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Barrier Breaching Processes and Barrier Spit Breach, Stone Lagoon, California

By

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ABSTRACT

Review of the literature of barrier island and barrier spit breaching reveals there is a paucity of information on the physical processes beyond qualitative reporting of case studies, despite the significant potential environmental and societal consequences that unintended breaches can bring. A breach susceptibility index is introduced to classify breaching potential by storm surge or equivalent inundation mechanism. A recent breach of the barrier spit enclosing Stone Lagoon, located on the Pacific Ocean coast, Humboldt County, northern California, provides background for the discussion. The spit is believed to have breached seaward between March 13 and 15, 2002. Aerial photography was flown four times at approximately weekly intervals from March 18, documenting breach closure, movement of the ephemeral ebb shoal, and initial recovery of the barrier spit.

Additional Keywords: Barrier islands, inlets, Humboldt Lagoons State Park, Big Lagoon, Mecox Pond, Little Pikes Inlet, overwash, storm surge

INTRODUCTION

In a coastal context, a breach is a new opening in a narrow landmass such as a barrier spit or barrier island that allows water to flow between the water bodies on each side. Breaching can occur naturally or be artificially induced, and it can have positive or negative consequences. Coastal ponds, lagoons, and blocked river mouths are sometimes breached purposefully and, usually, temporarily. Common reasons for induced breaching are: (a) to reduce water level in the water body that might cause flooding of neighboring property; (b) to decrease or to increase salinity in the lagoon or bay, depending on the situation; (c) to promote water exchange or flushing for improving water quality; and (d) to facilitate migration of marine organisms. Photographs in Figure 1 were taken several hours after a breach was cut by backhoe at Mecox

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Pond, facing the Atlantic Ocean on the south shore of Long Island, New York. Without almost annual artificial breaching, water level rises in the pond, and basements of bordering residences flood. The artificial breaching, or "pond letting" as referred to by the residents, has been conducted at Mecox Pond for more than a century. The breach is left unattended to close under littoral processes, as documented by Smith and Zarillo (1988). Several California river entrances such as the Carmel River, Russian River, and Salinas River are artificially breached for such purposes as prevention of flooding of farmland and to open migration paths for salmon.

Unintended breaching of barrier islands and spits can be a serious concern in developed areas or where critical habitat is endangered. A breach can cause loss of human life, flooding and wave attack, loss of property or access to property, loss of habitat, exposure of the bay or estuarine environment to ocean waves, and unwanted changes in salinity and water level. Figure 2 shows Little Pikes Inlet, the name of the breach that opened from the seaward side on eastern Long Island, New York (Terchunian and Merkert 1995), in December 1992. The barrier island breach gradually increased in width from about 30 to 1,500 m, forming a semi-permanent inlet that was later closed at considerable expense. Besides loss of structures in the path of the breach, its presence denied access to homes and the county park located on the western side. Tide range and salinity in the back bay increased while the breach was open. Breaching of the barrier island or spit near a jetty, such as reported by Sorensen and Schmeltz (1982) for Moriches Inlet, New York, can compromise the structure by stranding it. For these reasons, the New York District of the U.S. Army Corps of Engineers, in cooperation with the State of New York, has developed a breach-contingency plan for the south shore of Long Island that includes strategic stockpiles of sand and rapid communication lines between Federal and State Governments to close breaches quickly that may open during storms.

Breaching can lead to formation of a new inlet that may compete favorably for dominance of the tidal prism and stability with existing inlets in the same bay system, possibly promoting their closure. A trend toward closure of an existing inlet, particularly if stabilized by jetties, can make navigation unreliable and may hold environmental consequences because of changes in water level and circulation pattern. Breaching of barrier islands, spits, and river mouths occurs throughout the United States every year. Despite its potential significance, barrier breaching has received little study as compared to other coastal geomorphic processes. Basco and Shin (1999) developed a one-dimensional (1D) model of overwash and incipient breaching (their model did not scour a deep gorge) by combining 1D storm surge and wave models with the SBEACH model of beach profile change (Larson and Kraus 1989; Larson et al. 1990). The work of Basco and Shin is pioneering and reveals many questions to be answered. Visser (1998) summarized engineering analysis performed in The Netherlands to understand and model breaching of dikes.

The northern coastal stretch of Humboldt County, located in northern California, is characterized by a succession of headlands defining pocket beaches and lagoons backed by mountain slopes and meadows. The Humboldt Lagoons State Park is comprised of four lagoons that are isolated from the Pacific Ocean by wide and high barrier sand spits extending between adjacent headlands (see cover photograph of this issue of *Shore & Beach*). From south to north they are Big Lagoon, Dry Lagoon (drained in the early 1900's to serve as farmland), Stone Lagoon, and Freshwater Lagoon (Figure 3). The region is bounded on the south by a large headland, Patricks Point, and on the north by Redwood Creek, part of the Redwood National

Park. North- and south-directed longshore sediment transport rates are large along this coast, but migration of a long spit extending north of the mouth of the Mad River located further to the south (Komar, Borgeld, and Allen 2000) and other evidence indicates that the net direction of transport is to the north (Costa and Glatzel 2002).

Fed by small streams, Big Lagoon and Stone Lagoon are prone to breach during or near the end of the rainy season (Joseph 1958) that occurs from October to April, Figure 4, when the water level in the enclosed lagoons can rise considerably above mean sea level in the Pacific Ocean. Recent breaching of Stone Lagoon, believed to have occurred between March 13 and 15, 2002, is the subject of this paper, serving as a case study and focus for review of breach processes.

BREACH PROCESSES

Breaching potential is achieved if the water level on one side of a narrow barrier spit or island exceeds some critical elevation in relation to the crest of the barrier. Duration of higher water level is also a contributing factor. Breaching can happen in two ways (Pierce 1970). A breach may occur if running surface water scours a trough between the sea and the body of water protected by the barrier. Such inundation can proceed from either the seaward side or the bay (estuary, lagoon, river) side, and this process typically occurs from the sea side during times of sustained high water levels (storms and storm surge). As another mechanism, if the barrier spit is relatively narrow, seepage through the porous sediment driven by differences in water elevation can liquefy the sediment-water mixture, allowing large volumes of material to be transported quickly as slurry. This breaching is typically from the bay side, and it is not necessary for the water level to have reached the top of the barrier spit or island.

Breaches opened artificially by digging a narrow channel across a barrier separating water bodies of different levels will quickly deepen and widen, the water slicing through the barrier, cutting steep side slopes. Growth and stability of the breach will depend on maintenance of a sufficiently strong flow, as driven by a tidal exchange, river flows, or wind. Typically, artificially opened breaches close naturally, such as at Stone Lagoon, and waves disperse the ebb shoal while moving it onshore. The ebb shoal generated during a breach is an ephemeral feature, unlike the flood shoals and flood wing spits that often become permanent and vegetated because they are sheltered from sea waves.

Breaching potential is minimized if the barrier is high and wide, for which barrier elevation and volume above mean sea level are key factors for resisting inundation and erosive wave attack during times of the higher water level. On the Atlantic Ocean and Gulf of Mexico coasts of the United States, breaching typically occurs from the seaward side through the combination of elevated water level (storm surge is an increase in average water level above the predicted astronomical tide) and large waves accompanying tropical storms, hurricanes, and northeasters. Figures 1 and 2 are examples of breaching from sea to bay. At lower lying areas along the Pacific Ocean coast, breaching of barriers from the seaward side also occurs, such as at the mouths of small river and lagoon entrances that open and close periodically, possessing beaches that do not reach adequate elevation to resist opening. Inman (1950) discusses the role of extreme tides in influencing spit evolution at Mugu Lagoon, California.

At times of intense precipitation by coastal storms or through rainfall in the watershed, breaching can occur from the landward side because of unusually high bay, estuary, lagoon, or river water level, causing either seepage and failure of the barrier or scour by water flow over the barrier toward the sea. For the barrier spits of the Humboldt County lagoons, small streams and runoff during the rainy season gradually raise the water level and cause breaching from lagoon to ocean by seepage and failure.

BREACH SUSCEPTIBILITY INDEX

Natural breaching from the seaward side depends on elevation and width of the land barrier, elevation of the surge, duration of the surge, and wave height and period, as leading factors among others. Here we introduce a quantity termed a "breach susceptibility index" that explains in part the tendency for barriers to breach from the seaward side. The breach susceptibility index B is defined as:

$$B = S_{10}/R \qquad (1)$$

where S_{10} is the effective surge level for the 10-year storm (as defined by water level), and R is the diurnal tidal range. The logic behind the index is that barrier islands and spits will build to at least a minimal elevation given by the highest regular tide, wave and wind set up, and wave runup. If the surge of a representative storm (also accompanied by set up and runup) approaches the diurnal tide range, then breaching is likely. The parameter S_{10} refers to an effective 10-year storm surge, because definition of such a quantity for the Pacific coast of the United States is difficult. On the northern Pacific coast, tropical storms are absent, but there are several independent contributions to extreme water levels from ENSO (El Niño-Southern Oscillation) events, infragravity waves or surf beat – long-period surface waves (Inman and Jenkins 1989 – who also discuss wave runup and set up for the Pacific coast; Komar, Diaz-Mendez, and Marra 2001), tsunami (seismic waves), and local and distant storms. The steep continental slope of the Pacific coast suppresses storm surge, and a 0.3- to 0.9-m surge is considered large (e.g., Komar 1986; Flick 1998; Komar, Diaz-Mendez, and Marra 2001). In contrast, on the Atlantic and Gulf coasts, storm surges can exceed 4 m, typically exceeding 1 m each year. In defining the breach susceptibility index, the 10-year storm surge is employed as a quantity that is statistically stable yet describes a relatively frequent occurrence that might cause breaching. The index is intended as a regional overview and does not include specifics of the barrier island or spit configuration, which would need to be considered at the next step of quantification. Similarly, duration of the storm surge is not explicitly included, although it is accounted for implicitly in the 10-year surge.

Through consultation of a number of references, representative values of the breach susceptibility index were compiled as listed in Table 1. The index varies over more than an order of magnitude, with smaller values associated with the northwest Pacific and larger values with the Louisiana and Texas coasts. The relatively small tidal range on the Louisiana and Texas coasts indicates that sand-deficient parts of those coasts, having low barrier islands and spits where wind cannot readily build dunes, will be susceptible to inundation and breaching during storms. Breaching and overwash of Padre Island, Texas, the longest continuous barrier island in the world, is well known. Price (1947) reports as many as 45 temporary breaches in the island after passage of a hurricane in 1933, and Hayes (1967) mentions "numerous hurricane channels" cut after the 1961 Hurricane Carla. The northwest Pacific coast is relatively robust in resisting breaching from the seaward side, because the large tide range allows waves to create high and wide beach berms (if sediment is available), and the surge is relatively weak. In summary, it appears that for areas with a breaching susceptibility index greater than a critical value around unity are more prone to breach from the seaward side than those that have a value much less than unity.

HUMBOLDT LAGOONS

The barriers enclosing the lagoons of the Humboldt Lagoons State Park are spits that emanate from the rocky headlands and are composed mainly of medium sand, pebbles, and some cobble carried by the longshore current. Spits are narrow sand bodies that grow toward open water from a sand source. The longshore spits fronting the lagoons of Humboldt County are remarkable in being straight and of near-constant width. Spit recurving is a commonly observed morphologic feature at natural tidal inlets (those unmodified by structures), whereby the terminus of the spit will curve bayward. Schwartz (1972) compiled classic papers on spit geomorphic processes; Kraus (1999) presents simple mathematical models describing spit elongation; and Kraus and Seabergh (2002) describe physical and mathematical modeling of spits at inlets. Growth of the spits in a straight line from headland to headland, as well as their relatively constant width, indicates that surge and tidal processes, which cause spit recurving, overwash, and breaching, are weak compared to longshore processes. Pierce (1970), Leatherman (1981), and Byrnes and Gingerich (1987), among others, describe overwash processes of barrier islands and spits. The Humboldt lagoon barrier spits are similar in uniformity to spits observed in the interior of bays and lakes, where the tidal range is moderate and storm waves attenuated.

The competing transporting mechanisms at a breach or inlet on a tidal coast are depicted in Figure 5. Positional and locational stability of a breach or inlet, as well as cross-sectional area of the channel through the opening, are determined by a balance of the sweeping action of the tidal (and river) current and the delivery of sediment by the longshore current (Bruun and Gerritsen 1959, 1960; Kraus 1998). Although breaches of the Humboldt County lagoons are initiated during higher elevations of lagoonal water, discharge of the excess water to achieve approximate equality with sea level occurs within a day or so. After that, tidal action controls the sweeping force, and the lagoonal surface areas are too small to maintain the necessary velocity for the breach gorge to be self-scouring.

Table 2 lists various factors and their associated time scales that influence development of spits and elongation of barrier islands. An alongshore-directed current is required to transport sediment from its source. As the subaqueous platform of the spit is established (Meistrell 1972), the spit emerges, and onshore-directed motions associated with wave run up raise its elevation. The maximum elevation achieved by this process occurs at high tide. During times of high mean water level, wave action can wash sediment landward as sheets. The overwash process (the hydraulic action) produces the geomorphologic feature of washover – fans of sediment deposits.

No dedicated study exists of the physical processes of breaching of the Humboldt Lagoons State Park barrier spits, the few studies available primarily concern biology and chemistry. Residents and park officials are well aware of breaching in Big Lagoon, which occurs annually, and of Stone Lagoon, which occurs every several years. Big Lagoon has a greater drainage area than Stone Lagoon, and a bigger surface area to maintain tidal exchange, so breaches of the Big Lagoon spit tend to persist longer than those of Stone Lagoon (Joseph 1958; Markle 1996). Joseph (1958) documents five breach events (one of these being artificial) of Big Lagoon from October 1956 to January 1958. Analysis showed that breaching occurs if the water elevation in the lagoon reaches 3 to 4 m above mean sea level in the ocean. For these breaches, excess water drained from the lagoon over a period of about 24 hr. Markle (1996) documents breaching of Stone Lagoon during March 18 to May 19, 1989, and again from February 26, 1993 to "early May." He also mentions an artificially induced breach on June 13, 1993, and states there was a "brief breach" on May 31, 1987. With this background established, the March 2002 breach of Stone Lagoon is described next.

MARCH 2002 BREACH OF STONE LAGOON

In discussion with local residents, it is believed that Stone Lagoon breached on its southern side between March 13 and 15, 2002. The Stone Lagoon spit has tended to breach on its southern end, as can be seen by the more narrow width and elevation in Figure 6, a time with no breach present. Persistent breaching on its southern end is attributed to: (a) a line of rocks located on the southern end, aligned normal to the shore (Figure 7; picture taken 5 months before the March 2002 breach), that may tend to promote local erosion on the downdrift (north) side; (b) erosion of the southward end if sediment is not supplied from the headland source area; (c) efficiency of flow in being located nearer to open water in the lagoon; and (d) pre-existing weakness from previous breaches that does not allow full recovery of spit elevation and width.

Available photographic documentation of the March 2002 breach is summarized in Table 3. The collection includes many photographs, of which only a few can be presented here. The first ground photographs were taken from the eastern bluff (eastern side of Stone Lagoon) on March 16. Figure 8 shows a calm sea, wing spit on the northern side of the breach, and a large multi-crested flood shoal at relatively low tide. Ground photographs were taken near low tide on March 18 from within the breach on the north side. A large log was found lying on the edge of the south bank of the breach (Figure 9), and the horizontal portion on top of the spit berm was measured to be 8 m long. This log was visible in the aerial photographs and served as a scale in their rectification and comparison. Figures 9 and 10 show the presence of steep side banks, estimated on site to be 3.4 m high from crest to toe, along with another 1-m elevation estimated from the toe to the edge of the water in the breach at low tide.

Other ground photographs show debris lines on the interior of the spit north of the breach. The highest debris lines were near the top of the spit, indicating the high water level in the lagoon before the breach took place. Upon breaching, the spit was cut from the lagoon to the ocean, and ground observation showed that the interior margin of the north barrier spit near the breach had been scarped (to at least 2 m) by the current (probably the ebb current upon incipient breaching) that ran parallel to it. The scarping diminished with distance from the breach.

Vertical aerial photographs for March 18, March 27, April 6, and April 18 are shown in Figure 11. The photographs were taken near predicted low tide (Table 3) and can be compared at approximately the same water level. The breach initially cut through the barrier spit at a mild oblique angle from shore normal, trending northwest to southeast, as evidenced by the shear bank on the south side. Within a few days (March 18), a broad spit had formed on the south side, and a narrower wing spit had also formed on the north side, redirecting the flow along a southwest-to-northeast axis. The minimum width of the breach was 91 m +/-5 m as determined from the March 18 photograph. An ebb shoal deposit is observed on March 27 that is located slightly to the north with respect to the breach, a location consistent with the inferred initial orientation of the breach. By April 6, the breach had closed at low tide, but was observed to have water in it on higher tide. The ebb shoal had begun welding to shore, and it evidently spread north and south to form a wide deposit across the breach by April 18. The flood shoal appears to diminish in area; however, there is no transporting force to remove sediment from this shoal. The apparent diminution in areal extent of the flood shoal and breach margins is an artifact of water level in the lagoon that rose after the breach closed.

The sequence of four photographs was rectified by reference to the log on the south side of the breach and other features common to all photographs. The result of tracing the interpreted dry beach perimeter is shown in Figure 12. The interpreted dry shorelines on the northeastern side of the barrier spit and on the straight southeastern bank do not show significant change in location, owing to their relatively steep slopes. The perimeter of the flood shoal and large spit located on the southeastern side of the breach decreases each week of sampling because of the mild slopes of these deposits. According to Figure 3, infilling of the lagoon by creeks and runoff from the bluffs can be expected to overcome evaporation for the months of March and April.

CONCLUDING DISCUSSION

Review of the literature revealed that there is a paucity of information on the physical processes associated with breaching of barrier islands and spits beyond qualitative reporting of case studies, despite the significant potential environmental and societal consequences that unintended breaches can bring. In fact, the word “breach” does not appear in the indexes of most references and textbooks on coastal geomorphology and coastal engineering. Breaching can occur from either the seaward side or the bay (estuary, lagoon, river) side, depending on relative water elevation. The breaching process can occur either by scour produced by surface water flow or by seepage and liquefaction. Narrow breaches widen and deepen quickly, and the side banks of a breach are initially very steep after breaching. Depending on the magnitude of water exchange between the sea and the bay, a breach can quickly close, as at Stone Lagoon, or remain open and perhaps become a dominant inlet such as at Little Pikes Inlet, thereby jeopardizing the stability of existing inlets and jetties.

A susceptibility index was introduced to estimate the tendency of barrier islands and spits to breach from inundation from the seaward side. Defined as the ratio of the effective 10-year storm surge and the diurnal tidal range, a breaching susceptibility index value greater than unity indicates greater possibility for breaching than a value less than unity. The breaching susceptibility index explains in part why breaching and inundation are commonly observed processes on the Texas and Louisiana coasts, and why they are less so on the Pacific coast, with barrier islands and spits on the Atlantic coast intermediate in potential to breach.

Barrier spits enclosing lagoons can also breach by gradual rise in water level on the backside, likely through seepage and failure by liquefaction. Previous work (Joseph 1958) found that a critical water level in the enclosed Big Lagoon about 3-4 m above local mean sea level of the Pacific Ocean triggered breaching from the lagoon side. Barrier spits across Big Lagoon, Stone Lagoon, and Freshwater Lagoon are approximately of the same width and elevation, as all share the same littoral system. Breaching of the barrier spit across Big Lagoon occurs more frequently than at Stone Lagoon because Big Lagoon is fed by more streams. Rapid filling and more frequent reaching of critical water elevation at Big Lagoon are responsible for more frequent breaching there as compared to Stone Lagoon.

The March 2002 breach of Stone Lagoon closed to low tide water exchange within a week after opening. Breach orientation appeared to shift substantially, caused by strong infilling by longshore transport and encroachment of the associated spit that had formed on the south side of the breach. Both banks of the interior of the initial breach were steep. The width of the relatively narrow breach area greatly increased through welding of the ephemeral ebb shoal deposit to the beach. Water level in the lagoon began rising after breach closure, and within a month much of the flood shoal and breach spits were submerged.

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a. Looking north toward Mecox Pond.

b. Looking east, at breach cut through the beach berm.

Figure 1. Mecox Pond, breached the morning of February 14, 1998, (photographs by N. Kraus, afternoon of February 14).

Figure 2. Little Pikes Inlet (barrier island breach), Long Island, New York, shortly after opening (photograph by N. Kraus, December 18, 1991; looking east toward Westhampton Village, with Atlantic Ocean on the right).

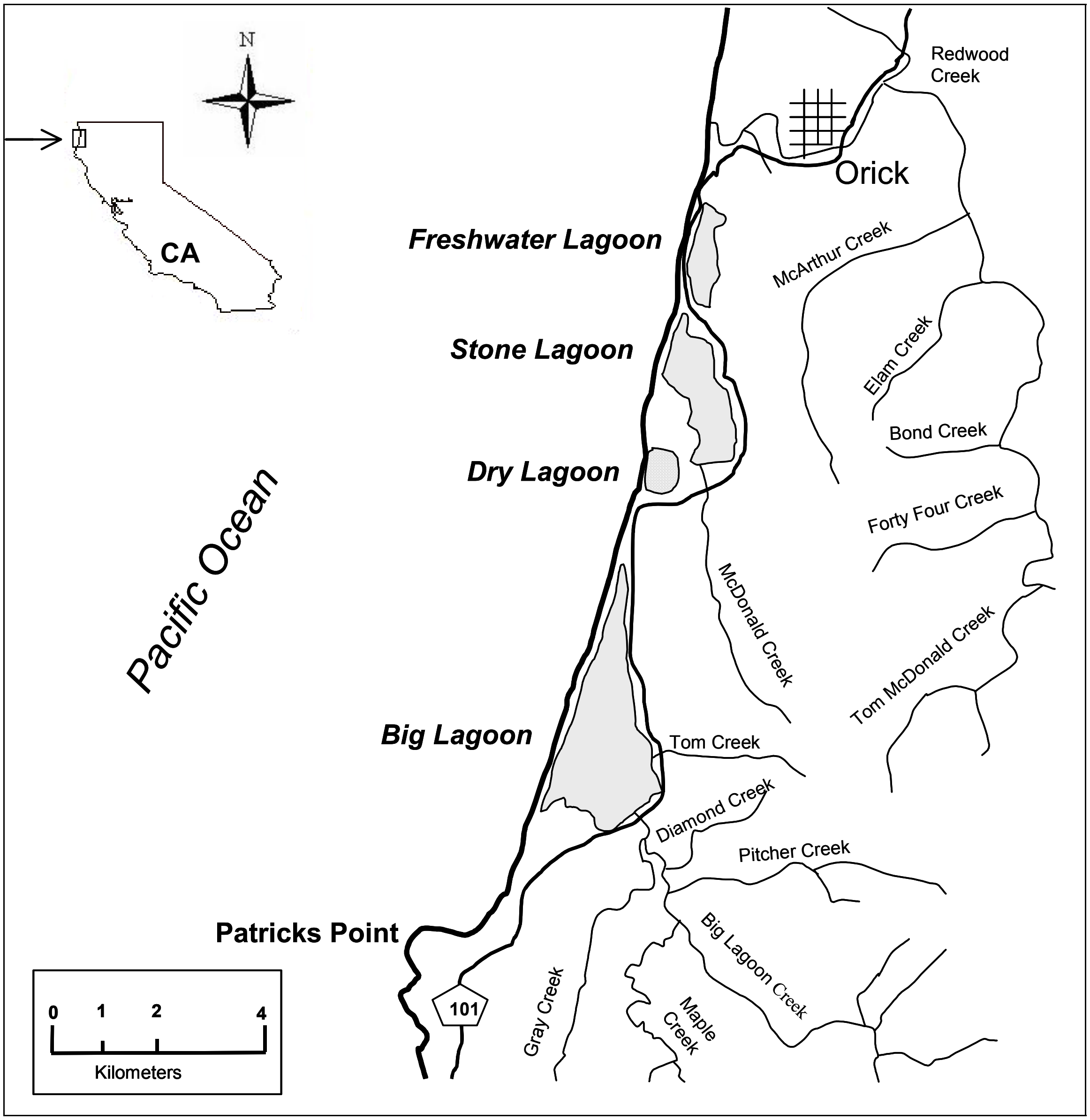


Figure 3. Location map, Stone Lagoon, northern California.

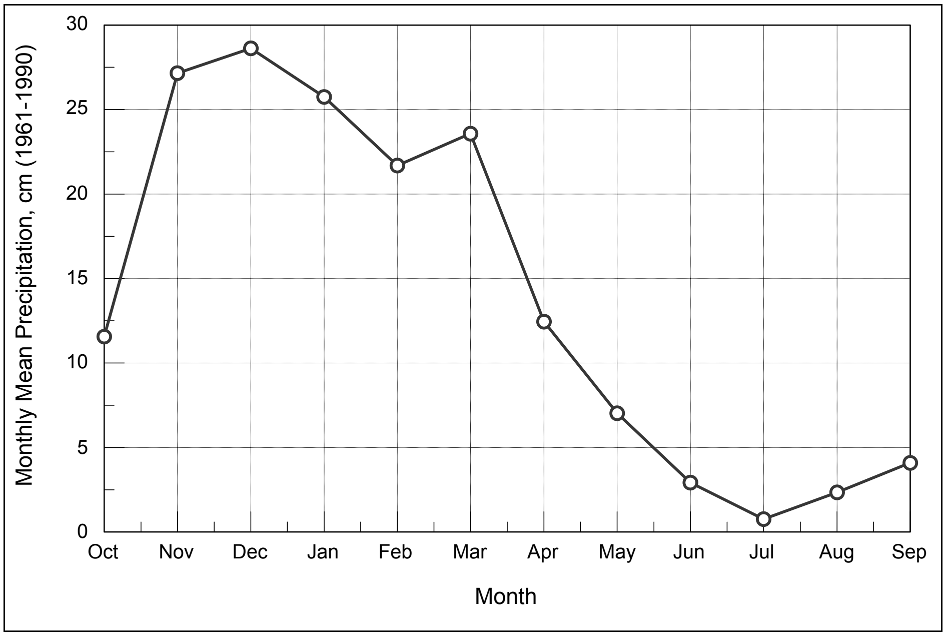


Figure 4. Mean annual rainfall by month (data obtained from Desert Water Institute; http://www.wrcc.dri.edu/cgi-bin/cliNORMNCDC.pl?caoric.

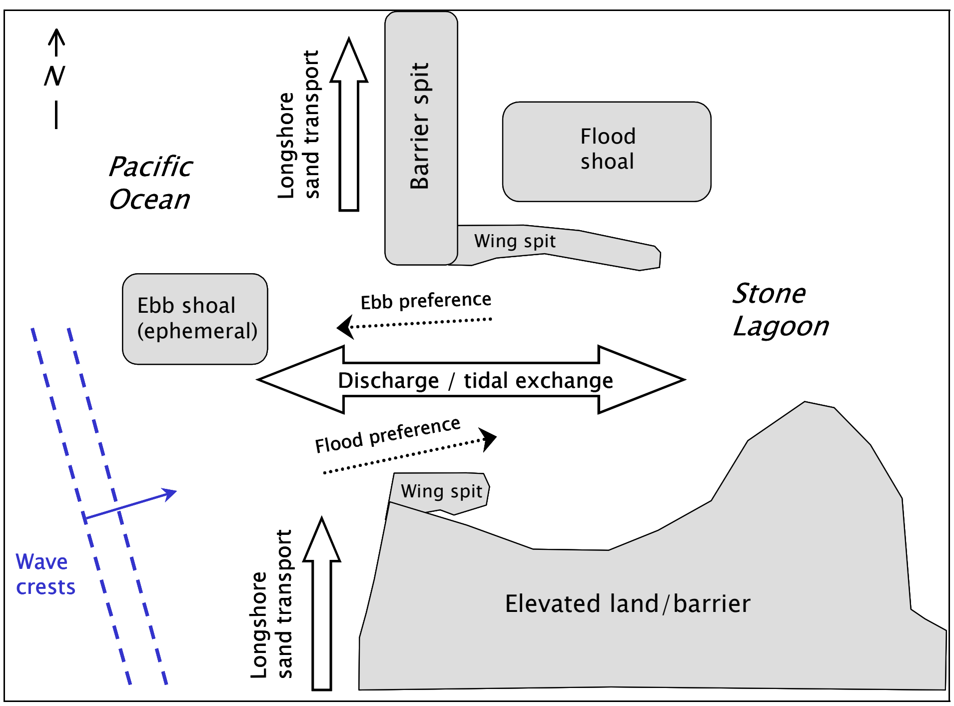


Figure 5. Transporting mechanisms at a breach.

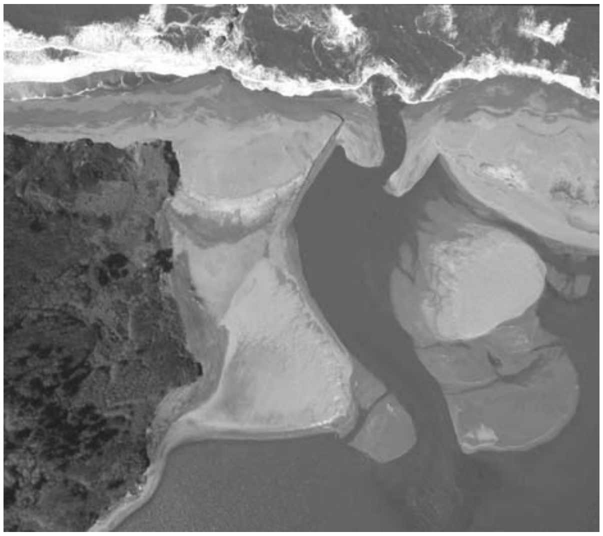
Figure 6. Stone Lagoon, looking northeast, December 1999 (photograph by G. Todoroff).

Figure 7. Southern end of Stone Lagoon spit, looking east, October 10, 2001 (photograph by G. Todoroff).

Figure 8. Stone Lagoon spit breach, looking west, March 16, 2002 (photograph by G. Todoroff).

Figure 9. Stone Lagoon breach with log hanging over south bank, looking southeast, March 18, 2002 (photograph by A. Militello).

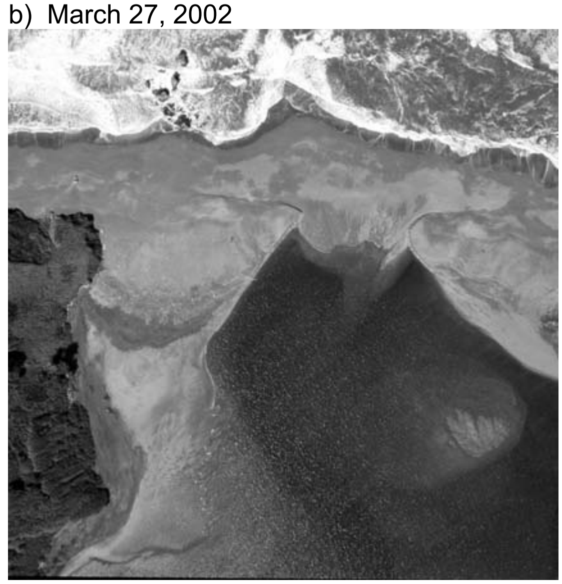
Figure 10. Stone Lagoon breach, looking east, March 18, 2002 (photograph by A. Militello).



a) March 18, 2002

b) March 27, 2002

c) April 6, 2002



d) April 18, 2002

Figure 11. Time sequence (a-d) of vertical aerial photographs, Stone Lagoon breach, with Pacific Ocean at top of pictures (photographs by G. Todoroff).

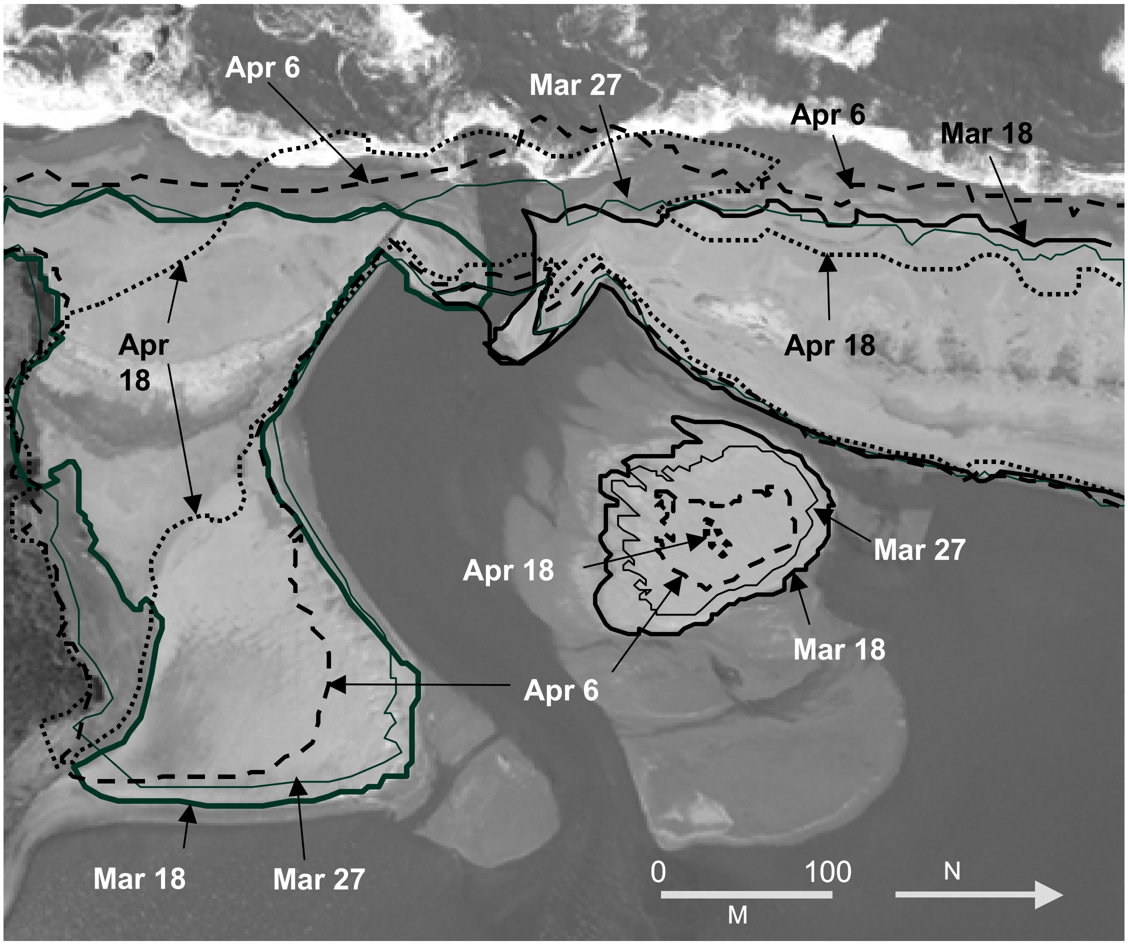


Figure 12. Stone Lagoon: contours of dry perimeters at four sampling times within 1 month after breaching.

Table 1. Representative values of the breach susceptibility index $B = S_{10}/R$ for selected locations

Location, USA	**Surge, S_{10} (m)**	**Diurnal Tide Range, R (m)**	**Breach Susceptibility Index, B**
New York, New Jersey	1.5	1.5	1.0
Florida (Atlantic side)	1.0	1.0	1.0
Louisiana, Texas	1.5	0.5	3.0
Northern Calif., Oregon, Wash.	0.5	2.0 to 2.5	0.25 to 0.2

Table 2. Parameters controlling spit geometry and evolution, and the associated processes (from Kraus 1999)		
Spit Parameter	**Short Term**	**Long Term[1]**
Length	Longshore transport rate; proximity to inlet channel; strength of channel current	Sediment supply; geologic controls; breaching (bayward or seaward); cyclic & intermittent forcing
Elongation speed	Longshore transport rate; grain size; proximity to inlet channel; beach slope and depth-contour gradients parallel to spit	Cyclic and intermittent forcing[2]
Width	Run-up elevation; tidal range; depth-contour gradients perpendicular to spit	(see Overwash fans below)
Overwash fans	Storm surge; frequency of storms	Dunes and other blocking features; depth of receiving bay or lagoon
Elev. above mean sea level	Run up; tidal range	Aeolian transport; relative sea-level change; tsunami
Depth of closure	Wave height and period; tidal range; grain size	Extreme storms; elapsed time
Tendency to recurve	Proximity to channel; channel current; wave focusing; extreme storms	Cyclic and intermittent forcing

1. Long-term processes encompass those of short-term processes in same category.
2. Cyclic and intermittent forcing arises from seasonal and annual changes in wind and waves, arrival of storms and weather fronts, annual and inter-annual change in water level, etc.

Table 3. Photograph availability, year 2002, local time	
Date and Time	**Comments**
March 16, 1500	Ground, from mainland, east side of spit
March 18, 1115	Aerial, 3 hr after low tide; 5 days after breach
March18, 1300	Ground, from north side of spit
March 27, 1515	Aerial, 90 min before low tide
April 6, 1415	Aerial, 30 min after low tide
April 18, 1100	Aerial, 30 min after low tide