitos Lagoon Inlet		San Dieguito River Inlet	
Tidal Prism	62,362	m^3	57,272	m^3
Mean Bed Sediment Size (D$_{50}$)	−3 PHI		0 PHI	
Closures	2/26/87	(33)*		
	5/1/87	(176)	3/16/87	(4)*
	11/2/87	(22)	3/23/87	(7)
	12/6/87	(9)	5/6/87	(5)
	1/9/88	(6)	11/11/87	(6)
	3/11/88	(40)	12.10/87	(7)
	5/23/88	(Summer)	1/1/88	(17)

*Number of days closed in parentheses.

The inlet to Los Penasquitos Lagoon remains constricted and closes soon after high storm or tidal flows, while the San Dieguito River inlet remains open long after flow has subsided. The relative location of bridges at the two inlets may also account for differences in their stability. The bridge at the San Dieguito River inlet is positioned farther upstream, while the bridge at Los Penasquitos Lagoon is located at the inlet just seaward of its confluence with the lagoon. As a result, the Los Penasquitos Lagoon inlet is unable to maintain concentrated flow or migrate to adjust to sedimentation within its channel. Thus, flow velocities are more spatially variable at the Los Penasquitos Lagoon inlet than at the San Dieguito River inlet. Flow velocities at Los Penasquitos Lagoon inlet are comparable to those at the San Dieguito River inlet in the inlet gorge section, but decrease through the throat section. At the Los Penasquitos Lagoon inlet, material within the throat section can only be removed by larger stormflow discharges, or by dredging.

Sedimentation by wave-related processes causes these smaller inlets to become unstable. During aggradation, inlet channels adjust in a manner similar to the processes described by BRUUN (1968). As sedimentation occurs, inlet geometry evolves into a narrow, deep channel. This provides sufficient flow velocity to remove littoral sediments from the mouth and channel, until sedimentation increases to a point at which channel flow velocity is diminished causing abrupt inlet closure (see Background section of this paper). Flow velocities in sandy inlets were usually sufficient in removing sediment supplied by littoral drift. In contrast, flow within the armoured cobble inlet was not capable of scouring bed material as effectively.

CONCLUSIONS

The morphology of the inlets to the Tijuana and San Dieguito Rivers, and the Los Penasquitos Lagoon are dynamically and predictably modified by tidal, wave-related, and stream stormflow processes. Inlet geometric form and stability vary according to the effective tidal prism, exposure to wave energy, stream stormflows, and bed material characteristics.

These smaller inlets are more susceptible to the interaction of high wave energies and small tidal prisms than larger, navigable inlets else-

where. This study showed that the cross-sectional area of small inlet channels responds to variations in tidal range, and that ebb tidal flows during spring tides effectively remove littoral sediment that accumulates within the inlet. Stream stormflows are effective at scouring littoral sediment from inlets and restoring inlet stability. Bed sediment size is an important variable in determining the ability of tidal flows to scour littoral-derived sediment from the inlet. Cobble-size bed sediment tends to armour the bed causing inlet instability.

The stability of the study inlets ranged from fairly stable at the Tijuana River, to occasionally unstable at the San Dieguito River, to mostly unstable at Los Penasquitos Lagoon. Reasons for this are: (1) the effective tidal prism and watershed is largest at the Tijuana River, and smallest at the San Dieguito River and Los Penasquitos Lagoon inlets; (2) sediment size and supply is variable between locations, with the greatest abundance of large sediment existing at Los Penasquitos Lagoon inlet.

Morphodynamics observed at the study inlets illustrated the extreme complexity in measuring and isolating process-response relationships. It is particularly difficult to capture important episodic events when one must rely on manual measurement techniques (*e.g.* topographic cross-sectional surveys). Thus, field measurements should be combined with numerical models in order to study important high magnitude/low recurrence frequency processes.

ACKNOWLEDGEMENTS

LITERATURE CITED

BRUUN, P., 1968. Tidal inlets and littoral drift. *Bulletin No. 23/21,* Permanent International Association of Navigation Congresses.

BRUUN, P., 1978. *Stability of Tidal Inlets.* Amsterdam, Holland: Elsevier Scientific Publishing Co.

BRUUN, P., and GERRITSEN, F., 1961. Natural bypassing of sand at coastal inlets, pt. IV, paper no. 3273. *Transactions, ASCE,* 126, 823–51.

BRUUN, P., and GERRITSEN, F., 1974. Characteristics and behavior of Pacific coast tidal inlets. *Journal of the Waterways, Harbors and Coastal Engineering* Division, WW4, 389–97.

CALIFORNIA STATE COASTAL CONSERVANCY, 1985. Los Penasquitos Lagoon Enhancement Plan and Program.

FITZGERALD, D.M.; FINK, K.L., and LINCOLN, J.M., 1984. A flood-dominated mesotidal inlet. *Geo-Marine Letters,* 3, 17–22.

JENKINS, S.A., and SKELLEY, D.W., 1985. Alternatives for maintaining tidal circulation in the Batiquitos Lagoon, California. *SIO Reference Series no. 85-19.* San Diego, California: Scripps Institution of Oceanography, University of California, San Diego.

JOHNSON, J.W., 1973. Characteristics and behavior of Pacific coast tidal inlets. *Journal of Waterways, Harbors and Coastal Engineering* Division (ASCE) pp. 325–39.

LIN, C., 1988. The Stability of Small Beach Inlets: A Case Study. *Proceedings of Beach Preservation Technology '88,* Problems and Advancements in Beach Nourishment. Florida Shore and Beach Preservation Association, Tallahassee, Florida, March 23–25, 1988.

MEHTA, A.J., 1987. Hydraulics and stability of a small inlet. *Shore and Beach.* 55, 96–100.

MEHTA, A.J., 1988. Tidal inlet hydraulics. *Journal of Hydraulic Engineering* (ASCE) 114(11), 1321–38.

MEHTA, A.J., and WINTON, T.C., 1981. Dynamic model for closure of small inlets due to storm-induced littoral drift. *Symposium of International Association for Hydraulic Research,* Paper no. 2, New Delhi, India.

MUDIE, P.J.; BROWNING, P.M., and SPETH, J.W., 1976. The natural resources of San Diego and Batiquitos Lagoons. *State of California Department of Fish and Game Coastal Wetlands Series No. 2.*

MUDIE, P.J., and BYRNE, R., 1974. Pollen evidence for historic sedimentation rates in California coastal marshes. *Estuarine, Coastal and Marine Science,* 10, 305–16.

O'BRIEN, M.P., 1971. Notes on tidal inlets on sandy shores. *Technical Bulletin HEL 4-5, (May),* Hydraulic Engineering Laboratory, University of California, Berkeley.

O'HIROK, L.S., 1985. Barrier beach formation and breaching, Santa Clara River Mouth, California. Master's thesis, University of California, Los Angeles.

SMITH, G.L., and ZARILLO, G.A., 1988. Short-Term Interactions Between Hydraulics and Morphodynamics of a Small Tidal Inlet, Long Island, New York. *Journal of Coastal Research,* 4(2), 301–314.

STOW, D.A.; CHANG, H.H., and WEBB, C.K., 1989. Numerical modeling of processes that operate in southern California inlets. *Journal of Coastal Engineering,* (in review).

WEBB, C.K., 1989. Inlet Dynamics for Southern California. Master's thesis, San Diego State University, San Diego, California.

WEBB, C.K.; STOW, D.A., and BARON, K.S., 1989. Morphologic response of an inlet-barrier beach system to a major storm. *Shore and Beach,* 57(4), 37–40.

WILLIAMS, P. and ASSOC. 1986. Tijuana Estuary enhancement hydrologic analysis. Unpublished report to the California Coastal State Conservancy, 12 February.

WINTON, T.C., 1979. Long and short term stability of small tidal inlets. Master's thesis, University of Florida, Gainesville, Florida.

ZARILLO, G.A., and PARK, M.J., 1987. Sediment transport prediction in a tidal inlet using a numerical model: Application to Stony Brook Harbor, Long Island, New York, USA. *Journal of Coastal Research,* 3(4), 429–444.

□ RESUMEN □

La morfología de pequeños estuarios, comunes en la costa del Sur de California, responde a la dinámica mareal, fluvial y del oleaje, siendo, a menudo, inestables. Este artículo analiza la morfología de los estuarios y su relación con los diferentes agentes y parámetros sedimentarios, comparando valores espaciales y temporales de tres pequeños estuarios del Sur de California. Se muestra datos de campo topográficos y medidas de velocidad, así como fotografías aéras de los estuarios de Tijuana, Los Peñasquitos y San Diego. El análisis de los datos actuales y las series históricas obtenidas muestran que la morfología de estos pequeños estuarios cambia rápidamente en respuesta a variaciones del rango de marea. Las mareas vivas, así como las avenidas fluviales, son especialmente efectivas en la limpieza del material sedimentado y en la restauración del equilibrio del estuario. Los estuarios resultaron altamente inestables, incluso se cerraron ocasionalmente cuando coincidieron situaciones de temporal y mareas muertas. Los estuarios con sedimentos del tamaño de gravillas tienden a ser menos estables que aquéllos con arena, debido a la trabazón del lecho.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ RÉSUMÉ □

Les actions dynamiques (marée, houle, onde de tempête) auxquelles répond la morphologie des petits goulets de marée fréquents sur la côte Sud californienne la rendent souvent instable. La morphologie des goulets est analysée en fonction des différents types de matériaux, et comparée à la morpho-dynamique dans l'espace et le temps de trois deces goulets du Sud Californien. On a pu faire des nivellements et des mesures de vitesse, acquérir des photos aériennes des goulets de l'estuaire de la Tijuana, de la lagune de Los Penasquitos et de la riviére de San Dieguito. L'ensemble de ces données, comparé aux données hydrologiques d'archives correspondantes montrent que la morphologie des petits goulets change rapidement par rapport aux variations du marnage.

Les courants de marée de vive eau et les courants de temête provoquent une incursion des sédiments littoraux du goulet qui en restaure la stabilité. Lorsque les hautes vagues coincident avec les mortes eaux, les goulets deviennent instables et parfois se ferment. Les goulets développés dans les galets tendent à être moins stables que les goulets sableux, ce qui est dû au cuirassement du lit.—*Catherine Bressolier-Bousquet, Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Die Geomorphologie kleiner Gezeitenöffnungen, wie sie in Südkalifornien häufig vorkommen, wird gestaltet durch Gezeiten, Wellen und Strömungen bei Sturmfluten und ist meist unstabil. Diese Arbeit analysiert ihre Morphologie in bezug auf die Prozesse und Materialeigenschaften und vergleicht räumliche und zeitliche morphodynamische Muster von drei kleinen kalifornischen Gezeitendurchlässen. Topographische Messungen wurden durchgeführt und Luftaufnahmen herangezogen für das Tijuana River Estuar, die Los Penasquitos Lagune und den San Dieguito River. Analysen dieser Daten und zugehöriger aus den San Dieguito River. Analysen dieser Daten und zugehöriger aus den Archiven belegen, daß sich die Morphologie dieser Öffnungen sehr rasch mit Veränderungen des Tidenhubs umgestaltet. Springtidefluten und Sturmflutströmungen beseitigen Strandsedimente aus den Öffnungen und stellen deren stabile Lage weider her. Instabilität und gelegentlich sogar Verschluß kommt vor, wenn hohe Wellen mit Nipptiden zusammenfallen. Gezeitenöffnungen in gröberen Sedimenten haben die Tendenz zu geringerer Stabilität, verglichen mit jenen in sandiger Umgebung.—*Dieter Kelletat, Essen, FRG.*

Washover fan on Ocean Isle, North Carolina. Storm surge and waves from Hurricane Hugo eroded and breached this dune field at Ocean Isle, North Carolina, creating a large washover fan. Up to 30 m of dune erosion occurred in this area as a result of the hurricane; narrower dunes were often completely removed or breached. The quantity of sand moved landward as washover is significant: this deposit is up to 1.5 m thick, and covers nearly 500 m^2. (Photograph: Duke University Program for the Study of Developed Shorelines, Durham, North Carolina. Courtesy of Robert Thieler).