Barrier beach breaching from the lagoon side, with reference to Northern California

By

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ABSTRACT

During the dry season in California, when storm action is limited and river flow is weak, the mouths of many estuaries close, creating barrier beaches and ponding water in the backing lagoons. If these barrier beaches do not breach naturally or are not manually breached, flooding hazards can develop in adjacent low-lying areas. Many barrier beaches are breached manually to facilitate migration of salmon or the threatened steelhead trout. Natural and manual breaching of barrier beach lagoons holds consequences for species transiting or inhabiting such freshwater lagoons. This paper discusses the breaching processes of barrier breaches on the coast of northern California, for which a new breaching susceptibility index is introduced. Susceptibility of breaching from the lagoon side is found to be related to the ratio formed as the water-head difference between the lagoon and ocean divided by the width of the barrier beach. The index indicates that a barrier beach will tend to breach where it is most narrow, which is commonly observed. The head difference represents the destructive force promoting breaching, and the barrier width represents the constructive force resisting breaching. The susceptibility index is tested successfully through case studies of the Carmel River Lagoon, Lake Earl, Redwood Creek, Russian River Estuary, and Stone Lagoon.

This paper is based on a presentation made in a symposium entitled "Bar-Built Freshwater Lagoons" convened at the American Fisheries Society's 137th annual meeting held in San Francisco in September 2007. The symposium's goal was to promote exchange of information between biologists and physical-process researchers for the improved management of environmental resources associated with coastal lagoons fronted by barrier beaches. Such lagoons are referred to locally as bar-built estuaries or lagoons. They typically serve as habitats for one or more federally listed threatened or endangered species. Species of notable interest, but not representing a comprehensive list, are Pacific salmon, steelhead trout, and tidewater goby. Natural and manual breaching of barrier beach lagoons holds consequence for all species inhabiting or transiting coastal lagoons. A barrier beach is a long, narrow sand or gravel body aligned parallel to the coast that forms across estuaries and river mouths, and which is not submerged by the tide.

ADDITIONAL KEYWORDS: Coastal breaching, Carmel River Mouth, inlets, Lake Earl, Redwood Creek, Russian River Estuary, Stone Lagoon, breach susceptibility index.

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The present discussion concerns barrier spits, although it could also pertain to barrier islands.

The United States contains the largest number (405) and greatest length (4,900 km) of barrier islands of any country (Pilkey 2003). Although less evident than those of the Atlantic and Gulf coasts, barrier beach features in the form of spits are present on the west coast of the United States. Approximately 338 km (or 20%) of the California coastline has been classified as barrier sand and gravel spits (Converse 1982). In California, coastal lagoons can be tidal or non-tidal, saline, brackish or fresh, and with entrances that are always, never, rarely, or periodically open. Opening of an inlet through breaching governs the depth, duration, and frequency of flooding in the lagoon, as well as tidal exchange and salinity.

Engineering aspects of coastal breaches were reviewed for *Shore & Beach* readers by Kraus *et al.* (2002), which included a case study of Stone Lagoon, California. The analytical emphasis of that paper was on breaching from the ocean side. In the present paper, the literature review is updated, and focus is given to breaching from the lagoon side of central and northern California barrier beach lagoons, for which a breaching susceptibility index is introduced.

BREACH PROCESSES

Pierce (1970) described the process of natural breaching of barrier beaches as occurring in two ways. A breach may open if running surface water or overflow scours a trough between the sea and the body of water (referred to as a lagoon here, but also estuary, closed river

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14. ABSTRACT
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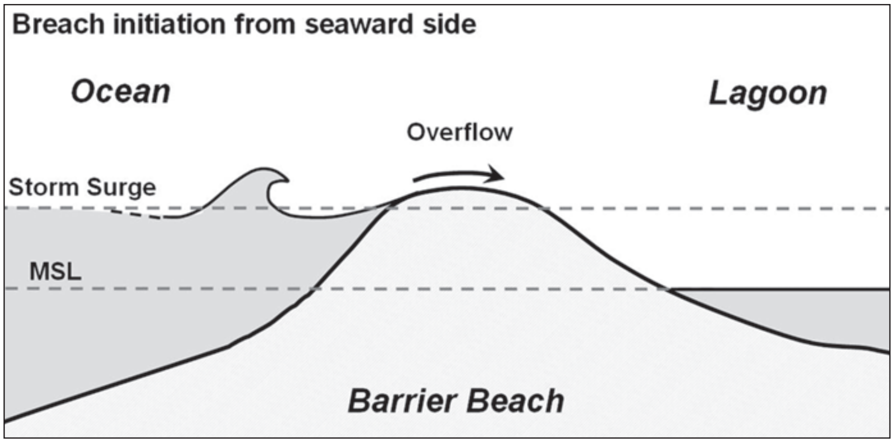

Figure 1. Barrier beach breaching from the sea side.

Figure 2. Barrier breaching from the lagoon side.

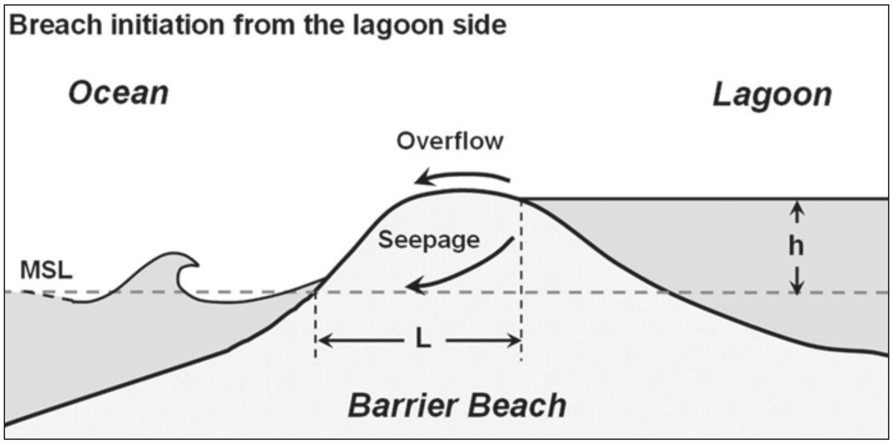

Figure 3: Location map depicting Lake Earl, Redwood Creek, Stone Lagoon, Russian River Estuary, and Carmel River Lagoon, California

mouth, or bay) protected by the barrier or if the water flows through an existing low in the barrier beach. Such inundation can proceed either from the seaward side or from the lagoon side. On U.S. Atlantic Ocean and Gulf of Mexico coasts, this process typically occurs from the sea during times of sustained high water level and high waves, in particular during the surge associated with northeasters or tropical storms (Kraus *et al.* 2002). On the California coast, barrier beaches commonly breach from the lagoon side through filling by groundwater inflow, runoff, river inflow, and direct precipitation that cause overflow at the lowest part of the barrier.

The second mechanism identified by Pierce (1970) occurs if the barrier beach is relatively narrow so that seepage through the porous sediment driven by differences in water elevations between the ocean and lagoon liquefies the sediment-water mixture, allowing large volumes of material to be transported quickly as slurry. This type of breaching typically occurs from the bay or lagoon side, and it is not necessary for the water level to reach the top of the barrier beach. Breaching by seepage and possibly liquefaction is observed to occur frequently on the narrow barrier beaches along the South African coast (Zietsman 2004). Stretch and Parkinson (2006) state that 70% of South African estuaries can be classified as temporarily open. These barriers are typically narrower and lower than those along the northern California coast. Breaching processes have been reviewed by Kraus and Wamsley (2003), and action of the water table and its change by tide elevation and wave run-up (Horn 2002) have yet to be explored for their influence on the breaching process. Figures 1 and 2 are schematics summarizing the natural breaching processes from the seaward side and from the lagoon side of a barrier beach.

In many communities, if the water level becomes high, lagoons and coastal ponds are manually breached to prevent flooding of adjacent private property and infrastructure, and to improve water quality of stagnant lagoons (see review by Wamsley and Kraus 2005). At some sites, especially along the coast of California, biologists attempt to evaluate the best season and conditions for breaching to replicate and maintain the natural ecological functioning of the system (Elwany *et al.* 1997, 1998,

2003; Hofstra and Sacklin 1987). A breach can be manually induced by digging a narrow channel across the barrier separating water bodies of different levels. The trench or pilot channel will quickly deepen and widen, the water slicing through the barrier and cutting steep side slopes (Kraus *et al.* 2002; Wamsley and Kraus 2005). The pilot channel is usually opened just before the tide in the ocean turns to low to maximize the duration of seaward flow. Initial strong ebb flow minimizes the possibility of beach and littoral sediment entering the lagoon or pond, covering its bottom and creating flood shoals, removing sediment from the beach in the process. On the other hand, if formation of a flood delta is a desired goal, as for habitat creation, the pilot channel should be opened with approach to high tide. Growth and stability of a breach from the lagoon side will depend on the flow as driven by the initial stored water volume behind the barrier beach (Stretch and Parkinson 2006), tidal prism, river flow, set up of water against the lagoon side of the barrier beach by wind, and longshore and cross-shore sediment transport on the ocean side.

Figure 4: (above) Lake Earl, 2002. Copyright © 2002-2007 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org; (below) Lake Earl, December 2005, the day the barrier was breached (photograph courtesy Art Reeve, Del Norte County).

Figure 5: (above) Redwood Creek, 2005. Copyright © 2002-2007 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org; (below) Redwood Creek, October 2005, three weeks before breaching (photograph courtesy David Anderson, National Park Service).

Typically, manually opened coastal breaches of small lagoons close naturally by wave-driven longshore sediment transport (Smith and Zarillo 1988; Goodwin and Williams 1991). Waves also disperse the material originally ejected from the breach while moving it onshore. The ebb shoal created 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 (Kraus et al. 2002). Closure of seasonally open small tidal inlets was investigated by Ranasinghe and Pattiaratchi (2003), who demonstrated that onshore transport of material can induce closure if the longshore sediment transport rate is small or inadequate. Smakhtin (2004) investigated temporarily open small inlets through the volume of water introduced in relation to a quantity called the lagoon volume capacity that serves as a model parameter. Stretch and Parkinson (2006) performed small-scale physical model experiments on breaching of narrow barriers and also analyzed earth dike data (Wahl 2004). From their own and other data, they developed an expression for the final width of a breach that opens from the lagoon

Figure 6 (above): Stone Lagoon, 2002. Copyright © 2002-2007 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

Figure 7 (below): Russian River Estuary, 2002. Copyright © 2002-2007 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

Figure 8: Carmel River Lagoon, 2004. Copyright © 2002-2007 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

side (omitting longshore sand transport), finding that this width scaled as the cube root of the total volume of water that flows through the breach. Battalio *et al.* (2007) discuss application of a closure criterion that has been applied to several barrier breaches in California. This criterion depends on the ratio of wave power and tidal power, introduced by O'Brien (1971) as modified by Johnson (1973). Battalio *et al.* (2007) applied this criterion with success to Crissy Field, an ephemeral inlet located on the southwest side of the entrance to San Francisco Bay.

Komar *et al.* (2001) describe breaching of New River Spit, located in southern Oregon. The river, entering on the southern end of the spit, veers sharply to the north where the permanent mouth is located. The mouth was documented to have migrated 4.7 km to the north between 1967 and 1997. Temporary breaches occur naturally where the river turns, owing to erosion of the lagoon-side bank and relatively low elevation of the spit there. Manual breaching is also performed on the southern end to mitigate flooding. Komar *et al.* (2001) hypothesize that breaches on the southern end of the spit close readily because of the rapid response of the more coarse-grained, cliff-derived sediment there, as opposed to the predominantly sandy sediment to the north where the river mouth is located.

Progress has recently been made in quantitative numerical modeling of coastal breaches. Kraus (2003) introduced a mathematical model of breaching based on geomorphic considerations and found that it produced an exponential growth toward equilibrium. Predictions qualitatively agreed with observations in the laboratory and the field; rapid opening, called incipient breaching, followed by a more gradual growth stage toward equilibrium. The model indicates that depth and width of the pilot channel (deeper but narrower, or shallower but wider) have strong bearing on the growth of the breach. Kraus and Hayashi (2005) extended this model to include numerous coastal physical processes such as hydrodynamics in the breach (flow, water level, waves), sediment transport through the breach, longshore sediment transport by waves and breach closure by channel infilling, and driving of the model by time series of water levels and waves. Wamsley *et al.* (2007) validated the breach-opening portion of the Kraus and Hayashi (2005) model through a large-scale two-dimensional laboratory experiment.

Breaching potential for opening naturally from the seaward side 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. In contrast, at times of intense precipitation or through accumulated rainfall in the watershed, on the California coast breaching commonly initiates naturally from the lagoon side. As is shown below, breaching from the lagoon side appears to be primarily controlled by water elevation difference between the lagoon and ocean and by the width of the barrier beach.

Table 1. Estimated susceptibility index for breaching from the lagoon side

Location, California	h (m)	L (m)	h/L (percent)	Season when breaches tend to occur naturally
Carmel Lagoon	3	30-75	4-10	Fall to early winter
Lake Earl	3	60-20	3-5	Fall to early winter
Redwood Creek	3	25-40	8-12	Fall
Russian River	2-3	60-80	3-5	Fall to early winter
Stone Lagoon	3-4	30-50	8-13	Winter to spring

SUSCEPTIBILITY INDEX FOR BREACHING FROM THE LAGOON

Large uncertainty exists in empirical predictive formulas for earth dam breaching (Wahl 2004), where conditions are expected to be monitored or known more closely than for barrier beaches and spits. In analyzing data for 108 earth dam failures, Wahl (2004) found that predictors for final breach width had an uncertainty of about plus-or-minus one-third order of magnitude, and analytical predictors for initiation of breaches (conditions at time of breach) were lacking. Similar uncertainty is expected in examining barrier beach breaching. In this light, we provide a heuristic derivation of a critical condition for breaching from the lagoon side, which leads to a breach susceptibility index. Breaching is envisioned as a failure of barrier beach due to pressure exerted upon it by elevated water in the lagoon. The breach process could be a combination of overland flow and seepage at described by Pierce (1970). The intent is to identify leading parameters governing breaching initiated from the lagoon side.

Suppose h is the water-head difference in the lagoon to mean sea level (MSL) on the ocean side (notation defined in Figure 2). The average hydrostatic force F_W exerted by the water in the lagoon on the barrier beach can be approximated as:

$$F_w = 1/2\ \rho g h \times hW \qquad (1)$$

where the first factor in the product is the average pressure exerted by the elevated lagoon water on the barrier beach, and the factor hW is the surface area of the barrier upon which the pressure is applied, W being the alongshore length of the barrier under consideration on which the water pressure acts. The resisting force of the barrier beach F_B is expected to be proportional to the weight of the sediment on the barrier:

$$F_B = (\rho_s - \rho)(1-P) g \times hWL \qquad (2)$$

where the first factor gives the immersed weight of per unit volume of the sediment (ρ_s = density of sediment, ρ= density of water; P = porosity; g = acceleration due to gravity), and the second factor is the volume of a rectangular barrier, in which L = average width of the subaerial barrier from ocean to lagoon. The notation L for width across the barrier corresponds to the common notation of length of a coastal inlet, and W for length of the barrier where breaching is expected corresponds to the width of an inlet.

If it is assumed that the lagoon will breach if the force of the water reaches some percent κ of the resisting weight, the critical condition for breaching becomes:

$$F_W \geq \kappa F_B \qquad (3)$$

This inequality leads to:

$$h/L \geq 2\kappa(1-P)(\rho_S/\rho - 1) \qquad (4)$$

For quartz sand, the product multiplying 2k is approximately unity, giving:

$$h/L \geq 2\kappa \qquad (5)$$

The quantity h/L is called the hydraulic gradient, and it is well known to geotechnical engineers who deal with ground water seepage and earth dam failure. Equation 5 does not imply that barriers must necessarily breach because of seepage; rather, it is intended only to identify the main controlling variables. The barrier beaches along the coast of California, especially northern California, can have substantial variations in grain size consisting of silt, sand, and gravel, including sediment with heavy elements such as magnesium and iron. Thus, the sediment grain size and its porosity and average density may vary from that of uniform quartz sand. Inclusion of this possible variation was beyond information available for this initial study. Breaching of New River Spit, Oregon, is a candidate site for investigation of grain size and breaching (Komar *et al.* 2001).

In summary, susceptibility of breaching from the lagoon side is expected to be related to the ratio formed as the water-head difference divided by the width of the barrier beach. This intuitive observation indicates that a barrier beach will tend to breach at its narrowest extent, which is commonly observed. The head difference represents the destructive force promoting breaching, and the barrier width represents the constructive force resisting breaching. Elevation of the barrier does not enter, because the water-head difference is the related active variable. Breaching from the lagoon side will likely occur at the lowest portion of the barrier beach, for which overland flow would take place first. In summary, for barrier beaches that tend to breach from the lagoon side, there is a critical value of the beach susceptibility index at which they are more prone to breach than for smaller values.

This breach susceptibility index differs from the one introduced by Kraus *et al.* (2002) for predicting breaching from the seaward side. That susceptibility index is related to the ratio of storm surge elevation representing the destructive force and tide range representing the constructive force (and related to elevation of the barrier beach).

The susceptibility index for breaching from the lagoon side is next examined through five case studies that mainly rely on information from the literature and analysis of aerial photographs. Often, these barrier beaches are breached manually to avoid flooding, and it is assumed that such breaches are initiated with approach to maximum possible water level to alleviate flooding around the lagoon perimeter.

Lake Earl

The Lake Earl and Lake Tolowa lagoon complex, referred to collectively as Lake Earl, is located 11 km north of Crescent City in Del Norte County, in the Smith River Plain (Figures 3 and 4 [above]). Water quality and lagoon elevation rely on breaching of the barrier beach. Inflows of water into this lagoon system include direct precipitation onto the lagoon and surface runoff from surrounding areas (80%), and groundwater seepage (20%), in addition to tidal inflow when the barrier beach is breached (Anderson and Schlosstein 2003). Water is lost from the lagoon through breaching that typically occurs during late fall and winter. Evapotranspiration and groundwater seepage lower the water level in the summer. Annually, Lake Earl cycles through three phases as a function of rainfall and manual breaching as generalized by Lowe (2003) for the 16 years from 1987-2003. From October to mid-December, the lagoon initially fills with water. Manual breaching of the lagoon may occur sometime from late autumn to February, depending on water level, to prevent overfilling and flooding of surrounding low-lying areas. The threat of flooding is associated with a lagoon level of approximately 3 m above MSL. Water level in the lagoon drops to less than 1 m within two days after breaching (TetraTech 1999). From March to September the lagoon slowly refills, while losing some water through evaporation.

Natural breaching at Lake Earl occurs during periods of high lagoon level, and it does not necessarily take place every year. Based upon estimates found in the literature and modeling of rainfall, groundwater, and surface runoff in the area, Anderson and Schlosstein (2003) estimated that if Lake Earl is not manually breached, it is likely to breach naturally when the lagoon elevation reaches 3.7-4.3 m MSL. Records at a water level gauge made available to us by the Del Norte County Engineer's Office indicate that the lagoon breached naturally at 3.1 m on 11 May 2005 and at 2.9 m on 4 May 2006. Once breaching is initiated, the lagoon surface drops to the same elevation regardless of the initial elevation (Lowe 2003). Typically, the later in the year the lagoon is breached, the longer it will take to close because of reduced seasonal wave activity.

Lagoon elevations and barrier beach widths were assembled for breaching occurrences from 1987 to present to estimate the breach susceptibility index for Lake Earl (Lowe 2003; Anderson and Schlosstein 2003). The head difference between the lagoon and MSL was 3 m, with an average barrier beach width of between 60 and 120 m (Table 1). Thus, the breach susceptibility index for Lake Earl is 3-5 percent (κ values of half these), depending on the combination of parameters. Larger values indicate a greater incidence of breaching. A narrower beach and greater head difference produce a larger susceptibility index or possibility of a breach occurring. Figure 4 (below) is a picture of the barrier beach just before it was mechanically breached in December 2005. At that time the water level in the lagoon was 2.6 m MSL.

Redwood Creek Estuary

Redwood Creek Estuary is located in Orick, about 5 km north of Stone Lagoon (discussed below) in Humboldt County, and about 55 km north of Eureka (Figures 3 and 5). The mouth of Redwood Creek River is open to the Pacific Ocean most of the year, allowing sea water to be exchanged with the estuary. At the end of summer, when precipitation is infrequent, the river flow and tidal prism are not sufficient to maintain the inlet. As a result, a barrier beach forms at the mouth of the inlet, sealing the estuary from the ocean.

Most of the lower portion of the Redwood Creek basin, including the barrier beach, is located within Redwood National and State Parks. Land to the north and south of the estuary is privately owned. When Redwood Creek Estuary is closed and the water level rises at the beginning of the fall season, privately owned lands are flooded. Staff of the Redwood National and State Parks prefers that breaching of the barrier beach occur naturally, to avoid premature flushing of juvenile Chinook salmon into the ocean (Ziemer 1994). Little information on the water level and width of the barrier beach at the time of breaching is available. Staff of Redwood National Park provided pictures taken before and after the 2005 and 2007 breaches which, together with aerial photographs were examined to estimate the width of the barrier. In 2005, the water level gauge installed at the end of the south levee recorded a level of 3.1 m MSL at the time of the breach. The width of the barrier is estimated to be approximately 25 to 40 m. Evidence found on site shortly after the 2005 breach suggested that the barrier was manually breached (Anderson, 2006). However, the 2007 breach is believed to have occurred naturally and at similar water level and barrier beach width to the 2005 breach. The susceptibility index for the natural breaching of Redwood Creek barrier beach is estimated to be 8-12 percent.

Figure 5 (below) is a photograph taken three weeks before the 2005 breach when the water level in the lagoon was 2.7 m. The picture shows the swash of the waves during high surf over the lower portion of the barrier beach and sand on the surface of the barrier being wetted by groundwater probably seeping from the lagoon to the ocean. Barrier beaches might be lowered by seepage, initiating overflow from the lagoon to the ocean.

Stone Lagoon

Stone Lagoon is one of four lagoons of Humboldt Lagoons State Park and is located 50 km north of Eureka (Figures 3 and 6). This stretch of northern coastal California is characterized by steep, rocky headlands punctuated by pocket beaches and lagoons backed by mountain slopes and meadows. A straight, predominantly uniform-width barrier beach stretches between headlands separating Stone Lagoon from the Pacific Ocean. Stone Lagoon, fed by small streams, usually breaches from October to April, during or near the end of the rainy season (Joseph 1958). Although natural breaching of Stone Lagoon is initiated by a large water-head difference between the lagoon waters and the ocean, once the barrier is breached, the water level in the lagoon reaches near equality with sea level within a day or so.

Breaching of Stone Lagoon occurs every several years (Kraus *et al.* 2002). Markle (1996) recorded breaches occurring from March 18 to May 19, 1989, and from 26 February 1993 to early May 1993, in addition to a manual breach on June 13, 1993 and a brief breach on 31 May 1987. Kraus *et al.* (2002) document a breach on the southern side of Stone Lagoon that opened sometime between 13 March and 15 March 2002.

These breaches form at the southern end of the barrier beach, just north of a group of rocks offshore that might act as a porous groin in limiting longshore sediment transport in their vicinity. Stone Lagoon continues to breach at the same general location, the southern end of the barrier beach. Prior to these natural breaches, the water-head difference between the lagoon elevation and MSL in the Pacific Ocean is typically 3-4 m with a barrier width of 30-50 m on average, giving a breach susceptibility index of 8-13 percent.

Russian River Estuary

The Russian River Estuary (Figures 3 and 7) is located approximately 95 km northwest of San Francisco in Sonoma County. Near the mouth of the Russian River, the coast is punctuated by small pocket beaches separating steep, rocky cliffs. For portions of the year, the mouth of the river is functionally closed by a barrier beach because the tidal prism coupled with the stream flow are insufficient to keep the inlet open year round (Rice 1974). The Russian River Estuary and watershed are designated as critical habitat for threatened stocks of salmon and steelhead. The estuary must be maintained for fish production and passage as well as for flood control, channel maintenance, water storage, and hydroelectric power generation. Development of a management plan that satisfies all of these needs is difficult. To date, there is no regular pattern of barrier beach closing and breaching; however, under recent flow conditions, the barrier beach must be manually breached several times in the fall. The Russian River Estuary typically remains open naturally in the winter and spring, and oftentimes remains open until the early summer (Entrix Inc. 2001).

The primary action in the management of this estuary is manual breaching of the barrier beach that forms across the mouth of the estuary. The mouth of the Russian River is managed as an estuary (defined as the beach-open condition) rather than a lagoon (beach-closed condition), thus limiting the bar-closed episodes to 7-10 days (Entrix Inc. 2001). In addition, the water level in the estuary is kept below 2 m. The short duration of barrier closure promotes water quality yet decreases flooding hazards that develop in the beach-closed condition (Entrix Inc. 2001; Merritt Smith Consulting 1998, 1999, 2000). By analyzing aerial photography found in Goodwin and Cuffe (1994) to estimate barrier beach width during breaching and lagoon elevations at the time of manual breaches, a susceptibility index for this estuary was found to be between 3% and 5%.

Carmel River Lagoon

Carmel River Lagoon (Figure 3 and Figure 8) is located about 200 km south of San Francisco. It and the adjacent approximately 2-km-long barrier beach called Carmel River State Beach are popular recreational sites just south of Monterey Bay. Unconsolidated bluffs topped with expensive residences and a portion of Scenic Drive bound the northern end of the barrier beach. Carmel Lagoon provides habitat for multiple threatened and protected species including the California red-legged frog and a distinct population of steelhead. This area also lies within the boundaries of the Monterey Bay National Marine Sanctuary and is designated an Area of Special Biological Significance by the state of California.

The barrier beach fronting Carmel River Lagoon has been routinely breached to drain the lagoon since the early 20th century (Carmel River Technical Advisory Committee 2007). Lagoon elevation must be manipulated by manual breaching in the winter months when it approaches 3 m to prevent flooding of homes built in the lowlands surrounding the lagoon as well as the parking lot for Carmel River State Beach. If the beach were allowed to breach naturally, residential neighborhoods north of the lagoon would be inundated. After the beach is breached around its midsection, the rapid outflow from the lagoon incises a wide, nearly straight channel in the beach. The breach allows the lagoon to drain to a level that significantly reduces and, in some cases, eliminates habitat for steelhead and other aquatic species.

In addition, because of an increase in water demand on the Carmel River with the growing population on Monterey Peninsula, less water is reaching the lagoon than in the past. Low lagoon elevation is altering water quality and is a concern for threatened species in the lagoon. Manual breaching has recently come under scrutiny because of its consequences for aquatic life. Government agencies in the area are attempting to develop a management strategy for breaching that will prevent flooding of low-lying houses and protect the roads from being undercut by bluff erosion, while maintaining enough water in the lagoon for the aquatic species to survive and thrive (Carmel River Technical Advisory Committee 2007).

Carmel River State Beach varies in width seasonally. The beach is constrained on the north and south ends by underlying granodiorite outcrops separated by approximately 180 m of fine to coarse sand. Generally, the northern end of the beach is wider (~75 m) than the southern end (~30 m; Carmel River Technical Advisory Committee 2007). In 2005, a winter breach was manually manipulated at the northern end of the beach to prevent the deep channel that forms when breached in the midsection of the beach. This breach location slowed the draining of the lagoon. It maintained higher water level and was considered successful in terms of the aquatic species. However, meanders developed in the outflow channel, which ultimately undercut the bluffs and threatened the bluff-top houses and road, eroding the parking lot. Since that erosion occurrence, manual beaching has avoided the north end of the beach, and breaches have been cut through the southern end. With the underlying bedrock shelf on this end as well, the lagoon has been successfully breached while maintaining sufficient water for the aquatic species to thrive, yet preventing flooding of the low-lying houses and protecting the bluffs.

In the present study, beach width and lagoon elevation at the times of breaching were estimated from aerial photographs to determine the breach susceptibility index for the Carmel River Lagoon. An average water-head difference between the lagoon and MSL was found to be 3 m with an associated beach width of between 30 m and 75 m at the time of breaching. The beach width varied greatly depending on where the lagoon breached and the resulting meanders in the outlet channel. The breach susceptibility index for Carmel River Lagoon was found to be between 5% and 10%. Once again, the susceptibility index is greater with a larger water-head difference between the ocean and the lagoon and a narrower beach width.

CONCLUDING DISCUSSION

In northern California, natural breaching of barrier beaches differs from that on the Atlantic and Gulf coasts of the United States in that it tends to occur from the lagoon side rather than from the sea. A susceptibility index was introduced to estimate this tendency. Barrier beaches along the coast of northern California typically breach by a gradual rise in lagoon water surface, which increases the water-head difference between the lagoon and the ocean. The lagoons then breach by overflow at their narrowest section, perhaps promoted by weakening through seepage, which could create a local elevation low in the barrier beach.

The breach susceptibility index *h*/*L* is the ratio of the water-head difference between the lagoon and ocean divided by the width of the barrier beach, commonly called the hydraulic gradient. The head difference *h* represents the destructive force promoting breaching, and the barrier width *L* represents the constructive force resisting breaching. A barrier beach will tend to breach at its narrowest extent. This breaching susceptibility index differs from the one introduced by Kraus *et al.* (2002) for predicting susceptibility of breaching from the seaward side. That index is formed as the ratio of storm surge elevation representing the destructive force and tide range representing the constructive force (and related to elevation of the barrier beach).

In summary, for wide barriers that tend to breach from the lagoon side, such as those in northern California, there is a critical value for the beach susceptibility index *h*/*L* of about 5%-10% at which barrier beaches are prone to breach. The five studied lagoons tend to breach at a water-head difference of about 3 m relative to local MSL in the Pacific Ocean. This result cannot be taken as general, however, because it likely relates to the northern California wave and littoral regime, tide range, and sediment supplies responsible for building the barrier beaches. Also, critical values of the breach susceptibility index found here are underestimates, in that much of the data concerns manual breaches likely done slightly before the water level in the lagoons reaches a level to cause overflow, increased seepage, and natural breaching. Much could be learned about barrier breaching from the lagoon side through site-specific monitoring.

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